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Analyses of the Effectiveness of Power Optimizers in Heterogeneous PV Plants

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ABSTRACT

The number of photovoltaic (PV) plants integrated or applied in buildings is steadily growing. However, these installations often have complex geometries, resulting in strings of PV panels with varying orientations, partial shading, and different levels of sunlight exposure. These factors can cause a loss of power in the PV To maximize the amount of power produced by PV plants characterized by non-uniform operating conditions, it has become common practice to use power optimizers or microinverters. In this study, the energy analyses of different mock-ups of PV plants, constituted by different kinds of PV modules (mono, bifacial and PVT) installed at the University of Catania are presented. All the mock-ups are made up of different types of PV modules, such as mono, bifacial, and PVT, connected in series and linked to a single inverter. Each PV module or group of homogeneous PV modules is equipped with power optimizers. This allows them to operate at the Maximum Power Point (MPP) point. Moreover, the power generated by one PV module managed by power optimizers has been compared with the power generated at MPP, determined through an electronic load, which allows for tracking of the I-V curve. Globally, the results of this research provide interesting observations on the performances and the monitoring of PV plants equipped with power optimizers, as well as verify the ability of the optimizers to effectively exploit the maximum power from the different components of the investigated PV mock-ups. The outcomes of this study may constitute a useful baseline for designers who foresee installing power optimizers in existing or new PV plants.

1. INTRODUCTION

The numerous benefits of photovoltaic (PV) energy systems have determined a continuous growing of their number and size all over the world. Indeed, PV plants use the solar resource, which is a worldwide available energy source, not generate GHG emission and noisy during their operation, are modular and easy to install in open field, or inbuilt environment [1] applied (BAPV) or integrated in the buildings (BIPV) [2]. As a result, the Global Market Outlook Report for Solar Power 2023-2027 predicts almost 402GW of new solar installations in 2023 and 800 GW by 2027, bringing the total operational capabilities to surpass 2TW at the beginning of 2025 and 3.5TW at the end of 2027 [3]. Another plus of solar energy remains the price, which has led in the European Countries to an increment of 44% being installed 14.1GW in 2022, achieving reaching a total installed capacity of 46.1GW. The different components of PV plants can be subject to diverse kinds of faults mainly caused by the external operating conditions: shading effects, module soiling, inverter failure, and mismatch due to variation in manufacturing or aging of PV modules, which determine meaningful energy losses [4]. Thus, fault detection is fundamental to identify malfunctioning by comparing the discrepancies between the measured and calculated PV plants 'performances, while the fault diagnosis (FDi) allows the identification and localization of faults [5].

Faults in a PV plant can be distinguished in permanent (e.g. delamination, bubbles, yellowing of cells, scratches and burnt cells) and temporally (e.g. partial shading effects, soiling and snow). A very common kind of faults can be categorized as Hot Spot, which arise when some cells in a PV string/array have different I-V curves [6], caused by soiling and dust accumulation [7, 8] degradation of the cells, and so on.

Total or partial shadowing of the PV module can be considered as a particular case of the mismatch fault. Indeed, along with reducing the power output, partial shading also determines local heating, raising the temperature of the cell generating thermal stress on the entire module (i.e., hotspot) that could lead to failure of the whole PV module. In extreme conditions, the solar cells' the reverse bias voltage may surpass its breakdown voltage, resulting in cracks and a short circuit at the serial branch to which the cell is connected.

Non-uniform shading can be caused by moving cloud, nearby building, leaf falling from tree, dust, due to which the solar cells/modules receive unequal irradiance and dissimilar cell temperature. Under the uniform irradiance level, the output characteristics curve exhibits a single peak but if there is partial shade, the P-V curve will have several peaks due to use of bypass diodes [9].

The most common external environmental parameters affecting the performance of a solar PV module are the solar irradiance, temperature, humidity, geographic location [10].

However, the system architecture also influences solar PV system output power and performance characteristics. The study [11] highlighted that under specific shading conditions, with an irradiance level of 50% respect to STC, the Total cross-tied (TCT) configuration produces 4.75% and 2.21% more power output than the Series-parallel (SP) and Bridge-linked (BL) respectively.

