

**PROPOSED MODEL FOR ARC-FLASH INCIDENT
ENERGY IN PHOTOVOLTAIC DC SYSTEMS**

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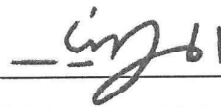
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Dedicated to My Family Members

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LIST OF ABBREVIATIONS

AC	:	Alternate Current
CFD	:	Computational Fluid Dynamic
DC	:	Direct Current
EPRI	:	Electric Power Research Institute
IEEE	:	Institute of Electrical and Electronics Engineers
MHD	:	Magnetohydrodynamic
NFPA	:	National Fire Protection Association
PPE	:	Personal Protective Equipment
PV	:	Photovoltaic
OSHA	:	Occupational Safety and Health Act

ABSTRACT

Full Name : [Mohammed Alhassan Mohammed Salim]

Thesis Title : [PROPOSED MODEL TO CALCULATE ARC-FLASH INCIDENT ENERGY IN PHOTOVOLTAIC DC SYSTEMS]

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In the light of recent global expansion of solar photovoltaic (PV) arrays, and its corresponding Direct Current (DC) installations, the risk of DC arc flash on photovoltaic plants has raised a safety preoccupation. It is necessary to develop a realistic and precise criterion to evaluate the arc flash levels in DC equipment which combines several solar photovoltaic circuits with considerable fault current available. Electrical safety standards committees are currently tackling arc flash in many different DC systems. They encourage industry professionals to participate in the development and refinement of various models that need to be vetted and verified to ensure that they are applicable and accurate. Alternate Current (AC) arc flash risk analyses are getting more and more well known. However, the risks of DC arc flash particularly those resulting from photovoltaic arrays, are less well understood. In contrast to arc flash of AC systems, few research and industry standards have quantified the risk associated with DC arc flash on photovoltaic systems. Much of the recent literature and empirical studies indicated that the models available in the industry for the incident energy evaluation of DC arc flash lack accuracy when applied for photovoltaic plants and improvement is required. This work is an attempt to contribute toward the aforementioned model development. A magnetohydrodynamic (MHD) is applied in this thesis to perform arc flash simulation for photovoltaic arrays. The MHD

simulation is performed through Ansys® software, ANSYS Fluent®, for fluid mechanic equations in conjunction with Ansys® Maxwell® for electromagnetic equations. The simulated model, configuration and photovoltaic array built to emulate the testing setup of two cases out of the recently published test results by Electric Power Research Institute (EPRI). The physical aspects of electric arcs in photovoltaic systems are presented in this thesis. Then, the DC electric model of the magnetohydrodynamic (MHD) method is described in this thesis. The author lays forth the assumptions, computational and the necessary simulation scenarios to fully comprehend the MHD model. The empirical model which has been proposed by EPRI for incident energy calculation on photovoltaic arrays is compared to the resultant MHD simulation results and compared to some other available industry models. MHD simulation results are concluded to reasonably accurate for the simulated cases. For arc flash calculations, IEEE and NFPA want to launch arc testing and create a standard photovoltaic model. The MHD simulation technique proposed in this study has been found to be relevant for future standardized model development and may contribute to an IEEE or NFPA initiative aiming to build a theoretical and/or empirical combination photovoltaic arc model.

ملخص الرسالة

الاسم الكامل: محمد الحسن محمد سالم

عنوان الرسالة: نموذج مقترح لحساب طاقة القوس الكهربائي للتيار المستمر في أنظمة الخلايا الشمسية الكهروضوئية

التخصص: الهندسة الكهربائية

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في ضوء التوسع العالمي الأخير لمجموعات الخلايا الشمسية الكهروضوئية وتركيبات للتيار المستمر المصاحبة لها، فقد ازدادت المخاوف المتعلقة بالقوس الكهربائي للتيار المستمر. وبالتالي يصبح من الضروري تطوير معيار واقعي ودقيق لتقييم مستويات القوس الكهربائي في معدات التيار المستمر التي تجمع بين العديد من الدوائر الكهروضوئية.

في الوقت الحاضر تعمل العديد من لجان معايير السلامة العالمية على تطوير نموذج لحساب القوس الكهربائي في العديد من أنظمة التيار المستمر المختلفة. كما يدعون المهنيين والباحثين في هذا المجال على المشاركة في تطوير وتحسين النماذج المتوفرة لمراجعتها والتحقق منها لضمان أنها قابلة للتطبيق وتحقيق الدقة المطلوبة.

بالرغم من أن نماذج حساب القوس الكهربائي للتيار المتردد أكثر شهرة ومفهومة بشكل أوسع، فإن القوس الكهربائي للتيار المستمر لا سيما تلك الناتجة عن مجموعات الخلايا الشمسية، لا تزال غير مفهومة بشكل جيد ولم تحظ بالقدر الكافي من البحث. وعلى عكس البحوث المتعلقة بالقوس الكهربائي في أنظمة التيار المتردد، تعتبر البحوث المرتبطة بالقوس الكهربائي للتيار المستمر لأنظمة الخلايا الشمسية شحيحة ونادرة. كما تشير الكثير من البحوث والدراسات التجريبية الحديثة إلى أن النماذج المتاحة لتقييم طاقة القوس للتيار المستمر لا تتمتع بالدقة اللازمة عند تطبيقها على محطات الطاقة الشمسية وأنها تتطلب مزيداً من التحسين.

هذه الرسالة محاولة للمساهمة في تطوير نموذج لتقييم وحساب طاقة القوس الكهربائي للتيار المستمر. استخدمت الهيدروديناميكية المغناطيسية في هذه الرسالة لمحاكاة القوس الكهربائي في مجموعات الخلايا الشمسية.

تم تنفيذ محاكاة الهيدروديناميكية المغناطيسية من خلال برنامج Ansys .

استخدم Ansys Fluent لديناميكا الموائع بالتزامن مع Ansys Maxwell لحل معادلات الكهرومغناطيسية.

تم تقديم وبناء النموذج المحاكى لمجموعة الخلايا الشمسية لحالتين من الاختبار المنشورة مؤخراً من قبل معهد بحوث الطاقة الكهربائية (EPRI). كما تمت مناقشة الجوانب الفيزيائية للقوس الكهربائي في أنظمة الخلايا الشمسية في هذه الرسالة، مع الأخذ في الاعتبار الافتراضات وسيناريوهات المحاكاة اللازمة لفهم النموذج الهيدروديناميكية المغناطيسية بشكل كامل. تمت مقارنة النموذج التجريبي الذي اقترحه معهد بحوث الطاقة الكهربائية (EPRI) لحساب طاقة القوس بنتائج المحاكاة الهيدروديناميكية المغناطيسية ومقارنتها ببعض النماذج المتاحة الأخرى.

لخصت هذه الرسالة منهجية لمحاكاة وتقييم القوس الكهربائي لتركيبات للتيار المستمر في مجموعات الخلايا الشمسية الكهروضوئية باستخدام الهيدروديناميكية المغناطيسية. كما خلصت هذه الرسالة على أن المنهجية المقترحة دقيقة بشكل معقول وبأن استخدامها يمكن أن يساهم في مبادرة معهد المهندسين الكهربائيين (IEEE) أو جمعية الحماية من الحرائق الوطنية (NFPA) التي تهدف إلى إنشاء نموذج قياسي لتقييم طاقة القوس الكهربائي لتركيبات للتيار المستمر في مجموعات الخلايا الشمسية الكهروضوئية.

CHAPTER 1

INTRODUCTION

1.1 Arc Flash Definition, Requirements and Standards

As equipment fail or due to an accidental short circuit that might occurs while service and or repair, an arc flash in an electric circuit may occur. As intense light form, rising temperatures, sound and pressure waves, flying shrapnel, molten metal, and vapors that pose a safety danger, arc flash may emit a high amount of energy. This could lead to an extremely high risk for both electrical workers and equipment.

Assessments of the risk of arc flash on AC systems are widely recognized, and incident energy calculation techniques are used for a variety of equipment types and source voltages [1]. The calculation method is described in IEEE Guide for Performing Arc flash Hazard Calculation, IEEE-1584, and is supported by a number of industrial testing [2] [3].

In order to mitigate the potential harm caused by arc flash, various types of Personal Protective Equipment (PPE) are offered. The PPE selection parameters are based on the maximum energy, or arc flash incidence energy, that is feasible. The incident energy, which is generally given as cal/cm^2 , is defined as the quantity of thermal energy impressed on a surface at a specific distance from the source and released during an electric arc event. The computation of incident energy must also yield the safe border distance from a potential arc flash hazard.

In compliance with the Occupational Safety and Health Act (OSHA), National Electrical Safety Code (NESC) the owners or operators of plants, industries and utilities shall alert workers at the site of arc flash hazards. As in Figure 1, OSHA arc flash regulations can be complied with by labeling electrical equipment [4].

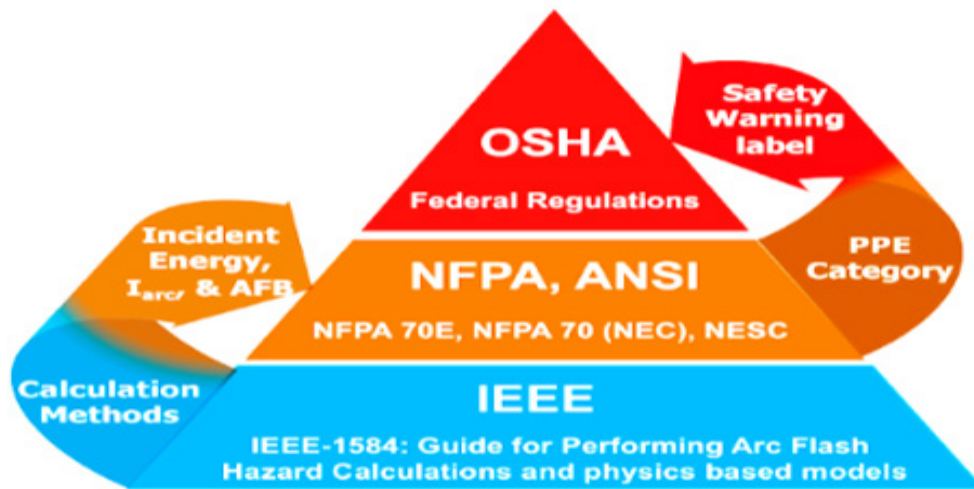


Figure 1 Arc Flash Assessment Standard Requirements

1.2 Statement of the Problem

Arc flash on DC systems is relatively unexplored, and industrial studies have yet to back up the majority of the theoretical calculation approaches available [5 - 8].

In 2002, IEEE issued the standard 1584 "IEEE Guide for Performing Arc Flash Hazard Calculations" to give arcing current computation and incident energy estimation based on 300 laboratory testing data sets in order to assess potential arc flash hazards. Arc flash calculations and studies are commonly performed using the IEEE 1584 standard, which is currently considered the industry main standard. In 2018 this standard has been updated with more added factors and backed with more than 1500 tests concerning the Electrodes configuration impact on the calculation model. However, only alternating current systems can benefit from the empirical model derived in this standard.

Several models are currently available to calculate incident energy for DC systems and consequently photovoltaic systems. The models available vary in conservatism to ensure that employees have the appropriate PPE in the worst-case scenario. However, these models are presumed non adequate or overly conservative when applied to photovoltaic array [5 - 11].

The overly burdensome PPE may reduce the mobility of workers, reduce productivity, and increase the likelihood of an accident and leads to apparent safety threats [11].

At the moment, NFPA 70E is the standardized model to estimate Arc Flash Energy for DC systems and photovoltaic systems are not an exemption.

DC arc dangers have become a major worry as large-scale solar arrays and DC buses have proliferated in the power system.

It is presumed that DC arc hazards might much extreme when compared to the AC current . AC system have a zero crossing periodically, thus current will eventually be damped after a certain period of time [7] [8]. Depending on voltage, arc might be extinguished or restrike. Moreover, 1.25 times AC arc heat flux might be produced by a DC due to rms and average currents [11-13].

Detailed testing has been the most effective method of establishing a DC arc flash model; nevertheless, rigorous testing is time demanding and limited by laboratory capacity. Several empirical DC arc models have been developed using restricted arc testing data to approximate real arcing currents and voltages; however, these models are only valid within the data gathered [11].

Thus, this thesis addresses the DC electric arc particularly on photovoltaic arrays and arc modelling and simulation respectively to provide a contribution to the industry standard development.

It presents a magnetohydrodynamic MHD simulation as a technique to understand arc behavior and predict arc flash threats in photovoltaic arrays. Moreover, provides a sound theoretical framework for future model validation by industry committees.

The model used in the MHD simulation is developed to make the test setup for arc in a box configuration of the recent performed by Electric Power Research Institute (EPRI), which made it possible to predict the interaction for electric arc and compared it to the performed tests by EPRI.

Furthermore, the developed empirical model by Electric Power Research Institute (EPRI) for incident energy calculation on photovoltaic arrays is presented and verified in this thesis in compared to the MHD simulation results and to the other available industry models.

1.3 Thesis Motivations

Concerns regarding DC arc flash have grown as photovoltaic arrays have become more common in power systems.

Large-scale photovoltaic arrays with hundreds or even thousands of individual photovoltaic modules have lately been built. In a photovoltaic plant a single aggregation point, like combiner boxers or inverter-input combiner compartments, may have a combined DC output capacity of higher than 1MW, 1000V, and 1000A.

In an electrified electrical system, any equipment failure or human error can cause arc flashes, causing equipment damage, fires, and worker injuries or death.

Recent literature and test reports concluded the available DC arc flash estimation or prediction models are not adequate for photovoltaic arrays. A precise estimation of arc flash energy is a crucial step to determine the risk of an arc flash for adequate system protection and reduction or mitigation of potential threats.

Electrical safety standards committees are currently tackling arc flash in many different DC systems. They encourage industry professionals to participate in the development and refinement of various models that need to be vetted and verified to ensure that they are applicable and accurate.

1.4 Thesis Objectives

- To propose MHD simulation approach to simulate and estimate Arc Flash energy on photovoltaic arrays. The physical aspects of the Arc Flash in photovoltaic systems are presented in this thesis. Then, the DC arc model of the MHD method is described in this thesis. The computational assumptions and the necessary simulation scenarios are considered to fully comprehend the MHD model.
- To compare the MHD simulation approach results to Electric Power Research Institute (EPRI) empirical model also to compare it to some other available industry models.

1.5 Thesis Organization

Chapter 1 introduces general arc flash concepts and relevant industry practices. The problem statement is also elucidated alongside thesis motivation and objectives in this chapter.

Chapter 2 presents the previous work related to DC arc flash in photovoltaic systems and describes the limitations of the existing DC arc flash estimation models.

Chapter 3 describes the MHD simulation approach, numerical model, and assumptions. In this chapter, the DC arc in a photovoltaic system is researched and modelled from a physical standpoint. The modelling methodology and software are explained in this section. Also, explains the basis of the utilized MHD model geometry, boundary conditions and mesh.

Chapter 4 presents the simulation result and shows the MHD simulation results comparison to the other industry models.

Chapter 5 depicts the conclusions and suggests future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Arc Flash Hazards

The formation of an electric arc, which creates a sparkling bridge in the space between two electrodes, depends on the presence of adequate voltage in an electrical system and a route to ground or a lower voltage. If a system's electrical voltage is high enough and there is a route to ground or a lower voltage, an electric arc will emerge.

The schematic diagram in Figure 2 shows the flash characteristics. A very massive quantity of lethal energy will be discharged into the atmosphere during an arc flash event. Any malfunction or human mistake in an electrical system that is electrified has the potential to result in an arc flash event, which may injure or even kill nearby staff and bystanders. After the electric arc is formed, the arcing current will ionize the air, and as a consequence of the ionization process, a huge quantity of heat will be produced. The very high temperature experienced during an arc flash may also cause nearby metals, such as aluminum or copper conductors, to melt. As a consequence, the explosion will also expel the molten metals.

