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SIMULATION OF FAULT DETECTION IN PHOTOVOLTAIC ARRAYS

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ABSTRACT

In solar systems, faults in the module and inverter occur in proportion to increased operating time. The identification of fault types and their effects is important information not only for manufacturers but also for investors, solar operators and researchers. Monitoring and diagnosing the condition of photovoltaic (PV) systems is becoming essential to maximize electric power generation, increase the reliability and lifetime of PV power plants. Any faults in the PV modules cause negative economic and safety impacts, reducing the performance of the system and making unwanted electric connections that can be dangerous for the user. In this paper have been classified all possible faults that happen in the PV system, and is presented to detect common PV array faults, such as open-circuit fault, line-to-line fault, ground fault, shading condition, degradation fault and bypass diode fault. In this studies examines the equivalent circuits of PV arrays with different topological configurations and fault conditions to evaluate the effects of these faults on the performance of a solar system, taking into account the influence of temperature and solar radiation. This work presents the validation of a simulated solar network by measuring the output curves of a low-power photovoltaic array system under real outdoor conditions. This method can be useful in future solar systems.

Keywords: photovoltaic (PV) arrays, electric faults, common PV array faults, fault detection, partial shading,

1. INTRODUCTION

Every situation of modern life depends on electricity. Solar-generated electricity is a very clean and desirable way to compensate our reliance on fossil fuels produced electricity [1]. PV systems operate quietly and have low maintenance requirements. It can offer extremely high reliability, and with the modularity features, the PV systems have very flexible system sizing for integration into buildings and for decentralized applications down to minimal load demands.

However, electric faults in PV arrays generate significant power losses, therefore it is necessary for effective ways to detect and classify these faults in order to improve system efficiency and reliability [2, 4]. Operational faults of the photovoltaic system is one of the important factor affecting the power-generation efficiency. But besides this, the performance of a photovoltaic system depends on the temperature of operation of the solar panels, solar radiation. Overall, the problems related to solar systems thus fall into three main categories: environmental effects, panel specific problems, electrical fails. Many cases can lead to failure. A possible way to identify to abnormal heat caused by faults, to measure the surface temperature of the PV modules by thermal camera. But the process is time consuming and we cannot provide testing of solar panels at all times [3].

2. PHOTOVOLTAIC (PV) MODULE MODELLING

To simulate the operation of a solar cell, the first step is to establish its electronic model. Solar panels are composed of multiple solar cells connected in series. A photovoltaic array can be made by connecting multiple solar panels. In this section, a one diode solar cell model is described in order to simulate photovoltaic arrays of dimensions N_s x N_p, which means the array is composed of N_p strings connected in parallel, and each string is composed of N_s solar panels connected in series. Both internal and wire resistance is represented by an ohmic resistance in this case. A capacitor can also be connected in parallel to the diode, representing the parasitic capacitance between the two poles of the diode, but because of its value, it is negligible. Fig. 1. shows this model [5].

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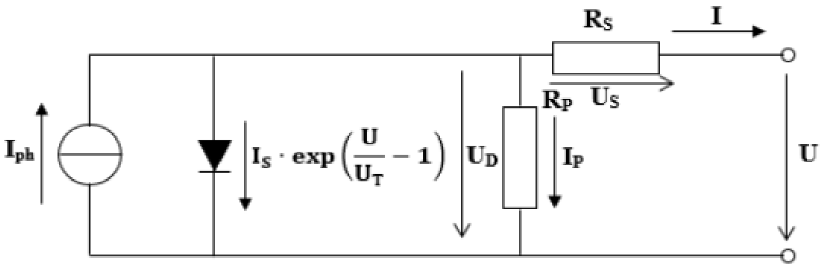

Figure 1. The circuit model of the solar cell

The produced current of the current generator depends on the intensity of illumination. The output current can be described with the following equation [3, 4, 5]:

$$I = I_{ph} - I_D - I_P. \tag{1}$$

The photocurrent I_{ph} can be described with the following equation [4, 5]:

$$I_{ph} = \frac{\beta(I_{sc} + K_i(T - T_r))}{1000} \tag{2}$$

The ID diode current can be defined by the help of the I_s diode saturation current, depending on the voltage and constants. [4, 5]:

$$I_D = I_S \left[exp\left(\frac{e \cdot U_D}{n \cdot k \cdot T \cdot N_S}\right) - 1\right] \tag{3}$$

