Diagnostic architecture: A procedure based on the analysis of the failure causes applied to photovoltaic plants

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1. Introduction

The problems related to the electrical energy production are becoming more and more important, in particular, in recent years. A more rational use of energy resources or the use of energy production from renewable sources are the strategies typically adopted worldwide, to obtain both the goal of reducing emissions of pollutants and a lower environmental impact. Among the available technologies that play a key role, particularly interesting are: photovoltaic (PV), wind, biomass and fuel cells. In particular, among these photovoltaics had the greatest spread throughout the country. In fact, photovoltaic systems can also be made in small size, can be easily connected to the national grid thus creating a network of Distributed Generation (DG) or used for the production combined with high efficiency, even local, thermal and electrical energy.

The basic element of these systems is the photovoltaic panel, PV panel in the following. This item is definitely very reliable but despite its performance is highly dependent on many factors, it may fail or degrade in several ways. This consideration leads to the necessity to study in detail the performance in terms of both reliability and availability of the plants that are characterized by a return on investment on the time horizon of at least 20 years which not consider the possible operational errors. Already in the early stages of design, reliability problems and potential failures should be suitably considered in order to ensure appropriate countermeasures in a more rapid and less expensive way. The *reliability* can be defined as the capacity of the PV panel to maintain its functionality over time, under specified environmental conditions and use [1]. Indeed, the *maintainability* is the capacity of the PV panel, in given conditions of use, to maintain an operating state in which it can perform the required function, when maintenance is performed in the given conditions and with

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Table 1
Failures frequency [9].

#	Failure subsystem	Frequency, %
1	Inverter	43
2	AC subsystem	14
3	External	12
4	Support structure	6
5	DC subsystem	6
6	Modules	2

appropriate procedures and resources [1]. It can be stated that the assessment of the reliability and maintainability can be made only if the failure modes of the PV panel are known and taken into account in a correct way. The evaluation of PV system long term reliability is mandatory and it should include both a complete and partial outage of the system. In fact, a system working at a level below expectations can be considered in partial outage. For example, a small power loss due to damaged single cell can be considered a failure in PV system. In literature several papers consider the reliability of PV components and in particular that of PV modules [2–8]. A fewer number of publications consider the failures of the overall PV system. In [9], for example, a failure analysis shows that inverters, AC subsystems, support structure, DC subsystems and modules contribute in important but in different way to the PV system failures. Golnas in [9] presents a very interesting analysis of the system reliability starting from the operator's perspective and Pareto's table concerning the frequency of the abnormal state of the failures.

In Table 1 is shown the frequency of failures to be attributed to the subsystems before mentioned [9].

In this paper a detailed review of the most important failure causes of a photovoltaic plant is proposed in order to identify the parameters that have to be monitored. This analysis can be used for the design of a more efficient diagnostic system. The paper deals with topics included in a long term research concerning PV plants composed by set of PV panels, their reliability and modelling as far as the prevision of the energy production [10–23]. This paper is a part of broader research activities carried out by the authors in recent years [10–24].

The paper is organized in the following manner. In Section 2 a PV systems overview is presented. In Section 3 the possible failure causes are discussed. The diagnostic architecture is presented in the following Section 4. Section 5 reports the experimental results and the discussion of the experimental results. Conclusions are finally drawn in Section 6.

2. PV systems overview

The system under study is a grid-connected photovoltaic system with one main inverter. As well written in [9] a PV system can be seen as *"a compilation of systems and components, ranging from simple hardware like wire interconnects to complex units like tracker controllers and inverters, which makes the rigorous treatment of the overall system reliability a challenging task, but one that is essential to the on-going maturation of the industry*".

It consists, as depicted in Fig. 1 in a simplified way, of three main subsystems, photovoltaic modules connected in series and parallel, power conditioning subsystem that includes inverters and BOS (Balance Of System) subsystem that is composed by generator and module junction box, solar cable connectors, fuses, DC and AC wires, DC and AC switches.

Module junction boxes connect solar cells to the outside world by joining the connection cables of the cell strings and interconnecting them with the bypass diodes. On the other hand, generator junction box consolidates the multiple string cables of the PV generator. Moreover, it includes DC switching contactors and performs protection functions against over voltages by employing string fuses and against lightening through surge suppressors. Mounting structure failures are excluded from the considered system as their contribution to PV plant outages is very small, less than 1% [8]. Besides, string diodes will be out of our scope as well, since grid connected PV are recently built without string diodes to avoid losses associated to their forward bias current. Therefore, current modules, nowadays, can withstand reverse current up to seven times the short circuit one.

3. Failure causes analysis

The reliability model of PV plant can be obtained by dividing the whole system into different functional subsystems, each of which fulfills its respective function. Afterwards, the potential failure causes and sub causes in each subsystem have been identified and described in the following part of this section. Failure causes can be derive from PV modules (as described in Section 3.1), from inverters (as discussed in the following Section 3.2) and, finally, from BOS (as presented in the Section 3.3).

3.1. PV module failure causes

The core of every photovoltaic system is the array of PV modules. The PV modules represent the power generation subsystem and any failure associated with their operation

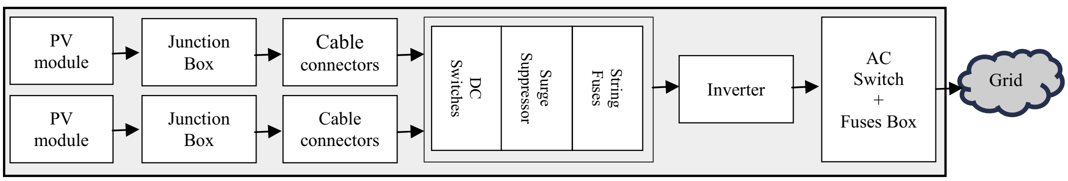

Fig. 1. Simplified schematic diagram of photovoltaic plant.