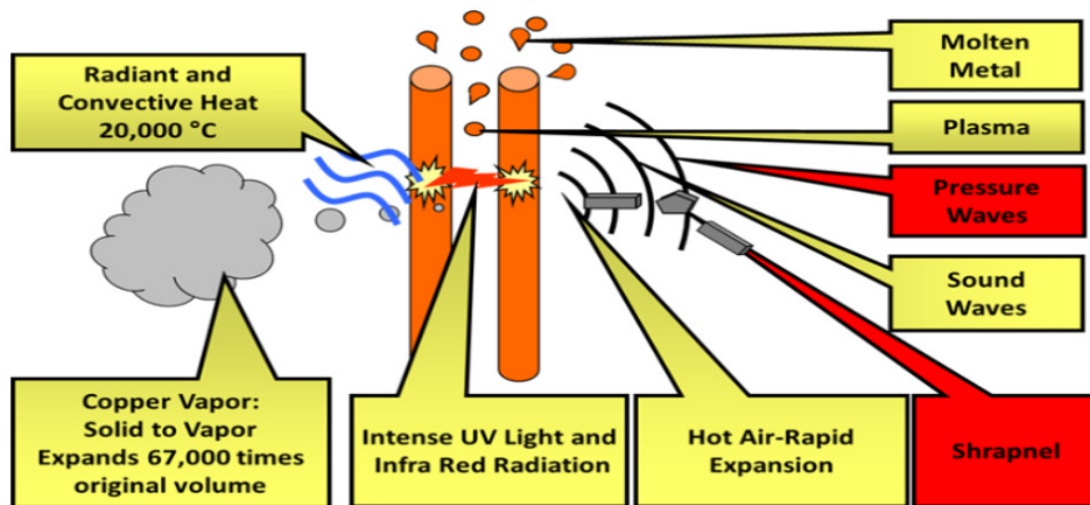


Figure 2 Arc Characteristics

In the United States, there are more than five arc flash explosions that happen at work 24/7. Arc flash incidents result in serious injuries to more than 2,000 employees each year, which may be deadly or very incapacitating. Additionally, electrical incidents rank seventh in terms of fatal workplace incidents [14].

As in Figure 3 due to greater understanding of electrical safety, both the number of fatal injuries and the frequency of electrical occurrences have continuously decreased. From 1992 to 1996, there were 327 fatal electrical injuries on average every year, but from 2009 to 2013 that figure dropped to 161. According to the Occupational Safety and Health Administration (OSHA), there were 110 electrical fatalities in total in 2014 (from January 1 through December 31), with non-electrical employees accounting for 70% of these deaths [15] [16].

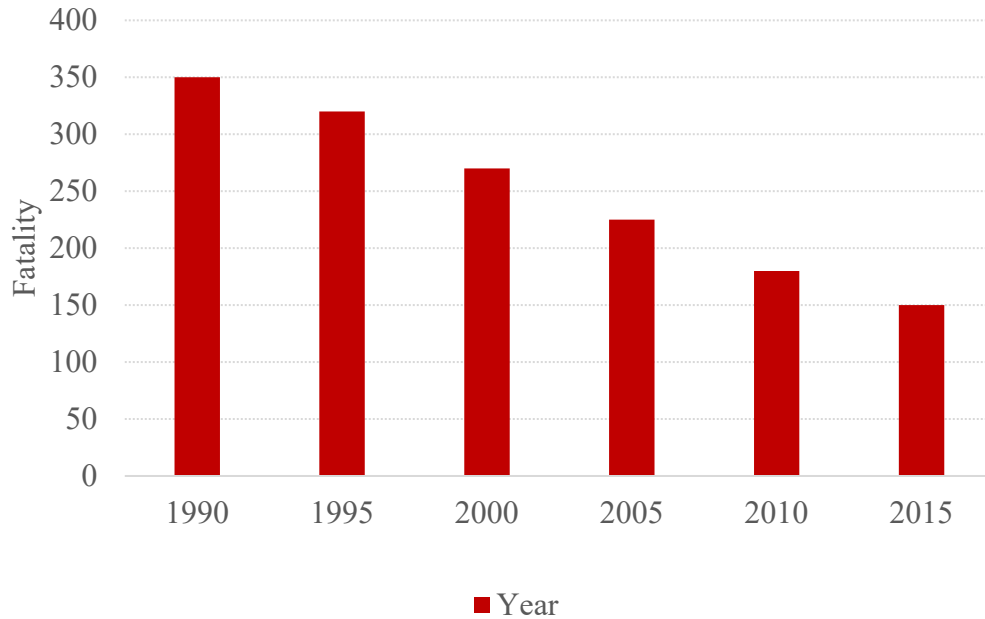


Figure 3 USA Arc Flash Recorded Incidents [16]

Due to the great energy that is released quickly during an arc flash occurrence, various personnel dangers are created. Arc flash hazards are often divided into the following categories:

Burn injuries are the main risk associated with arc flashes because of the very high temperatures of the gas and plasma that are created during an arc flash incident. Electrical burns have been ranked as the second-most expensive injury, and they may result in enormous medical and disability expenditures [17] [18]. Electrical injuries often have annual direct expenses between \$150,000 and \$370,000, with one case's total costs exceeding \$12 million [19]. Despite accounting for less than 2% of all accidents among electrical workers, electrical injuries were responsible for between 26 and 52% of the utility's overall worker injury expenditures [20]. The electric arc and blast explosion were contributing factors in around 10% of serious burn injuries that occurred at work, according to studies from the Washington State Department of Labour and Industries [21].

Workers may be directly hit by the explosion and the released materials, such as metal particles, during an arc flash incident. The weak areas of the human body are susceptible to piercing injuries from the materials ejected during an arc flash explosion [22].

An arc blast is characterized by intense pressure and rapid pressure build-up; the blast pressure produced during an arc flash event may pose a serious threat to anyone standing directly in front of the event, as the high-pressure impinging may cause damage to their organs like the lungs or the brain. Workers may also be knocked off their feet or possibly injured by projectile pieces due to pressure waves with propel force [23].

Arc flash's abnormally intense light may harm people's sensitive eye tissues and result in temporary or even permanent disability. The arc flash event might harm the eyes if the system voltage exceeds 200 volts [24]. The data indicates that 4.2% of all arc flash-related injuries are eye-related [25] [26]. According to the Occupational Safety and Health Administration (OSHA), eye injuries at work are expected to impact medical expenses, severance pay, and recovery durations [27].

Workers are expected to maintain the standard precautions, such as safety glasses or masks, when positioning themselves in the possible arc flash danger regions, taking into account the eye protection in the most recent edition of NFPA 70E.

During an arc flash incident, a loud noise will be made that might cause temporary or even long-term hearing damage. When the maximum sound pressure level exceeds 140dB, a person without the proper ear protection may have trauma or even eardrum rupture [28] [29].

2.2 Arc Flash Calculation Models

2.2.1 Industry Standardized Models to Calculate AC systems Arc Flash

In 1982, with the work done by Lee [14], the arc flash phenomenon in electrical power systems was first discussed in relation to the protection of workers lives. IEEE Std 1584-2002, IEEE Guide for Conducting Arc flash Hazard Calculations, has been developed after his work in 2002, that later transformed into the assessment of the incident energy through which a worker might be exposed to during an arc flash case [3]. The formulas for assessing the incident energy were revamped with the additional testing, the model range increased, and new electrode configurations were introduced to accurately model real electrical equipment. Although with the comprehensive update of IEEE-1584 in 2018, the standard still lacks single-phase AC and DC systems and of course the photovoltaic systems [2].

Today, AC arc flash studies carried out with power system analysis tools, such as ETAP [30], SKM [31], EasyPower [32], etc. However, due to the non-standardization of assessing the probability or extent of determination, photovoltaic systems are usually overlooked.

2.2.2 Industry Standardized Models to Calculate DC and PV Systems Arc Flash

As DC arc flash is not discussed by IEEE 1584, NFPA 70E is the pioneering source of information to provide guidance into DC arc flash hazard analysis. However, NFPA 70E concentrated on theoretical models with not enough testing to support the guidelines as was performed for three-phase AC systems in IEEE 1584.

In addition, as per the recent industry tests and literature publication e.g. 2020 measurements of [10] and [33], it has been concluded that current standardized models are found to be lacking the required accuracy to be utilized for a photovoltaic array as a power source.

Moreover, [10] added that it might be necessary to separately define DC power systems into specific types (e.g., batteries, capacitors, and photovoltaic systems) and provide tailored incident-energy models for each type.

2.2.3 NFPA 70E to Calculate PV Systems Arc Flash

Doan has introduced the most commonly used model for estimation in 2010 [5]. This method is now the most globally recognized technique for the assessment of DC arc flash incident energy and is being implemented for DC incident energy estimations by the National Electrical Safety. This approach is based on the arc model of Ralph Lee, which suggests that the arc is a radiant spherical source, and that the arc's overall electrical energy transforms to heat energy [34] [35]. Based on the maximal power transfer theorem [14], the electrical arc power in this model is determined. When the arc resistance is equal to the source resistance, the maximum electrical arc power is 25% of the bolt fault, as seen in Figure 4.

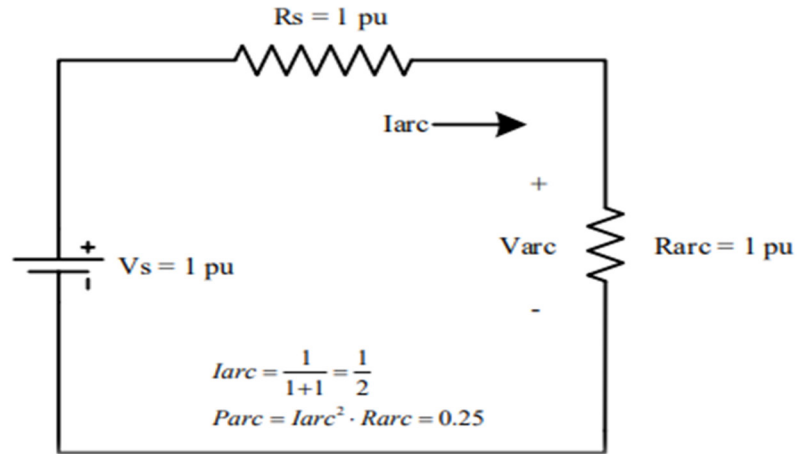


Figure 4 Maximum Power Transfer to DC Circuit [36].

The maximum power of the arc as presented in [37] is seen in equation (2.1), applying previously mentioned observation and the maximum power transfer theorem. Then, the

energy is multiplied by time, at the maximum power of the arc. The time is the arcing fault clearing time.

Doan [37] assumed the energy of the arc to be a sphere, radiating uniformly in all directions, using the working distance to determine the sphere's surface area, using equation (2.2) to quantify the incident energy:

$$P_{max} = \frac{\left(\frac{V_{sys}}{2}\right)^2}{R_{sys}} \quad (2.1)$$

$$IE_{maxpower} = 0.005 \left(\frac{V_{sys}^2}{R_{sys}} \right) * \frac{T_{arc}}{D^2} \quad (2.2)$$

Where,

P_{max} maximum power of the arc (W)

V_{sys} system voltage (V)

R_{sys} system resistance (Ω)

$IE_{maxpower}$ estimated incident energy at the maximum power point (cal/cm²)

T_{arc} arcing time (s)

D worker's distance from the arc (also known as working distance) (cm)

However, [37] emphasizes that this approach is a tentative hypothesis of the calculation of incident energy, and additional investigation is required to measure the DC arc flash outcomes.

This approach assumed open air arc; no consideration of the enclosure, and therefore [37] suggests multiplying the arc element in the enclosure that has been verified by [38] and [39]. However, this factor will differ following system design parameters; fault current , electrode configuration, enclosure size, voltage, gap distance, etc.

Moreover, this neglects system inductance while (L/R) considered vital to anticipate protective devices response, this would impact fault magnitude and might increase clearing time [40]. Higher incident energy estimations are anticipated from this method, which would result into an conservative PPE [10] and [18].

In photovoltaic systems, the fault current is significantly higher than the normal operating current for typical AC systems and battery supplied DC systems, providing the overcurrent protective mechanism to sense and function effectively under a fault condition to clear the fault. However, fault current and operating current do not have the same differentiation for photovoltaic supplied DC systems, delaying the operation of overcurrent protective devices, especially fuses. Figure 5 shows a typical photovoltaic array I-V Characteristic curve, observing the slight difference between the maximum power point current (9.0 A) and the short circuit current (9.5 A).

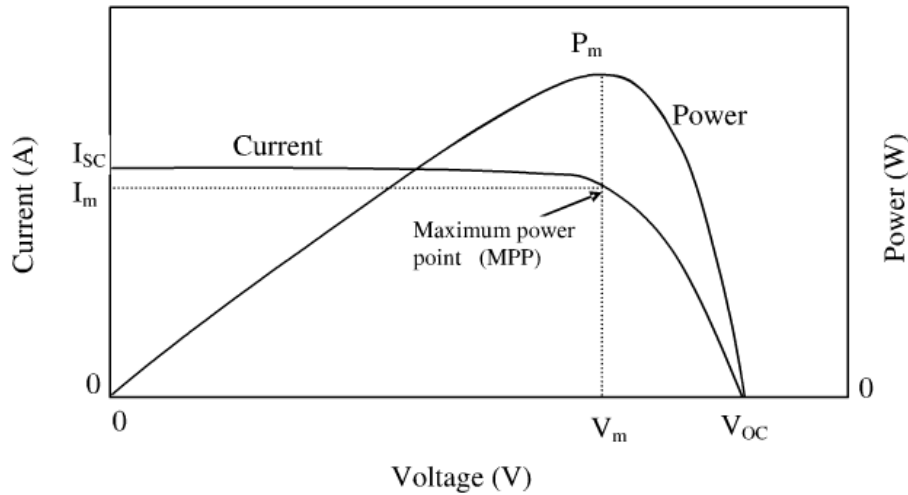


Figure 5 I-V Characteristic [19]

The Maximum Power Method have been proved as overly conservative for photovoltaic systems [8] [10] [33] [41] [43]. It is generally assumed that a higher magnitude fault would produce higher incident energy, but that is not always the case and is dependent on the clearing time and arc voltage. A fault that has a higher current magnitude, but quickly clears, may not result in a higher energy incident than a fault at a lower current magnitude, but it takes longer to clear. Accordingly, the importance of investigating where the fault current is high, and instances can not be overlooked as that result in long clearing times when performing photovoltaic array studies [42] [43].

2.2.4 Empirical Models to Calculate PV Systems Arc Flash

Figure 6 displays the standard DC arc testing system and its equivalent circuit. [42] summarized, the earliest testing of DC arcs was performed at low current for the use of electrical arcs for illumination. Some of these tests and resultant arc models included: Ayrton 1902, Steinmetz 1906, Nottingham 1923, Hall, Myers, and Vilicheck 1978 [44 - 48]. However, these models/results are not popularly used as they do not provide or have detailed test parameters and procedures.

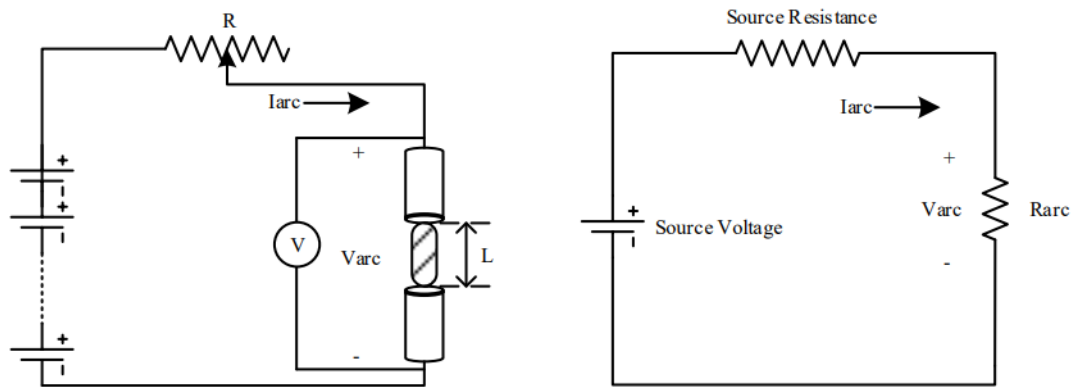


Figure 6 DC Arc Test Circuit and Equivalent Circuit [48]

In 1991, Stokes and Oppenlander [49] conducted the most extensive open-air tests to develop the I-V characteristics of series arcs (horizontal and vertical orientation) and are one of the leading models for the method of semi-empirical. Over 200 open-air single-phase AC and DC arc tests have been conducted which can be recognized as the most complete open-air research of free-burning arcs [49]. They used a 6kV DC power supply and produced 0.1 to 20kA arc current between copper series and aluminium electrodes with

a gap width of 5, 20, 100 and 500 mm respectively. This DC arc model was cited in the NFPA 70E 2015 edition for the DC arc estimation [49].

