Detection, location, and diagnosis of different faults in large solar PV system—a review

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Abstract

Over the past decade, the significance of solar photovoltaic (PV) system has played a major role due to the rapid growth in the solar PV industry. Reliability, efficiency and safety of solar PV systems can be enhanced by continuous monitoring of the system and detecting the faults if any as early as possible. Reduced real time power generation and reduced life span of the solar PV system are the results if the fault in solar PV system is found undetected. Therefore, it is mandatory to identify and locate the type of fault occurring in a solar PV system. The faults occurring in the solar PV system are classified as follows: physical, environmental, and electrical faults that are further classified into different types as described in this paper. Once a fault is located and detected, an appropriate diagnosis method needs to be used to rectify it. In this paper, a comprehensive review of diverse fault diagnosis techniques reported in various literature is listed and described. This paper helps the researchers to get an awareness of the various faults occurring in a solar PV system and enables them to choose a suitable diagnosis technique based on its performance metrics to rectify the fault occurring in solar PV systems.

Keywords: diagnosis techniques; different fault; PV system

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1 INTRODUCTION

The increase in industrial expansion and energy consumption leads to a rise in global power demand per capita. For the past decade, conventional energy sources (CES) were used to meet this increasing demand. But the main drawbacks of using CES to meet the demand are: increasing cost of generation, depletion of available resources and environmental concerns i.e., emission of various gasses, which leads to global warming. These drawbacks of CES created a necessity of using renewable energy sources (RES) like solar, wind, hydro, tidal, biomass and geothermal, because of their advantages like safer and environmental friendliness in meeting the demand [1, 2]. The main objective of various renewable energy technologies is to convert RES into the electrical power so that it can be injected into the power grid to meet the consumer demands. Among all the available RES, solar PV system is considered as the finest method to convert environmental energy into electrical power due to its endless and environmentally friendly advantages [3]. According to the survey, the power generated from solar photovoltaic (solar PV) systems installed globally by the end of the year 2019 is 633 GWp in which installation in India is about 35.06 GWp.

Despite its various advantages, as the solar PV system are exposed to harsh environmental conditions due to its installation in outdoor environment, the optimal efficiency of the system drops down to 15% to 20% [4]. Authors in [5] have reported that the solar PV system suffers an annual degradation rate of 0.923% when it is operated at harsh environmental conditions. In addition, the efficiency drop in a solar PV system is because of the effect of various kinds of faults and failures, which the system suffers. According to the test results conducted in 2010, the annual power loss in the solar PV system is about 18.9% due to its faults and failures [6]. Therefore, like any system that produces electrical energy, this sensitive solar PV system requires monitoring and supervision control to detect, classify and diagnose the fault that may occur to reduce the losses and thereby ensure the proper functioning of the system.

The general block diagram of the solar PV monitoring system is shown in Figure 1. The objective of the solar PV monitoring system is to analyze all the possible data, which affects the performance of solar PV system in real time and to give the correct information about the that occurred in the solar PV system. For the past few years, there has been a rise in the interest in this system. Hence, the different researchers have dedicated their work to developing cost effective, low cost, and viable solar PV monitoring systems without compromising on the desired performance [7]. Hence, to identify the correct type of fault that can occur in the solar PV system, it is necessary to understand all possible types of faults that may occur in it. This paper presents an overall idea about the various faults occurring in the system. In addition, the effect of various faults on the operation of solar PV panel's willbe discussed.

Once the fault is detected in the solar PV system, based on the type of fault an appropriate diagnosis technique should be used to rectify it. Since there is an increase in interest in solar PV monitoring systems, many researchers have developed their own technique to rectify the fault occurring in solar PV systems. This paper focuses on various techniques available in the literature to rectify the fault occurring in solar PV systems. Further, a comparative study on different diagnosis techniques used in the detection of faults in solar PV systems will be discussed. In addition, the strengths and limitations of the different diagnosis techniques will be analyzed, along with their challenges.

The paper is organized as follows: section 2 provides an overview of the modeling of solar PV systems along with their subcomponents to understand their behavior. Section 3 addresses the various faults that can occur in solar PV systems along with their sources. Various diagnosis techniques in rectifying the different faults presented in section 3 are presented in Section 4. Finally, section 6 includes a summary and conclusion of this work.

2 MODELING OF PV SYSTEM

Solar cells are semiconductors with a p-n junction fabricated in the form of thin wafers. When solar radiation falls on these cells a photo current proportional to the radiation is generated when the energy of the photon is greater than the band gap energy of the semiconductor material.

In order to predict the behavioral patterns of the PV system under different atmospheric conditions, modeling the system is essential. There are various types of modeling designs available for different needs. The most opted modeling design is the one-diode model. As the design is simple and as the speed in calculating the values of modeling parameters is faster this model is preferred over the others. One of the major advantages of using one-diode model is that it gives minimum error in its I-V curve and P-V curve analysis.

2.1. The one-diode model:

Many PV cells that produce an electric current when irradiated with light are combined to form a PV module. The energy produced in a PV generator comes from this PV module. A bypass diode, which prevents the cells from acting like receivers, is connected between each series of cells in a PV module. The diode also prevents the cells from heating up during the period of partial illumination in turn preventing losses and increasing the efficiency of the module. The solar cell here can be treated as a photo generating current source connected in a shunt across a diode [10]. The resistance characteristics show that there is a recombination of charge carriers at the junction region due to the series of internal resistance. The one diode model of the PV cell is shown in Figure 2.

The PV cell can be perceived as a current source connected in a shunt across a diode. It exhibits exponential characteristics like that of a p-n diode.

The expressions for output current voltage and power are given below [8, 11].

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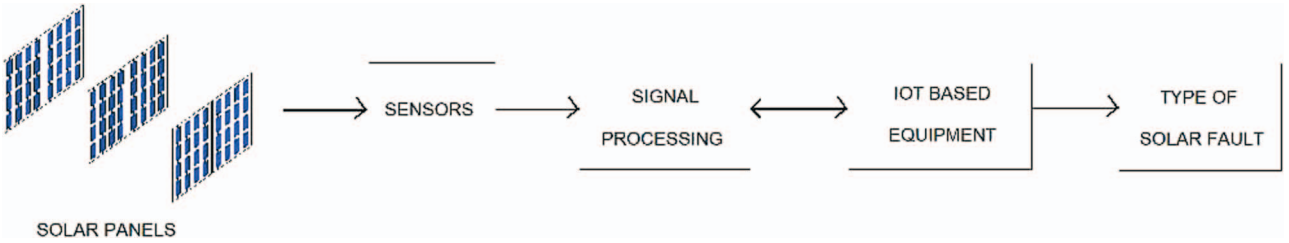

Figure 1. *General block diagram of solar PV monitoring system*

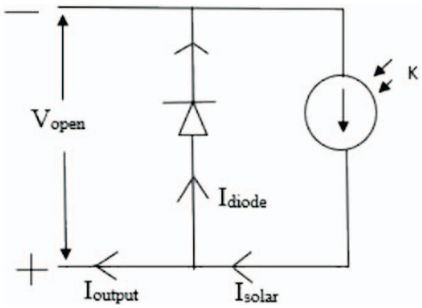

Figure 2. *PV cell as a current source*

The output current produced by the solar cell is given by Eq (1)

$$I_{output} = I_{solar} - I_{rb}\left(\exp^{\frac{qV}{akT}} - 1\right) \tag{1}$$

The corresponding open circuit voltage (V_{open}) and Output power (P_{out}) is given by Eqn. (2) and Eqn. (3) respectively.

$$V_{open} = \frac{akT}{q} lnln\left(\frac{(I_{solar} - I_{output})}{I_{rb}}\right) \tag{2}$$

$$P_{out} = V_{open}\left[I_{solar} - I_{rb}\left(\exp^{\frac{qVopen}{akT}} - 1\right)\right] \tag{3}$$

Consider a PV cell with series and shunt resistance whose equivalent circuit in one diode model is shown in Figure 3. In this type of PV model has five parameters (R_{series}, I_{shunt}, R_{shunt}, m, I_{solar}) [12, 13].

Using the basic laws of electric circuits, we get.

$$I_{solar} = I_{diode} + I_{shunt} + I_{output}$$

$$I_{output} = I_{solar} - I_{diode} - I_{shunt}$$

$$I_{output} = I_{solar} - I_{rb}\left[\exp\left\{\frac{q\left(V_{open} + I_{output}R_{series}\right)}{akT}\right\} - 1\right] - \frac{V_{open} + I_{output}R_{series}}{R_{shunt}} \tag{4}$$

Equation (4) represents the output current obtained by utilizing a single solar cell. Practically a PV module consists of N number of solar cells connected in series to increase the power. The output current produced by N number of solar cells connected in series can be calculated by using the following equation

$$I_{output} = I_{solar} - I_{rb}\left[\exp\left\{\frac{q\left(NV_{cell} + I_{output}NR_{series}\right)}{NakT}\right\} - 1\right] - \frac{NV_{cell} + I_{output}NR_{series}}{NR_{shunt}} \tag{5}$$

The different variables presented in the above equation are: K is the solar radiance, I_{output} is the output current in Amperes, I_{solar} represents photo generated current in Amperes, I_{rb} denotes the reverse bias saturation current in Amperes, I_{diode} refers to the diode current in Amperes, V_{open} represents the terminal/output voltage in Volts, P_{out} denotes the output power in Watts, $R_{series}$is the series internal resistance of the cell in ohms, R_{shunt} is the shunt internal resistance of the cell in ohms, q = 1.6 × 10^{-19} which represents the charge of one electron in Coloumb, 'a' signifies diode's ideality factor, k = 1.38 × 10^{-23} J/K known as the Boltzmann constant, T indicates the cell's temperature in degree celsius. N represents the number of cells connected in series and V_{cell} represents the output voltage produced by a single solar cell in volts.

