

Partial Discharge Testing and Detection under PWM Voltage

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Dedicated to my beloved family. Without their unconditional love and endless support I will not be where I am today.

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Abstract

Partial Discharge detection and measurement is an important part of electric insulation design. However, in PWM (pulse width modulation) voltage source converter environments, the noise resulting from switching voltage (rise and fall times of tens of nanoseconds) makes detection and extraction of partial discharge difficult. Unique methods of partial discharge detection are needed to address and decouple the noise from partial discharge measurements. PWM voltage can feature high switching speeds and high dv/dt during voltage switching. These PWM voltage behaviors are not found in traditional utility high voltage applications, and the effects that this type of voltage has on insulation and associated partial discharge behavior are not well understood. A good understanding of partial discharge behavior is vital to effective insulation design in high voltage power electronic systems.

To better understand the behavior of partial discharge in a PWM voltage source environment, a partial discharge testing platform is designed. This testing platform features a 3kV Si half-bridge converter to apply PWM voltage at varying switching frequency (5-60kHz) and dv/dt (11-16V/ns). An additional full-bridge 10kV SiC converter provides extra voltage capability for partial discharge testing. Converters with wide bandgap semiconductors can feature high switching frequency and dv/dt not currently possible with Si converters. The effect that switching frequency and dv/dt has on partial discharge behavior will become more of an issue as wide bandgap semiconductors are operated at full potential. The output voltage from this converter will be applied to test subjects chosen to model types of partial discharge: surface, internal, and corona discharge. This testing platform requires an effective method of partial discharge detection that is not interfered by voltage switching transient noise. Three electrically isolated methods of detection are explored to determine the most effective methods of partial discharge detection in the presence of PWM voltage switching

transient noise: optical detection, electromagnetic detection, and acoustic detection. Post-processing wavelet denoising techniques are applied to remove any remaining noise from partial discharge signals. With effective partial discharge detection and a testing platform with test subjects chosen to model types of discharge, the effects of PWM voltage on partial discharge behavior are demonstrated. Methods of partial discharge classification and identification are demonstrated as well to show methods to effectively identify defects in insulation caused by partial discharge due to PWM voltage.

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Chapter 1

Introduction

Power electronic converters at medium voltage (MV) are becoming more feasible and useful to assist in a wide array of grid applications like microgrids [20, 16]. These microgrids require medium voltage ($5kV - 35kV$) converters to interface with distributed energy resources and battery systems. Proper insulation system design for MV power electronic converters are of vital importance, to prevent insulation breakdown that can lead to system failure and potential power grid disturbance [17]. For proper insulation design, the voltage stresses of which the insulation must withstand must be understood [17]. This insulation system can then be tested under high voltage stresses to ensure effectiveness.

A generally well accepted method for insulation system testing is detection of partial discharge [2, 36, 35]. Partial discharge is defined as a localized electrical discharge that only partially bridges the insulation between conductors and which can or can not occur adjacent to a conductor [2]. Traditional methods of partial discharge testing involve applying an AC sinusoidal voltage waveform, with low background noise, to a test object or piece of insulation and measuring for partial discharge.

The insulation systems in power electronic converters are exposed to voltage waveforms based on pulse width modulation (PWM). In MV converters this voltage can have very short rise or fall times, or high dv/dt ($> 100V/ns$) [16]. This PWM voltage often operates at very high frequency compared to AC sinusoidal voltage (50 or 60Hz). This high dv/dt and increased voltage impulses due to high frequency can result in greater electrical stress on insulation and potentially shorter insulation lifetime. Therefore, insulation design testing for MV converters

requires PWM voltage applied to test subjects to ensure proper insulation performance in operating conditions. Additionally new methods of partial discharge detection and classification are needed to understand partial discharge in a new PWM voltage environment.

1.1 Types of Partial Discharge

Partial discharges are the result of electrical stress conditions in insulation or on the surface of insulation. There are four [36] common types of partial discharge based on the location of occurrence:

- Corona discharge: Occurring in gaseous dielectrics in the presence of non-homogeneous fields.
- Surface discharge: Occurring across the insulation surface.
- Internal (Void) discharge: Occurring in defects, voids or cavities within solid insulation.
- Contact discharge: Occurs on floating metal in high field conditions.

A corona is a partially ionized region adjacent to a conductor [7] which creates a change in the electric field between conductor and ground. If this electric field is large enough, the corona can cause a partial discharge. Corona discharge is typically repetitive because the gaseous region is regenerative and returns to conditions before the discharge [7]. Corona discharge typically occurs due to sharp metal points in the presence of a gas causing the in-homogeneous fields [35]. Surface discharge is the result of charge carriers emission along an insulation surface due to surface or leakage currents [27]. Surface discharge is similar to corona discharge in the medium in which it occurs but can cause permanent damage to physical insulation. The physical insulation is not regenerative in the way that a gaseous medium can be. Surface discharge can be the result of insufficient creepage specification and degradation of insulation surface due to contamination such as dust. Voids or defects within insulation material result in an electric field when in the presence of an ac voltage [7]. If this electric field is large enough the gas within the void can break down due to free electrons. This breakdown can result in progressively worse damage to the insulation.

Contact discharge occurs when a metal in a system is at a floating voltage relative to a nearby conductor. In the presence of ac voltage, a capacitive voltage division is developed between the floating metal and the conductor which can lead to an electric field between two points larger than electric fields elsewhere in the insulating medium [7]. This potentially large electric field can lead to electric breakdown. Each type of partial discharge is indicative of a different type of insulation issue. The ability to differentiate between partial discharge types is important to diagnose potential failures in an insulation system before they occur.

1.2 Partial Discharge due to PWM Voltage

Insulation in the presence of a PWM voltage is susceptible to partial discharge if the induced electric field is large enough. The types of partial discharge in a PWM voltage system are the same as with a sinusoidal voltage but not with the same behavior [37]. There are two major problems introduced by PWM voltage for partial discharge detection: the high frequency transient noise associated with the repetitive voltage impulses [8, 26, 38, 23] and insufficient methods for partial discharge classification [23, 25, 30]. Traditional partial discharge testing methods typically involve a coupling capacitor in series with a coupling device to filter out the 60 or 50Hz sinusoidal waveform leaving only any potential partial discharge waveform [2]. With a PWM voltage, the transient noise due to the voltage impulses has much higher harmonic frequency content and is typically larger in amplitude than potential induced partial discharge [37, 23]. Partial discharge classification and identification methods based on PWM voltage are not well defined compared to AC sinusoidal voltage. For AC sinusoidal voltage, methods such as phase resolved partial discharge (PRPD) are commonly used to identify the type of partial discharge [2, 13, 14]. By looking at the PRPD pattern, a partial discharge can be identified as a corona, void, surface, or floating discharge. This classification can aid in determining which part of the insulation system is likely experiencing partial discharge as well as determine appropriate response. A similar classification system is not as of yet well defined for partial discharges as a result of PWM voltage. Also, there are still questions about the impact that PWM voltage will have on the likelihood and frequency of

partial discharge. PWM voltage can lead to a reduction in lifetime of insulation [23, 25, 24] and an increase in partial discharge amplitude, quantity [30, 31, 12].

1.3 Motivation for This Work

High voltage converters are finding increased commercial use of with increased use distributed energy resources in electrical grid and microgrid applications. With increased use of power electronic converters at high voltages comes a need for more robust methods of insulation testing for safe and reliable operation. This thesis focuses on partial discharge testing specifically for insulation used with high voltage power electronic converters. Conventional partial discharge testing fails to accurately assess the performance of insulation in power electronic converter operation due to the difference in testing voltage waveform. A 60Hz AC voltage does not feature the high dv/dt voltage impulses of the high switching frequency characteristic to PWM voltage in power electronic converters. Due to this the insulation performance under 60Hz AC voltage can not be expected to be the same as under a high frequency PWM voltage.

Additionally, the traditional partial discharge detection methods used in 60Hz AC testing are not effective in a power electronic converter environment due to voltage switching noise. In this thesis alternative detection methods will be explored for higher voltage switching noise immunity. Then, a power electronic converter will be designed and constructed to deliver a high voltage PWM voltage at varying dv/dt and switching frequency. With alternative detection methods and a HV power electronic converter, insulation can be tested to better understand partial discharge behavior in a high voltage power electronic converter environment. With a partial discharge testing platform designed that accurately reflects power electronic converter operating conditions, partial discharge can be classified again. This will allow for a better understanding of insulation performance and potential failures under the influence of PWM voltage.

Chapter 2

Literature Review

This project focuses on partial discharge detection and classification based on discharge type in the presence of PWM voltage. Research of this type can be split into two primary categories: methods of partial discharge detection in the presence of PWM voltage and resulting transient switching noise and discharge type classification methods and strategies. The former can further be split into hardware detection methods and post-processing partial discharge extraction methods.

2.1 Partial Discharge Detection

2.1.1 Inductive Coupling

Inductive coupling testing methods such as the HFCT and the Rogowski coil are composed of a ferrite core, one primary winding and several secondary windings [41]. The partial discharge current flows through the primary winding inducing a voltage signal in the secondary coil. HFCTs are still subject to the noise produced by the fast switching transients and the detected inrush current will have a magnitude much larger than the that of the partial discharge [38]. However, inductive coupling testing methods have advantages in potential bandwidth and their non-intrusive testing approach. Typical HFCT have frequency ranges of hundreds of kilohertz to hundreds of megahertz [6, 19, 6, 11] Depending on the risetime of the switching transients, the increased frequency range of the inductive coupling methods

provide more usability when compared to capacitive coupling techniques despite the impact of inrush current

2.1.2 Electromagnetic

Partial discharge creates RF electromagnetic waves that propagate away from the source and can be detected by devices such as stator slot couplers and ultra-high frequency antennas [33, 18]. Stator slot couplers typically operate in the lower frequency range (50kHz-20MHz) and therefore are too negatively impacted by the fast voltage switching transients. UHF antennas operate in the frequency range of 300MHz-3000MHz [33, 18, 21]. Although the voltage switching transients produce EMI, it is easier to discern the partial discharge at higher frequencies(> 400MHz) where the voltage switching frequency content is less dominant [26]. However, UHF antennas are subject to variability in magnitude of produced PD signal as a function of distance [21].

2.1.3 Optical

Partial discharge events produce light typically in the ultraviolet spectrum that can be used as an indicator of partial discharge. The advantage of optical detection is electrical isolation from the converter produced voltage. UV cameras can be easily used to identify the occurrence of partial discharge, but this is only a qualitative observation [29]. Photomultiplier tubes are another effective method for partial discharge, using photoemission to capture light as electrons, making it a very sensitive device [39]. The PMT is a quantitative method of PD detection, but noise produced by voltage switching is detected as EMI in PMT applications[39]. Additionally optical methods are ineffective for detecting internal partial discharge [39].

2.1.4 Acoustic

Partial discharge events cause a shockwave that produces a vibration that can be detected by ultrasonic sensors [5, 3]. This method maintains the advantage of electric isolation. Ultrasonic sensors are commonly used for PD localization [5, 3, 10]. The voltage switching

transients produce an acoustic noise as well, but this sound profile differs from that of typical partial discharge and is easily distinguishable. However, acoustic emission sensors typically have a large sampling size, too large for effective partial discharge testing. Additionally, partial discharge testing for localization purposes becomes complicated in environments where the propagation path is not straight forward [22].

2.2 Partial Discharge Extraction

2.2.1 Filtering

Applying a high pass filter to a partial discharge detection method serves to attenuate lower frequency components so that the measurement system is not over saturated. Partial discharge pulse rise times tend to be in the ns range while voltage switching rise times are much larger (500-1000) for IGBT modules [34, 38]. However, faster switching devices are becoming more common such as SiC and GaN devices, whose voltage switching transients can have significant frequency components up to hundreds of megahertz [11].

2.2.2 Wavelet Analysis

The wavelet transform analyzes a signal both in frequency and time domain. In wavelet transform decomposition, a signal is separated into high-frequency components of the signal “details”, and low-frequency components “approximations” [32]. Wavelet denoising methods are effective in suppressing noise from a PD signal but are susceptible to loss of lower amplitude partial discharge. Additionally, if the signal to noise ratio is not already favorable, wavelet denoising will be poor [32].

2.3 Partial Discharge Classification

2.3.1 Phase Resolved Analysis

Phase resolved partial discharge analysis has long been a standard method of partial discharge extraction and pulse classification for AC sinusoidal voltage systems [28]. PRPD

Methods applied to PWM converters show the difference of partial discharge pattern between AC sinusoidal voltages and PWM voltages [24]. However, phase resolved PD characteristics are not well defined and differ based on the type of converter making general analysis difficult [24]. Additionally, the usefulness of phase resolved analysis is limited in VS-PWM drives. Due to the variety of PWM techniques applied in high voltage power electronic converters, applied voltage waveforms can vary greatly. With inconsistent waveforms for phase resolved analysis, PD classification and comparison across different types of PWM waveform can be difficult and of limited use.

2.3.2 Time Resolved Analysis

Time resolved partial discharge analysis maintains partial discharge shape and sequence, and the most common method of time-resolved partial discharge analysis is Pulse Sequence Analysis [15] and Pulse Shape Analysis [34]. Pulse sequence analysis allows better characterization of local PD defects because it does not rely on distributions of magnitude and phase of PD. The advantages of pulse shape analysis are risetime based noise suppression, but in non-electrical detection methods such as acoustic detection, some PD pulses may be attenuated [10].

2.3.3 Frequency Domain Analysis

Frequency domain analysis, most represented in the time-frequency map, is an effective way to cluster measurement data based on its source [9]. This method has been proven as effective in separating partial discharge from noise, which typically clusters tightly [15, 23]. However, specific partial discharge type classification is not defined based on this method, and noise clustering is subject to variability based on the voltage switching rise time.

2.4 Chapter Summary

In this chapter methods of partial discharge detection and analysis are researched. Partial discharge detection methods need to be effectively electrically isolated such that the transient

noise from PWM voltage switching does not overwhelm and obscure the partial discharge signal. Electromagnetic, optical, and acoustic detection methods are currently the most promising methods of partial discharge detection and are explored further in [chapter 3](#). Once partial discharge signals are effectively detected in the presence of voltage switching transient noise, methods of classification and analysis will provide further information about the PD signal. Information such as the type of partial discharge and the severity and frequency of PD. This analysis is important for a partial discharge testing platform to identify type and severity of insulation defect. In the project, phase resolved analysis and pulse sequence analysis methods will be further explored to determine effectiveness for different types of PWM voltage waveform.

Chapter 3

Evaluation of Different Testing Methods

The first and arguably the most important part of a partial discharge testing platform is the detection method. The detection method is the sensor that detects when a partial discharge has occurred in insulation or a test subject. Ideally, the harshest effects of voltage switching noise will be minimized through the use of an electrically isolated detection method. In this chapter several types of partial discharge detection are explored: optical detection, electromagnetic detection and acoustic detection. These detection methods are tested to determine first its capability of detecting partial discharge and second its capability to operate in the presence of voltage switching noise. If the detection method can successfully detect partial discharge in the presence voltage switching noise, it will be utilized in the partial discharge testing platform.

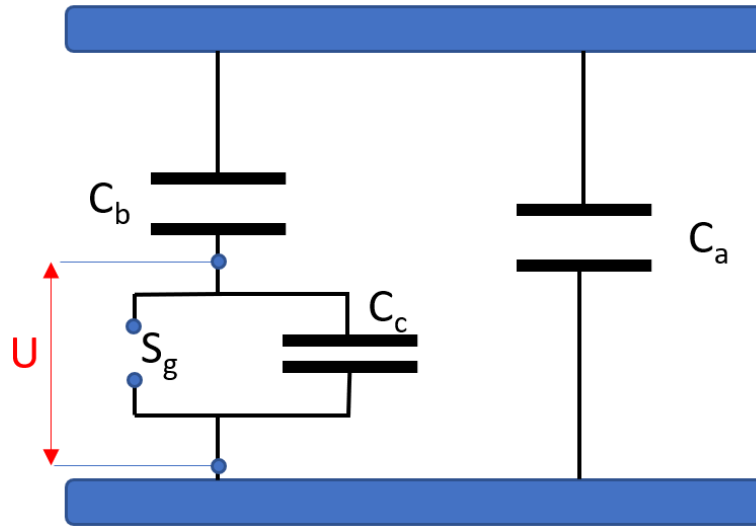
3.1 Partial Discharge Detection

3.1.1 Conventional PD Testing

Partial discharge testing is important for high voltage AC applications such as switchgear and transformers commonly used in utility substations. These systems operate consistently and at voltages as high as 700kV and sometimes higher. The conventional testing method,

or the apparent charge method, has been the standard measurement technique since the 1970's and is primarily focused on high voltage applications such as these, where the applied voltage is sinusoidal with a frequency of 60Hz or 50Hz typically. The apparent charge is measured because the partial discharge acts similarly to transient changes in capacitance in the insulation of a system. As such, a partial discharge can be modeled as [Figure 3.1](#) [35]. Apparent charge, or displaced charge, is an easier method of partial discharge detection when compared to measuring current or voltage changes. Current and voltage changes due to partial discharge are very difficult to detect in a high voltage system because they are several orders of magnitude smaller in comparison to system voltage and current. Additionally, passive elements of an insulation fault or test subject, the RLC value, will alter the corresponding wave forms resulting from the partial discharge. This means that comparison and analysis of partial discharge behavior across different insulation mediums would be very difficult.

