IMPROVED INTELLIGENT METHOD FOR DETECTION AND CLASSIFICATION OF DC SERIES ARC FAULT IN PHOTOVOLTAIC SYSTEM

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DEDICATION

To Allah the Almighty, who saw me through the challenging periods of this study and give me ability, strength and wisdom to complete this thesis. Words cannot express my dept of gratitude to Allah, who gave me the good health, knowledge and strength to complete the thesis. I could not have made it without his grace and mercy. I would forever remain grateful.

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ABSTRACT

Series Arc Fault (SAF) is a failure that occurs between two electrical contacts and electrical circuitry. However, it is considered one of the common malfunctions of photovoltaic (PV) systems that causes serious problems, including fires and electric shocks. There are several reasons that can cause this type of failure, including incorrect installation, irregular maintenance, and environmental factors. The process of SAF detection and diagnosis is considered a significant problem as many plants with a substantial increase in their capacities are continuously coming into existence. However, to achieve safe maintenance, reliability, and productivity of large-scale PV plants, it is essential to develop a new intelligent method that presents a precise automatic detection and protection of any maloperation among thousands of PV modules. In this research, the characteristic and the behaviour of the DC series arc fault signals are analysed and modelled; nine models with different properties regarding each model are simulated. In addition, an intelligent detection and classification method that can precisely detect and classify the DC series arc fault in the PV system among the other normal or abnormal conditions are developed. Also, a validation to achieve all the requirements and further improve in the efficiency of the proposed method are presented through a comprehensive comparison with the previous methods based Artificial Intelligence including Artificial Neural Network (ANN), SVM, Fuzzy, HMM, and Convolutional Neural Network (CNN). The comparison is carried out in terms of high accuracy, fault classification ability, reliability, safety, and the Computational Complexity/Effort of the power plants. Two systems are designed and built, where each system has two levels. A change detection approach is developed in the first system using ANN which incorporates four different models with various dimensions of CNN to classify the input signal. In the second system, a Multilayer Perceptron (MLP) is used to detect abnormal signals, while a Bi-Directional Long Short-term Memory (MLP-BiLSTM) is developed to classify abnormal signals precisely. The presented systems can distinguish between different cases of signal input, including normal (inverter start-up and load change), short circuit fault, and SAF. Furthermore, various models of DC series arc fault alongside with the practical experimental records are employed with PSCAD as a tool for creating these models. Python code is used to build and evaluate the performance of the proposed methods. The performance evaluation of the two proposed systems is carried out by considering several scenarios, where each system has its own features, such as removing the vanishing, dropout problems and ensuring reliability. The achieved accuracy is approximately 98% using the proposed systems. The results demonstrated that the proposed systems have the ability to detect the series arc with a high accuracy and outperform the existing works.

