Original Research Paper

Current indicator based fault detection algorithm for identification of faulty string in solar PV system

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Abstract

The maximum power generation in the solar photovoltaic (PV) array is reduced due to the abnormal conditions such as module mismatch, string faults and damage of the PV modules, which reduces the efficiency and reliability of the system. Conventional protection devices fail to detect the faults, which leads to protection issues and fire threats in the PV plants. This paper proposes a new fault detection algorithm to identify the faults in the PV array and the PV string. A simple analysis is developed for fault detection under different fault conditions, such as line–line (L-L) fault, line–ground (L-G) fault and short-circuit fault with multiple strings, and the values of their current indicator and threshold are predetermined. Based on these values, the proposed fault detection algorithm identifies the fault in the PV array and the PV string, with a reduced number of current sensing devices. The effectiveness of the proposed algorithm is tested and verified through MATLAB simulation and experimentation under various operating conditions of the solar PV plant.

1 | INTRODUCTION

Due to the increasing environmental pollutions and global warming, an urgent transition is needed from the conventional energy sources to the renewable (non-conventional) energy sources. Solar photovoltaic (PV) is the best alternative energy source to generate a large amount of power and reduce these problems across the world [1]. The PV system is categorised into two divisions. One is the DC side, which mainly consists of the PV array with blocking diodes and storage system. The other is the AC side, which consists of inverter and the grid system. The frequently occurring faults in the DC side of the PV array are string faults, short-circuit faults, arc faults and mismatch faults [2]. The short-circuiting between the two different potentials in the PV array are mainly due to animal chewing, DC junction box corrosion, water ingress or mechanical damage [3]. To protect the PV array from overcurrent the conventional protection devices are installed with the PV system. The ground fault protection devices (GFPD) and overcurrent protection devices (OCPD) are installed in accordance with the U.S. National Electric Code standards [4]. Line–line (L-L) fault occurs between two points on the same string or two adjacent strings. The L-L and line–ground (L-G) faults can appear in any string in the PV array, so the protection device is installed in each string [5].

A L-L fault could not be identified when the current flowing through the string is less than that of the OCPDs. These undetected faults may result in fire hazards and reduction of power output [6]. In the existing methods, though the fault is detected, it is difficult to locate and identify the faulty string. The blocking diodes presence cuts off the reverse current here and makes the OCPD devices inefficient [7]. Remarkably, the existing methods do not discuss the effects of L-L and L-G faults through the analysis of PV array and location of fault in PV string, especially in the presence of blocking diodes. This paper proposes the detection and classification of L-G faults, L-L faults and multi-string faults of PV array and identifies the faulty string. Many fault detection methods proposed in the past can be categorized into three groups namely, signal processing, machine learning techniques and statistical methods.

1.1 | Signal analysis method

From the input signal and the feedback output signal, the time domain reflectometry method recognizes the fault status of the

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PV array. The time domain reflectometry method is applied to find the open-circuit and short-circuit faults that occur in a PV array by the change of response waveform. Since the PV system is off-line, it affects the system’s productivity [8, 9]. The spread spectrum time domain reflectometry is used to detect the LG fault by correlating the peaks of the generated and reflected waveforms without disconnecting the inverter [10]. These methods require a function generator, and the frequency of the transmitted signal can be affected by the presence of long DC cables and grounding of the system.

1.2 Artificial intelligence/machine learning methods

Zhao et al., proposed a decision tree to identify and categorise the PV faults with the training datasets. For developing these techniques, dataset features used in this algorithm are temperature, PV array voltage, current and irradiance. The limitations of the algorithm are, difficulty in getting the datasets from all possible fault conditions and treating the mismatch faults in normal PV conditions [11]. To overcome these limitations a graph-based semi-supervised learning algorithm and a two-stage support vector machine technique are introduced. A semi-supervised learning algorithm requires less number of labelled datasets to detect the faults, and a two-stage support vector machine technique requires extensive data features to detect the faults. A multiresolution signal decomposition method is used to extract the key features from the datasets. However, these techniques require reference module to detect the faults and require more time to diagnose specific faults [12, 13].

Akram et al. and Syafaruddin et al. introduced a neural network-based algorithm to identify the short-circuit faults. In [14] an intelligent probabilistic neural network has been used to distinguish the L-L faults and the open-circuit faults. In [15] a three-layer neural network has been used to approximate the voltage, current and temperature across every module. As the size of the PV array increases a greater number of layers are required, which makes the algorithm more complex. These learning methods may not give precise results. This may not cover all possible faults under different irradiation conditions. To differentiate partial shading faults and short-circuit faults in the PV array [16] proposed a method based on fuzzy logic. [17] and [18] proposed neural network-based methods, which are complex in nature, and has high implementation cost. These methods typically detect faults at the array level only.

