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# Comparative Analysis of Photovoltaic Faults and Performance Evaluation of Its Detection Techniques

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**ABSTRACT** Faults detection and analysis in PV system are considered critical for ensuring safety and increasing output power of PV arrays. PV faults do not only reduce output power and efficiency but also lessen the working life time of a system. Most common and chronic PV faults are line to line, line to ground, shadowing fault, and arc fault while less common and acute faults are hotspot, degradation, bypass diode, and connection faults. Event of PV fault detection failures, such as most recent in Mount Holly, USA in 2011 evinced the improvement in current fault detection and mitigation techniques to shrink such failures. There are various limitations in the existing fault detection techniques, as identified in this paper, which may cause misdetection of the faults. This paper is focused on mathematical formulation of various PV faults and lead to the latter's critical analysis in terms of efficiency, accuracy, complexity, and reliability. The presented work also helps to identify nature and causes of occurrence of a PV fault. This research work serves as a special set of references and recommendations for researchers and PV manufacturing industry to improve fault detection prospects in solar PV systems.

**INDEX TERMS** PV faults, fault detection, line to line fault, line to ground fault.

## I. INTRODUCTION

The annual global PV installations are expected to increase by 18% as generation capacity of 123GW is expected in 2019 according to IHS report [1]. Probability of fault occurrence is increased as dependency on solar PV technology is increased worldwide [2]. In 2018 solar power loss due to fault occurrence and degradation has recorded 17.5 % of total power output [3]. While, still fault such as line to line fault, ground fault, hot spot and shading fault can occur undetected [4]. Fault type and occurrence ratio varies with respect to PV type and its configuration [5]. It is endeavored that end user awareness regarding solar PV fault occurrence, its impact and troubleshooting will save up to 15% power loss in PV system [6]. Prior knowledge of fault is of key importance for successful mitigation and shutting down of PV system during very short span of fault occurrence period [7]. There is not always a single reason of any specific fault occurrence but sometimes multiple reasons for any fault occurrence [8]. Investigating acute and chronic reasons of fault is also of upmost importance for selection of detection techniques. Line to line fault, line to ground fault, open circuit fault and arc faults are categorized as acute fault because all these faults need quick detection and mitigation while remaining faults are chronic in nature; they do not occur suddenly [9]. There are certain technical challenges in fault detection and mitigation in each fault scenario. These challenges are addressed in different ways by researchers. Still there is a need of comprehensive analysis of fault detection techniques in terms of limitations, advantages, detection time, complexity, and

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reliability as well as set of recommendations for researchers and manufacturers [10]. Typically, there are some non-current carrying parts in PV array, such as frame of PV module, mounting racks, distribution panels, metal enclosures, power converters and chassis of endues appliances [11]. During normal operation these conductors do not pass current but there is always a potential risk of electrical shock from these conductors when an electrical connection is established between current carrying conductors and above-mentioned non-current carrying conductors due to faults, such as; melting of insulation, corrosion, wrong wiring, and wire cut-off, results in line to ground fault [12]. National Electrical Code of US strongly recommends equipment grounding in article 690.43 [13]. Line to Line fault occurs in PV system due to several reasons, such as; external connection between two wires or internally due to hotspot and low irradiance. Line to line faults can be categorized in two types that are internal and external [1]. Internal line to line fault is said to that fault which occurs inside Solar PV plate due to several reasons, while external line to line fault is accidental short circuit between two wires or among many wires at multiple places [14]. Hot-spot and shadowing fault also occurs because of continuous changing shadow profile over PV array. Hot-spot heating usually occurs in the shaded cells of the module when a large reverse bias occurs due to series connected cells in large number which results in high power dissipation in poor cell. Due to high power dissipation in small area results in over-heating or hot-spot. This over-heating and hot-spot in turn leads to cell cracking, glass cracking, degradation of solar cell, melting of solder, and some other destructive effects [15]. Likewise, high discharge of electricity between two conductors causes ARC fault [16]. This high electricity discharge results in heat, which breaks the wire's insulation and trigger an electrical fire [17]. Chronic fault that occur in solar PV array are degradation fault losses (DF), shadowing fault loss (SF), snail fault loss (Sn F). DF losses are assumed as a reduction in parametric values of PV array, SF is put in place by varying solar irradiance, SF can be instigated by considering one PV panel as load while Snail faults are introduced in system by disconnecting PV cells in panel [18]. Building shadows, clouds cover, dust accumulation on PV panel surface, bird droppings, and tree shadows cause partial shading (PS) [20]. General faults due to power electronics such as, fault in power conditioning units, faults in inverter or charge controller circuitry lead to ac-dc arcing hazards or even fast spreading fire risks [21]. PV systems installations worldwide either adopt National Electric Code (NEC) or International Electro-Technical Commission (IEC) standards to avail protection against various PV array faults [19].

Selection of fault detection technique is not only dependent on the type and severity of fault but also on the conditions in which fault occurs. Occurrence of multiple faults on same time and sometimes in the scenario where fault does not seem but it has already occurred, which make detection very complex [22]. However, several methods can detect single fault. There is a need of investigation that can identify fault and fault occurrence conditions in which specific fault detection techniques can be adopted. However, we can categories fault detection into four basic techniques, which are, model-based difference technique (MDT), real time difference detection technique (RTD), output signal analysis technique (OSA) and machine learning techniques (MLT) [23], [24]. Model based detection compares real values od parameters with the simulation, while, real time difference compares real time instantaneous values with reference values to identify faults. In output signal analysis method different signal processing techniques are applied on output data sample. Whereas in machine learning technique classifiers are trained which then identify faults based on trained data. Detection variables are important agent in the detection procedure of any fault. Detection algorithms are mostly based on time domain comparison of these variables. In case of PV faults power output mostly depends upon I and V, but there are several other factors which indirectly effects the power output. Hence, mathematically each fault should be analyzed based on reference values which are set as a benchmark for fault detection. Mathematical formulation of each fault is necessary as it identifies fault detection variable [25].

The structure of this paper follows, section II consists of classification of fault, having mathematical formulation of fault indicators, section III consists of detailed explanation of fault detection techniques which are, MDT, RTD, OSA, and MLT. Section IV contains analysis of different fault with detection techniques and mathematical formulation of each fault. Section V and VI consists of discussion and conclusion respectively. Moreover, mathematical modeling of PV cell and analyzing mathematical formulation of faults, a detailed comparison is performed by comparing different parameters such as, detection variable in each techniques, complexity and advantages of each techniques, number of extra equipment or sensors involved in the detection process, detection capability test for each fault and failure probability of different techniques in case of different faults. In addition to it, detection of each fault under each detection mechanism is evaluated which results in awareness of solar PV scientist, researchers, and end user to adopt relatively efficient, reliable, and accurate detection technique.

## II. CLASSIFICATION OF PV FAULTS

In this paper, faults are classified on the basis severity, more severe faults are termed as acute faults while less severe faults are termed as chronic faults. Short circuit fault, and open circuit faults are acute faults as they shutdown PV system which results in no output power, however short circuit and open circuit faults at module level are sever but do not shutdown the PV system [26]. Whereas partial shading fault (PS), shading fault (SF), bypass diode fault (BF), hotspot fault (HS), degradation fault (DF) and general fault (GF) are termed as chronic faults because of less severity. Figure (2) and (3) shows classification and schematics of PV faults.

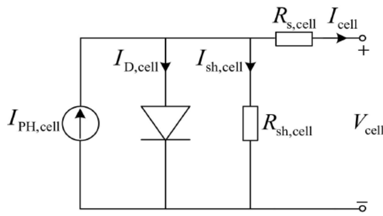


**FIGURE 1.** Single diode model of solar cell.

### A. MATHEMATICAL FORMULATION OF FAULT INDICATORS

In single diode model solar cell is simulated as photo-generated current source that is connected in parallel to diode. Considering losses due to solar cell material, resistance characteristics, the series internal resistance of cell consists of recombination of PN junction region, material resistance, contact resistance and parallel internal resistance of cell that varies with leakage current at the edge. The equivalent circuit of the single diode model is shown in figure (1). The adoption of single diode modeling is mostly due to easy simulations and less time requirement for simulation. In [27] authors have proposed an empirical formula for reduction of simulation time. Various PV models are found in literature having different computational time and accuracy such as, Gompertz, the modeling accuracy for most of them is directly related to their complexity and computational [28]. Mathematically current and voltage characteristics of the solar cell is given by [29], that is;

$$I_{cell} = I_{PH} - I_o\left[\exp\left(\frac{q\left(V_{cell} + R_s.I_{cell}\right)}{akT}\right) - 1\right] - \frac{V_{cell} + R_s.I_{cell}}{R_{Sh}} \quad (1)$$

where $V_{cell}$ and $I_{cell}$ are output voltage and current of solar cell respectively; $I_o$ is the reverse saturation current of diode, a is the ideality factor of the diode, T is cell temperature, q is charge on electron, k is Boltzmann constant ($1.381 \times 10^{-38}$ J/K), $I_{ph}$ is the photocurrent, $R_s$ and $R_{sh}$ are the series and parallel internal resistance respectively.

In addition to above, PV module consists of solar cells connected in series. As described in Eq. (1) the voltage and current characteristics can be illustrated as [29];

$$I_{cell} = I_{PH} - I_0\left[\exp(\frac{V + R_s.I}{aVt}) - 1\right] - \frac{V + R_s.I}{R_{sh}} \quad (2)$$

In Eq. (2) $V$ and $I$ are the output voltage and current of the module respectively, however $V$ of the module is the product of voltage of single cell and number of cell, that is, $V = N_{cell}.V_{cell}$, $I_o$ is the reverse saturation current of diode, $I_{ph}$ is the photocurrent, $R_s$ and $R_{sh}$ are the series and parallel internal resistance respectively, whereas $R_s = R_{s,cell}.N_{cell}$ and same is for $R_{sh}$.

Voltage and current are usually used as an indicator of fault. Voltage indicator is taken as ratio between instantaneous voltage and open circuit voltage, while current indicator is ratio between instantaneous value and short circuit current value. $Voc$ and $Isc$ are open circuit voltage and short circuit current respectively, and can be calculated mathematically as follows [30];

$$I_{Sc} = N_P\left(\frac{I_{scm_{STC}}}{1000}.G + K_I\left(T - T_{STC}\right)\right) \quad (3)$$

$$V_{oc} = N_s\left(V_{ocm_{STC}} + K_V\left(T - T_{STC}\right) + V_t.In\left(\frac{I_{SC}/N_P}{I_{scm_{STC}}}\right)\right) \quad (4)$$

where $N_S$ and $N_P$ are number of PV module and PV strings respectively; $I_{scm\_STC}$ is the short circuit current at standard test conditions that are irradiation=1000 W/m$^2$ and $T_{STC} = 25^0$C; whereas $V_{ocm\_STC}$ is open circuit voltage of module at STC. $K_I$ and $K_V$ are temperature coefficients of current and voltage respectively; while $G$ is irradiance received by module; $T$ and $V_t$ are temperature and thermal temperature of PV module. $I_{sc}$ and $V_{oc}$ will increase as number of PV modules in each string (row) increases, as $N_s$ and $N_p$ are multiplicative factor. Both have impact on specific faults which are discuss in latter portion. While in case of fault free operation voltage and current indicators are ratio of output voltage $V_m$ to the open circuit and output current $I_m$ to the short circuit current respectively. $V_m$ and $I_m$ can be calculated mathematically as follow [30], which will also increase if we increase number of PV modules in a row;

$$I_m = N_P\left(\frac{I_{mm_{STC}}}{1000}.G + K_I\left(T - T_{STC}\right)\right) \quad (5)$$

$$V_m = N_s\left(V_t.In\left(1 + \frac{I_{SC} - I_m}{I_{SC}}\left(e^{\frac{V_{OC}}{N_s.V_t}} - 1\right)\right) - \frac{I_m}{N_P}Rs\right) \quad (6)$$

where Rs is the series equivalent resistance of the module and $I_{mm\_STC}$ is the output current at STC during fault free operation.

## III. FAULT DETECTION TECHNIQUES

Four basic detection principles which are, model-based detection (MBD), real time detection (RTD), output signal analysis (OSA) and machine learning techniques (MLT), are commonly used for fault detection [23].

