Fundamentals of the commissioning tests of large-scale PV power plants

Utility solar | Large-scale PV contractors must perform tests to verify the correct operation of a new installation. Jorge Coelle and Leonardo Perez outline the minimum aspects to consider for the commissioning of large-scale PV plants using a methodology that has been successfully implemented in the commissioning of more than 40 PV facilities worldwide

In order to guarantee their investment, developers of PV facilities require the contractor to perform a series of tests that determine the correct operation of an installation prior to its commissioning. These tests are referred to as the commissioning tests of a PV project and are essential in both technical and economical terms.

The purpose of the main tests involved in the commissioning of PV plants is to reduce the uncertainty of the final performance of the PV plant under construction. Dealing with this uncertainty is essential for the three main parties involved in the construction of a PV plant: the owner, the contractor and the bank which finances the construction. For the owner, this methodology assures the quality of the components and installation while providing accurate information for the energy production estimation. For the contractor, it is useful to guarantee that total installed peak power and PV plant performance agree with the purchase contract. For the bank, it is clearly useful to reduce an important parameter – the risk – and to offer better credit conditions.

Methodology

Enertis Solar specialises in the provision of integral services within the solar PV market. Its approach focuses on the implementation of quality-control processes in each phase of the project, from PV module manufacturing to the design, installation and operation of a large PV plant. The company is a pioneer in the implementation of quality-assurance programmes: in the past it has proposed the carrying out of extensive quality control for PV modules [1], the monitoring of power degradation in PV modules [2], the introduction of electroluminescence (EL) imaging in the quality control of large PV plants [3], a methodology for estimating the actual installed peak power from the measurement of a sample of PV modules in the lab, the implementation of additional field tests to estimate peak power [4], and so on.

The methodology proposed in this paper for the commissioning has a wider scope and includes certain procedures that aim to verify not only the PV modules, but also the whole construction, components and performance.

It is important to note that these procedures should be included in advance in construction contracts in order to facilitate aspects such as fixing the price to the actual installed peak power or the acceptance and rejection of components, among others.

The proposed methodology can be divided into four main groups:

1. Mechanical completion
2. Electrical completion
3. Monitoring system
4. Availability and performance ratio.

The aim of this paper is to describe some of the tests included in the above-mentioned groups; these tests should be regarded as the minimum requirement for a good commissioning.

Mechanical completion

The mechanical completion includes all inspections related to the support structure (or trackers). The inspections should be performed from the very beginning of the construction in order to avoid recurrent errors and thus minimise the cost of solving any potential issue regarding the structures or their installation. For instance, if a batch of structures is not accepted because of galvanising defects, and a new consignment is therefore necessary, the installer will then have to discontinue work until the new material arrives, resulting in delays and extra costs. This kind of situation can be avoided if the mechanical completion verification is carried out during the construction and not just before the commissioning. Table 1 presents crucial aspects that need to be included within the mechanical completion review.

Electrical completion

The electrical completion includes many inspections that can be done during the construction stage (peak power, insulation resistance, visual inspections, etc.). There are many others, however, that can be performed only when the facility is in operation (voltage drops, efficiency of inverter, infrared (IR) thermography, etc.). For this reason it is very important to dedicate considerable effort to seamlessly accommodating the inspections in the construction and testing schedules. The electrical comple-

Mechanical completion
• Inspection to ensure structure built in accordance with plant layout designs (spacing, tilt, orientation, etc.)
• Visual inspection of support structures, including galvanising defects, rust, cracks, torque, etc.
• Foundations inspection

Table 1. Main aspects of the mechanical completion.

Electrical completion
PV modules and strings
• Verification of peak power • Verification of I_{sc} and V_{oc} • Polarity • IR thermography
AC/DC boxes and system
• Visual inspection (fuses, control terminals, fuse holders, cable entry, cable glands and seals, etc.) • Test of breakers and protections • Electrical continuity and insulation resistance of cables • Electrical grounding • Voltage drops
Inverters
• Visual inspection • Efficiency of the inverter • Maximum power point tracking • Verification of voltage and current
Transformers
• Visual inspection • Torque of connections

Table 2. Main aspects of the electrical completion.

