DC ARC DETECTION AND INTERRUPTION IN PHOTOVOLTAIC POWER SYSTEMS

CHEAH YI MIN

UNIVERSITI TUNKU ABDUL RAHMAN

DC ARC DETECTION AND INTERRUPTION IN PHOTOVOLTAIC POWER SYSTEMS

CHEAH YI MIN

A project report submitted in partial fulfilment of the
requirements for the award of Bachelor Bachelor of Engineering
(Honours) Electrical and Electronic Engineering

Lee Kong Chian Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

May 2023

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

Signature :

Name : CHEAH YI MIN

ID No. : 18UEB03392

Date : 18 May 2023

APPROVAL FOR SUBMISSION

I certify that this project report entitled **"DC ARC DETECTION AND INTERRUPTION IN PHOTOVOLTAIC POWER SYSTEMS"** was prepared by **CHEAH YI MIN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Electrical and Electronic Engineering at Universiti Tunku Abdul Rahman.

Approved by,

Signature :

Supervisor : Ir Dr. Chua Kein Huat

Date : 18 May 2023

Signature : Lim

Co-Supervisor : Ir Dr. Lim Boon Han

Date : 18 May 2023

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my supervisor, Ir Dr. Chua Kein Huat, and co-supervisor, Ir Dr. Lim Boon Han, for their unwavering support and guidance throughout this project. Their expertise and knowledge have been instrumental in the success of this study. I also extend my thanks to Huawei for their generous support and resources, particularly Mr. Yong Chian Haw for his valuable guidance during the testing process. Last but not least, I would like to acknowledge the invaluable contributions of Uncle Ho from UTAR Sungai Long Campus Workshop, who provided me with indispensable assistance in designing and fabricating the DC arc generator.

ABSTRACT

This project focuses on the design and fabrication of a reliable and safe direct current (DC) arc generator for DC arc fault testing in photovoltaic (PV) systems. The project aims to evaluate the effectiveness of the DC arc fault protection features in the Huawei Solar Inverter SUN2000-2KTL-L1 through various tests including arc fault circuit interrupter (AFCI), insulation resistance (R_{ISO}) monitoring, residual current monitoring (RCD), and rapid shutdown. The tests were conducted under real-world conditions using an on-site PV system. The results demonstrate the effectiveness of the Huawei Solar Inverter in mitigating the risks associated with DC arc faults, including the prevention of fires caused by DC series arc faults, protecting against electrical shocks caused by dc arc fault and ensuring system safety and reliability by monitoring insulation resistance before the DC circuit is completed. The rapid shutdown feature allows for the safe and swift shutdown of the PV system, reducing the risk of damage or injury. The project contributes to the development of DC arc fault protection in the PV industry and provides valuable insights into the capabilities of the Huawei Solar Inverter SUN2000-2KTL-L1 in handling DC arc faults, ensuring the safety and reliability of PV systems.

TABLE OF CONTENTS

CHAPTER

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS / ABBREVIATIONS

AC	Alternating Current
AFCI	Arc Fault Circuit Interrupters
AI	Artificial Intelligence
DC	Direct Current
FFT	Fast Fourier Transform
GHG	Greenhouse Gas
ICT	Information and Communications Technology
IEC 60327	DC arc detection and interruption in photovoltaic power systems
MPPT	Maximum Power Point Tracking
NEC 2011	National Electrical Code 2011
PV	Photovoltaic
RCD	Residual Current Device
R_{ISO}	Insulation Resistance
RS	Rapid Shutdown
UL 1699B	STANDARD FOR SAFETY "Photovoltaic (PV) DC Arc-Fault Circuit Protection"
WT	Wavelet Transform

CHAPTER 1

INTRODUCTION

1.1 General Introduction

The transition from non-renewable to renewable energy is essential in reducing greenhouse gas emissions and preserving a livable climate for all. Solar photovoltaic (PV), has grown significantly in recent years and now generates over 821 TWh of electricity globally. (Piotr Bojek, 2021).

However, as PV systems scale up in size and complexity, the risk of DC arc faults causing fires and other hazards increases. This could result in higher fire risk and monetary losses in the event of a fire. Although the cause of the PV system fire event may differ in every case, the root cause will still be the generation of an arc, which could directly or indirectly ignites the PV system.

Direct Current (DC) arc is the most common fault phenomenon in the PV system. It could be generated from cable insulation rupture or loosening of cable joints. In a PV system, numerous distributed DC sources, such as the PV modules, exist. Unlike the alternating current (AC) system, the series arc may be impeded due to the AC crossing through zero current twice per cycle. The arcing current could be constant in the DC system, and a longer arc duration is expected. Thus, once the DC arc occurs, it is harder to be extinguished and will cause fire accidents in the PV plant.

Attributing to the DC arc fault hazards, the installation of DC arc protection device for PV systems with 80V or above has been introduced as a requirement in the USA since the 2011 National Electrical Code (NEC) was published. Subsequently, UL developed UL 1699B standard to examine the arc fault protection performance in the PV system of the protection device, such as the device included arc fault detection and circuit interruption function – The Arc-Fault Circuit Interrupter (AFCI). Furthermore, the IEC 63027 was explicitly drafted to address the DC source's unique aspects in the PV system. These integrated requirements and standards promote the development of PV systems in a safer direction.

In response, manufacturers have developed solar inverters with DC arc fault protection devices. However, DC arc faults remain a serious threat, and in the past, they have caused significant fires that burned down entire buildings. Moreover, DC series arc faults can be challenging to detect due to external noises. Therefore, testing must be done before commissioning a PV system to ensure its DC arc fault protection is fully functioning. For existing PV systems, regular testing of their DC arc fault protection is crucial to prevent hazards and ensure safety.

1.2 Importance of the Study

DC arc-fault could produce a high heat level that leads to a fire in the PV system. For example, in 2011, a fire occurred on the 1.13 MW PV system in Mount Holly, North Carolina, which was installed with more than 5,000 PV modules. The investigation found that the cause of the fire was a ground fault due to cable insulation breakdown, which led to a large area of flame (Alam et al., 2015a). DC arc fault is highly hazardous for PV systems as the heat of DC arcs could reach more than 3,000 °C. This level of heat could melt metals such as copper and aluminium. A DC arc fault will not only destroy the PV power plant, but it may also be fatal to the personnel handling the PV system.

Moreover, with the DC arc hazard, the investors in PV systems will be discouraged and eventually set back PV technology advancement. Hence, this study is essential to investigate the method of DC arc detection and interruption in photovoltaic power systems. With the study made, a DC arc generator could be developed to test and evaluate the DC arc fault protection device in the PV system such as the AFCI to reduce the DC arc fault risk. Additionally, with the guidance of standards such as the NEC 2011, UL 1699B, and the upcoming IEC 63027, the protection scheme for PV systems against DC arc fault can be better evaluated and tested. Thus, ensuring the DC arc can be detected and distinguished within the time requirement from the standards. Consequently, it reduces the PV system's risk of DC arc fault. Eventually, this study would help advance the PV industry and support the achievement of the Net Zero ambition.

1.3 Problem Statement

DC arc faults in PV systems can pose significant hazards to both personnel and equipment. Despite the enforcement of standards such as NEC and UL1699B, many solar inverter manufacturers claim that their inverters with DC arc fault protection features can handle DC arc faults. However, on-site conditions can affect the detection of DC arc faults, and it is crucial to ensure that these inverters are functioning effectively. Therefore, to evaluate the actual performance of commercialized inverters with DC arc fault protection features on-site, a DC arc generator that can simulate DC arc faults in a controlled environment should be developed. The design and construction of such generators must adhere to specific technical requirements to ensure accurate testing results.

1.4 Aim and Objectives

This project aims to design and fabricate a DC arc generator that is reliable and safe for the user to evaluate the effectiveness of DC arc fault protection in the PV system. The objectives of this project are:

1. Develop a DC arc generator for DC arc fault testing.
2. Set up an on-site PV system that simulates real-world conditions for DC arc fault testing.
3. Evaluate the effectiveness of the DC arc fault protection feature in Huawei Solar Inverters.

1.5 Scope and Limitation of the Study

This study aims to investigate the effectiveness of DC arc fault protection mechanisms in photovoltaic (PV) systems. The study will focus on designing and constructing a high-voltage DC arc generator prototype to evaluate the effectiveness of the DC arc fault protection feature in the Huawei Solar Inverter SUN2000-2KTL-L1. The testing procedure will follow the UL 1699B standard, which specifies the requirements for DC arc protection compliance in PV DC sources.

However, the study is limited to evaluating the DC arc fault protection feature in the Huawei Solar Inverter SUN2000-2KTL-L1 only. Additionally, the evaluation of DC arc faults and their protection mechanisms is limited to PV systems only, as the UL 1699B standard used as a reference only applies to PV DC sources and not other DC sources.

1.6 Contribution of the Study

The contribution of this study is multifaceted. Firstly, it presents the design and fabrication of a reliable and safe DC arc generator for DC arc fault testing. Secondly, it evaluates the effectiveness of the DC arc fault protection feature in the Huawei Solar Inverter SUN2000-2KTL-L1 through various tests, including AFCI, R_{ISO} monitoring, RCD, and rapid shutdown. Thirdly, it sets up an on-site PV system to simulate real-world conditions for testing, providing valuable insights into the capabilities of the Huawei Solar Inverter in handling DC arc faults. This project contributes to the development of DC arc fault protection in the PV industry and provides valuable information for researchers, manufacturers, and operators in the field. The results of this study can be used to improve the safety and reliability of photovoltaic systems, preventing the occurrence of DC arc faults and protecting the safety of personnel and assets.

1.7 Outline of the Report

This project involves the design and fabrication of a reliable and safe DC arc generator for DC arc fault testing, and the evaluation of the effectiveness of the DC arc fault protection feature in the Huawei Solar Inverter SUN2000-2KTL-L1. The project includes the setup of an on-site PV system to simulate real-world conditions for testing, and various tests were conducted, including AFCI, RISO monitoring, RCD, and rapid shutdown testing. The results demonstrate the inverter's ability to effectively detect and interrupt DC series arc faults, prevent risks associated with low insulation resistance and earth faults, and provide vital safety features to protect against electrical shocks caused by DC arc faults. The project contributes to the development of DC arc fault protection in the PV industry and provides valuable insights into the capabilities of the Huawei Solar Inverter SUN2000-2KTL-L1 in handling DC arc faults.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter provides a comprehensive overview of DC arc faults in photovoltaic (PV) systems, which pose a significant safety hazard due to the potential for high heat generation and devastating fires. The discussion covers the differences between DC and AC arc faults, the types and causes of DC arcs in PV systems, and the challenges associated with DC arc detection. Additionally, this chapter delves into conventional methods for detecting DC arc faults and the UL 1699B PV DC arc-fault circuit protection standard, which sets the requirements for protecting PV systems against arcing faults. Moreover, this chapter emphasizes the critical role of various protection features, such as Arc Fault Circuit Interrupters (AFCIs), Insulation Resistance (Riso) protection, Residual Current Devices (RCDs), and Rapid Shutdown (RS) function in mitigating electrical hazards and ensuring the safe operation of PV systems. Lastly, the chapter will explore the requirements and design considerations for building a reliable DC arc generator for research and testing purposes.

2.2 DC Arc Faults in PV Systems

DC arc faults in PV systems pose a significant safety hazard as they generate high heat, which can lead to devastating fires in the PV plant. This section aims to provide an overview of DC arc faults in PV systems, covering the differences between DC and AC arc faults, types and causes of DC arcs in PV systems, and challenges associated with DC arc detection in PV systems. Understanding these factors is crucial to effectively detect and prevent DC arc faults in PV systems, ensuring the safety of personnel and the PV plant.

2.2.1 Difference between DC Arc Faults and AC Arc Faults

Figure 2.1 illustrates the distinct characteristics of DC and AC. The most significant difference between them is that the DC arc lacks a current zero crossing point, which means it cannot be self-extinguished. When insulation breakdown occurs in cables or there are loose joint connections between PV modules in a PV system, DC arc faults can form. The high heat generated by these faults can result in a catastrophic blaze in the PV plant. As such, it's crucial to be aware of the potential dangers of DC arc faults in PV systems (England, n.d.).

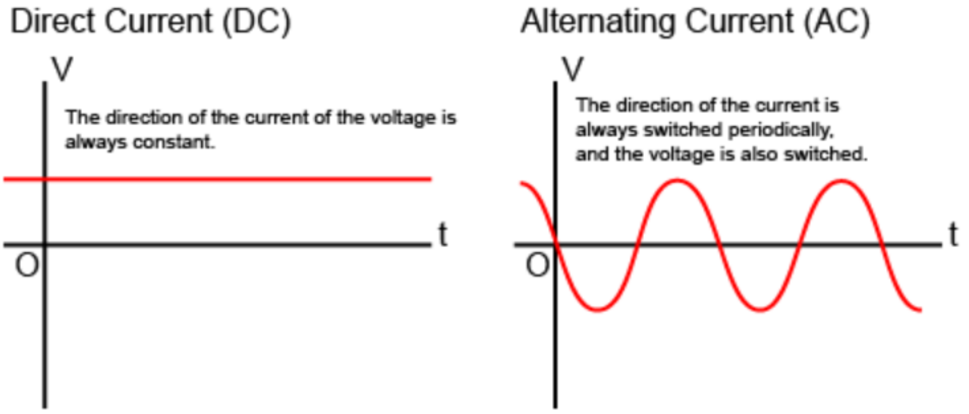


Figure 2.1: Different characteristic of DC and AC (Matsusada Precision, 2021)

2.2.2 Types and Causes of DC Arcs in PV Systems

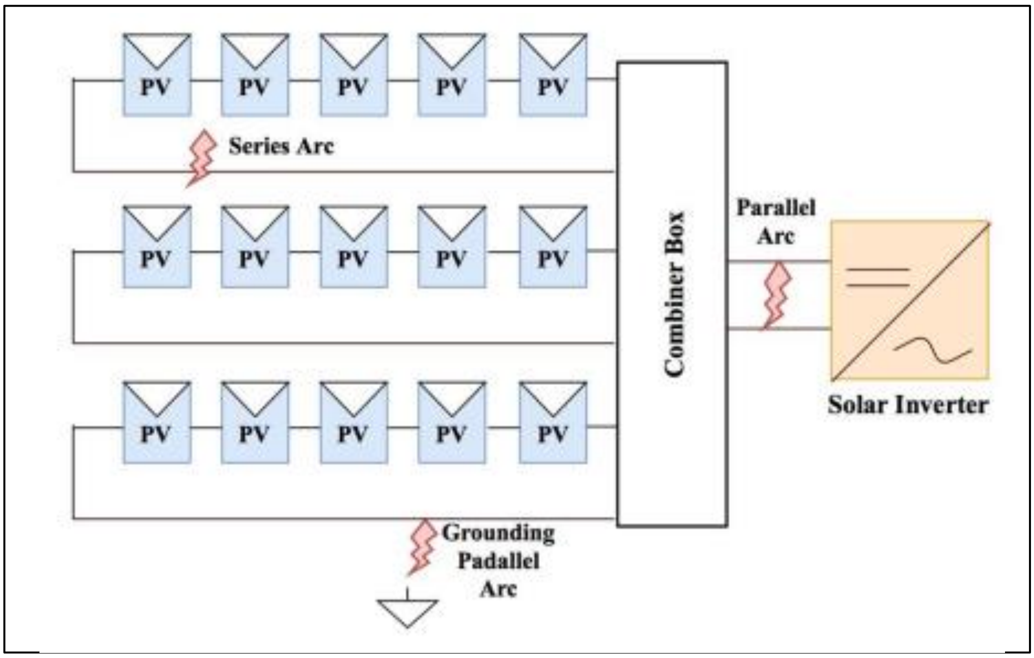


Figure 2.2: Type of DC arc faults (Lu et al., 2018)

According to Figure 2.2, DC arc faults are categorized into three types. The most common DC arc fault is the series DC arc fault. PV modules in the PV systems are typically connected in series to achieve higher output voltage. For example, the voltage range of the MPPT is around 520 V – 800 V for the

Huawei SUN2000-50KTL-M0 inverter. The long series connections of PV modules involve the ample contacts and connections, which increases the possibility of a series DC arc faults (Growatt, 2020). Unlike a parallel DC arc fault, a DC arc's current characteristics will not draw a current with opposite polarity. The DC arc will introduce an impedance, which reduces the current below the specific thresholds where it didn't melt the fuse or make the overcurrent protection device operate. If the series DC arc fault cannot be extinguished in time, it may propagate to the other nearby components and produce parallel DC arc faults. Therefore, AFCI must be installed for the PV system with the voltage level higher than 80 V according to the NEC 2011 standard to monitor and interrupt the circuit once the arc fault is found.

The second type is the parallel DC arc fault. Generally, parallel DC arc faults are caused by a partial short circuit between two adjacent wires or circuits with different potentials. The causes of parallel DC arc faults are similar to the series of DC arc faults. They could be caused by the insulation breakdown on cables or faulty connections. However, the characteristic of parallel DC arc fault is in contracts with the series DC arc fault. The more significant potential difference will draw a higher current than usual (Flicker and Johnson, n.d.).

The third type of DC arc fault is the ground DC Arc Fault. It is an electrical short circuit between a current-carrying conductor to the ground. It could result in a large fault current, increasing the risk of DC arc fault hazards. Possible causes of ground DC arc fault are the insulation failure of cables or incidental short circuits within the PV modules due to the deterioration of its enclosure (YE ZHAO, 2017). According to the NEC 2011, Ground-Fault Protection Devices (GFPD) must be installed in PV arrays.

Moreover, the PV system inverter can extinguish the series DC arc fault by opening the circuit and reducing the current flow in the series circuit to a low level or eliminating the DC flow to zero to ensure the series DC arc fault is extinguished. However, eliminating the parallel DC arc fault requires the opposite action. It must create a short circuit between the faulty conductor and reduce the voltage to zero. Therefore, if the PV inverter opens the circuit of the PV array, it will further strengthen the parallel DC arc fault (Johnson et al., 2012). Thus, it would create concern about how effectively the AFCI can differentiate between series or parallel DC arc faults and perform the corresponding action to extinguish the DC arc fault.

DC arc faults could form from the insulation breakdown of PV system components and could lead to a serious fire disaster in the PV plant. However, series DC arc faults are more difficult to detect due to many factors, such as the MQTT algorithm that will make the fault current back to its normal operation current level and there will be high frequency noises induced into the circuit from power electronic devices such as the converter and inverter (Omran et al., 2021). Furthermore, the method to distinguish series and parallel DC arc faults is in contrast. Therefore, the AFCI must be able to accurately differentiate the type of DC arc fault to monitor and control the DC arc faults in the PV system.

2.2.3 Challenges of DC Arc Detection in PV Systems

DC arc's intrinsic characteristic does not have the current zero crossing point, making it more sustainable and harder to be extinguished than the AC arc. To effectively detect the DC arc in PV systems, the characteristics of the DC arc must be studied. The randomness of the DC arc current can be represented by high-frequency noises. Therefore, most of the detecting methods and algorithms for the DC arc are based on current signal analysis with frequency and time domain. However, different factors could affect the DC arc noise in the actual scenario (Cao et al., 2013).

For example, the frequency components of the DC arc could be alternated due to the shape of the electrodes. Different shapes of electrodes will have different electrical field strengths. Furthermore, at long series PV modules connected with long cables would exhibit an antenna that would pick up radio frequency noises (Artale et al., 2021). Moreover, power electronics components such as the DC-to-DC converter and the DC-to-AC inverter would create a high-frequency interference in the DC circuit, which may lead to unwanted tripping of AFCI. Figure 2.3 illustrates the typical internal and external disturbance sources that could affect the DC arc's frequency component.

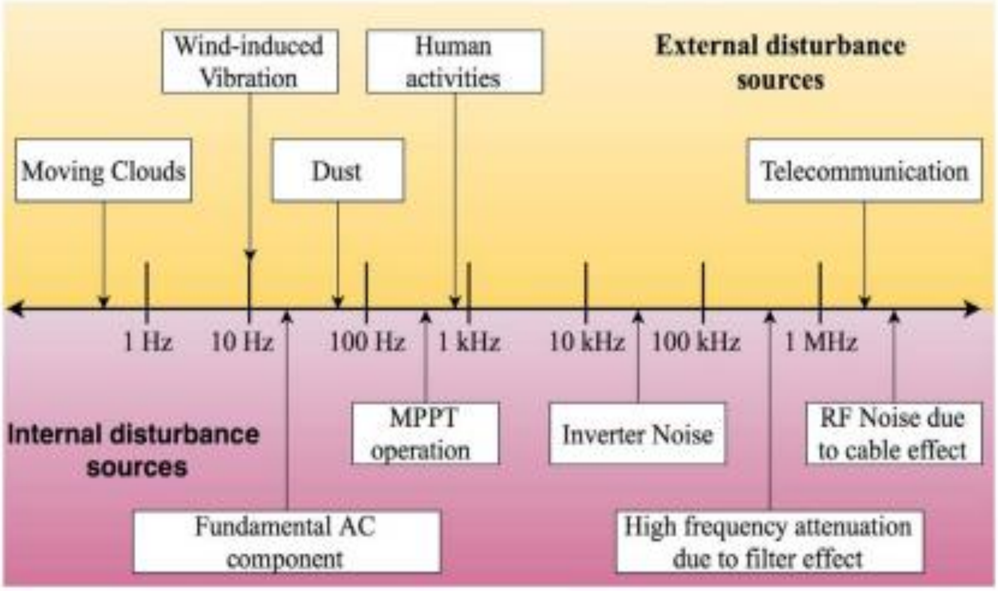


Figure 2.3: Disturbance sources from internal and external. (Alam et al.,2015)

Based on the study made for the challenges of DC arc detection in PV systems, it can be determined that DC arc would create a high-frequency noise, and it's used as the detection method. Despite this, various factors from internal and external sources could affect the DC arc noise such as MPPT operation, inverter noise, wind-induced noise and induced noise due to cable effect (Alam et al., 2015).

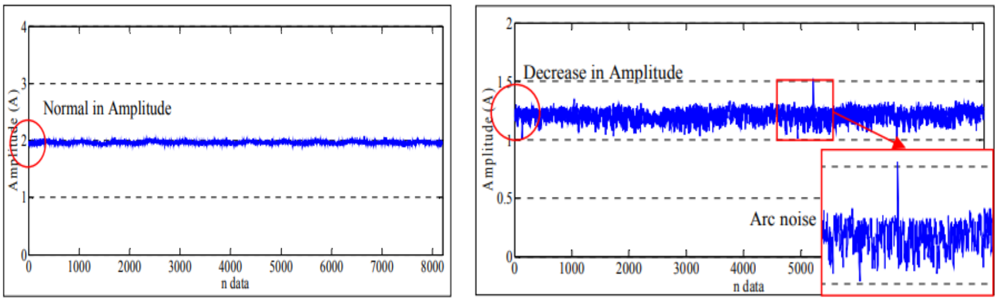
2.3 Methods of DC Arc Detection in PV Systems

The necessity for DC arc detection and protection devices has risen as various standards and regulations concerning DC arc protection in PV systems have been published. Investigations made depend primarily on the actual voltage and DC arc current measurements. In order to distinguish DC arc fault from normal operating conditions with many disruption factors, the researcher has conducted several studies to analyze DC arc fault based on the frequency and time domain properties of DC arcs.

2.3.1 Fast Fourier Transform (FFT) Method

Series DC arc fault could be hard to detect in time domain signal due to the influences such as the MPPT algorithm. Generally, a series DC arc fault can be determined by a sudden drop of current, forming a slope. However, the slope could be insignificant because the duration is too fast. Thus, analysing the DC arc fault in the frequency domain could be the alternative solution to determine the DC arc faults. FFT is a digital signal processing method that converts the current signals from the time domain to the frequency domain.

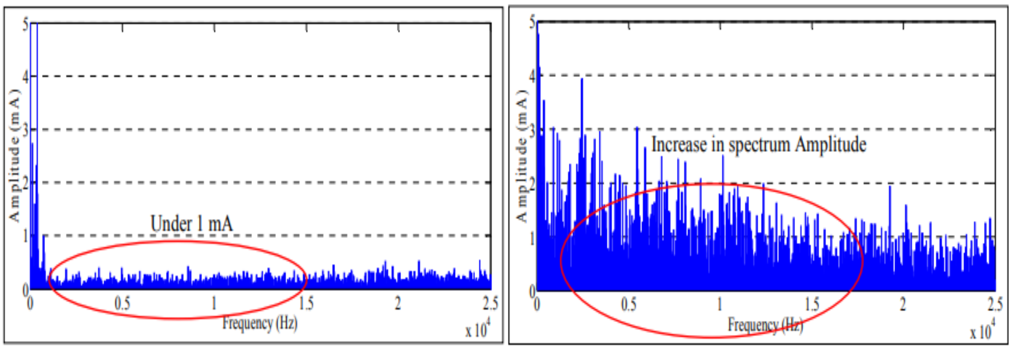
Based on the experiment by (Riza Alvy Syafi'i et al., 2018a), the changes in a current waveform and current spectrum were observed during normal conditions and series DC arc fault conditions. Figure 2.4 shows that during a series DC arc fault, the current waveform amplitude will decrease, and there will be a significant noise spike. On the other hand, in Figure 2.5, the current spectrum will have an amplitude lower than 1 mA during the normal condition. However, during an arc fault, the amplitude of the current spectrum will increase significantly. Furthermore, the series of DC arc faults will increase the frequency spectrum amplitude significantly from 1 kHz to 15 kHz.



a) Current waveform during normal condition

b) Current waveform during arc fault

Figure 2.4: Current waveform of a 2 A system (Riza Alvy Syafi'i et al., 2018)



a) Current spectrum during normal condition

b) Current spectrum during arc fault

Figure 2.5: Current spectrum of a 2 A system (Riza Alvy Syafi'i et al., 2018)

Figure 2.4 and Figure 2.5 clearly illustrate that by using the FFT method, the changes in the current spectrum amplitude are much more significant than the current waveform under normal condition. This shows that the FFT method can help detect the series DC arc fault.

2.3.2 Wavelets Transform

Wavelet Transform (WT) is a linear transformation that allows time localization for different frequency signals. It decomposes the subjected signal into multi-resolution, and with the adjustable windowing function, it provides a better frequency resolution for the desired frequency range. Hence, it will make the DC arc faults detection easier than the FFT.

The wavelet analysis approach uses a wavelet prototype function named a "mother wavelet" to decompose a differential signal into a sequence of time-domain, frequency-banded wavelet components. Wavelet transform could efficiently approximate discontinuous or fast functions like power system fault signals.

Based on the study by (Patil and Tarmale, 2018a), an analysis was performed to compare the effectiveness of DC arc detection between FFT and wavelet transform. Figure 2.6 shows that the distinguishable FFT frequency spectrum change is insignificant. However, the frequency bands are decomposed into different levels with the wavelet transform, as shown in Table 2.1. The results are illustrated in Figure 2.7. The results from the wavelet transform decomposition provide a significant distinguishable signal when there is a DC arc fault.

