ARC FLASH DETECTION THROUGH VOLTAGE/CURRENT SIGNATURES

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By

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ABSTRACT

Arc Flash events occur due to faults in electrical equipment combined with a significant release of energy across an electrical arc. Due to the large energy release, plasma is generated, pressures increase, and the plasma expands. Under these conditions the plasma becomes excited enough to liquefy metal causing physical damage to equipment and any humans in the vicinity.

This thesis investigates the state of art for detection of arc flash events and investigates a method of improving detection reliability, and speed by monitoring the high frequency voltage / current patterns utilizing methods similar to arc flash circuit interrupters (AFCI). A second alternative detection approach is determined through analysis of the physics of plasma development. The current state of art is based upon light detection. However this thesis experimentally investigates what happens before the arc event emits visible light.

The results show that current flows to ground during an arc event slightly prior to the production of light. Further it shows through analysis of the physics of plasma that a high speed plasma detector has the potential to identify an arc event before the presence of visible light. Through the design and construction of experimental test setups, and physics analysis, this thesis provides new paths for detecting arc events that present opportunities to improve detection time.

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Table of Contents

PERMISSION TO USE i

ABSTRACT ii

ACKNOWLEDGEMENTS iii

LIST OF TABLES x

LIST OF FIGURES xi

LIST OF ACRONYMS xiii

CHAPTERS 1

1. INTRODUCTION 1

1.1 Arc Flash 1

1.2 Arc Fault 1

1.2(a) Arc Fault Circuit Interrupter (AFCI) 1

1.3 Differences 3

1.4 Motivation 3

1.5 Objective 3

1.6 Thesis Outline 3

2. ARC FLASH PROBLEM AND LITERATURE REVIEW 6

2.1 Introduction 6

2.2 Danger of Arc Flash 6

2.3 Causes of Arc Flash 6

2.4 Prevention Methods 7

2.4.1 Arc Resistant Switchgear 7

2.4.2 Safety Standards 7

2.4.3 Training 8

2.4.4 Neutral Grounding Resistor (NGR) 12

2.4.5 Never Work Live 13

2.4.6 Arc Flash Analysis 13

2.5 Detection Methods 16

2.5.1 Light Based Detection 16

2.5.2 Current Assisted Light Detection 17

2.5.3 Pressure Detection 17

2.5.4 Heat Detection 17

2.5.5 Sound Detection 18

2.5.6 Bus Differential Measurement 18

2.5.7 Instantaneous Trip Current Energy Relay 19

2.5.8 Lockout-Tagout Program 19

2.5.9 Current Limiting Fuse 19

2.5.10 High Speed Camera 20

2.6 Interruption Methods 20

2.6.1 Instantaneous Circuit Breaker 20

2.6.2 Introduce a Second Fault 21

2.6.3 Containment Chamber with Breaker 22

2.6.4 Over Current Fuse 22

2.6.5 Current Limiting Fuse in Parallel with Explosive Bus 23

2.7 Personnel Protection 24

2.7.1 Personal Protective Equipment 24

2.7.2 Remote Operation 27

2.8 Testing 27

2.8.1 Test Process 27

2.9 Summary 29

3. ARC PHYSICS 30
3.1 Introduction 30
3.2 Arc Analysis 30
3.2.1 Development of an Arc 30
3.2.2 Plasma 34
3.3 Summary 37
4. PLASMA SIGNATURE DETECTION 38
4.1 Introduction 38
4.2 Proactive Approach 38
4.2.1 Industry Standard 38
4.3 Proactive Detection Advantage 39
4.4 Proactive Detection Limitations 39
4.4.1 Disconnect Time 39
4.4.2 Processing Power 40
4.4.3 Sensor Limitations 40
4.5 Summary 41
5. DANSK EXPERIMENTAL TEST SETUP 42
5.1 Introduction 42
5.2 Collaborative Research 42
5.3 Test Setup 42
5.4 Test Setup Oscilloscope Captures 47
5.5 Dansk Test Procedure & Repeatability 48
5.6 Summary 49
6. ANALYSIS METHODOLOGY 50
6.1 Introduction 50

6.2 Analysis Tool 50

6.3 Time Difference and Scope Properties 50

6.4 Summary 55

7. RESULTS AND EVALUATION 56

7.1 Introduction 56

7.2 Full Signal Frequency Spectrum 56

7.3 Pre-Arc Signal Analysis 59

7.4 Steady-State Condition 63

7.5 Immediately Prior to Arc Event 66

7.6 Summary 68

8. RESULTS AND EVALUATION REVISITED 69

8.1 Introduction 69

8.2 Sparky Experimental Test Setup 69

8.3 Spark Gap 70

8.4 Sparky Experimental Test Setup 71

8.5 Output Characteristic of Hipot Tester 73

8.6 Sparky Test Procedure & Repeatability 74

8.7 Summary 76

9. SPARKY TEST SETUP ANALYSIS 78

9.1 Introduction 78

9.2 Steady-State Analysis 78

9.3 Sparky Test Setup Arc Event Analysis 81

9.4 Further Analysis 84

9.5 Electric and Magnetic Field Arc Detection 85

9.6 Summary 88

10. CONCLUSION 89

10.1 Result of Analysis 89

10.2 Contributions 91

10.3 Future Work 92

REFERENCES 94

APPENDIX A: Dansk Test Setup Matlab Analysis Code 99

APPENDIX B: Sparky Test Setup Matlab Analysis Code 111

LIST OF TABLES

Table 1 PPE Apparel Descriptions [37] 25
Table 2: Protective Clothing Guidelines for the Electrical Arc Hazard [38] 26
Table 3 Voltage-current Regimes [41] 36
Table 4: Test Setup Parts List 47
Table 5: Matlab Analysis of Transition 59
Table 6: New Test Setup Equipment 70
Table 7: Electric and Magnetic Field Probes 85

LIST OF FIGURES

Figure 1: Arc Fault Current Example [8] ... 2
Figure 2: Is-limiter Arc Energy Limit [36] ... 24
Figure 3: IEC 61482-1 Recommended Test Setup ... 28
Figure 4: Referenced Drawing for Arc Development [40] ... 31
Figure 5: Saturation Regime [10] ... 31
Figure 6: Corona Inception Example [10] ... 32
Figure 7: Depiction of Inception of Streamers [10] ... 33
Figure 8: Breakdown and Progressing through Gap [10] ... 33
Figure 9: Rendering of an Arc Event [10] ... 34
Figure 10: Voltage-current characteristic showing Discharge Regions [41] ... 35
Figure 11: Test Setup Schematic Diagram ... 43
Figure 12: Test Setup Picture 1 ... 44
Figure 13: Test Setup Picture 2 ... 45
Figure 14: Test Setup Complete Picture ... 46
Figure 15: 4 kV Arc Event ... 47
Figure 16: Zoom in on Event ... 48
Figure 17: Original Voltage and Current ... 51
Figure 18: Corrected Waveform for Analysis ... 52
Figure 19: Low Pass Filter Frequency Response ... 53
Figure 20: Voltage and Current Time Domain Post Filter ... 54
Figure 21: Voltage and Current Time Domain Post Filter, Remove Ramping ... 55
Figure 22: Full Sampled Signal Voltage Frequency Spectrum ... 56
Figure 23: Full Sampled Signal Current Frequency Spectrum ... 57
Figure 24: Zoomed Voltage Spectrum Post Filter ... 58
Figure 25: Zoomed Current Spectrum Post Filter ... 58
Figure 26: Pre-Arc Captured Data; Voltage, Current ... 60
Figure 27: Separate Voltage Frequency Spectrum ... 61
Figure 28: Separate Current Frequency Spectrum ... 61
Figure 29: Zoomed Pre-Arc Voltage Spectrum Zoom ... 62
Figure 30: Zoomed Pre-Arc Current Spectrum Zoom ... 63

Figure 31: Voltage and Current Steady-State 64
Figure 32: Steady-State Voltage Frequency Spectrum Zoom 65
Figure 33: Steady-State Current Frequency Spectrum Zoom 65
Figure 34: Pre-Arc Event Time Domain, Post Steady-State Voltage and Current 66
Figure 35: Pre-Arc Voltage Zoomed, Post Steady-State 67
Figure 36: Pre-Arc Current Zoomed, Post Steady-State 67
Figure 37: Sparky Test Setup Schematic 70
Figure 38: Sparky Test Setup 71
Figure 39: Voltage Measurement Resistor Divider Network 72
Figure 40: Inside Box Showing Arc Gap, Light Detector 73
Figure 41: Hipot Tester Voltage Ramp (100x Reduction) 74
Figure 42: Voltage, Current, Light Repetition Example 1 75
Figure 43: Voltage, Current, Light Repetition Example 2 76
Figure 44: Steady-State Voltage, Current, and Light 78
Figure 45: Matlab Reproduced Plot of Voltage, Current and Light 79
Figure 46: Voltage Frequency Response 80
Figure 47: Current Frequency Response 80
Figure 48: Voltage, Current, Light – Full Spectrum 81
Figure 49: Zoom in on Current & Light 82
Figure 50: Measuring Time Difference 83
Figure 54: Arc Fault Current Example [42] 84
Figure 55: Voltage, Current, Light, Electric Field 86
Figure 56: Voltage, Current, Light, Magnetic Field 87

LIST OF ACRONYMS

AFCI	Arc Fault Circuit Interrupter
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
ATPV	Arc Thermal Protective Value
CEC	Canadian Electrical Code
CPR	Cardiopulmonary Resuscitation
CSA	Canadian Standards Association
DPD	Direct Plasma Detection
EMI	Electromagnetic Interference
EU	European Union
FFT	Fast Fourier Transform
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
MSHA	Mine Safety and Health Administration
NEC	National Electric Code
NFPA	National Fire Protection Association
NGR	Neutral Grounding Resistor
OSHA	Occupational Safety and Health Administration
PPE	Personal Protective Equipment
PSD	Plasma Signature Detection
UL	Underwriters Laboratories

CHAPTER 1
INTRODUCTION

1.1 Arc Flash

Arc flash is defined in IEEE Standard 1584-2002 as "a dangerous condition associated with the release of energy caused by an electric arc" and occurs due to an electrical breakdown between two phases or phase and ground conductors. Following a fault, the energy is stored until it reaches enough potential for expansion and discharge [**1**]. This is of particular concern to power safety, occupational health and safety, and protection engineers due to the potential damage to humans and equipment [**2**]. When the event occurs a significant amount of energy is released in many forms (heat, light, sound, pressure) and significant equipment and human damage can occur [**3**].

Current interruption systems react to the arc flash by disconnecting, shorting, or redirecting the power as fast as possible. However detection occurs by reacting to the arc event after it initiates. The energy output of the arc flash potentially reaches a high level before shutdown. This has the potential to cause equipment and human damage although to a lesser degree than if the arc event is not disconnected [**4**].

1.2 Arc Fault

An arc fault is a discharge of electrical energy through the air. Under normal operation two conductors are connected and the flow of electrons passes through the essentially zero resistance path. If the connection is corroded or impure, it will have resistance and heat is generated. Over time the heat will wear down the contact and result in small arcs between connections. These arcs begin as low current faults, but given enough time they have the potential to breakdown to another phase or ground conductor resulting in a dangerous high current fault [**5**].

1.2(a) Arc Fault Circuit Interrupter (AFCI)

The Canadian Electrical Code, Part 1 section 26-722, branch circuits for dwelling units (g) defines an AFCI as "a device intended to provide protection from the effects of arc-faults by recognizing characteristics unique to arcing and functioning to de-energize the circuit when an arc-fault is detected". These devices are called for within the Canadian

Electrical Code as a requirement in the sleeping facilities of new dwellings to protect the occupants [**6**].

AFCI's were developed by Square D and introduced in 1998 to improve electrical protection schemes by disconnecting power in the presence of an arc-fault. This system operates by monitoring both voltage and current and searching for the pattern or signature of an arc-fault event. During an arc-fault event, the voltage and current waveforms create a different magnitude and harmonic pattern that is detected and used to interrupt the arc-fault event before significant damage can occur. On a standard North American 60 Hz system, the detection is designed to occur within 70 ms [**7**].

During an arc fault the current flowing to ground does so across a low impedance path. This causes the load current to drop as the ground fault current flows. During this phase a discontinuity occurs in the current flow, creating a harmonic signature [**8**].

The following figure shows one example of an arc fault and the impact to the current on both the source and ground sides. It is important to note that this was done at 400 Hz, and under controlled test conditions. It does not represent an arc measured under actual conditions; instead it is a simulated outcome for research purposes.

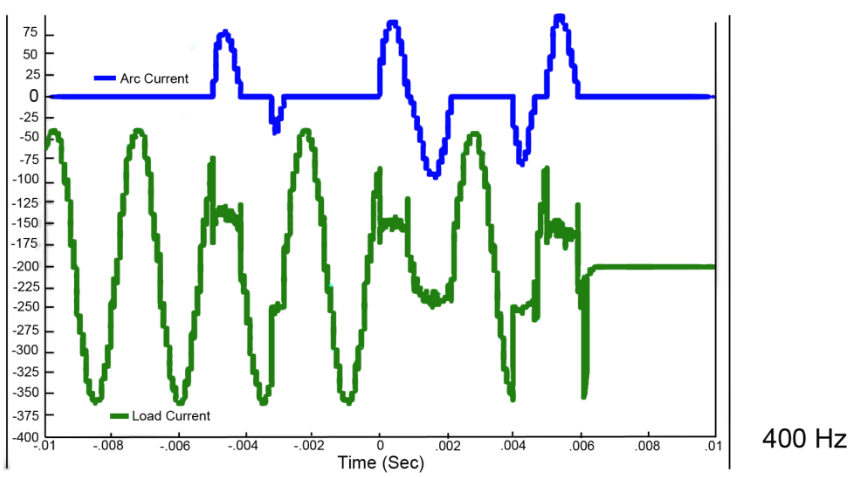

Figure 1: Arc Fault Current Example [8]

Figure 1 shows the impact on load current by an arc event. The arc current coincides with a discontinuity in the load current.

1.3 Differences

An arc-fault is related to an arc flash event, it is not possible to have an arc flash without an arc fault. The arc-fault is the release of electrical energy while the arc flash is the term used to describe the collective release of energy from a blast event (which includes an arc-fault) [**9**].

1.4 Motivation

Current arc flash detection schemes implement sensors that look for the properties of the arc flash. The properties can be detected only after the event has initiated, at which time the energy levels are increasing dramatically [**10**].

Since the detection does not identify the arc flash until after the initiation of the event, the protection scheme accepts that the event will occur. The motivation of this research is to begin with the boundary condition that the event does not need to occur if the detection and interruption occur prior to the event.

1.5 Objective

The purpose of this research is to design an experimental setup and investigate plasma properties as well as look at the high frequency voltage/current signatures for detecting an arc flash. Detecting the event as soon as possible allows system shut down before significant equipment and human damage occurs.

1.6 Thesis Outline

The contents of this thesis are arranged as follows:

> Chapter 1 provides a definition of both arc flash, and arc-fault events including the differences. While the thesis focuses upon prevention of arc flash, it is not possible to have a flash event without a fault. This background is important in order to understand the direction of the research. The thesis motivations and objectives are also provided.

Chapter 2 investigates the dangers of an arc flash event and how it is caused. It then analyzes current state of art methods to prevent, detect, and interrupt such an event. It also investigates the state of art in personnel protection, and testing/certification. The information presented provides an overview of state of art with an emphasis on the benefits and pitfalls of each technology. The research presented in this dissertation focuses upon detection of an arc flash and this is but one small part of the problem of arc flash events.

Chapter 3 presents an analysis of an arc flash and the energy produced or released in various forms. Particular attention is directed at the plasma created and the difference between creation of plasma and the moment visible light is produced. Because there is a period of time where plasma is produced without visible light, this reinforces the hypothesis that such an event can be detected and thus an arc flash identified prior to light sensor reaction.

Chapter 4 presents the theory behind the proactive arc flash detection scheme which is dubbed as plasma signature detection. The hypothesis is that the energy required to create plasma is great enough that it can be detected through high speed digital sampling coupled with signal processing algorithms. The hypothesis posits that a pattern exists before light appears, permitting detection. While the time benefits are minimal, the reliability of detection improvement drives additional research.

Chapter 5 provides an outline of the Dansk Test Setup, design, testing, and overview. Due to the complexity of the experimental setup and safety of arc flash research, an internationally recognized research lab in this area of work was contacted and the setup was created in collaboration with the engineers in this research laboratory. The system permitted analysis of a controlled arc incident while data was recorded and monitored.

Chapter 6 outlines the analysis methodology of the pattern recognition problem of identifying the plasma generation of an arc flash event during the initial stage of the event. The analysis techniques and tools are outlined to better inform the reader of the steps taken in order to satisfy the conclusions reached.

Chapter 7 presents the results, and an evaluation to provide additional insight into the technique presented. Spectrum analysis is utilized and the information is separated into sections (full spectrum, pre-arc, and steady-state). The data showed that the test setup suffered from some limitations, though it was useful in developing analysis methods and showing that the behaviour at high energy was similar to that occurring at lower energy levels.

Chapter 8 introduces the Sparky test setup and outlines the design/construction as well as the reasons behind the setup. In order to show that a pattern exists prior to the appearance of visible light, it is important to perform the tests using a setup capable of capturing the visible light spectrum. Such a system was constructed and setup to permit a distinction between pre-arc and detected light.

Chapter 9 presents the results of the analysis of data from the Sparky test setup including a response time measurement of the electric and magnetic fields produced by an arc event. The electric and magnetic fields were measured to show that they are slower than light detection and therefore not as beneficial. By adding light capture to the test setup the analysis was able to show that current flows across the spark gap before the appearance of visible light.

Chapter 10 contains conclusions, open issues, and topics of future work. The research concludes that the current does flow into the ground before the appearance of visible light. The detection method utilized was to monitor the ground current in order to verify the hypothesis that energy flows prior to the detection of visible light. In subsequent MSc thesis research the harmonic signature can be fully identified. The research presented within this disposition was able to identify that visible light is not the first available indication of an arc event. Further research is required to identify the pattern in the voltage/current that distinctively permits detection.

CHAPTER 2
ARC FLASH PROBLEM AND LITERATURE REVIEW

2.1 Introduction

This section analyzes why an arc flash event creates concern for electricians, engineers, and the general public, as well as analyze the current state of the art in arc flash detection and mitigation.

2.2 Danger of Arc Flash

Arc Flash events are associated with the dangerous release of significant amounts of energy in many forms. Throughout the following sections we will explore the causes, prevention methods, detection methods, interruption methods, personnel protection, and analysis of the energy released. The energy released is enough to kill, and create massive equipment damage.

2.3 Causes of Arc Flash

In order for an arc flash event to occur, the electrical system must operate outside of the operating parameters defined during design. This can occur through four primary methods:

1. Human error: When an electrician or maintenance professional is attempting a repair, mistakes can occur and if the system is energized an arc flash may occur. These include dropping tools or parts, mistakenly contacting energized equipment with tools, equipment, or cable, or during equipment installation [**11**].

2. Equipment Failure: Medium voltage switchgear is energized for significant lengths of time and while there are no visibly moving parts, there are potential sources for failures. Equipment needs to be monitored and maintained to ensure problems are identified. This will be further explored in the prevention section of this thesis [**11**].

3. Insulation Breakdown: Equipment or cables insulation can breakdown over time due to the heat and energy through the wire. This breakdown can cause shorts potentially leading to arc flash. Preventative maintenance and monitoring of the equipment prevents such problems [**11**].

4. Continuous Electrical Faults: If a fault occurs on an electrical network it causes stresses elsewhere that manifests as heat or rapid energy fluctuations. If these faults are left uncorrected they can exasperate the problem, which has the potential for an arc flash event [**11**].

2.4 Prevention Methods

In order to protect personnel and equipment, much research has been directed towards the prevention of arc flash events. What follows is an analysis of the state of art in this area.

2.4.1 Arc Resistant Switchgear

The name arc-resistant switchgear carries an implication that the equipment is capable of blocking or resisting the arc incident. However the switchgear does not resist the event, instead it is designed to help to eliminate potential injury by confining the arc event and venting the gases safely. This is done by minimizing the spread of an arc to adjacent compartments and attempting to isolate personnel from the arc zone [**12**]. This is different than standard switchgear since the arc regions are separated and vented instead of being built close together with the risk of increased pressure.

2.4.2 Safety Standards

NFPA 70E

NFPA 70E was first published in 1979, with the most recent edition released in 2009. The intent of the standard is to provide safe practices for employees performing activities where electricity is involved.

NFPA 70E has a section related to arc flash (electrical energy) and arc blast (the associated explosion), and defines the protective clothing and procedures to ensure safety of personnel [**13**].

NEC-2002

The National Electrical Code is a continuously updated standard meant to provide guidance on everything from cable materials, terminal boxes, arc flash and anything related to the safe installation of electrical systems [**14**].

NEC calls out the required Personal Protective Equipment (PPE) to be worn while interacting with live electrical systems, as well as the proper labeling and placement. The labels provide enhanced communication of the dangers present while working on live equipment, and serve as a reminder to personnel to wear the appropriate protective clothing [**15**].

OSHA 1910

The Occupational Safety and Health Administration workplace safety standard provide guidelines for a great number of industries that are enforced to ensure the safety of employees. The standard does not specifically define anything directly related to arc flash, but instead it enforces that any electrical hazard must be properly labeled, employees informed, and any personnel interacting with the dangerous components must have the appropriate training. OSHA does stipulate that an employer must meet NFPA 70E, which directly addresses arc flash hazards [**16**].

IEEE 1584

This is a guide that "provides techniques for designers and facility operators to apply in determining the arc-flash hazard distance and the incident energy to which employees could be exposed during their work on or near electrical equipment" [**9**].

The calculations, procedure, and analysis techniques within IEEE 1584 are utilized by other standards and publications in order to provide a model of the energy of an arc flash event.

2.4.3 Training

The first method of protecting personnel is to ensure that they are properly trained with knowledge of the safety standards, protocol, and protective equipment/methods available. Even with the best engineered switchgear, if the training is not provided the potential for danger is increased.

Reference [**17**] lists ten steps of an effective arc flash hazard safety program of which a summery follows:

1. Acknowledge – Be open to understanding and acquiring state of art knowledge of arc flash hazards and accept that protection is needed.

2. Evaluate – A corporation is in the business of generating revenue, so it is important to perform a study of the costs associated with not protecting personnel and equipment. Perform a study of the amount lost through fines, downtime, lawsuits, equipment replacement, and insurance premium increases and compare/contrast this with the cost of providing proper protection.

3. Define – In order to measure the success of the changes implemented start by defining the goals. Use the goals to drive a plan, budget, and timeline that afford a reasonable time and budget to ensure that your facility can achieve the aforementioned goals. Lastly perform an arc flash study before making changes and then repeat after all changes and compare the differences.

4. Analyze – The purpose of this step is to ensure that all information and resources are available to employees before they are asked to work on live equipment. The required resources are:

    a. Updated and accurate one line drawings of the distribution network within the facility with proper voltage ratings throughout.

    b. Updated and maintained database of the parameters of the equipment installed within the network. This information can be collected from the electrical equipment nameplates.

    c. Perform short circuit and equipment duty calculations to evaluate and ensure that breaking and equipment capabilities can operate under failure conditions. This information should be documented and followed and specified such that any maintenance performed ensures that equipment replacements continue to meet or exceed these specifications.

d. Protection devices (relays, fuses, breakers) are all designed around either a fixed or field selectable trip time. Ensure that the trip time of this equipment is properly specified to ensure coordination which ensures reliable operation of protection equipment.

e. IEEE-1584 or NFPA 70E provide arc flash hazard formulas and guidelines to complete worst case arc event calculations. These should be done before modifications to the facility and after in order to accurately reflect the impact of the changes made.

f. In areas identified to have the greatest risk of an arc flash event (example: areas with high potential fault levels), properly label, and secure the area. This ensures that only qualified personnel operate with the zone and that they are reminded of the dangers within.

5. Label – ANSI Z535 compliant labels are required to be present on the sections of the network that carry the highest probability of failure. This is based upon the arc flash calculations previously performed and serves as a last chance warning to employees to allow them to ensure that personal protective equipment to the correct level is worn.

6. Personal Protective Equipment (PPE) – PPE is the clothing and equipment worn by someone working on live switchgear. It is designed to protect against various levels of potential arc flash energy by protecting against the types of energy released by an arc flash event. NFPA 70E defines the PPE categories and ratings.

7. Work Permits – A work permit is a formal document that is required by NFPA 70E if live switchgear is being worked on when the voltage is above 50 V. The permit specifies the risk, potential arc flash energy levels, and the required

PPE. These permits should be signed by management (authorization to perform the work) and the electrician (acceptance of understanding and commitment to comply).

8. Safety Program – This is a program that every electrical facility should have in place. It ensures that programs are in place, documented, and instructed to the electricians to maintain compliance with the most up to date safety practices of standards committees and the company. This includes employee behaviours, lockout-tagout, shock hazard, testing tools, inspections, diagnostics and many other standard best practise safety procedures.

9. Training – Arc flash events carry the potential to cause significant damage to equipment and human lives. Cardiopulmonary resuscitation (CPR) training is an emergency procedure utilized to attempt to resuscitate an individual in cardiac arrest [**18**]. The training to perform this life saving procedure expires every 3 years and it is recommended that the courses be re-taken annually [**19**]. The training of electricians regarding the danger of arc flash and the proper strategies of avoiding injuries carries the potential to save lives and therefore should be retaken every two years. The training of the individuals working on the equipment is the best method to ensure safety of personnel.

10. System Maintenance – Over time electrical equipment needs to be de-energized, inspected and cleaned. During this time a full maintenance schedule, procedure, and plan should be implemented to ensure clean equipment, working breakers, proper insulation, etc.

The state of art, standards, and best practices are always in a state of flux. It is with this in mind that companies such as Canada Training Group [**20**] and Ehazard.com [**21**] have created programs to train personnel and update certifications and understanding of best safety practices. These courses are taught by researchers who dedicate their careers to research to ensure that the trainees are best prepared for the dangers of arc flash events.

These resources need to be utilized in order to ensure safety of personnel, and a decreased likelihood of arc flash incidents.

2.4.4 Neutral Grounding Resistor (NGR)

Power distribution networks are constructed with different grounding schemes. The most common grounding methods are solidly grounded, ungrounded, and neutral grounding resistor.

In a solidly grounded system the wye point of the supply transformer is directly connected to ground. This grounding method has the advantage of a fixed phase-to-ground voltage; however the disadvantage is that under fault conditions it is only limited by the impedance of the system [**22**].

An ungrounded system is one in which the wye point of the supply transformer is left disconnected. The advantage of such a system is that it can continue to operate when one phase suffers a fault and there is no point-of-fault damage. There are significant disadvantages; these include intermittent or arcing faults that can produce high transient voltages to ground. This can lead to break down of insulation and more serious failures, one example of which is arc flash [**22**].

A resistance grounded system is one in which the wye point of the supply transformer is connected to ground through a neutral grounding resistor (NGR). The NGR presents the same advantages of the solidly and ungrounded systems while eliminating transient over voltages, limiting the fault current, and minimizing point of fault damage [**22**].

The use of an NGR also has the advantage of reducing both the likelihood and incident energy level of an arc flash event between a single phase and ground. When an NGR is present, phase to ground faults are limited in the energy levels. Most arc flash events start out as a phase to ground fault and then through breakdowns escalate into phase-to-phase or bolted faults [**11**]. By limiting the phase to ground fault energy the probability of a phase to ground fault escalating into a phase to phase fault is reduced. However if the initial fault is phase to phase or bolted, the failure condition works in the same way as a solidly grounded or ungrounded system, and arc flash events are just as likely [**11**].

2.4.5 Never Work Live

Occupational Health and Safety Administration (OSHA) and Min Safety and Health Administration (MSHA) provide mandates for documented lockout procedures to ensure that no work is performed on live or energized equipment. It is recognized that the best way to prevent arc flash events is to never work in conditions where energy is present. If the power is removed from a system and the ability to restore power is locked and secure, the electrician performing the work can work with a relative assurance of safety [**11**].

Unfortunately there are scenarios where work must be done live. Such scenarios include situation where de-energizing would introduce additional hazards, interruption of an operation would damage equipment, or other similar scenarios [**11**].

As explained during an interview with an experienced professional who has worked in the arc flash industry for 30+ years (Mr. Gary Donner), the only way to prevent arc flash incidents is to never work energized. Mr Donner also stated that working live is putting faith in the reliability of the breaker to perform its function. Breaker manufacturers recommend that breakers be maintained every year in order to maintain reliability and rapid response time. Since large facilities can have thousands of breakers, the likelihood of having the resources to maintain every breaker is low.

2.4.6 Arc Flash Analysis

In order to properly educate staff for arc flash awareness an arc flash analysis needs to be performed. The analysis involves the collection of data regarding the electrical network and after analysis, enacting training and labelling systems [**11**].

Prior to performing the analysis, the following data must be collected [**11**]:

1. Short-Circuit Analysis

This is a study of the amount of short-circuit current through mathematical analysis of the potential currents at shorted events at various points in the electrical network.

2. One-Line Diagrams

From the time that the electrical network is initially designed, requirements change and the implementation differs from the initial design. As a result the documentation may not match the installed system. It is therefore important to have an updated single phase drawing of the electrical system that shows the power levels, and protection systems.

3. Protective Device Information

Accompanying a one-line diagram should be detailed information about the protection devices. It is important to have type, manufacturer, and settings of the devices.

4. Cable and Raceway Information

The impedance of the cables and transformers contributes to the short circuit current and therefore must be collected or calculated. In order to calculate the impedance the material and length must be collected.