3 PV FAULTS

PV arrays/cells are very fragile devices. These devices must be installed in an open atmosphere where there is solar radiation available most of the time. Being installed in the open surrounding, the cells face a lot of environmental and physical stress throughout the year. These factors may cause physical damages (like cracks, corrosion, delamination, etc) to the cells, due to which their efficiency gets reduced. The PV cells are very sensitive to light. They can produce current if they are irradiated by the solar radiation, without solar radiation they cannot produce any current. Due to various factors, if some parts of the array get shaded, there will be a huge mismatch in the IV characteristics. This mismatch can cause a rise in temperature, which can cause great damage to the cells. Apart from the faults occurring due

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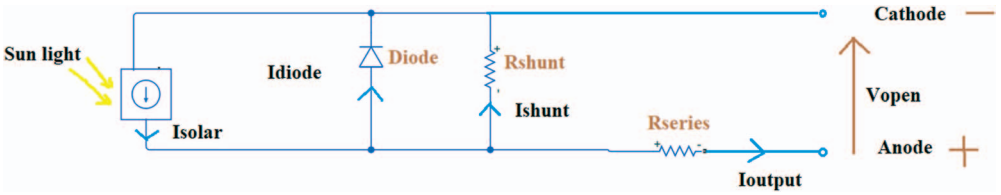

Figure 3. *Solar PV cell with series and shunt resistance*

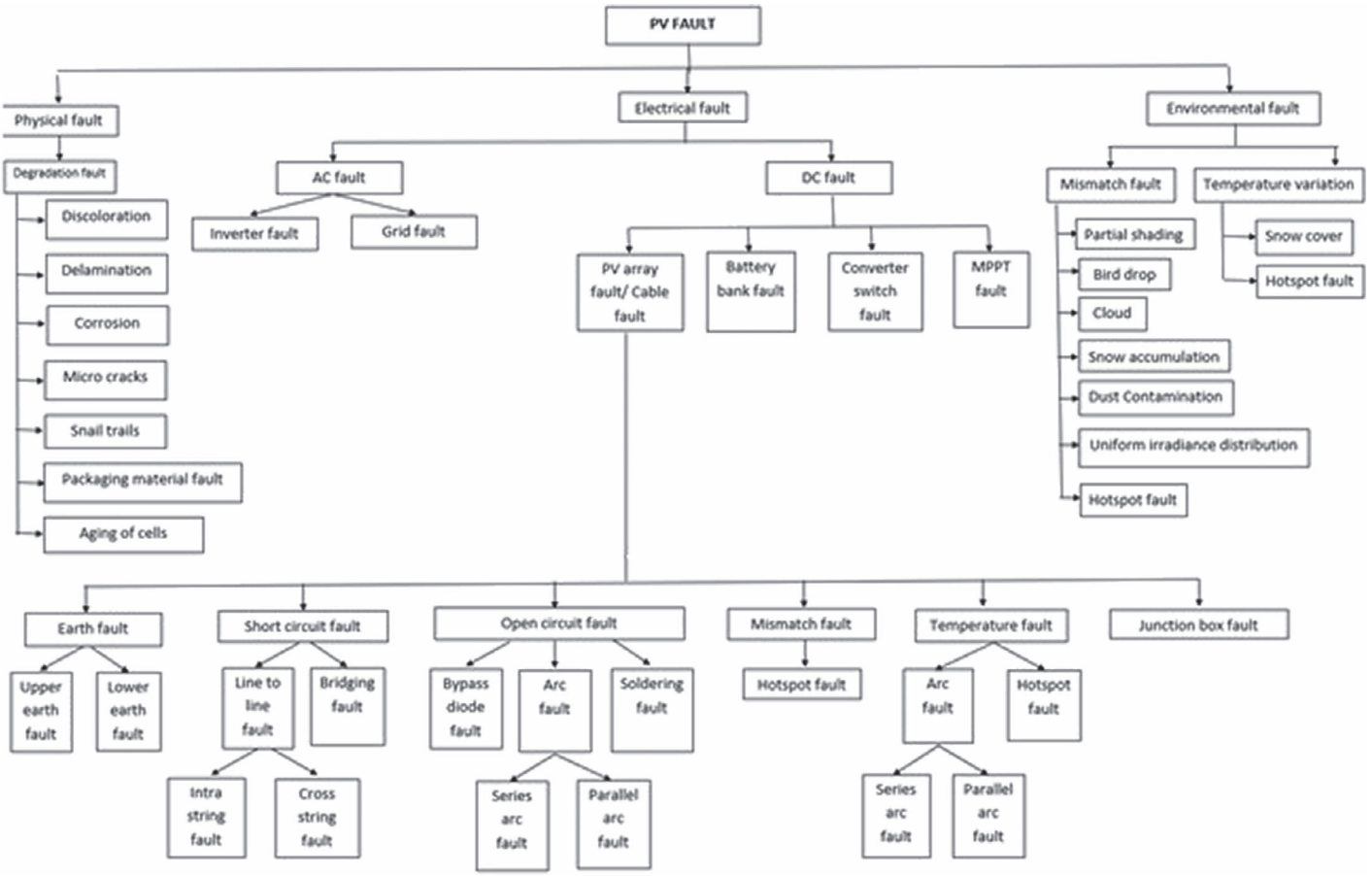

Figure 4. *Classification of solar PV faults*

to environmental and physical factors, electrical faults are also very common in PV systems. Most of electrical faults are caused mainly due to improper or loose connections of conductors or poor soldering between joints.

The various classes of faults occurring in the PV system cause a dip in the efficiency and thereby reducing the resultant power. These errors when left unnoticed may result in the wastage of power and decreased performance of the system, so it becomes necessary to identify and set them right to avoid any dangerous situation and to obtain a better-quality output. Predictive maintenance and proactive fault identification and correction are indispensable for an efficient operation of the system. The different types of faults that can exist in a solar PV system are shown in Figure 4.

3.1. Physical faults

Most of the physical faults in PV arrays, like degradation, encapsulation, cracks, corrosion occur either due to some mechanical stress or because of the nature of the material used in its manufacturing. Use of materials that are tough and resistant to corrosion can increase the lifetime of PV arrays and can also reduce the probability of occurrence of mechanical faults.

A. DEGRADATION FAULT:

The degradation of the solar cells may lead to increase in series resistance, decrease in parallel resistance and deterioration of the anti-reflection coating which may result in brightening of color of cells and can affect the photogenerated current [14]. The resultant power is almost reduced to half of the expected value due to this

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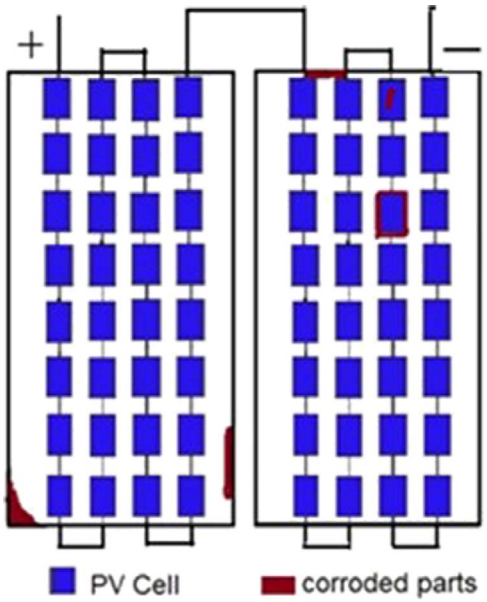

Figure 5. *Corrosion in the solar PV array*

degradation fault. This section 3.1.1 will deal with the different faults related to degradation fault.

B. **ENCAPSULATION FAILURE:**

Encapsulation failure is caused by Delamination or Discoloration of the PV module. The main reason for this defect is accumulation of salts, penetration of moisture and other external factors [8].

a) **DISCOLORATION:**

Discoloration of PV cells can be easily detected with our naked eyes. In this type of fault, we can observe that the white color of PV material changes to yellow or brown [15, 16], thereby reducing the intensity of light falling on the solar cells. This may lead to rising temperature because of which enormous may incur in the performance of the PV system. Some of the main causes of discoloration are thermal stress, exposure to UV light, accumulation of gasses or acids in between layers, corrosion of metallic contacts etc.

b) **DELAMINATION:**

Delamination is the occurrence of gaps or detachment between successive layers (between glass-encapsulant or encapsulant-cell or cell-encapsulant or encapsulant-back sheet) of the module, due to poor adhesion. Delamination of PV module causes increased light reflection (instead of absorption), moisture or gas penetration, which may lead to the occurrence of series of many other defects [15].

C. **CORROSION:**

Delamination or cracks in the encapsulation can cause moisture penetration into the module, which can lead to corrosion

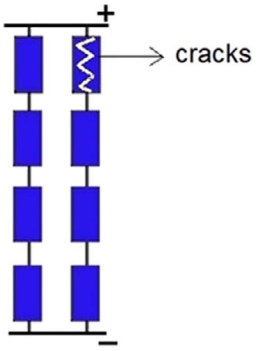

Figure 6. *Crack in solar PV panel*

of PV material. Metal contacts attached to the base of the cell, silver fingers present on top of the cell can get corroded easily if exposed to atmospheric oxygen, Sulfur, carbon-dioxide, and other corrosive gasses [17]. The damage caused in the PV panel due to the corrosion fault has been shown in Figure 5. Corrosion of metallic contacts can cause leakage current to flow in the system [8], and corrosion of conducting wire can increase its resistance, which can eventually lead to extremely high-power loss.