ABSTRAK

Kerosakan arka siri (SAF) adalah kegagalan yang berlaku antara dua kontak elektrik dan litar elektrik. Walau bagaimanapun, ia dianggap sebagai salah satu kerosakan biasa sistem fotovoltaik (PV) yang menyebabkan masalah serius, termasuk kebakaran dan kejutan elektrik. Terdapat beberapa punca yang boleh menyebabkan kegagalan jenis ini, termasuklah pemasangan yang salah, penyelenggaraan yang tidak teratur dan faktor persekitaran. Proses pengesanan dan diagnosis SAF dianggap sebagai masalah yang penting kerana banyak loji-loji dengan peningkatan yang ketara dalam kapasiti mereka wujud secara berterusan. Walau bagaimanapun, untuk mencapai penyelenggaraan yang selamat, kebolehpercayaan, dan produktiviti loji PV berskala besar, adalah penting untuk membangunkan kaedah pintar baharu yang menunjukkan pengesanan automatik yang tepat dan melindungi dari sebarang maloperasi di kalangan beribu-ribu modul PV. Dalam penyelidikan ini, ciri dan tingkah laku isyarat kesalahan arka siri DC dianalisis dan dimodelkan; sembilan model dengan sifat yang berbeza mengenai setiap model akan disimulasikan. Disamping itu, kaedah pengesanan dan klasifikasi pintar yang dapat mengesan dan mengklasifikasikan kerosakan arka siri DC dengan tepat dalam sistem PV antara keadaan normal atau tidak normal akan dibangunkan. Juga, pengesahan untuk mencapai semua keperluan dan meningkatkan tahap kecekapan kaedah yang dicadangkan akan dibentangkan melalui perbandingan komprehensif dengan kaedah sebelumnya berdasarkan Kepintaran Buatan termasuk Rangkaian Neural Buatan (ANN), SVM, Fuzzy, HMM dan Rangkaian Neural Konvolusi (CNN). Perbandingan dilakukan dari segi ketepatan yang tinggi, keupayaan klasifikasi kesalahan, kebolehpercayaan, keselamatan, dan Kerumitan Pengkomputeran/Usaha loji kuasa. Dua sistem direka dan dibina, di mana setiap sistem mempunyai dua tahap. Pendekatan pengesanan perubahan dibangunkan dalam sistem pertama menggunakan ANN yang menggabungkan empat model berbeza dengan pelbagai CNN untuk mengklasifikasikan isyarat input. Dalam sistem kedua, Perseptron Berbilang Lapis (MLP) digunakan untuk mengesan isyarat yang tidak normal, manakala Memori Jangka Pendek Panjang Dwi Arah (MLP-BiLSTM) dibangunkan untuk mengklasifikasikan isyarat yang tidak normal dengan tepat. Sistem yang ditunjukkan dapat membezakan antara kes berbeza bagi isyarat input, termasuk yang normal (pemula penyongsang dan perubahan beban), kesalahan litar pintas, dan SAF. Tambahan pula, pelbagai model kesalahan arka siri DC bersama dengan rekod eksperimen praktikal digunakan dengan PSCAD sebagai alat untuk mencipta model ini. Kod Phyton digunakan untuk membina dan menilai prestasi kaedah yang dicadangkan. Penilaian prestasi keduadua sistem yang dicadangkan adalah dijalankan dengan mempertimbangkan beberapa senario, di mana setiap sistem mempunyai ciri-ciri tersendiri, seperti menyingkirkan yang lenyap, masalah keciciran dan memastikan kebolehpercayaan. Ketepatan yang dicapai adalah kira -kira 98% menggunakan sistem yang dicadangkan. Keputusan menunjukkan bahawa sistem yang dicadangkan mempunyai keupayaan untuk mengesan arka siri dengan ketepatan yang tinggi dan mengatasi kerja - kerja yang sedia ada.

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LIST OF ABBREVIATIONS

SAF	-	Series Arc Fault
PV	-	Photovoltaic
PVC	-	Photovoltaic Cells
MPPT	-	Maximum Power Point Tracking
PSCAD	-	Power Systems Computer Aided Design
DC	-	Direct Current
AC	-	Alternating Current
CCC	-	Current Carrying Conductors
NEC	-	National Electrical Code
TI	-	Texas Instruments
AFCI	-	Arc Fault Circuit Interrupters
GFDI	-	Ground Fault Detector and Interrupters
PCA	-	Principal Component Analysis
WT	-	Wavelet Transform
DWT	-	Discrete Wavelet Transform
WPD	-	Wavelet Packet Decomposition
DFT	-	Discrete Fourier Transform
STFT	-	Short Time Fourier Transform
FFT	-	Fast Fourier Transform
AI	-	Artificial Intelligence
ML	-	Machine Learning
ANN	-	Artificial Neural Network
SVM	-	Support Vector Machines
CNN	-	Convolutional Neural Network
LSTM	-	Long Short-Term Memory
Bi-LSTM	-	Bidirectional Long Short-Term Memory
MLP	-	Multilayer Perceptron
ANNBM	-	Artificial Neural Network Based Model
EM	-	Estimation Model
RNN	-	Recurrent Neural Network