Figure 1. Oxide on a structure as a result of insufficient galvanising.

tion is divided into the four main subgroups shown in Table 2.

Monitoring system

The monitoring system is a very important tool for the correct operation and maintenance of the PV plant; the installed solution should be flexible, precise and adaptable. It is the authors' recommendation that the system offer two operation possibilities: a basic level and an analysis level.

Traditionally, the commissioning of the monitoring system has been based on checking the installation and verifying that the SCADA (supervisory control and data acquisition) provides reasonable values. In the authors' experience, this methodology is not effective, and ultimately the owner does not really know how the facility works. For this reason, the commissioning of the monitoring system should consist of two main procedures:

1. *Hardware and installation:* all sensors should be checked and the traceability of their calibration certificates verified. It is important that sensors be calibrated in a laboratory that complies with IEC 17025 [5] and be included in an annual calibration plan. Moreover, the correct installation of all components should be checked: many irradiance sensors, for instance, have been found with important tilt differences with respect to the modules.

2. *Data acquisition and communication:* the test should be performed to verify that the monitoring system operates in accordance with IEC 61724 [6]. The minimum scope of this procedure should consist of the verification of irradiance, temperature, voltage, current, power, etc., including the verification of:

- linearity of response
- stability
- integration
- zero integral value

Availability and performance ratio

Unavailability is defined as the period of time during which the PV facility is not producing energy at full capacity. It should be noted that losses of availability may occur within the PV plant premises, for which the operation and maintenance contractor is liable, or outside the PV plant facilities, i.e. in the transmission infrastructures. In the authors' experience, an availability of 98% is adequate and likely to be achievable by most of the large PV facilities.

Figure 2. An incorrectly installed omega junction.

The performance of a PV plant is expressed by the performance ratio (PR) factor, which is defined as a percentage representing the ratio between the expected energy output in real conditions (taking into account all of the losses that occur in the energy generation) and the theoretical energy output in ideal conditions.

The PR measurement should be carried out during a period of 240 hours of continuous operation. The protocol establishes that the availability of the plant must be 100% and the availability of the recorded data should be at least 99.9%.

The availability of the plant is analysed through the study of the low-voltage meter records, the alarm records of the inverters, and the trackers' position when applicable. In this test period, the protocol establishes that the real production (the energy produced by the plant during the test period) has to be greater than or equal to the theoretical production (the energy that the plant would produce in the guaranteed performance conditions).

Methodology application

A third party involved in the supervision of commissioning tests must be totally independent and possess extensive technical know-how. An accredited laboratory seems to be the best option for carrying out these services, since its staff includes experienced engineers and scientists with Ph.D. degrees who specialise in photovoltaic energy. Moreover, the IEC 17025 accreditation guarantees complete independence. Three different possibilities of collaboration exist and can be classified according to their confidence levels:

1. *Tests totally performed by an accredited laboratory* (high confidence level). This is the option preferred by the bank; however, in the case of large PV facilities, the cost can be high if the procedures and the selection of samples are not well designed.

2. *Tests partially performed by the contractor under supervision of an accredited laboratory* (medium–high confidence level). This option is a combination of critical tests performed by an accredited laboratory (peak-power measurement, inverter efficiency test, etc.) and simple tests performed by the contractor and supervised by the laboratory (IR thermography, polarity, etc.).

3. *Tests totally performed by the contractor under supervision of an accredited laboratory* (medium confidence level). This kind of

	Facility A
Total capacity	20MWp
Module technology	Crystalline
Total modules	100800
Structure type	10º fixed-tilt
	0º azimuth
Total inverters	40 (500kWp)

Table 3. Main characteristics of the tested PV plant.