1.3 Statistical methods

A statistical $T$-test method has been proposed to diagnose the faults by calculating the range of threshold limits using the real-time data recorded in the solar PV system. This technique requires three voltage sensors [19]. Hariharan et al. developed a technique to detect the fault in a solar PV system by distinguishing the permanent fault from the temporary fault (partial shading) with the available data collected in a PV system. However, this technique is not suitable, where the irradiation is differ among the modules in large capacity PV plants [20]. In addition, a method has been developed to detect the faults based on the measured current and voltage of the PV array using complex wavelet packet transforms [21]. X. Lin et al. proposed a reconfiguration technique to identify the PV array faults. It also bypasses the defective module considering the power loss, which is more than the threshold value. However, it requires a massive number of switches and so false detection may happen between L-L faults and temporary faults [22]. Silvestre et al. [23] introduced a fault detection method based on the evaluation of current and voltage indicators. Using the threshold values this method identifies the system faults. However, by reducing the number of monitoring sensors the computational complexity is reduced and, in this method, fault is detected in the array level.

Chouder et al. proposed a method based on power loss analysis to detect the faults. The difference between the reference and array power are used to identify faulty modules and strings [24]. To estimate the threshold limits, scheme [25] applied some scientific formulas which require costly sensors to measure the irradiance. However, these methods are not able to identify the type of fault and the location of the fault. To identify the estimated location of a fault in an array, the different methods based on voltage and current measurement give reasonable accuracy [26]. Guerriero et al. proposed a method which relates the measured and estimated string power, where each module has a wireless self-powered sensor, which works based on the MPPT algorithm [27].

A module based multipurpose sensor is used to detect faults in PV arrays by examining its expected and real efficiency [28]. These FFAs could not identify and locate faults, where the automated methods for fault detection without manual intervention is lacking, and a need for numerous sensors lead to costly schemes. Hu et al. used a two-section fault detection scheme to detect PV faults based on optimised voltage sensors. However, this method requires several voltage sensors within the PV strings, which is difficult to detect fault in large scale arrays [29]. Recently, Murtaza et al. developed a fault-finding algorithm by considering DC circuit analysis to detect the PV faults such as L-L faults and partial shading. This FFA requires six current sensors, for example, $n$ number of strings requires $2n$ number of current sensors [30]. However, this method requires a greater number of sensors. In most of the cases the fault detection is at the array level, they are quite about the location of string fault and these schemes require more number of sensors.

The proposed method is to detect the fault in PV array and locate the faulty string in PV systems. The fault detection is based on the current indicator signals that are calculated using the string current measurements. The proposed approach predicts the location of the of L-L faults in string (e.g. string 1 fault using status). The development of an analytical model to detect the fault location as a function of fault current levels, array voltage and PV module specifications. The proposed FDA also reduces the number of monitoring sensors compared to the existing algorithms ($n$ number of strings requires $n$ number of current sensors). This method not only distinguishes the PV array faults and detects the faulty string, with the number of
monitoring sensors being minimized. In the case of a permanent fault, the algorithm points out towards the exact strings with their specific faults. The FDA generates the status which identifies the array level and string level faults. By considering a $4 \times 4$ PV array configuration under various fault conditions the effectiveness of the proposed FDA is verified using MATLAB simulation and experimentation.

The paper is organized as follows: The PV system description is given in Section 2. Section 3 analyses and presents the simulation and experimentation. The validation of the proposed algorithm is tested through the simulation and the experimental results and is presented in Sections 5 and 6. The conclusion is given in Section 7.

## 2 | SYSTEM DESCRIPTION

Figure 1 shows the proposed grid-connected PV system under different fault conditions. A standard PV system composed of a PV array, an inverter, a DC–DC converter with MPPT, blocking diodes and current sensors. To get the desired output power the array consists of parallel and series connected modules. Bypass diodes and blocking diodes are present in the solar PV system. To prevent the backfeed current the blocking diodes are connected in series with each string. Parallel to the PV module, the bypass diodes are connected to prevent the formation of hotspots. Bypass diodes are connected in parallel with the PV module to prevent the formation of hotspots. Current sensors are connected with each string for measuring the string current. Using a single diode, the behaviour of strings is analysed with their specific faults. The FDA generates the status which identifies the array level and string level faults. By considering a $4 \times 4$ PV array configuration under various fault conditions the effectiveness of the proposed FDA is verified using MATLAB simulation and experimentation.

The paper is organized as follows: The PV system description is given in Section 2. Section 3 analyses and presents the simulation and experimentation. The validation of the proposed algorithm is tested through the simulation and the experimental results and is presented in Sections 5 and 6. The conclusion is given in Section 7.

### 2.1 | Fault Classification and Analysis

Generally, the faults that happen in the PV system can be classified as inter-string (3#) or intra-string (1# and 2#) as in Figure 1. This affects the power generation of the PV system and damages the PV modules. In Figure 1 a one module fault is created at panel 41 (1#), a two-module fault is created between panel 22 and 32 (2#) and then a multiple string fault is created between string 3 and string 4 (3#).