Table 2.1: Wavelet transform decomposition frequency band

Level	**Frequency Range, (Hz)**
D1	1.25 k to 2.5 k
D2	625 to 1.25 k
D3	312 to 625
D4	156 to 312

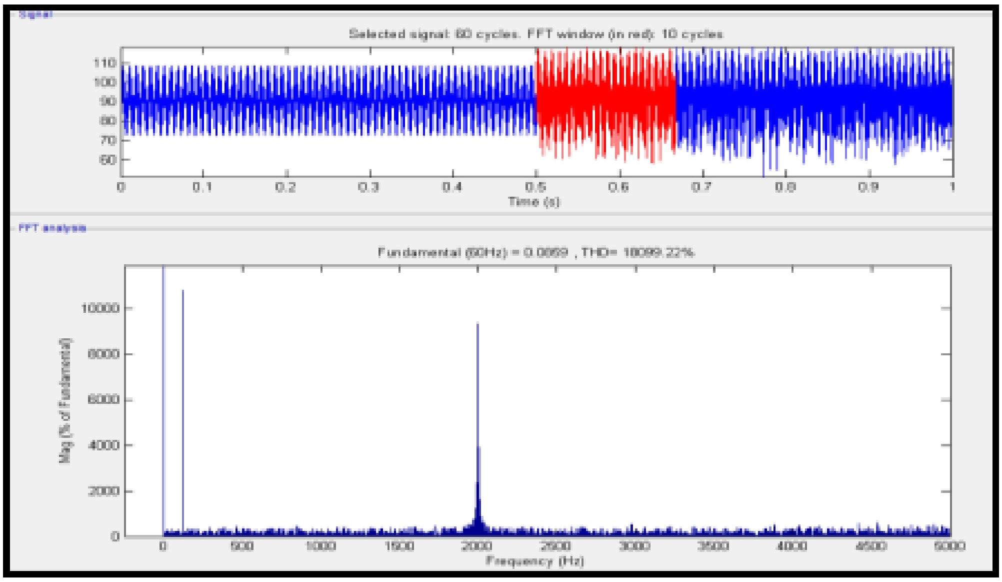


Figure 2.6: FFT results of DC arcing (Patil and Tarmale, 2018b).

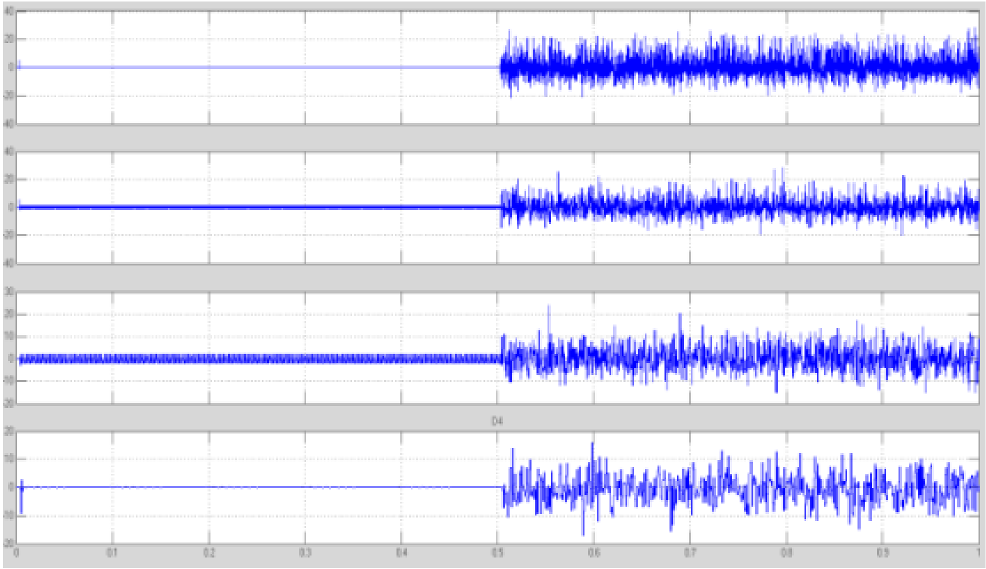


Figure 2.7: Wavelet transform decomposition signal (Patil and Tarmale, 2018c)

As a summary of the wavelet transform study, the wavelet transform method can detect the DC arc fault more effectively than the FFT method. Due to the power electronics equipment used in the PV system, such as the DC-DC converter and the inverter, switching noise will be induced into the circuit, affecting the FFT analysis. The targeted signal is decomposed into a different frequency band level with the wavelet transform. This provides a better frequency resolution to distinguish the DC arc fault.

2.3.3 Huawei AFCI solution

Huawei's AFCI solution is represented by the SUN2000 series inverter, which mainly adopts AFCI integrated with inverter technology and does not need to install additional AFD and AFI devices, as shown in Figure 2.8. In addition, Huawei inverters can be used in conjunction with Huawei optimizers, which can further realize the precise fault locating and the rapid shutdown function at the module level. It improves the safety of the system and the convenience of operation and maintenance (TÜV SÜD and Huawei Technologies Co., 2022a).

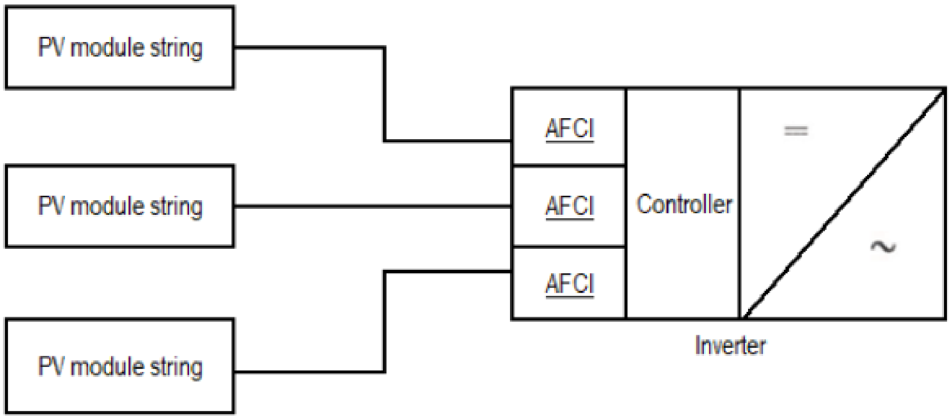


Figure 2.8: AFCI integrated with an inverter

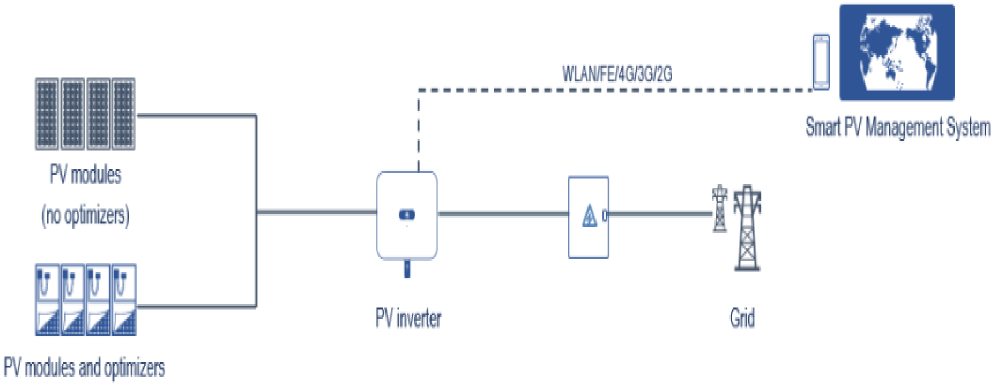


Figure 2.9: Huawei AFCI solution

Huawei's intelligent arc fault detection function integrates AFCI with deep learning technology based on a neural network algorithm, using information and communication technology (ICT) and artificial intelligence

(AI). In contrast to the manual detection method, AI uses a highly nonlinear model to calculate and iteratively analyze large amounts of data to discover high-dimensional feature rules that effectively differentiate between distinctive signals that are hard to be distinguished. The detection model could pick up on previously unknown spectral information using artificial intelligence and deep learning technologies while maintaining or increasing its noise adaptability. The model's capability for generalization has also been improved, allowing it to recognize arc properties more accurately across various settings.

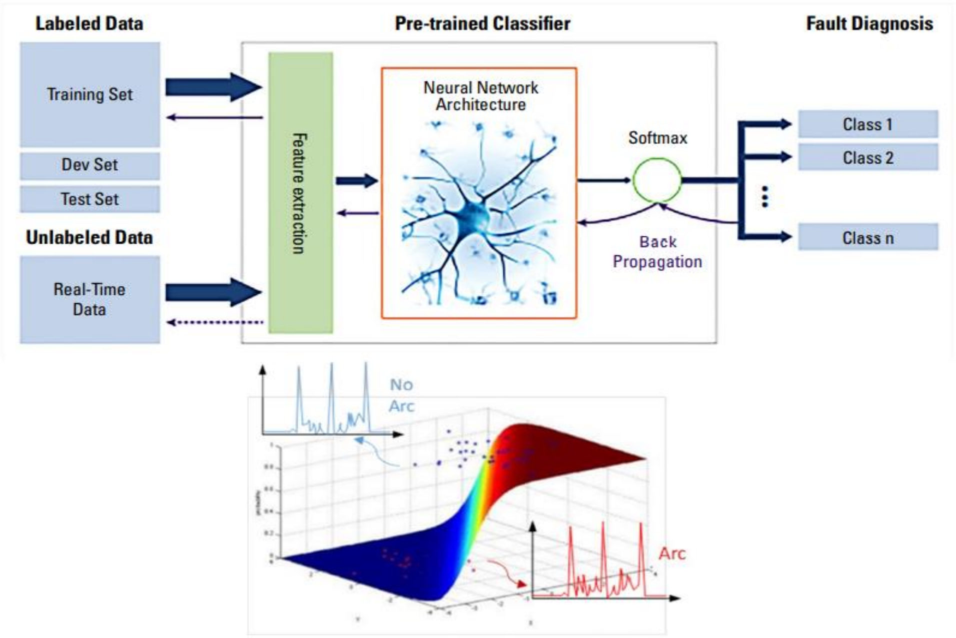


Figure 2.10: Schematic diagram of the neural network algorithm (TÜV SÜD and Huawei Technologies Co., 2022b)

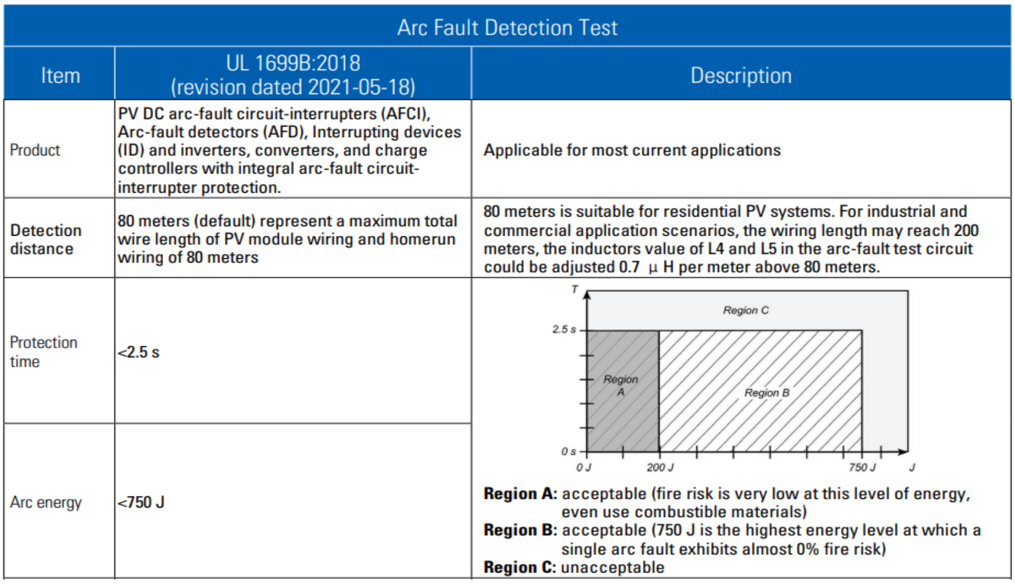
With the AI BOOST AFCI smart arc detection method from the Huawei AFCI solution, the AFCI can effectively distinguish between noise and arc characteristics, reducing the unwanted tripping caused by noise. Furthermore, it could support a maximum cable length of 200 m and up to 26 A input current. It could also precisely detect the fault location if the system is equipped with optimizers.

In summary, AI and deep learning technology could process conventional analytical methods such as the FFT and wavelet transform and further analyze the DC arc spectrum with a large amount of data. Then the AI model can distinguish and predict the DC arc fault, even with noise disruptions.

2.4 UL 1699B (PV DC Arc-Fault Circuit Protection Standard)

The UL 1699B is a standard that sets the requirements for the DC PV arc-fault circuit protection intended for use in solar PV electrical systems. This standard is intended to mitigate the effects of arcing faults that may pose a risk of fire ignition in PV plants. One of the devices covered in this standard is the DC AFCI, rated 1500 V or less and intended for use in DC electrical systems supplied by a PV source, such as a solar module. According to the standard, AFCI is a device installed in the PV system that can interrupt the power delivered to an arcing fault when the AFCI detects it. Furthermore, AFCI should protect the PV system from the unwanted effects of arcing.

To evaluate the performance of the AFCI, UL 1699B has developed the requirements and procedures of the arc fault detection test. According to Figure 2.5.1, the AFCI shall be capable of detecting and interrupting the arcing fault in Region A and Region B. For Region A, the arc interrupting event must be less than 2.5 seconds, and the limit energy cannot exceed 200 J; the arc in this region possesses a low fire risk. For Region B, the arc interrupting event must be less than 2.5 seconds, and the limit energy cannot exceed 750 J; 750 J is the highest energy level at which an arc fault exhibits almost 0% fire risk. However, for Region C, the arcing time is equal to or more than 2.5 seconds, or energy greater than 750 J, the AFCI device is considered non-compliant with the standard.



Arc Fault Detection Test		
Item	UL 1699B:2018 (revision dated 2021-05-18)	Description
Product	PV DC arc-fault circuit-interrupters (AFCI), Arc-fault detectors (AFD), Interrupting devices (ID) and inverters, converters, and charge controllers with integral arc-fault circuit-interrupter protection.	Applicable for most current applications
Detection distance	80 meters (default) represent a maximum total wire length of PV module wiring and homerun wiring of 80 meters	80 meters is suitable for residential PV systems. For industrial and commercial application scenarios, the wiring length may reach 200 meters, the inductors value of L4 and L5 in the arc-fault test circuit could be adjusted 0.7 µ H per meter above 80 meters.
Protection time	<2.5 s	**Region A:** acceptable (fire risk is very low at this level of energy, even use combustible materials) **Region B:** acceptable (750 J is the highest energy level at which a single arc fault exhibits almost 0% fire risk) **Region C:** unacceptable
Arc energy	<750 J	

Figure 2.11: UL 1699B AFCI testing requirements

2.5 DC Arc Fault Protection

Safety is a top priority in the design and operation of photovoltaic (PV) systems, which generate high levels of electrical energy that can pose risks to personnel and equipment. To mitigate these risks, several safety mechanisms are incorporated into PV systems, including Arc Fault Circuit Interrupters (AFCIs), Insulation Resistance (R_{iso}) protection, Residual Current Devices (RCDs), and Rapid Shutdown (RS) function. This section provides an overview of these safety mechanisms, including their working mechanisms, importance, and testing methods. Regular testing and maintenance of these safety mechanisms are necessary to ensure the ongoing safety and reliability of PV systems.

2.5.1 Arc Fault Circuit Interrupters (AFCIs)

Arc Fault Circuit Interrupters (AFCIs) are critical components of Photovoltaic (PV) systems as they help mitigate the hazards of electrical arcs and fires caused by electrical faults (Luebke et al., 2011). These devices are designed to detect electrical arcs that occur when there is an unintentional current path formed through an electrical insulation or a loose connection in a circuit. Electrical arcs can generate high levels of heat, creating a risk of fire, and causing damage to the electrical system.

In PV systems, AFCIs are particularly important due to the high levels of electrical energy generated by the system, which can cause arcs and fires if not properly protected. Additionally, PV systems are often installed in areas where fires can quickly spread, such as rooftops. The use of AFCIs in PV systems is mandated by the National Electrical Code (NEC) in the United States (NFPA, 2023)

To ensure the effectiveness of AFCIs in preventing electrical fires caused by arcing faults, regular testing and maintenance are necessary (Johnson et al., n.d.). One of the primary methods for evaluating the performance of AFCIs is the arcing test. This test is designed to simulate various arcing faults that may occur in a circuit and evaluate the AFCI's ability to detect and interrupt these faults.

During the arcing test, specialized test equipment is used to generate an arc fault in a controlled environment. The test equipment may generate arcing faults that simulate a variety of conditions, including series arcing, parallel arcing, or ground faults (SIEMENS, 2015). The arcing test is an essential step in ensuring the effectiveness of AFCIs in preventing electrical fires caused by arcing faults.

Overall, AFCIs play a crucial role in protecting PV systems against the hazards of electrical arcing and fires caused by electrical faults. Regular testing and maintenance, including the arcing test, are necessary to ensure that AFCIs are functioning properly and providing adequate protection.

2.5.2 Insulation Resistance (Riso)

Insulation resistance (Riso) protection is a critical safety mechanism for photovoltaic (PV) systems as it guards against electrical hazards resulting from compromised insulation. This subsection provides an overview of the background, working mechanism, importance, and testing methods for Riso protection in PV systems.

R_{iso} protection is a function that monitors the insulation resistance between a PV system's conductive parts and its grounding point, preventing hazards such as electric shocks, ground faults, and fires. Regular monitoring and testing of Riso can help identify potential issues and ensure the long-term performance of PV systems (Flicker et al., n.d.).

A healthy PV array has a R_{ISO} value greater than 20 MΩ, indicating a minimal risk of ground faults. If the R_{ISO} value falls between 20 and 3 MΩ, there may be potentially degraded insulation that requires attention before taking on operations and maintenance responsibilities. An intermittent ground fault may occur if the R_{ISO} value falls between 3 and 1 MΩ, leading to increased service costs. If the R_{ISO} value is less than 1 MΩ, there is permanent power loss and a risk of fire, which can lead to electrical arcing, heat dissipation in system components, and irreversible damage (Anders Rand Andersen, 2021). Inverters, which connect PV arrays to the electrical grid or energy storage systems, typically perform Riso monitoring.

To perform Riso testing, specialized insulation resistance testers are used, which apply a DC voltage to the PV system and measure the resulting current leakage. It is essential to ensure the system is disconnected from the electrical grid and energy storage to avoid damage to the tester or the PV system during testing (Araneo and Mitolo, 2019).

Regular Riso monitoring is critical in identifying potential insulation issues early, preventing costly damage, and reducing the risk of system failure. In conclusion, Riso protection is an essential aspect of PV system safety and efficiency.

2.5.3 Residual Current Device (RCD)

Residual Current Devices (RCDs) are critical components of photovoltaic (PV) systems, responsible for ensuring system safety. This subsection provides an overview of the background, working mechanism, importance, testing methods, for RCDs in PV systems.

An RCD is an essential protective device designed to automatically disconnect a circuit when it detects an imbalance between the live and neutral currents, indicating a potential fault. RCDs are crucial for PV systems as they protect against electrical hazards that may result from ground faults, insulation degradation, or other system issues (Solar edge, 2021).

RCDs operate by continuously monitoring the current flowing through the live and neutral conductors of a circuit. When an imbalance occurs due to a ground fault or leakage current, the RCD detects the difference and quickly disconnects the circuit, reducing the risk of electrocution and fire (GEYA, 2021).

The importance of RCDs in PV systems lies in their ability to provide an additional layer of protection for personnel and equipment. By detecting and disconnecting circuits in the event of a fault, RCDs help prevent accidents, reduce equipment damage, and ensure the safe operation of PV systems (LinElon, n.d.).

RCD testing is an essential part of routine PV system maintenance. The testing process typically involves using a dedicated RCD tester, which simulates a fault by injecting a small current imbalance into the circuit. The RCD should detect the simulated fault and disconnect the circuit within the specified time. This procedure verifies the correct functioning of the RCD and ensures that it will operate as intended in case of a real fault (Flicker et al., n.d.).

In conclusion, RCDs are vital components in PV systems that provide essential protection against electrical hazards. Regular testing and maintenance ensure the ongoing safety and efficiency of PV systems.

2.5.4 Rapid Shutdown

The rapid shutdown (RS) function is a fundamental safety feature for photovoltaic (PV) systems that allows for quick and safe de-energization of solar arrays during emergencies or maintenance (NFPA, 2023). This subsection provides an overview of the background, working mechanism, importance, testing methods, for rapid shutdown in PV systems.

The RS function is particularly important for firefighting operations as it reduces the risk of electrical shock and enables first responders to work safely and efficiently to protect people and property. Energized solar arrays pose a significant risk of electrical shock during firefighting operations as water or other conductive materials used to extinguish the fire can provide an electrical pathway (Tigo, 2022). RS ensures the rapid and safe de-energization of solar arrays, minimizing the risk of electrical shock and allowing firefighters to perform their duties without the added hazards associated with live electrical equipment.

Furthermore, RS is crucial in preventing parallel arc faults. While Arc Fault Circuit Interrupters (AFCI) are designed to address series arc faults, they do not provide protection against parallel arc faults. RS, combined with module-level power electronics like power optimizers, can offer additional protection against parallel arc faults (BENY, n.d.). Power optimizers continuously monitor the current and voltage of individual PV modules and can quickly disconnect the affected module from the system or reduce its output voltage in case of irregular conditions. This combination of RS and power optimizers ensures a higher level of safety and protection for PV systems, making them more reliable and secure for all stakeholders involved (Costa Lima et al., 2022).

In conclusion, the RS function is a critical safety feature in PV systems that enables swift de-energization of solar arrays in emergencies, assists firefighting operations, and provides protection against parallel arc faults.

2.6 DC Arc Generator

To evaluate the performance of the AFCI, a reliable DC arc generator that could generate a DC arc under controlled circumstances is essential. Several fundamental requirements need to be considered for a reliable DC arc generator, such as the electrodes, electrodes holder and the insulation of the DC arc generator. Figure 2.12 shows the overall DC arc generator design from the IEC 63027 standard derived from the UL 1699B.

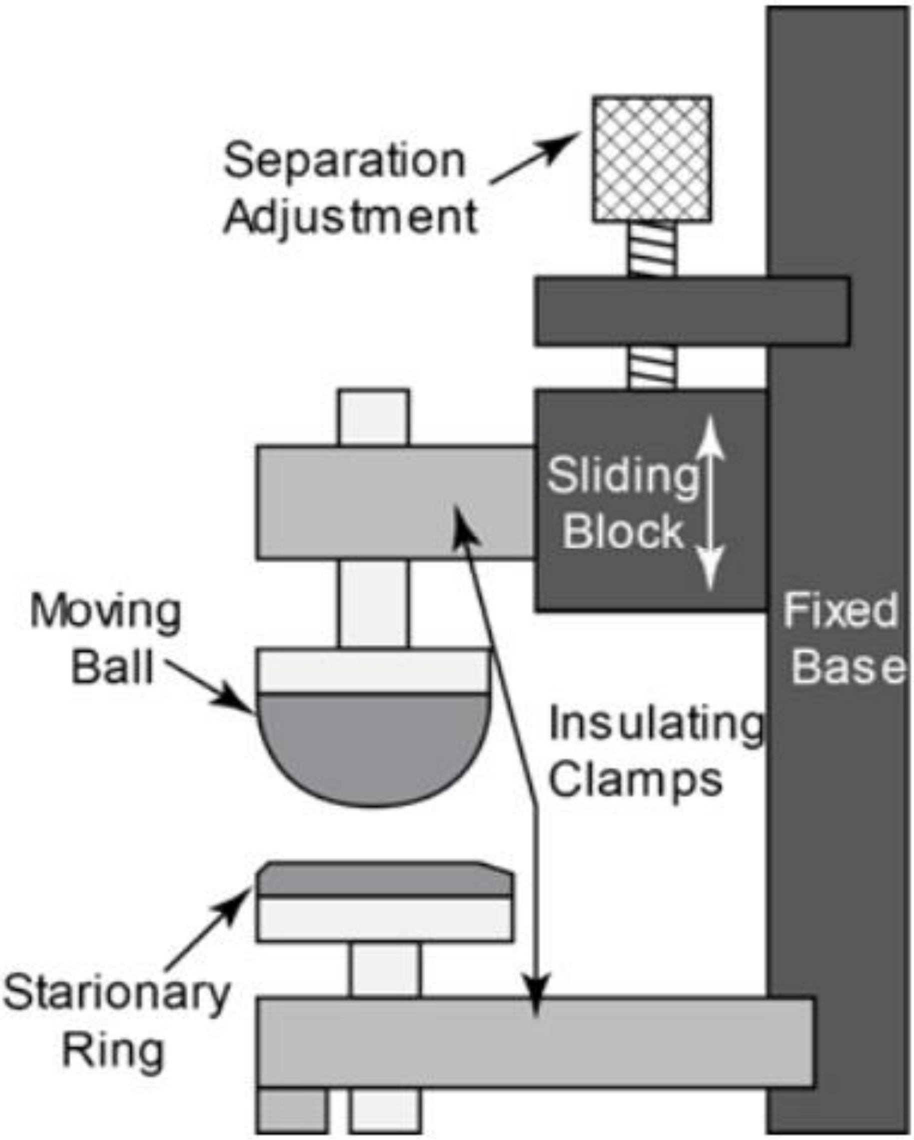
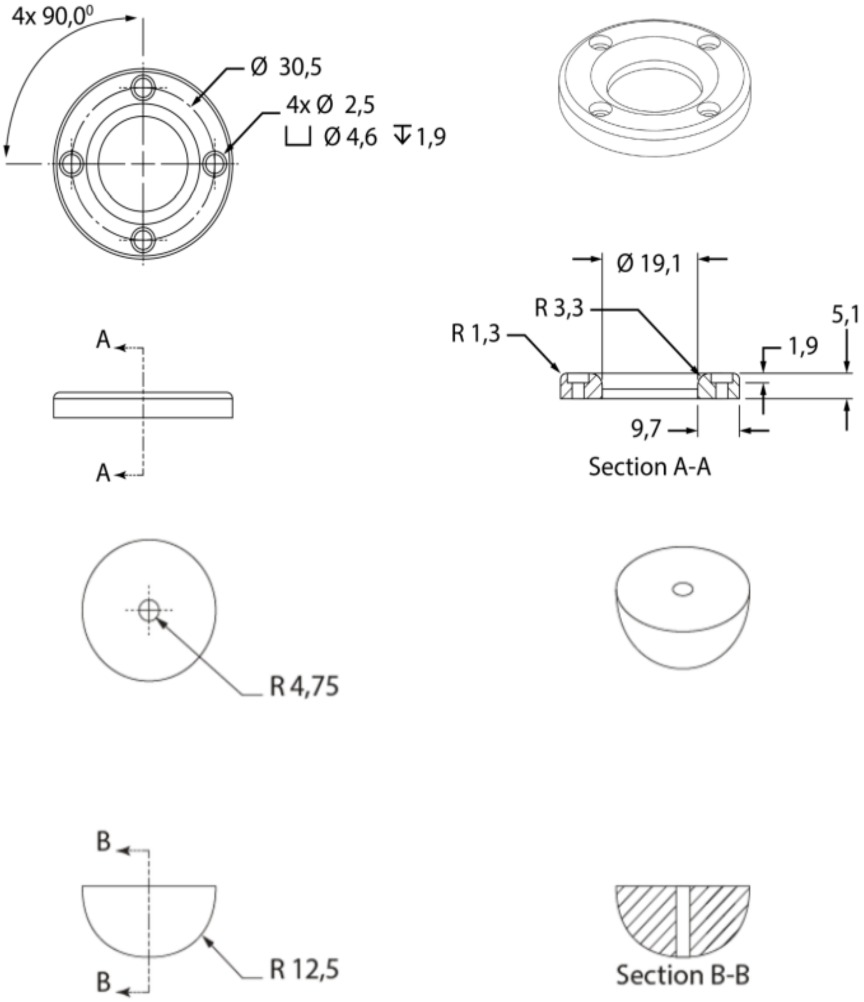


Figure 2.12: Overall design of the DC arc generator, (International Electrotechnical Commission, 2019)



Material: Class 1 Tungsten Nickel Copper alloy,
90 % Tunsten, 10 % Nickel Copper.

