Fault Detection of Solar Photovoltaic System

Eslam Shaheen, Abdel-Azem Sobaih and Essam Nabil

***Abstract*— This study discusses a workable fault-detection scheme for solar photovoltaic (PV) systems that was created based on power evaluation and observation against short circuit (line-to-line) faults. The goal is to maximize the power output from photovoltaic systems and improve their performance in the face of meteorological changes that might cause system failures such as wire disconnections and shorting between two potentials in the PV array. In order to identify the effectiveness factor and threshold indicator associated with a short circuit fault in a photovoltaic array, an explicit fault detection technique is developed. The validation of the suggested design scheme is supported by the simulation results on PV array. For a high number of PV modules, the processing effort is decreased, and the problematic area of the array is identified in a reasonable length of time. An explicit fault detection method can be employed to assess the effectiveness factor and threshold indication of each identified individual defective PV array element in order to guarantee MPPT of the utilized PV system.**

***Keywords*—— Fault detection; photovoltaic (PV) solar cells; voltage indicators; Short circuit fault of PV solar cells.**

I. INTRODUCTION

Research on fault detection in solar photovoltaic (PV) systems is essential because it may guarantee safety, increase system efficiency, and minimize downtime. PV system faults can be generically classified as follows: Open Circuit Faults: When there is a disruption in the electrical connection, the production of power is either reduced or absent. Short circuit faults can result in damage when current flows past a portion of the photovoltaic module. Partial Shading: When a section of the PV array is shaded, a significant power loss happens. Hotspots: Localized cell heating brought on by flaws or shadowing, which can permanently harm cells and diminish their efficiency. Component degradation: Over time, PV modules or inverters may deteriorate [1] [2].Numerous methods for defect detection in solar photovoltaic systems have been investigated. The most popular approach is Model-Based Approaches, which makes use of mathematical models to explain how solar PV cells behave in different scenarios (voltage, current, irradiance, temperature) [3]. In order to identify abnormalities, power signal monitoring examines the current, voltage, and power output of PV systems. With this method, problems in PV plants are found by creating "residuals," or fault indication signals, for every string and comparing them to a threshold value. Additionally, a regression-based method is suggested to determine the position of the fault based on measurements of the fault current and irradiance level [4] . In order to achieve real-time automatic fault detection and classification of a PV system, new DL approaches such as hybrid deep-learning (DL) model-based combination architectures are being developed [5].

One of the newest fields of science and engineering to develop in the years following World War II was artificial intelligence (AI), which includes machine learning (ML) as a subfield. The goal of AI is to comprehend and create intelligent things [6]. The failure diagnosis of a sensor covers the fault detection and isolation (FDI) and fault tolerance control (FTC) of a three-phase inverter used in photovoltaic systems [7]. In order to limit the harm caused by the defective PV module and shield the PV system from various losses, an appropriate fault detection system should be turned on [8]. Principal components analysis (PCA) is suggested as an alternate and efficient methodology to extract and choose more pertinent features, and support vector machines (SVM) are used to swiftly identify any issues that arise in a GCPV system [9]. The presented method uses a generalized likelihood ratio test (GLRT) chart to identify PV system problems and a machine learning-based Gaussian process regression (GPR) technique as a modeling framework [10] . Many of the Sustainable Development Goals (SDGs) of the UN can be achieved both directly and indirectly through the development of renewable energy systems, especially solar photovoltaic (PV) systems. Solar PV systems are essential for accomplishing these goals since they are frequently thought of as extremely effective ways to produce clean electricity [11].

The nominal MPPT control system is depicted in Fig. 1 which consists of a load, an MPPT controller, a PV array, and a DC/DC converter. Because short circuit faults are straightforward, prior approaches relied solely on voltage analysis to identify malfunctions, ignoring current changes. In order to improve decision accuracy, analyses were conducted using this research to identify (line-to-line) short circuit difficulties based on the power to integrate the influence of both current and voltage concurrently.

