Different Technology for Solar PV Array System Fault Detection

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Abstrac : If faults in any components (modules, connection lines, converters, inverters, etc.) of photovoltaic (PV) systems (stand-alone, grid-connected, or hybrid PV systems) are not detected and corrected quickly, they can have a significant impact on the efficiency, energy yield, as well as the security and reliability of the entire PV plant. Furthermore, some defects (such as arc faults, ground faults, and line-to-line faults) might contribute to the danger of fire. Fault detection and diagnostic (FDD) technologies are critical for PV plant system dependability, high efficiency operation, and safety.
The kinds and causes of PV system failures are described in this study, followed by a review and discussion of several approaches offered in the literature for FDD of PVS, with a focus on faults occurring in PV arrays (PVA). Methods that can accurately identify, locate, and categorize potential defects in a PVA are given special consideration. The merits and limitations of FDD techniques for large-scale integration are discussed in terms of practicality, complexity, cost-effectiveness, and generalization capabilities. Challenges and ideas for future research directions are also offered based on the evaluated publications.

***Index Terms* – Solar PV array system, Solar PV Faults detection, Fault classification**

I. INTRODUCTION

Due to its technological, economic, and environmental benefits, solar photovoltaic (PV) development is rapidly expanding across the world. PV is currently the most promising method of sustainable power generation to satisfy energy needs. With rising energy consumption, large-scale PV systems are becoming increasingly popular as a way to achieve energy goals. Thousands of large-scale PV facilities are being built to fulfill demand of hundreds of giga-watts. A large-scale PV system is made up of hundreds of thousands of solar modules that are all linked in different ways. The failure of one of them can wreak havoc on the entire system's functioning. The expansion of large-scale PV plant capacity need new techniques to actively monitor and detect any developing defects so that necessary corrective steps may be performed before any severe interruptions occur.
Photovoltaic (PV) systems have gained popularity as one of the most promising renewable energy sources owing to its almost-zero pollution during power generation, falling costs, improvements in semiconductor devices, ease system maintenance, and other factors. When system behavior deviates from intended performance, PV monitoring refers to detecting, classifying, and identifying fault situations [1-3]. PV system fault monitoring has become highly crucial due to the often severe and dynamic external conditions as well as the growing structural complexity of the PV system. According to the study [4,] failures can result in up to 18.9% power loss from the evaluated PV system.
In most cases, defects are discovered and corrected manually; however, this approach is not advised because it is time-consuming, incorrect, and possibly dangerous to the operator, especially in large-scale PV arrays. Instead, automatic fault monitoring for PV systems should be rapid and efficient.
Ground faults in ungrounded systems are intrinsically difficult to locate since the fault currents are insufficient to trace the fault site. Furthermore, because ungrounded power systems are not grounded, the locating process must be carried out while the system is still operational. Fault finding approaches now available [1]-[4] are either time consuming or need a considerable quantity of specialized gear, such as sensors, which adds to the cost and complexity.
The authors devised and published an unique ground fault location technique in [5]. It is based on the pattern identification of intrinsic high frequency noise generated by the recurrent switching events of power electronic (PE) converters interacting with parasitic components in the system (such as cable insulation capacitance and stray inductance). All ungrounded systems with parasitic elements that create a ringing circuit through ground and a method to activate that ringing circuit can use the suggested technique. The original research [5] shows the efficacy of the technique by simulating a suitable system on a computer.

II. SOLAR PV FAULT DETECTION TECHNIQUES

[1] presents a fault prevention and localization approach for ungrounded DC traction power systems. To enhance the leakage route resistance, many DC traction power systems use an ungrounded power circuit. Because of the relatively low fault current, ungrounded systems can continue to operate with a single ground contact, unlike solid- or low-resistance grounded systems. However, a second ground fault in another pole will produce a line-to-line fault, which might cause substantial system damage. The first ground contact, however, is difficult to detect due to the low ground current and even more difficult to localise because it can be observed by many detectors in the network. In ungrounded traction power systems, the suggested technique in this study employs a probe unit to identify and localize the initial single ground fault. The probe unit uses probe voltage to identify the fault, then analyses the response to DC or swept-frequency AC probe voltage to pinpoint the location of the problem. The suggested principles have been validated by computer simulations and hardware testing, and have shown to be effective.

