

THE IMPLANTATION OF A GRID-CONNECTED PV SYSTEM AT CEPEL

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ABSTRACT

This technical report presents the experience undertaken by CEPEL for implantation of a grid-connected PV system at its headquarters, located in Rio de Janeiro, RJ, Brazil. This technology, although considered far from Brazilian reach, is expected to grow significantly in the near future.

The paper describes briefly several aspects concerning the PV system and the DAS (data acquisition system) implemented in order to allow the continuous evaluation of its performance and operational conditions. The system was installed in December, 2002, and the data are still preliminary.

Keywords: Grid-connected PV systems; PV systems; Photovoltaics; Solar Energy

Introduction

The grid-connected PV systems are the application of Photovoltaics that has presented the biggest annual growth rate in the world. According to the data (IEA, 2002) published by the IEA – International Energy Agency, dated of the end of 2001, and concerning its member countries only, more than 68% of the total PV power installed in these countries is already grid-connected. These installations comprise an amount of 668.9MW_p (total of 982.2MW_p), and surpass all other terrestrial applications of PV combined.

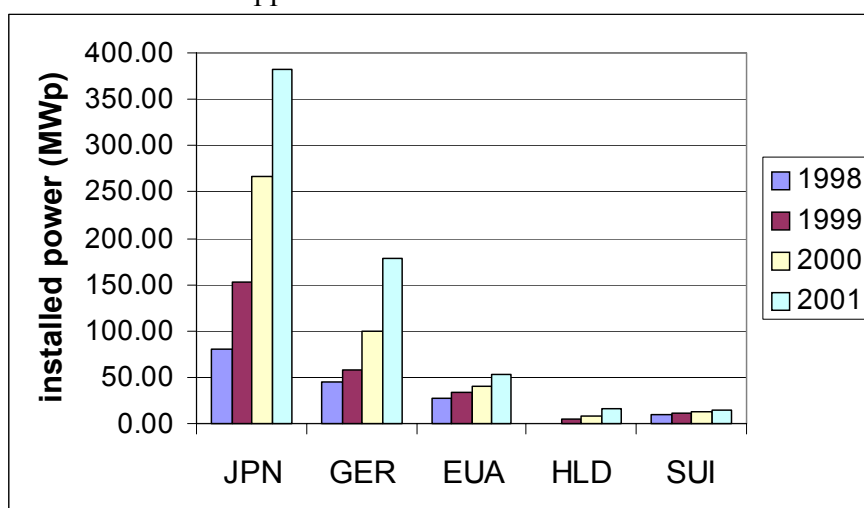


Figure 1. Grid-connected PV power 1998-2001 in selected countries

Figure 1 shows the increase of grid-connected PV systems in five selected countries (JPN-Japan, GER – Germany; USA – United States; HLD – Holland; SWI – Switzerland), in period 1998-2001, also according to the IEA data.

The analysis of the IEA data also indicate that since 1997 the annual increase rate of the PV power installed in its member countries has been greater than 40%.

This significant growth has occurred mainly in the developed countries and has been supported by the great subsidized governmental programs of Japan (New Sunshine program, among others), Germany (*Hundert Tausend Dächer Programme*/Program a Hundred Thousand Roofs) and USA (a Million Roofs Program), not to mention other countries. Figure 2 presents a set of rooftop grid-connected PV systems in a residential area of Japan.

We understand that it represents an important shift, since recently most of the PV specialists still believed that the main field for application of photovoltaics was the rural electrification, using stand-alone PV systems to supply energy to remote loads far from the electric grid.



Figure 2. Residential rooftop systems in Japan (Source: SHARP)

However, even considering the important growth of the last years, the installation of grid-connected PV systems in a scale large enough to affect a country's generation, has not yet been achieved anywhere, and it is expected to happen only in a long-term future.

