AN 800 KW PV GENERATOR I-V CURVE

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ABSTRACT: This paper presents the measurement of the I-V curve of an 800 kW PV generator by means of an own-made capacitive load. Along the lines of some previous works, it is shown that an I-V curve analysis can also be applied to big PV generators and that, when measuring the operating conditions with reference modules and taking some precautions (especially regarding the operating cell temperature), it is still a useful tool for characterizing them and therefore can be incorporated into maintenance procedures. As far as we know, this is the largest I-V curve measured so far.
Keywords: I-V curve, in-field measurements, quality control, PV generator

1 INTRODUCTION

On-site I-V curves of PV generators are a useful tool for assessing not only the effective peak power but also for diagnosing possible performance anomalies (shadows, hot-spots, polarization, connection failures, etc.) They are usually applied to relatively low powers, typically below 100 kW, which is likely due to the practical difficulties of dealing with large currents. In fact, as far as we know, commercial I-V tracers are limited to 100 A. This restricts the possible analysis to modules or series. Nowadays, however, generators of up to 1.2MW are found in PV installations, which mean currents well above 1,000 A.

Along the lines of some previous works, this paper presents the I-V curve of an 800 kW generator by means of an own-made capacitive load, contributing to show that I-V curve analysis can also be applied to big PV generators [1,2]. As far as we know, this is the largest I-V curve measured so far. Once obtained, the I-V characteristics were extrapolated to Standard Test Conditions (STC) according to IEC-60891[3] using the incident irradiance, G, and the cell operation temperature, T_C, registered by means of two reference modules.

2 I-V CURVE MEASUREMENTS

a. The PV generator

The measurement took place at a 10 MW PV plant connected to the grid and located in Zamora (in the North-West of Spain) on the 15th of June 2012. This PV plant is made up of twelve 800 kW generators, each of which is connected to its respective inverter. Every generator consists of 712 parallel connected strings, each of which is made up of the series connection of 14, 80 W cadmium telluride modules. The nominal values of the PV generator, resulting from the flash-list information given by the manufacturer, are: short-circuit current: 1,350 A; open-circuit voltage: 851 V; and nominal power: 803,880 W.

Every inverter has 9 bipolar entries, able to accommodate the cables coming from an equal number of DC boxes in the field. These entries are paralleled inside the inverter through a flat bar. We connected our I-V tracer to this bar, thus measuring the whole generator. It is worth noting that, in this way, our measurements have been made at the inverter entry. In other words, corresponding results include all the losses up to this point (possible early degradation, module mismatching, DC wiring, etc).

b. The I-V tracer

We used an up-scaled in-house-made capacitive load based on insulated gate bipolar transistors (IGBT) that has been described in previous publications [4]. Figure 1 presents a simplified scheme. The key features are as follows:

- An 800 V/16.7 mF capacitor. Roughly, the capacitor charging process is described in terms of a time constant $\tau = RC$, with C being the capacitance and R being the resistance determined by the open circuit voltage (V_{OC}) and the short circuit current (I_{SC}) of the generator ($R = V_{OC}/I_{SC}$). Here τ = 10.5 ms, which leads to charging times of about 20 ms, large enough to avoid transient influences[4].
- A 900 A / 1,200 V IGBT. In this case, the current measured is nearly a 40% higher than the limit of the continuous IGBT current (400 A), but due to the very low charging times it causes no damage to the transistor.
- A 1,000 A/150 mV 0.5 class (uncertainty of ±0.5%) shunt resistance for measuring the current at the entrance of the load (figure 1b).
- A four wire connection configuration, with the voltage taken in the connection point, to avoid considering any voltage drop in the I-V tracer cables.
- A negative voltage capacitor pre-charge, using a battery, for assuring the capacitor to pass through the short-circuit point. Because of the large current value, there was a voltage loss in the I-V tracer cables of about 48 V between the connection point and the entrance to the load. The negative voltage pre-charge compensates for this fact by allowing the PV generator to pass through the short-circuit point during the charging process.

In order to minimize the noise/signal relation, we used a four isolated channel oscilloscope (Metrix Scopix OX7104-c) for acquiring the current and voltage signals coming from the generator and the irradiance and the cell operation temperature coming from the reference modules.

