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A practical technique for on-line monitoring of a photovoltaic plant connected to a single-phase grid

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ABSTRACT

Improving the reliability and enhancing the performance of photovoltaic (PV) plants are important objectives that increase the competitiveness of the PV systems, especially for grid connected PV plants, for which, every kilowatt-hour is crucial, since only kilowatt-hours that are fed into the grid are remunerated. Therefore, monitoring and automatic faults detection during the PV panels operation are necessary to ensure the optimal use of the energy generated by the PV plant, and to provide a reliable power supply. In this research paper, two current and voltage indicators are used to analyze and to distinguish, in real-time, the faults related to bypassed PV modules, open-circuits strings and partial shading for a PV plant connected to a single-phase grid. Moreover, the presented strategy allows determining the total number of faulty PV modules and/or strings. The efficiencies of these indicators are tested by experiments, using a Control and Data Acquisition System, which proved the effectiveness of the proposed approach.

1. Introduction

Over the last few decades, photovoltaic (PV) energy has become an effective source to produce electricity that can be used either in isolated sites or injected into the grid. For instance, at the end of 2009, the world's PV cumulative installed capacity was approaching 23 GW [1]. In 2011, more than 69 GW were installed globally and could produce 85 TWh, which allowed covering 20 million households need in electricity [1]. Although the material required for making the PV modules (Silicon) is abundant and inexpensive, the complexity of the construction techniques makes these modules relatively expensive [2]. However, technological advances are being made to enhance their competitiveness, such as the use of Maximum Power Point Tracking (MPPT) techniques, which track the Maximum Power Point (MPP) of the PV panels [3–5]. Moreover, other techniques focused on enhancing the PV cells yield by studying the material used for the PV modules fabrication [6], or the optimum methods for associating PV modules and strings [7]. In addition, several works concentrated in the PV energy optimization and management, which makes them a good solution, for both autonomous and grid-connected systems, thanks to their simplicity in installation [8,9].

Although the advanced techniques for the PV power generation, PV plants, and especially grid-connected systems are continuously exposed to factors that affect significantly the PV system performance. In particular, dust is a critical phenomenon that affects the power generated by the PV modules, since it decreases the system efficiency and tends to make PV systems an unattractive alternative energy source, particularly for the large domestic markets [10–12]. In general, it is constituted of small particles, that may include vegetation pollens, animal cells, sand and clay, and pollution factors like smoke, which its particles size and density depend on the geography and the climate [13,14].

Moreover, in addition to the ambient temperature, the increase in the PV cell temperature affects negatively the PV power generated [9,15]. In fact, when a part of the sunlight that strikes the PV cells is not converted to electrical energy, it is transformed to thermal energy in the PV cell. This causes the junction temperature to rise, and therefore the PV efficiency to decrease unless the heat is efficiently dissipated to the environment [9,15]. Thereby, as the thermal energy increases, the lattice vibration interferes with the charge carriers and the junction loses its power to separate charges. Hence, the band gap decreases and more electrons jump into the conduction band. This allows them to recombine easily with holes, which therefore reduces the open-circuit voltage V_{oc} considerably [9,15].

In addition to these factors, some temporarily faults, especially those related to the partial shading affect significantly the PV modules operation. Indeed, uniform solar radiation on the panel surface

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Nomenclature

α	ratio between the current indexes during normal operation and faults
β	ratio between the current indexes during normal operation and faults
η	coefficient to compensate measurements' errors (%)
DC	direct current
G	solar radiation (W/m^2)
I_m	current at MPPT during faulty operations (A)
I_{mmr}	current of the PV module at MPP (A)
I_{mo}	PV current at MPPT during normal operation (A)
I_{sc}	short-circuit current (A)
I_{scmr}	short-circuit current (A) of the PV module at Standard Test conditions (ST C)
MPP	maximum power point
$MPPT$	maximum power point tracking
NMB	number of bypassed modules
NEF_{String}	number of faulty strings
N_s	number of modules connected in series per string
N_{sc}	number of PV cells in series forming the PV module
N_p	number of parallel photovoltaic strings
NR_C	current indicator during faults
NR_{cfs}	current ratio during open-circuit fault
NR_{CO}	current indicator in normal operation
NR_V	voltage indicator during faults
NR_{vbm}	voltage ratio during bypassed PV module
NR_{VO}	voltage indicator in normal operation
P_{losses}	power losses (W)
PV	photovoltaic
PVP	photovoltaic panels
$PVPG$	photovoltaic power generation
R_{sm}	series resistance of the PV module (Ω)
T_a	ambient temperature at the panel surface (°C)
T_{cell}	operating PV cell temperature (°C)
T_r	PV cell temperature at STC conditions (°C)
TNR_{cfs}	current threshold
TNR_{vbm}	voltage threshold
V_m	photovoltaic voltage during faults at MPP (V)
V_{mo}	photovoltaic voltage in normal operation at MPP (V)
V_{oc}	open-circuit voltage of a photovoltaic panel (V)
V_{ocmr}	open-circuit voltage (V) of the PV module at STC conditions
V_T	thermal voltage (V)