The shunt current in the solar cell model I_P can be described with the following equation[4, 5]:

$$I_P = \frac{U_D}{R_P} = \frac{U + I \cdot R_S}{R_P} \tag{4}$$

The voltage is the following[5]:

$$U = U_D - U_S \tag{5}$$

Ideally $Rp \approx \infty$ and by shorting the circuit means: $R_D \gg R_s (R_{Cp} \gg R_s)$

3. DEFINITION OF TYPICAL FAULTS ON DC SIDE OF IN PV SYSTEM

Because some electrical faults, such as discrepancies, always occur in each array, they result in the available DC power of the array being significantly less than the predicted level. Table 1. shows the typical electrical faults of PV system [3,6].

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Table 1. Typical electrical faults of PV system [3, 4, 6]

Type of fault	Description of fault	Part
Upper ground fault	An unintentional path to ground with zero fault impedance occurs between the last two modules at PV string	DC
Lower ground fault	An unintentional path to ground with zero fault impedance occurs between the 2nd and the 3rd two modules at PV string with large backfeed current	
Series arc fault	An arc fault due to discontinuity in any of the current carrying conductors resulting from solder disjoint, cell damage, corrosion of connectors, rodent damage, abrasion from different sources	
Parallel arc fault	Insulation breakdown in current carrying conductors	
Line-to-line faults	An accidental short-circuit between two points in a string with different potentials	
Bypass diode faults	Short-circuit in case of incorrect connection	
Bridging fault	Low- resistance connection between two points of different potential in string of module or cabling	
Open-circuit fault	Physical breakdown of panel-panel cables or joints, objects falling on PV panels, and loose termination of cables, plugging and unplugging connectors at junction boxes	
MPPT faults	Problem in MPPT charge controllers	
Cabling faults	Disconnected cables	AC/DC
Inverter faults	Failure of each component of inverter such as IGBTs, capacitors, and drive circuitry can result in inverter failure	AC
Sudden natural disasters	Total blackout due to Lightning, storm, and so forth	AC/DC

In addition to electrical faults, in many cases there may be environmental problems in PV systems which can lead to performance degradation. The Hot spots is the most common issues with PV systems. Hot spots caused by the accumulation of dirt on the panels, shadow on the panels, badly soldered connections (it can happens during the production process). Besides many panel-specific problems can occur during operation, which can also lead to performance degradation.

Table 2. Typical environmental problems and panel-specific fails of PV system [3, 4, 6]

Type of fault		Description of fault
Environmental effects	Soiling	The bird droppings and dirt on the surface of a PV module
	Snow covering Hot spots	The worst temperatures depending on the geographical location and different weather conditions
	Irradiance distribution	Various irradiance intensity during the day
Panel specific problems	Degradation faults	Yellowing and browning, delamination, internal corrosion, micro-cracks, increasing of the internal series resistance

Fig. 2 shows a circuit diagram of the main faults that are analysed in this work.

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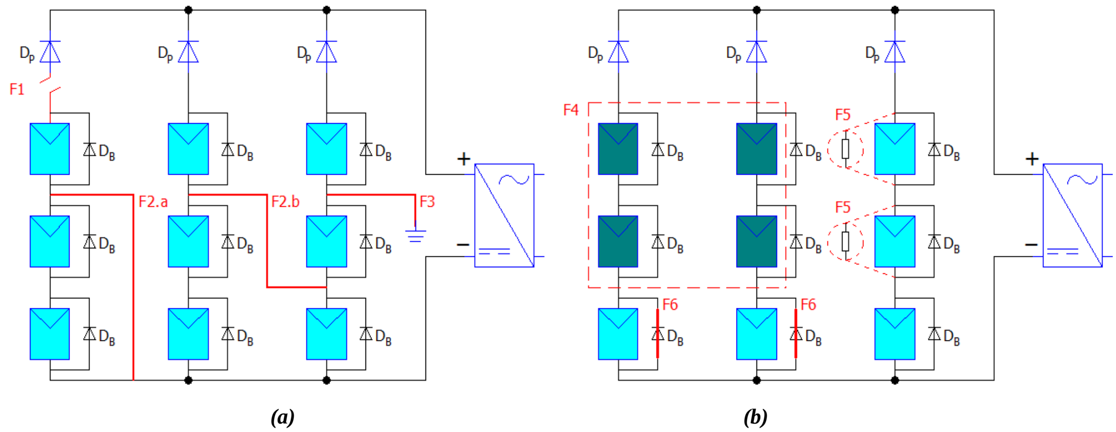

