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Photovoltaic Module Simultaneous Open-and Short-Circuit Faults Modeling and Detection using the I-V Characteristic

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Abstract— This paper created a new research space in the faults modeling and detection area of the industrial systems, especially photovoltaic generators. It reserved for modeling and detection the hybrid defects, like the presence of cells open- and short-circuit within the same photovoltaic cells group.

For a small investment, the new algorithm created a new platform. It exposed a display screen of the database, which presented the power of the PV module production in each period. The display screen allows real-time monitoring of the PV module production throughout the year, and detecting its anomalies.

Index Terms—PV Module, Modeling, Detection, Open-Circuit, Short-Circuit, Platform.

NOMENCLATURE

V_{Cell}	= Cell Voltage;
I_{Cell}	= Cell Current;
V_{Group}	= Group Voltage;
I_{Group}	= Group Current;
V_{Module}	= Module Voltage;
I_{Module}	= Module Current;
V_{String}	= String Voltage;
I_{String}	= String Current;
V_{PV}	= Generator Voltage;
I_{PV}	= Generator Current;
$V_{Cell_Open-Circuit}$	= Cell Open-Circuit Voltage;
$I_{Cell_Short-Circuit}$	= Cell Short-Circuit Current;
n_{CGroup}	= Cells Number in Group;
$n_{gModule}$	= Groups Number in Module;
$n_{mString}$	= Modules Number in String;
n_{SpV}	= Strings Number in Generator;

I. INTRODUCTION

Thanks to the underlying technology of the photovoltaic (PV) more quickly, due to the increased demand in the

world market, the photovoltaic capacity increased of an individual system (kW) to a photovoltaic plant (MW). Electrical accidents create malfunctions in the photovoltaic generator, and they make a remarkable degradation in its productivity. During this time, the system is incompatible, in terms of series connection with the resistance of the transmission line, which will lead to large variations in the I-V characteristic of its output.

Consequently, the analysis of the PV generator malfunctions is important information for modeling these defects and with the availability of powerful software, it can be simulated and their performance can be predicted and monitored. Also, with this modeling and the malfunctions analysis, the faults detection becomes more easy [1-2]. This detection simplify the tasks of prognostic, diagnostic and maintenance of the faulty components in a photovoltaic generator, these advanced functions improve its reliability, its availability and its security [3-5].

Practically, there are two defects types are the most dangerous, since its existence on a photovoltaic cell signified the absence of its power, this on the one hand. In another, it means a remarkable deterioration in the system productivity. These two defects are called short- and open-circuit.

So, the main paper objective is to propose a new algorithm capable firstly to model the PV module into healthy and faulty operation, especially when it subjected to the hybridization of cells short- and open-circuit. Secondly, this new algorithm is able to detect this faulty type that affects the PV generator power.

Currently, simulation techniques in real-time of the photovoltaic systems are developed and available in the market. These techniques can be grouped into four categories: 1) Special Software for photovoltaic applications

such as: PVSyst [6], PVSIM [7] and RETScreen [8]. 2) General Software in the form of general platforms such as: LABVIEW [9], MATLAB [10] and PSIM [11]. 3) Artificial Intelligence Tools, specifically: Expert System [12], Neural Networks [13] and fuzzy neural network [12, 14]. 4) Specific Approaches to simulate the PV generator behavior, such as: the addition of the I-V characteristics of the various PV generator components [15], and the electrical modeling of the I-V characteristic of each interconnection point in the PV generator [16].

However, it is still difficult to analyze the characteristics of the photovoltaic installation, within the same atmosphere conditions. In addition, these techniques use an expensive solar simulator, and their flexibility is limited, due to the equipment construction.

Also, the fault diagnosis subject in a photovoltaic generator occupies a very important part in the literature. There are several proposed methods and tools to support this area:

1) Reflectometry method: it's very effective for the detection and the localization of the PV strings faults, as it applied by [17]. Its principle resides in the application of a voltage signal, then to observe the response signal waveforms. Also, [18] used this method for the spread spectrum time type, to detect and predict ground and arc faults in a photovoltaic generator. This method does not require any frequency analysis of the voltage or the current signal, and it can detect the presence of the arc independently of the inverter operating state.

