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Fault detection and monitoring systems for photovoltaic installations: A review

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ABSTRACT

As any energy production system, photovoltaic (PV) installations have to be monitored to enhance system performances and to early detect failures for more reliability. There are several photovoltaic monitoring strategies based on the output of the plant and its nature. Monitoring can be performed locally on site or remotely. It measures production, focuses also on verification and follow-up of converter and communication devices' effective operation. Up to now, some faults diagnosis methods for PV components and systems have been developed. However, given the evolution of PV installations, more advanced monitoring techniques are continuously under investigation. In this paper, major photovoltaic system failures are addressed. Then techniques for photovoltaic monitoring proposed in recent literature are overviewed and analyzed to point out their differences, advantages and limits.

1. Introduction

An Accurate and consistent performance assessment of photovoltaic systems is essential for a sustainable industry development. On one side, for manufacturers, performance evaluation is a key criterion for their products quality. On the other side, for research investigations, it is a crucial indicator for identifying future challenges.

Further, for end-customers, a reliable performance evaluation can lead them with future decision-making.

Moreover, an effective operation and maintenance (O & M) program enables PV system production to reach its expected level of efficiency; which will consequently strengthen end-users confidence in such systems. However, operation and maintenance costs are significant [1]. Among the solutions proposed in literature to reduce these costs, *O & M best practices* and notably photovoltaic monitoring systems are widely recommended [2,3].

Monitoring PV systems consists in comparing results of the plant with forecasted ones, and providing reports to end users. These systems are mainly composed by sensors (electrical and environmental), a data acquisition system with adapted communication protocols. It also involves algorithms for data analysis.

With the increased interest in monitoring PV plants, more and more papers related to these systems are emerging. Most of them deal with one part of the monitoring system such as sensors, data acquisition… However, at our best knowledge, only few state of art papers are reported in the literature [4–7]. Each paper focuses on one specific issue. First of all, main features of some commercial products are described in [4,5].

Secondly, data measuring devices, data acquisition system, and data storage are overviewed in [5,6] as well as data transmission methods in [6] and dedicated software for monitoring systems in [5].

Furthermore, some of the elements to be used as a starting point for the development of algorithms dedicated to PV module diagnostic and prognostic are proposed in [4]. Moreover, data analysis methods for PV systems are presented in [7] and [6]. Finally, the report [8] states the constructive guidelines, methods and models that may be designed for analytical monitoring of PV systems.

Indeed, new diagnostic techniques and algorithms were proposed to monitor photovoltaic plants, to predict failures and to enhance PV system performance. Some of PV fault detection algorithms are based on electrical circuit simulation of PV generator [9–12]. Other ones use electrical signal approaches [13–32], such as the time domain reflectometry [18,19] or the maximum power point tracking (MPPT) analysis [10–12]. Predictive model approaches for PV system power production based on the comparison between measured and modeled PV system outputs are discussed in [11,13–18] and [33–41] Numerous monitoring systems employ statistical analysis concepts for PV system measurements [42–48] Further methods exploit artificial intelligence [49], particularly neural network [50–55], Bayesian belief network [56], fuzzy logic [57–59], learning method [60] or extension theory

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[61]. Some of these monitoring systems require climate field data or environmental and meteorological data from satellite observations [62,63].

In this paper, we shed some light on few of the numerous remaining questions about the monitoring systems and particularly reviewing all the analysis methods that are not mentioned in papers [3–6]. Also, we point out their differences, advantages and limits. Furthermore, different techniques of diagnosis and supervision in recent literature are exposed. PV system measurements are always required for these data analysis techniques: some of them are based exclusively on electrical and meteorological measurements. Other ones combine measurements and mathematical modeling. In our paper, both of the data analysis techniques are considered.

This paper is organized as follows: Section 1 gives a brief reminder of PV systems and PV generator model. Section 2 presents different failures that can occur in a PV installation. Section 3 details architecture of the diagnostic systems with a focus on sensors and data acquisition systems. Finally, Section 4 details the different monitoring methods presented above.

2. PV system and PV generator model

PV installations can be classified according to power levels i.e. residential, buildings, industrial and utility scale. They are also sorted according to their connection to the utility grid: Stand alone or grid connected systems. This study is limited on grid connected PV systems with or without local load. Fig. 1 illustrates the structure of such systems. They are mainly composed of PV modules connected to DC/AC inverter, generally via a junction box. Blocking diodes are usually included in the construction of each solar panel.