D. **CELL CRACKS:**

Cracks developed in the silicon substrate of the PV module are called cell cracks as shown in Figure 6. Apart from the silicon substrate, cracks may also occur in different layers of cell's lamination. Sometimes these cracks are very small (also called micro-cracks) that they cannot be seen with naked eyes, hence their detection can be done by Electroluminescence imaging. Some of the main reasons for occurrence of crack listed in [8, 18] are: mechanical stress while manufacturing, transportation or installation, shocks that may occur during the transportation, manufacturing defects, mishandling while packaging, aging of cells, High temperature and Hailstorms, snow cover, wind, rain.

E. **SNAILTRAILS:**

Snail trails are discoloration of silver fingers due to formation of silver carbonate nanoparticles (Ag2CO3) [18, 19]. Snail trails are formed due to the reaction of silver with carbon dioxide and moisture. These gasses can easily enter through cracks hence snail trails are mostly found near cell cracks and cell edges [18].

F. **PACKAGING MATERIAL FAULT:**

Unnecessary pressure applied during the packaging of PV cells may result in cracks on the cell. Any fault during manufacturing or packaging may reduce the output power of the PV cells.

G. **AGING OF CELLS:**

The average life expectancies of a PV system are about 30 years. As the cells become older many other defects like discoloration, delamination, cracks etc. may occur, which can lead to hotspots thereby reducing the cell efficiency.

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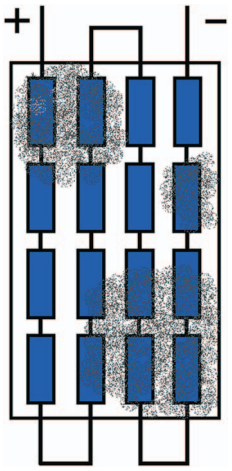

Figure 7. *Partial shadowing due to trees*

Figure 8. *Partial shading due to soiling*

3.2. Environmental faults:

Many environmental factors like the weather, solar radiation, shading conditions, temperature, etc. affect the working of PV array. These factors can cause severe damage to the cells that can or cannot be reversed. In this section the different types of environmental faults are described in this section.

A. MISMATCH FAULT:

When the electrical factors are altered considerably, for instance, when the cell's IV traits differ from each other, there arises a discrepancy in PV modules. These faults can cause permanent damage to panels and hence, a very high drain on power as a result. According to the researchers in [20], there are two kinds of mismatch faults: (i) temporary mismatch fault that occurs due to partial shading and temperature variation, which cause a change in open circuit voltage; and (ii) permanent mismatch fault that occurs due to cracks, hotspots or fault in soldering or degradation of cells. Overall output power gets reduced considerably. [20, 21]

B. PARTIAL SHADOWING:

Partial shading happens where a part of the module is slightly shadowed and thereby reducing the output power of the system. During partial shading, the shaded cells act as power dissipaters instead of power sources; this may raise the temperature of the cell. Hence, shaded cells serve as resistance. They result in hot spots, which can cause serious harm to the PV array. The major reasons for partial shading are: Bird drop, shading because of buildings and trees, leaves, Shading due to clouds, Snow cover, Dust contamination and Uniform irradiance distribution. Figures 7 and 8 indicate the partial shadowing in solar PV systems.

C. SNOW COVER:

During winter the Solar cells get covered by layers of snow. If not removed immediately, the cells experience partial shading for a long time which may lead to mismatch fault. Due to Mismatch in the IV characteristics the temperature of the cells increases which eventually leads to the formation of hotspots. The surface characteristics of the PV modules are greatly affected by the deposition of snow [22, 23]. The partial shadowing of solar PV panel due to snow is shown in Figure 9.

D. HOTSPOT FAULT:

Hotspot faults are also categorized as a type of temperature fault as it creates regions having relatively higher temperatures when compared with the overall panel. A few places have heat concentrated in them and have IV characteristics different from all the other panel regions. It is primarily because of the defective cell structures or the partly shaded panels. When the parameters are not perfectly mapped from the feeding side to the output side, there is a mismatch is created which in turn causes the localized heating on the surface of the panel. The hotspot fault has been illustrated in Figure 10. Hotspot heating happens when the value of the current during the operating period goes beyond the specified value of the current during a short circuit in the cells which are found to be faulty. The severity of the Hotspot fault depends on the mismatch level and duration. The occurrence of this fault can be mapped to various causes like aging, accumulation of dust, soil, snow, and some other agents on the surface of the panel. The hotspots created because of all the above said causes contributes to the hotspot faults. [24–27]

3.3. Electrical fault

The faults occurring in the connections between conductors, shorted circuits, faults due to the circuits which get opened and faults in the electrical appliances and measuring devices are all classified as electrical faults.

3.3.1. *Ac faults:*

Faults occurring on that side of the PV system where the alternating current circuit is present, which includes the grid of the distribution set up and the inverter, come under AC faults. Grid

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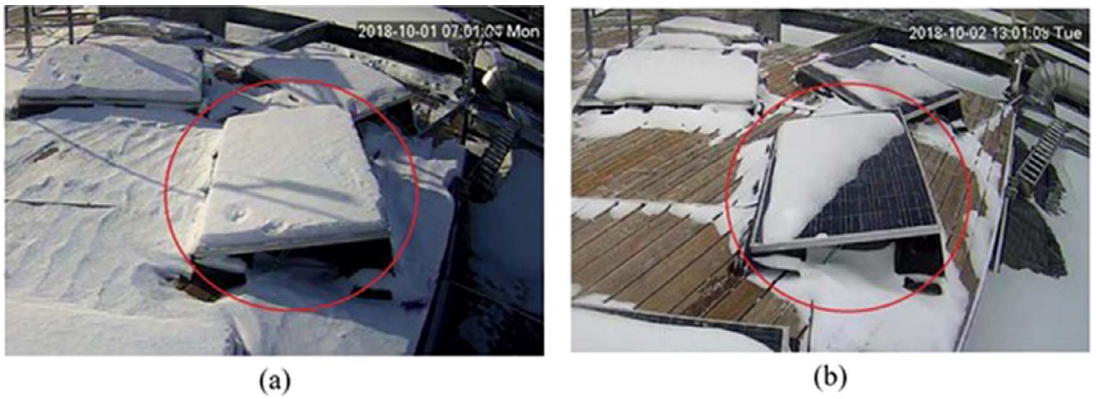

Figure 9. *Solar PV panel (a) full covered (b) partially covered due to snow*

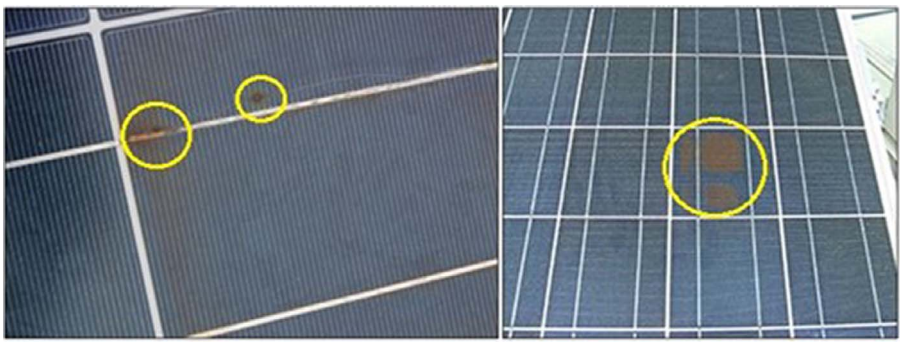

Figure 10. *Damaged cells due to hotspot fault*

and Inverter faults which comes under the category of AC faults is discussed below.

A. GRID FAULT

In a grid connected PV system the PV array output is connected in parallel with the power distribution system or the grid, through an inverter. During power failure in the utility grid, the PV output must be cut off from the grid, so that there is no flow of power from the PV system into the grid. Faults occurring in PowerStation, loose connection or damage in the transmission line, blackout, overloading etc. come under grid fault [20].

B. INVERTER FAULT

The output current produced by the PV array is DC in nature. This DC current of PV output is fed to the inverter which converts it into AC of the required frequency. The main reasons for invertor fault are improper installation, uncontrolled voltage current and enormous amount of load power [28]. Grid tied solar inverters play a major role in disconnecting the PV System from the grid during grid fault. This is done for safety reasons. The inability of inverters to perform this action can pose threat to the grid workers.

3.3.2. *Dc faults*

The different kinds faults that come under the category of DC faults are the: maximum power point tracker (MPPT) fault, battery bank fault, and PV array fault.

A. MPPT FAULT

Maximum PowerPoint tracker (MPPT) maximizes the power fed to the inverter from the PV array. It is basically an algorithm, included in the charge regulator, which extracts maximum power from the PV module under certain conditions. A malfunctional charge regulator may affect the working of MPPT. Any fault in MPPT reduces the output power and the output voltage [20].

B. BATTERY BANK FAULT

Solar cells can produce current if they are irradiated with solar radiation. To ensure continuous supply to the load, even when solar energy is not available, battery banks are used. The output of the PV array is connected to batteries which are charged during the day time and supply the load during the night time. Sometimes these batteries can become faulty and the main reason for this is abnormal charging conditions.