In 1993, Paukert [6] collated statistical literature regarding arc flash faults from those in the work of seven academics who performed a variety of arc tests and had their findings published. There were some DC testing and some alternating current tests. There were some layouts that were parallel, and those that were vertical. Currents in the arcing varied up to 100kA, while conductor spacing were anywhere up to 200mm (8in.). Paukert developed formulas for voltage and resistance for different electrode spacing, and he did so on the basis of the data that was acquired as an empirical model [6]. In 2013, Enrique model [8] became available to calculate the energy levels for solar farms. Doan (NFPA-70E), Paukert, Stokes and Oppenlander and Enrique Models are further discussed in chapter 4 where comparison is applied to MHD simulation.

2.3 Arc Flash Characteristics

A dynamic phenomenon that happens throughout time is the arcing phenomenon. The Poisson's formula [27] may be used to represent the arc lifetime's unpredictability. In an electrical system with sufficient voltage, it is possible to create an electric arc, which is an electrical breakdown of a medium's resistance (such as gas or air) by transferring it via a channel to ground or a lower voltage. Between two electrodes that are separated by a gas, an electric charge may be transmitted under certain circumstances. This section aims to provide a basic review of the physical processes that let large electric currents to flow through a gaseous medium and across the junctions between gases and metallic conductors as a starting point.

Arcs are formed when there is a dielectric breakdown of the air between two locations with sufficient electrical energy. A dielectric substance experiences dielectric breakdown when it becomes conductive, enabling unhindered electron transport across the medium. Electrons migrate quickly from higher to lower electric potentials as a consequence of air being conductive. Electrons travel quickly and produce a lot of heat, which leads to the formation of plasma. Between the "gaseous plasma cloud and the solid conductors," electrodes act as a transition. An arc is made up of the cathode and anode regions. There is a certain amount of heat associated with each area. The plasma column can reach temperatures of 13,000 K to 30000K. These temperatures are greater than the surface temperature of the sun by a factor of four. Arcs are accompanied by waves of heat and pressure. Pressure waves are therefore created by heat. Two processes—rapid air heating and metal expansion due to boiling—are in charge of producing pressure. Pressure waves

produced by arcing resemble the thunder waves produced by an electrical storm [27]. Each of the three portions of the arc has a distinct voltage profile, as shown in Figure 7.

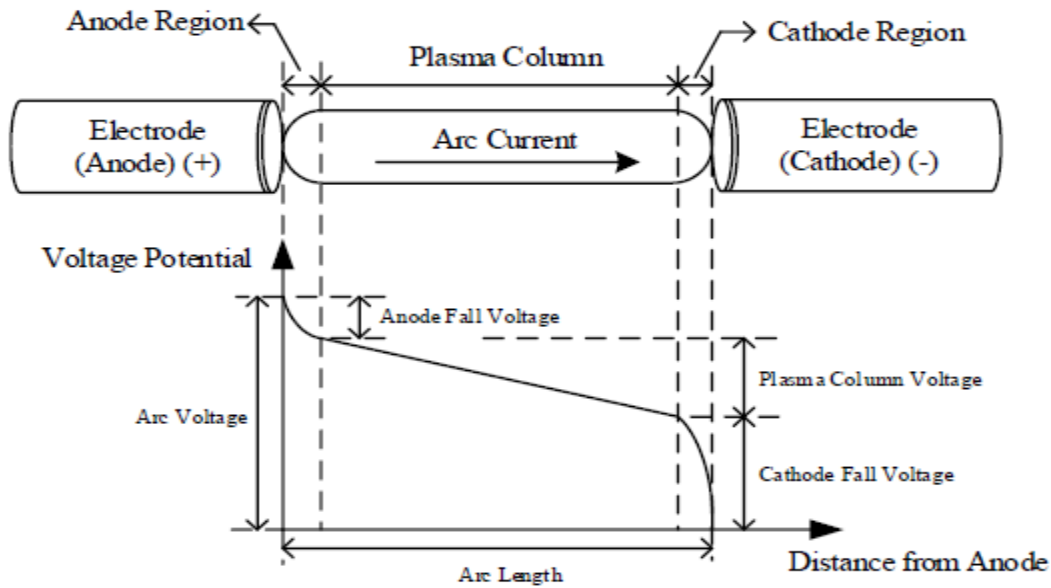


Figure 7 Zones and Arc Arrangement [51]

Voltage decreases along an arc's length. It is challenging to predict the length of an arc because electrode to electrode distance might vary [11]. The total length of the arpeggiator has a direct bearing on this voltage loss. Numerous variables, including as electrode orientation, gap length, external circumstances, and the available system voltage, affect arc length [12]. However, since the makeup of the air influences the resistance an arc must span, the voltage drop is not simply dictated by the duration of the arc. Because I^2R losses affect the production of thermal energy, bigger voltage dips imply a higher route resistance. Arcs may experience voltage decreases of up to 100 V/in, while solid conductors normally experience drops of less than 75 V/in.

High-pressure and low-pressure are the two main categories of free-burning arcs in the open atmosphere (or vacuum). Low-pressure arcs are more likely to develop than high-pressure ones when there isn't any air present. As a consequence, it is possible to discriminate between axisymmetric and non-axisymmetric high-pressure arcs. They do not stray in any manner from the axis of rotation and have a constant radius. Axial arcs, on the other hand, are simpler to manage. In arc welding, there are several instances of an axisymmetric arc. Dynamic objects are those that are not axisymmetric. Given the flexibility of the arc's length and central axis, [11] departure from the arc is common. These include "plasma jets," "arc extinguishment and reinitialization," "electronic forces," "burn-back of electrode material," and "thermal convection." Examples of non-axisymmetric arcs include arc flash and switching-related arcing.

CHAPTER 3

MHD STEPS AND METHODOLOGY

3.1 General Modeling Methodology

This thesis utilized Ansys® software, ANSYS Fluent®, for fluid mechanic equations through Finite Volume Method (FVM) and ANSYS Maxwell® for electromagnetic equations using the Finite Volume Method (FEM). ANSYS fluent manual, is the used reference for this method [52].

The MHD equations may well be calculated using a module in Ansys Fluent®, enabling the modeling for electrically conductive fluids considering a continuous presence of magnetic fields.

However, it is required to execute a connection between the Ansys Fluent® and the Ansys Maxwell® in order to retrieve the magnetic fields created by them at each moment of time for the modeling of an electric arc. To estimate the movement of the electric arcs in space, Ansys Fluent® requests the electromagnetic fields produced by the electric arcs from Ansys Maxwell®.

The simulation flow for executing the coupling between Ansys Fluent® and Ansys Maxwell® is shown in Figure 8. The program that controls the whole simulation, Ansys Fluent®, is in charge of starting Ansys Maxwell® and reading its output. Ansys Fluent® communicates the fluid's electrical conductivity data to Ansys Maxwell® at each iteration

so that it may update the information in its simulation environment, compute the magnetic field using the new data, and export it. This allows Ansys Fluent® to compute the Lorentz force, which will affect the direction of the electric arc movement, and updates the magnetic field produced by the fluid. This procedure makes up the simulation flow when direct current, or input with a constant current, is considered.

User-Defined Functions (UDF), which are user-programmed functions capable of considerably altering and enhancing Ansys Fluent®, are used to build the simulation flow shown in Fig.3.1. These functions are built through using C/C++ programming language and adhere to a set of software-defined macros [52].

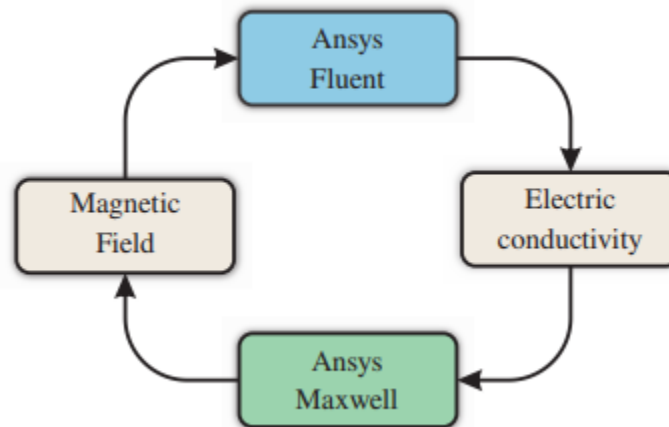


Figure 8 Fluent-Maxwell Coupling [52]

3.2 Numerical Model

A variety of physical processes combine rapidly during the production, persistence, and interruption phases of the electric arc, making it a very complicated event. As a result, complications with electromagnetic, thermodynamics, and fluid dynamics are all considered at once. The MHD theory, which treats the arc as an electrically conductive fluid in the presence of magnetic fields and specifies variables like density, velocity, pressure, and magnetic field in a macroscopic manner, may be used to predict these events [50 - 52].

The theory is represented numerically by the Navier-Stokes equations of fluid dynamics, which are made up of the mass, momentum, and energy conservation equations, and Maxwell's equations, which describe the electromagnetic fields with the direction of the electric arc's movement imposed by Lorentz force [50–52].

Information regarding the macroscopic behavior of the electric arc is provided by the magnetohydrodynamic definition, which is based on fluid dynamics and thermodynamic principles. The electric arc plasma's particle-by-particle description is essential for contextualizing the MHD model. All the many kinds of particles involved in this description—electrons, ions, atoms, and molecular species—each have their own state equation, the solution to which is a complex mathematical problem. From a computational standpoint, this must be simplified to be workable.

To begin, plasma is split into two fluids, one for the heavier particles (ions and neutrals) and another for the lighter particles (electrons). Conditions in the low-voltage electric arc,

such as arc roots and reignition, can only be examined by treating the plasma as two fluids, one for the arc column and another for the adjacent atoms and molecules in the electrodes, leading to a non-thermal equilibrium state. Plasma may be separated into two fluids, each of which has its own electron temperature and heavy particle temperature [50 - 52].

However, there are certain arc interruption scenarios in which taking into account and applying the necessity for different temperatures for electrons and heavy particles is unnecessary.

In order to model the arc's development on a macroscopic scale, magnetohydrodynamics is used. Plasma is treated as a homogeneous fluid in this approach. For equilibrium plasmas, this means using the MHD approach. With the assumption of local thermal equilibrium, the plasma may be treated as a single fluid, with a uniform temperature field (denoted by "T") and a uniform average velocity field (denoted by "u"), which simplifies the state equations for each particle.

Considering the foregoing, the modified Navier-Stokes equations (3-1), (3-2), and (3-3) are formulated to describe the relationship between the velocity, pressure, temperature, and density of a moving fluid, and are therefore referred to as the transport equations for the conservation of mass, momentum, and energy of the plasma as a single fluid. Additional discussion of these points may be found below:

Mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) \quad (3-1)$$

where ρ is the mass density (kg/m³) and $\vec{V}$ is the velocities vector.

Momentum conservation equation:

$$\frac{\partial(\rho v_i)}{\partial t} + \nabla \cdot (\rho v_i \vec{V}) = \nabla \cdot (\eta \nabla v_i) - \nabla p + \rho g_i + S_i \quad (3-2)$$

where v_i is the velocity in the i -direction, η is the dynamic viscosity (Pa s), p is the pressure (Pa), g_i is the acceleration of gravity in the i -direction (m/s²) and S_i is the term that describes other sources.

Energy conservation equation:

$$\frac{\partial(\rho H)}{\partial t} + \nabla \cdot (\rho H \vec{V}) = \nabla \cdot \left(\frac{\lambda}{c_p} \nabla H \right) + S_j \quad (3-3)$$

where H is the enthalpy (J), λ is the thermal conductivity (W/ (m K)), C_p is the specific heat (J/ (kg K)) and S_j represent other fonts.

Maxwell's equation:

$$\nabla \cdot \vec{E} = \frac{\rho_e}{\epsilon} \quad (3-4)$$

$$\nabla \cdot \vec{B} = 0 \quad (3-5)$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (3-6)$$

$$\nabla \times \vec{B} = \mu \vec{J} + \mu \varepsilon \frac{\partial \vec{E}}{\partial t} \quad (3-7)$$

where $\vec{E}$ is the electric field strength vector (V/m), $\vec{B}$ is the magnetic flux density vector (Wb/m²), ρ_e is the electric charge density (C/m³), $\mu = \mu_0$ is the air permeability ($4\pi \times 10^{-7}$ H/m) and $\vec{J}$ is the density of electric current in (A/m²).

Lorentz force, equations 3.8 and 3.9 impose two source terms in 3.2, the magnetic force (3-8) and the electrostatic force (3-9)

$$\vec{F}_m = \vec{J} \times \vec{B} \quad (3-8)$$

$$\vec{F}_e = \rho_e \vec{E} \quad (3-9)$$

Because mass can't be generated or destroyed, the total quantity of mass in a problem domain is guaranteed to be constant according to the principle of conservation of mass. Density, volume, and form are all variables that may change over time for a fluid (liquid or gas). In addition, mass may pass through the domain, but it doesn't build up or deplete; the same amount of mass that exits the domain enters it. The constant mass flow rate across a domain (or control volume) in computational problems follows from the conservation of mass equation (3-1).

When written in vector form, the first term represents a change in density at a specific location (the simulation's computational point), while the second represents a change in density associated with a move (entering or leaving the control volume). Momentum is the sum of a body's mass and its speed; hence its conservation is self-explanatory. Since momentum can't be generated or destroyed, the only way it can be altered is by the application of forces, as specified by Newton's laws of motion, which is why the quantity of momentum is said to be conserved within some problem domain.

Because momentum is a vector quantity with both magnitude and direction, it is more complicated to work with than mass or energy. The conservation of momentum holds in all three spatial dimensions simultaneously. Because of molecular collisions, the situation becomes considerably more complicated when dealing with a gas, since forces acting in one direction might alter the momentum acting in a different direction.

So, the first term in the Navier-Stokes momentum equation (3-2) for the electric arc represents the local change in the computational point of the momentum control volume; the second term expresses the difference of momentum relating to the input and output of the control volume; the third terms represent the accelerating force by pressure distribution;

and the fourth term represents the surface forces acting on the control volume, composed of two terms (t and u). This sixth term is often overlooked while dealing with arcs.

Energy cannot be made or destroyed, hence its total quantity is always the same inside some issue area thanks to conservation of energy. Although potential energy may be transformed into kinetic energy, the total amount of energy available inside the domain is always the same.

The third Navier-Stokes equation (3-3) thus defines, in the first term, the local rate of change of energy in the control volume, in the second term, the enthalpy difference of fluid entering and leaving the control volume, and in the third term, the work produced by the pressure change and pressure gradient, which is typically negligible in comparison to the enthalpy exchange. On the right side of the equation, the fourth term represents heat loss via conduction, the fifth represents heat loss via radiation which crucial in electric arc formulation, the sixth represents viscous dissipation, and the seventh represents electric energy dissipation in the control volume via ohmic heating, an additional term relating the fluid dynamics once again with the electric field.

Therefore, electromagnetic components reflecting ohmic heating and Lorentz force interaction with fluid dynamics must be stated when the Navier-stokes modified equations are applied to arc plasma, particularly in momentum equation (3-2) and energy equation (3-3). Therefore, equations (3-4) to (3-9) must be included in the problem solution to solve Maxwell's laws in the same computing time as Navier-Stokes.

Because of the Joule effect, the electric arc current from the arc generates ohmic heating, and magnetic forces are created. Plasma's gas and energy transport are generated by

magnetic fields, either those generated internally or from the outside. These elements alter the spatial distribution of heat and cold inside the container. Because of this, the plasma's thermal conductivity, viscosity, density, and specific heat values are altered, among other physical characteristics. Meanwhile, voltage and current density are distributed throughout the chamber based on the distribution of electric conductivity.

Finally, the radiative loss element in the energy equation represents the radiation heat transfer from the arc, a crucial phenomenon in the magnetohydrodynamic model [50 - 52].

