Photovoltaic plant maintainability optimization and degradation detection: Modelling and characterization



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# Photovoltaic plant maintainability optimization and degradation detection: Modelling and characterization

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ABSTRACT

Efficiency degradation due to modules soiling is a key factor in photovoltaic plants, which must be accurately taken into account in order to set a maintenance program, which optimizes the production/cost ratio.

In this paper a model is developed, which accounts for the losses in the energy production due to dust and other kind of dirt.

A small PV system with a proper measurement bench and a reference panel kept clean was set up allowing to identify different shading effects due to different kinds of soiling.

Early results allowed identifying different soiling factors on current and voltage. This will enable the development of a smart system optimizing the PV plant maintenance, especially for the module cleaning interventions.

## 1. Introduction

Photovoltaic (PV) modules represent the most reliable elements of a PV system: reliability tests results demonstrated a mean lifetime higher than 20 years. The reliability issue becomes more complex when a PV field is considered [1]. In this case, the reliability model has to include several other components such as, for example, by-pass diodes, string diodes, cables, connectors and so on, and this makes any faults difficult to be detected.

A continuous monitoring of the photovoltaic plant is mandatory in order to promptly detect the presence of an abnormal situation and for maintenance operations planning. It is well known that the evaluation of reliability and maintainability performances can be done if the failure conditions for the equipment under test are known. In order to maximize the aforementioned characteristics, failure modes would be taken into account, studied and predicted [2–4].

Among maintenance activities, one of the more considered is that related to the cleaning of the module surface. In literature, many studies analyse the efficiency degradation due to the presence of dust on PV modules [5]. Losses due to the dust have an important impact in PV module and plant performances: the worst case, related to this factor, has been evaluated around 7% in [6]. In [7] an economical model, which takes into account the impact of dust in terms of efficiency reduction and economical energy loss evaluation, is proposed, assuming that radiation data are provided by a measurement station located in the same place of the plant.

In this paper, starting from a work on the PV modules Maximum Power Point (MPP) monitoring, a new approach is proposed, where the electrical model of a PV module is used to reveal the soiling state based on measurements performed on a reference module. Different test conditions were used to develop and calibrate the proposed improved model:

- uniformly distributed dust on the module surface;
- module with one or more cells completely obscured;
- module with a number of cells partially obscured.

## 2. State of the art of PV modules monitoring systems

Typically, the Performance Ratio (PR) is the quantity measured for evaluating the overall behaviour of a PV plant. The performance of the power plant depends on quite a lot of parameters including the site location, the climate, the mismatches, the temperature, and dirt or dust on modules.

The main tasks of a monitoring system are to continuously measure the energy yield, to assess the PV system performance and to timely

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identify design defects or failures. In many large PV systems, this is done by mean of an analytical monitoring to prevent economic losses. To help the PV plant designers, some guidelines have been published [8,9] where the requirements of the so-called analytical or detailed monitoring include an automatic dedicated data acquisition system with a minimum set of parameters to be monitored. During the last years many low cost development boards as Arduino or STM32 Nucleo, enabled to add other parameters to better assess the PR (*e.g.* [10]).

More figures and parameters can be useful, not only to better foresee or merely to check with higher accuracy if the actual production is the expected one. The difference between expected and produced energy is the main parameter in the definition of a maintenance scheduling, then the performance of the plant for different radiation conditions is required [7], and also the knowledge of environmental (air and module temperatures, irradiance) and electrical parameters (voltage and current) is mandatory.

An optimized maintenance can increase the reliability of the system, and can reduce the plant downtime. The development of smart grids is increasing the introduction of a smart maintenance as, for example, in [11,12], which needs to acquire data of many figures and parameters of the plants connected to grids.

The main drawback of a monitoring system of a large PV plant could be represented by the management complexity, in terms of both hardware and software, of a large number of measurement sections, and then it is important to define clearly the target of the monitoring system.

The acquisition system presented here is for future smart maintenance systems of small to medium scale PV plants in micro and nano-grids.

The solution proposed is based on the use of a reference PV module, to define a flexible architecture to support the energy monitoring and to analyse the failure mode represented by the dust deposition on the PV surface. If a reference module is chosen following a statistical approach, it could represent, with a given confidence level, the behaviour of the PV plant in different conditions of dust deposition and aging, as proposed in [13].

