Failure Modes Analysis and Diagnostic Architecture for Photovoltaic Plants

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Abstract- Failure modes analysis and diagnostic architectures are very interesting aspects for plants based on PV panel. In fact, these plants are called to operate for many years. The monitoring of plant parameters and performances is a very important task that can be obtained by means a well-designed monitoring system. This approach allows to improve complex system maintenance policies and, at the same time, to achieve a reduction of unexpected failure occurrences in the most critical components.

I. Introduction

Photovoltaic (PV) systems are installed all around the world to produce electricity from solar energy. The evaluation of its long term reliability is fundamental for PV system [1] 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] - [7]. A fewer number of publications considered the failures of the overall PV system. In [8], a failure analysis shows that inverters, AC subsystems, support structure DC subsystems and modules contribute in 43%, 14%, 6%, 2% of PV system failures respectively. In this paper a detailed review of the most important failure modes 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.

II. PV Systems overview

The system under study is a grid-connected photovoltaic system with a main inverter. It consists, as depicted in Fig. 1, of three main subsystems, photovoltaic modules connected in series and parallel, power conditioning subsystem that includes inverters and BOS (Balance Of System) subsystem that consists of generator and module junction box, solar cable connectors, Fuses, DC and AC wires, DC and AC switches.

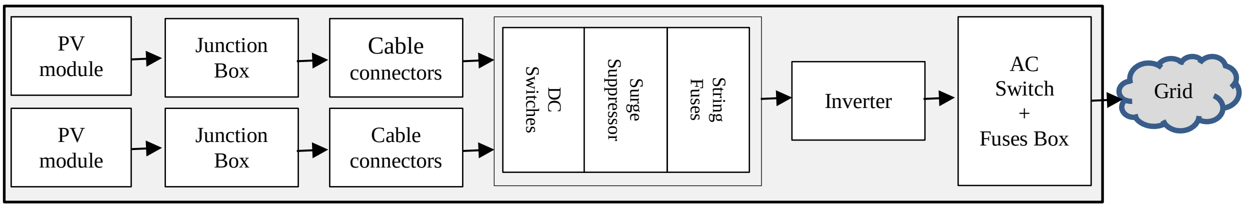

Fig. 1: Schematic diagram of photovoltaic plant.

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 its contribution to PV plant outages is very small, less than 1% [7]. 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 with their forward bias current. Therefore, current modules, nowadays, can withstand reverse current up to seven times the short circuit one.

III. Failure mode 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.

A. 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 will affect the overall performance of the PV system.

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 fortification 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). The D&D affects the intensity of solar energy converted to electricity [9]. Moisture ingress 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 with impermeable front- and back-sheets, water can permeate in and condense [10]. Therefore, the incoming irradiation is partially blocked by the moisture and the cells are partially shaded. This results in 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 component of PV module components [11]. Shattering of the top glass of encapsulation is considered another reason of failure. This is due to thermal stress, handling, wind or hail [11]. Module broken glass may keep module functioning correctly but the risk of an electrical shock and of a moisture infiltration increase.

Module Corrosion

The corrosion of the conductive parts of the cells and the interconnections through the encapsulant is the 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 electrical model [12].

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 buss strips that are soldered to the front and back contacts. A junction of several cells through interconnection elements. A failure of string ribbon is associated with loss of output power [13]. 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.

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 [14] - [15], handling and vibrations in transportation can induce or expand cracks. Finally, a module in the field experiences mechanical loads due to wind (pressure and vibrations) and snow (pressure). Cracking of cells occurs at 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 [16]. The consequences of cells cracking varies on PV performance as they participate in 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 cracks parallel to busbars have frequently the risk of separating cells areas of 16-25% [17]. In addition, these cracks can be directly related to the decrease of the filling factor and open circuit voltage.

Dust

In dry regions, dust is considered a detrimental agent whenever solar energy applications are concerned. When foreign particles fall on PV modules, they interfere with illumination quality by both absorbing and scattering light [18].

Dust deposition depends on its density, and size distribution. The accumulation of dust on the PV module surface can produce spots with varying concentrations. These spots vary in shape, location and concentration density. The variation in dust accumulation in any place can lead 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.

Many papers discussing the impact of dust on the performance of PV systems have been published and are therefore present in the literature. Experimental investigation on the reduction of PV output efficiency presented in [19] showed that the reduction of efficiency reached up to 11.6% when the dust deposition density was fixed at about 8 g/m^2. In addition, a single 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 [20]. [21] presented the results of a comparison that was done experimentally on two pairs of PV panels, the first being cleaned and the second being artificially polluted, results showed a deterioration in the performance of polluted PV panels.

Hot-spots

Hot spots are a very well-known phenomenon that occur in PV string and they are considered primary sources of PV failures and modules degradations. 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 [22]. Therefore, the temperature of a single cell or portion of cells becomes very higher than that of the surrounding 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 [23]. 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 between one solar cell and another may lead to mismatch losses at some operating point. Mismatch in PV modules 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 depend on the operating point of the PV module the circuit configuration and the ageing factor.