3.3 Geometry Model

The Electric Power Research Institute (EPRI) report number 3002014124 dated June 2018 [1]. The experiments done for Arc Flash on photovoltaic systems, served as the basis for the geometry used in this thesis. EPRI test setup is shown in Figure 9, three main types of test setups used in their Arc-flash experiments; Arc in a box shown in Figure 10, Combiner Box as shown in Figure 11, Mocked Inverter Cabinet as shown in Figure 12.

20 inches $\times$ 20 inches $\times$ 20 inches; length, width, and depth. For each test setup different options of conductor spacing have been utilized.

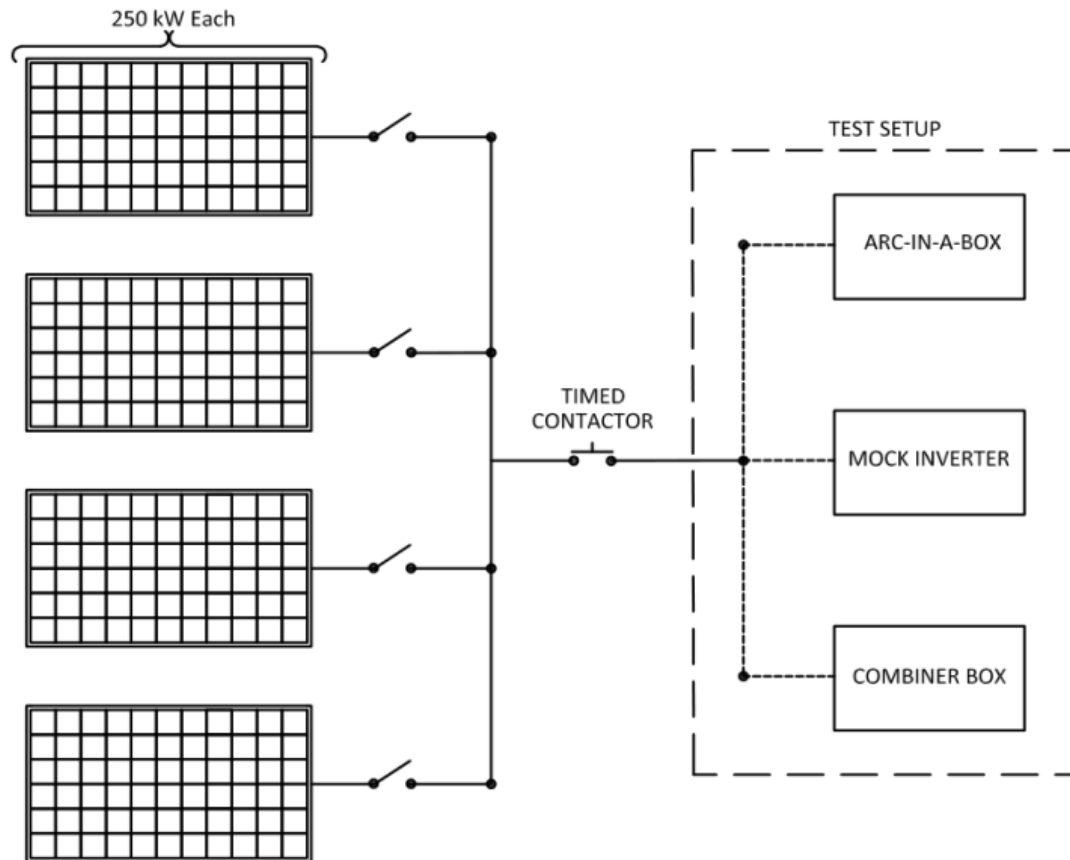


Figure 9 EPRI Three Test Setups [1]

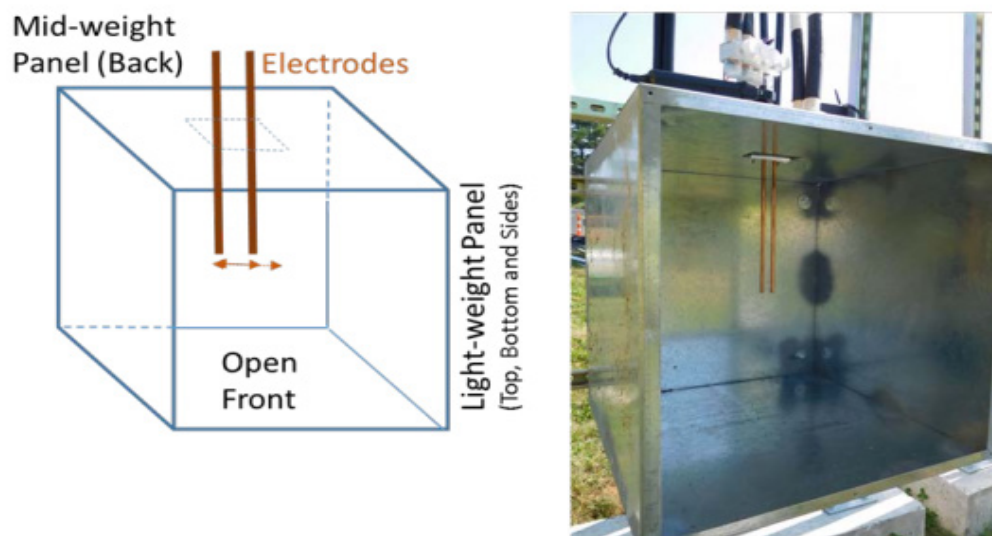


Figure 10 Arc in A Box [1]

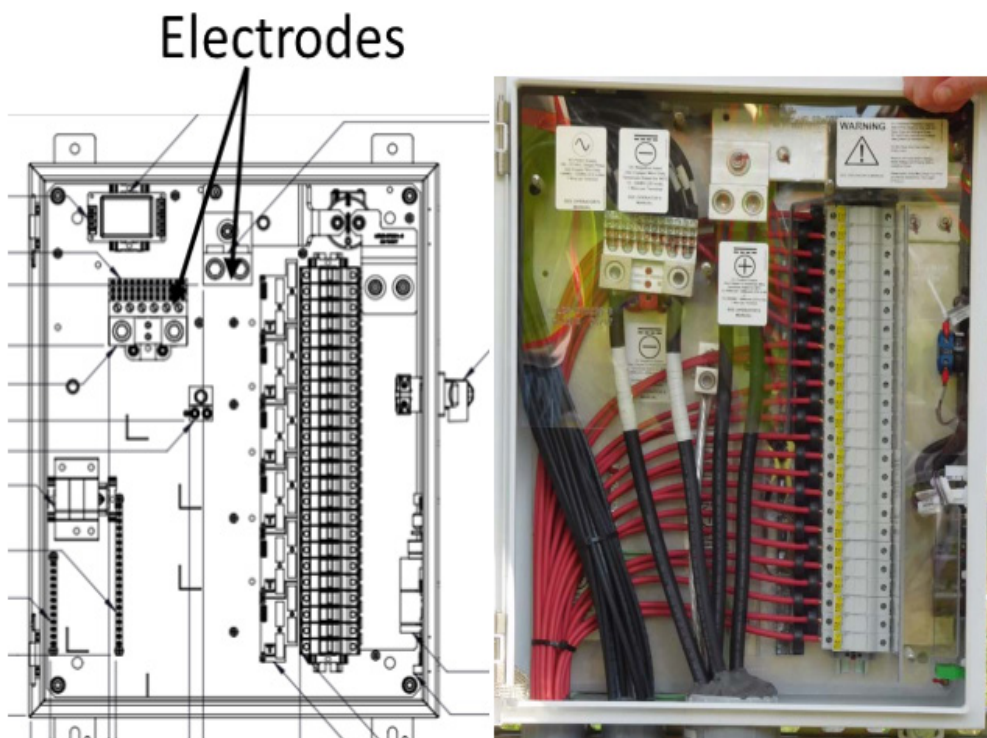


Figure 11 Combiner Box [1]



Figure 12 Mocked Inverter Cabinet [1]

The geometry for the MHD model in this thesis is taken from EPRI Arc in a box setup [1]. Geometry is developed through ANSYS Geometry Design Modeler. Arc in a box setup is used no inverter is considered in MHD geometry.

As in Figure 13 Arc in a box setup composed of a pair of parallel copper conductors that are arranged vertically and spaced apart by a gap, where the left conductor serves as the anode and the right conductor serves as the cathode. As in Figure 13, Figure 14 and Figure 15 two different electrode or conductor gaps (0.5 and 2 inch) has been considered for two different geometries to capture the impact of Electrode Gap on the Analysis These two

conductors are both modeled as copper conductors with a cross-sectional area of 6.35 mm x 6.35 mm and a length of 5.4 mm.

Both submerged in an air box that is 76.2 mm x 25.4 mm x 25.4. No consideration made for the enclosure metal box instead arc considered to be in an open-air environment.

The enclosure impact is well explained on IEEE 1584, and it is already well concluded in the industry. IEEE 1584 correction factors can be used to consider the impact of metal enclosure. MHD geometry has a notable reduced size to EPRI test setup, this has been done to decrease the computational burden.

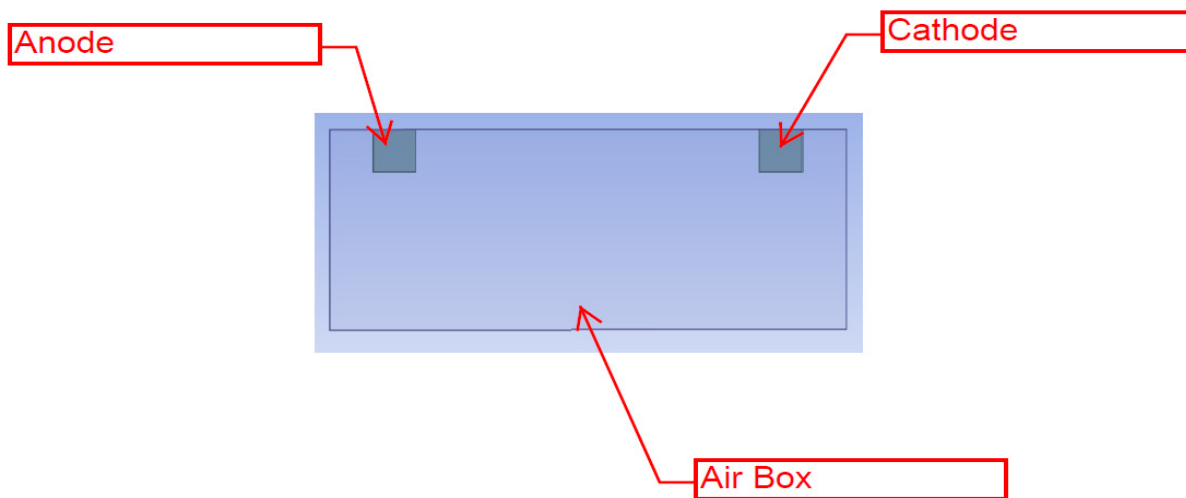


Figure 13 2 Inch Gap Side View

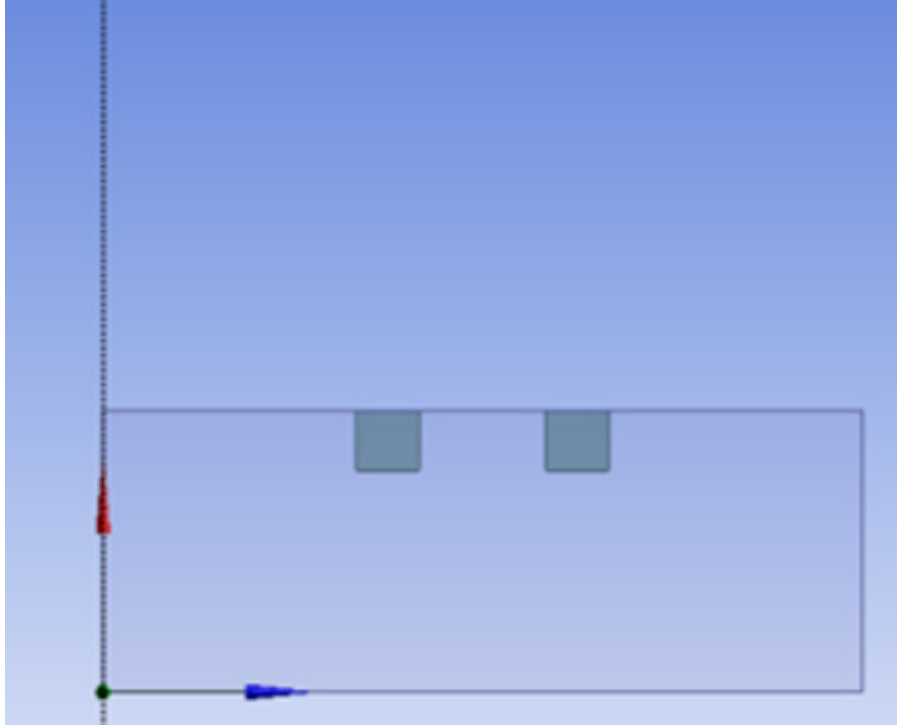


Figure 14 0.5 Inch Gap Side View

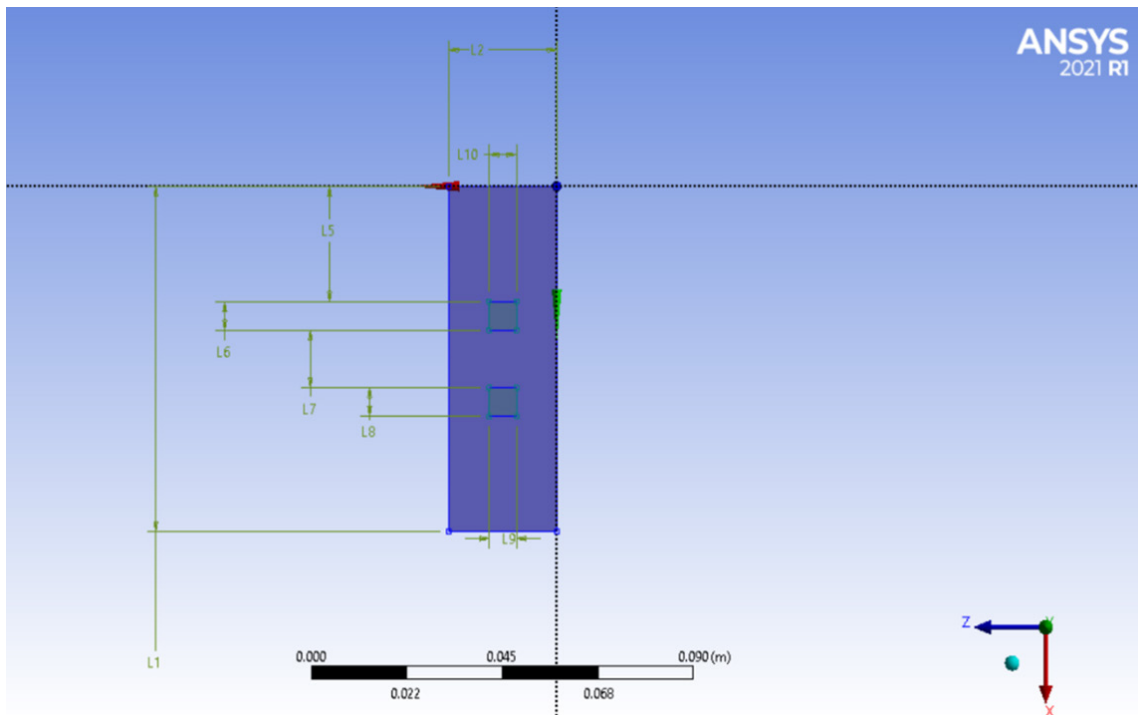


Figure 15 Geometry with Different Gaps Top View

3.4 Mesh Configuration and Description

It is necessary to discretize the domain into small subdomains (elements) to use the methods of built-in finite volumes and finite elements in ANSYS software to solve the set of equations, in each element when solving the MHD equations numerically, as well as any other system of differential equations that govern the behavior of fluids.

Ansys employs a discretization method that approximates a system of differential equations to a system of algebraic equations, which can be solved to obtain an approximation to the exact solution. The differential equations which define the system are integrated over the control volume. The grid defines the boundaries of control volumes while the computational node lies in the center of the control volume. The result is a set of linear algebraic equations: one for each control volume. Then, they must be solved iteratively or simultaneously.

