Implementation of high concentration photovoltaic grid connected power plant for training, research, innovation and solar electricity production

A Barhdadi1*, A Benazzouz1, B Fabrizio2 and D Verdilio2

1Semiconductors Physics and Solar Energy Research Team, École Normale Supérieure, Mohammed V University, PO Box: 5118-Takaddoum, Rabat, Morocco
2BECAR s.r.l, Beghelli Group, Viale della Pace, 1 Monteveglio, Bologna, Italy
*Senior Associate at Inter. Centre for Theoretical Physics, Trieste, Italy,

*E-mail: barhdadi@ictp.it

Abstract. In this paper, performance monitoring program is applied to a grid-connected high concentration photovoltaic power plant in order to identify any operational problem and to make sure of its optimal and continuous power generation working conditions. A preventive maintenance plan was also established and proposed for the whole system.

1. Introduction
CPV is far the leading technology and the appropriate solution for high Direct Normal Irradiation (DNI) regions as in the south of Morocco. It delivers the outstanding efficiencies at all levels (cell, module, and system) and the highest energy yield with comparison to the other solar technologies. It is also the best technology for solar systems operating at high temperatures with consistent energy production [1]. CPV has also a compelling cost advantage because of its leading LCOE (levelled cost of energy) in the target market [2]. It is also environmentally advantaged (no permanent shadowing, minimal impact to land, dual land usage, flexible layout sites, best cradle-to-cradle footprint) and does not need any water consumption for electricity generation. Moreover, CPV is a proven, certified, predictable technology with rapid deployment, scalability, and a strong solar market forecast [1].

Recently, the European Beghelli Group has developed and patented an innovative High Concentration PhotoVoltaic (HCPV) power generation system baptized "Life Tree". A demonstration prototype of this new system has been lately installed and implemented at the Teachers College (École Normale Supérieure, ENS) of Mohammed V University (UM5) [3] for training, research and innovation purposes. The installation is well furnished by the necessary meteorological equipments, locally grid-connected, and operating as any small PV power plant. This achievement has been performed in the framework of a scientific and technical cooperation agreement aiming at improving the system performances in terms of energy efficiency, technology, and cost-effectiveness. Researchers and PhD/Master's students from Semiconductors Physics and Solar Energy Research Team (PSES) are now developing training sessions and performing proper research activities on the system to reach the agreement objectives. They are also focusing on designing and developing innovative integrated and reliable components that should improve the system and boost its
competitiveness in the PV market. The purpose of this paper is to present some of the main results we obtained from the study of system performance monitoring after one year of effective and continuous operating.

2. Description of the system

The power generation system is composed by: (a) a sun tracker (heliostat), which hosts a set of 48 HCPV single modules of 64 cells each, (b) the DC/AC converters (inverters) and (c) the control electronics. The system’s nominal peak power is 8160 W at 1 kW/m² DNI and standard cells temperature of 25 °C. The system total weight is 3900 kg and its size is 7.670 x 5.560 m².

The tracker is based on a galvanized steel frame mounted on top of a steel pole which can rotate from east to west (azimuthal rotation) and from bottom to top (zenithal rotation) according to the two angular degrees of freedom. The tracker is specifically designed for the HCPV applications. It is a high accuracy bi-axial solar tracker, with typical tracking error lower than 0.1°. The azimuthal and zenithal rotations are driven by two electric brushless motors. Each motor is driven by an electronic PWM circuit embedded in the tracker’s control box. The tracking control is based on specifically developed hybrid algorithm. It is an astronomic algorithm which uses the sun ephemeris data, corrected by the sun disc’s position identified by the solar camera mounted on the top of the tracker. The tracker is equipped with an anemometer, which is mounted on its top nearby the solar camera. When the wind speed exceed 50 km/h the control box drives the zenithal motor to recover the tracker in 90° home position (fully horizontal) to minimize the surface exposed to the wind force and reach a safe position. The tracker’s home position can withstand 190 km/h wind speed.