Description of the technology

The grid-connected PV systems are normally installed in a building and do not use energy storage in batteries, injecting all energy generated directly into the electric grid. In developed countries, the installations include schools, public buildings, companies, homes, etc. These installations shall rely on severe technical and commercial regulations, specially when a great number of installations is involved.

The integration of PV array to façades and to the architecture of the buildings has become an important issue, being named BIPV – Building Integrated Photovoltaics.

Figure 3³ shows a diagram of a rooftop residential grid-connected PV system. The system comprises of only two main components: the PV array and the inverter. Protection devices (diodes, circuit breakers, surge arresters, etc.) are also necessary.

The injection of energy into the grid is done by an inverter, which converts the dc voltage/current generated by the PV array into a ac voltage/current compatible with the grid, injecting current in phase with the voltage, which means active power. The inverters are computer controlled devices and must meet severe standards for interconnection with the grid, continuously monitoring the electrical parameters and turning off automatically if any perturbation occurs (sub-voltages, frequency shifts, voltage peaks, etc.). They also search continuously the optimum performance of the PV array (MPPT – maximum power point tracking).

The residential rooftop systems, which have typically many kW_p total installed power, inject current into the low voltage grid (110V_{ac} or 220V_{ac}), while the bigger systems inject in higher

³ NEDO – New Energy and Industrial Technology Development Organization/Solar Energy Department (Japan)

voltage levels. The operation of the equipment is totally automatic, and there is no need for a human operator. When an instantaneous energy surplus occurs (generation higher than consumption of the building), the extra energy is fed into the public grid and is available for the other users.

In the developed countries, the installations use bidirectional Watt-hour meters, able to record independently the energy generated and consumed by the building. If the installed PV power is small compared to the consumption, the system can only reduce somewhat the consumption, otherwise can generate a monthly surplus.

In some countries, the kWh generated has a price higher than the kWh consumed, so that even a system that generates only a certain fraction of the consumed energy, can turn the monthly energy negative, what means that the user receives from the utility a monthly value, as the utilities are obliged by law to buy this energy.