Figure 2. Circuit diagram of the main faults in PV array systems. (a) open-circuit and short-circuit fault and grounding fault (b) partial shading degradation fault and bypass diode fault

3.1. Open Circuit Fault

An open-circuit fault (shown as F1 in Figure 2.) is an accidental disconnection at a normal conductor during operation. Open circuit faults are symmetrical between strings. If the solar panels of the PV system have the same technical specifications and that all of them are under the same solar radiation and temperature conditions, in an open circuit fault, the voltage at the output of each string is the same. This means that if a string has an open circuit fault, the voltage at the output of the remaining strings will still be the same.

The voltage at the maximum power point will be the same even if the array changes its number of strings – because. Adding or removing strings, the equivalent circuit is only changing the output current of the full array [3,4,6].

3.2. Line-to-Line Fault

Line-to-line faults (shown as F2.a and F2.b in Figure 2.) in PV array systems are symmetrical between strings. This type of faults causing low impedance between two different strings in the PV array. It could happen inside PV arrays and potentially may involve large fault current or dc arcs. This paper examines line-to-line faults which are defined as an accidental short-circuiting between two points in the array with different potentials. A line-to-line fault can reverse the current flow through the faulty string. The amplitude of the fault current depends on the voltage difference between the points of the strings that are causing the fault [4,7]. Over Current Protection Devices (OCPD) are used to detect line-to-line faults, but these devices have some limitations if the current is lower than a threshold. If the line-to-line fault occurs under low illumination

(e.g., during the night, night-to-day transition, during the morning, day-to-night transition), the current through the affected string/strings is not large enough to melt the OCPD, and the fault may remain undetected until sufficient illumination is present to clear the OCPD [4,7].

3.3. Ground Fault

A ground fault (shown as F3 in Figure 2.) establishes an unintentional low impedance path between one of the current carrying conductors (CCCs) and the ground/earth, and a large fire in a PV array often destroys the origin of the fault. Several potential reasons for ground faults:

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1. cable insulation damage during the installation, due to aging, impact damage, water leakage, and corrosion;
2. ground fault within the PV modules (e.g., degraded sealant and water ingress);
3. insulation damage of cables due to chewing done by rodents;
4. accidental short circuit inside the PV combiner box, often at the time of maintenance.

If a ground fault remains undetected, it may generate a dc arc within the fault and cause a fire hazard [4,7].

3.4. Partial Shading Fault

Partial shading is the phenomenon that a PV array receives uneven irradiation and temperature caused by passing clouds, adjacent buildings and towering trees and so on [8,9]. In the case of partial shading faults (shown as F4 in Figure 2), one part of the PV array is shaded while the other part is fully irradiated according to the current irradiation value resulting output power reduction. As the irradiation value is constantly changing, the actual irradiation value must also be taken into account when examining faults. When the PV array is partially shaded, the MPP current of the PV array declines obviously, but the short-circuit current and the open-circuit voltage of the PV array are basically invariant [3].

3.5. Degradation Fault

A degradation fault (shown as F5 in Figure 2) occurs attributed to the failure of the bond between different layers of the panel leading to delamination, some tiny cracks on the solar cell and frequent changes in temperature of the module with increasing internal series resistance. The decrease in output power could be the increase in the series resistance between the modules due to decreased adherence of contacts or corrosion caused by water vapor. When a degradation fault appears, the MPP current and voltage of the PV array are reduced. The short-circuit current and the open-circuit voltage of the PV array remain unchanged

3.6. Bypass Diode Fault

A bypass diode is usually connected in parallel across multiple cells to improve the operation of the solar system under the nonuniform condition. Bypass diode can fail due to lightning strikes or thermal runaway from frequent operation [10,12]. The recent study showed simulation results that damaged bypass diodes by lightning strikes to lead reverse current flowed from normal string to the failed string, which generates heat and burns out. [11,12]. Furthermore, bypass diodes can deteriorate due to the high temperature of thermal runaway by rapid transitioning from forwarding bias state to reverse bias [12,13,14]. In this regard, there is a study that released which changes in the electrical property at PV module caused by a failure of the bypass diode (shown as F6 in Figure 2). The failure bypass diodes lose their properties of forward and reverse bias to become a micro-resistance, and are in a short circuit state with solar cells that are connected to a fault bypass diode [12,15,16]. Furthermore, recent research reported, when the bypass diode is shorted failure while the PV system is stopped, the temperature of a junction box increases [12]. These mismatch factors change Maximum Power Point (MPP) of PV modules or strings bringing about the system output loss on the PV system. Even if only one full module is shorted by bypass diode, the maximum power and U_{oc} of the PV array drops significantly and short-circuit current remains the same as other normal strings.