Figure 2.13: Dimension of the arc generator electrodes.

Figure 2.13 shows the drawing of the hemisphere and ring-designed electrodes for the DC arc generator. As mentioned in the figure, the material of the electrodes should be made with Class 1 Tungsten Nickel-Copper alloy, 90 % Tungsten, 10 % Nickel Copper. It is an alloy suitable to operate in high-temperature environments and intended to withstand numerous DC arc fault testing (American Elements, 2022). Furthermore, the shape of the electrode is designed as a hemisphere and ring to simulate the PV module connectors: MC4 better. Figure 2.14 shows the metal contacts of the MC4; when the MC4 connectors are connected, the male pin will be fitted inside the female pin, which shows a similar physical contact with the hemisphere and ring electrodes.

Figure 2.14: MC4 connectors and the contact pins

Figure 2.15 shows the DC arc generated with the hemisphere and ring electrodes. It can be observed that the DC arc is present at the bottom of the electrode only. This is because the arcing tends to happen at the weakest point of the electrical field between the two electrodes or the nearest point between the two electrodes.

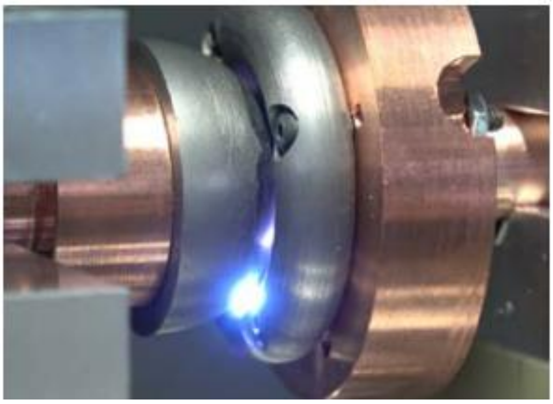


Figure 2.15: DC arc generated with the hemisphere and ring electrodes (Ameen et al., 2019)

Moreover, according to the study made by Hatton et al. (2016), the electrode holder used was the polycarbonate material, which was melted due to its limitation in dissipating heat from the arcing electrodes. Thus, aluminium was chosen as the electrode holder material for the new arc generator, as shown in Figure 2.16.

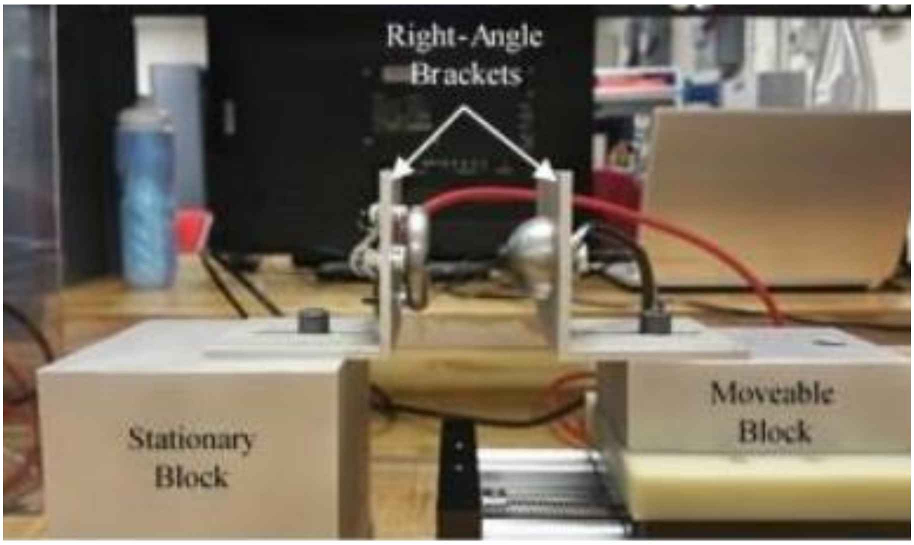


Figure 2.16: Aluminium electrode holder (Hatton et al., 2016)

Besides, the DC arc generator is intended to operate under high voltage, typically 80 V to 1000 V DC. Therefore, the electrical isolation of the electrodes from the rest of the arc generator is crucial to reduce the operator's electrical shock hazard. According to McMaster-Carr, the dielectric strength of the Garolite as the insulator is 350 V/.001 inches. If the Garolite used is 0.5 inches thick, the electrical insulation strength will be up to 175 kV.

2.7 Summary

This chapter addresses the topic of DC arc faults and their protection mechanisms in PV systems, starting with an explanation of the differences between DC and AC arcs and the three types of DC arc faults. It also discusses the challenges in DC arc detection and highlights the potential of AI and deep learning techniques to improve accuracy. The importance of the UL 1699B standard is emphasized, as it provides the main testing and certification guidelines for AFCIs in PV systems, ensuring safety and reliability through regular testing and maintenance. Key safety mechanisms, such as AFCIs, R_{iso} protection, RCDs, and RS functions, are addressed. Finally, the chapter outlines the design considerations for a reliable DC arc generator, which is crucial for evaluating the performance of AFCIs.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

This chapter addresses the topic of DC arc faults and their protection mechanisms in PV systems, starting with an explanation of the differences between DC and AC arcs and the three types of DC arc faults. It also discusses the challenges in DC arc detection and highlights the potential of AI and deep learning techniques to improve accuracy. The importance of the UL 1699B standard is emphasized, as it provides the main testing and certification guidelines for AFCIs in PV systems, ensuring safety and reliability through regular testing and maintenance. Key safety mechanisms, such as AFCIs, R_{iso} protection, RCDs, and RS functions, are addressed. Finally, the chapter outlines the design considerations for a reliable DC arc generator, which is crucial for evaluating the performance of AFCIs.

3.2 Work Plan of the Project

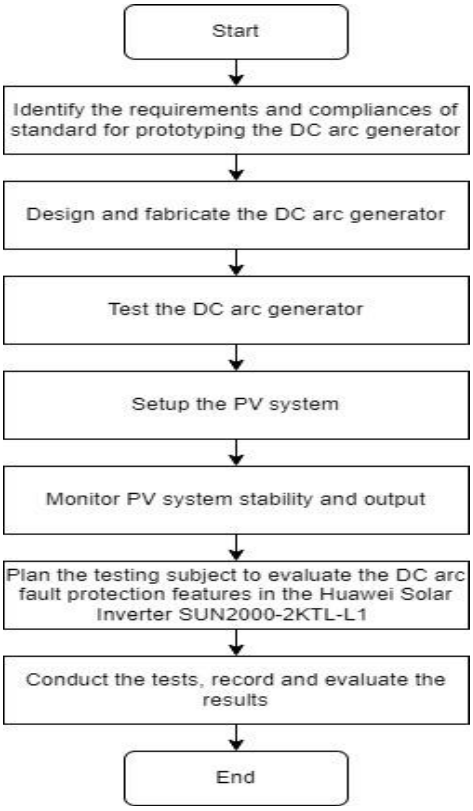


Figure 3.1: Work plan of the project

3.3 Requirements of the DC Arc Generator

The DC arc generator would be used to perform on-site testing to evaluate the performance of the AFCI in detecting and interrupting the series DC arc faults in the PV systems. The arc generator is required to operate at a high voltage level of 1500 V according to the standard UL 1699B. Therefore, the DC arc generator's insulation will be the primary concern of this project. This is to ensure the operator of the DC arc generator will not be harmed by the electrical shock hazard. Furthermore, the components required to fabricate the DC arc generator will be discussed in the following sub-sections.

3.3.1 The Electrodes of the DC Arc Generator

The DC arc generator's electrodes must withstand the high heat generated by the DC arc. Furthermore, the electrodes are designed in such a way that they can be easily replaced due to the accelerated degradation rate of the electrodes. Lastly, to comply with the standard UL 1699B, the dimensions and shape of the electrodes are fabricated according to Figure 2.13. Furthermore, the hemisphere and ring design of the electrodes better simulate the actual contact of the PV module connector MC4.

3.3.2 The Electrode Holder of the DC Arc Generator

From the study made in the literature review, the electrode holder material must be able to handle the heat dissipated by the electrode. The material suggested in the research is aluminium, which has a higher melting point than polycarbonate. Furthermore, aluminium is a material that can be easily extruded with the help of power tools. This characteristic would help in making an electrode holder compatible with the electrodes.

3.3.3 The Insulator of the DC Arc Generator

High operating voltage is the primary concern of the DC arc generator. The insulator must have high dielectric strength to provide electrical insulation of the current-carrying electrodes and electrode holders from the rest of the DC arc generator.

3.3.4 The Separation Method of the Electrodes

According to the DC arc generator sample from the standard UL 1699B, the separation method of the electrodes is by using the pull-apart method. The electrodes are first in contact and then pulled apart to generate a DC arc. Therefore, a linear rail must be fabricated to ensure the electrodes can be separated precisely.

3.3.5 The Separation Method of the Electrodes

The DC arc generator enclosure should provide the user with a clear view to observe the DC arc. Furthermore, the material should be lightweight and sturdy that can be carried around for on-site testing.

3.4 Designing the DC Arc Generator

SOLIDWORKS software is used to draw a draft idea for the DC arc generator. Components can be paired together in the software to ensure compatibility. The design of the hemisphere and ring are provided in Figure 3.2 and Figure 3.3. The ring electrode design is modified from the UL 1699B standard, the four M2 holes are removed, and an M8 countersunk spot is added in the middle. This will allow the electrical wire to have better contact with the electrode with the help of an M8 cable lug.

Furthermore, in Figure 3.4, an aluminium angle bar is used to fabricate the electrode holder. The aluminium angle bar has an adjustable M8 hole that can hold the electrodes with the M8 screw and nut. It is designed to be adjustable so that the user can adjust the position of the electrodes. Lastly, in Figure 3.5, the overall design of the DC arc generator is shown.

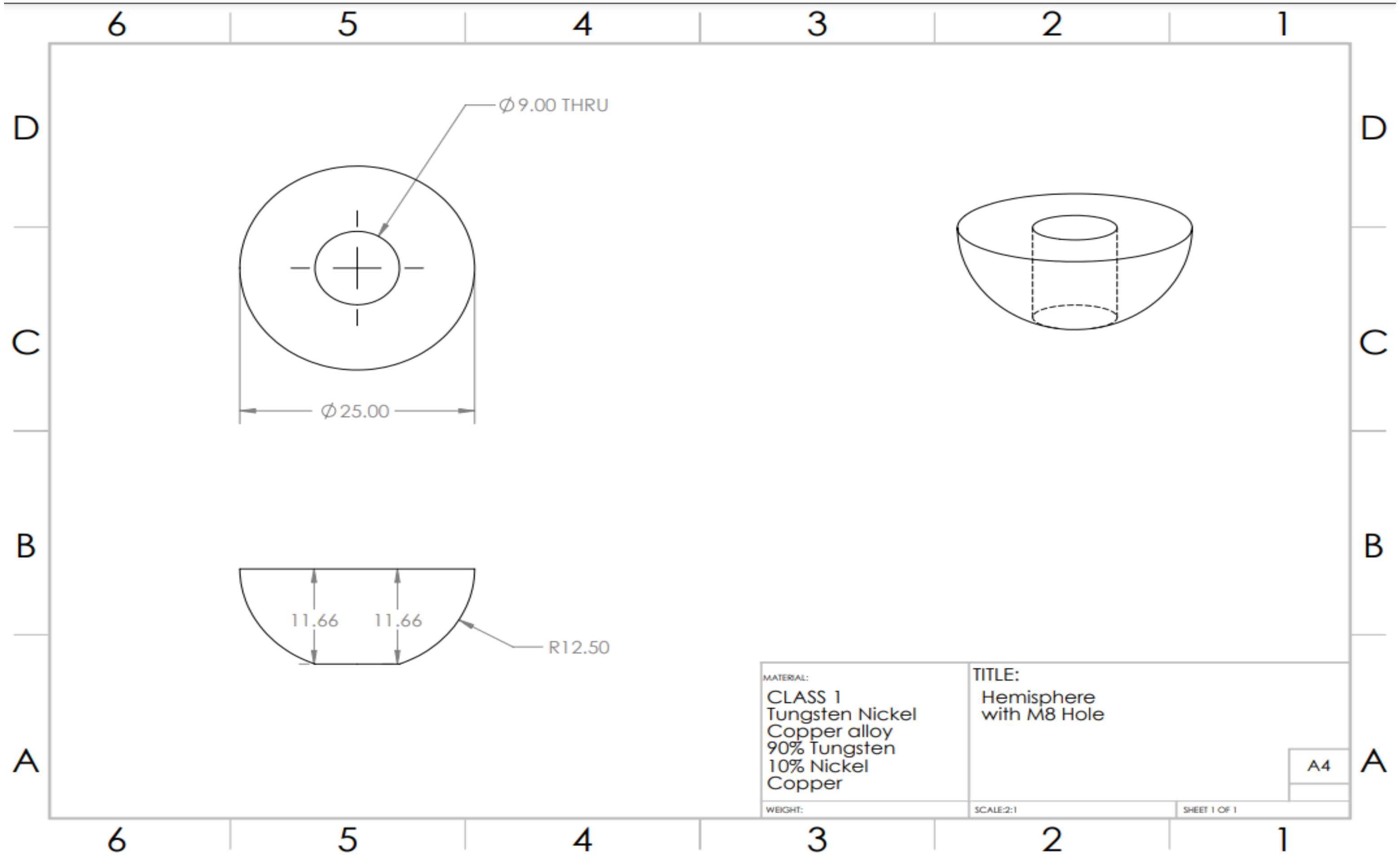


Figure 3.2: Hemisphere electrode with M8 hole drawing

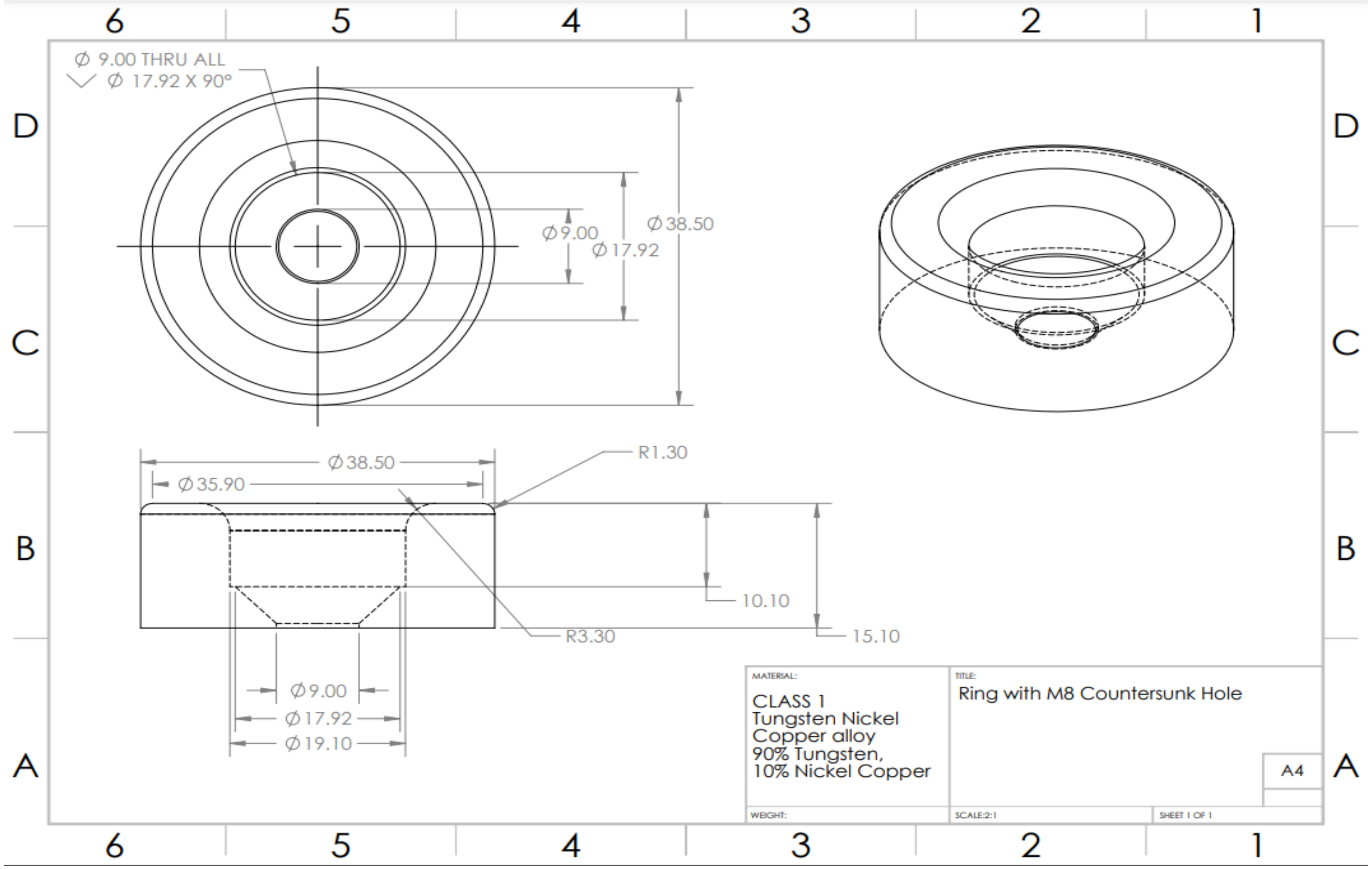


Figure 3.3: Ring electrode with M8 countersunk hole drawing

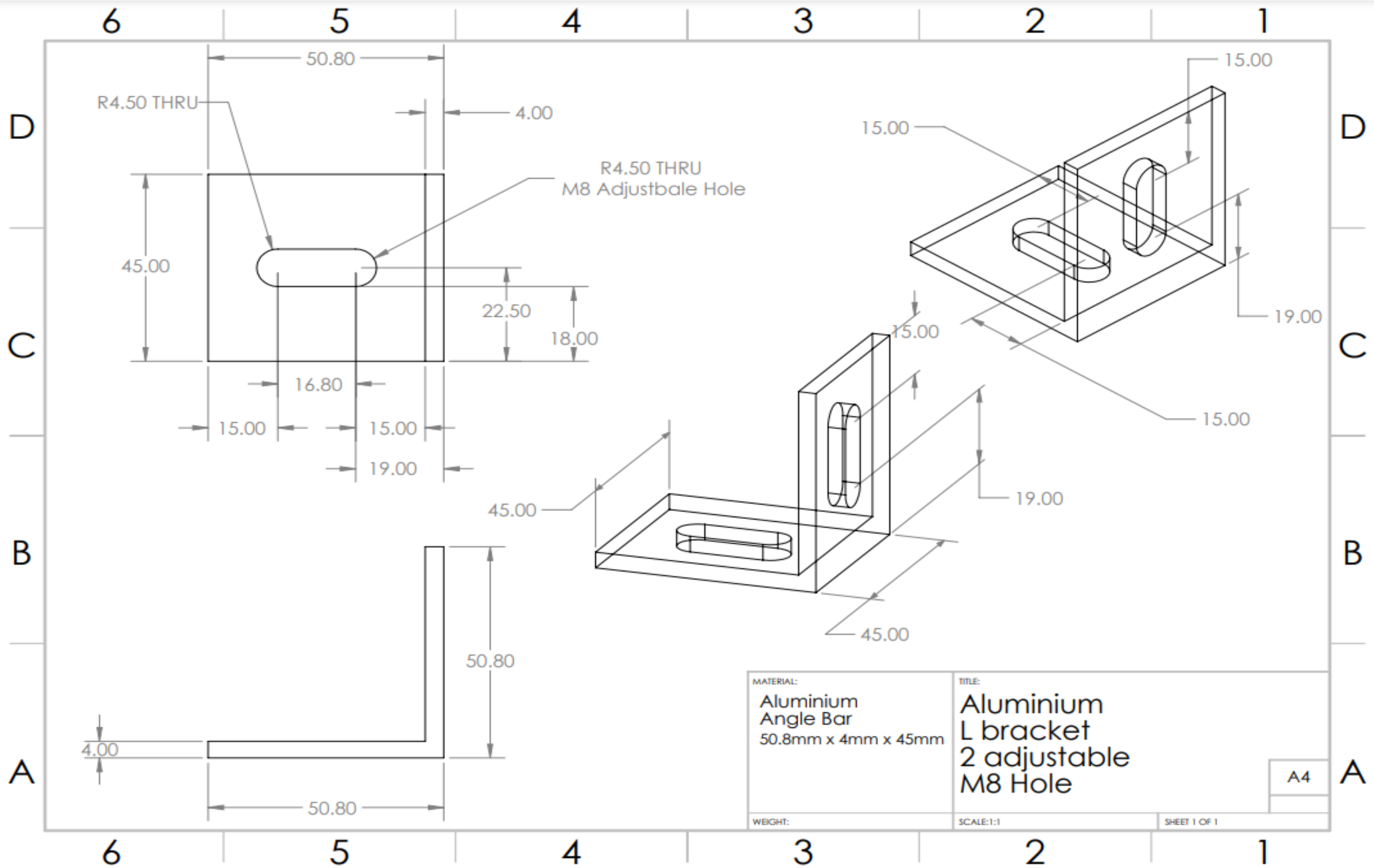


Figure 3.4: Electrode holder drawing

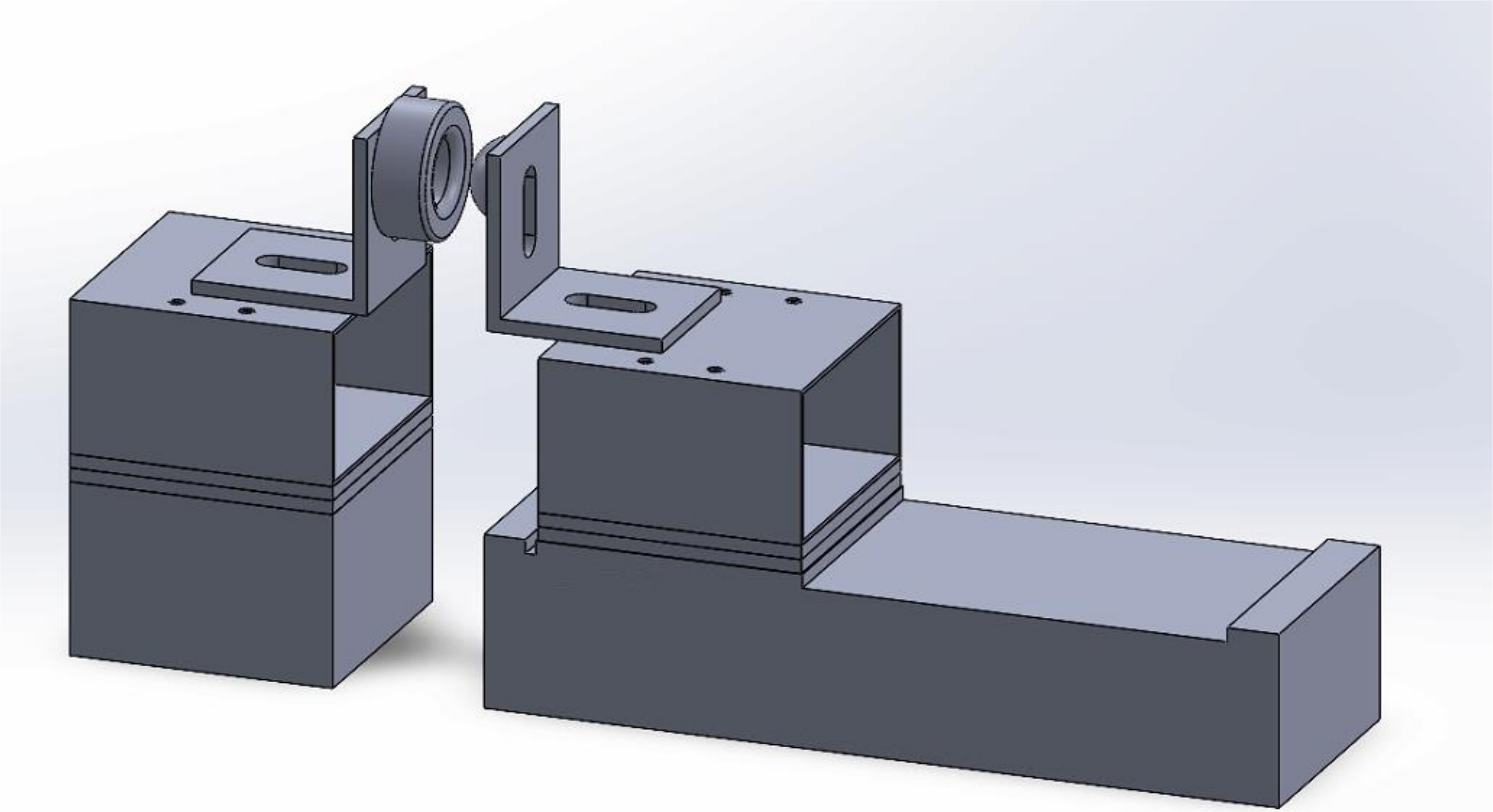


Figure 3.5: Overall design of the DC arc generator

3.5 Building the DC Arc Generator

The electrodes and electrode holder are fabricated according to the design in Figures 3.2, 3.3, and 3.4. However, due to limited resources, the Class 1 Tungsten Nickel Copper alloy specified is not commonly found in Malaysia. As a replacement material, steel is used, despite its lower melting point. To ensure easy replacement, the electrodes are designed accordingly. The electrodes and holders are fastened using an M8 screw and nut, which enables the M8 size cable lug to be firmly attached to the electrode holder, providing a solid contact. The cable lug is clamped to the 6 mm2 cables connected to the MC4 connectors, enabling the operator to easily simulate the DC arc by connecting the PV DC source to the DC arc generator with the MC4 connectors, as shown in Figure 3.9.

To insulate the current-carrying components from other parts of the DC arc generator, a busbar insulator SM35 is used. The rated voltage of the busbar insulator SM35 is 1500 VDC, which is suitable for this DC arc generator, as confirmed by (ElectroMechanica, 2022). Additionally, a simple linear guide mechanism was built for the First-Generation DC arc generator to achieve the pull-apart method. The handle of the linear guide mechanism is made of acrylic, providing sufficient insulation for the operator. To improve the precision of electrode separation, the Second-Generation DC arc generator was fabricated with a 3D-printer linear guide system, enabling the operator to control the separation distance more accurately. The DC arc generator enclosure is made of acrylic, providing the operator with a clear view of the DC arc simulation while also protecting the operator from the DC arc electrical shock hazard.

