



Cost effective second generation AC-modules: Development and testing aspects

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Abstract

In the framework of the European research project PV2GO, a new AC-module inverter was developed, taking into account all relevant aspects from a European market's point of view (standards, market, application, and research and development goals). The project goal was to achieve the overall system costs of 3 Euro per Wp for a modular plug-and-play photovoltaic system. For the photovoltaic-module, a standard 130-Wp Eurosolare module was chosen. The research and development (R&D) goal was to develop an advanced DC-control system consisting of a state-of-the-art programmable digital device and an Application Specific Integrated Circuit (ASIC) for the AC-control of the inverter. According to the topology concept, thermal and magnetic designs were optimized with regard to production technology and packaging for large-scale production. The new AC-modules were tested in a number of field-test sites in various parts of Europe and their reliability was assessed through Highly Accelerated Stress Tests. Efficiency and power quality have been tested in the laboratory. Further in the PV2GO project an optimization study of the manufacturing process of the new generation of AC-modules for high volume output was done. Another task was the pre-certification procedure to assure compliance with the European guidelines and standards.

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1. Introduction

AC-modules are a modular form of grid-connected photovoltaic systems. They have brought the well-known and highly acclaimed modularity of photovoltaics to the 100 watt-peak level (for grid-connected systems), allowing the installation of literally any size of grid-connected photovoltaic systems at almost the

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Nomenclature

ASIC	application specific integrated circuit
ASIC AASIC	ASIC with linear regulator
ASIC B ASIC	ASIC with switch mode down converter
PWM	pulse width modulator
DSP	digital signal processing
MOSFET	metal oxide semiconductor field-effect transistor
ENS	grid monitoring device as mandatory in Germany
DNO	distribution network operators
BOS	balance of system
MPP	maximum power point
R&D	research and development
STC	standard test conditions—irradiance 1000 W/m ² ; cell temperature 25 °C; spectrum air mass 1.5
S	switch
W _p , kW _p	watt peak, kilowatt peak
P	active power
P_r	rated power
ΔP	active power supplied to the grid before grid disconnection
Q	reactive power
Q_c	reactive power supplied by the resonance circuit's capacitor
Q_L	reactive power supplied by the resonance circuit's inductor
Q_{out}	reactive power output
ΔQ	inductive reactive power supplied to the grid before grid disconnection
Q_r	quality factor
L_d	inductive load
R_d	resistive load
ω_{grid}	grid frequency
ω_{island}	frequency at islanding condition
U_{grid}	grid voltage
U_{island}	voltage at islanding condition
U_{min}	under voltage of relay settings
U_{max}	over voltage of relay settings
f_{min}	lowest frequency of relay settings
f_{max}	highest frequency of relay settings
H_1	irradiation into array plane
G_0	irradiance at STC
Y_r	reference yield (H_1/G_0)—in-plane irradiation normalized on 1000 W/m ²
Y_{rSh}	reference yield after shadowing—in-plane irradiation on the shadowed photovoltaic array normalized on 1000 W/m ²
P_0	nominal photovoltaic array power at STC
E_A	DC energy produced by the array
Y_A	array yield (E_A/P_0)—DC energy generation of the photovoltaic array normalized on rated photovoltaic power at STC
E_{ac}	AC energy injected into grid
Y_f	final yield (E_{ac}/P_0)—AC energy generation of the photovoltaic system normalized on rated photovoltaic power at STC
L_C	capture loss ($Y_r - Y_A$)
L_{CA}	array capture losses ($Y_{rSh} - Y_A$)

L_{CSH}	shadowing losses in irradiation ($Y_r - Y_{rSh}$)
L_S	system loss ($Y_A - Y_f$)—inverter conversion losses (grid-connected system)
PR	performance ratio (Y_f / Y_r)
η_i	long term inverter efficiency (Y_f / Y_A)

same price per watt-peak. This has recently stimulated the creation of new product-market-combinations: 100 to approximately 800 watt-peak systems for direct sale for private marketing.

Because of the small system size the investment is well within reach of many people and the power can be (in the Netherlands: is allowed to be) fed directly into the grid without any additional requirements (“plug and play”). This has opened a new and successful market for grid-connected photovoltaic systems.

Further development of AC-modules (especially the inverter) in terms of performance, reliability, lifetime, size and price is essential to bring the total system price to a level that allows full competition with other sources of electricity. At present, AC-modules are commercially available at system prices ranging from 8 to 14 euro per watt-peak. A further reduction of the price by a factor of 2 is envisaged within the next five years.

As pointed out in the White Paper “Energy for the future” of the European Commission [1], the main target of photovoltaic R&D projects is a profound cost reduction for solar electricity generation down to 3 Euro/Wp on the mid term. To achieve this goal, a new generation of AC-modules needs to be developed, and production volume must be increased to a larger scale.

2. PV2GO project: objectives and strategic aspects

“Production and Verification of the second Generation of AC-Modules (PV2GO)” is a European research project within the fifth framework programme (FP5) of the European Community. In the framework of this research project a new generation of AC-modules is produced and tested in typical European field conditions. The AC-modules are designed for reliable operation during the typical photovoltaic module lifetime of twenty years; the cost of production is strongly reduced in comparison to current technology. This is achieved by reducing the number of components significantly. The efficiency of the photovoltaic module and the inverter allow high-energy yields.

The project consists of four phases: a first demonstration phase enables both end-users and utility companies to gain experience with an AC-module system based on state-of-the-art technology. At the same time, the demonstration systems function as a test case in terms of technical performance and customer expectations of an AC-module. This is used as input for the requirements of the new design.

The second R&D phase focuses on the improvement of the AC-module product in terms of performance, reliability and, especially, cost. Then a second generation of AC-modules is developed and tested in a laboratory environment.

The prototypes of the second generation AC-modules is field tested at a number of test sites in various parts of Europe in the third phase of the project and the reliability of the newly developed product is proven through Highly Accelerated Stress Tests.

The fourth phase is the optimization of the manufacturing process of the new generation of AC-modules for high volume output. Another task in this project is the pre-certification procedure to assure compliance of the newly developed product with the European guidelines and standards.

In the early stage of this project, new control electronics had to be determined within the boundaries of the cost and reliability targets. The requirements for control electronics in an AC-module inverter are demanding. In general, the pulse width modulator (PWM) of a converter is constructed by a specific integrated circuit. Although this circuit is a commercial of the shelf available, a separated integrated circuit for this function had to be avoided to be able to achieve the cost reduction targets.

The integration of functionality into Systems-On-Chip (SOC) is a recent trend that tends to become more and more attractive and feasible in both industrial and domestic products. Examples are the new high-speed Digital Signal Processor (DSP) range of Texas Instruments and Analog Devices. Companies like Atmel recently developed a platform on which micro processors and Field Programmable Gate Array’s (FPGA) functionality can be combined.

For PV2GO, the plan of implementing all regulation, modulation and communication functions into a DSP is being studied, but not chosen. Very interesting commercial of the shelf (COTS) control processors became available. New programmable controllers with PWM functions became available too. Although the specifications are good these devices were not selected for costs reasons. The new developments in switch mode technology have brought the decision to combine a fly back topology with a low cost general-purpose programmable controller for optimal cost price and lifetime expectancy.

Beside the study on new control electronics in the first year of this project, the following additional minor targets can be mentioned:

- The investigation of impact of different environments (within European continent) on lifetime of AC-modules.
- Different design variations of one basic design on reliability and costs (use same power electronics or topology with different packaging and control methods).
- Attitudes and behaviour of consumer buying AC-modules.
- Determine impact on society (by assessing/measuring the power supply quality and/ or social study).

It has been shown that there are several different potential markets with accompanying requirements for AC-modules:

- Utilities committed themselves to sell a minimum percentage of renewable energy.
- Private house owners: in the Netherlands this market segment is seen as the opening to the citizen. By means of several national initiatives and government subsidies (40%) people are encouraged to invest 2250 Euro for 4 AC-modules of 100 Wp (costs include installation).
- Office buildings of companies and institutes: more and more companies and institutes work on their environmental friendly image. AC-modules are easy and creatively to integrate in facades and works of art.

To further develop the market, the following aspects are important:

- Costs: the market will be further developed if the costs decrease. It is important to notice that the system costs contain a substantial part for the installation of the AC-module (AC-wiring, on the roof) and the mounting of the inverter to the module.
- Functionality: monitoring the functioning and yield of the system has shown very important. New technologies, especially wire-less communication between a personal computer and the inverter make low-cost (both component and system installation) possible. These developments make monitoring as a standard possible and give the product a high-tech image for private users.
- The main objectives of the PV2GO project are:
- Proof of cost reduction in photovoltaic systems in mass production.
- Increase of reliability of grid connected photovoltaic systems based on AC-modules.

3. AC-module: plug and play type

AC-module is an electrical product and is a combination of a single module and a single power electronic inverter that converts light into AC power when it is connected in parallel to the network. The inverter is mounted on the rear side of the module or is mounted on the support structure and connected to the module with a single point to point DC-cable. Protection functions for the AC side (e.g. voltage and frequency) are integrated in the electronic control of the inverter.

The main advantage of AC-modules is the modularity. Complicated DC wiring is not required and the solar power is directly available as AC-power. This modularity allows for very simple systems that can be easily expanded by simply paralleling AC-modules at the AC side.

AC-modules have recently been introduced as a commercial product, application can be found in a limited number of countries. It is expected that AC-modules will become available at the hardware store and that

people will buy and install them without consulting a certified electrical engineer and thus the number of users will grow dramatically in the next few years.

