CHARACTERIZING PHOTOVOLTAIC SYSTEM ARC-FAULTS

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

Characterizing Photovoltaic System Arc-Faults

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Photovoltaic (PV) system fire hazards pose a serious threat to public safety and finances. Arc faults are one of the main causes of electrical fires, shock hazards, and failures in PV systems, since it involves the release of concentrated radiant energy at the point of arcing in a small time period resulting in temperature exceeding 35,000 °F. Thus, arc fault detection is crucial for reliable and safe system operation and is a prerequisite for high penetration of PV. To develop effective arc fault detectors, a thorough understanding of the electrical characteristics of PV arcs is required, which is possible only by obtaining large samples of voltage and current waveforms. This paper describes a computer-controlled mechatronics testbed to facilitate scientifically repeatable arc generation conditions and waveform recording. Various combinations of electrode material and geometry, electrical voltage and current, and electrode gap separation profile can be studied as these factors are hypothesized to affect the electrical characteristics of the arc. The collected arc voltage and current waveforms are analyzed using the Fast Fourier Transform and Short-time Fourier Transform as initial investigations into the suitability of the two methods in arc fault detection.

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We are very grateful to Dr. Robert Balog for providing us with the opportunity to further this research project, enriching ourselves and the PV community in the process. We also thank Sawsan Shukri and Mr. Kais Abdulmawjood for their ever-present support and guidance throughout and beyond the project.

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NOMENCLATURE

PV	Photovoltaic
DC (dc)	Direct Current
AC (ac)	Alternating Current
FFT	Fast Fourier Transform
ICT	Instrument Control Toolbox (MATLAB)
TCPIP	Transmission Control Protocol/Internet Protocol
STFT	Short Time Fourier Transform
OEM	Original Equipment Manufacturer
AFD	Arc Fault Detector
AFCI	Arc Fault Circuit Interrupter

SECTION I

INTRODUCTION

Motivation

Solar photovoltaic (PV) energy systems are fire hazards, as shown in Figure 1. As with all electrical installations, there is a small risk of even properly installed systems burning down due to various factors or combinations thereof, often taking with them the surrounding infrastructure. The severity of the issue can be observed by the significant number of media reports on PV-attributed fires [1]-[5] and studies conducted by concerned parties [6]-[9]. One of these studies, by the Fraunhofer Institute for Solar Energy, mentions that PV fires in the most part are due to inexperienced workers fitting the system, incompatible and/or low-quality parts being used, or regulations not being followed. In addition, the rapid development of solar technology implies the possibility of overlooked hazards and standards not mature enough to ensure safety of the user and the installation process.

Figure 1. An example of solar PV fires.

According to the PVPS (Photovoltaic Power Systems Programme) report by the International Energy Agency in 2019 [10], the total capacity of global solar PV installations that can be reported with any certainty is 505.4 GW. Although a large portion of the capacity is from utility-scale installations, many solar modules are installed on rooftops, public spaces, schools, hospitals, residences and warehouses. In the US alone, over 51,000 residential fires caused nearly 500 deaths, 1,400 injuries, and $1.3 billion in property damage in 2014 [11]. Undetected threats in PV systems can add drastically to this statistic as the number of installations increase.

Besides posing a risk to public safety, PV fires can cause significant financial harm as well. Case in point is the high-profile lawsuit of Walmart against Tesla [12] for the property damage caused by Tesla-supplied solar panels to 7 out of 240 similarly outfitted Walmart outlets. In this particular case, the connectors for the systems, which have been in the market for years, seem to have been the main culprit. It was also discovered that Tesla was planning on covertly replacing the faulty equipment in the secret "Project Titan"[13], which did not happen in time to prevent any accidents and was not secret enough. The example of Walmart v. Tesla is very appropriate to show that PV safety is not simply in the development of better solar cells, but in the re-working of the entire supply chain which is involved in the root hazard.

Hazards in electrical systems are unavoidable because of the human element and other random factors such as weather and natural disasters. The liability may be the OEM, the installer, the systems integrator, the architect or the engineer. Aside from such obvious weak links, accidents may still occur due to external factors as in the case of the Hongkou Stadium fire in Shanghai [14], shown in Figure 2. As such, better monitoring and detection technologies, strict enforcement of the regulations and standards, better management, and most of all, quality and compatible parts can help to minimize the risk and reduce the impact of the hazards.

Figure 2. Fire at the Shanghai Hongkou Soccer Stadium in Shanghai, China on March 28, 2017.

PV System Arc Faults

Arc faults are one of the primary causes of fires, shock hazard, and system failures in PV systems [15]. As the term broadly encapsulates a range of electrical faults, it can be defined simply as the formation of a current channel across a distance (in air) when enough voltage is applied across it. The process of arcing involves the release of concentrated radiant energy in a small time period, thus resulting in extremely high temperatures— exceeding 35,000 °F (19,400 °C) under appropriate conditions [16]. Such high temperatures can cause insulation and nearby items to combust and has high potential to cause electrical fires.

In the case of ac systems which generally operate at higher energy than small-scale PV systems, arcing events sometimes directly vaporize the metal electrodes at the point of arc, producing arc blasts. However, when considering utility scale PV (shown in Figure 3), the many cells are combined to operate at much higher voltages, and thus at those sections of the system the potential for arc blasts occurring are much greater.

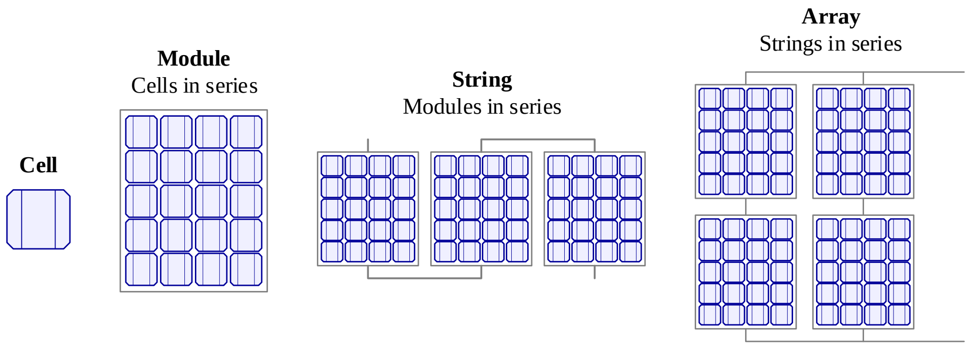

Figure 3. Scaling and nomenclature of PV systems.

Arc fault detectors (AFDs) and arc fault circuit interrupters (AFCIs), now required for use in homes, prevent series arc faults in alternating current (ac) circuits and are quite different from dc circuit arc faults which occur in PV systems. Dc electrical arcs in PV systems can be caused by loose electrical connections (series arc fault) or abrasion of conductors secured to the mounting frame due to thermal expansion, vibration, nesting rodents, or failure within the PV modules (parallel arc fault). Another major difference between ac and dc arcs is that dc arcs can persist undetected due to the stabilizing effect of dc power on arcing current.

The problem of arcing faults exists for small-scale residential systems as well as large-scale utility systems and can pose significant threats to human safety. As long as there are insufficient countermeasures for dc arc faults, the PV industry will have significant concerns about liability and the impact upon widespread adoption of photovoltaic energy. Thus, arc fault detection is extremely important for reliable and safe system operation and is a prerequisite for high penetration of PV.