Mesh is the collective name for this collection of tiny elements, and the definition of the elements has a direct impact on the accuracy of the answers. The mesh of the simulated geometry is shown in Figure 16.

A variety of mesh choices were created using various techniques, element sizes, and element counts, and the best orthogonal quality was chosen to be used.

The ANSYS meshing tool was used to generate the mesh, which according for different meshing techniques and approaches to size and check the mesh quality [53]. The obtained mesh contains 96,928 total number of elements and 104824 total number of nodes.

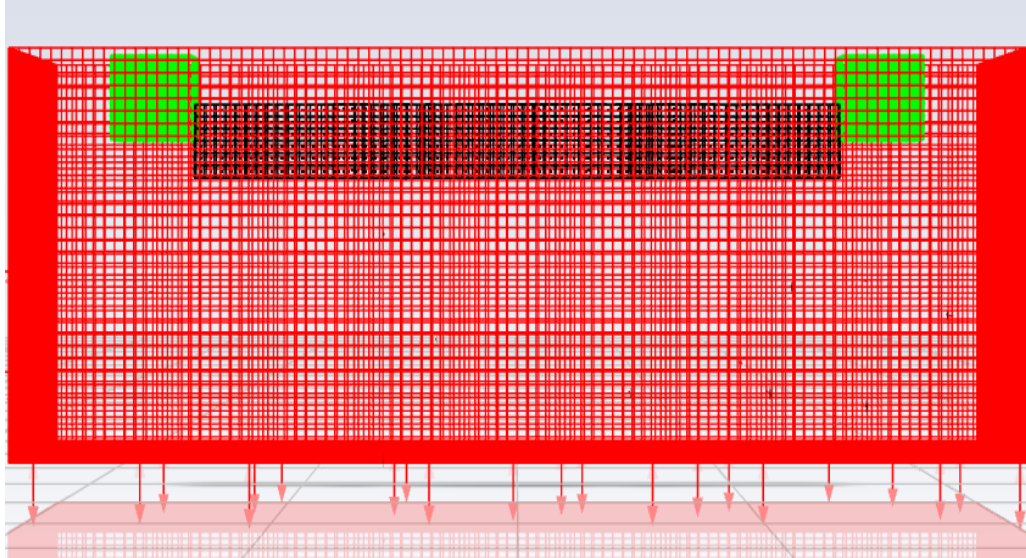


Figure 16 Mesh of The Simulated Geometry

3.5 Boundary Conditions

As shown in Table 1 , domain boundaries must be specified with data and initial values for accurate modeling of electric arcs.

Table 1 Boundary Conditions

Boundary	Temperature	Electrical Potential	Magnetic Potential
Fluid or Air Walls	300K	0	Coupled
Interfaces between air and conductors	Coupled	Coupled	Coupled
Anode	300K	Short Circuit Current Density in A/m^2 at Maximum Power Voltage (Refer to Table 2)	0
Cathode	300K	0	0

The conductors are in an open-air environment; the walls of the fluid domain are depicted as outflow.

Standard atmospheric pressure 101,325 Pa and 300 K (ambient temperature) have been used to establish the air box temperature.

There is a coupling between the air and copper conductor's 'interface'.

Copper, which does not change its physical characteristics with temperature, is employed in the solid domains (conductors or electrodes). The material physical properties are available in the Ansys default library.

The "box" around the air-based conductors stands in for the fluid (Air) domain.

As in Figure 17, Figure 18, Figure 19, Figure 20, Figure 21, Ansys® User Defined Function are used to define the air's physical properties. Electrical Conductivity, Thermal Conductivity, Viscosity, Density and Specific Heat are specified as per plasma mixing rules [53] [54].

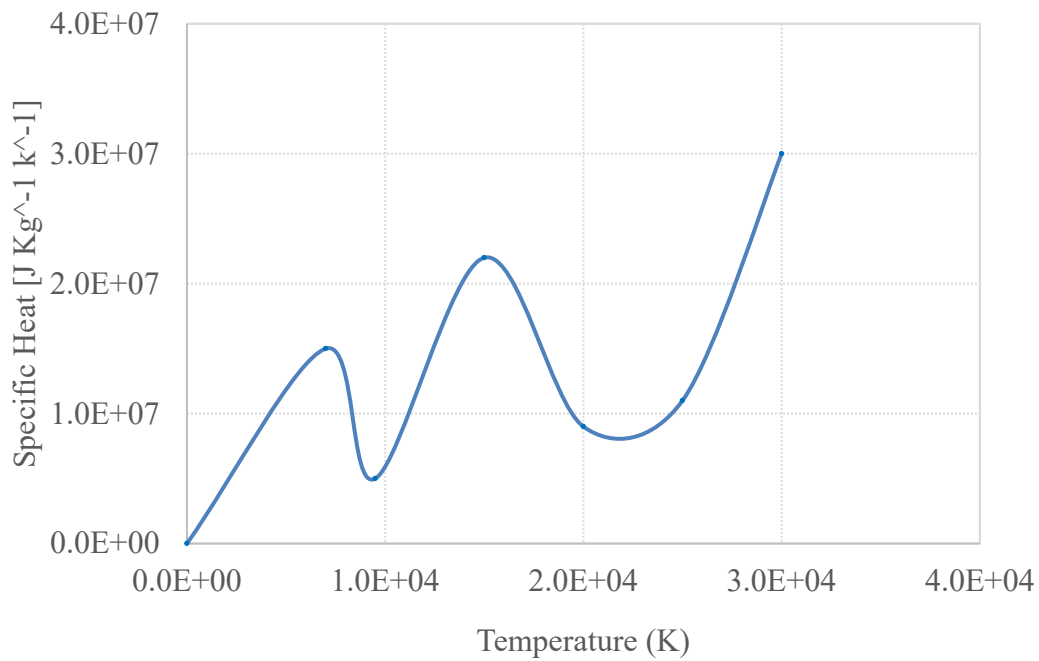


Figure 17 User Defined Air Specific Heat [54]

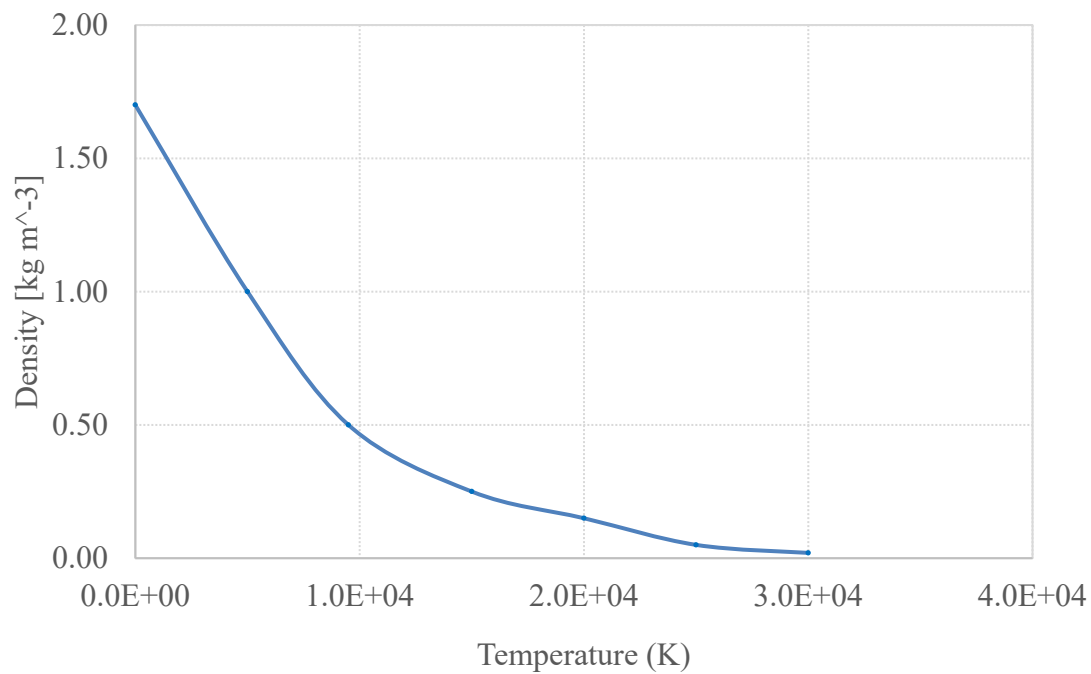


Figure 18 User Defined Air Density [54]

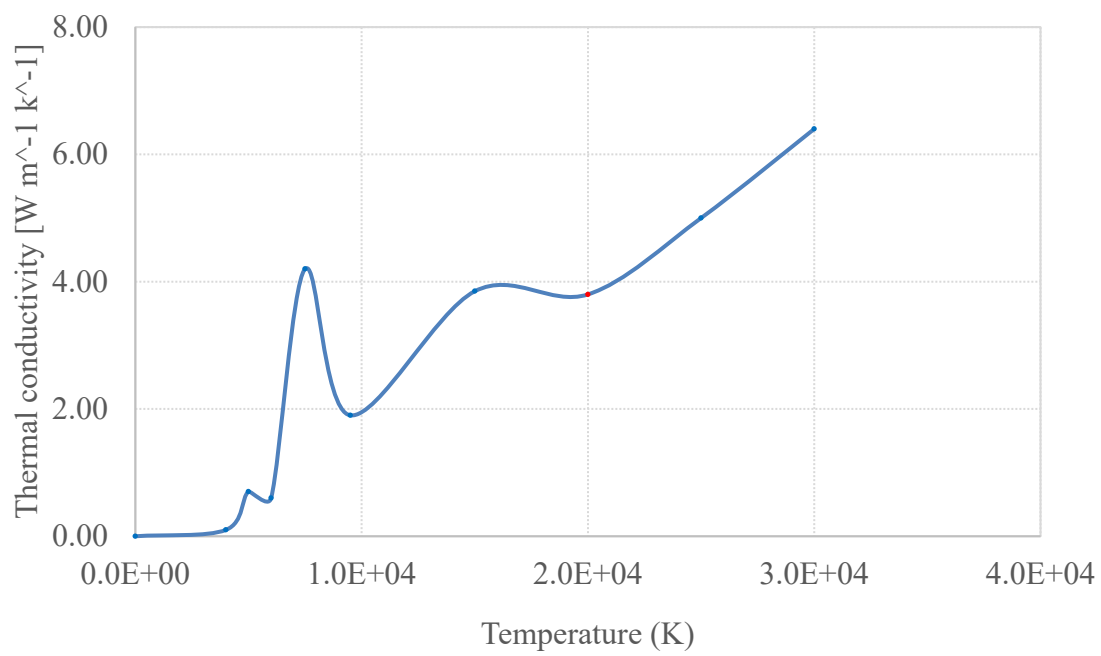


Figure 19 User Defined Air Thermal Conductivity [54]

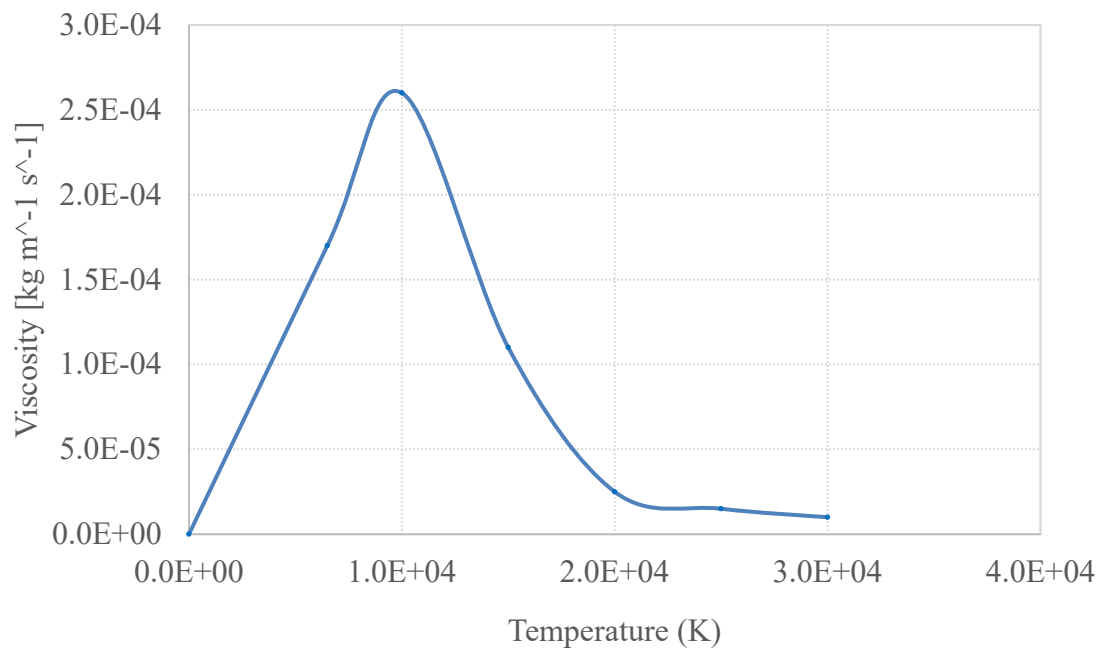


Figure 20 User Defined Air Viscosity [54]

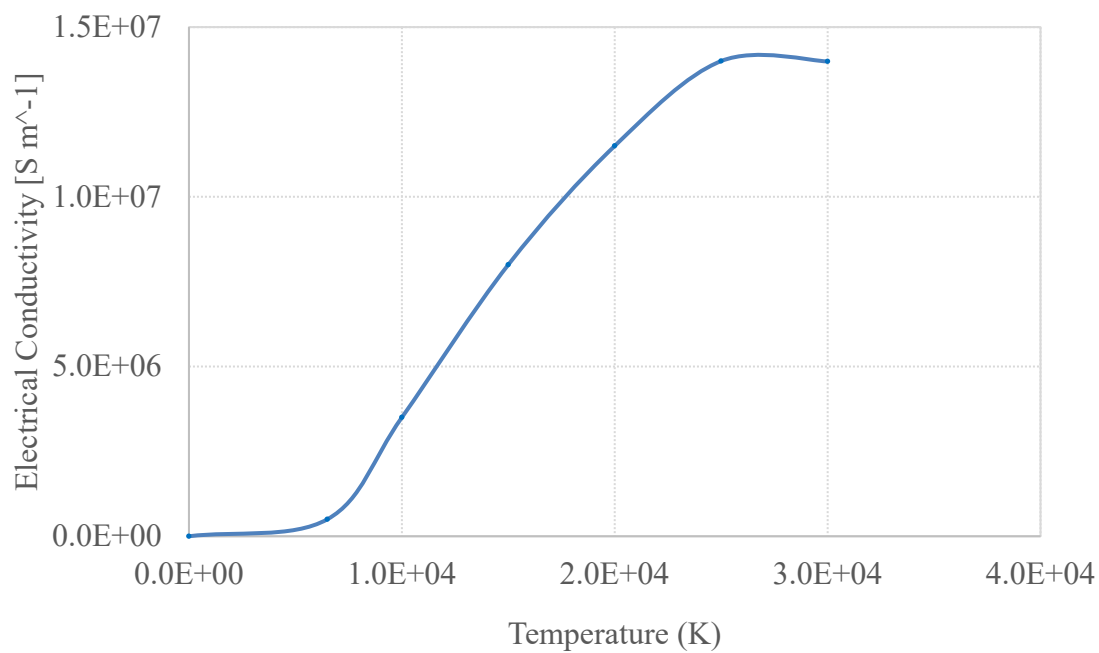


Figure 21 User Defined Air Electrical Conductivity [54]

Current flows from the Anode to Cathode; 0 V is specified at the tip of the Cathode.

Anode current input is defined as current density on the conductor tip and voltage patched to the anode.

For each case current and voltage values are considered as per the Maximum Power Point on I-V characteristics, no consideration for night mode, dark or low illumination conditions.

For better understanding of the selected current and voltage, photovoltaic array, a combination of series and parallel modules will serve as a source with certain current (I), voltage (v), and power. As shown in Figure 22 (I-V) characteristics of the photovoltaic array dictate output values during daytime and dark conditions.

The current flowing through a short circuit is shown by the I-V curve in the upper left corner of the first quadrant when the voltage is zero. This is the current that is measured with the output terminals in a short circuit (zero voltage). When there is no current flowing, the voltage at the bottom right of the curve is referred to as the open-circuit voltage. This is the voltage when the output terminals are open, and it was measured at zero current.