4. PV ARRAY CONFIGURATION FOR VAIDATION

The first step of this research was to experimentally validate the electric model of a PV array. The configuration structure of the PV array and fault types set in Figure 3. P-U curve of the array was measured under different fault conditions in order to validate the model.

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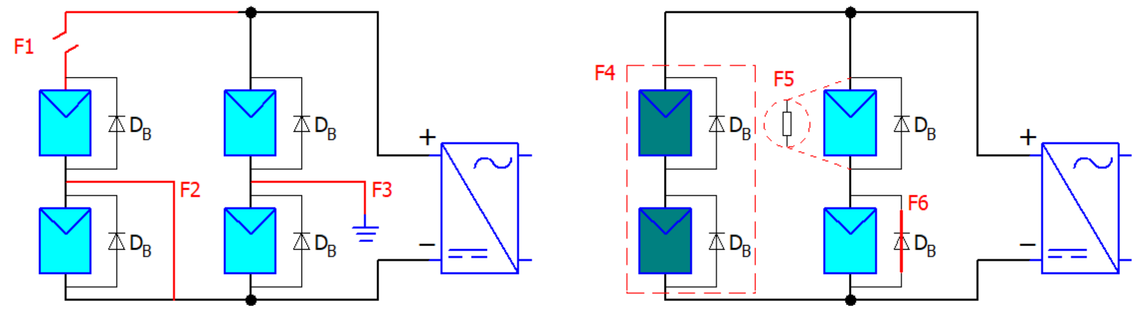

(a) *(b)*

Figure 3. Circuit diagram of the PV system for validation. (a) open-circuit and short-circuit fault and grounding fault (b) partial shading degradation fault and bypass diode fault

The 20W solar panels was connected two in series in one string and two strings in parallel. The output of the PV array with Uoc = 42.6 V and Isc = 2.41A was measured. The array was connected to a variable load to obtain the U-I values measuring the voltage and current with a digital multimeter, MAXWELL MX-25 328. Eight 500 W R-500WFEH Halogen Floodlight lamps were used to simulate solar radiation, and radiation was measured 800 W/m^2 with a PCE-SPM 1 Solar Power Meter. The related parameters of each PV panel under STC (G = 800 W/m^2 and T = 25 ∘C) are P_{mpp} = 20 W, U_{mpp} = 17.49 V, I_{mpp} = 1.14 A, Ns = 36, V_{oc} = 21.67 V, and I_{sc} = 1.22 A and CT = −0.33%/ ∘C.

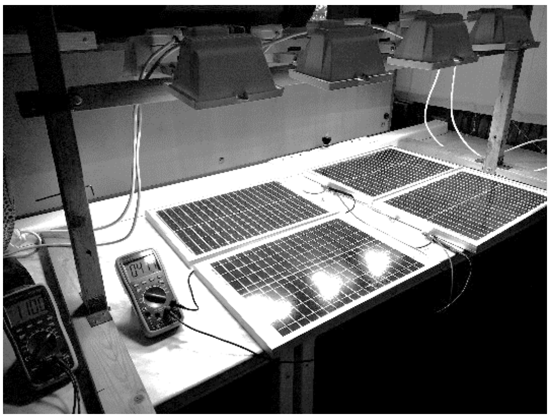

Figure 4. Measured PV array for validation

Figure 4. shows a photo of the PV array used in the lab to measure the U-I curve in order to validate the electric model. The electric model was validated using Matlab and Simulink, comparing the U-I curve obtained experimentally to the output characteristic curves generated by the model. The output characteristic curves of the PV array under fault types set are shown in Figure 5.

