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A novel fault diagnosis technique for photovoltaic systems based on artificial neural networks

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ABSTRACT

This work proposes a novel fault diagnostic technique for photovoltaic systems based on Artificial Neural Networks (ANN). For a given set of working conditions - solar irradiance and photovoltaic (PV) module's temperature - a number of attributes such as current, voltage, and number of peaks in the current–voltage (I–V) characteristics of the PV strings are calculated using a simulation model. The simulated attributes are then compared with the ones obtained from the field measurements, leading to the identification of possible faulty operating conditions. Two different algorithms are then developed in order to isolate and identify eight different types of faults. The method has been validated using an experimental database of climatic and electrical parameters from a PV string installed at the Renewable Energy Laboratory (REL) of the University of Jijel (Algeria). The obtained results show that the proposed technique can accurately detect and classify the different faults occurring in a PV array. This work also shows the implementation of the developed method into a Field Programmable Gate Array (FPGA) using a Xilinx System Generator (XSG) and an Integrated Software Environment (ISE).

1. Introduction

Over the past few years, the number of photovoltaic (PV) systems has increased rapidly at the global level. Grid-connected PV plants with size varying from a few kWp (domestic systems) to hundreds of MWp (commercial/industrial and utility-scale systems) represent worldwide the power technology with the highest growth rate. As reported in Refs. [1], at the end of 2014 the total installed PV capacity was 177GWp. This result is not only related to the incentives given by governments during the past years but also to the recent attainment of the grid-parity in key countries such as Germany and Italy [2,3].

The need for higher performance, efficiency, and reliability is linked to the recent interest in fault diagnosis techniques that are today more and more proposed in the literature. A remote monitoring and fault detection method, which relies on a satellite-based systems to generate the necessary climate data at the desired location, is presented in Ref. [4]. The proposed technique leads to the detection of four different categories of failures. 1) Constant energy losses due, for example, to the degradation of PV modules, to the soiling effect, to PV module or string failures, etc. 2) Variable energy losses due, for example, to shading phenomena [5], to soiling effects [6–8], to mismatch effects [9–11], to disconnections of the PV system from the electrical grid, to inverter's power limitation, to Maximum Power Point Tracker (MPPT) failures, to the temperature effect, etc. 3) Losses due to the presence of snow. 4) Losses due to blackouts [12]. The proposed technique leads to a reduction of the computational and simulation costs but, on the other hand, the costs for data loggers and communication systems are high. Nowadays, as the overnight capital cost of PV plants has dramatically decreased, the development of cheap monitoring systems is necessary.

A monitoring circuit measuring the operating voltage (V_{mpp}) and current (I_{mpp}), the open circuit voltage (V_{oc}), and the short circuit current (I_{sc}) of PV modules is proposed in Ref. [13]. The circuit can detect the shadow propagation along a PV string, the number of shaded subpanels, as well as the efficiency of the MPPT. In Refs. [14], the authors proposed a low-cost on-board monitoring device that

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improves the system's reliability and efficiency. The method takes as an input the measure of the PV panel's current, voltage, and temperature. A novel technique for the transmission of the current, voltage, and temperature quantities based on a low cost smart monitoring system is proposed in Ref. [15]. A data acquisition board sends the data to a central control system using the Power Line Carriers (PLC) communications technology, avoiding additional installations costs.

In general, fault detection methods for PV systems can be grouped as visual (browning, discolouration, surface soiling, and delamination), thermal (hot spot), and electrical (transmittance line diagnosis, dark/illuminated current–voltage measurement, and RF measurement) [16]. In this paper we focus on an electrical method. Fault detection based electrical methods for photovoltaic systems are based on:

- Methods that do not require climate data (such as solar irradiance and temperatures): in Ref. [17] the authors developed a method based on the Earth Capacitance Measurement (ECM) to detect the disconnection of a PV module. The Time-Domain Reflectometry (TDR) technique proposed in Ref. [18] was used to detect the disconnection of a PV string as well as the impedance change due to degradation. In Refs. [19], a statistical approach based on the Analysis of Variance (ANOVA) and on the non-parametric Kruskale Wallis (KW) tests was investigated;
- Methods based on the analysis of the current voltage characteristic (I–V characteristic): in Refs. [20], the (dI/dV) - V characteristic is used to detect the partial shadow interesting a PV array. In Refs. [21], the authors calculate the Fill Factor (FF), the series resistance (Rs), and the shunt resistance (Rsh) starting from the I–V characteristic and provide some performance indicators. A method based on the evaluation of some current and voltage indicators is introduced in Ref. [22] as automatic fault detection for Grid-Connected Photovoltaic (GCPV) systems;
- Methods that use a Maximum Power Point Tracking (MPPT) approach: an automatic supervision and fault detection procedure based on the analysis of the power losses was proposed in Ref. [23]. The method leads to the identification of three groups of faults (faulty module, faulty string, and a group of different faults such as partial shadow, ageing, and MPPT failure) and of a false alarm. The method presented in Ref. [24] detects faults occurring in both the PV array and in the inverter on the base of a power losses analysis. The technique developed in Ref. [25] is based on the relation between the simulated and the measured string powers. This method determines the number of open and short-circuited PV modules in a string;
- Methods based on Artificial Intelligence (AI) techniques: a learning method based on Expert Systems is developed in Ref. [26] to identify two types of fault (due to the shading effect and to the inverter's failure). The effectiveness of Artificial Neural Network (ANN) based techniques was shown in Ref. [27]. A method for the identification of short-circuited PV modules is presented in Ref. [28]. In Refs. [29], an ANN is used in order to classify different types of faults occurring in a PV array. In this case, the ANN takes as inputs the current and the voltage at maximum power point, and the temperature of the PV module. Different methods based on the Takagie Sugeno Kahn Fuzzy Rule (TSKFRBS) have been described in Refs. [30,31].

Other strategies comprise: a method based on the extended correlation function and on the matter element model was presented in Ref. [32]. In Refs. [33], a Decision Tree (DT) technique was used to examine two different types of faults using an Over-Current Protection Device (OCPD). The first type of fault is the line-to-line fault that occurs under low irradiance conditions, and the second is the line-to-line fault occurring in PV arrays equipped with blocking-diodes [34]. An equivalent circuit model was proposed in Refs. [35] and [36] for the calculation of the PV generator's insulation resistance and leakage current. This model can be used to analyse the risk of electric shock and for the design of protections. Sources of failure and PV modules diagnostics are reviewed in Ref. [37].

The main contribution of this work is to present a new technique for the isolation and identification of the faults occurring in a PV system and its implementation into a FPGA. In particular, the technique is able to localize and identify faults occurring in: PV cells, PV modules, PV strings, and bypass-diodes. The proposed technique is based on the analysis of a set of attributes (such as current, voltage and number of peaks) of the I–V characteristic that indicate the normal and the faulty operations. The analysis is performed using two different Algorithms:

- Algorithm 1 implements a signal threshold approach and isolates the faults that have a different combination of attributes;
- Algorithm 2 consists of an ANN-based approach to identify the faults that are characterized by the same combination of attributes.

The paper is organized as follows: the next section presents the main types of faults occurring in a PV array. The proposed fault diagnosis technique is provided in Section 3. Results and discussion are given in Section 4.

2. Faults in photovoltaic arrays

The faults occurring in a PV system are mainly related to the PV array, the inverter, the storage system, and the electrical grid. This work aims at detecting the faults occurring in the PV array and, with reference to Table 1, eight different faults are investigated. This type of faults are usually connected to: the failure of a solar cell or a PV module, a line disconnection, the degradation effect, corrosion and manufacturing defects, the presence of snow, the effect of soiling, and etc.

3. The proposed fault diagnosis technique

The fault diagnosis technique developed in this work is able to identify one normal and eight faulty modes. As shown in Fig. 1, firstly the difference between the measured and the simulated PV array output power is compared with a threshold (*Th*) in order to detect the possible presence of a fault. Then, the analysis of the main attributes in the I–V characteristic of each string forming the PV array leads to the faults identification and localization. The schematic of the developed fault diagnosis system that is based on two different Algorithms, is depicted in Fig. 2.

3.1. Attributes identification

In order to understand what changes can affect the attributes of an I–V characteristic, a number of simulations have been carried out considering both normal operation and different fault conditions. The simulations have been performed using a MatLab/Simscape™ tool. As an example, Fig. 3a shows the Simscape™ based model for a PV string formed by four series-connected modules, in case of connection fault [38]. Standard blocks representing the PV modules, resistances, current and voltage sensors have been used. A PV module block consists of four series-connected PV modules, and these are made by 18 series-connected solar cells as depicted in Fig. 3b. The solar cell block is defined by equation (1) [39] [40], where Iph is the photo-generated current, I0 is the dark saturation