3.1. Advantages and disadvantages of AC-modules

For photovoltaic systems from 100 to 800 W_p, AC-modules are currently regarded as one of the most optimal system solutions for end-user applications. There are no DC interconnections between modules at all. DC cabling and DC marshalling boxes are not required as the DC wire is integrated in the AC-modules. This leads to several distinct advantages, like

- Low purchase investment and modular extendibility based on 100–150 W_p units.
- Plug and play concept allowing easy and cheap installation (up to 2.25 Ampere, local power generation is allowed in the Netherlands).
- Higher energy yield due to MPPT per a small number of cells (typically 36 or 72 cells).
- Because people can install the photovoltaic system by themselves AC-module are ideal for end-user applications. Besides that the BOS costs are low due to the plug and play characteristics.
- DC wiring expertise is not necessary for installation.
- DC safety equipment, switches, fuses, conductors etc. are not needed, leading to reduced expense and simplified installation and design.

An AC-module is an electrical product and is fully assembled in the factory. The electrical connection to the network is simple by means of a 2-wire connection. Additional AC-modules can easily be added to the system and connected in parallel without concerns about module orientation and size. It can be standardized and thus mass-produced, meaning that economies of scale will reduce their cost.

AC arrays have less susceptibility to damage from nearby lightning strikes. Electromagnetic induction from lightning strikes near a DC array can have serious effects on the photovoltaic system. AC arrays reduce induced voltage problem by reducing the area of the conductor loop, again by eliminating series connections of the modules on the DC side.

There are also some significant disadvantages to AC-modules:

- Since the inverters are mounted directly on the backs of photovoltaic modules, they must operate in a very harsh thermal environment, which shortens component lifetimes.
- Small inverters are less efficient than large ones, which mitigate part of the overall system efficiency gain due to the elimination of mismatch loss.

Probably the biggest concern is that of life cycle cost: these inverters need to be inexpensive enough that we can put one on the back of every photovoltaic module and not increase the cost of photovoltaic power. This is supposed to be reached by the previously mentioned economies of scale.

4. Design of AC-module inverter

This task was carried out by means of a questionnaire that was distributed to the project partners. On the basis of this questionnaire the requirements in the field of marketing, standards, functionality, mass production demands, lifetime and reliability were inventoried. A concept product specification document was set-up which describes an AC-module consisting of an existing 72 cells poly crystalline photovoltaic module of Eurosolare and a new inverter. Concrete project goals, in order of priority are:

- (1) User cost price. System all-in: 3 Euro/W_p (inverter: 0,5 Euro/ W_p, BOS: 0,5 Euro/ W_p, PV-module: 2 Euro/ W_p)
- (2) Reliability (better than the Sunmaster 130S of which several thousands have been produced)
- (3) Efficiency (European efficiency > 90%)
- (4) Functionality (e.g. monitoring options)

A number of research and development goals were identified to increase reliability and reduce costs. To increase the reliability the design focuses on the integration of the functions on application specific integrated chips. Secondly the design implementation is set-up for large-scale production volumes. Chip integration and large-scale production offers cost reduction. To reduce the costs on a fundamental basis, an optimal power electronic concept from an integral design point of view (power conversion, control, thermal design and enclosure) is examined and developed. The project goal for cost reduction is verified by means of a comparison of the new PV2GO inverter with a currently commercially available inverter (the Sunmaster 130S) [2]. To verify the reliability improvement, the inverters are tested according to highly accelerated stress tests and the calculation of the expected failure rate and the comparison with the Sunmaster 103S.

The self-controlled H-concept Bridge is considered as a point of departure due to its simplicity, higher efficiency, low-cost control techniques and matured technology [2]. To further improve this DC-AC converter, the control and the MOSFETS, the goal will be the integration of this converter on a single ASIC, the 'H-bridge ASIC'. This integration step offers the integration of approximately 20 components on one single chip or hybrid circuit.

All intelligence and control functions now depend on the primary DC/DC converter. This converter is based on hard-switching techniques [3]. Two conventional topologies (Push-pull topology with discontinuous secondary current and Fly back topology) are examined thoroughly by means of simulations, prototype development and evaluation. Both topologies are assessed in the field of:

- Utilization of power components, efficiency and costs.
- Easiness of control of the DC/DC converter, applicability for direct ASIC control.
- EMI aspects.
- Applicability for planar magnetic.
- Possibilities for diagnoses, shunt-less operation and frequency shift down algorithm.

As mentioned, all control is done by the primary converter controller. In contrast with the HICAAP project [3], in which an ASIC was used as a substitute for a μ -controller, the goal within PV2GO is firstly to replace the more expensive and complex pulse width modulation controller by an ASIC, and secondly to integrate other analogue functions, which are currently, implement in discrete components, for instance, the DC power supply and the MOSFET gate driving circuit. Initially the μ -controller is maintained, as it needed for flexibility during development.

Sunmaster 130S and the PV2GO inverter were analysed with regard to lifetime and enclosure design. One challenge for the new design was to maintain the environmental condition requirements and integrate a heat sinking and a planar magnetic transformer solution that takes advantage of new available manufacturing processes. An improved heat sinking solution may increase long-term reliability. Key aspects for the enclosure design considered are:

- Easy assembly for manufacturing.
- Fast and reliable module mounting construction.
- Optimal DC and AC wiring.
- IP65 water resistant.

Figs. 1(a) and (b) show the prototype of the PV2GO inverter with and without enclosure.

5. Experimental results and discussion

Besides converting DC to AC current, the PV inverter has the task to guarantee safe and efficient operation, to track the maximum power of the PV array and to maintain good quality of the grid current. In this research work, several tests have been carried out on the PV2GO inverter and the results of the tests are included in this chapter. The purpose of the tests is to determine the main electrical characteristics of the inverter when the inverter is applied in a grid connected PV-system.

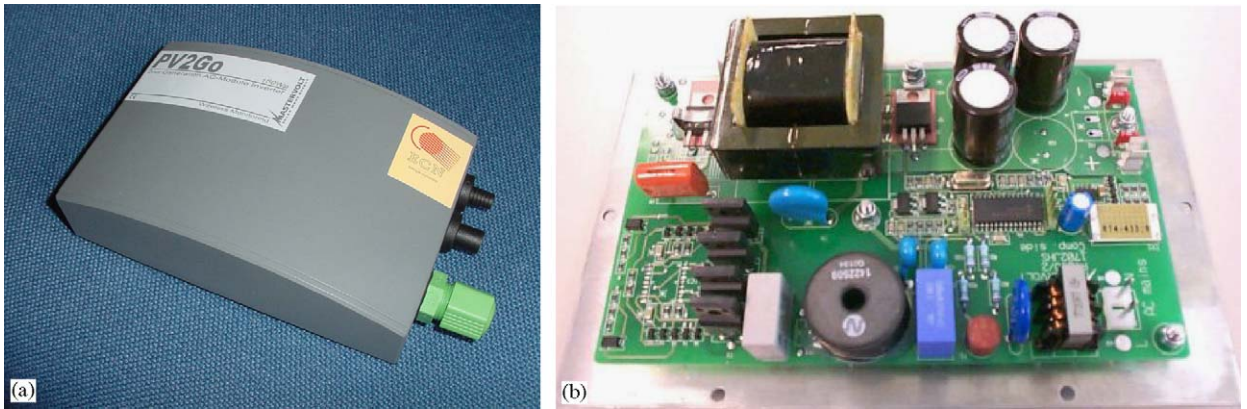


Fig. 1. (a) The second prototype of the PV2GO inverter. (b) The second prototype of the PV2GO inverter without enclosure.

The tests are divided into functional tests under laboratory conditions including performance, EMC, grid compatibility, safety and reliability; a MPP tracker test under outdoor conditions and reliability tests in a climatic chamber. Furthermore field tests have been carried out under typical European field conditions.

5.1. Electrical performance and power quality tests under laboratory conditions

5.1.1. Static power and European efficiency

The static power efficiency is the ratio of the active output power to the active input power. In this test, the static power efficiency of the inverter is determined for twenty or more power levels under nominal conditions and the efficiency data is used to calculate the European efficiency, which is a proposed measure for the averaged efficiency in relation to irradiation for the European countries. The European efficiency is calculated with the formula [4].

$$\eta_{EU} = 0.03\eta_{5\%} + 0.06\eta_{10\%} + 0.13\eta_{20\%} + 0.10\eta_{30\%} + 0.48\eta_{50\%} + 0.20\eta_{100\%}. \quad (1)$$

The index percentage of the efficiency is the load percentage of the rated power. The calculated European efficiency for the PV2GO inverter is $\eta_{EU} = 92.2\%$ at $U_{dc,nom}$.

5.1.2. Static and dynamic energy efficiency

The static and dynamic efficiency is the part of the inverter's specification and is measured in compliance with the procedure for grid-connected inverters described in IEC 61683 [5].

The energy efficiency is the ratio of the output energy to the input energy. Static energy efficiency is measured for three array configurations (minimum, nominal and the maximum inverters input voltages) and five power amplitudes (10%, 25%, 50%, 75% and 100% of P_{rated}). Additionally to the static energy efficiency, the dynamic energy efficiency is measured at an averaged available power equal to the inverter's rated output power.

The averaging period of the tests per power amplitude value is 3 min. Due to this integration time these tests take into account the tracking behaviour of the inverter.

Figs. 2(a) and (b) show the static and dynamic energy efficiency of the module inverter.