As the solar radiation received by the photovoltaic module is the most prominent factor that affects the power output, it is important to control and limit the losses of power due to solar irradiation non-uniformity on a PV plant.

Solar inverters allow the PV plants to operate at MPP conditions. Currently, there are three main types of solar inverters: string inverters, optimized string inverters (power optimizers + string inverters), and microinverters.

Although up-to-date solar inverters and PV technology can ensure that each module continues to produce power even under partial or total shading, string inverters are only capable of optimizing power output at the string level, rather than at the level of a single module. Currently, microinverters and optimizers are emerging as leading technologies to improve the efficiency of solar modules, especially in non-ideal conditions like shading.

Microinverters are small inverters attached to each PV module, in such a way that each module operates independently. Microinverters are especially beneficial in challenging variable environmental conditions (e.g. if one PV module is totally or partially shaded, the others continue to perform at their peak power, ensuring minimal impact on the overall system efficiency. This feature is particularly advantageous for roofs with irregular shapes or orientations or those subjected to partial shading.

Studies developed in California indicate that homes with microinverters allowed to achieve a 5-10% increase in energy output compared to traditional string inverter systems [12].

Micro inverters work at a lower voltage compared to the DC voltage in string systems, making the installation process safer and quicker. Power optimizers are module-level power electronics (MLPEs) integrated into each solar module; they augment the energy output of individual modules. However, they still rely on a central inverter to convert DC to AC.

Power optimizers regulate the voltage of each module, ensuring that underperforming modules do not degrade the overall system performance. Provide both system and module-level monitoring. Their cost-effectiveness is a significant selling point, offering many of the benefits of microinverters but at a lower price.

Microinverters offer a slight edge in highly variable environmental conditions due to their module-by-module independent inversion of DC to AC. While effective in shaded conditions, power optimizers may not provide the same optimization level in complex roofing layouts.

This research presents the analyses developed through the monitoring system of the PV plant installed at the University of Catania. One peculiarity of this PV plant is determined by the presence of heterogeneous PV modules, which have also different azimuth and tilt angles. In this plant, each PV module o group of homogeneous PV modules is equipped with power optimizers, which should allow they can function at MPP. The whole system constituted a single sting connected in series and coupled to a single inverter.

The outcomes of the analyses performed aimed to provide interesting and original data regarding the performances and the monitoring of PV plants equipped with power optimizers. Moreover, as the monitoring system allow to derive MPP of some of the PV modules tracking its I-V curve through an electronic load. The comparison between the power extracted from the PV module through the optimizers and that one established through the electronic load has been presented. The analyses performed have evidenced the power optimizers' limits to effectively exploiting the maximum power when the different PV modules operate under very inhomogeneous conditions.

2. MATERIAL AND METHODS

2.1 Power optimizer

This section describes the operating principles of the utilized power optimizers marketed by Solar Edge firm, which perform per module MPPT and enable performance monitoring of each module. This typology of power optimizers enables the inverter to maintain a fixed string voltage, at the optimal point for DC-AC conversion by the inverter, regardless of string characteristics, individual module performance and environmental conditions [13].

Usually, each module or group of homogeneous modules is integrated with a power optimizer, which are serially connected to form a string; multiple strings can be connected in parallel to the same input of the inverter. The inverter continuously adapts the current it draws from the PV array to keep the input voltage constant.

Figure 1 shows a PV plant with 8 modules, each providing 250W of power, which is maintained at the module's MPP by an input control loop within the corresponding power optimizer. Consequently, an input current I_{in} and voltage V_{in} are established to ensure the transfer of 250W from the module to the DC bus. Assuming an V_{MPP}=32V, the input current results 7.81A (250W/32V). The input voltage to the inverter is controlled by a separate feedback loop. Assuming, for the sake of simplicity, the inverter requires a constant 400V, the input current to the inverter is 5A (2000W/400V).

Thus, the DC bus current flowing through each of the power optimizers is 5A with an output voltage of 50V (250W/5A). In this case, the power optimizers are acting as up converters, converting the 32V input voltage to the target 50V output voltage.