Codes and Standard

The National Electrical Codes in 2011 required all roof-top PV system greater than 80 V to have series AFDs. In 2014, the requirement was extended to all PV systems greater than 80 V. So far, the trend of PV system fires has been increasing, but that may simply be due to the steep increase in PV installations rather than any inadequacy in the technology or codes. However, research into better and more encompassing detection technology is necessary for reliable PV technology and to support increased PV penetration.

The UL-1699B standard [17] developed by the Underwriters Laboratory requires every Arc Fault Circuit Interrupter (AFCI) or Arc Fault Detector (AFD) to pass the arc test with the power of 300–900 W. In short, passing the arc test implies that the AFCI or AFD must respond within 2.5 s and before 750 J of energy has dissipated across the arc.

Need for Systematic Approach

Detecting the arc fault in a PV system is made difficult because of the background noise from other elements in the system— dc microgrids, inverters and MMPT optimizers, which may result in false positive detection. Also, the self-inductance of long cables and capacitive nature of PV modules in the network may result in false negative or non-detection. As such, a universal arc detector must be robust enough and sensitive enough to detect the arc fault, but not too sensitive to be fooled by background noise.

Arcs are highly chaotic phenomena, and thus tuning a detector to find patterns in arcing waveforms is difficult. Existing AFDs work on the principle of frequency analysis using the Fast Fourier Transform (FFT) at high sampling rates [18] and depend on certain signals to detect the occurrence or persistence of an arcing event. However, the accuracy of the detection methods come into question because of their failure in preventing all accidents in the instances of PV fires after the adoption of the 2014 NEC clause. Clearly there is still a problem. The issue with adopting the existing solutions can be explained by the low compatibility of FFT methods for the detection of highly aperiodic events, since the basic assumption while taking the Fourier transform of a signal is that the signal is periodic. However, it is possible that multiple signatures in combination or certain difficult to realize patterns may exist, which can be discovered through a systematic machine learning based approach and can be used to identify dc arcing events with full certainty.

Introduction to the Project

As an investigation and verification practice, using an arc generator connected to a PV system is a common method used to study the characteristics of an electric arc [17]. This project involves the development and automation of a mechatronics testbed for precise computer control of the electrical arc parameters— which include the arc voltage and current, the separation profile between the electrodes (velocity) and the electrode shape and material. Numerous test cases were designed to account for the effects of all these parameters individually and together on the arc waveforms, which were collected and stored.

The collected waveforms will be used to develop a “replay testbed”, in which pre-recorded arcs signals generated in this project can be combined with other electrical signals, such as from the power electronics dc/dc optimizers and inverters, from real-world PV systems. Arbitrarily mixing the ratio of these signals will emulate the arbitrary placement of the arc fault within a PV array, thus enabling testing for no-detection (false-negative) due to signal attenuation and false-detection (false-positive) due to benign system signals.

Previous Publications

The Renewable Energy and Advanced Power Electronics Research lab, where this project is being conducted has been working on PV arc fault and arc flash detection since 2014, when the prototype arc fault generator shown in Figure 4 was developed. Further enhancements to the arc generator are described in [19] and [20]. Other literature generated in the period 2014-2018 includes methods to detect arc flashes and faults (Table 1), and an evaluation method for arc fault detection algorithms [21]. The background intellectual property is listed in Table 1.

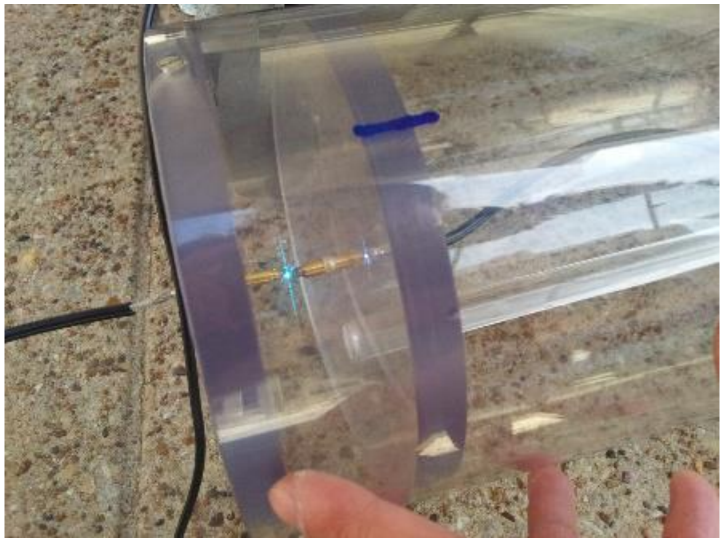

Figure 4. First generation arc fault detector.

Table 1. Background intellectual property.

U.S. Patent Number 9,329,220 ("Method and System for Detecting Arc Faults and Flashes Using Wavelets") • Issued: May 3, 2016 •Discloses a method and system for detecting an arc event in AC and DC systems through application of a wavelet transform. • https://patents.google.com/patent/US9329220B2/en •Z. Wang and R. S. Balog, "Arc Fault and Flash Signal Analysis in DC Distribution Systems Using Wavelet Transformation," IEEE Transactions on Smart Grid, vol. 6, no. 4, pp. 1955-1963, July 2015
U.S. Provisional Patent Application No. 62/515,071 ("Method to Determine Arc Faults and Arc Flashes") •Filed: June 5, 2017 •Discloses a method and system for detecting an arc in AC and DC systems through application of support vector machine concepts. •Z. Wang and R. S. Balog, "Arc Fault and Flash Detection in Photovoltaic Systems Using Wavelet Transform and Support Vector Machines," in IEEE 43rd PV Special. Conf (PVSC), June 2016, pp. 3275 - 3280.

Wang et al.[22] explored the utility and effectiveness of using frequency analysis to detect arc faults in their paper. The authors concluded that Fast Fourier Transform (FFT) and Short Time Fourier Transform (STFT) were not suitable for the detection of abrupt changes like arc faults and advocated wavelet transform as a more suitable alternative. However, since commercial Arc Fault Detectors (AFDs) in use today are based on FFT methods [18], we hypothesized that there may be certain frequency signatures in arcing voltage and current waveforms that can be discovered given enough data. This suggests an application for machine learning.

Ameen et al.[20] mention the possibilities of automating the arc generation and data collection processes using the testbed developed in their paper, which we adopted for our project. The testbed enabled large data collection and minimized errors due to human interaction. Other salient features of the design are large electrodes and joining plates which allow for maximum conductivity and heat dissipation, and a precision stepper motor for better electrode movement control. A computer drawing of the testbed without the stepper motor and electrical connections is shown in Figure 5. The detailed construction of the testbed can be found in [20].