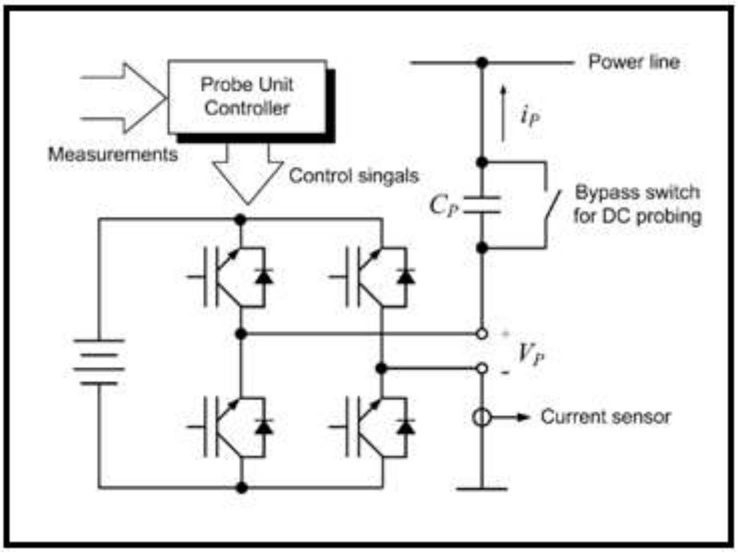

Fig.1. A schematic of probe unit using full-bridge inverter that can generate voltages with arbitrary amplitude and frequency [1]

Although ungrounded systems can function with a single ground contact, it is critical to notice and localise the fault as soon as possible since a second ground fault could result in a devastating line-to-line fault. By providing probing voltage through the ground connection from a substation, the suggested protection method is capable of detecting the initial ground fault. Once a ground fault has been discovered, the probe unit uses DC or swept-frequency AC response analysis on probe current to pinpoint the problem. Without de-energizing the bus, the suggested algorithm may be run while the traction system is in use.
The suggested technique allows for quick detection and precise location of the initial ground contact, allowing for prompt preventive action to increase system dependability. It's worth noting that if several ground connections are present when the lines are probed, the estimated position will be inaccurate, albeit a ground fault will still be identified. However, because the probe unit may probe the line at a high frequency, the chances of several ground connections occurring at the same time are slim.
In operational circumstances, Time Domain Reflectometry was utilized for diagnostic monitoring of a major photovoltaic (PV) facility [2]. We were able to detect, identify, and pinpoint the most frequent fault situations, including as circuit breaks, insulation flaws, and wiring abnormalities, by evaluating the waveforms generated when a step-voltage stimulation is propagated down the electrical line linking the PV generators to the inverter. Testing groups of three paralleled strings (panels) yielded the best balance between analysis time and precision: this system was able to detect a problem in a short amount of time, but its location was established individually with high precision by repeating the test on the single strings. In just a few days, the entire 1 MW PV facility was put to the test.