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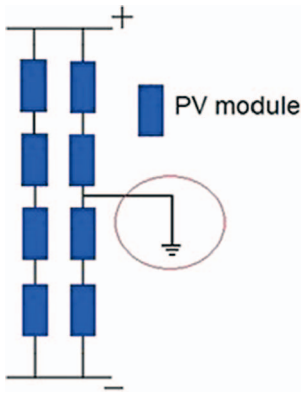

Figure 11. *Short circuit between the PV module and the ground*

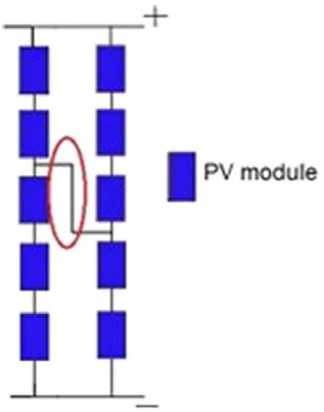

Figure 12. *Line to line fault*

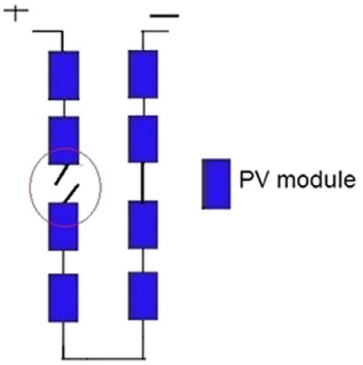

Figure 13. *Open circuit fault*

C. PV ARRAY FAULT

The seven types of PV array faults which are discussed in the following section are: Earth fault, Line-to-Line fault, Bridging fault, Open circuit fault, Arc fault, Bypass diode fault and Junction box fault.

(i) EARTH FAULT

Earth fault or ground fault is a type of short circuit fault which is shown in Figure 11. It happens when a circuit generates an accidental route to the ground [20]. To safeguard the customer or user from potential electrical shock and other hazards, every non-conducting metal is connected to the earth or grounded. When these non-conducting metals encounter the current carrying conductors, a massive number of current passes through them and then into the ground [9]. In the PV array, the mismatch fault is caused by the enormous rise in the current flowing through the non-current carrying conductors. This fault is known as the ground fault. They are of two kinds, i.e. lower earth fault and upper earth fault.

(ii) LINE TO LINE FAULT:

The line-to-line fault in a PV array as shown in Figure 12 occurs due to an accidental short circuit between two varying potentials or sometimes between array cables. This fault occurs in two ways with respect to its position, when within the same string, it is called intra string fault and when within neighboring strings, it's called cross string fault. There is a change in the VI plot of a PV system due to voltage reduction [24].

(iii) BRIDGING FAULT:

The bridging fault occurs when a connection of low resistance happens between PV modules. These faults are caused by physical damage, corrosion, or insulation failure of cables and, lead to voltage decline and current swings. The line-to-line fault is often termed as bridging fault when it has zero fault impedance [20, 29].

(iv) OPEN CIRCUIT FAULT:

When the line that carries the current and is connected in series manner with the load is removed from the circuit or disconnected then, an open circuit fault occurs. The predominant factor which causes this fault is the improper or loose plugging or connections between the various component of the system. The open circuit fault occurring in the PV panel is shown in Figure 13. Due to the open-circuit fault, short-circuit current and highest value power output generated decreases with the increase in the number of disconnected strings and the voltage is maintained almost close to the normal value [13, 15].

(v) ARC FAULT:

Arc faults are primarily due to the complex combination of connecting structures used in the circuitry for holding together various series and parallel combinations of component connections. The illustration of the arc faults is shown in Figure 14. When the joints that are soldered have an improper connection or when there are faulty connections or loose connections between the components or when the failure of insulators used in the circuitry occurs it results in various arc faults. Due to arc fault very, high temperature is reached. This results in the materials that are prone to combustion getting exposed to the arc. When proper precautions are not taken, arc faults can result in fire accidents

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as the arc ionizes the air resulting in plasma discharge which initiates fire [9, 30–32]. The arc fault is further classified as series arc and parallel arc faults. Due to the existence of an extremely high potential difference in parallel arc fault, a large current is drawn in shunt arc fault as compared to series arc fault [24, 33].

(vi) **BYPASS DIODE FAULT:**

There is a shunt connection between a selected few cells in the PV panel and the bypass diodes. Under normal conditions (i.e., when the cells are not shaded), no current flows through the diode. During partial shading, the shaded cells act as power dissipaters instead of power sources; this may raise the temperature of the cell. To prevent the shaded cells from behaving like resistors, the parallel connection of the components and the bypass diodes is inevitable. The after effects of the shading problem are set right using bypass diodes [34]. When the PV cell is shaded, these bypass diodes provide a path for the current to flow thereby preventing the heating up of PV cells.

When the bypass diode that is used is a faulty one it may lead to the formation of hotspots due to the accumulation of heat caused due to the defective component and shading problem [15]. The high temperature due to a fault in the bypass diode can cause fire and damage the PV array. Therefore, an antiparallel connection of the diode becomes the solution to one problem and it may end up being the problem by itself when the component used is a defective one [15, 34].

(vii) **JUNCTION BOX FAILURE:**

Energy loss from the system is one of the major reasons for junction box failure. Burnt bypass diode, improper connections can also lead to a fault in junction box [9].

4 FAULT IDENTIFICATION METHODS

4.1. Statistical method

In this section the different statistical method used by various researchers in determining the different types of faults is discussed.

4.1.1. *K nearest neighbor method (KKN):*

K nearest neighbor is an algorithm used to find and classify string connected faults in the PV system. Open circuit faults, partial shading and line to line faults can be corrected using this algorithm [35].

4.1.2. *Exponentially weighted moving average method (EWMA):*

In this method various electrical parameters like current, voltage and power under different insolation and temperature are noted for a non-defective cell. These parameters are then compared with that of a faulty cell. The difference in the values of these parameters for an ideal and faulty cell is used as a fault indicator. The type of fault is then identified using the EWMA chart [35].

4.1.3. *Univariate and multivariate exponentially weighted moving average (EWMA):*

Like the EWMA method univariate and multivariate EWMA chart is used to determine the faults. The approach to detection and diagnosis of the fault is also like that of the EWMA method. The only difference is that the multivariate EWMA can identify the type of fault only after utilizing the univariate EWMA scheme [35].

4.1.4. *Multiscale-weighted generalized likelihood ratio test method (MS-WGLTR):*

The chief objective of the MS-WGLTR technique is to lessen the probability of missed-identification of faults or false alarms in the PV system. This method is also used for the monitoring and detection of faults.

4.1.5. *Statistical t-test*

The statistical t-test is based on statistical methods, by taking into consideration the environmental and electrical parameters and is used for automated detection and fault diagnosis. The faults in the PV panel, PV string and MPPT controller can be effectively identified using this method. The detection of fault is done by comparing the ideal and measured parameters. Any difference in measured and ideal values indicate the presence of a fault. The measured and ideal values of the DC power to voltage ratio help us find the location of a fault [35].

4.2. Intelligent techniques

4.2.1. *Kernel based extreme learning machine (KELM):*

KELM is an enhanced model of ELM that is well-defined, good in quality, has a considerably rapid learning pace and ensures better performance. This KELM model uses a vector that is intended to be the input for the fault detection model. PV array is likely to have common faults like partial shading, aging and short-circuited that can be identified using this technique. The Nelder–Mead Simplex method improves the parameters of KELM and improves accuracy [35].

4.3. Hybrid computational technique

4.3.1. *Adaptive neuro-fuzzy inference system (ANFIS):*

ANFIS is a composite model that comprises the computing systems inspired by the biological neural design which is also referred to as the artificial neural network (ANN) and Fuzzy logic system. ANN can learn and predict values for different sets of data inputs and on the other hand fuzzy logic has reasoning and computational capability. Therefore, the ANFIS method contributes goods of both the techniques to settle an efficacious model for the detection and classification of faults in the PV system [35].

4.3.2. *Radial base function—Kernel extreme learning machine (RBF-KELM):*

RBF-KELM model operates on the principle of the algorithm based on simulated annealing technique which is a single solution

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algorithm which tries to build the entire solution to the specified fault or problem from one fundamental solution by improving it in consecutive steps. The simulated annealing algorithm is used to obtain a solution which is optimized in all dimensions. This technique has proven to be useful in detecting and classifying the variety of faults occurring in the PV module with greater efficiency. [36, 37]

4.4. Other simulation methods

4.4.1. *Local outlier factor method (LOF):*

The local outlier factor algorithm is a comparative technique used in fault detection and analysis. It identifies the fault occurrence by fetching the datapoints and performing the comparison between the value under observation and its neighboring values. The faulty strings are identified with precision since the string currents are varying parameters. This factor of the localized strings is continuously calculated. One can detect a defect with the knowledge of string values and the threshold value, when the measured value of the string is more than the threshold limit then a fault is said to have occurred. Environmental faults and electrical faults like shading faults and open circuit and short circuit faults are accurately predicted using this LOF algorithm. The LOF method has proved its versatility and is predominantly used to study large systems [35, 38, 39].

4.4.2. *Extension diagnosis method:*

The extension diagnosis expands the observation domain. The fuzzy logic is a multi-valued logic. Extension diagnosis expands the limit of the fuzzy set and allows for analyzing more data. The changes in the various observed values of the module are recorded. The observed values are processed and analyzed by the application of extension principles and matter element theory. The efficiency and accuracy of this method are phenomenal, [37, 39, 40].