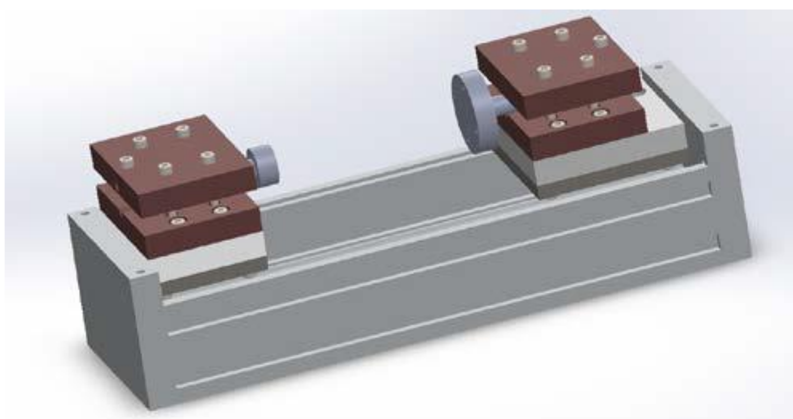

Figure 5. SolidWorks conceptual drawing of the mechatronics testbed.

SECTION II

METHODOLOGY

Objectives of the Paper

In order to design an effective and robust PV arc faults detector, the features of these arc faults must be characterized. To develop a better understanding of PV arc faults, a public free access database will be created with numerous arc faults electrical signatures in order to assist developers and researchers to contribute in developing effective DC arc faults detectors to be used in real world.

To achieve this, the project consists of the following objectives:

1. Mechatronics test bed for precise and repeatable control of the arc generation process will be designed and developed. The mechatronics test bed will be controlled using MATLAB Instrument Control Toolbox. As arc faults are highly chaotic, large number of experiments will be performed with different parameters of electrode geometry, electrode gap profile, electrical current, and electrical voltage.
2. Spectral plot of the data using will be generated using FFT.
3. Process of data generated by testbed and FFT and STFT analysis for future projects.

Project Design

Studying characteristics of arc faults is difficult due to the chaotic nature of the arcs themselves, which makes systematic large data collection in real-world systems nearly impossible. One solution to this problem is to construct a testbed for generating dc arcs and create a library of arcing voltage and current waveforms which can be used for studying arc characteristics and developing detection methods.

As mentioned in the introduction, previous work by the REAPER Lab research group on PV arc-fault detection led to the development of a mechatronics arc-generator testbed, which was developed further in this project. The arc generator system is shown in Figure 6.

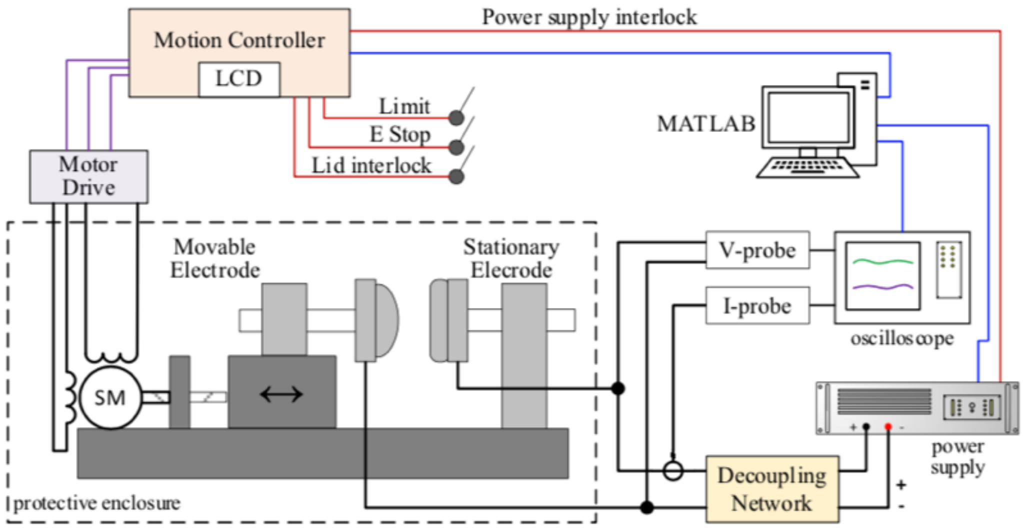

Figure 6. Overall arc generator system diagram. Note: The Decoupling Network is still in the development phase and is not part of the current system.

The system consists of a test bed which includes the two electrodes, stepper motor to move the two electrodes, and a microcontroller to control the stepper motor. This test bed was developed based on designs in previous research papers. The LPC 4088 microcontroller is connected to the computer, as well as the MDO4104C oscilloscope, which is used to record voltage and current data of an arc, and the MagnaPower DC power supply. These three devices are controlled by a MATLAB code. The actual set up of our system is shown in Figure 7.

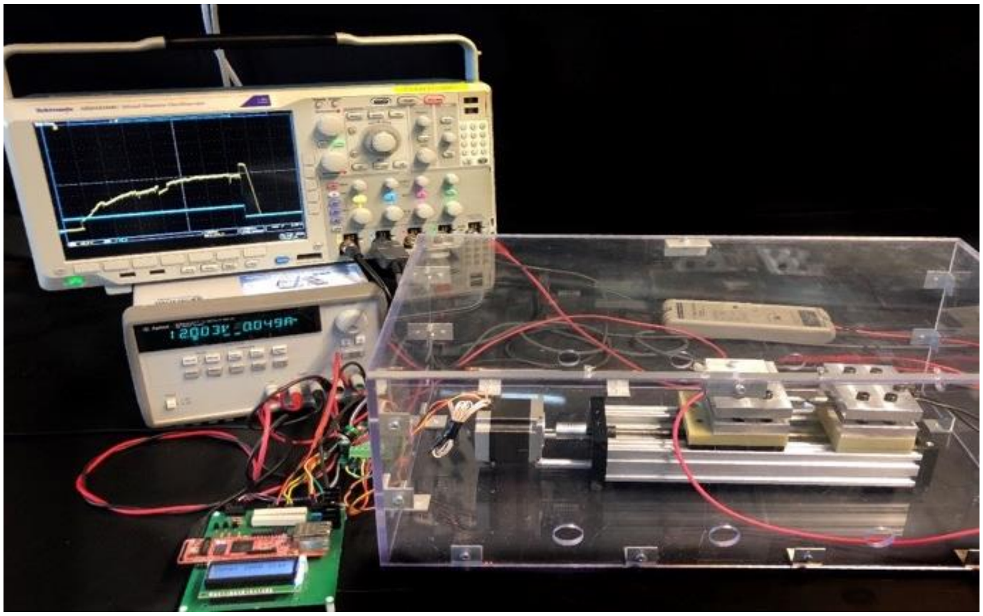

Figure 7. Arc generator hardware set-up.

Purpose of Using Arc Generator System

Ideally an arc occurs infrequently and we cannot predict when it will happen. Thus, waiting for an arc to happen is time consuming. Also, arcs are chaotic in nature. Thus, a large number of arc samples are needed in order to arrive at a generalized description that robustly characterizes all DC arcs. The Arc Generator system was used to eliminate undesired variables and factors that affect the arc results. This whole system provides us with an automated, controllable, and precise arc generator with automated data collection to have a systematic study of DC arc. This will help us to run large numbers of experiments that will provide us with enormous numbers of data for analysis and characterization.

