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Fault Diagnosis in Microgrids with Integration of Solar Photovoltaic Systems: A Review

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Abstract: Microgrids are essential components to help create the future electric grid which features a significant penetration of renewable and clean energy resources. However, a critical challenge in the protection of microgrids is the fault detection and diagnosis process, particularly in the presence of high uncertainties and varying topologies of microgrids. Faults in microgrids can cause instabilities, inefficient power generation, and other losses. Therefore, not only does it matter to understand various fault/failure modes and their root causes and effects, but it is also essential to develop real-time automated diagnosis tools to capture early signatures of fault evolution and enable proper mitigating actions. Given the significance of this issue, the present paper starts with a review of different failure modes occurring in various components of grid-connected photovoltaic systems, before offering a deeper review of the state of the art of fault diagnosis techniques specifically applied to solar photovoltaic systems in microgrids.

Keywords: microgrid, microgrid protection, fault detection and diagnosis, solar photovoltaic systems.

1. INTRODUCTION

Energy production is one of the most important requirements for economic development across the globe. For many years, modern humanity has used conventional sources of energy such as coal, oil and natural gas to generate energy in centralized unidirectional power plants. This type of energy production suffers from several disadvantages such as adverse environmental impacts, low energy efficiency, non-optimal usage of grid assets, and wide-spread blackout due to the hierarchical topology of the power grid (Farhangi, 2010).

One promising alternative to overcome the mentioned shortcomings of the conventional grid is the *smart grid*. Indeed, a smart grid is an intelligent grid which combines information technology, digital equipment and communication systems into the power grid in order to form a more flexible power grid with wide-area monitoring and control capabilities. In addition, the integration with distributed energy resources (DERs) and particularly renewable energy sources is facilitated using smart grid (Jadidi et al., 2019).

The first step towards the evolution of the smart grid from the existing power grid is smart *microgrid*. Indeed, microgrids are small-scale power grids that contain a cluster of distributed generation (DG) units, energy storage systems (ESS) and controllable loads. Microgrids are the basic components of the smart grid which can operate in grid-connected mode or islanded mode. A smart microgrid acts as a single controllable entity. For this reason, it typically uses a hierarchical control architecture equipped with a variety of sensing devices (Parhizi et al., 2015).

Nowadays, the penetration of renewable energy resources into the microgrids is increasing rapidly due to the clean and sustainable features of these resources. One common type of renewable energy systems is solar photovoltaic (PV) array. Although renewable energy systems are well-developed and have been used for many years, they encounter different types of fault/failure modes which may result in highly annual costs. By using a fault diagnosis scheme, different types of faults in the distributed components of the microgrid (including renewable energy resources) can be detected and predicted (Hare et al., 2016). Therefore, the total operation costs will be decreased with timely maintenance. In addition, it is worth mentioning that the information obtained from fault detection and diagnosis (FDD) unit can be further processed and used by control systems to accommodate fault effects using appropriate fault-tolerant control (FTC) methods (Zhang and Jiang, 2008). In this regard, it is firstly necessary to understand the different failure modes in microgrid components, before reviewing the different approaches that can be used for fault diagnosis.

This paper focuses on microgrids with the integration of solar PV systems. It begins with a review of different failure modes occurring in various components of grid-connected PV systems, and then offers a deeper review of the state of the art of fault diagnosis techniques specifically applied to PV systems in microgrids. The rest of the paper is organized according to the following structure: Section 2 describes different fault/failure modes in grid-connected PV systems. Section 3 presents cutting-edge FDD in PV systems, and reviews different approaches found in the relevant literature; and lastly, some conclusions are drawn in Section 4.