The apparent charge of a partial discharge pulse is defined as the charge at which, if injected within a very short time between terminals of the test object in a specified test circuit, would give the same reading on the measuring instrument as the PD current pulse itself [1]. This measurement is typically represented in picocoulombs. Consistency in testing method is important to maintain reliable results that are repeatable. Partial discharge behavior can be effected by the duration of voltage application, the rate at which voltage is increased or decreased during tests, and environmental factors such as humidity and pressure near a test subject. Background noise is also a concern and most directly effects the minimum magnitude of partial discharge that can be detected. All of these potential disturbances and inconsistencies are difficult to completely eliminate and therefore must be managed in a way that can be repeated. An example recommended PD measurement circuit is shown in [Figure 3.2](#). This equivalent circuit represents the test circuit design used in the Phenix Technologies AC Dielectric test system used for this project [Figure 3.3](#). In this configuration, a coupling capacitor serves to isolate the partial discharge signal from the utility voltage and current. The coupling device in series with the test subject, further expanded in [Figure 3.1](#), serves to create a voltage signal equivalent to the partial discharge across the test subject.



- C_a = Virtual test object capacitance
- C_b = Stray capacitance of PD source
- C_c = Internal capacitance of PD source
- S_g = Spark gap
- U = Voltage drop across PD source

Figure 3.1: Partial discharge model in insulating medium. (replicated from [35])

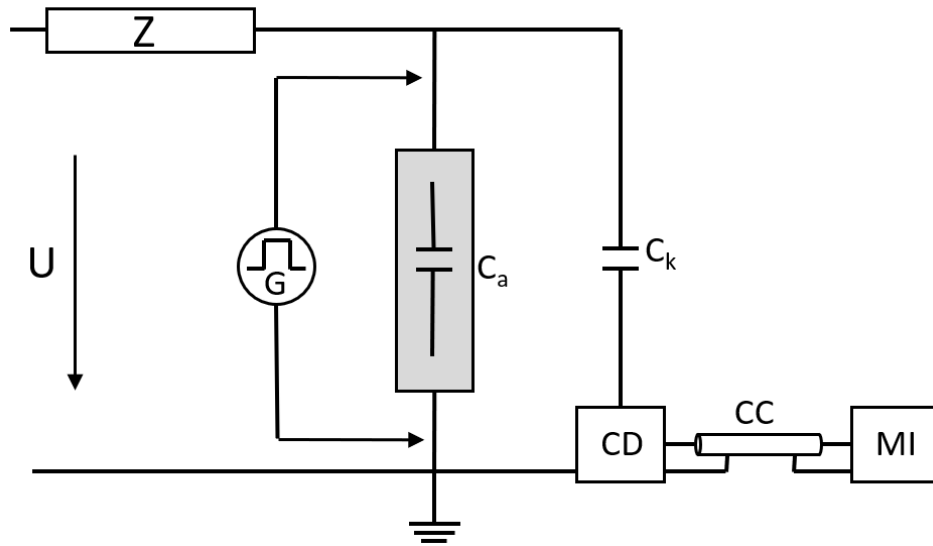


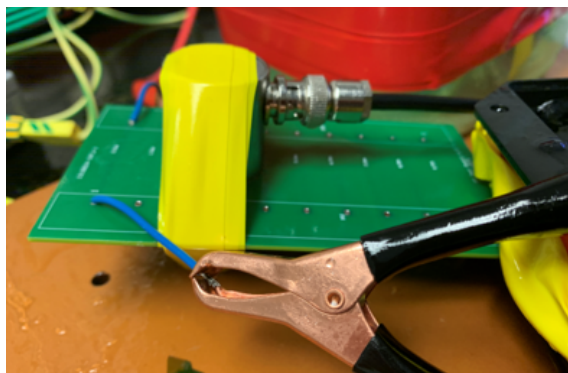
Figure 3.2: Test circuit for partial discharge measurement - Coupling device in series with test object. (replicated from [1])



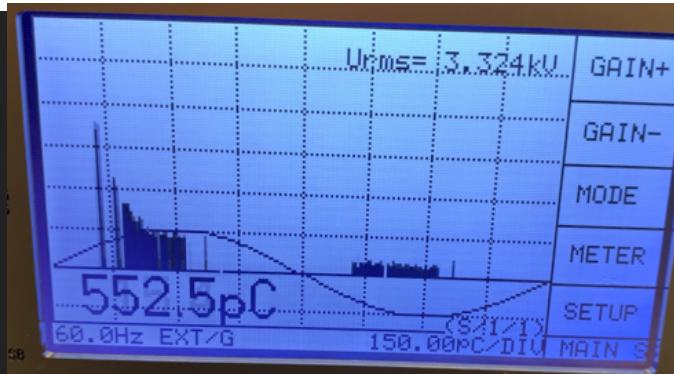
Figure 3.3: Phenix AC Dielectric 30kV Test System

As discussed previously, conventional testing methods are ineffective for partial discharge testing in a PWM voltage environment. This is because of the noise characteristic to voltage switching at high frequencies. In converter operating environments, the methods of decoupling a partial discharge signal from high voltage and current are not effective. These methods operate effectively in AC 60/50Hz environments because the frequency content of a partial discharge signal spans a much larger range. Therefore, the 60 or 50Hz fundamental frequency can be effectively filtered out without effecting the magnitude of a partial discharge signal. However, in converter environment where voltage and current has a switching frequency as high as 100kHz and higher, these large voltage and current signals can no longer be easily decoupled. With conventional testing methods, the partial discharge signal will be completely masked by noise.

However, conventional partial discharge testing is an important part of the experimental process of this project. The conventional partial discharge assisted in verification and test subject design. In this project, detection methods are tested for noise effectiveness against PWM voltage noise, and test subjects are designed with the goal of representing several types of partial discharge that could occur. With the AC dielectric test system, it was possible to test both potential test subjects and detection methods simultaneously. Examples of early test subjects and their phase resolved partial discharge patterns are shown in [Figure 3.4](#) and [Figure 3.5](#).



(a) PCB testboard

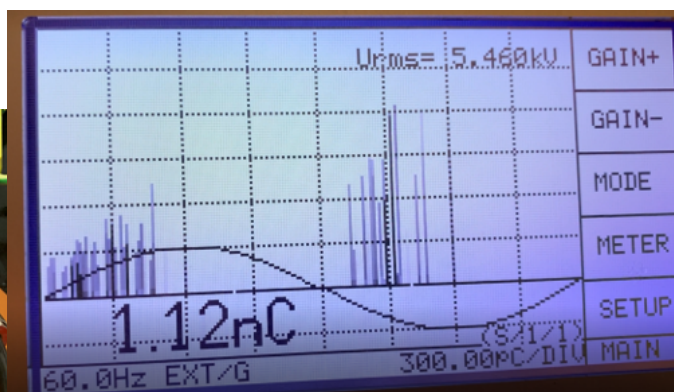


(b) Apparent partial discharge at 3.3kV

Figure 3.4: A PCB was designed to test internal discharge with a physical medium for an acoustic sensor to connect to. The phase resolved partial discharge pattern shows the type of partial discharge occurring in the test subject.



(a) Point and plane submerged in Silicon-gel mixture



(b) Apparent partial discharge at 5.4kV

Figure 3.5: A point and plane configuration was tested in a silicon-gel mixture to test for internal discharge due to bubbles in the mixture.

3.1.2 Acoustic PD Testing

A partial discharge breakdown creates a localized release of energy. This energy produces electrical, mechanical, and chemical changes in the material surrounding the partial discharge. The presence of mechanical signals emitted from the partial discharge means that acoustic emission testing can be utilized to detect the acoustic waves that travel from the partial discharge location. Acoustic emission testing is commonly used for high voltage utility transformer partial discharge testing. Acoustic emission testing has the advantage of immunity to electromagnetic interference very common to switching yards. Additionally this immunity enables effective online condition monitoring. To perform acoustics emission testing, the Physical Acoustics Micro-II AE system ([Figure 3.6](#)) was used along the Phenix Technologies AC Dielectric testing equipment, acting as a source. The acoustic sensors are piezoelectric sensors [40] that create electric charge in response to changes of mechanical stress resulting from partial discharge micro-explosions within an insulating material. The AE system operates by measuring this electric charge against a predetermined or floating AE threshold as shown in [Figure 3.7](#). If the acoustic signal amplitude at any part of the waveform surpasses the threshold, the acoustic signal is recorded. For partial discharge testing, the AE threshold must be properly tuned to avoid ambient environmental noise from being captured. Environmental noise can be limited to improve the accuracy of partial discharge testing. This may be effective and worthwhile in a standard utility application where the noise due to utility voltage is relatively easy to limit. However, in a PWM voltage application the noise as a result of converter operation heavily outweighed any environmental noise that could be picked up by the acoustic sensors and software noise tuning was found to be suitable for this application. A number of testing samples were used to determine samples with effective physical coupling interfaces for acoustic emission testing. For example, [Figure 3.8](#) shows three test subjects that demonstrated an effective environment in which acoustic sensors can be applied to detect partial discharge. A major limitation of the acoustic sensors is the environment in which they can be utilized. A strong acoustic couplant is required to establish proper transmission of acoustic energy from the structure to the sensor. Therefore, it is difficult to utilize acoustic sensors of this type in some typical operating



Figure 3.6: Micro-II Digital AE system

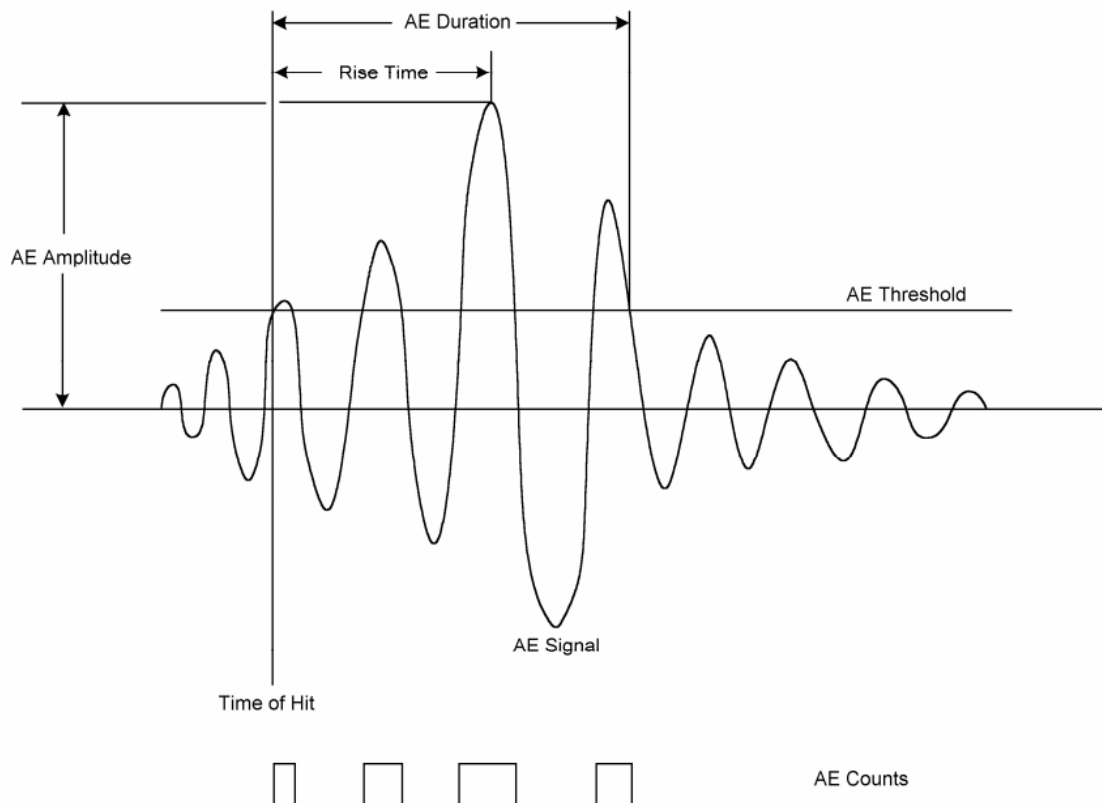


Figure 3.7: AE Hit Feature Extraction Diagram, [Acoustics]

environments in which both partial discharge and PWM voltage could be expected, such as electric machines. Partial discharge commonly occurs in the windings of a high voltage electric machine. This phenomena can be effectively simulated using a twisted pair to test partial discharge detection methods. For acoustic emissions testing, a system similar to the Micro-II could be used however, this is ineffective due to inability to couple the sensors to the test subject.

An example of an acoustic waveform as the result of a partial discharge is shown in [Figure 3.9](#). One of the prime advantages of acoustic partial discharge testing is the ability to locate the source of the partial discharge. Due to the time it takes for acoustic waves to travel through a medium, sensors located in different locations will have different time of partial discharge. If the location of the acoustic sensors is known and the speed of the acoustic waves can be determined for the tested material, the location of the partial discharge can be calculated using [Equation 3.1](#). At least four sensors are required to perform the calculation. This method was tested using the PCB busbar with 4 acoustic sensors shown in [Figure 3.10](#). The (x_n, y_n, z_n) coordinates for each of the four sensors and the velocity of the waveform v is established as a constant based on expected physical medium. T is the time of partial discharge detection for the first sensor to detect a particular partial discharge and t_n is the additional time it took for each of the other sensors to detect that partial discharge. Using this data the (x, y, z) coordinates for the PD can be determined.

$$\begin{aligned}
(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2 &= (v + T)^2 \\
(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2 &= (v + (T + t_2))^2 \\
(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2 &= (v + (T + t_3))^2 \\
(x - x_4)^2 + (y - y_4)^2 + (z - z_4)^2 &= (v + (T + t_4))^2
\end{aligned} \tag{3.1}$$

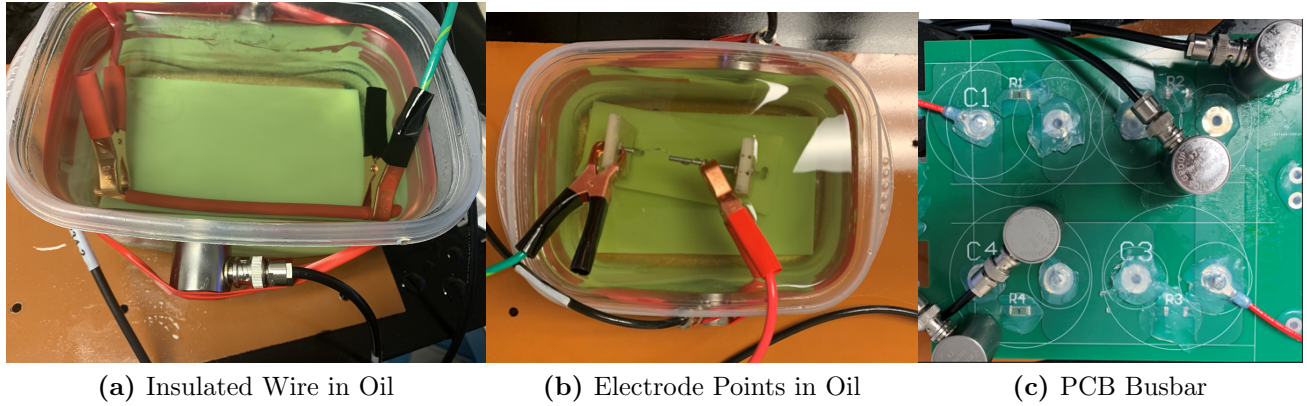


Figure 3.8: Test subjects connected to 60Hz AC voltage. Acoustic sensors are attached to oil tub or pcb to capture acoustic emissions resulting from partial discharge.