Program Flow of MATLAB Code

A MATLAB code was written to coordinate between different hardware devices and to generate repeatable and precise DC arc faults. The flow of the MATLAB code is shown in Figure 8. First, MATLAB launches a connection to the MagnaPower DC power supply, MDO 4104C Tektronix Oscilloscope and stepper motor. Next, the program sets up the oscilloscope to have same settings and parameters in order to get accurate results. Then, MATALB loads profile excel file and reads it. The profile excel file includes the electrical profile, which contains the voltage and current, the electrode profile, which consists of electrode geometry and material, and the gap profile, which contains the direction, distance, and time of separation. An example of a profile excel file is shown in Figure 9. The electrical profile is used to set the voltage and current of Magna DC Power Supply. The gap profile is loaded calculate the periods and steps of the stepper motor. The stepper motor starts running, and at the same time, the oscilloscope starts capturing the waveforms of voltage and current during the arc. After the stepper motor stops, MATLAB downloads the waveforms from the oscilloscope and saves it to the computer.

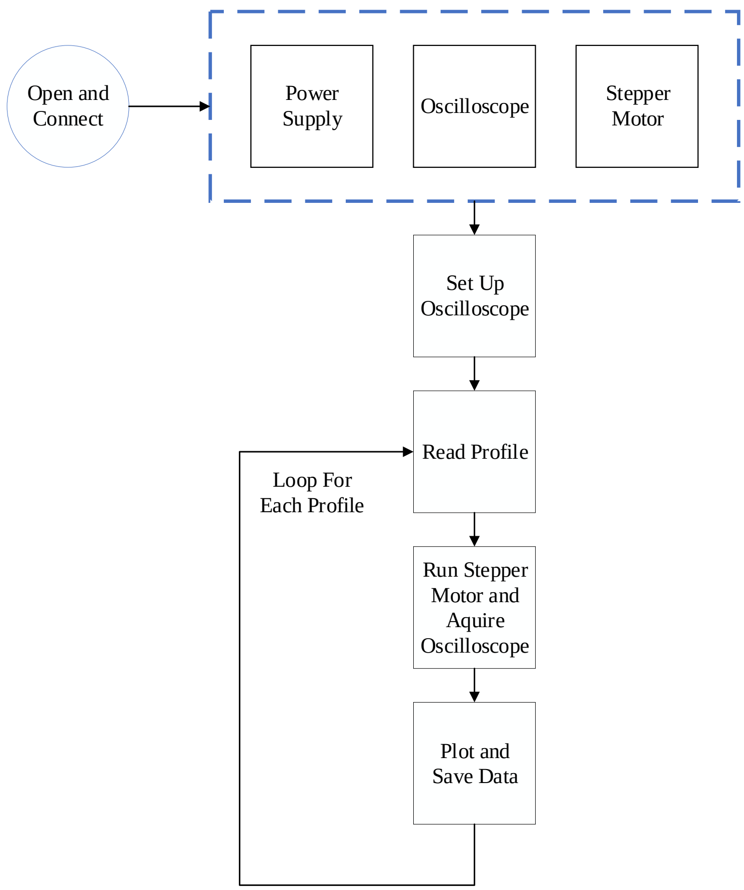

Figure 8. Program overview flowchart.

	A	B	C
1	Electrode Profile	Electrical Profile	Gap Profile
2	2	1	3

Figure 9. An example of a ‘recipe’— a combination of electrode, electrical and gap profiles.

Stepper Motor Control

The stepper motor is used to move the electrodes depending on the gap profile to generate the arc. To activate and control the motor, the stepper motor was connected to a TB6600 stepper motor driver energized by the DC supply. The purpose of the TB6600 stepper motor driver is to generate the voltage pulses to drive the two phase stepper motor. The stepper motor driver is connected to LPC 4088 QuickStart Board microcontroller that is used to control the steps and period of the stepper motor. Also, the LPC 4088 QuickStart Board microcontroller is connected to the computer to allow MATLAB to control, send and receive data to the motor. The stepper motor connections are shown in Figure 10.

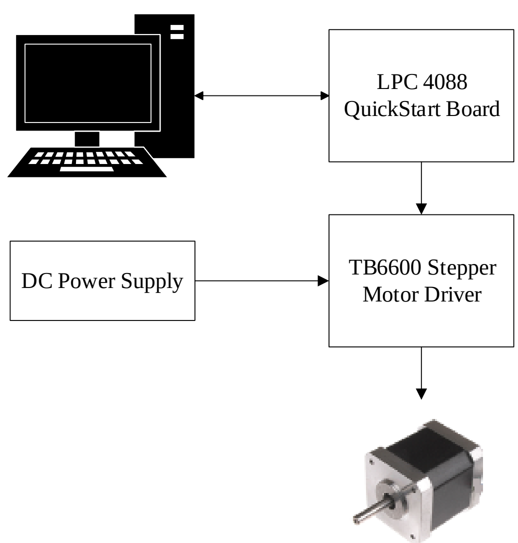

Figure 10. Stepper motor connections.

The code flow to control the stepper motor using MATLAB is shown in Figure 11. MATLAB starts by establishing a connection to LPC 4088 QuickStart Board microcontroller.

Next, MATLAB calculates stepper motor steps and period and send the data to LPC 4088 QuickStart Board microcontroller that has been programed using MBED to run the stepper motor according to the values entered in MATLAB. If the stepper motor stops running, LPC 4088 QuickStart Board microcontroller will send a signal to MATLAB. Then, the stepper motor will return to home.

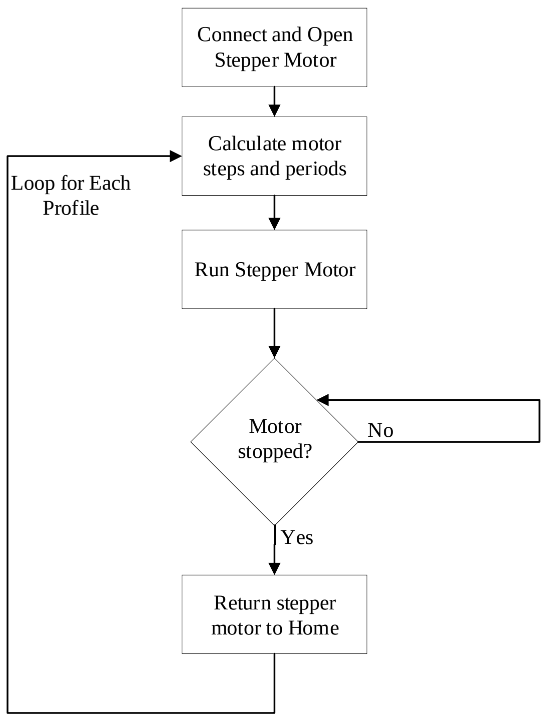

Figure 11. Flowchart of MATLAB code for controlling the stepper motor.

Oscilloscope Control

The MDO 4104C Tektronix oscilloscope is used to capture voltage and current waveforms of the arc. This oscilloscope was chosen due to its higher sampling rates, faster capture duration, better interfacing with external storage devices, better interaction and communication with external devices, and faster data transfer rates. The MDO 4104C Tektronix oscilloscope has the ability to capture up to 20 million data points at 500 MS/s. However, it takes a long time to download and save all of the points. Thus, a tradeoff between data transfer duration and resolution had to take place in order to have a lower run time. The oscilloscope was connected to MATLAB through ethernet. Figure 12 shows the code flow to control the oscilloscope though MATLAB with the help of MDO4104C scope Programming Manual.