2. FAULTS IN PV SYSTEMS

Before providing a review on the available literature on fault detection and diagnosis methods in PV systems, it is essential to describe possible faults and failure modes, as well as their respective causes and effects. In a microgrid, faults may occur in different components including transmission lines and cables, power electronic converters, distributed energy resources and sensing devices. The following paragraphs

Table I. Faults in grid-connected PV systems

Component	Failure Mode	Cause	Effect
PV Array	• Degradation/Aging	Over exposer and corrosion	Reduction in output power Change in output voltage and current waveforms
	• Open/Short Circuit Faults	Decrease in cell resistance, manufacturing defects, corrosion, and mismatched cells	
	• Hot-Spots	Overheating and poor thermal conductivity	
	• Cell Cracks	During cell/module production process, wafer slicing, and PV panel wiring	
	• Fractured Glass	Natural occurrence, poor packaging in transportation and installation	
	• Delamination	Degradation of cell coating and moisture intrusion in modules	
	• Change in Radiation Intensity/ Shading Fault	Debris accumulation on the surface due to dust/bird dropping/leaves etc., partial shading caused by trees/buildings etc., heavy snow, and radiation change during day	
	• Faults in By-Pass Diodes	Overheating, manufacturing defect, and incorrect connections	
	• Line-to-Line (L-L) Fault	Unintentional connection between two nodes in PV array	
	• Line-to-Ground (L-G) Fault	Conductor connection with the ground or neutral conductor	
	• Ground Fault	Unintentional connection between modules in a PV string and ground	
	• Arc Fault	Damage in cells, corrosion of connectors, and insulation breakdown	
Power Converter	• MPPT Fault	Sensor fault in DC/DC converter with MPPT algorithm or problem in controller	Reduction in output power
	• Component Faults	High thermal and mechanical stress, reduction of capacitance and switch failure	Change in waveforms and unstable output voltage and power
AC Grid	• Transmission Lines	Physical contacts between three phases, overloading, total blackout due to lightening, natural disaster	Short circuit and fault current
	• Grid Failure	Line tripping, equipment failure, and disconnection due to faults or maintenance services	Unbalanced power

provide more information about the failure modes in a solar PV system.

Solar PV systems utilize solar radiation to generate DC electricity directly from the sunlight (Singh, 2013). In normal operating conditions, the output power of the PV system is very close to the predicted output power. However, during faulty operations, the output power and performance of the system decrease. It is crucial to identify which faults are happening in the system, and how they can be detected and accommodated. In PV systems, faults may occur in different components including internal parts of a PV array (cell, module, bypass diodes, and connections between them), sensors/actuators/components of power electronic converters that are normally used for microgrid integration (DC/DC converter equipped with maximum power point tracking (MPPT) algorithm, and AC/DC converter in hybrid microgrids), and AC side of the grid (Madeti and Singh, 2017a). Table I summarizes the most common faults in the different components of grid-connected PV systems, and their possible causes and effects. In a hybrid microgrid, the main faults in DC side of the PV system include open/short circuit faults in cell/module/string level and partial shading, and the main faults in AC side include grid malfunctions and faults in power electronic converters.

3. FAULT DIAGNOSTICS FOR PV SYSTEMS

Renewable energy systems are normally installed in outdoor environments. Because of the continuous exposure of these systems to harsh environmental conditions, they encounter a variety of faults. Therefore, a well-designed FDD scheme is required for the continuous monitoring of the system in order to detect the existence of any faults in the system (*fault detection*), determine which location and component has failed (*fault isolation*), and estimate the magnitude of the fault (*fault identification*) (Zhang and Jiang, 2008). As a result, the performance of these systems can be improved by minimizing the power losses caused by faults. Also, the information obtained from the FDD unit can be used by operators and/or controllers to take corrective actions for timely maintenance and fault accommodation. Depending on the type of renewable energy system, different parameters are measured to implement FDD methods. For instance, the output voltage and current of resources as well as grid characteristics in microgrid framework are some parameters that are measured. In addition, meteorological data such as total irradiance and ambient temperature (for PV systems), and wind speed and direction (for wind turbines) are other parameters used for monitoring renewable systems.