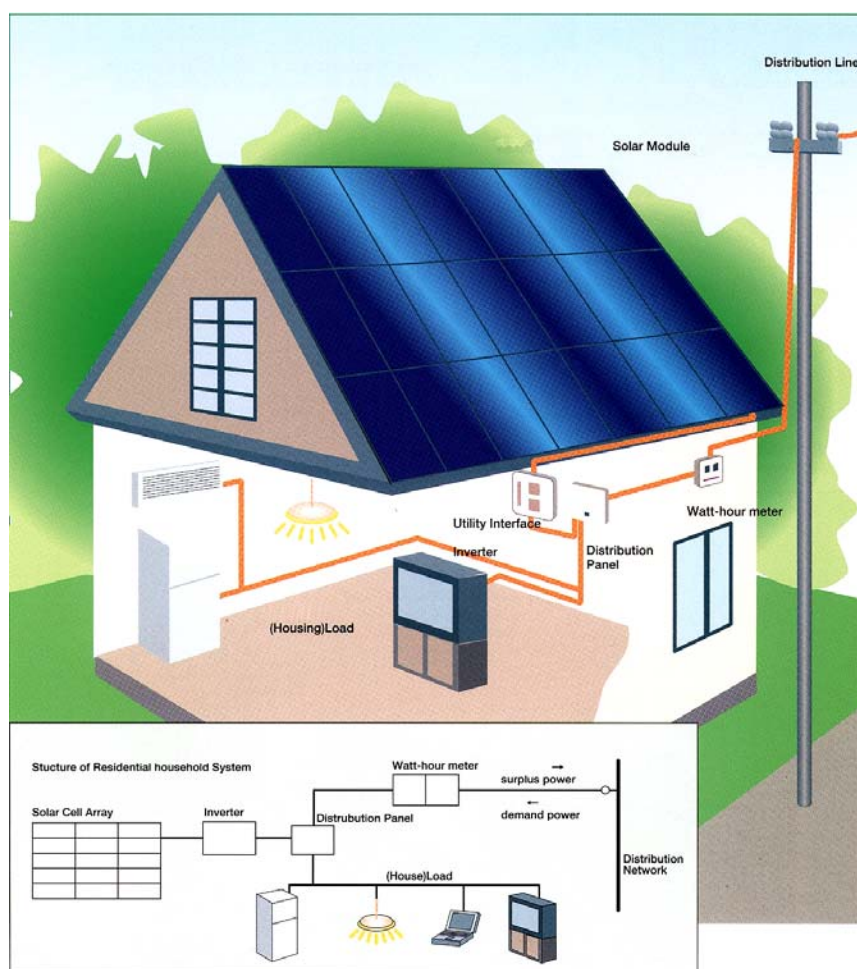


Figure 3. Residential rooftop PV system (Source: NEDO¹ – Japan)

BRAZILIAN EXPERIENCE

This technology is not well-known in Brazil, as there is only a very small number of grid-connected systems, mostly in universities or research institutes, installed for demonstration, training and research.

The most known systems in Brazil belong to: CHESF (Companhia Hidroelétrica do São Francisco, Recife-PE), which, as far as we know, installed the first grid-connected PV system

in Brazil; IEE/USP (Instituto de Eletrotécnica e Energia da Universidade de São Paulo, São Paulo-SP) and LABSOLAR/UFSC (Universidade Federal de Santa Catarina, Florianópolis-SC).

Following this tendency, CEPEL decided to implant a grid-connected PV system in its headquarters in Rio de Janeiro, aiming to increase the knowledge about this technology in Brazil. The main objective was to gain real experience in the design, specification, installation and operation of this kind of system, since CEPEL had a large former experience just in stand-alone PV systems used for rural electrification.

We expect that this experience will help to create in-country expertise about grid-connected PV systems and contribute for the development of applications of photovoltaics in Brazil.

PV system of CEPEL

The system of CEPEL was purchased through an international bidding (CEPEL, 2002), granted to the company BP Solar do Brasil and was installed in December, 2002. Up to May, 2003 the system was not commissioned and was operating experimentally (parcially). The system has 16.32kWp and is installed in the roof of one of the buildings (Block J) of the CEPEL's main laboratory, located in the campus of UFRJ (Rio de Janeiro Federal University). It injects energy into the low-voltage grid (220V_{ac}) and is described in detail in the items 4.1 to 4.3 below.

The total PV power and the energy generated are small if compared to the installed power and to the consumption of the building (Block J) respectively. So, as the effect of the system in the consumption of CEPEL is even smaller, no energy surplus, to be fed into the public grid, is generated.

PV Array

The PV array comprises 204 BP580F modules, associates 17 modules in series and 12 in parallel. The mono-Si BP580F modules are considered the best commercially available nowadays. The cell enclose the technology known as LGBG (Laser Grooved Buried Grid) which result in a nominal efficiency in the range of 16%-17%.

The PV modules' characteristics in the STC (Standard Test Conditions⁴) are as follows:

- nominal power (P_{max}): 80W_p
- open circuit voltage (V_{oc}): 22.0V
- short circuit current (I_{sc}): 4.7A
- voltage at nominal power (V_{mp}): 18.0V
- current at nominal power (I_{mp}): 4.44A
- number of cells: 36 (series)
- weight: 7.5kg
- dimensions: 530mm x 1188mm

⁴ Irradiance of 1000W/m²; cell temperature of 25°C; spectrum AM1.5 (*air mass* 1.5).