2) Thermograph method: it based in the faults detection on the non-electrical parameters, such as: average temperature, spatial and temporal thermal variations. This method was chosen by [19] for the detection of the mismatch fault in the PV module, since this approach can make an effective analysis of the temperature distribution throughout the module, with a low cost. Another work published by [20], It used a thermal camera, based also on the temperature distribution analysis for the faults detection. A new system of MPPT is developed to change the operating point correspond to an optimized MPP. This can reduce the MPPT time. Also, it can used to calculate the reference voltage of the MPP [32-34].

3) The third method used for the faults diagnosis of the PV generator is based on the study and the analysis of its operating parameters.

[21] developed a simple empirical model to describe the PV generator performance. This model is based on estimating the energy losses of each defects category, by the control of these five parameters only at the PV generator: Horizontal solar irradiance, Ambient air temperature, PV module temperature, In-plane solar irradiance, DC power from array. By against, [22] provided a fault detection algorithm, it used the comparison of the simulated and measured performance. It also analyzes the losses present in

the PV generator, by comparing the errors amount of the direct current and voltage deflection, and a set of thresholds errors. Another work published by [23] developed software to determine the fault localization, it based on the monitoring of the relationship between direct current and alternating current from the PV system.

The work done by [24] presents a new procedure for the faults detection of photovoltaic generator. It based on *a)* the analysis of power losses, particularly: the thermal capture losses and diverse capture losses, *b)* the ratios of direct currents and voltages with the actual work conditions, as the environment illumination, and the evolution of the module temperature. The same research group has developed in 2014 a detection algorithm based on the evaluation of new currents and voltages indicators [25]. After a simulation study that was performed to verify the evaluation of these indicators, computer analysis has been reduced and the number of monitoring sensors too. The fault detection procedure can be integrated in the inverter, without using a simulation software or additional external hardware.

In this context, we have published for the faults modeling in a PV generator the document [26], which presents the continuity of the two published documents [27-28]. In this works, we have proposed a model of the faulty PV generator, when one of its basic components like cells, bypass and blocking diodes submit to one of these faults: short-circuit, open-circuit, impedance and reversed polarity. For the diagnosis part, we have published the paper [29], which presents the continuity of the two published papers [30-31]. In summary, these works are intended to diagnosing the presence of one of these faults: short-circuit, open-circuit, impedance and reversed polarity affecting one of the PV generator basic components, by using two approaches: *a)* analysis of the I-V characteristic of the generator hierarchical, and *b)* the artificial intelligent tools.

Consequently, the work contribution lies in the proposed new algorithm for 1) modeling the presence influence of the hybridization of cells open- and short-circuit in the same photovoltaic module groups. This modeling can provide very important information in the form of a database, which used thereafter in the diagnosis of this faulty type. 2) The second part of the contribution lies in the development of an algorithm, able to detect this faulty type with a high accuracy. This algorithm results an important platform, for the four modes detection of the PV module operation. It's based on the study and the analysis of the I-V characteristic of all defective basic components of the PV module.

II. OPEN- AND SHORT-CIRCUIT CELLS MODELING & DETECTION ALGORITHMS WITHIN THE PV GENERATOR

The section objective resides in the new algorithm presentation, which reserved to modeling and detecting the presence influence, of the cells open- and short-circuit hybridization on the PV module shown in Fig.1. The new algorithm is based on the analysis of the I-V characteristic of the PV module components. The main advantage of this

algorithm is presented in its ability to make the modeling and the detection of this faulty type independently of the irradiation, the temperature and the cells number constituting the PV generator of series / parallel type.

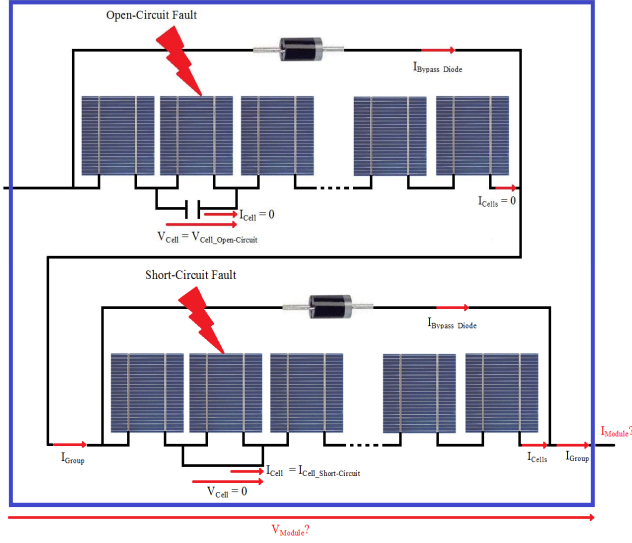


Fig.1. Photovoltaic Module Description

The proposed algorithm consists of two main parts:

A. Modeling Algorithm of Cells Short- and Open-Circuit Influence on the PV Module Operation

The I-V characteristic of a healthy PV module is

$$\begin{aligned} & \text{If } Module \subset \forall Group_{Healthy} \\ & \begin{cases} V_{Module} = nc_{Healthy_Group} \times ng_{Healthy_Module} \times V_{Cell_Imposed} \\ I_{Module} = I_{Cell_Healthy} \end{cases} \quad (1) \\ & \text{End} \end{aligned}$$

But, the I-V characteristic of a PV module contains at least one open-circuit cell is

$$\begin{aligned} & \text{If } Module \subset \exists Group_{Healthy} \ \& \ \exists Group_{Open-Circuit} \\ & \begin{cases} V_{Module} = nc_{Group} \left[\begin{aligned} & (ng_{Healthy_Module} \times V_{Cell_Imposed}) + \\ & (ng_{Open-Circuit_Module} \times V_{Cell_Open-Circuit}) \end{aligned} \right] \\ I_{Module} = \min(I_{Group_{Healthy\&Open-Circuit}}) \end{cases} \quad (2) \\ & \text{Else} \end{aligned}$$

If Module $\subset \forall$ Group_{Open-Circuit}

$$\begin{cases} V_{Module} = nc_{Group} \times ng_{Module} \times V_{Cell_Open-Circuit} \\ I_{Module} = I_{Bypass-Diode} \end{cases}$$

End

End

Also, the I-V characteristic of a PV module contains at least one short-circuit cell is

$$\text{If } Module \subset \exists Cell_{Healthy} \ \& \ \exists Cell_{Short-Circuit}$$

$$\begin{cases} V_{Module} = \sum_{ng_{Module}} (nc_{Group} - nc_{Short-Circuit_Group}) \times V_{Cell_Imposed} \\ I_{Module} = I_{Cell_{Healthy}} \end{cases} \quad (3)$$

Else

If Module $\subset \forall$ Cell_{Short-Circuit}

$$\begin{cases} V_{Module} = 0 \\ I_{Module} = I_{Cell_{Short-Circuit}} + I_{Bypass-Diode} \end{cases}$$

End

End

Consequently, the I-V characteristic of a PV module contains at least one short- and open-circuit cells is

$$\begin{aligned} & \text{If } Module \subset \left\{ \begin{aligned} & \exists Group_{Not_Open-Circuit} \ \& \\ & \exists Group_{Defective} \subset \left\{ \begin{aligned} & \exists Cell_{Open-Circuit} \ \& \\ & \exists Cell_{Short-Circuit} \end{aligned} \right\} \end{aligned} \right\} \\ & \begin{cases} V_{Module} = \left[\begin{aligned} & \sum_{ng_{Not_Open-Circuit_Module}} \left[\begin{aligned} & (nc_{Group} - nc_{Short-Circuit_Group}) \\ & \times V_{Cell_Imposed} \end{aligned} \right] \\ & + \sum_{ng_{Open-Circuit_Module}} \left[\begin{aligned} & (nc_{Group} - nc_{Short-Circuit_Group}) \\ & \times V_{Cell_Open-Circuit} \end{aligned} \right] \end{aligned} \right] \\ I_{Module} = \min(I_{Group}) \end{cases} \quad (4) \\ & \text{Else} \end{aligned}$$

If Module $\subset \forall$ Group_{Defective} $\subset \left\{ \begin{aligned} & \exists Cell_{Open-Circuit} \ \& \\ & \exists Cell_{Short-Circuit} \end{aligned} \right\}$

$$\begin{cases} V_{Module} = \sum_{ng_{Module}} (nc_{Group} - nc_{Short-Circuit_Group}) \times V_{Cell_Open-Circuit} \\ I_{Module} = I_{Bypass-Diode} \end{cases}$$