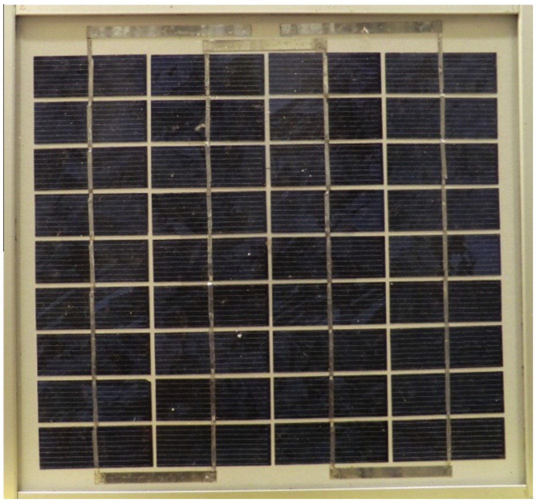

Fig. 2. Picture of a typical PV module [22].

will affect the overall performance of the PV system. Fig. 2 depicts a typical PV module [22].

The failure modes of PV module can be classified as

- Encapsulation failures.
- Module corrosion failures.
- Broken interconnection and solder buses failures.
- Cells cracking failures.
- Dust failures.
- Hot-spots failures.

In the following sub-sections a brief description of each of the aforementioned failure causes will be given.

3.1.1. Encapsulation failure

The main function of an encapsulant material is to protect the components of a PV module from foreign impurities and moisture along with the reinforcement from mechanical damage. An encapsulant also acts as an electrical insulator between cells and other module components to prevent leakage current and binds all of the components together. Encapsulation failure occurs in both early and long term degradation. One of the major reason of encapsulation failure is Discoloration and Delamination (D&D). This failure can occur in both early and long term degradation and it can be found at the interface between the encapsulant material and solar cell [24]. Moreover, it is more frequent to find this failure in hot and humid environment. The D&D affects the intensity of solar energy converted to electricity [25]. Moisture input is considered another cause for encapsulation failure and a reason for the increase in the series resistance of the PV electrical model. Modules can be constructed with impermeable front – and back – sheets where moisture can diffuse in from the sides. Even in presence of the impermeable front and back sheets, water can permeate in and condense [26]. Therefore, the incoming irradiation is partially blocked by the moisture and the cells are partially shaded. This phe-nomena leads to a reduction of the current generated by some cells and they may even become reversed biased with respect to the other cells in the string if the shading becomes severe. Furthermore, Ethylene Vinyl Acetate (EVA) sheets reacts with the moisture to form acetic acid that speeds up the corrosion process of the inner compo-nents of PV module [27]. Shattering of the top glass of encapsulation is considered another reason of failure. This is due to thermal stress, handling, wind or hail [27]. Module broken glass may keep module functioning correctly but the risk of an electrical shock and of moisture infiltration increases. A better description of the above mentioned failures has been reported in [25–27].

3.1.2. Module corrosion

The corrosion of the conductive parts of the cells and the interconnections through the encapsulant is responsible for the deterioration of the PV module, which results in the increase of the series resistance and the decrease of the parallel resistance of the PV panel electrical model [28].

3.1.3. Broken interconnection and solder buses failure

Solar cells are equipped with two basic elements, the front and the rear contacts, allowing to deliver the current to external circuit. Electrical current is carried by buses strips that are soldered to the front and back contacts. A failure of string ribbon is associated with loss of output power [29]. Interconnection break occurs as a result of thermal expansion and contraction or repeated mechanical stress. Moreover, thicker ribbon or kinks in ribbon contribute in breaking of interconnections, and result in short-circuited cells and open-circuited cells.

3.1.4. Cells cracking

Cells cracking is a common problem encountered in PV modules. They may develop in different stages of the module lifetime: during manufacturing the soldering induces high stresses into the solar cells [30,31], handling and vibrations in transportation can induce or expand cracks. Finally, during the functioning on the field, a module is subjected to mechanical loads due to wind (pressure and vibrations) and snow (pressure). Cracking of cells occurs with a rate of about 1% per year. Although 1% failure rate is small, it leads to significant power degradation because it causes around 1–10% open circuit cell failures [32]. The consequences of cells cracking on PV performance is a decrease of the filling factor and open circuit voltage in addition to cells mismatching. Over long periods, through 200 humidity cycle, it is possible to see that 7% of cracked cells develop an electrically disconnected cell areas and that cracks parallel to busbars have risk of separating cells areas of 16–25% [33].

3.1.5. Dust

In dry regions, dust is considered a detrimental agent whenever solar energy applications are concerned. When foreign particles fall on the PV modules, they interfere with illumination quality by both absorbing and scattering the light [34].

The dust deposition depends on its density and size distribution. The accumulation of dust on the PV module surface can produce spots with different concentrations.

These spots vary in shape, location and concentration density. The differences in dust accumulation in any place can leads to different transmittance of light into the module, thus leading to small random areas on the PV module with less exposure to solar radiation. It also increases the possibility to trigger the hot spot effect when the operating current of a module exceeds the short circuit current of the most covered cell. When this case occurs, the affected cells are forced into reverse bias and thus dissipate power.

In the literature, many papers discussing the impact of dust on the performance of PV systems have been published. The experimental investigation on the reduction of PV output efficiency presented in [35] has shown that the reduction of efficiency can be up to 11.6% when the dust deposition density is about 8 g/m^2. In addition, a sin-gle dust storm can reduce the output power by 20% and a reduction of 50% could be experienced if no cleaning is performed on modules for long time that exceeds six months [36]. In [22] the results of an experimental comparison between two pairs of PV panels are discussed, where one PV panel is cleaned and the second artificially polluted.