Bi-RNN	-	Bi-Directional Recurrent Neural Network
1D CNN	-	One Dimensional Convolution Neural Network
2D CNN	-	Two-Dimensional Convolution Neural Network
3D CNN	-	Three-Dimensional Convolution Neural Network
HMM	-	Hidden Markov Model
FC	-	Fully Connected
FCNN	-	Fully Connected Neural Network
VSC-HVDC	-	Voltage Source Converter-Based High Voltage Direct Current
PHM	-	Population Health Management
BBN	-	Bayesian Belief Networks
V	-	Voltage Signal
GW	-	Gigawatt
FEA	-	Finite Element Analysis
EN	-	European Standard
V-I	-	Voltage - Current
EMF	-	Electromotive Force
RF	-	Radio Frequency
RMS	-	Root Mean Square
SNR	-	Signal to Noise Ratio
MCD	-	Minimum Covariance Determinant
FIR	-	Finite Impulse Response
IIR	-	Infinite Impulse Response
PEC	-	Photoelectrochemical
SR-MT	-	Service Request Management Tool
GPS	-	Global Positioning System
EV	-	Electric Vehicle
VGG	-	Visual Geometry Group
FPGA	-	Field Programmable Gate Arrays
ASIC	-	Application Specic Integrated Circuit

LIST OF SYMBOLS

v_{ij}^{xy}	-	The unit value at a specific position defined by (x, y) i^{th} layer and j^{th} feature map
$tanh()$	-	The function of the hyperbolic tangent
b_{ij}	-	The feature map bias
m	-	An index over the feature maps set in the $(i-1)^{th}$ layer linked to the Current feature map
w_{ijm}^{pq}	-	The value measured at (p, q) kernel position
K^{th}	-	The value of feature map
Qi	-	The width of the kernel
Pi	-	The height of the kernel
R_i	-	The 3D kernel size along the temporal dimension
R_{gap}	-	Variable resistor
i_{gap}	-	Gap current
e_{gap}	-	Electromotive pulse force
x_{gap}	-	The distance between the cathode and the anode
x_{crit}	-	The boundary between the quenching stages and arc's burning
λ	-	Slope
V_{dc}	-	DC voltage average before the arc
V_0	-	Constant parameter related to arc length
A	-	The drop in the electrode voltage
B	-	The gradient in voltage
L	-	The length of the arc
C, D	-	The arc’s nonlinear characteristic constants
X, Y, Z	-	The constants
a, b	-	Parameters related to the length of the arc and the material of the electrode
v	-	The arc voltage
i	-	The arc current
τ	-	Time constant

τ_c	-	Time constant in cassie model
τ_m	-	Time constant in mayr model
P_0	-	The power required for cooling
P	-	The arc power
g	-	The conductance of the arc
T	-	The number of the right cases of series arc fault detection
F	-	Represent the number of mistakes.
Pr	-	Precision
TR	-	The number of rightly predicted true noticing
FR	-	Represent the number of undetected faults

CHAPTER 1

INTRODUCTION

1.1 Introduction

Recently, renewable energy has become an essential power source due to the change in climate and the concerns of decreasing fossil fuel resources. The technology of photovoltaic (PV) system can be considered a good choice of energy generation to achieve this demand due to its suitable characteristics, such as compatibility with the environment, lower costs for PV modules [1], short installation time, and low maintenance cost [2][3]. Therefore, the installation capacity of the global power plant of PV has been raised from 1.3 GW to 177 GW between 2000 to 2014 [3]. At the end of 2016, approximately 310 GW capacity was generated from the installed global PV [4]. The development of solar power is continuously increased worldwide, especially the grid-connected PV generation or the residential rooftop solar panels that can support the microgrids and the main loads.