String	V_M [A]	I_M [V]	P_M [W]	Power deviation
1	617.81	7.87	4864	−1.43
2	622.80	7.85	4892	−0.87
3	625.63	7.65	4784	−3.06
4	626.45	7.73	4842	−1.88
5	635.90	7.70	4899	−0.74
6	634.08	7.73	4901	−0.69
7	624.41	7.78	4855	−1.62
8	629.88	7.63	4803	−2.68
9	626.82	7.55	4731	−4.13
10	627.94	7.69	4832	−2.09
11	619.30	7.59	4703	−4.69
12	631.50	7.77	4908	−0.54
13	634.38	7.83	4969	0.69
14	630.73	7.77	4901	−0.69
15	634.43	7.65	4856	−1.60
16	635.81	7.76	4937	0.03
17	628.40	7.80	4902	−0.67
18	635.54	7.70	4896	−0.79
19	627.41	7.76	4866	−1.40
20	635.21	7.74	4918	−0.35
21	627.06	7.81	4898	−0.74
22	622.44	7.68	4778	−3.19
23	629.54	7.82	4925	−0.20
24	635.69	7.72	4905	−0.60

Table 4. Peak-power measurement results (array field 1, combiner box 1).

collaboration is usually the most affordable and most attractive option for the contractor, because the externalisation of tests is minimised.

In collaboration types 2 and 3, the laboratory should at least perform all tests on a randomly selected sample and compare the results with those obtained by the contractor. If these are in agreement, the results of the contractor can be validated.

Examples of application

The commissioning testing proposed in this paper has been successfully implemented in more than 40 PV plants worldwide, in Spain, Italy, the USA, Puerto Rico, India, etc. Some of the results obtained in the commissioning of different PV facilities will be presented in this section.

Mechanical completion: visual inspection of support structures

Figs. 1 and 2 show an example of typical defects detected during the mechanical completion of a large PV plant. Fig. 1 shows that oxide is present on the structure two weeks after its installation. It is very important to perform an adequate galvanising of the profiles, since the high humidity in tropical locations can be critical for the failure of the project. Fig. 2 shows an incorrectly installed omega junction typically used to fix the modules to the structure.

Electrical completion: peak-power measurement of strings

This test is performed to measure the maximum power of the strings in standard test conditions. It is important to point out that the main purpose of the test is to measure the maximum power in order to detect any defects in the installation and connection of the modules, and not to establish an accurate characterisation. The reason for this is that the on-site measurement of maximum power depends on the soiling, electrical interconnection and existing solar spectrum conditions during the test period. Nonetheless, all precautions for minimising measurement uncertainty should be taken during the tests, which should therefore be carried out by experienced technicians.

The following equipment was used for the maximum-power measurement procedure:

- A reference cell in accordance with IEC 60904-2 [7].
- A temperature sensor to measure cell temperature.
- An electronic load equipped with a data logger to obtain *I-V* curves.

The *I-V* curve was obtained in accordance with IEC 60904-1 [8], while temperature and irradiance corrections were performed in accordance with IEC 60891 [9]. The test was conducted on a sunny day; to minimise spectral errors, the measurements were taken during the period two hours before and after solar noon, when the irradiance in the plane of the modules was above 700W/m^2.

The facility was a 20MW PV plant: the main characteristics are presented in Table 3.

Table 4 shows the test results of 24 strings measured directly in a combiner box and their power deviation values with respect to the nominal value. The power losses due to mismatch and cabling are not considered in the calculation of the nominal power. Fig. 3 shows the peak power of each string within the tolerance range of the modules. The error bars correspond to an uncertainty of ±5% (K = 2). According to the results shown in Table 4, the deviation with respect to the nominal power is lower than the uncertainty of the measurement: all strings can therefore be considered to conform.