3.1.6. Hot-spots

Hot spots are a very well-known phenomenon that occurs in PV string and they are considered as the primary sources of PV failures and modules degradation. Hot spot heating occurs in a PV module when the current capability of a particular cell or cells is lower than the operating current of the cell string. This condition results in a reverse bias current flowing in the affected cell(s) and power dissipation equal to the product of the reverse voltage and the string current [37]. Therefore, the temperature of a single cell or portion of cells becomes very higher than that of the sur-rounding cells. Over time, hot spots will permanently degrade the PV panels and decrease the overall performance of the PV plant. Moreover, contact delamination, melting of encapsulation layers, and cells damage will occur.

Shading conditions, mismatch between cell electrical characteristics, and bypass diode failure contribute in the occurrence of hotspots [38]. In the field, solar cells arrays might be subjected to shadows from both predictable sources, weather and environmental conditions, as well as from such unpredictable sources as birds or fallen leaves. The electrical output of the shadowed solar cell arrays can be considerably improved if each row of parallel cell strings (series blocks) is shunted by a diode. On the other hand, the differences in any part of the *I–V* curve (current versus voltage characteristic curve of th PV panel) between one solar cell and another may lead to mismatch losses at some operating point. The mismatch in PV mod-ules occurs when the electrical parameters of one solar cell are significantly altered from those of the remaining devices. The impact and power loss due to mismatch depends on the operating point of the PV module, the cir-cuit configuration and the ageing factor.

3.2. PV inverters failure causes

The inverters are considered the brain of the PV system and represent an expensive and complex element in the plant. Field experience has shown that the inverter is the most vulnerable component [3]. In [39] an investigation carried out on 126 systems provided 190 failure events, and results have shown that inverters dominate the outage causes of PV plants by 76%. Data concerning the reliability of the PV modules and BOS components can be found also in [40]. Another survey reported in [8] describes the inverters as the leading cause of PV systems failure. The same conclusion is reported in [41], which states that 65% of outages of 213 events for 103 PV systems were due to inverters. The inverter failures can be classified into three major categories: manufacturing and inadequate design problems, control problems and electrical components failures.

A study in Botswana [42] reported that both tropical operating conditions and lightening effects cause 77% of inverter failures. Thermal management and heat extraction mechanisms of switching components and capacitors, are considered one of the design and manufacturing flaws problems in inverters [43].

Control problems are related to the interaction between the inverter and the grid, at the AC side, and between the inverter and the PV panels array (the considered PV system), on the DC side [3,44]. The components of PV inverters are exposed to electrical and thermal stresses during their operation. In [45] the electrolytic capacitors are considered as the most particularly troublesome component, meanwhile [44] is focused on IGBT as the leading component in the failure of PV inverters.

3.3. BOS failures

The failures of BOS components are considered the major reason behind the presence of non-producing modules in PV field. For example, a failure in a single fuse can get an entire string out of service. A ten years survey [6] was carried out by Sandia National Laboratories on 35 PV systems, and results showed that failure of BOS components such as switches, fuses, dc contactors and surge arrestors were responsible for 54% of the non-producing modules, around 10,000 non-working modules. The DC and AC wires in addition to connectors of modules junction boxes contributed in 6.2% of the 68,739 non-working modules [6].

Bypass diode failure is considered another reason of BOS failures since they are usually supplied inside module junction box. They are manufactured inside PV modules only for sophisticated module types [46]. Its main function is to allow the current to pass around the shaded or cracked cells and thereby reduces the power losses within the module itself. Hence, the hot spots will be avoided and a long lifetime of the system will be guaranteed [47]. The bypass diodes have a junction temperature reaching upwards 150–200 °C but since they are characterized by a significant self-heating [48], the main reason of their failure is the thermal stress.

4. Diagnostic architecture specifications

The smart monitoring of PV plants must be able to carry out the necessary performance measurements, evaluate the ageing of PV panels and early detect the possible failures previously described. This requires the measure of both electrical and environmental parameters at PV panel, string or plant level. The most significant parameters that can be considered are: current and voltage, temperature and irradiance. The monitoring of these parameters, both in online and offline way, in different position on the plant allows to evaluate the actual state of the system. The project budget, the size of the plant, operation and maintenance costs, and system criticality are factors that determine the necessary level of monitoring and diagnostic. Therefore, the string level monitoring could be a suitable option in medium and large PV systems to fulfill the balance between optimum costs and a faster detection of underperforming strings.

On the other hand, the size of photovoltaic plant plays a critical role in the design of smart monitoring systems. Deploying wired sensors in small sized plants is currently more economic and less complex. On the contrary, a wireless network is more suitable for medium sized plants; it will be cheaper in terms of fiber and cupper lines used in wired sensors. Moreover, the bandwidth will be sufficient for transmitting data. A hybrid sensor network architecture might be a solution for large scaled plants by selecting the proper sensor type for measuring electrical and environmental parameters, and suitable locations for their implementation.

Therefore, the implementation of the system monitoring requires the definition of architectures whose complexity depends on the size of the plant and which possible failure modes of the system must be identified. Fig. 3 shows a possible schematics diagram of the PV sys-tem smart performance monitoring.

Three stages can be identified:

- *Data nodes*: set of sensing units.
- *Data acquisition*: measurements, pre-processing, data storing.
- *Data analysis*: evaluation and estimation PV performance.

The first stage is considered the key point for the achievement of a reliable and accurate database for the smart monitoring system. The second stage requires the definition of a proper hardware and communication network. The third stages, from an implementation point of view, is the more flexible and less expensive one. It can be implemented by using different analytic techniques.

Starting from the analysis performed in the previous section it can be seen that most of the failure mode could be detected by means of the evaluation of the efficiency of the PV panel. It has been shown that a very effective way for evaluating the PV module efficiency is based on the comparison of measured data with a model of the sys-tem [49,50]. This approach can be implemented in an effi-cient way only if an *ad hoc* and low-cost measurement system is available. The hardware must allow the measure-ment of the current, voltage, temperature and be able to get information about the solar radiation level. Moreover it has to be able to work as a MPP tracker as well as mea-sure the *I–V* curve of the PV panel. In addiction the hard-ware must be able to communicate with a central unit that by analyzing all data performs the monitor of the whole system. With this kind of architecture, the failure modes previously discussed can be detected as reported in Table 2.