### A. MODEL BASED DETECTION TECHNIQUE (MBD)

In this technique the basic principle of difference measurement is applied in such a way that simulated output is differenced to real time output and based on that value it is decided that weather fault exists or not [23]. Figure. 3 below shows the complete process of detection. As shown in figure, Voltage and current (V and I) are sensed when system is on load and off load. Real time computation based on sensed values is done and then compared with MATLAB simulation result. Values in MATLAB based simulation are provided by the manufacturer of PV module. Moreover, lot of already built models are present in MATLAB library which are used by many researchers. However, MATLAB simulations with optimized values can help PV industry to build modules based

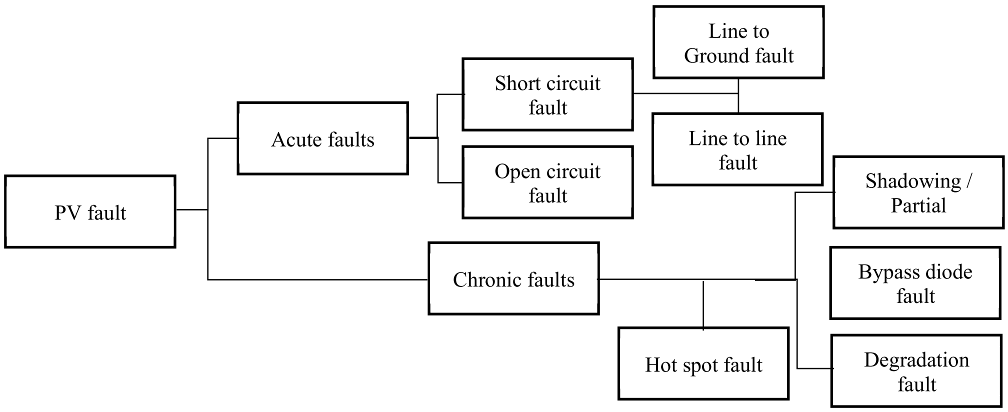


**FIGURE 2.** Classification of faults.

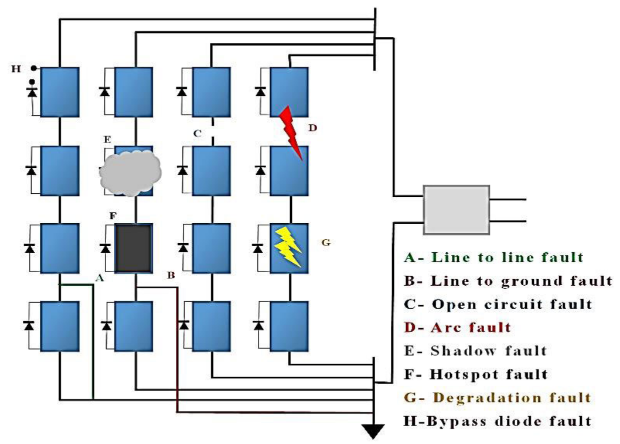


**FIGURE 3.** PV faults schematics.

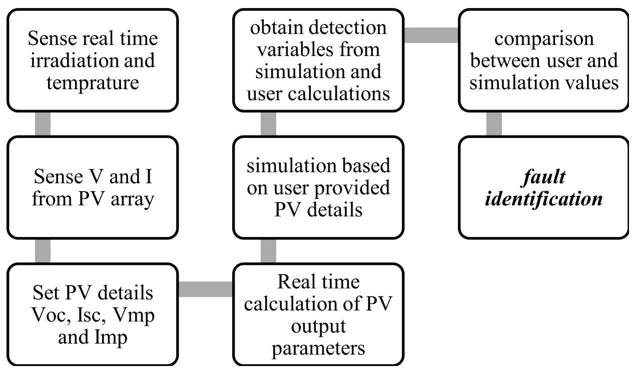


**FIGURE 4.** Process flow chart of model-based detection [23].

on prescribed values for specific region to minimize losses due to faults.

Open circuit voltage (Voc), Short circuit current (Isc), Voltage at maximum power point ($V_{mp}$), Current at maximum power point ($I_{mp}$) are some of variables which are mostly used in this method. While simulated values of all variables are compared with the detected real time values. Based on which fault severity and type is decided. Different faults can be detected by using this technique. Type of fault detection depends upon variable selected for comparison along with little computation and logic.

### B. REAL TIME DIFFERENCE METHOD (RDM)

Real time difference method is like Model based difference method but the only difference is that real time modeling is not required RDM. Real time experimentations are used to extract data to set the threshold limits of detection variables which is to be used in offline mode. The calculated and computed real time values are compared with already set threshold values to detect the faults. The upper and lower limits of the threshold values are identifying and then the current detected value and operating status of PV system is identified by evaluating the following parametric conditions [23]. Figure (5) further clarifies the concept. RDM techniques is widely used in literature. Several faults have been detected; however, a complete comparison is presented at the end of this paper. Different faults have been detected through RDM using different detection variables.

### C. OUTPUT SIGNAL ANALYSIS (OSA)

Usually, due to occurrence of fault output terminal characteristics changes, however environmental conditions are usually ignored in the process of detection. Shading fault, ground fault and short circuit faults effects the output parameters. Arc fault causes output power quality problem even at a stage after inverter. In output signal analysis technique detection variables are sensed and signal samples are formed then signal processing algorithms for analysis [23]. Real time-based time and frequency analysis are usually performed which is then compared to theoretical analysis that results

$$PVoperational\ Status\ at\ run\ time = \begin{cases} Normal: & Vthreshold\_{lower} < V\ det < Vthreshhold\_upper \\ Faulty: & otherwise \end{cases}$$

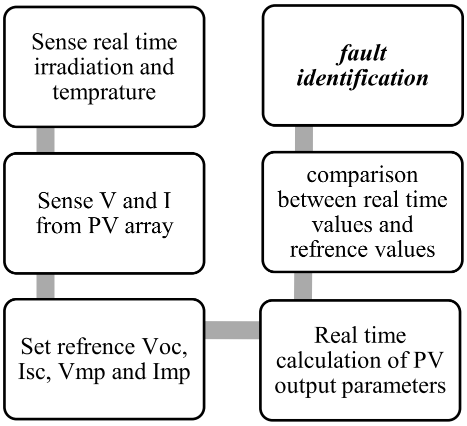


FIGURE 5. Process flow diagram of real time difference technique [23].

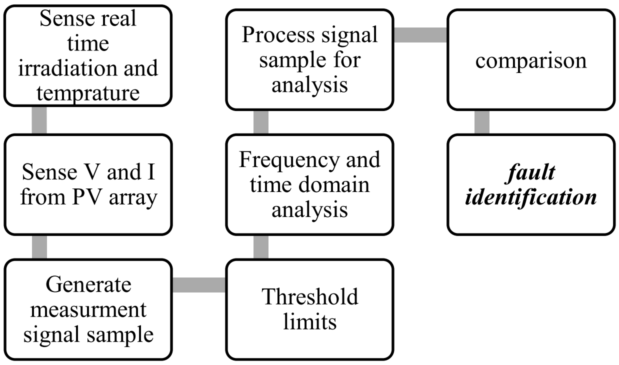


FIGURE 6. Flow chart of output signal analysis mechanism [23].

in identification of severity and nature of fault. For a better understanding, the flow process for the OSA approach is presented in Figure (6). Several faults have been detected in literature by this technique. In output signal analysis different algorithms are applied on data set which is extracted form output signal. OSA is the most efficient, reliable, and accurate technique of fault detection.

### D. MACHINE LEARNING TECHNIQUES (MLT)

Machine learning techniques emerged as fast and accurate in data driven fault diagnosis, such as artificial neural networks (ANNs), fuzzy logic systems and modern-day clustering and classification techniques. Well trained artificial model can precisely predict the real time parameters for both ideal and faulty conditions. When instantaneous parameters are sensed then based on that every fault can be diagnosed. A detailed survey has been conducted in later part of this article. While figure 7 shows the process flow chart of machine learning techniques, which is suggested by [23].

### E. IMPACT OF ARRAY SIZE ON FAULT

Size of PV array depends upon the load requirements. Increasing the number of PV module in a string increases output current while increase parallel operation increases voltage output. There are many configurations are in use, such as Series parallel (SP), Honey comb (HC), Total cross

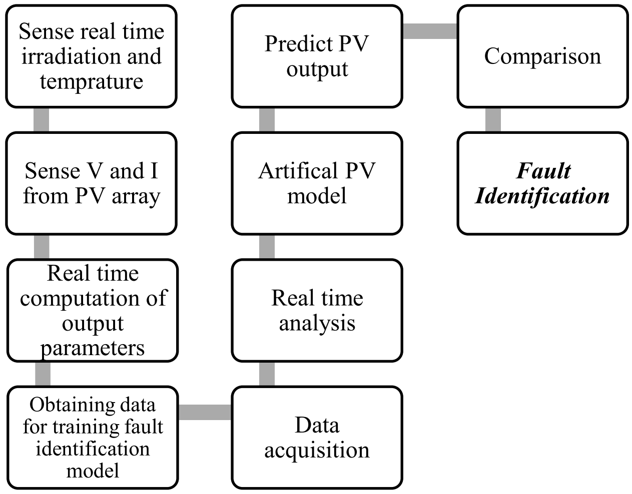


FIGURE 7. Process flow chart of machine learning techniques [23].

tied (TCT), and some others also. Impact of different faults in different configuration is studied my many researchers. However, impact of different faults varies with respect to dimension and size of an array, as discussed in different equations above. Table below gives a brief review.

## IV. ANALYSIS OF PV FAULTS WITH DETECTION TECHNIQUES

Ten different faults and their detection techniques are reviewed in terms of advantages, limitations, number of steps involved in detection, number of false detections, as well mathematical formulation of each fault is discussed to provide a justification of detection variables which are used as detection parameter.

### A. LINE TO GROUND FAULT (LG)

Line to ground fault is said to the fault when a single of multiple line is directly connected to ground due to some disturbances and other environmental impacts. This is sort of fault also occurs due to mishandling of PV system during repair of routine cleaning. Line to line fault is identified in figure (2).

#### 1) MATHEMATICAL FORMULATION OF LG/LL FAULT

When line to line or line to ground fault occurs in one PV string or PV array, under this scenario the voltage indicator can be calculated as follow [31].

$$R_{VS} = \frac{(N_s - 1)}{N_s} \cdot \frac{V_m}{V_{OC}} = \beta R_{VM} \tag{7}$$

$$\beta = 1 - \frac{1}{N_s} \tag{8}$$

where Ns is number of PV modules in one string which in our case is 6 as our PV array is of 6 × 6; $\beta$ varies with change in Ns, in case of more PV modules in string, such as (9 × 2) or (6 × 4) etc., will reduce threshold for LL and LG fault, which in result will increase the probability of occurrence of said faults; whereas $R_{VS}$ is the voltage indicator during

**TABLE 1.** Impact of different faults under different Ns and Np.

| Fault | With increasing Ns/Np in string | With decreasing Ns/Np in string | Impact of threshold |
|---|---|---|---|
| **LL** | Difficult to detect due to low threshold | Easy to detect due to low threshold | Fault threshold decreases with increase in Ns/Np |
| **LG** | Difficult to detect due to low threshold | Easy to detect due to low threshold | Fault threshold decreases with increase in Ns/Np |
| **HS** | Higher impact on whole PV system | Low impact on whole PV system | Threshold is independent of Ns/Np |
| **SF** | Higher impact on whole PV system | Low impact on whole PV system | Threshold is independent of Ns/Np |
| **BFD** | Very low impact as it is mostly concerned to single PV module | Very low impact as it is mostly concerned to single PV module | Threshold is independent of Ns/Np |
| **SC** | Very high impact | Very high impact | SC is very fast occurring fault; threshold is not considered in SC case |

short circuit fault occurrence. So minimum threshold for short circuit fault detection can be defined as [31]:

$$T_{VS} = \varepsilon\beta R_{VM} \tag{9}$$

where $\beta$ is allowed offset coefficient for short circuit fault detection, i.e. $\beta = 2\%$ [32]; where $T_{VS}$ is short circuit fault threshold. But when short circuit fault occurs in more than one string then $T_{VS}$ should be less than $R_V$. The voltage of the short-circuited portion is equal to the reduced portion of the output voltage of PV array.

#### 2) DETECTION ANALYSIS OF LG FAULT

Line to Ground fault or line short circuit fault is detected using multiple techniques by many researchers. Detailed analysis has been done in terms of accuracy, advantages, limitations, complexity, and reliability. As mentioned in previous section, in literature four basic detection techniques are employed in literature. However, mechanism of detection and algorithm for detection varies.