5.1.3. Static and dynamic MPP efficiency

The maximum power point efficiency is a measure for the inverter's ability to operate the PV-array in its maximum power point. The MPP efficiency includes deviations from the MPP due to the non-ideal behaviour of the tracking algorithm and due to the 100 Hz ripple in the DC power in case of a single-phase electric system.

The static MPP efficiency is the ratio of the absorbed DC energy to the maximum available input energy. At ten different power amplitudes and for the nominal array condition, the static MPP efficiency is measured over

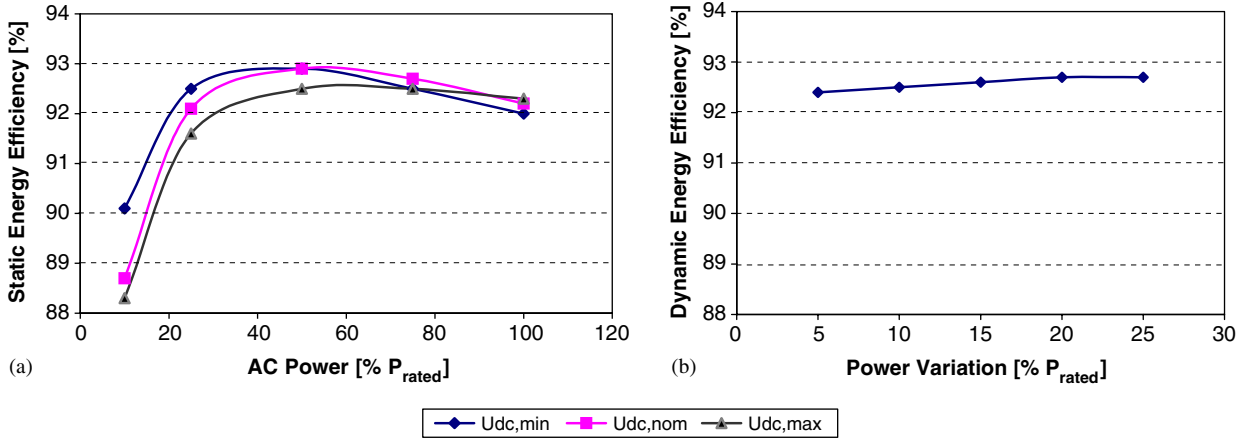


Fig. 2. (a) Static energy efficiency versus AC power. (b) Dynamic energy efficiency versus $P_{variation}$.

a period of 60 s. The maximum available input energy is a value of the solar simulator, no ripple or tracking algorithm influences this value. Therefore instead of the maximum available energy the maximum available power is used.

The dynamic MPP efficiency is the ratio of the absorbed DC energy to the maximum available input energy during each averaging period. Additionally to the static MPP Efficiency the dynamic MPP efficiency is measured at an averaged power equal to 50% of the rated power of the inverter. This averaged available power has a square-wave shaped modulation with a duty cycle of 50%. At four different modulation frequencies (0.25, 0.50, 0.75 and 1.00 Hz) the MPP efficiency is measured for six different modulation depths, variations from 0% to 25%. The averaging period of the test per modulation is 120 s.

Two maximum power points are determined: one MPP for the minimum value of the modulation and one MPP for the maximum value of the modulation. As the duty cycle of the modulation is $\delta = 50\%$ the average value of the minimum and maximum is the effective maximum power point. Figs. 3(a) and 3(b) show the static and dynamic MPP efficiency.

5.1.4. MPP tracking range

The MPP tracking range at $P_{ac} = 100\%$ of P_{rated} is determined as the voltage range at which the MPP efficiency is higher than 0.95 times the static MPP efficiency at 100% P_{rated} of the test Static MPP Efficiency. The MPP tracking range is measured in 25 quasi-static steps of U_{dc} -values from 0 V to the maximum voltage level given in the inverter's specification. No data is available for voltages below 26 volt because the inverter switched off as a result of the minimum input voltage. Fig. 4 shows the diagram of the tracking range.

5.1.5. Power factor

The power factor is measured for twenty different power amplitudes. The available power values are 0–100% in steps of 5% of the inverter's rated power. The power factor is expected to be higher than 0.9 for power amplitudes higher than 25% of P_{rated} . Fig. 5 shows the comparison of measured power factor with that of different DNO guidelines.

5.1.6. Harmonics

For acquisition of the measurements an average of 64 samples has been chosen in order to filter the low-frequency fluctuations introduced by the MPP tracker. The results are shown in Figs. 6(a) and 6(b).

Current harmonics at 10 and 30% of rated power are not limited by standards. However, the current harmonics at these levels are normalized to the current fundamental of the full system output. Comparing them to the limits from IEEE 929:2000 [6] and IEC 61727 [7] that have to be applied for 100% of rated power, shows that results are well within the limits. Harmonic spectra of inverter output currents at 10% and 30% as

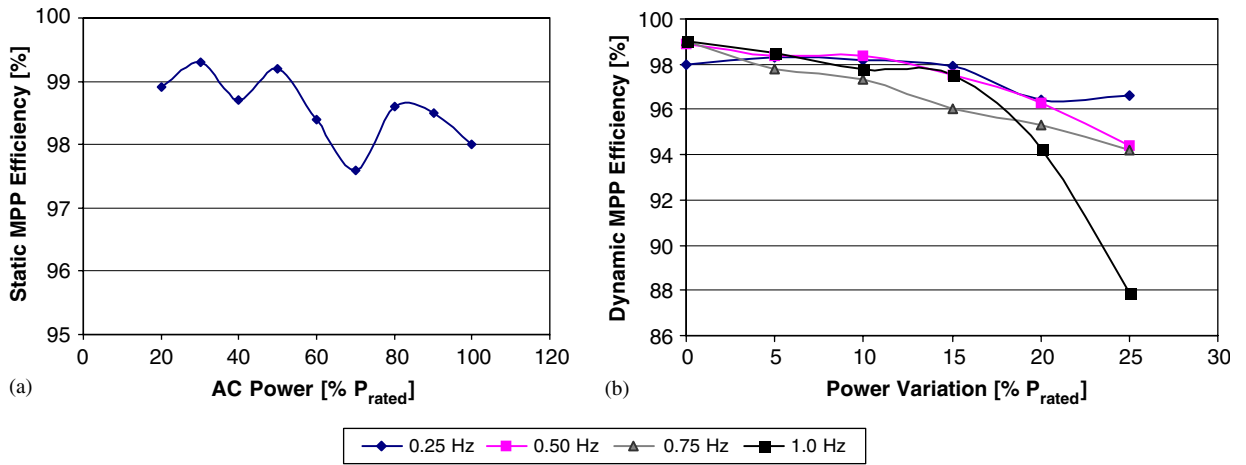


Fig. 3. (a) Static MPP efficiency versus AC power. (b) Dynamic MPP efficiency versus power variation (2 min data).

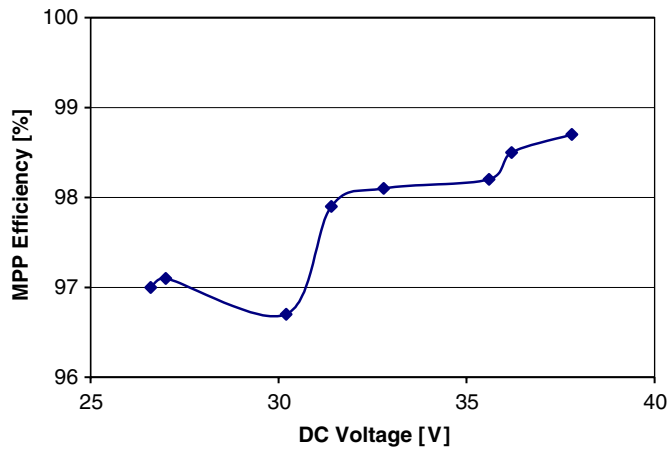


Fig. 4. Static MPP efficiency versus input voltage.

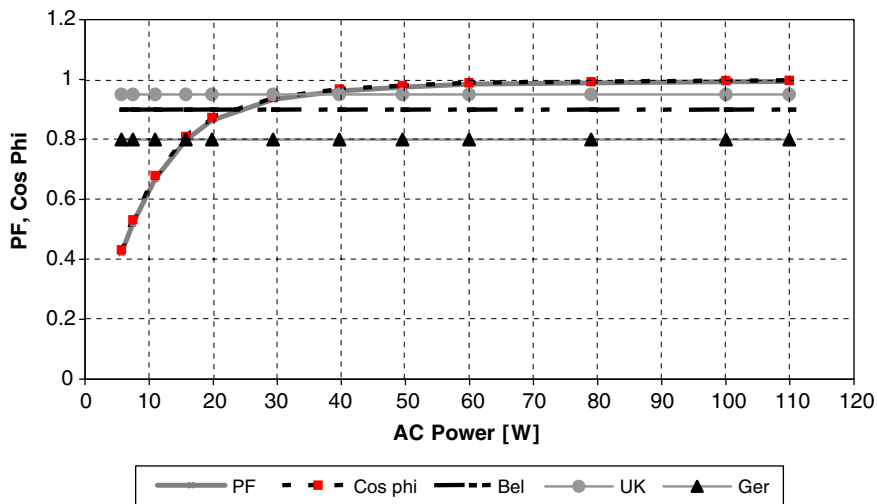


Fig. 5. Cos ϕ and power factor as a function of AC power and limits from different DNO guidelines.

well as 100% of rated power normalized on current fundamental of AC power are also compared to the limit values according to [6] and [7].