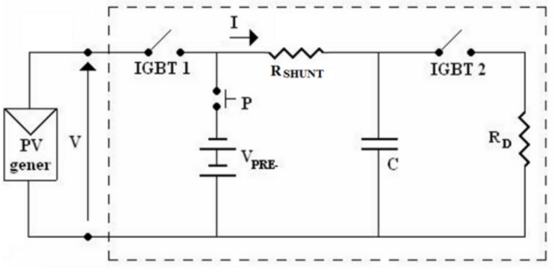

Figure 1: Simplified circuit design. Both IGBTs function as switchers, RD is the capacitors discharge resistance, VPRE the pre-charge battery (acted by switcher P) and C the capacitor.

c. Measuring conditions

Measuring operating conditions, i.e. incident irradiance (G) and cell operation temperature (T_C), were registered (through I_{SC} and V_{OC}) from two reference modules, previously stabilized and calibrated outdoors at the IES-UPM facilities. The calibration traceability is referred to the CIEMAT. Due to technological factors, the corresponding uncertainty for these modules is higher than for crystalline silicon modules: 5.0% in I_{SC}, V_{OC} and P_M. These modules are from the same batches, and therefore, of the same type, as those that make up the generator. The use of reference modules is the best option when trying to reduce the uncertainty associated to spectral, angular and thermal responses [2,5,6]. They were installed in the generator's structure in a position free from shadows. Just as a precaution to prevent the uncertainty associated with the effect of dust in the measurements, the reference modules were installed more than 15 days in advance, thus guaranteeing similar dust coverage, as can be observed in Figure 3.

The main source of uncertainty when measuring the I-V curve of large PV generators on-site is that associated with the T_C determination [2]. The bigger the generator and the higher the wind speed, the larger the T_C spread among the generators and, therefore, the less representative the value given by a single reference module. To limit the corresponding uncertainty, it is worth guaranteeing the following: charging times of around 20 ms, incident irradiance of more than 800 W/m2, diffuse/global irradiance proportion (D/G) lower than 20%, and wind speed lower than 3 m/s. As presented in Table 1, in this case the weather conditions easily fulfilled these requirements. In any case, a thermographic inspection of the installation showed mean temperature differences between the reference module and the modules forming the generator lower than 3 ºC.

3 RESULTS

Figure 4 presents the evolution of the current (light line) and the voltage (dark line) during the charging process. As it can be observed, the charging time is more than 18 ms, which allows fill factor errors to be avoided in the measurement [4,7,8]. Despite it is not relevant for the final results, it is interesting to note the acute peak current (≈1,600 A), at the beginning of the capacitor charging process. It occurs due to the displacement of majority carriers, inside both the *p* and *n* zones, required to adapt the length of the depletion zone of the *p-n* junction to the solar cell applied voltage. Switching on the capacitor means the PV generator suddenly changes from open circuit to short circuit conditions. Hence, the length of the depletion zone must be significantly reduced. This process usually lasts for less than 0.2 ms and does not affect the measurement. In fact, it only appears in I-V curves when they are captured with a relatively high sampling frequency. Here, we have used 12.5 kHz. On the other hand, as a precaution to prevent any difference between the voltages reached at the capacitor terminals and the real open circuit voltage, the latter is also measured just before the charging process.

Figure 3: View of the reference modules installation above the generator: there are no appreciable differences in dirtiness.

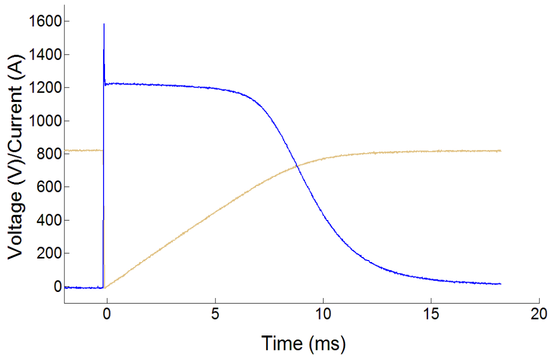

Figure 4: Evolution of I and V during the charging process. The displacement current peak can be observed at t=0.

Once obtained, the curves were extrapolated to Standard Test Conditions (STC) in accordance with IEC-60891 (procedure 1) using the current and voltage temperature coefficients given by the manufacturer, which are α =0.04 %/ºK and β=-0.27 %/ºK, respectively. It is worth noting that V_{OC}^* and I_{SC}^* have been calculated by linear extrapolation from the points around them [3,9]. The series resistance (R_S) was supposed constant throughout all the operating conditions and estimated assuming a variable fill factor, following the equations proposed by Green [10]. This method has been demonstrated a good approximation [11]. The curve correction factor (κ) was fixed at 1.25x10-3 Ω/ºC. Figure 5 shows the I-V curve under real operating conditions (dark line) and once extrapolated to STC (light line). Table 1 and 2 present, respectively, the operating conditions during the measurement process and the main characteristics of one of the I-V curves obtained. Table 3 summarizes the mean values obtained after 4 measurements. The average maximum power of the PV generator resulted $P^*_{M,IEC-60891}$= 784044 W. It is worth mentioning that the uncertainty of the measured power in one curve is less than 1.5% and that of the extrapolated power is lower than 5.0%. These values have been calculated following a type B evaluation as established by the “Guide to the expression of the uncertainty in measurement” [12]. The main uncertainty factors have been the calibration of the reference modules and the temperature coefficients [13].