##### *a: LINE TO GROUND FAULT DETECTION USING MBD*

Different detection variables are used in the process of fault detection. Detection variable means the factor or variable which is to be used for analysis based on which we decide about the occurrence of fault. In Model based detection technique, three different approaches by different researcher under different scenarios are compared. Detection variables are different which are based on calculation proposed by respective paper. Table 1 explains each approach in brief, which consists of detection variable i.e. variable which is used as a factor in calculations to observe and detect fault, advantages and limitations, false fault detected i.e. fault detected when there is no fault, no. of steps required during the process of fault detection and additional sensors and

**TABLE 2.** Different cases of line to ground fault detection scheme under model difference-based detection.

| Ref | Detection variable | Advantages | Limitation | False fault detected | No. of steps required | Additional sensors or devices required |
|---|---|---|---|---|---|---|
| **[33]** | $P_{dc}$ | Economic and suitable for small PV systems | Requires manual intervention for fault localization, Overlapping fault signature | 03 | 06 | 02 |
| **[34]** | $V, I, I_{dc}$ | Accurate detection even in the presence of noise | Threshold limit varies from site to site | 03 | 04 | 02 |
| **[35]** | $V, I$ | Cell level fault can also be detected, Ability to diagnose fault in the presence of blocking diode | Fault detection is not possible in shadowing condition | 02 | 04 | 02 |

devices required. While technological comparison in terms of techniques applied, complexity and reliability are presented in detail individually.

Where $P_{dc}$ is output dc power, $I_{dc}$ is output DC current. These results are based on random simulation of 150 different entries of data set. In [29] authors investigate kind of fault by applying two different test procedures on active and passive part of residential PV system. Alarm signal is generated if fault is detected in system. Flash test method is used in active part while wild test is used to identify fault in passive part. In both test alarm signal is analyzed. In [30] neuro-fuzzy approach is followed in detecting line to ground fault. Membership values are assigned to detecting variables and on the bases of pre-defined rules that came from experience, LG fault is detected. This system seems very beneficial as it has neural networks which learns from experience and then provide crisp output based on real time input. In [30] some special cases of short circuit current have been discussed and special attention is paid to low short circuit current which arises because of line to ground short circuiting i.e. 105-110 % of normal current. Blocking and bypass diode are usually used in PV panel to stop these current but sometime short circuit current is too low to be stopped such as case of shadow or low operating conditions. To address above mentioned issue author in [31] dynamic state estimation-based algorithm is implemented for detection of low short circuit current.

### b: LINE TO GROUND FAULT DETECTION USING RDM

Detection of line to ground fault is not efficient through real time difference measurement because line to ground fault suddenly reduces the output to minimum possible value. Upper and lower of threshold values cannot be possible in a case of LG fault because it results only minimum current that approaches to zero through diode.

### c: LINE TO GROUND FAULT DETECTION USING OSA

Line to ground fault has been detected by many researchers using OSA technique. OSA is accurate but scaling down voltages, current and other primary detection variables limits its reliability. Table [2] shows different methods and techniques for LG fault detection using output signal analysis. Different researchers use several detection variables. However, in case of spread spectrum time domain reflectometry (SSTDR) data acquisition devices are mostly used. In operations of high sensitivity OSA fault detection method is employed.

In [32], spread spectrum time domain reflectometry (SSTDR) is used by analyzing common mode model (CMM) of full bridge inverter for detection of high impedance ground fault in solar PV system. The technique followed and applied by the author is proven effective and reliable in many cases. While in [61], proposed quickest fault detection technique by using sequential change detection framework algorithm. Multiple measuring device are installed to record different output signal of PV system. Different numerical regression methods were employed for the purpose of finding co-relation of faulty signal and signal received from different meters in normal conditions. Modelling of post-change signal identifies the severity of fault. Whereas [33], implements pattern recognition approach which employs multi resolution signal decomposition for extraction of necessary features that are; output voltage, current and irradiance level which acted as an input to fuzzy inference system. In [34], decision tree model was proposed. Tree was trained with data set. Results were 98% accurate to the data set.

### d: LINE TO GROUND FAULT DETECTION USING MLT

Machine learning technique has not provided efficient results in detecting line to ground fault yet. Machine learning technique works on the bases of trained data. In the case

**TABLE 3. Line to ground fault analysis using OSA technique.**

| Ref | Detection variable | Advantages | Limitations | False fault detected | No. of steps required | Additional sensors or devices required |
|---|---|---|---|---|---|---|
| **[36]** | $I_{cm}, F_r$ | Accurate in detecting high impedance fault | If multiple faults occur at a time then resonant frequency varies which itself results in malfunctioning, that is not discussed | 01 | 06 | 02 |
| **[37]** | $P_{dc}, V, D$ | Highly adaptive | Multiple parameters are required for the recording of output data | 02 | 03 | 02 |
| **[38]** | $V, I$ | Ideal to handle multiple data with noise. | Poor response to continuous change in irradiation level. | 02 | 05 | 01 |
| **[35]** | *SSTDR* | Fault detection irrespective of fault levels, Can be implemented in the absence of irradiation level, Highly accurate in detection. | Requires base line data for assessment, Accuracy decreases as the distance of fault from the device increases. | 01 | 05 | 01 |

of short circuit due to LG fault MLT only switch off PV system to stop damage.

### B. LINE TO LINE FAULT (LL) DETECTION

Line to line fault is created by accidental short circuit between two points in solar PV system. Line to line faults can be categorized in two types that are internal and external. Internal line to line fault is said to that fault which occurs inside Solar PV plate due to several reasons, while external line to line fault is accidental short circuit between two wires or among many wires at multiple places. External LL fault detection techniques are completely different from internal LL fault detection techniques. External detection techniques are easy and less complex as compared to internal fault detection techniques.

#### 1) LINE TO LINE FAULT DETECTION USING MBD

External LL fault detection techniques are completely different from internal LL fault detection techniques. External detection techniques are easy and less complex as compared to internal fault detection techniques. Here in this review comparison we address internal ones only. Table 3. presents complete analysis of LL fault detection on the difference principle of Model based detection. Three different techniques are compared with different detection variables.

While $V_{mp}$, $I_{mp}$ are voltage and current at maximum power point and $N_P$ is number of peaks. Comparison in above table clearly shows that technique applied in [39] very simple and require less computation and peripheral accessories and sensors. One diode model is modified with a novel approach for early detection of faults in PV module, more specifically shadowing fault, and fault on DC side, i.e. before inverter. This technique is proposed in [40]. In this technique simplicity of the one diode model is combined with the flexibility with extended capacity of control chart of exponentially weighted moving average to detect continually changing condition of PV system. The benefit of one diode model is that it can be easily calibrated due to its limited capacity of calibration, which can be used to predict huge PV system's maximum power coordinates of voltage, current and power using temperature and irradiance values. later, the difference between the instantaneous and predicted values is calculated and used as fault indicators. While in [39] fault identification is done based on anomalies analysis in voltage current (V-I) characteristics. Six different techniques were implemented and simulated and results were compared. 4% difference was recorded in both values in all six techniques. However, this activity operated good during fault conditions. Unlikely in [41] an innovative model-based fault detection for early detection of short circuiting current due to line to ground fault and shading of PV module along with faults on DC side is proposed. This approach also usually combines different features of one diode model, such as the flexibility, and simplicity with the extended capacity of an exponentially weighted

**TABLE 4. Different cases of line to line fault detection scheme under model difference-based detection.**

| Ref | Detection variable | Advantages | Limitation | False fault detected | No. of steps required | Additional sensors or devices required |
|---|---|---|---|---|---|---|
| **[39]** | $V, I, N_p$ | Has detected six different fault combinations. | Suitable only for PV system with MPPT. | 03 | 04 | 02 |
| **[40]** | $V_{mp}, I_{mp}$ | Severity of fault can be detected very easily. | Applicable only to small PV system. | 03 | 06 | 03 |
| **[41]** | $V_{mp}, I_{mp}$ | Easy to integrate with PV with MPPT | Cannot differentiate Electrical and shade faults | 03 | 05 | 01 |

moving average (EWMA) control chart to detect incipient changes in a PV system. The one-diode model, which is easily calibrated due to its limited calibration parameters, is used to predict the healthy PV array's maximum power coordinates of current, voltage and power using measured temperatures and irradiances.

#### 2) LINE TO LINE FAULT DETECTION USING RDM

Line to line fault has been detected by selecting several detection variables using real time difference method.

In table [4] brief comparison of different detection schemes is given. Five different techniques and approaches are found in literature based on different perspective. However, most of detection variables used in real time detection method are primary.

Where $P_{dc}$ is output DC power, $d$ is duty cycle, $\lambda$ is power coefficient, $L$ array is loss and STC is standard test condition. Form the above comparison [54] proposed easy, efficient, and less complex method but when there is large expanded PV system then method proposed by [53] gives good results. In [38] very detailed analysis is performed by establishing multiple cases that are; introducing different inverters, different shadowing scenario, impact of different faults, different cases with string length and PV configurations etc. however, in good engineering design less complexity and low cost is preferred. While in [38]–[40], [41] optimization techniques are applied for identification of faults. Comparison is between the parameters when fault is occurred with the optimized value of parameters.

#### 3) L-L FAULT DETECTION USING OSA

Six different were found in literature for detection of line to line fault detection as shown in table [5]. Detection variable selected are same as selected in other methods. However, in [42] current outlier has been detected which itself is a cumbersome task. Outlier is the very different value among other values of same variable. While wavelet coefficient is also used as detection variable which is most likely same as outlier but the only difference is wavelet coefficient is combination of several values while outlier is single value. OSA is computationally tough technique as compared to other techniques.

Where $I_{ol}$ is current outlier, $V_{wc}$, $I_{wc}$ are the wavelet coefficient of voltage and current respectively and DAQ is data acquisition. In [45] very less computation is required that is why it is preferred.

#### 4) LINE TO LINE FAULT DETECTION USING RDM

As Line to line fault is very common occurring fault. Machine learning techniques consists of many algorithms based on data sets. Table [6] shows brief detail of different techniques for LLF detection using MLT.

In [46], machine learning technique is applied for regular health monitoring of PV system. Software simulation is used to model the temperature dependent relation for the series resistance and ideality factor which is used as a classifier for fault identification. The simulation results demonstrate the high accuracy of the proposed fault classifier. In [47], [48], authors propose artificial neural network (ANN) model for fault identification but ANN is less suitable because error might be high in some cases while high accuracy is most important factor to be considered. While in [49], author applied latterly primed adaptive resonance theory (LAPART) neural network algorithm for identification of fault at module level. The said algorithm can interpret both smooth and perturbated behavior of PV caused by cloud cover or etc. In [50], author detected line to line fault by employing multi resolution signal decomposition and two stage support vector mechanism. The proposed technique is economical because it only requires measurement of voltage and current. Trained by a minimum portion of data, this algorithm presents satisfactory accuracy in detecting L-L faults under different operating conditions. In addition to above [51] used MPPT based sensor less fault detection technique but it was not reliable and very less accurate.

### C. INTERNAL SHORT CIRCUIT FAULT (SC) DETECTION

Short circuit fault occurs when two or more than two wires connects without any resistive path between/among them.

**TABLE 5.** Line to line fault detection using real time detection method.

| Ref | Detection variable | Advantages | Limitations | False fault detected | No. of steps required | Additional sensors or devices required |
|---|---|---|---|---|---|---|
| [42] | $P_{dc}, d$ | Number of faulty units can be detected at a time. | Accuracy decreases as the length of string increases | 02 | 06 | 03 |
| [43] | $V, I$ | Can effectively detect shading fault only, but is very helpful in exact localizing of fault. | High cost of realization | 03 | 04 | 02 |
| [44] | $\lambda, L_{array}$ | Simple, robust, and highly efficient detection. | Reference Panel is required for measurement | 02 | 03 | 03 |
| [45] | $V_{mp}, I_{mp}$ | Simple detection procedure and suitable for large PV systems | Threshold value may vary from site to site. | 02 | 05 | 02 |
| [54] | $I_{sc}$ | Accurate and simple detection process | Tested for STC only | 01 | 02 | 01 |

**TABLE 6.** Line to line fault detection using OSA method.

| Ref | Detection variable | Advantages | Limitations | False fault detected | No. of steps required | Additional sensors or devices required |
|---|---|---|---|---|---|---|
| [46] | $I_{ol}$ | Easy to implement | Not accurate when number of samples are less | 01 | 06 | 02 |
| [47] | $I_{ol}$ | Highly accurate | Slow response to detection | 02 | 03 | 02 |
| [48] | $V_{wc}, I_{wc}$ | Can easily detect islanding operation as well | Poor diagnosing and localization capability | 02 | 05 | 01 |
| [37] | $P_{dc}, V, D$ | Highly adaptive | Multiple parameters are required for the recording of output data | 02 | 03 | 02 |
| [38] | $V, I$ | Ideal to handle multiple data with noise. | Poor response to continuous change in irradiation level. | 02 | 05 | 01 |
| [49] | $V, I$ | Accurate in differentiating shade fault and LL fault during detection process | Requires DAQ and additional signal processing tools. | 01 | 02 | 01 |

In PV solar system it may be internal or external. Internal SC fault is said to the fault that occurs inside solar PV module.