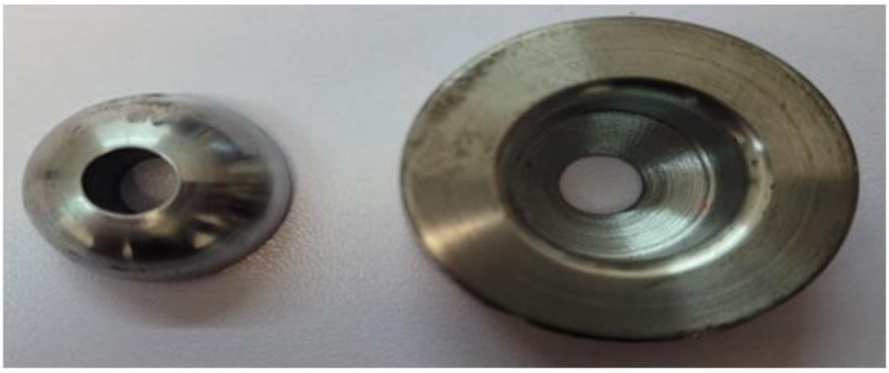


Figure 3.6: The hemisphere (Left) and the ring (Right) electrode

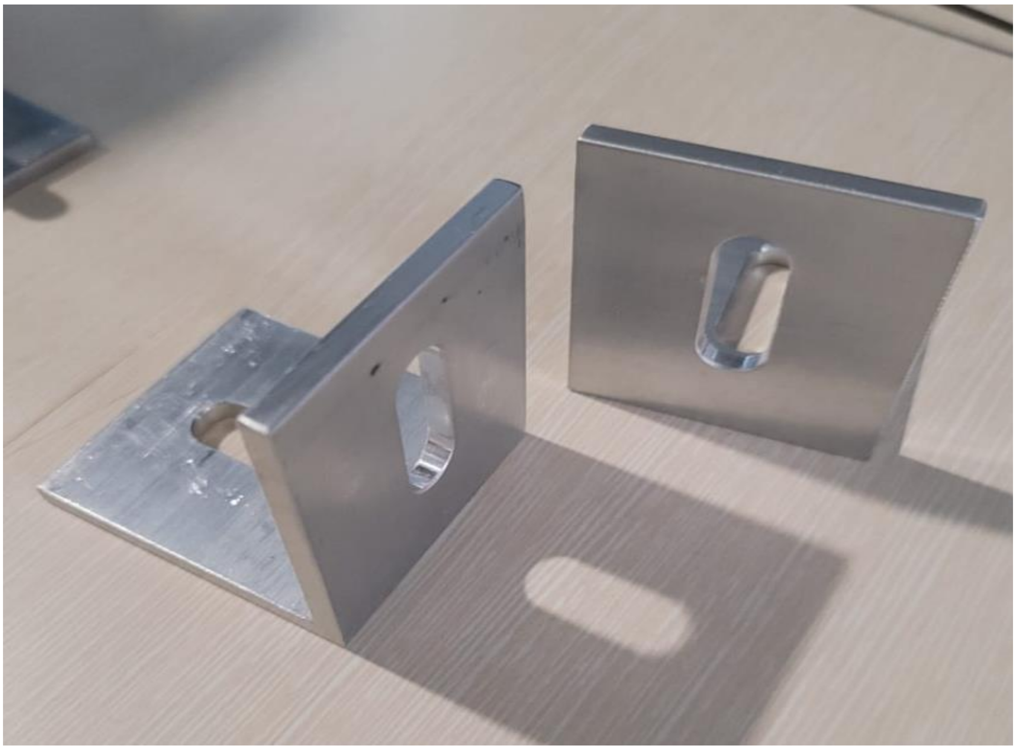


Figure 3.7: The aluminium electrode holders

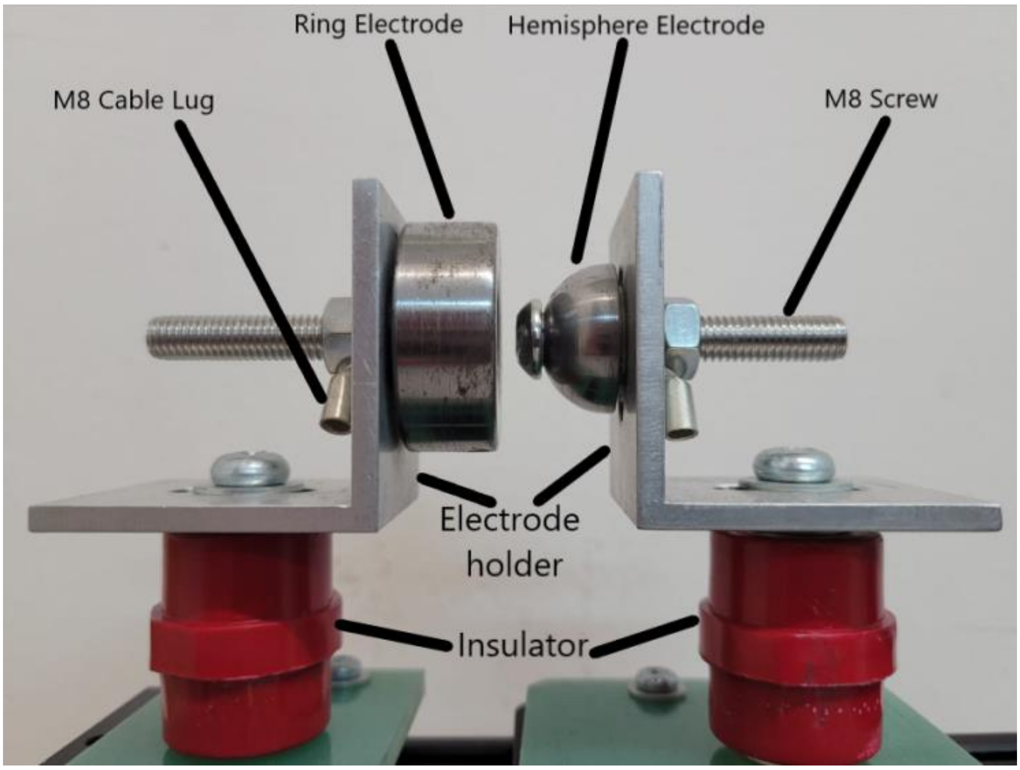


Figure 3.8: The assembly of electrodes, electrodes holder, M8 screw, M8 cable lug and the insulators.

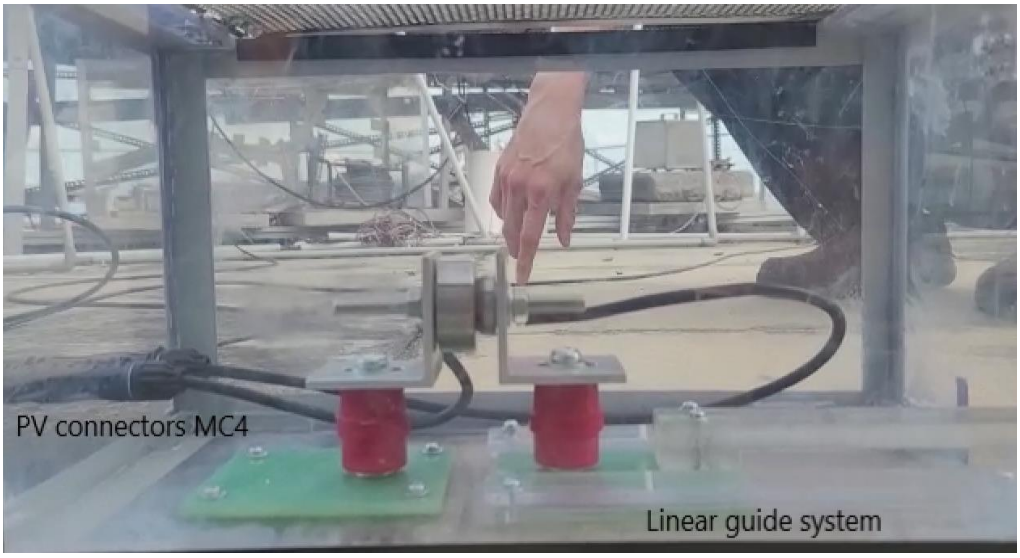


Figure 3.9: The overview of the First-Generation prototype of the DC arc generator.

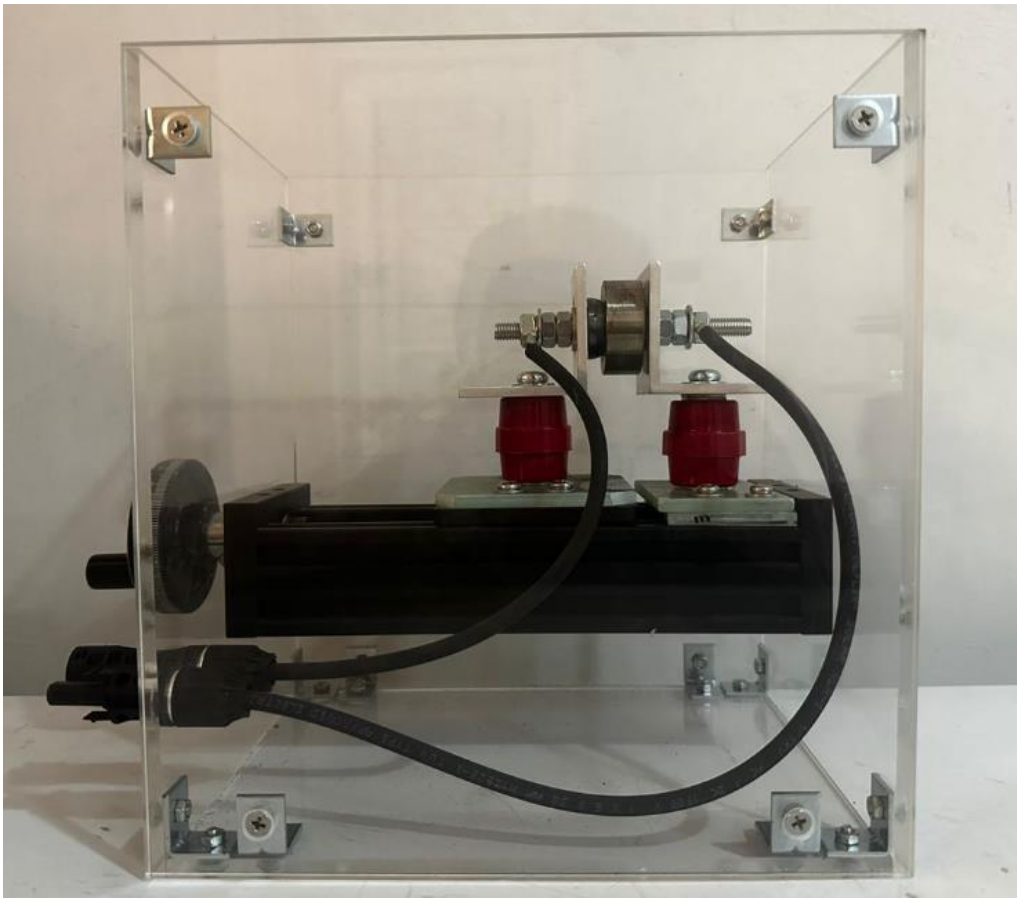


Figure 3.10: The overview of the Second-Generation prototype of the DC arc generator.

3.6 Testing the DC Arc Generator

The testing of the DC arc generator involves several steps to ensure its safety and proper functioning. Firstly, a visual inspection of the generator and its components should be performed, checking for any damage, loose connections, or other issues that may affect its performance. Then, a series of tests should be conducted. The test results will then be recorded in the results and discussion chapter.

3.6.1 Continuity Test for the DC Arc Generator

The continuity test is an essential step in testing a DC arc generator to ensure that the electrodes are correctly aligned and connected, and that there is no continuity between the current carrying conductor and the enclosure/handle.

To perform this test, a multimeter with a continuity test function is required. Two continuity tests are carried out to confirm the proper functioning of the DC arc generator.

The first test is used to check the contact of the electrodes when they are in contact. The multimeter is set to the continuity test function and the leads are connected to each electrode. By bringing the electrodes into contact, continuity can be verified. This test is illustrated in Figure 3.11.

The second continuity test is crucial to ensure the operator's safety when simulating a DC arc fault, by ensuring that there is no continuity between the current carrying conductor and the enclosure/handle. To conduct this test, the multimeter leads are connected to the current carrying conductor and the enclosure/handle, as shown in Figure 3.12. If the multimeter indicates a continuity reading, further investigation is necessary as there may be an issue with the generator.

By conducting two continuity tests using a multimeter, any potential issues with the DC arc generator can be identified early, preventing potential safety hazards during its operation. The continuity test ensures that the electrodes are properly aligned and connected, and that there is no continuity between the current carrying conductor and the enclosure/handle, leading to the safe and proper functioning of the DC arc generator.

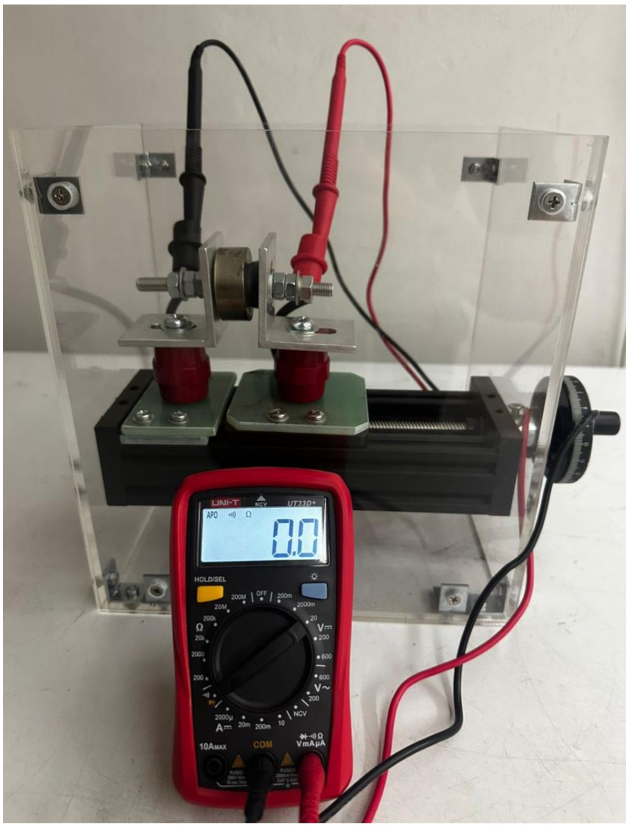


Figure 3.11: First continuity test, between the electrodes.

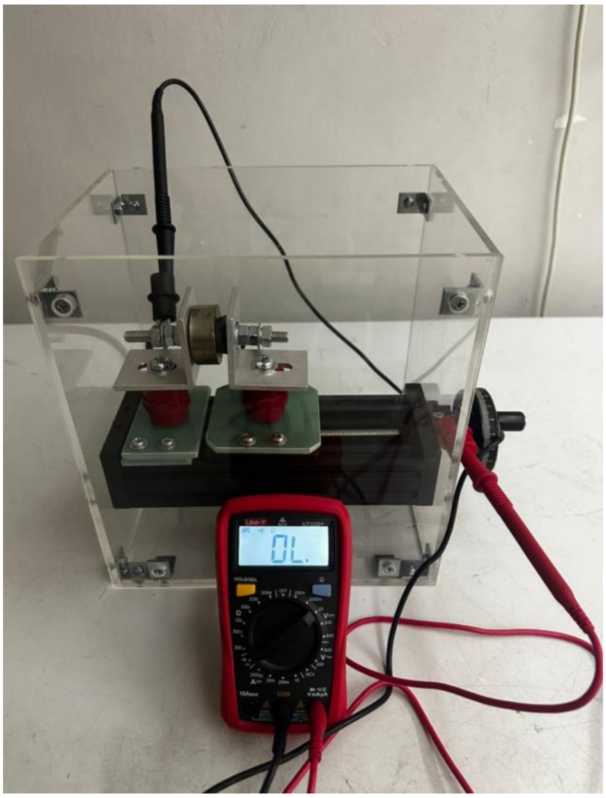


Figure 3.12: Second continuity test, between current carrying conductor and the handle of the DC arc generator.

3.6.2 Insulation Resistance Test for the DC Arc Generator

The insulation resistance test is a crucial step in testing a DC arc generator, as it ensures that the generator's insulation resistance is high enough to prevent flashover and protect the operator from harm when connected to a high voltage PV system.

To conduct this test, an insulation resistance tester capable of injecting up to 1000 VDC is required, as illustrated in Figure 3.13. During the test, a voltage of 1000 VDC is injected between the current carrying conductor and the handle or enclosure of the DC arc generator, as shown in Figure 3.14. This confirms that the insulation resistance of the DC arc generator is sufficient to prevent flashover and protect the operator.

By performing the insulation resistance test early, potential issues with the generator's insulation resistance can be identified and addressed, preventing safety hazards during its operation. As a result, the insulation resistance test is essential to ensure the safe and proper functioning of the DC arc generator.

Figure 3.13: The insulation resistance tester.

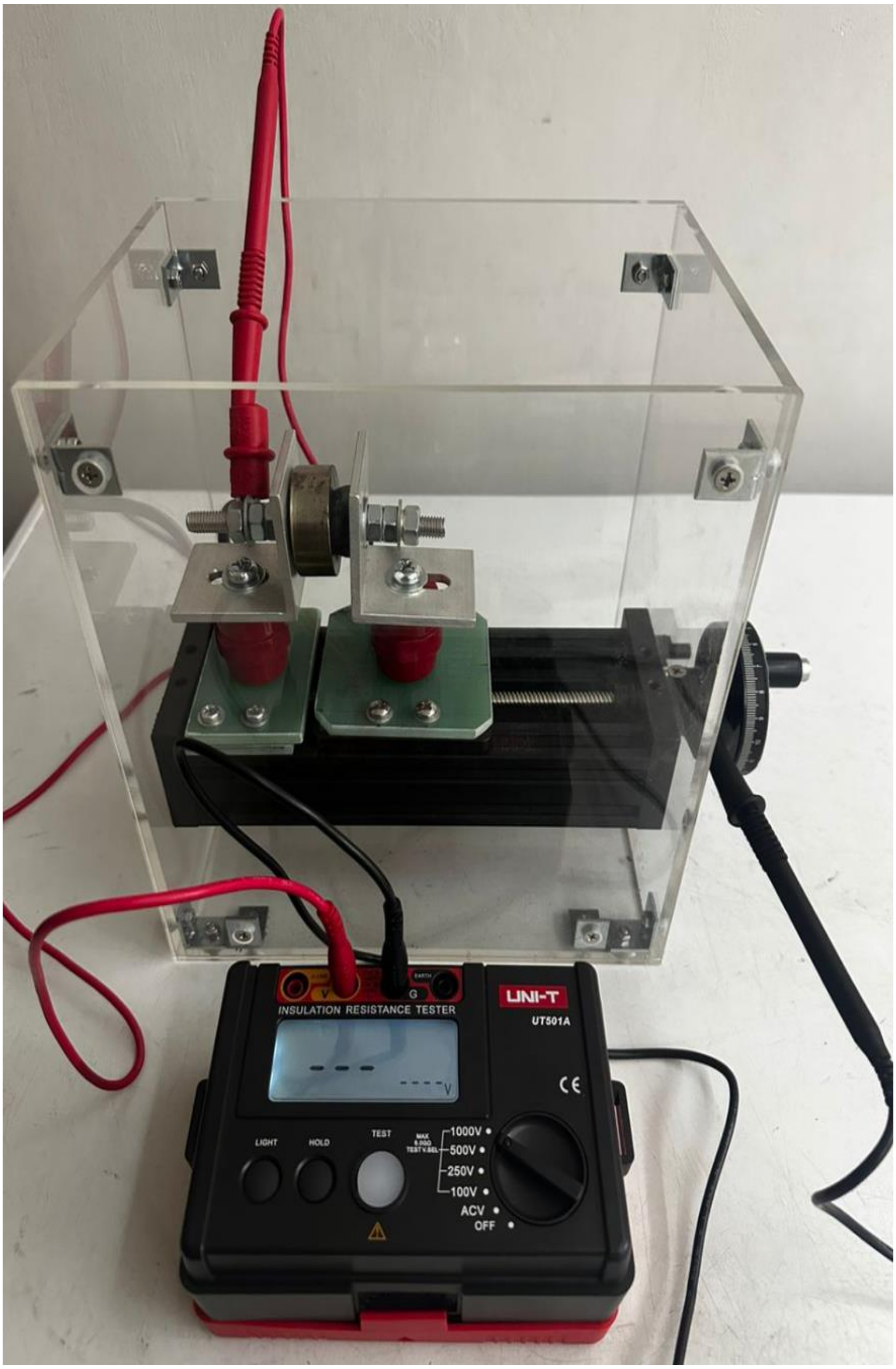


Figure 3.14: The setup for insulation resistance test for the DC arc generator.

3.6.3 Contact Resistance Test for the DC Arc Generator

The contact resistance test is a critical step in testing a DC arc generator. It is designed to ensure that the resistance between the electrodes when they are in contact is low and that there is a good connection between the electrodes.

To conduct this test, a multimeter is used to measure the resistance between the electrodes when they are in contact, as shown in Figure 3.15. The setup used for this test is shown in Figure 3.16.

The contact resistance test is essential to ensure that there is a good connection between the electrodes and that the resistance is low. By conducting this test, any potential issues with the electrodes' contact resistance can be identified early, preventing potential safety hazards during its operation.

In summary, by using a multimeter to measure the resistance between the electrodes when they are in contact, the contact resistance test ensures that there is a good connection between the electrodes and that the resistance is low. This test is critical to ensure the safe and proper functioning of the DC arc generator, and any issues can be identified early to prevent potential safety hazards during its operation.

Figure 3.15: Multimeter using the resistance measurement function.

Figure 3.16: The setup for contact resistance test for the DC arc generator.

3.7 Setting up the PV System

The aim of this section is to provide a detailed explanation of the essential equipment required to establish an on-site PV system that can simulate real-world conditions for DC arc fault testing, allowing for on-site evaluation of the DC arc fault protection features of the solar inverter. The simulation of real-world conditions is crucial, as it replicates external factors that could potentially hinder DC arc detection, leading to the failure of the DC arc fault protection function to detect and interrupt the circuit. By following this methodology, the effectiveness of the solar inverter's DC arc fault protection features against DC arc faults can be established, ensuring the safety and reliability of the PV system. The maintenance of a dependable and secure PV system is vital in preventing damage and hazards related to DC arc faults.

3.7.1 Location of the PV Site

The location selected for the PV system is the UTAR Sungai Long Campus KB Block rooftop, estimated to have site dimensions of 10 m x 5m as shown in Figure 3.17. This location is considered an ideal spot due to the availability of an AC power supply that can power the solar inverter, allowing it to export the generated power into the UTAR electrical power system. Additionally, the site has fewer shading issues, making it appropriate for PV system installation.

Figure 3.17: PV site on the UTAR Sungai Long Campus KB Block Roof Top

3.7.2 Equipment of the PV System

The necessary equipment for the PV system has been made possible through the support provided by Huawei, who has provided funding and assisted in securing equipment sponsorship from Sunview group. Sunview group has supplied seven solar panels for the PV system setup, while the funding has been used to acquire the essential equipment, including the SUN2000-2KTL-L1 solar inverter and seven Huawei Smart PV Optimizer SUN2000-600W-P solar power optimizers. Detailed specifications for each of the equipment will be provided in the next subsection.

3.7.3 Solar Panels of the PV System

In this subsection, the specifications of the solar panels utilized in the PV system will be discussed. From Figure 3.18, the solar panels used are Qcells, manufactured in Malaysia, with a nominal power output of 330W. The short circuit current, I_{SC}, is 10.15 A, and the open circuit voltage, V_{OC}, is 40.62 V.

The seven solar panels will be connected in series To achieve a total nominal power output of 2310W (330W x 7 panels). The open circuit voltage of the PV system will be the sum of the V_{OC} of each panel, which is 284.34 V (40.62 V x 7 panels). The short circuit current of the PV system will be equal to the I_{SC} of a single panel, which is 10.15 A.

ENGINEERED, DESIGNED AND QUALITY TESTED BY Q CELLS IN GERMANY

Q.PEAK DUO-G7 330

PERFORMANCE AT STANDARD TEST CONDITIONS*

Nominal Power* (+5W/-0W)	P_{MPP}	[W]	330
Short circuit current*	I_{SC}	[A]	10.15
Open circuit voltage*	V_{OC}	[V]	40.62
Current at maximum power	I_{MPP}	[A]	9.67
Voltage at maximum power	V_{MPP}	[V]	34.14
Maximum system voltage	V_{SYS}	[V]	1000 (IEC) 1000 (UL)
Weight	M	[kg / lbs]	18.7 / 41.2

*Measurement tolerances: P_{MPP} ±3%; I_{SC}, V_{OC} ±5% at STC: 1000W/m², 25±2°C, AM 1.5 according to IEC 60904-3. Data given are rated (nominal) values.

329320157051802510

Hanwha Q CELLS Malaysia Sdn. Bhd.,
Lot 1, Jalan SP 2, Seksyen 2, Selangor Science Park 2,
63300 Cyberjaya, Selangor, Malaysia

Q CELLS

Made in Malaysia

DANGER!
Risk of electric shock!
DO NOT connect or disconnect plug contacts while system is under load current. Refer to the Installation and Operation Manual before installing, operating or servicing this unit.

DANGER!
Risque de choc électrique!
NE PAS connecter ou déconnecter les connecteurs lorsque le système est en charge. Consultez le manuel d'installation et d'utilisation avant installation, utilisation et entretien du produit.

Fire Rating: Class C / Type 2
Design load: 55 lbs/ft²
Fuse Rating: 20 A
For field connections, use minimum No.12 AWG copper wires insulated for a minimum of 90 °C

U.S. Patent No. 9,893,215 (solar cells)

EMAIL service@q-cells.com
WEB www.q-cells.com

Figure 3.18: Specification of the Qcells solar panel.

3.7.4 Solar Power Optimizers of the PV System

The solar power optimizer utilized in the PV system is the Huawei Smart PV Optimizer SUN2000-600W-P as shown in Figure 3.19. Its function is to ensure that each solar panel operates at its maximum power point, thereby increasing the overall energy output and efficiency of the PV system.

The Huawei Smart PV Optimizer SUN2000-600W-P is crucial in this project by enabling the rapid shutdown function of the PV system for safety purposes. This function allows for the quick and efficient shutdown of the PV system in emergency situations, minimizing the risk of accidents and injuries.

In the evaluation of the DC arc fault protection feature in the solar inverter, the rapid shutdown function will be tested.

In terms of specifications, the Huawei Smart PV Optimizer SUN2000-600W-P can take in an input of 10-80 VDC, 14.5 A, and 600 W, with a maximum output of 80 VDC and 15 A. Its IP68 enclosure enables it to withstand extreme weather conditions, making it an ideal choice for the PV system setup.