5. Identify Possible System Operating Modes

Determine if it is possible to connect multiple mains in parallel on the system, if it is then the short circuit current increases significantly.

6. Perform an Over-current Protection Coordination Study

This study investigates the trip settings of relays and protective equipment within the network to determine the ideal trip time response to ensure effective coordination. The ideal coordination ensures that the protective device nearest to the fault trips prior to any relay's upstream.

7. Perform Shock Hazard Analysis

This study is mandated by NFPA 70E [**23**] and provides exposure voltage, boundary requirements, and personal protective equipment to ensure safety of personnel.

Now that all of the required information has been collected, the arc flash analysis can be performed. For any location determined as a possible arc flash region of the network the following must be determined [**11**].

1. Flash Protection Boundary

The paper "Reducing the Flash Hazard" defines the flash protection boundary as: "the distance from live parts within which a person could receive a second-degree burn during an arc-flash event" [**11**].

2. Incident Energy

As defined by NFPA 70E, incident energy is the amount of energy impressed on a surface (person) generated during an electrical event at a specific distance from the arc source [**24**].

Incident energy is measured in cal/cm^2 and can either be calculated using NFPA 70E provided formulas, derived from a lookup table within IEEE 1584-2008, or computed using commercially available software [**11**].

3. Hazard/Risk Category and Required Personal Protective Equipment (PPE)

Once the incident energy is known the level of hazard and required personal protective equipment can be determined by the table listed within NFPA 70E [**11**].

4. Review Design Changes

The final step of the arc flash analysis is to review the findings and determine if any design/implementation changes are needed in order to reduce the risks.

Following the completion of an arc flash study the results should be utilized to improve safety. Equipment should be labelled, training programs should initiate, provide information to facility safety programs, implement any design changes, and ensure that future changes take arc flash into consideration and update the analysis [**11**].

2.5 Detection Methods

Arc flash has presented a concern for electricians, electrical engineers, management, certification bodies, and anyone associated with the electrical power industry. This concern has resulted in research into methods of detecting an arc flash, with the intent of interrupting the event before the incident energy reaches extremely dangerous levels.

2.5.1 Light Based Detection

One aspect of an arc flash event is the significant release of energy in the form of light. As stated in [**25**], “Arc-Flash light intensity ranged from 108,000 lux, measured 3 meters away from the arc-flash source, to more than 249,000 lux”.

The significant amount of light released can thus be detected using optical sensors. The sensors are either point or fiber optic loop sensors. The fiber optic sensors are more difficult to retrofit, and are prone to damage during installation and thus should be avoided for the more reliable point sensors [**26**].

Current state of art provides solutions capable of providing a trip signal to the breaker 500 μs after the light is first detected [**27**]. The light is only detected once the arc energy reaches a point that it can feed and sustain an arc with enough energy to release a significant amount of light. Typical light levels of arc events are not detected until 100,000 lux or greater [**25**]. If the point sensor is installed in an ideal location and is able to capture the initial stages of the flash event, then the trip signal is provided to the breaker to disconnect.

2.5.2 Current Assisted Light Detection

In the previous section, light based detection was discussed. For current assisted light detection it helps to realize that the light detection scheme is the same as in the previous section. This detection scheme introduces the ability to detect current levels and only trip if the current level is above a predefined setting and light is detected. The goal is to maintain light detections rapid speed and reduce occurrences of false tripping [**26**]. False or nuisance tripping occurs when the light sensors measure high light levels from non arc flash sources (example: camera flashes, high intensity flashlights).This is generally implemented using a current transformer and monitoring for a level that is higher than the normally operating current, but lower than short circuit currents.

2.5.3 Pressure Detection

Arc flash events create a significant increase in pressure. Through the use of pressure sensors installed inside substations, equipment can identify an arc flash and initiate a trip. Pressure waves travel at the speed of sound allowing for detection to occur somewhere from 8 – 18 ms from the beginning of the arc flash event [**28**].

Pressure detection may not be entirely reliable as it is difficult to properly place sensors and it may require additional equipment to redirect pressure waves to the sensors [**28**].

2.5.4 Heat Detection

Arc flash events often begin as faulty electrical connections that increase the temperature within the switchgear. The insulation breaks down over time causing a more serious fault which may lead to an arc flash event. The addition of temperature sensors to the inside of the switchgear makes it possible to detect the temperature rise associated with the insulation breakdown and identify an arc flash event before it begins [**28**]. The difficulty with such a solution is that not all arc flashes begin through heated insulation and therefore not all flash events would be detected. Additionally temperature changes will not respond as quickly as light or pressure detection, which creates risk around these sensors.

2.5.5 Sound Detection

Arc flash events can create sound waves with a magnitude as high as 140 dB measured 2 feet from the arc source [**1**]. Occupational Safety and Health Administration states that "exposure to impulsive or impact noise should not exceed 140 dB peak sound pressure level" [**29**].

The incredible amount of sound generated is detectable using acoustic sensors. The sensors monitor for noises that reach arc flash levels of magnitude and notify the breaker to disconnect. There are currently no systems utilizing this approach due to the fact that noises from other sources (machinery and equipment) will cause false trips and needlessly interrupt power.

2.5.6 Bus Differential Measurement

2.5.6.1 High Impedance Bus Differential

Many current transformers are connected in parallel to an electronic relay with a high impedance input. Voltage across the high impedance input is measured and utilized for arc flash detection. The benefit of this implementation is that it is fast, but it is also very expensive both to initially purchase and to maintain due to the validation tests and the current transformers can only be used for bus differential [**4**].

2.5.5.1 Low Impedance Bus Differential

This is similar to the high impedance scheme but the current transformers can be of differing ratios and in addition to bus differential, they can be connected to feeder protection relays for additional monitoring capability. The detection technique utilized is more complex than the high impedance bus differential, but the cost is reduced because there is no need to purchase dedicated current transformers for the feeder protection system. The current transformers can be connected to other relays, meters, or transducers without interference [**1**].

2.5.7 Instantaneous Trip Current Energy Relay

In order to detect arc energy levels rapidly, during maintenance periods facilities institute a requirement that staff enable instantaneous trip mode for over current protective relays. In this mode coordination is disabled, but the relay will signal the breaker the instant any current exceeds operating levels a trip condition will be reported [**4**].

This method provides a reasonable response time (30-50 ms), but in order to operate the operator must toggle a switch. Relying upon the operator to modify equipment parameters requires training, and a method of locking the settings until the task is completed. This reduces the reliability of this implementation.

2.5.8 Lockout-Tagout Program

A lockout-tagout program is a method of securing an electrical network from being energized until the lockout device (typically a padlock) and the tag notification are removed. The safest way to maintain electrical equipment is to only work in an energy free state. This means to isolate the energy source from the area under maintenance. When the isolation system has been enabled and has safely removed power from the maintenance area a padlock and notification tag are installed to show that the system is only to be reenergized by authorized personnel [**30**].

2.5.9 Current Limiting Fuse

A current limiting fuse is a device that for the operating range of which current limiting operates (specified by the manufacture of each fuse) will limit the short circuit fault current. The limit occurs by the fuse opening or clearing the fault in a worst case of one half-cycle [**31**].

Because the energy is cleared so quickly a design engineer can select a current limiting fuse that enters limiting mode at an energy level similar to the short circuit fault current of the system (determined through a short circuit analysis). If the correct fuse is specified and installed then the current limiting fuse is an effective means of limiting the energy available during an arc flash event, though consideration of the grounding implementation of the network is required [**31**].

2.5.10 High Speed Camera

There are no companies currently making use of high speed cameras to detect arc flash events and trigger the disconnect device. However during in lab tests of arc flash events high speed cameras are used that capture images at a rate of 2000 frames per second. It was found that the initial visible arc light can be detected with relatively strong accuracy and thus utilized for analysis of the behaviour of the equipment under test [**32**].

Unfortunately the cost of creating a high speed visual analysis system with accurate arc flash detection is likely too much to convince electrical design engineers to install anywhere there is risk of arc flash incidents.

Of additional interest is the fact that high speed photography has been utilized to monitor for high current vacuum arcs [**32**]. In the research it was found that the details of the image are not important, so they utilized photodiodes to monitor for extreme light variations at a speed of 10^6 frames per second [**32**]. This extreme speed allows rapid response to the arc flash light, but since the implementation is ignoring the full frame data, it is more similar to light based detection methods already deployed.

2.6 Interruption Methods

After an arc flash event has been identified, there is a need to interrupt the energy before it reaches catastrophic levels. Interruption of the energy is performed by mechanical devices which carry unique problems as discussed in the following sections.

2.6.1 Instantaneous Circuit Breaker

A circuit breaker is a device designed to monitor current loads and disconnect the load if the current moves outside the predefined specifications. Breakers are designed as multiuse devices, in that they can be cycled from connected to disconnected and back many times. They are rated and approved by safety standards defined by groups such as Underwriters Laboratory (UL) [**2**].

Many breakers allow short term over current conditions, with the purpose of allowing a delay before disconnect, in contrast an instantaneous circuit breaker responds with minimal delay. An instantaneous breaker can interrupt the load very quickly, with times ranging from 13 to 130 ms [**2**].

Since a breaker is a mechanical device, it needs to be maintained and tested to ensure proper operation. Manufacturers typically recommend a maintenance of each installed breaker once per year in order to prevent the disconnect element from seizing and to allow time to look for indications to replace aging breakers [**2**]. As explained by Mr. Gary Donner during an interview, this can be costly for large electrical networks utilizing hundreds or thousands of breakers and this cost (time and money) generally results in the maintenance schedule not meeting manufacturer recommendations.

2.6.2 Introduce a Second Fault

Upon detection of an arc flash there is very little time to disconnect the load before incident energy levels reach dangerous levels. As explained in section 2.6.1, circuit breakers will disconnect the load in anywhere from 13 to 130 ms. In this time the incident energy levels increase rapidly, becoming dangerous.

Accepting that the time required for the breaker to disconnect is not easily modified, one can instead investigate methods of redirecting the energy away from the arc flash event to afford the breaker time. The introduction of a second fault is one such method.

A mechanical quenching device (commonly referred to as a crowbar) “shorts the arc fault effected busbar system inside 2 ms and takes the destructive energy of the arc. The three phase short-circuit fault introduced by the quenching device is switched off by the incoming circuit-breaker” [**33**].

The introduction of a second fault allows the current to dissipate elsewhere in the system, however this energy does create additional stress upon the electrical supply equipment, it is expected that the stress and damage is less than that of a full arc flash. Admittedly no research into a direct comparison could be located to validate this assumption.

2.6.3 Containment Chamber with Breaker

Continuing along the same idea as the quenching device is a system that introduces a unique second fault creating a similar outcome. This system is a fast energy capture device built into a containment chamber.

The idea is to monitor for arc flashes using light sensors. When a flash event is detected a plasma gun is enabled to release plasma inside the containment chamber near an electrode gap. Instead of the arc flash continuing in the detected location, the energy has a lower resistance path within the containment chamber. Inside the chamber the energy (heat, pressure, gasses, etc) is contained, vented, and maintained long enough for a disconnect device such as a breaker to remove the load. Upon receiving the trigger signal from the protective relay, the containment chamber reacts and transfers the arc energy in a response time between 1 to 2 ms [**34**].

Important differences between quenching with a crowbar system and utilizing a containment chamber are that the containment chamber can be reused (after a maintenance process), it causes lower stresses upon the power generation equipment, and it safely handles the energy [**34**].

There may be risks to this approach since it is a relatively new system, it needs to be further investigated and tested to ensure that it is safe for personal protection equipment.

2.6.4 Over Current Fuse

An over current fuse is a one-time energy disconnect device that is designed to be the weakest point within an electrical system. When the energy levels reach the breaking point, heat is generated inside the chamber of a fuse and the element blows open, disconnecting the circuit. Fuses are rated and tested by the same safety organizations as breakers, though the standards differ. Similar to breakers, fuses are offered in different models such as fast acting, time delay, current-limiting, or non-current-limiting. The fuses utilized for arc flash protection are fast acting as they respond quickly to over current conditions [**2**].

One problem identified with fuses is the aging property. Over time the disconnect properties of fuses change based upon the environment and the energy levels of operation. Due to this it is recommended that fuses are regularly tested, re-certified, and replaced [**35**].

2.6.5 Current Limiting Fuse in Parallel with Explosive Bus

Once an arc flash event is detected a trigger signal is provided to the explosive element on the bus device. The explosive bus device is in a parallel circuit with a current limiting fuse. The rating of the current limiting fuse is significantly lower than the expected load on the system.

After the bus has been broken apart through the explosive event, the current limiting fuse prevents the arc event from growing and disconnects the circuit as soon as possible. This ensures that power is safely disconnected and prevented from feeding the arc flash event. The speed of this process allows the main conductor (bus) to be opened in less than 1 ms, which then forces the device into the current limiting mode [**36**].

Figure 2 shows the energy level of a typical arc flash event, contrasted with the potential energy level under the same circumstances with a current limiting fuse in parallel with an explosive bus. Because the disconnection time is significantly improved, the level of energy available for the arc flash is greatly reduced.

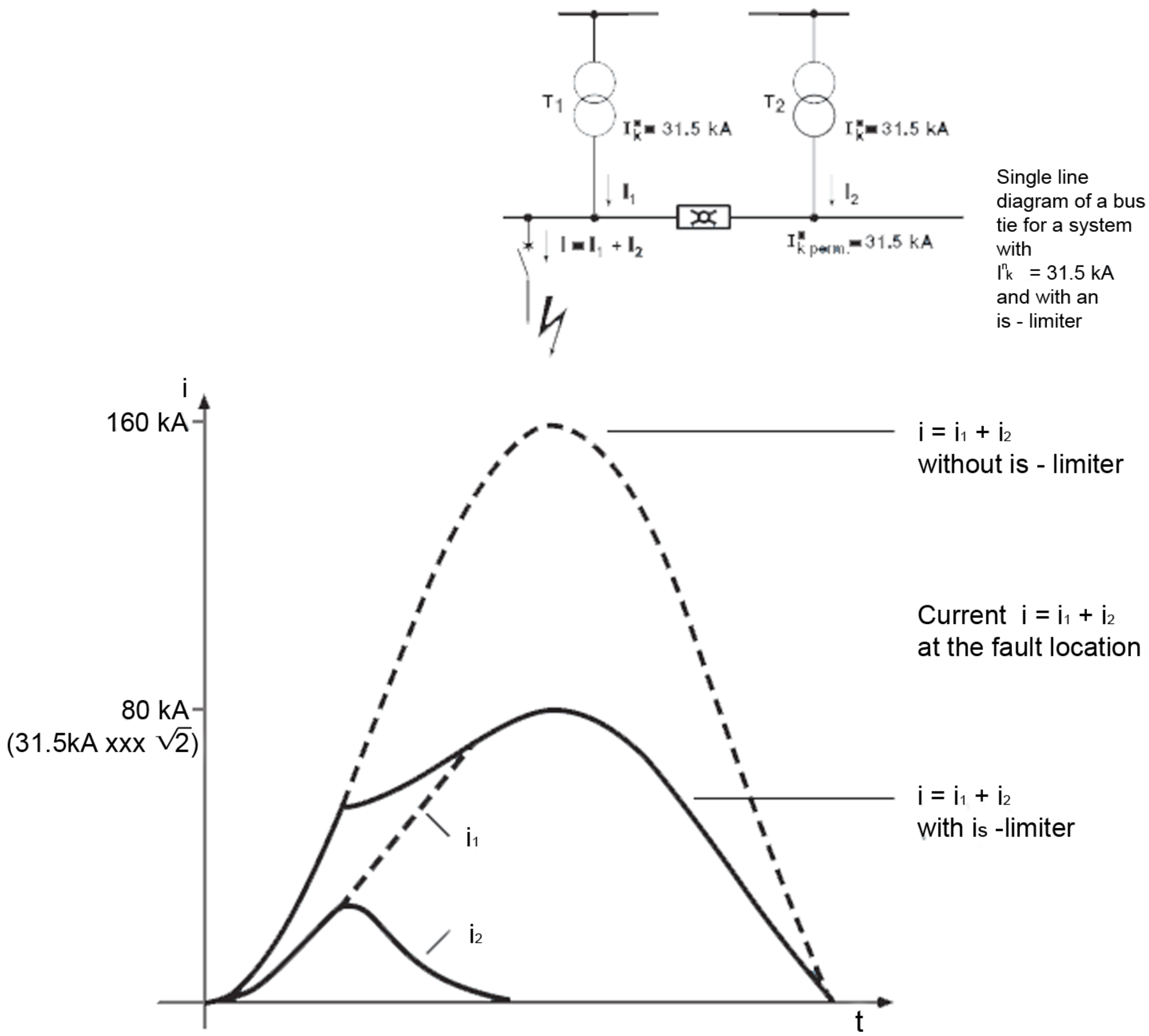

Figure 2: Is-limiter Arc Energy Limit [36]

2.7 Personnel Protection

Upon completion of arc flash studies, training, and posting warning signs, it is important to ensure that electricians have the equipment available to protect them, as well as an understanding of when the different equipment must be utilized.

2.7.1 Personal Protective Equipment

Personal protective equipment (PPE) was first popularized in 1994 as a result of OSHA 1910.269 Apparel requirement which stipulates that apparel must "not increase the extent of the injury" [**37**].

Over time similar requirements were listed by Canadian agencies, IEEE, ANSI, and NFPA. These organizations added their own spin on the requirements and worked together to continue to improve the research and requirements to ensure the safety of personnel [**37**].

Various materials are utilized to construct the apparel utilized by electricians in protective roles. Table 1 lists the PPE equipment and the standards that define the ratings, test methods, and materials.

Table 1 PPE Apparel Descriptions [37]

Apparel Item	**Applicable Standard**
Clothing	ASTM F1506 or IEC 61482
Rainwear	ASTM F1891
Fall Protection Harness	ASTM F887
Hairnets and Beardnets	NFPA 70E-2009 and ASTM F1506
High Visibility Clothing	EU EN471, ANSI 107, CSA Z96
Gloves	ASTM D120
Cleanroom Garments	ASTM F1506
Underwear	NFPA 70E-2009
Winter wear	None
Face shields	NFPA 70E-2009
Shoes	NFPA 70E-2009
Respirators	NFPA 70E-2009
Disposable arc-rated materials	ASTM F1506
Hearing Protection	ASTM F1959
Hard Hats	None
Arc Flash Blankets	ASTM F2676-09
Arc Flash Shields	ASTM F2522

There are a significant number of options for PPE and each option is applied differently in each scenario. It is important to be aware of the arc flash risk and potential incident energy prior to making PPE recommendations. The correct PPE can save lives.

Table 2: Protective Clothing Guidelines for the Electrical Arc Hazard [38]

Proposed Protective Clothing Classes		Flame Resistant (FR) Clothing System		Estimated Incident Energy for Onset of Second Degree Burn
Proposed Range of Calculated Incident Energy cal/cm^2	Clothing Class No.	Clothing Description (No. of Layers)	Total Weight oz/yd^2	Arc Thermal Performance Exposure Value (ATPV) or Break open Threshold Energy (E_{BT}) cal/cm^2
0-2	0	Untreated Cotton	4.5-7	n/a
2-5	1	FR Shirt	4.5-8	5-7
5-8	2	T-Shirt plus FR Shirt and Pants	9-12	8-18
8-25	3	T-Shirt plus FR Shirt/Pants plus FR Coverall	16-20	25-50
25-40	4	T-Shirt plus FR Shirt/Pants plus Double Layer Switching Coat	24-30	40->60

Table 2 presents a range of incident energy levels alongside the different protective clothing that can work to prevent a second degree burn. This table was populated through testing many materials and coatings and served as the basis for protective clothing manufacturers when designing protective suits [**38**].

The higher the incident energy the heavier the PPE required. As the weight increases, the comfort level and tolerable time decreases. If there is too much weight, it can create frustration with the PPE and restrict movement. For this reason the highest PPE clothing is only worn for short periods of time.

2.7.2 Remote Operation

In addition to proper PPE, electricians have the option available to perform maintenance remotely. Systems of this type utilize either robotics to manage tools and equipment, or remote controlled switchers. The purpose is to allow the electrician to perform the required work from a safe distance in case something does happen.

These systems offer an added layer of safety for personnel, but they carry a significant cost. Robotic systems can be expensive and it is difficult to justify a budget for a significant purchase that will only be utilized a few times a year.

2.8 Testing

As research into the cause and effect of arc flash incidents has evolved, standards groups have worked to ensure best practise protocols are followed to ensure a safe working environment.

Additionally the testing of what happens during an arc flash incident has evolved and the standards now define methods of testing equipment and apparel to ensure test lab independence in the certification process.

2.8.1 Test Process

IEC 61482-1 provides a test platform and procedure for performing testing of clothing and materials for arc flash safety performance [**39**].

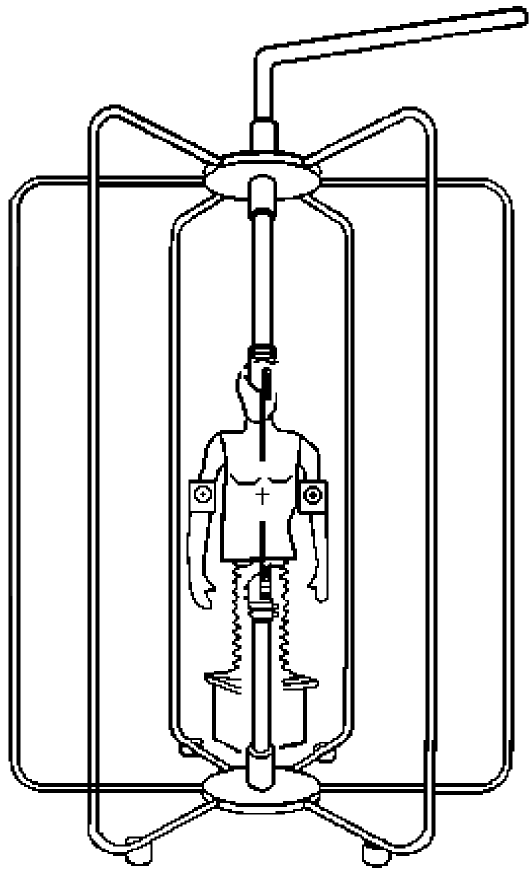

Figure 3: IEC 61482-1 Recommended Test Setup [39**]**

Figure 3 shows the recommended test platform as outlined by IEC 61482-1. The operation of the setup is to create an arc event between two electrodes in the center of the setup (bottom and top center). The distance between electrodes is 300 mm, and following each use measurements are performed and adjustments made to ensure that this distance remains constant [**39**].

The testing is done to evaluate the protective qualities of the fabric under test. The fabric is installed into the region where the mannequin is shown in Figure 3. An arc is created between the two electrodes and the effect on the fabric is measured both in terms of heat transfer, resistance to flame, and electrical conduction [**39**].

2.9 Summary

Chapter 2 provided an overview of the problems caused by arc flash events and the associated dangers. There is no simple solution to detect or prevent, but due to the risk to personnel and potential cost of damages one can justify the desire to expand the state of art. Arc flash is caused by a fault or faults in the electrical system. Though steps are taken to prevent and improve safety the only method to perfectly prevent arc flash events is to never work on live electrical equipment. Instead state of art offers methods to react to the event and attempt to minimize the damage by disconnecting the energy before it reaches peak. While current detection methods are available to respond to arc flash rapidly, the interruption techniques are many times slower. There is active research in the area of interruption techniques and personnel protection with the state of art outlined in this chapter. The information presented in chapter 2 provides an overview of the state of art of arc flash research.

CHAPTER 3
ARC PHYSICS

3.1 Introduction

An electrical arc exists for a fraction of a second, and during that period many stages of development occur which are important to defining the behaviour and operation. This next section examines the electrical nature of an arc event beginning at inception, continuing during development and ending with extinguishing. During these stages particles are transformed into the fourth state of matter; plasma. Plasma is energetic and requires significant energy to generate, thereby becoming a potentially important factor when attempting to locate a voltage/current indication that an arc is imminent. The following section investigates further into plasma, and its relationship to arc development.

3.2 Arc Analysis

An arc flash event occurs as a result of an arc event that grows due to feeding a significant amount of the energy. As discussed previously, such an event results in the release of energy in many different forms. However in order to better detect such an event; one needs to understand the formation development through analysis.

3.2.1 Development of an Arc

The following section is paraphrased from an installation and configuration guideline document and presentation published by Littelfuse Selco, who manufacturers arc flash sensors [**40**]. In order to best explain the development of an arc event, they created a series of drawings of a cross sectional of components which have been recreated in Figures 4 – 9 which follow [**40**]. These figures are used to showcase the dark discharge region of plasma development as defined and explained in section 3.2.2 and Figure 10.

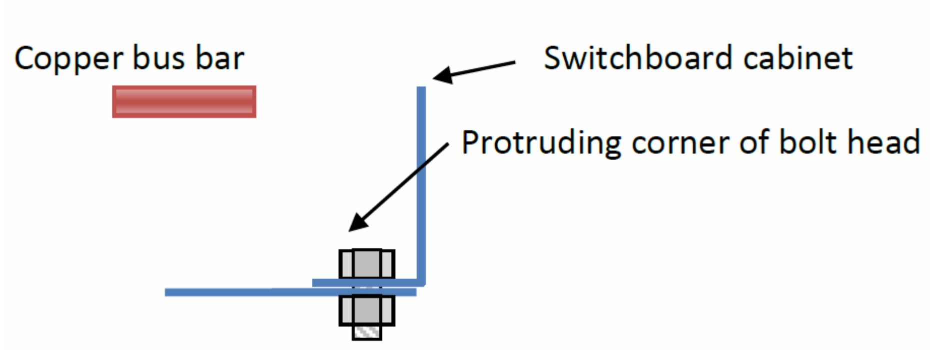

Figure 4: Referenced Drawing for Arc Development [40]

Figure 4 depicts a copper bus bar installed inside a cabinet, with a mounting bolt, depicting the nearest point for an arc event.

3.2.1.1 Saturation Regime

Safety and design standards provide recommended clearance guidelines between the bus bar and the bolts in the switchboard depending upon the voltage of the system. Under normal operation the distances exceed the strength of the electric field as it does not have the strength to traverse the gap [**10**].

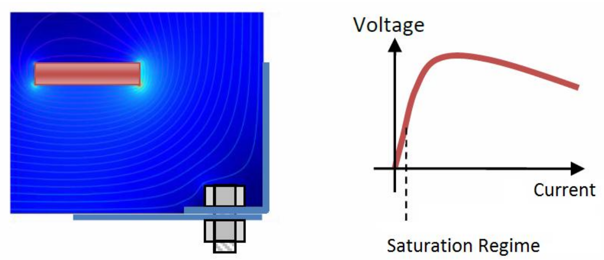

Figure 5: Saturation Regime [10]

In the presence of a fault (caused by lightning, dropped tool, etc) the electric field is strengthened, and what was an acceptable (by standards) gap begins to energize. This is the beginning of the dark discharge division of an arc regime, which will be discussed in detail in section 3.2.2 [**41**]. Figure 5 depicts the instant following a fault, where the voltage/current has reached the saturation regime of development.

3.2.1.2 Corona

The corona occurs during the end of the dark discharge division of the first arc regime. The corona is defined as "a phenomenon ... which occurs in regions of high electric field near sharp points, edges, or wires in electrically stressed gases prior to the point of electrical breakdown" [**41**].

If there is enough current feeding into the arc gap, the corona forms which produces light in the visible spectrum. This is considered part of the dark discharge regime, if there is not sufficient current there will be no light produced [**41**]. This process is depicted in Figure 6 wherein the next stage of arc development occurs.

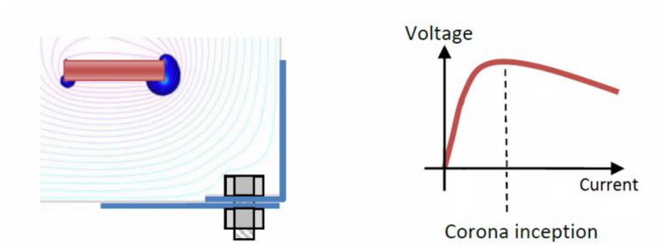

Figure 6: Corona Inception Example [10**]**

3.2.1.3 Streamers and Leaders

If the electric potential continues to increase (the fault persists) then as the discharge continues in the Townsend Regime (depicted in Figure 10), it will reach a breakdown voltage. At this moment the next regime is entered, this is the glow discharge regime [**41**]. During this process the discharge transitions from corona to a streamer which results in energy passing the space charge layer. The energy released is termed streamers, and is depicted in Figure 7 [**10**]. When comparing Figure 7 and 6 one observes that the corona and streamer appear to occur at nearly the same time. This follows the theory presented in the analysis of Figure 10. The corona is the first visible light artifact of an arc, but the streamers begin at almost the same instant.

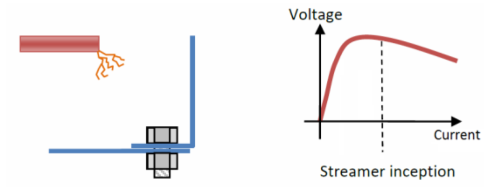

Figure 7: Depiction of Inception of Streamers [10]

As the electric potential increases (fault persists), a streamer forms across the gap between potential points (bus bar and bolt in this example). As this streamer is forming, a transition occurs where plasma is completes the path across the gap. The plasma is energetic enough now to produce visible light. During the transition across the gap, the plasma is known as the leader [**10**]. This leader is the first arc released and it signifies the start of the glow discharge region. This is depicted in Figure 8.