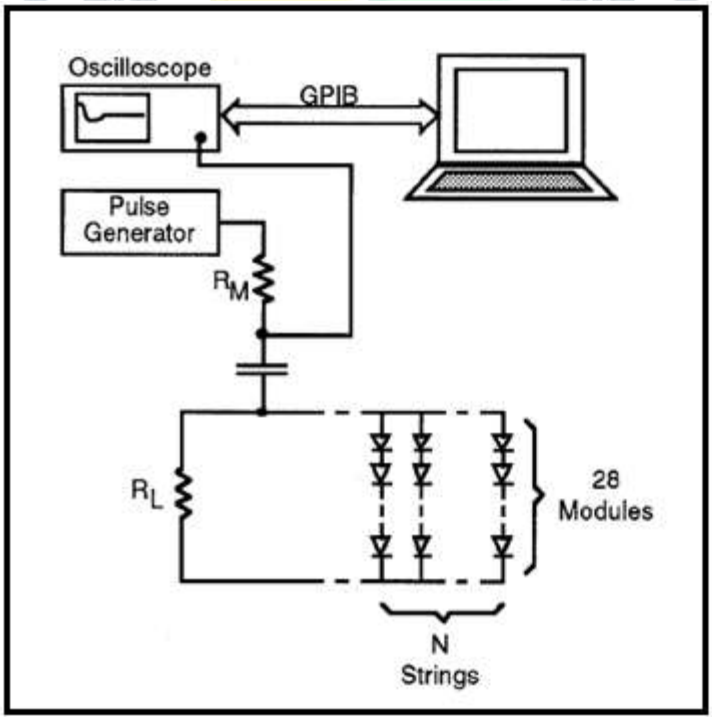

Fig.2. Step excitation voltage based approach [2]

The spread spectrum time domain reflectometry (SSTDR) approach was used to develop a PV arc-fault detection system [3]. SSTDR is a reflectometry method that has been commercially utilized to identify aircraft wire problems, but it may be used for a variety of other purposes. The SSTDR technique was utilized to identify both ground and arc faults in a PV array. SSTDR has been shown to be capable of detecting both series and parallel arcs, as well as predicting the presence of future arc faults by detecting changes in impedance even in the absence of light or at extremely low solar irradiation. This technique can identify the existence of arc independent of the inverter's working state and does not require frequency domain analysis of voltage or current signals. The suggested approaches may be used to identify both ground and arc faults, and they are independent of solar irradiance or PV array DC voltage and current measurements. Experiments were carried out using various arc fault resistances and fault sites. Regardless of the value of fault resistances or the position of faults within the array, the suggested approach can confidently identify the presence of fault resistance. All of the test scenarios were thoroughly examined, as well as the potentials and limits of the suggested arc fault prediction and detection approach.

Long-term exposure of photovoltaic (PV) systems to severe and changing external conditions can lead to the development of fault situations over their operational lifetime [4]. The current method is for system operators to manually monitor the PV system's status. It is, however, time-consuming, imprecise, and potentially hazardous. As a result, automated problem identification and diagnosis is a vital responsibility for ensuring PV system dependability and safety. Current state-of-the-art approaches are either too complicated or can't offer sufficiently specific fault information with high accuracy. This paper provides a technique for automatically detecting and diagnosing faults in string-based PV systems. It does fault identification and diagnostic tasks by combining an artificial neural network (ANN) with a traditional analytical approach. The expected power is predicted using a two-layered ANN, which is then compared to the measured power from the real PV system. The open circuit voltage and short circuit current of the PV string, computed using analytical formulae, are utilized to identify any of the six stated fault categories based on the difference between the ANN predicted power and the measured power. The suggested approach has a quick detection time, a small structure, and a high level of accuracy.