5.1.7. Summary of the electrical characteristics

The main electrical characteristics of the PV2GO module inverter are shown in the Table 1.

5.2. MPPT performance outdoors test

In addition to checking the MPP tracker performance indoors, outdoor measurements are useful. Outdoor measurements have the advantage that the actual maximum power point tracker behaviour can be observed with a real PV array, so that potentially unrealistic interactions between MPP tracker and solar simulator can be avoided. The test set-up for the monitoring of the MPPT performance for outdoor test is shown in Fig. 7.

The PV2GO inverter was connected to solar array and at irradiance levels of 300 W/m^2 , 605 W/m^2 and 915 W/m^2 data were acquired of U_{dc} , I_{dc} , P_{dc} and G_i with a sample rate of 1 kHz and tracking behaviour have been analyzed. The tracking behaviours of the inverter at 915 W/m^2 are shown in Figs. 8(a)–8(c). Fig. 8(a) shows the irradiance G_i and the DC power P_{dc} versus time. This plot gives information about the power deviation as a result of the search algorithm of the MPP tracker. Fig. 8(b) shows the DC voltage versus time. In the voltage swing a 100 Hz ripple can be seen, which is a result of the 50 Hz grid frequency. Fig. 8(c) shows the DC power P_{dc} versus the DC Voltage U_{dc} . This plot is a part of the IV curve of the PV array and shows if the MPP tracker finds the Maximum Power Point. No abnormal situations are found during the analysis of the measuring data.

5.3. Electromagnetic compatibility

For CE certification electromagnetic compatibility (EMC) tests are prescribed. In the EMC test the repercussions of the inverter to the grid and the surrounding area are measured. The inverter must keep the legal limits that are specified in the standards. Disturbances of the grid and the surrounding area must not lead to malfunctioning or destruction of the inverter. The immunity tests are also prescribed in the standards. The compliance was tested in the laboratory conditions.

Electromagnetic emission caused by the inverter may not violate the limit values that are fixed in European standards. In a detail EMC test the measurements were carried out for the conducted emission AC and DC sides, radiated emission, total harmonic distortion and flicker in accordance with the European standards EN 55014 [8], EN 55022 [9], EN 61000-3-2 [10], and EN 61000-3-3 [11] respectively.

Electromagnetic immunity of the module inverter has been tested by investigating the electrostatic discharge, radiated immunity, electric fast transient, impulse voltage, conducted immunity and voltage dips in accordance with the European standards EN 61000-4-2 [12], EN 61000-4-3 [13], EN 61000-4-4 [14], EN 61000-4-5 [15], EN 61000-4-6 [16] and EN 61000-4-11 [17] respectively. Tests results are summarized in Table 2.

The limit values for the emissions are partly crossed. For fulfilling the limit values of the conducted emissions, a modification of the EMC filters will be necessary.

The measurement of the radiated emission in the GTEM cell shows a slight overstepping of the limit values. The results of the GTEM cell may have a measurement uncertainty. In this case a free field test is recommended.

The inverter passed the immunity tests perfectly. During the EMC test no disturbances of the inverter was noticed.

5.4. Islanding

‘Islanding’ can be defined as the continued operation of a distributed generation unit while the grid is tripped due to fault conditions or for maintenance purposes. The grid section including the distributed generation unit in islanding is referred to as a power island. Similar definitions can be found in the literature [18–21].

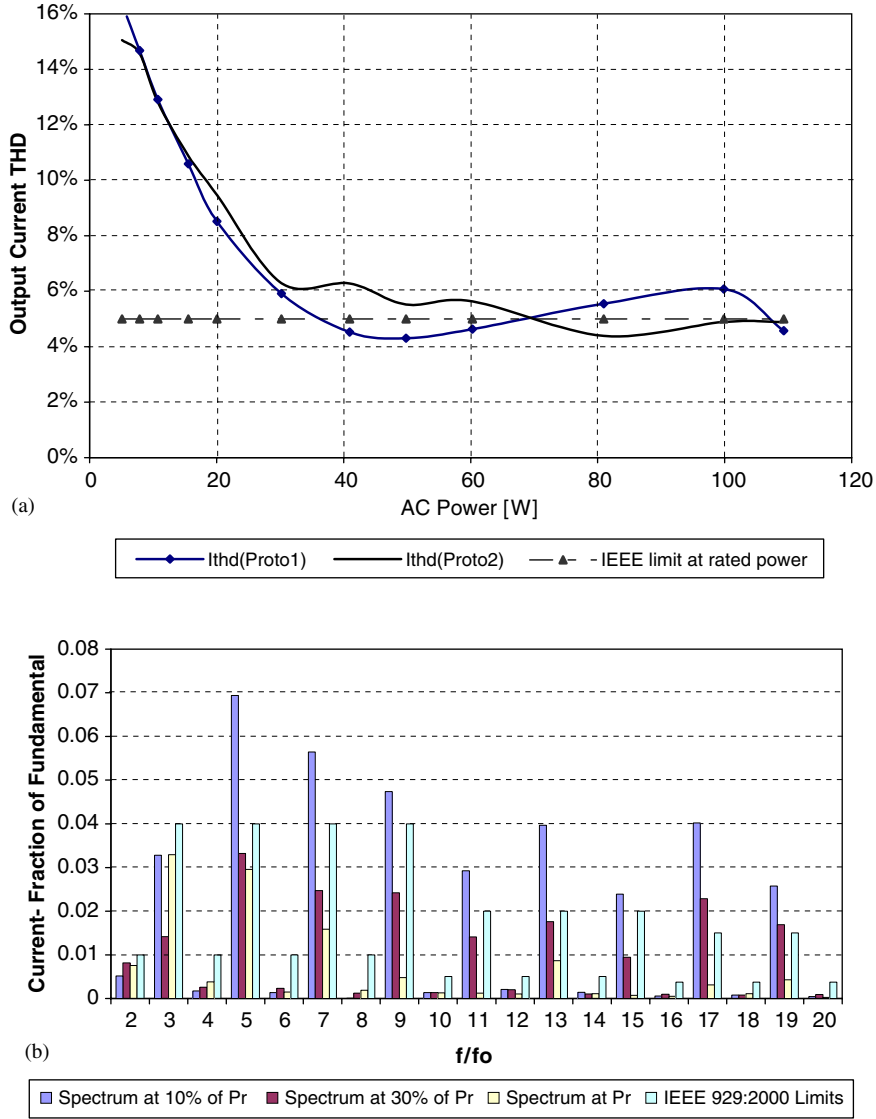


Fig. 6. (a) Current THD as a function of AC power and limit value according to IEEE 929:2000. (b). Harmonic spectrum of inverter output currents, normalized on current fundamental of AC power and limit values according to IEEE 929:2000; $I_1(10\%) = 70 \text{ mA}$, $I_1(30\%) = 178 \text{ mA}$, $I_1(100\%) = 435 \text{ mA}$.

In principle, every self-commutated inverter is able to operate in islanding mode [23]. If no particular control algorithm for islanding prevention is applied, the load conditions under which islanding occurs depend only on the inverter's frequency and voltage limits. Assuming constant active and reactive output power before and after grid disconnection, the power balance leads to voltage and frequency in islanding operation is implied by the following equations.

$$\frac{\Delta P}{P} = 1 - \frac{U_{\text{grid}}^2}{U_{\text{island}}^2}, \quad (2)$$

$$\frac{\omega_{\text{island}}}{\omega_{\text{grid}}} \frac{\Delta P}{P} - \frac{\Delta Q}{Q} = \left(\frac{\omega_{\text{island}}^2}{\omega_{\text{grid}}^2} - 1 \right) \frac{Q_c}{Q} + \frac{\omega_{\text{island}}}{\omega_{\text{grid}}} - 1. \quad (3)$$

Table 1

The main electrical characteristics of the inverter (measured)

Power efficiency at 100% P_{rated}	92.5%
Maximum measured power efficiency	93.1%
European efficiency	92.2%
Stand-by losses at night	0.16 W and 12 VA
MPP efficiency above 10% P_{rated}	>98%
Maximum measured MPP efficiency	99.3%
MPP tracking range	26.6–37.8 V _{mpp}
Power factor	>0.9
Harmonics and THD	Within the limit of IEEE 929:2000

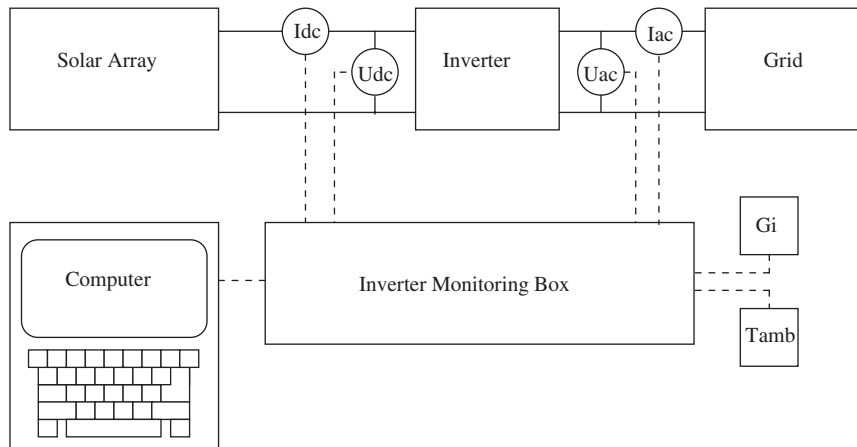


Fig. 7. MPP tracker test set-up.