#### 3.1 | L-G fault

Ground faults increase the risk of fire hazards. L-G is the typical fault that happens in the PV array. The fault is created between S (starting point) and G (ending point) in the first string (i.e. one module short-circuited) as shown in Figure 2. In the first string, the module 41 is short-circuited so that the voltage in the module is 0V. The string currents are measured by connecting a current sensor in each string. The $V_{pv}$ is measured by connecting the voltage sensor across the PV array output terminals. Under normal operation, the $V_{pv}$ and $I_{pv}$ are given below

$$V_1 = V_2 = V_3 = V_4 = V_{pv}$$

$$I_{pv} = 4I_1 \text{ or } 4I_2 \text{ or } 4I_3 \text{ or } 4I_4$$

Where $V_{1}$, $V_{2}$, $V_{3}$ and $V_{4}$ are the string voltages of each string and $I_{1}$, $I_{2}$, $I_{3}$ and $I_{4}$ are the string currents of each string. Under the L-G fault condition, the nominal voltage is expressed as

$$V_{nominal} = \left[ N_{S+} + N_{G-} \right] \times V_{oc}$$

Where, $N_{S+}$ denotes the number of modules in between the S and the positive potential, the number of modules present between G and the negative potential is determined by $N_{G-}$.

The nominal voltage of the PV array is calculated as given below,

$$V_{nominal} = [ 3 + 0 ] \times V_{oc}$$

If $V_{pvarray} > 3V_{oc}$ the blocking diode gets reversed biased, else (if $V_{pvarray} < 3V_{oc}$) it is forward biased. Under reverse biased condition the faulty string current is zero and the remaining currents are same. To analyse the steady state performance of the test system an L-G fault is created at the first string. Under this condition, the BD is forward biased for the given PV parameters. The complete analysis is given below. The string currents $I_{2}$, $I_{3}$ and $I_{4}$ remain same and the faulty string current is less than the other currents.

$$I_1 < ( I_2 = I_3 = I_4 )$$
### TABLE 1 Parameters of the Solar PV

| Components      | Model          | Specifications                                      |
|-----------------|----------------|----------------------------------------------------|
| PV modules      | Thin film      | At STC $P_{mp} = 100 \text{ W}$, \(I_{mp} = 2.7 \text{ A}\), \(V_{mp} = 36.9 \text{ V}\), \(V_{oc} = 50.1 \text{ V}\), \(I_{sc} = 3.2 \text{ A}\) |
| PV array        | 4 × 4 modules  | At STC $P_{mp} = 1392.6 \text{ W}$, \(I_{mp} = 10.85 \text{ A}\), \(V_{mp} = 146.71 \text{ V}\), \(V_{oc} = 199.87 \text{ V}\), \(I_{sc} = 12.89 \text{ A}\) |

![FIGURE 2 L-G fault in PV array](image1)

The PV array current is given

$$I_{pv} = 3I_2 + I_1 \text{ or } 3I_3 + I_1 \text{ or } 3I_4 + I_1$$ (6)

The fault is evaluated using the $P-V$ and the $I-V$ characteristics under normal condition (no-fault), the PV array fault and the string fault under standard test conditions (STC—a temperature of 25 °C and irradiance of 1000 W/m²) for one module fault is given in Figure 3. It is inferred that the voltage of the post-fault array is less than the voltage of the pre-fault array. When one module fault occurs in the first string the string current \(I_1\) is reduced and the open-circuit voltage is reduced to 150 V.

#### 3.2 L-L fault

The chewing of wires by rodent animals causes the failure in the insulation cables and L-L fault happens. Mechanical damages in the junction box also cause the L-L fault. The L-L fault with the mismatch of more than one module is created in the second string (2#). The L-L fault is introduced from the starting point S to the ending point G (module 22 and 32) as shown in Figure 4. The second string gets open-circuited and the current flowing through the string becomes 0 A. The PV array voltage remains the same. The string currents are measured using the current sensors present in each string. Under L-L fault condition the nominal voltage is given by

$$V_{nominal} = \lfloor 1 + 1 \rfloor \times V_{oc}$$ (7)

An L-L fault is introduced at the second string to observe the steady state performance of test system for the given PV

![FIGURE 3 P-V and I-V characteristics of L-G fault under STC](image2)

![FIGURE 4 L-L fault in PV array](image3)
parameters. For these parameters, the BD gets reverse biased under the fault condition $V'_{pvarry} > 2V_{oc}$. Under this condition the second string current is zero and the remaining currents are equal as shown below,

\[ I_2 = 0, \quad I_1 = I_3 = I_4 \quad (8) \]

\[ I_{pv} = 3I_1 \text{ or } 3I_3 \text{ or } 3I_4 \quad (9) \]

Figure 5 gives the $P-V$ and $I-V$ characteristics under normal and abnormal conditions. It is noted that the maximum PV power and PV current under faulty conditions are less compared to that during normal conditions.