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(*Eslam Shaheen: Essam Nabil).*

Eslam Shaheen is with the Industrial Electronics and Control Eng. Dept., Faculty of Electronic Engineering, Menoufia University, PO Box 32952, Menouf, Egypt (e-mail: eslam.shaheen7790@gmail.com).

Abdel-Azem Sobaih is with the Industrial Electronics and Control Eng. Dept., Faculty of Electronic Engineering, Menoufia University, PO Box 32952, Menouf, Egypt (e-mail: abdazimsopeh@gmail.com).

Essam Nabil is with the Faculty of Electronic Engineering, and Faculty of Applied Health Sciences Technology, Menoufia University, PO Box 32952, Menouf, Egypt (e-mail: essam.abdelaziz@el-eng.menofia.edu.eg).

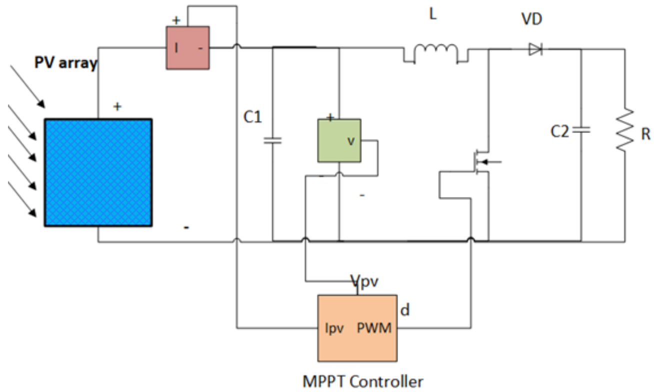

Fig. 1. solar PV system with MPPT controller.

The structure of this document is as follows: Section II describes the modeling of the PV module, while Section III analyzes defects in the PV array. The PV array's fault detection design is explained in Section 4. The application of fault detection in PV systems is implemented in Section 5. Section 6 simulates the paper's results. In Section 7, the conclusion and future directions are presented.

II. MODELING OF THE PV MODULE

A useful and promising paradigm for solar energy production is the single-diode model. The PV model is made up of a PV solar cell that generates current and is coupled to a diode in parallel and series, shunt resistance loads, as seen in (Fig. 2). Below is a mathematical representation of the solar cell's typical voltage and current.:

$$I_{cell} = I_{PH,cell} - I_{0,cell}\left[exp\left(\frac{\left(V_{cell+R_{s,cell}I_{cell}}\right)}{akT}\right) - 1\right] - \frac{V_{cell+}R_{s,cellI_{cell}}}{R_{sh,cell}} \quad (1)$$

The PV output current is represented by I_{cell}, the PV output voltage is represented by V_{cell}, the PV photocurrent is represented by $I_{PH,cell}$, the diode reverse saturation current is represented by $I_{0,cell}$, a represent the ideality factor of the diode, the solar cell temperature is represented by T, the charge of electrons is represented by q $(q = 1.602 * 10\text{^}(-19)$ c), the Boltzmann constant is represented by k $(k = 1.381 * 10\text{^}(-23) J/K)$, and the series resistance is represented by $R_{s,cell}$, and the parallel resistance is represented by $R_{sh,cell}$.

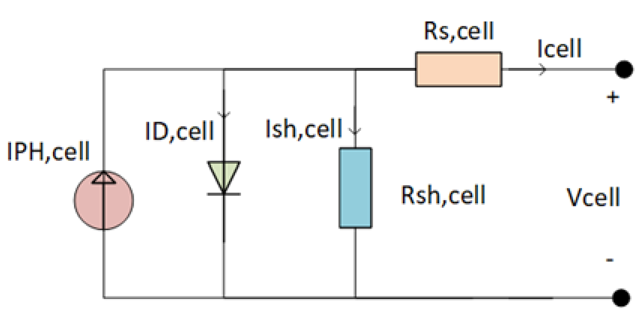

Fig. 2. Single diode model of the solar cell.