First, MATLAB starts a VISA™ serial connection and opens the MDO 4104C Tektronix oscilloscope. Next, different commands are sent to oscilloscope to set it up. These commands include setting vertical scaling for CH1(Voltage) as 20V/div and for CH2(Current) as 1A/div to get the whole waveform for different electrical profiles, setting channels' vertical positions at zero, and setting number of data points as 100 K. These settings are used to ensure same conditions for all waveform to have accurate and fair results. After setting up the oscilloscope, and before the motor starts running, the state of the oscilloscope will be changed to run state to start to capture the new arc data. The oscilloscope state will be as run state until the LPC 4088 QuickStart Board microcontroller sends a signal to MATLAB when the motor stops running. Then, MATLAB will send a command to the oscilloscope to stop acquiring data.

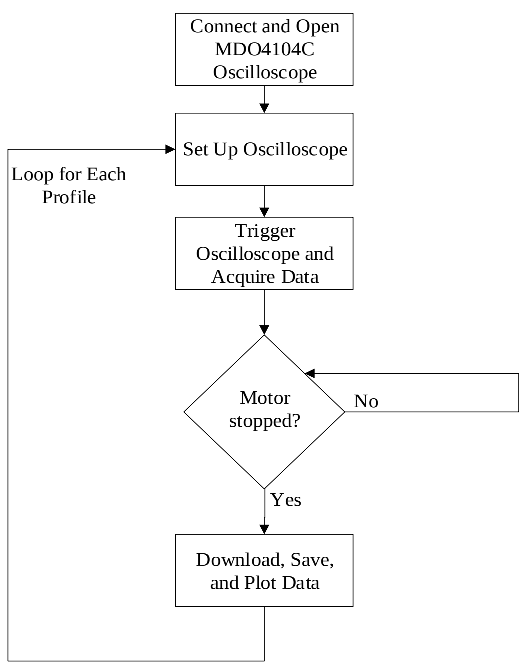

Figure 12. Flowchart of MATLAB code for controlling the oscilloscope. The trigger is based on the motor

Effect of Factors on Electrical Characteristics of the Arc

In this project, there are some factors that may influence the electrical characteristics of the arc. We want to study the effects of these factors on the arc results. These factors are:

- Electrode Geometry and Material (Figure 13, 14).
- Electrode Gap Separation Profile (Figure 15, 16).
- Electrical Voltage and Current.

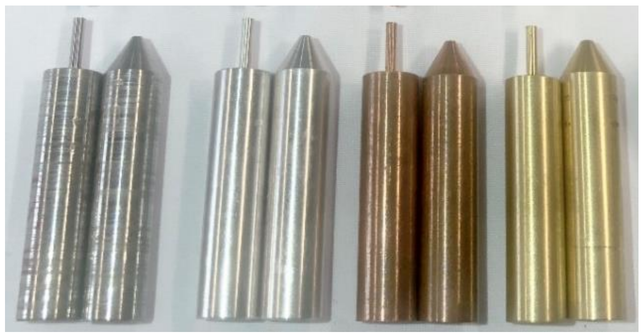

Figure 13. Examples of electrodes with cylindrical and conical geometry, and different materials.

Figure 14. Examples of electrodes with titanium ball and ring geometry.

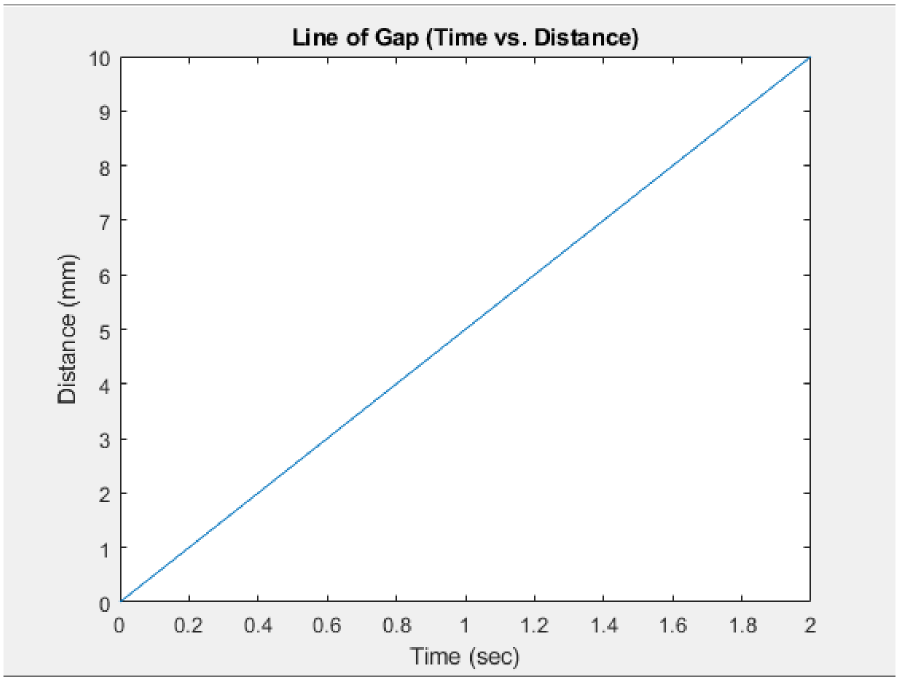

Figure 15. An example of gap profile used in the experiments. The velocity in the example is constant, but more complicated profiles are possible.

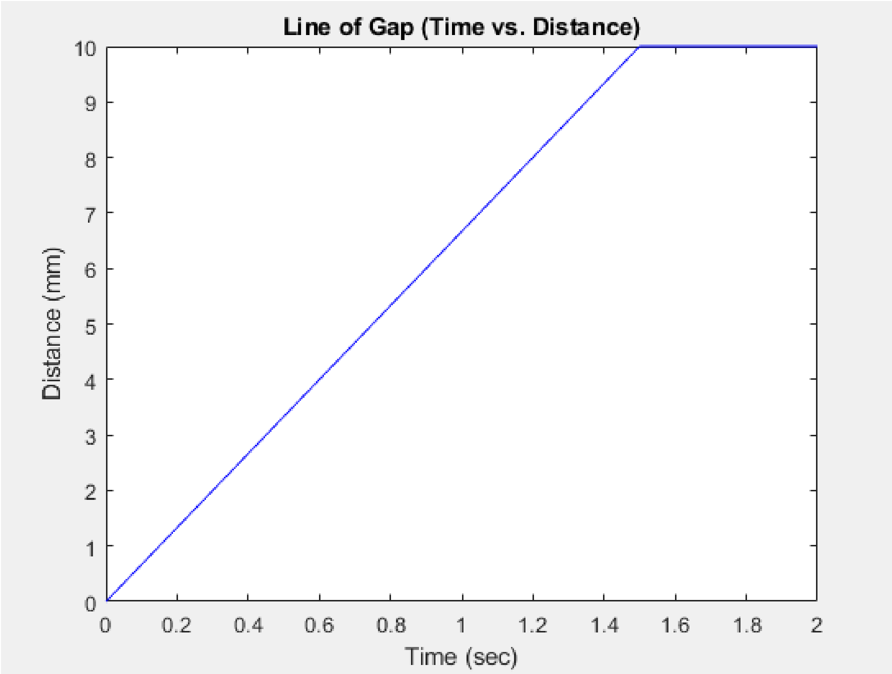

Figure 16. Another example of gap profile used in the experiments.

