Electric Power Systems Research 151 (2017) 26–39

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Diagnostic method for photovoltaic systems based on six layer detection algorithm

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ARTICLE INFO

Article history:
Received 19 March 2017
Received in revised form 1 May 2017
Accepted 15 May 2017

Keywords:
Photovoltaic system
Photovoltaic faults
Fault detection
LabVIEW
Fuzzy logic

ABSTRACT

This work proposes a fault detection algorithm based on the analysis of the theoretical curves which describe the behaviour of an existing grid-connected photovoltaic (GCPV) plant. For a given set of working conditions, solar irradiance and PV modules' temperature, a number of attributes such as voltage ratio (VR) and power ratio (PR) are simulated using virtual instrumentation (VI) LabVIEW software. Furthermore, a third order polynomial function is used to generate two detection limits (high and low limit) for the VR and PR ratios obtained using LabVIEW simulation tool.

The high and low detection limits are compared with real-time long-term data measurements from a 1.1 kWp and 0.52 kWp GCPV systems installed at the University of Huddersfield, United Kingdom. Furthermore, samples that lies out of the detecting limits are processed by a fuzzy logic classification system which consists of two inputs (VR and PR) and one output membership function.

The obtained results show that the fault detection algorithm can accurately detect different faults occurring in the PV system. The maximum detection accuracy of the algorithm before considering the fuzzy logic system is equal to 95.27%, however, the fault detection accuracy is increased up to a minimum value of 98.8% after considering the fuzzy logic system.

1. Introduction

Despite the fact that Grid-Connected Photo-Voltaic (GCPV) systems have no moving parts, and therefore usually require low maintenance, they are still subject to various failures and faults associated with the PV arrays, batteries, power conditioning units, utility interconnections and wiring [1,2]. It is especially difficult to shut down PV modules completely during faulty conditions related to PV arrays (DC side) [3]. It is therefore required to create algorithms to facilitate the detection of possible faults occurring in GCPV installations [4].

There are existing fault detection techniques for use in GCPV plants. Some use satellite data for fault prediction as presented by Tadj et al. [5], this approach is based on satellite image for estimating solar radiation data and predicting faults occurring in the DC side of the GCPV plant. However, some algorithms do not require any climate data, such as solar irradiance and modules' temperature, but instead use earth capacitance measurements in a technique established by Takashima et al. [6].

Some fault detection methods use an automatic supervision based on the analysis of the output power for the GCPV system. Chouder and Silvestre [7], presented a new automatic supervision and fault detection technique which use a standard divination method ($\pm 2\sigma$) for detecting various faults in PV systems such as faulty modules in a PV string and faulty maximum power point tracking (MPPT) units. However, Silverstre et al. [8] presented a new fault detection algorithm based on the evaluation of the current and output voltage indicators for analyzing the type of fault occurred in PV systems installations.

A photovoltaic fault detection technique based on artificial neural network (ANN) is proposed by Chine et al. [9]. The technique is based on the analysis of the voltage, power and the number of peaks in the current-voltage (I–V) curve characteristics. However, Refs. [10,11], proposed a fault detection algorithm which allows the detection of seven different fault modes on the DC-side of the GCPV system. The algorithm uses the t-test statistical analysis technique for identifying the presence of systems fault conditions.

Other fault detection algorithms focus on faults occurring on the AC-side of GCPV systems, as proposed by Platon et al. [12]. The approach uses $\pm 3\sigma$ statistical analysis technique for identifying the faulty conditions in the DC/AC inverter units. Moreover, hot-spot detection in PV substrings using the AC parameters characterization was developed by Ref. [13]. The hot-spot detection method

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http://dx.doi.org/10.1016/j.epsr.2017.05.024
0378-7796/

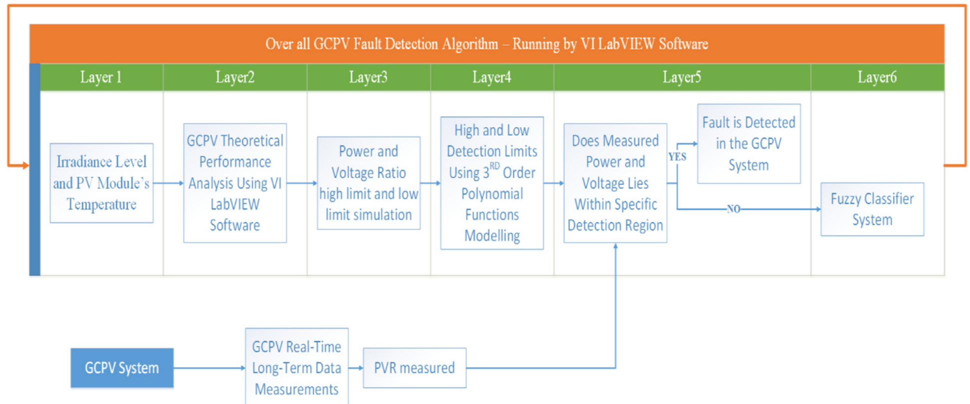

Fig. 1. Over all GCPV fault detection algorithm layers.

can be further used and integrated with DC/DC power converters that operates at the subpanel level. Nevertheless, the analysis of the current and voltage indicators in a GCPV system operating in partial shading faulty conditions is created by Silvestre et al. [14].