In these equations P and Q indicate the inverter's operating point. Q_C is the reactive power supplied by the resonance circuit's capacitor. ΔP and ΔQ are active and inductive reactive power supplied to the grid before grid disconnection. They can be adjusted by tuning the test load. For a given capacitor and inverter power, it is possible to determine a so-called non-detection zone (NDZ) in the ΔP – ΔQ -domain where an inverter with predefined voltage and frequency limits will operate in islanding mode [24]. The NDZ has been recorded for the operating conditions indicated in Table 3.

The NDZs have been recorded at 30% and 100% rated power for different values of Q_C or Q_r by applying the test circuit from Fig. 9. Samples have been taken by stepping through the ΔP – ΔQ -domain in steps of 5% of the inverter's rated power.

As Fig. 10 shows, the sizes of the NDZ generally correspond to the theoretical NDZ, indicating the proper functioning of the inverter power control algorithms and of its frequency and voltage relay settings.

5.5. Reliability tests

5.5.1. Highly accelerated life testing

Highly accelerated life testing (HALT) is used to validate reliability of inverters by uncovering potential design and component weaknesses. The HALT process applies environmental stresses that shift the stress curve toward the strength curve, simulating normal product ageing. The failures that may occur over a longer period in real life are shifted or accelerated to a point where the stress-strength curves overlap. This overlap is an indication of unreliability. So what might have taken months or even years to expose fault become evident in days.

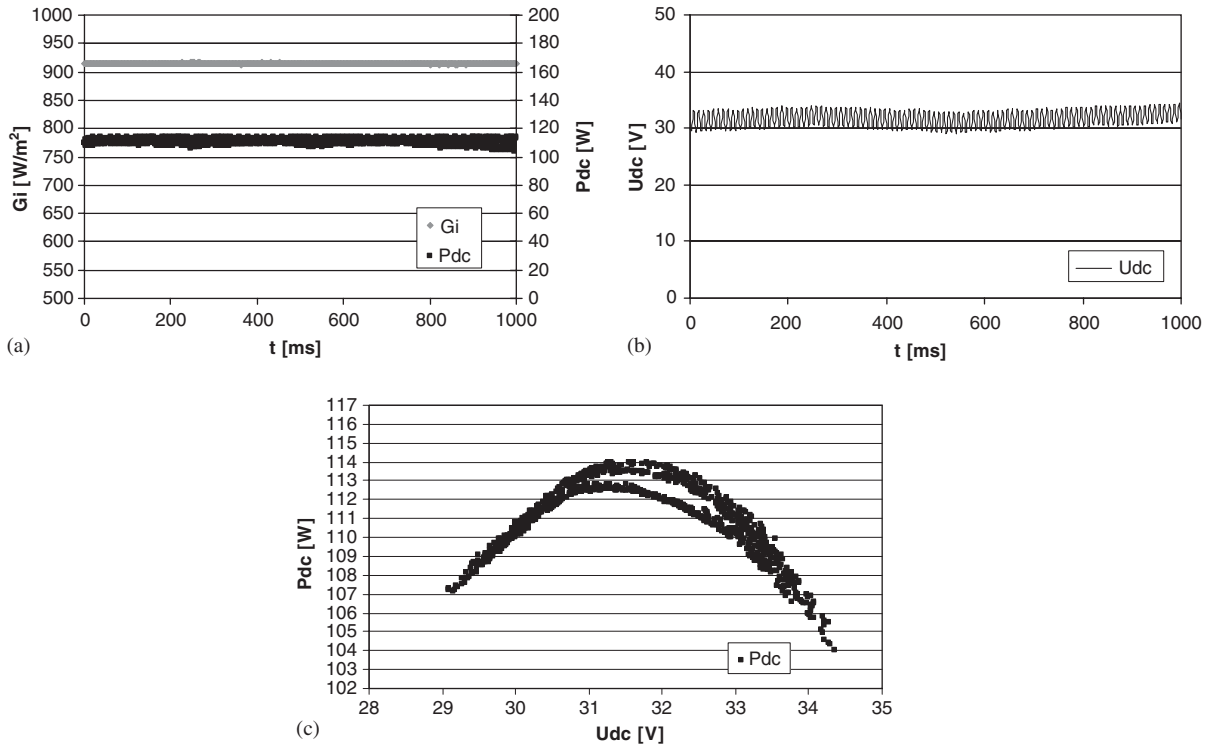


Fig. 8. (a) Global irradiance and DC Power versus time. $G_i = f(t)$ and $P_{dc} = f(t)$. (b) DC voltage versus time at 915 W/m^2 . $U_{dc} = f(t)$. (c) DC power P_{dc} versus the DC Voltage U_{dc} at 915 W/m^2 . $P_{dc} = f(U_{dc})$.

During the testing period, a cold environment is applied first, in 10°C increments, pausing long enough at each set point to stabilize the product, from ambient temperature until -30°C or until failure occurs. Temperatures are cycled from cold to hot 100°C .

If the product fails at low temperature, it should be re-tested after it reaches normal operating temperature. If it fails to restart at this point, it is considered a hard failure and must be corrected. Failed units must be re-tested to determine if the component is at fault or the design itself. Soft failure is a term that refers to faults or failures that seemingly heal themselves. A soft failure is an operating limit and a hard failure is a destructive limit.

5.5.1.1. Test results. The highly accelerated life test have shown that the PV2GO inverter can operate within and beyond the specified temperature of $-20^\circ\text{C} < T_{amb} < 40^\circ\text{C}$. For ambient temperatures higher than 55°C the inverter is progressively deteriorating its power by switching the output power on and off.

Two soft failures were found. First the inverter operates outside the maximum power point at temperatures higher than $T_{amb} = 60^\circ\text{C}$. Secondly at a temperature of $T_{amb} = 120^\circ\text{C}$ the inverter switched off. The inverter did not start its normal operation at lower temperatures. At room temperature the inverter had to be reset by tuning off and on the input voltage and grid voltage. No explanations were found for the two found soft failures.

At temperatures higher than $T_{amb} = 90^\circ\text{C}$ the core of the transformer saturates. This leads to a hard failure. The switching device in series with the primary winding of the transformer became defective twice.

5.5.2. High temperature tests

High temperature tests are done by placing inverters (visually and electrically examined) into a climatic chamber with controlled temperature and relative humidity. No inverters have failed during the complete

Table 2
EMC test results

Tests	Requirements	Results
Emission		
Conducted emission at AC side	EN 55014	Violation of limit value at 17 and 21 MHz ^a
Conducted emission at DC side	EN 55014	Violation of limit value between 500 and 800 kHz and 8 and 17 MHz ^b
Radiated emission	EN 55022	Violation of limit value ^c
Total harmonic distortion	EN 61000-3-2	Passed
Flicker	EN 61000-3-3	Passed
Immunity		
Electrostatic discharge	EN 61000-4-2	Passed
Radiated immunity	EN 61000-4-3	Interruption at 80, 204 and 760 MHz ^d
Electric fast transient	EN 61000-4-4	Passed
Impulse voltage	EN 61000-4-5	Passed
Conducted immunity	EN 61000-4-6	Passed
Voltage dips	EN 61000-4-11	Passed

^aConducted emission caused by the inverter violates the limit value at 17 and 21 MHz. Post measurement with 17 MHz in the quasi peak and average mode, shows the exceeding of the limit values of 5–8 dB μ V. The switching transients of the semiconductors are probably the reasons for the peaks.

^bA violation of the limit values was determined between 500 kHz and 800 kHz, as well as 8 MHz and 17 MHz. But this measurement is not necessary for the CE certification and has a purely informative character.

^cThe radiated emission was measured with a GTEM cell. The result shows the violation of the limit value. In this case a measurement in a free field with a 10 m test side is necessary. Due to unavailability of an open-air test side, a comparative measurement could not be made. If necessary, the reduction of this emission can be difficult. An electrical shield of the board and the components could be expensive. A source of interference is the transformer. A screen winding can reduce the emission. The peak at 433 MHz is due to the radio module because the transmit frequency is 433 MHz.

^dRadiated immunity test could not be carried out with electrical field strength of 3 V/m (for household environment), because the inverter itself causes an electrical field strength higher than 3 V/m. Hence the test was carried out with 10 V/m (for industrial environment). It was observed that at the frequencies of 80, 204 and 760 MHz the inverter interrupted. The new start-up occurs automatically. It is possible that the interruptions were caused by distortions of the grid (e.g. ripple-control signal).

Table 3

Operating points and size of the resonant circuits as well as corresponding quality factors for the tests carried out with the PV2go-inverter ($P_r = 100$ W)

	$Q_C = 50/15$ VAr	$Q_C = 100$ VAr	$Q_C = 250/75$ VAr
30% of P_r	$Q_r = 0.5^a$	$Q_r = 3.33$	$Q_r = 2.5$
100% of P_r	$Q_r = 0.5$	$Q_r = 1$	$Q_r = 2.5$
Required in	UK	Most EU/Australia	USA

^aQuality factor Q_r is the ratio of the reactive power Q_c and active power P .

test and therefore all inverters have passed the reliability test. This test procedure is in accordance with IEC 68-2-3 [25].

5.6. Field tests

Field tests have been carried out with conditions according to IEC 61724 [26] in a number of field-test sites in various parts of Europe. The objective of the field test is to evaluate the performance of the AC-module under actual meteorological conditions. Module voltage and current, inverter output power as well as meteorological parameters are logged using a modular data acquisition system.