These variables are initialized in the electrode, electrical and gap profiles. Examples of these profiles are shown in Figure 17, Figure 18, and Figure 19 respectively. Large numbers of experiments will be conducted with different configuration of these factors to observe the impact of these factors on the DC arc faults.

	A
1	Flat_Brass
2	Flat_StainlessSteel
3	Cone_Brass
4	Cone_StainlessSteel
5	Ball&Ring_Titanium

Figure 17. List of electrode profiles.

	A	B	C
1	Profile #	Volt	Current
2	1	10	0.2
3	2	20	0.3
4	3	30	0.4

Figure 18. Example list of electrical profiles. However, voltage of 200 V and current of 1 A was used in the actual experiments.

	A	B	C
1	Direction	Distance (mm)	Time (sec)
2	1	5	1
3	1	10	0.5
4	1	8	0.4

Figure 19. Example list of gap profiles.

Fast Fourier Transform of the Recorded Waveforms

After the data is collected from the automated arc generation system, the data is analyzed using FFT. The FFT code flow is shown in Figure 20. First, MATLAB loads arc voltage and current data from previous experiments. Then, MATLAB sets up the parameters of FFT such as sampling frequency. Using the parameters, MATLAB generates and plots the FFT for arc voltage and current waveforms. Finally, the generated data and waveforms are saved in the computer. The code is looped iteratively for each arc study.

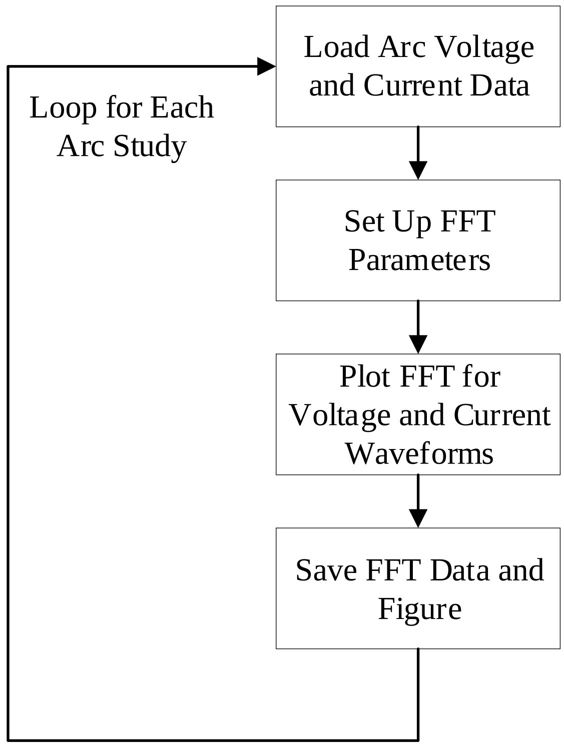

Figure 20. FFT decomposition program flowchart.

Short-Time Fourier Transform of the Recorded Waveforms

The data collected was also analyzed using STFT through MATLAB. The code flow of STFT is shown in Figure 21. The main consideration for the analysis technique with shorter sampling period was to better capture in time the onset of the arcing event, which cannot be done exactly using FFT due to its low time resolution. Similar to the FFT program, the collected data is loaded to MATLAB. Then, MATLAB sets up the STFT parameters and plots the data for both voltage and current waveforms. Finally, the graphs and data will be saved in the computer. The code is nested in a loop to be repeated for each arc study.

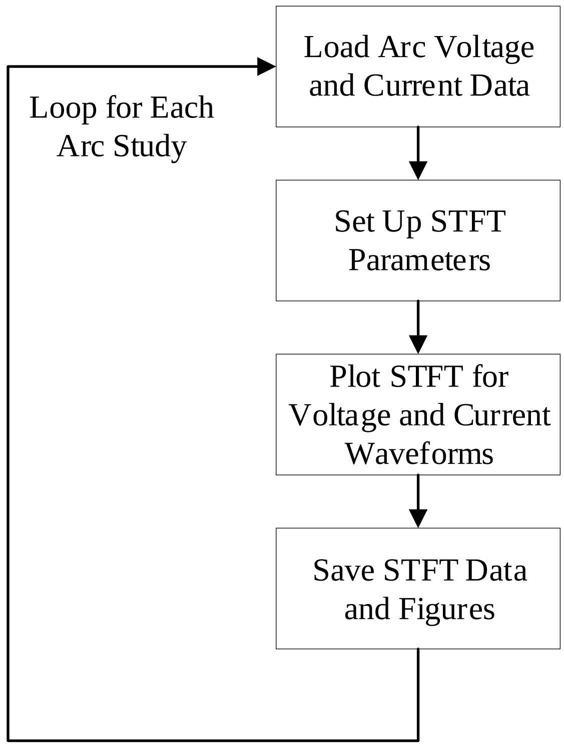

Figure 21. STFT decomposition program flowchart.

SECTION III

RESULTS

The two figures, Figure 22 and Figure 23, show the arc voltage and current waveforms recorded over the course of multiple experiments. Figure 22 shows the first arc generated using the pair of electrodes, whereas Figure 23 shows the arc captured after four more ‘runs’. Here, each observation was taken over the period of one ‘step’— which refers to both the motor’s smooth movement in one direction (and corresponding movement of the moving electrode). After each step is completed, the motor returns to its orientation before the step, completing one ‘run’. Both outputs had the same profile configuration which is shown in Figure 24. Electrode 1 refers to flat electrode geometry and stainless-steel electrode material, electrical voltage was 200V, electrical current was 1A, gap separation distance was 5mm, gap separation time was 0.5 s, and direction was 1 which refers to the two electrodes moving apart. Before arcing, during arcing, and after arcing parts can be clearly noticed from the voltage across the arc waveforms. It can be observed, from the voltage waveform, that the voltage across an arc increases as the gap separation distance increases. The green line shows the ideal voltage waveform, which corresponds to first experiment voltage waveform. The notches in the voltage curve that increased over multiple consecutive runs, circled in Figure 23, are as of yet an uninvestigated phenomenon. A probable cause for the notches is corrosion of the electrode tips due to the high temperature and ionization. A point to note here is that the appearance of these notches over the course of repeated or persistent arcs may complicate the detection process, especially if the detector works purely on time-series data.

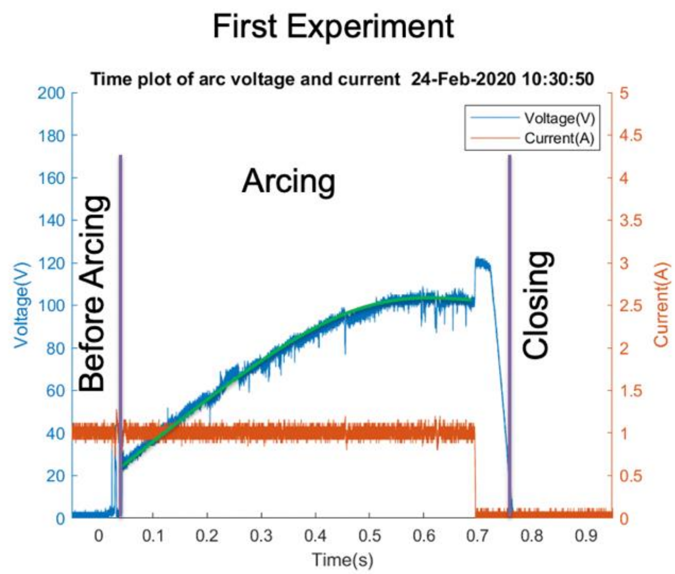

Figure 22. First experiment arc voltage and current waveforms.