Generally, there are two main approaches for implementing FDD schemes: (1) *model-based* methods, and (2) *model-free* or *signal-based* methods. Both approaches can be based on *quantitative* and *qualitative* methods. Model-based schemes mainly consist of two stages: (1) *residual generation* which is the difference between the measured output and the estimated output obtained from the mathematical model or state/parameter estimator, and (2) *residual evaluation* which is used to detect and identify any possible fault in the system, sensors or actuators. Signal-based schemes normally rely on historical process data and use feature extraction methods and sometime signal processing techniques for fault detection. In the technical literature, different types of model-based and signal-In the technical literature, different types of model-based and signal-based FDD approaches for PV systems can be found. Tables II and III show the widely used model-based and signal-based approaches, respectively.

Table II. Model-based FDD approaches for grid-connected PV systems

Design Approaches	Ref.	Considered Faults
Artificial Neural Network (ANN)	Chine et al. (2016)	Module Faults / Connection Faults between Modules / Shading Fault
	Mekki et al. (2016)	Shading Fault
Probabilistic Neural Network (PNN)	Zhu et al. (2018)	Open/Short Circuit Faults / Shading Fault/Degradation
	Garoudja et al. (2017a)	Short Circuit Faults between Modules
Elman Neural Network (ENN)	Liu et al. (2018)	Open Circuit Faults / Shading Fault
Fuzzy Logic	Dhimish et al. (2017a)	Module Faults / Shading Fault
	Tadj et al. (2014)	Module/String Faults / Shading Fault
Adaptive Neuro Fuzzy (ANF)	Kaid et al. (2018)	Short Circuit Faults / Mismatch Fault / Bypass Diode Fault
	Belaout et al. (2018)	Short Circuit Fault / Shading Fault / Increased Series Resistance Losses / Bypass Diode Faults
Threshold-Based Method	Silvestre et al. (2016)	Open/Short Circuit Faults / Shading Fault / Inverter Faults
	Dhimish et al. (2017b)	Module Fault / Shading Fault in PV Array with Different Configurations
Adaptive Threshold Method	Ammiche et al. (2018)	Abrupt/Random/Drift Faults in Different Components of Grid-Connected PV System
Observer-Based Methods	Youssef and Sbita (2017)	Inverter Faults
	Poon (2015)	Inverter Faults
Decision Tree Analysis	Madeti and Singh (2017b)	Open/Short Circuit Faults / Module Faults / Shading Fault / MPPT Faults/Inverter Faults
	Hachana et al. (2016)	Shading Fault / Bypass Diode Fault / MPPT Fault
	Chine et al. (2014)	Module/String Faults / Shading Fault/Degradation / MPPT Fault / Inverter Faults
Polynomial Regression Model (PRM)	Ventura and Tina (2016)	DC/AC Side Faults in Inverter Level
Exponentially Weighted Moving Average (EWMA)	Mansouri et al. (2018a)	Shading Fault / Mismatch Fault / Bypass Diode Fault
	Garoudja et al. (2017b)	Shading Fault / Module Faults
Wavelet-Based Multiscale Exponentially Weighted Moving Average (WM-EWMA)	Harrou et al. (2019)	Open/Short Circuit Faults / Shading Fault
Weighted Generalized Likelihood Ratio Test (WGLRT)	Mansouri et al. (2018b)	Shading Fault / Mismatch Faults / Connection Failure / Bypass Diode Fault
T-Test Statistical Analysis	Dhimish et al. (2017c)	DC/AC Side Faults / Module Faults / Bypass Diode Fault / MPPT Fault / Inverter Faults
Matter-Element Model	Chao et al. (2008)	Module/String Faults
K-Nearest Neighbors (KNN)	Madeti and Singh (2018)	Open Circuit Faults / Shading Fault / Line-to-Line Faults
Genetic Algorithm	Das et al. (2018)	Open/Short Circuit Faults / Faults in PV Array under Non-uniform Irradiance and Temperature