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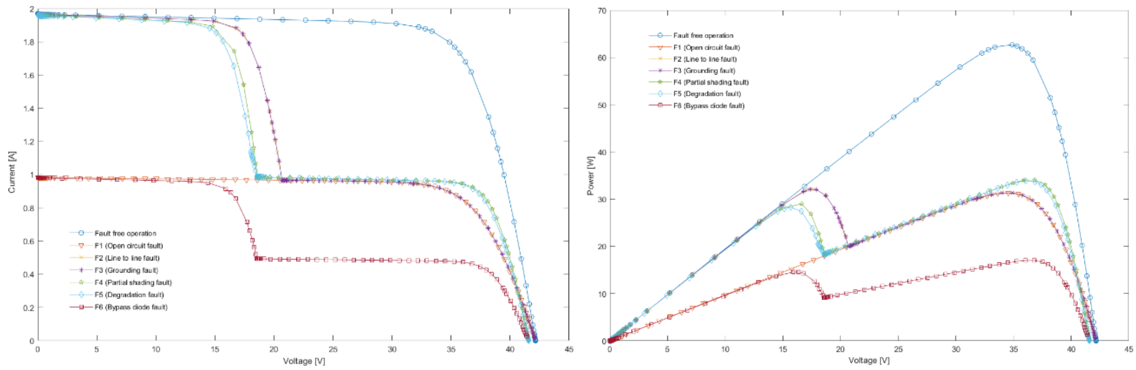

(a) *(b)*

Figure 5. The output characteristic curves of the PV array under common fault conditions. (a) power-voltage curves (b) current-voltage curves.

5. INTERPRETATION AND SIMULATION OF THE MOST COMMON FAULTS

After the validating, a typical solar PV array with 6×5 PV modules is simulated. Figure 6 show the model for PV modules in MATLAB/Simulink. 6 modules in series per string and 5 strings in parallel. Using the widely used one-diode model for each individual solar panel, this paper builds simulation PV array (2.4 kW) in MATLAB/Simulink consisting of 6×5 PV panels that is capable of studying faults among panels. The related parameters of each PV panel under STC (G = 1000 W/m^2 and T = 25 ◦C) are P_{mpp} = 80 W, V_{mpp} = 17.7 V, I_{mpp} = 4.52 A, Ns = 36, V_{oc} = 21.9 V, and I_{sc} = 5 A and CT = −0.32%/ ◦C. MATLAB/Simulink models of PV array (Figure 6) under electrical faults are developed to study the performance of the faulted PV array.

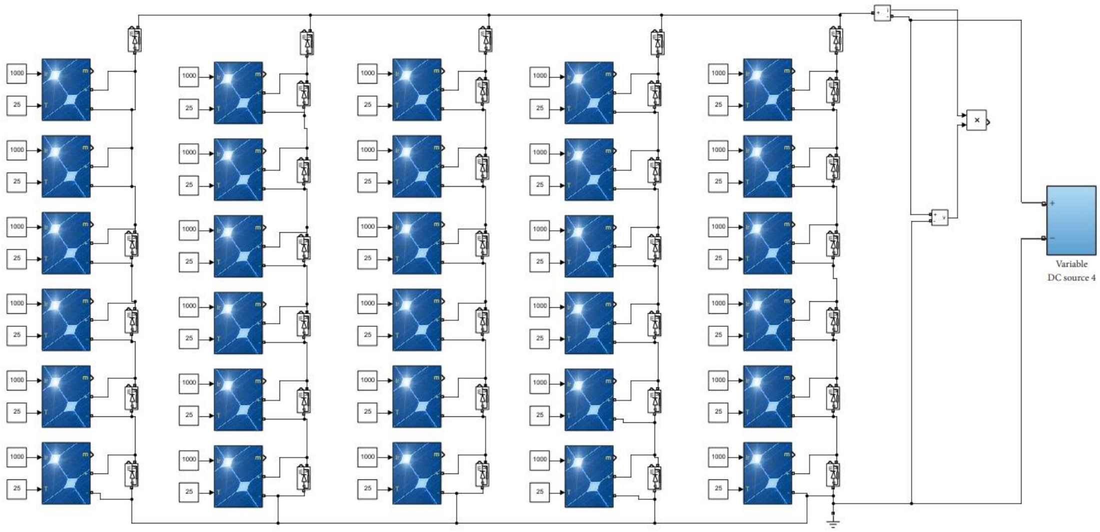

Figure 6. Schematic diagram of a PV farm system with 6×5 modules

This research studies six common fault types in 12 cases and compared the results with the normal condition. The characteristics of the PV panel with different types of faults are shown in Figures 7–12.