Whereas the maximum PV voltage remains the same due to reverse-biased blocking diode and this will isolate the faulty string under this condition. The faulty PV string gives the open-circuit voltage at 100 V.

### 3.3 Line–line with multiple string faults

The L-L with multiple string fault is introduced between S and G (third and fourth string). In this fault, the lower three modules of the third string and the lower two modules of the fourth string create a parallel connection. This configuration is shown in Figure 6 and the $I-V$ and $P-V$ characteristics are shown in Figure 7. From Figure 7 it is seen that under fault condition, the maximum PV power, $I_{pv}$ and $V_{pv}$ are reduced compared to that in the free fault conditions. Under L-L with multiple string condition, the nominal PV array voltage is

\[ V_{nominal} = \left[ 1 + \frac{2}{2} \right] \times V_{oc} \quad (10) \]

The multiple string fault is created between the third and the fourth strings. Under this condition, the BD is forward biased for the PV parameters. Hence, the string currents $I_1$ and $I_2$ are equal and the $I_3$ current is less than $I_4$ current. The string current of the multiple string fault is given by

\[ I_1 = I_2, \quad I_3 < I_4 \quad (11) \]

\[ I_{pv} = 2I_1 + I_3 + I_4 \text{ or } 2I_2 + I_3 + I_4 \quad (12) \]

### 4 Proposed Fault Detection Method

This proposed algorithm is developed to detect the faults in the array and the string with a reduced number of sensors. In this section, a simple mathematical analysis is carried out for calculating the threshold values and current indicator values. Further, the algorithm for this method is explained with the flow chart and the tables.
4.1 Fault detection thresholds

The most common fault in the PV system is the L-L fault that occurs in the strings of the PV array. When the short-circuit fault occurs, the output voltage and the current of the PV array gets reduced. The ratio of the maximum string current to the short-circuit current in one module is known as the current indicator $R_I$.

$$R_I = \frac{I}{I_{sc}},$$  \hspace{1cm} (13)

where $I$ represents the maximum string current under fault-free condition and $I_{sc}$ is the short-circuit current of one module in the array. The threshold value is represented as

$$T_c = \gamma \times R_I \times \mu$$  \hspace{1cm} (14)

Where $\gamma$ is given by

$$\gamma = 1 - \frac{N_k}{N_k}$$  \hspace{1cm} (15)

The number of modules in the PV string is represented as $N_k$. To avoid detection of a false fault, the offset of 2% is fixed with respect to the $T_c$ value.

$$T_c = 0.75 \times R_I \times 1.02$$  \hspace{1cm} (16)

When one or more modules are short-circuited or multiple string faults occur, the value of $T_c$ ($R_I$) must be less than the threshold value, that helps to detect the type of faults. The $\gamma$ value depends on the PV array configuration and the threshold value calculated, according to the array configuration. The fault in the PV array is identified by comparing the current indicator value ($R_{IM}$) and the threshold value. The current indicator of the PV array in fault condition based on the equation is expressed as,

$$R_{IM} = \frac{I_M}{I_{sc}}$$  \hspace{1cm} (17)

Where $I_M$ and $I_{sc}$ are the output of the string current and the short-circuit current during the fault condition.

4.2 Flowchart for the proposed algorithm

When the PV system is under fault, the $V_{pv}$ and $I_{pv}$ will get decreased based on the fault conditions. The flowchart of the proposed algorithm for detecting faults is shown in Figure 8. The complete procedure for the proposed algorithm is explained below.

The constants used for the computation in the proposed algorithm are given in Table 2. For L-L faults with single mod-
ule, two modules and multiple string mismatches under standard test conditions, the values of the array current are given by \( \varepsilon_1, \varepsilon_2, \varepsilon_3 \). The threshold value for fault detection is given by \( T_c \).

### 4.3 Algorithm

#### 4.3.1 To find the fault in the PV array

**Step 1.** Initialise the PV parameters \((N_k\text{ and } R_f)\)

**Step 2.** Measure the string currents, array voltage and array current.

**Step 3.** Calculate the threshold value \( T_c \) using the Equation (16).

**Step 4.** If the array current is less than \( \varepsilon_1 \), the status shows 1, which means a one module fault has occurred in the PV array, else go to Step 5.

**Step 5.** If the array current is between \( \varepsilon_2 \) and \( \varepsilon_3 \) the status shows 2, which means a two module fault has happened in the PV array, else go to Step 6.

**Step 6.** If the array current is less than \( \varepsilon_3 \) and maximum power point current, and if any string current is greater than 3 A, the status shows 3, which implies that a multiple string fault is in PV array else there is no fault in the PV array and it will go to Step 2.

#### 4.3.2 To find the fault in PV strings

**Step 1.** If the status shows 1 set \( i = 1 \) and check the condition \( R_{f_k} < T_c \) and \( R_{f_k} + 1, i + 2, i + 3 < T_c \). If it is true, there is a one module fault in the first string, else increment \( i \) = \( i + 1 \) and repeat until \( i = 4 \).