PV systems can exploit the sun’s energy to generate electricity. Small but powerful generating units can considerably decrease a household’s net power consumption from the grid. Large infrastructure with a large number of units can be used to support power generated by more traditional plants and fatten it into the grid [5]. The number of PV installations providing power is rapidly increasing as their popularity grows due to lower installation costs and higher electricity costs. PV systems are being installed in many homes and utilities worldwide to produce power to their loads. Power supply networks have traditionally been centralised, with large power generators, a transmission and distribution network, and distributed loads. A central station monitors and controls the generators and network infrastructure. Troubles, such as an arc fault that can lead to a fire, and taking immediate action to control the situation can be easily performed because of the high monitoring level of generators. With PV systems, generation is becoming more decentralised and less centralised. Individual modules and cable connections receive less direct oversight due to the large size of many utility scale systems and the distributed nature of household systems. A whole array or string may be monitored in a large utility scale system, but individual modules may not be.

Increasing the number of PV systems and the level of DC voltage has the high probability of generating DC arc faults (in the USA, between 600 and 1000 V can be typically produced by utility-scaled PVC solar farms, and between 120 and 600 V can be typically generated by PV building systems) [6]–[10]. Without proper scheduled maintenance of connectors, cables, conductors and other components of the system (these components usually suffer from deterioration due to the effect of weathering and aging), the DC arc potentially occurs in the PV systems [11]. In accordance with the summaries of [12]–[36], arc faults are considered to be prevalent events in PV systems [21]–[30]. Severe damage in system components can be caused by the plasma with an elevated temperature created by the sustained arcs [37]. Arc fault creates a path in the air for the current, and this path might be created from the presence of any cut-off in the conductors that carry the current or the insulation failure in the nearby carrying conductors of the current. Any category of an arc fault is dangerous to the PV system and can result in fire, which may lead to burnout isolation and fire risks in the surrounding area to the PV plant that contains flammable materials [38]–[43]. Three types of arc fault, namely, parallel, ground and series, are found in the PV system. A parallel and ground arc fault occurs because of any existence of arc fault between any two nearby conductors at various potentials. The overcurrent function is usually used to easily detect the high-frequency noise introduced in the DC current inside the PV array. However, some parallel arc faults need PV string short-circuiting, module-level disconnects or module terminals after they have been disconnected from the inverter for arc de-energizing. As shown in Figure 1.1, a series arc fault can occur in accordance with any arc generated from the discontinuity of any current-carrying conductors [44]–[46]. The discontinuity is commonly due to the damage of a cell, connectors' corrosion, solder disjoint, damage by a rodent, and abrasion from various sources. When the DC operating voltage is equal to or higher than 80 V, the National Electrical Code (NEC-2011) states that a PV system needs a protection device against the series arc fault. These protection devices are termed as arc fault circuit interrupters (AFCIs)

[47][48]. AFCI and ground fault detector and interrupter devices are mounted in the PV system inverter. Any fault that occurs can be read out through a display that is located on the front panel of the inverter.

AFCI devices are often used to stop the PV system operation when a series arc fault occurs. However, they might not have the ability to respond correctly in the existence of a parallel arc fault. Consequently, parallel and series arc faults can be easily recognised from each other by detecting the sudden drop in the current/voltage, which is related to the increase in noise in the DC current. All series of arc faults can be extinguished via the PV array disconnection from the inverter. This process can be done by opening one of the terminals in each string of the PV. However, series arc faults are still the most challenging to be detected because of their low current compared with parallel arc faults. Therefore, many researchers have attempted to establish an effective detection method that can precisely identify them.