At the K.U. Leuven test site, the two PV2GO AC-modules (PV2GO 1 and PV2GO 2 inverters) have been under field test. AC-modules and monitoring work are trouble-free since 1 July 2002. The meteorological data

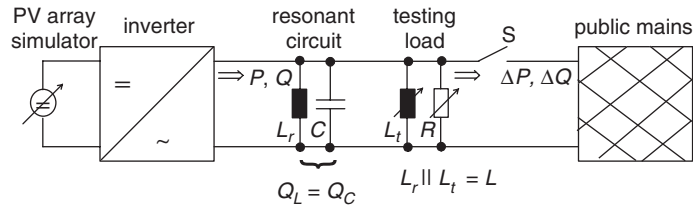
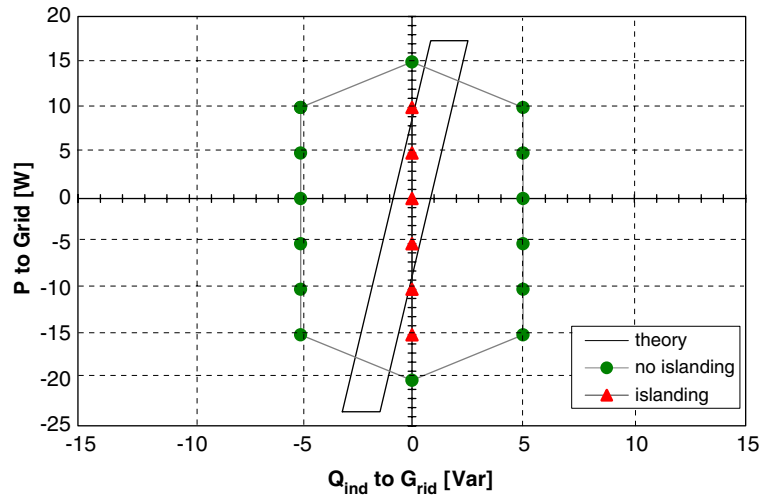


Fig. 9. Test circuit for islanding protection [22].

Fig. 10. Non-detection zone, $P = P_r$, $Q_C = 100 \text{ VAr}$ ($Q_r = 1$), $\text{NDZ} = 150 \text{ W VAr}$.

and performance parameters are monitored by a *Gantner IDL 100* data logger. The sampling interval is set to one second, while storing measured data as five-minute average values in the logger's RAM. These data are downloaded automatically by a PC once per day and stored for further evaluation.

Fig. 11 shows the yield and losses of both modules normalized on the reference yield before shadowing, thus indicating the system performance being independent of the solar irradiation at the particular months. Final yield normalized to reference values as indicated in Fig. 11 is equal to the monthly performance ratio. On an annual basis, the performance ratio of 0.76 for both AC-modules is very high; regarding that 9% of the reference yield during the test year is lost as a consequence of shadowing.

Array capture losses are low in winter due to the lower module temperature. The very low array capture losses from November to February originate from low module temperature but also indicate that the MPP tracking of the module inverters works well.

Fig. 12 gives the example of a winter day for irradiance an output power of the two AC-modules. In the morning there are clear sky conditions while starting around noon the sky becomes more and more overcast. In the late afternoon the sky is fully covered by clouds. During the whole day the AC-modules' output powers follow rather exactly the shape of the solar in-plane irradiance indicating proper performance of both AC-modules for different characteristic sky conditions.

For the same day efficiency has been calculated from five-minute average values of power (Fig. 13). This efficiency curve measured in the field is very well comparable to the one that measured in the laboratory, indicating a good performance of the PV2GO inverter also in the field.

The field tests carried out at the ECN location in the Netherlands from August 2002 to February 2003 are intended to verify system performance ratio, power efficiency of the inverter and system behaviour during the period. Ten AC-modules are mounted, free of any obstacles, with their array plane facing south, a tilt angle of 30° and an azimuth of 174° (Fig. 14). The equipment used for the test set-up is shown in Table 4.

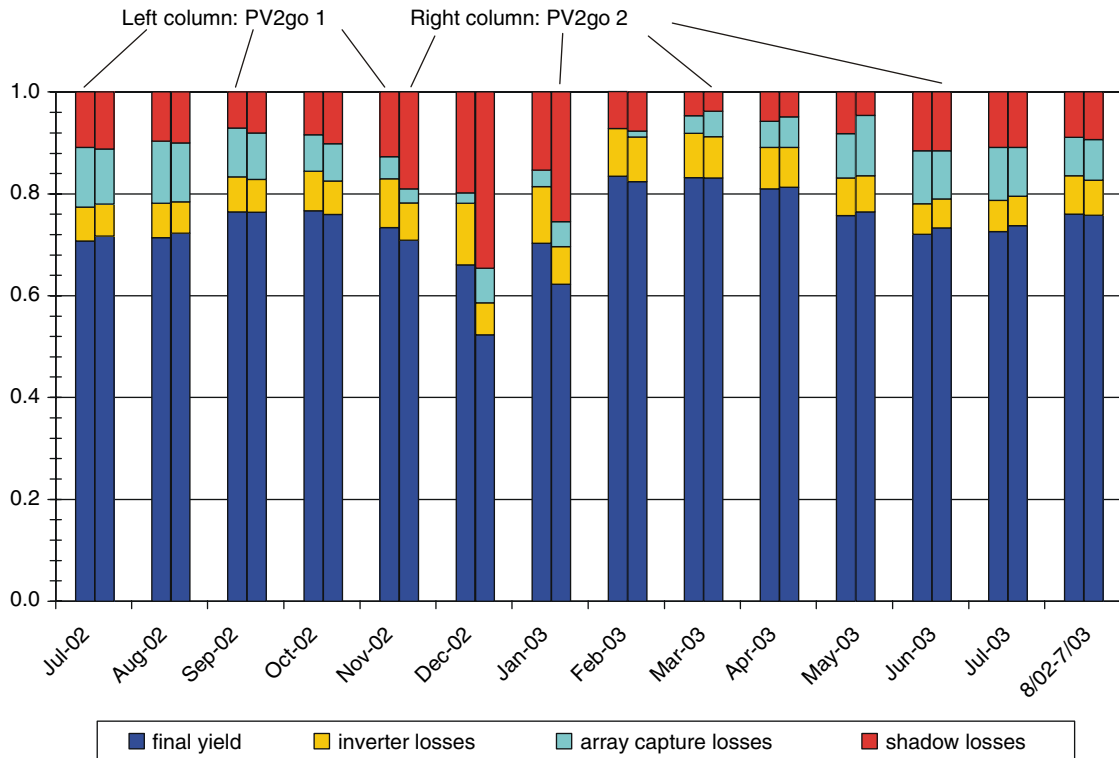


Fig. 11. Comparison of daily yield and losses for the two AC-modules after normalization on reference yield throughout the year.

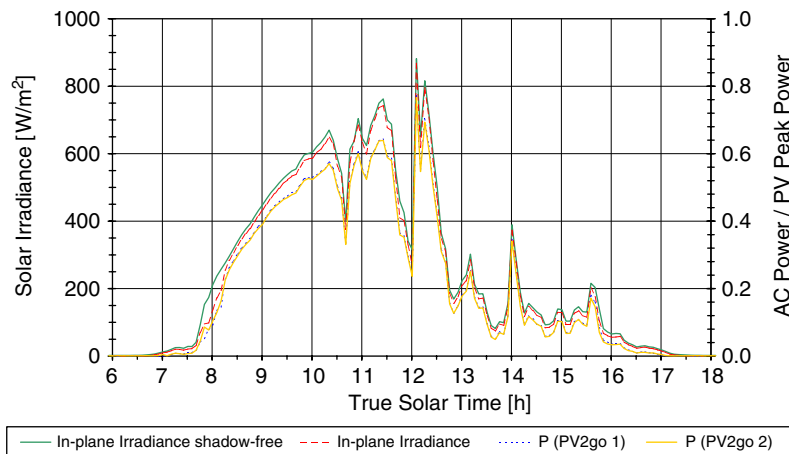


Fig. 12. Solar in-plane irradiance (shadowed and shadow-free) and normalized AC power output for two AC-modules on a winter day (28/02/2003).

Each system consists of a PV2GO inverter and a Eurosolare PL160 solar panel. All systems show the same energy yield during the monitored period. The performance ratio of the tested systems are between 0.70 and 0.80 if a sufficiently irradiation level is available. A performance ratio of about 0.75 means the system works properly.

The inverter is not limiting the power as a result of an overload condition due to the higher specified power of the solar panel with respect to the power of the inverter.

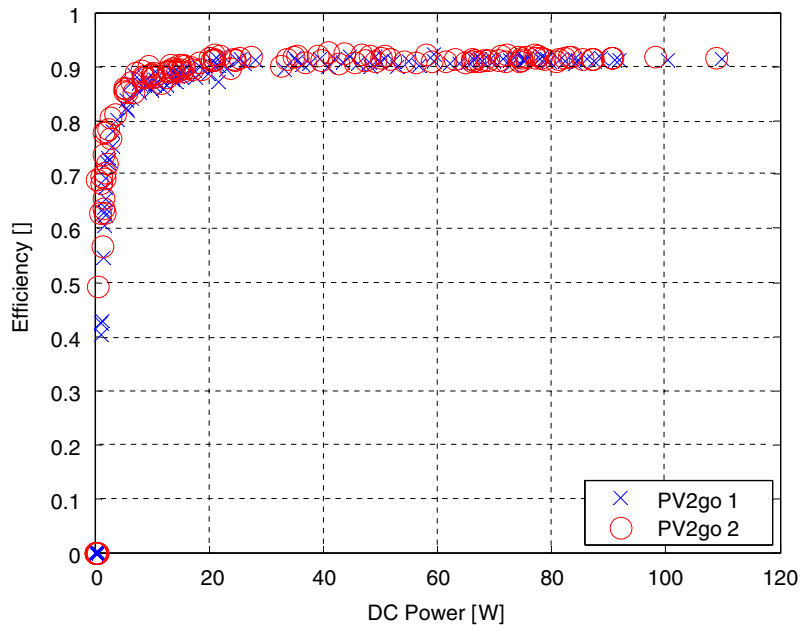


Fig. 13. Efficiency values as a function of DC power, based on five-minute average values (28 February 2003).