A comprehensive review of the faults, trends and challenges of the grid-connected PV systems is explained by Obi & Bass, Alam et al. and Khamis et al. [15–17].

Currently, fuzzy logic systems widely used with GCPV plants. Boukenoui et al. [18] proposed a new intelligent MPPT method for standalone PV system operating under fast transient variations based on fuzzy logic controller (FLC) with scanning and storing algorithm. Furthermore, Ref. [19] presents an adaptive FLC design technique for PV inverters using differential search algorithm. However, to the best of our knowledge, few of the reviewed articles used a fuzzy classifier system in order to investigate the faulty condition occurring in the DC-side of the GCPV system.

Since many fault detection algorithms use statistical analysis techniques such as [7,10–12], this work proposes a fault detection algorithm that does not depend on any statistical approaches in order to classify faulty conditions in PV systems. Furthermore, some existing fault detection techniques such as Refs. [20,21] use a complex power circuit design to facilitate the fault detection in GCPV plants. However, the proposed fault detection algorithm depends only on the variations of the voltage and the power, which makes the algorithm simple to construct and reused in wide range of GCPV plants.

In this work, we present the development of a fault detection algorithm which allows the detection of possible faults occurring on the DC-side of GCPV systems. The algorithm is based on the analysis of theoretical voltage ratio (VR) and power ratio (PR) for the examined GCPV plant. High and low detection limits are generated using 3rd order polynomial functions which are obtained using the simulated data of the VR and PR ratios. Subsequently, if the theoretical curves are not capable to detect the type of the fault occurred in the GCPV system, a fuzzy logic classifier system is designed to facilitate the fault type detecting for the examined PV system. A software tool is designed using Virtual Instrumentation (VI) LabVIEW software to automatically display and monitor the possible faults occurring within the GCPV plant. A LabVIEW VI is also used to log the measured power, voltage and current data for the entire GCPV system, more details regarding the VI LabVIEW structure is presented in Ref. [11].

The main contribution of this work is the development and the theoretical implementation of a simple, fast and reliable GCPV fault detection algorithm. The algorithm does not depend on any statistical techniques which makes it easier to facilitate and detect faults based on theoretical curves analysis and fuzzy logic classification system. In practice, the proposed fault detection algorithm is capable of localizing and identifying faults occurring on the DC-side of GCPV systems. The types of fault which can be detected are based on the size of the GCPV plant, which will be discussed in the next section. The algorithm is based on a six layer method working sequentially as shown in Fig. 1.

This paper is organized as follows: Section 2 describes the methodology used which includes the PV theoretical power curve modelling and the proposed fault detection algorithm, while Section 3 explains the validation and a brief discussion of the proposed fault detection algorithm. Finally, Section 4 describes the conclusion and future work.

2. Methodology

2.1. Photovoltaic theoretical power curve modelling

The DC side of the GCPV system is modelled using the 5-parameter model. The voltage and current characteristics of the PV module can be obtained using the single diode model [22] as follows:

$$I = I_{ph} - I_o\left(e^{\frac{V+IR_s}{nsV_t}} - 1\right) - \left(\frac{V+IR_s}{R_{sh}}\right) \quad (1)$$

where I_{ph} is the photo-generated current at STC, I_o is the dark saturation current at STC, R_s is the module series resistance, R_{sh} is the panel parallel resistance, ns is the number of series cells in the PV module and V_t is the thermal voltage and it can be defined based on:

$$V_t = \frac{AKT}{q} \quad (2)$$

where A the ideal diode factor, k is Boltzmann's constant and q is the charge of the electron.

The five parameter model is determined by solving the transcendental Eq. (1) using Newton–Raphson algorithm [23] based only on the datasheet of the available parameters for the examined PV module that was used in this work as shown in Table 1. The power produced by the PV module in watts can be easily calculated along with the current (I) and voltage (V) that is generated by Eq. (1), therefore:

$$P_{theoretical} = I \times V \quad (3)$$

The Power–Voltage (P–V) curve analysis of the tested PV module is shown in Fig. 2. The maximum power and voltage for each irradiance level under the same temperature value can be expressed by the P–V curves.

The purpose of using the analysis for the P–V curves, is to generate the expected output power of the examined PV module,