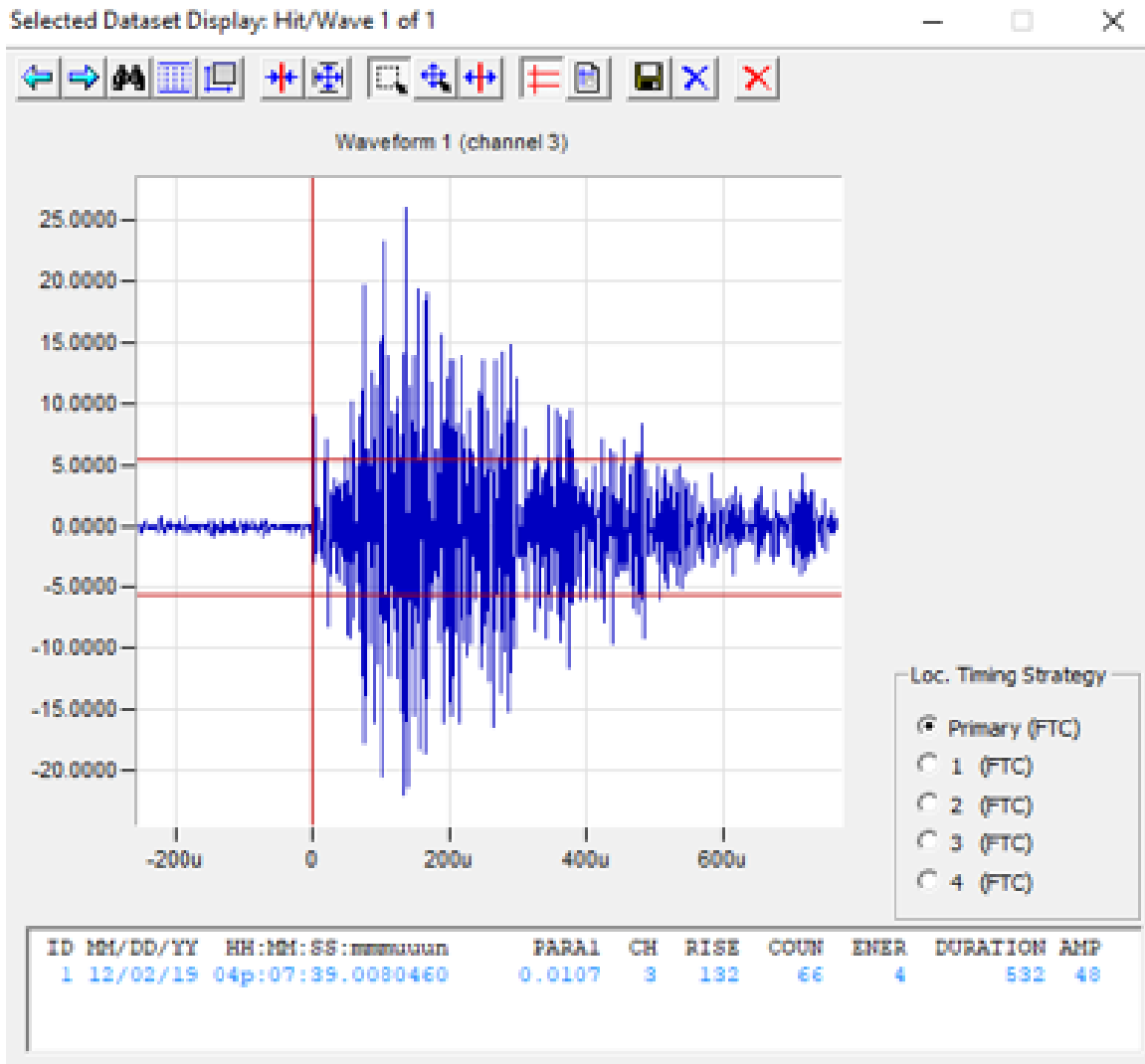


Figure 3.9: Partial Discharge Waveform recorded by Acoustic Sensor

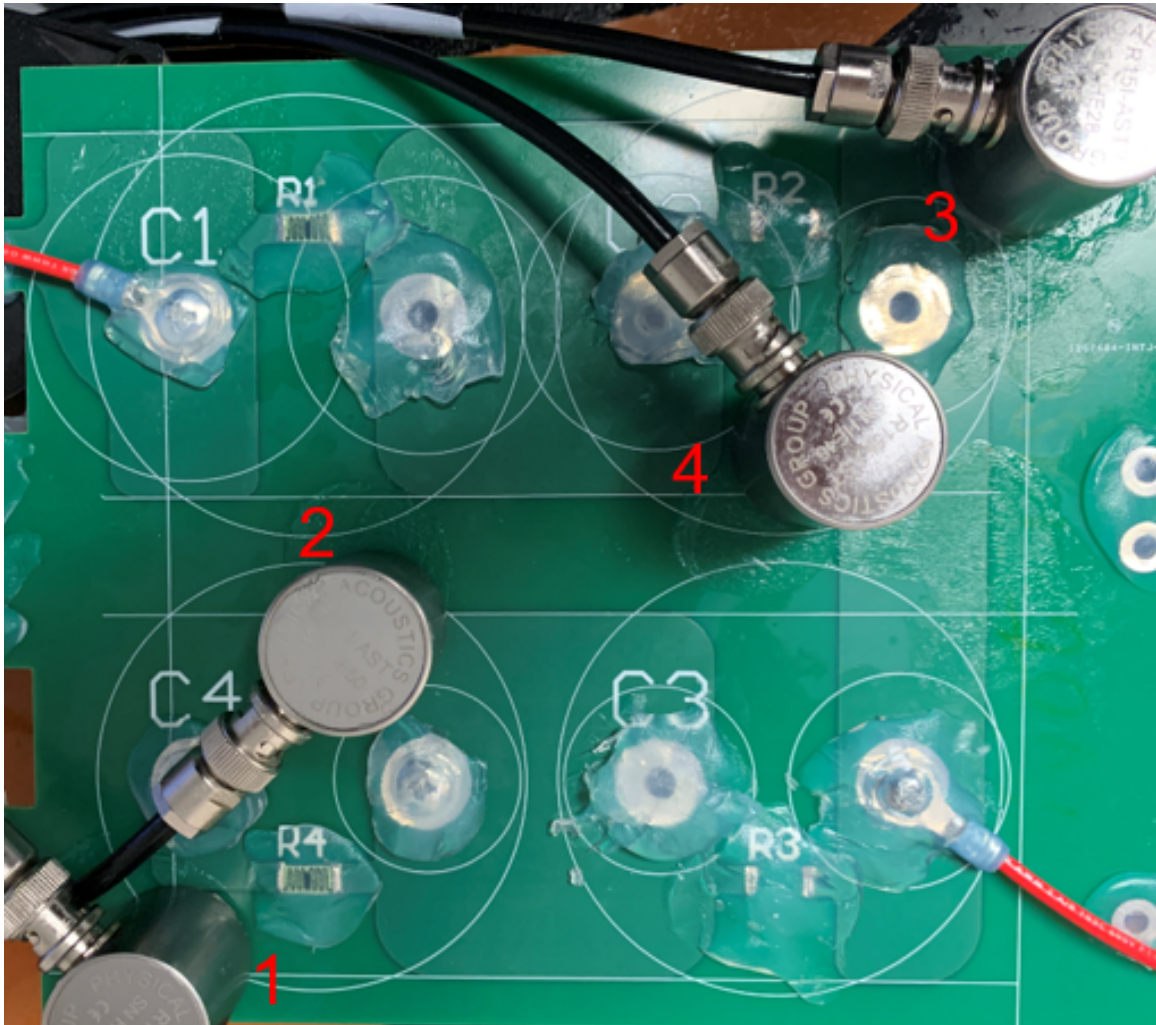


Figure 3.10: PCB Busbar test subject. The four acoustic sensors used to test localization methods are labeled. This PCB was previously damaged in the region nearest to sensor 4.

However, there are limitations to the effectiveness of PD localization due to different types of acoustic waves:

- Longitudinal - particles of the medium oscillate along the direction of wave propagation.
- Transverse - particles of the medium vibrate perpendicular to the direction of wave propagation.
- Surface - propagate along the boundary between two medium.

Longitudinal waves are faster than the other two types of waves. The acoustic measurement received by a sensor corresponds to a partial discharge but can be of any type of wave, the type of wave effects the time values and velocities used in the localization calculation. In order for a localization of a specific partial discharge to be considered accurate and reliable, the detected acoustic wave needs to be longitudinal and traveling across a direct path. The type of acoustic wave and the path taken can be assessed from the waveform shape. If the acoustic wave has taken an indirect path and propagated through several layers of different materials, leading to attenuation, the waveform will have a rounded off or 'egg-shape' to it. If the acoustic wave has taken a direct path and has not passed through several layers, the waveform will appear more triangular, with a sharp rise to the peak. In [Figure 3.11](#), this effect can be seen, where an acoustic wave on channel 4, closest to the source of partial discharge, takes a very direct path and is not attenuated. Channel 1 is the sensor located furthest from the partial discharge and by consequence is heavily effected by the attenuation of the signal as it passes through the layers of the PCB busbar.

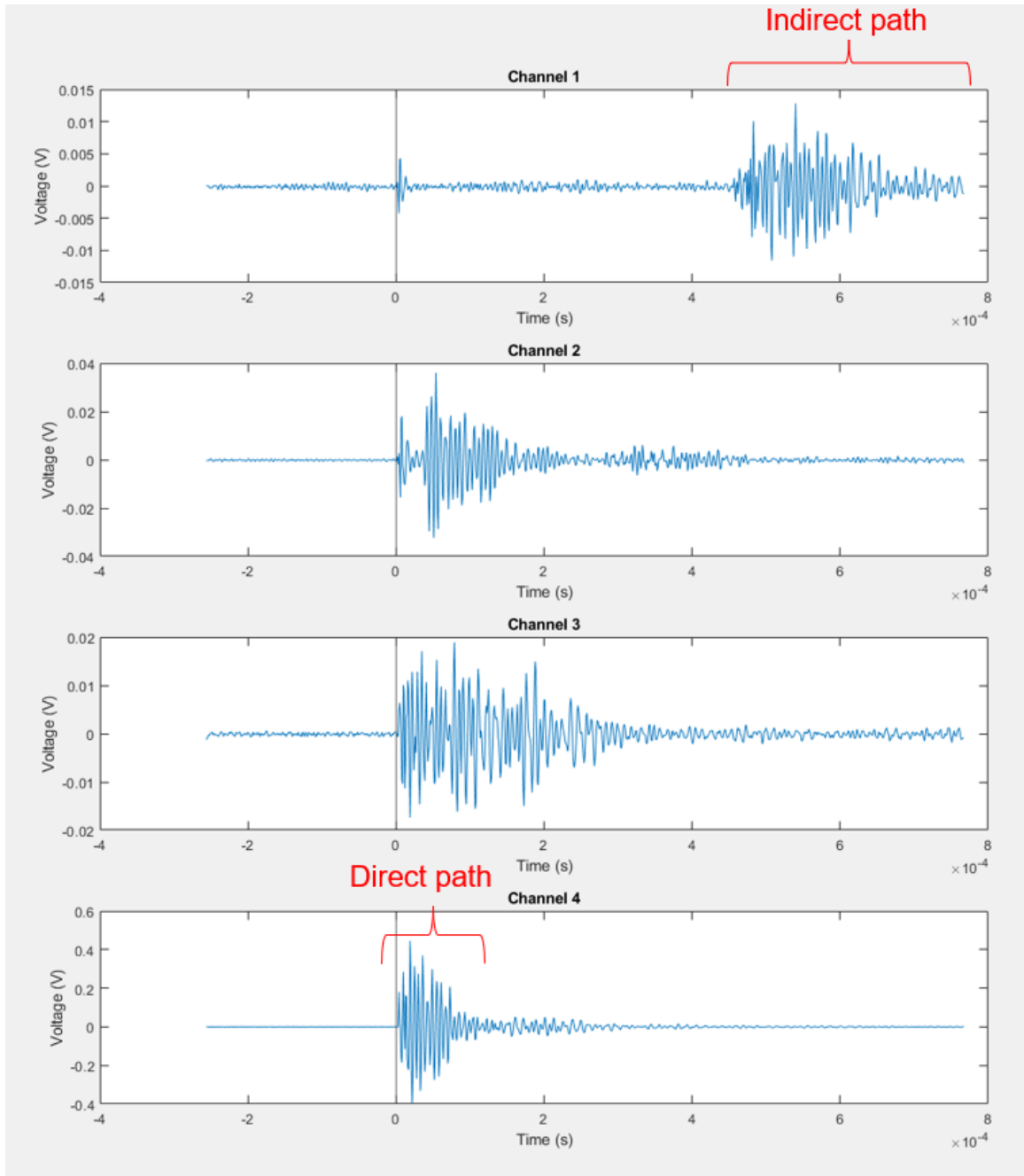


Figure 3.11: Partial Discharge recorded on 4 acoustic sensors for localization.

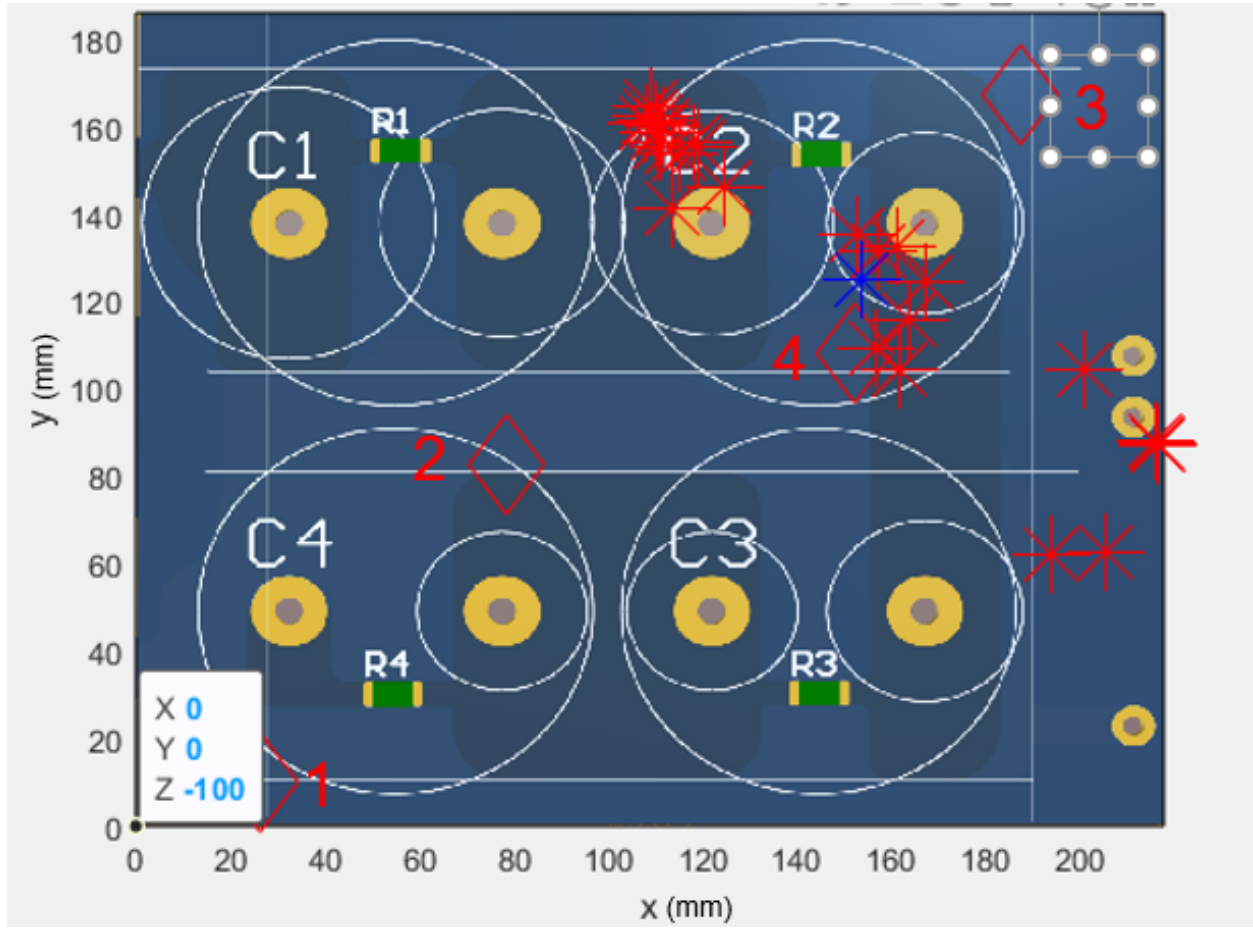


Figure 3.12: Localization of Partial Discharge based acoustic partial discharge detection by four sensors. The red stars represent the location of an individual Partial discharge and the blue star represents the average location of all detected partial discharge.