In Table 2 the detectability can be thought as the procedure and the parameter/index to be evaluated in order to detect the analyzed failure.

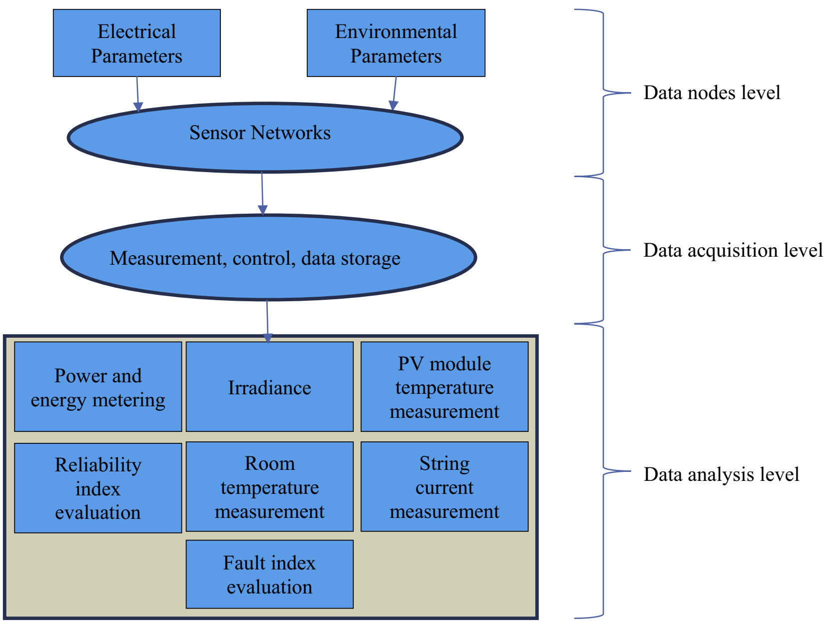

Fig. 3. PV smart monitoring system.

Table 2
Failure modes detection strategies.

Failure mode	Detectability	Requirement
Encapsulation	MPP value of the PV panel is below the value given by the model. Output of the other PV panels are good. We can compare the actual and model MPP	The PV panels have to be clean
Module corrosion	Model approach: a comparison between the value assigned to the series resistance during the characterization of the PV panel and the value estimated by means of the model	This failure mode can be detected only if the model algorithm allows to evaluate the parameter of the electrical model
Cells cracking	Model approach: open circuit voltage decrease so we have to compare the value obtained by the actual characteristic with the value given by the model	*I–V* curve has to be obtained by means an electronic load
Dust	It can be detected comparing the actual and model MPP. All PV panels of the string show the same problem	An algorithm that compares all the MPPs value
PV inverter: general failure		If the plant has centralized or string inverter, the data base alarms has to be read by the monitoring system
BOS 1. Theft 2. Broken fuse 3. Broken cable	No string current	The three failure mode can be detected by means of devoted sensors

5. Experimental results and discussion

In this section a discussion concerning data obtained considering the dust deposition, selected by the previous failure modes table, will be given (Table 2). At this aim, it is interesting to illustrate a brief description of the measurement system used during the experimental tests on PV panels in the laboratory and how it has been designed and realized. The test chamber has been described in a previous papers [12] but a brief notes will be also given in the following.

The experimental activity has been implemented by using a sun simulator and a test chamber. The fundamental part is the light source that has been properly designed. The most important point in this step is to ensure the stability of the light source in order to operate under the hypothesis of measurement repeatability. We recall that the repeatability condition of measurement is the condition of measurement, out of a set of conditions that includes the same measurement procedure, same operators, same measuring system, same operating conditions and same location, and replicate measurements on the same or similar objects over a short period of time.

For this scope a luminous source made up by a matrix of 3 × 3 LED array has been designed and assembled [12]. In particular, 9 arrays of 4 LED Oslon Star White by OSRAM have been used. The necessary stability and repeatability of the test conditions is mandatory to control in an appropriate way both the supply current and the cooling system. In this way a good emitting stability of the LEDs is obtained and ensured. Moreover, in order to ensure the maximum level of the stability, the system has been turned on in advance in order to operate when thermal regime is reached. In order to obtain the maximum possible level of repeatability the experimental setup has been located in a climatic chamber with controlled temperature and humidity. The complete *I–V* and *P–V* characteristic curves (power vs voltage characteristic curve) have been acquired. In Fig. 4a an example of *I–V* curve experimentally obtained is reported while in Fig. 4b the *P–V* characteristic on which the Maximum Power Point (MPP) is highlighted can be seen. Represented points have been obtained by using the average measured values and errors bar have been computed as the experimental relative standard deviation with a coverage factor of $k = 3$. The acquired data have been obtained by a PV panel operating at about 25 °C with the following characteristic: $P_{max} = 5$ W, $V_{mp} = 17.5$ V,