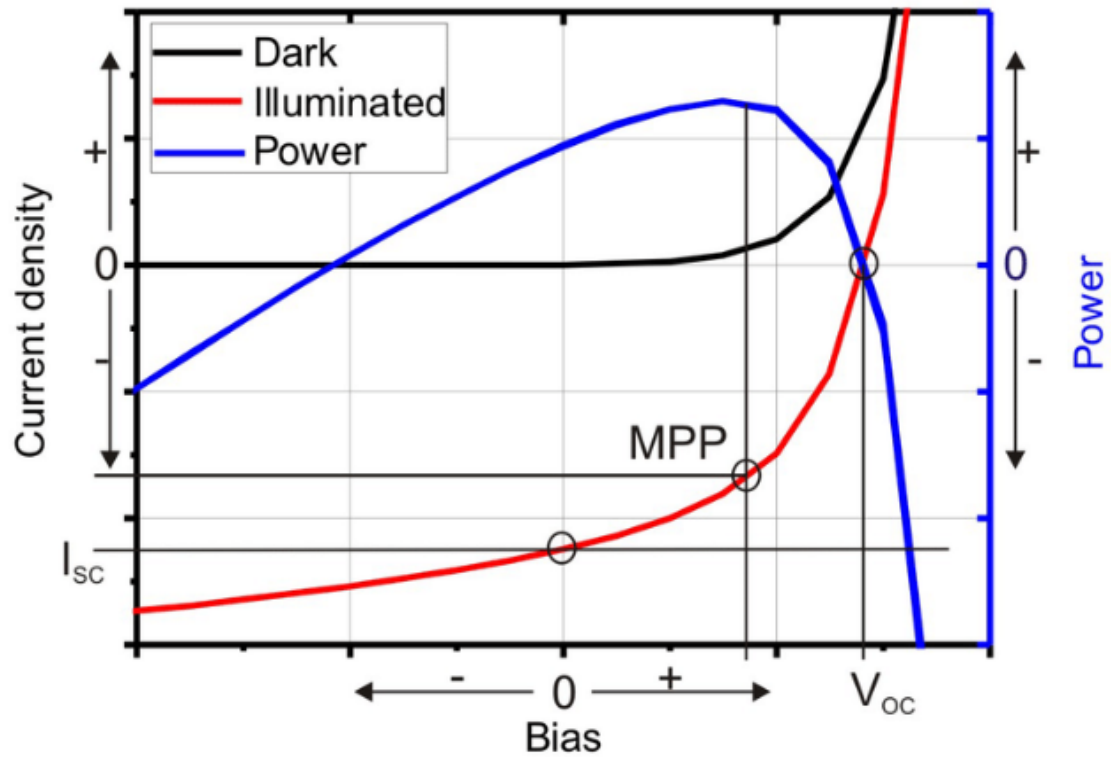


Figure 22 I-V Characteristics [9]

The parameters that are taken into consideration are the maximum power voltage and the maximum short circuit. DC arc-flash situations during low illumination conditions are not taken into consideration; as a result, various modules of photovoltaic systems, such as single-diode and two-diode models, are not aimed to be reflected in the MHD model. Despite this, there is still a possibility of danger occurring in such circumstances. Additionally, this is discussed in the assumption section 3.7.

3.6 Case Studies and Assumptions

Two cases shown on Table 2 has been evaluated, the values of current and voltage at Maximum Power point are considered from EPRI report [1].

Table 2 Study Cases

Case	Name Plate / Adjusted maximum power point	PV- Array Power Rating (W)	Conductors Gap (inch)	Maximum Power Voltage (V)	Maximum Short Circuit Current (A)	Cathode Grounded
Case 1	Nameplate	990,967	2	693	1430	Yes
Case 2	Nameplate	990,967	0.5	693	1430	Yes

The following assumptions have been considered:

- Plasma is considered as a continuous fluid (air) and at Local Thermal Equilibrium (LTE).
- Vapors and Melting near the electrodes are not considered.
- The inductive currents are neglected since there is no power frequency in DC.
- The gas is incompressible.

- Laminar flow is considered for air arc and the turbulence flow is neglected.
- Arc in a box setup is the considered configuration in this thesis. The focus is simulating the arc flash in array side inverter impact or load contribution are not considered.
- Parallel phase to ground arc is considered.
- Photovoltaic arc-flash hazard in arrays during low illumination conditions are neglected. Thus, the non-linear characteristics of I-V curve are not considered for the photovoltaic system as a power source. Instead, maximum power point is assumed as the operation point with the maximum fault clearing time (2 seconds) this to have the most conservative arc flash results from arc voltage and arc current prospective.

CHAPTER 4

MHD SIMULATION RESULTS VS OTHER INDUSTRY

MODELS

4.1 MHD Simulation

Ansys fluent used to simulate the created models. A simulation time step of 5us has been used. However, for the initial 1000 iteration 5ns has been used to initialize the model and to set the boundaries. Total simulation time of around 36 hours for each case have been required to simulate around 100 ms. As shown in Figure 23 for both cases electrode spacing, 7000K hot zone has been applied to initialize the arc at first time step. The simulation result data were collected using an Ansys results module and exported into a series of graphs, figures and tables to simplify the representation and analysis.

For case 1, as shown in Figure 24 the maximum power voltage 693V applied after 450 iterations of 5ns to simulate the maximum current density which corresponds to the short circuit voltage of 1430A. While 0 V has been set for cathode tip, to initialize the current direction.

As shown in Figure 25, the short circuit current applied on the Anode tip has a current density of 35,464,070.92814 A/m², Anode tip surface area is around 0.0000403225 m².

The arc flash development is shown in Figure 26 and Figure 27. The arcs are colored according to the temperature level in the colormap.

For case 2, similar to case 1, the maximum power voltage 693V applied after 450 iterations of 5ns to simulate the maximum current density which corresponds to the short circuit voltage of 1430A. While 0 V has been set for cathode tip, to initialize the current direction.

The short circuit current applied on the Anode tip. The arcs are colored according to the temperature level in the colormap.