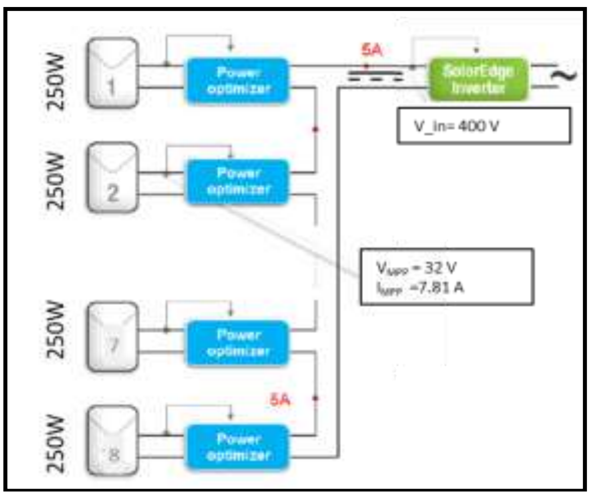

Figure 1. Electrical operating parameters of PV plant equipped with power optimizer during no shading condition

Figure 2 shows a condition of partial shading with module #7 shaded and consequently it produces only 90W. As the other 7 modules are not shaded, they still produce 250W. The power optimizer of the shaded module maintains it at its maximum power point, which is now lowered due to the shading; assuming V_{MPP}=28V, the current is 3.21 A (90W/28V). The total power produced by the string is now 1840W. Since the inverter maintains the same input voltage of 400V, the input current to the inverter will be 4.6A, as well as the DC bus current. Therefore, the power optimizers of the 7 un-shaded modules will have an output of 54.34V (250W/4.6A), while the power optimizer at the shaded module will output 19.56V (90W/4.6A). In this way the input to the inverter is still 400V, as required. In this case, the 7 power optimizers producing 250W each are essentially acting as up converters, converting the 32V input voltage to a 54.34V output voltage, whereas the power optimizer of module #7 is acting as a down converter, converting the 28V input voltage to a 19.56V output voltage.

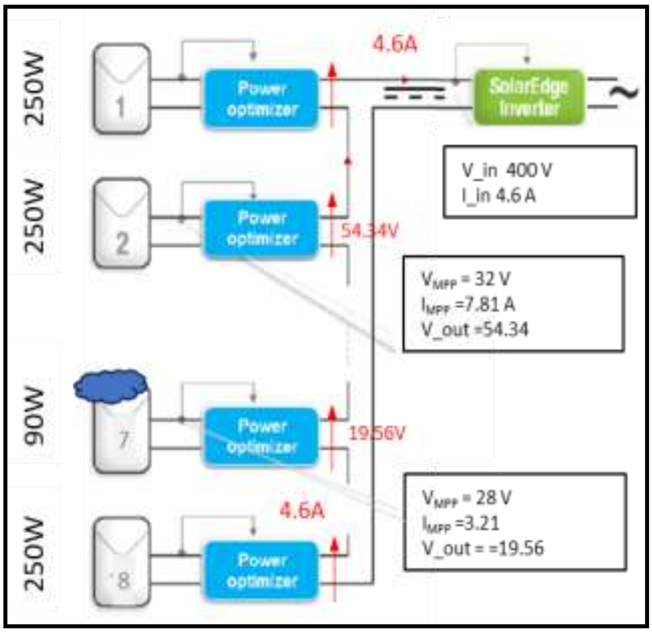

Figure 2. Electrical operating parameters of PV plant equipped with power optimizer during partial shading condition

As demonstrated by this example, each of the modules is operating at its maximum power point, regardless of operating conditions. The fixed string voltage maintained by the power optimizers permits to serially connect in a string mismatched module.

The number of modules in a single string is not dependent on module output voltage and therefore a wide string length range is permitted. However, it has to be considered the Voltage range of operation allowable by the power optimizers.