Table III. Signal-based FDD approaches for grid-connected PV systems

Design Approaches	Ref.	Considered Faults
Kernel Extreme Learning Machine	Wu et al. (2017)	Short Circuit Faults / Shading Fault/Degradation
	Chen et al. (2017)	Open/Short Circuit Faults / Shading Faults/Degradation
Fuzzy Logic	Badihi et al. (2019)	Power Loss Fault in Microgrid Level / Inverter Faults
	Chen and Bazzi (2013)	Inverter Component Faults
Decision Tree Analysis	Zini et al. (2011)	Power Loss Fault in Microgrid Level
	Madeti and Singh (2017c)	Module Faults in String Level
	Zhao et al. (2012)	Module/String Faults
Wavelet Transform	Kim (2016)	Inverter Faults in Microgrid Level
Two-Stage Power-Based Method	Khoshnami and Sadeghkhani (2018)	Open Circuit Faults / Line-to-Line Faults / Line-to-Ground Faults / Module Faults

3.1. Neural Network-Based Methods

Neural network-based methods have been widely used throughout the literature. In Chine et al. (2016) a novel fault diagnosis technique based on an artificial neural network (ANN) is proposed, and two algorithms are developed to isolate and diagnose different types of faults in a PV array. These methods are also implemented on a field programmable gate array (FPGA) and are experimentally tested. A fault detection method based on ANN for a PV system under partially shaded conditions is considered in Mekki et al. (2016), and an ANN model is used to estimate the output voltage and current of the PV system under variable operating conditions. The PV array output characteristics under different fault conditions are investigated in Zhu et al. (2018), in which a probabilistic neural network (PNN) fault diagnosis model is also presented. A PNN-based classifier is introduced in Garoudja et al. (2017a) for fault detection and diagnosis in the DC side of the grid-connected PV system. Also, PNN method is compared with the feed-forward back-propagation ANN classifier for noiseless and noisy data to show the effectiveness of the proposed method.

Various mismatches such as partial shading and open circuit faults in PV systems are considered in Liu et al. (2018), and a novel condition monitoring method based on Elman neural network (ENN) for fault detection and classification is proposed. Lastly, some authors use kernel extreme learning machine (KELM) approaches for fault diagnosis in PV array. For instance, Wu et al. (2017) present an intelligent fault diagnosis method based on an improved radial basis function (RBF) KELM for identifying short circuit, degradation and shading faults. In Chen et al. (2017), the Nelder-Mead simplex (NMS) optimization method is utilized to optimize KELM parameters to improve fault classification performance. Then, the optimized KELM is used to train the fault diagnosis model of a PV array.

3.2. Fuzzy Logic Methods

In the technical literature, many papers use fuzzy logic approaches for fault detection. In Dhimish et al. (2017a), the theoretical curves which describe the dynamic behaviour of a grid-connected PV system are analysed, and polynomial functions are used to generate upper and lower limits for the obtained curves. A fuzzy logic classifier processes the samples that lie out of the limits for fault identification. Tadj et al. (2014) develop a fault detection method based on satellite image approach to estimate solar radiation and DC output power. Then, a fuzzy logic technique is used to improve the obtained model from data for fault detection. In Kaid et al. (2018), the main characteristic variables of a PV array are modelled using an adaptive neuro-fuzzy inference mechanism, and it is experimentally shown that the overall performance of the system is improved by the proposed method. A multiclass adaptive neuro-fuzzy classifier has been presented in Belaout et al. (2018) for the classification of 5 types of faults in a PV array, and the results are compared with an ANN classifier.

Some papers investigate fuzzy logic applications to power electronic converters in grid-connected PV systems. For instance, in Chen and Bazzi (2013), a generalized approach for FDD in power electronic converters based on data-driven methods is presented. The PV system in stand-alone mode is utilized as a testing platform, and open circuit and short circuit faults in different components of boost converter are diagnosed. In Badihi et al. (2019), a grid-connected PV system in microgrid level is considered. The effects of PV power loss fault and different types of faults in power converter on the microgrid are investigated, and an FDD scheme based on fuzzy logic is presented. Also, this paper considers the presence of dynamic loads in a hybrid microgrid which acts as disturbance sources for fault detection.