The high concentration single module is composed by 64 (8 x 8) III-V, triple junction cells, assembled on 8 aluminium fins which are facing the module’s front side to release the heat in excess. Each cell has its own anti-parallel silicon diode to bypass the cell current in case of single cell’s shadowing. Each cell outputs typically 2.65 V, while the photocurrent at Maximum Power Point (MPP) is about 1 A. The technical characteristics of each HCPV single module are shown in Table 1.

| Size (cm³) | Active Area (m²) | Weight (kg) | Operating Temperature (°C) | Conversion Efficiency | Open Circuit Voltage (V) | Short Circuit Current (A) | MPP Voltage (V) | Peak Power (W) |
|-----------|-----------------|------------|----------------------------|----------------------|--------------------------|--------------------------|---------------|--------------|
| 91.2 x    | 0.732           | 32         | - 40 to + 85               | 22 %                 | 198                      | 1.1                      | 176           | 170          |
| 91.2 x    | 17.4            |            |                            |                      |                          |                          |               |              |

The sun radiation is concentrated on the cells by parabolic high reflection mirrors. Fig. 1 shows the optical converter’s section structure associated to each cell. The optical system is a single reflection type. The sun rays cross the frontal glass and hit the parabolic reflector which concentrates on the secondary optic element (SOE). The SOE homogenizes the light on the cell’s surface, thanks to its kaleidoscope behaviour and also enhances the angular performance, allowing a wide angular acceptance of the optical system. The angular acceptance is defined as the maximum angle misalignment which keeps the output power greater than 95% of the maximum. The concentrated sun coming out of the prism lights the solar cell. The geometric concentration factor is about 1350 X (the ratio between the paraboloid’s front area (110 mm²) and the cell’s area (9 mm²)). Basically, the system is designed to operate at very high efficiency under sunlight intensities more than 1000 times higher than in the case of traditional PV [4].
Each HCPV single module is connected to its own inverter which converts the 170 V DC power input into 230 V AC 50 Hz single phase power output. The input is electrical insulated from the output, keeping a high level of electrical safety at system level. In fact the maximum voltage at module level is the module’s cell open circuit voltage, lower than 200 V DC. This feature is quite important because it minimizes the problems related to the lack of insulation at module level, a known trouble of all PV systems.

The inverter is made of a double high frequency power converting stage: the input inverter operates the MPPT (Maximum Power Point Tracking) algorithm which continuously looks for the maximum power point. The inverter’s output stage is the inverter which injects the current into the grid synchronously with the grid voltage, in sinusoidal shape at the 50 Hz grid frequency. The grid injected current is proportional at any time to the available input DC maximum power extracted by the MPPT algorithm. The inverter, controlled by a specific microprocessor, keeps synchronized with the grid frequency by means of a digital PLL, and implements all the output protections to suddenly interrupt the current injection if the grid parameters are not compliant with the safety operating conditions. Each inverter allows the maximum possible energy yield of the HCPV generator, since every single module is independent from the others and there is no problem of module shadowing, mismatching or misalignment. Any aging effect of the system which could eventually lead to mismatching conditions is completely eliminated, since each module will always inject into the grid its maximum available power in any condition. The inverters are connected to the three phase junction box for the connection to the HCPV generator to the 400 V grid.

The control system is based on a specific electronic board (COVECO) included in the metal sealed box fixed to the HCPV generator. The box is visible in fig. 18, which also shows the two brushless motors which manage the two tracker movements. The COVECO board embeds a LINUX CPU which runs the proprietary SW driving the tracker and monitoring the HCPV generator’s operation. The COVECO board is also equipped with a simple 2 rows characters display with 4 keys as a basic man-machine interface for simple installation start up procedures, such as running the motors to move the tracker. The more complete control interface is implemented on a remote computer connected to the COVECO via Ethernet or DSSS radio.

The solar camera device is mounted on the top of the tracker and embeds the CCD camera, the wide angle irradiation sensor, and the narrow angle irradiation sensor. The irradiation sensors are
monitored by the control box. The sensors are calibrated at the moment of installation and are used as reference sensors to measure the irradiation levels and estimate the generator efficiency.

A very important system’s function is the “tracker scan”. This function allows to automatically analyzing the angular performance of the whole tracker (and obviously of every single module). Starting the scan procedure, the tracker automatically, while it continues to track the sun position, adds a variable angular offset which is changed in small steps, one at a time; each offset step is kept for the time needed to complete an I-V acquisition (embedded in each inverter) from all the modules; at each step the I-V data is stored and a new step is defined; a complete matrix is scanned of all the angles around the sun pointing position. For each offset angle the maximum power output of each module is calculated and the maximum power output of the whole generator is then calculated.