4.4.3. *Nonlinear autoregressive exogenous neural network (NARX) and Sugeno fuzzy inference:*

This technique which operates on the fundamentals of nonlinear autoregressive exogenous neural networks and the principles of Sugeno's fuzzy inference system is primarily used to classify the various anomalous behavior of the cells in the PV panels. The NARX technique is particularly propitious in determining the time sequence [41]. The NARX system predicts the maximum power that can be produced by a PV module and determines the possible defects and faults that have a probability of occurrence. The above said NARX algorithm when operated on the fuzzy system can predict various faults such as partial shading and electrical faults such as those occurring due to disconnected strings that result in an open circuit and ground faults. To precisely predict the maximum power in the system various parameters including temperatures and other environmental factors are recorded and analyzed using this algorithm [41–43].

4.4.4. *The footprint method:*

The footprint algorithm is highly capable of detecting failure sources. This method first produces an error pattern by comparing the measured power output with that of the simulation value. This error pattern is then compared with the typical error pattern of selected system faults and the type of error detected. This method is used to detect minor energy loss due to partial shading or inverter malfunctioning [44].

4.4.5. *K-means algorithm:*

The K-means, a centroid-based machine learning algorithm, is used to find the faulty areas with greater accuracy from the thermal image of solar field. This algorithm works by dividing n observations into k clusters such that each observation comes under the cluster with the nearest mean [45].

Initially, the number of clusters k is determined followed by assuming the centroid and grouping such that each group contains objects with similar properties. Next, the distance between the object and the centroid is calculated. Subsequently, objects are grouped based on minimum distance. Coordinates of the new centroids are calculated. These steps are iterated until the centerC_k no longer changes. [45]

4.4.6. *Average Silhouette method:*

This method is centered on calculating the average silhouette of observations for unlike values of k. The silhouette value determines how well each object holds within its cluster which is the quality of clustering. The silhouette width (SW) is a validation index for an object to measure the number of clusters and varies from -1 to $+1$. The highest value pertains to the optimum number of clusters. A high average silhouette width specifies a good clustering [45].

4.4.7. *Ultrasonic inspection:*

The faults in the fielded modules are determined using this technique. The Ultrasonic inspection is grounded on the propagation of ultrasonic waves in the object being tested. Before PV module production, the transmitted waves are used to locate cracks, voids, and de-bonded lamination structures whereas after they are fielded, they are used to detect unbounded cells and degradation cracks in the module. This technique can be categorized into two methods. Initially, we got the transmission method, where the attenuation of the ultrasonic signal is measured, and the data coordinates of defects are logged. In addition, faults and their size are detected. Next, we got the pulse-echo method, high frequency sound energy is used to transmit through the materials. The ultrasonic pulses are reflected when there is a discontinuity or defect in the path. Here, apart from the data given before, we are additionally provided with the z-axis value. The causes of module degradation are determined by this method. The technical data provided aids with the manufacturers in enhancing the product reliability. In the methods discussed earlier, PV modules

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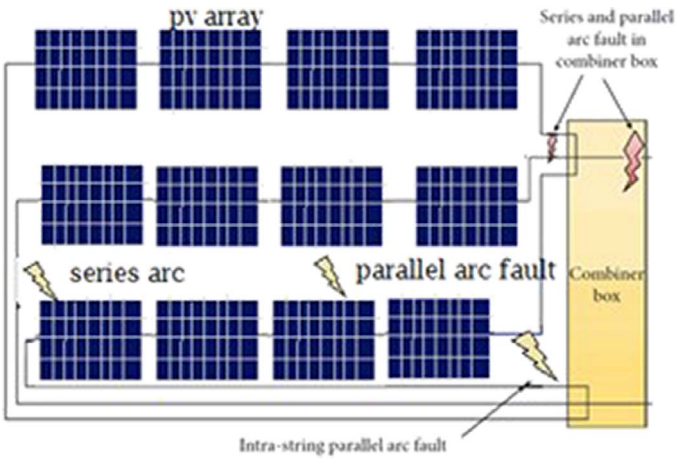

Figure 14. *Arc fault*

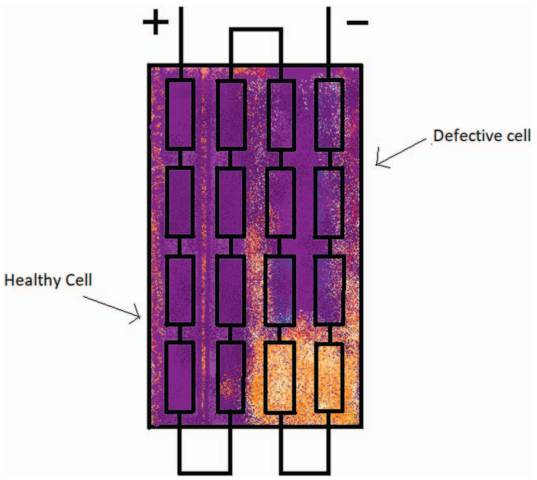

Figure 15. *Detection of faults using LIT technique*

combined with an x-y indicator are scanned with the help of a moving ultrasonic transducer [15].

4.4.8. *Electroluminescence imaging:*

Electroluminescence Imaging, a PV module characterization technique, is non-destructive and renders greater accuracy in fault detection, namely micro cracks, broken cell interconnections and shunts. It provides fast, real-time, and high image resolution, which enables the electrode imperfections to be evaluated more precisely. Solar cells with different conversion efficiency which occur due to an increase in cell series resistance and/or reduction in cell parallel resistance are identified using this technique. The electrical connections of solar cells and their quality are evaluated by the EL method [46].

EL method is expensive and can be conducted only offline. It is potentially limited to darkness i.e. usually practiced indoors or outdoors, when the sun's down. In this method, light is emitted by electrical excitation due to the recombination of holes and electrons and as the glow grows to be noticeable, the faults are exposed and therefore, the cell efficiency reduces at specific voltages [15, 47].

4.4.9. *Lock in thermography (LIT):*

The Lock-in thermography-based method of fault rectification and detection has proved to be extremely efficient in locating the position of hotspots or regions where the heat is concentrated in the various components that are present in the PV module and also helps to detect the loss of power occurring in the cells present in the panel. The technique makes use of an external device used to provide excitation in the form of current pulses of varied modulation that can be inserted into the system. This injected current pulse distinguishes the faulty areas by increasing their temperatures. The regions with higher regions are now assumed to be defective. The areas with defective shunt connections are recognized with the help of a thermography camera. The different classifications of the defective shunts are detected by injecting the various modulated versions of the current pulse. This method is typically suited for small values and is performed in dark regions with the lack of an illuminating source. This approach has shown significant success in detecting the faults that occur in local shunts in the PV module. One of the major advantages of this method is that it doesn't need physical contact with the module to precisely predict the faulty area [15, 48, 49]. Figure 15 shows the simulation output for this technique.

4.4.10. *Power loss analysis (PLA) technique:*

The vital parameters of the PV module are closely monitored in order to estimate the power losses. Real time simulation is performed on the recorded observations. It is a comparative technique where in the measured values are compared with simulated values. It is mainly used in the detection of faults caused to due partial shading and it can isolate the string or module with defects from the good ones. The errors are isolated based on the simulated values. [15, 24, 50]

4.4.11. *Comparison between measured and modeled PV system outputs (CMM) technique:*

The output power of the modules is estimated in most of the approaches that employ this method. The various real-time parameters in the cell are calculated or measured and accordingly the output is predicted from the observed data. The other important parameters that are considered are temperature and environmental radiation used to for illuminating. These factors influence the simulation results and in the prediction of faulty regions. The estimated output values are analyzed along with the measured values of the output values and the defective places are determined [15, 24, 37].

4.4.12. *Protection device based technique:*

The design of PV modules essentially consists of protection circuits to cut off the circuit in the case of a deleterious fault. The

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ground fault detection and interrupt devices are used to prevent the failure cases in the PV module. Some of the most common defects in the PV system are the ones that occur between conductors and those that occur between a conductor and the ground. Therefore, it becomes indispensable to identify and isolate the faulty strings or arrays in the PV module by estimating the difference in the value of current flowing through the strings and arrays of the PV modules [15, 51].

4.4.13. *ARC fault detector (AFD) techniques:*

The arc fault detection devices are compact, modular devices that are installed in the PV panels along with protective equipment. Arc fault detector (AFD) is a part of Arc fault circuit interrupter (AFCI). Apart from AFD, AFCI also have arc fault interrupting device. AFD detects abnormal frequencies (that may be due to arc fault) and Arc fault interrupting device disconnects the circuit in case of fault detected by the AFD [52]. Hence, the main operation of AFCI is to instantly trip the circuit when they detect dangerous electric arcs [15].

4.4.14. *Novel non-iterative fault detection technique:*

It was aimed to estimate the fault and its location for low voltage DC micro-grids. This technique has higher accuracy and rapid fault detection during internal faults. The scheme proposed for fault detection and the diagnosis was grounded on the violations in the Cumulative Sum (CuSum) threshold index [30, 53].

4.4.15. *Electromagnetic radiation analysis:*

Using electromagnetic radiation analysis, DC arc fault is detected in a PV system. Its frequency spectrum is examined using a fourth-order Hilbert antenna to obtain the frequency corresponding to the highest amplitude of the radiation signal. Even when the noise from the inverter exists, arc faults are differentiated by this method. Experimental analysis indicates that the characteristic frequency will always be in the range of 39 MHz in the presence of arc faults which can be used as a parameter for detection [30, 54].

4.4.16. *Discrete wavelet transforms:*

In discrete wavelet transforms, a given signal is disintegrated into wavelet packets of data which in turn helps in flaw detection and its location. The data and features extracted are examined on a comparative basis with their threshold limits. This method shows good accuracy with no requirement for additional sensors in fault detection [30, 55].

4.4.17. *A decision tree algorithm:*

This technique is notably valuable and has been recently discovered and the model is able to spot faults straightaway with 99% accuracy. It has a high training cost and may not work as expected with unknown data that is different from the training set. Trained model with good accuracy may have favorable significance [30, 56].