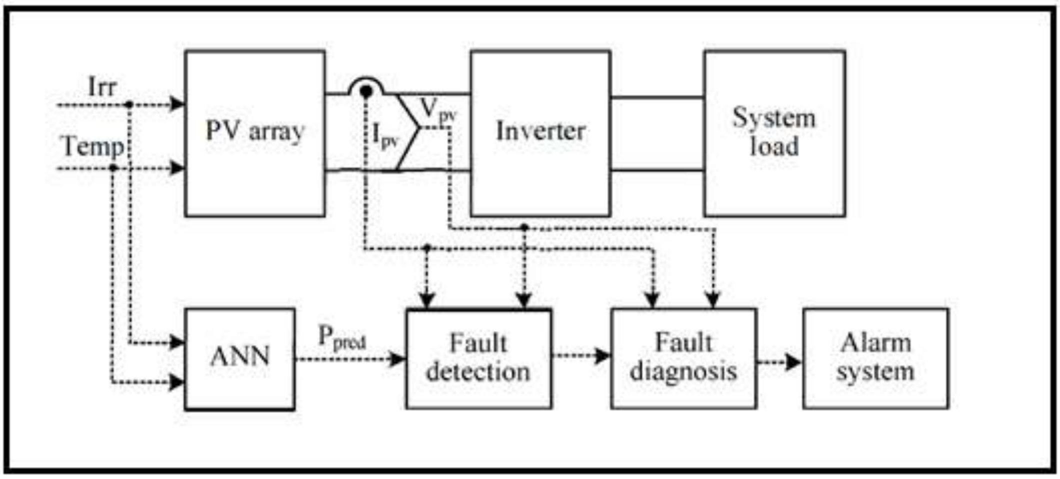

Fig.3. The PV system with fault detection and diagnosis [4]

With irradiance and temperature as inputs, the efficient multilayer ANN is utilized as a predictor to estimate the predicted power. To detect the presence of a defect, the estimated power is compared to the measured power from the real system. Following problem identification, fault diagnosis is carried out by comparing the estimated open circuit voltage of the PV string with the measured open circuit value using analytical formulae. The entire procedure is depicted in a flowchart. This approach has a simple structure, is quick to discover faults, is accurate, and does not require any prior understanding of the PV system. Simulation findings are used to verify the efficacy of the suggested fault detection and diagnostic approach. The findings demonstrate that the suggested technique is capable of accurately identifying the incidence and kinds of faults.

Advances in power electronics have favored DC distribution in recent years, particularly for transportation systems such as ships. As a result, this strategy proposes a defect location method based on pattern identification of intrinsic high frequency noise associated with converter switching occurrences. This technique [5] uses a hardware laboratory test to show the viability of the strategy. A low voltage DC system was utilized, which was typical of the important high frequency characteristics of a genuine Zonal Electrical Distribution System for ships. The experimental test findings closely match the results produced from a computer simulation model of the circuitry, demonstrating the approach's capacity to correctly identify multiple fault sites in the laboratory setting. The technique is determined to be viable and may be used to create an effective ground fault finding system for converter-dominated DC systems.

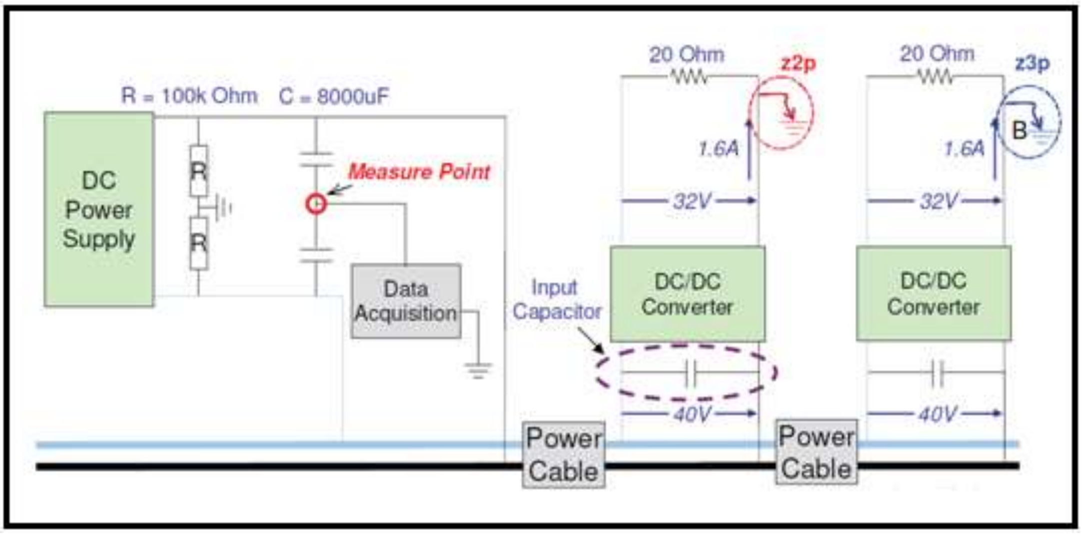

Fig.4. Ground fault detection system for ungrounded DC system [5]

Experimental test findings closely match the simulation results, demonstrating the approach's capacity to distinguish distinct fault sites in the actual world. The strategy is shown to stay successful with a smaller target frequency range when filtering techniques are used.