3. Procedure

The optimal operating and continuous productivity of the system is threatened by uncontrollable criteria such as random failures and climatic conditions. This is why an appropriate and systematic performance monitoring is necessary to identify any operational problem before implementing the fitting solution to make sure of an optimal and uninterrupted activity of the system. To do this, we applied the International Electro-technical Commission Standard IEC 61724 for the performance monitoring of photovoltaic plants [5]. In the beginning, we defined our monitoring strategy according to the above standard. This strategy, detailed in our recent published report [6], is based on the following three steps: (1) Purpose of the performance monitoring and therefore the end use of data recorded (2) Selection of system parameters that should be monitored and the level of accuracy required. (3) Definition of monitoring period or time monitoring ($T_m$) and maximum recording intervals (MRIs) required. In our case, MRIs is set at 10 min and $T_m$ is calculated from the date when the power plant starts operating for the first time at ENS (April 4th, 2013) until the date when we started doing its performance monitoring (Marsh 27th 2014). $T_m$ is then set at 8640 hours (360 days). Hence, our strategy is in perfect conformity with the international standards and recommendations for monitoring the performance of photovoltaic installations.

Before starting the performance analysis, it was necessary to check the measurement quality of all system sensors. The checking includes power and energy supplied by each inverter, global normal irradiation, ambient and cell temperatures, humidity, and tracker angles. A reasonable set of limits was defined for each recorded parameter based on its known characteristics, the PV plant and the environment. The limits define the maximum and minimum allowable values for the parameter. Data that falls outside these limits or are otherwise inconsistent with other data are not included in the subsequent analyses.

To evaluate the quality of our checking process, two indicator parameters have to be calculated: The checking duration ($T_d$) in hours and the data availability ($D_a$) defined by the ratio between $T_m$ and $T_d$. In our case, $T_d = 1488$ hours and $D_a = T_m/T_d = 5.8$

4. Performance analysis and results

4.1. Performance analysis in sunny days

To identify the performance problems in the system, we focus mainly on the very well sunny days of the year. Those can be easily identified by historical measurements of DNI and daily power supplied by the system. For these sunny days, the measurements recorded between 11 h and 15 h are collected. During this period, PV modules are in similar operating conditions to standard test conditions in laboratory. Indeed, in this period, there is no shading, the air mass is not so high, and there is no cloud. In such conditions, sources of losses in term of energy production are at the minimum and operational performance problems of the system are easily identifiable.

In this analysis, we evaluate PV cells temperature and their coefficient of thermal degradation. We calculate also the coefficient of performance of each module for each sunny day identified. The cell temperature $T_{cell}$ is estimated by the following equation according to the CEI 82-25 Italian Electro-
technical Commission Standard [7]. There are several other relationships, but Italian manufacturers recommend the use of this formula.

\[ T_{\text{cell}} = T_{\text{amb}} + (\text{NOCT} - 20) \times E_{\text{DNI}} \times (4 \times I_p)^{-1} \]  \hspace{1cm} (1)

\( T_{\text{amb}} \) is the mean temperature measured between 11 h and 15 h. \( E_{\text{DNI}} \) is the Direct Normal Irradiation (in kWh) received between 11 h and 15 h. \( I_p = 0.9 \text{kWp} \).

The performance thermal degradation coefficient \( K_{\text{thermic}} \) is calculated by the following relationship normalizing the performance coefficient relative to the temperature since we mainly consider operational issues.

\[ K_{\text{thermic}} = 1 \text{ si } T_{\text{cell}} \leq 25 \text{ iC} \]  \hspace{1cm} (2)

\[ K_{\text{thermic}} = 1 - (T_{\text{cell}} - 25) \times \sigma \text{ if } T_{\text{cell}} > 25 \text{ iC} \]  \hspace{1cm} (3)

\( \sigma \) depends on the cell technology. In our case, \( \sigma = 0.106 \% \)

To calculate the performance ratio PR (also called coefficient of performance), we used the following formula which takes into account the effective power supplied by the system (\( P_f \)), its peak power (\( P_{\text{STC}} \)), the measured irradiation (\( H \)) and irradiation \( H_{\text{STC}} \) corresponding to the peak power (\( H_{\text{STC}} = 0.9 \text{kWp/m}^2 \)).

\[ R_p = \frac{P_f}{P_{\text{STC}}} \times (K_{\text{thermic}} \times \frac{H}{H_{\text{STC}}})^{-1} \]  \hspace{1cm} (4)

Fig. 2 provides a graphical analysis of the system performance in the sunny days considered in this exercise. The figure shows the evolution of PR for each sunny day and identifies the coefficient of nominal performance in green line. This coefficient is about 85%, when the performance ratio is below 85% the power plant is not operating at the top of its nominal performance. The graphical analysis reveals the presence of a serious operational problem during the summer months and significant measurements instability from the pyrheliometer (area circled in read).