### 1) SHORT CIRCUIT FAULT DETECTION USING MBD

It is not that much severe as compared to external SC fault. Detection of internal fault is difficult. Different computational techniques such as pattern recognition, image processing is used for detection of internal SC fault. Short circuit fault is the only fault which can be easily detected by several methods as shown in table [7]. Some detection variable used for detection, are primary while some are secondary. Primary detection variables are those which can be measured directly while secondary detection variables are the result of primary detection variable along with some calculations, such as, APRE i.e. absolute performance ratio error. It can also be seen that same detection variable is used

**TABLE 7. Line to line fault detection using machine learning.**

| Ref | Detection variable | Advantages | Limitations | False fault detected | No. of steps required | Additional sensors or devices required |
|---|---|---|---|---|---|---|
| **[50]** | $I$ | Good classification accuracy | High cost of realization | 03 | 05 | 03 |
| **[51]** | $P_{mp}$ | Efficient training model is adopted | With increase in mismatch probability of failing increases | 02 | 05 | 03 |
| **[52]** | $V, I$ | Simple control technique | Temperature effects are ignored | 01 | 05 | 03 |
| **[53]** | $P_{dc}$ | No interior detail is required of PV cell | Fault of similar signature cannot be detected | 04 | 07 | 04 |
| **[54]** | $P_{dc}$ | Predictive control of fault occurrence | Need lot of sensor data and other data collection devices | 05 | 07 | 06 |
| **[55]** | $V, I$ | Highly accurate for small PV systems | Requires extensive data set. | 03 | 05 | 03 |

by different researchers applying different techniques results differently. So, it is deducted that algorithm and approach followed can increase efficiency in terms of advantages, limitations, false fault detection, no. of steps required for detection and additional sensors and device utilization. However, in some cases reliability and complexity are matter of concern.

Where, *APRE* is absolute performance ratio error, $P$ loss is the DC power dissipation at output, $I_p$ is the value of current at dissipated power rate. It can be easily concluded form above comparison and analysis that [52] proposed an easy and less complex approach for the fault Short circuit fault detection. Detection techniques and requirement mostly depends upon application in which solar PV is adopted as a source of energy. In sensitive and low voltage application computational time and accuracy are not compromised. In addition to other work, [53] has designed very efficient and intelligent automatic system for fault detection in grid connected PV system. A diagnostic signal is introduced which shows fault location by calculation of ratio between AC and DC power. Special software was designed which on the bases of algorithms identifies various types of faults, such as, PV string fault, inverter fault etc. While in [54], threshold value of partial loss that yield in PV system in normal and fault conditions is set and then it is compared to fault current loss which decides the magnitude of fault and its nature. In [55] simple ratio between $V_R$ and $P_R$ identifies the nature of fault through GUI interface of specially designed software based in intelligent algorithms. A fault diagnosis technique based on sampling of data to estimate intrinsic parameters of the panel is discussed in [37]. Unlike prior-art approach the proposed method uses dynamic V-I characteristics to determine fault parameters. Apart of rapid parameter estimation proposed method provides in-depth understanding of panel condition with the drift of the fault parameters. Least square method along with fuzzy logic is used for fault identification in PV system. Bishop model of PV system is simulated for the said purpose in MATLAB in [56]. The overall results of this approach are very encouraging and could lead to a low-cost diagnostic approach. Fault detection algorithm which is based on analysis of theoretical curves of PV system is proposed in [57]. 60% detection accuracy is claimed in [58], but accurate training of algorithm to act reliably in every environment is still a difficult task. For a standard operating condition given number of attributes i.e. voltage ratio and power ratio are simulated in LabVIEW software. Moreover, a third order polynomial is used to generate low and high limit of power and voltage ratio which is compared to the real time data. Data sample which exceeded the limit are processed by fuzzy logic to characterize fault intensity and type. The maximum detection accuracy recorded is 98.8%.

### 2) INTERNAL SC DETECTION USING RDM

Short circuit fault is also common fault like LL and LG faults. It can be detected by several techniques having simple primary detection variables. Table 8 shows brief comparison among different methods and techniques for short circuit detection using real time difference method. However, details of each method are explained in different sections of different faults. [40] and [61] are comparatively efficient and easy techniques for detection. Adoption of specific technique for short circuit detection depends upon the application and scenario. So, there is no final verdict on the efficiency and advantage of any specific fault detection technique. Usually robust and easily implementable techniques are preferred.

*SC fault detection using OSA and MLT is not possible as signal collection during open circuit is not possible whereas SC fault cannot be forecasted.*

**TABLE 8.** Brief comparison of short circuit fault detection based on model difference method.

| Ref | Detection variable | Advantages | Limitations | False fault detected | No. of steps required | Additional sensors or devices required |
|---|---|---|---|---|---|---|
| [18] | *APRE* | Very accurate | Complex and time-consuming computation, Multiple sensors are needed for accurate localization of fault | 03 | 07 | 04 |
| [24] | $P_{loss}$ | Simple detection procedure and can be easily integrated with any PV system. | Elevated sensor requirement | 02 | 05 | 05 |
| [19] | $V, I, I_{dr}$ | Accurate detection even in the presence of noise | Threshold limit varies from site to site | 03 | 04 | 02 |
| [32] | $P_{dc}, I_R, R_V$ | Less instrumentation errors, Simple computation and robust | Can detect and diagnose Open circuit fault only. | 03 | 04 | 02 |
| [56] | $V, I, N_P$ | Has detected six different fault combinations. | Suitable only for PV system with MPPT. | 03 | 04 | 02 |
| [53] | $R_P, R_V$ | Compact, simple, and fit for implementation in robust environment | Multiple additional sensors are required for accurate fault detection. | 03 | 06 | 02 |
| [57] | $I_P$ | Remote sensing and modularity capability | Applicable only in PV connected in series string as well as very high implementation cost. | 02 | 03 | 02 |
| [58] | $P_{dc}$ | Suitable for simulation-based calculation | Data logger is required for practical implementation, Difficult to sense voltage and current in real time. | 01 | 07 | 01 |
| [59] | $V_{mp}, I_{mp}$ | Severity of fault can be detected very easily. | Applicable only to small PV system. | 03 | 06 | 03 |
| [41] | $V_{mp}, I_{mp}$ | Easy to integrate with PV with MPPT | Cannot differentiate Electrical and shade faults | 03 | 05 | 01 |
| [60] | $R_P, R_V$ | Can detect MPPT fault as well. | Require data acquisition (DAC) for detection. | 02 | 06 | 02 |
| [61] | $R_P, R_V$ | Use statistical data T test to improve rule set | High implementation cost | 03 | 04 | 02 |
| [62] | $V, I$ | Use of BEE algorithm to improve detection accuracy, Comparatively better solution for larger PV systems in which multiple faults occur at a time. | Complex in terms of training algorithm which is supposed to be reliable | 40% | 06 | 02 |

### D. OPEN CIRCUIT FAULT DETECTION (OC)

Mostly wiring of solar PV system is not covered in shield which results in degradation due to environmental effects. Conductors breaking and pulling out of its joint are due to mentioned effects, which cause open circuit fault (OC) and as an after effects short circuit fault also occurs mostly due to connection failure.

#### 1) MATHEMATICAL FORMULATION OF (OC) FAULT

When open circuit fault occurs in one PV string, under this scenario the current indicator can be calculated as follow [28].

$$R_{IO} = \frac{(N_P - 1)}{N_P} \cdot \frac{I_m}{I_{SC}} = \alpha R_{IM} \tag{10}$$

$$\alpha = 1 - \frac{1}{N_P} \tag{11}$$

where $N_P$ is number of PV string which in our case is 6 as our PV array is of $6 \times 6$, mathematically it looks like increasing number of PV module in array reduces threshold of OC fault but technically OC circuit fault has no threshold value in case of small systems, such as, $9 \times 2$ or $6 \times 4$, while in bigger

**TABLE 9.** Short circuit fault detection techniques using real time difference method..

| Ref | Detection variable | Advantages | Limitations | False fault detected | No. of steps required | Additional sensors or devices required |
|---|---|---|---|---|---|---|
| [63] | $V, I$ | Localization is easy and can be achieved by grouping. | System become complex as array size increases | 01 | 03 | 02 |
| [64] | $P_{dc}, E_{loss}, I, V$ | Only MPPT sensors are required. No additional sensors are required | Perfect for Solar PV system with MPPT distributed. | 03 | 06 | Nil |
| [65] | $V, I$ | Easily integrated to any PV system | But gives perfect result only in MPPT solar PV system | 02 | 04 | Nil |
| [66] | $V, I$ | No current sensor is required, Voltage sensors are placed to get optimized results, highly accurate in fault localization, cost effective with respect to size of PV array. | Noise free wireless sensors are required to detect fault accurately | 01 | 04 | 05 |
| [43] | $\lambda$, $L_{array}$ | Simple, robust, and highly efficient detection. | Reference Panel is required for measurement | 02 | 03 | 03 |
| [44] | $P_{dc}$ | Accuracy depends open MPPT technology used. | Can sense a smaller number of parameters | 01 | 04 | Nil |

systems (in MW range) threshold value does matter; whereas $R_{IO}$ is the current indicator during open circuit fault occurrence. So minimum threshold for open circuit fault detection can be defined as [27]:

$$T_{IO} = \varepsilon \alpha R_{IM} \tag{12}$$

where $\varepsilon$ is allowed offset coefficient for open circuit fault detection, i.e. $\varepsilon = 2\%$ [20]; where $T_{IO}$ is open circuit fault threshold. But when open circuit fault occurs in more than one string then $T_{IO}$ should be greater than $R_I$. The current of the faulty string is equal to the reduced portion of the output current of PV array.

### 2) DETECTION OF OC FAULT USING MBD

Same as other faults, OC fault can be detected by using four basic techniques. Table 9 consists of different techniques followed to detect OC fault. Different PV analyzer which are mostly used for OC fault detection are based on these techniques. Brief comparison is also done among five different approaches having several detection variables used. Some of them are repeated in case of different faults because some time same approach is used for detection of multiple fault. While detail analysis of each fault detection technique is also discussed below. Advantages and limitations of each technique is explained in different perspective.

$P_{dc}$ is output DC power, $I_R$ and $R_V$ are current through series resistance of solar cell while $Rv$ is resistance offered by solar cells. $V_{mp}$, $I_{mp}$ are voltage and current at maximum power point. In [37] statistical test was performed on data which was stored via DAQ boards. Statistical t-test had to examine the grid connected PV system and then identification of proper algorithm that can diagnose fault on DC side. Solar irradiance and module temperature were selected as a parameter for statistical tests. An extra data storage and processing device is used in this process which makes it complex. While in [55], satellite image approach is used that is, comparison between solar radiation with ground solar radiation with the help of fuzzy logic algorithm which leads to the nature of

**TABLE 10.** Different cases of open circuit fault detection scheme under model difference-based detection.

| Ref | Detection variable | Advantages | Limitations | False fault detected | No. of steps required | Additional sensors or devices required |
|---|---|---|---|---|---|---|
| **[67]** | $P_{dc}$ | Economic and suitable for small PV systems | Requires manual intervention for fault localization, Overlapping fault signature | 03 | 06 | 02 |
| **[32]** | $P_{dc}, I_R, V_R$ | Less instrumentation errors, Simple computation and robust, | Can detect and diagnose Open circuit fault only, | 03 | 04 | 02 |
| **[59]** | $V_{mp}, I_{mp}$ | Severity of fault can be detected very easily. | Applicable only to small PV system. | 03 | 06 | 03 |
| **[41]** | $V_{mp}, I_{mp}$ | Easy to integrate with PV with MPPT | Cannot differentiate Electrical and shade faults | 03 | 05 | 01 |
| **[68]** | $R_P$, $R_V$ | Can detect MPPT fault as well. | Require data acquisition (DAC) for detection. | 02 | 06 | 02 |

defect in PV system. In addition to above, [28]–[62], [63] which are discussed in LG fault scenario are efficient too. In terms of accuracy [63] is better approach for fault detection but it is too expensive that is why it is less compatible.