Figure 4. Support structure for installation on the roof



Figure 5. General view of the installation

The connection of 17 modules in series results in open circuit voltage of up to 374Vdc, which present a significant risk of personal injury. Therefore, the installation can only be performed by skilled personnel and employing adequate equipment. The assembly of a PV array on the roof of a building that was not designed with this aim proved to be the greatest challenge to the installation of the system. The best solution would be to redesign and re-build the roof of the building to receive the PV array. However, this solution was discarded, as it would have a huge cost. To overcome this cost, the array was installed along the walls of the roof, using support structures similar to those used in ground installations (adapted). This was a very cost-effective solution. Each structure, shown in Figures 4 and 5 supports 8 or 9 PV modules. Another important issue is the protection against atmospheric discharges, implemented by varistors ($V_{rms}=460V$; $V_{dc}=615V$; $I_{max}=8kA$) and spark-gaps connected to the cc conductors of the PV array, as presented in figure VI. This electric diagram represents a junction box installed on the roof (one of them can be seen in Figure 4, under the sub-array at left). There are six junction boxes, each corresponds to a sub-array and to a respective inverter. The blocking diodes ($I_d=12A$; $V_{rrm}=600V$) are also enclosed in the junction boxes. The metallic parts (structures) were connected to the grounding conductors of the Franklin captors already installed along the perimeter of the roof.

Inverters

The system includes 6 inverters SMA Sunny Boy SWR 2500U, whose specifications, according to the documentation of the manufacturer (4,5) are the following:

- nominal output ac power (P_{ac-nom}): 2200W
- maximum output ac power (P_{ac-max}): 2500W
- grid voltage (V_{ac}): 211-264V
- grid frequency (f_{ac}): 59.3-60.5Hz
- total harmonic distortion (THD): <4%
- input dc voltage - MPPT (V_{pv}): 234-550V
- maximum dc input voltage (V_{pvoc}): $\leq 600V$
- maximum dc input current (I_{pv}): 13A
- maximum input dc power (P_{pv}): 2710Wp
- self consumption: < 7W
- maximum efficiency (η_{max}): >94%

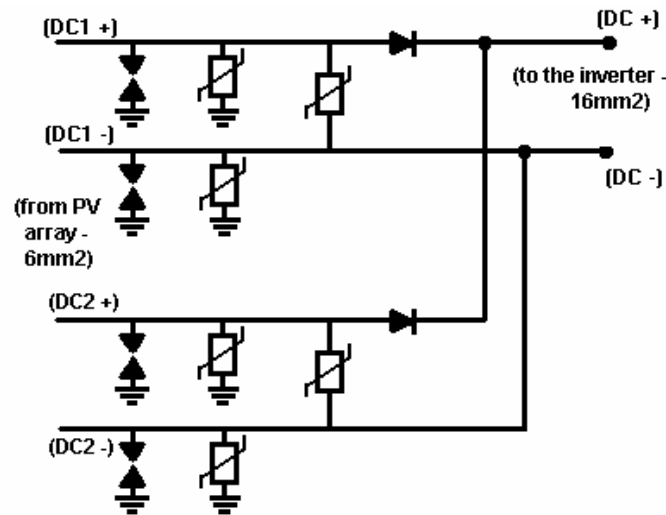


Figure 6. PV array junction box

Also, according to the manufacturer's documentation, this inverter is certified according to the standards for grid-connection of most countries, including USA (UL1741–Underwriters Laboratories Inc. and NEC 690 – National Electric Code *Article 690*), Australia (“*Australian Guidelines*” and IEC950 – *International Electrotechnical Commission*), United Kingdom (“*Engineering Recommendation G77*”) and Germany (regulations of VDEW–*Verband der Elektrizitätswirtschaft*/Association of the German Electric Utilities e DIN-VDE 0126 – *Deutsches Institut für Normung/German institute of Standards*). The inverters are connected to the secondary coil of a transformer that feeds the building (Block J), which has a primary coil of 480Vac (Δ -connection), a secondary coil of 220V_{ac} (Y-connection, center grounded) and a nominal power of 225kVA. The 6 inverters are Δ -connected to the 3 secondary coils, each pair of inverters in parallel, as presented in Figure 7.