## 3. PV module modelling

Many different models of PV panels can be found in the literature. However, for many applications the single-diode equivalent circuit (Fig. 1) represents an excellent trade-off between accuracy and simplicity. In fact, sometimes the potential advantages of more complex models, containing different exponential terms, are masked by the measurement uncertainty of their parameters.

The model of Fig. 1 can be further simplified, because in many cases the shunt resistance $R_{sh}$ can be neglected.

In order to consider the dependence of the model parameters on the environmental conditions (in particular on $T_c$ and $G$, the cell temperature and the irradiance, respectively), the following well-known expressions can be employed [14]:

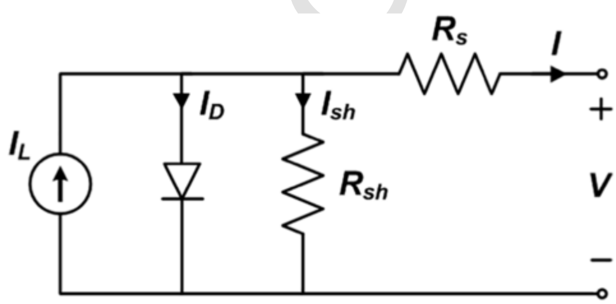



**Fig. 1.** Single-diode equivalent circuit of a PV cell or module.

$$I_{sc}\left(G,T_c\right) = I_{sc0}\frac{G}{G_0}\left[1+\alpha\left(T_c-T_0\right)\right] \tag{1}$$

$$V_{oc}\left(G,T_c\right) = V_{oc0}\left[1+\beta\left(T_c-T_0\right)\right] + V_{T0}\ln\left(\frac{G}{G_0}\right) \tag{2}$$

$$V_T\left(T_c\right) = V_{T0}\frac{T_c}{T_0} \tag{3}$$

where $V_{oc0}$, $V_{T0}$, and β are the open circuit voltage at STC (Standard Test Conditions), the thermal voltage at STC, and the voltage temperature coefficient of the PV module respectively. It should be noted that the series resistance $R_s$ is just slightly affected by irradiance and temperature, hence it can be considered as constant.

For a known cell temperature $T_c$ and solar irradiance G, all the parameters can be estimated with closed-form expressions from the currents at the short circuit voltage, the maximum power point, and the open circuit voltage. These quantities can be easily measured, but they are often declared by the manufacturer of the module under STC. Hence, an estimation of the model parameters from the datasheet is possible, but best results are obtained from direct measurement, because of manufacturing tolerances.

## 4. Monitoring system for soiling effects studies

In order to improve the model and estimate dust deposition or other kind of dirt on the glass surface of the PV module, an *ad-hoc* test bench was set up with three 240 Wp monocrystalline modules having the following figures declared by the manufacturer at STC: $V_{oc} = 37.4$ V, $I_{sc} = 8.6$ A, $V_{mp} = 29.6$ V, $I_{mp} = 8.12$ A, *Power tolerance* = 3%. Each module is composed by 60 mono-crystalline silicon cells (156 × 156 mm), placed in series, with a by-pass diode every 20 cells. The modules used in the test bench, were produced from the same batch of manufacture, and flash tests showed that they are almost identical. Furthermore, they are mounted close together with the same Tilt Angle (28°) and orientation (Azimuth Angle = 180° - South) in order to work in the same conditions.

While one of the modules will always be kept clean for reference, the other two can be intentionally covered by controlled quantities of dust or other shadowing samples of different diameters, in order to emulate other soiling causes (*e.g.* bird droppings). Fig. 2 shows a picture of the PV modules of the test bench. The irradiance is measured by a sensor made with a mono-Si reference cell, kept carefully clean.

