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Fault-tolerant power extraction strategy for photovoltaic energy systems

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ABSTRACT

Photovoltaic (PV) arrays are subject to various types of environmental disturbances and component-related faults that affect their normal operation and result in a considerable energy loss. The nonlinear current-voltage (I-V) characteristic curve of the PV array prevents the detection and isolation of the faults and also makes the tracking of the maximum power operating point (MPP) more difficult. Fault detection and identification (FDI) techniques methods have been proposed to detect the presence of faults and isolate them. Many maximum power point tracking (MPPT) methods have been proposed to find the best operating point in the presence of disturbed environmental conditions. However, existing FDI methods do not consider the tracking of the MPP in faulted operating conditions, and available MPP tracking methods do not consider the occurrence of faults in the PV system. The objective of this study is to propose a fault-tolerant control (FTC) strategy to detect the presence of abnormal operating conditions and reconfigure the MPPT procedure to search for the new suboptimal operating point. The FDI method is based on monitoring the PV panel generated power for the presence of abrupt changes; the MPPT reconfiguration is based on a combination between Incremental Conductance (IncCond) Algorithm and an Improved Current-based Particle Swarm Optimization (ICPSO) tracking technique. Simulation and experimental results show an excellent performance of the proposed FTC method in the presence of various types of faults.

1. Introduction

Reliability of Photovoltaic (PV) energy generation systems becomes an important issue as demand for renewable energy sources increases from day to day. The exposure of PV arrays to the outdoor environment results in a disturbed operation caused by variable weather conditions and components degradation. PV arrays are therefore subject to various types of faults that affect their normal operation and lead to a considerable energy loss. Degradation signs of PV panels have been studied to identify different sources of faults. The effect of a parasitic resistance on the performance of PV modules was investigated in van Dyk and Meyer (2004), the variations in series and parallel resistances give a sign of possible aging of PV modules. Such degraded panels may cause a general mismatch fault on the whole PV array. Mismatching fault occurs when the electrical parameters of one module are different from that of the remaining modules in a given PV installation, this fault is the most common in PV systems and may cause irreversible damage (van Dyk et al., 2002). Partial shading is a particular case of the mismatch fault, it arises when a number of PV modules are subject to a different level of solar irradiation from the rest of the installation, such temporary fault was studied extensively in the literature (Ahmed and Salam, 2015). Wiring-related faults are common in electric circuits, there are mainly two types of faults in PV-based installations: Line-to-Ground and Line-to-Line faults. In Bower and Wiles (2000), the line-ground fault was studied only on the AC side of the PV system, whereas the authors in Stellbogen (1993), Boutasseta et al. (2013) investigated its effect on the DC side. Line-to-line fault occurs when a short-circuit between the cables of two or more PV modules with different potential is detected (Zhao et al., 2013).

To mitigate the effect of such issues, fault detection and identification (FDI) methods have been proposed to monitor the state of the PV system and warn the user of degradation signs of the PV array and any other unexpected change in the systems' normal operation. Furthermore, FDI techniques allow the detection of wiring-related faults that may not be detected in some conditions using conventional over-current protection devices (Zhao et al., 2015). In Akram and Lotfifard (2015), a review of fault diagnosis methods on the DC side of PV arrays is given, some of the methods take into account only detection of faults and some of them make both detection and classification. In this work we consider all types of faults presented but we take into

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account only fault detection, as fault classification will not have much impact on the fault tolerant control algorithm.

On the other hand, the nonlinear nature of the Power-Voltage (P-V) characteristic curve of PV cells has made the control procedure more difficult. Many maximum power point tracking (MPPT) algorithms were developed to extract maximum power from PV panels by searching the nonlinear curve for the optimal operating point. The first algorithm that has been proposed is the Perturb & observe (P&O) algorithm, this algorithm searches the P-V curve for the maximum power point (MPP) by perturbing the actual operating point of the PV system and analyzing its effect on the output power until it reaches the optimal operating point (Salameh and Taylor, 1990). Such periodic change in the reference value generates oscillations around the maximum power point. The amplitude of the oscillations can be reduced by choosing a variable step perturbation (Lalili et al., 2011). The limitations of this method in the case of a sudden change in solar irradiation stimulated more research work on MPPT algorithms (Esram and Chapman, 2007; Salas et al., 2006). Most of the proposed methods deal with the problem of sudden change in solar irradiation (Ramaprabha et al., 2012), and some of them manage to control the PV module in the case of partial shading (Ishaque et al., 2012; Boutasseta, 2012; Prasanth Ram and Rajasekar, 2017). In the PSO-based MPPT algorithm proposed in Miyatake et al. (2011) to control PV arrays under partial shading, authors used the voltage variable as a particle in the particle swarm optimisation procedure; such approach slows the convergence of the algorithm because of the large space of search that extends to the open-circuit voltage. In Ishaque et al. (2012) the duty cycle is chosen to track the global MPP by eliminating the need for a regulator in the PSO-based MPPT algorithm. Such choice may lead the PV system to undesirable operating regions given that it lacks direct correspondence with the physical system, and degraded performance in normal operating conditions given the absence of a voltage or current regulation in addition to low robustness in the presence of load change. Fault tolerance in PV panels was the subject of the research work in Lin et al. (2014), where the authors propose a reconfiguration mechanism of the PV cells in other to bypass faulted ones, to the extent of our knowledge this is the only work that was reported on the subject. In this work, we propose a fault-tolerant algorithm based on the reconfiguration of the controller, the designed algorithm switches between an Improved Current-based PSO (ICPSO) and Incremental Conductance (IncCond). The ICPSO MPPT procedure gives reduced search space for the optimisation process, we add a convergence criterion to guarantee its stability and improve its transient performance and we design a switching mechanism that allows smooth transitions between the algorithm designed for fault-free condition and the Improved Current-based PSO (ICPSO) designed for faulted operating conditions. The proposed control strategy is also proven to be robust to load variations that may affect the FDI algorithm detection decision.