End

End

B. Cells Short- and Open-Circuit Detection Algorithm on the PV Module Operation

If the I-V characteristic of the PV module is

$$\begin{cases} 0 < V_{Module} < ng_{Module} \times nc_{Group} \times V_{Cell_Open-Circuit} \\ 0 < I_{Module} < I_{Cell_Short-Circuit} \end{cases} \quad (5)$$

means the presence of a healthy PV module. But, if its I-V characteristic is

$$\begin{cases} \left[\begin{aligned} & nc_{Group} (V_{Cell_Open-Circuit} + (ng_{Module} - 1) \times V_{Cell_Imposed}) \\ & \leq V_{Module} \leq \\ & nc_{Group} (V_{Cell_Imposed} + (ng_{Module} - 1) \times V_{Cell_Open-Circuit}) \end{aligned} \right] \\ 0 < I_{Module} < I_{Cell_Short-Circuit} \\ \text{Where : } 0 < V_{Cell_Imposed} < V_{Cell_Open-Circuit} \end{cases} \quad (6)$$

indicates the presence of an open-circuit module contains at least one healthy PV group. Because, if its I-V characteristic is

$$\begin{cases} V_{Module} = ng_{Module} \times nc_{Group} \times V_{Cell_Open-Circuit} \\ 0 \leq I_{Module} \leq I_{Cell_Short-Circuit} \end{cases} \quad (7)$$

means the presence of an open-circuit module, which all its PV groups are defective. Also, if its I-V characteristic is

$$\begin{cases} V_{Cell} \leq V_{Module} \leq [(ng_{module} \times nc_{Group}) - 1] \times V_{Cell} \\ 0 < I_{Module} < I_{Cell_Short-Circuit} \\ \text{Where: } 0 < V_{Cell} < V_{Cell_Open-Circuit} \end{cases} \quad (8)$$

indicates the presence of a short-circuit module with at least one healthy cell. Because if all the cells module are short circuited, so its I-V characteristic becomes

$$\begin{cases} V_{Module} = 0 \\ I_{Module} \geq I_{Cell_Short-Circuit} \end{cases} \quad (9)$$

Finally, if the I-V characteristic of the PV module is

$$\begin{cases} \left\{ \begin{array}{l} (V_{Cell_Open-Circuit} + V_{Cell_Imposed}) \\ \leq V_{Module} \leq \\ [(ng_{Module} \times nc_{Group}) - 1] \times V_{Cell_Open-Circuit} \end{array} \right\} \\ I_{Module} > 0 \end{cases} \quad (10)$$

means the presence of faulty hybrid module contains healthy, open- and short-circuit cells. But, if each one of its groups contains at least one cell short-circuit, and also cell open-circuit. So, its I-V characteristic becomes

$$\begin{cases} \left\{ \begin{array}{l} ng_{Module} \times V_{Cell_Open-Circuit} \\ \leq V_{Module} \leq \\ [(ng_{Module} \times nc_{Group}) - ng_{Module}] \times V_{Cell_Open-Circuit} \end{array} \right\} \\ 0 \leq I_{Module} \leq I_{Cell_Short-Circuit} \end{cases} \quad (11)$$

IV. SIMULATIONS RESULTS

For the performance testing of the proposed algorithm, we have used for modeling the I-V characteristic cell the one diode model.

The simulation of the proposed algorithm, which reserved to modeling and detecting the faulty influence of a cells open- and short-circuit hybridization results the followings Figs. 2 to 5.

Fig. 2 presents the first interface into the platform proposed for modeling and detecting the PV module faults. It shows that the PV module is in the normal operation.

Fig. 3 presents the second interface into the platform proposed for modeling and detecting the PV module faults.

It shows the faulty module operation under the existence influence of fifteen short-circuit cells.

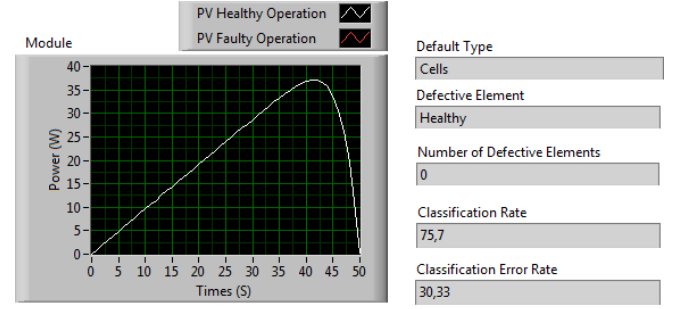


Fig. 2. Faults Modeling and Detection Platform: Presence Case of Healthy Cells.