is not always guaranteed, since the presence of buildings or trees shades, existence of clouds and daily sun angle changes [9,16]. The impact of the shade depends on the PV panel type, fill factor, bypass diode characteristics and string configuration [9,17]. Bypass diodes are used to protect the PV panels against damage caused by reverse bias on partially shaded cells [9,18] (please see Appendix). The bypass diode limits the effect of shading to the only neighboring group of cells protected by the same bypass diode [9,26]. Indeed, when a bypass diode begins conducting, the module voltage drops by an amount corresponding to the sum of cell voltages protected by the same bypass diode plus the diode forward voltage. The shade affects nonlinearly the PV power generated, in such a way that a small amount of shade on a portion of an array can cause a large reduction in output power [9,17–19].

Therefore, the automatic monitoring and faults detection in grid-connected PV systems are necessary to maintain the good quality of the PV power generated from one hand, and to minimize the cost of the energy produced by the system, from the other one [9,20]. For instance, the evaluation of the PV system performance is critical for the components manufacturers, since it is considered a quality index for existing products, in such a way that it is used for evaluating the products quality and therefore, guiding future decision-making. Moreover, in research, the system performance is considered a key metric to identify future needs. In fact, in the literature many methods have been conceived to evaluate the performance of a PV plant. For instance, some researches involves the analysis of efficiency indictors related with the solar radiation and the ambient temperature, the Performance Ratio (PR) and the Corrected Performance Ratio (CPR), respectively [21]. These two ratios are used to evaluate the performance of PV plants connected to the grid by comparing the measured and the estimated panels' yields. Moreover, some approaches have compared measured and modeled PV system outputs, to identify faults by using the predicted and the measured values for the PV panels' power generation [22,23]. Other researchers focused in using circuit-based models to estimate the yield of the PV panel, and comparing it with the estimated model [24]. Nevertheless, this approach can be applied to PV plants characterized by a simple configuration; otherwise, the use of circuit-based models may be problematic for large-scale plants, for which many sensors are required [25].

Furthermore, several researches identify the faults by using Artificial Intelligence techniques, namely the Artificial Neural Network (ANN) [26,27] and statistical data analysis for supervision of PV systems [28,29]. However, these methods are expensive, since they require a large number of historical data to perform the network training, and their implementation can be complicated for on-line applications.

Generally, researches focused on faults related with short circuits in PV modules, mainly caused by bypassed diodes and earth faults [30], over current and voltage disturbances [31,32]. Accurate simulations of the PV system behavior have demonstrated good results in fault detection and diagnostic in PV systems [27]. However, these techniques require sophisticated simulation software environments and high computational cost.

In previous works, the authors presented a practical strategy to control the connection of a single-phase PV plant to the grid [33] in which, it has been shown that the control depends significantly on the PV panels efficiency and the accuracy of the measured photovoltaic power [9,33]. Thus, it is necessary to diagnosis the faults of the PV operation, especially in some special situations, namely during partial shading on the PV panels. Hence, in the present work, the authors use a practical and simple strategy to monitor and to detect faults related to short-circuit currents, open-circuit voltage and partial-shading. The adopted strategy allows also the fault type to be distinguished and the number of faulty modules and/or strings to be identified using current and voltage indicators, by comparing them to their respective thresholds. Moreover, the strategy does not need any information about the pattern of shadow to perform the diagnostic, only the output voltage and current are required. Moreover, experimental work has been carried out to show the effectiveness of the proposed strategy.

According to this, the present paper is organized as follows: first, the principle of the fault detection strategy is explained in depth in Section 2. Section 3 describes the experimental set and the methodology used to test the presented approach and to diagnosis faults that may occur in the PV modules and strings. The results of the adopted strategy for faults diagnosis in PV grid connected systems are presented and discussed in Section 4. Finally, conclusions are presented in Section 5.