**Step 2.** If the status shows 2 set \( i = 1 \) and check the condition \( R_{f_k} < T_c \) and \( R_{f_k} + 1, i + 2, i + 3 < 0.001 \). If the condition is true, there is a two module fault in the first string, else increment \( i \) = \( i + 1 \) and repeat until \( i = 4 \).

**Step 3.** If the status shows 3 set \( i = 1 \) and check the condition \( R_{f_k} < T_c \) and \( R_{f_k} + 1, i + 2, i + 3 < T_c \). If the condition is true there are multiple string faults between the first and the second strings, else increment \( i \) = \( i + 1 \) and repeat until \( i = 4 \).

Finally, at the end of all the steps, the condition again goes to Step 2. For better understanding, the complete steps are summarized in Table 3.

The proposed algorithm will effectively detect the PV array and PV string faults under different irradiation conditions by replacing the threshold values given in Table 4. The different irradiance values give different thresholds to detect the PV string faults. These threshold values are calculated using the Equation (16) given in Section 4.1. At STC (temperature of 25°C and irradiance of 1000 W/m²) the threshold value is 0.641.

### 5 SIMULATION RESULTS

Table 1 gives the simulation parameters. The analysis of the proposed algorithm is validated in simulation and experimentation by considering the three cases:

I. The condition I represents one module fault in the first string with the mismatch of 25%. Here 25% means the fault location covers one module out of four modules.

II. The condition II represents L-L fault in the second string and the mismatch of 50%. Here 50% means the fault location covers two modules out of four modules.

III. The condition III represents the L-L fault with multiple strings (the third and the fourth strings), where the third string is 75% mismatched and the fourth string is 50% mismatched.

#### 5.1 Under 1000 W/m²

**5.1.1 Condition I: L-G fault**

Figure 9(a) shows the simulation results of array parameters under L-G fault condition. From the figure, it is observed that the algorithm shows the status \( S = 0 \) before \( t_f = 0.16 \) s, indicates that the PV array is without fault. After \( t_f = 0.16 \) s the status shows one, which means that the fault occurred in the PV array. To identify the fault, the algorithm requires a string current and the threshold values. The string currents are sensed by the current sensors and are given to the proposed algorithm, this algorithm compares the string currents with the threshold value and identifies where the fault occurred. Figure 9(b) shows the simulation results of the string current under L-G fault conditions. From this figure, it is observed that at \( t_f = 0.16 \) s the status shows 1, that implies L-G fault is in the first string.

**5.1.2 Condition II: L-L within string fault**

In the L-L string fault, two modules are short-circuited. L-L fault is introduced in the second string at 0.16 s as shown in Figure 10(a). The two-module mismatch is identified using the
TABLE 3  Summarized steps for the proposed algorithm

| Array fault condition | String currents | Status of the fault in PV array | Module fault condition | String fault | Status of the fault in PV string |
|-----------------------|-----------------|-------------------------------|-----------------------|--------------|---------------------------------|
| Case 1: L-G fault     | Faulty string current is less than 2 A and the other three string currents are same | 1 | \( R_{II} < T_c, R_{II,3,4} > T_c \) | first string | 1 |
|                       |                 |                               | \( R_{II} < T_c, R_{II,3,4} > T_c \) | second string | 2 |
|                       |                 |                               | \( R_{II} < T_c, R_{II,3,4} > T_c \) | third string | 3 |
|                       |                 |                               | \( R_{II} < T_c, R_{II,3,4} > T_c \) | fourth string | 4 |
| Case 2: L-L fault     | Faulty string current is 0 A and the other three string currents are same | 2 | \( R_{II} < T_c, R_{II} < 0.001 \) | first string | 5 |
|                       |                 |                               | \( R_{II} < T_c, R_{II} < 0.001 \) | second String | 6 |
|                       |                 |                               | \( R_{II} < T_c, R_{II} < 0.001 \) | third string | 7 |
|                       |                 |                               | \( R_{II} < T_c, R_{II} < 0.001 \) | fourth string | 8 |
| Case 3: Multiple string fault | Faulty first string current is less than 2 A and the second string current is greater than 3 A. The other two string currents are same. | 3 | \( R_{II} < T_c, R_{II,3,4} > T_c \) | 1-2 string | 9 |
|                       |                 |                               | \( R_{II} < T_c, R_{II,3,4} > T_c \) | 2-3 string | 10 |
|                       |                 |                               | \( R_{II} < T_c, R_{II,3,4} > T_c \) | 3-4 string | 11 |

TABLE 4  Threshold values for different irradiance

| Irradiance (W/m²) | Threshold values |
|-------------------|------------------|
| 1000              | 0.641            |
| 900               | 0.5732           |
| 800               | 0.4989           |
| 700               | 0.4456           |

current sensors available in each string. Under these faults, the array voltage remains the same because the blocking diode in the second string is reverse biased (second string is isolated from the PV array and open circuited). To identify the fault in the array and PV string, the proposed algorithm is divided into two parts: (1) array level fault identification, (2) string fault identification. Once the PV array fault is identified the string fault identification starts identifying the faults in the string. To identify the string level faults, the algorithm needs the string current readings. Figure 10(b) shows the string currents under L-L fault in the second string. From Figure 10(a,b) it is evident that the proposed algorithm effectively identifies the fault in the array and the PV string.