3.3. Threshold-Based Methods

Several papers try to develop and design FDD schemes based on threshold methods. Threshold limits and confidence bounds are normally used to capture the healthy dynamics of the system and distinguish between healthy and faulty operations. In Silvestre et al. (2016), a new approach for the remote monitoring and fault detection of a grid-connected PV system is presented. The monitored data and parameters are evaluated using threshold-based methods in real-time, and the methodology is experimentally validated in a grid-connected PV system located in Spain. Dhimish et al. (2017b) consider different configurations of PV arrays, and analyse their performance in different faulty conditions. A threshold-based method is used during the procedure. In Ammiche et al. (2018), an adaptive threshold method with a fuzzy logic filter is designed and applied to the fault detection of a grid-connected PV system. The developed method is based on moving window principal component analysis (MW-PCA) to generate adaptive thresholds for fault detection.

3.4. Decision Tree-Based Methods

Some papers use decision tree-based methods for fault detection and classification. A new FDD scheme for a grid-connected and islanded PV system is presented in Madeti and Singh (2017b). In order to obtain information about solar irradiance, ambient temperature and output current and voltage of the PV system, different types of sensors are used. This information is processed by a decision tree-based algorithm for fault classification. In Hachana et al. (2016), real-time data from PV array is used to model the system. Then, certain parameters are selected and evaluated to distinguish different PV faults. Finally, a decision tree algorithm is used for fault diagnosis. Chine et al. (2014) use the ratio between DC and AC power to determine the location of faults in a grid-connected PV system. In this paper, inverter faults and MPPT faults are also investigated, and experimental databases of a grid-connected PV system are used for validation of the proposed technique.

The reliability of large-scale grid-connected PV systems are assessed in Zini et al. (2011), and fault tree and probability analysis for the system are proposed. A new fault detection method based on decision tree is proposed in Madeti and Singh (2017c) to monitor the terminal characteristic of PV strings and arrays. Also, the proposed approach reduces the number of sensors using an optimization algorithm. A decision tree-based fault detection and classification method in a PV array is presented in Zhao et al. (2012). In order to train the decision tree model, some measurements of the PV systems such as PV array voltage, current, ambient temperature and irradiance are used.

3.5. Other Approaches

In this subsection, other model-based and model-free approaches available in the literature are introduced. In Poon (2015), an observer-based FDD method for switching power electronic converters is designed and experimentally implemented. The proposed scheme can be integrated with the converter control systems without any additional computation hardware. Applications of adaptive observers on sensors fault detection and isolation of a three-phase inverter are investigated in Youssef and Sbita (2017). A fault-tolerant control (FTC) method is also introduced to replace the erroneous measurement by corresponding estimated value in the case of faults in a PV system.

A model-based FDD scheme for the detection of faults on the DC side of the grid-connected PV system is proposed in Garoudja et al. (2017b). An exponentially weighted moving average (EWMA) control chart is used for this purpose. Mansouri et al. (2018a) combine the advantages of EWMA, multi-objective optimization and wavelet representation to develop a novel technique for PV power system monitoring. In addition, the proposed method, called wavelet optimized EWMA, is compared with classical EWMA and Shewhart charts. The problem of measurement noise gathered from PV systems is discussed in Harrou et al. (2019). A robust and flexible FDD method based on EWMA algorithm is also introduced for DC side faults of the PV systems.