3. CASE STUDY

The case study concerns a "heterogeneous" PV system built at the University of Catania (IT), constituted by different mock-ups, where both PV and PVT modules are mounted. All mock-ups are connected in series and coupled to a single inverter. Figure 3 shows the above-mentioned PV-PVT modules, which are identified as follows:

Figure 3. Layout of monitored PV plant

(#1) V_PV: monofacial PV module vertically oriented with south-west exposure and peak power of 250W at STC [14];

(#2) V_bPV: bifacial PV module vertically oriented with south-west exposure and peak power of 340W at STC [13];

(#3-4) PVT: PVT modules facing south, tilt angle of 15°, and peak power of 250W at STC [13];

(#5-6) PV: PV modules facing south, tilt angle of 25°, and peak power of 250W at STC;

(#7-8) PV: PV modules facing south, tilt angle of 25°, and peak power of 250W at STC;

Moreover, a second further bifacial module, called V_bPV_{el}, having the same characteristics of module #2, is mounted vertically. This last bifacial module is connected to an electronic load, which allow of carrying out the I-V curves.

Each photovoltaic (PV) module or a group of uniform PV modules is fitted with power the S440 model power optimizers produced by the firm SolarEdge [15]. These power optimizers have a nominal input power of 440W, an operating output voltage range of 8-60V, and an approximate efficiency of 98.6%. The optimizers are connected in series with a single-phase inverter with a nominal power of 3kW [16], also produced by the SolarEdge company. Such system configuration allows for monitors of the main operative parameters of each module (i.e. current, voltage and power of each PV module, current, voltage and power on the secondary circuit) and thanks to the power optimizer each PV module should operate at its maximum power point (MPP).

4. RESULTS AND DISCUSSION

The analyses presented here consist of observing the functioning of the system under different operating conditions, intending to verify the ability of the power optimizer to extract the maximum power from each PV module. In particular, two scenarios are studied, the first in the absence of shading, while the second in the presence of shading in some modules.

Moreover, the comparisons between the power provided by (#2) and its twin module allow us to evaluate the ability of the power optimizer to obtain the MPP under very extreme operating conditions. Two scenarios are studied, the first in the absence of shading, while in the second some modules are partially shaded. In particular, modules #7 and 8# have been shaded, maintaining fully lightened module 2# (which has a twin module connected to the electronic load).

4.1 No shading condition

This section shows the monitoring data observed during a clear day (May 5th). Figure 4 shows the power produced by the module, the voltage output from the optimizer (secondary circuit), and the incident solar irradiation on the modules, for modules #7 and #2 observed during the day.

It has been noted that all the modules are completely illuminated.

In the absence of shading, module #7 presents a regular behaviour, with electric efficiencies ranging in the order of 10-11%, performances that are poor but completely in line with the characteristics of this module. Otherwise, module #2, which is vertically mounted, presents a fluctuating behaviour. In detail, before 10:30, it presents an efficiency of approximately 18%, subsequently from 10:30 to 12:00 a drastic decrease of efficiency is observed, to only 8%, subsequently the efficiency rises again attaining values of approximately 17%. It should be noted that the low efficiency observed from 10:30 to 12:00 arose from the shadow created by a horizontal overhang mounted above this module. Subsequently, from 12:00 onwards, any shadow no longer affects the module, which returns to producing electricity with efficiencies of 17%.

As previously explained the power optimizer modifies the output voltage in such a way each module works at the MPP, modifying the voltage output on the secondary circuit. It can be noticed that the output voltage of both modules has been within the allowable voltage range for almost all day.