Nonetheless, solar cells coupled in series make up a PV module in most cases. Equation (1) states that a PV module's current and voltage characteristics can be expressed as:

$$I = I_{PH} - I_0\left[exp\left(\frac{(V_+ R_S I)}{aV_t}\right) - 1\right] - \frac{V_+ R_S I}{R_{sh}} \quad (2)$$

where I and V stand for the PV module's output current and voltage, respectively, I = I_{cell} and V = $N_{cell}V_{cell}$; N_{cell} are the series connection number of solar cells; I_{PH} is the photocurrent of the PV module, I_{PH} = $I_{PH,cell}$; I_o is the reverse saturation current of the diode, I_o= $I_{o,cell}$; V_t is the thermal voltage, V_t = N_{cell}kT/q; R_s and R_{sh} are series and parallel equivalent resistance, R_s = $N_{cell}R_{s,cell}$ and R_{sh} = $N_{cell}R_{sh,cell}$.

Through this section, the mathematical model of the solar cell has been described, which will be relied upon in the upcoming sections.

III. ANALYSIS OF SOLAR PHOTOVOLTAIC CELL FAULT SITUATIONS

To lessen the negative impacts of hot spots, the PV module is made up of parallel bypass diodes and series solar cells [12]. Series PV modules are linked to create a PV string, which is then linked in parallel to create a PV array. Fig. 3 depicts the PV array structure, which is made up of three parallel PV strings. Blocking diodes are arranged in series in Fig. 3 to stop reverse current from flowing through the string. The faults considered in Fig. 3 are open circuit fault (F1), short circuit fault at the same branch (F2), and short circuit fault (line-to-line) (F3).

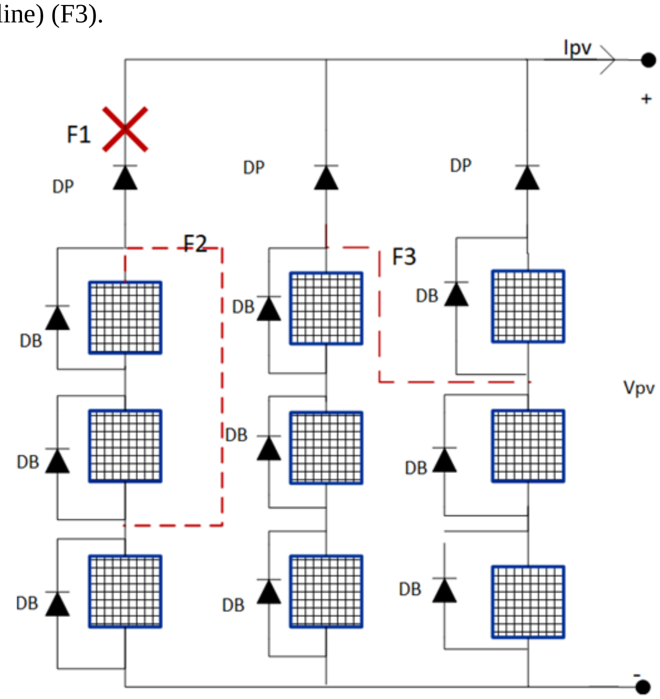

Fig. 3. The PV array configuration structure under open-circuit and short-circuit faults.

In a photovoltaic system, open-circuit and short-circuit are two of the most frequent problems that could occur [13] [14].

A broken wire between a group of solar cells causes an open-circuit failure. In Fig. 3, the open-circuit fault is displayed at location 'F1'. The poorly connected wires between PV strings are the cause of the short-circuit issue. Furthermore, as demonstrated at "F2" and "F3" in Fig. 3, vibration, abrading, and prolonged aging of PV arrays are thought to be significant causes of short-circuit faults. Through this section, the types of faults under study and the effects resulting from these faults on the proposed solar cell array have been described.