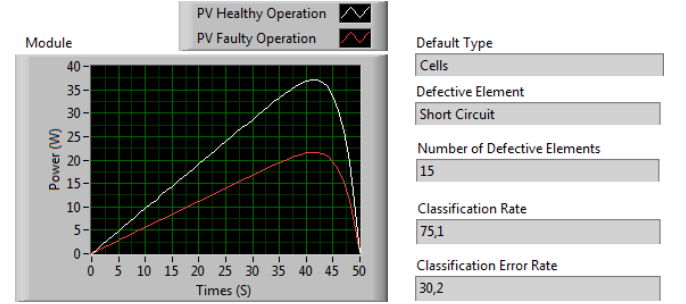


Fig. 3. Faults Modeling and Detection Platform: Presence Case of Short-Circuit Cells.

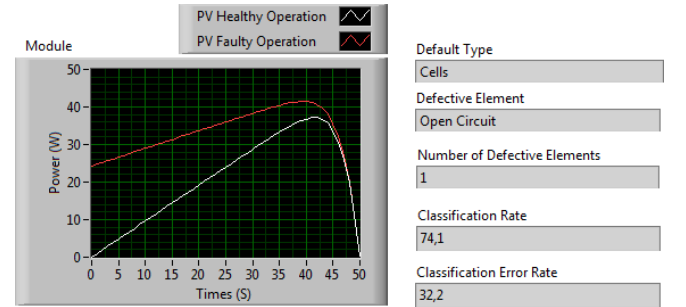


Fig. 4. Faults Modeling and Detection Platform: Presence Case of Open-Circuit Cells

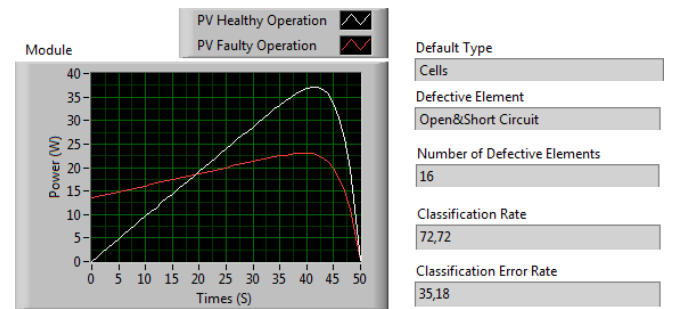


Fig. 5. Faults Modeling and Detection Platform: Presence Case of Open- and Short-Circuit Cells

Fig. 4 presents the third interface into the platform proposed for modeling and detecting the PV module faults. It shows the faulty module operation under the existence influence of a single open-circuit cell.

Fig. 5 presents the fourth interface into the platform proposed for modeling and detecting the PV module faults. It shows the faulty module operation under the existence influence of sixteen short- and open-circuit cells.

For the algorithm evaluation, we have chosen two evaluation criteria and after a large number of testes, we have found the following results:

1) The detection rate: the proposed algorithm can calculate the detection rate by the following formulation:

$$\text{The detection rate} = \frac{\text{detected observations number}}{\text{total observations number}} \quad (12)$$

So, it can detect the various operating modes of the PV module with a detection average rate of 72.72%.

2) The detection error: the proposed algorithm can calculate the detection error rate by the following formulation:

$$\text{The detection error rate} = \frac{\text{falsely detected observations number}}{\text{detected observations number}} \quad (13)$$

So, it shows that it has a significant detection error. It's in average about 35.18%. The increase in the value of the detection error is due to the existence of common areas of the faults detection between the different operation modes of the PV module.

VI. CONCLUSION

In this work, we have developed a new algorithm capable to ensuring a better modeling and detection functions, of the four module operation modes: normal operation, operation with short-circuit cells, operation with open-circuit cells, and particularly operation with cells short- and open-circuit hybridization.

The proposed algorithm ensured a better fault detection function in a PV module, with an acceptable rate and a high error.

The future work of this algorithm is intended to improve more its performance, for increasing more the detection rate, and also for reducing more the detection error.

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