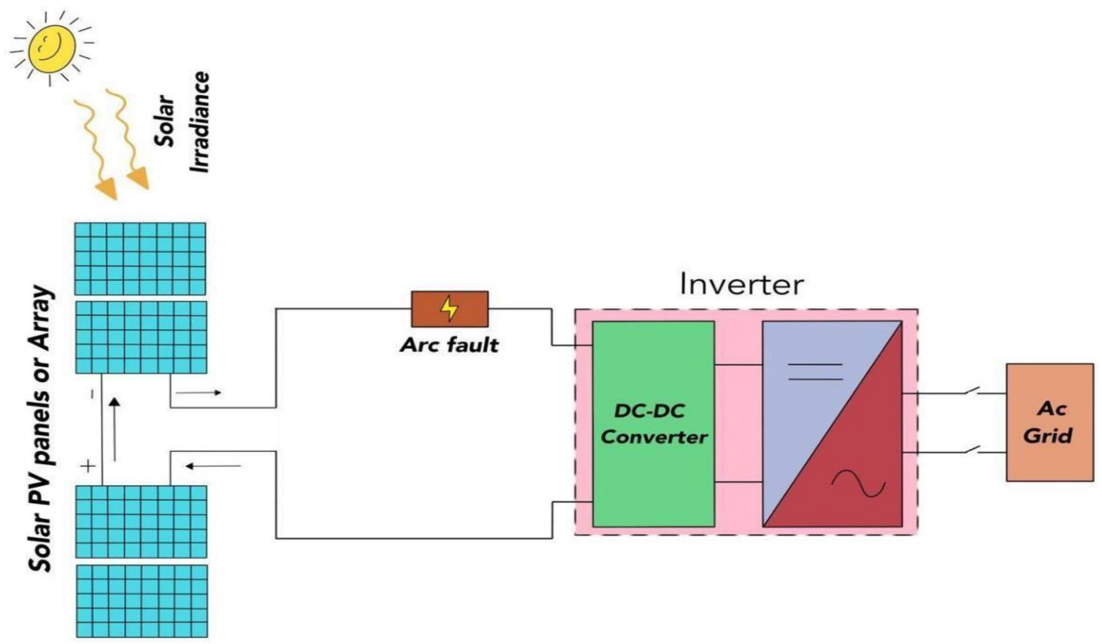

Figure 1.1 DC series arc fault in PV system

1.2 Motivation

Several special conditions are considered in the development of DC arc fault detection for PV systems. The motivation of this work can be summarised as follows:

1. In recent years, the use of the PV system as a source of clean energy and an alternative to fossil fuels that cause pollution has significantly increased, where it converts the solar energy to the electrical energy used in the homes.

2. High voltages as 600 V in the U. S. and reaching to 1000 V in other countries are used in modern grid-interactive models [6][7]. High-voltage DC arcs are more challenging to extinguish, especially when they are energised.

3. A substantial percentage of a PV system's DC wiring is not encapsulated within an enclosure. Wiring of string (such as run conductors of home) is commonly trimmed to the PV modules' frame and racking's backside. Some exposed faults may occur in the conductors, posing a higher risk to nearby flammable materials.

4. Three types of arc fault can occur in the PV system: series, parallel and ground. However, parallel and ground arc faults can be detected in accordance with the associated high current compared with the series arc fault. Overcurrent protection can be used to detect parallel and ground arc faults.

5. Series arc fault is difficult to be diagnosed with the overcurrent protection method. An electrical shock hazard and fires can occur because of this arc fault. Therefore, it acts as an attraction point for researchers to find different detection methods for avoiding the risks associated with it. The wiring between modules contains a large number of connectors due to the configurable characteristic of the string design. Each one of them represents a distinct point of failure.

1.3 Problem Statement

The process of series arc fault detection and diagnosis in large-scale PV plants is considered to be an important problem because many plants with a substantial increase in their capacities continuously emerge. However, a new intelligent method that presents a precise automatic detection and protection of any maloperation amongst thousands of PV modules must be developed to achieve safe maintenance, reliability and productivity of large-scale PV plants. These conditions can be summarised as follows:

(a) Overcurrent protection can be used to detect parallel and ground arc faults. Series arc fault is difficult to be diagnosed with the overcurrent protection method [49][50]. Once an arc or fire starts, the PV modules can continue to feed power to the fire in daylight, even in cloudy conditions [51]. A comprehensive dataset of series arc fault signals regarding more than one model should be generated to simplify the study of a critical issue of series arc faults in the PV system. Electric arc models used for simulation can be divided into three forms: physical principle-based models, conventional V–I empirical models obtained from measured data, and heuristic models [52]. Each model has a special characteristic different from the other. One model used in many previous studies leads to inadequate results of the detection method. Therefore, more than one model is needed to acquire DC series arc fault dataset.