5.1.3  Condition III: L-L with multiple string fault

The multiple string fault is introduced between the third and the fourth strings to observe the performance of the proposed algorithm as shown in Figure 11(a,b). Figure 11(a) infers that the proposed algorithm exactly identifies the fault at \( t_{fo} = 0.16 \) s by showing status equal to 3, which is the PV array fault. Figure 11(b) shows the string currents under multiple string fault conditions. From this figure, it is clear that the third string current is less than the other three string currents and the fourth string current is higher than the other three string currents. With these string current values, the string level proposed algorithm identifies the faults in the string. From Figure 11(a) it is observed that the status shows 12 at \( t_{fo} = 0.16 \) s, which means a multiple string fault is detected between the third and the fourth strings.

The above results clearly show that the fault detection algorithm detects the array level and string level faults effectively.

The string currents, the array voltage, the array current and the power readings for different L-L faults are summarised in Table 5. The readings without fault is mentioned as \( F = 0 \) and the L-L fault is mentioned as \( F = 1 \). The normal reading of the string current is 2.7 A. When the L-G fault occurs in the first string the string current gets reduced to 1.94 A and the other string currents are raised to 2.91 A. Here, the array voltage gets reduced. When the L-L fault is introduced in the second string, the string current becomes 0 A because the blocking diode is reverse biased. Here, the array current gets reduced. When the multiple string fault is created between the third and the fourth strings the string current in the third string is 2.9 A and the faulty fourth string is 3.03 A. With these values, the proposed fault detection algorithm detects the L-L faults for the simulation results.

5.2  Under 700 W/m² irradiance

5.2.1  Condition I: L-G fault

Figure 12(a) shows the simulation results of array parameters under L-G fault condition. From the figure, it is observed
that the algorithm shows the status $S = 0$ before $t_{fo} = 0.16$ s, indicates that the PV array is without fault. After $t_{fo} = 0.16$ s the status shows one, which means that the fault occurred in the PV array. To identify the fault, the algorithm requires a string current and the threshold values. The string currents are sensed by the current sensors and are given to the proposed algorithm, this algorithm compares the string currents with the threshold value and identifies where the fault occurs. Figure 12(b) shows the simulation results of the string current under L-G fault conditions. From this figure, it is observed that at $t_{fo} = 0.16$ s the status shows 1, that implies L-G fault is in the first string.

**FIGURE 9** Simulation results of L-G fault. (a) Array parameters. (b) String parameters

**FIGURE 10** Simulation results of L-L fault. (a) Array parameters. (b) String parameters
5.2.2 Condition II: L-L within string fault

In the L-L string fault, two modules are short-circuited. L-L fault is introduced in the first string at 0.16 s as shown in Figure 13(a). The two-module mismatch is identified using the current sensors available in each string. Under these faults, the array voltage remains the same because the blocking diode in the first string is reverse biased (first string is isolated from the PV array and open-circuited). To identify the fault in the array and PV string, the proposed algorithm is divided into two parts: (1) array level fault identification and (2) string fault identification. Once the PV array fault is identified the string fault identification starts identifying the faults in the string. To identify the string level faults, the algorithm needs the string current readings. Figure 13(b) shows the string currents under L-L fault in the first string. From figure 13(a,b) it is evident that the proposed algorithm effectively identifies the fault in the array and the PV string.

5.2.3 Condition III: L-L with multiple string fault

The multiple string fault is introduced between the first and the second strings to observe the performance of the proposed algorithm as shown in Figure 14(a,b). Figure 14(a) infers that the proposed algorithm exactly identifies the fault at $t_{fo} = 0.16$ s by showing status equal to three, which is the PV array fault. Figure 14(b) shows the string currents under multiple string fault conditions. From this figure, the first string current is less than the other string currents and the second string current is higher than the other three string currents. With these string current values, the string level proposed algorithm identifies the faults in the string. From Figure 14(a) it is observed that the status shows nine at $t_{fo} = 0.16$ s, which means a multiple string fault is detected between the first and the second strings.

The above results clearly show that the fault detection algorithm detects the array level and string level faults effectively.