IV. METHOD OF FAULT DETECTION

A. Definition of Indicators for Voltage and Current

In this work, open circuit and short circuit faults can be identified by defining the fault characteristic quantities. These are the definitions of the voltage and current indicators for the PV system:

$$R_V = \frac{V}{V_{oc}} \tag{3}$$

$$R_I = \frac{I}{I_{sc}} \tag{4}$$

where V_{oc} is the open-circuit voltage of the PV array, V is the MPP output voltage, I is the MPP output current, I_{SC} stands for the PV array's short-circuit current, $\boldsymbol{R_V}$ and $\boldsymbol{R_I}$ are the PV voltage and PV current indicators, respectively.

$$I_{sc} = N_P \left(\frac{I_{scm_{STC}}}{1000} \mathrm{G} + K_I(\mathrm{T} - T_{STC}) \right) \tag{5}$$

$$V_{oc} = N_s \left(V_{ocm_{STC}} + K_V(T - T_{STC}) + V_t \ln \left(\frac{I_{sc}/N_p}{I_{scm_{STC}}} \right) \right) \tag{6}$$

where N_P and N_s stand for the number of parallel and series modules in a PV string. $I_{scm_{STC}}$ and $V_{ocm_{STC}}$ are the short- and open-circuit current and voltage, respectively, of the PV array at Standard Test Conditions (irradiation: G_STC = 1000W/m2, temperature: T_STC = 25◦C), K_I , K_V is the short- and open-circuit voltage temperature coefficient, T is the PV array temperature, Vt is the PV array's thermal voltage, and G is the radiation the array receives.

Equations (2) and (3) can be used to express the PV system's voltage and current indicators when it is operating faultlessly, as displayed below:

$$R_{VM} = \frac{V_m}{V_{OC}} \tag{7}$$

$$R_{IM} = \frac{I_m}{I_{sc}} \tag{8}$$

As demonstrated below, R_{VM} stands for the fault-free voltage indication, V_m is the output MPP voltage under fault-free conditions, R_{IM} is the indicator of current at fault-free mode and I_m for the output MPP current in the fault-free state [15].

$$I_m = N_P \left(\frac{I_{mm_{STC}}}{1000} \mathrm{G} + K_I(\mathrm{T} - T_{STC}) \right) \tag{9}$$

$$V_m = N_s \left(V_t \ ln \left(1 + \frac{I_{sc} - I_m}{I_{sc}} \left(e^{\frac{V_{oc}}{N_s V_t}} - 1 \left(V_t \ ln \left(1 + \frac{I_{sc} - I_m}{I_{sc}} \left(e^{\frac{V_{oc}}{N_s V_t}} - 1 \right) \right) - \frac{I_m}{N_P} R_s \right) \right) \right) \right) \tag{10}$$

B. Determining Fault Detection Threshold

I. Short circuit faults(line-to-line) of PV array

Fig. 3 shows that the PV output voltage drops to almost zero when a short circuit fault occurs in one section of the module while the other is routinely exposed to radiation. As a result, the output power of the PV array likewise nearly drops to zero. During short circuit, the power residual can be calculated as follows:

From equation (2) :

$$P = V * I \tag{11}$$

$$P_{free} = V_{free} I_{PH} - V_{free} I_0 \left[\exp\left(\left(\frac{((V_{free} + R_s I_{free})}{aV_t} \right) - 1 \right) \right] - \left(\frac{V_{free} * V_{free} + R_s V_{free} I_{free}}{R_{sh}} \right) \tag{12}$$

$$P_{fault(sc)} = V_{fault(sc)} I_{PH} - V_{fault(sc)} I_0 \left[\exp\left(\frac{(V_{fault(sc)} + Rs\ I_{fault(sc)})}{aV_t} \right) - 1 \right] - \frac{V_{fault}(sc) * V_{fault}(sc) + R_s V_{fault(sc)} I_{fault(sc)}}{R_{sh}} \tag{13}$$