Various other approaches can be found in the literature, including the following: a fault detection algorithm based on wavelet transform is presented in Kim (2016). In this paper, multi-level decomposition wavelet transformation is utilized to detect and diagnose possible faults in the inverter. K-nearest neighbours (KNN) method is used in Madeti and Singh (2018) to implement a string level fault detection and diagnosis for a PV array. Also, the PV system is modelled using experimental data. Das et al. (2018) employ metaheuristic optimization method as fault detection method in a PV array. The output power of the PV array is estimated using a simulation model, and a mathematical optimizer based on genetic algorithm (GA) is used to predict the fault patterns in the PV array. In order to reduce false alarms and missed detection rates of PV systems, Mansouri et al. (2018b) propose an improved statistical fault detection method based on multiscale weighted generalized likelihood ratio test (MS-WGLRT). A set of real data is used to prove the effectiveness of the proposed method. Authors in Dhimish et al. (2017c) use *t*-test statistical analysis to develop a fault detection algorithm to diagnose faults in DC and AC side of a grid-connected PV system. MPPT faults and inverter faults are also considered in the paper. A power-based FDD scheme for a PV array is presented in Khoshnami and Sadeghkhani (2018). The proposed scheme consists of two stages. The first stage detects the disturbances using the amplitude of the normalized super-imposed component of PV power, while the second stage differentiates faulty conditions from partial shading. Ventura and Tina (2016) develop a physical model for a PV system to estimate DC and AC powers. During the procedure, polynomial regression models are used and explained, and a methodology for monitoring a PV system is presented. Lastly, a novel fault diagnosis method based on the extended correlation function and the matter-element method is developed in Chao et al. (2008).

4. CONCLUSIONS AND FUTURE DIRECTIONS

Condition-based monitoring and fault diagnosis are essential for the reliable operation of microgrids with high penetration of renewable energy systems. In this brief review paper, various faults and fault detection and diagnosis techniques in DC and AC sides of grid-connected PV systems in microgrid frameworks are discussed. The intention of this paper was to provide useful information about different types of faults which may occur in components of PV systems including cell/module faults, bypass diodes, inverter faults and grid failures. Also, a comprehensive review on different model-based and signal-based fault detection and diagnosis techniques are presented and discussed in details.

Finally, it is worth mentioning that the majority of prior researches in fault detection and diagnosis of grid-connected PV systems only considered either DC side faults (at module/string level in a PV array), or AC side faults (with integration to the high-inertia power grid). However, in a microgrid framework, there is a strong coupling between different components of the system. Any sudden change in microgrid components may have adverse impacts on the reliability of fault detection and diagnosis schemes. Therefore, the robustness of fault detection and diagnosis unit against microgrid disturbances requires further investigations. Also, additional research must be conducted in model-based and model-free approaches for fault detection and diagnosis, as well as their integration with novel fault-tolerant control methods.

REFERENCES

Ammiche, M., Kouadri, A., Halabi, L.M., Guichi, A., and Mekhilef, S., (2018). Fault detection in a grid-connected photovoltaic system using adaptive thresholding method. *Solar Energy*, 174, pp. 762-9.

Badihi, H., Jadidi, S., Zhang, Y.M., Su, C.Y., and Xie, W.F., (2019). AI-driven intelligent fault detection and diagnosis in a hybrid AC/DC microgrid. *The 1st International Conference on Industrial Artificial Intelligence (IAI)*, Shenyang, China.

Belaout, A., Krim, F., Mellit, A., Talbi, B., and Arabi, A., (2018). Multiclass adaptive neuro-fuzzy classifier and feature selection techniques for photovoltaic array fault detection and classification. *Renewable Energy*, 127, pp. 548-558.

Chao, K.H., Ho, S.H., Wang, M.H., (2008). Modeling and fault diagnosis of a photovoltaic system. *Electric Power Systems Research,* 78(1), pp. 97-105.

Chen, W., and Bazzi, A.M., (2013). A generalized approach for intelligent fault detection and recovery in power electronic systems. *IEEE Energy Conversion Congress and Exposition,* pp. 4559-4564.