As more and more plants with progressively enormous capacities come into existence, problem detection and diagnosis in large-scale photovoltaic (PV) plants is projected to become a major issue. It is critical to create techniques that allow for the automated identification and localization of any malfunction among thousands of PV modules in order to preserve the safety, dependability, and productivity of large-scale PV facilities. A method for detecting PV plant failures was developed that involved the production of fault indicator signals known as "residuals" for each string and comparing the residuals to a threshold value [6]. In addition, a regression-based method for estimating fault location as a function of fault current and irradiance level data is suggested. The suggested method is shown using intra-string line-line faults as an example. Simulations are used to verify various line-line fault case studies, which are then tested on an experimental setup at a solar PV facility.

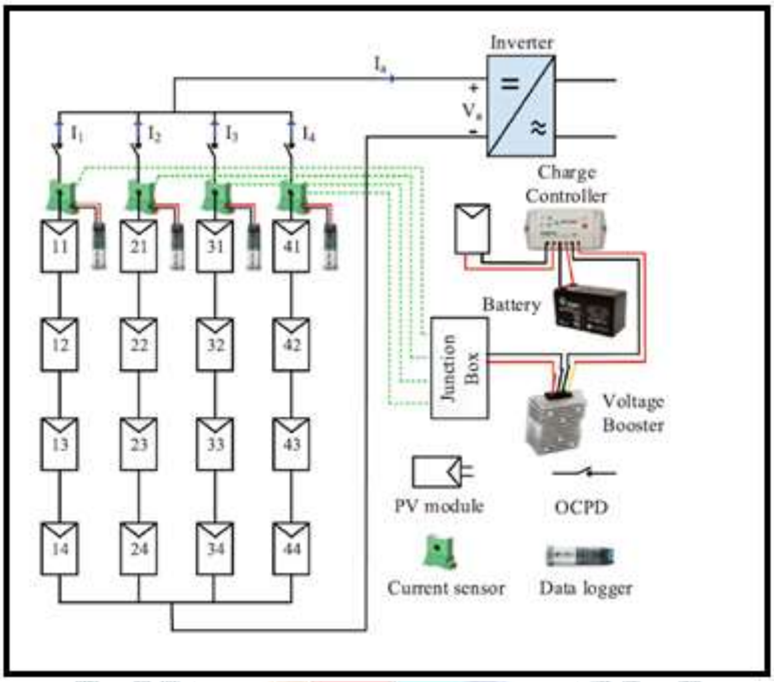

Fig.5. Solar PV fault analysis system model set up [6]

String level monitoring, independent of plant size, may considerably improve visibility on the dc side of PV plants, according to the research. Given that current protection devices are largely designed to prevent inverters and dc side fires, the suggested technique complements existing protection equipment by detecting and locating PV faults quickly, thereby extending the life of PV modules. Making the given technique adaptable to fluctuations in module degradation state is a natural extension of the proposed approach.

Due to the severe working environment, many defects in photovoltaic (PV) arrays are unavoidable. As a result, locating and identifying defects is critical for the PV array. This paper proposes a technique for identifying faults and their locations using PV string current time series [7]. It is decided to use a time series sliding window (TSSW). Each current location in the TSSW has its local outlier factor (LOF) computed.

When a certain number of LOFs consistently exceed the threshold value, the PV string is considered faulty. The results of the experiments demonstrate that the suggested approach can identify short circuit faults, open circuit faults, and shadow faults in PV strings under various irradiance conditions.