Each module is monitored by a STM32 Nucleo board, which acquires the I-V curve applying the capacitive load technique [15], because it needs a short time to obtain the curve. This is almost mandatory for outdoor operating modules because the irradiance can change during the curve acquisition. Fig. 3 shows a schematic diagram of the acquisition system made using the STM32 Nucleo F334R8 board, which is equipped with two ADCs to acquire at the same sampling times the current and the voltage of the module during the charge of the capacitor. The current is measured by mean of a shunt resistor. Its resistance has been chosen to get a minimum voltage very close to zero. The ambient and modules temperatures are measured with PT100s, while the irradiance is measured with an analog direct sensor. Some signal conditioning circuits have been added, to meet the requirements of the microcontroller board analog inputs. The cell temperature is measured with a PT100 placed in the middle of the module,

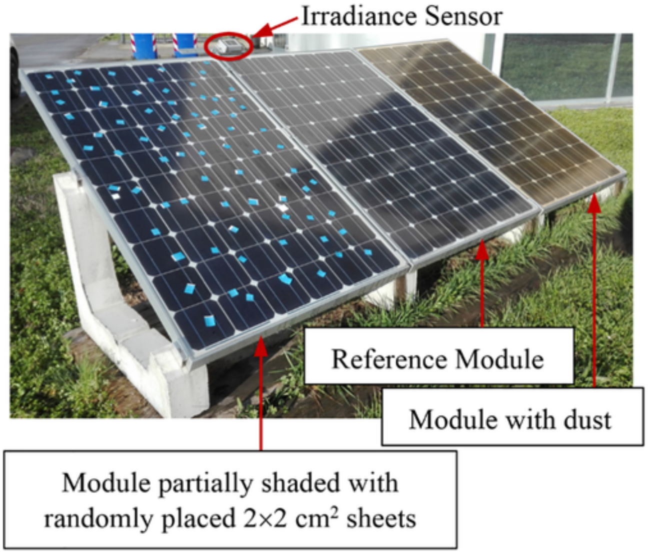



**Fig. 2.** Test bench for experimental evaluation of the energy reduction due to dust and partial shading: modules and irradiance sensor.

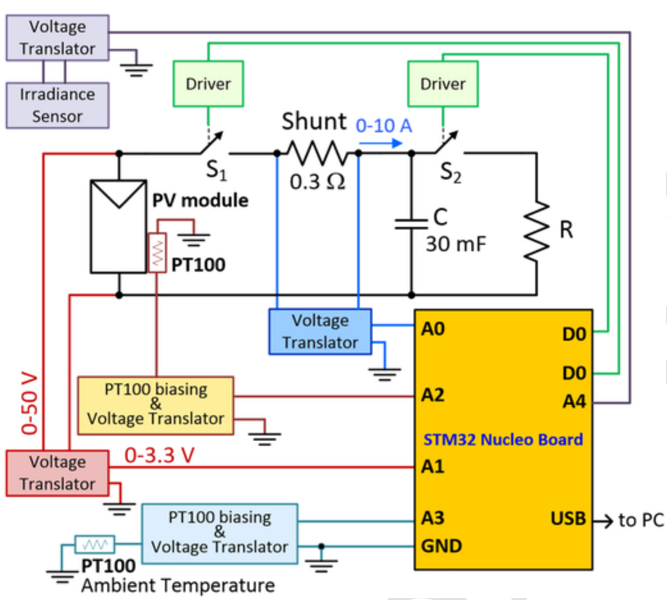



**Fig. 3.** Schematic diagram of the acquisition system made to assess how the dirt can affect the efficiency of a module. Each module of Fig. 2 is monitored with a PT100, two relays, a shunt resistor, a capacitor, a discharge resistor, and a STM32 Nucleo board, together with biasing, conditioning and driver circuits, to measure its temperature and the I-V curve.

on the backside. Two digital outputs are used to drive two solid-state relays ($S_1$ and $S_2$). The I-V curve acquisition starts closing $S_1$ with the capacitor $C$ not charged (short circuit); when $C$ is fully charged (open circuit), the acquisition can be stopped opening $S_1$, and $C$ can be discharged through $R$ closing $S_2$.

The acquired data are sent *via* USB to a PC, where some applications run to process and store them. Fig. 4 shows some screenshots of the applications developed for PC, tablets and smartphones to control the acquisitions and to monitor the acquired curves. When the PV plant can operate, to avoid service interruptions, the I-V curve can be acquired early in the morning and or toward the sunset, at low irradiance levels, just a moment before the start, or just after the stop of the service.

In this work, the sampling time is short because at this stage it is important to collect as much as possible data to get statistical information, which can be useful to implement a smart system.