$$Power\ Residual = P_{free} - P_{fault(sc)} \tag{14}$$

$$\text{Power Residual} = I_{PH} V_{free} - I_{PH} V_{fault} - V_{free} I_0 \left[\exp\left(\frac{(V_{free} + Rs\ I_{free})}{aV_t} \right) - 1 \right] + V_{fault} I_0 \left[\exp\left(\frac{(V_{fault} + Rs\ I_{fault})}{aV_t} \right) - 1 \right] - \frac{V_{free} * V_{free} + R_s V_{free} I_{free}}{R_{sh}} + \left(\frac{V_{fault} * V_{fault} + R_s V_{fault} I_{fault}}{R_{sh}} \right) \tag{15}$$

$$\text{Power Residual} = R_{pp} = I_{PH}(V_{free} - V_{fault}) + I_0(V_{free} - V_{fault}) - V_{free} I_0 [\exp(\frac{(V_{free} + Rs\ I_{free})}{aV_t} + \frac{V_{fault} I_0 [\exp(V_{fault} Rs\ I_{fault}))}{aV_t} + \left(\frac{V_{fault} * V_{fault} - V_{free} * V_{free} - R_s V_{free} I_{free} + R_s V_{fault} I_{fault}}{R_{sh}} \right) \tag{16}$$

In this case, P_{free} and $P_{fault(sc)}$ represent the output power under free and short circuit fault conditions, respectively.

The PV array's output voltage drops to almost nothing when a short circuit malfunction occurs. In the case of a short circuit fault, the voltage, current, and power signals can be calculated as follows:

$$R_{V(sc)} = \frac{V_{mp(sc)}}{V_{oc}} \quad (17)$$

$$R_{I(sc)} = \frac{I_{mp(sc)}}{I_{sc}} \quad (18)$$

$$R_{P(sc)} = \frac{V_{mp(sc)} * I_{mp(sc)}}{V_{oc} * I_{sc}} \quad (19)$$

In the event of a short circuit defect, the voltage indicator is denoted by $R_{V(sc)}$, the current indication by $R_{I(sc)}$, and the power indicator by $R_{P(sc)}$; In the event of a short circuit defect, $I_{mp(sc)}$ denotes the MPP output current, and $V_{mp(sc)}$ denotes the MPP output voltage. When a short circuit fault occurs, the PV fault detection threshold value can be determined by:

$$T_{P(sc)} = \varepsilon R_{P(sc)} \quad (20)$$

The power threshold in the event of a short circuit fault is $T_{P(sc)}$ and the power indicator value $R_{P(sc)}$ (provided by Equation (20)) must be below the threshold value of $T_{P(sc)}$ when a short circuit fault occurs on the PV Module and decrease gradually to become zero.

V. Application of Fault Detection in PV Array

First Step Specify the starting settings, such as the PV array's number of parallel strings (Np) and number of series modules (Ns). The temperature of the PV modules (T); the amount of radiation the modules receive (G). Identify the five electrical parameters (Iph, Io, n, Rsh, and Rs) in Step 2. Step 3: Calculate the maximum power point (Impp, Vmpp, Pmpp) of the current, voltage, and power under free conditions. Step4: At the state of a short circuit defect, measure the maximum power point current, voltage, and power (Impp, Vmpp, Pmpp). Step 5: Calculate the fault characteristic quantities, which include the PV array's voltage of open circuit and current in short circuit (Voc, Isc). Step 6: Determine the power residual (Res (Pmpp)) Power Residual $= P_{free} - P_{fault(sc)}$, When the power residual is zero, there isn't any flaw; It indicates the presence of a fault if it has a value. Step 7: Evaluate the indicators for power, voltage, and current, $R_{V(sc)}$, $R_{I(sc)}$ and$R_{P(sc)}$. Step7 Compute Power Threshold$T_{P(sc)}$; $T_{P(sc)} = \varepsilon R_{P(sc)}$. If the power indicator is below the power threshold and progressively approaches zero, it indicates a short circuit; if not, there might be another issue. Fig. 4 displays a flowchart of the suggested fault detection technique.

