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Fault detection and diagnosis methods for photovoltaic systems: A review

A. Mellit[a,b,*], G.M. Tina[c], S.A. Kalogirou[d]

[a] Renewable Energy Laboratory, Faculty of Sciences and Technology, University of Jijel, P.O. Box .98, Jijel 18000, Algeria
[b] The Abdus Salam International Centre for Theoretical Physics (ICTP), Starada Costiera, 11-34151 Trieste, Italy
[c] DIEEI: Department of Electric, Electronic and Computer Engineering, University of Catania, v.le A. Doria 6, 95125 Catania, Italy
[d] Department of Mechanical Engineering and Materials Science and Engineering, Cyprus University of Technology, P.O. Box 50329, Limassol 3603, Cyprus

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ABSTRACT

Faults in any components (modules, connection lines, converters, inverters, etc.) of photovoltaic (PV) systems (stand-alone, grid-connected or hybrid PV systems) can seriously affect the efficiency, energy yield as well as the security and reliability of the entire PV plant, if not detected and corrected quickly. In addition, if some faults persist (e.g. arc fault, ground fault and line-to-line fault) they can lead to risk of fire. Fault detection and diagnosis (FDD) methods are indispensable for the system reliability, operation at high efficiency, and safety of the PV plant. In this paper, the types and causes of PV systems (PVS) failures are presented, then different methods proposed in literature for FDD of PVS are reviewed and discussed; particularly faults occurring in PV arrays (PVA). Special attention is paid to methods that can accurately detect, localise and classify possible faults occurring in a PVA. The advantages and limits of FDD methods in terms of feasibility, complexity, cost-effectiveness and generalisation capability for large-scale integration are highlighted. Based on the reviewed papers, challenges and recommendations for future research direction are also provided.

1. Introduction

There has been an increased attention to the photovoltaic (PV) energy systems during the last decade owing to the many advantages that these systems have such as: it is a worldwide available energy source, it is pollution free, it has noiseless operation, it is modular and easy to install, it is a reliable method of energy conversion, and it is able to be installed and/or integrated in the buildings. As a result, the number and size of PV systems (PVS) have increased rapidly all over the word. The PV market grew by 75 GW in the year 2016, while the total capacity has reached 303 GW around the globe [1]. With reference to IRENA (International Renewable Energy Agency) [2] the price of photovoltaic modules dropped by 80% between 2009 and 2015, and the actual cost is less than 1 USD/Wp.

Photovoltaic systems are subject to different variety of failures that can involve all PVS components (modules, cabling, protections, converters and inverters), mainly due to the external operating conditions. Faults in PVS are caused by: shading effects, module soiling, inverter failure, and mismatch due to variation in manufacturing or aging of PV modules (PVM). The main catastrophic failures in PV arrays (PVA) are: the line-to-line (LLF), ground (GF) and arc (AF) faults [3]. An analysis of some important failure modes associated to PV modules (PVM), Balance of System (BOS) and PVA has been given in [4]. Faults in PVS may cause a huge amount of energy loss as well as risk of fires. For example, Fig. 1 shows the number of incidents related to fires of various magnitudes that involved PVS installations in Italy. The Italian data analysis [5] showed that the number of fires peaked in 2012 following the first wave of installations. Some recommendations for preventing the fire hazards in PVS are reported in [5]. Guidelines for the mitigation of electrical faults that may result in a fire are also given in [6,7].

To ensure reliable and safe operation of PV installations, monitoring and fault diagnosis (MFD) systems should accompany these installations to timely detect and solve problems. Addressing these issues, numerous monitoring and fault diagnosis methods have been studied in literature, which vary in rapidity, complexity and sensors requirements, and the capability for the identification of a large number of faults [8,9].

Fault detection and diagnosis (FDD) for grid-connected photovoltaic (GGPV) plants, is a fundamental task to protect the components of PVS (modules, batteries and inverters), particularly PVM, from damage and to eliminate possible fire risks [6,10]. The main task of fault detection (FDe), in PVS, consists of comparing the difference between the measured and calculated parameters with reference values, in order to verify the occurrence of any fault, while the fault diagnosis (FDi) method aims to identify the type of faults and localise the faults based on *a priori* knowledge or search techniques [11]. Fault localisation

* Corresponding author at: Renewable Energy Laboratory, Faculty of Sciences and Technology, University of Jijel, P.O. Box .98, Jijel 18000, Algeria.
E-mail address: amellit@ictp.it (A. Mellit).