4.4.18. *Probabilistic neural network:*

This method was broadly used to detect pattern recognition problems and faults, for parallel processing and self-learning in a PV array. Besides, a PV model incorporated with standard and nominal operating is used to train the PNN network. PNNs are much faster than multilayer perceptron networks but slower than networks at classifying new cases. It is used in modeling structural deterioration of storm water pipes and character recognition [30, 57, 58].

4.4.19. *Artificial neural network:*

The neural network composed of three layers in a feed-forward fashion is made use of in detecting the electrical faults that occur in the PV modules. This technique has proven to offer the best efficiency when compared with the other neural network models, if offers almost 99% efficiency. The usage of one neural network layer will not be providing the appropriate results in fault detection, hence several ANN layers are clubbed and automatic fault detection is performed. The accuracy of this technique is extremely good [30, 37, 59].

4.4.20. *Multi-layer perceptron ANN:*

Environmental faults caused to due to shading can be detected in the multilayer perceptron model. The dataset that is to be used for training the model was taken from the recorded observation of the essential parameters in the PV module and the training was performed based on the Resilient Back Propagation Algorithm. The faults diagnosis was based on the computational analysis which was used to approximate the vitals. This method has significantly outperformed the traditional methods of fault detection [30, 37, 60].

4.4.21. *Laterally primed adaptive reference theory (LAPART):*

The LAPART is a class of the ANN method which is used to detect faulty strings in the PV system. A very few essential quantities required for training the model are collected from the observed on-site module and fed into the system for processing. This technique performs a quick deep learning approach in analyzing the datasets and locating the faults [30, 61, 62].

4.4.22. *Electrical signal approaches:*

This method is one of the most reliable methods when compared to other visual and thermal approaches. Here, the faults are detected and the faulty areas are located by using MATLAB algorithms. This makes it fast, easy and automatic. The measured values and simulated values are compared detailed analysis is performed and the loss analysis of the given system is made [8].

4.4.23. *IV curve analysis:*

Another method used for failure analysis is the IV curve diagnosis. The deformation in the curve indicates the faulty modules. This approach gives results without any delay and hence is very

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useful in instant monitoring of power delivered. It has two different approaches, one is used to analyze the faults in single or independent strings by considering some ratios at the operating points, while the other method is used to identify the failures in identical strings [8].

4.4.24. ***Earth capacitance measurement:***
This is an electrical method which is independent of the climate data. It is used to detect the defective connections in single strings. This is mostly preferred for the complete inspection of the PV system and during the conditions of major disasters. Here the value of the earth capacitance of the string containing faults is compared with that of a good string [8].

4.4.25. ***Time domain reflectometry:***
This method is used to detect the degradation and the location of the fault by analyzing the waveform changes. Here the input signal of the PV generator and the reflected signals are compared and the electrical characteristics of the transmission line are determined. The faulty connections in the strings as well as the impedance changes caused by the defective connections are evaluated from the analysis of the reflected signal. The initial conditions of installation are extremely important in this approach. This method is mostly preferred for the periodic checking of the system [8].

4.4.26. ***Spread spectrum time domain reflectometry:***
SSTDR is an improvised version of the TDR technique. This method is mainly used for the detection of ground and arc fault in the system [30].

4.4.27. ***Language theory and petri nets:***
This method detects all the abnormal behavior of the PV system by identifying a normal model and comparing that with the models which have undergone some changes. It is independent of the previous states of the model. It can detect various kinds of faults without errors and it is quite accurate [8].

4.4.28. ***Satellite monitoring:***
This method is a remote monitoring approach. The irradiance data and other weather- related information are recorded using satellites and the necessary changes are made in order to optimize system performance. The on-site measurements are replaced by the values calculated from the satellite monitoring techniques [14].

4.4.29. ***Kalman filter technique:***
Series arc fault is among the major flaws that take place in a PV system. Delayed series arc fault detection causes dangerous consequences such as electrical shock and fire hazards. Kalman filter helps to identify the series arc faults by deriving an approach that is grounded on examining high-frequency components of the voltage signal. Accurate results for different scenarios are shown including various arclength, movement of electrodes, temporary shadings, and different kinds of noise. It is noted for its precise results and instant response [14].

4.4.30. ***Visual inspection:***
In the method, the system and its specific components are monitored in order to detect potential issues. Shade analysis is performed with the aid of an apparatus called the **SolmetricSuneye,** which can spot inherent discrepancies because of the various disturbances that cause shading. This approach also helps to identify the grime (for instance leaf litters, bird turds, discarded ruins) formed on the modules. One of the major shortcomings of this method is safety [63].

4.4.31. ***Infrared thermography of PV panels:***
The quality of PV panels is examined using this method. This method is generally preferred for the large PV system. Here unmanned aerial vehicles are used to gather data about the various parameters linked with the PV panel. Aerial IR thermography has higher accuracy and faster response time but it is not economical. Together, thermal imaging and visual cameras turn out to be consistent and reasonable methods. Faults as in malfunctioned and cracked cells, defective solder junctions, and so on are commonly detected by IR thermography [63].

4.4.32. ***Insulation resistance analysis:***
The leakage current in a PV system is represented by the insulation resistance of the PV string. The decline in the fill factor eventually decreases the insulation resistance and hence results in a failed model. It is a cost-effective diagnosis method yet provides lower accuracy of detection [63].

4.4.33. ***Real time sensors:***
Although the economic nature of this method may not be in a way to fit your budget, nevertheless this method gives the maximum accuracy. The PV panel self-orients itself in the direction of the irradiance in order to maximize the output and sensors are used to keep a track of the panel. Sensors can also be employed to check the quality and control the vitals of the PV module. These real-time sensors have evolved in such a way that they offer an efficient approach to measuring the electrical parameters and isolating faulty lines by sending information and helping in the remote monitoring of the system. Devices such as thermocouples and pyranometer are employed to measure the temperature of the module and the irradiance value. Embedded systems have a key role to play in this technique of fault detection [63, 64].

4.4.34. ***FMEA approach:***
The failure mode effect analysis algorithm is not too expensive and it provides us with a solution which is not very precise. The

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various possible failure modes are analyzed and the predictive maintenance technique is followed as the cause effect analysis is performed on the dataset and the probable solutions are estimated. This technique has proved its worth in a variety of domains like space, electronic manufacturing etc. The FMEA approach foresees the possible faults that can damage the working of a PV module [63, 65].

4.4.35. ***Auto regressive integrated moving average model:***
For a continuous generation of output power, it is necessary that the PV module should be reliable but the power generation is greatly influenced by the various environmental factors. Therefore, a proper model is required to predict the possible failure modes during the operation of the system. This is statistical technique where the time sequence data is used to estimate the future outcomes. The regressive modeling approach is chosen as the system when trained with that algorithm learns to heal itself and predict the possible failure stages and faults with a brilliant accuracy [63, 64, 66].

In further works, it would be useful to investigate the potential impacts of different faults on PV cell parameters [67–69] and general performance figures [69]. Multifunctional PV units like heat insulation solar glass—HISG [70–75] and thermally resistive PV glazing—TRPVG [76] can be evaluated in terms of fault sensitivity. Besides solar intensity and ambient temperature as main climatic parameters, humidity can be examined as a potential fault source in solar PV systems [77, 78]. For further reading and works pertinent to solar energy utilization in solar collectors, PV panels, and heaters/coolers can be referred in [79–96].

5 CONCLUSION

The various techniques used for fault detection and rectification of the faults occurring in PV panels have been discussed in this paper. The classification of the faults occurred has also been done and it is important to distinguish the faults as it makes the detection and troubleshooting much easier. Fault detection is an essential part of PV panel maintenance as it enhances the performance of the overall system as the detected faults can be corrected before major damages occur which a significant effect on the power has generated. Most of the available methods used to rectify the various faults occurring in the solar panels which are discussed above have proven to be efficient.

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AUTHOR CONTRIBUTIONS

G.R. Venkatakrishnan: Writing — original draft; R. Rengaraj: Writing — original draft; S. Tamilselvi: Conceptualization; J. Harshini: Formal Analysis; Ansheela Sahoo: Formal Analysis; C. Ahamed Saleel: Funding acquisition; Mohamed Abbas: Resources; Erdem Cuce: Writing — review and editing, Supervision; C. Jazlyn: Investigation; Saboor Shaik: Writing — review and editing, Supervision; Pinar Mert Cuce: Formal analysis; Saffa Riffat: Supervision