Due to the effect of the attenuated and indirect partial discharge acoustic waves recorded by any given sensor, but most likely the sensors located furthest from the source of the PD, it is difficult to trust any individual calculated partial discharge location. If any of the four recorded partial discharge waves is overly effected by attenuation or took too indirect a path the calculation of the PD location will be invalid. While in an application such as an oil power transformer, these limitations can be easily mitigated due to consistency of the medium, PCBs for power electronics applications can be very complex with many different potential medium changes between the source of a partial discharge and the location of the sensors. In this example, a PCB busbar was tested which has a relatively simple layout compared to other potential power electronic converter pcb design. However, the results of PCB design on the path of acoustic signals can still be seen in [Figure 3.12](#). The location of the insulation damage on this PCB busbar is nearest to sensor 4, at the interface between the copper planes and the fr4 insulating material. The localization of the partial discharge signals however is very sporadic. Although the PD localization does trend close to the actual location of the partial discharge there are inconsistent results, with some PD appearing to occur off of the board entirely. In a medium such as a PCB, acoustic localization can be very inconsistent, and can be expected to perform worse in more complex PCB layouts.

3.1.3 Electromagnetic PD Testing

Partial discharge in insulation creates RF electromagnetic waves that propagate away from the location of the discharge. This electromagnetic wave can be fairly easily by an antenna. However, the antenna by itself does not solve the problem of partial discharge detection in the presence of PWM voltage switching noise. However, an ultra-high frequency antenna can be used in conjunction with a very high pass filter. A high pass filter operating in the 100-1000MHz range can prove effective for partial discharge testing because of the sporadic nature of partial discharge. A partial discharge signal will be smaller in magnitude over a larger frequency range. PWM voltage noise will be dominant at lower frequency, up to 1-10s of megahertz, but at higher frequencies, the noise will be less dominant. Due to this a very high pass filter in the range of 100-1000 MHz will effectively attenuate noise and allow for detection of small partial discharge electromagnetic waves even in the presence of

voltage switching electromagnetic interference. However, too high of a high pass filter, and the partial discharge signal can begin to be attenuated as well. 300MHz was found to be an effective compromise of PWM voltage noise attenuation and partial discharge detection.

3.1.4 Optical PD Testing

The small explosion in insulation that is a partial discharge produces light that can be detected with a highly sensitive sensor. This light can be one effective method of partial discharge detection in certain environments where a direct line of sight to the partial discharge can be maintained. Photo multiplier tubes, like the PMT 1002 by Thor Labs, operate by using photo-emission to capture light as electrons. The PMT focused detection method is highly sensitive but requires a controlled environment. The best possible sensitivity with a PMT is reached by operating it in a very dark environment to limit external light from hiding potential partial discharge. With a well controlled environment, the PMT can be used to detect partial discharge very effectively [Figure 3.13](#) and [Figure 3.14](#). The PMT model 1002 was chosen due to the large range of photo wavelengths that it could detect.

However, the usefulness of partial discharge testing is limited. Due to the necessity of a controlled, dark space, the PMT does not have a likely industry application as even slight ambient light can create large amounts of noise. Additionally, the PMT is only effective for partial discharge that occurs external to solid insulation, whether that is corona or surface discharge. Due to the PMT operating on the visible light spectrum, internal or void discharges in insulation can not be detected as the light emitted by these partial discharges likely cannot escape the insulation.



Figure 3.13: Partial Discharge Testing of a twisted pair using photomultiplier tube in a dark environment

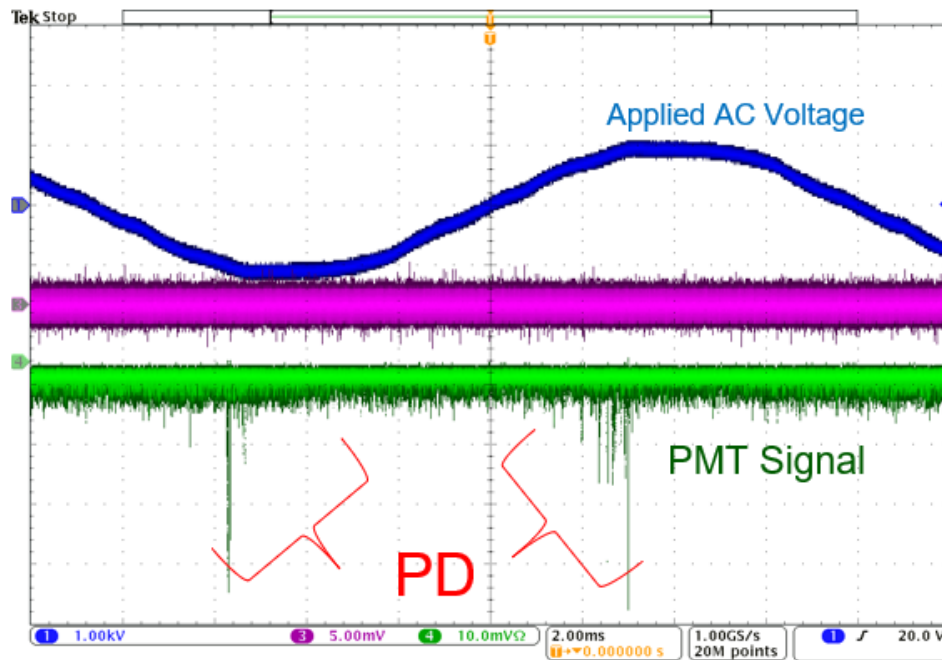


Figure 3.14: Partial Discharge optical signal recorded by PMT

3.2 PD Noise

Three detection methods were tested extensively in an 60Hz AC environment using the AC dielectric test system to verify their ability to detect partial discharge. These detection methods, acoustic emission testing, electromagnetic testing, and optical testing, all have advantages and disadvantages in terms of application and usefulness, but still needed to effectively detect partial discharge in the presence of PWM voltage switching. This section covers the performance of the detection methods in a power electronic converter operating environment. In order to test performance of these detection methods in the presence of noise, the Si-based half bridge converter with a PCB test board and a high voltage resistor in series to the low-side device [Figure 3.15](#). The PCB test board was chosen as the test device for the noise testing primarily because the acoustic sensors need a physical medium to couple to [Figure 3.16](#). Additionally, the PCB test board was found to have partial discharge inception voltages of 1.5kVrms and higher depending on selected lead. Therefore the converter could safely be operated to 1kV without concern that partial discharge would occur. This allowed for operation at high enough voltage to ensure robust detection performance in the presence of noise. The design of this converter is covered in depth in [chapter 4](#).

The potential advantage of acoustic emission testing for power electronic converters are in application and potential for non-intrusive operation, so that online partial discharge testing could occur. However, PWM voltage switching noise produces substantial acoustic noise as well as electrical noise. As the voltage increases, the magnitude of the acoustic noise increases as well. An example of acoustic PWM voltage noise is shown in [Figure 3.17](#). Not only does noise make it difficult to detect partial discharge, but in the case of the acoustic sensors, the noise may make partial discharge detection impossible entirely. Acoustic sensors have a limited bandwidth and can become saturated if too much acoustic noise is being detected. As the magnitude of acoustic noise increases the acoustic sensors will eventually become saturated, and will no longer be able to detect every acoustic wave that is occurring. Acoustic noise magnitude increases as the voltage of the system increases which means that higher and higher voltage avoiding saturation is very difficult. This process is illustrated in [Figure 3.18](#).

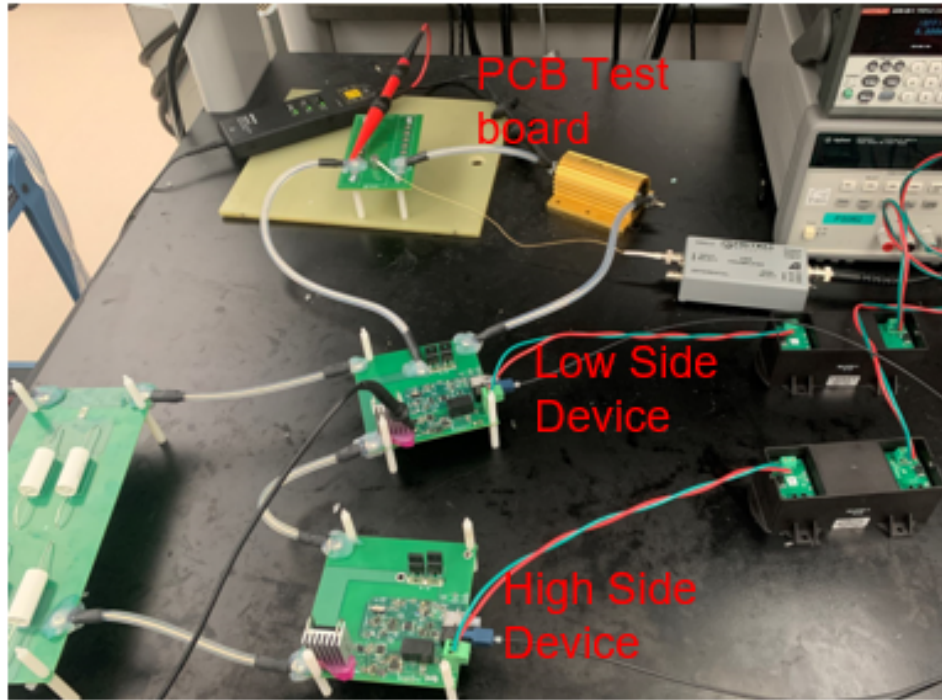


Figure 3.15: 3kV Si-based Half-bridge converter with test subject and high voltage resistor connected in series to low-side device

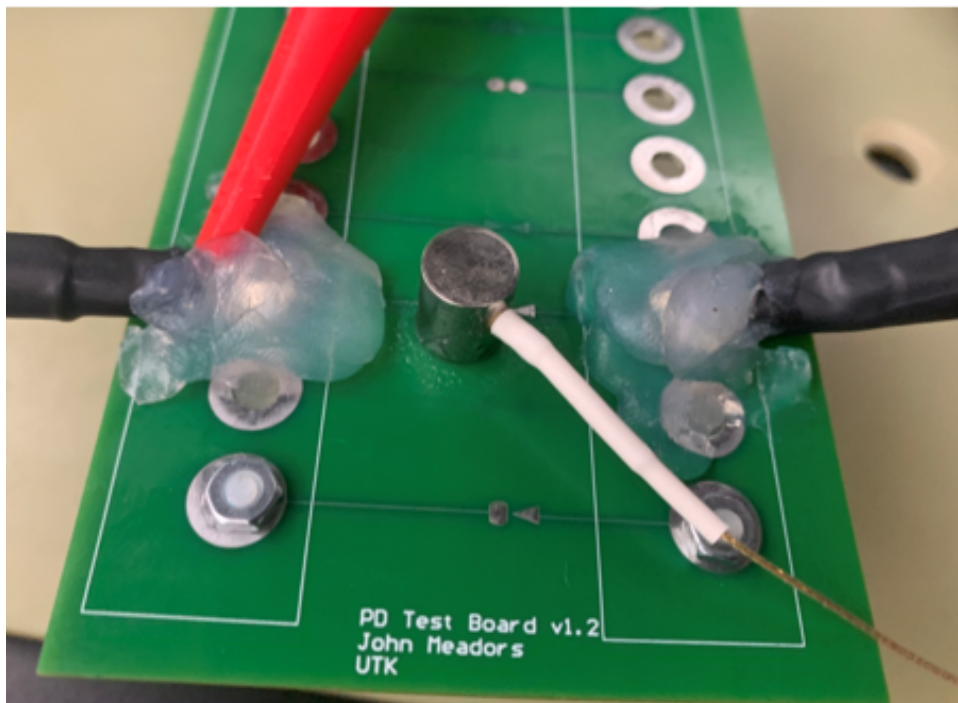


Figure 3.16: PCB testboard chosen for noise testing due to relatively high inception voltage and easily surface to couple an acoustic sensor.

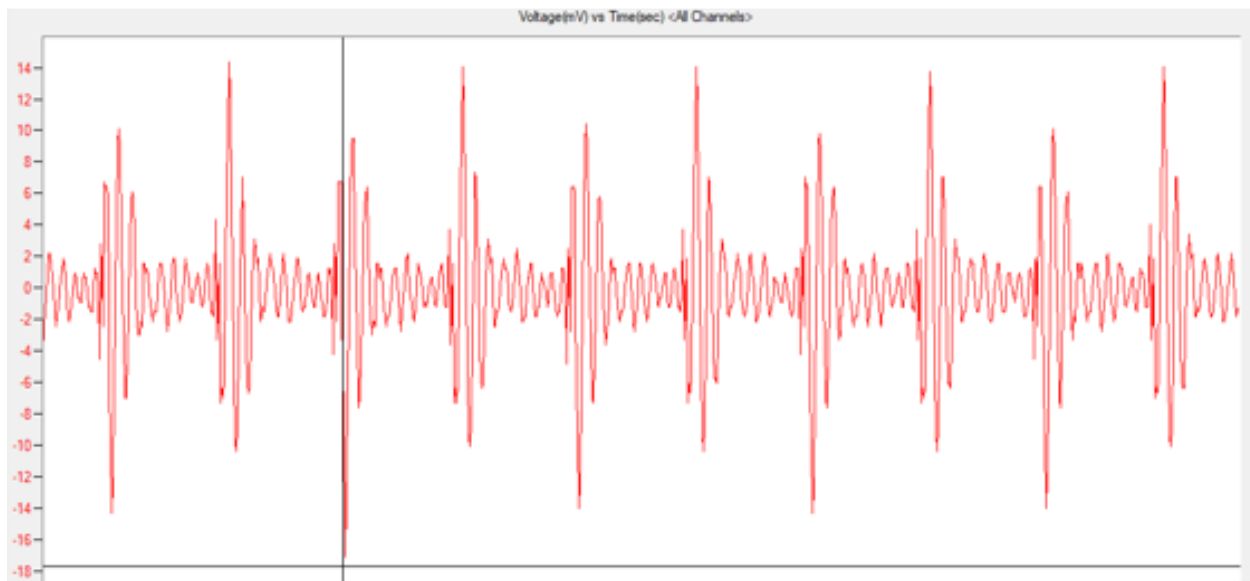


Figure 3.17: Acoustic emissions of PWM Voltage Noise

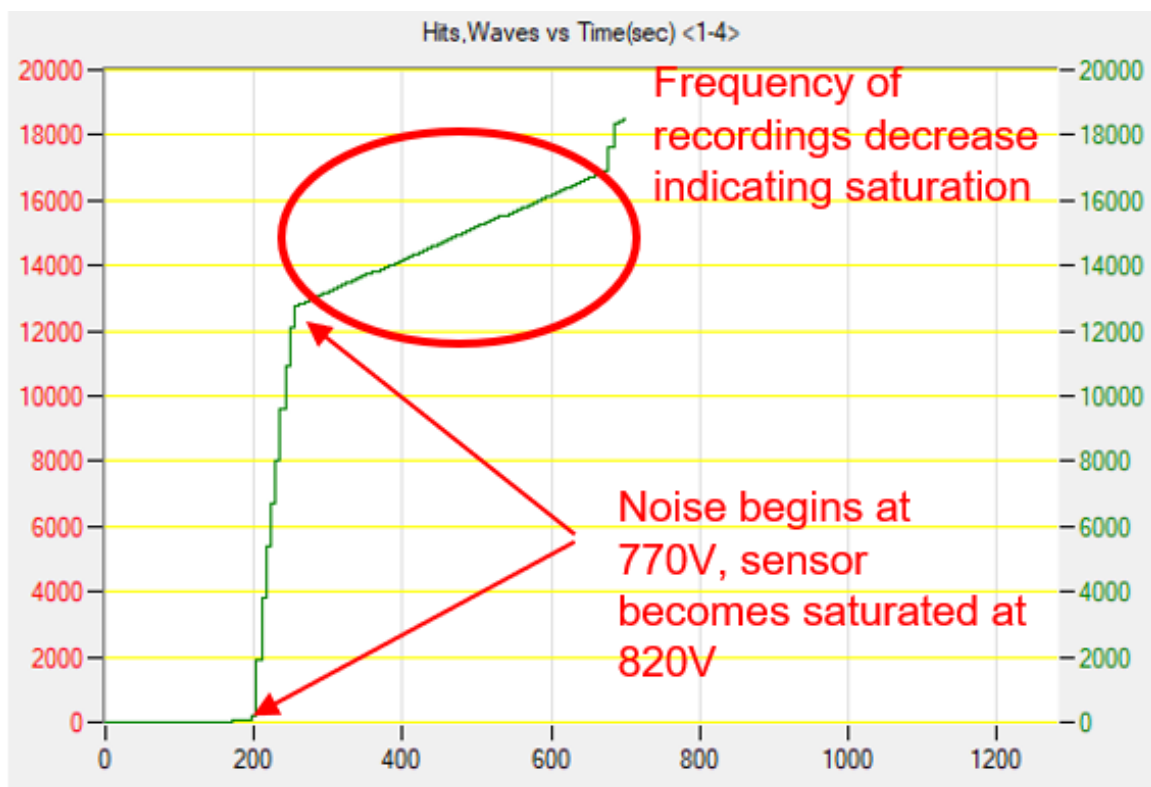


Figure 3.18: Saturation of Acoustic sensors due to noise

During this test, the operating voltage of the system was increased to 1000 V and then decreased again. The acoustic noise grew until at 770V the acoustic sensors began recording it because it surpassed the set threshold. Quickly after this, at 820V the sensors became saturated. This is indicated by the reduction in hits per second. At this point, even if partial discharge could be separated from noise, it may not be detected at all. At this point the only solution is to increase the threshold at which acoustic detection will be recorded. However, the trade-off is that this reduction in sensitivity will effect partial discharge detection as well. In order for acoustic sensors to operate at 5-10kV where internal discharge can start to be a problem, too high of a threshold would be required, rendering acoustic sensors too ineffective for partial discharge testing. For this reason acoustic detection was not pursued further for PWM voltage converter partial discharge testing.