The inverters are certified in the NEMA⁵ 4X class of protection, allowing outdoor installation. However, the manufacturer forbids its exposition to direct solar radiation and recommends to avoid the direct incidence of rain. Considering this fact and also the tropical conditions of Rio de Janeiro, CEPEL decided to install the inverters indoors. They were installed in the transformer compartment (substation), which is a weather protected place.

The inverter panel is shown in Figure 8. The protection of each inverter comprises 2 circuit breakers: a 20A single-phase breaker for the cc input and a 16A two-phase breaker for the ac output. The system is protected by an extra 50A 3-phase circuit breaker (not visible in Fig. 8).

The electronic protection of the inverters⁶ operate as follows:

- under/overvoltage – the inverter shuts off within 0.1s if the ac voltage gets out of the specified range (213Vac-262Vac)
- shift in frequency - the inverter shuts off within 0.1s if the ac frequency gets out of the specified range (59.3Hz-60.5Hz), while the ac voltage lies between –30% and +15% of the nominal value (voltage range for reliable frequency measurements);
- rate of change in frequency – the inverter shuts off within 0.2s if the ac frequency varies drastically ($>0.5\text{Hz/s}$);
- grid impedance – the inverter shuts off within 5s if the grid impedance changes drastically or reaches a high value;
- ground leakage – the inverter shuts off if a current leakage to ground is detected in the PV array;
- islanding – detection based on the ac voltage and the ac frequency, according to the standard UL1741;
- short-circuit – detection based on the ac current;

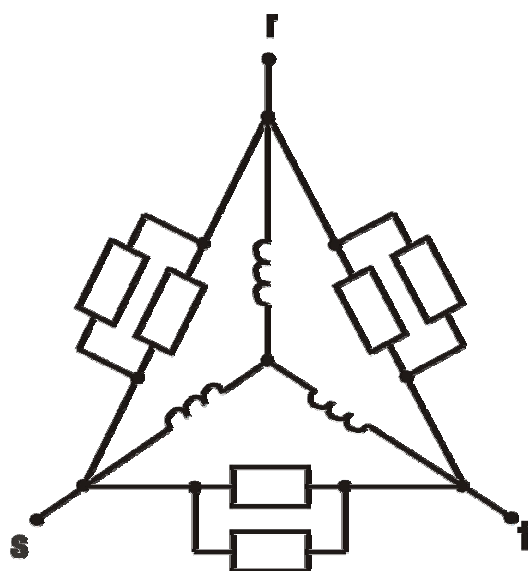


Figure 7. Δ -connection of the inverters to the secondary coil of a transformer

The electronic protection is controlled by two independent and redundant circuits. The parameters that control the actuation of the protection (ranges and rates of variation) are configurable by a EEPROM that is prepared only by the manufacturer. This can represent a difficulty, which actually happened in CEPEL, since the default range for the ac voltage

⁵ National Electrical Manufacturers Association - USA

⁶ The values presented are default.

proved not to be adequate and a new version was requested from the manufacturer (Germany). We believe that it would be better if these parameters could be changed directly by the user.



Figure 8. Inverter panel

Monitoring

The PV system is completely monitored by a real-time Data Acquisition System, which measures and stores the environmental and electrical quantities relevant for the continuous analysis of the operational conditions.

The monitoring system is based on a PC-compatible microcomputer and a data acquisition equipment “Sunny Boy Control Plus”, supplied by the manufacturer of the inverter specially for the evaluation of PV-plant performance. The software, compatible with MS-Windows 98, allows the access to the data both locally (keyboard and monitor) and through the intranet (CEPEL’s internal computer network). In the future these data will be made also available in real-time through the internet. The data is measured in 10s intervals, and 10min averaged values are stored in computer files.