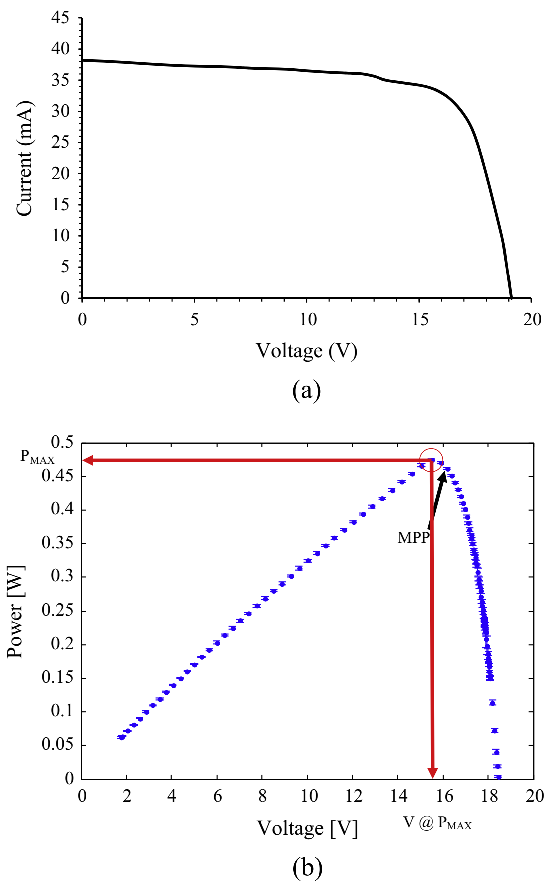

Fig. 4. (a) *I–V* characteristic curve of a PV panel, (b) *P–V* characteristic curve of a PV panel.

Table 3
Results of the measurements performed during the test period.

# PV panel	MP considered for new PV (W)	MP considered for used PV (W)	Test conditions	Conditions classification (see Fig. 7)
1	0.474	0.457	Horizontal, no rain, 34 days	Increasing level ↑
2	0.471	0.443	Horizontal, no rain, 34 days	
3	0.448	0.418	Horizontal, no rain, 34 days	
4	0.467	0.455	Horizontal, rain, 34 days	
5	0.468	0.438	Horizontal, rain, 34 days	
6	0.506	0.489	30°, rain, 24 days	
7	0.470	0.454	30°, rain, 24 days	
8	0.474	0.456	Horizontal, rain, 21 days	
9	0.478	0.466	Horizontal, no rain, 21 days	
10	0.505	0.494	Horizontal, no rain, 21 days	

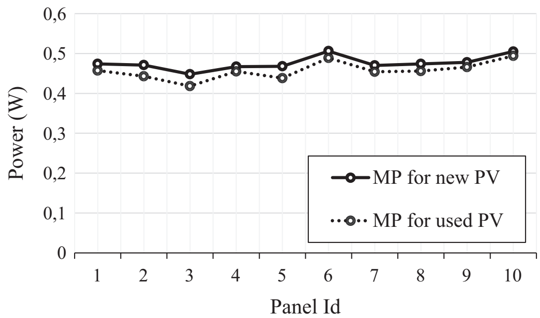

Fig. 5. MP for new or as good as new PV panels and for used PV panels.

I_{mp} = 0.285 A, V_{oc} = 21.3 V, I_{sc} = 0.31 A, panel dimension 245 × 232 mm and panel active area = 210 × 185 mm. The tested PV panel is depicted in the previous Fig. 2.

Table 3 reports the experimental data obtained by testing 10 PV panels. For each PV panel the MPP value has been obtained in two different conditions: first the PV panels have been tested when new or as good as new and carefully clean, second the same PV panels have been tested after a certain number of days during which they were exposed to the weather conditions according to a pattern reported in the last column of Table 3. In the following Fig. 5 the Maximum Power (MP) values obtained experimentally for new and used PV panels have been drawn.

Fig. 6 reports the Box Plot concerning MP values for PV panels that have had an homogenous life: PV panels # 1, 2, 3, 8, 9 and 10. The graph shows how the average value decreases going from the new PV panels to the used PV panels. It is also possible to see an increase of the data variability.

In Fig. 7 the trend of the percentage decrease in the value of the MP is depicted. Here the x axis is qualitative.

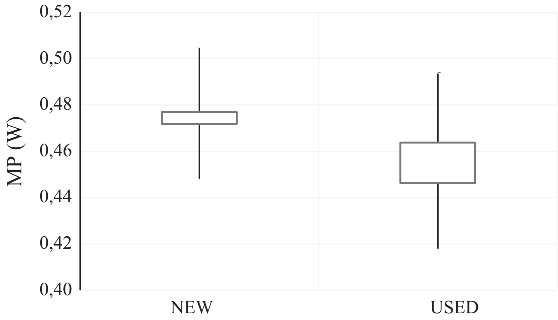

Fig. 6. Box plot for PV panels # 1, 2, 3, 8, 9 and 10 in no rain conditions.

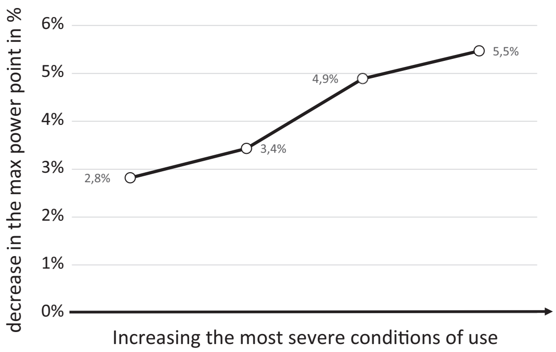

Fig. 7. Trend of the percentage decrease in maximum power.

Data are taken in compliance with the previous Table 3. Going from left to right the conditions of use become more demanding, and the intervals of observation and maintenance tend to increase. The measured MP variations due to the dust can be considered compliance to the data published in literatures [26,35].

The above graph allows us to do a very important deduction about the metrological characteristics of the measuring system to be used.

In fact, if it is considered appropriate to be able to grasp the decrease in the maximum power point of the leftmost, the utilized measurement system must have metrological characteristics that permit such identification.

In practice, the choice of the measuring system in each component, for example sensors, is influenced by the minimum deviation that you want to grasp and the graph mentioned in Fig. 7 can be used to this purpose. More precisely, the uncertainty of the measuring system should comply with the requirement fixed by the aforementioned figure and table. Moreover, the components which realize the measuring system have to be selected having in mind the requirements on the measurement uncertainty.

Finally, it should be noted that this level of uncertainty can be easily reached by using simple commercial grade sensors for the analysis of the current and the voltage. As far as the radiation measurement is concerned the actual results has been obtained by means a radiometer of medium level.