The UHF antenna was tested with the 3kV Si-half bridge converter to ensure that the antennas would operate effectively in the presence of PWM voltage EMI (electromagnetic interference). The antennas were positioned nearby to the PCB test board using two coaxial cables of different length at first. Without high pass filters connected as shown in [Figure 3.19](#), the EMI that results from high voltage switching is immediately apparent. At only 100V, the signal is too noisy for any use in partial discharge detection. Adding the 300MHz high pass filter greatly improves performance of the UHF antenna. At this point, another issue becomes apparent however. The coaxial cables allow a significant amount of noise to impact the signal. In [Figure 3.20](#) three different configurations were tested. The two coaxial cables of different lengths and the antenna and filter connected directly to the oscilloscope. The longest cable has a significant amount of apparent noise, and the shorter cable still sees certain amount of signal noise due to EMI. With no cable, the antenna signal is almost completely noise free, and suitable enough for the purposes of these testing requirements. Partial discharge will be easily detected in this operating environment. The UHF antenna detection method does have certain limitations. Although effective in this testing environment, immunization against environmental EMI is much more difficult in more active use cases.

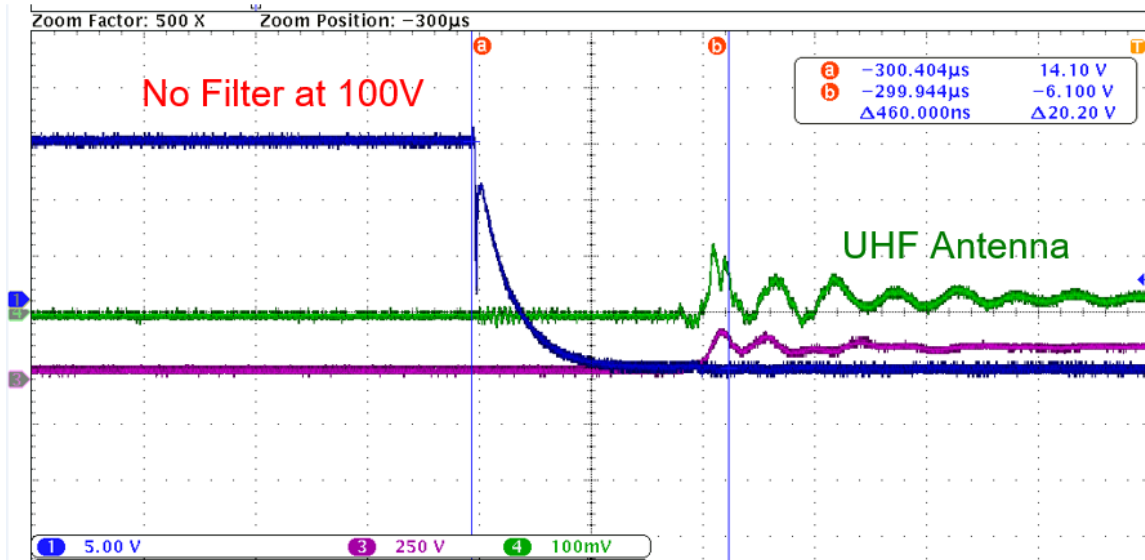


Figure 3.19: PWM Voltage EMI without high pass filter

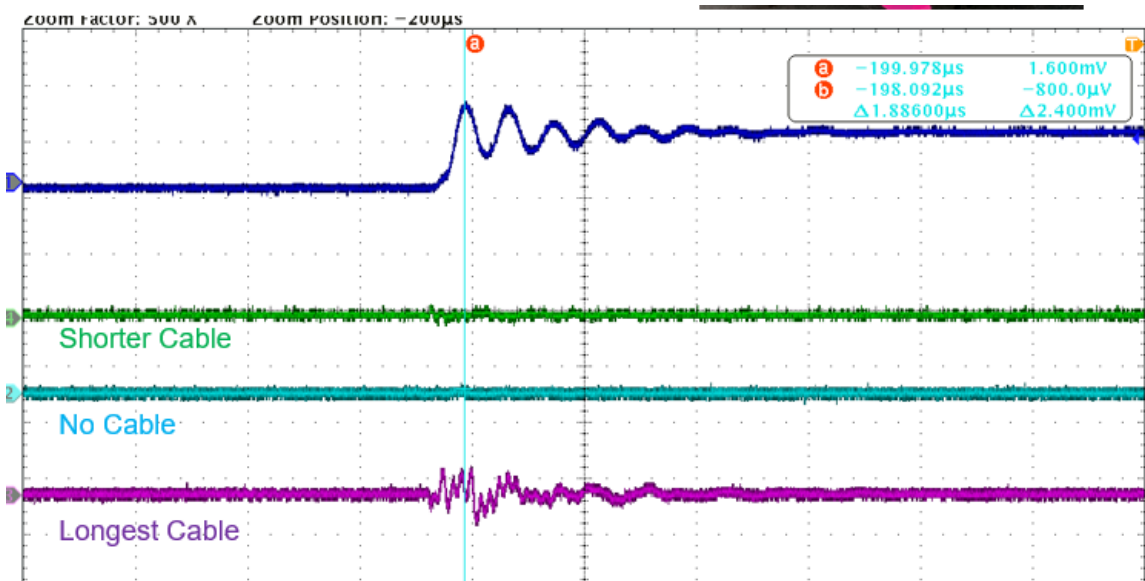


Figure 3.20: PWM Voltage EMI with high pass filter and varying coaxial cable length

In an industry application where communication, controls, and several different machines may operate at different frequencies or have unique EMI noise, isolating an UHF antenna to noise becomes much more difficult. For this reason, the UHF antenna has limited applications. It would likely not prove useful for online partial discharge testing or monitoring. For the purposes of this experiment in which environmental noise is limited to voltage switching however, the UHF antenna can prove effective.

The photo multiplier tube utilized for optical detection is very effective for partial discharge detection in the presence of voltage switching noise. The PD signal to noise ratio is very good, making the PMT an excellent detection method for PWM voltage partial discharge testing. However, the PMT requires more preparation. The greatest source of noise that makes partial discharge testing is actually ambient light noise that the photo multiplier tube sensor may pick up from the testing environment. Then PMT is very sensitive and voltage switching does not emit significant light especially compared to a partial discharge. However, the sensor can be easily saturated by ambient light. To combat this a black box was assembled ([Figure 3.21](#)). The PMT sits on top of the black box with the sensor pointing down through a hole towards the test subject such that any light emitted due to partial discharge is recorded. The PMT cannot be used for partial discharge testing of internal defects in a test subject due to the nature of relying on light. However, this information can be utilized to determine where in a test subject the partial discharge is likely occurring, if the question is of internal or external defects. With the black box included in the test setup, the photo multiplier tube is a very effective detection method for external or optically exposed partial discharge. [Figure 3.22](#) shows that the effect of voltage switching noise on the performance of the photo multiplier tube is virtually not existent. The signal produced by the PMT shows no impact due to voltage switching even when operating up to 2kV. The photo multiplier tube performs better than the UHF antenna in terms of noise immunity even with the high pass filter. The PMT also has the advantage of sensitivity. The PMT is relying on optical light emitted during a partial discharge and because the voltage switching transient emits no light, or at least not enough to be detected by the PMT, the photo multiplier tube does not need any further filtering to limit noise.

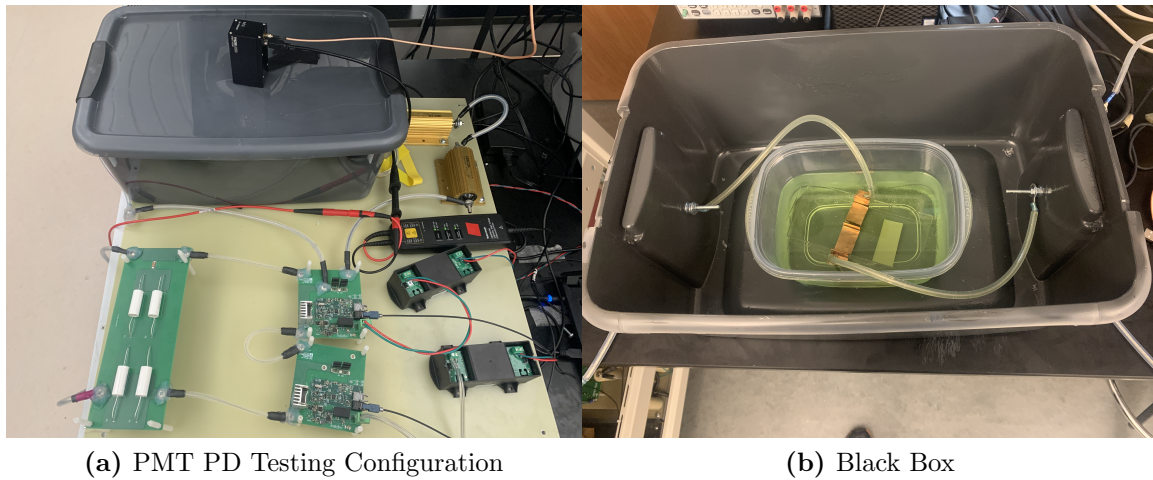


Figure 3.21: Black box for partial discharge testing with PMT. The black box limits ambient light.

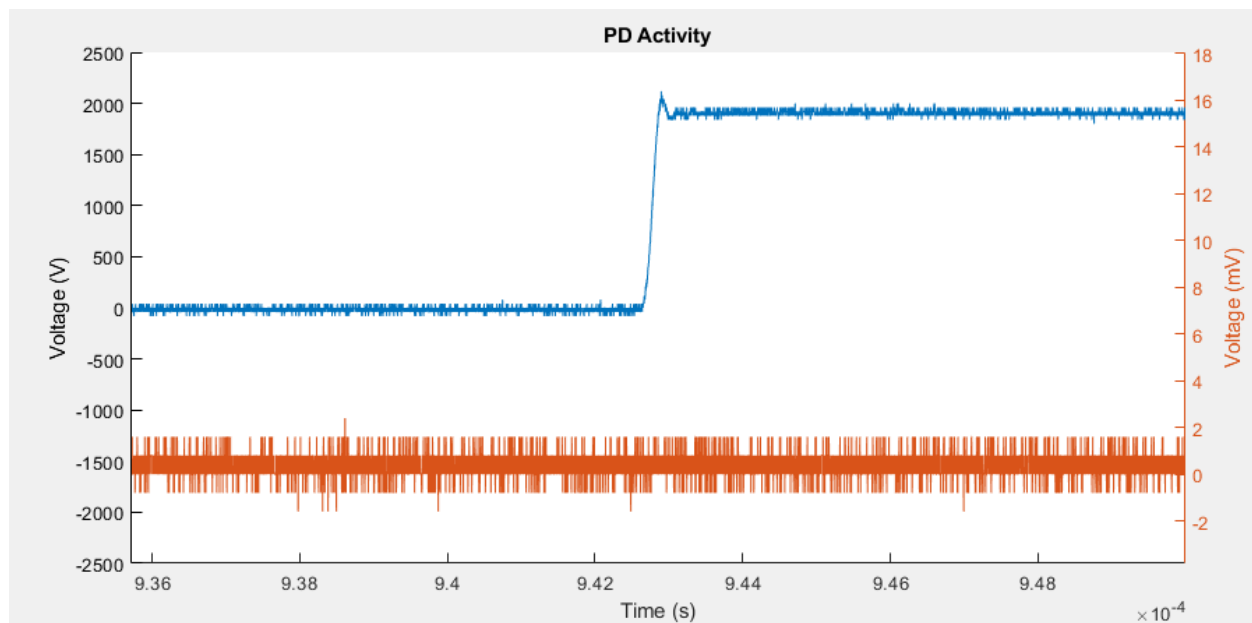


Figure 3.22: PWM Voltage noise with photo multiplier tube

The high pass filter utilized by the UHF antenna has a dampening effect on the partial discharge signal as well as on the voltage switching noise. Therefore the UHF antenna will have less signal sensitivity compared to the photo multiplier tube. If not for the added setup requirements for testing and the inability of internal discharge detection, the PMT would likely be the ideal PD detection method on all fronts.

3.3 Detection Selection and Verification

Three electrically isolated partial discharge detection techniques were explored to determine potential effectiveness in the presence of PWM voltage switching noise. However, due to a practical inability to effectively limit acoustic noise as a result of voltage switching, acoustic emission testing will not be pursued further. Acoustic emission testing in a 60Hz AC environment is the most effective at internal discharge testing due to sensitivity and ability to be located very close to source of discharge while isolated from noise outside of insulation medium that it is coupled to. Electromagnetic testing with an ultra-high-frequency antenna and high pass filter is the most robust partial discharge testing method for this testing method as it can effectively detect any type of partial discharge. It is not limited by physical constraints. The UHF antenna setup here does suffer from limited sensitivity as a result of the high pass filter having a necessary attenuation of signals below 300MHz. As a result of this, the UHF antenna can detect partial discharge but not at very small magnitudes.

The UHF antenna and PMT detection methods were both initially tested using a twisted pair. A simple twisted pair can have a relatively low inception voltage. Additionally, the magnitude of partial discharge due to a twisted pair increases quickly after inception. To check effectiveness of the partial discharge testing methods, the twisted pair [Figure 3.23](#) is a good place to start.