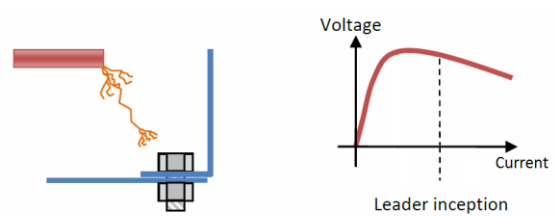

Figure 8: Breakdown and Progressing through Gap [10]

3.2.1.4 Glow to Arc Transition

Once the leader completes the journey across the gap, the potential of the bus bar equals that of the bolt. If there is not enough power to sustain the created arc, it diminishes. In medium-voltage power systems with enough energy, the voltage between the bar and the bolt is maintained and the arc is sustained [**10**]. This is the glow-to-arc transition [**41**] and the spark begins to transform into an arc [**10**].

3.2.1.5 Arc

Once the glow-to-arc transition completes, if there is enough energy feeding the fault then the cold spark will change into a hot arc. At this point the arc causes a rise in temperature, pressure, fault current, and conductivity resulting in damage [**10**]. The resulting conclusion to the arc development is depicted in Figure 9.

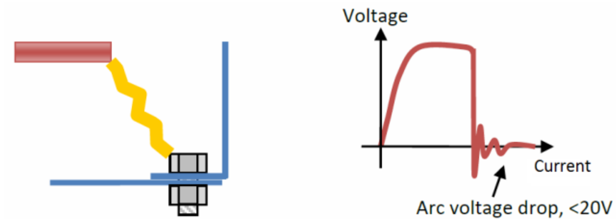

Figure 9: Rendering of an Arc Event [10]

3.2.2 Plasma

Plasma is the fourth state of matter and was identified by Sir William Crookes in 1879. Plasma is created by starting with a solid and adding energy in the form of heat or pressure. The solid will transition into a liquid, gas, and finally plasma. The transition from a gas into plasma is identified by the separation of atoms into electrons and positively charged ions. The term plasma was first coined in 1928 and was defined as an “approximately electrically neutral collection of ions and electrons which may or may not contain a background neutral gas, and which is capable of responding to electric and magnetic fields” [**41**].

The lifespan of plasma from generation to arc is broken into three regions that are separated by the amount of current present. The three regions are referred to as, dark discharge, glow discharge, and arc discharge [**41**]. The behaviour of voltage and current and separation of the discharge regions is shown in Figure 10.

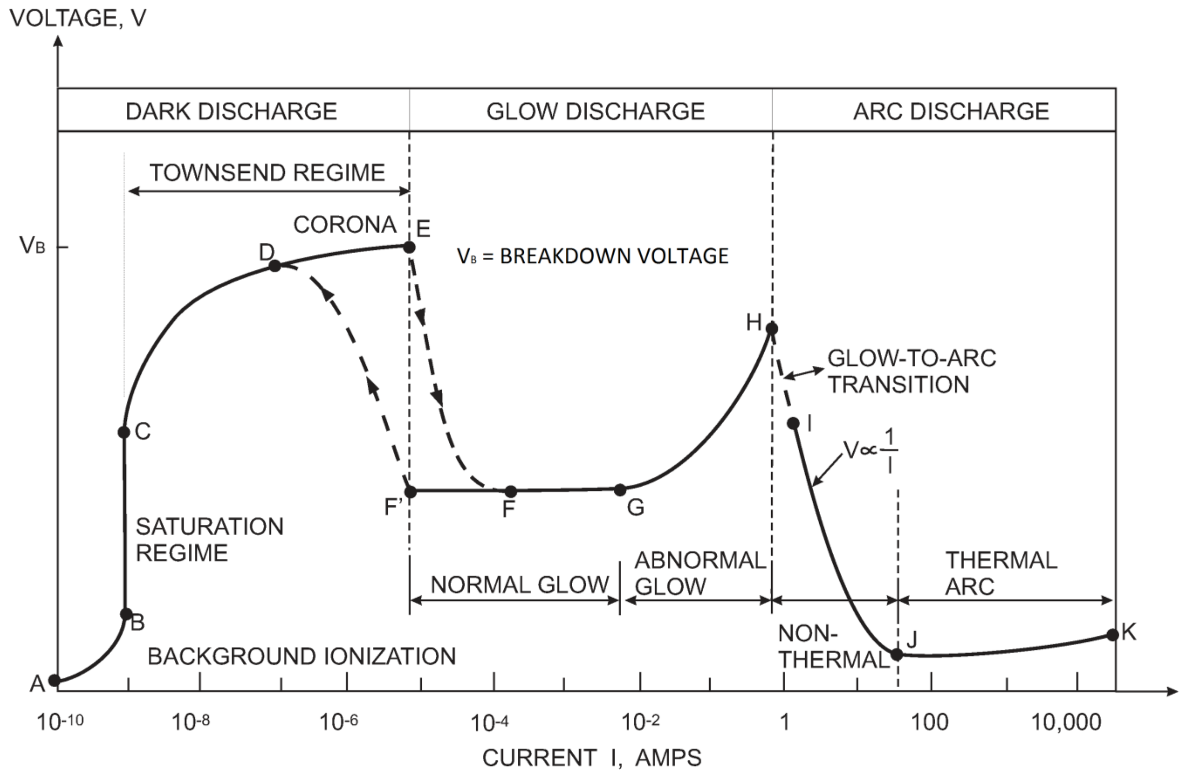

Figure 10: Voltage-current characteristic showing Discharge Regions [41]

Each one of the discharge regions are further separated into regimes based upon the same voltage-current relationship. These sub-regions are identified on Figure 10 and listed in Table 3.

Table 3 Voltage-current Regimes [41]

(1)	Dark discharges
	(A) Background ionization
	(B) The saturation regime
	(C) The Townsend regime
	(D) Corona discharges
	(E) Electrical breakdown
(2)	Glow discharges
	(F) The normal glow discharge
	(G) The abnormal glow discharge
(3)	Arc discharges
	(H) The glow-to-arc transition
	(I) Nonthermal arcs
	(J) Thermal arcs

Cosmic rays, radioactive materials, or other sources produce ionization in the air. The ionization exists in the form of ions or electrons, which are swept out during the background ionization regime. The amount swept out increases as does the voltage [**41**].

During the saturation regime all ions and electrons produced by background radiation are removed and there is no additional source to replace [**41**].

The Townsend regime is of significant importance as this is where many changes occur. "The electrons in the discharge volume acquire sufficient energy from the electric field that they ionize some of the neutral background gas, leading to a very rapid, exponentially increasing current as a function of voltage" [**41**].

The next stage is the Corona discharge, which is the first time wavelengths of visible light are produced (though at low levels), and occurs at sharp edges or points along the energized element [**41**]. The formation of the Corona marks the end of the dark discharge regime [**41**].

The regimes from background ionization until electrical breakdown and glow discharge are all part of the encompassing regime definition of dark discharge. The name is applied due to the fact that outside of the corona and the streamers, there are no wavelengths created within the visible light spectrum [**41**]. The dark discharge regime carries importance to this research. This regime and into the early stages of the glow discharge regime all occurs before light sensors can detect the presence of an arc event. During this phase, plasma detection or voltage/current harmonics present a potential to detect an arc before light sensors.

Following an increase in voltage/current (energy stored in plasma, released during arc event) and the conclusion of the dark discharge regime is a transition into glow discharge.

Plasma is of significant importance to an arc flash event as inside is an electric field composing the primary source of energy [**39**]. The air plasma field consists of "O_2, N_2 molecules, O, N and electrode material atoms, O+, N+ and electrode material ions (not in a gas), plus free-electrons (e-) (These are also not in a gas)" [**39**].

3.3 Summary

Chapter 3 presents an overview of the process involved in an arc event from the perspective of voltage/current, and light produced. There is particular attention directed towards the plasma created, and the timing of visible light production. The process of plasma production begins with a dark phase where outside of the corona and streamers (which create very little light, comparatively) no visible light is produced. The information presented in chapter 3 is pertinent towards determining if there is any voltage/current signature present on the electrical network that would indicate the dark phase of plasma production.

CHAPTER 4
PLASMA SIGNATURE DETECTION

4.1 Introduction

The hypothesis of this thesis is that the energy required in order to convert matter from a solid to a gas, to plasma requires enough energy that the process will affect the power signal on the transmission line. This section explores this concept, explains the benefits compared to industry standards, and the potential benefits and limitations.

4.2 Proactive Approach

During the initial stage of an arc flash event, air/metal particles are broken down and the formation of plasma begins. This occurs during the dark discharge regime when no light is output, however energy is building and being absorbed by the particles surrounding the conductor nearest to the location of the pending arc. By monitoring the voltage and current on the power system during this stage, the goal is to determine a detection method that enables the event could to be identified prior to an arc flash occurring.

4.2.1 Industry Standard

The most rapid detection method available in industry is to monitor the visible light spectrum searching for intense energy that indicates an arc flash event is occurring. This is a reactive approach that is not triggered until the fault has crossed the spark gap. Further if the detection sensors are poorly installed, or not in the same region as the event the detection time will be slowed or, at worst, will not occur. From the state of art review in section 2.5.1, the reaction time of such systems is 500 μs after the light reaches intensity levels exceeding trip intensity, or (optimally) 2 ms after initiation of the arc event.

A proactive approach presents an opportunity to monitor an entire section of a power system for the pattern that indicates the initial formation of plasma. Energy consumed during this stage is large enough that some indication on the power system is hypothesised.

4.3 Proactive Detection Advantage

If a pattern or indicator is identified, an algorithm could be created which presents an opportunity to monitor a greater portion of the electrical network while reacting before the event has reached critical stage. The potential reaction time improvement is minimal (1 to 1.5 ms) compared to light based methods, but the reliability increase from a current monitoring solution warrants an investigation. Current monitoring solutions improve reliability as they cannot be blocked and are capable of monitoring a substation while permitting simple verification using readily available tools (voltmeter). As represented in Figure 2, a reduction in time has the potential to reduce the fault energy. Because light based detection is only as reliable as the installer and the location of the fault event, the improved reliability provides an opportunity to improve detection schemes. Reducing nuisance trip events (false positives), and increasing detection accuracy (false negatives) improves the overall safety of the electrical network.

4.4 Proactive Detection Limitations

The proactive detection approach has benefits that warrant the research, however it also carries limitations.

4.4.1 Disconnect Time

The detection of the formation of plasma is only half of the equation. Once plasma is detected, the energy source needs to be removed in order to prevent the impending arc flash event. This research is only focused upon the detection aspect of an event. While this is only a small part of the problem, there is benefit to such an exercise.

Current detection mechanisms rely upon a reactive detection system. Once an arc flash has developed and is occurring, the protective system will detect the phenomenon and indicate to a disconnect device (typically a breaker) to interrupt power. This is akin to detecting a bullet after it has been fired and is travelling towards the intended target. Good information, but it is much more beneficial to be notified when the gun is removed from the holster, providing more reaction time.

In the discussion of arc flash the time difference from the start of plasma generation to the production of visible light (flash event) is in the order of milliseconds at most. The length of time is dependent upon the amount of energy required to discharge through the spark gap. However if the detection can be made before the flash event occurs then an extremely fast acting disconnect or delay system presents an opportunity to stop the detected plasma generation from escalating into an arc flash event. The combination of these permits arc flash prevention, instead of arc flash mitigation, potentially saving millions of dollars and more importantly lives.

4.4.2 Processing Power

In order to monitor the voltage and current of the system with enough accuracy to ensure micro-second events are located, the signal processing must be performed in fractions of micro-seconds.

The analysis methods are explored in Analysis Methodology, but for research purposes a standard personal computer running mathematical analysis software is sufficient. For real-time protection and monitoring, a protection relay requires a processor with the capability to perform a complex mathematical routine similar to the routines shown in both Appendix A or Appendix B, at a rapid speed (sub microsecond). This mathematical routine is sufficiently complex, and the time slice requires sampling at greater than 75 MHz.

While greater processing power is not impossible to overcome, the speed restrictions present a limitation that may require parallel processing, new algorithms, or other technological enhancements to the process. However these tools may introduce cost increases that are not practical to the end user.

4.4.3 Sensor Limitations

Because of the time sensitive nature of the signal processing required, the sensors to measure voltage and current must introduce no time delay and maintain a significant level of measurement accuracy. As shown in section 5.2, it can be difficult to locate such sensors even for research purposes.

When measuring the high voltage/current levels associated with arc flash events, capable sensors must be utilized. Furthermore the speed of sampling is much greater than typically utilized in power system monitoring.

For example, the industry standard for monitoring high voltage is to connect one side of a transformer across the energized monitor signal and divide the high voltage to something more manageable. Or when measuring high currents, industry makes use of current transformers to monitor the current flow. These solutions work great for 50/60 Hz systems typical in power networks, but they have an inductance which limits high frequency bandwidth.

This high frequency bandwidth limitation is another obstacle to plasma signature detection as special sensors would either have to be developed or located that can handle both the high energy and the high frequency. In either event the cost of such a system may prove prohibitive, but future research is required.

4.5 Summary

Chapter 4 outlines the theory driving the thesis hypothesis. By monitoring the voltage and current at a high frequency and using a test setup to determine if any pattern or change in the signal can be detected to indicate plasma production. State of arc detection systems have a limitation that they require the arc flash to have occurred and rely upon reaction time of the disconnection device. The potential advantage of locating a signature indicating the pending arc event is to be proactive and detect an arc flash in advance of the damage, in addition to the increased reliability. This technique comes with limitations. The time saved by being proactive is likely to be minimal, and the greater challenge is still going to be the time it takes to safely remove power. The processing power and sensors required to monitor the energy have the potential to increase complexity and costs relative to available solutions. Through an investigation of the research methods, benefits, and limitations, a better understanding of the objective is provided.

CHAPTER 5

DANSK EXPERIMENTAL TEST SETUP

5.1 Introduction

A high voltage/current power system with appropriate safety equipment and trained personnel is required in order to successfully initiate an arc flash test. Such a capable laboratory was located in Denmark where the engineers had the training and tools required. This experimental investigation was carried out in collaboration with the laboratory in Denmark. The following section outlines this relationship, and the test setup constructed, alongside oscilloscope captures of the arc events.

5.2 Collaborative Research

Testing of arc flash phenomenon requires a facility with the voltage and current capability as well as experienced staff capable of performing the tests in a safe and effective manner. Several laboratories were contacted (including Kinectrics in Toronto and Littelfuse in Illinois) and while creating an arc flash event was often possible, they did not have the appropriate equipment to sample the voltage and current at high frequency. Particularly the high voltage signal sensor was difficult to locate or design. Most oscilloscope probes are designed to withstand less than a few hundred volts with a wide frequency range. High voltage oscilloscope probes are generally restricted to low frequency ranges. This matches standard high voltage test systems which are tuned to the power system operating frequency. A voltage probe was located that permitted up to 75 MHz and 20 kV. This probe was relatively expensive which deterred local setup of the Dansk test setup.

One lab in particular was very eager and willing to work towards testing this unique scenario and had the capabilities and equipment including the required voltage sensor. Global Lightning Protection Services (Formally Highvoltage.dk) assisted in the creation of a test setup and sampling system. The work was done in collaboration with this laboratory.

5.3 Test Setup

Typical arc flash tests are initiated through the use of a piece of copper wire of small gauge (22 AWG) wrapped around two high voltage electrodes. When the high voltage is applied (ex. 4 kV) the copper wire is burnt away leaving a trail of plasma in its path which serves as an ignition path for the arc to traverse. Because the electrodes are carrying enough energy to feed this path, an arc flash develops.

For the purposes of analyzing the formation of plasma, it was decided that it would be beneficial to initiate the arc flash without an ignition source. This modification to the test setup better models a real world arc flash event which provides separation between the beginning of plasma generation and the start of the arc.

The setup is constructed with a high voltage capacitor discharged across a spark gap. The schematic diagram of the test setup is shown in Figure 11.

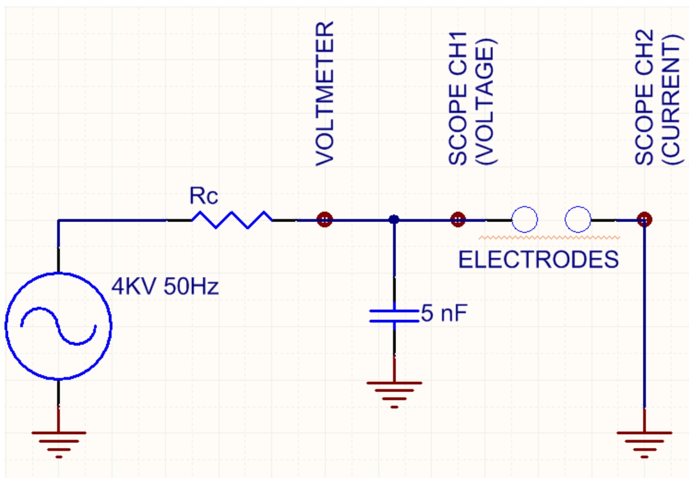

Figure 11: Test Setup Schematic Diagram

The test setup comprises of a high voltage power source (4 kV), a charge resistor (Rc) and a capacitor (5 nF). The capacitor is charged to 4 kV and is known to be this value by monitoring the voltage with the voltmeter. It is then discharged via the spark gap which triggers when the electrodes are close enough that the energy potential is able to breakdown the dielectric of air. During this time, the voltage is measured on CH1 of the scope using a high frequency high voltage probe (75 MHz), and the current is measured using CH2 of the scope. The current is measured through a ground wire as a voltage across a small resistor.

In Figure 12, the capacitor is shown, along with the grey high voltage probe, and the electrodes (silver metal balls). One of the balls is in a fixed position while the second is slowly moved closer until an arc is observed. The Scope is recording voltage/current information throughout this process.

In Figure 13, the oscilloscope and connections are shown as a reference for reproduction.

In Figure 14 the entire test setup is shown. At the far end of the picture is the voltmeter, used to ensure proper charging of the capacitor.

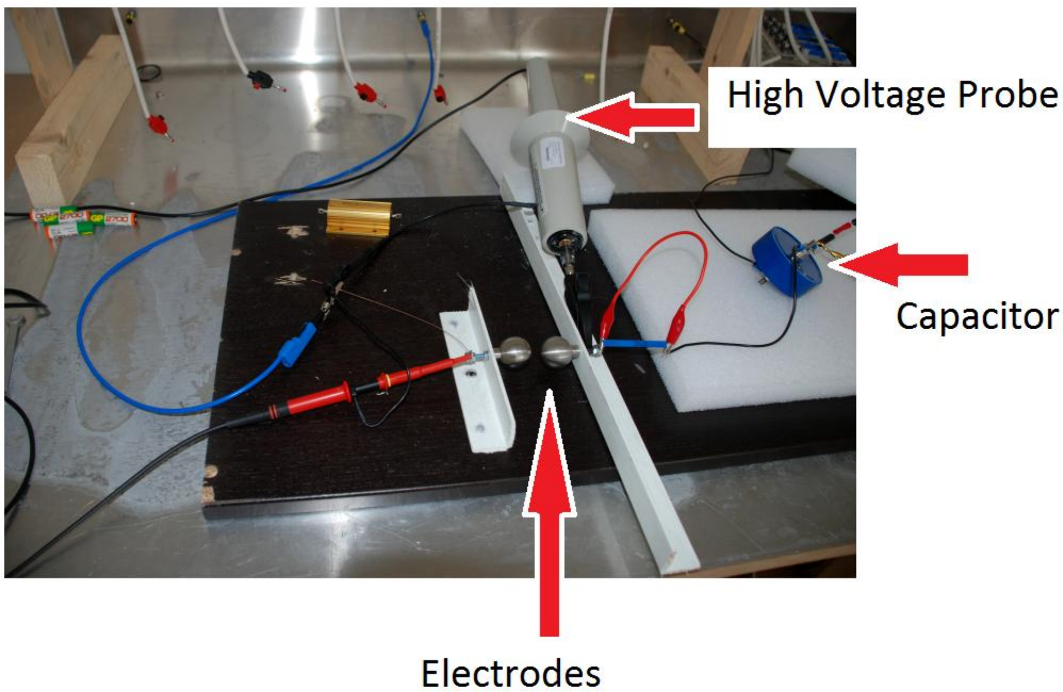

Figure 12: Test Setup Picture 1

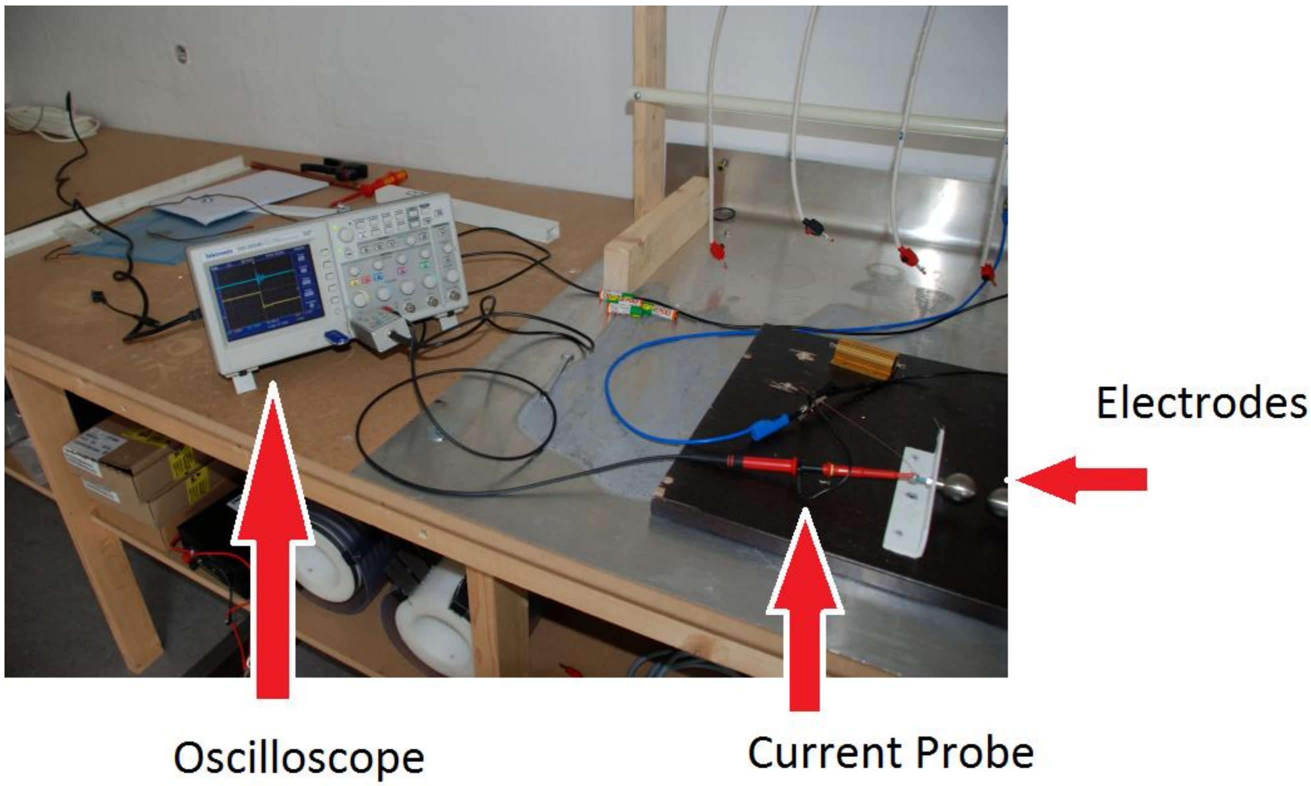

Figure 13: Test Setup Picture 2

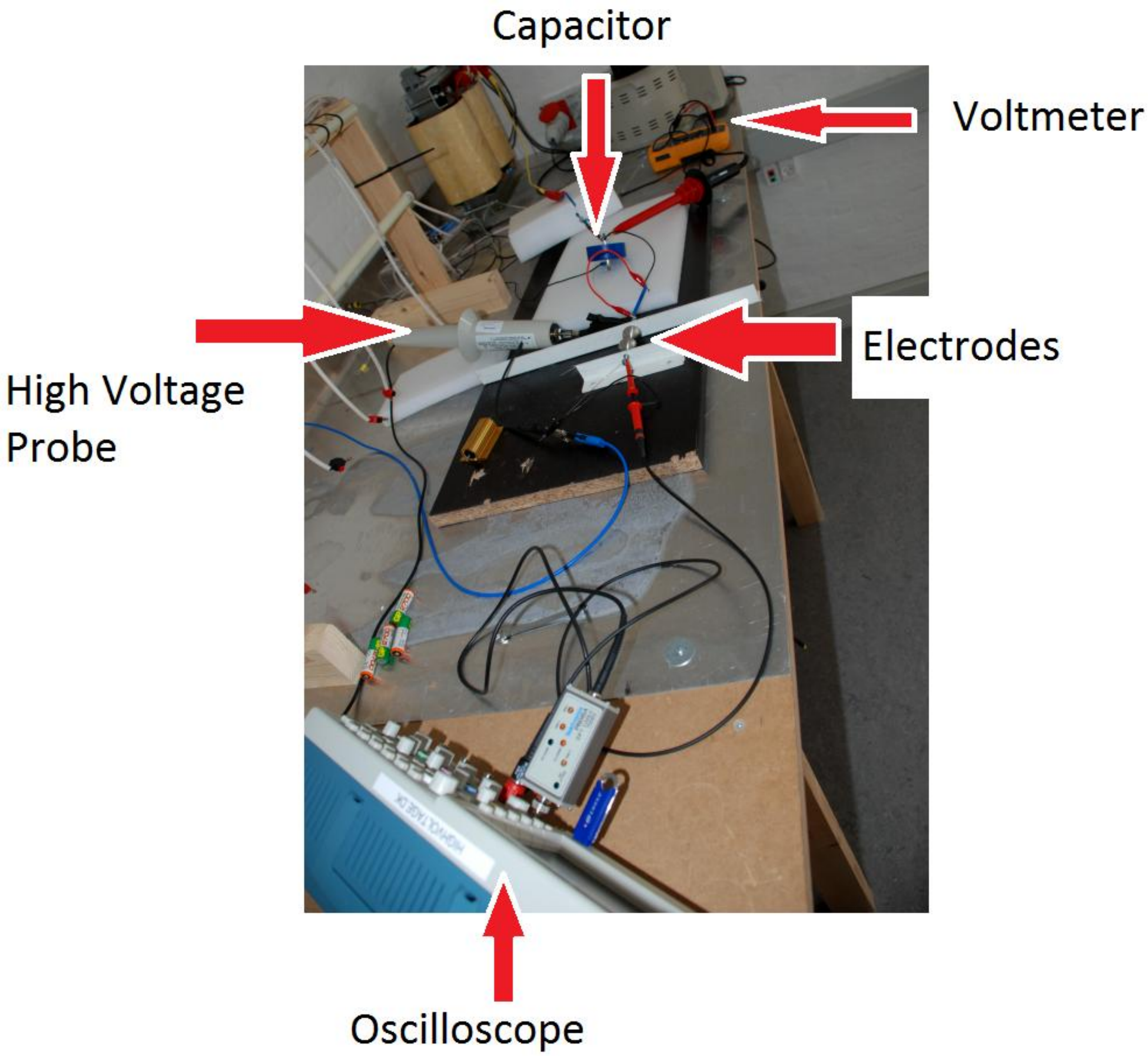

Figure 14: Test Setup Complete Picture

The test resulted in comma separated data files containing sampled voltage and current measurements, as well as scope waveforms.

Table 4 lists the components and materials used to construct the Dansk setup and is provided as a reference for reproducing the experiment.

Table 4: Test Setup Parts List

Tektronix TDS 2024B – 200 MHz Oscilloscope
Tektronix PMK-PHV 641-L, 100:1, 380 MHz – Current Measurement
Tektronix P6015A High Voltage (20 kV DC/40kV Peak 100 ms Pulse), High Bandwidth (75 MHz) – Voltage Measurement
Steel Round Electrodes Used for Spark Gap
4 kV Voltage Source
100 mΩ Current Measurement Resistance

5.4 Test Setup Oscilloscope Captures

The captures from the oscilloscope provide an opportunity to gain a preliminary understanding of the events. Observations determined by inspecting Figure 15, the voltage (CH1) begins with 4 kV potential, but once the spark is established this diminishes as it is shorted to ground. During this time the current also starts oscillating, as the circuit is now complete and a path for energy to flow has been established. Within one division on the oscilloscope (approximately 2.5 µs) the entire process has dampened.

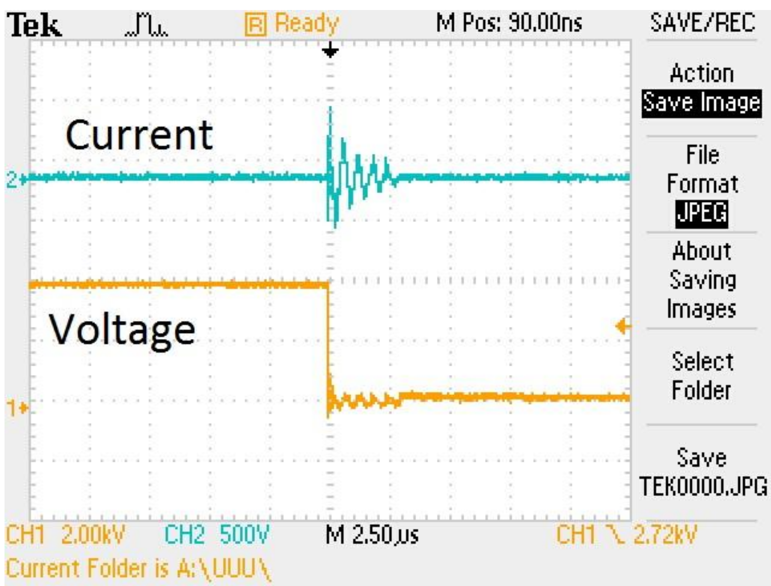

Figure 15: 4 kV Arc Event

A second oscilloscope waveform capture was taken with the signal zoomed in to show the time difference between the flow of current and the start of the drop in voltage. As shown in Figure

16, the current begins to flow approximately 9 ns before the voltage drops. This time variation will be analyzed in section 6.3.