Figure 3.19: Huawei Smart PV Optimizer SUN2000-600W-P

3.7.5 Solar Inverter of the PV System

This subsection will be discussing the solar inverter used in the PV system. The SUN2000-2KTL-L1, as shown in Figure 3.20, is the solar inverter utilized in this PV system. This inverter is manufactured by Huawei and is part of the SUN2000 series solar inverters, which integrate DC arc fault protection functions such as AFCI, R_{ISO} monitoring, RCD for residual current monitoring and rapid shutdown. These protection functions will be tested in this project to ensure their effectiveness against the DC arc faults.

The SUN2000-2KTL-L1 is a smart inverter that works together with the SolarFusion app as shown in Figure 3.21. Data is logged in real-time and sent to the app, which provides details about the tripping alarm, the reason for the tripping, and the time and date of the event. The app also allows online monitoring of the PV system.

In terms of specifications, the SUN2000-2KTL-L1 has a maximum input voltage of 600 VDC and a maximum input current of 12.5 A.

Figure 3.20: The Huawei SUN2000-2KTL-L1 solar inverter.

Figure 3.21: The FusionSolar App

3.7.6 Overview of the PV System

In Figure 3.22, an overview of the PV system is illustrated. Seven 330W solar panels are connected to the Huawei Smart PV Optimizer SUN2000-600W-P. The optimizers are connected in series and then connected to the Huawei SUN2000-2KTL-L1 solar inverter. Real-time data is logged by the inverter, and it can be accessed through the FusionSolar app to monitor the PV system. Fault alarms are also notified by the FusionSolar app to the operator, which helps to identify the faults during upcoming tests.

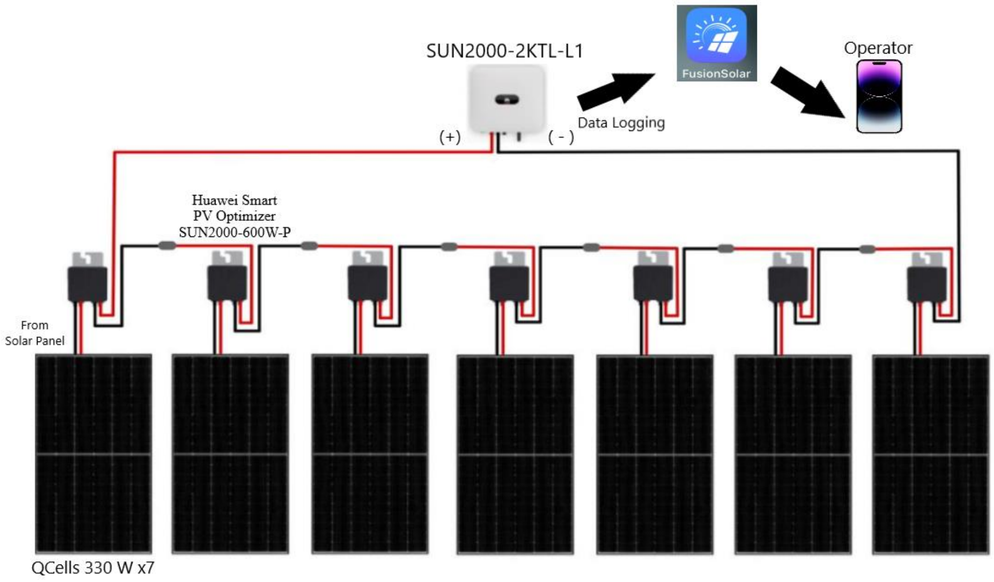


Figure 3.22: Overview of the PV system.

3.8 DC Arc Fault Protection Features Testing

In this section, several tests will be explained to evaluate the DC arc fault protection features of the PV system. The first test to be conducted is the DC series arc fault test in different positions of the PV system without AFCI enabled, followed by the DC parallel arc fault test. Next, the DC series arc fault test with AFCI enabled will be carried out, followed by the R_{ISO} test, the RCD test, and finally, the rapid shutdown test.

In the following subsection, details will be provided about the equipment required for the tests, the testing procedures, circuit diagrams, and the data that need to be recorded during the tests to evaluate the effectiveness of the DC arc fault protection feature in the Huawei SUN2000-2KTL-L1 solar inverter against the DC arc faults.

3.8.1 DC Series Arc Faults in Different Positions of the PV system

The purpose of this test is to analyze the variation in DC arc behavior at different positions of a PV system, including the positive terminal, negative terminal, and between the solar panels, as well as in different solar irradiance levels. To conduct this test, the required equipment includes a DC arc generator, multimeter, and digital vernier caliper. Figure 3.23 provides the circuit diagram for the DC series arc fault at the positive terminal, which serves as the basis for the test. The procedure for conducting the DC series arc faults in different positions is as follows:

1. Set up the testing circuit according to the circuit diagram shown in Figure 3.23 for the positive terminal.
2. Ensure that the AFCI function in the inverter is switched OFF using the FusionSolar App to prevent it from interrupting the DC series arc.
3. Verify that the electrodes of the DC arc generator are in the closed position.
4. Connect the multimeter to the DC arc generator to measure the voltage across the electrodes.
5. Slowly separate the electrodes of the DC arc generator to simulate the DC series arc.
6. Stop the separation when the DC arc is extinguished and observe the strength of the DC arc.
7. Record the voltage across the electrodes.
8. Disconnect the DC arc generator from the circuit.
9. Measure the distance between the electrodes using the digital vernier caliper.
10. Repeat steps 1 to 9 eight times to obtain adequate data for the positive terminal.
11. Replace the circuit connection with the circuit diagram shown in Figure 3.24 for the negative terminal and in Figure 3.25 for the DC series arc between the solar panels.
12. Repeat steps 1 to 9 eight times for each connection to obtain adequate data for the negative terminal and between the solar panels.
13. Compare the data collected from the different positions to identify any variations in DC arc behavior and take appropriate measures to mitigate the associated risks.

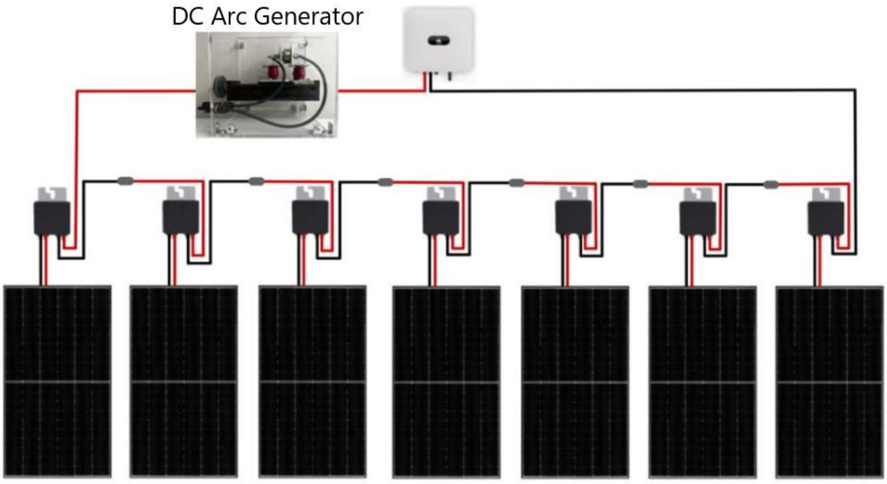


Figure 3.23: DC Series Arc Faults in Positive Terminal

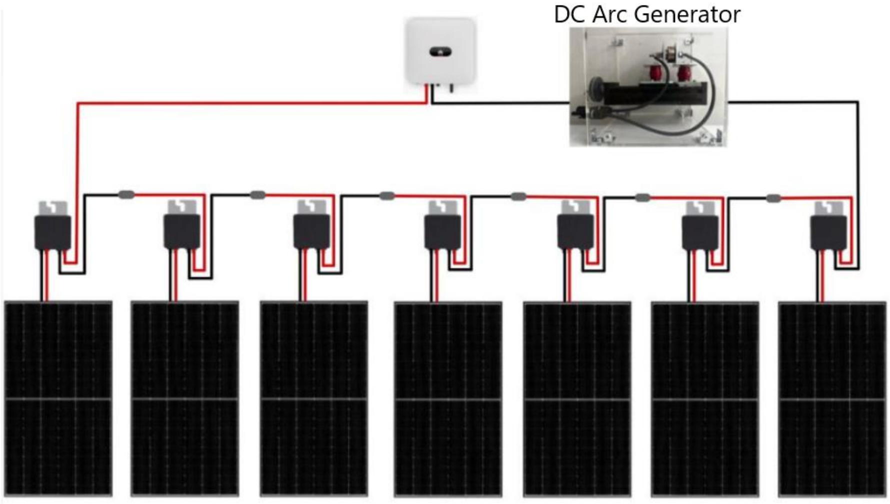


Figure 3.24: DC Series Arc Faults in Negative Terminal

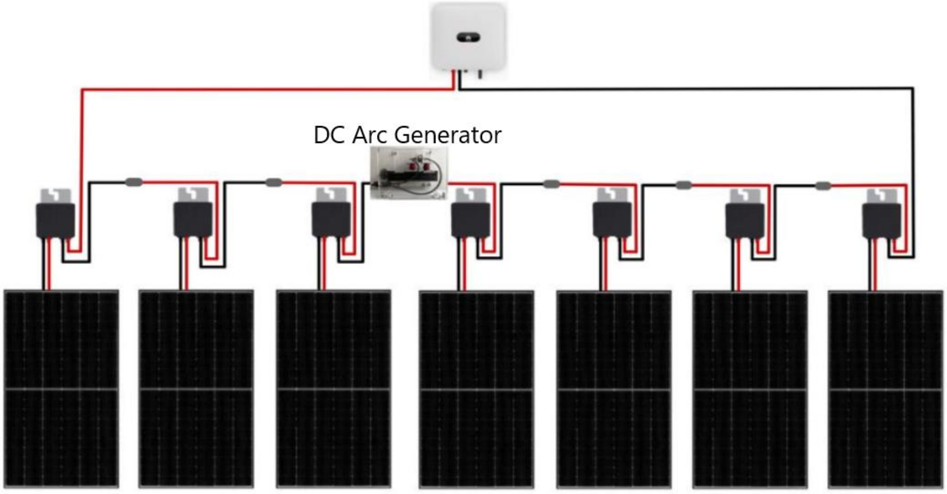


Figure 3.25: DC Series Arc Faults In between Solar Panel

3.8.2 DC Parallel Arc Fault

The purpose of conducting the DC parallel arc fault test is to observe the strength of the DC parallel arc fault as compared to the DC series arc fault and examine how the DC parallel arc strength is affected when the solar panel voltage is reduced. The required equipment for this test includes a DC arc generator, multimeter, and digital vernier caliper. Figure 3.26 shows the circuit diagram for the DC parallel arc testing.The procedure for conducting the DC Parallel Arc Fault is as follows:

1. Set up the testing circuit according to the circuit diagram shown in Figure 3.26.
2. Ensure that the electrodes of the DC arc generator are in the open position.
3. Connect the multimeter to the DC arc generator to measure the voltage across the electrodes.
4. Close the contact of the electrode of the DC arc generator to make a short circuit between the positive and negative terminals.
5. Observe the reading of the FusionSolar app, which should show 0 power output from the solar panels, and no fault will be detected.
6. Slowly separate the electrodes of the DC arc generator and observe the strength of the DC parallel arc fault.
7. Stop the separation once the DC arc is extinguished.
8. Record the voltage across the electrodes.
9. Disconnect the DC arc generator from the circuit.
10. Measure the distance between the electrodes using the digital vernier caliper.
11. Repeat steps 1 to 10, reducing the number of solar panels by one each time, starting from 7 panels and continuing until only 1 panel remains.

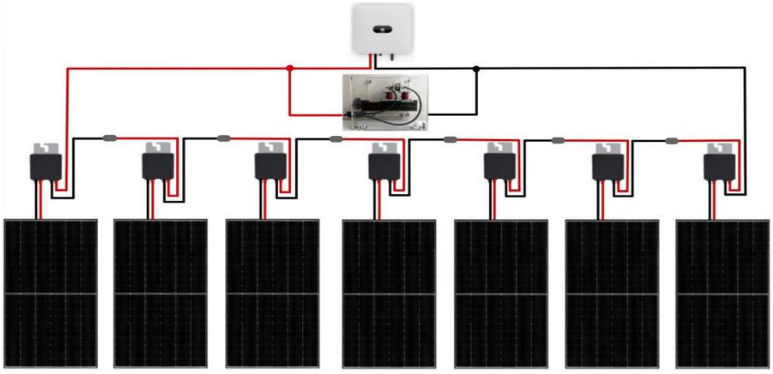
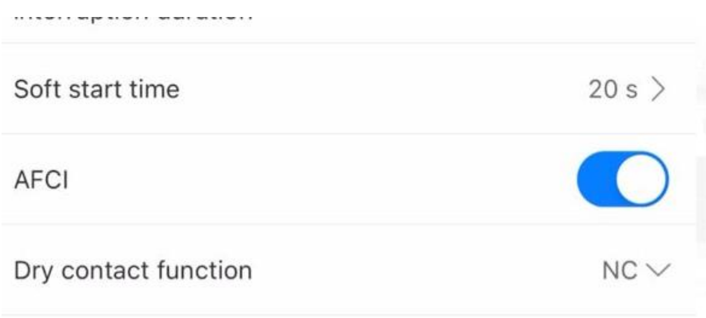


Figure 3.26: DC Parallel Arc Fault Circuit Diagram

3.8.3 DC Series Arc Fault with AFCI Enabled

The purpose of conducting the DC Series Arc with AFCI Enabled test is to evaluate the effectiveness of the AFCI function in the Huawei Solar inverter SUN2000-2KTL-L1 against the DC series arc fault in on-site conditions. The test requires the use of a DC arc generator, multimeter, digital vernier caliper, and camera. Figure 3.28 shows the circuit diagram for this testing. The procedure for conducting the DC Series Arc with AFCI Enabled is as follows:

1. Construct the testing circuit as shown in Figure 3.28.
2. Ensure that the AFCI function is switched ON in the FusionSolar App as shown in Figure 3.27.
3. Set up the camera to record the operation of AFCI in interrupting the DC series arc fault.
4. Verify that the electrodes of the DC arc generator are in the closed position.
5. Connect the multimeter to the DC arc generator to measure the voltage across the electrodes.
6. Slowly separate the electrodes of the DC arc generator to simulate the DC series arc.
7. Observe the AFCI in interrupting the DC series arc fault.
8. Stop the separation once the DC series arc is extinguished.
9. Stop the video recording and record the timing for the AFCI to detect and interrupt the DC series arc, as well as the voltage across electrodes.
10. Observe if the FusionSolar sends any notification to the operator regarding the DC arc fault.
11. Disconnect the DC arc generator from the circuit.
12. Measure the distance between electrodes using the digital vernier caliper.
13. Repeat Steps 1 to 12 by eight times.



Soft start time 20 s

AFCI

Dry contact function NC

Figure 3.27: AFCI function “ON”

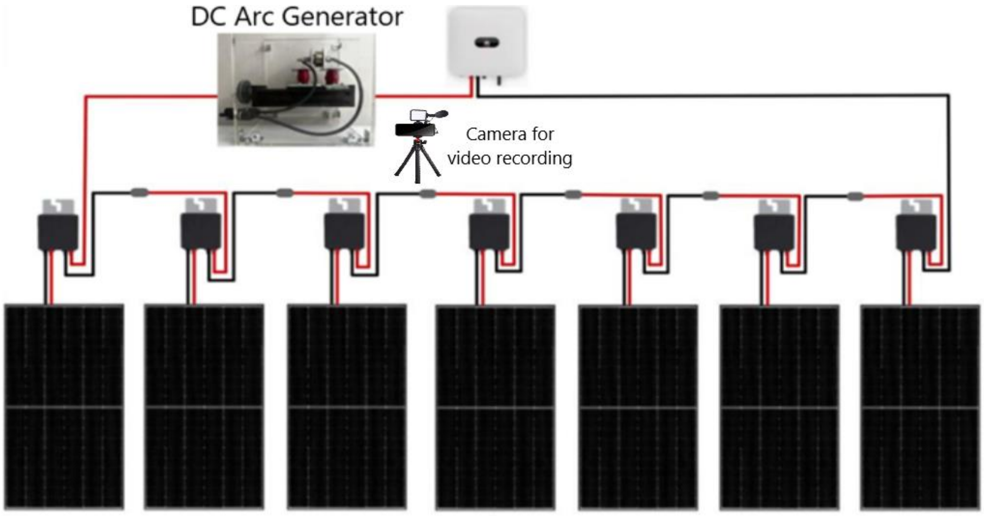


Figure 3.28: DC series arc fault with AFCI enabled testing setup.

3.8.4 Insulation Resistance (R_{ISO}) Monitoring Function Testing

The purpose of this test is to ensure that the insulation resistance value is always monitored by the inverter before allowing the DC circuit to complete the circuit and permit the PV system to start generating power. The testing circuit is constructed as shown in Figure 3.29, where a short circuit to ground is created using the DC arc generator, resulting in a low insulation resistance for the PV system. Next, the inverter reaction to this fault will be observed. The required equipment for this test includes a DC arc generator and a wye connector. The procedure for conducting the insulation resistance (R_{ISO}) monitoring function testing is as follows:

1. Shut down the inverter with the AC supply and the DC switch.
2. Construct the testing circuit as shown in Figure 3.29.
3. Make sure the DC arc generator is in a closed position, creating a short circuit to ground.
4. Switch on the inverter AC supply and DC switch.
5. Observe the inverter indication light.
6. Check the FusionSolar app for low insulation resistance alarms.
7. Repeat the experiment three times to obtain a more accurate study.

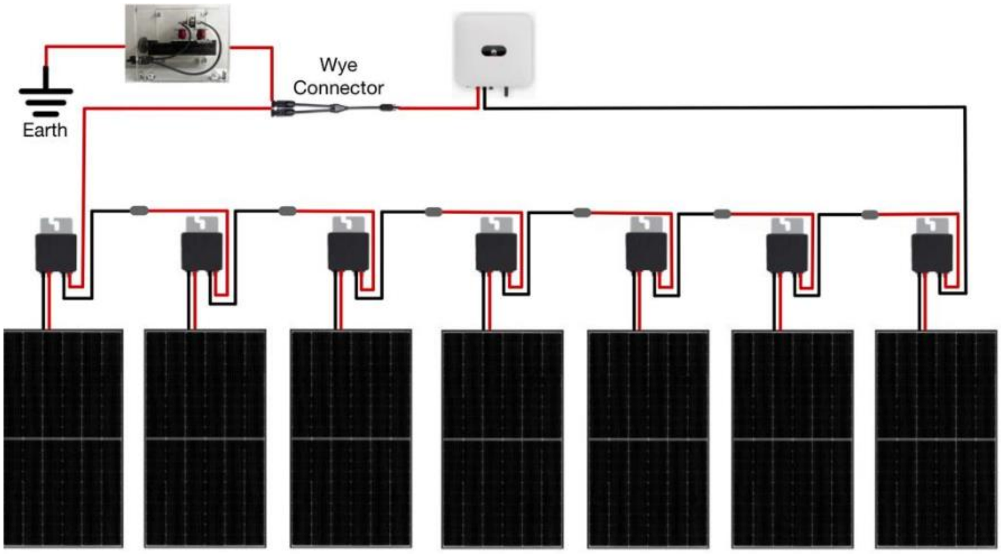


Figure 3.29: Insulation resistance (R_{ISO}) monitoring function testing setup

3.8.5 Residual Current Monitoring Function (RCD) Testing

The effectiveness of the RCD function in the Huawei solar inverter SUN2000-2KTL-L1 against abnormal residual current during the operation of the PV system will be verified through this test. A short circuit to earth will be simulated during normal operation of the PV system, and the required equipment for this experiment is a DC arc generator and a wye connector. Figure 3.30 shows the setup for this testing. The procedure for conducting this testing is as follows:

1. Set up the testing circuit as shown in Figure 3.30.
2. Ensure that the electrodes of the DC arc generator are in the open position.
3. Switch on the inverter and let it operate in normal condition.
4. When the PV system is operating in normal condition, close the contact of the electrodes of the DC arc generator to create a short circuit to earth.
5. Observe the indication lights of the inverter.
6. Next, observe the FusionSolar app for abnormal residual current alarms.
7. Repeat the experiment three times to obtain accurate results.

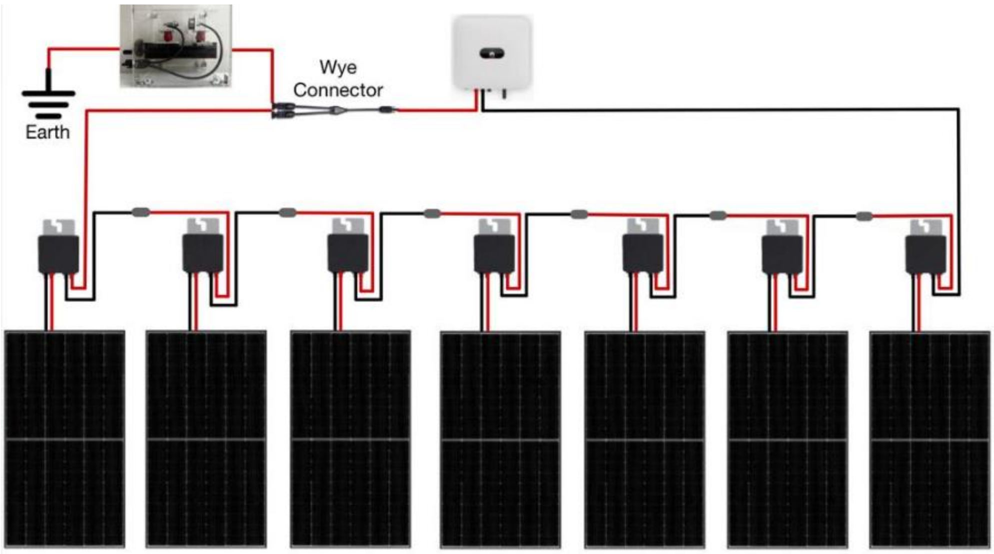


Figure 3.30: Residual current monitoring function (RCD) testing setup

3.8.6 Rapid Shutdown Testing

The purpose of this test is to evaluate the ability of the Huawei Smart PV Optimizer SUN2000-600W-P and Huawei Solar inverter SUN2000-2KTL-L1 to stop a DC parallel arc fault. During this fault, the inverter goes into "sunlight detection mode" because of the zero power output from the solar panels, which is similar to the night condition. This means that no fault alarm will be triggered, and the DC parallel arc fault will not be handled unless the rapid shutdown function is activated. The required equipment for this test includes a DC arc generator and a camera for video recording. The testing procedure is as follows:

1. Set up the testing circuit as shown in Figure 3.31.
2. Set up the camera for video recording to observe how the inverter and optimizer handle the DC parallel arc fault.
3. Ensure that the electrodes of the DC arc generator are in the open position.
4. Close the contact of the electrodes to create a parallel short circuit between the positive and negative terminal.
5. Observe the inverter indication lights.
6. Observe the FusionSolar App for the sunlight detection mode and 0 power output from the solar panels.
7. Slowly separate the electrodes to generate a DC parallel arc fault.
8. Stop the separation once the DC parallel arc is formed and let it sustain.
9. Switch OFF the AC supply of the inverter to trigger the rapid shutdown.

10. Record the observation and repeat the experiment three times for accurate study.

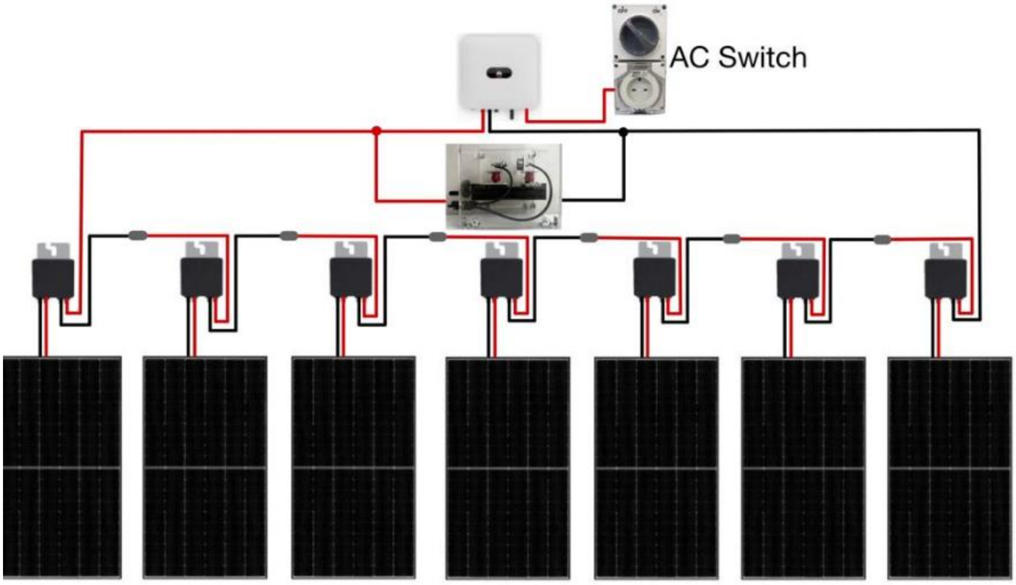


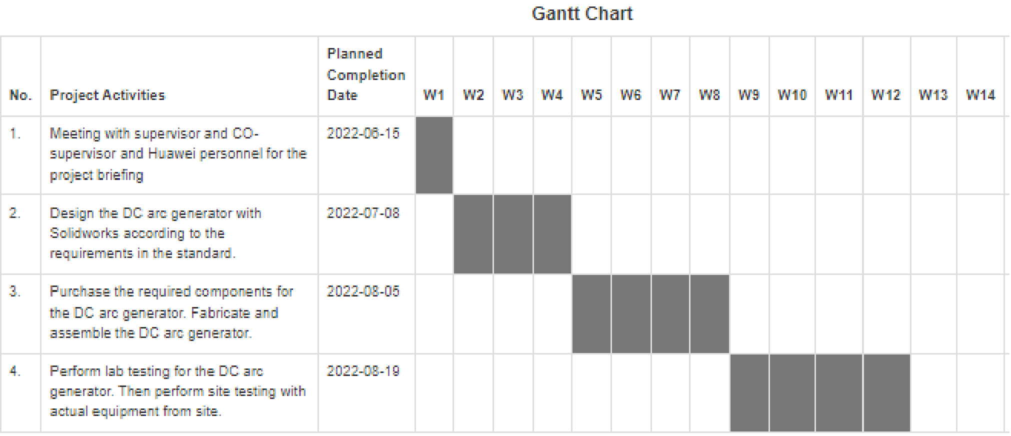
Figure 3.31: Rapid shutdown testing setup.

3.9 Summary

Chapter 3 of this study outlines the methodology used to evaluate the effectiveness of the DC arc fault protection features in a photovoltaic (PV) system using the Huawei SUN2000-2KTL-L1 solar inverter. The chapter begins by specifying the requirements for the DC Arc Generator, including the materials, dimensions, and design of the electrodes, electrode holder, insulator, and enclosure. The DC Arc Generator was designed, built and tested for its safety, continuity, insulation resistance, and contact resistance.