Monitoring system: DC voltage verification

The verification of the DC voltage presented in this section was carried out at two large PV plants located in India: Table 5 shows the main characteristics of the plants.

This test aims to verify data provided by the SCADA system for the measurement of the DC voltage in the inverter. The equipment used was a high-precision wattmeter that had been accurately calibrated. The DC

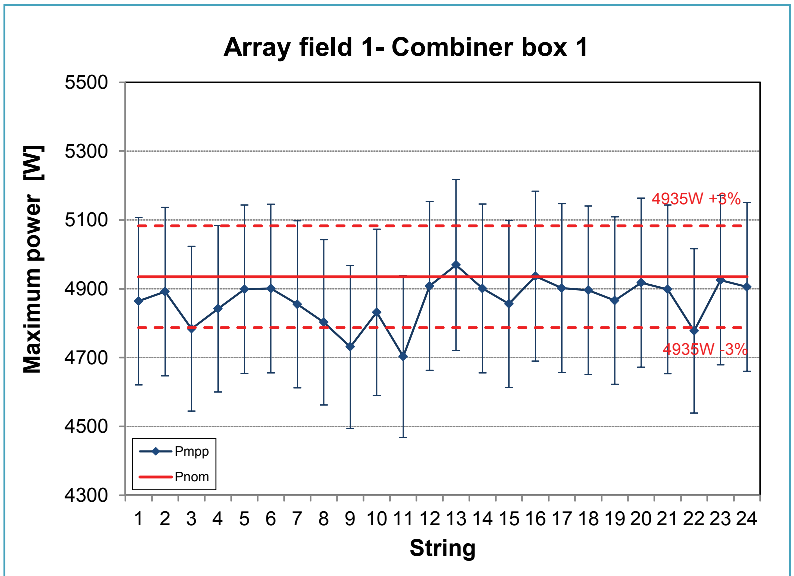

Figure 3. Peak-power position of each string in the tolerance range of the modules (±3%).

	Facility A	Facility B
Total measurements	361	361
Accepted	346	351
Rejected	15	10
Gaps	0	0
% rejected	4.15	2.77

Table 6. Results of the DC voltage verification in the monitoring system.

	Facility A	Facility B
Total capacity	5.5MWp	16.7MWp
Module technology	CdS/CdTe (First Solar FS 382)	CdS/CdTe (First Solar FS 382)
Total modules	67200	203100
Structure type	20° fixed-tilt, 0° azimuth	20° fixed-tilt, 0° azimuth
Total inverters	7 (680kWp)	22 (680kWp)

Table 5. Main characteristics of the tested PV plants in India.

voltage values were measured and recorded by the wattmeter; these measurements were then compared with the values displayed by the SCADA system, taking into consideration the uncertainty of measurement.

Data acquisition was performed during sunny days without clouds. To minimise spectral errors, measurements were taken during the period three hours before and after solar noon, when the incident irradiance was greater than 500W/m^2. The measurements were collected in one of the lines of the DC input of the inverter.

In accordance with the acceptance and rejection criterion of IEC 61724, the measurement is accepted when the SCADA measurement does not differ from the wattmeter value (reference value) by more than ±1%. Table 6 shows the accepted and rejected measurements.

Results of the DC voltage verification at facility A indicate that out of 361 measurements during the test, 15 samples exceeded the 1% limit: these samples represented 4.15% of the total number. However, better results were obtained at facility B, with the percentage of rejected measurements being 2.77%.

Facility A			
Date	*E* [kWh]	I_{gen} [Wh/m^2]	*PR* [%]
27 Feb	33,891	7,384	82.79
28 Feb	33,622	7,448	81.42
01 Mar	31,183	6,556	85.80
02 Mar	34,859	7,701	81.66
03 Mar	34,571	7,774	80.21
04 Mar	34,659	7,733	80.85
05 Mar	34,029	7,548	81.32
06 Mar	33,713	7,367	82.54
Total	270,526	59,509	82.0

Table 7. Performance ratio calculations for facility A.