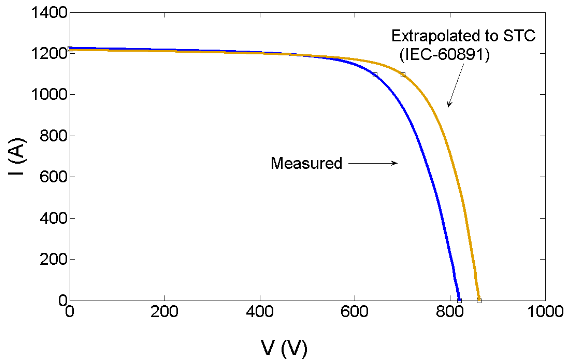

Figure 5: I-V curve measured (dark line) and extrapolated to STC (light line).

Another way of obtaining the maximum power at STC is to calculate the maximum power from the measured curve and then translate it by using

$$P_M^* = P_M \times \frac{G^*}{G_M} \times \frac{1}{1+\delta(T_C - T^*)}$$

where subscript $_M$ means measured, superscript * means STC and δ=-0.24 %/ºK is the power temperature coefficient given by the manufacturer [2,14]. Despite its simplicity, there is experimental evidence of this equation being as good as more complex ones [15]. This way, the average maximum power resulted in $P^*_{M,\delta}$ = 742728 W. The difference between both extrapolation methods gives an idea of the uncertainty associated with these procedures and of the coherence of the temperature coefficients. In this case the difference is 5.5 %, higher than what has been obtained in other cases and probably due to incoherencies between the temperature coefficients.

Location	**Zamora (NW of Spain)**
Date	**15th of June, 2012**
Hour	**15:37**
G [W/m^2]	**992**
D [W/m^2]	**112**
T_C [ºC]	**42.5**
Wind speed [m/s]	**<2.0**
Air mass	**1.17**
t_{CHARGE} [ms]	**18.6**

Table 1: Operating conditions during the measurements

	Measured values	STC values
I_{SC} [A]	**1225.7**	**1237.0**
V_{OC} [V]	**820.2**	**860.3**
I_M [A]	**1095.4**	**1114.8**
V_M [V]	**641.7**	**699.0**
$P_{M,\ IEC-60891}$ [W]	**702872**	**779267**
FF	**0.699**	**0.732**
$P_{M,\ \delta}{}^*$ [W]	**702872**	**740617**
κ [Ω/ºC]	**1.25 x 10^{-3}**	**1.25 x 10^{-3}**
R_S [Ω]	**0.114**	**0.097**

Table 2: Main results of one of the I-V curves obtained.

	Mean ± Δ		
$I_{SC}{}^*$ [A]	**1240.0**	±	**6.4**
$V_{OC}{}^*$ [V]	**862.3**	±	**5.1**
$I_M{}^*$ [A]	**1114.6**	±	**4.2**
$V_M{}^*$ [V]	**703.4**	±	**10.6**
$P_{M,\ IEC-60891}{}^*$ [W]	**784044**	±	**11067**
FF^*	**0.733**	±	**0.003**
$P_{M,\ \delta}{}^*$ [W]	**742728**	±	**4894**

Table 3: Mean and standard deviation values of the I-V curves obtained.

As has been presented in previous works, I-V curve measurements can be compared with those made using a wattmeter [2]. For this PV generator, the analysis with the wattmeter results in a extrapolated maximum power of $P^*_{M,Watt}$ = 757.811 W. The difference between both procedures (2.0%) is within the uncertainty range, what indicates coherence and validates the results obtained.

4 CONCLUSIONS

This paper presents the measurement of the I-V curve of an 800 kW PV generator by means of an own-made capacitive load. It has been shown that I-V curve analysis can also be applied to big PV generators and that, when taking some precautions (especially regarding the T_C), it is still a useful tool for characterizing them and therefore can be incorporated into maintenance procedures.

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