The Dansk experimental test setup consisted of a high power energy source that charged a capacitor. Upon reaching peak potential, a spark gap was adjusted until an arc event occurred. This was monitored and captured at high frequency using an oscilloscope and associated probes. Through collaboration with a specialized laboratory a test setup was created and tested using safe and professional methods, permitting study.

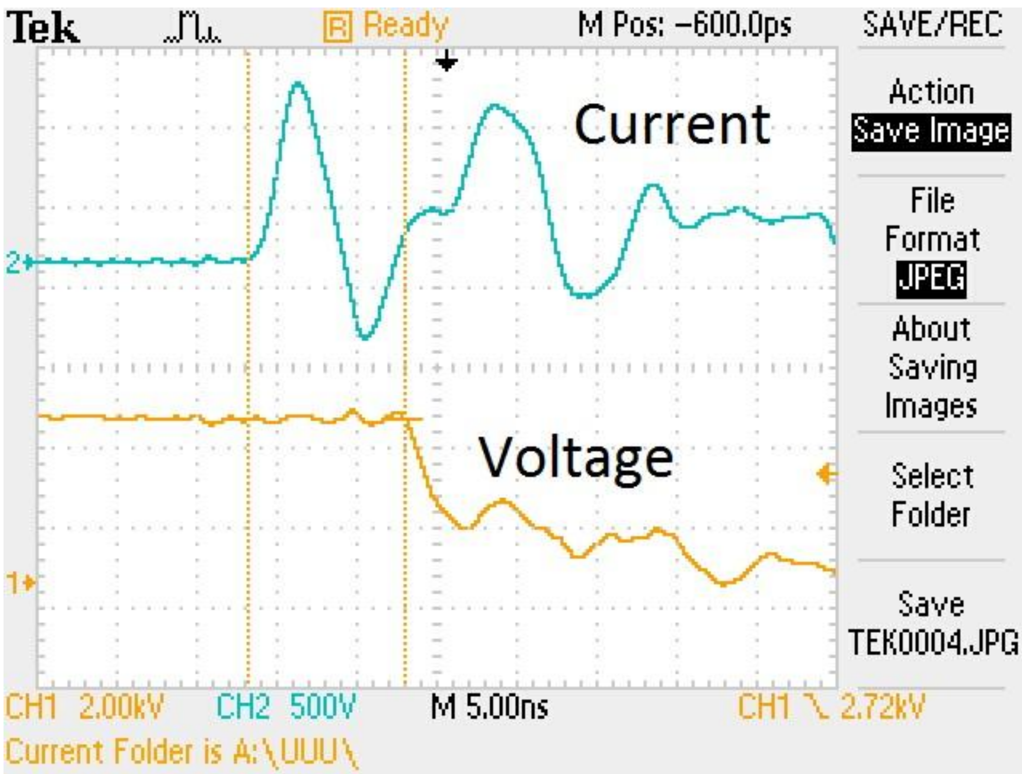

Figure 16: Zoom in on Event

5.5 Dansk Test Procedure & Repeatability

The Dansk test setup procedure begins by ensuring the electrodes are sufficiently separated to ensure no discharge during setup. The power source is then energized and the voltmeter monitored until a measurement of 4 kV is achieved. At this time the power source is disabled.

The electrodes are then moved at an unknown speed (though slowly), until an arc occurs. The oscilloscope triggers off the drop in voltage, and the data is recorded.

The tests were performed multiple times on two separate occasions. While the final waveform timing patterns were the same, due to the variability in speed of the moving electrodes, the exact nature of the test was not perfectly repeatable. However the information important to this analysis was observed on each test. That is the timing of the voltage and current was always the same.

5.6 Summary

The test setup consisted of a high power energy source that charged a capacitor. Upon reaching peak potential, a spark gap was adjusted until an arc event occurred. This was monitored and captured at high frequency using an oscilloscope and associated probes. Through collaboration with a specialized laboratory a test setup was created and tested using safe and professional methods, permitting study.

CHAPTER 6
ANALYSIS METHODOLOGY

6.1 Introduction

This section provides an understanding of the tools and methods employed to search the collected data for information that indicates the formation of plasma. As well it discusses problems found with the oscilloscope and probes while measuring data at such high speeds.

6.2 Analysis Tool

In order to analyze the captured waveform, samples were saved in a comma separated file (CSV) format and imported into a custom Matlab script. The script plots relevant information using time domain, and frequency domain spectrum in an effort to search for a pattern in the signal indicating the formation of plasma.

Time domain information provides an opportunity to verify that the captured data correlates with the oscilloscope capture, as well as providing an easier visualization of the arc event.

Frequency domain spectrum analysis is implemented using Fourier transforms (FFT), and presents information in a frequency spectrum. This can be used to visualize where the energy is located across frequency providing an opportunity to search for energy in unexpected frequency bands indicating plasma generation.

6.3 Time Difference and Scope Properties

An inspection of the oscilloscope plot in Figure 16 reveals that the current begins to flow before the voltage shows any reaction. Initially this was hypothesized to be a product of the arc flow and streamer development. However upon discussion with the oscilloscope manufacturer and consulting the documentation for the probes the time difference was determined to be a product of the differences in phase delay introduced by the scope and the two different probes utilized. Documentation for the P6015A High Voltage probe reveals that there is an expected propagation delay of 14 ns over 100 ft, and the typical value provided by Tektronix is 6 ns. Further delay is caused by the time difference between the two channels. As it was explained during a conversation with Tektronix technical support, there is a skew that occurs on an oscilloscope between two channels. This can be corrected on some high end scopes through the use of the deskew feature, but was not available on the scope used in the test setup. Instead the data was aligned by shifting the voltage 10.5 ns in time such that a drop in voltage correlated with a rise in current. Once the arc begins to pass energy, the point where the voltage is measured proceeds towards zero as it is now equivalent to ground (or very close to), while all energy is dissipated across the internal resistance of the capacitor.

The original scope capture after processing by the developed analysis tool is shown in Figure 17.

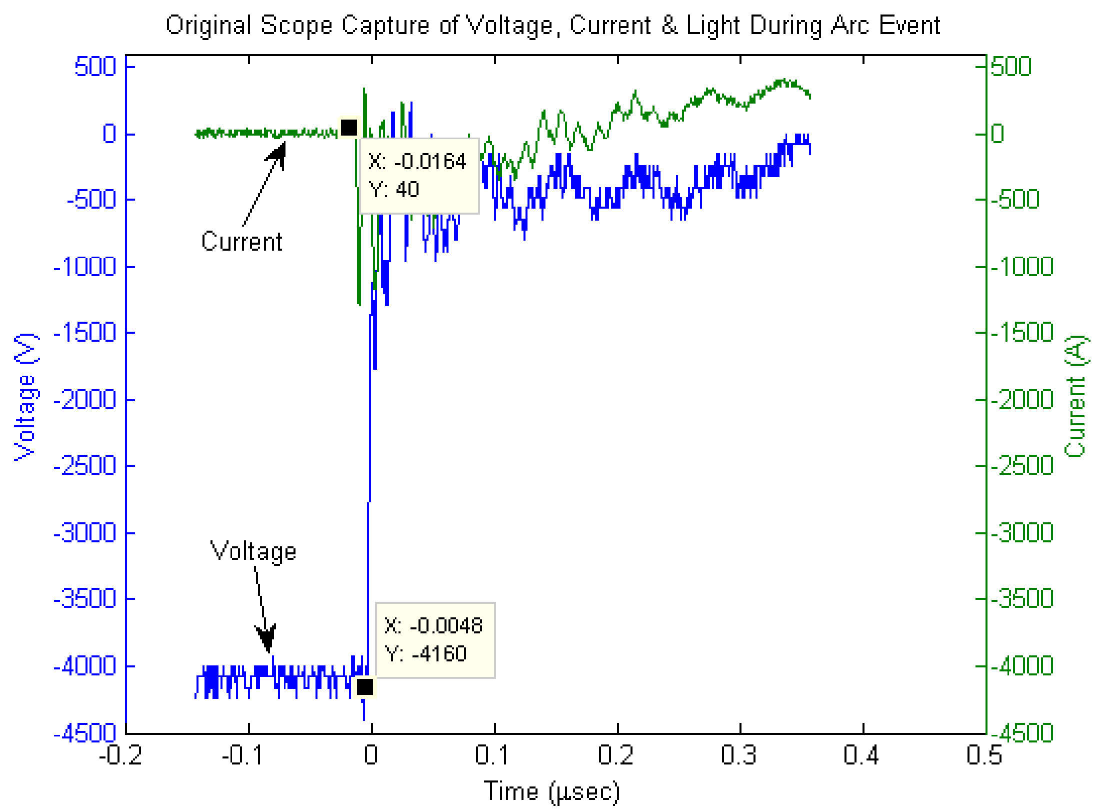

Figure 17: Original Voltage and Current

There are a few distinctive items to note. The voltage waveform starts at -4000, which is the incorrect sign. The power supply is increasing the potential to positive 4000, so this must be corrected in the analysis. Further the current waveform shows the same opposite sign behavior and again must be corrected.

The next correction to be performed is based upon Ohm's law. The current measurement is actually a voltage reading across a 100 mΩ resistor and thus Ohm's law must be used to convert from voltage into current.

The next modification is the start time of the readings. The scope marks the zero time point as the moment a trigger occurs. This means there is negative time in the analysis which is not beneficial. This is corrected by simply introducing an offset in time to move every sample such that the first sample is zero.

The next modification is to remove the propagation delay and channel skewing by shifting the voltage waveform by 10.5 ns.

The corrected waveform is shown in Figure 18. Current is in blue and voltage is in red.

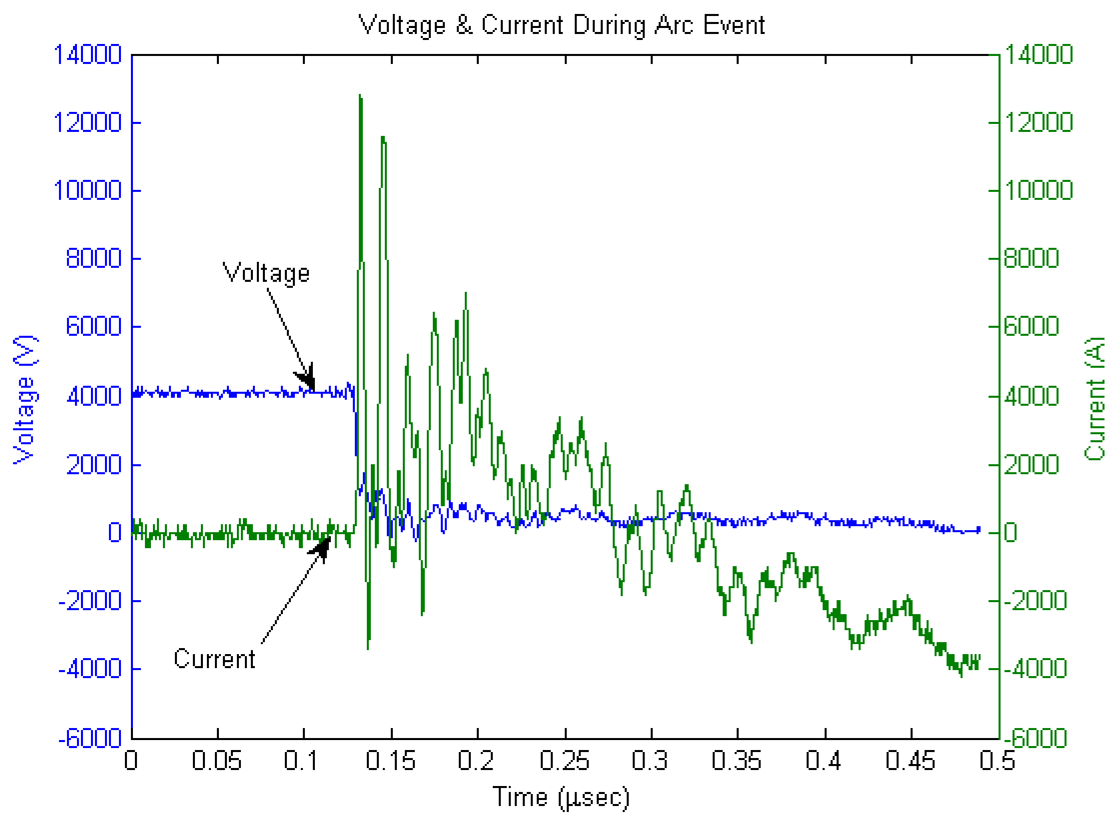

Figure 18: Corrected Waveform for Analysis

One final adjustment required is to remove the high frequency noise from the captured data. The oscilloscope used is rated to monitor signals up to 200 MHz, and does this with a sample rate of $5x10^9$ samples per second (or 0.2 ns/sample).

The probes are only rated to 75 MHz (voltage) and 380 MHz (current). This means that the high frequency information needs to be removed as it is marked as noise by the specifications of the test equipment.

In order to remove the high frequency noise in the signal a low pass filer was implemented. The filter has a stopband starting at 200 MHz and passband corner at 150 MHz with a 60 dB roll-off during the transition band. Figure 19 shows the performance characteristic of the designed low pass filter implemented for both the voltage and current signals.

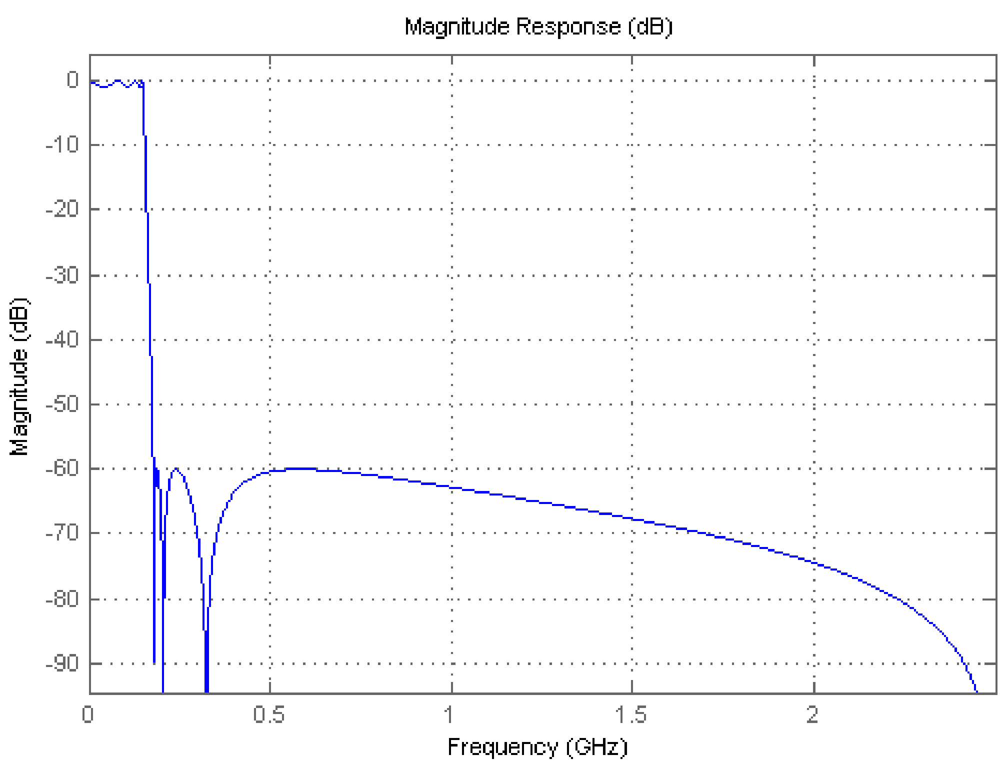

Figure 19: Low Pass Filter Frequency Response

After filtering the voltage and current, the time domain signals were again plotted to show the result.

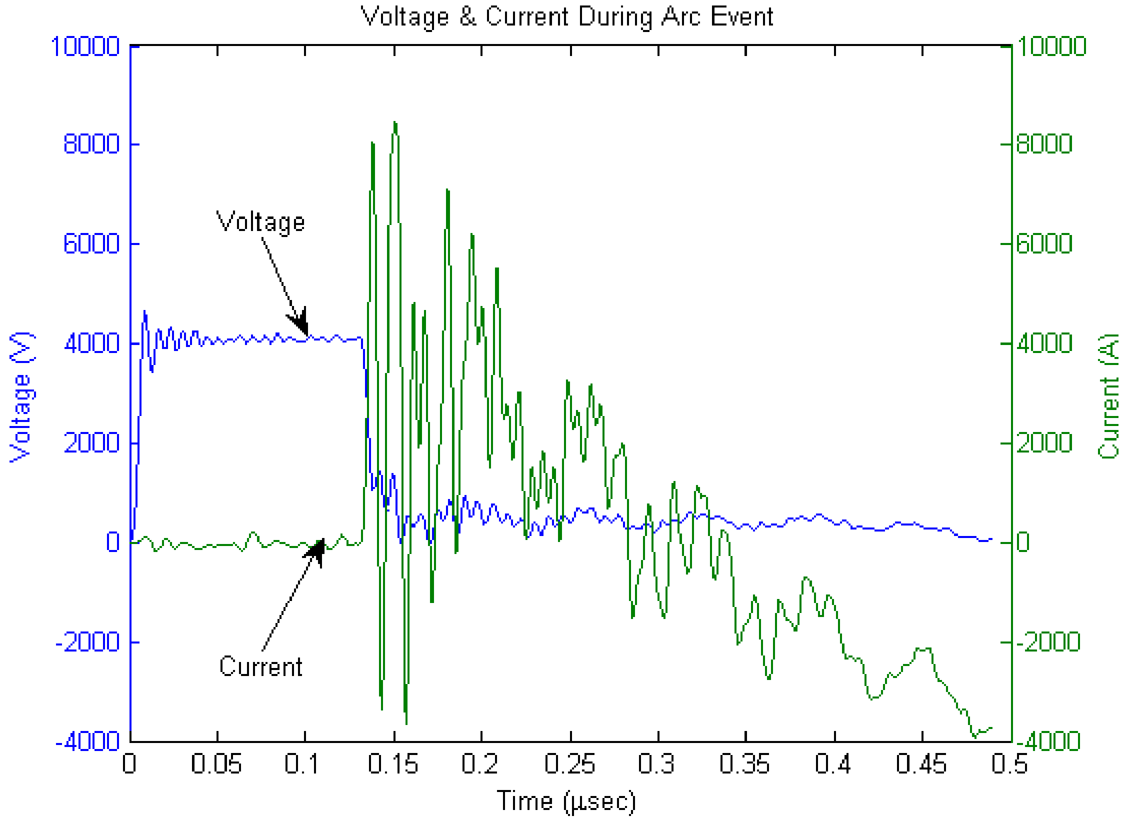

Figure 20: Voltage and Current Time Domain Post Filter

Observing Figure 20 it can be seen that the voltage has a ramping time which is introduced by the phase shift of the filter. This ramping time is not desired for our analysis and therefore must be removed before further study. In order to remove the startup effects the first 0.5×10^{-7} seconds of data from both the current and voltage waveforms were deleted.

This is performed by inspection. The time array was opened and 0.5×10^{-7} was located and the entry into the array marked. This was then used as the starting point for entry into the current and voltage arrays in order to remove the ramping data.

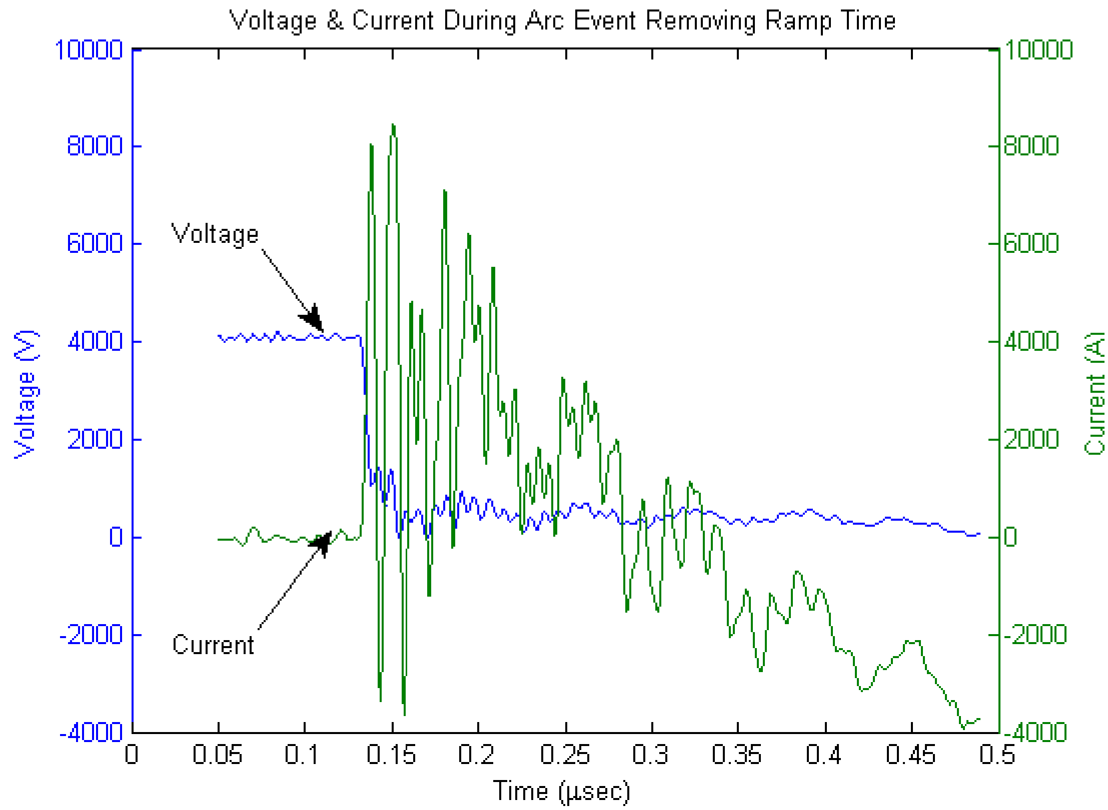

Figure 21: Voltage and Current Time Domain Post Filter, Remove Ramping

The signals shown in Figure 21 are the result of data correction and are fed into the analysis system for further study.

6.4 Summary

Chapter 6 provides a background of the data analysis and the tool utilized. Further it investigates artifacts within the data collected from the Dansk experimental test setup, and details required adjustments. The experimental setup errors made it difficult to determine the behaviour of the voltage/current during an arc event.

CHAPTER 7

RESULTS AND EVALUATION

7.1 Introduction

This section presents the analysis results and an evaluation of the output. Through Matlab scripts, a suite of analysis functions were performed to search for proactive indication of an arc event through plasma signature detection.

7.2 Full Signal Frequency Spectrum

The first analysis step taken was to perform an FFT and plot the frequency spectrum of both the voltage and current components independently. This was performed for the entire captured signal (from start through to extinguished arc). This is important to note and will be explored later.

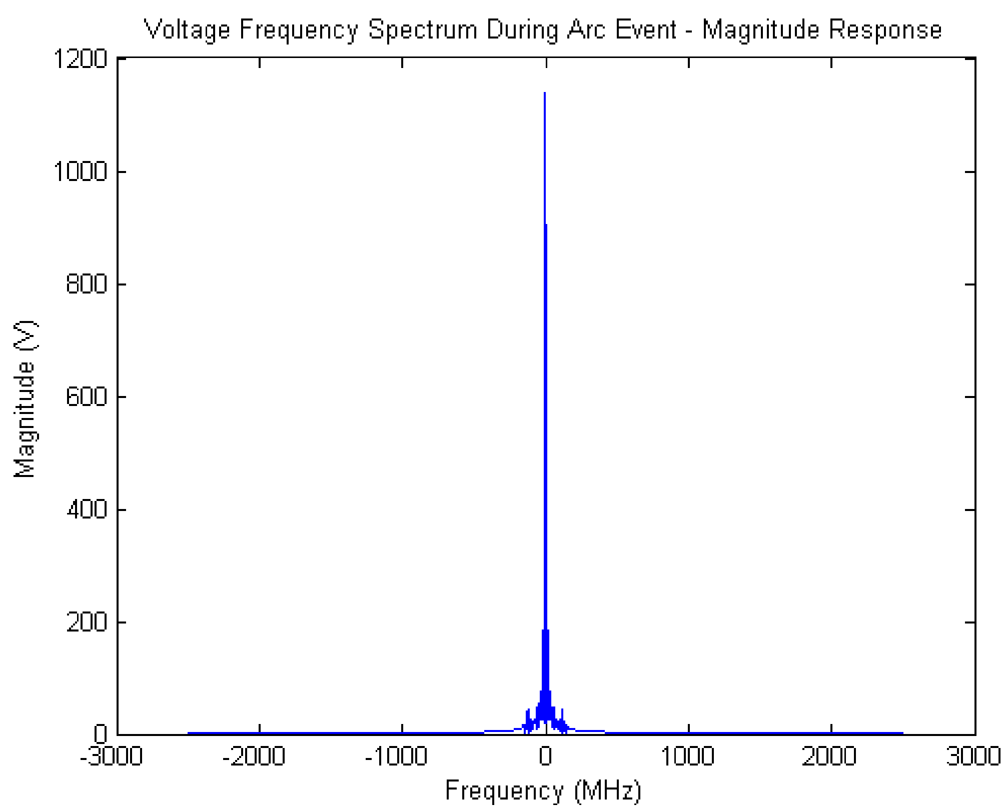

Figure 22: Full Sampled Signal Voltage Frequency Spectrum

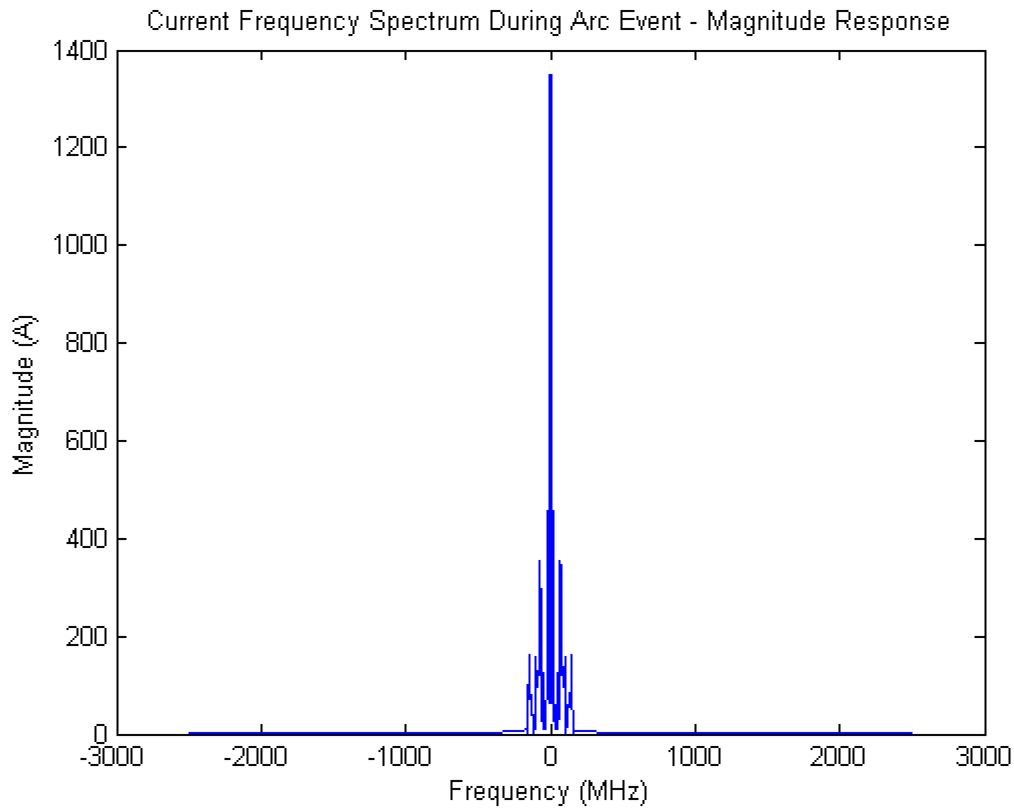

Figure 23: Full Sampled Signal Current Frequency Spectrum

In the previous two figures one observes that the frequency components containing energy continue into high frequency bands. However the bulk of the energy is less than 1 GHz which follows what is expected since the signals have been filtered with a passband corner of 150 MHz. The next series of figures limit the 'x' scale to 200 MHz in order to provide a better visualization of the frequency spectrum of the voltage and current.