The string currents, the array voltage, the array current and the power readings for different L-L faults are summarised in Table 6. The readings without fault is mentioned as $F = 0$ and the L-L fault is mentioned as $F = 1$. The normal reading of the string current is 1.9 A. When the L-G fault occurs in the first string the string current gets reduced to 1.07 A and the other string currents are raised to 1.94 A. Here, the array voltage gets reduced. When the L-L fault is introduced in the first string the string current becomes 0 A, because the blocking diode is reverse biased. Here, the array current gets reduced. When the multiple string fault is created between the first and the second strings the string current in the first string is 0.99 A and the faulty second string is 2.05 A. With these values, the proposed

### Table 5: Summarised simulation results under 1000 W/m²

| Fault | $V_{pp}$ | $I_{pp}$ | $P_{pp}$ | $I_1$ | $I_2$ | $I_3$ | $I_4$ |
|-------|---------|---------|--------|------|------|------|------|
| L-G   | $F = 0$ | 146     | 10.8   | 1576  | 2.7  | 2.7  | 2.7  |
|       | $F = 1$ | 127.4   | 10.6   | 1350  | 1.94 | 2.91 | 2.91 |
| L-L   | $F = 0$ | 146     | 10.8   | 1576  | 2.7  | 2.7  | 2.7  |
|       | $F = 1$ | 146     | 8.35   | 1219  | 2.78 | 0    | 2.78 |
| MS    | $F = 0$ | 146     | 10.8   | 1576  | 2.7  | 2.7  | 2.7  |
|       | $F = 1$ | 146     | 10.59  | 1349  | 1.79 | 2.90 | 3.03 |
FIGURE 12  Simulation results of L-G fault. (a) Array parameters. (b) String parameters

FIGURE 13  Simulation results of L-L fault. (a) Array parameters. (b) String parameters
FIGURE 14  Simulation results of multiple string fault. (a) Array parameters. (b) String parameters

TABLE 6  Summarised simulation results under 700 W/m²

| Fault | $I_f$ | $V_{pv}$ | $I_{pv}$ | $P_{pv}$ | $I_1$ | $I_2$ | $I_3$ | $I_4$ |
|-------|-------|----------|----------|----------|-------|-------|-------|-------|
| L-G   | $F = 0$ | 144      | 7.5      | 1080     | 1.9   | 1.9   | 1.9   | 1.9   |
|       | $F = 1$ | 132.7    | 6.9      | 916      | 1.07  | 1.94  | 1.94  | 1.94  |
| L-L   | $F = 0$ | 144      | 7.5      | 1080     | 1.9   | 1.9   | 1.9   | 1.9   |
|       | $F = 1$ | 115      | 5.99     | 689      | 0     | 1.99  | 1.99  | 1.99  |
| MS    | $F = 0$ | 144      | 7.5      | 1080     | 1.9   | 1.9   | 1.9   | 1.9   |
|       | $F = 1$ | 133      | 6.93     | 922      | 0.99  | 2.05  | 1.94  | 1.94  |

FIGURE 15  Experimental setup

fault detection algorithm detects the L-L faults for the simulation results.

6 | EXPERIMENTAL RESULTS

To verify the above simulation results the hardware setup is shown in Figure 1. The thin-film modules connected in parallel and series configuration are used in the PV array. Industrial standard inverter with Perturb and Observe MPPT algorithm are used. The Data Logger switch is used to get the data from the array. The current sensors are linked to the data logger switch. The data are recorded through the data acquisition unit. Current sensors are connected with 4–20 mA output at the end of each string for the string current measurements. To create the faults a manual switch is connected to the PV strings. The experimental setup is shown in Figure 15. The switch is used to create the fault conditions. The experimentation fault condition is made using the connecting probes with a switch connected between the modules as shown in Figure 16.
FIGURE 16  Faults in PV array. (a) L-G fault. (b) L-L fault. (c) Multiple string fault

6.1 | Case 1 L-G fault

Figure 17 (a,b) show the performance analysis of the PV array and the string fault of the proposed algorithm under L-G fault. Until $t_f$ the status shows zero, which means that the PV array is without fault and at $t_f$ the L-G fault is created between S and G in the second string. The proposed algorithm effectively shows the status $= 1$ which means one module fault is found in the PV array. The proposed algorithm identifies the faults in the PV array by taking string currents dataset. Under the L-G fault condition the string currents, $I_2 = 1.6$ A, $I_1 = I_3 = I_4 = 3.0$ A. The string currents are sent to the program to check the condition $R_{12} < T_C$ & & $R_{13} > T_C$ & & $R_{14} > T_C$ & & $R_{14} > T_C$. If the condition is true the status shows two, that means one module fault is in the second string. The complete experimental results are given in Table 7.
### Table 7 Summarised experimental results

| Fault | $F = 0$ | $F = 1$ |
|-------|---------|---------|
| L-G   | $V_{pe}$ | $I_{pe}$ | $P_{pe}$ | $I_1$ | $I_2$ | $I_3$ | $I_4$ |
|       | 146     | 11.2    | 1635     | 2.8   | 2.8   | 2.8   | 2.8   |
|       | 124.4   | 10.6    | 1318     | 3.0   | 3.0   | 3.0   | 3.0   |
| L-L   | $V_{pe}$ | $I_{pe}$ | $P_{pe}$ | $I_1$ | $I_2$ | $I_3$ | $I_4$ |
|       | 143     | 9.6     | 1372     | 2.39  | 2.39  | 2.39  | 2.39  |
|       | 142     | 7.2     | 1022     | 2.42  | 0     | 2.42  | 2.42  |
| MS    | $V_{pe}$ | $I_{pe}$ | $P_{pe}$ | $I_1$ | $I_2$ | $I_3$ | $I_4$ |
|       | 140     | 11.2    | 1368     | 2.9   | 2.9   | 2.9   | 2.9   |
|       | 124.4   | 11      | 1368     | 3.0   | 3.0   | 3.2   | 2.0   |