Chen, Z., Wu, L., Cheng, S., Lin, P., Wu, Y., and Lin, W., (2017). Intelligent fault diagnosis of photovoltaic arrays based on optimized kernel extreme learning machine and IV characteristics. *Applied Energy*, 204, pp. 912-931.

Chine, W., Mellit, A., Pavan, A.M., and Kalogirou, S.A., (2014). Fault detection method for grid-connected photovoltaic plants. *Renewable Energy*, 66, pp. 99-110.

Chine, W., Mellit, A., Lughi, V., Malek, A., Sulligoi, G., and Pavan, A.M., (2016). A novel fault diagnosis technique for photovoltaic systems based on artificial neural networks. *Renewable Energy*, 90, pp. 501-512.

Das, S., Hazra, A., and Basu, M., (2018). Metaheuristic optimization-based fault diagnosis strategy for solar photovoltaic systems under non-uniform irradiance. *Renewable Energy*, 118, pp. 452-467.

Dhimish, M., Holmes, V., Mehrdadi, B., and Dales, M., (2017a). Diagnostic method for photovoltaic systems based on six-layer detection algorithm. *Electric Power Systems Research*, 151, pp. 26-39.

Dhimish, M., Holmes, V., Mehrdadi, B., Dales, M., Chong, B., and Zhang, L., (2017b). Seven indicators variations for multiple PV array configurations under partial shading and faulty PV conditions. *Renewable Energy*, 113, pp. 438-460.

Dhimish, M., Holmes, V., and Dales, M., (2017c). Parallel fault detection algorithm for grid-connected photovoltaic plants. *Renewable Energy*, 113, pp. 94-111.

Farhangi, H., (2010). The path of the smart grid. *IEEE Power and Energy Magazine,* 8(1), pp. 18-28.

Garoudja, E., Chouder, A., Kara, K., and Silvestre, S., (2017a). An enhanced machine learning based approach for failures detection and diagnosis of PV systems. *Energy Conversion and Management*, 151, pp. 496-513.

Garoudja, E., Harrou, F., Sun, Y., Kara, K., Chouder, A., and Silvestre, S., (2017b). Statistical fault detection in photovoltaic systems. *Solar Energy*, 150, pp. 485-99.

Hachana, O., Tina, G.M., and Hemsas, K.E., (2016). PV array fault diagnostic technique for BIPV systems. *Energy and Buildings*, 126, pp. 263-274.

Hare, J., Shi, X., Gupta, S., and Bazzi, A., (2016). Fault diagnostics in smart micro-grids: A survey. *Renewable and Sustainable Energy Reviews*, 60, pp. 114-124.

Harrou, F., Taghezouit, B., and Sun, Y., (2019). Robust and flexible strategy for fault detection in grid-connected photovoltaic systems. *Energy Conversion and Management*, 180, pp. 1153-1166.

Jadidi, S., Badihi, H., Zhang, Y. (2019). A Review on Operation, Control and Protection of Smart Microgrids. *IEEE 2nd International Conference on Renewable Energy and Power Engineering (REPE)*, pp. 100-104.

Kaid, I.E., Hafaifa, A., Guemana, M., Hadroug, N., Kouzou, A., and Mazouz, L., (2018). Photovoltaic system failure diagnosis based on adaptive neuro fuzzy inference approach: South Algeria solar power plant. *Journal of Cleaner Production*, 204, pp. 169-182.

Kim, I.S., (2016). On-line fault detection algorithm of a photovoltaic system using wavelet transform. *Solar Energy*, 126, pp. 137-45.

Khoshnami, A., and Sadeghkhani, I., (2018). Two-stage power–based fault detection scheme for photovoltaic systems. *Solar Energy*, 176, pp. 10-21.

Liu, G., Yu, W., and Zhu, L., (2018). Condition classification and performance of mismatched photovoltaic arrays via a pre-filtered Elman neural network decision making tool. *Solar Energy*, 173, pp. 1011-1024.

Madeti, S.R., and Singh, S.N., (2017a). A comprehensive study on different types of faults and detection techniques for solar photovoltaic system. *Solar Energy*, 158, pp. 161-185.