To diagnose and find the problem string in a PV array, a current time series change detection methodology based on LOF is proposed in the method. To test the suggested approach, a 1.8kW laboratory grid connect photovoltaic system is used. Short circuit fault, shadow fault, and open circuit fault are three common PV array problems that are investigated.

Arc faults endanger photovoltaic (PV) systems' ability to operate safely. [8] A parallel capacitor-based arc fault detection and localization method is suggested. A PV system's branches are paralleled by five capacitors. The system checks for both series and parallel arc errors. The capacitor currents' amplitudes and polarities are determined, and the capacitor currents are subjected to discrete wavelet transformation (DWT). The findings show that under distinct fault types and locations, the distributions of absolute amplitudes, polarities, and spectrums of capacitor currents are unique, which may be utilised to identify and locate arc faults in PV systems.

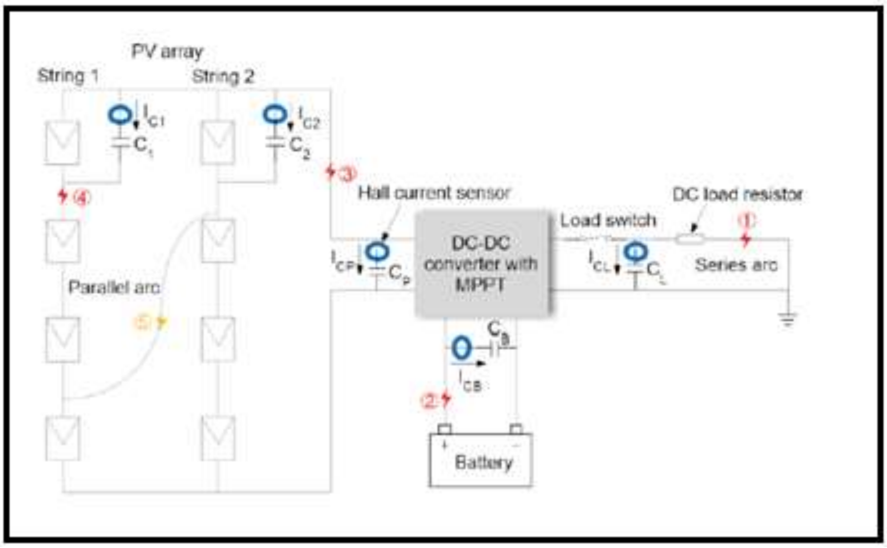

Fig.6. Circuit diagram and arc generation setup in solar PV system [8]

The capacitor currents' amplitudes and spectrums are investigated. The amplitudes, polarities, and spectrums of the capacitor currents exhibited distinct distributions when the arc occurred at different places. It is possible to detect and locate series and parallel arc defects in the PV system using the amplitude, polarity, and spectrum distribution diagrams, as well as separate arc from switch actions.

Due to the existence of power electronic converters and low cable impedances, a DC microgrid requires quick fault identification and isolation of defective sections. Due to the necessity for quick disconnection, there is a limited amount of time and data available for online fault distance calculation. Some existing approaches assume that source capacitors are connected at only one end of the cable, and therefore that only one end of the cable contributes to the fault current [9]. In multi-source DC microgrids, when fault current is provided from both ends, this may not be the case. In multi-source DC microgrids, when fault current is provided from both ends, this may not be the case. Furthermore, conventional communication-based solutions need data synchronization or a high-speed communication network. This paper offers an online fault localization technique for multi-source DC microgrids that does not rely on communication to address these concerns. A mathematical model of a faulty cable segment with sources at both ends is developed. The fault distance is calculated using this model and the data. The residual analysis confidence level is used to quantify the model's consistency with the data. To show the efficacy of the proposed method, a ring-type multi-source DC microgrid system is studied and simulated using a real-time digital simulator.