Even if not shown in Fig. 3, an IR camera is used during the tests to measure the temperature of the whole set of modules.

This device will highlight the presence of any hot spots, allowing a better relating of the electrical behaviour with some kinds of faults. Fig. 5 shows an IR picture of the PV array without hot spots.

## 5. Preliminary experimental results

As an example, Fig. 6 shows some measurement results of the I-V curves obtained by a module, at the same level of irradiance, with different kinds of dirt.

The results of Fig. 6 are in agreement with the effects of soiling shown in [5].

When the soiling causes a soft shading, the effect on the module characteristics are shown in Fig. 7. Here the measured $I_{sc}$ is lower than the one of the reference module, thus by inverting the Eq. (1), it is possible to evaluate the effective irradiance of the rays at the front glass surface:

$$G' = \delta G \tag{4}$$

where G is the irradiance measured by the irradiance sensor, and $\delta \leq 1$ can be defined as the current soiling factor, which takes into account the filtering effect of the dirt on the module. Once $I_{sc}$ and G are known, it is possible to evaluate δ.

As can be seen in Fig. 8, when the soiling causes a hard shading (*i.e.* when a solid, such as accumulated dust, blocks the sun light in a clear and definable shape – *e.g.* birds' droplets covering entirely some cells), the voltage ($V_{mp}$ and/or $V_{oc}$) decrease consistently. The curves with one and two obscured cells in Fig. 6 are in agreement with this behaviour. In this case, $I_{sc}$ remains more or less the same, thus Eq. (4) will give a soiling factor $\delta \cong 1$, but it is possible to define a soiling factor related to the open circuit voltage:

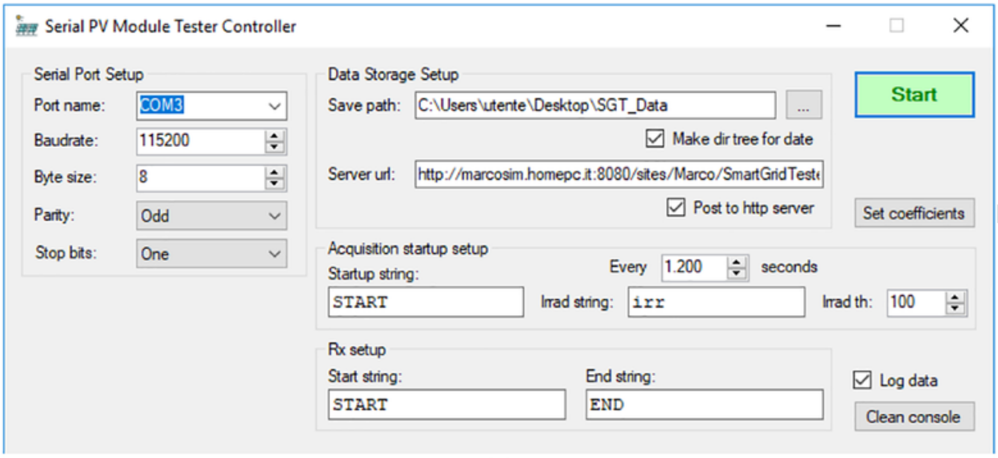
$$\rho = V_{oc}/V_{oc\_ref} \tag{5}$$

where $V_{oc\ ref}$ is the open circuit voltage of the reference module kept clean.

In the case of cells entirely obscured, can be effective the insertion of by-pass diodes across one or more cells in series. Typically, the whole cells series is divided in sub-series, each one equipped with a by-pass diode. When one or more cells of a sub-series are obscured (or in open-circuited failure mode) the effect on the module I-V characteristic is the reduction of the $V_{oc}$ (with a sub-series of n cells, it is reduced of $n{\cdot}V_{oc\ cell}$, where $V_{oc\ cell}$ is the open circuit voltage of a cell). Thus, considering this kind of degradation in a module composed by a series of cells with k by-pass diodes and obscured cells in $i \leq k$ different sub-series, Eq. (2) can be rewritten as follows:

$$V_{oc}\left(G, T_c\right) = \\ = (k - i) \times \left\{ V'_{oc0}\left[1 + \beta'\left(T_c - T_0\right)\right] + V'_{T0}\ln\left(\frac{G}{G_0}\right)\right\} \tag{6}$$

where $V_{oc0}'$, $V_{T0}'$, and $\beta'$ are the open circuit voltage at STC, the thermal voltage at STC, and the voltage temperature coefficient of the sub-series, respectively.