In [Figure 3.24](#) a partial discharge signal as recorded by the antenna can be seen and is much larger in magnitude compared to the voltage switching noise. Additionally, the antenna connected directly to the oscilloscope is proven here to be the optimal setup configuration. The magnitude of the partial discharge detected is not adversely effected by the increased distance from the test subject, but the signal is effected by the voltage switching noise to a

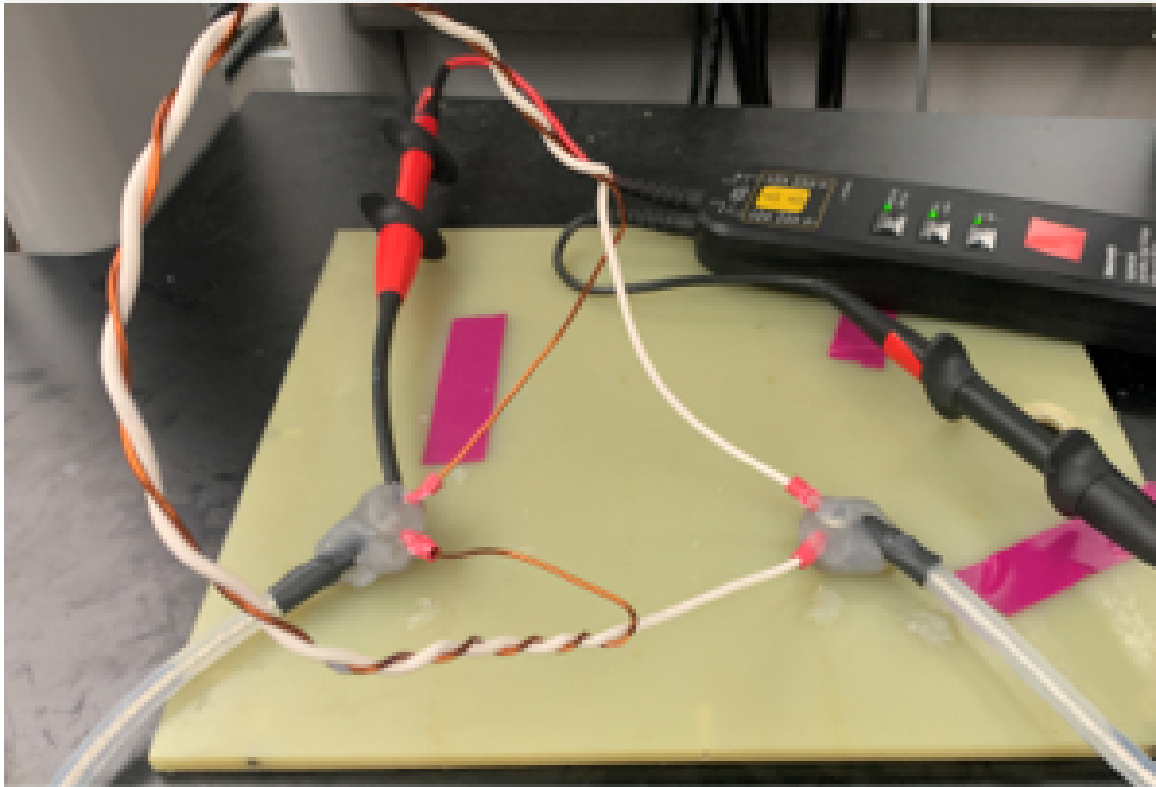


Figure 3.23: Twisted Pair - verification of UHF Antenna detection Method

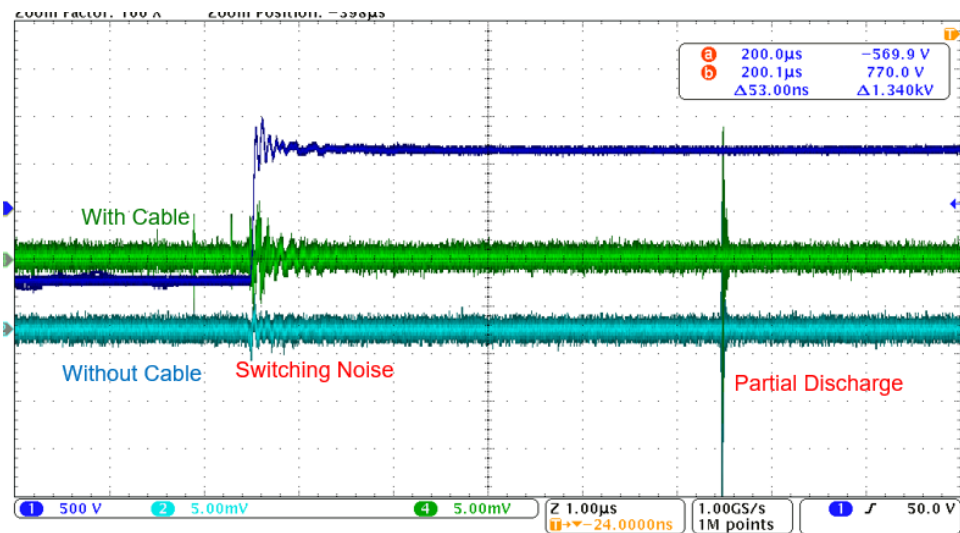


Figure 3.24: UHF Antenna Detection - Partial Discharge Waveform and switching voltage noise

much smaller degree. For this reason, the UHF antenna configuration in which the antenna is connected directly to the oscilloscope will be used for all further partial discharge testing.

In [Figure 3.25](#) the inception of partial discharge on the twisted pair is recorded. It is easy to determine that the partial discharge is in fact partial discharge and not any form of external noise by two ways. First, any voltage level that partial discharge is detected at, the converter is then tested to that voltage with the test subject disconnected. All operating conditions are the same except for the lack of test subject. Therefore, if no 'partial discharge' signal occurs then it is not environmental noise. Additionally, the effect of the partial discharge breakdown can be seen on the voltage waveform. The voltage is measured across the test device for reference and analysis. When a partial discharge occurs, a dip can be seen in the applied voltage. If a partial discharge can be imagined as a brief change in the capacitance in an insulation system as demonstrated in [Figure 3.1](#), then the brief change in insulation capacitance would lead to a reduction in applied voltage. Once partial discharge begins in a twisted pair, it is likely to continue until the voltage applied to the insulation is decreased below extinction voltage. In [Figure 3.25](#) the partial discharge can be seen to occur at every switching cycle once it begins. Partial discharge in a twisted pair is likely to occur at and around voltage changes, which in the case of a PWM voltage converter is at the switching events. The partial discharge of a twisted pair when detected by a UHF antenna is very large immediately. This reflects expectations of partial discharge behavior in a twisted pair and the sensitivity capabilities of this UHF antenna setup. For these reasons the UHF antenna detection method can be confidently confirmed as effective for partial discharge detection in the presence of PWM voltage.

The twisted pair as mentioned is an effective test subject to verify partial discharge is occurring due to low inception voltages and large PD signals produced by the twisted pair. The same methods of PD verification are utilized for the photo multiplier tube. However, verification is easier for the PMT as virtually no noise is detected on the PMT as a result of voltage switching. If a signal is detected on the PMT, it likely will be a partial discharge signal. However, the same effects on the applied voltage waveform can be seen with an partial discharge regardless of detection method utilized. [Figure 3.26](#) shows that the partial

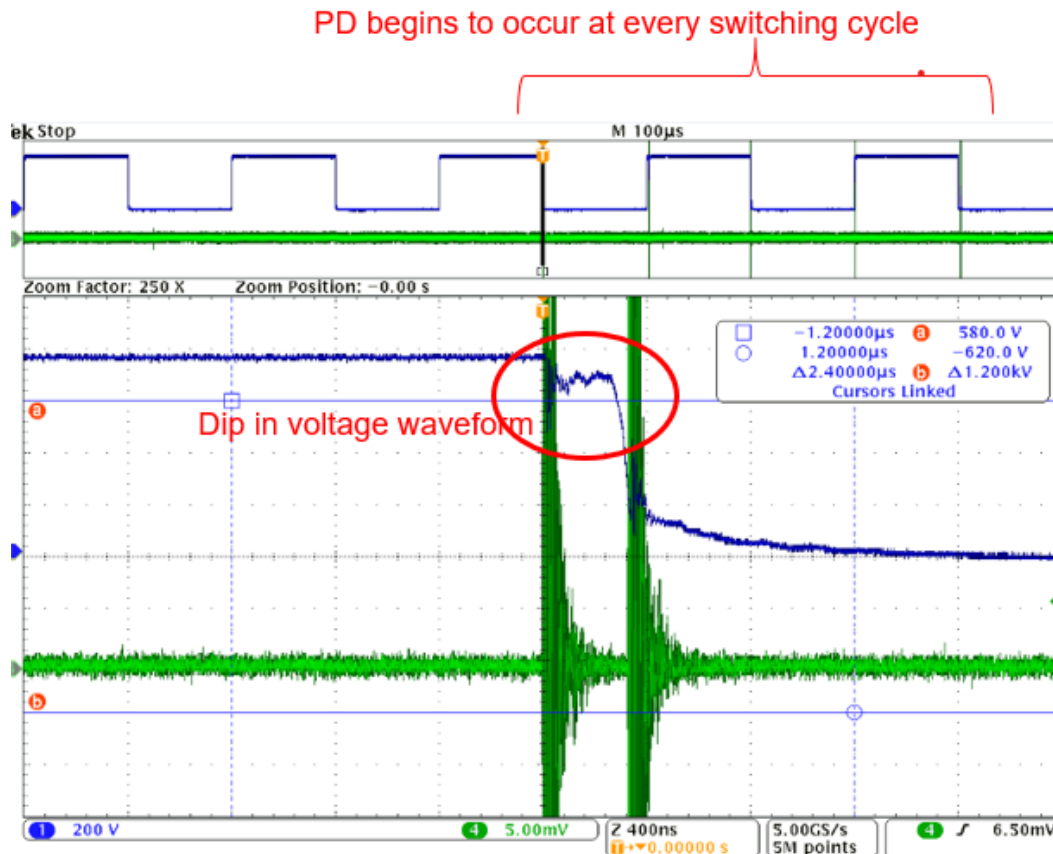


Figure 3.25: Inception voltage for Twisted Pair - UHF Antenna Detection

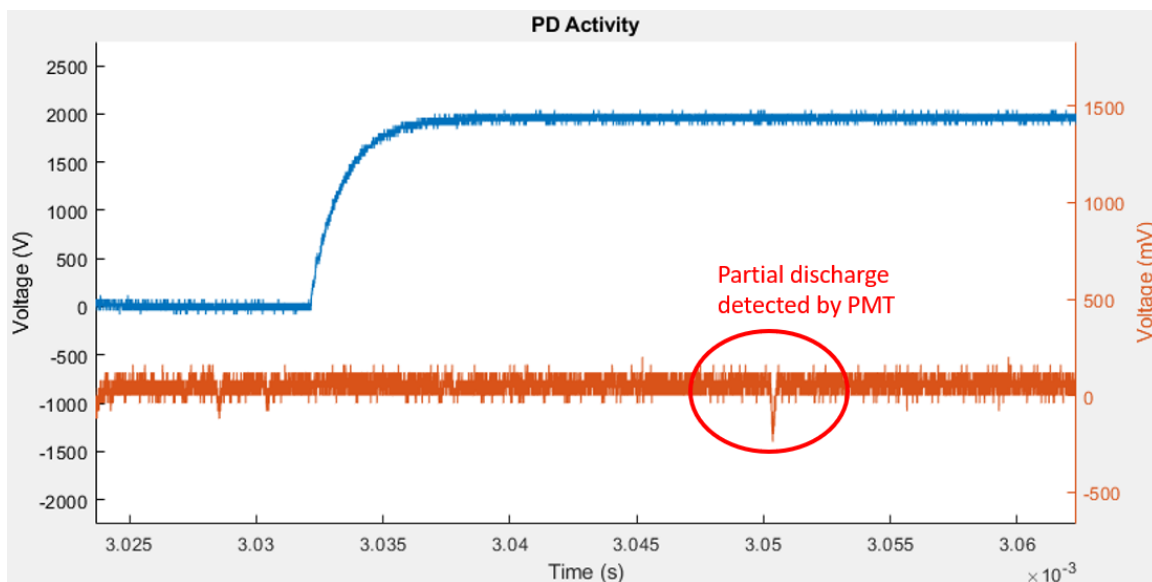


Figure 3.26: Photo multiplier tube Detection - Partial Discharge Waveform

discharge occurs approximately $20\mu\text{s}$ after voltage switching. This result similarly reflects the partial discharge behavior as detected by the UHF antenna. The partial discharge detected here is smaller than what is typically detected by the UHF antenna. This shows that the PMT is capable of detecting smaller signals with its increased sensitivity in the right environment. Additionally, due to PMTs practical voltage switching noise immunity, it is easier to distinguish small partial discharge signals as partial discharge signals.

3.4 Chapter Summary

Partial discharge detection is the first step in establishing an effective partial discharge testing platform. Detection methods that are electrically isolated and capable of limiting the effect of voltage switching noise on detection capability are vital. Without effective detection methods partial discharge could not be studied and could not be prevented or designed for. This chapter establishes two effective partial discharge detection methods: electromagnetic detection utilizing a ultra-high-frequency antenna with very high pass filter and optical detection utilizing a photo multiplier tube. These detection methods have their limitations in application and capability. Neither of these detection methods are foolproof or ready for commercial application. However, for the purpose of this project, these detection methods cover the inabilities of each other and provide a capable means of detection for the purpose of studying partial discharge behavior.

Chapter 4

Testing Platform Design

The testing platform design covers all of the considerations that go into designing a testing platform for partial discharge testing in the presence PWM voltage except for detection methods, which are covered in [chapter 3](#). This includes the converter design for producing PWM voltage and considerations and prototyping for good partial discharge test subjects. The converter functionality is verified as well as the test subjects in the presence of PWM voltage. Additionally, a 10kV SiC converter is utilized in the place of the designed Si half-bridge converter to aid in partial discharge testing at higher voltages and with different voltage waveforms.

4.1 Design Requirements

In order to test the effectiveness of alternative partial discharge testing methods in the presence of PWM voltage switching noise, a high voltage power electronic is designed to operate as a partial discharge testing platform. The primary requirement for this converter is high operating voltage. The driving force behind partial discharge in a faulty insulation system is local electric stress concentrations, which are more likely to occur when insulation is exposed to high voltage. The design however has very low current requirements. The system will essentially run open circuit, with partial discharge essentially acting as a very fast and small current pulse. This current pulse resulting from a PD typically decays in approximately a microsecond.

For initial testing, a simple converter design was preferred to keep overall system noise low. The partial discharge testing methods should be effective in the presence of switching noise, but as an initial test, limiting the number of switches in the system was prioritized. A half-bridge converter with two switches would help limit the overall effect of noise from device switching. Additionally, outputting a simple square PWM voltage waveform with a constant duty cycle enables testing the effect of PWM voltage switching on partial discharge testing and partial discharge behavior while limiting potential impact from more complex converter operation such as space vector modulation control. Due to these requirements, a high voltage silicon mosfet [Figure 4.1](#) was chosen as the switch for this converter. A 10 kV silicon-carbide full-bridge converter will also be used to test partial discharge behavior in a more realistic power electronic application.

4.2 System Overview

A half-bridge converter design was chosen due to ease of operation and limited number of switches to limit overall system noise. 4500V silicon MOSFETs were chosen, and the half-bridge converter was designed to operate at 3kV. The system overview layout is shown in [Figure 4.2](#), with the lab setup shown in [Figure 4.3](#). The converter requirements and design considerations primarily relate to high voltage operation, as the current requirements are very low. To this end, extra care was needed in isolating low voltage control systems and the high voltage rail, which operates up to 3kV.

The Silicon MOSFET switches are each contained on the gate driver board, which hosts most of the control, low voltage power, and protection of the system. The gate driver board acts as the connection point between DC power, the switches and the low side loop between switch and test device. The gate driver design will be covered in the next section in more depth.

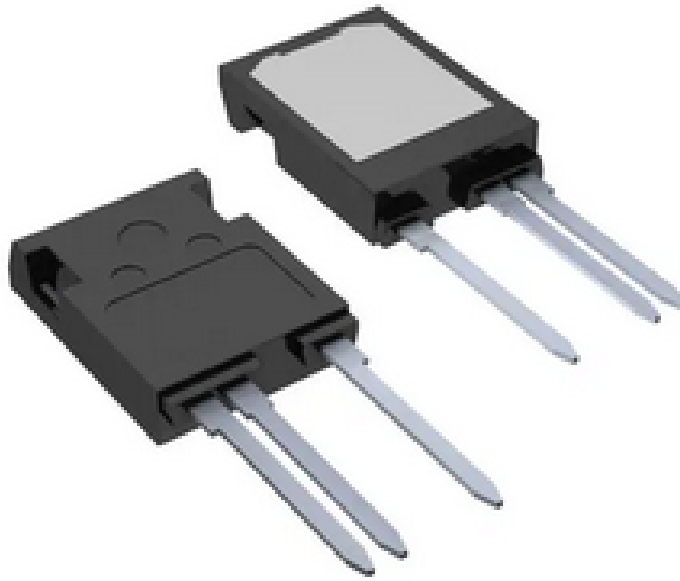


Figure 4.1: IXYS 4500V/ 1.4A N-Channel MOSFET used in full bridge converter for PD testin