The PV system was set up, specifying the location, equipment, solar panels, solar power optimizers, and solar inverter including brand, model, and power rating. The testing methodology for DC arc fault protection features of the Huawei solar inverter was then detailed, including the reasons for each test, equipment required, circuit diagrams, and testing procedures for DC series arc faults in different positions of the PV system, DC parallel arc fault, DC series arc fault with AFCI enabled, insulation resistance (R_{ISO}) monitoring function testing, residual current monitoring function (RCD) testing, and rapid shutdown testing.

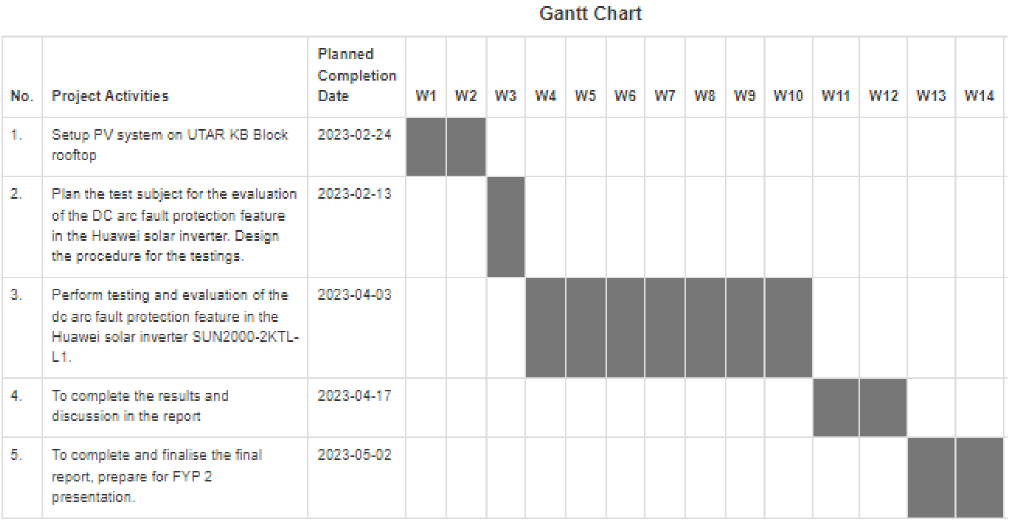
3.10 Project Work Plan



Gantt Chart

No.	Project Activities	Planned Completion Date	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
1.	Meeting with supervisor and CO-supervisor and Huawei personnel for the project briefing	2022-06-15	■													
2.	Design the DC arc generator with Solidworks according to the requirements in the standard.	2022-07-08		■	■	■										
3.	Purchase the required components for the DC arc generator. Fabricate and assemble the DC arc generator.	2022-08-05					■	■	■	■						
4.	Perform lab testing for the DC arc generator. Then perform site testing with actual equipment from site.	2022-08-19									■	■	■	■		

Figure 3.32: Project Gantt Chart for Semester 1



Gantt Chart

No.	Project Activities	Planned Completion Date	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
1.	Setup PV system on UTAR KB Block rooftop	2023-02-24	■	■												
2.	Plan the test subject for the evaluation of the DC arc fault protection feature in the Huawei solar inverter. Design the procedure for the testings.	2023-02-13			■											
3.	Perform testing and evaluation of the dc arc fault protection feature in the Huawei solar inverter SUN2000-2KTL-L1.	2023-04-03				■	■	■	■	■	■	■				
4.	To complete the results and discussion in the report	2023-04-17											■	■		
5.	To complete and finalise the final report, prepare for FYP 2 presentation.	2023-05-02													■	■

Figure 3.33: Project Gantt Chart for Semester 2

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter focuses on the testing and evaluation of DC arc fault protection feature in Huawei solar inverter SUN2000-2KTL-L1. The chapter begins with the testing of the DC arc generator to ensure its safety when connected to high voltage PV systems. The PV system's output is then discussed, followed by two subchapters on DC arc fault simulation tests, including DC series arc faults in different positions of the PV system and DC parallel arc faults. The chapter then goes on to evaluate the effectiveness of the DC arc fault protection features in the Huawei Solar Inverter SUN2000-2KTL-L1, including AFCI, R_{ISO} monitoring, RCD, and rapid shutdown tests. These tests demonstrate the inverter's ability to detect and interrupt DC series arc faults, prevent risks associated with low insulation resistance and earth faults, and provide vital safety features to protect against electrical shocks caused by ground faults.

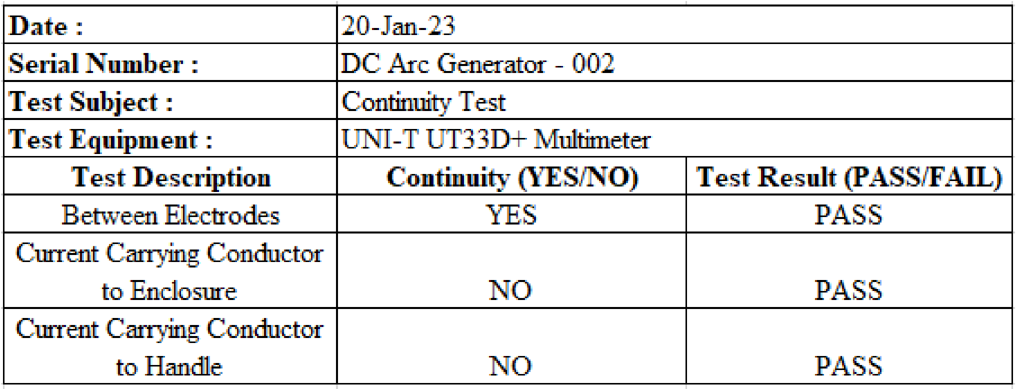
4.2 DC Arc Generator Testing

In this section, the results of the DC arc generator testing are discussed. Three tests were conducted to ensure the safety and effectiveness of the DC arc generator. These tests include the continuity test, insulation resistance test, and contact resistance test. The results of each test are analyzed and discussed in detail.

4.2.1 Continuity Test

In this subsection, the results of the continuity test of the DC arc generator will be discussed. The test was performed to ensure that there was continuity between the electrodes when they were in the closed position and no continuity between the current-carrying conductor, handle, and enclosure for operator safety. The test report for the continuity test of the DC arc generator is provided in Table 4.1 below.

Table 4.1: DC arc generator continuity test report.



Date :	20-Jan-23	
Serial Number :	DC Arc Generator - 002	
Test Subject :	Continuity Test	
Test Equipment :	UNI-T UT33D+ Multimeter	
Test Description	**Continuity (YES/NO)**	**Test Result (PASS/FAIL)**
Between Electrodes	YES	PASS
Current Carrying Conductor to Enclosure	NO	PASS
Current Carrying Conductor to Handle	NO	PASS

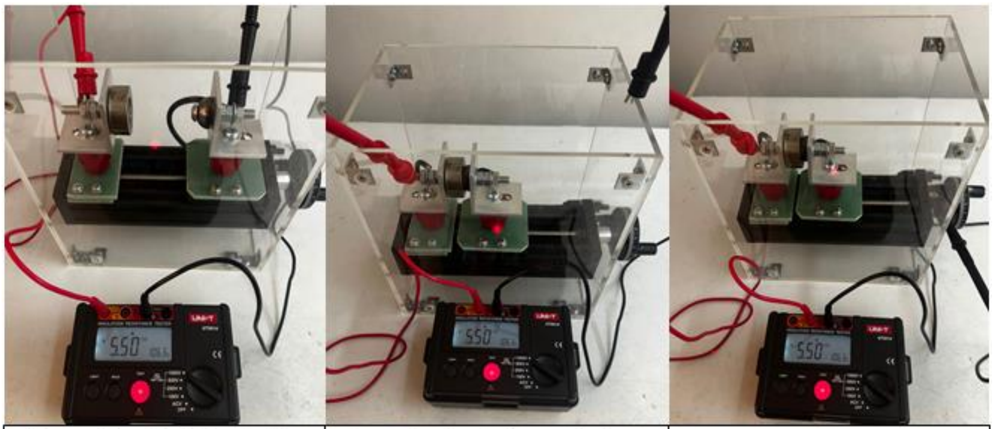
The test results in Table 4.1 indicate that there is continuity between the electrodes when they are in the closed position, which is essential for the DC arc generator to function properly. Additionally, the test results show that there is no continuity between the current-carrying conductor and the handle or enclosure, indicating that the generator is safe for the operator to handle during dc arc fault simulation. The DC arc generator passes the continuity test and meets the safety requirements for operation in the PV system.

4.2.2 Insulation Resistance Test

In this subsection, the insulation resistance test results of the DC arc generator will be discussed. The test was conducted to measure the insulation resistance between the electrodes in the open position and between the current-carrying conductor, enclosure, and handle to ensure that the insulation resistance was high enough to prevent flashover when the DC arc generator was connected to the high voltage PV system. Table 4.2 below provides the test report for the insulation resistance test of the DC arc generator.

Table 4.2: DC arc generator insulation resistance test report.

Date :	20-Jan-23	
Serial Number :	DC Arc Generator - 002	
Test Subject :	Insulation Resistance Test	
Test Equipment :	UNI-T UT501A Insulation Resistance Tester	
Test Voltage :	1000 VDC	
Test Description	**Insulation Resistance (Ω)**	**Test Result (PASS/FAIL)**
Between Electrodes in Open Position	>5.50 G	PASS
Current Carrying Conductor to Enclosure	>5.50 G	PASS
Current Carrying Conductor to Handle	>5.50 G	PASS



Between Electrodes in Open Position | Current Carrying Conductor to Enclosure | Current Carrying Conductor to Handle

Figure 4.1: Insulation resistance testing of the DC arc generator.

The setup of the insulation resistance testing of the DC arc generator is shown in Figure 4.1, and the test report for the insulation resistance test of the DC arc generator is shown in Table 4.2. The test results indicated that the insulation resistance between the electrodes in the open position, current-carrying conductor to enclosure, and current-carrying conductor to handle was greater than 5.50 GΩ, passing the test requirement. These results demonstrated that the DC arc generator had good insulation properties and was safe to use when connected to the high voltage PV system. It is important to note that the highest insulation resistance that the equipment can measure is 5.50 GΩ, which means that the actual insulation resistance of the DC arc generator could be even higher than the measured value. Overall, the results of the insulation resistance test showed that the DC arc generator had adequate insulation properties, ensuring the safety of the operator during operation.

4.2.3 Contact Resistance Test

In this subsection, the contact resistance test results of the DC arc generator will be discussed. The purpose of this test was to measure the contact resistance between the electrodes when they were in the closed position. The test aimed to ensure that the resistance between the electrodes was low and indicated good contact. The results of this test would provide insights into the performance of the DC arc generator and its ability to generate a DC arc fault. Table 4.3 below presents the test report for the contact resistance test of the DC arc generator.

Table 4.3: DC arc generator contact resistance test report.

Date :	20-Jan-23	
Serial Number :	DC Arc Generator - 002	
Test Subject :	Contact Resistance Test	
Test Equipment :	UNI-T UT33D+ Multimeter	
Test Description	**Test**	**Test Result (Ω)**
Contact between Electrodes in Closed Position	1	0.1
	2	0.1
	3	0

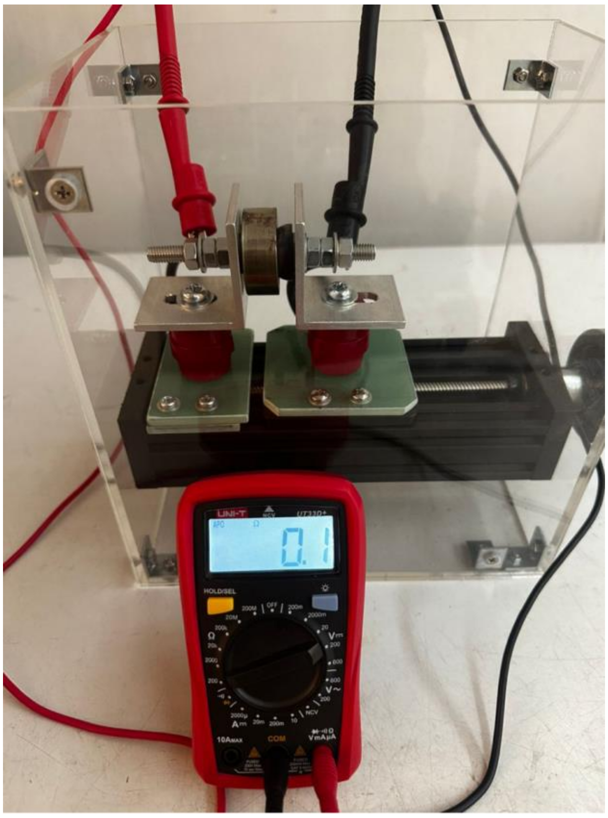


Figure 4.2: DC arc generator continuity test report.

The setup of the contact resistance testing of the DC arc generator is shown in Figure 4.2. As shown in Table 4.3, the contact resistance between electrodes in test 1 and test 2 was 0.1 Ω, indicating good contact between the electrodes. In test 3, the contact resistance was 0 Ω, which also indicated good contact. These results demonstrated that the DC arc generator had low contact resistance, ensuring the smooth flow of current and safe operation.

4.2.4 Summary

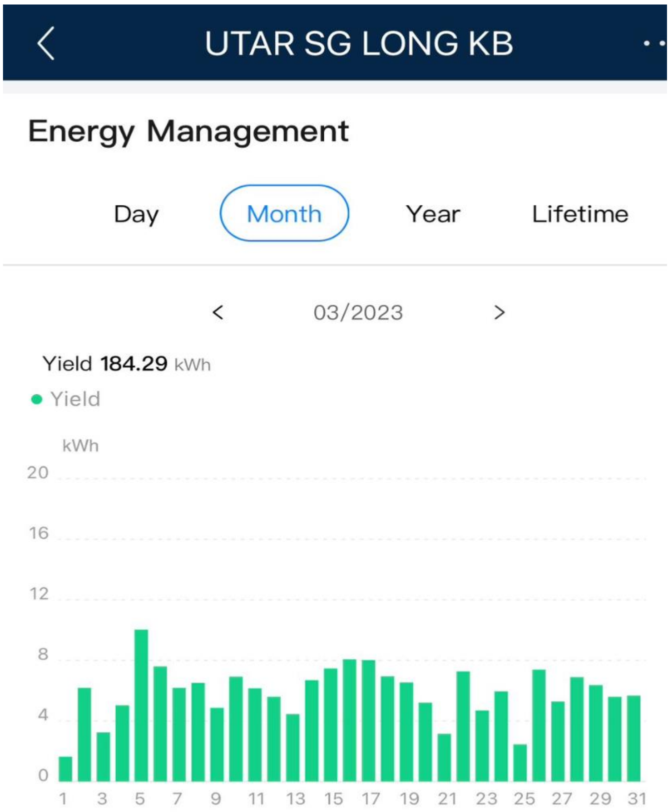
The results of the DC arc generator testing were discussed. The continuity test, insulation resistance test, and contact resistance test were conducted to ensure the safety and effectiveness of the DC arc generator. The results showed that the DC arc generator passed all three tests, indicating good continuity, high insulation resistance, and low contact resistance. These results demonstrated that the DC arc generator had good insulation properties, was safe to use when connected to the high voltage PV system and could generate a DC arc fault smoothly and safely.

4.3 PV System Performance

In this section, the performance of the PV system is discussed. It is essential to ensure that the PV system setup is stable and can generate electricity smoothly for DC arc testing. Figure 4.3 shows the PV site setup on UTAR Sungai Long Campus KB Block rooftop for DC arc testing. The results of the PV system's yield during March 2023 are presented in Figure 4.4. The total yield for the PV system during March 2023 was 184.29 kWh. 184.29 kWh is equivalent to powering approximately 553 LED lights with a power consumption of 5 W each for 30 days. It can also run a 1,000 W air conditioner for about 18.43 hours.

Figure 4.5 and 4.6 show the peak output of the system, which can go up to 1.4 kW around 12 pm, and the system input voltage is around 150V, which is higher than the NEC requirement of 80V that requires the PV system to have AFCI protection. These results demonstrated that the PV system had good performance, indicating that it was suitable for DC arc testing.

Figure 4.3: PV site setup on UTAR Sungai Long Campus KB Block rooftop for DC arc testing.



Yield 184.29 kWh

Figure 4.4: Yield of the PV system for March 2023.

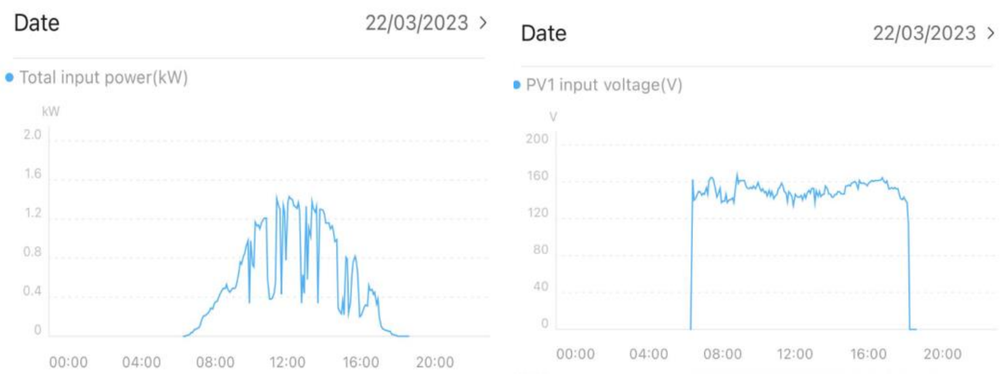


Figure 4.5: Yield of the PV system for 22 March 2023.

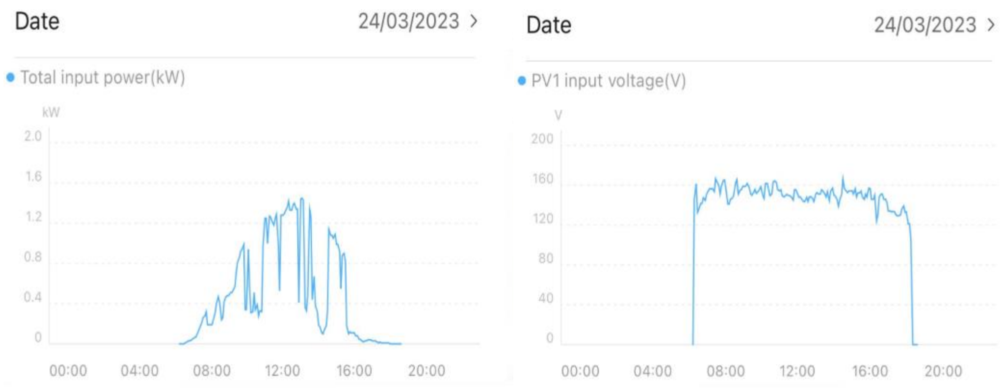


Figure 4.6: Yield of the PV system for 22 March 2023.

4.4 DC Arc Fault Simulation Test

In this section, the behavior of DC arc faults was studied through the DC series arc faults in different positions of the PV system test and the DC parallel arc fault test. Parameters were recorded, and the results were analyzed to interpret the DC arc fault behavior. The destructive effects of DC arc faults on the PV system were observed, and the differences between DC series arc and parallel arc were compared.

4.4.1 DC Series Arc Faults in Different Positions of the PV System Test

In this subsection, the results and discussion for the DC series arc faults in different positions of the PV system will be presented. The purpose of this test was to determine if there were any differences in the occurrence of series faults in different positions of the PV system. Three positions were tested, namely the positive terminal, negative terminal, and in between the solar panels, as illustrated and explained in methodology 3.8.1 DC Series Arc Faults in Different Positions of the PV system.

The testing setup for the DC series arc faults in different positions of the PV system is shown in Figure 4.7. Figure 4.9 illustrate the measurement of the electrode gap after the DC arc fault test, using the digital vernier caliper. To prevent the AFCI function of the inverter from interrupting the DC series arc, it was switched off. The parameters measured were the voltage across the electrode and the gap between the electrode after the DC arc was extinguished. Furthermore, the strength of the DC arc fault was observed and categorized into four levels, namely mild, moderate, severe, and catastrophic which is illustrated in Figure 4.9 and Figure 4.10.

Figure 4.7: Testing setup for DC series arc faults

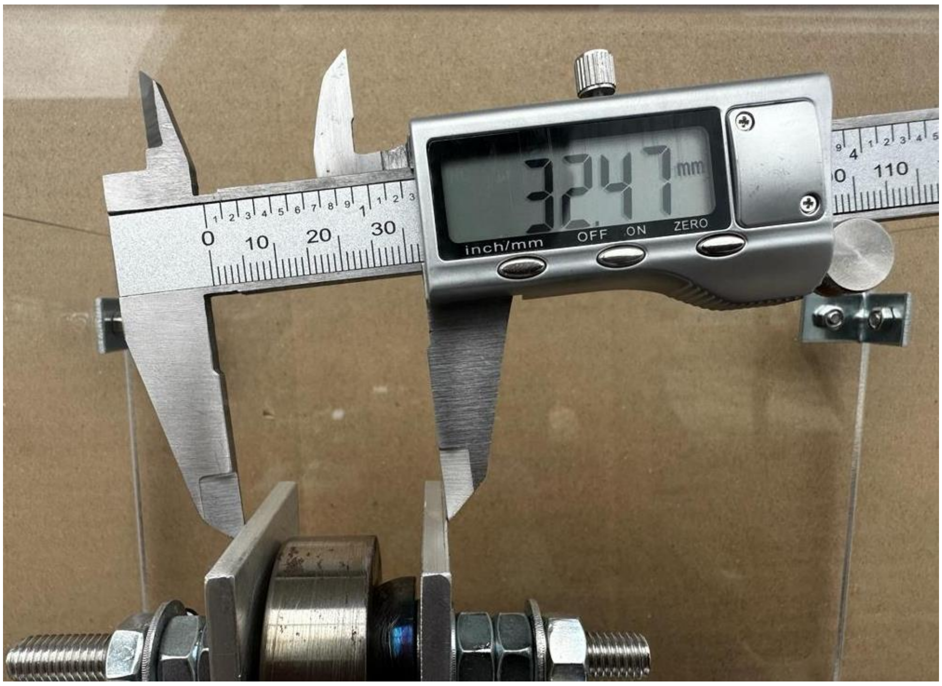


Figure 4.8: Measuring the electrode gap after the DC arc fault test.

Figure 4.9: (Left) Mild DC arc, (Right) Moderate DC arc.

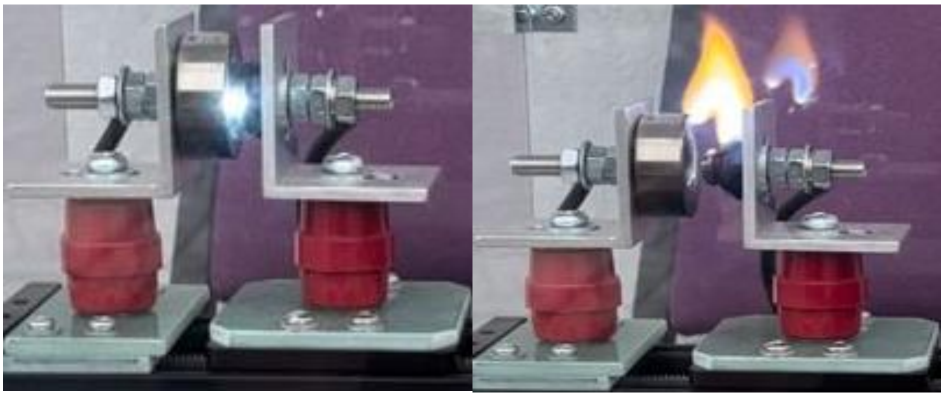


Figure 4.10: (Left) Severe DC arc, (Right) Catastrophic DC arc.

The results of the DC series arc faults in different positions of the PV system test, presented in Table 4.4, include important parameters such as the voltage across the electrode, electrode gap, and arc strength observation. Figure 4.11 to 4.13 provide visual representation of the DC series arc faults in different positions of the PV system.

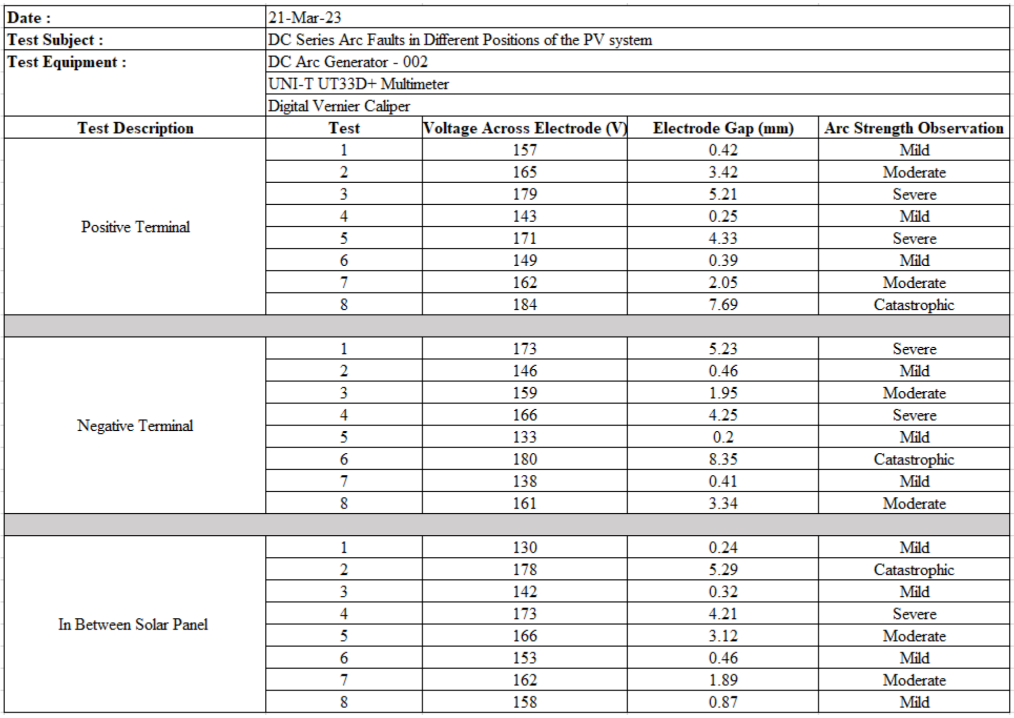
The voltage across the electrode is a crucial parameter that was measured during the test as it provides an indication of the strength of the solar irradiance, which can affect the output of the PV system. The results show that there is a correlation between the voltage across the electrode and the strength of the DC arc fault. In general, higher voltage across the electrode was observed during severe and catastrophic arc faults, indicating stronger solar irradiance levels during those tests. This suggests that during stronger solar irradiance, the output of the PV system is stronger, and the DC arc fault strength will also be stronger.

The electrode gap is another important parameter that was measured during the test. It indicates the distance required for the DC arc to be extinguished, which can provide an indication of the strength of the arc. The results show that a smaller electrode gap was associated with milder arc faults, while a larger gap was required to extinguish severe and catastrophic arc faults. This also indicates that in larger scale PV systems with higher power outputs, the DC arc gap will be larger, which means that the damage from the DC arc fault will be spread more easily and be harder to extinguish.