B. PV inverters failure causes

Inverters are considered the brain of the PV system and considered an expensive and complex element in the system. Field experience has shown that the inverter is the most vulnerable component [2]. An investigation in [24] was carried out on 126 system that provided 190 failure events, and results show that inverters dominate the outage causes of PV plants by 76%. Another survey reported in [7] depicted that inverters are the leading cause of PV systems failure. The same conclusion is reported in [26], that 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 [27] 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 [28].

Control problems are related to the interaction between the inverter and the grid, at the AC side, and between the inverter and the PV array, on the DC side [2], [29]. The components of PV inverters are exposed to electrical and thermal stresses during their operation. [30] consider the electrolytic capacitors as the most particularly troublesome component, and [29] focused on IGBT as the leading component in the failure of PV inverters.

C. BOS failures

Failures of BOS components are considered the major reason behind the presence of non-producing modules in PV field. For example, a failure in single fuse can get an entire string out of service. A ten years survey [5] 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 that were found, 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 68739 non- working modules [5].
Bypass diode failure is considered another reason for BOS failures since they are usually supplied inside module junction box. They are manufactured inside PV modules only for sophisticated module types [31]. 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 [32]. The bypass diodes have a junction temperature reaching upwards 150-200 °C but since they possess a significant self-heating [33], the main reason of them failure is the thermal stress.

IV. Diagnostic architecture

Smart monitoring of PV plants is drawing the attentions of decision makers and utilities owners in order to carry out the necessary performance measurements, evaluate the ageing of panels, and early detection of operation failures previously described. This requires the measure of both electrical and environmental parameters at panel, string or plant level. The most significant parameters can be considered current and voltage, temperature and irradiance. The monitoring of these parameters both online and offline modes in different position on the plant allows one to evaluate the actual state of the system. The project budget, size of the plant, operation and maintenance costs, and system criticality are the factors that determine the necessary level of monitoring. 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 proper 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. 2 shows a possible schematics diagram of the PV system smart performance monitoring.

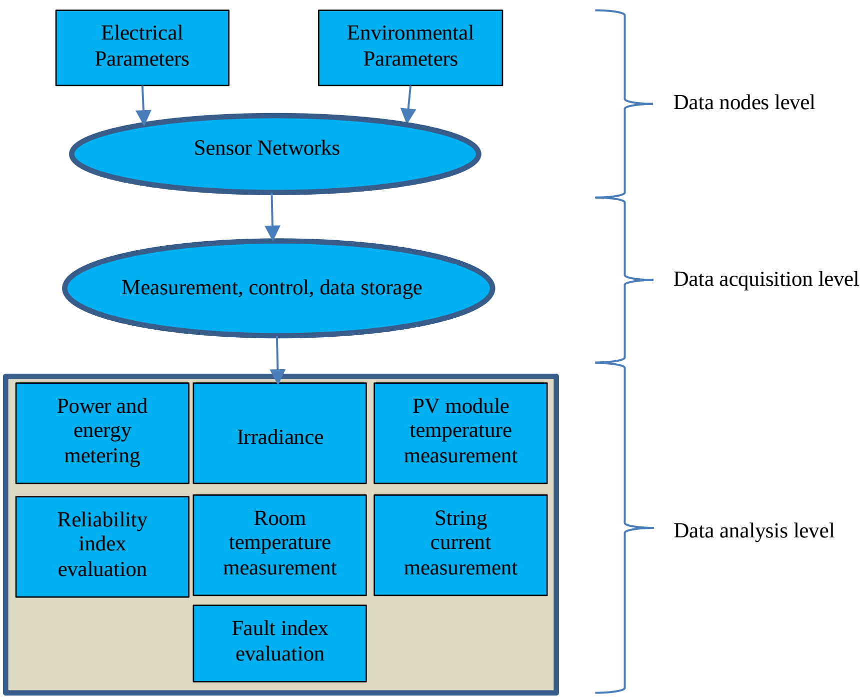

Fig. 2. PV smart monitoring system

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 a 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 that based on the comparison of measured data with a model of the system [34]. That approach can be implemented in an efficient way only if an *ad hoc* and low-cost measurement system is available. The hardware must allow the measurement 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 measure the I-V curve of the PV panel. In addiction the hardware must be able to communicate with a central unit that analyzing all data performs the monitor of the whole system.

With the use of such a hardware the failure modes previously discussed can be detected as reported in Table I.

Table 1: Failure modes detection strategies.

Failure mode	Detectability	Requirement
Encapsulation	MPP value of the panel is below the value given by the model. Output of the other panels is good. We can compare the actual and model MPP.	The panels have to be clean.
Module corrosion	Model approach: a comparison beetween the value assigned to the series resistance during the characterization of the 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	IV curve has to be obtained by means an electronic load
Dust	It can be detected comparing the actual and model MPP. All 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

V. 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 them behavior 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. In fact, this optimization results in an increased production efficiency leading then to higher returns for investors.

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