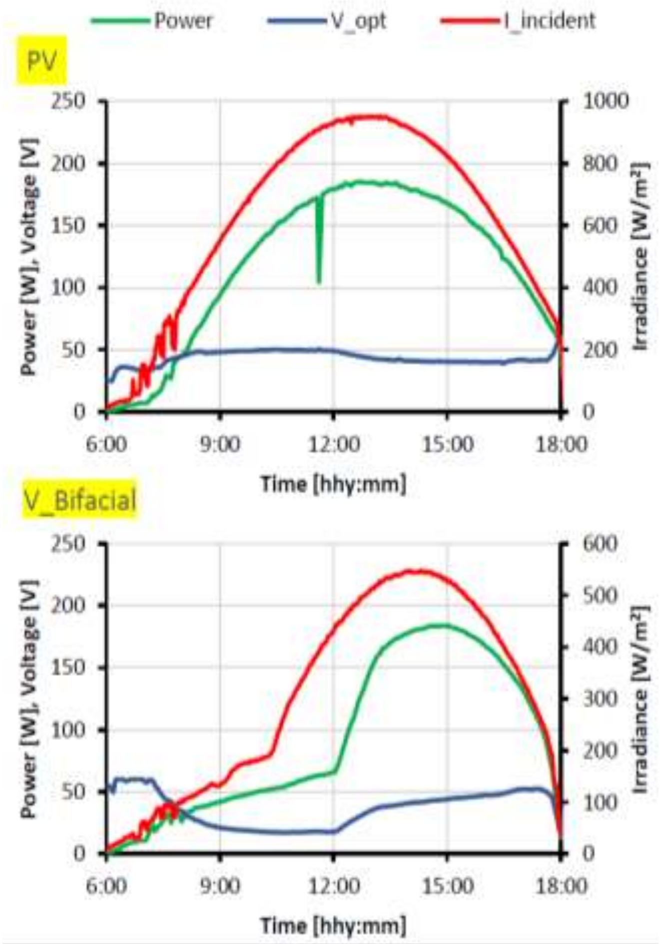

Figure 4. Power, output voltage and incident irradiation for modules #7 (above) and #2) (below)

Figure 5 shows the operating parameters in the whole plant at 13:00.

Although the whole system operates under clear sky, without accidental shadowing, it can be observed as the power produced by the diverse modules is dissimilar, #7 and #8 generate about two times the power of #1. So, in the absence of power optimizers the power produced by the plant will be penalized by the presence of an underperforming PV module.

The actual operating conditions define the total power generated by the plant, which is the simple summation of the power of each module, and consequently, the current circulating in the secondary circuit, as the inverter's voltage is fixed, which is 4.3A. Focusing on modules #2 and #7 we observe that the output voltages from the power optimizer are 37.9V and 42.9V respectively, matching with the power of the two modules 154 and 185W. Reasonably, looking at the irradiation on the POA, these powers are in line with the maximum power point under the current operating conditions.

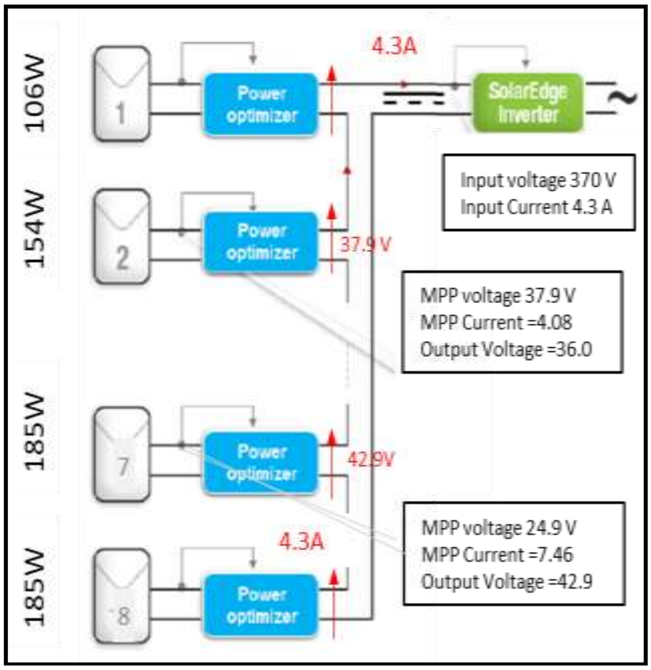

Figure 5. Electrical operating parameters considering no shading condition-13:00 of May 5th

This figure demonstrates as the use of power optimizers allows to achieve the maximum power in each individual module, even for these heterogeneous systems.

It is worth observing that from approximately 6:00 to 7:00, the operating limit of 60V is reached by the power optimizer mounted in module #2. Thus, even under the ordinary operation of the plant, it is possible to highlight a critical state, which limits the potential power producible. However, as this condition happens with low solar irradiation, it does not meaningfully influence electricity production.

4.2 Partial shading condition

This section shows the monitoring data observed on a clear day (May 3rd), where two modules (#7 and #8) have been shaded. In detail, the shading has been arranged from 11:50 to 14:30. Figure 6 shows the power produced by the module, the voltage output from the optimizer (secondary circuit), and the incident solar irradiation on the modules, for modules #7 and #2 observed during the day.