#### 3) OC FAULT DETECTION USING RDM

Open circuit fault detection is comparatively easy as compared to other faults because very common primary detection variables can be used for detection. Table 10 present brief comparison among different approaches in terms of detection variables, advantages, and limitations, no of false fault detected, no. of steps required in detection process and no. of additional sensors used.

From above review it can be concluded that based in real time difference method [38] proposed an effective technique with a very little requirements but in terms of cost and practicality [39] is preferred in most of literature. Where $P_{dc}$ is output DC power, d is duty cycle, λ is power coefficient, $L$ array is loss and STC is standard test condition. Form the above comparison [41] proposed easy, efficient, and less complex method but when there is large expanded PV system then method proposed by [53] gives good results. In [63] very detailed analysis is performed by establishing multiple cases that are; introducing different inverters, different shadowing scenario, impact of different faults, different cases with string length and PV configurations etc. however, in good engineering design less complexity and low cost is preferred.

#### 4) OC FAULT DETECTION USING OSA

Open circuit fault detection is detection of connection failure. Two different approaches are present in literature under the category of Output signal analysis. Connection failure may be internal and external. Table 11 has a brief detail of two different techniques.

Both techniques are scenario based. it is difficult to comment on specific technique for best approach.

#### 5) OC FAULT DETECTION USING MLT

Open circuit fault is very easy to be detected because it generally is dependent on zero or minimum value of current. Table 14 shows brief detail of different techniques.

### *E. DETECTION OF ARC FAULT (AF)*

An arc fault is a high-power discharge of electricity between two or more conductors. This discharge translates into heat, which can break down the wire's insulation and possibly trigger an electrical fire. These arc faults can range in power from a few amps up to thousands of amps high and are highly variable in terms of strength and duration. Photovoltaic (PV) arc-faults can lead to fires, damage property, and threaten the safety of building occupants [72], [73].

#### 1) MATHEMATICAL FORMULATION OF ARC FAULT

NFPA 70E and IEEE 1584 are two most common codes for arc fault calculation [27]. There are two distinct mathematical equations found in literature. ARC is established between two conductors or metal body. Eq. 13 refers to NFPA method for calculating ARC;

$$E_{MB} = 1038.7 DB^{-1.4738} \times t_A [0.0093\, F^2 + 0.3453\, F + 5.9673] \quad (13)$$

where Arc flash is denoted by $E_{MB}$ in equation, DB is working distance between the conductors during fault, $t_A$ is the arc duration, $F$ is short circuit fault current. Whereas,

**TABLE 11.** Open circuit fault detection using real time detection method.

| Ref | Detection variable | Advantages | Limitations | False fault detected | No. of steps required | Additional sensors or devices required |
|---|---|---|---|---|---|---|
| **[42]** | $P_{dc}, d$ | Number of faulty units can be detected at a time. | Accuracy decreases as the length of string increases | 02 | 06 | 03 |
| **[43]** | $V, I$ | Can effectively detect shading fault only, but is very helpful in exact localizing of fault. | High cost of realization | 03 | 04 | 02 |
| **[45]** | $V_{mp}, I_{mp}$ | Simple detection procedure and suitable for large PV systems | Threshold value may vary from site to site. | 02 | 05 | 02 |

**TABLE 12.** Open circuit fault detection using OSA.

| Ref | Detection variable | Advantages | Limitations | False fault detected | No. of steps required | Additional sensors or devices required |
|---|---|---|---|---|---|---|
| **[46]** | $I_{ol}$ | Easy to implement | Not accurate when number of samples are less | 01 | 06 | 02 |
| **[49]** | $V_{wc}, I_{wc}$ | Can easily detect islanding operation as well | Poor diagnosing and localization capability | 02 | 05 | 01 |

Eq. 14 refers to IEEE 1584 code for arc calculation.

$$log[E_n] = k_1 + k_2 + 1.081\ log[I_a] + 0.0011G$$
$$and\ E = 4.184\ C_f \times E_n(t \div 0.2) \times (610^x \div D^x) \quad (14)$$

where E is the arc flash energy, $E_n$ is the normalized arc flash energy, $I_a$ is the arcing current, $C_f$ is the calculation factor, t is the duration of the arc, D is the distance between conductors, X is the distance X-factor, $k_1$ and $k_2$ are constants, and $G$ is the conductor air gap. In case of arc fault, no reference is selected to compute fault and to identify severity of arc. As arc fault results due to high current.

#### 2) ARC FAULT DETECTION USING MBD

Model based detection technique cannot detect arc fault because of the reason, that is occurrence and rate of expansion or spreading of arc fault is very fast. Said technique requires computational time for detection. Severity factor is ignored in the case of arc fault because arc itself is severe fault.

#### 3) ARC FAULT DETECTION USING RDM

Arc fault has not been detected efficiently and effectively by real time difference method. Prior prediction of ARC fault is research gap which needs to be addressed.

#### 4) ARC FAULT DETECTION USING OSA

ARC fault mostly occurs due to mechanical connections malfunctioning in different zones of PV systems. It disturbs power quality even after inverter section, i.e. in AC side. Four different approaches have been found in literature. Mostly secondary detection variable is used for detection of fault. [65] used Tsallis entropy of current which is a generalization of the standard Boltzmann–Gibbs entropy, i.e. energy of current at its occurring time. [66] used Fourier coefficient of sensed, [67] used signal power ratio (SPR) while [68] used frequency of radiated signal as a detection variable. Table [13] compares all different approaches.

Where $I_{TE}$ is Tsallis entropy of current, $I_{fc}$ is Fourier coefficient of current signal, SPR is signal power ratio, and FRS is frequency of radiated signal. Comparing all above listed techniques two results can be concluded, that are [66] is best in terms of very less computation is required and very easy to implement but on other side complete package of ARC fault can only be detected by the approach used by [68].

### F. HOT SPOT FAULT (HS) DETECTION

Hot-spot heating usually occurs in the shaded cells of the module when a large reverse bias occurs due to series connected cells in large number which results in high power dissipation in poor cell. Due to high power dissipation in

**TABLE 13.** Open circuit fault detection using machine learning techniques.

| Ref | Detection variable | Advantages | Limitations | False fault detected | No. of steps required | Additional sensors or devices required |
|---|---|---|---|---|---|---|
| [50] | $I$ | Good classification accuracy | High cost of realization | 03 | 05 | 03 |
| [51] | $P_{mp}$ | Efficient training model is adopted | With increase in mismatch probability of failing increases | 02 | 05 | 03 |
| [53] | $P_{dc}$ | No interior detail is required of PV cell | Fault of similar signature cannot be detected | 04 | 07 | 04 |
| [69] | $P_{dc}$ | Predictive control of fault occurrence | Need lot of sensor data and other data collection devices | 05 | 07 | 06 |

**TABLE 14.** ARC fault detection using OSA.

| Ref | Detection variable | Advantages | Limitations | False fault detected | No. of steps required | Additional sensors or devices required |
|---|---|---|---|---|---|---|
| [70] | $I_{TE}$ | Economic compared to FFT techniques | Adaptive control of threshold limits | 01 | 03 | 01 |
| [71] | $I_{FC}$ | Both time and frequency domain analysis improve detection accuracy | Can detect only series arc fault | 01 | 05 | 01 |
| [72] | $SPR$ | Insensitive to inverter noise level. | Can detect both series and parallel arc faults. | 01 | 04 | 02 |
| [73] | $F_{RS}$ | Highly accurate and noise independent. | Suitable only for small PV system | 01 | 04 | 01 |

small area results in over-heating or hot-spot. This over-heating and hot-spot in turn leads to cell cracking, glass cracking, degradation of solar cell, melting of solder, and some other destructive effects [15]. Likewise, high discharge of electricity between two conductors causes ARC fault [16]. This high electricity discharge results in heat, which breaks the wire's insulation and trigger an electrical fire [17].

### 1) MATHEMATICAL FORMULATION OF HOTPOT/SHADING FAULT

When some part of PV system is shaded while remaining part is completely exposed to solar irradiance, the output current drastically reduces. During partial shading fault occurrence, the voltage and current indicators can be calculated as:

$$R_{VP} = \frac{V_{mp}}{V_{OC}} \tag{15}$$

$$R_{IP} = \frac{I_{mp}}{I_{SC}} \tag{16}$$

where $V_{mp}, I_{mp}$ are the output voltage and current at maximum power point; $R_{VP}$ and $R_{IP}$ are the voltage and current indicators during partial shading fault. When PV module receives maximum irradiance then $V_{mp}, I_{mp}$ can be given as [27];

$$I_{mp} = N_P(\frac{I_{mmSTC}}{1000}.G_p + K_I\,(T - T_{STC})) \tag{17}$$

$$V_{mp} = N_s(V_t.In\left(1+\frac{I_{SC}-I_{mp}}{I_{SC}}\left(e^{\frac{V_{OC}}{N_S.V_t}}-1\right)\right) - \frac{I_{mp}}{N_P}Rs) \tag{18}$$

where $G_p$ is the maximum irradiance value received by PV module during partial shading scenario. So, threshold $T_{IP}$ of partial shading fault is defined as [83];

$$T_{IP} = \varepsilon R_{IP} \tag{19}$$

When PV array is all shaded then $R_I$ should be less than $T_{IP}$. Note that, in case of shading and hotspot fault, threshold is independent of number of PV modules in each string in an

**TABLE 15.** Hotspot fault detection techniques based on model difference method.

| Ref | Detection variable | Advantages | Limitations | False fault detected | No. of steps required | Additional sensors or devices required |
|---|---|---|---|---|---|---|
| **[67]** | $P_{dc}$ | Economic and suitable for small PV systems | Requires manual intervention for fault localization, Overlapping fault signature | 03 | 06 | 02 |

**TABLE 16.** Hot Spot fault detection using real time difference method.

| Ref | Detection variable | Advantages | Limitations | False fault detected | No. of steps required | Additional sensors or devices required |
|---|---|---|---|---|---|---|
| **[64]** | $P_{dc}, E_{loss}, I, V$ | Only MPPT sensors are required. No additional sensors are required | Perfect for Solar PV system with MPPT distributed. | 03 | 06 | Nil |
| **[43]** | $V, I$ | Can effectively detect shading fault only, but is very helpful in exact localizing of fault. | High cost of realization | 03 | 04 | 02 |
| **[45]** | $V_{mp}, I_{mp}$ | Simple detection procedure and suitable for large PV systems | Threshold value may vary from site to site. | 02 | 05 | 02 |

array, but as seen in *equ. (17 & 18)* output voltage and current at MPPT drastically increases with increase of *Ns* and *Np*. So, it can be concluded that with the increase in number of PV modules in a row or string in an array increases impact of SF and HS fault on PV systems.

#### 2) HOTSPOT DETECTION USING MBD

Only single detection variable has been used for detection on Hot spot PV fault based on model-based difference technique. Only single approach has been found in literature based on model-based difference method which is shown in table [16]. Output DC power (Pdc) is taken as detection variable. Same approach is followed above for detection of line to line fault detection.

#### 3) HOT SPOT DETECTION USING RDM

Using real time difference method, several researchers selected different detection variables. Same detection variable can be used for detection of several faults, it mainly depends upon computational algorithm which is used. Hotspot fault usually results in cracks and snails in Solar PV. Table [17] shows brief comparison among different techniques followed by researcher for detection of hot spot fault detection using real time difference method. [62] proposed comparatively efficient and easy implementable technique but is involved with more detection variables which results in increased computational resources and time.

#### 4) HOT SPOT DETECTION USING OSA

Only single technique has been found in literature for detection of hotspot fault using signal processing technique. Table 18 has a brief detail. Impedance and capacitances of solar cells are taken as detection variables. As it changes the impedances and capacitances of solar cell modules. However extra instruments are required in this approach which makes it computationally complex and less reliable but it detects accurately.