REFERENCES

[1] Tsai W-T, Kuo K-C. An analysis of power generation from municipal solid waste (MSW) incineration plants in Taiwan. *Energy* 2010;**35**:4824–30.
[2] Mercure J-F, Salas P. An assessement of global energy resource economic potentials. *Energy* 2012;**46**:322–36.
[3] Madeti SR, Singh SN. A comprehensive study on different types of faults and detection techniques for solar photovoltaic system. *Sol Energy* 2017;**158**:161–85.
[4] Espinosa AR, Bressan M, Giraldo LF. Failure signature classification in solar photovoltaic plants using RGB images and convolutional neural networks. *Renew Energy* 2020;**162**:249–56.
[5] Sarikh S, Raoufi M, Bennouna A *et al.* Characteristic curve diagnosis based on fuzzy classification for a reliable photovoltaic fault monitoring. *Sustain Energy Technol Assess* 2021;**43**:1.
[6] Firth SK, Lomas KJ, Rees SJ. A simple model of PV system performance and its use in fault detection. *Sol Energy* 2010;**84**:624–35.
[7] Madeti SR, Singh SN. Monitoring system for photovoltaic plants: a review. *Renew Sust Energ Rev* 2017;**67**:1180–207.
[8] Triki-Lahiani A, Abdelghani AB-B, Slama-Belkhodja I. Fault detection and monitoring systems for photovoltaic installations: a review. *Renew Sust Energ Rev* 2018;**82**:2680–92.
[9] Sonawane P, Jog P, Shete S *et al.* A comprehensive review of fault detection & diagnosis in photovoltaic systems. *IOSR Journal of Electronics and Communication Engineering (IOSR-JECE)*. 2019;**14**:31–43.
[10] Zaki SA, Zhu H, Yao J. Fault detection and diagnosis of photovoltaic system using fuzzy logic control. In *E3S Web Conf*. E3S Web Conf. Volume 107, 2019. 2019 4th International Conference on Sustainable and Renewable Energy Engineering (ICSREE 2019), 2001. https://doi.org/10.1051/e3sconf/201910702001.
[11] Hazra A, Das S, Basu M. An efficient fault diagnosis method for PV systems following string current. *J Clean Prod* 2017;**154**:220–32.
[12] Sabbaghpur Arani M, Hejazi MA. The comprehensive study of electrical faults in PV arrays. *Act to prohibit and regulate the pollution of the waters of the state amendment 1921* 2016;**2016**:1–10.
[13] Pei T, Hao X. A fault detection method for photovoltaic systems based on voltage and current observation and evaluation. *Energies* 2019;**12**:1712.
[14] Nilsson D. *Fault Detection in Photovoltaic Systems*. Digitala Vetenskapliga Arkivet, 2014. URN: urn:nbn:se:kth:diva-153945.
[15] Abdul Mawjood K, Refaat SS, Morsi WG. 2018. Detection and prediction of faults in photovoltaic arrays: A review. In *2018 IEEE 12th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG 2018)*. IEEE, 1–8. https://doi.org/10.1109/CPE.2018.8372609.
[16] Sarikh S, Raoufi M, Bennouna A *et al.* 2018. Photovoltaic discoloration and cracks: experimental impact on the IV curve degradation. In *International Conference on Electronic Engineering and Renewable Energy*. Proceedings of the 9th International Renewable Energy Congress (IREC), Hammamet, Tunisia, 26–28 March 2018, 609–16.

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[17] Abd, Allah S, Gharabawy E. Review on corrosion in solar panels. *Int J Smart Grid* 2018;**2**:218.

[18] Singh D, Kathuria RS. Fault prediction and analysis techniques of solar cells and PV modules. *Int J Eng Sci Res Technol* 2018;**7**:384–99.

[19] Yang H, Chang J, Wang H *et al.* Power degradation caused by snail trails in urban photovoltaic energy systems. *Energy Procedia* 2016;**88**:422–8.

[20] Mahalakshmi R, Karuppasamypandiyan M, Bhuvanesh A *et al.* Classification and detection of faults in grid connected photovoltaic system. *Int J Sci Eng Res* 2016;**7**:149–54.

[21] Niazi KAK, Yang Y, Sera D. Review of mismatch mitigation techniques for PV modules. *IET Renew Power Gener* 2019;**13**:2035–50.

[22] Andrews RW, Pollard A, Pearce JM. The effects of snowfall on solar photovoltaic performance. *Sol Energy* 2013;**92**:84–97.

[23] Heidari N, Gwamuri J, Townsend T *et al.* Impact of snow and ground interference on photovoltaic electric system performance. *IEEE J Photovoltaics* 2015;**5**:1680–5.

[24] Appiah AY, Zhang X, Ayawli BBK *et al.* Review and performance evaluation of photovoltaic array fault detection and diagnosis techniques. *pg 1110* 2019;**2019**:1–19.

[25] Bharadwaj P, Karnataki K, John V. 2018. Formation of hotspots on healthy PV modules and their effect on output performance. In *2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A joint conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC)*. IEEE, 676–80.

[26] Wang Y, Itako K, Kudoh T *et al.* Voltage-based hot-spot detection method for PV string using projector. *IEEE International Conference on Power and Renewable Energy (ICPRE)* 2016;**2016**:570–4.

[27] Wendlandt S, Drobisch A, Buseth T *et al.* 2010. Hot spot risk analysis on silicon cell modules. In *25th European Photovoltaic Solar Energy Conference and Exhibition*. EUPVSEC, 4002–6.

[28] Batzelis E, Samaras K, Vokas G *et al.* Off-grid inverter faults: diagnosis, symptoms and cause of failure. *Mater Sci Forum* 2016;**856**:315–21.

[29] Nehme B, Msirdi NK, Namaane A *et al.* Analysis and characterization of faults in PV panels. *Energy Procedia* 2017;**111**:1020–9.

[30] Pillai DS, Rajasekar N. A comprehensive review on protection challenges and fault diagnosis in PV systems. *Renew Sust Energ Rev* 2018;**91**:18–40.

[31] Strobl C, Meckler P. 2010. Arc faults in photovoltaic systems. In *2010 Proceedings of the 56th IEEE Holm Conference on Electrical Contacts*. IEEE, 1–7. https://doi.org/10.1109/HOLM.2010.5619538.

[32] Miao W, Liu X, Lam KH *et al.* Arc-faults detection in PV systems by measuring pink noise with magnetic sensors. *IEEE Trans Magn* 2019;**55**:1–6.

[33] Artale G *et al.* 2020. DC series arc faults in PV systems. Detection methods and experimental characterization. In Cosentino V, D'Acquisto L. (eds.) *24th IMEKO TC4 International Symposium and 22nd International Workshop on ADC and DAC Modelling and Testing, IWADC 2020*. Elsevier, 135–40.

[34] Vieira RG, de Araújo FMU, Dhimish M *et al.* A comprehensive review on bypass diode application on photovoltaic modules. *Energies* 2020;**13**:2472.

[35] Zinger DS. Review on methods of fault diagnosis in photovoltaic system applications. *J Eng Sci Technol Rev* 2019;**12**:53–66.

[36] Wu Y, Chen Z, Wu L *et al.* An intelligent fault diagnosis approach for PV array based on SA-RBF kernel extreme learning machine. *Energy Procedia* 2017;**105**:1070–6.

[37] Basnet B, Chun H, Bang J. An intelligent fault detection model for fault detection in photovoltaic systems. *J Sens* 2020;**2020**:1–11.

[38] Hairudin M. *Photovoltaic Module and System Fault Analysis*. Murdoch University, Australia, 2016.

[39] Ding H, Ding K, Zhang J *et al.* Local outlier factor-based fault detection and evaluation of photovoltaic system. *Sol Energy* 2018;**164**:139–48.

[40] Wang M-H, Chen M-J. Two-stage fault diagnosis method based on the extension theory for PV power systems. *Int J Photoenergy* 2012; **2012**:1–10.

[41] Mohanty S, Patra PK, Sahoo SS. 2015. Prediction of global solar radiation using nonlinear auto regressive network with exogenous inputs (narx). In *2015 39th NationalSystems Conference (NSC)*. IEEE, 1–6.

[42] Samara S, Natsheh E. Intelligent PV panels fault diagnosis method based on NARX network and linguistic fuzzy rule-based systems. *Sustainability* 2020;**12**:2011.

[43] Boussaada Z, Curea O, Remaci A *et al.* A nonlinear autoregressive exogenous (NARX) neural network model for the prediction of the daily direct solar radiation. *Energies* 2018;**11**:620.

[44] Drews A, de Keizer AC, Beyer HG *et al.* Monitoring and remote failure detection of grid-connected PV systems based on satellite observations. *Sol Energy* 2007;**81**:548–64.

[45] Et-taleby A, Boussetta M, Benslimane M. Faults detection for photovoltaic field based on K-means, elbow, and average silhouette techniques through the segmentation of a thermal image. *pg 1110* 2020;**2020**:1–7.

[46] Drabczyk K, Kulesza-Matlak G, Drygała A *et al.* Electroluminescence imaging for determining the influence of metallization parameters for solar cell metal contacts. *Sol Energy* 2016;**126**:14–21.

[47] dos Reis Benatto GA *et al.* Drone-based daylight electroluminescence imaging of PV modules. *IEEE J. Photovoltaics* 2020;**10**:872–7.

[48] Wu D, Zweschper T, Salerno A *et al.* Lock-in thermography for nondestructive evaluation of aerospace structures. *NDT net* 1998;**3**.

[49] Razani M, Parkhimchyk A, Tabatabaei N. Lock-in thermography using a cellphone attachment infrared camera. *AIP Adv* 2018;**8**:35305.

[50] Chouder A, Silvestre S. Automatic supervision and fault detection of PV systems based on power losses analysis. *Energy Convers Manag* 2010;**51**:1929–37.

[51] Falvo MC, Capparella S. Safety issues in PV systems: design choices for a secure fault detection and for preventing fire risk. *Case Studies in Fire Safety* 2015;**3**:1–16.

[52] Johnson J, Strauch J, Kuszmaul S *et al.* 2011. Photovoltaic DC arc fault detector testing at Sandia National Laboratories. In *2011 37th IEEE Photovoltaic Specialists Conference*. IEEE, 3614–9.

[53] Bhargav R, Bhalja BR, Gupta CP. Novel fault detection and localization algorithm for low-voltage dc microgrid. *IEEE Trans Ind Informatics* 2019;**16**:4498–511.

[54] Xiong Q, Ji S, Zhu L *et al.* A novel DC arc fault detection method based on electromagnetic radiation signal. *IEEE Trans Plasma Sci* 2017;**45**: 472–8.