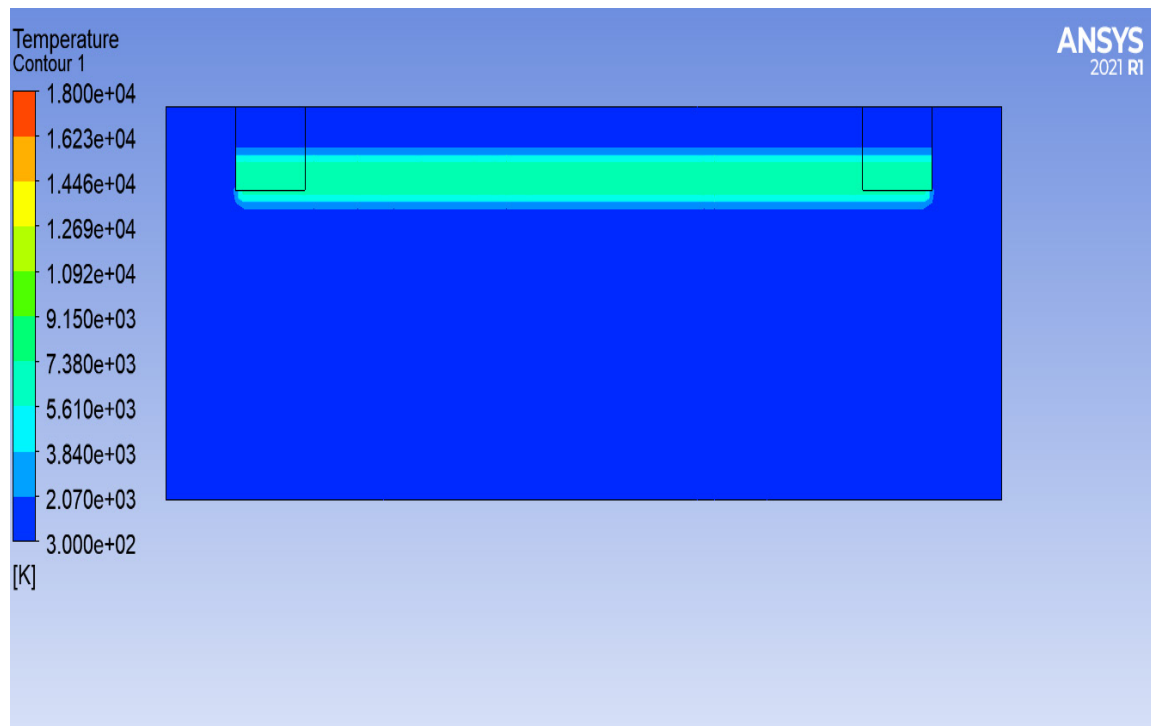


Figure 23 Hot Zone for Arc Initialization

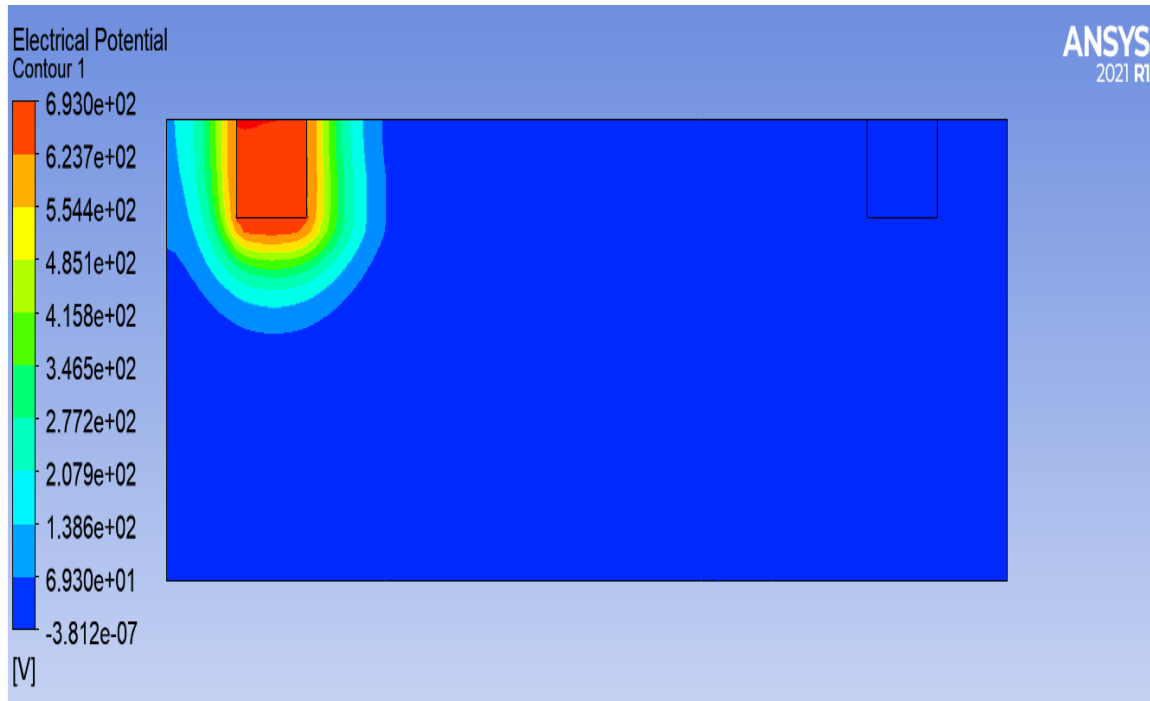


Figure 24 Maximum Power Voltage on Anode

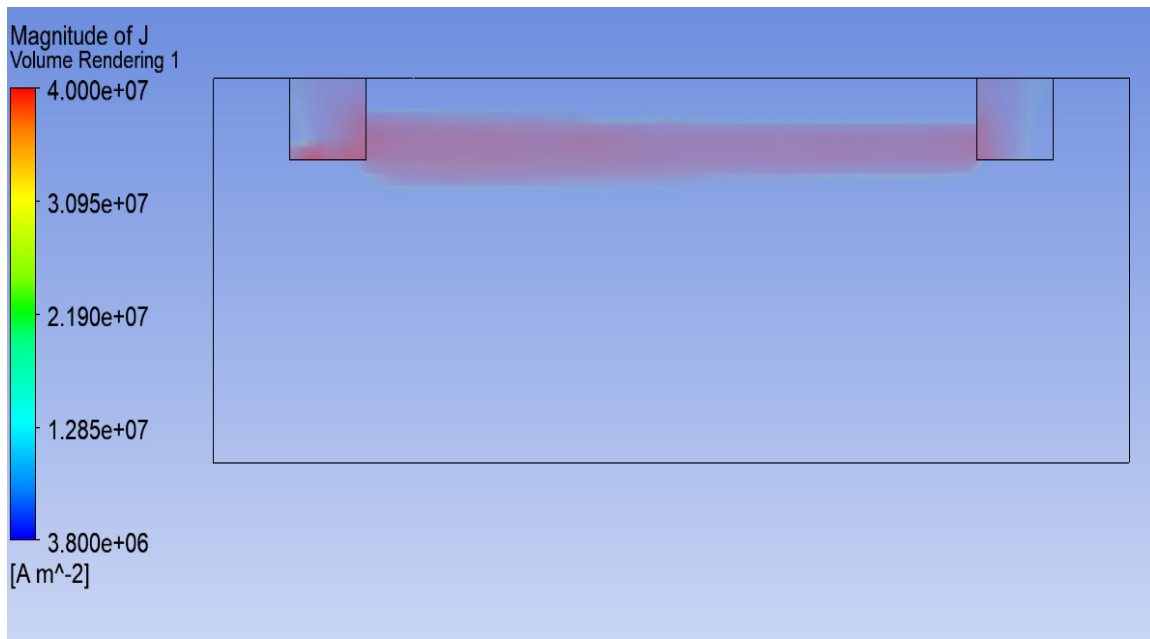


Figure 25 Current Density Across Hot Zone Anode and Cathode

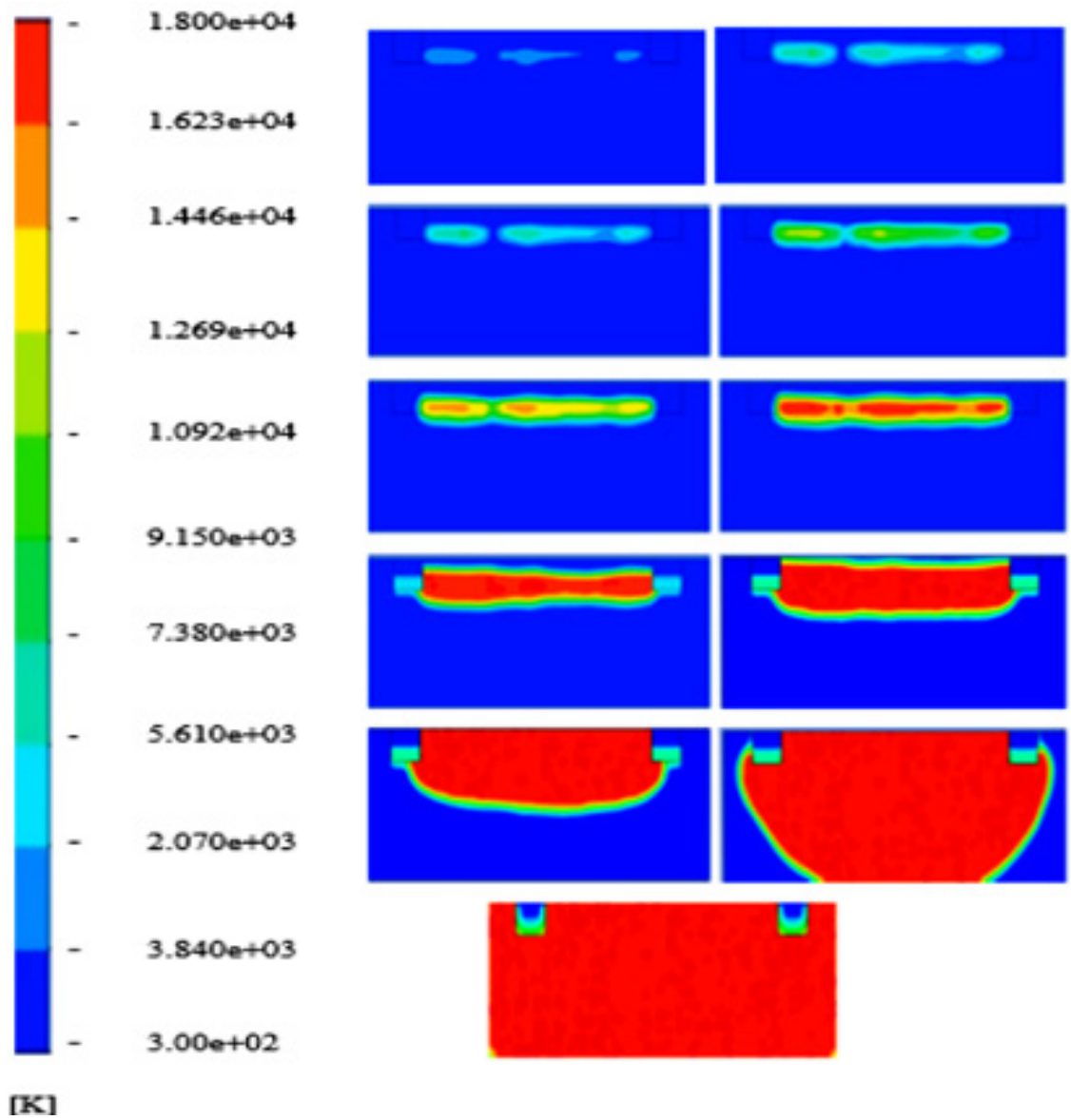


Figure 26 Case 1 Arc Moment Development

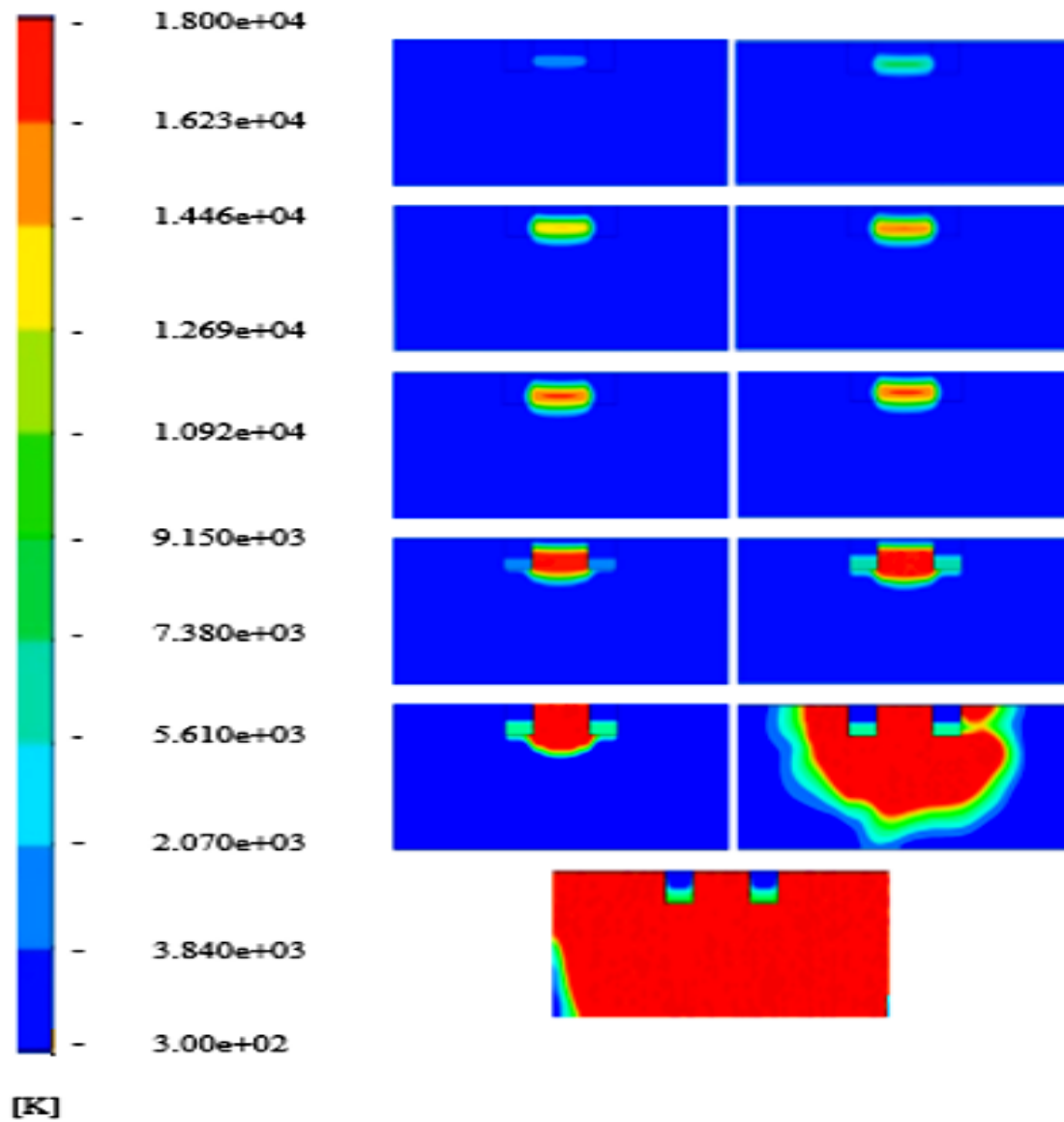


Figure 27 Case 2 Arc Moment Development

4.2 MHD Results Analysis vs Industry Arc Flash Calculation Model

General IEEE and NFPA DC model format for arc flash calculation as per the best practice of the DC Arc Flash Working Group [55] [56] is:

$$E = (V_{arc} \cdot I_{arc} \cdot T) \cdot 0.239 \cdot (1/4\pi \cdot D^2) \cdot kb \quad (4.1)$$

Where,

E = incident energy, cal/cm²

V_{arc} = arc voltage, V

I_{arc} = arc current, A

T = fault duration, secs

0.239 = factor converting arc energy joules to calories

$(1/4\pi \cdot D^2)$ = Energy transfer assuming arc will be transmitted into all direction from the source to the surface of a sphere at a distance D

D = Working distance (cm), from arc source to electrical worker (IEEE 1584)

The factor kb = is a configuration-correction factor (IEEE 1584)

It can be observed from equation 4.1, Arc voltage (V_{arc}) and Arc current (I_{arc}) are the most important values to be capture while performing arc testing or simulation.

Given that:

- 1- The fault clearing time is considered as per the maximum possible clearing time (2 seconds rule) as per IEEE 1584.
- 2- Working distance is a fixed standardized and known value for enclosure as per IEEE 1584.
- 3- The factor k_b configuration-correction factor is a fixed known value as per IEEE 1584.

Thus, the main difference between all the industry models is how they measure, assume, or estimate V_{arc} and I_{arc} .

Enrique model is nothing but assuming the highest amount of energy from the array and the maximum power point voltage and current can directly be used to calculate the energy levels. Thus, $V_{arc} = V_{\text{maximum power}}$ and $I_{arc} = I_{\text{maximum power}}$.

Doan model relies on the maximum power theory presupposes that the maximum amount of arc power will be transmitted. Thus, the Arc Voltage and current are considered to be $V_{arc} = V_{oc}/2$ and $I_{arc} = I_{sc}/2$.

Paukert and Stokes and Oppenlander models consider that the arc has a nonlinear resistance. A table of nonlinear relationships is empirically developed to calculate the resistance of the arc for multiple electrode gaps. V_{arc} and I_{arc} are calculated with reference to the nonlinear resistance.

The proposed model by EPRI model is also similar to other industry models in terms of utilizes the same general format for arc flash calculation. However, the following assumptions have been introduced by EPRI according to their test to customize the general format for photovoltaic systems.

EPRI proposed model consider the following assumptions for it:

1. For photovoltaic systems, arc current can be assumed to be equal to the short circuit current $I_{arc} = I_{sc}$ = short-circuit current, A
2. For photovoltaic systems, arc voltage of 300 Vdc is assumed for 1500 Vdc photovoltaic systems with ideal open circuit voltage higher than 800 Vdc.

In this section the EPRI test results and model [1], and other industry Paukert model [6], Doan model [37], Stokes & Oppen [5], and Enrique model [8], for arc flash on photovoltaic array are compared to MHD simulation.

Thus, In the MHD simulation, both V_{arc} and I_{arc} were captured to be compared to EPRI test results and industry models. The arc incident energy is also reported. Ansys software provide the value in w/m^3 or w/m^2 , cal/cm^2 is obtained with 18 inch as a working distance.

All the data manipulation required to obtain these values is done through Ansys Results which is a sub module of Ansys Fluent.

For case 1, Arc voltage distribution is shown in Figure 28, the arc current distribution is shown in Figure 29. The reported arc current is averaged to around 1229.9 A.. The reported arc voltage is 312 Vdc. Arc incident energy distribution is Figure 30 averaged 2.9 cal/cm^2

considering 2 seconds as fault clearing time. Similarly for Case 2 as shown in Figure 31, Figure 32 and Figure 33.

MHD simulation results have been compared to other industry models as shown in Table 3 also shown in Figure 34, Figure 35 and Figure 36. MHD simulation results shown very reasonable accuracy specially when compared to EPRI test.