6. Conclusions

The monitoring of the critical components of a PV system, from the reliability point of view, allows to achieve an improvement of the plant performances. Moreover, by understanding their behavior in terms of failure causes during the actual working conditions, it is possible to optimize both the availability and the maintainability of the most critical subsystem as well as of the whole PV plant. Monitoring activities can provide useful information allowing to implement very effective maintenance policies. It would be noted that a condition based maintenance (CBM) program can be very interesting in this situation. In fact, the increment of the efficiency of the operations and maintenance policy allows to increase the PV's profitability. Furthermore, this optimization results in an increased production efficiency leading then to higher returns for investors. Discussion concerning experimental results for dust deposition and metrological characteristic of the measuring systems has been also given. Obtained results lead to consider that the given hypothesis about the decrement in the MP are true. Finally, a criterion of choice about the metrological performance of the measuring system has been provided.

References

[1] M. Lazzaroni, L. Cristaldi, L. Peretto, P. Rinaldi, M. Catelani, Reliability engineering, in: Basic Concepts and Applications in ICT, Springer, 2011, http://dx.doi.org/10.1007/978-3-642-20983-3. ISBN 978-3-642-20982-6, e-ISBN 978-3-642-20983-3 Springer-Verlag, Berlin Heidelberg.

[2] I. Mougharbel, A. Makkawi, H. Ghazal, Optimal solution for the connectivity of PV systems on a scheduled availability of the grid: case study for Lebanon, in: International Conference on Renewable Energies for Developing Countries (REDEC), 2012, vol. 28, no. 29 November, vol. 28(29), 2012, pp. 1–5.

[3] Giovanni Petrone, Giovanni Spagnuolo, Mummadi Veerachary, Reliability issues in photovoltaic power processing systems, IEEE Trans Indust Electron 55 (7) (2008).

[4] Matthew Muller, Sarah Kurtz, Jose Rodriguez, Three years of observed failures and performance related issues associated with on-sun CPV module testing, in: Proceedings of the AIP Conference, vol. 1477, Spain, 2012.

[5] Larry N. Dumas, Alex Shumka, Photovoltaic module reliability improvement through application testing and failure analysis, IEEE Trans. Reliab. R-31 (3) (1982) 228–234.

[6] A.L. Rosenthal, M.G. Thomas, S.J. Durand, A ten year review of performance of photovoltaic systems, in: Conference on the Record of the Twenty Third IEEE Photovoltaic Specialists Conference 1993, 1993, pp. 1289–1291, http://dx.doi.org/10.1109/PVSC.1993.346934.

[7] R.H. Bonn, Developing a next generation PV inverter, in: Proceedings of 29th IEEE Photovoltaic Specialist Conference, 2002, pp. 1352–1355.

[8] A review of PV inverter technology cost and performance projections, in: Navigant Consulting, Burlington, MA, NREL subcontract Rep. NREL/SR-620-38771, 2006.

[9] A. Golnas, PV system reliability: an operator's perspective, IEEE J. Photovolt. 3 (1) (2013) 416–421.

[10] M. Catelani, L. Ciani, L. Cristaldi, M. Faifer, M. Lazzaroni, P. Rinaldi, FMECA technique on photovoltaic module, in: Proceedings of IEEE – International Instrumentation And Measurement Technology Conference (I2MTC) – Binjiang, Hangzhou, China – May 2011, pp. 1717–1722 (http://dx.doi.org/10.1109/IMTC.2011.5944245, WOS: 000297171900346, Scopus ID: 2-s2.0-80051913451).

[11] F.Bellocchio, S. Ferrari, M. Lazzaroni, L. Cristaldi, M. Rossi, T. Poli, R. Paolini, Illuminance prediction through SVM regression, in: Environmental Energy and Structural Monitoring Systems (EESMS), 2011 IEEE Workshop on Issue Date: 28–28 September, Milan, Italy, 2011, pp. 1–5 (Print ISBN: 978-1-4577-0610-3, Digital Object Identifier: http://dx.doi.org/10.1109/EESMS.2011.6067051, Scopus ID: 2-s2.0-81355153394).

[12] M. Catelani, L. Ciani, L. Cristaldi, M. Faifer, M. Lazzaroni, M. Rossi, Characterization of photovoltaic panels, in: Proceeding of 2012 IEEE International Energy Conference and Exhibition of The Effects of Dust (ENERGYCON), 9–12 September 2012, Florence, Italy, pp. 45–50 (ISBN: 978-1-4673-1453-4, http://dx.doi.org/10.1109/EnergyCon.2012.6348198, WOS:000309449100001, Scopus ID: 2-s2.0-84870776286).

[13] L. Cristaldi, M. Faifer, S. Ierace, M. Lazzaroni, M. Rossi, An approach based on electric signature analysis for photovoltaic maintenance, in: Proceedings of The 2nd International Congress on Maintenance Performance Measurement and Management, University of Sunderland, UK, 12–13th September 2012, pp. 1–8.

[14] S. Ferrari, A. Fina, M. Lazzaroni, V. Piuri, L. Cristaldi, M. Faifer, T. Poli, Illuminance prediction through statistical models, in: IEEE Workshop on Environmental Energy and Structural Monitoring Systems (EESMS), 2012, Issue Date: 28–28 September. 2012, Location, Perugia, Italy, pp. 90–96 (Print ISBN: 978-1-4673-2737-4, http://dx.doi.org/10.1109/EESMS.2012.6348406. Scopus ID: 2-s2.0-84870801344).

[15] S. Ferrari, M. Lazzaroni, V. Piuri, A. Salman, L. Cristaldi, M. Rossi, T. Poli, Illuminance prediction through extreme learning machines, in: IEEE Workshop on Environmental Energy and Structural Monitoring Systems (EESMS), 2012, Issue Date: 28–28 September 2012, pp. 97–103 (Perugia, Italy, Print ISBN: 978-1-4673-2737-4, http://dx.doi.org/10.1109/EESMS.2012.6348407, Scopus ID: 2-s2.0-84870826262).