Because of the quick isolation of the problem and hence less available data, fault detection in a DC microgrid is a difficult process. Furthermore, unlike conventional systems, the presence of DC capacitors on both ends of the cable owing to power electronic converters allows fault current from both ends of the cable to contribute. This research uses voltage and current transients during faults to provide an online fault location approach that does not rely on communication.

A mathematical model of the faulty network is created, which is then employed in the fault location estimation process. To properly detect the problem and its associated fault resistance, the model is subjected to an estimation-based technique. The computed degree of confidence further confirms the estimated values. Internal problems are discovered with an inaccuracy of less than 2% and a confidence level of more than 95%. Both pole–pole and pole–ground faults may be solved using the suggested approach.

Unlike synchronous generators, the photovoltaic (PV) sources' short-circuit current is limited by grid-connected inverters and closely tied to normal circumstances, which has an influence on power system protection. The first half of this study examines the influence of the grid-connected PV (GCPV) system on traditional distance protection [10]. The second part of this study examines the protection of the power lines (distribution feeders) that link the PV power plants (PVPP) to the grid. To minimise this impact, a particular coordination between the grid side's over-current protection and the PVPP side's distance protection was utilised. This coordination necessitates delaying distance protection while keeping the inverter connected to the grid, which is accomplished via the fault ride-through (FRT) function in conjunction with inverter management during a fault state. The second section looks into the potential of employing double-end-impedance-based fault location on PVPP power lines, as well as various FRT techniques for reducing the impact of inverter control loops on fault location accuracy.

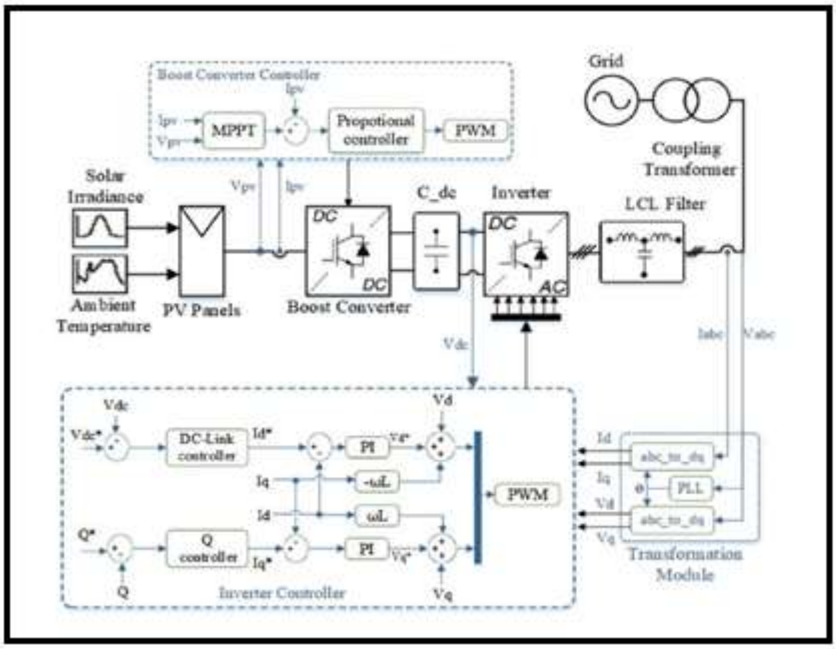

Fig.7. Control structure of the GCPV system [10]

The proposed coordination method between the PVPP distance relay and the grid OCR relay provides the best solution to eliminate this influence by utilizing inverter control features such as FRT capability, which provides voltage and frequency references during islanding mode, and reactive power injection to support grid voltage during fault conditions [10].
Except in cases when the grid side transformer capacity is very limited, the double-end fault location was effectively implemented and simulated with excellent accuracy. As a result, the accuracy of the fault location is indirectly determined by the value of the remote current sent to the grid side; the grid side transformer at the end of the distribution line determines how much grid side remote current may be shared during a fault state. Because it ensures the quality of the output currents, VCCF-FRT gives the greatest accuracy for the doubled end fault location when the grid current is relatively modest (120 kVA).