### G. SHADING/PARTIAL SHADING FAULT DETECTION

Power output reduces due to partial shading. There are two reasons due to which shading effects output. Non uniform irradiance and sometimes dark cell acts as a load. It also sometime results in hotspot. Hot-spot and shadowing fault also occurs because of continuous changing shadow profile over PV array Hot-spot heating usually occurs in the shaded cells of the module when a large reverse bias occurs due to series connected cells in large number which results in high power dissipation in poor cell. Due to high power dissipation in small area results in over-heating or hot-spot. This over-heating and hot-spot in turn leads to cell cracking, glass cracking, degradation of solar cell, melting of

**TABLE 17.** Hotspot fault detection using OSA.

| Ref | Detection variable | Advantages | Limitations | False fault detected | No. of steps required | Additional sensors or devices required |
|---|---|---|---|---|---|---|
| **[74]** | *Zs, Cs* | Accurate detection variables | For real time measurement external instruments are required | 01 | 03 | 01 |

**TABLE 18.** shading fault detection using OSA.

| Ref | Detection variable | Advantages | Limitations | False fault detected | No. of steps required | Additional sensors or devices required |
|---|---|---|---|---|---|---|
| **[46]** | $I_{ol}$ | Easy to implement | Not accurate when number of samples are less | 01 | 06 | 02 |
| **[49]** | $V_{wc}, I_{wc}$ | Can easily detect islanding operation as well | Poor diagnosing and localization capability | 02 | 05 | 01 |
| **[37]** | $P_{dc}, V, D$ | Highly adaptive | Multiple parameters are required for the recording of output data | 02 | 03 | 02 |

solder, and some other destructive effects [15]. Likewise, high discharge of electricity between two conductors causes ARC fault [16]. This high electricity discharge results in heat, which breaks the wire's insulation and trigger an electrical fire [17]. A reconfiguration technique that finds the optimal configuration in a reduced computational time is proposed by [75].

#### 1) SF DETECTING USING OSA

Table 17 consists of a brief detail and comparison of three techniques used for shading fault detection using OSA. Same techniques were used for detection of multiple faults using OSA. MBD and RDM methods are less efficient in shadow fault detection therefore very less amount of contribution is found in literature. Tradeoff will be required on certain parameters based on requirement of operation. All three technique are equally accurate.

#### 2) SF DETECTING USING MLT

Table 18 has a brief detail and comparison of three techniques used for shading fault detection using OSA. Same techniques were used for detection of multiple faults using OSA. MBD and RDM methods are less efficient in shadow fault detection therefore very less amount of contribution is found in literature.

Partial shading or shading fault is not same for a long course of time because shadowing profile continuously changes with time to time. Model based difference method and real time difference method for detection of shading fault are inefficient. Therefore, no such detection mechanism has been found in literature.

### *H. BYPASS DIODE FAULT DETECTION (BFD)*

This use of bypass diodes allows a series (called a string) of connected cells or panels to continue supplying power at a reduced voltage rather than no power at all. Bypass diodes are connected in reverse bias between a solar cell (or panel) positive and negative output terminals and has no effect on its output. Ideally there would be one bypass diode for each solar cell, but this can be rather expensive so generally one diode is used per small group of series cells [34]–[77].

#### 1) BYPASS FAULT DETECTION USING MBD

Bypass diode fault is detected in literature by three different techniques as seen in table 19. However, bypass diode fault detection is simple. Same techniques which are employed for LL and LG fault detection can be used for bypass fault detection. The only difference is location of fault detection mechanism.

While $V_{oc}$ is open circuit voltage. [30] proposed an efficient method for bypass fault detection which requires less steps, sensors and computational time and results in accurate results. In [71] statistical test was performed on data which was stored via DAQ boards. Statistical t-test had to examine

**TABLE 19.** Shadowing fault detection using machine learning.

| Ref | Detection variable | Advantages | Limitations | False fault detected | No. of steps required | Additional sensors or devices required |
|---|---|---|---|---|---|---|
| [50] | $I$ | Good classification accuracy | High cost of realization | 03 | 05 | 03 |
| [76] | $V, I$ | Simple control technique | Requires DAQ | 01 | 07 | 04 |
| [53] | $P_{dc}$ | No interior detail is required of PV cell | Fault of similar signature cannot be detected | 04 | 07 | 04 |
| [62] | $V, I$ | Use of BEE algorithm to improve detection accuracy, Comparatively better solution for larger PV systems in which multiple faults occur at a time. | Complex in terms of training algorithm which is supposed to be reliable | 40% | 06 | 02 |
| [69] | $P_{dc}$ | Predictive control of fault occurrence | Need lot of sensor data and other data collection devices | 05 | 07 | 06 |

**TABLE 20.** Bypass diode fault detection techniques comparison using model-based difference method.

| Ref | Detection variable | Advantages | Limitation | False fault detected | No. of steps required | Additional sensors or devices required |
|---|---|---|---|---|---|---|
| [34] | $V, I, I_{dr}$ | Accurate detection even in the presence of noise | Threshold limit varies from site to site | 03 | 04 | 02 |
| [77] | $P_{dc}, V_{oc}$ | Fuzzy classifiers nuisance tripping | Detection variable are very sensitive to irradiation, that may lead to erroneous detection | 03 | 05 | 02 |
| [68] | $R_P$, $R_V$ | Can detect MPPT fault as well. | Require data acquisition (DAC) for detection. | 02 | 06 | 02 |

the grid connected PV system and then identification of proper algorithm that can diagnose fault on DC side. Solar irradiance and module temperature were selected as a parameter for statistical tests. An extra data storage and processing device is used in this process which makes it complex.

### 2) BYPASS FAULT DETECTION USING RDM

Only single paper used real time difference method for detection of bypass diode fault. However same technique is used for multiple fault detection as discussed above. Table [20] shows brief explanation of technique followed for bypass diode fault detection using real time difference method. Special algorithm is to be followed/implemented to detect bypass diode fault. We cannot detect BDF directly. This is also called indirect fault detection.

### 3) BYPASS FAULT DETECTION OSA

Only single paper used real time difference method for detection of bypass diode fault. However same technique is used for multiple fault detection as discussed above. Table [23] shows brief explanation of technique followed for bypass diode fault detection using output signal processing

**TABLE 21.** Bypass fault detection using RDM0.

| Ref | Detection variable | Advantages | Limitations | False fault detected | No. of steps required | Additional sensors or devices required |
|---|---|---|---|---|---|---|
| **[42]** | $P_{dc}, d$ | Number of faulty units can be detected at a time. | Accuracy decreases as the length of string increases | 02 | 06 | 03 |

**TABLE 22.** Bypass diode fault detection using OSA.

| Ref | Detection variable | Advantages | Limitations | False fault detected | No. of steps required | Additional sensors or devices required |
|---|---|---|---|---|---|---|
| **[48]** | $V_{wc}, I_{wc}$ | Can easily detect islanding operation as well | Poor diagnosing and localization capability | 02 | 05 | 01 |

**TABLE 23.** Degradation fault detection using real time difference method.

| Ref | Detection variable | Advantages | Limitations | False fault detected | No. of steps required | Additional sensors or devices required |
|---|---|---|---|---|---|---|
| **[42]** | $V_{oc}, V$ | Concurrent and accurate fault detection | Using array output voltage and predicting single PV module voltage is not possible. | 02 | 04 | 02 |

**TABLE 24.** Degradation fault detection using OSA.

| Ref | Detection variable | Advantages | Limitations | False fault detected | No. of steps required | Additional sensors or devices required |
|---|---|---|---|---|---|---|
| **[46]** | $I_{ol}$ | Easy to implement | Not accurate when number of samples are less | 01 | 06 | 02 |

technique. While machine learning technique is not found as much efficient in detection of BFD. Machine learning techniques are mostly based on classifier training-based pattern recognition, which usually incorporate image data. In case of bypass fault detection, it looks inefficient.

### I. DEGRADATION FAULT DETECTION

Degradation mechanisms may involve either a gradual reduction in the output power of a PV module over time or an overall reduction in power due to failure of an individual solar cell in the module [23].

A gradual degradation in module performance can be caused by:

1) Increases in $R_S$ due to decreased adherence of contacts or corrosion (usually caused by water vapor.
2) Decreases in $R_{SH}$ due to metal migration through the p-n junction.
3) Antireflection coating deterioration.

In model-based difference technique degradation fault has been not detected yet.

#### 1) DEGRADATION DETECTION USING RDM

Degradation fault is mainly considered as reduction in output power or voltage. Usually $V_{oc}$ and voltages at different nodes are taken as a detection variable. [38] proposed degradation fault analysis technique by using output voltage loaded and unloaded as a detection variable. Table 22 contains explanation of only technique found in literature.

**TABLE 25.** Degradation fault detection using MLT.

| Ref | Detection variable | Advantages | Limitations | False fault detected | No. of steps required | Additional sensors or devices required |
|---|---|---|---|---|---|---|
| **[69]** | $P_{dc}$ | Predictive control of fault occurrence | Need lot of sensor data and other data collection devices | 05 | 07 | 06 |
| **[78]** | $I, V$ | Very high accuracy | Need lot of computational efforts and algorithms trainings, lot of cascaded steps involved in detection process of faults, degradation fault accuracy is not clearly mentioned. | 7 % | 12 | 01 |

**TABLE 26.** Technique selection priority for specific fault detection.

| Fault/ Detection technique | MBDM | RDM | OSA | MLT |
|---|---|---|---|---|
| **LG** | Fair | Good | Good | Excellent |
| **LL** | Fair | Excellent | Fair | Fair |
| **OS** | Good | Fair | Fair | Fair |
| **SC** | Fair | Fair | Excellent | Good |
| **SF** | Excellent | Excellent | Fair | Fair |
| **HS** | Excellent | Excellent | Fair | Good |
| **BPF** | Poor | Poor | Poor | Good |
| **AF** | Excellent | Excellent | Poor | Poor |
| **DF** | Fair | Fair | Fair | Good |

#### 2) DEGRADATION DETECTION USING OSA

Degradation fault is very uncommon fault and has a very low impact on power output. Only single technique has been found in literature because of less working life time of OSA mechanism. Table 23 shows brief detail of DGF detection using OSA.

#### 3) DEGRADATION DETECTION USING MLT

Machine learning techniques are also of less working life time. It cannot be implemented over long course of time. Specially in case of degradation which takes more than year. Table 24 shows brief detail of DGF detection using MLT.

## V. DISCUSSION AND RECOMMENDATIONS

This research work carried out detection analysis, mathematical formulation of fault, comparison among four basic detection techniques in previous sections. In this section comparative analysis of advantages and limitations of each technique and implications from the review are utilized to recommend a generalize performance evaluation of various fault detection approaches.

### A. ADVANTAGES AND LIMITATIONS OF DETECTION TECHNIQUES

Model based detection method, real time difference method and machine learning methods need PV modeling before implementation of algorithm for fault detection. So, it is understood that detection accuracy will be dependent on accuracy in modelling, and therefore preciseness and reliability of detection approach depend upon accurate parameter extraction. MLT, OSA and RDM techniques can enhance fault detection speed as compared to MBD as real time modeling cannot help in accurate detection. Noise in sampling of output signal effects the accuracy but despite that OSA technique is accurate, product oriented and comedically reliable. While on other hand machine learning techniques do not require any reference values for comparison and calculation of fault and if classification is properly trained then localization of fault becomes very easy.

### B. FAULT DETECTION PERFORMANCE ANALYSIS

The implications drawn from the analysis in this research work can be used to evaluate performance of each technique.

Parameters for performance evaluation are complexity, extra sensors required, detection time, detection steps, and false fault detection. The most important challenge in fault detection is to counter the unique operating characteristics which result due to changing environmental conditions. To be more precise OSA and MLT are more prone to environmental effects. While in terms of complexity OSA and MLT are less preferred. OSA and MLT require more expertise and high computational accuracy. MBD and RDM are more reliable and require less detection time and are reported robust technique for fault detection. Moreover, single fault can be detected by using multiple techniques. Table [28] shows priority wise selection of specific technique for specific fault detection. Priority for selection of specific technique is categorized as poor, fair, good, and excellent in terms of efficiency.

It has been gained from the review that one fault can be detected through several techniques and algorithms but detection efficiency, accurate detection, complexity, and reliability are not always same which concludes that special protocols should be defined for each specific fault detection in different scenarios and conditions. Some recommendations are given below:

a) Solar PV system depends upon solar irradiance, temperature, and environmental effects. History of solar irradiance, temperature, and environmental factors identifies the history of reasons of fault occurrence.
b) Keeping in consideration above mentioned conditions, machine learning technique is best for shadowing loss detection and mitigation.
c) Model based difference method is best for shadowing loss detection, only in conditions when exact shadow analysis and fault detection is not possible, that is in over dusty and snowfall conditions.
d) Line to line and line to ground fault are external faults. Both faults do not rely on history and cannot be forecasted. So, simple model-based detection technique is preferred for detection of both faults.
e) Arc fault occurs due to many run-time circumstances that therefore real time monitoring of PV system is very necessary for Arc fault detection. However, run time monitoring of PV system is complex and less reliable.
f) Hotspot fault is extended version and after effect of shadowing fault but the only difference is that, hotspot fault spreads internally in PV module which is also to mitigate internally therefore, output signal analysis is the only way left to analyze voltage and current signal waveform digitally and then mitigate fault through adopting of signal processing algorithms.
g) General faults and degradation losses can be mitigated by simple model based different methods. Degradation faults is not considered as a major fault but one school of thought in researchers believe that loss and reduction by any mean in PV system is considered as a fault.