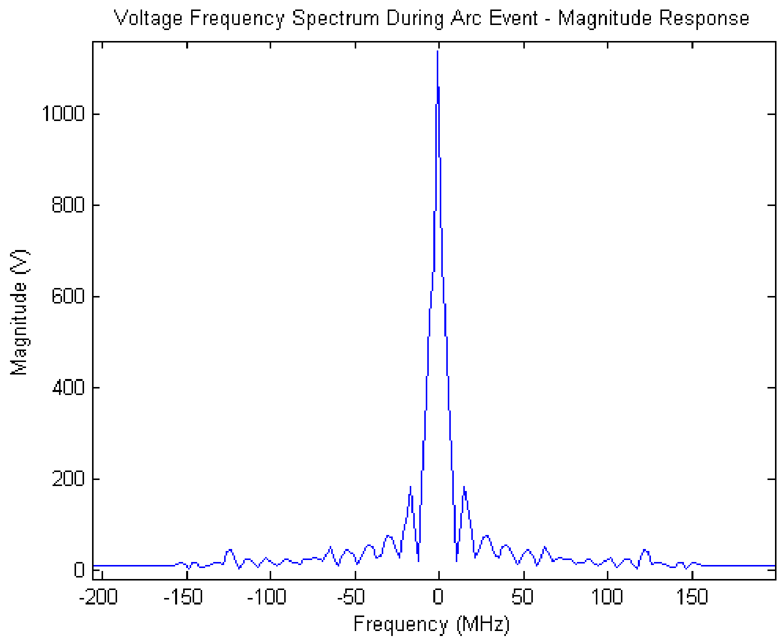

Figure 24: Zoomed Voltage Spectrum Post Filter

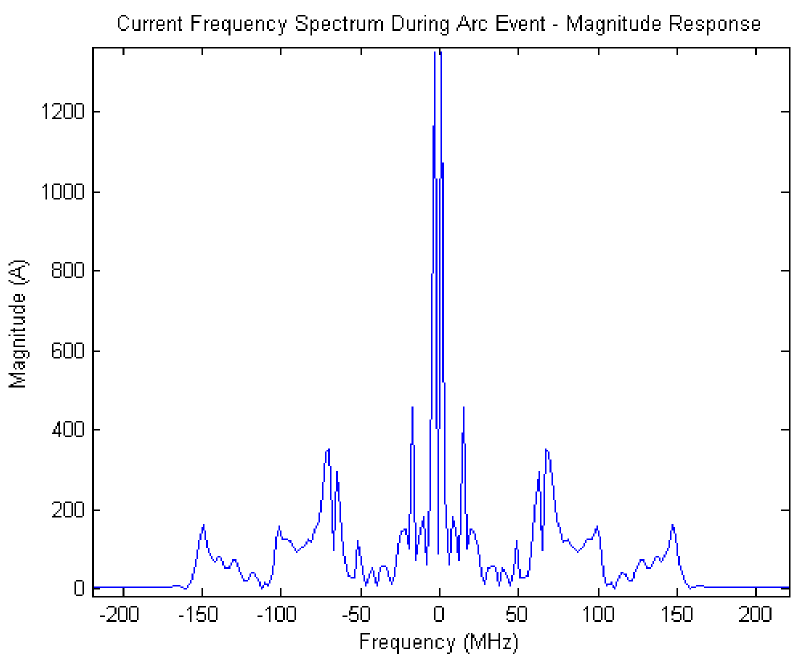

Figure 25: Zoomed Current Spectrum Post Filter

The analysis up until this point was performed across the entire captured spectrum, from initial plasma generation through complete dissipation of energy. The purpose of this thesis is to review the first stage of plasma generation and search for voltage/current property indication. Thus the next stage in the analysis was to remove all data prior to the first voltage drop in order to analyze the information leading to the event.

7.3 Pre-Arc Signal Analysis

The goal of this research is to investigate patterns in noise, or frequency spectrum that would indicate a developing arc event. The next stage in analysis is to separate the pre arc information from the rest of the data and perform an analysis on the signal.

This was done by inspection of the captured data. When an arc has fully developed a drop in voltage from the steady-state of 4 kV is expected, at the point this occurs the data is separated.

Table 5: Matlab Analysis of Transition

Sample Number	Voltage (V)
410	4054.234
411	4024.957
412	3989.424
413	3947.212
414	3897.94

Table 5 shows the original captured data from the oscilloscope showing the voltage transition from 4 kV to the start of the arc and a drop to 3.84 kV. The last used data point will be array index 411 as shown in Table 5.

After extracting and correcting the pre-arc data, the voltage/current captured waveform was plotted in order to better visualize the information under analysis.

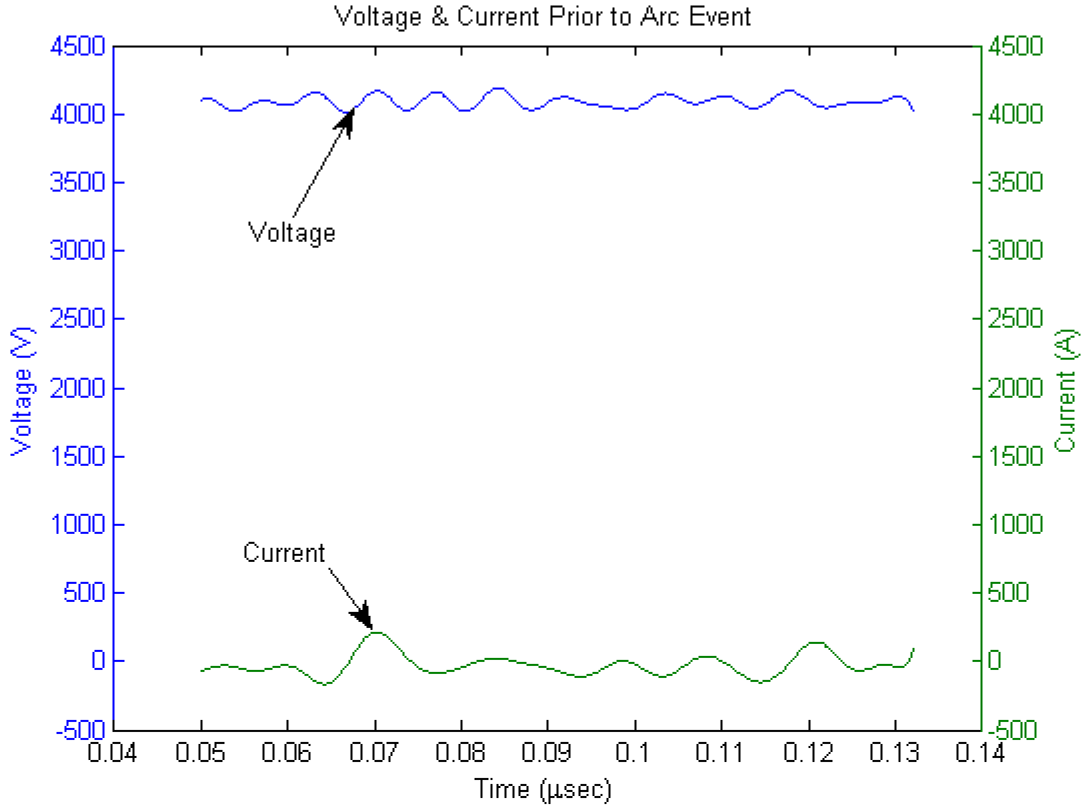

Figure 26: Pre-Arc Captured Data; Voltage, Current

In Figure 26, the voltage and current remain essentially constant throughout the band of data under analysis. There is relatively no current flow and the voltage remains near 4 kV. This is as expected in an electrical power system that does not have an arc occurring.

Now that the pre-arc data has been extracted and corrected we can perform the analysis to look for the existence of data in the waveform that would indicate that an arc event is about to occur. The voltage and current signals were plotted in frequency spectrums.

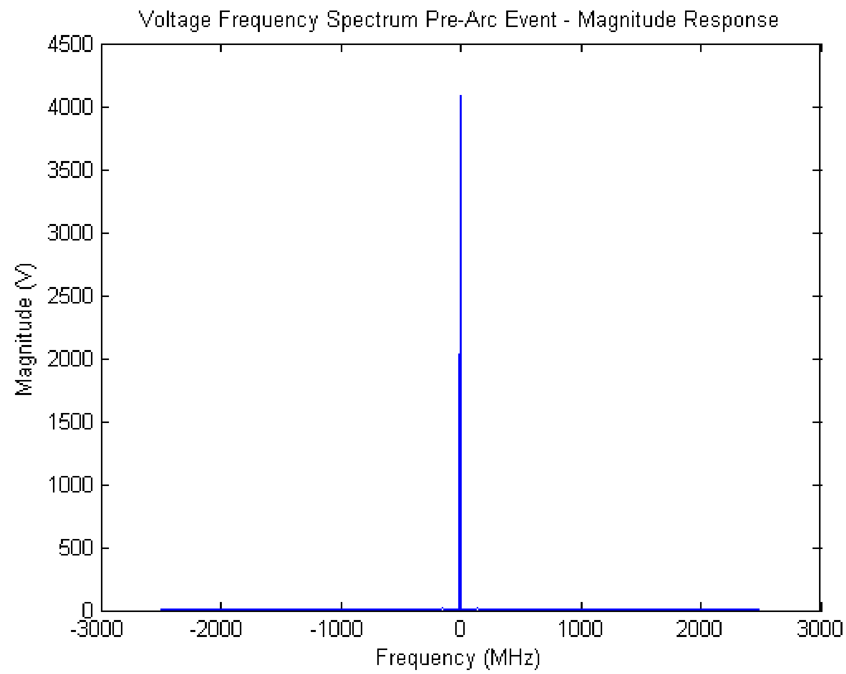

Figure 27: Separate Voltage Frequency Spectrum

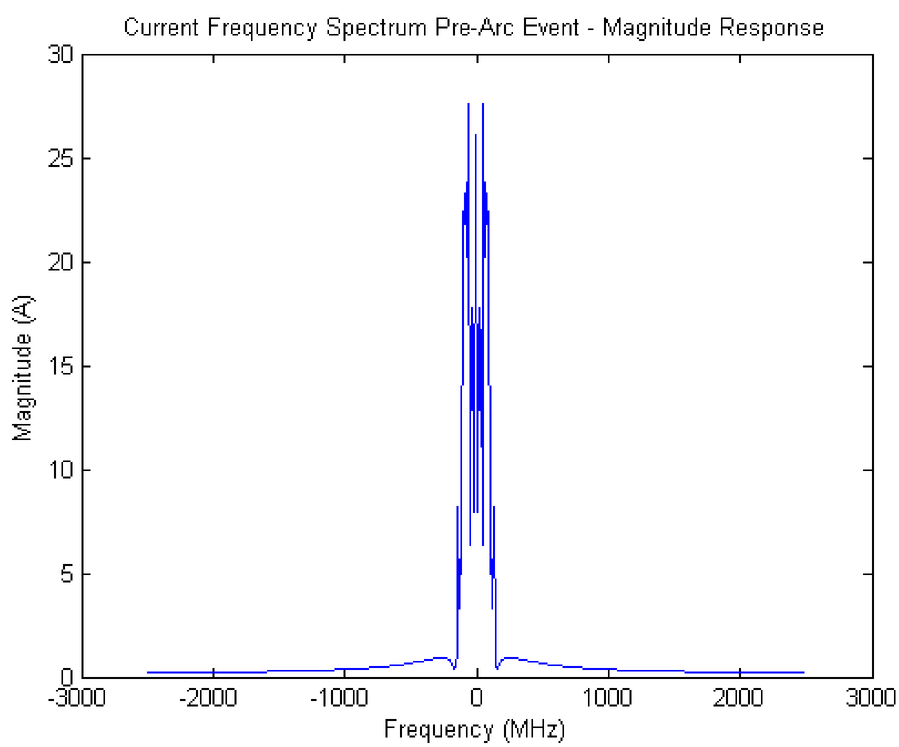

Figure 28: Separate Current Frequency Spectrum

Similar to the analysis done in section 7.2, the previous two figures show frequency components containing energy in high frequency bands. Again the bulk of the energy is less than 150 MHz which follows what is expected since the signals have been filtered with a passband corner of 150 MHz. Figures 29 and 30 limit the 'x' scale to 200 MHz in order to provide a better visualization of the frequency spectrum of the voltage and current. The zoomed in signals follow.

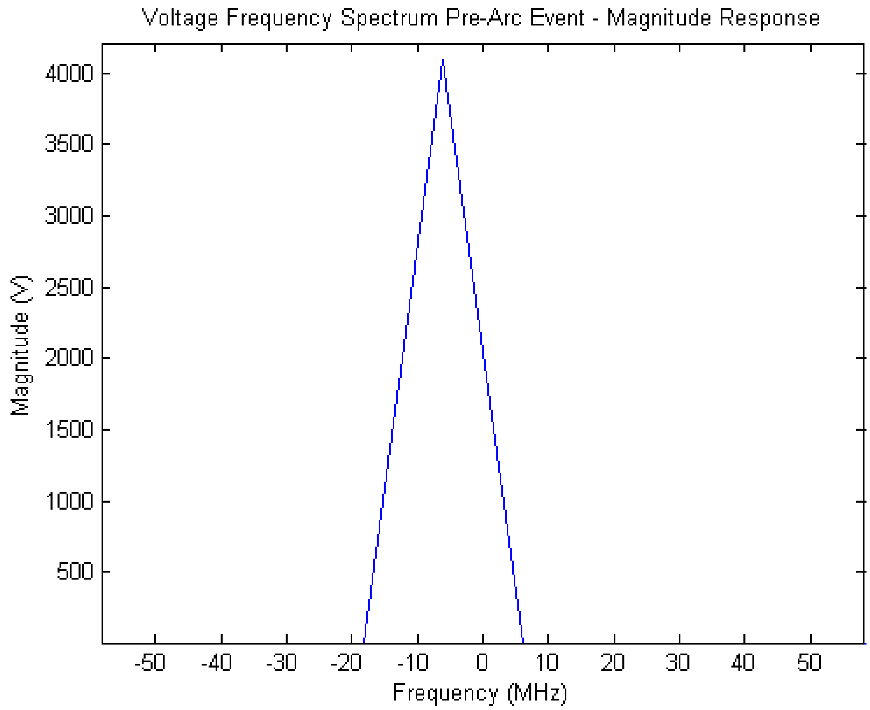

Figure 29: Zoomed Pre-Arc Voltage Spectrum Zoom

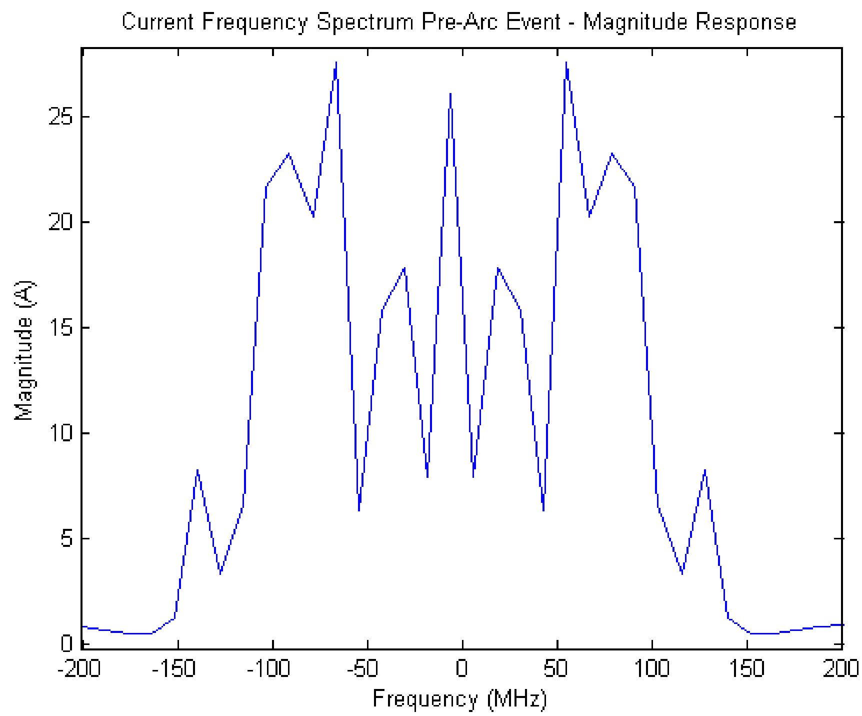

Figure 30: Zoomed Pre-Arc Current Spectrum Zoom

Now that the time and frequency domain (FFT) information for voltage and current pre-arc event are plotted, it should be noted that a further separation can be performed. The time domain plot in Figure 26, shows that there is enough information remaining to separate the signal in order to get a view of the steady-state response of the system vs. the pre-arc event period.

7.4 Steady-State Condition

In order to isolate the steady-state properties of the signal the pre-arc data was separated into two sections directly in half. In this way, the steady-state was marked as the first half of the signal, with the pre-arc the second half.

First plot the time domain response of the steady-state condition, as shown in Figure 31.

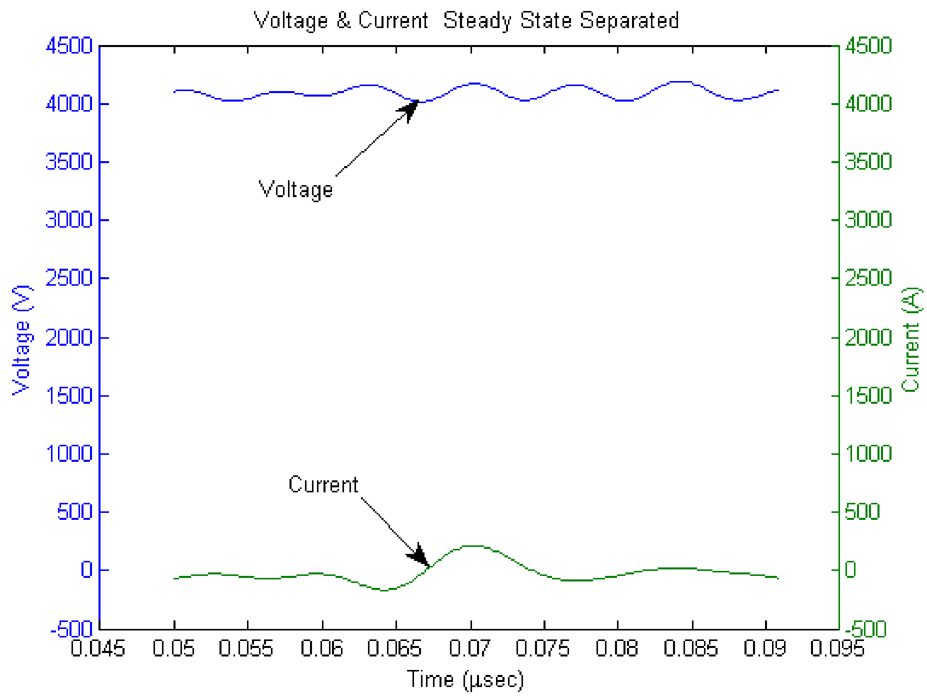

Figure 31: Voltage and Current Steady-State

Figures 32 and 33 plot the frequency response using FFT. These signals are zoomed in order to best show the energy range of the system.

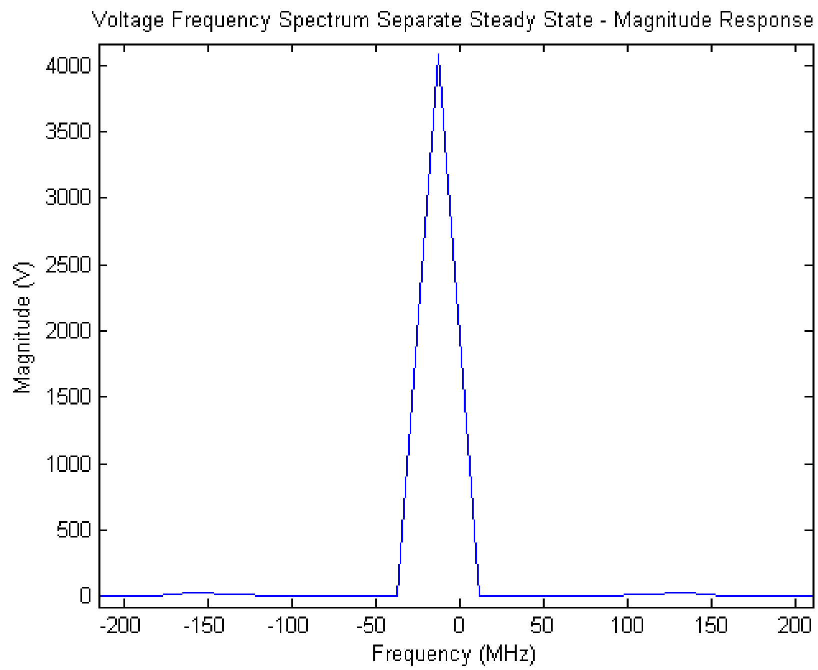

Figure 32: Steady-State Voltage Frequency Spectrum Zoom

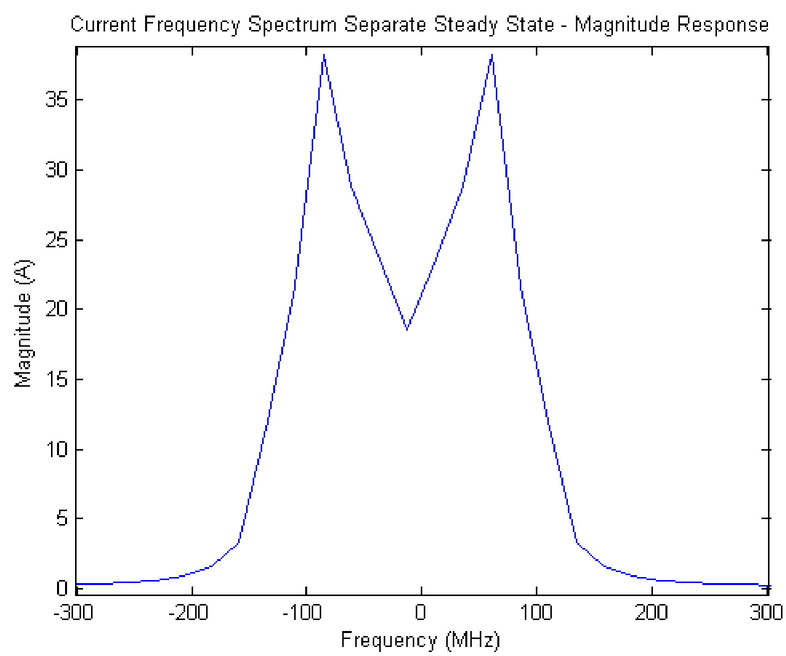

Figure 33: Steady-State Current Frequency Spectrum Zoom

7.5 Immediately Prior to Arc Event

Now that the properties of the steady-state have been plotted, the process can be repeated for the pre-arc system information that occurs after the steady-state response. This region is plotted in the time domain (Figure 34), followed by the frequency spectrum (zoomed in FFT) for both voltage (Figure 35) and current (Figure 36).

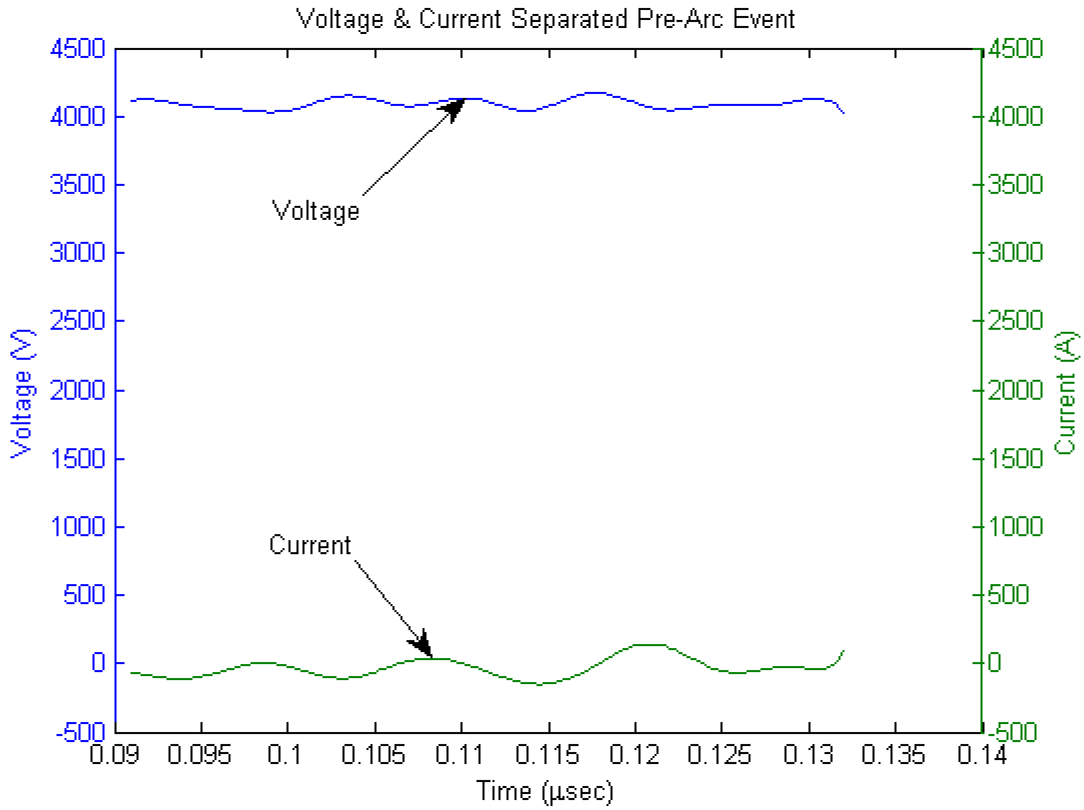

Figure 34: Pre-Arc Event Time Domain, Post Steady-State Voltage and Current

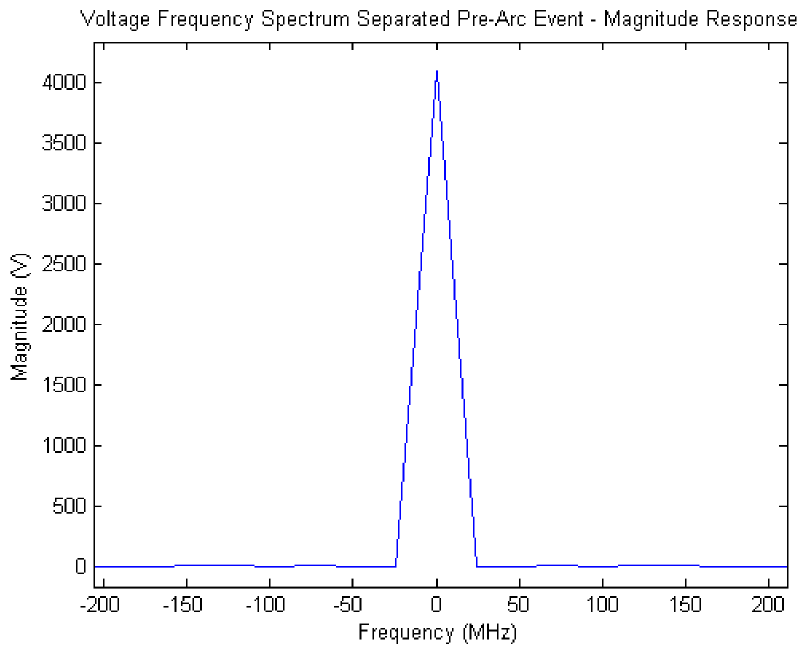

Figure 35: Pre-Arc Voltage Zoomed, Post Steady-State

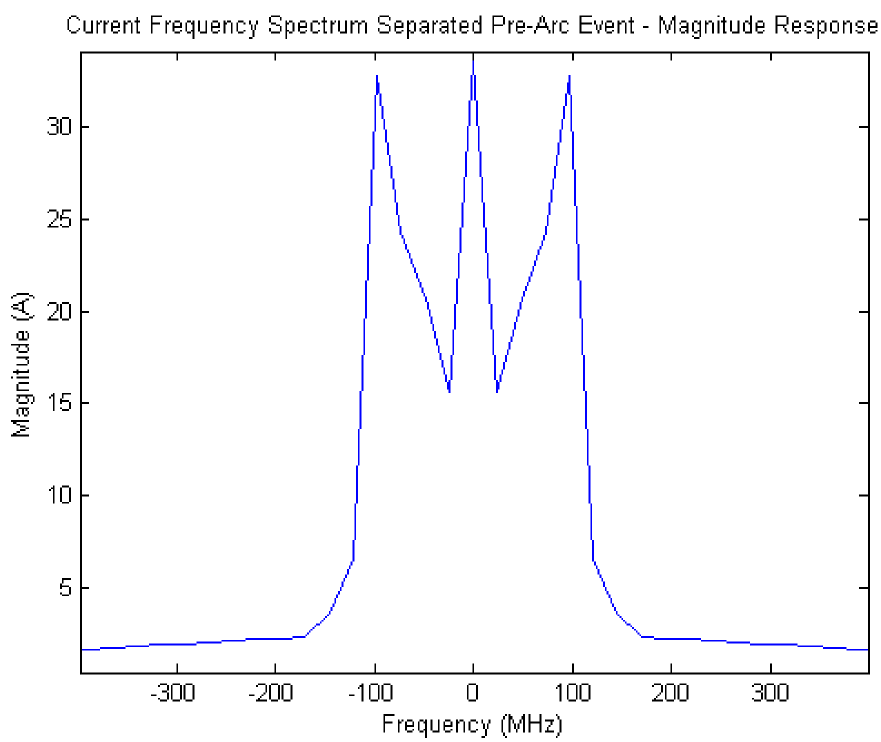

Figure 36: Pre-Arc Current Zoomed, Post Steady-State

Through inspection of every plot and analysis thus far, one observes that there is nothing of significance detected outside of the noise. This indicates that there may be nothing to locate during the generation of plasma. In order to ascertain this some adjustments to the test setup are required.

7.6 Summary

Chapter 7 presents an analysis of the data recorded from Dansk experimental test setup. This data is broken into sections, full spectrum, pre-arc, and steady-state. The goal is to locate any pattern in the data that would indicate an arc is pending. Because the Dansk experimental test setup did not include a light sensor, clear conclusions were not possible and any identified patterns in the signal were not as significant since the separation point between light detection and patterns in the power could not be identified.