The arc strength observation was categorized into four levels, namely mild, moderate, severe, and catastrophic. This parameter provides a qualitative assessment of the strength of the DC arc fault and was used to identify the severity of the damage caused by the fault. However, as shown in Figure 4.9, even a mild DC series arc could lead to further insulation breakdown of cables and connectors, which could result in more severe hazards and fires. This highlights the importance of installing AFCI in the PV system to detect and interrupt the DC arc.

The results of the DC series arc faults showed a similar trend for all three positions tested. As the voltage increased, the severity of the DC arc fault also increased. A higher voltage resulted in a larger electrode gap and a stronger DC arc. Overall, these results emphasize the importance of proper design and installation of PV systems to minimize the risk of DC arc faults and the importance of incorporating safety features such as AFCI to protect against these hazards.

Table 4.4: DC series arc faults in different positions of the PV system test report



Date :	21-Mar-23			
Test Subject :	DC Series Arc Faults in Different Positions of the PV system			
Test Equipment :	DC Arc Generator - 002			
	UNI-T UT33D+ Multimeter			
	Digital Vernier Caliper			
Test Description	**Test**	**Voltage Across Electrode (V)**	**Electrode Gap (mm)**	**Arc Strength Observation**
Positive Terminal	1	157	0.42	Mild
	2	165	3.42	Moderate
	3	179	5.21	Severe
	4	143	0.25	Mild
	5	171	4.33	Severe
	6	149	0.39	Mild
	7	162	2.05	Moderate
	8	184	7.69	Catastrophic
Negative Terminal	1	173	5.23	Severe
	2	146	0.46	Mild
	3	159	1.95	Moderate
	4	166	4.25	Severe
	5	133	0.2	Mild
	6	180	8.35	Catastrophic
	7	138	0.41	Mild
	8	161	3.34	Moderate
In Between Solar Panel	1	130	0.24	Mild
	2	178	5.29	Catastrophic
	3	142	0.32	Mild
	4	173	4.21	Severe
	5	166	3.12	Moderate
	6	153	0.46	Mild
	7	162	1.89	Moderate
	8	158	0.87	Mild

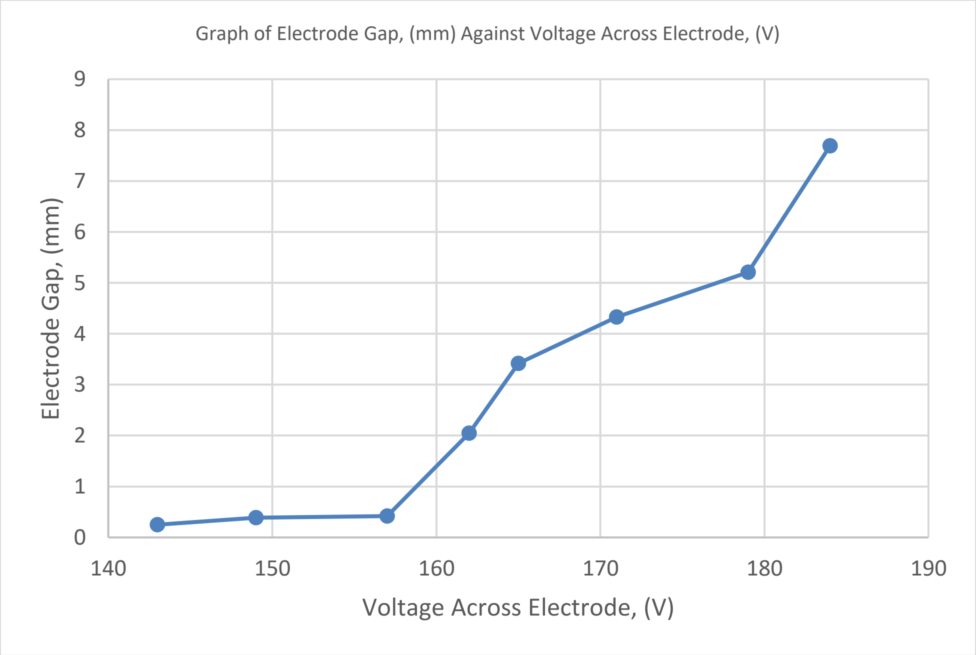


Figure 4.11: DC series arc fault in positive terminal

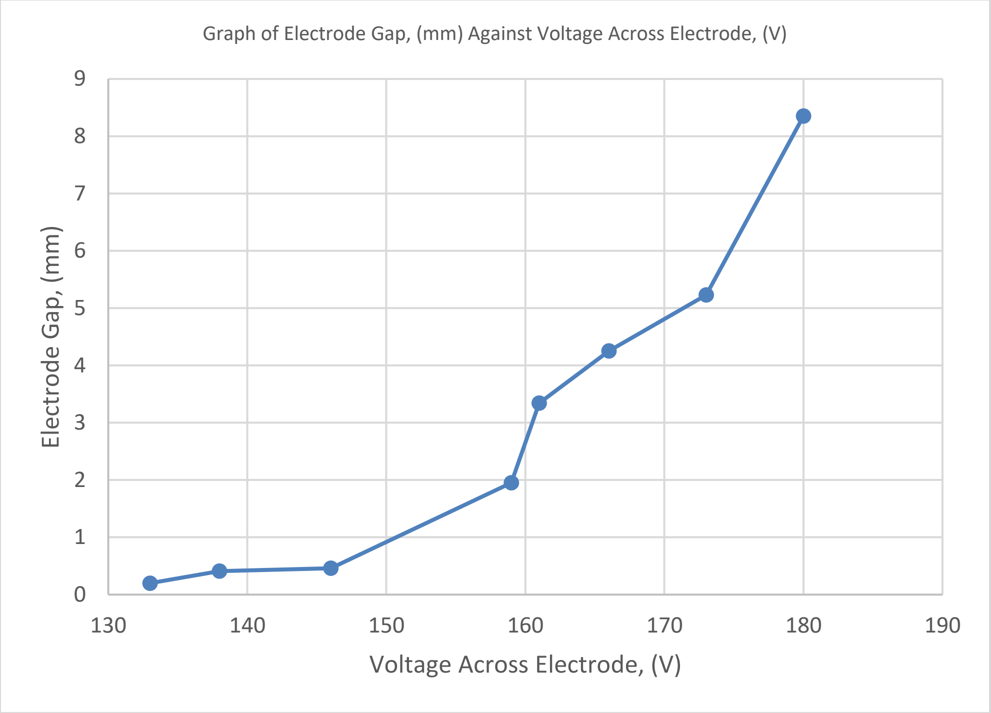


Figure 4.12: DC series arc fault in negative terminal

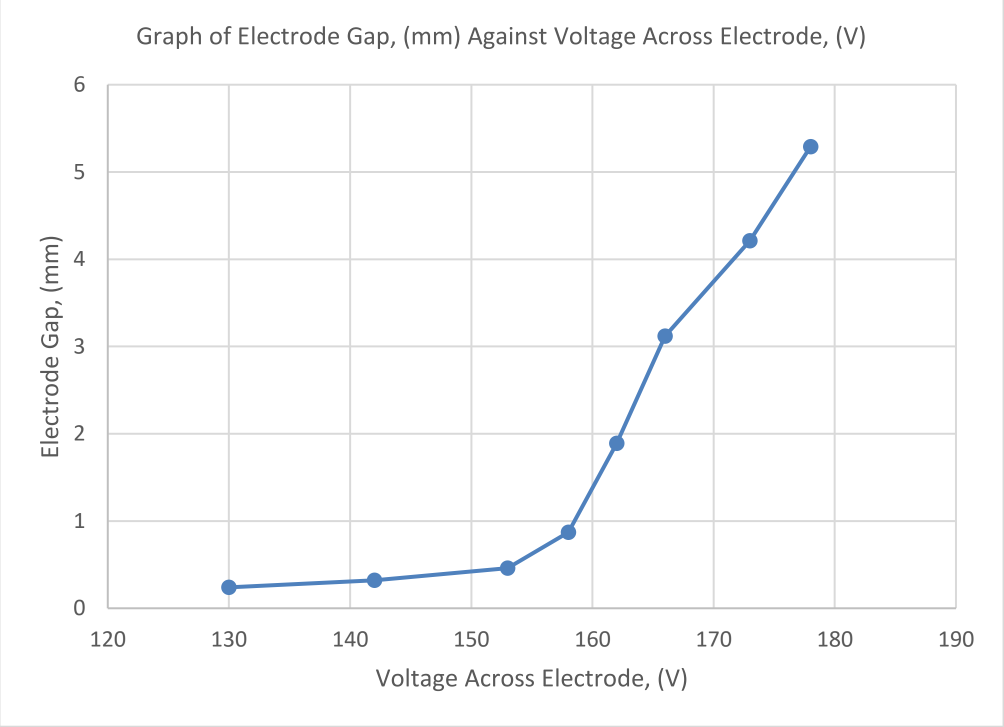


Figure 4.13: DC series arc fault in between solar panel

4.4.2 DC Parallel Arc Fault Test

In this subsection, the results and discussion of the DC parallel arc fault test will be presented. The purpose of this test was to investigate the difference between DC series arc faults and DC parallel arc faults. The theoretical expectation is that DC parallel arc faults would be stronger than DC series arc faults due to the parallel connection of solar panels. For safety reasons, the number of solar panels used in the test was reduced to five in series, and the test was performed five times, with one panel being removed each time until only one panel remained. The parameters measured were similar to those in the DC series arc fault test in subsection 4.4.1, which were the voltage across the electrode and the gap between the electrode after the DC arc was extinguished. The strength of the DC arc fault was observed and categorized into four levels, namely mild, moderate, severe, and catastrophic, which are illustrated in Figure 4.9 and Figure 4.10.

In order to simulate a DC parallel arc, the electrodes of the DC arc generator were first opened. Then, the electrodes were closed to short circuit the positive and negative terminal of the PV system. During this parallel short circuit, the inverter detected 0 power output from the solar panels, as there was a short circuit path. The inverter did not send any notification, but only tried to detect sunlight as the zero-power output situation was similar to night time.

It is important to note that this is a dangerous situation, as even if no DC arc is formed during the parallel short circuit, the current flow through the cables is higher, which causes a higher temperature in the cables. The temperature of the cables was then scanned with a thermal scanner and found to be high during the parallel short circuit. As shown in Figure 4.14, 4.15, and 4.16, these thermal scanner results illustrate the potential danger of a DC parallel arc fault. The temperature of the electrodes, connector, and cables increased significantly during the parallel short circuit, indicating a higher current flow due to the fault. This can lead to insulation breakdown and eventual fire hazards. Therefore, it is important to take appropriate measures to prevent and detect DC parallel arc faults, such as monitoring the temperature of the PV system during operation.

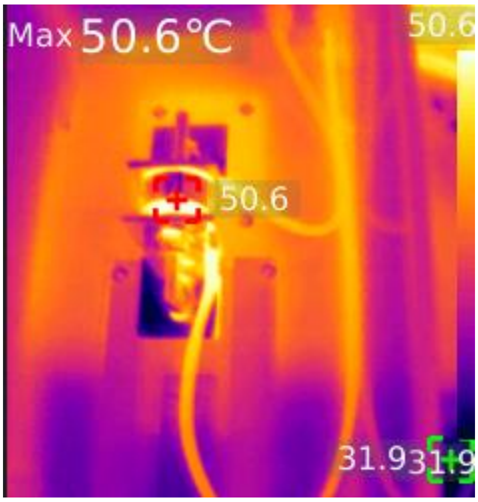


Figure 4.14: Thermal scanner results for the electrodes, 50.6 °C

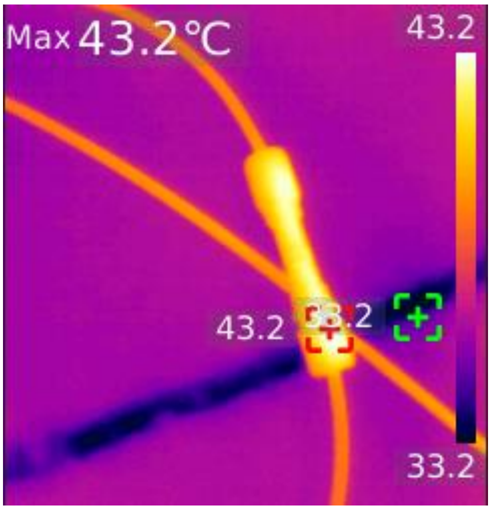


Figure 4.15: Thermal scanner results for the connector, 43.2 °C

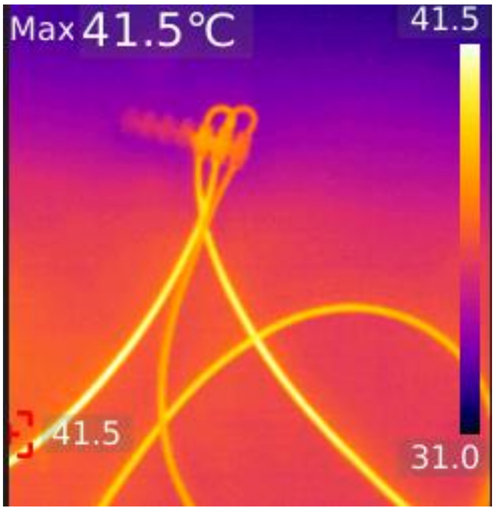


Figure 4.16: Thermal scanner results for the cables, 41.5 °C

In Figure 4.14 to 4.17, which depict the DC parallel arc fault test, it can be observed that as the electrodes slowly separate apart after a parallel short circuit, the voltage across the electrodes increases. This increase in voltage is accompanied by an increase in arc strength. Figure 4.14 shows a mild DC arc with a voltage of 18 VDC, while Figure 4.15 shows a moderate DC arc with a voltage of 22 VDC. Figure 4.16 shows a severe DC arc with a voltage of 41 VDC, while Figure 4.17 shows a catastrophic DC arc with a voltage of 83 VDC. These results confirm the theoretical prediction that DC parallel arc faults are generally stronger than DC series arc faults, as the parallel connection allows for a higher current flow and therefore a stronger arc.

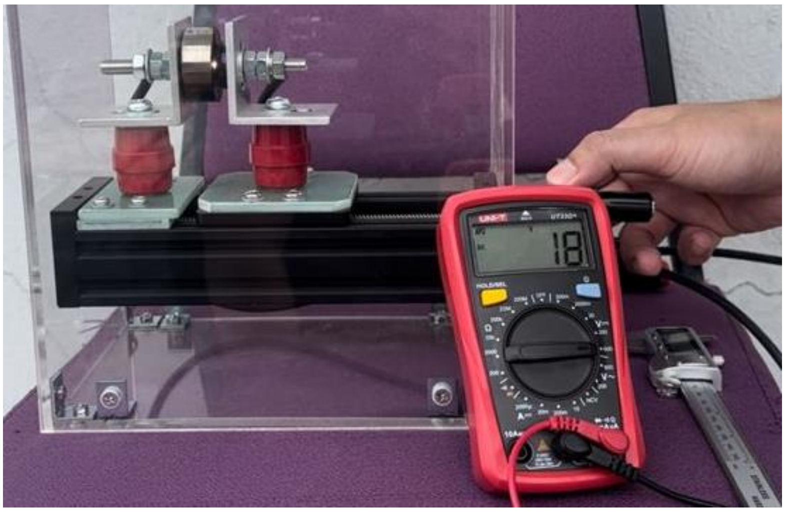


Figure 4.17: DC parallel arc fault, 18 VDC. (Mild DC arc)

Figure 4.18: DC parallel arc fault, 22 VDC. (Moderate DC arc)

Figure 4.19: DC parallel arc fault, 41 VDC. (Severe DC arc)

Figure 4.20: DC parallel arc fault, 83 VDC. (Catastrophic DC arc)

The results of the DC parallel arc fault test showed that higher numbers of solar panels produced stronger power output, resulting in higher voltage across the electrodes. This increased voltage also led to larger electrode gaps and stronger arc fault strength. As shown in Table 4.5, even with only three solar panels, the voltage of 111 V still produced a strong arc fault that could cause damage to the PV system.

Moreover, when the number of solar panels was reduced to two, the voltage dropped to 74 V, which is lower than the NEC requirements for PV systems to install arc fault protection. However, the DC parallel arc still exhibited a significant strength that could lead to serious fire hazards.

Even with only one solar panel, the voltage across the electrodes was 36 V, and the arc strength remained visibly strong. Due to the nature of DC arcs, the arc will not self-extinguish without a zero-crossing point, which means that even this low voltage could cause damage to the system.

In comparison to DC series arc faults, DC parallel arc faults require lower voltage levels to produce a strong arc due to the higher current flow. This is because parallel arcs exhibit lower resistance and impedance compared to series arcs, which require higher voltages to produce a strong arc.

Overall, the results of the DC parallel arc fault test highlight the importance of implementing appropriate safety measures to prevent and detect DC parallel arc faults in PV systems.

Table 4.5: DC parallel arc faults test report.

Date :	21-Mar-23				
Test Subject :	DC Parallel Arc Faults				
Test Equipment :	DC Arc Generator - 002				
	UNI-T UT33D+ Multimeter				
	Digital Vernier Caliper				
Test Description	**Test**	**Number Solar Panel**	**Voltage Across Electrode (V)**	**Electrode Gap (mm)**	**Arc Strength Observation**
Parallel Short Circuit Between Positive Terminal and Negative Terminal of the PV System DC Circuit	1	5	185	10.81	Catastrophic
	2	4	148	8.85	Catastrophic
	3	3	111	7.9	Catastrophic
	4	2	74	5.52	Severe
	5	1	36	0.23	Moderate

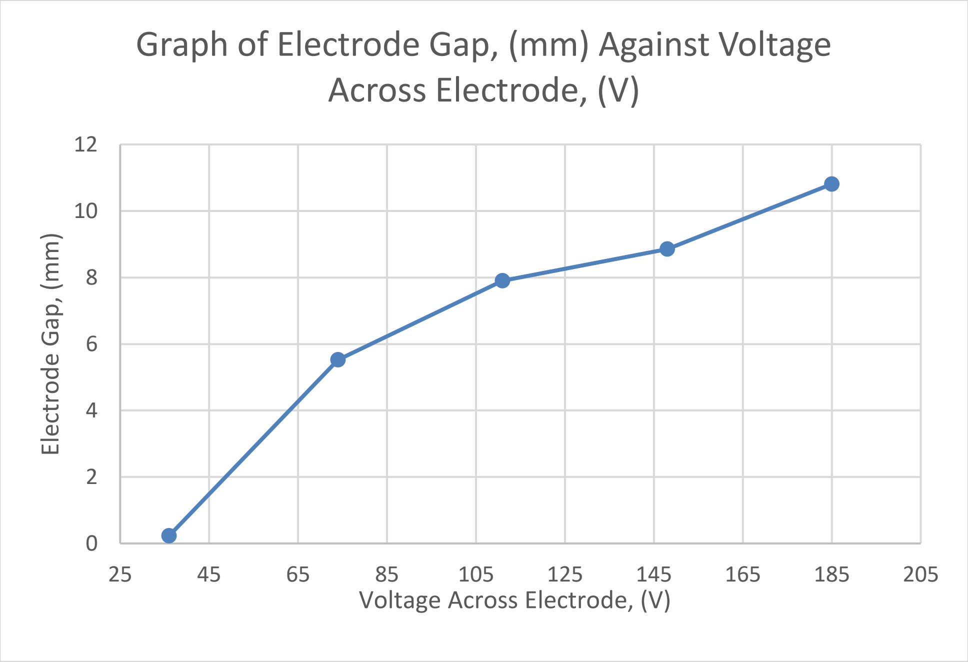


Figure 4.21: DC parallel arc fault results

4.5 DC Arc Fault Protection Features in Huawei Solar Inverter SUN2000-2KTL-L1 Test

This section evaluates the effectiveness of the DC arc fault protection features in the Huawei Solar Inverter SUN2000-2KTL-L1. Various tests were conducted to assess the inverter's ability to handle DC arc faults, including the AFCI function, insulation resistance (R_{ISO}) monitoring, residual current monitoring (RCD), and rapid shutdown testing. The results of these tests were analyzed to determine the inverter's capability to mitigate the risks associated with DC arc faults. Additionally, the Huawei Smart PV Optimizer SUN2000-600W-P was also tested for its ability to handle DC parallel arc faults.

4.5.1 DC Series Arc Fault with AFCI Enabled Test

The results of the DC series arc fault with AFCI enabled test are being discussed in this subsection. The effectiveness of the arc fault protection features in the Huawei solar inverter SUN2000-2KTL-L1 against the DC series arc fault in on-site conditions was evaluated. The parameters measured during the test were the voltage across the electrodes, the gap of the electrodes, and the time required for the AFCI to detect and interrupt the DC series arc, which were recorded on video footage. The test aimed to prove that the Huawei solar inverter SUN2000-2KTL-L1 is capable of handling DC series arc faults with their AI BOOST AFCI technology.

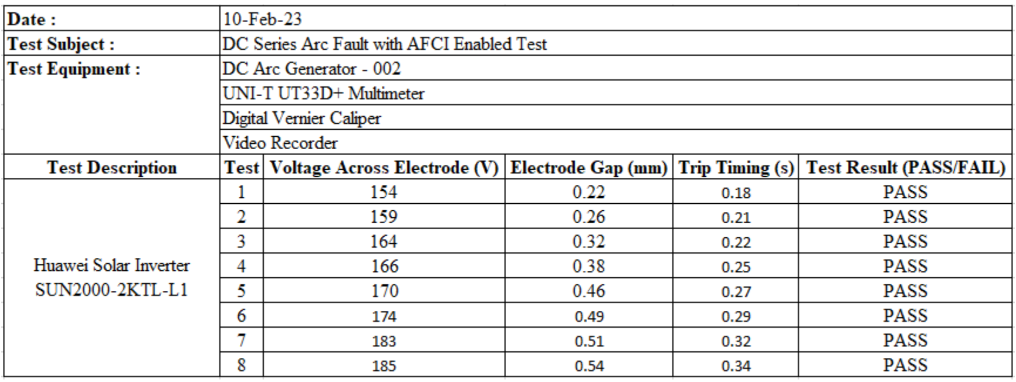
Table 4.6 presents the results of the eight tests conducted to evaluate the AFCI function of the Huawei solar inverter. As shown in Figure 4.22, the voltage across the electrode increased as the electrode gap increased, indicating that the DC arc during higher voltage is stronger. However, with AFCI enabled, the electrode gap required for the series arc to extinguish was significantly decreased compared to the DC series arc fault test without AFCI. This is because the AFCI detected the DC series arc and interrupted it before it could grow stronger. Furthermore, the time required for the Huawei solar inverter's AFCI to detect and interrupt the DC series arc was relatively fast, with the fastest time being 0.18 s and the longest being 0.34 s. The video was slowed down to the millisecond to observe the extinguishing of the DC arc, and as observed, weaker DC arcs were extinguished faster, while stronger arcs required slightly longer tripping times.

All eight tests passed the UL1699B test standard, where the tripping time of the AFCI is below 2.5 s. The results demonstrate the effectiveness of the AFCI function of the Huawei solar inverter SUN2000-2KTL-L1 in detecting and interrupting DC series arc faults in on-site conditions. The use of AFCI technology can prevent the occurrence of fires caused by DC series arc faults in photovoltaic systems, ensuring the safety and reliability of the system.

Moreover, the Huawei solar inverter provides an important notification feature that alerts operators of a DC series arc fault through the FusionSolar app, as shown in Figure 4.23. This notification feature provides operators with immediate information on the occurrence of the DC arc fault, allowing for timely repair and maintenance to prevent the fault from escalating into a severe fire hazard.

Overall, the results of the DC Series Arc Fault with AFCI Enabled Test demonstrate the effectiveness of the Huawei solar inverter SUN2000-2KTL-L1 in mitigating the risks associated with DC series arc faults. Its combination of AI BOOST AFCI technology and notification features provides a high level of protection against these faults, ensuring the safe and reliable operation of PV systems. The implementation of AFCI technology in photovoltaic systems is essential to prevent the occurrence of DC series arc faults and protect the safety of personnel and assets.

Table 4.6: DC series arc fault with AFCI enabled test report.



Date :	10-Feb-23				
Test Subject :	DC Series Arc Fault with AFCI Enabled Test				
Test Equipment :	DC Arc Generator - 002				
	UNI-T UT33D+ Multimeter				
	Digital Vernier Caliper				
	Video Recorder				
Test Description	**Test**	**Voltage Across Electrode (V)**	**Electrode Gap (mm)**	**Trip Timing (s)**	**Test Result (PASS/FAIL)**
Huawei Solar Inverter SUN2000-2KTL-L1	1	154	0.22	0.18	PASS
	2	159	0.26	0.21	PASS
	3	164	0.32	0.22	PASS
	4	166	0.38	0.25	PASS
	5	170	0.46	0.27	PASS
	6	174	0.49	0.29	PASS
	7	183	0.51	0.32	PASS
	8	185	0.54	0.34	PASS

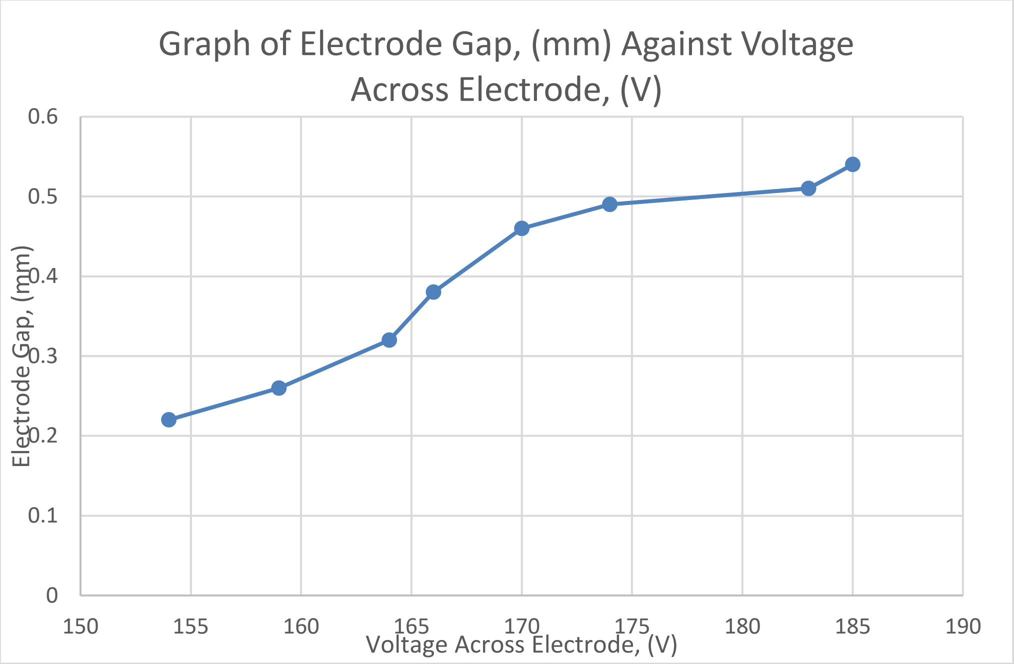
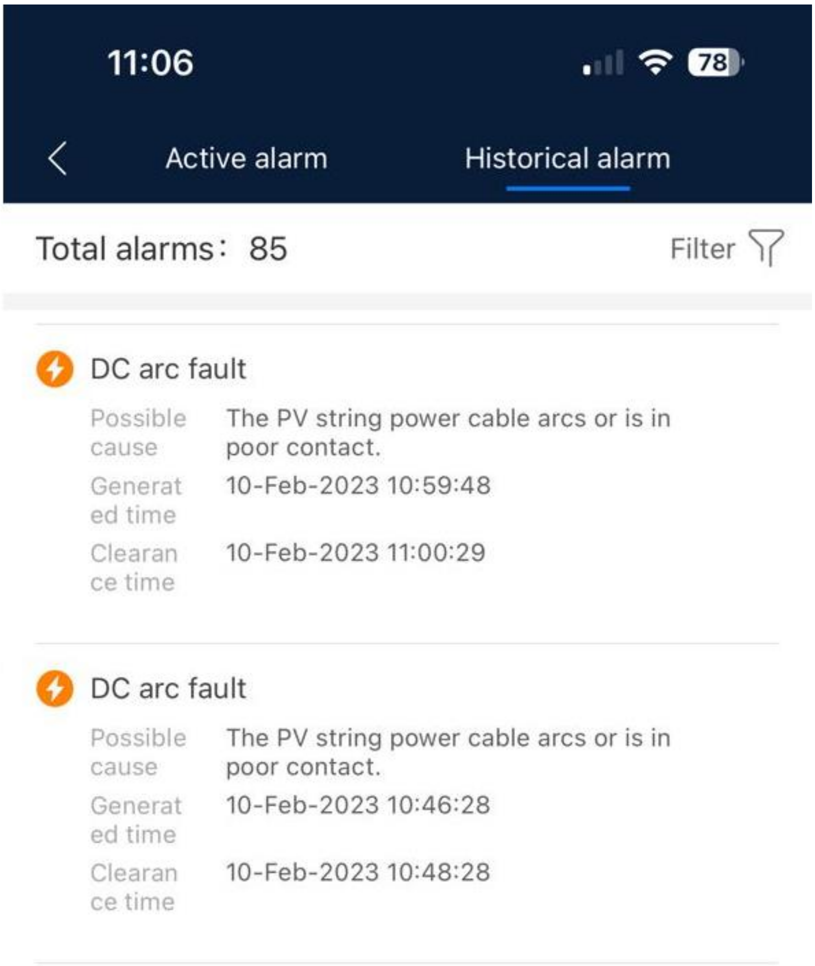


Figure 4.22: DC series arc fault with AFCI enabled test.