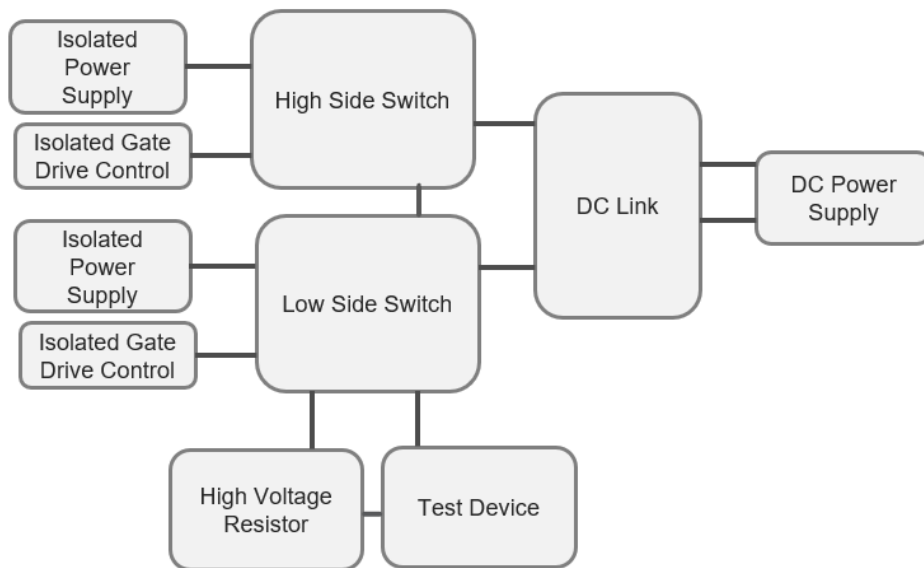


Figure 4.2: 3kV Si Half-bridge Converter Diagram

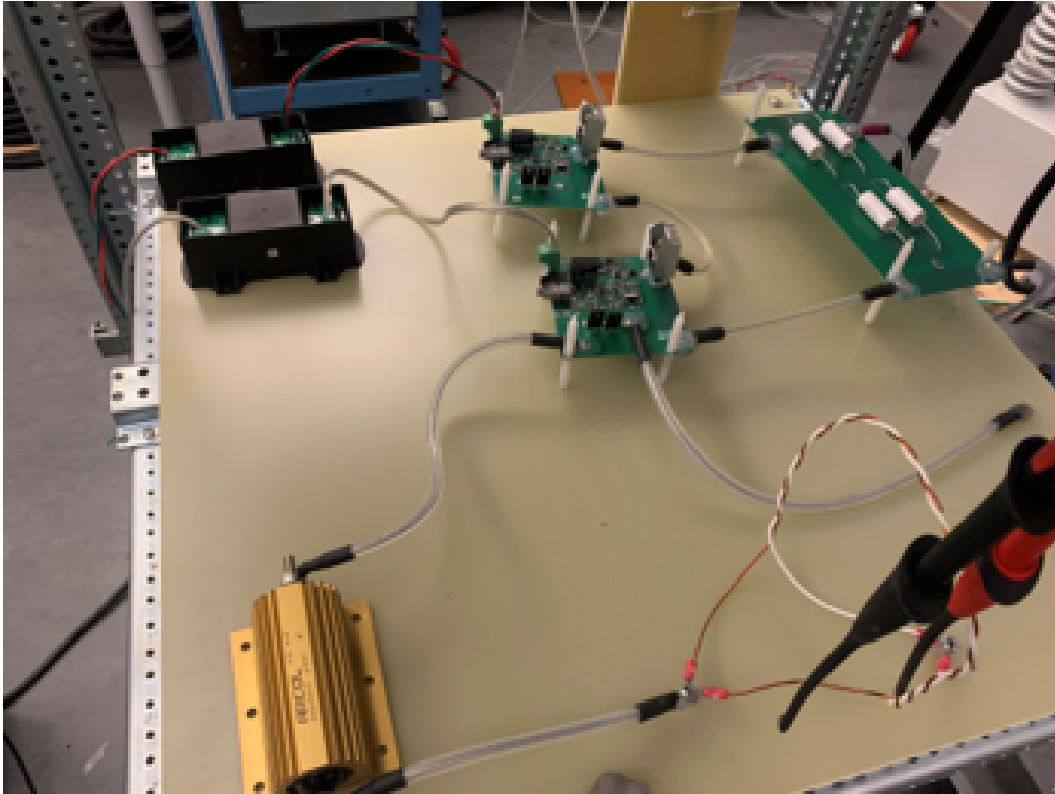


Figure 4.3: 3kV Si Half-bridge Converter

4.3 Gate Driver Board Design

The gate driver board as shown in [Figure 4.4](#) served as the main board for this half-bridge converter design. The gate driver circuit, protection, controls, switch and heat-sink all resided on one board together. This reduced overall design complexity and enabled a modular design should a more complex circuit operation be pursued later.

4.3.1 Gate Driver

The gate driver circuit as shown in [Figure 4.5](#) serves to provide necessary voltage in order to drive the switch into the on or off state. Additionally it must provide sufficient current in order to charge and discharge the switch input capacitance and in order have quick response and thereby fast switching, the gate loop should be low impedance. The gate resistor has to meet the power rating:

$$P_{Rg} = (V_{CC} - V_{EE}) * Q_g * f_s \quad (4.1)$$

This converter will not run past 30kHz, and the MOSFET has a gate charge ($Q_g = 88nC$). Therefore the gate resistors have to have a power rating requirement of approximately 53mW. The gate resistor is what controls the speed of the switching transients in this converter design. To that end, the gate resistance is modulated through partial discharge testing in order to change the dv/dt capability of the converter. Pulse withstanding resistors are designed specifically to handle high surge pulse events such as applications like this one. Gate resistance varying from 200 Ω to 10 Ω will be used to vary the turn on and turn off times of the converter.

The gate driver must have a operating voltage range in order to push the MOSFET into the open and closed positions. For this design, 15V for turn-on and -5V for turn-off are required. The peak source and sink capabilities must meet the gate current requirements based off of gate voltage and gate resistance values:

$$I_{source/sink} > (V_{CC} - V_{EE})/R_g \quad (4.2)$$

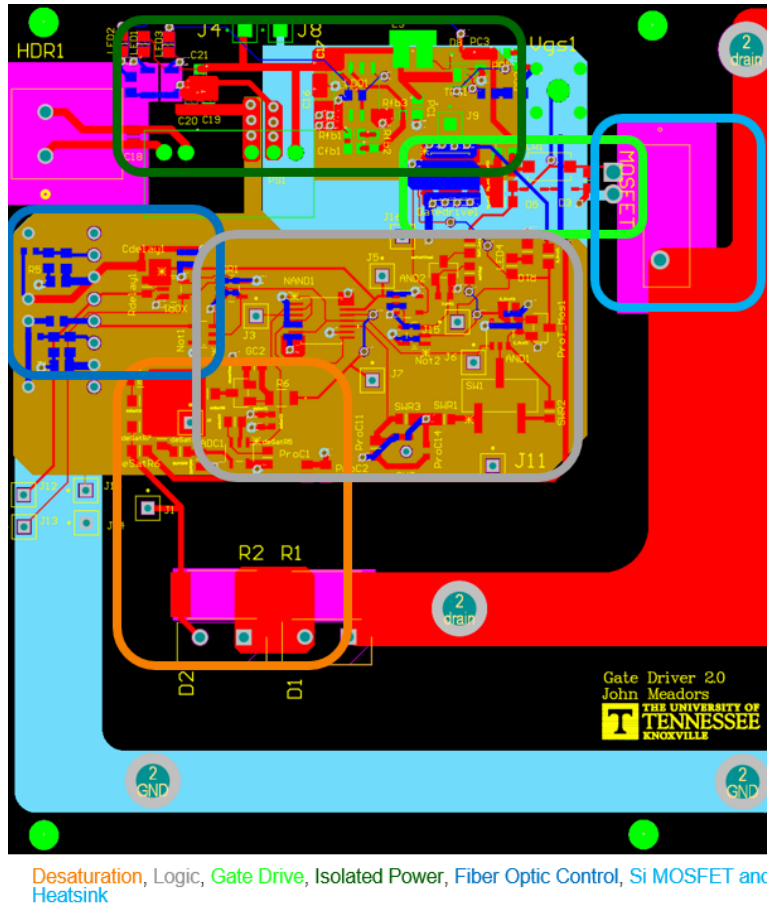


Figure 4.4: 3kV Gate Driver Board

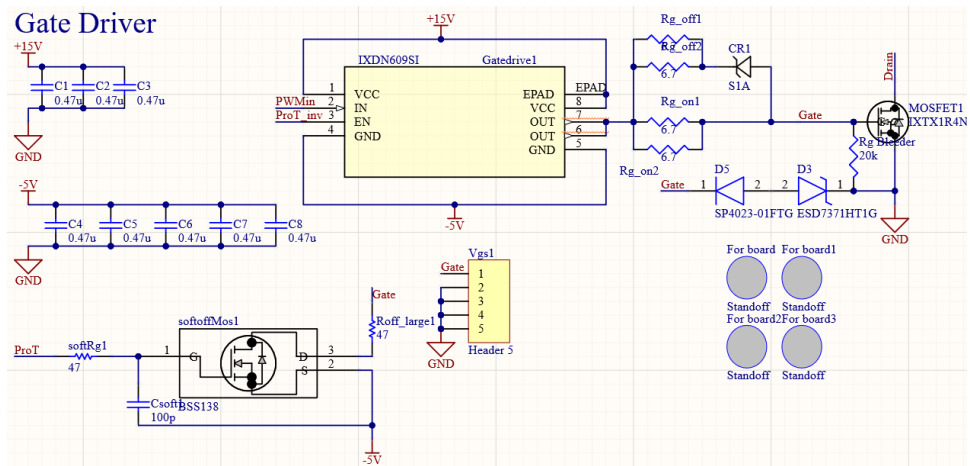


Figure 4.5: Si MOSFET Gate Driver Circuit

The lowest desired gate resistance for high dv/dt turn-on capability is 5Ω leading to a source/ sink current capability requirement of:

$$I_{source/sink} > 4A \quad (4.3)$$

The propagation delay must also be minimal, less than 1% of minimum expected switching period. The maximum switching frequency that will be used with this converter is 60kHz. The minimum propagation delay resulting will be:

$$Propagation\ Delay < 1/(60kHz) * .01 < 167ns \quad (4.4)$$

The chosen gate driver to meet these requirements with parameters is shown in [Table 4.1](#).

4.3.2 Isolated Power

The isolated power supply circuits as shown in [Figure 4.6](#) provide voltage for operation of the low voltage systems on the board, such as the gate drive circuits, control, communication, and protection. This includes required voltage for driving the switch into on and off positions. The isolated power supply must have a suitable galvanic isolation capability; greater than voltage rating of the switches. The CM transient immunity must be greater than the dv/dt during switching. Also, of course the output power must be greater than the power dissipated on the secondary side.

This power dissipated is defined by:

$$P_{out} > P_{sw} + P_{iso} + P_{gd} \quad (4.5)$$

Table 4.1: IXYS IXDN609SI Gate Driver IC

Operating Voltage	4.5V to 35V
Peak Source/ Sink Current	9A
Rise/ Fall time	7/ 5ns
Propagation Delay	40ns
Pull-up/ Pull-down resistance	0.5/ 0.33 Ω
Quiescent Power Dissipation	23mW

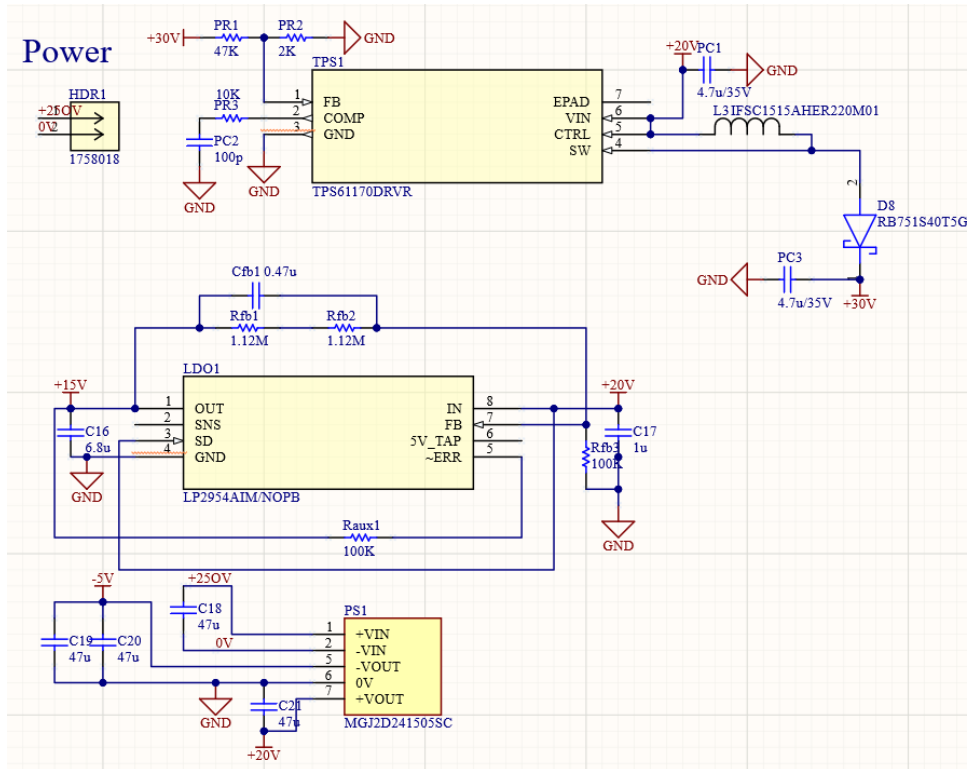


Figure 4.6: Si Mosfet Isolated Control Power Circuit

The power dissipated during switching was calculated previously in [Equation 4.1](#). P_{gd} refers to the gate driver power dissipated, and P_{iso} is the secondary side of the isolator power consumption.

The secondary of the signal isolation circuit or the fiber optics circuit can consume approximately 100mW on both the sending and receiving fiber optic circuit according to device datasheet. To accommodate this $P_{iso} > 200mW$. The gate drive, IXDN609SI from IXYS can be expected to consume approximately 23mW during operation according to the device datasheet. Overall the isolated power supply must be able of supplying approximately:

$$P_{out} > 53mW + 200mW + 23mW \quad (4.6)$$

$$P_{out} > 276mW \quad (4.7)$$

Additionally, the isolated power supply will be utilized to supply voltage to different circuits that require -5V, GND, 15V and 30V. The isolated power supply must have suitable galvanic isolation capability for the power semiconductors utilized, which are 4500V Si MOSFETs. The isolation power supply must have suitable common mode (CM) transient immunity capability; it must be larger than any possible dv/dt during switching transients. For this high voltage application, CMTI larger than 50V/ns will be suitable. The MGJ2 series isolated power supply from Murata was chosen for this project [Table 4.2](#).

Table 4.2: Murata MGJ2 Series Isolated Power Supply

Isolation Voltage	5.2kVdc
CM transient immunity	200V/ns
Output Voltage	20V to -5V
Output Power	2W

The isolated power supply meets all requirements except for voltage range. This power supply has three voltage outputs, -5V, GND, and 20V. Two additional power control circuit are utilized on the gate driver board to create a 15V voltage rail required for the gate driver circuit and a 30V rail required for the desaturation circuit.

4.3.3 Signal Isolation

The fiber optic control schematic shown in [Figure 4.7](#) demonstrates the designed isolated communication circuit for the gate driver board. A DSP micro-controller serves to generate the gate signal that will be used by the gate driver circuit to drive the high voltage switches into the on or off state. Due to the nature of the half-bridge converter design, the two gate signals do not share the same ground, and the local grounds of the micro-controller and gate drives need to be isolated to safely transfer control signals from the input to the output of the gate drive. For this design, fiber optic based signal isolation was used to prevent EMI from the high voltage converter from effecting the control signal. The controlling PC is located in a separate room from the converter circuit and fiber optic cables prevent signal interference as well as degradation.

4.3.4 Desaturation Protection

Desaturation protection was considered for the design of this converter to protect the high voltage MOSFETs in the case of a short circuit event. When a very high current flows through the MOSFET, the desaturation circuit ([Figure 4.8](#)) will put the switch into desaturaiton mode. Due to the nature of partial discharge testing, there is a potential risk of a short circuit event causing too high current flow through the switches, which are only rated for 1.4A. Although this is primarily mitigated by the high voltage resistors in series with the test device, redundant protection methods improve reliability. Additionally, the desaturation protection can protect the devices in the case of a control failure where both switches are closed together, causing a short from supply voltage to ground.

Fiber Optics

The image displays two circuit diagrams for fiber optic modules, labeled R5 and T1.

Module R5 (AFBR-2529Z): This module has four pins: HOUSING_PIN_1 (PIN), HOUSING_PIN_2 (VCCR), VEER, and DATA_OUT. The DATA_OUT pin is connected to a PWM signal. The circuit includes a -5V supply, a 100nF capacitor (C12), a 100mH inductor (L1), and a 100nF capacitor (C10). The output is connected to GND via a 100nF capacitor (C11).

Module T1 (AFBR-1624Z): This module has four pins: HOUSING_PIN_1 (DATA_IN), HOUSING_PIN_2 (VCCR), VEER, and DATA_OUT. The DATA_IN pin is connected to a gateDrive signal. The circuit includes a -5V supply, a 100nF capacitor (C15), a 100mH inductor (L2), and a 100nF capacitor (C13). The output is connected to GND via a 100nF capacitor (C14).