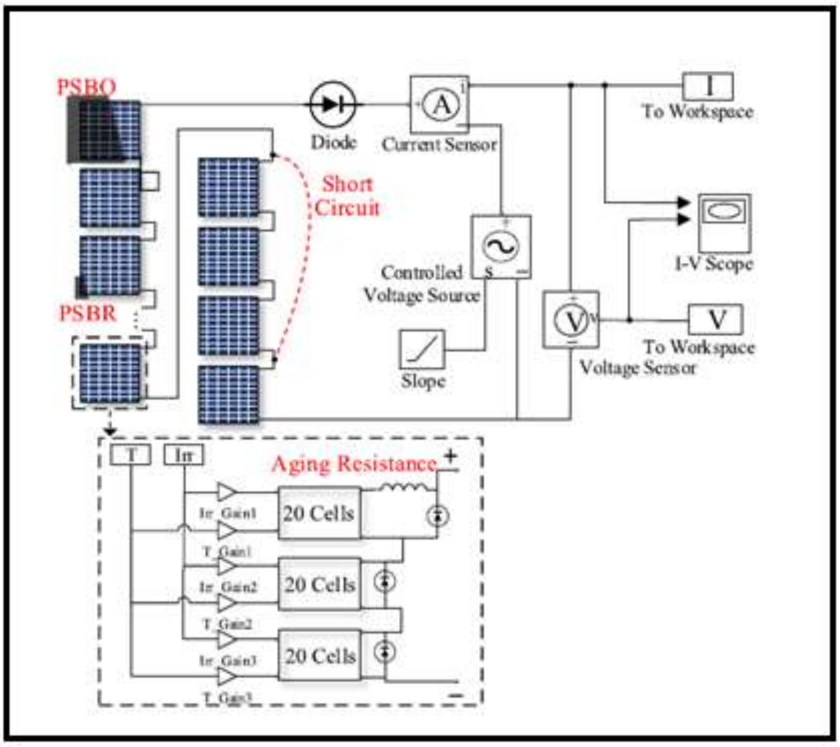

Fig.8. I-V testing circuit and PV module modeling via MATLAB/Simulink [11]

One of the methods [11] looks into a newly built fault diagnosis technique for a PVS using the three stages below. First, by studying I-V curves from various faults, including hybrid faults of the PVS under standard test conditions, optimum fault characteristics are derived (STC). To standardize fault characteristics into those covered by the STC, the trust-region-reflective (TRR) deterministic method is coupled with the particle-swarm-optimization (PSO) metaheuristic algorithm. To create the defect diagnostic model, a multi-class adaptive boosting (AdaBoost) method is used, which is the stage-wise additive modelling using multi-class exponential (SAMME) loss function based on the classification and regression tree (CART) as the weak classifier. The fault diagnosis model's efficacy might be maintained over time by changing the feature standardization equations to standardize fault characteristics into those covered by the STC on a regular basis. PV modules of various sorts are utilized to validate the fault diagnostic method's generalization.
In compared to other machine-learning algorithms, the PV diagnostic model based on the SAMME-CART method can achieve better accuracy. Both numerical simulations and actual data demonstrate that this research outperforms prior studies in terms of

classification and generalization. The proposed fault diagnostic model's generalization ability is validated by various modules, and it concludes that when fault data is insufficient, the suggested fault diagnostic model can still retain excellent accuracy by leveraging data from other PVS.

III. CONCLUSION

This article provides an overview of PVS fault detection and diagnosis methods. PV's dependability, efficiency, and operating cost have all become critical elements in increasing its competitiveness in the energy market. Many approaches for problem identification and diagnosis have been studied in attempt to overcome this issue, as illustrated in this study.

Methods based on ANN and FL can differentiate between faults with similar signatures and categories potential problems. The primary disadvantages are that they need more sophisticated abilities in terms of real-time implementation (experimental realisation) and databases (of various defects), which are not always accessible.

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