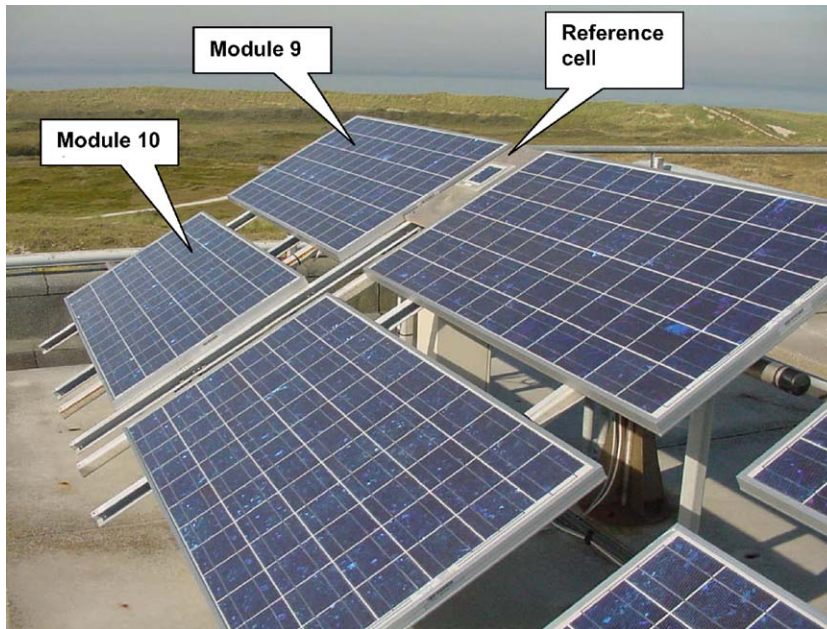


Fig. 14. Test site at ECN roof-top location of building 40.

Efficiency data acquired by laboratory tests show the same efficiency curves of the inverters. For irradiance levels higher than 300 W/m^2 the solar panel voltage is constant within small limits and independent of the solar panel's current. Once again all ten PV2GO systems are working well and no malfunctioning of the systems are found.

Table 4
Overview of test equipment

Test equipment	Additional information
Solar module	Eurosolare PL160
Inverter	PV2Go 2nd generation 150 Wp
Total number of AC-modules	10
Analytical monitored modules:	
AC module No 9	Inverter Nr. 0244, PV module: A0203026
AC module No 10	Inverter Nr. 0240, PV module: A0203015
Datalogger	PC-based system, programmed at ECN (Program: Zimpro 2.5)
Data-acquisition	Burr Brown 16 channel analog input board (PCI-20089W-1A)
Irradiance	Shell Irradiance indicator ($10 \times 10 \text{ cm}^2$)
Module temperature sensor	Analog Devices AD590
Ambient temperature sensor	Miery meteo, LM35
DC and AC voltage sensor	Resistor divider and galvanic isolation
DC current sensor	LEM LA 25-NP (5 primary turns)
AC current transformer	Faget RM-60D (1/0,1 A)
DC and AC power meter	ECN broadband multiplier (Burr-Brown MPY 534)
AC energy counters	EMH Type EIZ-EWWC-7393 single phase, 1A/230V, class 1

Table 5
Proposed design changes

Tested items	Proposed changes
EMC	Fine tuning for full compliance
Safety	No action needed
Performance	No action needed
Islanding	No action needed
Field test	Good results, no defects
HAST	>60 °C working outside maximum power point (compensate in firmware)

6. Proposed design changes

This chapter describes the proposed design changes based on the results of the tests carried out in laboratories and fields. The performance of the developed inverter is nearly in compliance with the design specifications. Table 5 shows a list of technical changes for full compliance and the final technical design of the inverter.

EMC: The test results show the inverter does not fully meet the requirement for conducted emission (AC-side). For conducted emission there is a small violation of the limit value at 17 and 21 MHz. Reduction of the disturbances is relative simple to reduce by fine tuning of the primary driver circuits of the semiconductor and additionally, if necessary modifying the filter of the secondary circuits. With one of these modifications full compliance with the requirement is to be expected.

For radiated emission there is a possible violation at 50 MHz. Additional measurements are necessary to confirm the violation.

Safety: None technical improvements are necessary.

Performance: The previous results are compared with the design specifications. Based on the results it can be concluded that the electrical performance of the inverter complies with the design specifications. Only the

stand-by power is a bit higher than the design target. In spite of it the standby power is only a small portion of the yearly energy yield. We decided that no further action is needed.

An inverter with an ASIC in the secondary circuit has comparable (somewhat better) performance results with the conventional design. To improve components cost price the initial goal was to use ASIC technology. But the cost price analysis shows that the secondary AC side ASIC is far more expensive than conventional parts.

Islanding: The island protection is based on frequency and voltage measurement. Test confirm that the island protection operates conform expectation.

Halt: The inverter operates outside the maximum power point at temperatures higher than 60 °C. Most logical cause of this is small changes in electrical properties or tolerances of some components when the temperature will increase. Possible solution is tuning tolerances in the firmware or when necessary adding a temperature compensation.

Test results show that if the temperature rises higher than 90 °C the core of the transformer will saturate. Saturating of the core only occurred at high temperatures and never occurred at normal temperatures. Designing a transformer is always a consideration between specifications (dimensions, temperature, losses, etc.) and cost price. Based on the test result we can conclude that the design of the transformer is optimum.

At an ambient temperature of 120 °C the inverter switched off. This temperature is extremely high and not a realistic ambient condition. Most components will operate then outside their temperature limit. Further research is not necessary.

Field test: The performance ratio describes the efficiency of a PV-system in reference to the irradiation. All loss mechanism is considered at this calculation as array capture losses, mismatching losses and inverter losses. The calculated performance ratio shows that the inverter works well. During the monitoring period, no system failures or defects occurred.

6.1. Optional changes

Based on the results and new technology, few changes can be made for further improvement and that are shown in Table 6.

MPPT: The MPP Tracker of the inverter is now a quite basic algorithm. In spite of this the test results show an excellent performance of the implemented MPP Tracker. Based on new knowledge, integration of a more intelligent algorithm is possible, which may improve the MPP efficiency and energy yield.

Temperature control: The temperature control complies with specifications but may be further improved. The operation temperature of the electrical components is an important factor to guarantee a long lifetime of the inverter. For this a temperature control is used. For ambient temperatures higher than 55 °C the inverter is progressively reducing its power by switching the output on and off. A more elegant way of temperature control is limiting the output power when the maximum temperature is reached. Then the inverter delivers energy to the grid during the whole day, but not always on maximum power.

This measure will improve lifetime of the inverter without affecting the yearly energy yield. Other discussing point is the maximum allowed internal temperature. Now the electrical components work amply within the specified limits. We can consider increasing the maximum temperature with a few degrees, which may further improve the energy yield.

Table 6
Optional changes

Items	Optional changes
MPPT	More intelligent algorithm
Temperature control	Now: reducing power by switching inverter ON and OFF. Other way: limiting power
Anti-islanding	Land specific requirements For example: G83 (UK), UL1741 (US)

Anti islanding: The islanding protection is based on monitoring of the voltage and frequency window. Now-a-days, this method is not sufficient in all countries in Europe. More country specific requirements can be complied with implementing islanding protection algorithms.

Conclusion

- The performance of the developed inverter is nearly in compliance with the design specifications. Minor changes to the design may be necessary to comply with the requirements. EMC compliance is a subject of improvement.
- The topology has proven to be reliable in field and laboratory- safety and highly accelerated stress tests.

7. Pre-certification of PV2GO

The CE mark is the official marking required by the European Community for all electrical and electronic equipments that will be sold anywhere in the European Community. It states to the buyer or user that this product fulfils all essential safety and environmental requirements as they are defined.

For the developed AC-module inverter the following standards apply:

- Electrical Safety
- Electro Magnetic Compatibility (EMC)
- Emission
- Immunity

For CE certification, EMC tests are prescribed. In the EMC test the repercussions of the inverter to the grid and the surrounding area are measured. The inverter must keep the legal limits which are specified in the standards. Disturbances of the grid and the surrounding area must not lead to malfunctioning or destruction of the inverter. The immunity tests are also prescribed in the standards. The compliance was tested in the accredited EMC laboratory of two of the project partners.

The electrical safety conformity was checked by the independent institute KEMA in the Netherlands. The safety checks were performed on: used components, power interface, marking, hazards, wiring physical requirements, electrical requirements, plug and connectors etc.

EMC: The test results show the inverter does not fully meet the requirement for conducted emission (AC-side). For conducted emission there is a small violation of the limit value at 17 and 21 MHz. Reduction of the disturbances is relative simple to reduce by fine tuning of the primary driver circuits of the semiconductor and if additional necessary modifying the filter of the secondary circuits. With one of these modification is full compliance with the requirement expected.