(b) Along with the drive to increase renewable energy usage, the installed capacity of solar power system has grown exponentially [3]. The presence of multiple sources in a fault condition is the primary cause of difficulty in fault identification and location. Therefore, the protection of this system against DC series fault is an important issue [53][54]. However, creating a precise detection and classification method is challenging; therefore, attempts to develop a detection and classification method with high accuracy are not presented [52]. The detection algorithm should be able to classify and distinguish the arc fault from no-fault conditions. The algorithm must not send false detection signals due to environmental noises or standard operating conditions [52]. Therefore, further work is required to develop a detection and classification method that is more accurate and reliable.

(c) Some of the critical issues, such as accuracy, fault classification ability, reliability, safety and computational complexity/effort, should be considered during the development of artificial intelligence (AI)-based detection method. These issues can cause a series of problems that can influence the detection method progress, which results in a performance degradation [52]. Consequently, the performance of the proposed method should be validated to ensure its efficiency.

1.4 Research Objective

The main aim of this research is to achieve a detection and classification method for DC series arc fault in the PV system with high accuracy. The research objectives are as follows:

(a) To model and simulate the DC series arc fault signals based on the characteristic and behaviour of the DC series arc. Nine models with different properties are simulated.

(b) To establish an effective and intelligent structure for the precise detection and classification of DC series arc faults with low complexity and high accuracy. The developed method guarantees the reliability and safety of DC network protection by fast and accurate detection of series arc faults. The detection and classification method can precisely discriminate between the exact series arc fault, other similar faults that can occur in the PV system, and the noise present in practice. A change detection method is proposed to be incorporated for detecting any changes that may occur in the signals. In this case, an alert is sent to the classification model for starting the classification process.

(c) In order to validate and satisfy all the required criteria, as well as to achieve better efficiency; a two-step of evaluation process is used. first, the dataset was validated by conducting an experimental to obtain real dataset of DC series arc fault. Second, the proposed method is evaluated in terms of (high accuracy, fault classification ability, reliability, safety, and the Computational Complexity /Effort) in comparison to previous methods based on AI-based methods (artificial neural network [ANN], support vector machine [SVM], fuzzy, HMM, convolutional neural network [CNN]).

1.5 Research Scope

The series arc fault is one of the most important causes of failure of PV systems. The models that are simulated to generate the DC series arc fault included some constants; each one can simulate different cases. In this model, the adaptable arc variables are arc time constant (τ). The arc time constant (τ) is an important parameter that describes the circuit breaker and electrical fuse circuit breaker function. A computer code based on Kovitya and Lowke's (1985) ablation arch model was created to study the transient behaviour of ablation-stabilised arches [55]. The second adaptable parameter is the cooling constant (P). Cooling power is used in heat rays or thermomembrane anemometers. The basic concept is to measure the required current to keep the temperature of the overheated wire constant or the temperature change in the wire heated with a constant current [56]. Two constant parameters influence the mathematical equations of the arc model, which are (a) and (b), and the constant values are mentioned in Chapter Three in accordance with Table 3.1. For arc time constant, a parameter influencing the conductance dependency is τ (a). For the cooling power, a parameter affecting the conductance dependency is P (b).

These concepts are used to collect a variety of case studies for evaluating the proposed algorithm. The scope of this study is limited to detect and classify the DC series arc faults and ignores other faults, such as parallel, ground, double-ground or arc faults between different strings of a solar power system.

This study intended to identify and recognise the DC series arc fault rather than the other faults that may occur in the PV system. The proposed approach was evaluated on the basis of a number of specific criteria in accordance with previous studies.

Testing the proposed methods on a large-scale PV system does not reveal the problems in practical use because two separate stages are used for detection and classification.