Serial PV Module Tester Controller
Serial Port Setup
Port name: COM3
Baudrate: 115200
Byte size: 8
Parity: Odd
Stop bits: One
Data Storage Setup
Save path: C:\Users\utente\Desktop\SGT_Data
Make dir tree for date
Server url: http://marcosim.homepc.it:8080/sites/Marco/SmartGridTeste
Post to http server
Start
Set coefficients
Acquisition startup setup
Startup string:
START
Every 1.200 seconds
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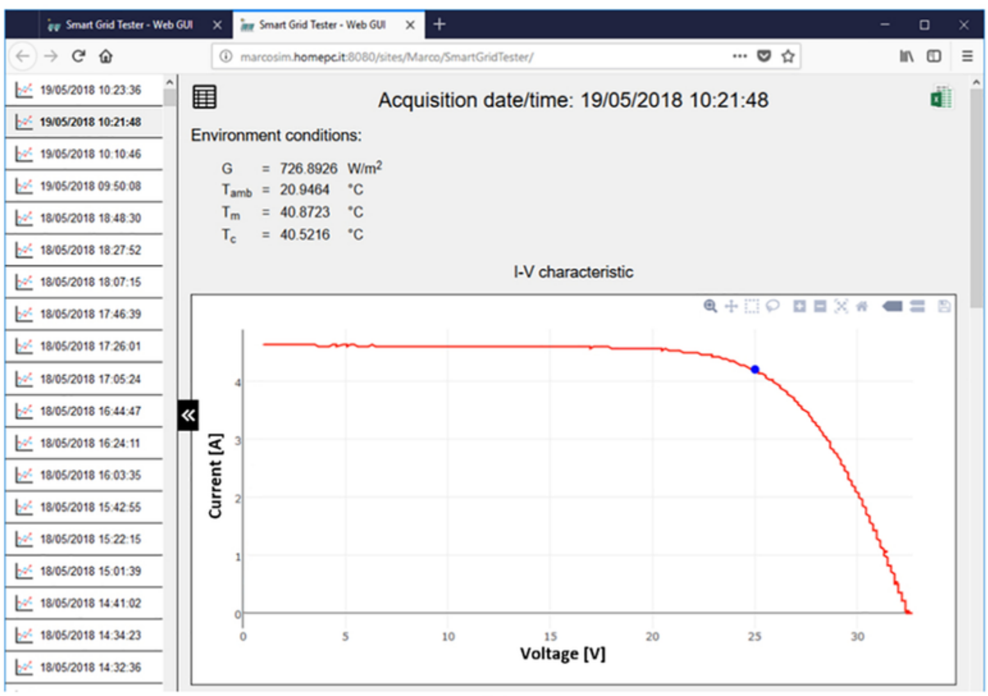
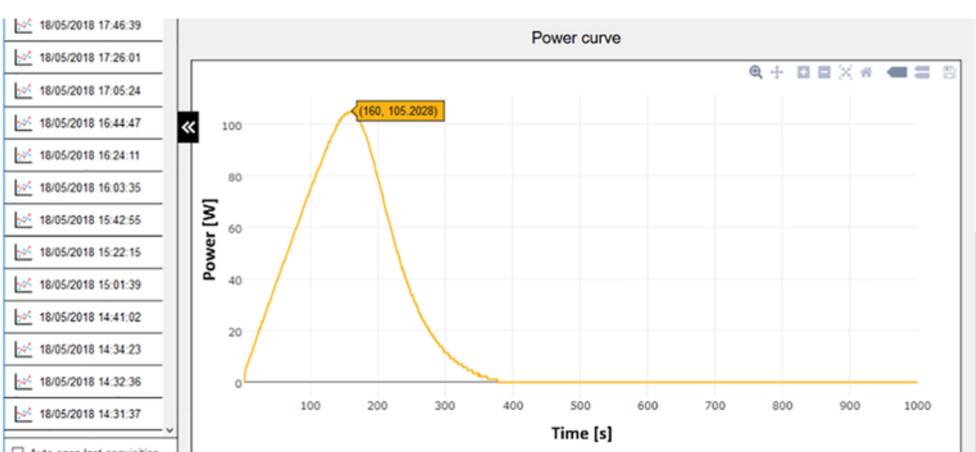
Irrad th: 100
Rx setup
Start string:
START
End string:
END
Log data
Clean console