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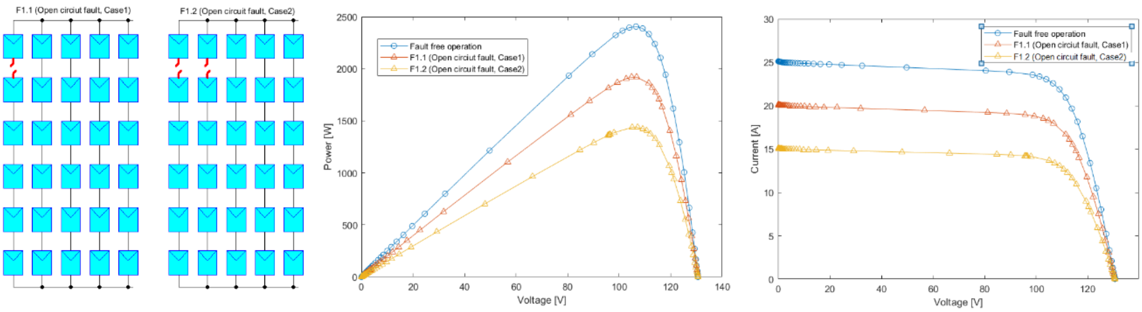

Figure 7. The PV array configuration for Open circuit fault

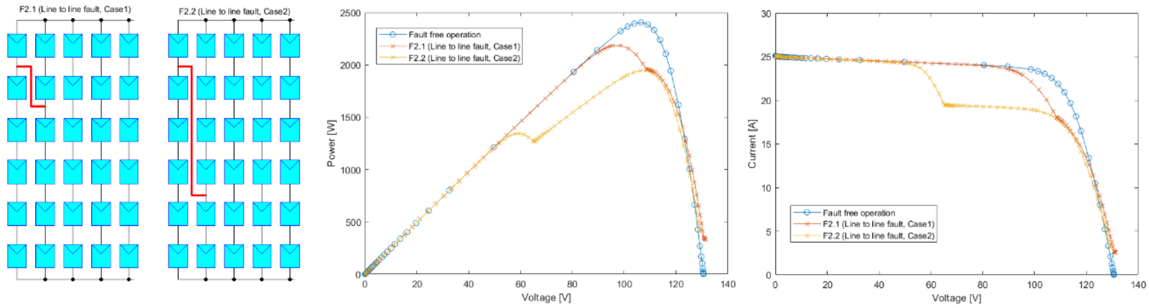

Figure 8. The PV array configuration for Line to line fault

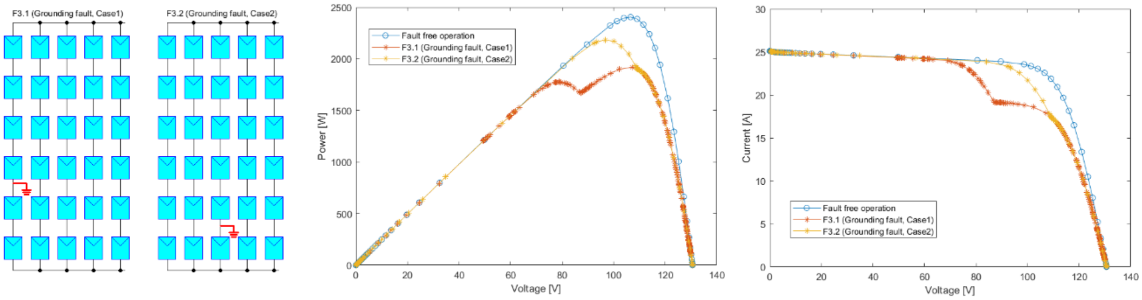

Figure 9. The PV array configuration for Grounding fault

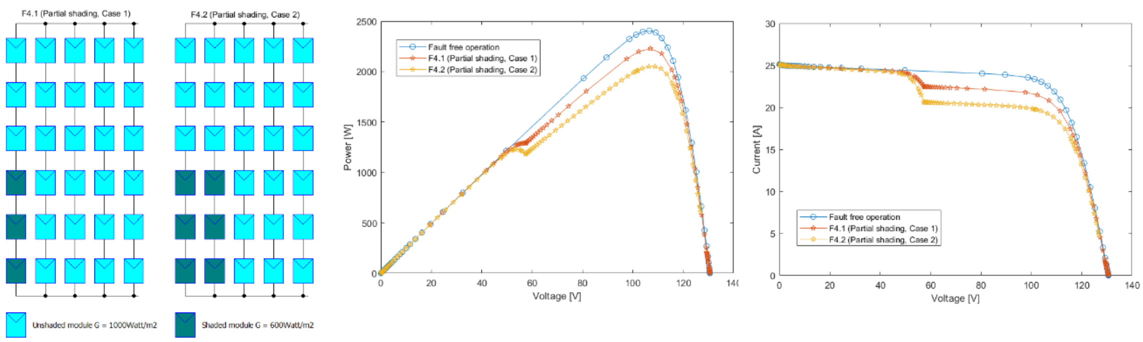

Figure 10. The PV array configuration for Partial shading

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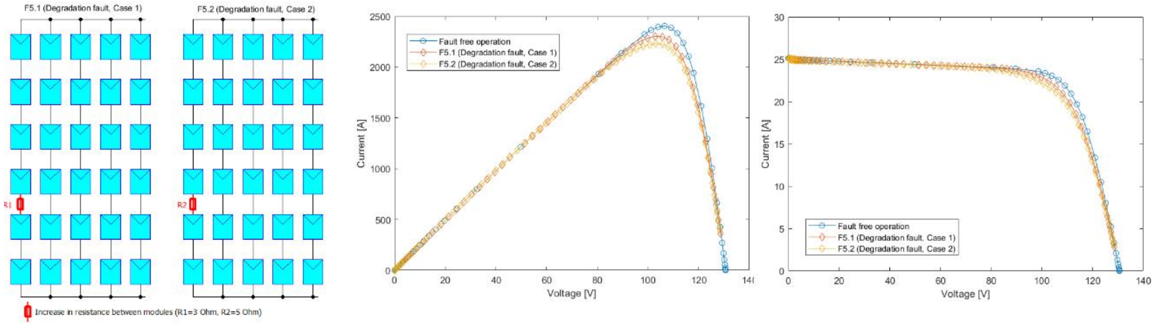

Figure 11. The PV array configuration for Degradation fault

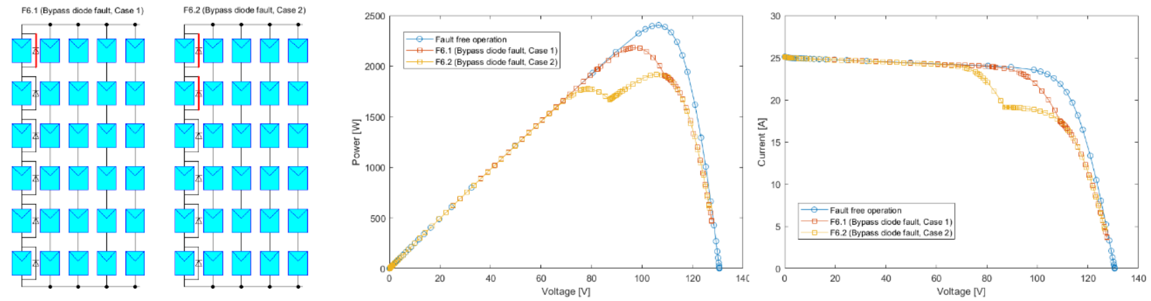

Figure 12. The PV array configuration for Bypass diode fault

7. RESULTS AND DISCUSSION

When different faults appear in a PV array, the output characteristic of PV array are very different in many cases. Electric faults in PV arrays can generate a local and global maximum point in the P-U curve at the output of the array. In this paper, a comprehensive definition of faults in DC side of PV system based on location and structure is presented. The performance of a typical PV array has been examined under typical fault conditions such as open-circuit fault, line-to-line fault, grounding fault, shading condition, degradation fault, bypass diode fault. To better visualize the P-U data under normal and fault conditions, the U-I and *P*-U characteristics of the array have been evaluated. Simulation experimental results show both normal operational curves and fault curves.

8. CONCLUSIONS

The off-line method used in this research can make difference many types of faults but cannot detect the location of the fault within the PV array. It would be useful to develop special MPPT schemes to track the maximum peak under these conditions and further methods capable of determining these locations. In a future work, the characterization method can be implemented inside an algorithm to detect and classify these common faults in a photovoltaic array system by only measuring the voltage and the current at the output of a photovoltaic array to obtain the P-U curve.
But a more accurate result can be obtained by measuring the current and voltage of each string, because this gives a more accurate picture of the exact location of the faults. In order to design an algorithm based on the characterization method, it is important to measure the temperature of the PV modules, solar radiation and the VP curve at the output of an array fast enough (<1s) to prevent significant solar radiation variations.

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