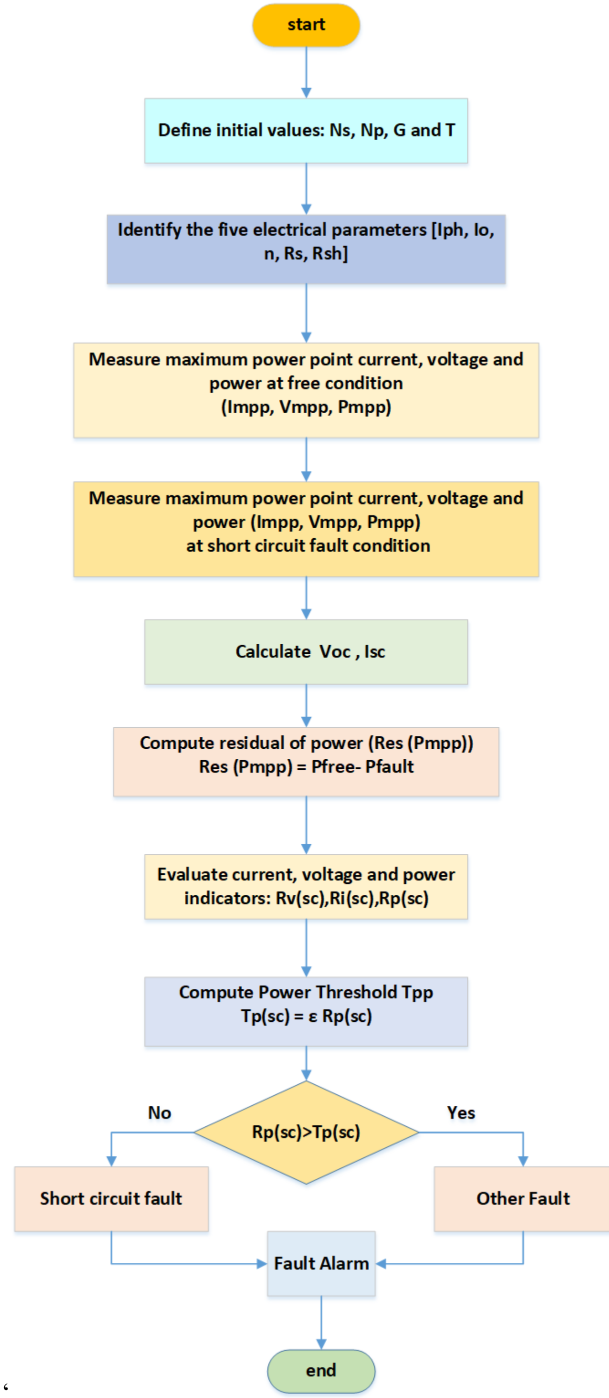

Fig. 4. Flow chart for the suggested fault detection technique.

VI. RESULT S AND DESCUSSION

Both the fault detection unit and the PV array must be modeled using MATLAB or Simulink in order to guarantee the efficiency of the fault detection method. Fig. 5 depicts the construction of the PV array arrangement, and the parameters of the PV array are listed in Table 1 [16].The simulation Results is conducted using a nominal controller design available in [17] with sampling time of 1*10^(-6) seconds.