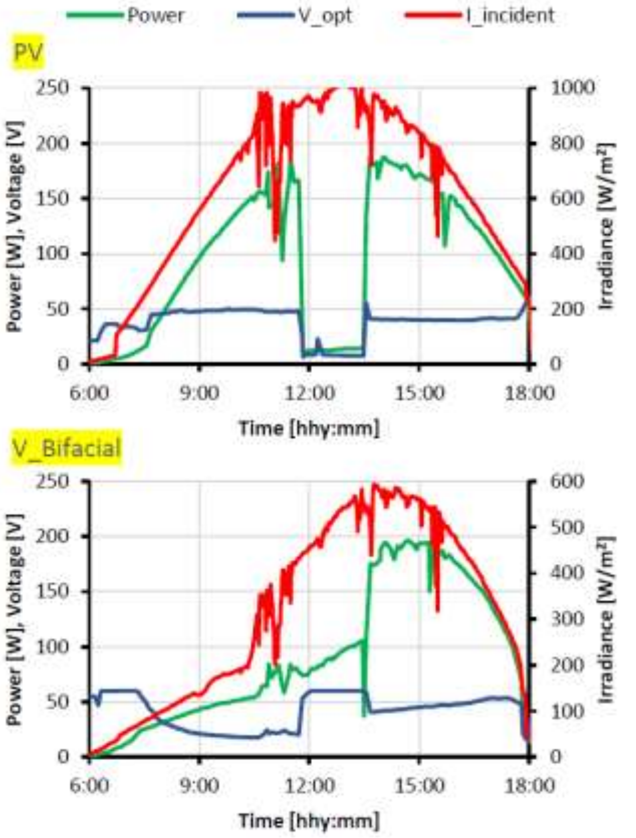

Figure 6. Power, output voltage and incident irradiation for modules (#7) (above) and (#2) (below) with shading

As expected, as soon as module #7 is shaded the power drops dramatically, as well as the output voltage from the power optimizer. Observing the results of module #2, it can be noted that from 11:50 to 14:30 there is a reduction in the power produced, despite not being affected by any shading. This is because as the power produced by the whole system diminishes, even the secondary circuit's current drops, and consequently, the power optimizer mounted in #2 must surge the voltage to operate at MPP. What happens in this particular state is that the power optimizer #2 reaches the maximum permissible output voltage, that is 60V.

Figure 7 shows the operational electrical parameters established in the circuit due to the shading.

The shading on #7 and #8 PV modules causes the abrupt decrease of the achievable, which is reduced to just 14W. Consequently, the inverter, which operates at a fixed voltage determines the current circulating in the secondary circuit.

However, another constraint emerges as the optimizers of the shaded modules, #7 and #8, must convert the voltage in such a way as to obtain the highest current in the secondary circuit. As previously mentioned, the optimizer utilized can operate within the range 8-60V.

Observing the operating condition at 13:00, as shown in Figure 7, the maximum achievable current in the secondary circuit is 1.65A (14W/8V). Therefore, when one or more PV modules experience faults causing a sharp decrease in power output within the string, the current circulating in the secondary circuit is consequential from the power produced by the most underperforming PV. So, under these critical conditions, the current in the secondary circuit is determined by the most underperforming module's power divided by the minimum achievable voltage of the optimizer.