CHAPTER 8

RESULTS AND EVALUATION REVISITED

8.1 Introduction

Through the analysis of the previous section one observes that there is nothing located beyond the noise floor of the system. This however, is not enough to state that there is no noticeable change during the dark phase of plasma development, since the test setup was not built to measure the point when light appeared. This chapter begins with a new test setup, capturing the light, voltage, and current in an effort to properly measure the energy of the system.

8.2 Sparky Experimental Test Setup

In order to ensure the most accurate data is collected we have to identify problems encountered with the original test setup and data. They are as follows:

1. No Light Detection
2. No Time Errors from Oscilloscope & Probes

To deal with these limitations the test setup has been modified with the addition of a light detection device, and working in advance to remove timing offsets from the scope. Synchronization between channels is avoided by using a better quality scope, and a matching set of probes. There is still a delay from the event occurrence and recording the data, however Sparky has a uniform delay wherein it is equivalent between all captured channels. Considering the speed of light and the velocity of current flow through probes wires (6 ft long) it is estimated to have a uniform delay of 9 ns from event occurrence to recording of data.

Table 6: New Test Setup Equipment

Device	Make/Model
High Potential Tester	Slaughter Hipot Tester 02975
Spark Plug	Champion Copper Plus
High Voltage Meter	Resistor Divider Network
Current Meter	Voltage Across 1 Ω Resistor
Oscilloscope	Yokogawa DL9040 Oscilloscope

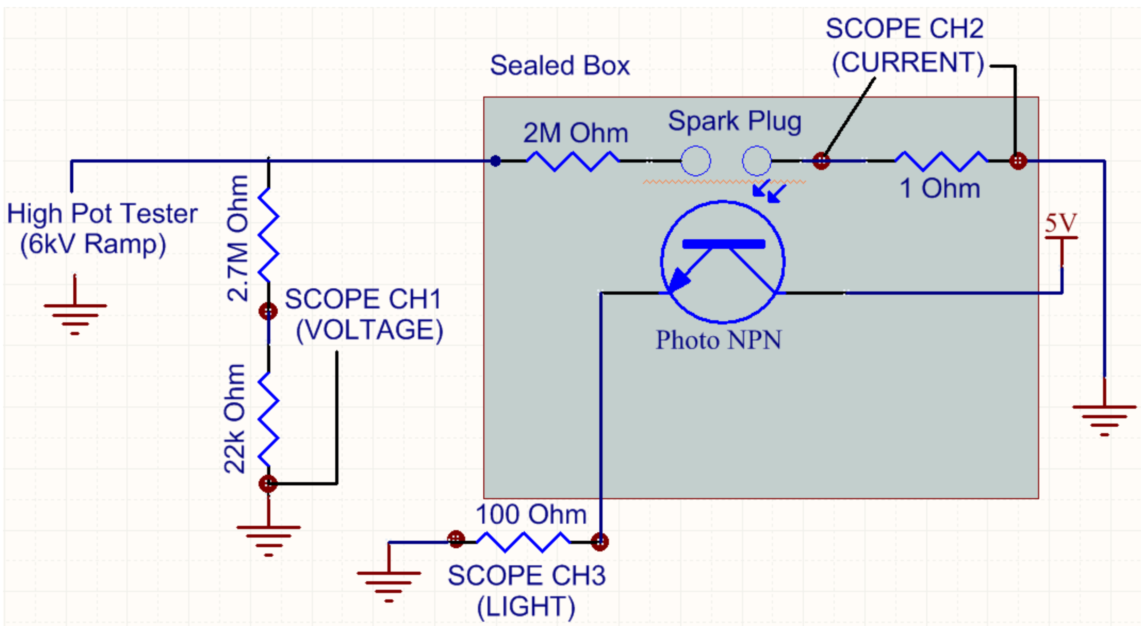

Figure 37: Sparky Test Setup Schematic

The original test setup was performed in an arc flash laboratory. Unfortunately, it is not cost effective or easy to repeat the test. Therefore the new test setup modifies the configuration slightly based upon available equipment at the expense of high levels of current.

8.3 Spark Gap

The new test setup uses a spark plug and the spark gap within. The chosen spark plug has a gap of 0.610 mm, which through testing provided a spark at approximately 2.3 kV.

The higher the spark gap, the greater the voltage required to arc across, and the more intense the light. A rule of thumb is available to estimate the voltage required to arc across a spark plug in open air. It states that for every cm of gap, it takes 30 kV to initiate an arc. For the chosen spark plug, 1.83 kV is estimated to be required to create an arc.

In order to get a bright light for detection, the gap was widened and the spark voltage measured. It was found to spark at 4.85 kV; using the previous rule of thumb this places the gap at 1.6 mm. The gap was measured and found to be TODO mm, which is close to the expected value.

8.4 Sparky Experimental Test Setup

The second test setup was constructed and tested in order to ensure it operated as expected. The following series of pictures show the constructed setup and wiring.

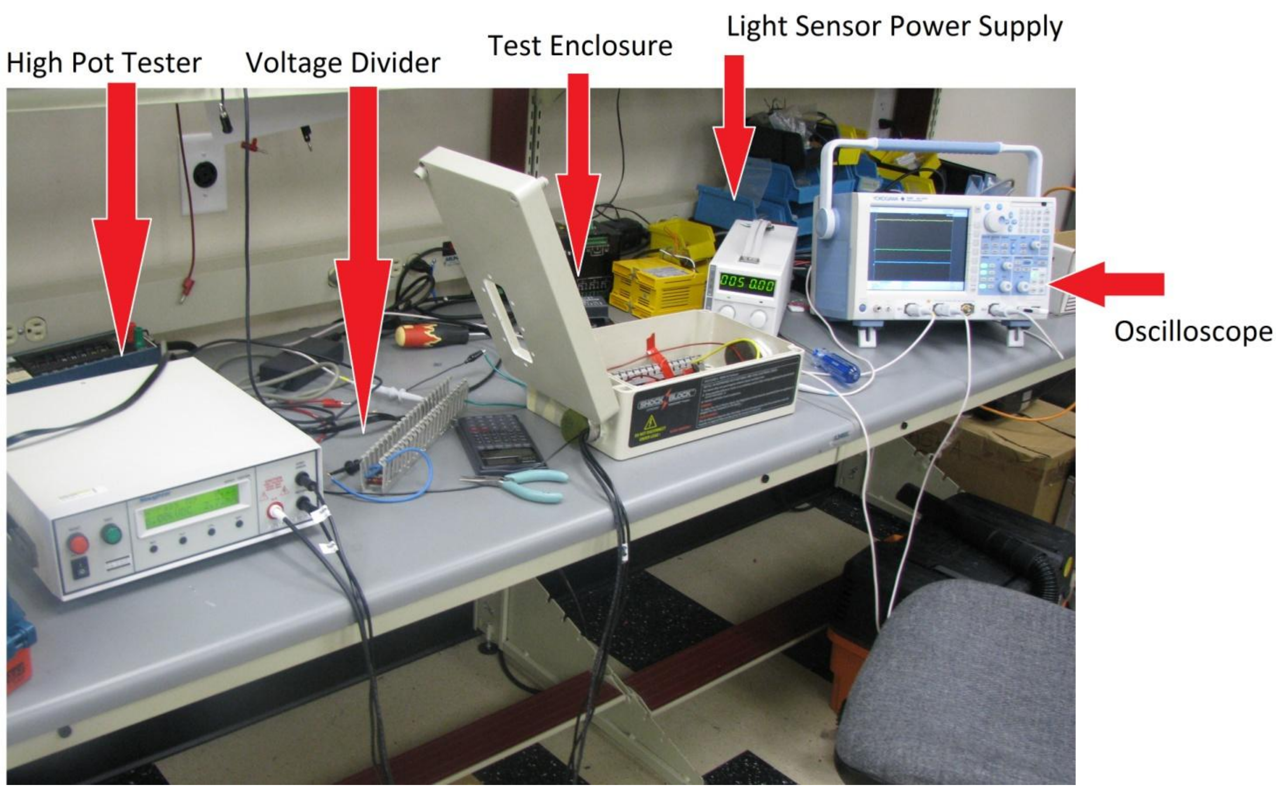

Figure 38: Sparky Test Setup

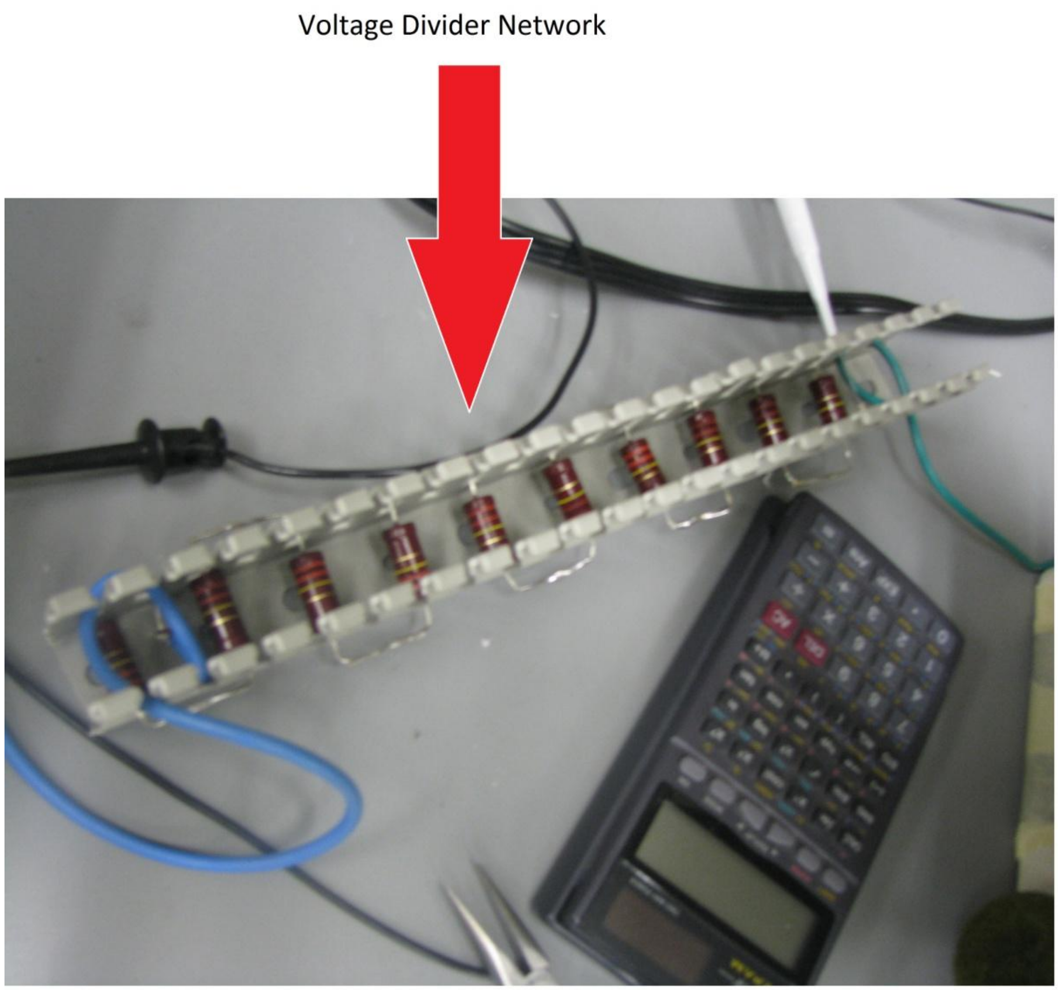

Figure 39: Voltage Measurement Resistor Divider Network

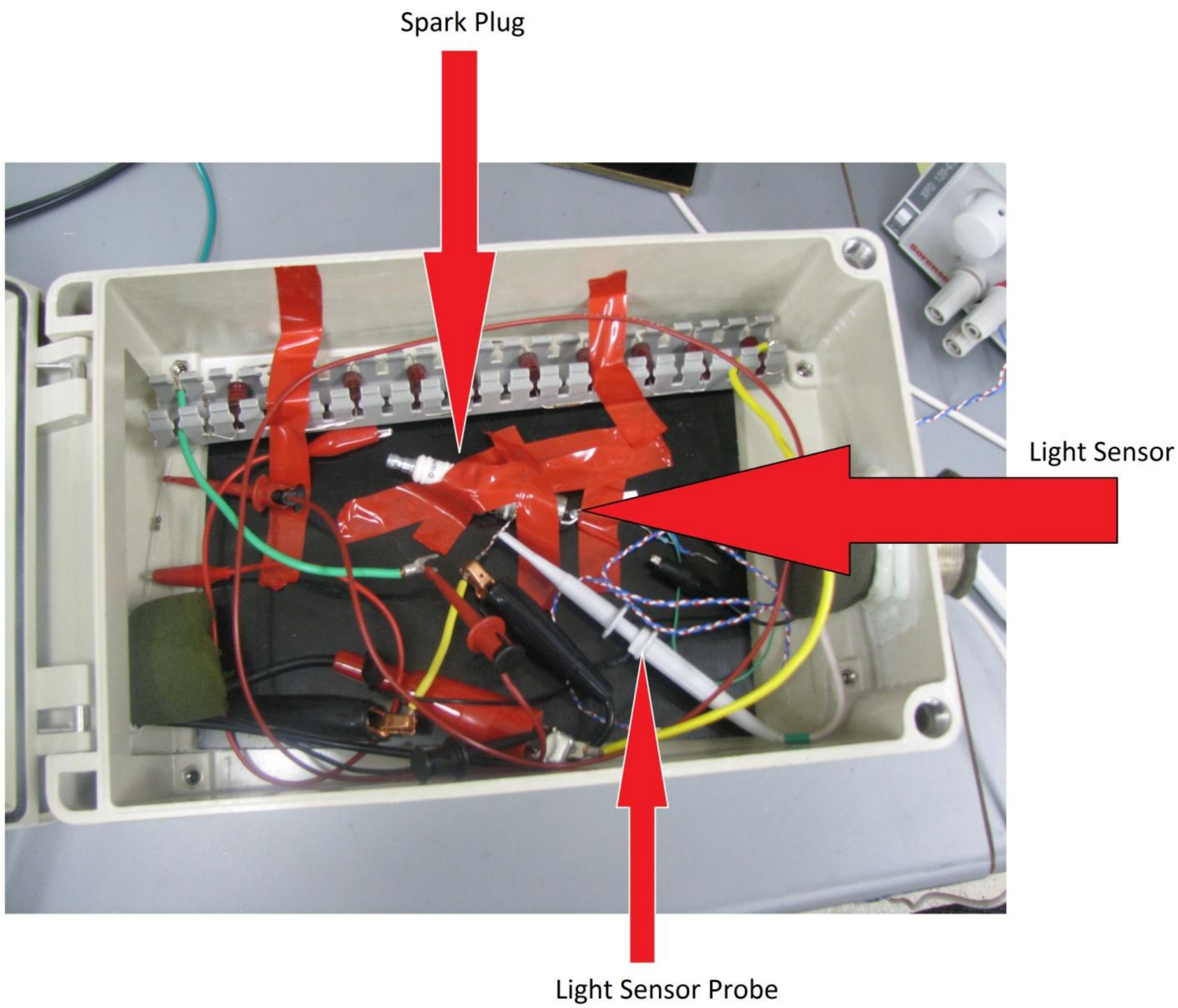

Figure 40: Inside Box Showing Arc Gap, Light Detector

8.5 Output Characteristic of Hipot Tester

A hipot tester is designed to test devices to ensure that the distance between input and output or power and ground is enough to avoid breakdown that may cause arcs and safety hazards. The particular hipot tester utilized can only output 6 mA maximum, so it is not designed for the high energy levels output during arc flash testing. This difference necessitates the importance of understanding the characteristics of the device to ensure the arc is not impacted by the behavior of the source as the voltage ramp progresses from 0 to 6 kV.

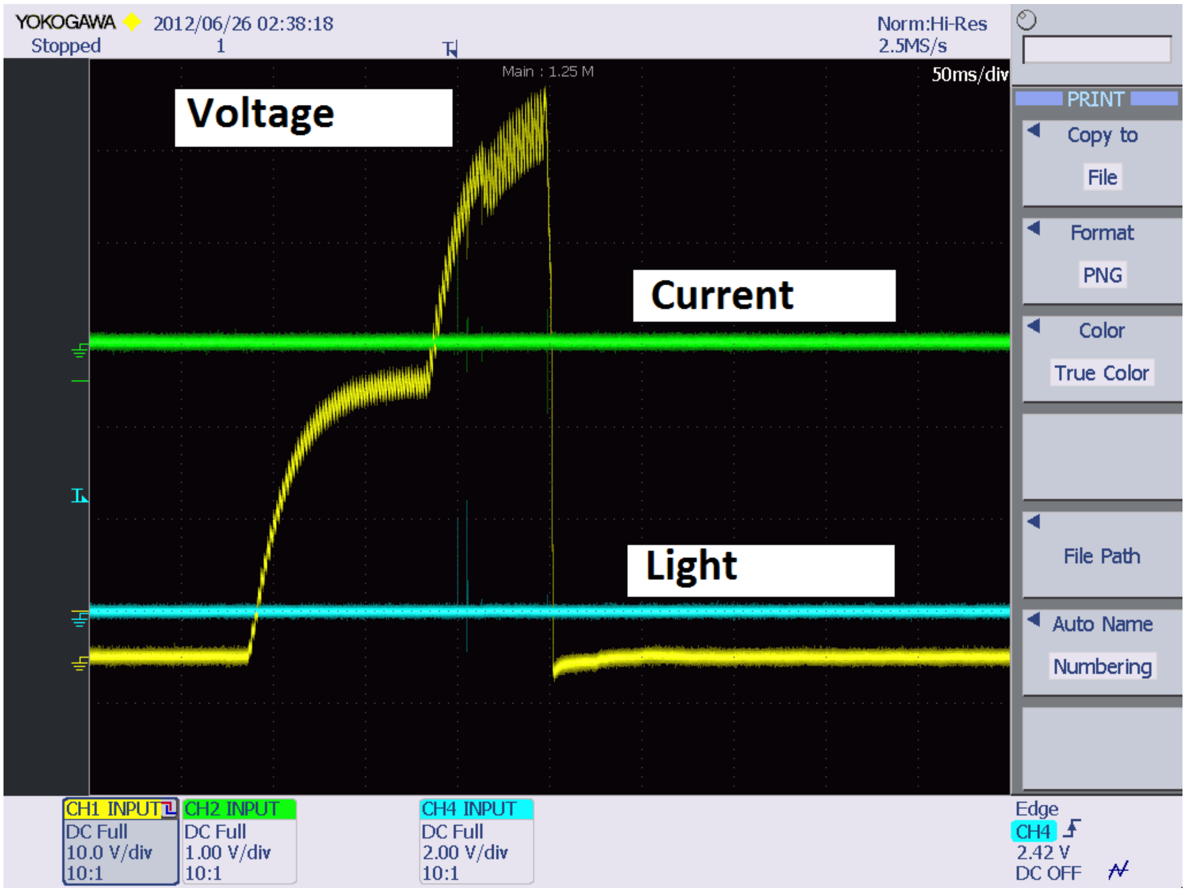

Figure 41: Hipot Tester Voltage Ramp (100x Reduction)

Figure 41 shows the hipot tester does not provide a linear ramp of voltage. Instead there are several steps and partially linear regions. This process is not ideal if an arc occurs during the ramp cycle of the hipot tester since the oscillations of the tester and the voltage ramp may mask the behavior of the initial stages of the arc. Due to this the test setup has an additional series resistance prior to the spark plug. This increases the breakdown voltage to almost 6 kV, which is the end of the hipot ramp process. In fact in the analysis of the data graphs will show that the voltage is stable and flat prior to and during the initial stages of the arc event, ensuring that the ramping pattern does not impact the test data.

8.6 Sparky Test Procedure & Repeatability

Referring to Figure 37, channel 3 on the oscilloscope was connected to the light sensor output and was setup as the trigger point. Channel 1 (Voltage), and Channel 2 (Current), data was combined with Channel 3 (Light) and stored at 5 gig-samples per second on a USB memory stick.

The test was repeated ten times and in each repetition the same timing of current and light detection occurred.

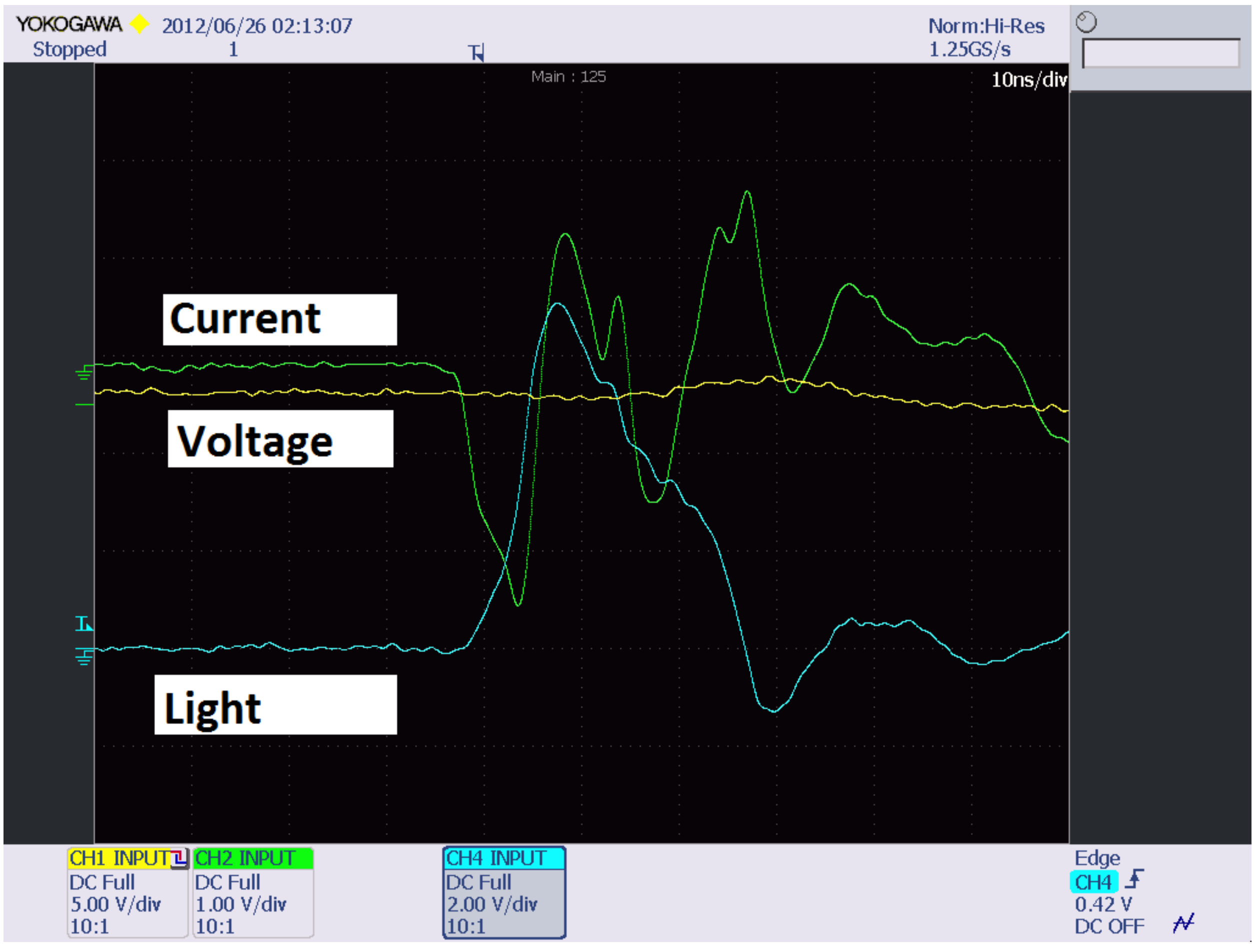

Figure 42: Voltage, Current, Light Repetition Example 1

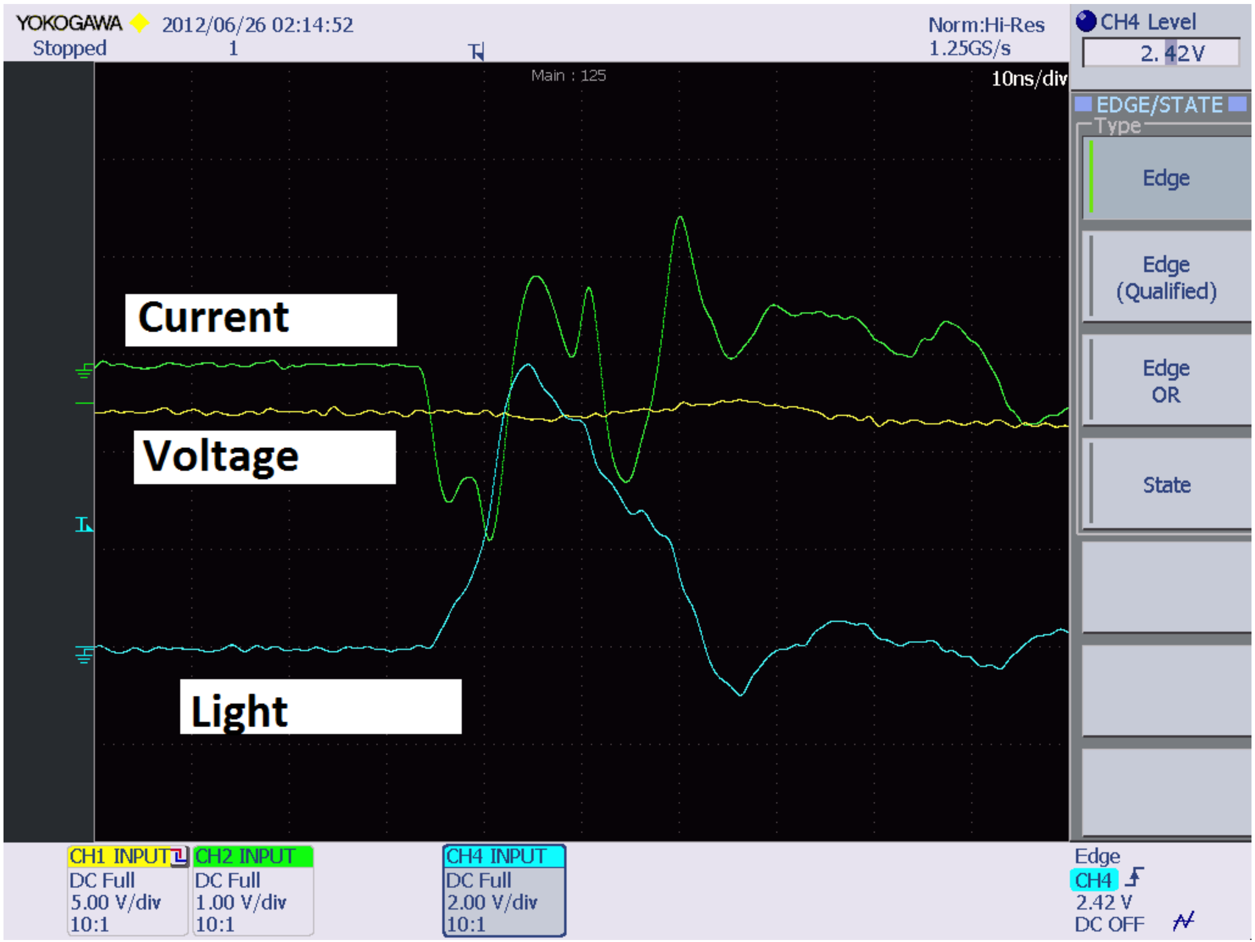

Figure 43: Voltage, Current, Light Repetition Example 2

Figures 42 and 43 show additional test results as captured by the oscilloscope, observe that the current flows prior to the light in each run of the test. This repeatability provides confidence in the accuracy of the results obtained from the Spark experimental setup.

8.7 Summary

In order to improve the analysis of an arc a second experimental test setup was constructed. This setup utilized a light sensor and a scope with matching probes to remove time discrepancies. Arc flash involves high power and dangerous conditions. The Sparky experimental setup was designed around lower power levels in order to avoid the requirement of specialized laboratories. The spark gap is set to a fixed distance and a hipot tester is setup as the low current, high voltage source. The light sensor was used as the trigger on the scope and provided a clear distinction between start of current and beginning of the visible spectrum of the arc event.

CHAPTER 9

SPARKY TEST SETUP ANALYSIS

9.1 Introduction

This chapter presents the captured waveforms and data for analysis in order to discover the timing of the flow of current as compared to light to indicate that an arc event is imminent. Additionally in the interest of completeness, the electric field and magnetic fields were monitored in order to identify the relative speed of these detection approaches compared to light.

9.2 Steady-State Analysis

Before a complete analysis of an arc is performed the steady-state operating conditions are analyzed in order to appreciate the changes occurring as a result of the arc flash. Additionally, this provides an opportunity to verify the Matlab routines by comparing the oscilloscope screen capture against the reproduced Matlab graph.