[55] Kumar BP, Ilango GS, Reddy MJB *et al.* Online fault detection and diagnosis in photovoltaic systems using wavelet packets. *IEEE J Photovoltaics* 2018;**8**:257–65.

[56] Zhao Y, Yang L, Lehman B *et al.* 2012. Decision tree-based fault detection and classification in solar photovoltaic arrays. In *2012 Twenty-Seventh Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*. IEEE, 93–9.

[57] Kebir ST, Cheggaga N, Ilinca A *et al.* An efficient neural network-based method for diagnosing faults of PV Array. *Sustainability* 2021;**13**: 6194.

[58] Rakesh N, Banerjee S, Subramaniam S *et al.* A simplified method for fault detection and identification of mismatch modules and strings in a grid-tied solar photovoltaic system. *Hunted Heretic; the Life and Death of Michael Servetus, 1511–1553* 2020;**21**:2.

[59] Jiang LL, Maskell DL. 2015. Automatic fault detection and diagnosis for photovoltaic systems using combined artificial neural network and analytical based methods. In *2015 International Joint Conference on Neural Networks (IJCNN), Killarney, Ireland*. IEEE, 1–8. https://doi.org/10.1109/IJCNN.2015.7280498.

[60] Aslam M, Lee J-M, Hong S. A multi-layer perceptron based deep learning model to quantify the energy potentials of a thin film a-Si PV system. *Energy Rep* 2020;**6**:1331–6.

[61] Jones CB, Stein JS, Gonzalez S *et al.* 2015. Photovoltaic system fault detection and diagnostics using laterally primed adaptive resonance theory neural network. In *2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC)*. IEEE, 1–6.

[62] Alam MK, Khan FH, Johnson J *et al.* 2013. PV faults: Overview, modeling, prevention and detection techniques. In *2013 IEEE 14th Workshop on Control and Modeling for Power Electronics (COMPEL)*. IEEE, 1–7.

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[63] Bosman LB, Leon-Salas WD, Hutzel W *et al.* PV system predictive maintenance: challenges, current approaches, and opportunities. *Energies* 2020;**13**:1398.
[64] Lazzaretti AE, Costa CH, Rodrigues MP *et al.* A monitoring system for online fault detection and classification in photovoltaic plants. *Sensors* 2020;**20**:4688.
[65] Colli A. An FMEA Analysis for Photovoltaic Systems: Assessing Different System Configurations to Support Reliability Studies-Introduction to PRA Analysis for PV Systems. Brookhaven National Lab. (BNL), Upton, NY (United States), 2012.
[66] Pasari S, Shah A. 2020. Time Series Auto-Regressive Integrated Moving Average Model for Renewable Energy Forecasting. In Sangwan KS, Herrmann C (eds.) *Enhancing Future Skills and Entrepreneurship: 3rd Indo-German Conference on Sustainability in Engineering*. Cham: Springer. 71–7.
[67] Young CH, Riffat SB, Cuce E. High capacity energy efficiency solar glass. In *Fourteenth International Conference on Sustainable Energy Technologies*, 25–27 August 2015. Nottingham, United Kingdom.
[68] Cuce E. *Development of innovative window and fabric technologies for low-carbon buildings*. Ph.D. Thesis. Nottingham: The University of Nottingham, 2014.
[69] Cuce E, Cuce PM, Bali T. An experimental analysis of illumination intensity and temperature dependency of photovoltaic cell parameters. *Appl Energy* 2013;**111**:374–82.
[70] Cuce E, Riffat SB. A smart building material for low/zero carbon applications: heat insulation solar glass—characteristic results from laboratory and in-situ tests. *Int J Low-Carbon Technol* 2017;**12**:126–35.
[71] Cuce E. Toward multi-functional PV glazing technologies in low/zero carbon buildings: heat insulation solar glass - latest developments and future prospects. *Renew Sust Energ Rev* 2016;**60**:1286–301.
[72] Cuce E, Cuce PM, Young CH. Energy saving potential of heat insulation solar glass: key results from laboratory and in-situ testing. *Energy* 2016;**97**:369–80.
[73] Cuce E, Riffat SB, Young CH. Thermal insulation, power generation, lighting and energy saving performance of heat insulation solar glass as a curtain wall application in Taiwan: a comparative experimental study. *Energy Convers Manag* 2015;**96**:31–8.
[74] Cuce E, Young CH, Riffat SB. Thermal performance investigation of heat insulation solar glass: a comparative experimental study. *Energy Build* 2015;**86**:595–600.
[75] Cuce E, Young CH, Riffat SB. Performance investigation of heat insulation solar glass for low-carbon buildings. *Energy Convers Manag* 2014;**88**:834–41.
[76] Cuce E, Cuce PM. Optimised performance of a thermally resistive PV glazing technology: an experimental validation. *Energy Rep* 2019;**5**:1185–95.
[77] Cuce E, Cuce PM, Bali T. Impact of humidity on current parameters of solar cells. *Journal of Energy Systems* 2019;**2**:84–96.
[78] Tripathi AK, Ray S, Aruna M *et al.* Evaluation of solar PV panel performance under humid atmosphere. *Mater Today* 2021;**45**:5916–20.
[79] Yunus Khan TM, Soudagar MEM, Kanchan M *et al.* Optimum location and influence of tilt angle on performance of solar PV panels. *J Therm Anal Calorim* 2020;**141**:511–32.
[80] Samylingam L, Aslfattahi N, Saidur R *et al.* Solar energy materials and solar cells thermal and energy performance improvement of hybrid PV/T system by using Olein palm oil with MXene as a new class of heat transfer fluid. *Sol Energy Mater Sol Cells* 2020;**218**:110754. https://doi.org/10.1016/j.solmat.2020.110754.
[81] Kumar R, Gaurav, Kumar S *et al.* Experimental investigation of impact of the energy storage medium on the thermal performance of double pass solar air heater. *Sustain Energy Technol Assess* 2021;**48**:101673. https://doi.org/10.1016/j.seta.2021.101673.
[82] Benoudina B, Attia MEH, Driss Z *et al.* Enhancing the solar still output using micro/Nano-particles of aluminum oxide at different concentrations: an experimental study, energy, exergy and economic analysis. *Sustain Mater Technol* 2021;**29**:e00291. https://doi.org/10.1016/j.susmat.2021.e00291.
[83] El M, Attia H, Driss Z *et al.* Phosphate bed as energy storage materials for augmentation of conventional solar still productivity. *Environ Prog Sustain Energy* 2021;**40**:1–9. https://doi.org/10.1002/ep.13581.
[84] Prasad AR, El M, Attia H *et al.* Energy and exergy efficiency analysis of solar still incorporated with copper plate and phosphate pellets as energy storage material. *Environ Sci Pollut Res* 2021;**28**:48628–36.
[85] Akram N, Montazer E, Kazi SN *et al.* Experimental investigations of the performance of a flat-plate solar collector using carbon and metal oxides based Nanofluids. *Energy* 2021;**227**:120452. https://doi.org/10.1016/j.energy.2021.120452.
[86] Kumar R, Nadda R, Kumar S *et al.* Heat transfer and friction factor correlations for an impinging air jets solar thermal collector with arc ribs on an absorber plate. *Sustain Energy Technol Assessments* 2021;**47**:101523. https://doi.org/10.1016/j.seta.2021.101523.
[87] Santhosh, Kumar PC, Naveenkumar R, Sharifpur M *et al.* Experimental investigations to improve the electrical efficiency of photovoltaic modules using different convection mode. *Sustain Energy Technol Assess* 2021;**48**:101582. https://doi.org/10.1016/j.seta.2021.101582.
[88] Huddar VB, Razak A, Cuce E *et al.* Thermal performance study of solar air dryers for cashew kernel: a comparative analysis and modelling using response surface methodology (RSM) and artificial neural network (ANN). *pg 1110* 2022;**2022**:1–18. https://doi.org/10.1155/2022/4598921.
[89] Sheik MA, Aravindan MK, Beemkumar N *et al.* Investigation on the thermal management of solar photo voltaic cells cooled by phase change material. *J Energy Storage* 2022;**52**:104914. https://doi.org/10.1016/j.est.2022.104914.
[90] Sharma J, Soni S, Paliwal P *et al.* A novel long term solar photovoltaic power forecasting approach using LSTM with Nadam optimizer: a case study of India. *Energy Sci Eng* 2022;**10**:2909–29.
[91] Murugan M, Saravanan A, Elumalai PV *et al.* An overview on energy and exergy analysis of solar thermal collectors with passive performance enhancers. *Alex Eng J* 2022;**61**:8123–47.
[92] Ziaee O, Zolfaghari N, Baghani M *et al.* A modified cellular automaton model for simulating ion dynamics in a li-ion battery electrode. *Energy Equip Syst* 2022;**10**:41–9.
[93] Taslimi MS, Maleki Dastjerdi S, Bashiri Mousavi S *et al.* Assessment and multi-objective optimization of an off-grid solar based energy system for a Conex. *Energy Equip Syst* 2021;**9**:127–43.
[94] Sharifi M, Amidpour M, Mollaei S. Investigating carbon emission abatement long-term plan with the aim of energy system modeling; case study of Iran. *Energy Equip Syst* 2018;**6**:337–49.
[95] Zare S, Ayati M, Ha'iri Yazdi MR *et al.* Convolutional neural networks for wind turbine gearbox health monitoring. *Energy Equip Syst* 2022;**10**:73–82.
[96] Sabzi S, Asadi M, Moghbelli H. Review, analysis and simulation of different structures for hybrid electrical energy storages. *Energy Equip Syst* 2017;**5**:115–29.

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