The quantities monitored are the following:

- global solar radiation (W/m^2); on the plane of the PV array (Kipp & Zonnen CM3 pyranometer)
- global solar radiation (W/m^2) on the horizontal (Kipp & Zonnen CM11 pyranometer);
- ambient temperature ($^{\circ}\text{C}$);
- relative humidity (%);
- wind speed (m/s) and direction ($^{\circ}$) near the PV array;
- temperature of the PV array ($^{\circ}\text{C}$), measured at two different points;
- dc voltage (V), dc current (A) and dc power (W) generated by the PV array, for each inverter;
- ac current (A) and ac power (W) injected into the grid, for each inverter;
- ac voltage (V) for each phase;
- ac frequency (Hz);

In order to provide an independent record of the total energy injected into the grid, a conventional Watt-hour meter was installed for each inverter (also visible in Figure 8).

Performance Estimates

Based on the knowledge of the characteristics of the components (inverters and PV modules), a computer simulation was implemented, trying to predict the energy yield of the system. This simulation employed simple computer modeling for each component and used as input real solar radiation data (global radiation on the horizontal plane – 10 min averages) of an entire year measured by a meteorological station of CEPEL, equipped with a pyranometer.

Table I. Monthly generation calculated

month	energy (kWh)
Jan	1901.1
Feb	2108.0
Mar	1740.7
Apr	1392.3
May	1257.7
Jun	1072.4
Jul	1223.3
Aug	1536.4
Sep	1374.1
Oct	1921.2
Nov	1682.4
Dec	2234.6
Total	19444.3

Table II. Monthly generation measured

month	energy (kWh)	delta (%)
Apr	2078.9	-49.3
May	1722.8	-37.0
Jun	1509.6	-40.8
Jul	1540.8	-26.0
Aug	1654.2	-7.7
Sep	1634.7	-19.0
Total	11857.8	

The results obtained are presented in Table I, where it can be seen that a total yearly generation of approximately 19.5 MWh was expected. This result was not considered accurate, due to the simplification adopted in the computer models. Considering the expected total presented in Table I, the system would generate an yearly amount of 1.19 kWh per W_p installed, or an yearly average of 53.3 kWh/day.

The energy consumption of CEPEL is in the range of approximately 220 MWh/month (winter) to 350 MWh/month (summer), so the PV generation was expected to reach 1% of consumption, at best.

Taking into account the average tariff of US\$ 0.0411/kWh⁷ (R\$ 0.1192)⁸ paid by CEPEL, the value of the yearly energy generated by the system would be US\$ 799.06 (R\$ 2317.27).

⁷ CEPEL is subject to a Time-of-Use tariff (*tarifa horo-sazonal azul*), which charges separately the energy consumption and the power demand, both off-peak and in-peak. For comparison purposes, it was considered only the average cost per kWh

The PV system was installed in December 2002, but the data acquisition system was installed only in March, 2003. However, as already stated, the system was actually considered in experimental operation until May, 2002 and several shut-offs were necessary during this period.

Extrapolating from the set of measured data available up to September, 2002, table II, which contains the estimated monthly generation of the system, was prepared.

The analysis of tables I and II indicates that the prior calculations underestimated the monthly energy yield by up to approximately 50% (column **delta** in Table II).

The average daily generation in the period reached 55.5 kWh/day.

This result, however, does not take into account the actual values of solar radiation and is yet preliminary, therefore, shall be confirmed by a more complete and reliable set of measured data.

Conclusion

The present work discusses several technical issues related to the installation of the grid-connected PV system of CEPEL, along with the characteristics of the equipment.

According to a preliminary analysis, the performance of the system is much better than what was originally expected.

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IEA – International Energy Agency; PVPS – Photovoltaic Power Systems Programme. Annual Report 2001; July 2002.

SMA; Sunny Boy Control and Control Plus User Manual; issue 2.2

SMA; Sunny Boy Installation and Operator's Manual; issue 1.2.

SMA; Sunny Boy Technical Description; issue 1.2.

off-peak, (the peak is between 17h30m and 20h30m), in the period from January,2003 to September,2003. For comparison purposes, the residential tariff is approximately 3 times this value.

⁸ The exchange rate is R\$2.9/US\$.