PV module is a combination of PV cells that produce electrical power when exposed to light. They constitute the part responsible on producing energy in a PV generator. Each serie of cells is connected to a by-pass diode. This diode prevents modules from behaving like receivers and consequently avoids from heating up the cells during partial illumination. I-V and P-V curves of PV generator are based on an elementary cell, modeled by the equivalent circuit presented in Fig. 2. Series and parallel resistances (R_s and R_p respectively) take into account the power loss phenomena.

This model is the most used one in literature related to PV monitoring. Moreover, it is the model presented in the EN 50530 standard [64]. Its parameters are detailed below. Various monitoring approaches are based on these parameters, such as series resistance measurement, shunt resistance measurement…However some of references mentioned in this paper relies on the two diode model [12] and [22].

The one diode PV model is expressed by (1).

$$I_{PV} = I_{ph} - I_0\left(e^{\frac{U_{PV} + I_{PV}.\,R_s}{m.\,UT}} - 1\right) - \frac{U_{PV} + I_{PV}.\,R_s}{R_p} \quad (1)$$

$$I_0 = C_0 T_{mod}^3 e^{-\frac{U_{gap}}{U_T}} \quad (2)$$

$$U_T = \frac{k\ T_{mod}}{e_0} \quad (3)$$

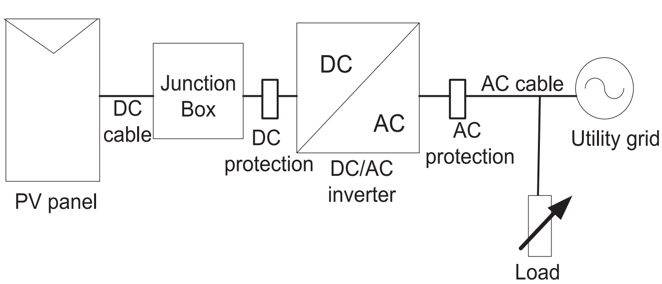

Fig. 1. Schematic diagram of grid connected PV system with local load.

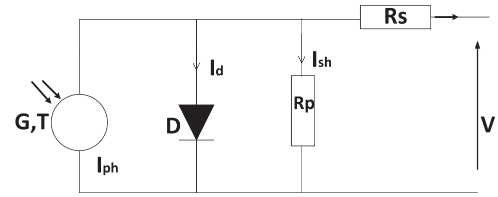

Fig. 2. PV cell equivalent model.

$$T_{mod} = T + \frac{c}{1000\ \frac{W}{m^2}}.\ G \quad (4)$$

With

I_{PV}: Module current (A)
I_0: Diode saturation current (A)
I_{ph}: Photocurrent (A)
U_{PV}: Module voltage (V)
U_T: Temperature voltage (V)
U_{gap}:Bang gap voltage (V)
R_s:Series resistance (Ω)
R_p:Parallel resistance (Ω)
T: Ambient temperature (K)
T_{mod}:Module temperature (K)
G: Irradiance (W/m^2)
C: Temperature model constant
e_0:Elementary charge
k: Boltzmann constant
m: Diode factor

The inverter is equipped by an MPPT that optimizes the match between the solar array and the grid, and therefore enhances the system to reach maximum power P_{mp} which is presented in Fig. 3.

3. Photovoltaic system failures

3.1. PV module failures modes

The PV array is the main component of the PV installation, any breakdown associated to the module will affect the system performances. The failure modes at the generator level are presented below. All these fails are classified according to their symptoms, their effects and their consequences. Fig. 4 regroups causes classification as proposed in [65] according to events detailed below and resumed in Tables 1–4.

3.1.1. Encapsulation failures

This mode is caused notably by delamination and discoloration that appear frequently in humid and hot conditions. This defect is located between encapsulant and active cells. This default can occur due to salt accumulation, contaminations, moisture penetration or external factors. In one hand, delamination results in reflection and ultimately power loss. In order to detect this anomaly, thermography, ultrasonic

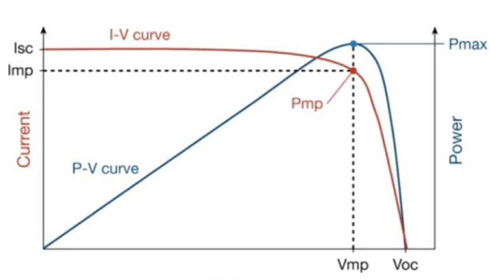

Fig. 3. I–V and P–V characteristics of PV model.

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