1.6 Thesis Outline

The thesis is organised into five chapters as follows:

Chapter 1 gives an overview of the DC series arc in PV system. The motivation, aim, objectives and scope this work are highlighted.

Chapter 2 gives the background of the PV system structure, DC series arc fault. The general theories of ANN, CNN and its types, multilayer perceptron (MLP), and bi-long short-term memory (Bi-LSTM) technologies are discussed in details. The related studies of the DC series arc fault detection methods are described with the challenges and limitations.

Chapter 3 presents and explores the design phases and the design details of the proposed detection and classification methods of the DC series arc fault in PV system.

Chapter 4 explores the implementation and evaluation of the proposed method to prove the fulfilment of the requirement with case studies. A comparison between the proposed method and the related systems is presented through a tabular checklist.

Chapter 5 concludes the thesis and provides directions for future work.

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LIST OF PUBLICATIONS

Journal with Impact Factor

1. **Alaa, H. O.**, Dalila, M. S., Siti Maherah H., Sadiq H. A., Nasarudin, A., Haidar, S.. Development of an Intelligent Detection and Classification Method of DC Series Arc Fault in Photovoltaic System Using Multilayer Perceptron and Bi-Directional Long Short-Term Memory**.** CSEE Journal of Power and Energy Systems, IEEE. **Accepted (Q1, IF 3.938).**

2. **Alaa, H. O.,** Dalila, M. S., Siti Maherah H., Sadiq H. A., Haidar S., (2021). Utilizing Different Types of Deep Learning Models for Classification of Series Arc In Photovoltaics Systems**"**, Computers & Electrical Engineering journal, ELSEVIER, 2021, 96, 107478. **(Q1, IF 3.818).**

Indexed Journal

1. **Alaa, H. O.**, Dalila, M. S., Siti Maherah, H., Nasarudin, A. and Haider, S.,(2020) . A novel intelligent detection schema of series arc fault in photovoltaic (PV) system based convolutional neural network. Periodicals of Engineering and Natural Sciences, 8(3), pp. 1641-1653. **(Indexed by Scopus).**

2. **Alaa, H. O.**, Dalila, M. S., Siti Maherah H., Sadiq H. A., Nasarudin, A., (2021). MODELS, DETECTION METHODS, AND CHALLENGES IN DC ARC FAULT: A REVIEW**.** *Jurnal Teknologi*, 83:4 p.p 1–16. **(Indexed by Scopus).**

3. **Alaa, H. O.**, Dalila, M. S., Siti Maherah H., Sadiq H. A., Nasarudin, A., . DC Series Arc Fault in Photovoltaic (PV) System: A Case Study. Indonosian Journal of Electrical and Computer Science. **Accepted**. **(Indexed by Scopus).**

Indexed Conference Proceedings

1. **Alaa, H. O.**, Dalila, M. S., Siti Maherah H., and Sohrab M. (2020). An Intelligent Classification Method of Series Arc Fault Models Using Deep Learning Algorithm. 8th International IEEE Power and Energy Conference (**Best Paper Award, Indexed by Scopus**).

2. **Alaa, H. O.**, Dalila, M. S., Siti Maherah H., Sadiq H. A., Nasarudin, A.(2020). A Survey of Different DC Faults in a Solar Power System. 2020 8th IEEE Conference on Systems, Process and Control, December 2020, Malaysia, (**Indexed by Scopus).**

3. **Alaa, H. O.**, Dalila, M. S., Siti Maherah H., Sadiq H. A, (2022) .A Comprehensive Study of Various DC Faults and Detection Methods in Photovoltaic System (PV). Lecture Notes on Data Engineering and Communications Technologies/ Springer, 117, p.p657-676. (**Indexed by Scopus).**

4. **Alaa, H. O.**, Dalila, M. S., Siti Maherah H., (2021). A Novel Intelligent Tracking Controller based on Human Reaction towards Light. 5th International Conference on Electrical, Electronic, Communication and Control Engineering, (ICEECC 2021). AIP Conference Proceedings. **Accepted.** (**Indexed by Scopus).**