This paper is organised as follows: in the following section, the model of the PV array is developed and the effect of selected types of faults on PV arrays is analysed. In Section 3 the proposed FTC algorithm is presented. Section 4 gives simulation results of the proposed approach, compared with a classical MPPT algorithm. Experimental results are given in Section 5. Conclusions are given at the end.

2. Fault analysis of PV arrays

2.1. Linearized model of the PV array

The one-diode equivalent circuit of a PV cell as shown in Fig. 1 is chosen because of its faster numerical computation and acceptable accuracy. The circuit consists of a controlled current source I_{ph}, a diode traversed by a current I_d with series and shunt internal resistances R_s and R_{sh} respectively. The controlled current source is dependent on the level of solar irradiation and the temperature of the cell surface as follows:

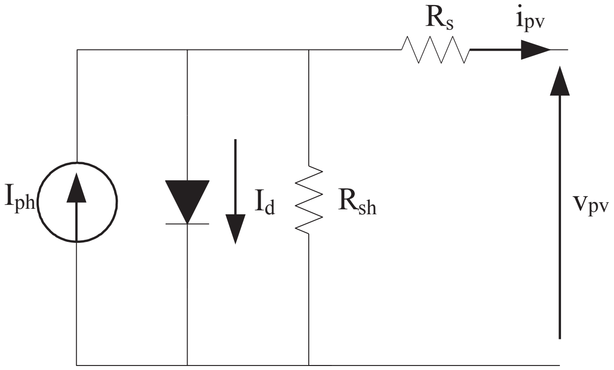

Fig. 1. The equivalent circuit of a PV cell.

$$I_{ph} = (I_{ph,n} + K_I \Delta_T)\frac{G}{G_n} \tag{1}$$

where $I_{ph,n}$ is the nominal generated current (given at nominal conditions: $T = 25\,^{\circ}\mathrm{C}$ and $G = 1000\,\mathrm{W/m^2}$), K_I is the short-circuit current/temperature coefficient, $\Delta_\mathrm{T} = T - T_n$ (T and T_n are the current and nominal temperatures), G and G_n are the current and nominal irradiations.

The current in the diode I_d is given by:

$$I_d = I_0\left[\exp\left(\frac{v_{pv} + R_s i_{pv}}{aV_t}\right) - 1\right] \tag{2}$$

where the saturation current of the diode I_0 is given as follows:

$$I_0 = \frac{I_{sc,n} + K_I \Delta_T}{\exp\left(\frac{V_{oc,n} + K_V \Delta_T}{aV_t}\right) - 1} \tag{3}$$

where $I_{sc,n}$ is the nominal short-circuit current, $V_{oc,n}$ is the nominal open-circuit voltage. K_V is the open-circuit voltage/temperature coefficient, a is a diode constant, V_t is the thermal voltage of the array: $V_t = N_s kT/q$, with N_s cells connected in series. k is the *Boltzmann* constant and q is the electron charge. R_s is the series resistance which depends on the material used to construct the PV cell and its effect is stronger in the voltage source operating region. R_{sh} is the shunt resistance, its effect is stronger in the current source operating region (Villalva et al., 2009). For a PV array with N_{pp} parallel panels and N_{ss} series panels, the output current is given as follows:

$$i_{pv} = I_{ph}N_{pp} - I_0 N_{pp}\left[\exp\left(\frac{v_{pv} + R_s\left(\frac{N_{ss}}{N_{pp}}\right)i_{pv}}{aV_t N_{ss}}\right) - 1\right] - \frac{v_{pv} + R_s\left(\frac{N_{ss}}{N_{pp}}\right)i_{pv}}{R_{sh}\left(\frac{N_{ss}}{N_{pp}}\right)} \tag{4}$$

In the following sections, we consider a PV array composed of $N_{ss} = N_{pp} = 5$ panels with the characteristics given in Table 1.

The dynamic conductance g_{pv} is obtained by taking the derivative of (4) with respect to voltage as follows:

Table 1
MSX60 PV panel characteristics at STC.

Parameter	Value
Maximum power ($P_{\max}$)	60 W
Voltage at $P_{\max}$ (V_{mp})	16.8 V
Current at $P_{\max}$ (I_{mp})	3.56 A
Short-circuit current (I_{sc})	3.87 A
Open-circuit voltage (V_{oc})	21.0 V
Temp. coef. of I_{sc}	0.003 A/K
Temp. coef. of V_{oc}	−0.008 V/K