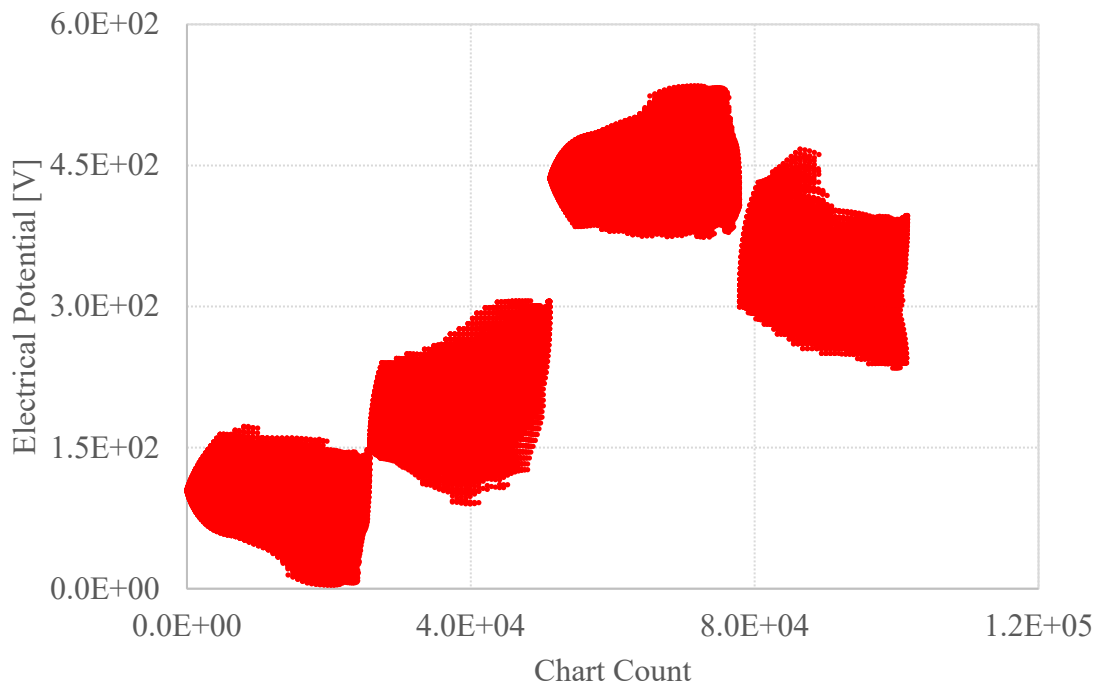


Figure 28 Case 1 Arc Voltage Distribution in MHD Simulation

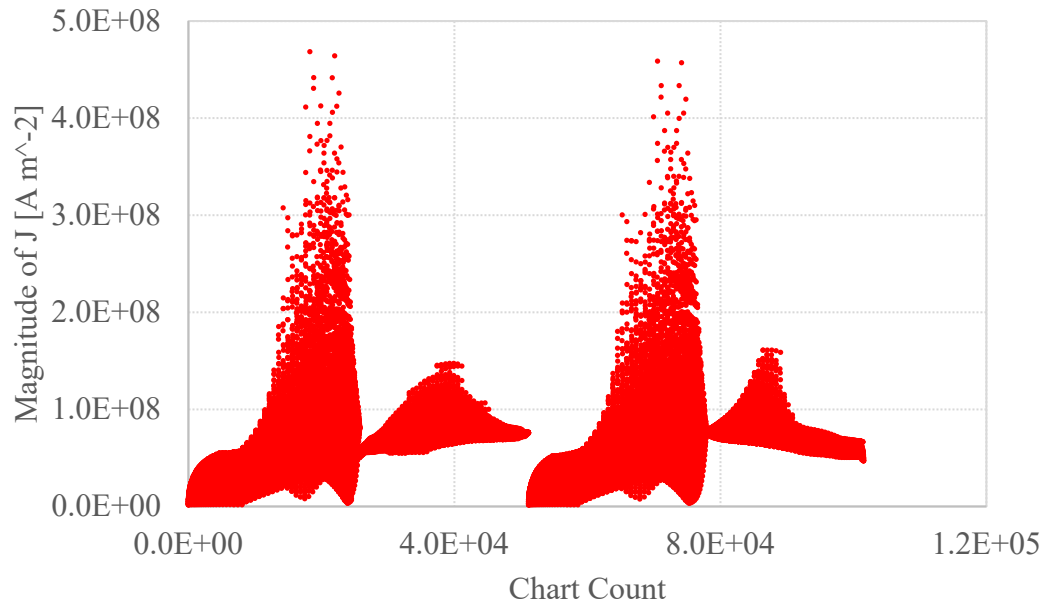


Figure 29 Case 1 Arc Current Distribution in MHD Simulation

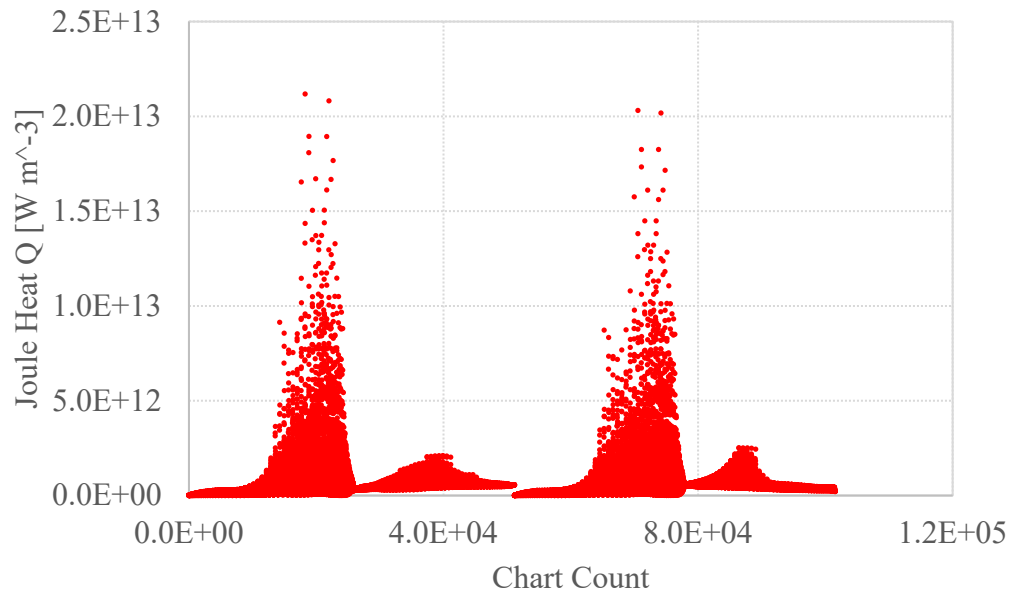


Figure 30 Case 1 Joule Heat Distribution in MHD Simulation

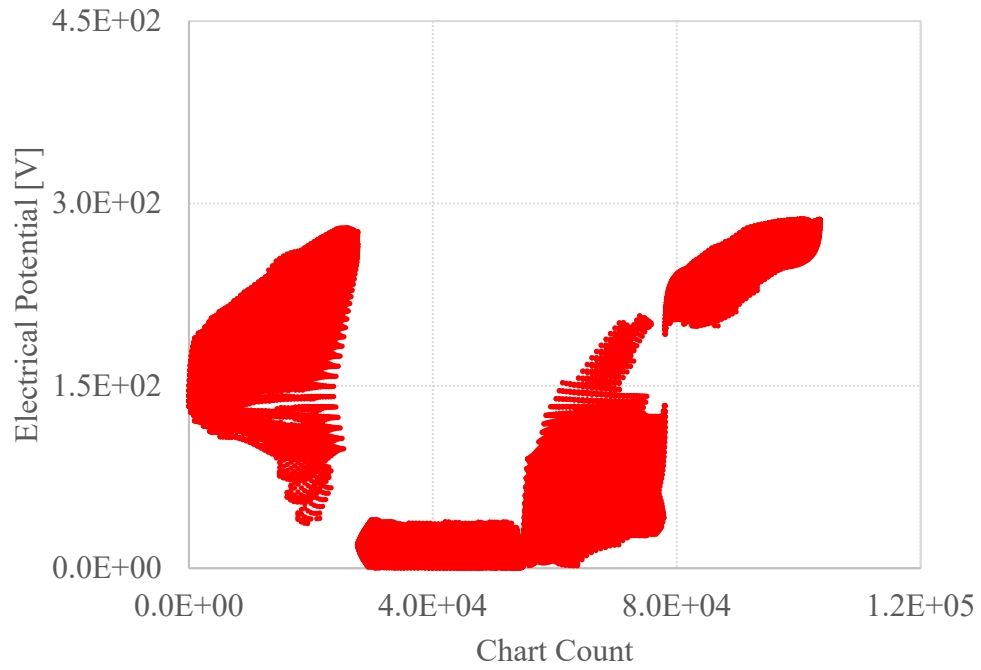


Figure 31 Case 2 Arc Voltage Distribution in MHD Simulation

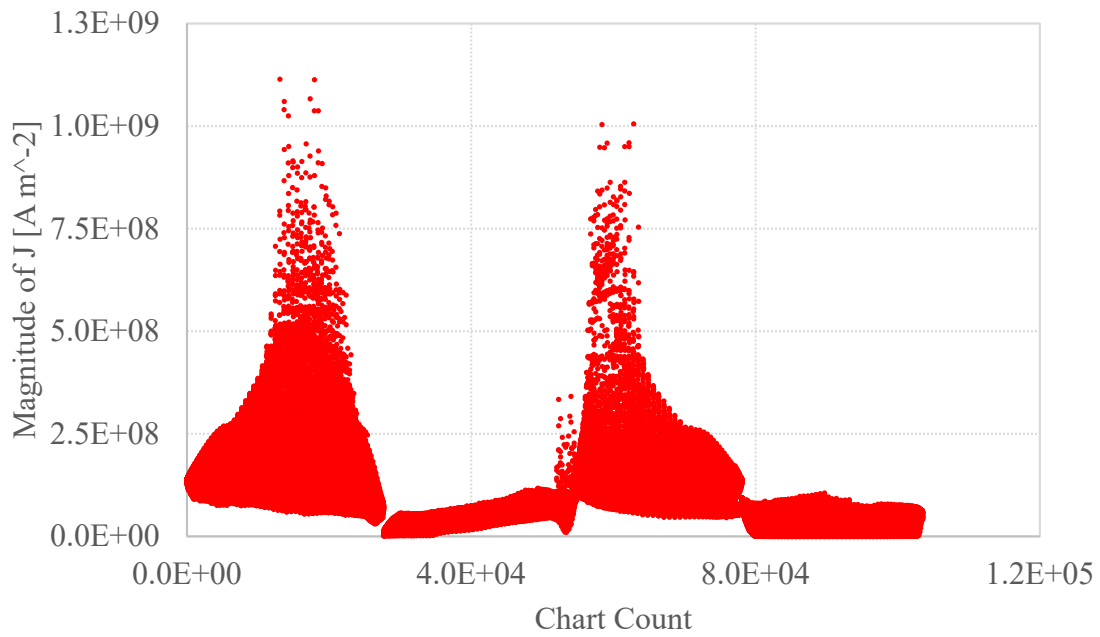


Figure 32 Case 2 Arc Current Distribution in MHD Simulation

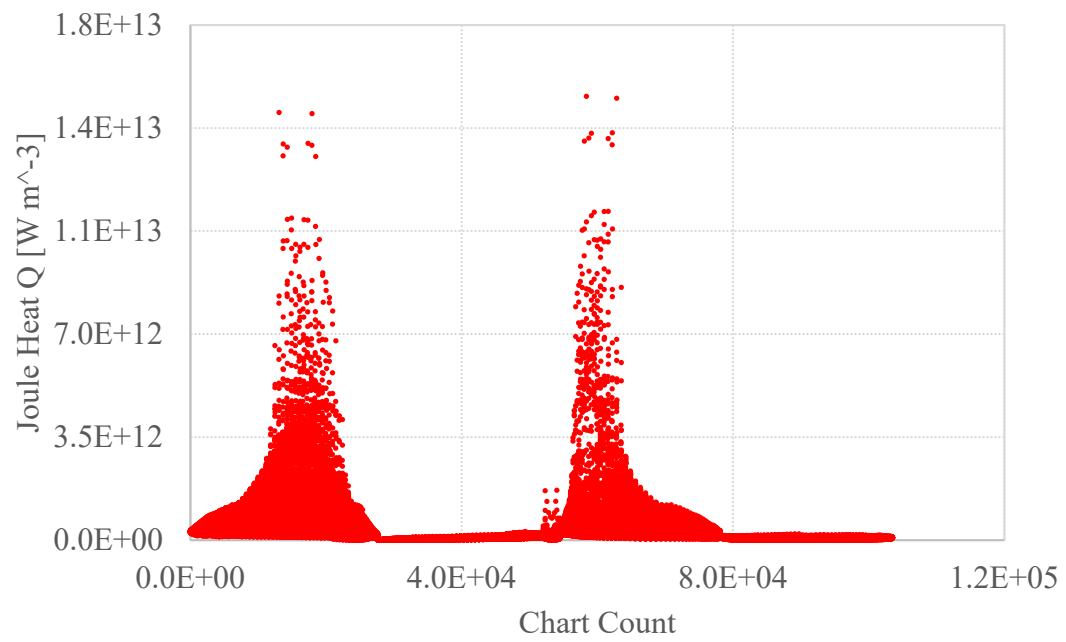


Figure 33 Case 2 Joel Heat Distribution in MHD Simulation

Table 3 MHD vs Industry Models and EPRI Test

		Case 1	Case 2
Arc Voltage (V)	MHD	312.00	201.00
	EPRI Test	310.00	216.00
	Paukert	109.70	55.20
	Stokes and Oppenlander	110.30	64.10
	Doan	77.50	393.60
	Enrique et al.	596.40	616.20
Arc Current (A)	MHD	1229.90	1410.00
	EPRI Test	1109.00	1478.00
	Paukert	1070.10	1432.90
	Stokes and Oppenlander.	1069.20	1415.30
	Doan	626.10	770.40
	Enrique et al.	1156.80	1429.90
Arc Incident Energy (cal/cm²)	MHD	2.97	4.02
	EPRI Test	2.00	3.60
	Paukert	4.65	3.17
	Stokes and Oppenlander	4.67	3.59
	Doan	9.45	12.12
	Enrique et al.	25.01	31.64

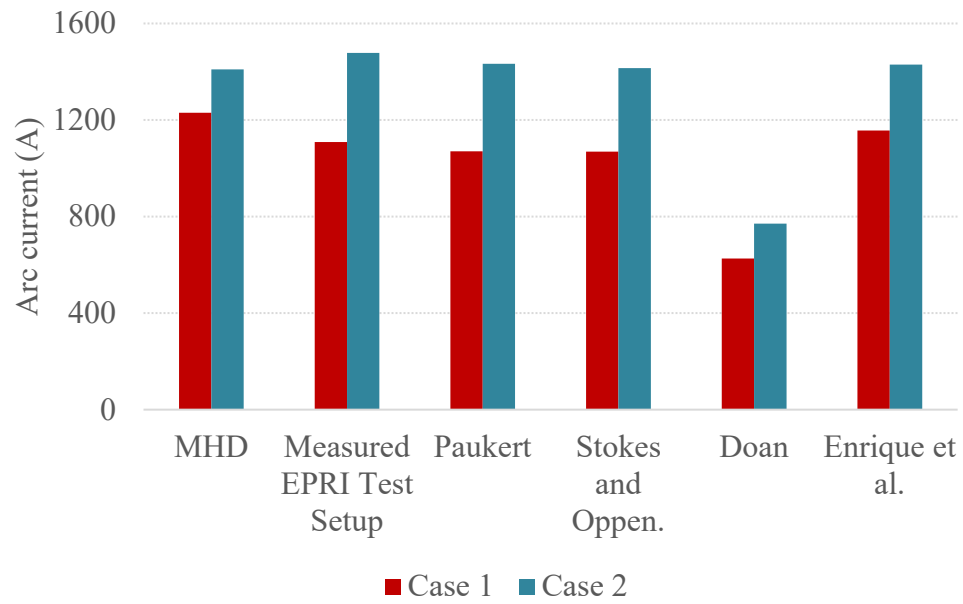


Figure 34 MHD Arc Current vs Industry Models and EPRI Test

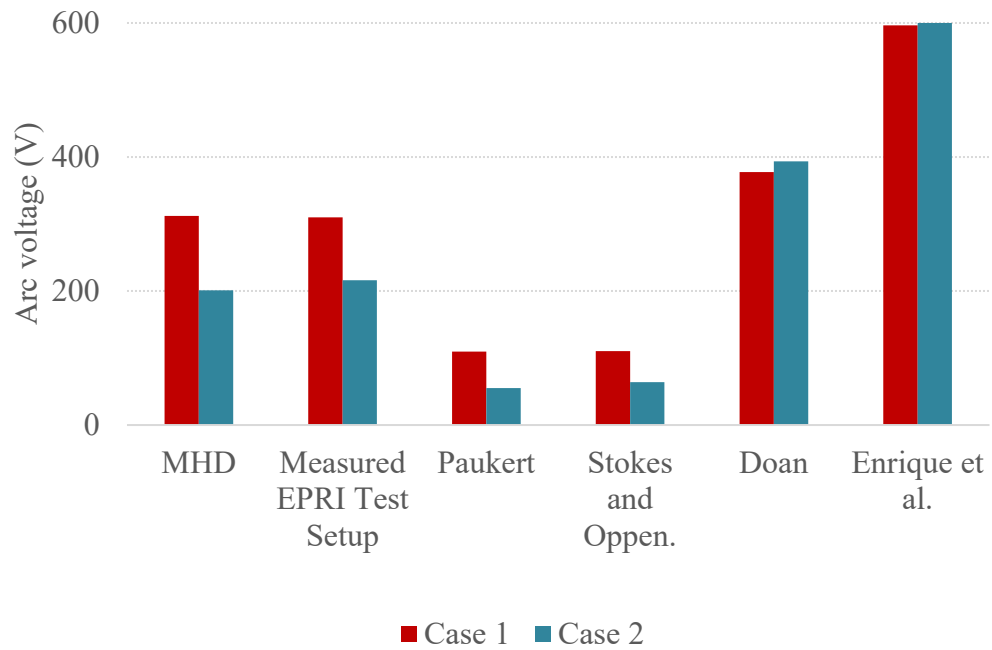


Figure 35 MHD Arc Voltage vs Industry Models and EPRI Test

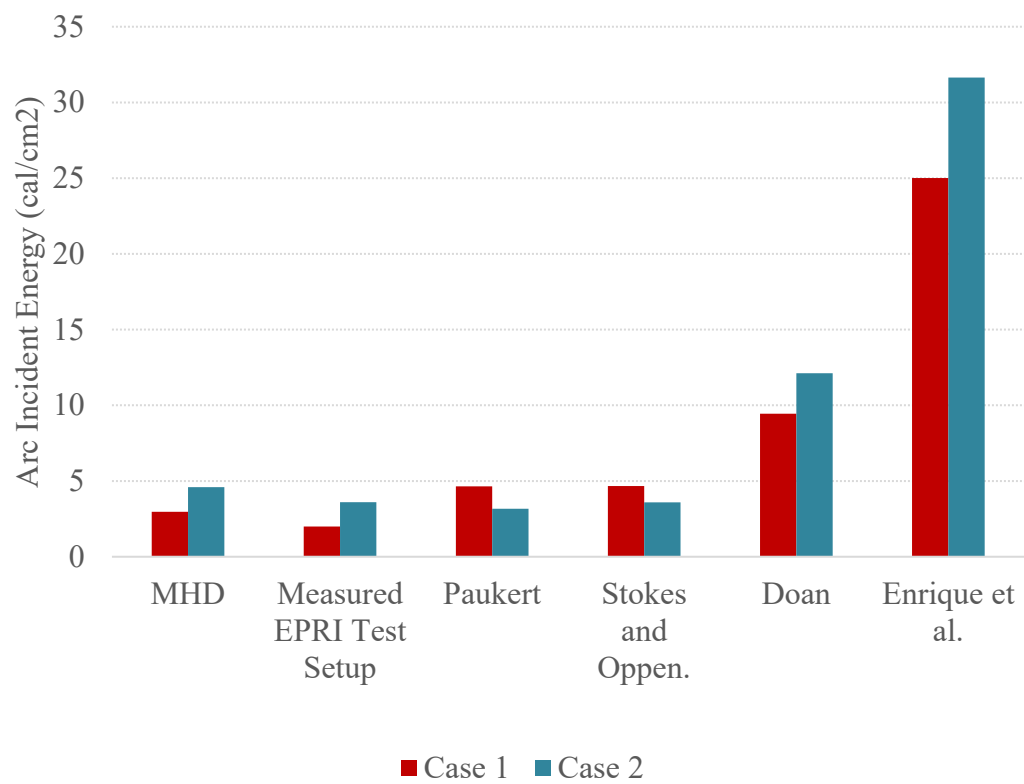


Figure 36 MHD Arc Incident Energy vs Industry Models and EPRI

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

- In light of the dearth of studies devoted to photovoltaic systems arc flashes, this thesis employs the MHD technique to simulate the electric arc in a photovoltaic system using a Ansys Fluent® and Ansys Maxwell® software.
- The physical aspects of electric arcs in photovoltaic systems are presented in this thesis. Then, the DC electric model of the magnetohydrodynamic (MHD) method is described in this thesis. The author lays forth the assumptions, computational and the necessary simulation scenarios to fully comprehend MHD model.
- The resultant arc voltage and current through the MHD model simulation have been compared to a recent EPRI published tests and other industry models. MHD simulation results are concluded to be accurate for the simulated cases.
- The resultant incident energy from MHD simulation were used to verify the new developed model to calculate arc flash in photovoltaic systems which developed by EPRI and compared to available industry models.
- For arc flash calculations, IEEE and NFPA want to launch arc testing and create a standard photovoltaic model. The MHD modeling technique proposed in this study has been found to be relevant for future standardized model development and may contribute to an IEEE or NFPA initiative aiming to build a theoretical and/or empirical combination photovoltaic arc model.

- This thesis did not discuss the photovoltaic arc-flash hazard in arrays during low illumination conditions. The non-linear characteristics of I-V curve is not considered for the photovoltaic system as a power source. Instead, maximum power point is assumed to have the most conservative arc flash results from arc voltage and arc current prospective. Thus, further consideration and studies might be needful to study the impact of different operating points on the photovoltaic I-V curve in conjunction with different clearing times.
- Although the model proposed in this thesis can provide an estimate for the arcing incident energy, the new arc model still must be validated by more arc tests due to the fact that the arc is challenging to simulate conclusively from physical standpoint.
- The effect of inverter short circuits on arc flash estimates needs additional investigation. In this thesis, just the array side of a photovoltaic system is examined; the role of the inverter is ignored. ERPI's test report suggests that the inverter has a negligible effect on photovoltaic systems, but this hypothesis has to be tested over a wider range of configurations.
- Impact of protection devices, such as fuses, should also be investigated. Since this is related to the clearing time of the incident energy, it will have a direct bearing on the energy levels. In this work, the maximum operating time of 2 seconds is assumed to obtain the most conservative result. However, further study of the impact of protection devices might be helpful to investigate the possible mitigation techniques.

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