[16] S. Ferrari, M. Lazzaroni, V. Piuri, A. Salman, L. Cristaldi, M. Faifer, Computational intelligence models for solar radiation prediction, in: 2013 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), pp. 757–762, 6–9 May 2013, http://dx.doi.org/10.1109/I2MTC.2013.6555517, ISSN:1091-5281 Print ISBN:978-1-4673-4621-4, e-ISBN: 978-1-4673-46 22-1. Scopus: 2-s2.0-84882249618.

[17] L. Ciani, L. Cristaldi, M. Faifer, M. Lazzaroni, M. Rossi, Design and implementation of a on-board device for photovoltaic panels monitoring, in: 2013 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), pp. 1599–1604, 6–9 May 2013, http://dx.doi.org/10.1109/I2MTC.2013.6555684, ISSN:1091-5281 Print ISBN:978-1-4673-4621-4, e-ISBN: 978-1-4673-46 22-1. Scopus: 2-s2.0-84882275698.

[18] S. Ferrari, M. Lazzaroni, V. Piuri, L. Cristaldi, M. Faifer, Statistical models approach for solar radiation prediction, in: 2013 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), pp. 1734–1739, 6–9 May 2013, 1091, http://dx.doi.org/10.1109/I2MTC.2013.6555712, ISSN:-5281 Print ISBN:978-1-4673-4621-4, e-ISBN: 978-1-4673-46 22-1, Scopus-ID: 2-s2.0-84882251553.

[19] L. Cristaldi, M. Faifer, M. Rossi, L. Ciani, M. Lazzaroni, S. Toscani, Photovoltaic plant efficiency evaluation: a proposal, in: Proceedings of the 12th IMEKO TC10 Workshop on Technical Diagnostics, IMEKO – International Measurement Confederation, June 6–7, 2013, Florence, Italy, pp. 260–265, ISBN 978-88-903149-8-8, Scopus ID: 2-s2.0-84881595497. <http://www.imeko.org/publications/tc10-2013/IMEKO-TC10-2013-043.p>.

[20] S. Ferrari, M. Lazzaroni, V. Piuri, A. Salman, L. Cristaldi, M. Faifer, A data approximation based approach to photovoltaic systems maintenance, in: Proceedings of the 2013 IEEE Workshop on environmental energy and structural monitoring systems EESMS 2013, Trento, Italy, 11–12 September 2013, Piscataway (New Jersey), IEEE, 2013 September 7–12, ISBN 978-1-4799-0628-4, http://dx.doi.org/10.1109/EESMS.2013.6661694. Scopus: 2-s2.0-84892649720.

[21] L. Cristaldi, M. Faifer, M. Lazzaroni, M. Rossi, S. Toscani, Photovoltaic plant maintenance: a method base on economic evaluation of PV system losses, in: Sari Monto, Miia Pirttilä, Timo Kärri (Eds.), Proceedings of the Maintenance Performance Measurement and Management Conference (MPMM 2013), 12–13th September 2013, Lappeenranta, FINLAND, ISBN 978-952-265-443-4, pp. 98–111. Conference webpage <http://www.lut.fi/web/en/mpmm2013>.

[22] Marcantonio Catelani, Lorenzo Ciani, Loredana Cristaldi, Marco Faifer, Massimo Lazzaroni, Electrical performances optimization of photovoltaic modules with FMECA approach, Measurement 46 (2013) 3898–3909, http://dx.doi.org/10.1016/j.measurement.2013.08.003. ISSN: 0263-2241, ELSEVIER, Sopus ID: 2-s2.0-84883522357.

[23] S. Ferrari, M. Lazzaroni, V. Piuri, A. Salman, L. Cristaldi, M. Faifer, S. Toscani, A computational intelligence approach to solar panel modelling, in: Proceedings of the 2014 IEEE International Instrumentation and Measurement Technology Conference

(I2MTC), May 12–15, 2014, Radisson Montevideo Victoria Plaza Hotel & Conference Center, Montevideo, Uruguay, 2014, http://dx.doi.org/10.1109/I2MTC.2014.6860947, Publication Year: Page(s): 1261–1266, INSPEC Accession Number: 14467497, ISBN: 978-1-4673-6385-3, ISSN: 1091-5281, Scopus ID 2-s2.0-84905695434, WOS: 14467497, Publisher: IEEE, Piscataway, NJ, USA.

[24] M. Lazzaroni, S. Ferrari, V. Piuri, A. Salman, L. Cristaldi, M. Faifer, Models for Solar Radiation Prediction based on Different Measurement Sites, Measurement, vol. 63, Elsevier, March 2015, pp. 346–363, http://dx.doi.org/10.1016/j.measurement.2014.11.037, ISSN: 0263-2241.

[25] N.C. Park, J.S. Jeong, B.J. Kang, D.H. Kim, The effect of encapsulant discoloration and delamination on the electrical characteristics of photovoltaic module, Microelectron. Reliab. 53(9–11) (2013) 1818–1822, http://dx.doi.org/10.1016/j.microrel.2013.07.062.

[26] M.D. Kempe, Modeling of rates of moisture ingress into photovoltaic modules, Solar Energy Mater. Solar Cells 90(16) (2006) 2720–2738.

[27] T. Swonke, R. Auer, Impact of moisture on PV module encapsulants, in: Proceedings of SPIE 7412, Reliability of Photovoltaic Cells, Modules, Components, and Systems II, 74120A, 2009.

[28] V. Saly, M. Ruzinsky, J. Packa, P. Redi, Examination of solar cells and encapsulations of small experimental photovoltaic modules, in: 2nd International IEEE Conference on Polymers and Adhesives in Microelectronics and Photonics, 2002, POLYTRONIC 2002, 2002, pp. 137–141.