For radiated emission there is a possible violation at 50 MHz. Additional measurements are necessary to confirm the violation.

Safety test: The PV2GO inverter fully complies with the CE requirements.

8. Optimization study: an overview

An optimization study of a high-volume production process for AC module inverters and its potential cost reductions is carried out. The following points have been considered for this study:

- Investment cost related to production volume.
- Electronic design consideration.
- Enclosure technology and system integration.
- Future vision on module manufacturing processes and cost reduction.

In this study, a lay-out of a manufacturing facility for large-scale production of solar inverters was investigated. The resulting manufacturing flow diagram is suitable for production of 10.000–100.000 PV2GO inverters per year.

Since consumable material costs are affecting the module Wp cost by a 60%, a significant cost reduction is expected as consequence of a more rational usage off all materials involved in the manufacturing chain: i.e.: thin wafers, high conversion efficiency and high process yields. Further benefits are expected when large solar cells are produced because of better equipment and labour exploitation.

Engineering efforts seem to be necessary to develop equipment particularly designed to process thin and large Silicon wafers with acceptable yield. An important development effort is also needed to boost the cell efficiency to 15% and 17% at least for mc-Si and CZ-Si respectively. High efficiency is the key point to decrease the module Wp cost. Some producers are already able to produce high efficiency solar cells but a strong development work is still needed to transfer such results on large wafers with high production rate.

Use of a different module assembling technology of thin and large wafers is associated with high efficiency performances. The feasibility of a new assembling technology particularly suited for large and thin wafers was already demonstrated at laboratory level.

9. Cost analysis: an overview

In the design specification, the following project goals were defined. Project goals for user cost price:

Inverter	0.5 Euro/Wp
BOS	0.5 Euro/Wp
PV-modules	3.0 Euro/Wp
System cost	4.0 Euro/Wp

A user cost price of 4.0 Euro/Wp for the total photovoltaic system is a very ambitious goal for the project. The photovoltaic modules take the greatest part of the system costs. It is very difficult to achieve a module price of 3 Euro/Wp, because the prices increased in the last few years.

The calculation of the price per Wp is based on the rated power of 120 W of the inverter. The inverter cost price is the manufacturing price. Normally the gross margin varies from 30–60% depending on kind of product and volume. For high volume markets this is about 30%. The dealer usually gets 10%. In Table 7, a margin of 30% for the dealer price is included.

The user cost price of 0.5 Euro/Wp for the inverter can be achieved with a mass production of 50,000 units. This was calculated with the rated power of 120 W of the inverter. If a larger module is used, like a Eurosolare PL160 with 140 W, then a user cost price of 0.5 Euro/W can be achieved with a smaller production of 10,000 units. For the comparison, the current market prices were determined. Table 8 shows the current market prices of photovoltaic inverters classified in three power categories.

The cost price calculation is based on the Inverter Database 2002 of the Photon magazine. These prices include tax for the German market. Table 8 shows the average of the inverter prices in each power categories. To compare these prices with the PV2GO inverter, a recalculation for the dealer price and the cost price was necessary. The prices without tax reduce at 10% for the dealer price and a further reduction of 30% for the cost price.

Table 7
Estimated cost price of the second prototype

Units	1000 +	10000 +	50000 +
Manufacture price	82 Euro	54 Euro	44 Euro
Dealer price	107 Euro	70 Euro	57 Euro
Manufacture price/Wp	0.68 Euro/W	0.45 Euro/W	0.36 Euro/W
Dealer price/Wp	0.88 Euro/W	0.59 Euro/W	0.47 Euro/W

Table 8
Prices of PV-Inverter

	< 1 kW	1–2 kW	2–5 kW
Consumer price ex. tax	1.14 Euro/W	0.85 Euro/W	0.66 Euro/W
Dealer price (–10%)	1.03 Euro/W	0.78 Euro/W	0.60 Euro/W
Cost price (–30%)	0.80 Euro/W	0.60 Euro/W	0.46 Euro/W

For the small rated power of the PV2GO inverter, a very good cost price is achieved. The recalculation of the inverter cost price (< 1 kW) delivers an average price of 0.8 Euro/W. The estimated costs for the PV2GO inverter is only 0.45 Euro/W with a production of 10,000 units.

At the beginning of the project the integration of micro-controller, PWM-controller and other functionality into an ASIC were identified as major changes to gain a lower cost price. Further studies in the second year of the project showed interesting development in primary control possibilities. At first new DSP technology seemed the ideal single chip solution but at a later stage this DSP has been discarded because of problems with functionality and cost price. Second option was to use a microchip controller with internal PWM controller. This device had limited programming space and communication features. Finally a Flash micro controller was chosen in combination with a fly back converter. The design of the primary control is ultimately simplified by using a micro controller, thereby limiting the need for a primary ASIC. Based on new facts a feasibility study concerning the implementation of the auxiliary supply and the gate driver has been performed. The second ASIC has been developed for the control electronics on the AC side. As these two applications require different silicon technologies, namely high voltage and high current, the ASICs have deferent cost prices.

The estimated costs for the inverter reached the aim of 0.5 Euro/Wp from an annual production of 10,000 units. Also the costs for roof mounting system and flat roof systems are going today for 0.4–0.5 Euro/Wp. The costs for AC cabling and connection of the modules to the mains have to be added. This is relatively independent of the system size. An amount of 20–40 Euro for small systems is to be estimated. The aim for the costs of the inverter and the BOS could be reached. The costs of the PV-modules are the problem. The expected price reduction of the modules was not reached now. Through the great demand the prices are high in the last few years. In future a price reduction is to be expected.

The comparison of the system costs shows that the AC modules are competitive. The costs of the inverters and other BOS are on a low level. For small PV-systems a very favourable price/power ratio is reached. Under the condition as in the Netherlands, where these inverters can be directly connected without supplementary measures, very good mark chances are probable. In countries, where an ENS is needed, small systems are more expensive.

To improve components cost price the initial goal was to use ASIC technology. Also changing and simplifying the concept have achieved price reduction.

The primary DC side ASIC has a cost price advantage of 16% when using ASIC B with switch mode power supply at high volumes. With ASIC A based on the prototype 2 design, no cost price reduction can be achieved. The secondary AC side ASIC is far more expensive than conventional parts. Although production costs are not included, the conventional H-bridge control will always be cheaper.

Purely based on cost price at the in this project calculated production numbers, ASIC technology cannot compete with conventional SMT.

The conventional EE42 transformer is up till now almost 10% less expensive. This can change in the future because of the large-scale planar magnetic production and using higher switching frequencies simplifying the transformer design.

10. Market analysis

The solar electricity market is booming. In 2000, cumulative installed capacity of photovoltaic systems around the world surpassed the landmark figure of 1000 MWp. At the same time, global shipments of photovoltaic cells and modules have been growing at an average annual rate of 33% for the past few years.

The worldwide photovoltaic industry is investing heavily in new production facilities and technologies. At the same time, political support for the development of solar electricity, has led to far-reaching support and promotion frameworks being put in place in several countries. This clear commitment, industrial and political, to the expansion of the photovoltaic industry implies that the current surge of activity in the solar electricity sector represents a mere foretaste of the massive transformation and expansion that this sector will experience in the coming decades.

Yet much work still needs to be done to transform potential into reality. One crucial step in this process is to bring a far broader range of participants into the sector, especially in the investment finance, marketing and retailing areas. At the same time, there is a need to transmit the message to the socio-economic and environmental benefits that solar electricity will bring to regions that proactively support and encourage its uptake.

It is expected that photovoltaic systems will contribute substantially to the main stream power production, although it is still necessary to develop photovoltaics into a cost-effective and clean power source, available to the utility companies and the building owners.

11. Conclusion

The main target of photovoltaic R&D projects is a profound cost reduction for solar electricity generation down to 3 Euro/Wp on the mid term. The reliability of the inverter part of an AC-module does not comply with the typical PV-module lifetime at this moment. Therefore the newly developed inverter of the new generation AC module was designed for low-cost production and reliable operation during the typical PV-module lifetime of 20 years.

A promising lifetime expectancy figure of the inverter part of the AC-module was achieved. Namely, the mean time between failure (MTBF) of the second prototype PV2GO inverter using Bellcore TR332 (Method 1, Parts count, Case 1, $T_{amb} = 40^{\circ}\text{C}$ and 50% rated electrical stress) is about 25 years. The reliability improvement achieved is strongly expressed with the following comparison: the same MTBF calculations on an “off the shelf” similar PV inverter gave about 15 years. Beside this, the new AC modules were tested in a number of field-test sites in various parts of Europe and their reliability was also assessed through highly accelerated stress tests. The outcomes of all these tests were very successful.

The production cost of the second prototype PV2GO inverter is strongly reduced while still ensuring a high efficiency of $\eta_{EU} = 92.2\%$. This is achieved by reducing the number of components significantly. Topology concept, thermal and magnetic design were optimized with regard to production technology and packaging for large-scale production. Cost calculations showed that the end-user price of the PV2GO inverter, based on 10,000 piece production, can be 0.5 Euro/Wp. According to a manufacturing process study in the fourth year of the project, the goal to achieve a turnkey system cost of 3 Euro/Wp for a modular plug-and-play AC-module PV system can be met with the PV2GO concept.

A successful pre-certification test assures compliance with the European guidelines and standards. Further energetic performance and power quality have been tested in the laboratory; these results do cope with the specification and are competitive.

Acknowledgement

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