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Nomenclature

Terminology

ABC-DE	Artificial Bee Colony- Deferential Evolution
AC	Arc Fault
AIT	Artificial Intelligence Technique
ANN	Artificial Neural Network
ANOVA	ANalysis Of VAriance
BBN	Bayesian Belief Network
BIPV	Building Integrated PV
BkD	Blocking Diode
BOS	Balance of System
BpD	Bypass Diode
DF	Diode Fault
DS	Diagnosis System
EC	Eaton Corporation
ECM	Earth Capacitance Measurement
ETNN	Extension Theory with Neural Networks
ENN	Extension Neural Networks
EVA	Ethylene Vinyl Acetate
FDD	Fault Detection & Diagnosis
FDe	Fault Detection
FDi	Fault Diagnosis
FDM	Fault Detection Method
FFT	Fast Fourier Transform
FL	Fuzzy Logic
GA	Genetic Algorithm
GBSSL	Graph-Based Semi-Supervised Learning
GS	Grid connected
GCPVS	Grid-Connected PV System
GF	Ground Fault
GFD	Ground Fault Detectors
GSM	Global System Mobile;
HS	Hot Spot
I-VCA	I-V Characteristic Analysis
JB	Junction Box
JBF	JB Fault
K-NN	k-Nearest Neighbour
LAPART	LAterally Primed Adaptive Resonance Theory
LLF	Line to Line Fault
LS-PVP	Large-Scale PV Plant
MCD	Minimum Covariance Determinant
FPGA	Field Programmable Gate Array
ASIC	Application Specific Integrated Circuit
API	Application programmer interface
MPP	Maximum Power Point
MS	Monitoring System
MFD	Monitoring and Fault Diagnosis system
OCPD	OverCurrent Protection Device
PID	Potential Induced Degradation
PLA	Power Losses Analysis
PR	Power ratio
PV	PhotoVoltaic
PVA	PV Array
PVAF	PVA Fault
PVM	PV Module
PVMF	PVM Fault
PVP	PV Plant
PVS	PV System
PVStr	PV String
RF	Radio Frequency;
SAPVS	Stand-Alone PVS
SPA	Signal Processing Approach
SPRT	Sequential Probability Ratio Test
SNL	Sandia National Laboratories;
SS-PVA	Small-Scale PV Array
SS-PVP	Small-Scale PV Plant
SS-PVS	Small-Scale PV System
STC	Standard Test Conditions
SVM	Support Vector Machine
TDR	Time-Domain Reflectometry;
TSKFR	Takagi Sugeno Kahn Fuzzy Rule
VR	Voltage Ratio

Symbol

FF	Fill Factor
Im	Current at MPP
Isc	Short circuit current
Rs	Series resistance
Rsh	Shunt resistance
Vm	Voltage at MPP
Voc	Open circuit voltage
Ta	Air temperature
Tc	Cell temperature
G	Solar irradiance

remain a big challenge, particularly in large scale PV plants [12]. The effectiveness of the monitoring and detection systems is also strictly related to the architecture of the PVP particularly for small scale PV plants (SS-PVP) with distributed maximum power point tracking (DMPPT) [13]. A review on the application of non-electrical methods (e.g. infrared, thermal imagining) for FDi of PVS is presented in [14,15]. The most common techniques on image analysis can detect and localise faults, but they have been applied and verified only for SS-PVP. A brief review on fault detection and monitoring systems is published recently in [16], in which the authors addressed the major PVS failures.

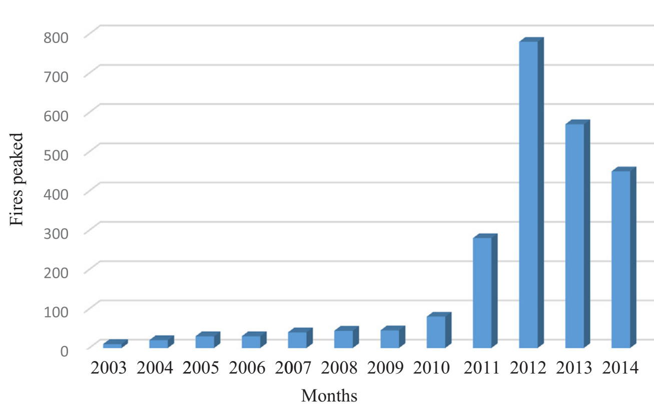

Fig. 1. Fires related to PVS installations, courtesy of Italian National Fire Corp, Statistical Service (INFCS).

This paper aims to review the current state of fault detection and diagnosis (FDD) for PVS based on electrical methods. Different fault types are reported in this paper by presenting for the concerned elements (cell, module, string and array), the cause as well as the effects. The FDD methods presented are discussed in terms of complexity; ability to detect, identify and locate faults; the response time, and the generalisation capability so as to be able to be applied for a variety of PV plants. Special attention is given to the FDD methods that can detect and classify accurately the faults occurring on PVA (DC side). Finally, the advantages and limits or the various methods are presented and