Madeti, S.R., and Singh, S.N., (2017b). Online modular level fault detection algorithm for grid-tied and off-grid PV systems. *Solar Energy*, 157, pp. 349-364.

Madeti, S.R., and Singh, S.N., (2017c). Online fault detection and the economic analysis of grid-connected photovoltaic systems. *Energy*, 134, pp. 121-135.

Madeti, S.R., and Singh, S.N., (2018). Modeling of PV system based on experimental data for fault detection using kNN method. *Solar Energy*, 173, pp. 139-151.

Mekki, H., Mellit, A., and Salhi, H., (2016). Artificial neural network-based modelling and fault detection of partial shaded photovoltaic modules. *Simulation Modelling Practice and Theory*, 67, pp. 1-3.

Mansouri, M., Al-Khazraji, A., Hajji, M., Harkat, M.F., Nounou, H., and Nounou, M., (2018a). Wavelet optimized EWMA for fault detection and application to photovoltaic systems. *Solar Energy*, 167, pp. 125-136.

Mansouri, M., Hajji, M., Trabelsi, M., Harkat, M.F., Al-khazraji, A., Livera, A., Nounou, H., and Nounou, M., (2018b). An effective statistical fault detection technique for grid connected photovoltaic systems based on an improved generalized likelihood ratio test. *Energy*, 159, pp. 842-856.

Parhizi, S., Lotfi, H., Khodaei, A., and Bahramirad, S., (2015). State of the art in research on microgrids: A review. *IEEE Access,* 3, pp. 890-925.

Poon, J., (2015). *Model-Based Fault Detection and Identification for Power Electronics Systems*, University of California at Berkeley.

Silvestre, S., Mora-López, L., Kichou, S., Sánchez-Pacheco, F., Dominguez-Pumar, M., (2016). Remote supervision and fault detection on OPC monitored PV systems. *Solar Energy*, 137, pp. 424-433.

Singh, G.K., (2013). Solar power generation by PV (photovoltaic) technology: A review. *Energy*, 53, pp. 1-3.

Tadj, M., Benmouiza, K., Cheknane, A., and Silvestre, S., (2014). Improving the performance of PV systems by faults detection using GISTEL approach. *Energy Conversion and Management*, 80, pp. 298-304.

Ventura, C., and Tina, G.M., (2016). Utility scale photovoltaic plant indices and models for on-line monitoring and fault detection purposes. *Electric Power Systems Research*, 136, pp. 43-56.

Wu, Y., Chen, Z., Wu, L., Lin, P., Cheng, S., and Lu, P., (2017). An intelligent fault diagnosis approach for PV array based on SA-RBF kernel extreme learning machine. *Energy Procedia*, 105, pp. 1070-1076.

Youssef, F.B., and Sbita, L., (2017). Sensors fault diagnosis and fault tolerant control for grid connected PV system. *International Journal of Hydrogen Energy*, 42(13), pp. 8962-8971.

Zhang, Y.M., Jiang, J., (2008). Bibliographical review on reconfigurable fault-tolerant control systems. *Annual Reviews in Control,* 32(2), pp. 229-252.

Zhao, Y., Yang, L., Lehman, B., de-Palma, J.F., Mosesian, J., Lyons, R., (2012). Decision tree-based fault detection and classification in solar photovoltaic arrays. *The 27th Annual IEEE Applied Power Electronics Conference and Exposition,* pp. 93-99.

Zhu, H., Lu, L., Yao, J., Dai, S., and Hu, Y., (2018). Fault diagnosis approach for photovoltaic arrays based on unsupervised sample clustering and probabilistic neural network model. *Solar Energy*, 176, pp. 395-405.

Zini, G., Mangeant, C., and Merten, J., (2011). Reliability of large-scale grid-connected photovoltaic systems. *Renewable Energy*, 36(9), pp. 2334-2340.