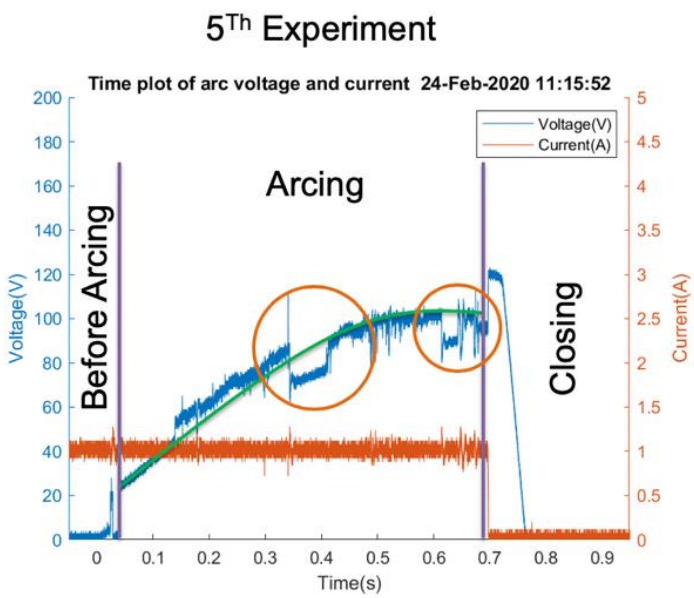

Figure 23. Fifth experiment arc voltage and current waveforms.

Electrode	Voltage	Current	Distance	Time	Direction
1	200 V	1 A	5 mm	0.5 s	1

Figure 24. Profile configuration of both experiments in Figures 22 and 23.

FFT was applied to both of Figure 22 and Figure 23. Figure 25 shows the FFT of voltage waveform of Figure 22, Figure 26 shows the FFT of current waveform of Figure 22, Figure 27 shows the FFT of voltage waveform of Figure 23, and Figure 28 shows the FFT of voltage waveform of Figure 22.

Also, STFT was applied to the voltage waveforms of Figure 22 and Figure 23. In the Figures 29 and 30, it can be observed at a glance that the STFT provides time information regarding the onset of an arc, which the FFT cannot. The initial investigations validate the need for further research into the possibility of using STFT instead of the more popular FFT for arc fault detection.

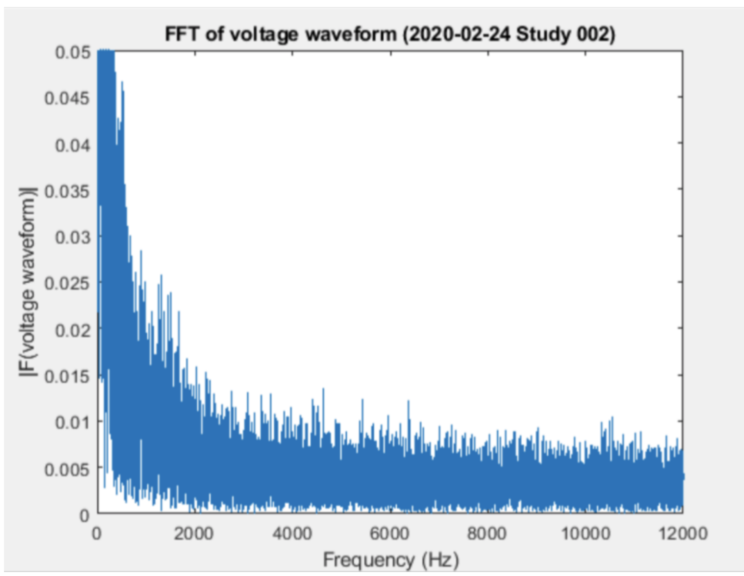

Figure 25. FFT of voltage waveform of study in Figure 22.

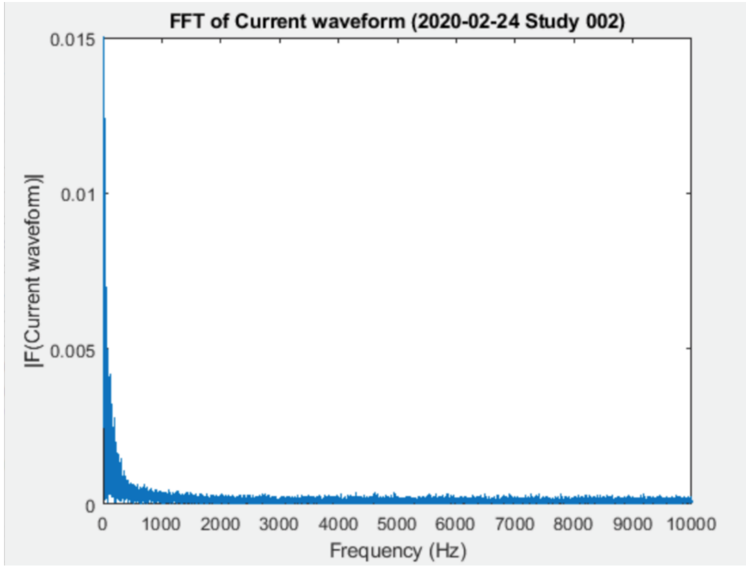

Figure 26. FFT of current waveform of study in Figure 22.

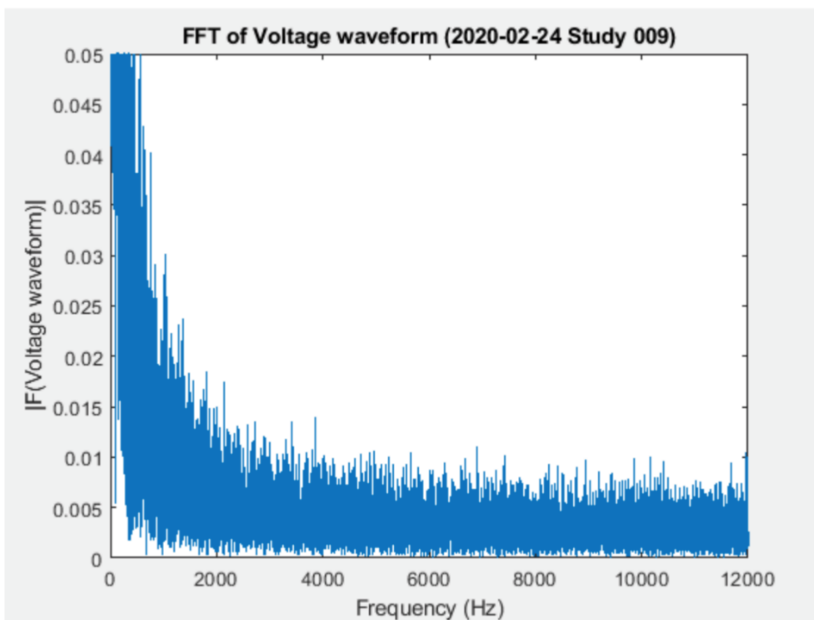

Figure 27. FFT of voltage waveform of study in Figure 23.