With increasing adoption of PV solar systems across the world results in increasing probability of fault occurrence. Above proposed recommendations can help in reduction of false detection of fault but also reduce expected loss of power due to faults.

## REFERENCES


[1] M. K. Alam, F. Khan, J. Johnson, and J. Flicker, "A comprehensive review of catastrophic faults in PV arrays: Types, detection, and mitigation techniques," *IEEE J. Photovolt.*, vol. 5, no. 3, pp. 982–997, May 2015, doi: 10.1109/jphotov.2015.2397599.

[2] W. I. Bower and J. C. Wiles, "Analysis of grounded and ungrounded photovoltaic systems," in *Proc. IEEE 1st World Conf. Photovoltaic Energy Convers. (WCPEC) Joint Conf. PVSC, PVSEC PSEC)*, Waikoloa, HI, USA, Dec. 1994, vol. 1, pp. 809–812, doi: 10.1109/WCPEC.1994.520083.

[3] N. G. Dhere and N. S. Shiradkar, "Fire hazard and other safety concerns of photovoltaic systems," *J. Photon. Energy*, vol. 2, no. 1, Dec. 2012, Art. no. 022006, doi: 10.1117/1.jpe.2.022006.

[4] S. Forman, "Performance of experimental terrestrial photovoltaic modules," *IEEE Trans. Rel.*, vol. R-31, no. 3, pp. 235–245, Aug. 1982, doi: 10.1109/tr.1982.5221326.

[5] R. Kase and S. Nishikawa, "Fault detection of bypass circuit of PV module—Detection technology of open circuit fault location," in *Proc. IEEE Int. Conf. Elect. Mach. Syst.*, Nov. 2016, pp. 1–4.

[6] Y. Zhao, J.-F. De Palma, J. Mosesian, R. Lyons, and B. Lehman, "Line–line fault analysis and protection challenges in solar photovoltaic arrays," *IEEE Trans. Ind. Electron.*, vol. 60, no. 9, pp. 3784–3795, May 2013, doi: 10.1109/tie.2012.2205355.

[7] C. Huang, L. Wang, R. S.-C. Yeung, Z. Zhang, H. S.-H. Chung, and A. Bensoussan, "A prediction model-guided Jaya algorithm for the PV system maximum power point tracking," *IEEE Trans. Sustain. Energy*, vol. 9, no. 1, pp. 45–55, Jan. 2018, doi: 10.1109/tste.2017.2714705.

[8] H. S. Sahu and S. K. Nayak, "Extraction of maximum power from a PV array under nonuniform irradiation conditions," *IEEE Trans. Electron Devices*, vol. 63, no. 12, pp. 4825–4831, Dec. 2016, doi: 10.1109/ted.2016.2616580.

[9] D. S. Pillai, J. Prasanth Ram, M. Siva Sai Nihanth, and N. Rajasekar, "A simple, sensorless and fixed reconfiguration scheme for maximum power enhancement in PV systems," *Energy Convers. Manage.*, vol. 172, pp. 402–417, Sep. 2018, doi: 10.1016/j.enconman.2018.07.016.

[10] J. Li, H. You, J. Qi, M. Kong, S. Zhang, and H. Zhang, "Stratified optimization strategy used for restoration with photovoltaic-battery energy storage systems as black-start resources," *IEEE Access*, vol. 7, pp. 127339–127352, 2019, doi: 10.1109/access.2019.2937833.

[11] M. A. Hannan, Z. A. Ghani, M. M. Hoque, P. J. Ker, A. Hussain, and A. Mohamed, "Fuzzy logic inverter controller in photovoltaic applications: Issues and recommendations," *IEEE Access*, vol. 7, pp. 24934–24955, 2019, doi: 10.1109/access.2019.2899610.

[12] S. You, G. Kou, Y. Liu, X. Zhang, Y. Cui, M. J. Till, W. Yao, and Y. Liu, "Impact of high PV penetration on the inter-area oscillations in the U.S. eastern interconnection," *IEEE Access*, vol. 5, pp. 4361–4369, 2017, doi: 10.1109/access.2017.2682260.

[13] *Solar PV Systems, National Electrical Code, ANSI/NFPA-70*, Nat. Fire Protection Assoc., Quincy, MA, USA,, 2011, Art. no. 690.

[14] E. Scolari, L. Reyes-Chamorro, F. Sossan, and M. Paolone, "A comprehensive assessment of the short-term uncertainty of grid-connected PV systems," *IEEE Trans. Sustain. Energy*, vol. 9, no. 3, pp. 1458–1467, Jul. 2018, doi: 10.1109/tste.2018.2789937.

[15] Y. Wang and B. Ren, "Fault ride-through enhancement for grid-tied PV systems with robust control," *IEEE Trans. Ind. Electron.*, vol. 65, no. 3, pp. 2302–2312, Mar. 2018, doi: 10.1109/tie.2017.2740858.

[16] D. S. Pillai and N. Rajasekar, "A comprehensive review on protection challenges and fault diagnosis in PV systems," *Renew. Sustain. Energy Rev.*, vol. 91, pp. 18–40, Aug. 2018, doi: 10.1016/j.rser.2018.03.082.

[17] *IEEE Guide for Terrestrial Photovoltaic Power System Safety*, IEEE Standard 1374-1998, SASB/SCC21-SCC21-Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage, Oct. 1998.

[18] W. Chine, A. Mellit, A. M. Pavan, and S. Kalogirou, "Fault detection method for grid-connected photovoltaic plants," *Renew. Energy*, vol. 66, pp. 99–110, Jun. 2014, doi: 10.1016/j.renene.2013.11.073.

[19] S. Silvestre, A. Chouder, and E. Karatepe, "Automatic fault detection in grid connected PV systems," *Sol. Energy*, vol. 94, pp. 119–127, Aug. 2013, doi: 10.1016/j.solener.2013.05.001.

[20] E. Koutroulis and F. Blaabjerg, "A new technique for tracking the global maximum power point of PV arrays operating under partial-shading conditions," *IEEE J. Photovolt.*, vol. 2, no. 2, pp. 184–190, Apr. 2012, doi: 10.1109/jphotov.2012.2183578.

[21] D. S. Pillai, N. Rajasekar, J. P. Ram, and V. K. Chinnaiyan, "Design and testing of two phase array reconfiguration procedure for maximizing power in solar PV systems under partial shade conditions (PSC)," *Energy Convers. Manage.*, vol. 178, pp. 92–110, Dec. 2018, doi: 10.1016/j.enconman.2018.10.020.

[22] Y. Zaho, *Fault Analysis in Solar Photovoltaic Arrays*. Boston, MA, USA: Northeastern Univ., 2011.

[23] D. S. Pillai, F. Blaabjerg, and N. Rajasekar, "A comparative evaluation of advanced fault detection approaches for PV systems," *IEEE J. Photovolt.*, vol. 9, no. 2, pp. 513–527, Mar. 2019, doi: 10.1109/jphotov.2019.2892189.

[24] M. Sabbaghpur Arani and M. A. Hejazi, "The comprehensive study of electrical faults in PV arrays," *J. Elect. Comput. Eng.*, vol. 2016, pp. 1–10, 2016, doi: 10.1155/2016/8712960.

[25] S. Gul, A. Ul Haq, M. Jalal, A. Anjum, and I. U. Khalil, "A unified approach for analysis of faults in different configurations of PV arrays and its impact on power grid," *Energies*, vol. 13, no. 1, p. 156, Dec. 2019, doi: 10.3390/en13010156.

[26] R. Platon, J. Martel, N. Woodruff, and T. Y. Chau, "Online fault detection in PV systems," *IEEE Trans. Sustain. Energy*, vol. 6, no. 4, pp. 1200–1207, Oct. 2015, doi: 10.1109/tste.2015.2421447.

[27] Y. Mahmoud and A. Ulhaq, "Computational time quantification of the single diode PV models," in *Proc. 8th Int. Renew. Energy Congr. (IREC)*, Amman, Jordan, 2017, pp. 1–5, doi: 10.1109/IREC.2017.7926022.

[28] Y. Mahmoud and E. El-saadany, "Accuracy comparison between Gompertz and polynomial based PV models," in *Proc. IEEE Energy Convers. Congr. Expo. (ECCE)*, Montreal, QC, Canada, Aug. 2015, pp. 3278–3281, doi: 10.1109/ECCE.2015.7310121.

[29] H. Patel and V. Agarwal, "MATLAB-based modeling to study the effects of partial shading on pv array characteristics," *IEEE Trans. Energy Convers.*, vol. 23, no. 1, pp. 302–310, Mar. 2008, doi: 10.1109/tec.2007.914308.

[30] I. Yahyaoui and M. E. Segatto, "A practical technique for on-line monitoring of a photovoltaic plant connected to a single-phase grid," *Energy Convers. Manage.*, vol. 132, pp. 198–206, Jan. 2017, doi: 10.1016/j.enconman.2016.11.031.

[31] M. Villalva, J. Gazoli, and E. Filho, "Comprehensive approach to modeling and simulation of photovoltaic arrays," *IEEE Trans. Power Electron.*, vol. 24, no. 5, pp. 1198–1208, May 2009, doi: 10.1109/tpel.2009.2013862.

[32] M. Tadj, K. Benmouiza, A. Cheknane, and S. Silvestre, "Improving the performance of PV systems by faults detection using GISTEL approach," *Energy Convers. Manage.*, vol. 80, pp. 298–304, Apr. 2014, doi: 10.1016/j.enconman.2014.01.030.

[33] M. Davarifar, A. Rabhi, A. El Hajjaji, and M. Dahmane, "New method for fault detection of PV panels in domestic applications," presented at the 4th Int. Conf. Smart Cities Green ICT Syst., 2013

[34] L. Bonisgrone, M. D. Rabhi, G. M. Tina, and A. E. hajjaji, "Neuro-fuzzy fault detection method for photovoltaic systems," *Energy Procedia*, vol. 62, pp. 431–441, 2016, doi: 10.1016/j.egypro.2014.12.405.

[35] A. Haque, K. V. S. Bharath, M. A. Khan, I. Khan, and Z. A. Jaffery, "Fault diagnosis of Photovoltaic Modules," *Energy Sci. Eng.*, vol. 7, no. 3, pp. 622–644, Mar. 2019, doi: 10.1002/ese3.255.

[36] G. Wang, C. C. Youn, and A. M. Stankovic, "DC-side high impedance ground fault detection for transformerless single-phase PV systems," in *Proc. North Amer. Power Symp. (NAPS)*, Charlotte, NC, USA, 2015, pp. 1–6, doi: 10.1109/NAPS.2015.7335209.

[37] L. Chen, S. Li, and X. Wang, "Quickest fault detection in photovoltaic systems," *IEEE Trans. Smart Grid*, to be published, doi: 10.1109/tsg.2016.2601082.

[38] Z. Yi and A. H. Etemadi, "Fault detection for photovoltaic systems based on multi-resolution signal decomposition and fuzzy inference systems," *IEEE Trans. Smart Grid*, vol. 8, no. 3, pp. 1274–1283, May 2017, doi: 10.1109/tsg.2016.2587244.

[39] W. Chine and A. Millet, "Fault diagnosis in photovoltaic arrays," presented at the IEEE Int. Conf. Clean Elect. Power, Jun. 2015.

[40] E. Garoudja, F. Harrou, Y. Sun, K. Kara, A. Chouder, and S. Silvestre, "Statistical fault detection in photovoltaic systems," *Sol. Energy*, vol. 150, pp. 485–499, Jul. 2017, doi: 10.1016/j.solener.2017.04.043.

[41] F. Harrou, Y. Sun, B. Taghezouit, A. Saidi, and M.-E. Hamlati, "Reliable fault detection and diagnosis of photovoltaic systems based on statistical monitoring approaches," *Renew. Energy*, vol. 116, pp. 22–37, Feb. 2018, doi: 10.1016/j.renene.2017.09.048.