(a)


Smart Grid Tester - Web GUI
Acquisition date/time: 19/05/2018 10:21:48
Environment conditions:
G = 726.8926 W/m2
Tamb = 20.9464 °C
Tm = 40.8723 °C
Tc = 40.5216 °C
I-V characteristic
Current [A]
Voltage [V]

(b)


Power curve
(160, 105.2028)
Power [W]
Time [s]
Auto open last acquisition

(c)

**Fig. 4.** Screenshots of the software applications made for the monitoring system: (a) window of the tool to manage measurement and connection setup (left); web app to analyse the acquired data: (b) the window showing the irradiance, the temperatures and the I-V curve; (c) the window showing the module power during the I-V curve acquisition.

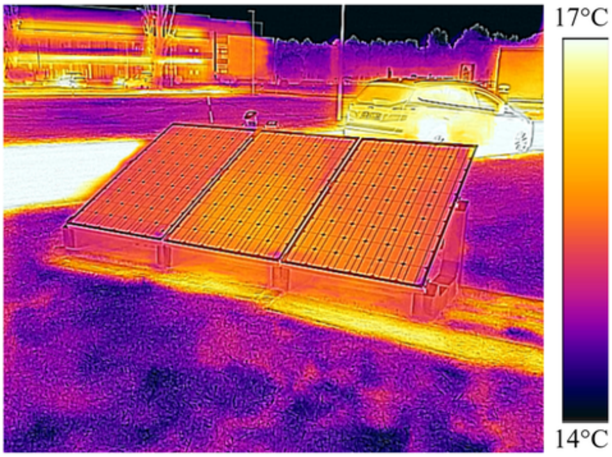



**Fig. 5.** Thermal image by the FLIR IR camera used to monitor the temperature of the PV array front side.

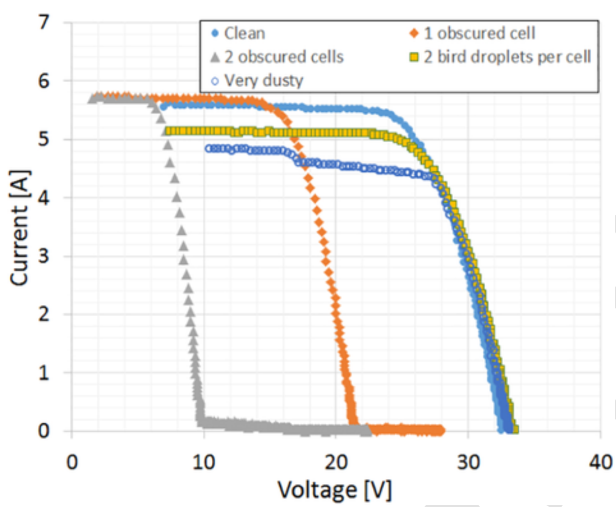



**Fig. 6.** Effect of the dirt on the I-V curve of a 240 Wp mono-Si module ($G = 940\,\mathrm{W/m^2}$). In the case of 2 obscured cells, these ones were in two different series by-passed by a diode (the modules under tests are made using 60 cells in series with a by-pass diode every 20 cells).

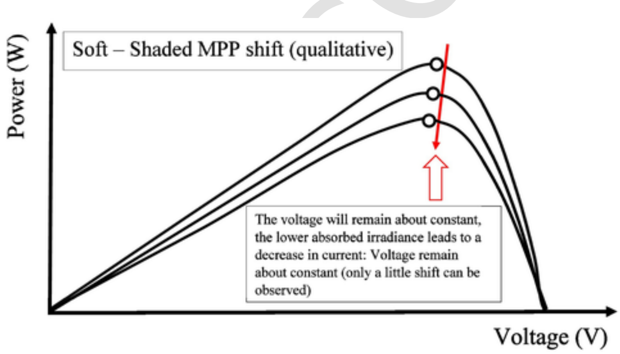



**Fig. 7.** Voltage – Power characteristic for a PV module in case of soft shading. It can be observed that the MPP point shift in a way that the voltage at which the MPP occurs remain about constant [5].