Facility B			
Date	*E* [kWh]	I_{gen} [Wh/m^2]	*PR* [%]
11 Mar	89,972	6,444	83.33
12 Mar	89,963	6,412	83.74
13 Mar	54,851	3,693	88.65
14 Mar	100,720	7,009	85.77
15 Mar	105,255	7,293	86.13
16 Mar	84,606	6,251	80.80
17 Mar	104,679	7,458	83.77
18 Mar	101,908	7,402	82.17
Total	731,955	51,962	84.07

Table 8. Performance ratio calculations for facility B.

Availability and performance ratio

The performance of a PV plant is commonly specified in terms of its PR, which is represented by a percentage given by the ratio between the expected and theoretical energy outputs. On the basis of the data provided by the energy meters and the irradiance measured in the PV facilities during an eight-day period, the PR was calculated for both of the facilities detailed in Table 5: the results are given in Tables 7 and 8.

It should be noted that the PR includes the following losses: spectral, angular, shading, soiling, temperature, irradiance level, mismatch, low-voltage wiring, inverter, MPP tracking, availability, degradation, transformation (at plant transformer) and medium-voltage wiring (from plant transformer to plant energy meter).

However, neither the medium-voltage wiring losses from the plant's energy meter to the network operator's high-voltage transformer, nor the high-voltage transformer losses, where the recording energy meter is located, are included in the calculation.

"The results of the implementation of the proposed methodology demonstrated a reduced uncertainty in the final performance of the plants in all cases."

Conclusions

It is worth noting the importance of assuring quality-control aspects throughout the entire implementation process, beginning at the PV module manufacturing stage and continuing beyond the commissioning, to the operation and management of PV plants that are up and running.

This paper has described some key aspects of one specific step of the quality-control process: the commissioning tests. This was considered to be the most critical stage for the future performance and reliability of a PV installation. The proper commissioning of a new PV installation allows the accurate determination of essential aspects: the detection of early failures and the assurance of availability once the plant is in operation.

The results of the implementation of the proposed methodology for the commissioning tests of large PV plants demonstrated a reduced uncertainty in the final performance of the plants in all cases. The consequence of this is an increase in investor confidence in the PV market. ■

Authors

Jorge Coello has14 years' experience in the solar energy sector and currently manages the R&D department at Enteris Solar.

Leonardo Perez is currently a Ph.D. candidate in photovoltaic solar energy at the Solar Energy Institute of the Polytechnic University of Madrid.

References

[1] Coello, J. et al. 2008, "Quality control during the supply of PV modules: Fundamental key to guarantee the profitability of PV installations", Proc. 23rd EU PVSEC, Valencia, Spain, pp. 3784–3787.

[2] Coello, J. 2011, "Degradation of crystalline silicon modules: A case study on 785 samples after two years under operation", *Proc. 26th EU PVSEC*, Hamburg, Germany, pp. 3500–3503.

[3] Coello, J. 2011, "Introducing electroluminescence technique in the quality control of large PV plants", *Proc. 26th EU PVSEC*, Hamburg, Germany, pp. 3469–3472.

[4] Coello, J. et al. 2012, "Verification of the installed peak power in the commissioning tests of large PV plants", *Proc. 27th EU PVSEC*, Frankfurt, Germany, pp. 3983–3985.

[5] ISO/IEC 17025:2005, "General requirements for the competence of testing and calibration laboratories".

[6] IEC 61724:1998, "Photovoltaic system performance monitoring – Guidelines for measurement, data exchange and analysis".

[7] IEC 60904-2:2007, "Photovoltaic devices – Part 2: Requirements for reference solar devices".

[8] IEC 60904-1:2006, "Photovoltaic devices – Part 1: Measurement of photovoltaic current-voltage characteristics".

[9] IEC 60891:2009, "Procedures for temperature and irradiance corrections to measured I–V characteristics".