The current and voltage indicators under free and fault situations, as well as the fault detection thresholds, are the outputs of the fault detection unit. The PV array's current and voltage in real time act as the fault detection unit's inputs. Next, to identify problems with PV arrays, thresholds are checked with the voltage and current indicators. The proposed approach is not only able to identify the type of PV array problems but also detects them. Fig. 5 illustrates the two faults that are executed in the PV array in this work. The PV array has two different kinds of faults. The fault-free condition is the first scenario, and the short circuit fault (shown in Fig. 5) under different weather circumstances is the second. Therefore, this approach is evaluated and verified in this study under varied irradiations.

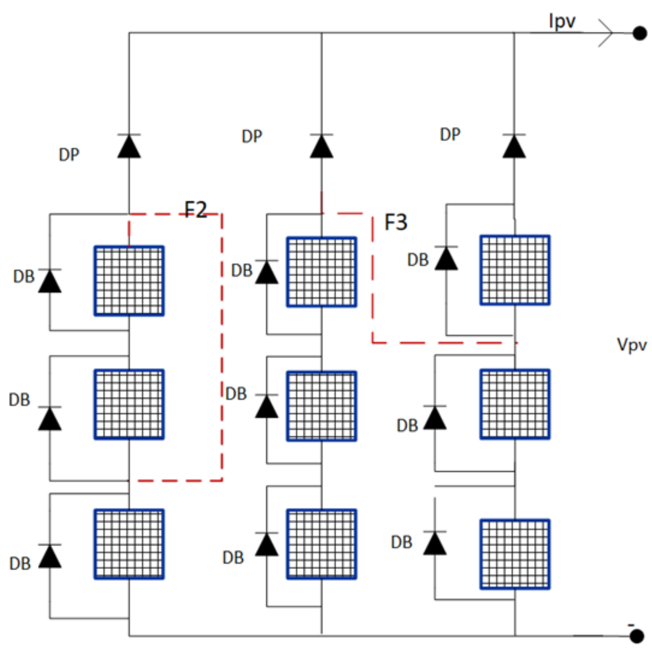

Fig. 5. The PV array's setup structure in the event of a short circuit.

TABLE 1.

DETAILS OF THE PV MODULE.

parameters	value	parameters	value
Power at maximum point	59.85 W	MPP (maximum power point) voltage	17.1 V
Open circuit voltage	21.1 V	MPP (maximum power point) current	3.5 A
Short circuit current	3.80V	Number of module cells	36

A) NO FAULT SCENARIO

First, the PV array is exposed to 1000 w/m2 of radiation at a constant temperature of 25 °C. The PV array is operating in the defective free mode, which causes the output voltage curve to increase and then stabilize, as shown in Fig. 6, Fig. 7 and Fig. 8 show that in the fault-free mode, the voltage indication Rv (free) and the power indicator RP (free) are both near the voltage threshold value Tvs and the power threshold value TP, respectively.

B) SHORT CIRCUIT FAULT CASE

The normal mode is when the PV system receives a single irradiation of 1000 w/m2 between 0 and 0.05 seconds. After 0.05 sec, five PV modules are short circuited between the PV strings shown as F3 in Fig. 5. The solar PV output voltage results under fault-free conditions and short circuit fault conditions are shown in Fig. 6. The solar voltage indicator, threshold under fault-free and short circuit fault conditions are shown in Fig. 7. Power indicator, threshold in fault-free condition, and short circuit fault condition are shown in Fig. 8. Fig. 9 demonstrates The Power Residual versus Voltage Residual at fault - free case and short - circuit case. The output voltage decreased so the voltage indicator $R_{V(sc)}$ is below the threshold valueT_{vs} and decreases gradually to be close to zero as shown in fig. 6, fig. 7. The power indicator$R_{P(sc)}$ also become below the threshold value $T_{P(sc)}$ as shown in fig. 8. At the beginning (free – mode) the voltage and the power residuals are close to zero. However, the voltage and power residuals have a value after 0.05 seconds. This indicates a short circuit fault as shown in Fig. 9.