![Graphical analysis of system performance](image)

**Figure 2.** Graphical analyses of system performance in sunny days

In order to identify the source of the above problem (in the summer months), a monitoring of the maximum power supplied by the system was conducted.
4.2. Monitoring of the maximum power output
The maximum power measured at each inverter was reported on Fig. 3, which shows the evolution of this parameter during the monitoring period.

![Graphical analysis of the maximum AC power provided by each PV module](image)

**Figure 3.** Graphical analysis of the maximum AC power provided by each PV module

The graph shows the presence of limitation in the power in the same period where the coefficient of performance of the system has had its lowest levels (area circled in blue). This allows us to deduce that the operational problem is coming either from the inverters or from the PV modules. However, since the maximum monthly power has increased after cleaning the modules, we can conclude that the operational problem exists because of the accumulation of dust on the modules surface. During the summer, the probability of precipitation is low and therefore the likelihood of accumulation of dust on the modules is high.

![Graphical analysis of the monthly performance ratio of each PV module](image)

**Figure 4.** Graphical analysis of the monthly performance ratio of each PV module

4.3. Monthly performance coefficient of each PV module
As we did in the case of performance analysis in sunny days, an additional analysis of the monthly performance was performed in order to detect other sources of losses in the system. The results of this investigation are shown in Fig. 4 where the curves clearly reveal the impact of cleaning on the system.
performance and the presence of a performance problem in the winter season. This last behaviour can be explained by both shading and air mass effect. In the following section, we examine these issues.

4.4. Sources of losses in winter

4.4.1. Shading effect. Our analysis revealed that the system installation is suffering from some partial shading. The shading effect appears especially in the winter when the sun elevation in the sky is relatively the lowest. Fig. 5 shows the impact of shading on the system production in a typical winter day.

![Figure 5. Impact of shading on the system power generation in the winter](image)

Inside the blue frame, the curves show that the power production starts late in the morning after 10 am due to more than one-hour partial shading on the modules surface. This shading comes from the Solar Energy Laboratory building that has been under construction when the system installation was achieved.

4.4.2. Air Mass effect. PV modules are usually tested under STC characterized by an Air Mass fixed at 1.5 (AM 1.5). This parameter is among the factors that have a significant effect on PV module efficiency, particularly in the case of CPV technology. In winter, because the sun is lower on horizon than in summer, solar radiations is going through a larger atmosphere thickness and then undergo more significant changes and mitigations. AM is then obviously higher in winter, therefore PV modules efficiency is lower especially for CPV that produce only from direct sunrays.

5. Conclusion

The performance monitoring of the grid-connected CPV power plant shows that, apart from uncontrollable problems related to climate and physical conditions of the installation site, there are completely controllable issues, which are due only to a lack of cleaning and regular maintenance. Indeed, accumulation of dust on the surface of modules, instability of pyrheliometer measurements, and the long time response to the possible operational problems, are all things that can regularly be verified and avoided. For such problems, we have proposed appropriate solutions to eliminate them or at least reduce their impact. These solutions are integrated into a maintenance plan that we have established and whose implementation will optimize the energy production of the plant and ensure
measurement accuracy of its sensors. The proposed plan will also allow a performance prediction and prevent possible malfunctions. To increase the continuity of production in response to different possible anomalies, we have also proposed the installation of an alarm system. All these issues will be presented in details in our next publication, which is still under progress.

6. References

[1] Mark C 2012 Why CPV? The CPV value proposition CPV Consortium Report
[2] Brett P 2011 Cost and LCOE Generation Technology GTM Research Report
[3] Barhdadi A, Jaziri H, Carpanelli M, Borelli G, Verdilio D 2013 Implementation of a HCPV grid connected power system for training and research at the university Int. Conf. on Renewable Energy (Amman, Jordan)
[4] Beghelli SpA Magazine 2011 High concentration Photovoltaic System (Italy)
[5] International Electrotechnical Commission 1999 Photovoltaic system performance monitoring – Guidelines for measurement, data exchange and analysis, International Standard IEC 61724
[6] Benazzouz A 2014 Surveillance de performance et mise en place de la maintenance préventive d’une centrale photovoltaïque à très haute concentration connectée au réseau basse tension Master thesis ENSA Kenitra (Morocco)
[7] Italian Electrotechnical Commission 2010 Guide for design and installation of photovoltaic (PV) systems connected to MV and LV networks (Italy)

Acknowledgment

This work has been supported by IRESEN (Institut de Recherche en Énergie Solaire et Énergies Nouvelles) Moroccan Institute, in the framework of PROPRE.MA Inno-Project.