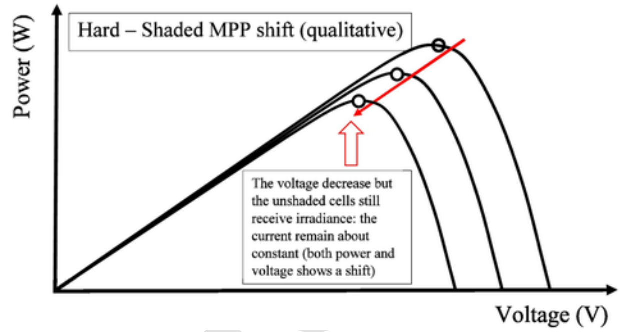



**Fig. 8.** Voltage – Power characteristic for a PV module in case of hard shading. It can be observed that the MPP point shift in a way that the voltage at which the MPP occurs change considerably. This is because the current tends to remain unchanged [5].

If one consider a system based on a multi-string PV array, it should be noted that the current imbalance due to the shading in a string could affect also the currents in the string connected in parallel to the considered string. This effect is due to the presence of the common inverter connected to the parallel strings. Let's now consider the case of hard dust on a surface of a PV array with single string. In this case a reduction of the string voltage will be observed. However, the inverter is able to detect this voltage reduction and immediately regulates it. Moreover, when there is unequal hard dust on different strings connected in parallel, a voltage mismatch shall be observed. Thus, having partial shading, different parallel strings deliver different voltages to the inverter. To obtain the optimum voltage at which the maximum power is delivered, it is a very hard task for the inverter. This leads to the situation theoretically shown in Fig. 9. The situation has been experimentally observed, as depicted in the aforementioned Fig. 6. These aspects have been also excellently discussed in [5].

The consequence is that, in order to consider also a case like this (*i.e.* the case of partial shading), it is mandatory to include in the algorithm of the smart maintenance tool, the search for maximums on the whole I-V curve and then select the absolute maximum.

## 6. Conclusions

A small PV system with a proper measurement bench was set up for an experimental campaign, to evaluate the feasibility of a low-cost

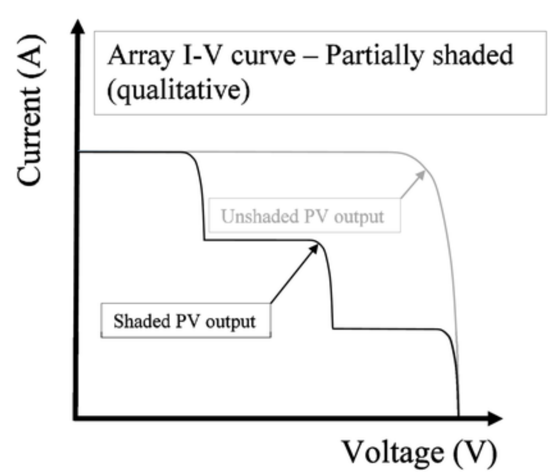



**Fig. 9.** I-V characteristics of a PV array under partial shading condition [5]. (Qualitative figure).

monitoring system to control the PV modules soiling and activate a smart cleaning programme.

Two soiling factors were introduced, to account for effects of dust and partial shading, and measurements are in progress, at different environmental conditions, to collect a large number of data over a long period. The idea is to obtain a database for statistical analysis purposes. This, together with climate data, can be added to a forecast algorithm not only to better evaluate and foresee the energy production, but also to identify in advance degradations due to soiling which can remain for long time, or to reveal open circuit faults. In both cases, this allows to optimize the PV plant maintenance. The proposed approach can be advantageously used both in small and medium-large PV plants. However, in this last case, in order to limit the complexity and the costs of the monitoring system, a simplified approach can be suggested: instead of monitoring the single module, it is possible to operate at the string level. At the current stage, the system here proposed could be considered a valid starting point to assess if it is cost-effective also for large plants, although the model could be improved in the future.

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