[29] G.B. Alers, Solar Photovoltaic Module Failure Analysis, Microelectronics Failure Analysis: Desk Reference, sixth ed., 2011.

[30] A.M. Gabor, M.M. Ralli, L. Alegria, C. Brodonaro, J. Woods, L. Felton, Soldering induced damage to thin Si solar cells and detection of cracked cells in modules, in: Proceedings of 21st EUPVSEC (WIP, Dresden, Germany, 2006), pp. 2042–2047.

[31] J. Wendt, M. Träger, M. Mette, A. Pfennig, B. Jäckel, The link between mechanical stress induced by soldering and micro damages in silicon solar cells, in: Proceedings of 24th EUPVSEC (WIP, Hambrug, Germany, 2009), pp. 3420–3423.

[32] Ronald G. Ross Jr., Photovoltaic array reliability optimization, IEEE Trans. Reliab., R-31(3) (1982).

[33] S. Kajari-Schröder et al., Criticality of cracks in PV modules, Energy Proc. 27 (2012) 658–663.

[34] K. Dastoori, G. Al-Shabaan, M. Kolhe, D. Thompson, B. Makin, Charge measurement of dust particles on photovoltaic module, in: 8th International Symposium on Advanced Topics in Electrical Engineering (ATEE), May 2013, 2013, pp. 1–4.

[35] Hai Jiang, Lu Lin, Ke Sun, Experimental investigation of the impact of airborne dust deposition on the performance of solar photovoltaic (PV) modules, Atmos. Environ. J. 45 (2011) 4299–4304.

[36] Muhammed J. Adinoyi, Syed A.M. Said, Effect of dust accumulation on the power outputs of solar photovoltaic modules, Renew. Energy 60 (2013) 633–636.

[37] K.A. Kim, P.T. Krein, Hot spotting and second breakdown effects on reverse *I–V* characteristics for mono-crystalline Si photovoltaics, in: Energy Conversion Congress and Exposition (ECCE), 2013 IEEE, September 2013, pp. 1007–1014.

[38] K.A. Kim, P.T. Krein,"Photovoltaic hot spot analysis for cells with various reverse-bias characteristics through electrical and thermal simulation, in: 14th Workshop on Control and Modeling for Power Electronics (COMPEL), 23–26 June 2013, 2013 IEEE, pp. 1–8.

[39] A.B. Maish, C. Atcitty, S. Hester, D. Greenberg, D. Osborn, D. Collier, M. Brine, Photovoltaic system reliability, in: Conference Record of the Twenty-Sixth Photovoltaic Specialists Conference, 1997, IEEE, 1997, pp. 1049–1054.

[40] N.G. Dhere, Reliability of PV modules and balance-of-system components, in: Conference Record of the Thirty-First Photovoltaic Specialists Conference, 3–7 January 2005, IEEE, 2005, pp. 1570–1576.

[41] R. Kaplar, Reinhard Brock, Sandeepan DasGupta, M. Marinella, A. Starbuck, A. Fresquez, S. Gonzalez, J. Granata, M. Quintana, Mark Smith, S. Atcitty, PV inverter performance and reliability: What is the role of the IGBT? in: 37th IEEE Photovoltaic Specialists Conference (PVSC), June 2011, 2011, pp. 1842–1847.

[42] G.O. Anderson, The role, reliability and limitations of solar photovoltaic systems in Bostwana, in: Proceedings of the 9th International Conference on Harmonics Quality Power, vol. 3, October 2000, pp. 973–982.

[43] S. Harb, R.S. Balog, Reliability of a PV-module integrated inverter (PV-MII): a usage model approach, in: 38th IEEE Photovoltaic Specialists Conference (PVSC), 2012, pp. 001756–001761, 3–8 June 2012, http://dx.doi.org/10.1109/PVSC.2012.6317934.

[44] Z.J. Ma, S. Thomas, Reliability and maintainability in photovoltaic inverter design, in: 2011 Proceedings – Annual Reliability and Maintainability Symposium (RAMS), January 2011, pp. 1–5.

[45] W. Bower, R. West, A. Dickerson, Innovative PV micro-inverter topology eliminates electrolytic capacitors for longer lifetime, in: Proceedings of the IEEE 4th World Conference on Photovoltaics and Energy Conversion, vol. 2, 2006, pp. 2038–2041.

[46] AN3432 Application note, How to Choose a Bypass Diode for a Silicon Panel Junction Box, September 2011 <http://www.st.com>.

[47] M.C. Alonso-García, J.M. Ruíz, Analysis and modelling the reverse characteristic of photovoltaic cells, Solar Energy Mater. Solar Cells 90 (7–8) (2006) 1105–1120.

[48] S. Silvestre et al., Study of bypass diodes configuration on PV modules, Appl Energy 86(9) (2009) 1632–1640, http://dx.doi.org/10.1016/j.apenergy.2009.01.020 (Elsevier).

[49] L. Cristaldi, M. Faifer, M. Rossi, S. Toscani, M. Catelani, L. Ciani, M. Lazzaroni, Simplified method for evaluating the effects of dust and aging on photovoltaic panels, Measurement 54(August) (2014) 207–214, http://dx.doi.org/10.1016/j.measurement.2014.03.001 <http://www.sciencedirect.com/science/article/pii/S0263224114000955> (Elsevier, ISSN 0263-2241).

[50] L. Cristaldi, M. Faifer, M. Lazzaroni, A.F.M.M. Khalil, M. Catelani, L. Ciani, Failure modes analysis and diagnostic architecture for photovoltaic plants, in: Proceedings of the 13th IMEKO TC10 Workshop on Technical Diagnostics Advanced Measurement Tools in Technical Diagnostics for Systems' Reliability and Safety, June 26–27, 2014, Warsaw, Poland, pp. 206–211, ISBN: 978-1-63266-984-1.