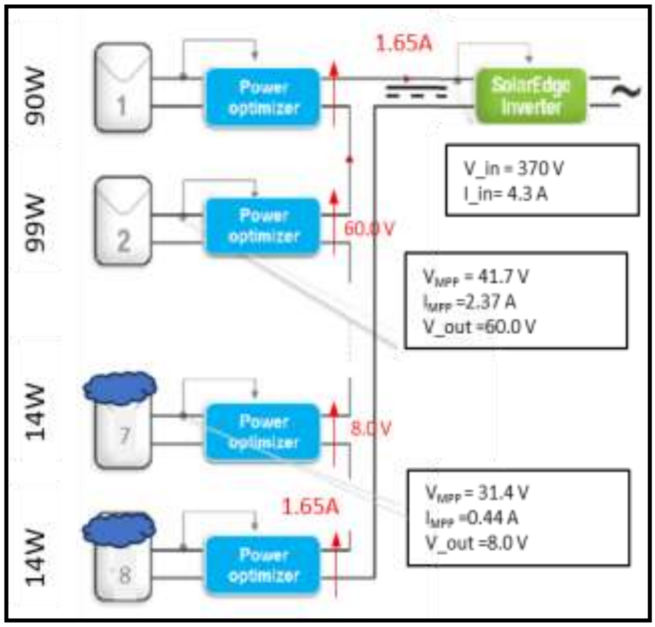

Figure 7. Electrical operating parameters under shading condition – 13:00 of May 3rd

Due to the low current established in the secondary circuit, the optimizers installed on the unshaded modules have to surge the voltage to exploit the highest achievable power. Here the risk is that the optimizers 'maximum output voltage (60V) is gotten. This is what happens in our system. Indeed, module #2, generate a power of only 99W (60×1.65), while it could generate about 154W as observed for the same module under similar value of solar irradiance (see Figure 5).

Although the power optimizers allow to improve the efficiency of the system, they are not able to guarantee that all the modules operate at MPP under these critical conditions. We are observing a loss of power in the unshaded modules, of about 36%.

Additionally, we have tracked the I-V and P-V curves of V_bPV_{el}, which is a vertical installation of module #2, contemporaneously with the monitoring performed through the optimizers and the inverter.

Figure 8 shows the I-V and P-V curves of the V_bPV_{el} module, carried out using an electronic load [17].

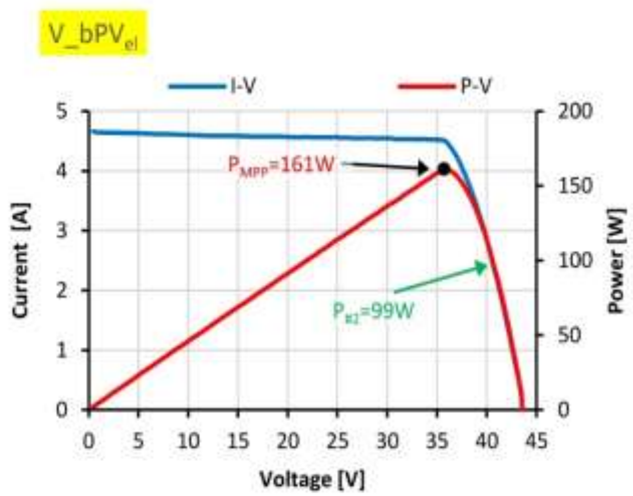

Figure 8. I-V and P-V curves of V_bPV_{el} at 13:00

The P-V curve shows that the module could produce 161W under the operating conditions at 13:00. However, due to the operational limitations discussed, it is only producing 99W, with a loss of 38.5%.

5. CONCLUSIONS

This research presents the analyses developed through the monitoring system of the PV plant installed at the University of Catania. One peculiarity of this PV plant is determined by the presence of heterogeneous PV modules, which have also different azimuth and tilt angles. In this plant, each PV module or group of homogeneous PV modules is equipped with power optimizers, which should allow they can operate at MPP. The whole system constituted a single string connected in series and coupled to a single inverter.

The outcomes of the analyses performed aimed to provide interesting and original data regarding the performances and the monitoring of PV plants equipped with power optimizers. Moreover, as the monitoring system allow to derive MPP of some of the PV modules tracking its I-V curve through an electronic load.

The analyses performed have evidenced the power optimizers' limits to effectively exploiting the maximum power when the different PV modules operate under very inhomogeneous conditions Although the presence of power optimizers allows tracking the maximum power point for different modules that have different characteristics or different operating conditions (e.g. incident solar irradiation due to different exposures), this study have highlighted operating conditions that limit the extraction of maximum power from each module.

Therefore, with a view to improving the production efficiency of PV systems, it is necessary to study systems capable of bypassing the modules that present too unfavorable operating conditions, guaranteeing the other modules the extraction of the maximum possible power, or increasing the operating limits in terms voltage output from the optimizers.

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