Total alarms： 85

DC arc fault

Possible cause: The PV string power cable arcs or is in poor contact.
Generated time: 10-Feb-2023 10:59:48
Clearance time: 10-Feb-2023 11:00:29

DC arc fault

Possible cause: The PV string power cable arcs or is in poor contact.
Generated time: 10-Feb-2023 10:46:28
Clearance time: 10-Feb-2023 10:48:28

Figure 4.23: DC arc fault alarm in the FusionSolar app.

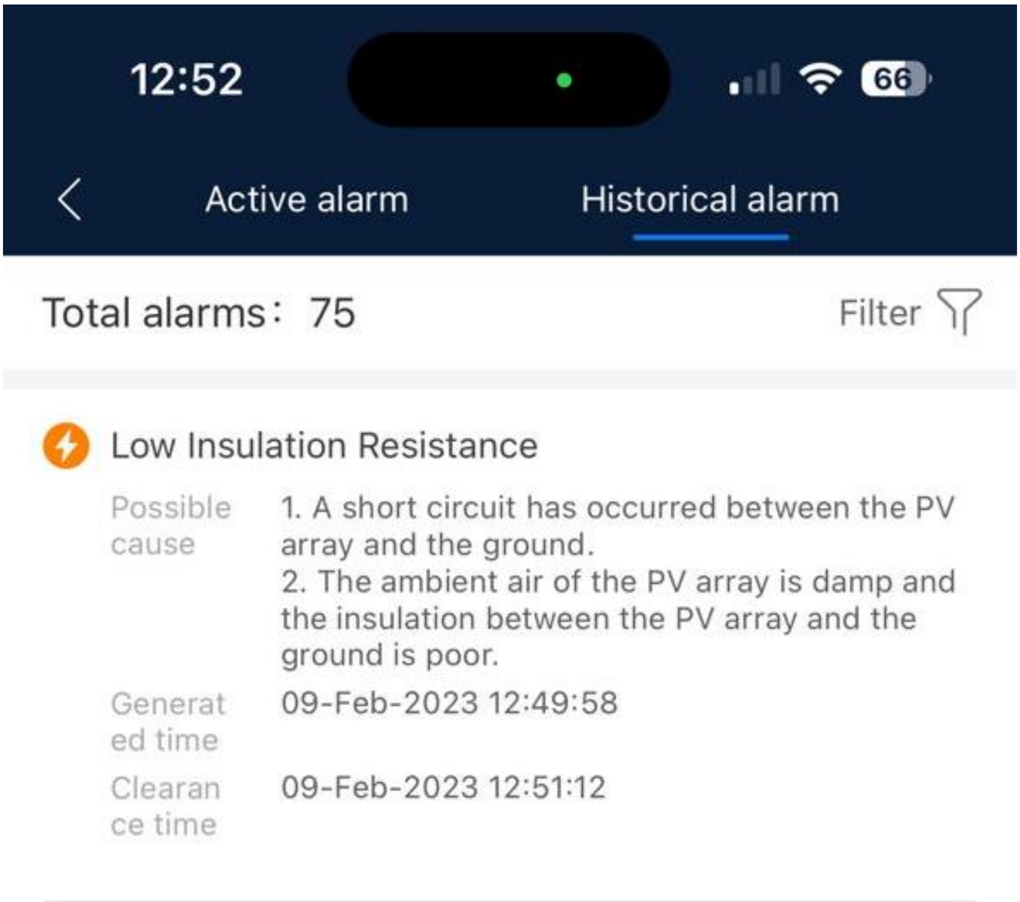
4.5.2 Insulation Resistance (R_{ISO}) Monitoring Function Test

The insulation resistance (R_{ISO}) monitoring function test was conducted to ensure that the Huawei Solar Inverter SUN2000-2KTL-L1 is capable of measuring the insulation resistance of the PV system before allowing the DC circuit to be completed and start generating power. During the test, the inverter was switched off, and a short circuit was created from the positive terminal to the earth. When the inverter was switched on, it detected a low insulation resistance due to the short circuit to earth and prevented the DC circuit from being completed to prevent a DC arc fault from occurring.

Figure 4.23 shows the red LED lighting up for the DC circuit on the inverter, indicating that there is issue in the DC circuit, and the DC circuit is not being completed. Additionally, Figure 4.24 shows that the FusionSolar App sends a Low Insulation Resistance alarm to alert the operator of the low insulation resistance in the system. This feature allows the operator to take immediate action to address the issue and prevent potential DC arc faults from occurring.

The Insulation Resistance (R_{ISO}) Monitoring Function Test demonstrates the effectiveness of the Huawei Solar Inverter SUN2000-2KTL-L1 in ensuring the safety and reliability of PV systems by monitoring the insulation resistance before allowing the DC circuit to be completed and generating power.

Figure 4.24: Red LED lights up for DC circuit on the inverter



Total alarms: 75

Low Insulation Resistance

Possible cause	1. A short circuit has occurred between the PV array and the ground. 2. The ambient air of the PV array is damp and the insulation between the PV array and the ground is poor.
Generated time	09-Feb-2023 12:49:58
Clearance time	09-Feb-2023 12:51:12

Figure 4.25: FusionSolar App sends a Low Insulation Resistance alarm.

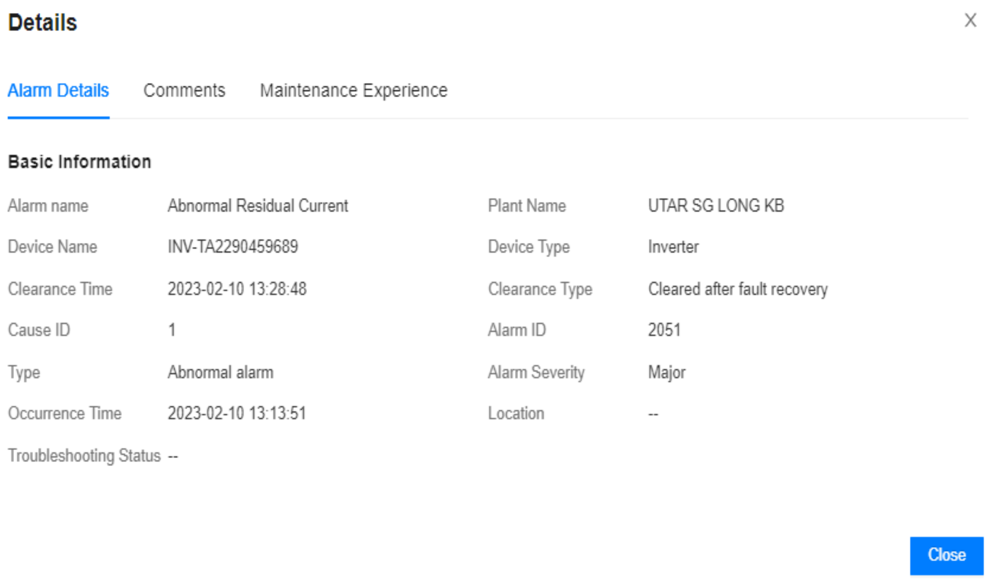
4.5.3 Residual Current Monitoring Function (RCD) Test

In the RCD test, the effectiveness of the Huawei Solar Inverter SUN2000-2KTL-L1 in detecting abnormal residual currents was evaluated. The RCD function serves as an important safety feature to protect against electrical shocks caused by ground faults. To test this function, a short circuit was created from the positive terminal to the earth, resulting in an abnormal residual current that triggered the RCD of the inverter. The circuit was then interrupted to prevent the DC circuit from generating power and ensure the safety of the system and its operators.

The Huawei Solar Inverter SUN2000-2KTL-L1 also provides a visual indication of the ground fault through a red LED light on the AC circuit, as shown in Figure 4.26. This enables operators to quickly identify and address any issues. In addition, the FusionSolar app sends a low insulation resistance alarm, as shown in Figure 4.27, providing an immediate notification to the operator for timely maintenance and repair to prevent the fault from escalating.

The RCD testing results demonstrate the effectiveness of the Huawei Solar Inverter SUN2000-2KTL-L1 in detecting abnormal residual currents and interrupting the circuit to ensure the safety and reliability of the photovoltaic system. The use of such advanced features and technologies in the inverter ensures the safe and efficient operation of the PV system.

Figure 4.26: Red LED lights up for AC circuit on the inverter



Basic Information

Alarm name	Abnormal Residual Current	Plant Name	UTAR SG LONG KB
Device Name	INV-TA2290459689	Device Type	Inverter
Clearance Time	2023-02-10 13:28:48	Clearance Type	Cleared after fault recovery
Cause ID	1	Alarm ID	2051
Type	Abnormal alarm	Alarm Severity	Major
Occurrence Time	2023-02-10 13:13:51	Location	--
Troubleshooting Status	--		

Figure 4.27: FusionSolar App sends a Low Insulation Resistance alarm.

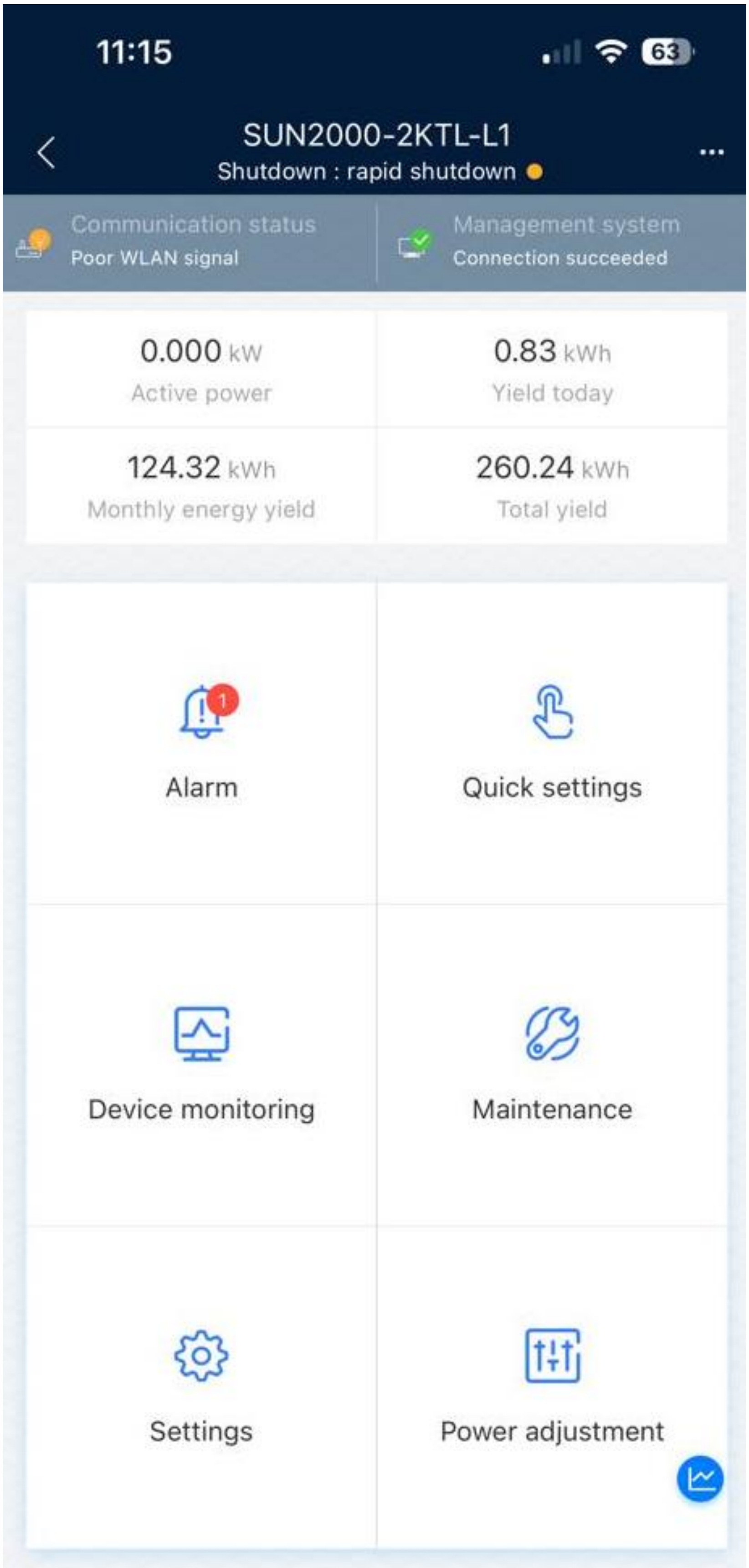
4.5.4 Rapid Shutdown Test

The rapid shutdown test was conducted to evaluate the Huawei Smart PV Optimizer SUN2000-600W-P and Huawei Solar inverter SUN2000-2KTL-L1's ability to stop a DC parallel arc fault, a type of arc fault that poses a unique challenge as it cannot be detected by the solar inverter's AFCI protection features. During a DC parallel arc fault, the solar inverter will not detect any DC arc fault alarm because the power output of the solar panels to the inverter will be 0. The inverter will then go into sunlight detection mode, which tries to detect the power output from the solar panel. However, due to the parallel short circuit, there will be a temperature increase for the cables and connectors, which could eventually lead to insulation breakdown and cause serious arc faults.

To address this problem, rapid shutdown testing was performed, where the Huawei Smart PV Optimizer SUN2000-600W-P and Huawei Solar inverter SUN2000-2KTL-L1 were paired together. When rapid shutdown was triggered to stop the DC parallel arc fault by switching off the AC supply of the inverter, the power optimizer stopped the supply of the solar panel, which could stop the parallel arc fault from progressing. In addition, during a DC parallel arc fault, the AC supply switch of the inverter can also act as a fireman switch, rapidly shutting down the entire PV system and allowing firefighters to work safely without the risk of electrical shock.

The rapid shutdown alarm in the FusionSolar app, as shown in Figure 4.28, also provides an important notification feature to alert operators of the rapid shutdown, enabling operators to be immediately notified of the rapid shutdown and take the necessary steps to address any issues that may arise.

The results of the rapid shutdown test demonstrate the effectiveness of the Huawei Smart PV Optimizer SUN2000-600W-P and Huawei Solar inverter SUN2000-2KTL-L1 in addressing the risks associated with DC parallel arc faults. The rapid shutdown feature allows for the safe and quick shutdown of the PV system, reducing the risk of damage or injury. The combination of DC series arc fault protection features, and rapid shutdown capabilities provides a high level of safety and reliability in photovoltaic systems, ensuring the safety of personnel and assets.



Communication status
Poor WLAN signal

Management system
Connection succeeded

0.000 kW Active power	0.83 kWh Yield today
124.32 kWh Monthly energy yield	260.24 kWh Total yield

Figure 4.28: Rapid shutdown alarm in FusionSolar app

4.5.5 Summary

This section evaluates the DC arc fault protection features of the Huawei Solar Inverter SUN2000-2KTL-L1, through tests including AFCI function, R_{ISO} monitoring, RCD, and rapid shutdown. The results demonstrate the inverter's effectiveness in detecting and interrupting DC series arc faults and preventing risks associated with low insulation resistance, earth faults and DC parallel arc faults. AFCI technology is crucial in preventing fires caused by DC series arc faults, while R_{ISO} monitoring ensures system safety and reliability by monitoring insulation resistance before the DC circuit is completed. The RCD function provides vital safety features, protecting against electrical shocks caused by ground faults. The rapid shutdown feature allows for a safe and swift shutdown of the PV system, reducing the risk of damage or injury. The combination of these features provides a high level of safety and reliability in photovoltaic systems, safeguarding personnel and assets.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

After conducting all the tests and evaluations, it can be concluded that the aim and objectives of this project have been successfully achieved. The design and fabrication of a reliable and safe DC arc generator for DC arc fault testing was accomplished, and the on-site PV system was set up to simulate real-world conditions for testing. The effectiveness of the DC arc fault protection feature in Huawei Solar Inverter was evaluated through various tests including AFCI, R_{ISO} monitoring, RCD, and rapid shutdown, and the results showed that the inverter is able to effectively detect and interrupt DC series arc faults, prevent risks associated with low insulation resistance and earth faults, and provide vital safety features to protect against electrical shocks caused by dc arc faults. Overall, this project contributes to the development of DC arc fault protection in the PV industry and provides valuable insights into the capabilities of the Huawei Solar Inverter SUN2000-2KTL-L1 in handling DC arc faults. To ensure the safety of PV sites, the necessity of conducting DC arc fault protection feature testing is recognized. This testing procedure ensures the effective functionality of the protection feature and maintains a secure environment for PV installations. By regularly conducting these tests, potential risks associated with DC arc faults, low insulation resistance, and earth faults could be effectively mitigated.

5.2 Recommendations for future work

This project has successfully evaluated the effectiveness of DC arc fault protection features in the Huawei Solar Inverter SUN2000-2KTL-L1. However, there are opportunities for future work to further advance the field of DC arc fault protection in PV systems.

One recommendation is to expand the testing to include other brands of solar inverters and DC arc fault protection devices. By testing and comparing the performance of various DC arc fault protection devices in real-world conditions, this can help identify the most effective solutions and guide future standards and regulations.

Another recommendation is to continue developing and refining the DC arc generator. While the current generator meets the UL1699B standard requirements, further improvements can be made to increase its reliability and accuracy. Additionally, calibration and certification by relevant authorities can help establish it as a qualified testing equipment, making it easier for PV site owners and installers to use for testing DC arc fault protection features.

Finally, the development of new technologies and strategies for DC arc fault protection should continue to be explored. As PV systems become more widely adopted and integrated into power grids, the risk of DC arc faults and their potential hazards will increase. Continued research and development in this area can help ensure the safe and sustainable growth of the PV industry.

REFERENCES

Alam, M.K., Khan, F., Johnson, J. and Flicker, J., 2015a. A Comprehensive Review of Catastrophic Faults in PV Arrays: Types, Detection, and Mitigation Techniques. *IEEE Journal of Photovoltaics*, 5(3), pp.982–997.

Alam, M.K., Khan, F., Johnson, J. and Flicker, J., 2015b. A Comprehensive Review of Catastrophic Faults in PV Arrays: Types, Detection, and Mitigation Techniques. *IEEE Journal of Photovoltaics*, 5(3), pp.982–997.

Ameen, R. et al., 2019. Mechatronics Arc Generator for Photovoltaic Arc Fault Detector Testing. *2019 IEEE 46th Photovoltaic Specialists Conference (PVSC)*. 2019 pp. 1306–1311.

American Elements, 2022, *Tungsten Nickel Copper Alloy | AMERICAN ELEMENTS* ® [Online]. Available at: https://www.americanelements.com/tungsten-nickel-copper-alloy [Accessed: 10 September 2022].

Anders Rand Andersen, 2021, *Isolation Resistance Faults in Photovoltaics | Riso testing in solar arrays* [Online]. Available at: https://emazys.com/isolation-resistance-faults-in-photovoltaics/ [Accessed: 23 April 2023].

Araneo, R. and Mitolo, M., 2019. On the Insulation Resistance in High-Power Free-Field Grid-Connected Photovoltaic Plants. *Proceedings - 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2019*.

Artale, G. et al., 2021. Characterization of DC series arc faults in PV systems based on current low frequency spectral analysis. *Measurement: Journal of the International Measurement Confederation*, 182.

BENY, *Premium Rapid Shutdown Device Firefighter Safety Switch Supplier | BENY New Energy* [Online]. Available at: https://www.beny.com/module-level-rapid-shutdown/?gad=1&gclid=CjwKCAjwrpOiBhBVEiwA_473dKxHlYhhi8MN_mYyC6cQjbZXFU2qDxkHWdnVs7IaSX5SwRDcsCnNbxoC1bYQAvD_BwE [Accessed: 23 April 2023].

Cao, Y. et al., 2013. Arc fault generation and detection in DC systems. *Asia-Pacific Power and Energy Engineering Conference, APPEEC*. 2013 IEEE Computer Society.

Costa Lima, J.P., Da Cunha Lima, A., Bellinaso, L.V. and Michels, L., 2022. Explanatory Review about Rapid Shutdown Systems and Standards to Increase Safety in Photovoltaic Systems. *2022 14th Seminar on Power Electronics and Control, SEPOC 2022*.

ElectroMechanica, 2022, *SM35-10KV 35mm | BUSBAR INSULATOR H 35mm M8 | L - Termination and Wiring : Busbar insulators | ElectroMechanica* [Online]. Available at: https://www.em.co.za/SM35 [Accessed: 11 September 2022].

England, B., *An Investigation into Arc Detection and Fire Safety Aspects of Photovoltaic Installations,*

Flicker, J. and Johnson, J., *Electrical Simulations of Series and Parallel PV Arc-Faults,*

Flicker, J., Johnson, J., Albers, M. and Ball, G., *Recommendations for CSM and R iso Ground Fault Detector Trip Thresholds,*

Flicker, J., Johnson, J., Albers, M. and Ball, G., *Recommendations for CSM and R iso Ground Fault Detector Trip Thresholds,*

GEYA, 2021, *Residual Current Device (RCD) for Solar Inverters* [Online]. Available at: https://www.geya.net/residual-current-device-rcd-for-solar-inverters/ [Accessed: 23 April 2023].

Hatton, P.C., Bathaniah, M., Wang, Z. and Balog, R.S., 2016. Arc generator for photovoltaic arc fault detector testing. *2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC)*. 2016 pp. 1702–1707.

International Electrotechnical Commission, I., 2019. *IEC 63027 ED1 DC arc detection and interruption in photovoltaic power system,*

Johnson, J. et al., 2012. Differentiating series and parallel photovoltaic arc-faults. *Conference Record of the IEEE Photovoltaic Specialists Conference*. 2012 pp. 720–726.

Johnson, J. et al., PHOTOVOLTAIC DC ARC FAULT DETECTOR TESTING AT SANDIA NATIONAL LABORATORIES.

LinElon, *Enhancing Solar System Safety: The Importance of Type B RCD RCCB Prote* [Online]. Available at: https://at-ele.com/blogs/news/enhancing-solar-system-safety-the-importance-of-type-b-rcd-rccb-protection [Accessed: 23 April 2023].

Lu, S., Phung, B.T. and Zhang, D., 2018. Study on DC series arc fault in photovoltaic systems for condition monitoring purpose. *2017 Australasian Universities Power Engineering Conference, AUPEC 2017*. 5 February 2018 Institute of Electrical and Electronics Engineers Inc., pp. 1–6.

Luebke, C. et al., 2011. Field test results of DC arc fault detection on residential and utility scale PV arrays. *Conference Record of the IEEE Photovoltaic Specialists Conference,* pp.001832–001836.

Matsusada Precision, 2021, *Difference DC power and AC power| Tech | Matsusada Precision* [Online]. Available at:

https://www.matsusada.com/column/dc_and_ac.html [Accessed: 22 April 2023].

McMaster-Carr, *electrical-grade garolite | McMaster-Carr* [Online]. Available at: https://www.mcmaster.com/electrical-grade-garolite/multipurpose-flame-retardant-garolite-g-10-fr4-sheets-and-bars/ [Accessed: 10 September 2022].

NFPA, 2023, *NFPA 70: National Electrical Code* [Online]. Available at: https://link.nfpa.org/free-access/publications/70/2023 [Accessed: 23 April 2023].

Omran, A.H. et al., 2021. Models, detection methods, and challenges in DC Arc fault: A review. *Jurnal Teknologi*, 83(4), pp.1–16.

Patil, D.D. and Tarmale, P.R., 2018a. *Arc Fault Detection in DC Distribution System by Wavelet Transformation*,

Patil, D.D. and Tarmale, P.R., 2018b. *Arc Fault Detection in DC Distribution System by Wavelet Transformation*,

Piotr Bojek, 2021, *Solar PV – Analysis - IEA* [Online]. Available at: https://www.iea.org/reports/solar-pv [Accessed: 6 September 2022].

Riza Alvy Syafi'i, M.H. et al., 2018. Real Time Series DC Arc Fault Detection Based on Fast Fourier Transform. *2018 International Electronics Symposium on Engineering Technology and Applications (IES-ETA)*. 2018 pp. 25–30.

SIEMENS, 2015. *5SM arc fault detection units for photovoltaic systems SENTRON Arc fault detection units 5SM arc fault detection units for photovoltaic systems*,

Solar edge, 2021. RCD Selection for SolarEdge Inverters - Application Note.

Tigo, 2022, *Everything You Need to Know About Rapid Shutdown* [Online]. Available at: https://www.tigoenergy.com/post/blog-everything-you-need-to-know-about-rapid-shutdown [Accessed: 23 April 2023].

TÜV SÜD and Huawei Technologies Co., Ltd., 2022a. *Distributed PV AFCI Technical White Paper*,

TÜV SÜD and Huawei Technologies Co., Ltd., 2022b. *Distributed PV AFCI Technical White Paper*,

YE ZHAO, 2017. *GROUND-FAULT ANALYSIS AND PROTECTION IN PV ARRAYS*,