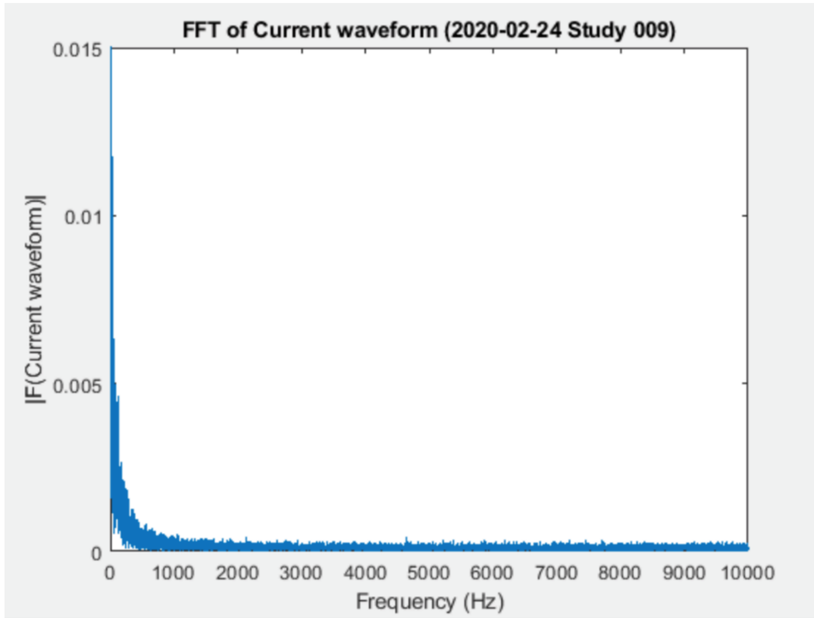

Figure 28. FFT of current waveform of study in Figure 23.

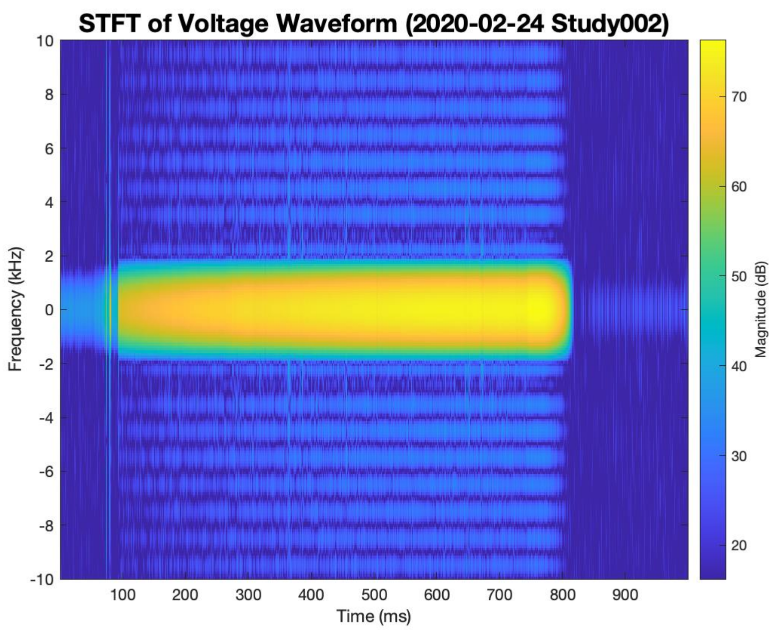

Figure 29. STFT of voltage waveform of study in Figure 22.

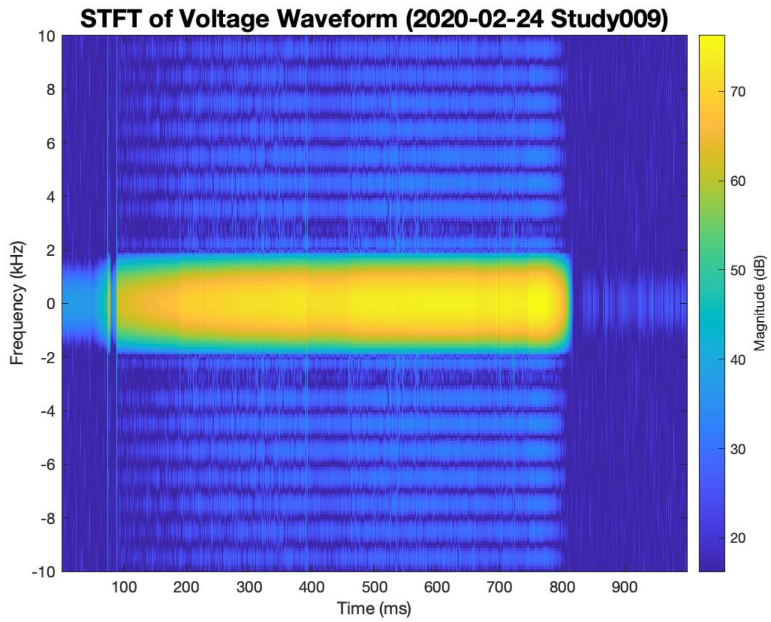

Figure 30. STFT of voltage waveform of study in Figure 23.

SECTION IV

CONCLUSION

“The best arc-fault is the one that never happens” – Jay Johnson, Sandia Labs.

Detecting arc faults in PV and other dc systems is challenging, yet critically important as undetected arcs can lead to property damage and injuries or death due to electrical fires or electrical shock. The challenges to detecting dc arcs stem from the background electrical noise (from inverters, dc/dc optimizers and other equipment) and system impedances which can attenuate the signal. Thus, finetuning a detector to ignore the noise (false-positive) and yet capture the signal (avoid false-negative) becomes difficult.

The automated dc arc generating system described in the thesis provides a highly controllable, precise method to generate large numbers of arcing waveforms under specific conditions. The generated data can be used to develop an algorithm to detect dc arcs or tune existing algorithms to do so. The system can demonstrate the efficacy of detection algorithms, compliant to the UL1699B standard, and is thereby useful to manufacturers and researchers of arc fault detection technology design and prototype hardware.

Comparing the FFT and STFT of the collected waveforms indicates that STFT may be more effective as a tool for arc fault detection due to its ability to closely capture the onset of arcing in time, whereas FFT may be better employed to study the characteristics in depth due to its greater frequency resolution. The results obtained show a need for further investigation into the tools used for analysis and the potential of using the arc generator for tuning arc fault detection methods.

Although we were unable to fully achieve the objectives due to closure of the lab caused by the COVID-19 outbreak, initial tests run on the system proved the system's ability to capture multiple sets of arcing waveforms according to input 'recipes' prepared by the user. Once the lockdown on laboratory facilities is lifted, further work will be carried out, including testing the robustness of the control program code, arcing waveform library creation, FFT analysis, and possibly machine learning to study the characteristics of dc arcs.

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