#### 6.2 Case 2: L-L module fault

Figure 18(a,b) shows the L-L fault experimental waveforms. From the figure, it is observed that up to $t_{fo}$ the PV array has no fault and at $t_{fo}$ an L-L fault is introduced in the string to analyse the proposed algorithm’s performance. Under fault conditions the proposed algorithm effectively shows the status equal to two, that means L-L fault in the array. After finding the PV array fault, the proposed algorithm is used to identify the fault in the PV string. To identify the PV array string fault the proposed algorithm requires all string current readings and the threshold value. With these values, the proposed algorithm checks the condition and gives the status. In this condition, the proposed algorithm gives the status five, that means L-L fault is in the first string of the PV array. The complete data are given in Table 7 for better understanding.

#### 6.3 Case 3: L-L fault in multiple string

The multiple string fault is created between the third and the fourth string to validate the effectiveness of the proposed algorithm as shown in Figure 19(a). From this figure, it is seen that up to $t_{fo}$ the status shows zero which means that there is no fault in the PV array and after $t_{fo}$ the status shows three, which means multiple string fault in the PV array. The proposed algorithm works to find the string faults after it detects the fault in the PV array. Figure 19(b) shows the experimental results for the string current fault and the status of the proposed algorithm. From this figure it is seen that at $t_{fo}$ the status indicates that there is a multiple string fault between the third and the fourth strings.

The string currents and the array voltage, current, power readings for different L-L faults for experimental results are summarised in the Table 6. The readings without fault is mentioned as $F = 0$ and the L-L fault is mentioned as $F = 1$. The normal reading of the string current is 2.8 A. When the L-G fault occurs in string 1, the string 1 current gets reduced to 1.6 A and the other string currents are raised to 3 A. Here, the array voltage gets reduced. When the L-L fault is introduced in the second string then the string current is 0 A because the blocking diode is reverse biased. Here, the array current gets reduced from 9.6 to 7.2 A. When the multiple string fault is induced in between string 3 and string 4 the string current in the third string is 3.2 A and the faulty fourth string is 2 A. Here, the irradiance gets changed due to the climatic conditions. With these values the proposed algorithm detects the L-L faults for the experimentation results.
This paper has proposed a new algorithm to identify the faults in the PV array and the PV string. A simple analysis is carried under different fault conditions such as L-L fault, L-G fault and short-circuit fault with multiple strings for the given PV parameters to observe the blocking diode conditions. The proposed fault detection algorithm is developed based on the current indicator and their threshold values. The effectiveness of the proposed algorithm is validated through the simulation and experimentation results by considering three cases. It is inferred from these results that the proposed algorithm can effectively detect the faults in the PV array and in the PV strings. The main advantage of the proposed fault detection algorithm is that the faults are identified in less time when compared with machine learning algorithms with huge datasets, and with a less number of sensors. This algorithm can be extended to any irradiation by changing the threshold values of the string and the PV array.

7 CONCLUSION

This paper has proposed a new algorithm to identify the faults in the PV array and the PV string. A simple analysis is carried under different fault conditions such as L-L fault, L-G fault and short-circuit fault with multiple strings for the given PV parameters to observe the blocking diode conditions. The proposed fault detection algorithm is developed based on the current indicator and their threshold values. The effectiveness of the proposed algorithm is validated through the simulation and experimentation results by considering three cases. It is inferred from these results that the proposed algorithm can effectively detect the faults in the PV array and in the PV strings. The main advantage of the proposed fault detection algorithm is that the faults are identified in less time when compared with machine learning algorithms with huge datasets, and with a less number of sensors. This algorithm can be extended to any irradiation by changing the threshold values of the string and the PV array.

NOMENCLATURE

- NEC: National Electric Code
- OCPD: overcurrent protection devices
- GFPD: ground fault protection devices
- FDA: fault detection algorithm
- BD: blocking diode
- $V_{pp}$: maximum PV array voltage
- $I_{pp}$: maximum PV array current
- $V_{oc}$: open-circuit voltage of PV array
- $I_{sc}$: short-circuit current of PV array
- $I_1$: first string current
- $I_2$: second string current
- $I_3$: third string current
- $I_4$: fourth string current
- $R_I$: current indicator
- $N_k$: number of modules in PV string
- $\xi_1$, $\xi_2$, $\xi_3$: values of array current under faults

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