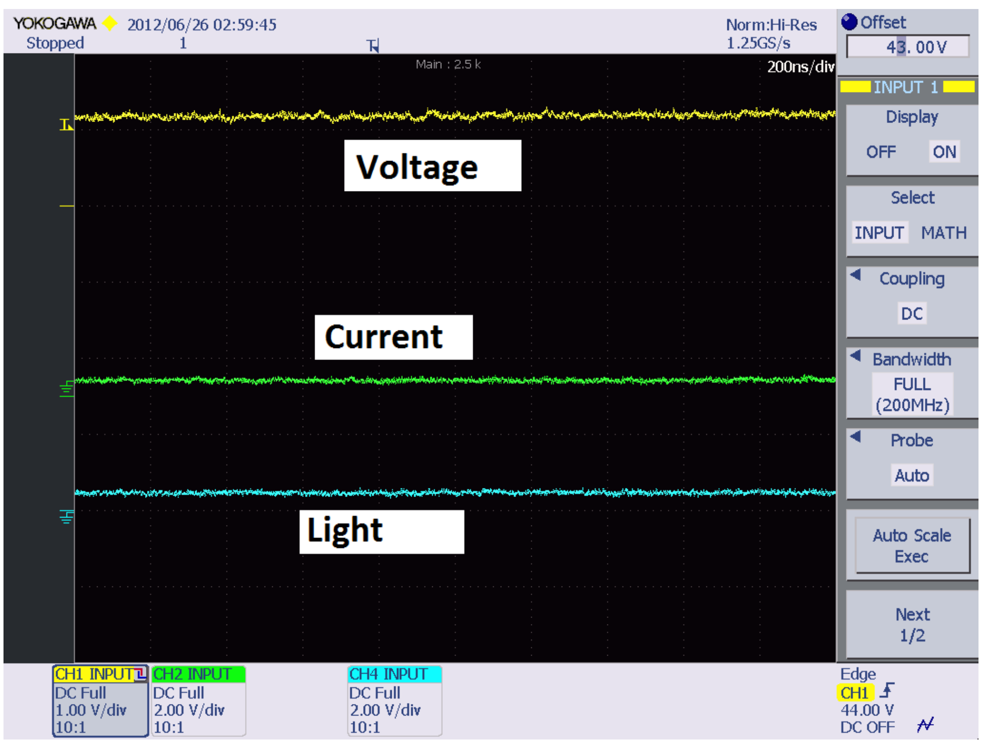

Figure 44: Steady-State Voltage, Current, and Light

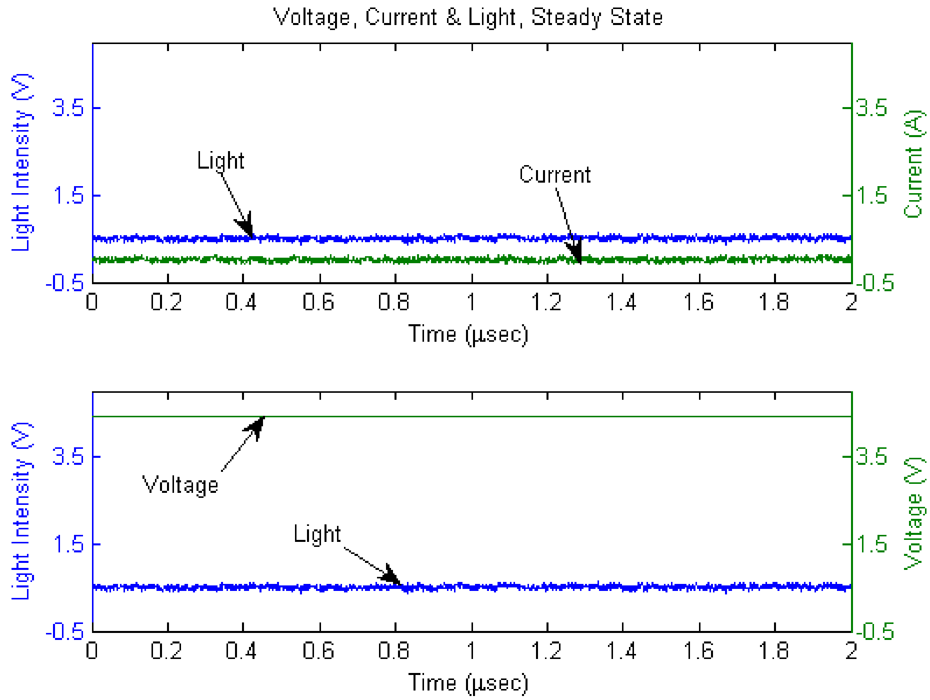

Figure 45: Matlab Reproduced Plot of Voltage, Current and Light

The previous figures show both the oscilloscope data and Matlab time domain information of the steady-state conditions of the test environment. The scale of the voltage was divided further by 10 for the Matlab plot in order to permit the current and light to be displayed with similar resolution as the oscilloscope screen. For the analysis outside of the time domain the voltage magnitude will remain at the actual values.

The light information is present as a trigger for the start of the arc event and as such is not important for the purposes of the steady-state analysis.

The magnitude response of the voltage and current signals plotted in the frequency domain are shown in the following graphs.

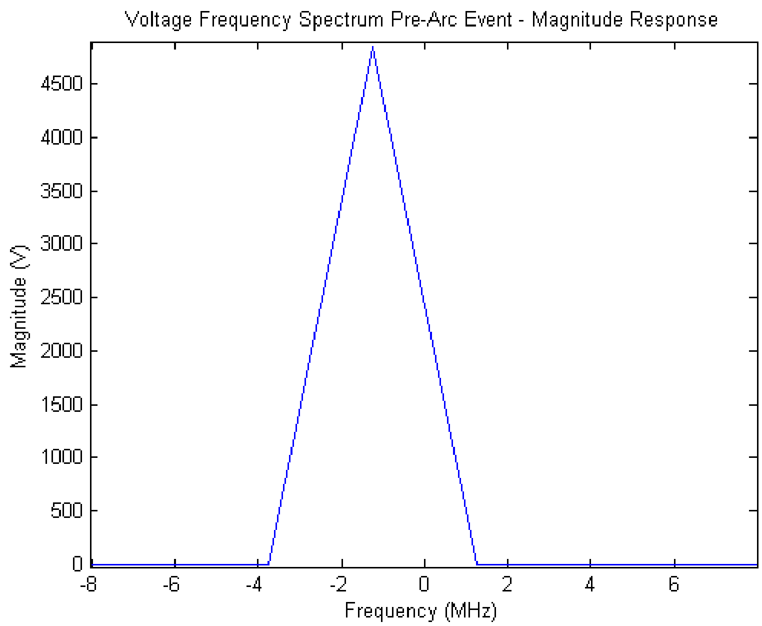

Figure 46: Voltage Frequency Response

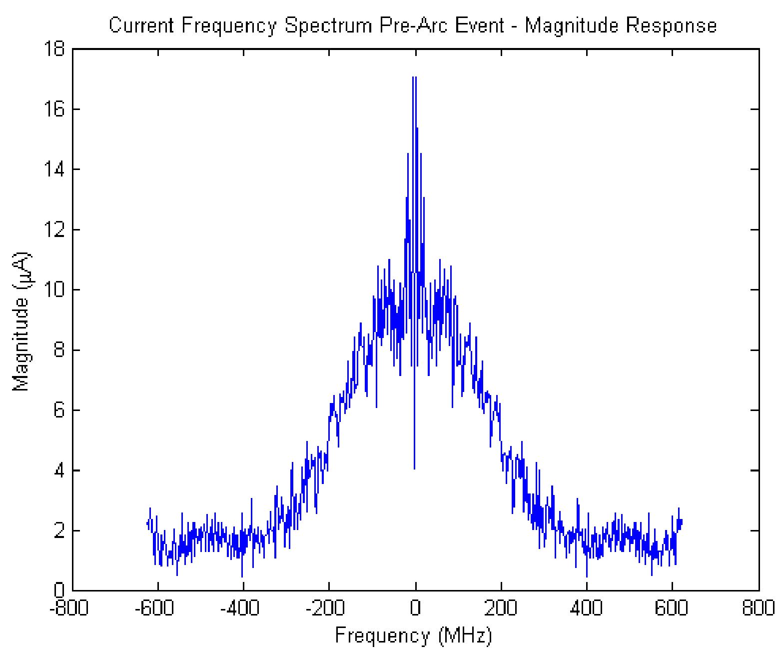

Figure 47: Current Frequency Response

Since there is no arc present, the voltage is constant through the measurement, and the current is not flowing, indicated by the fact that the current waveform only measures what appears to be noise. The magnitude of the current does not exceed 20 µA which can be established as the noise floor of the test setup.

9.3 Sparky Test Setup Arc Event Analysis

An arc event is now introduced across the spark gap in order to record/analyze the information. First the data was plotted in the time domain in Figure 48.

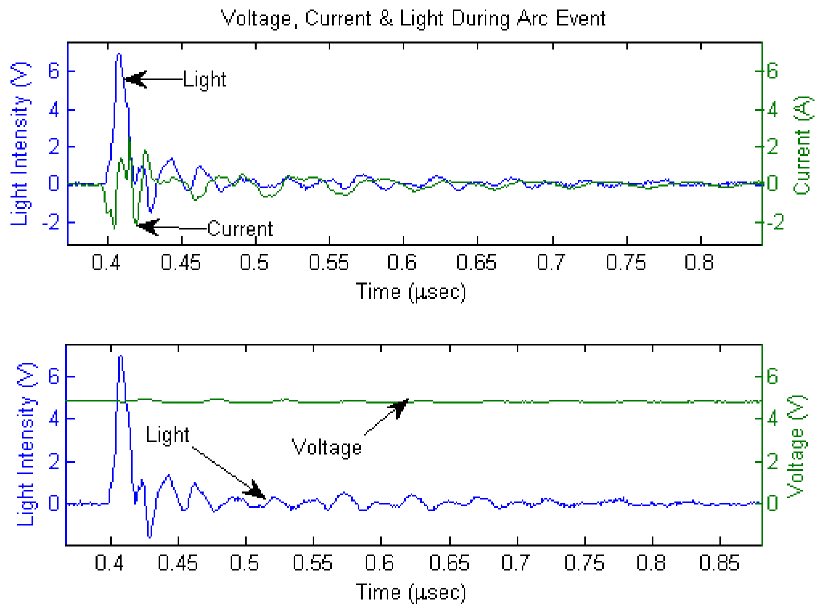

Figure 48: Voltage, Current, Light – Full Spectrum

Figure 48 shows a plot of an arc event. The voltage shows some ripple, but does not drop off as per the previous test setup. The Sparky test setup uses a constant voltage source such that when these events occur, the voltage is maintained at the high level. The current shows that it actually begins to flow before or at the same time as the light is sensed, and travels in the negative direction.

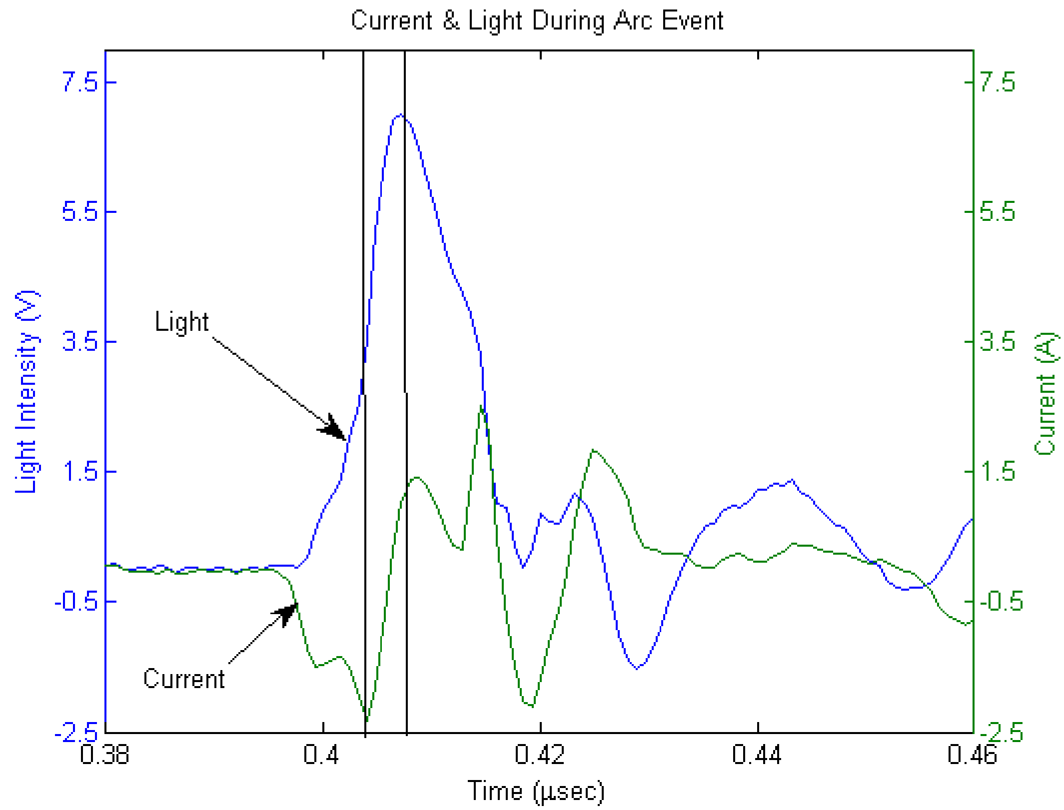

Figure 49: Zoom in on Current & Light

By zooming in on the region where the current and light sensors reach respective peaks, it is easier to observe the speed difference. The light waveform reaches peak after the current, as shown in Figure 49.

In order to better measure this difference the waveform was zoomed in further. The resulting measurement is shown in Figure 50. As observed, the minimum gain between light and current sensors is 4 ns. While this is not a gain of substantial value, it is important to be reminded of the energy of the arc under test. This arc has energy of 4 kV, with sub 5 mA current. Compared to an arc flash scenario with hundreds of volts and amperes, the test is very low.

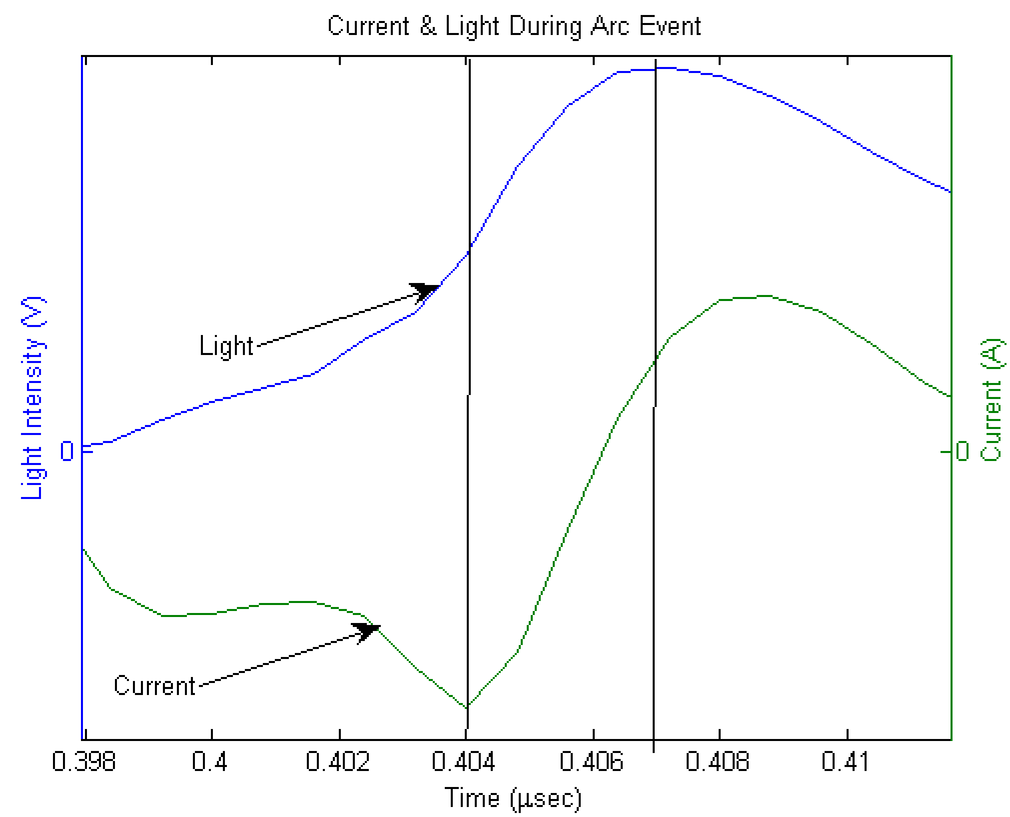

Figure 50: Measuring Time Difference

This seems to indicate that the dark discharge region is drawing negative currents as the dielectric of air is broken down and the arc formation begins. The time difference of 4 ns is low, but the amount of time the arc generation spent in the dark discharge region of plasma development is significantly shorter than would be expected during a high energy arc flash scenario. This is due to the distance and energy released during the tests compared to an arc flash event. In order for an arc flash to occur, more energy feeds into the arc gap region and it takes a longer time to develop.

By observation of Figure 50 one recognizes that a strong conclusion can be obtained. Current is detected in the ground path very early on, and Sparky test setup shows that this occurs before the presence of light.

Through observation of the pre-arc waveform presented, it is clear that the process of generating the arc does not have any impact on the voltage and current prior to the flow of current in the dark discharge region. The results follow a similar conclusion found by analyzing the Dansk setup in 7.3 Pre-Arc Signal Analysis.

One difference between Dansk test setup and Sparky is that Sparky is setup to measure the light. Inspection of Figure 50 shows that current conducting through the ground path begins before light.

9.4 Further Analysis

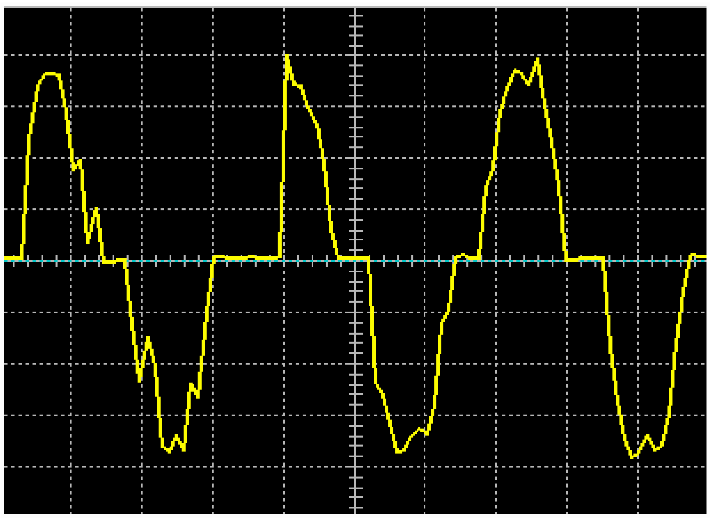

Figure 51: Arc Fault Current Example [42]

Figure 51 is pertinent to the hypothesis and analysis. The figure shows the transient current waveform captured with 12-bit resolution and 520 µseconds per sample (32 samples per 60 Hz waveform). This data was taken by research investigating the arcing properties of many different systems, in order to develop AFCI technology. It is important to note that during the periods of active arcing, there are high frequencies present in the captured waveform. [**42**] This is especially interesting as this indicates that a similar detection solution for Arc Flash is possible.

The Sparky experimental test setup monitored the fault current and verified the hypothesis that voltage/current patterns exist prior to light detection. Now that it has been identified that the current flows prior to the existence of visible light, research into the pattern recognition of such an event is justified. Further research and data collection are required to determine the algorithm required in order to detect discontinuities on the supply side of the fault, which can then be differentiated from other events (disconnection of device, power down, etc), creating a standard model pattern recognition problem. This is similar to the path taken when AFCI technology was developed, and will require a significant amount of testing in order to generate a database of sufficient size to create an accurate algorithm.

9.5 Electric and Magnetic Field Arc Detection

In the interest of performing a complete analysis and since the measurement equipment was available, meters for both electric and magnetic fields were used to determine applicability of these fields to measuring arc events.

Table 7: Electric and Magnetic Field Probes

Field Measured	Manufacturer	Model	Description
Electric Field	Credence Technologies	ScanEM-HC Model CTM032	Near Field EMI probe for Magnetic Field
Magnetic Field	Credence Technologies	ScanEM-EQC Model CTM034	Near Field EMI probe for Electric Field

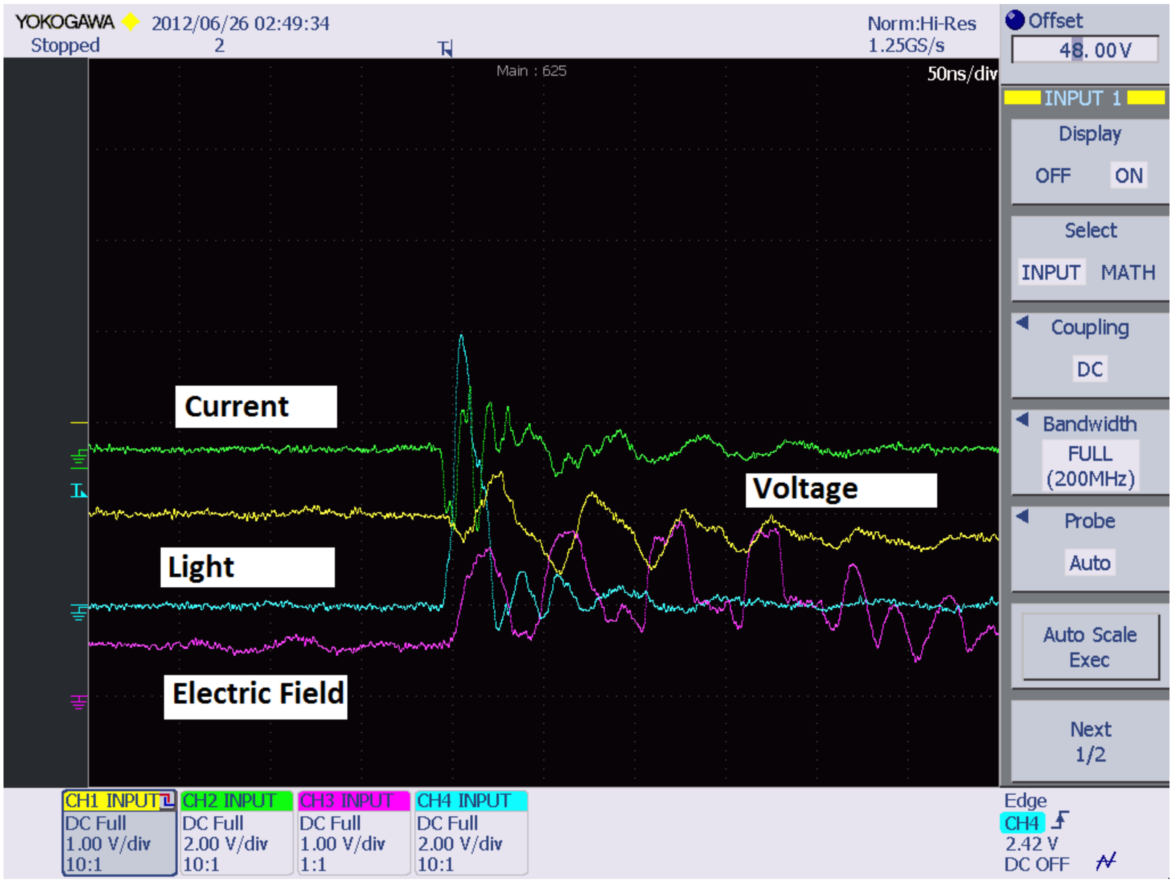

Figure 52: Voltage, Current, Light, Electric Field

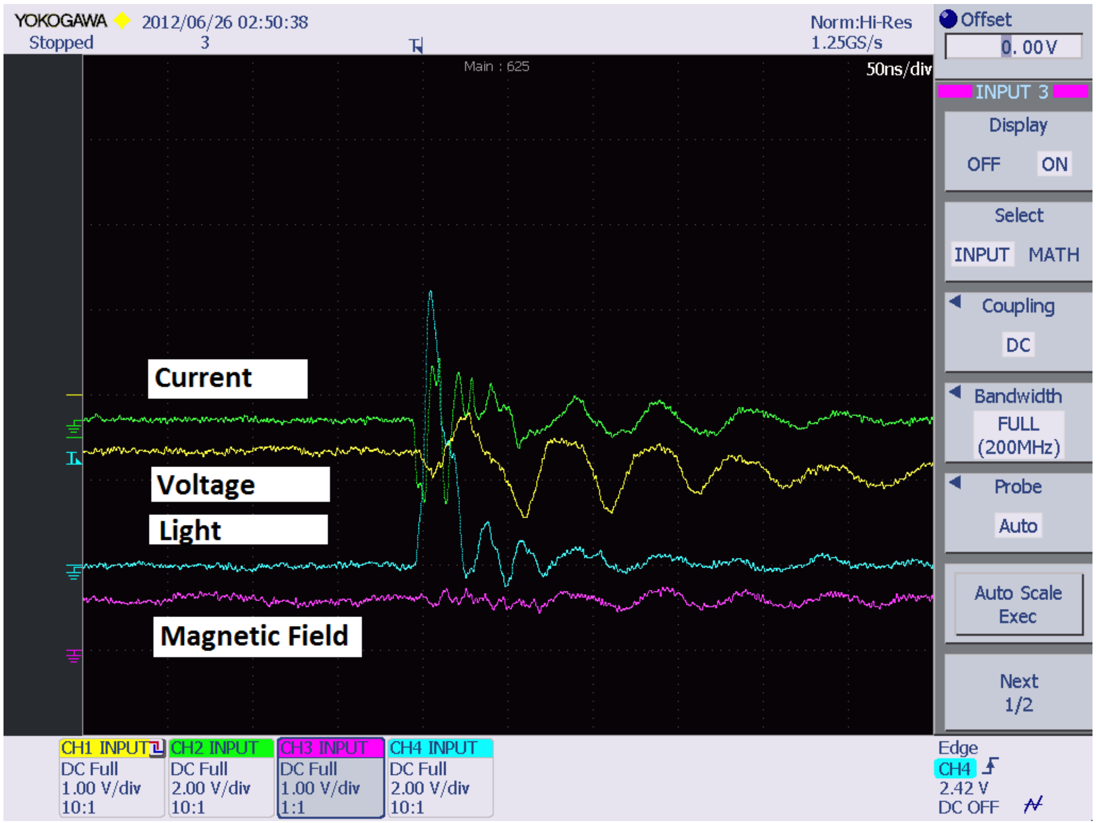

Figure 53: Voltage, Current, Light, Magnetic Field

In Figures 52 and 53 some conclusions can be made regarding the use of the electric or magnetic fields for high speed arc flash detection, which will be investigated.

Figure 52 shows that electric fields are strong enough to influence the meter and register enough to show that detection of the event is possible. However it is important to note that the electric field does not exist until the arc has output enough light for detection and the event has started. From the oscilloscope screen capture it is observed that 20 ns of separation between the light reaching peak and the electric field peak. This is not significant, but this test was performed in a clean environment, in order to rely upon the electric field to detect an arc event one would need to understand the installed measurement environment likely through a calibration during installation. If the noise in the environment is too great, it may be difficult to identify an arc event. However if the noise floor is low, and the radio antenna is not obscured by the substation enclosure, it may be possible to detect the arc event. However any detection by electric fields will be slower than light detection as the field does not exist until the arc has formed and persisted for a period of time (~20 ns).

Conversely magnetic fields are not a viable method of detecting an arc event. As shown inFigure 53, the magnetic field is so weak that even under ideal conditions it does not produce enough energy to be easily identifiable. Until the event has diminished, there appears to be no magnetic field and therefore arc detection would be too slow to provide value.

9.6 Summary

Chapter 9 presents the results and analysis from the Sparky experimental test setup. This chapter also presented an analysis of the electric and magnetic field which permits the opportunity to show that the speed of such detection schemes lags behind other technologies. The electric and magnetic fields performed as expected based upon industry research presented in Chapter 2, wherein light is a faster detection method.

Sparky experimental test setup captured light data which afforded the opportunity to investigate patterns in the energy prior to detection of light. The results show that current flows through the arc path before light is present, showing that current flows through the arc prior to the production of visible light.

CHAPTER 10
CONCLUSION

10.1 Result of Analysis

Detecting arc events through plasma signature detection (PSD) or direct plasma detection (DPD) are two new theories presented by this thesis. The techniques were researched as alternatives to the current state of art methods which wait until the arc event is established before detecting and responding. PSD was experimentally proven, while DPD is presented for future experimental research.

PSD utilizes standard signal and power analysis tools at high frequency in order to monitor the behaviour of the voltage and current. This thesis has shown that current flows through the arc gap prior to the detectable presence of light.

DPD follows the physics of plasma generation to detect plasma during the dark regime, before the production of visible light. Through the use of sensors responding to plasma, it is possible to directly detect the formation of plasma and respond to the arc event before a light based solution.

The hypothesis was that the energy required to create the destructive power of an arc flash will also create a pattern in the voltage/current to indicate formation. The results of the study show that there is a pattern in the current that can be detected prior to the formation of visible light.

The techniques of PSD and DPD both present advantages compared to state of art light based detection.

PSD can monitor a substation without relying on proper positioning of light sensors and whether someone or something will block the sensor. This reliability improvement carries the potential to create a safer working environment for electricians or service professionals.

DPD and PSD both offer detection of the arc event earlier than light based methods, potentially reducing incident energy levels.

In order to better understand these detection methods a definition and understanding of the definition of an arc flash event compared to an arc fault and understanding of what occurs during an arc event is required. Further it is important to be aware of the fact that an arc flash is related to an arc fault. An arc fault is a recurring arc event with low energy and the potential to create a fire hazard through repetition creating heat. An arc flash may begin as an arc fault, but the result is an arc event that is fed by substantially more energy, resulting in the rapid production of plasma and the expansion to explosive results.