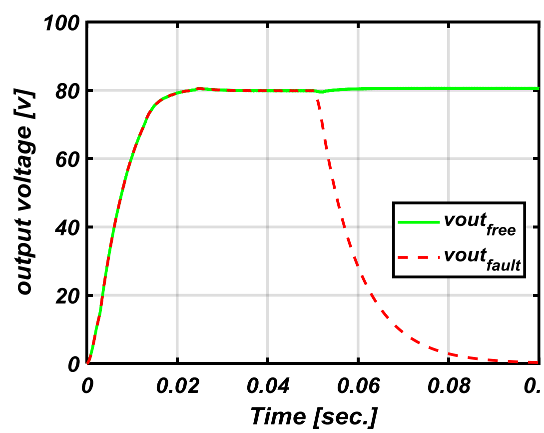

Fig. 6. The PV output voltage.

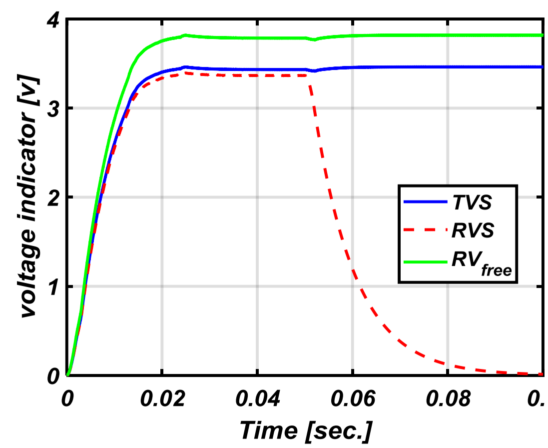

Fig.7. Voltage indicator, threshold.

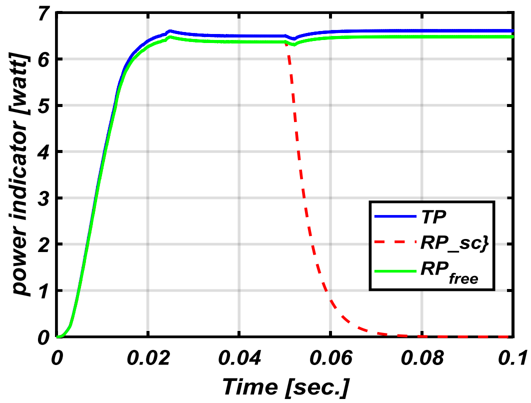

Fig. 8. Power indicator, threshold.

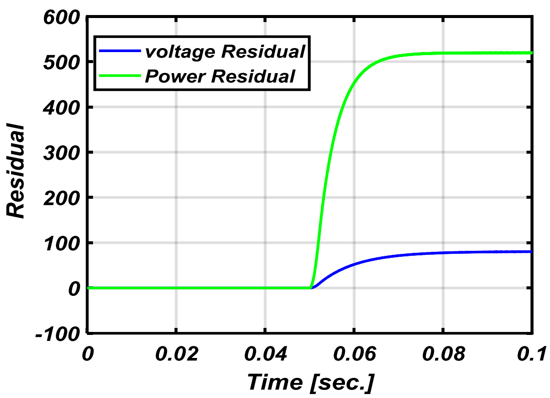

Fig. 9. The Power Residual versus Voltage Residual

VII. CONCLUSION

This paper addresses the viable and explicit process to identify short circuit defects in PV arrays; this work presents an integrated defect detection method based on power evaluation and observation. The computing effort is reducing for a large number of PV modules, and it takes a short and reasonable amount of time to identify the problematic part of the array. To ensure MPPT of the used PV system, the effectiveness factor and threshold indicator of each individual defective PV array element can be evaluated using an explicit fault detection approach. The suggested design approach for the successful identification of the failure scenarios in the solar PV array used is validated by the simulation results from PV arrays using MATLAB/Simulink. Future challenges regarding this research topic are moving towards detecting faults in large-scale PV systems with thousands of modules.

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