[42] N. Gokmen, E. Karatepe, B. Celik, and S. Silvestre, "Simple diagnostic approach for determining of faulted PV modules in string based PV arrays," *Sol. Energy*, vol. 86, no. 11, pp. 3364–3377, Nov. 2012, doi: 10.1016/j.solener.2012.09.007.

[43] M. Alajmi and I. Abdel-Qader, "Fault detection and localization in solar photovoltaic arrays using the current-voltage sensing framework," in *Proc. IEEE Int. Conf. Electro Inf. Technol. (EIT)*, Grand Forks, ND, USA, May 2016, pp. 307–312, doi: 10.1109/EIT.2016.7535257.

[44] R. Hariharan, M. Chakkarapani, G. Saravana Ilango, and C. Nagamani, "A method to detect photovoltaic array faults and partial shading in PV systems," *IEEE J. Photovolt.*, vol. 6, no. 5, pp. 1278–1285, Sep. 2016, doi: 10.1109/jphotov.2016.2581478.

[45] E. Garoudja, K. Kara, A. Chouder, S. Silvestre, and S. Kichou, "Efficient fault detection and diagnosis procedure for photovoltaic systems," in *Proc. 8th Int. Conf. Modelling, Identificat. Control (ICMIC)*, Algiers, Algeria, 2016, pp. 851–856, doi: 10.1109/ICMIC.2016.7804233.

[46] Y. Zhao, B. Lehman, and R. Ball, "Outlier detection rules for fault detection in solar photovoltaic arrays," in *Proc. IEEE 28th Annu. IEEE Appl. Power Electron. Conf. Expo. (APEC)*, Mar. 2013, pp. 2913–2920.

[47] Y. Zhao, F. Balboni, T. Arnaud, J. Mosesian, R. Ball, and B. Lehman, "Fault experiments in a commercial-scale PV laboratory and fault detection using local outlier factor," in *Proc. IEEE 40th Photovoltaic Specialist Conf. (PVSC)*, Denver, CO, USA, Jun. 2014, pp. 3398–3403, doi: 10.1109/PVSC.2014.6925661.

[48] I.-S. Kim, "On-line fault detection algorithm of a photovoltaic system using wavelet transform," *Sol. Energy*, vol. 126, pp. 137–145, Mar. 2016, doi: 10.1016/j.solener.2016.01.005.

[49] B. P. Kumar, G. S. Ilango, M. J. B. Reddy, and N. Chilakapati, "Online fault detection and diagnosis in photovoltaic systems using wavelet packets," *IEEE J. Photovolt.*, vol. 8, no. 1, pp. 257–265, Jan. 2018, doi: 10.1109/jphotov.2017.2770159.

[50] Y. Zhao, L. Yang, B. Lehman, J.-F. de Palma, J. Mosesian, and R. Lyons, "Decision tree-based fault detection and classification in solar photovoltaic arrays," in *Proc. 27th Annu. IEEE Appl. Power Electron. Conf. Expo. (APEC)*, Orlando, FL, USA, Feb. 2012, pp. 93–99, doi: 10.1109/APEC.2012.6165803.

[51] M. N. Akram and S. Lotfifard, "Modeling and health monitoring of DC side of photovoltaic array," *IEEE Trans. Sustain. Energy*, vol. 6, no. 4, pp. 1245–1253, Oct. 2015, doi: 10.1109/tste.2015.2425791.

[52] Syafaruddin, E. Karatepe, and T. Hiyama, "Controlling of artificial neural network for fault diagnosis of photovoltaic array," in *Proc. 16th Int. Conf. Intell. Syst. Appl. Power Syst.*, Hersonissos, Greece, 2011, pp. 1–6, doi: 10.1109/ISAP.2011.6082219.

[53] L. L. Jiang and D. L. Maskell, "Automatic fault detection and diagnosis for photovoltaic systems using combined artificial neural network and analytical based methods," in *Proc. Int. Joint Conf. Neural Netw. (IJCNN)*, Killarney, Ireland, 2015, pp. 1–8, doi: 10.1109/IJCNN.2015.7280498.

[54] L. Hernández-Callejo, "A comprehensive review of operation and control, maintenance and lifespan management, grid planning and design, and metering in smart grids," *Energies*, vol. 12, no. 9, p. 1630, Apr. 2019, doi: 10.3390/en12091630.

[55] Z. Yi and A. H. Etemadi, "Line-to-line fault detection for photovoltaic arrays based on multiresolution signal decomposition and two-stage support vector machine," *IEEE Trans. Ind. Electron.*, vol. 64, no. 11, pp. 8546–8556, Nov. 2017, doi: 10.1109/tie.2017.2703681.

[56] W. Chine, A. Mellit, A. M. Pavan, and V. Lughi, "Fault diagnosis in photovoltaic arrays," in *Proc. Int. Conf. Clean Elect. Power (ICCEP)*, Taormina, Italy, 2015, pp. 67–72, doi: 10.1109/ICCEP.2015.7177602.

[57] W. Wang, A. C.-F. Liu, H. S.-H. Chung, R. W.-H. Lau, J. Zhang, and A. W.-L. Lo, "Fault diagnosis of photovoltaic panels using dynamic current-voltage characteristics," *IEEE Trans. Power Electron.*, vol. 31, no. 2, pp. 1588–1599, Feb. 2016, doi: 10.1109/TPEL.2015.2424079.

[58] Andrianajaina, Sambatra, D. Razafimahefa, and N. Heraud, "PV fault detection using the least squares method," in *Proc. IEEE Eur. Conf. Power Electron. Appl.*, Oct. 2016, pp. 871–876.

[59] E. Garoudja, F. Harrou, Y. Sun, K. Kara, A. Chouder, and S. Silvestre, "Statistical fault detection in photovoltaic systems," *Sol. Energy*, vol. 150, pp. 485–499, Jul. 2017, doi: 10.1016/j.solener.2017.04.043.

[60] M. Dhimish and V. Holmes, "Fault detection algorithm for grid-connected photovoltaic plants," *Sol. Energy*, vol. 137, pp. 236–245, Nov. 2016, doi: 10.1016/j.solener.2016.08.021.
[61] M. Dhimish, V. Holmes, B. Mehrdadi, and M. Dales, "Multi-layer photovoltaic fault detection algorithm," *High Voltage*, vol. 2, no. 4, pp. 244–252, Dec. 2017, doi: 10.1049/hve.2017.0044.
[62] O. Hachana, G. M. Tina, and K. E. Hemsas, "PV array fault DiagnosticTechnique for BIPV systems," *Energy Buildings*, vol. 126, pp. 263–274, Aug. 2016, doi: 10.1016/j.enbuild.2016.05.031.
[63] X. Xu, H. Wang, X. Xu, and Y. Zuo, "Method for diagnosing photovoltaic array fault in solar photovoltaic system," in *Proc. Asia–Pacific Power Energy Eng. Conf.*, Wuhan, China, vol. 2011, pp. 1–5, doi: 10.1109/APPEEC.2011.5747701.
[64] J. SolÓrzano and M. Egido, "Automatic fault diagnosis in PV systems with distributed MPPT," *Energy Convers. Manage.*, vol. 76, pp. 925–934, Dec. 2013, doi: 10.1016/j.enconman.2013.08.055.
[65] S. Silvestre, M. A. D. Silva, A. Chouder, D. Guasch, and E. Karatepe, "New procedure for fault detection in grid connected PV systems based on the evaluation of current and voltage indicators," *Energy Convers. Manage.*, vol. 86, pp. 241–249, Oct. 2014, doi: 10.1016/j.enconman.2014.05.008.
[66] Y. Hu, J. Zhang, W. Cao, J. Wu, G. Y. Tian, S. J. Finney, and J. L. Kirtley, "Online two-section PV array fault diagnosis with optimized voltage sensor locations," *IEEE Trans. Ind. Electron.*, vol. 62, no. 11, pp. 7237–7246, Nov. 2015, doi: 10.1109/tie.2015.2448066.
[67] M. Davarifar, A. Rabhi, A. El Hajjaji, and M. Dahmane, "New method for fault detection of PV panels in domestic applications," in *Proc. 3rd Int. Conf. Syst. Control*, Algiers, Algeria, 2013, pp. 727–732, doi: 10.1109/ICoSC.2013.6750940.
[68] M. Dhimish, V. Holmes, B. Mehrdadi, and M. Dales, "Simultaneous fault detection algorithm for grid-connected photovoltaic plants," *IET Renew. Power Gener.*, vol. 11, no. 12, pp. 1565–1575, Oct. 2017, doi: 10.1049/iet-rpg.2017.0129.
[69] K. U. Rao, A. G. Parvatikar, S. Gokul, N. Nitish, and P. Rao, "A novel fault diagnostic strategy for PV micro grid to achieve reliability centered maintenance," in *Proc. IEEE 1st Int. Conf. Power Electron., Intell. Control Energy Syst. (ICPEICES)*, New Delhi, India, Jul. 2016, pp. 1–4, doi: 10.1109/ICPEICES.2016.7853546.
[70] N. L. Georgijevic, M. V. Jankovic, S. Srdic, and Z. Radakovic, "The detection of series arc fault in photovoltaic systems based on the arc current entropy," *IEEE Trans. Power Electron.*, vol. 31, no. 8, pp. 5917–5930, Aug. 2016, doi: 10.1109/tpel.2015.2489759.
[71] S. Chen and X. Li, "PV series arc fault recognition under different working conditions with joint detection method," in *Proc. IEEE 62nd Holm Conf. Electr. Contacts (Holm)*, Clearwater Beach, FL, USA, Oct. 2016, pp. 25–32, doi: 10.1109/HOLM.2016.7780002.
[72] H. Zhu, Z. Wang, and R. S. Balog, "Real time arc fault detection in PV systems using wavelet decomposition," in *Proc. IEEE 43rd Photovoltaic Spec. Conf. (PVSC)*, Portland, OR, USA, Jun. 2016, pp. 1761–1766, doi: 10.1109/PVSC.2016.7749926.
[73] Q. Xiong, S. Ji, L. Zhu, L. Zhong, and Y. Liu, "A novel DC arc fault detection method based on electromagnetic radiation signal," *IEEE Trans. Plasma Sci.*, vol. 45, no. 3, pp. 472–478, Mar. 2017, doi: 10.1109/tps.2017.2653817.
[74] K. A. Kim, G.-S. Seo, B.-H. Cho, and P. T. Krein, "Photovoltaic hot-spot detection for solar panel substrings using AC parameter characterization," *IEEE Trans. Power Electron.*, vol. 31, no. 2, pp. 1121–1130, Feb. 2016, doi: 10.1109/tpel.2015.2417548.
[75] Y. Mahmoud and E. El-Saadany, "Fast reconfiguration algorithm for improving the efficiency of PV systems," in *Proc. 8th Int. Renew. Energy Congr. (IREC)*, Amman, Jordan, Mar. 2017, pp. 1–5, doi: 10.1109/IREC.2017.7925993.
[76] H. Mekki, A. Mellit, and H. Salhi, "Artificial neural network-based modelling and fault detection of partial shaded photovoltaic modules," *Simul. Model. Pract. Theory*, vol. 67, pp. 1–13, Sep. 2016, doi: 10.1016/j.simpat.2016.05.005.
[77] A. Belaout, F. Krim, and A. Mellit, "Neuro-fuzzy classifier for fault detection and classification in photovoltaic module," in *Proc. 8th Int. Conf. Modelling, Identificat. Control (ICMIC)*, Algiers, Algeria, 2016, pp. 144–149, doi: 10.1109/ICMIC.2016.7804289.
[78] J.-M. Huang, R.-J. Wai, and W. Gao, "Newly-designed fault diagnostic method for solar photovoltaic generation system based on IV-curve measurement," *IEEE Access*, vol. 7, pp. 70919–70932, 2019, doi: 10.1109/access.2019.2919337.

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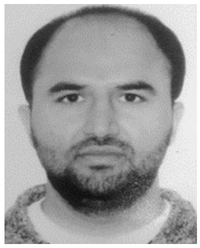

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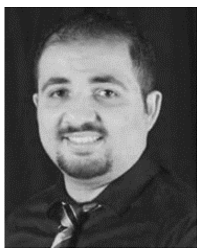

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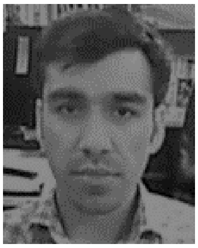

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