The explosive energy potentially resulting from an arc flash event necessitates protocol, training, and research into detection/prevention/mitigation tools. The best of the state of art focuses upon light based detection methodologies. Due to the high speed of light and the fact that arc flash events create such extreme light levels, such detection tools can be very successful. Combining light based detection with high speed interruption techniques such as instantaneous breakers or explosive interrupters provides a solution directed at preventing catastrophic consequences. However these technologies on their own are not enough to properly protect a worker. Anyone tasked with working on systems capable of producing an arc flash must be properly trained to avoid disaster, and be equipped with the proper level of personal protective equipment (PPE).

The reason for great precaution when working with equipment containing the potential for arc flash events is the significant energy levels produced. Arc flash events release energy in the form of plasma, light, sound, fire, molten metal, among other forms. Each of these has the potential for serious injury, and necessitates precautions. The examination of the energy released in various forms included particular attention paid to the plasma produced. During the production of plasma there exists a dark discharge stage. During this stage, voltage/current is modified, but no visible light is output.

Understanding the dark discharge stage of plasma production provides the basis for PSD and DPD detection of arc flash incidents. Due to the fact that plasma is produced before visible light, the potential exists for an arc event to be detected faster than light based methods. Through the use of significantly fast sampling and signal processing a reliable and robust detection solution carries the potential to reduce the hazard.

The Dansk test setup consisted of a high energy system with a spark gap and high frequency sampling. This system provided results that permitted analysis methods to be developed and data to be captured in a safe and controlled manner. However because no light detection was present, not enough information was available to properly conclude if the dark discharge region could be identified.

Lacking light based detection necessitated the design and construction of a lower power test setup. This test setup consisted of light based detection and provided a better picture of the information created during an arc event. It is from this test setup that one is capable of identifying that there is current prior to the occurrence of visible light. This matches with the expected behavior of plasma production, though the flow of current proceeds light detection.

The resulting data and analysis indicated that current flows through the pending arc path prior to the appearance of light. From the information presented about plasma physics pertaining to the dark discharge region of the plasma development cycle, this matches expectations. With this information and further research, PSD and DPD has the potential to reliably provide indication of a pending arc event before light sensors can react.

10.2 Contributions

The results of the research show that current flows through the ground path at minimum 8 ns prior to the formation of visible light, during the dark discharge regime of plasma production. This information shows that it is possible to detect the arc signature by monitoring voltage and current or monitoring directly for plasma. This research described experimental test setups and plasma physics to analyze signatures prior to arc flash detection with light sensors.

The following contributions resulted from the research presented:

1. Two experimental test setups which provide methods to initiate testing of the concepts.
2. The behaviour of current is such that it increases through the spark gap into the ground before light can be detected, providing a new detection method.
3. The physics of plasma production shows that there is a regime where no visible light is produced. This identification will lead to future research of plasma in this regime

potentially introducing an additional detection method. Further it offers an explanation of why the current flows prior to visible light.

10.3 Future Work

The experimental test setups utilized through this research were limited when compared with arc flash test environments, or real world arc flash events. The test setups lacked the high power levels, and high load currents. These limitations mean that the data collected needs to be compared against actual arc flash detection scenarios necessitating further study. The difficulty with such testing is that the high level of energy discharged during an arc flash is dangerous and requires a laboratory with equipment to generate and measure and contain the energy. This is possible as there are arc flash test facilities; however it is cost prohibitive to perform such testing.

In order to accurately detect high frequency patterns in the supply signal, meters and measurement tools for high energy voltage/current with high frequency range would need to be designed as they are not common or low in cost. This presents a challenge both for research/study and real world implementations. If the sensors required to perform arc flash detection are so costly that they cannot meet budgets of protection environments, it will be difficult to convince companies that PSD presents a viable option. Part of the reason no sensors are readily available is that there has not been a need to produce such devices. Under normal circumstances high energy levels only need to be monitored at 50/60 Hz so devices are optimized for such a purpose. As the contributions in this thesis are realized, future research may develop high energy sensors, or novel techniques of monitoring for arc flash events using PSD.

In order to better study the direct plasma detection (DPD) detection method a similar test setup must be constructed (as required for PSD). However instead of monitoring the voltage and current, a plasma probe would be needed. The probe must be capable of detecting the presence of plasma in the air (or an increase in the density) with a rapid response. Such sensors are available as they are typically used in research, such as a Langmuir Probe or Terahertz imaging. This detection method would require the design of a low cost sensor capable of detecting plasma for use in production environments.

Aspects of future work will require additional research projects leading to new solutions. The work is ongoing and finding definite conclusions will form part of subsequent MSc thesis work.

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APPENDIX A: Dansk Test Setup Matlab Analysis Code

```
% analyze waveform captures to search for arc flash
notification

%function Analyze(directoryname, voltfilename,
currfilename)
% Close all currently open graphs
close all

directoryname = 'ALL0005';
voltfilename = 'F0005CH1.csv';
currfilename = 'F0005CH2.csv';

cd(directoryname)

%read the voltage information from the CSV file
a1=csvread(voltfilename);
%ignore first 53 entries as these are part of the delay
time=a1(54:2500,1);
%store original time
orig_time=a1(1:2500,1);
%remove the offset caused by the delay in the probe
time=time-0.0000000106;
%reset first entry to 0 instead of -ve
time=time+0.000000142;
%time=time-0.000000006;
%ignore first 53 entries as these are part of the delay
voltage=a1(54:2500,2);
%store the original voltage for plotting also
orig_voltage=a1(1:2500,2);
%remove position offset
voltage=-voltage;
%orig_voltage=1-orig_voltage;
%voltage sampling frequency
TSv=time(2)-time(1);
FSv=1/TSv;
%convert to 200MHz - not needed, actual value computed
is correct
%FSv=FSv/25;
```

```
sprintf('Voltage Sampling Rate is: %0.0d GHz',
FSv/1000000000)
%size of the data
N=size(time,1);
tmax=(N-1)*TSv;

%read the current information from the CSV file
a2=csvread(currfilename);
%ignore last 53 entries as these are part of the delay
ctime=a2(1:2447,1);
%store original time
orig_ctime=a2(1:2500,1);
%reset first entry to 0 instead of -ve
ctime=ctime+0.000000142;
%ignore last 53 entries as these are part of the delay
current=a2(1:2447,2);
%store the original voltage for plotting also
orig_current=a2(1:2500,2);
%remove position offset
current=-current;
%orig_current=1-orig_current;
%convert voltage measurement of current into actual
current
%divide by 100mOhm in order to do this
current=current./0.1;
%current sampling frequency
TSc=ctime(2)-ctime(1);
FSc=1/TSc;
sprintf('Current Sampling Rate is: %0.0d GHz',
FSc/1000000000)
%size of the data
Nc=size(ctime,1);
ctmax=(Nc-1)*TSc;

% Plot The original voltage and current in time domain
figure
[AX,H1,H2]=plotyy(orig_time.*1000000,orig_voltage,
orig_ctime.*1000000, orig_current, 'plot')
%grid on
```

```
title('Original Scope Capture of Voltage, Current &
Light During Arc Event')
xlabel('Time (\musec)')
set(get(AX(1),'Ylabel'),'String','Voltage (V)')
set(get(AX(2),'Ylabel'),'String','Current (A)')
set(AX(1),'YLim',[-4500 600])
set(AX(1),'YTick',[-4500:500:600])
set(AX(2),'YLim',[-4500 600])
set(AX(2),'YTick',[-4500:500:600])
%set(H1,'LineStyle','--')
%set(H2,'LineStyle',':')


% Plot voltage and current in time domain
figure
[AX,H1,H2]=plotyy(time.*1000000,voltage,
ctime.*1000000, current, 'plot')
%grid on
title('Voltage & Current During Arc Event')
xlabel('Time (\musec)')
set(get(AX(1),'Ylabel'),'String','Voltage (V)')
set(get(AX(2),'Ylabel'),'String','Current (A)')
set(AX(1),'YLim',[-6000 14000])
set(AX(1),'YTick',[-6000:2000:14000])
set(AX(2),'YLim',[-6000 14000])
set(AX(2),'YTick',[-6000:2000:14000])



Fpass = 150000000;   % Passband Frequency
Fstop = 200000000;   % Stopband Frequency
Apass = 1;           % Passband Ripple (dB)
Astop = 60;          % Stopband Attenuation (dB)
Fs    = 5000000000;  % Sampling Frequency
h = fdesign.lowpass('fp,fst,ap,ast', Fpass, Fstop,
Apass, Astop, Fs);
Hd = design(h, 'ellip', ...
    'MatchExactly', 'both');

%plot the frequency response of the filter
```

```
%fvtool(Hd)

Fpass = 150000000;    % Passband Frequency
Fstop = 200000000;    % Stopband Frequency
Apass = 1;            % Passband Ripple (dB)
Astop = 60;           % Stopband Attenuation (dB)
Fs    = 5000000000;   % Sampling Frequency
h = fdesign.lowpass('fp,fst,ap,ast', Fpass, Fstop,
Apass, Astop, Fs);
Hdv = design(h, 'ellip', ...
    'MatchExactly', 'both');

%plot the frequency response of the filter
fvtool(Hdv)

current=filter(Hd, current);
voltage=filter(Hdv, voltage);

% Plot voltage and current in time domain
figure
[AX,H1,H2]=plotyy(time.*1000000,voltage,
ctime.*1000000, current, 'plot')
%grid on
title('Voltage & Current During Arc Event')
xlabel('Time (\musec)')
set(get(AX(1),'Ylabel'),'String','Voltage (V)')
set(get(AX(2),'Ylabel'),'String','Current (A)')
set(AX(1),'YLim',[-4000 10000])
set(AX(1),'YTick',[-4000:2000:10000])
set(AX(2),'YLim',[-4000 10000])
set(AX(2),'YTick',[-4000:2000:10000])

%remove the first 0.5x10^-7 worth of data to remove the
ramping time on the
%voltage signal
current=current(251:length(current));
voltage=voltage(251:length(voltage));
time=time(251:length(time));
ctime=ctime(251:length(ctime));
```

```
% Plot voltage and current in time domain
figure
[AX,H1,H2]=plotyy(time.*1000000,voltage,
ctime.*1000000, current, 'plot')
%grid on
title('Voltage & Current During Arc Event Removing Ramp
Time')
xlabel('Time (\musec)')
set(get(AX(1),'Ylabel'),'String','Voltage (V)')
set(get(AX(2),'Ylabel'),'String','Current (A)')
set(AX(1),'YLim',[-4000 10000])
set(AX(1),'YTick',[-4000:2000:10000])
set(AX(2),'YLim',[-4000 10000])
set(AX(2),'YTick',[-4000:2000:10000])

%plot voltage and current in frequency domain
% Time specifications:
StopTime = length(voltage)*TSc;                  %
seconds
t = (0:TSc:StopTime-TSc)';
N = size(t,1);
% Fourier Transform:
X = fftshift(fft(voltage));
% Frequency specifications:
dF = FSc/N;                          % hertz
f = -FSc/2:dF:FSc/2-dF;               % hertz
% Plot the spectrum:
figure;
plot(f./10^6,abs(X)/N);
title('Voltage Frequency Spectrum During Arc Event -
Magnitude Response');
xlabel('Frequency (MHz)');
ylabel('Magnitude (V)')

% Time specifications:
StopTime = length(current)*TSc;                  %
seconds
t = (0:TSc:StopTime-TSc)';
N = size(t,1);
```

```
% Fourier Transform:
X = fftshift(fft(current));
% Frequency specifications:
dF = FSc/N;                              % hertz
f = -FSc/2:dF:FSc/2-dF;                   % hertz
% Plot the spectrum:
figure;
plot(f./10^6,abs(X)/N);
title('Current Frequency Spectrum During Arc Event -
Magnitude Response');
xlabel('Frequency (MHz)');
ylabel('Magnitude (A)')

%Analyze2()
prea_voltage=voltage(1:411);
prea_current=current(1:411);
prea_time=time(1:411);

% Plot voltage and current in time domain
figure
[AX,H1,H2]=plotyy(prea_time.*1000000,prea_voltage,
prea_time.*1000000, prea_current, 'plot')
title('Voltage & Current Prior to Arc Event')
xlabel('Time (\musec)')
set(get(AX(1),'Ylabel'),'String','Voltage (V)')
set(get(AX(2),'Ylabel'),'String','Current (A)')
set(AX(1),'YLim',[-500 4500])
set(AX(1),'YTick',[-500:500:4500])
set(AX(2),'YLim',[-500 4500])
set(AX(2),'YTick',[-500:500:4500])


%plot voltage and current in frequency domain
% Time specifications:
StopTime = length(prea_voltage)*TSc;                  %
seconds
t = (0:TSc:StopTime-TSc)';
N = size(t,1);
% Fourier Transform:
X = fftshift(fft(prea_voltage));
```

```
% Frequency specifications:
dF = FSc/N;                          % hertz
f = -FSc/2:dF:FSc/2-dF;              % hertz
% Plot the spectrum:
figure;
plot(f./10^6,abs(X)/N);
title('Voltage Frequency Spectrum Pre-Arc Event -
Magnitude Response');
xlabel('Frequency (MHz)');
ylabel('Magnitude (V)')

% Time specifications:
StopTime = length(prea_current)*TSc;                    %
seconds
t = (0:TSc:StopTime-TSc)';
N = size(t,1);
% Fourier Transform:
X = fftshift(fft(prea_current));
% Frequency specifications:
dF = FSc/N;                          % hertz
f = -FSc/2:dF:FSc/2-dF;              % hertz
% Plot the spectrum:
figure;
plot(f./10^6,abs(X)/N);
title('Current Frequency Spectrum Pre-Arc Event -
Magnitude Response');
xlabel('Frequency (MHz)');
ylabel('Magnitude (A)')

if mod(length(prea_current),2)
    final=(length(prea_current)-1)/2;
else
    final=length(prea_current)/2;
end

s_s_current=prea_current(1:final);
s_s_voltage=prea_voltage(1:final);
s_s_time=prea_time(1:final);
```

```
% Plot voltage and current in time domain
figure
[AX,H1,H2]=plotyy(s_s_time.*1000000,s_s_voltage,
s_s_time.*1000000, s_s_current, 'plot')
title('Voltage & Current  Steady State Separated')
xlabel('Time (\musec)')
set(get(AX(1),'Ylabel'),'String','Voltage (V)')
set(get(AX(2),'Ylabel'),'String','Current (A)')
set(AX(1),'YLim',[-500 4500])
set(AX(1),'YTick',[-500:500:4500])
set(AX(2),'YLim',[-500 4500])
set(AX(2),'YTick',[-500:500:4500])


%plot voltage and current in frequency domain
% Time specifications:
StopTime = length(s_s_voltage)*TSc;                   %
seconds
t = (0:TSc:StopTime-TSc)';
N = size(t,1);
% Fourier Transform:
X = fftshift(fft(s_s_voltage));
% Frequency specifications:
dF = FSc/N;                           % hertz
f = -FSc/2:dF:FSc/2-dF;                % hertz
% Plot the spectrum:
figure;
plot(f./10^6,abs(X)/N);
title('Voltage Frequency Spectrum Separate Steady State
- Magnitude Response');
xlabel('Frequency (MHz)');
ylabel('Magnitude (V)')

% Time specifications:
StopTime = length(s_s_current)*TSc;                   %
seconds
t = (0:TSc:StopTime-TSc)';
N = size(t,1);
% Fourier Transform:
```

```
X = fftshift(fft(s_s_current));
% Frequency specifications:
dF = FSc/N;                          % hertz
f = -FSc/2:dF:FSc/2-dF;               % hertz
% Plot the spectrum:
figure;
plot(f./10^6,abs(X)/N);
title('Current Frequency Spectrum Separate Steady State
- Magnitude Response');
xlabel('Frequency (MHz)');
ylabel('Magnitude (A)')

apre_current=prea_current(final+1:length(prea_current))
;
apre_voltage=prea_voltage(final+1:length(prea_voltage))
;
apre_time=prea_time(final+1:length(prea_time));

% Plot voltage and current in time domain
figure
[AX,H1,H2]=plotyy(apre_time.*1000000,apre_voltage,
apre_time.*1000000, apre_current, 'plot')
title('Voltage & Current Separated Pre-Arc Event')
xlabel('Time (\musec)')
set(get(AX(1),'Ylabel'),'String','Voltage (V)')
set(get(AX(2),'Ylabel'),'String','Current (A)')
set(AX(1),'YLim',[-500 4500])
set(AX(1),'YTick',[-500:500:4500])
set(AX(2),'YLim',[-500 4500])
set(AX(2),'YTick',[-500:500:4500])


%plot voltage and current in frequency domain
% Time specifications:
StopTime = length(apre_voltage)*TSc;                 %
seconds
t = (0:TSc:StopTime-TSc)';
N = size(t,1);
% Fourier Transform:
X = fftshift(fft(apre_voltage));
```

```
% Frequency specifications:
dF = FSc/N;                          % hertz
f = -FSc/2:dF:FSc/2-dF;               % hertz
% Plot the spectrum:
figure;
plot(f./10^6,abs(X)/N);
title('Voltage Frequency Spectrum Separated Pre-Arc
Event - Magnitude Response');
xlabel('Frequency (MHz)');
ylabel('Magnitude (V)')

% Time specifications:
StopTime = length(apre_current)*TSc;                  %
seconds
t = (0:TSc:StopTime-TSc)';
N = size(t,1);
% Fourier Transform:
X = fftshift(fft(apre_current));
% Frequency specifications:
dF = FSc/N;                          % hertz
f = -FSc/2:dF:FSc/2-dF;               % hertz
% Plot the spectrum:
figure;
plot(f./10^6,abs(X)/N);
title('Current Frequency Spectrum Separated Pre-Arc
Event - Magnitude Response');
xlabel('Frequency (MHz)');
ylabel('Magnitude (A)')

%slew rate analysis

sr_current=current(616:653);
sr_voltage=voltage(616:653);
sr_time=time(616:653);

% Plot voltage and current in time domain
figure
plot(s_s_time,s_s_voltage./1000, 'r', s_s_time,
s_s_current, 'b')
grid on
```

```
title('Voltage, Current  & Light Immediately Before 
Light Detection')
xlabel('Time')
ylabel('Magnitude')

%plot voltage and current in frequency domain
% Time specifications:
StopTime = length(s_s_voltage)*TSc;                    % 
seconds
t = (0:TSc:StopTime-TSc)';
N = size(t,1);
% Fourier Transform:
X = fftshift(fft(s_s_voltage));
% Frequency specifications:
dF = FSc/N;                             % hertz
f = -FSc/2:dF:FSc/2-dF;                  % hertz
% Plot the spectrum:
figure;
plot(f,abs(X)/N);
title('Voltage Frequency Spectrum Separate Steady State 
- Magnitude Response');
xlabel('Frequency (in hertz)');
ylabel('Magnitude')

% Time specifications:
StopTime = length(s_s_current)*TSc;                    % 
seconds
t = (0:TSc:StopTime-TSc)';
N = size(t,1);
% Fourier Transform:
X = fftshift(fft(s_s_current));
% Frequency specifications:
dF = FSc/N;                             % hertz
f = -FSc/2:dF:FSc/2-dF;                  % hertz
% Plot the spectrum:
figure;
plot(f,abs(X)/N);
title('Current Frequency Spectrum Separate Steady State 
- Magnitude Response');
```

```
xlabel('Frequency (in hertz)');
ylabel('Magnitude')

%compute and plot the slew rate of the current waveform
for n = 1:(length(sr_current)-1)
   slew_rate(n) = abs(sr_current(n+1)-sr_current(n));
end

figure;
plot(time(1:length(slew_rate)),slew_rate);

cd ..

cd wave_matlab
wavetest(voltage, time);
%wavetest(current, time);
cd ..

return
```

APPENDIX B: Sparky Test Setup Matlab Analysis Code

```
% analyze waveform captures to search for arc flash
notification,
% test jig 2

%function TestJig2(directoryname, filename, samplerate)
directoryname='TestJig2';
%filename='012_Data.csv';
filename='000_Data.csv';
samplerate=1250000000;

% Close all currently open graphs
close all

cd(directoryname)

%read the voltage/current/light information from the
CSV file
a1=csvread(filename);
%load the number of samples and channels into data
points
[a,b]=size(a1);
%sample rate as period
period=samplerate^-1;
%create array for the time data
time=0:period:((a-1)*period);
%read in the voltage data
voltage=a1(1:a,1);
%store the original voltage for plotting also
orig_voltage=a1(1:a,1);
%remove voltage divider change (100:1)
voltage=voltage.*100;
%voltage sampling frequency
TSv=time(2)-time(1);
FSv=1/TSv;
%convert to 200MHz - not needed, actual value computed
is correct
%FSv=FSv/25;
```

```
sprintf('Voltage Sampling Rate is: %0.0d GHz',
FSv/1000000000)
%size of the data
N=size(time,1);
tmax=(N-1)*TSv;

%read in the current data
current=a1(1:a,2);
%store original current
orig_current=current;
%convert voltage measurement of current into actual
current
%divide by 1Ohm in order to do this, or since it is
1Ohm, just use it :)
%current=current./1;
%current sampling frequency
TSc=time(2)-time(1);
FSc=1/TSc;
sprintf('Current Sampling Rate is: %0.0d GHz',
FSc/1000000000)
%size of the data
Nc=size(time,1);
ctmax=(Nc-1)*TSc;

%read in the light data
light=a1(1:a,3);

% Plot The original voltage and current in time domain
figure
[AX,H1,H2]=plotyy(time.*1000000,orig_voltage./10,
time.*1000000, orig_current, 'plot')
%grid on
title('Original Scope Capture of Voltage, Current &
Light During Arc Event')
xlabel('Time (\musec)')
set(get(AX(1),'Ylabel'),'String','Voltage')
set(get(AX(2),'Ylabel'),'String','Current')
%set(H1,'LineStyle','--')
%set(H2,'LineStyle',':')
```

```
% Plot voltage and current in time domain
figure
%plot(time,voltage./1000, 'r', time, current, 'b',
time, light, 'g')
subplot(2,1,1);
[AX,H1,H2]=plotyy(time.*1000000,light, time.*1000000,
current, 'plot');
title('Voltage, Current & Light, Steady State')%During
Arc Event')
xlabel('Time (\musec)')
set(get(AX(1),'Ylabel'),'String','Light Intensity (V)')
set(get(AX(2),'Ylabel'),'String','Current (A)')
set(AX(1),'YLim',[-0.5 5])
set(AX(1),'YTick',[-0.5:2:5])
set(AX(2),'YLim',[-0.5 5])
set(AX(2),'YTick',[-0.5:2:5])

%set(H1,'LineStyle','--')
%set(H2,'LineStyle',':')
subplot(2,1,2);
[AX,H1,H2]=plotyy(time.*1000000,light, time.*1000000,
voltage./1000, 'plot');
xlabel('Time (\musec)')
set(get(AX(1),'Ylabel'),'String','Light Intensity (V)')
set(get(AX(2),'Ylabel'),'String','Voltage (V)')
set(AX(1),'YLim',[-0.5 5])
set(AX(1),'YTick',[-0.5:2:5])
set(AX(2),'YLim',[-0.5 5])
set(AX(2),'YTick',[-0.5:2:5])

% Plot current and light in time domain
figure
%plot(time,voltage./1000, 'r', time, current, 'b',
time, light, 'g')
[AX,H1,H2]=plotyy(time.*1000000,light, time.*1000000,
current, 'plot');
title('Current & Light During Arc Event')
xlabel('Time (\musec)')
```

```
set(get(AX(1),'Ylabel'),'String','Light Intensity (V)')
set(get(AX(2),'Ylabel'),'String','Current (A)')
set(AX(1),'YLim',[-2.5 8])
set(AX(1),'YTick',[-2.5:2:8])
set(AX(2),'YLim',[-2.5 8])
set(AX(2),'YTick',[-2.5:2:8])

set(AX(1),'XLim',[0.38 0.46])
set(AX(1),'XTick',[0.38:0.02:0.46])
set(AX(2),'XLim',[0.38 0.46])
set(AX(2),'XTick',[0.38:0.02:0.46])

%plot voltage and current in frequency domain
% Time specifications:
StopTime = length(voltage)*TSc;                  %
seconds
t = (0:TSc:StopTime-TSc)';
N = size(t,1);
% Fourier Transform:
X = fftshift(fft(voltage));
% Frequency specifications:
dF = FSc/N;                       % hertz
f = -FSc/2:dF:FSc/2-dF;            % hertz
% Plot the spectrum:
figure;
plot(f,abs(X)/N);
title('Voltage Frequency Spectrum During Arc Event -
Magnitude Response');
xlabel('Frequency (in hertz)');
ylabel('Magnitude')

% Time specifications:
StopTime = length(current)*TSc;                  %
seconds
t = (0:TSc:StopTime-TSc)';
N = size(t,1);
% Fourier Transform:
X = fftshift(fft(current));
% Frequency specifications:
```

```
dF = FSc/N;                              % hertz
f = -FSc/2:dF:FSc/2-dF;                   % hertz
% Plot the spectrum:
figure;
plot(f,abs(X)/N);
title('Current Frequency Spectrum During Arc Event -
Magnitude Response');
xlabel('Frequency (in hertz)');
ylabel('Magnitude')

prea_voltage=voltage(1:501);
prea_current=current(1:501);
prea_time=time(1:501);
prea_light=light(1:501);

% Plot voltage and current in time domain
%figure
%title('Voltage & Current Prior to Arc Event')
%xlabel('Time')
%ylabel('Magnitude')

% Plot voltage and current in time domain
figure
%plot(time,voltage./1000, 'r', time, current, 'b',
time, light, 'g')
subplot(2,1,1);
%plot(prea_time,prea_voltage./1000, 'r', prea_time,
prea_current, 'b', prea_time, prea_light, 'g')
[AX,H1,H2]=plotyy(prea_time.*1000000,prea_light,
prea_time.*1000000, prea_current, 'plot');
title('Voltage & Current Prior to Arc Event')
xlabel('Time (\musec)')
set(get(AX(1),'Ylabel'),'String','Light Intensity (V)')
set(get(AX(2),'Ylabel'),'String','Current (A)')
%set(H1,'LineStyle','--')
%set(H2,'LineStyle',':')
subplot(2,1,2);
[AX,H1,H2]=plotyy(prea_time.*1000000,prea_light,
prea_time.*1000000, prea_voltage./1000, 'plot');
```

```
xlabel('Time (\musec)')
set(get(AX(1),'Ylabel'),'String','Light Intensity (V)')
set(get(AX(2),'Ylabel'),'String','Voltage (V)')

%plot voltage and current in frequency domain
% Time specifications:
StopTime = length(prea_voltage)*TSc;                    %
seconds
t = (0:TSc:StopTime-TSc)';
N = size(t,1);
% Fourier Transform:
X = fftshift(fft(prea_voltage));
% Frequency specifications:
dF = FSc/N;                             % hertz
f = -FSc/2:dF:FSc/2-dF;                  % hertz
% Plot the spectrum:
figure;
plot(f./10^6,abs(X)/N);
title('Voltage Frequency Spectrum Pre-Arc Event -
Magnitude Response');
xlabel('Frequency (MHz)');
ylabel('Magnitude (V)')

% Time specifications:
StopTime = length(prea_current)*TSc;                    %
seconds
t = (0:TSc:StopTime-TSc)';
N = size(t,1);
% Fourier Transform:
X = fftshift(fft(prea_current));
% Frequency specifications:
dF = FSc/N;                             % hertz
f = -FSc/2:dF:FSc/2-dF;                  % hertz
% Plot the spectrum:
figure;
plot(f./10^6,(abs(X)/N).*10^3);
title('Current Frequency Spectrum Pre-Arc Event -
Magnitude Response');
xlabel('Frequency (MHz)');
```

```
ylabel('Magnitude (\muA)')

s_s_current=prea_current(489:501);
s_s_voltage=prea_voltage(489:501);
s_s_light=prea_light(489:501);
s_s_time=prea_time(489:501);

% Plot voltage and current in time domain
figure
plot(s_s_time,s_s_voltage./1000, 'r', s_s_time,
s_s_current, 'b', s_s_time, s_s_light, 'g')
grid on
title('Voltage, Current  & Light Immediately Before
Light Detection')
xlabel('Time')
ylabel('Magnitude')

%plot voltage and current in frequency domain
% Time specifications:
StopTime = length(s_s_voltage)*TSc;                  %
seconds
t = (0:TSc:StopTime-TSc)';
N = size(t,1);
% Fourier Transform:
X = fftshift(fft(s_s_voltage));
% Frequency specifications:
dF = FSc/N;                        % hertz
f = -FSc/2:dF:FSc/2-dF;             % hertz
% Plot the spectrum:
figure;
plot(f,abs(X)/N);
title('Voltage Frequency Spectrum Separate Steady State
- Magnitude Response');
xlabel('Frequency (in hertz)');
ylabel('Magnitude')

% Time specifications:
StopTime = length(s_s_current)*TSc;                  %
seconds
t = (0:TSc:StopTime-TSc)';
```

```
N = size(t,1);
% Fourier Transform:
X = fftshift(fft(s_s_current));
% Frequency specifications:
dF = FSc/N;                              % hertz
f = -FSc/2:dF:FSc/2-dF;                   % hertz
% Plot the spectrum:
figure;
plot(f,abs(X)/N);
title('Current Frequency Spectrum Separate Steady State
- Magnitude Response');
xlabel('Frequency (in hertz)');
ylabel('Magnitude')

%compute and plot the slew rate of the current waveform
for n = 1:(length(s_s_current)-1)
   slew_rate(n) = abs(s_s_current(n+1)-s_s_current(n));
end

figure;
plot(time(1:length(slew_rate)),slew_rate);

cd ..
return
```