Figure 4.7: Signal Isolation through fiber optic control

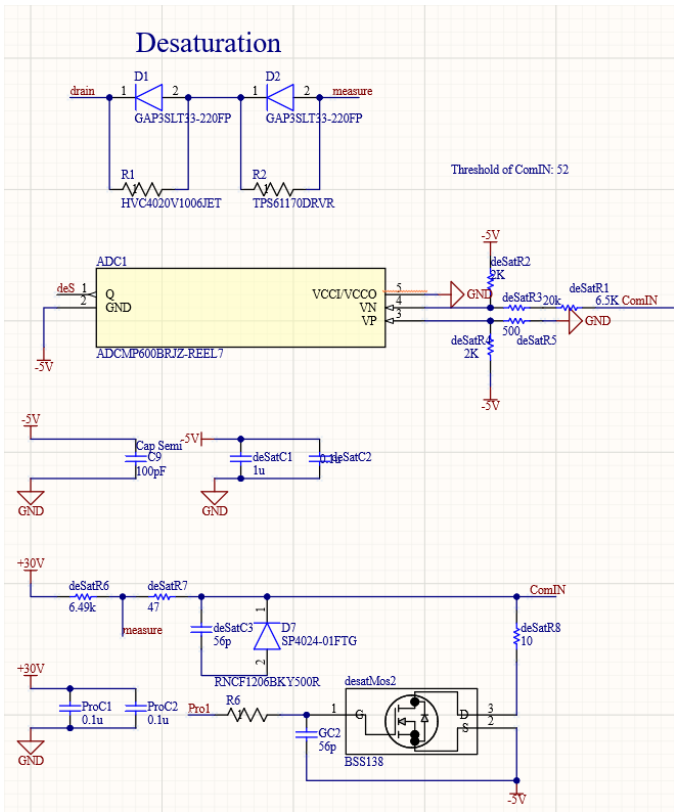


Figure 4.8: Desaturation Circuit

4.3.5 Gate Drive Logic

The gate drive logic circuitry shown in [Figure 4.9](#) serves to translate the PWM control signal from the fiber optic communication to a +15/-5V signal that is useful to the gate drive circuit. Additionally gate logic checks for faults, desaturation, and physical switch override. If there is a fault or the control override switch is flipped, the logic circuit will not transmit enable gate drive control, preventing the power MOSFET from being driven to the on position.

4.3.6 Silicon MOSFET and Heat-sink

In order to achieve safe operation of the converter at 3kV, the creepage and clearance between the high-voltage power loop and the gate loop needed to be managed. With FR-4 insulation of the PCB board a creepage of approximately 7mm was established between the source and drain legs of the switch on the PCB itself, shown in [Figure 4.10](#). The gate and source legs were extended further to establish more separation than was initially available with the TO-247 device package.

Due to minimal operating current a clip-on passive heat-sink was chosen to meet cooling requirements of the converter. The heat-sink passively disperses excess heat from primarily switching losses and because the circuit runs open circuit, and does not run for extended periods of time, the cooling requirements are minimal. If the converter were to be used for lifetime testing of insulation, an improved cooling solution would be needed, as operation cannot exceed past 2-3 minutes before temperatures are too high. For longer testing, a fan could be added to offset the prolonged heating effect.

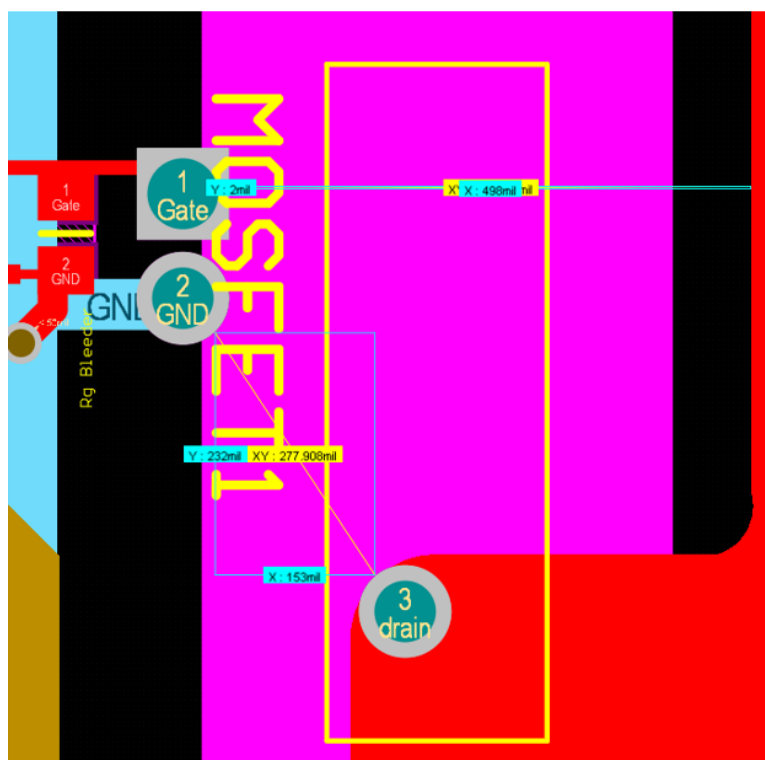
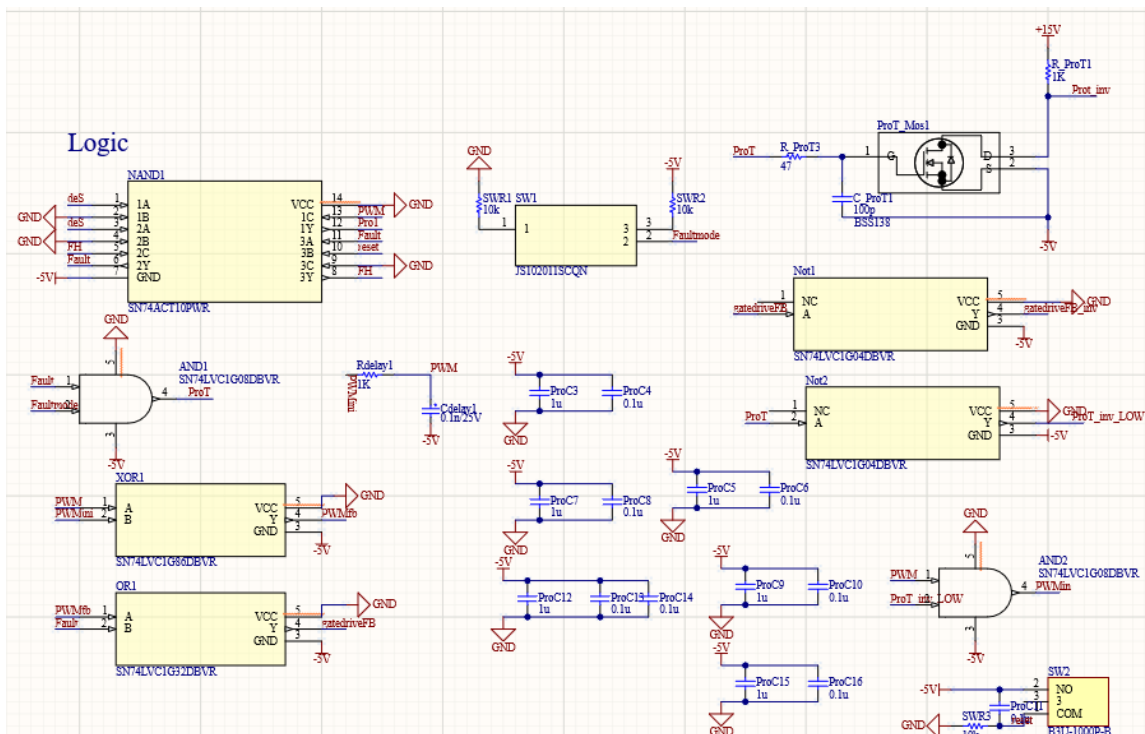


Figure 4.10: Creepage distance between Drain and Source/ Gate signals on gate driver PCB board.

4.4 Test Subject Setup

A key consideration of the testing platform is how the test subjects that will be the location of the partial discharges will interface with the converter and what types of test subjects are optimal for the study of partial discharge in different environments at a voltage level that is achievable using the 3kV Si converter or the 10kV SiC converter. In terms of test subjects, the inclusion of the SiC converter provides a lot of flexibility in choice. A variety of partial discharge test subjects is essential to gain a better understanding of how partial discharge of different types behave due to PWM voltage. Multiple partial discharge test subjects provide a better start at attempting to classify partial discharge that is the result of PWM voltage.

4.4.1 Test Subject

Finding good partial discharge test subjects proved to be one of the more difficult tasks of the project. The test subjects must produce partial discharge at low enough a voltage such that the available converters can produce it. This partial discharge at this low voltage must be large enough to be detected by either the photo multiplier or the UHF antenna, very small partial discharge that may occur very near inception voltage for many types of insulation (apparent charge $< 30pF$) is too small for in particular the UHF antenna to detect effectively. However, the test subject should be designed in a way that it can sustain these large partial discharge signals without fully breaking down. This last requirement proved to be the most difficult in particular for partial discharge test subjects designed to represent corona or surface discharge.

The test subject prototyping process involved verifying the test devices using the AC dielectric test kit and the chosen detection methods. The test device is tested using the AC dielectric test kit to verify that partial discharge inception voltage is low enough such that the 10kV SiC converter at least can produce an equivalent voltage. The AC dielectric inception voltage is measured as an RMS value with a frequency of 60 Hz. The converter operates with a fundamental frequency of 60Hz modulation index 0.8 and the voltage applied to the test subjects is controlled via applied bus voltage. The equivalent RMS voltage produced by

the converter for comparison to the AC dielectric test kit:

$$V_{RMS} = \frac{ModulationIndex * BusVoltage}{\sqrt{2}} \quad (4.8)$$

The SiC converter can be safely operated up to 7kV bus voltage for the purposes of this project. Due to this, the inception voltage of the test subject:

$$V_{inception} > 4000V_{RMS} \quad (4.9)$$

Prototyping the test subject using the AC dielectric test kit also gave the opportunity to verify that the detection methods (at least one) could detect partial discharge in the voltage switching noise free environment. This prototyping process is relatively robust and provided the test subjects featured in the next section for partial discharge behavior testing. However, partial discharge behavior in the AC dielectric test environment did not always reflect what could be expected under PWM voltage. For example, several subjects such as [Figure 4.11](#) were utilized with the goal of representing corona discharge. The partial discharge pattern found using the AC dielectric test kit reflected expectation ([Figure 4.12](#)) showing partial discharge occurring at the peaks of the sinusoidal voltage. Partial discharge is occurring across the air gap between the high voltage point and the grounded plane without the test subject fully breaking down. When the same test subject is tested with PWM voltage and the same configuration, the partial discharge results are starkly different. The point and plane test subject immediately goes into breakdown once inception voltage is reached as shown in [Figure 4.13](#). The voltage across the test subject is pulled down as a result. This behavior essentially makes these types of test subjects useless as a state of partial discharge across the test subject cannot be reached, and therefore the behavior of the partial discharge cannot be studied. This occurred with several test subjects attempted where the insulating material was either air or even oil. These results could indicate that corona discharge is more of a concern in a PWM voltage environment if the discharge is more likely to rapidly enter full breakdown. However, this observation and experience cannot be taken as anything more than anecdotal. The issue could also occur due to contaminated oil or too low of air gap separations, which were necessary due to a requirement of low inception voltage.



Figure 4.11: Corona Discharge Test subject: high voltage point and grounded plane

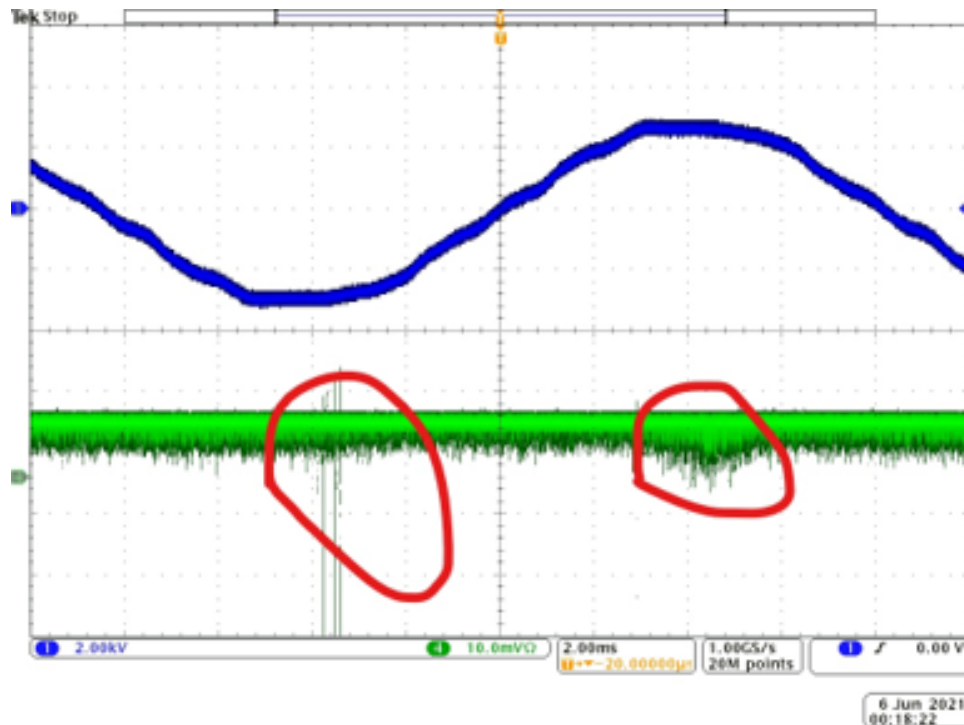


Figure 4.12: Corona Discharge Test subject PD pattern - AC Voltage

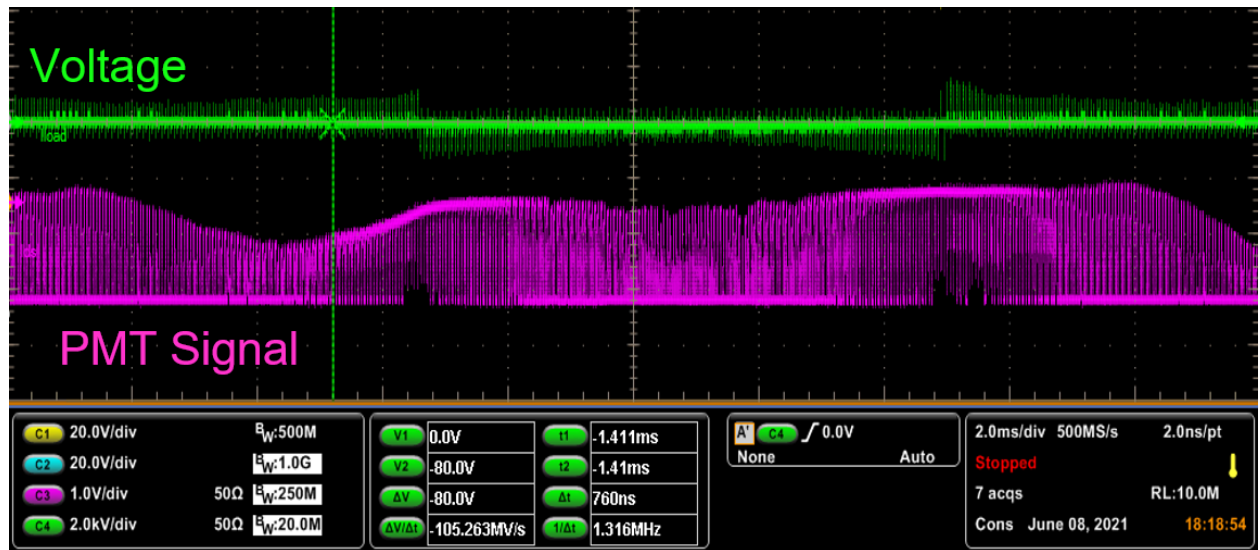


Figure 4.13: Corona Discharge Test subject PD pattern - PWM Voltage

Test subjects that proved useful for this project were test subjects that utilized some form of solid insulation barrier between high voltage and ground.

Twisted Pair

The twisted pair ([Figure 3.23](#)) is the first test subjects to be utilized for further partial discharge testing. As mentioned previously, the twisted pair was very useful for prototyping different partial discharge detection methods. The twisted pair gives insight into how an external partial discharge between two conductors might behave and what the partial discharge may look like. The partial discharge that occurs between the windings of a twisted pair can grow quite rapidly once a PD begins.

For this test subject, the partial discharge inception begins near the rated voltage capability of the wire insulation. The insulated wires used for the twisted pair are rated for 600V. The inception voltage of this test subject when a 60Hz AC voltage is applied is approximately 650V. This partial discharge rapidly increases as the voltage is increased further. [Figure 4.14](#) shows the phase resolved partial discharge pattern of the twisted pair. The partial discharge occurs on the rising edge closer to the peak of the applied voltage. The partial discharge signal is also very large compared to the ambient noise. On each half-cycle there is typically 1-2 partial discharge pulses that are larger (2-3x) than other partial discharge pulses nearby.

Insulated Inductor Winding

The next partial discharge test subject utilized is the insulated inductor shown in [Figure 4.15](#). The inductor was initially created for use in another project. However due to malfunctions during construction that led to bubbling between the the grounded surface and the interior windings, the inductor was not suitable for that project. However, the internal voids made the test subject ideal for partial discharge testing. The voids in this device make it a good test subject to model how internal discharge may behave in the presence of PWM voltage.

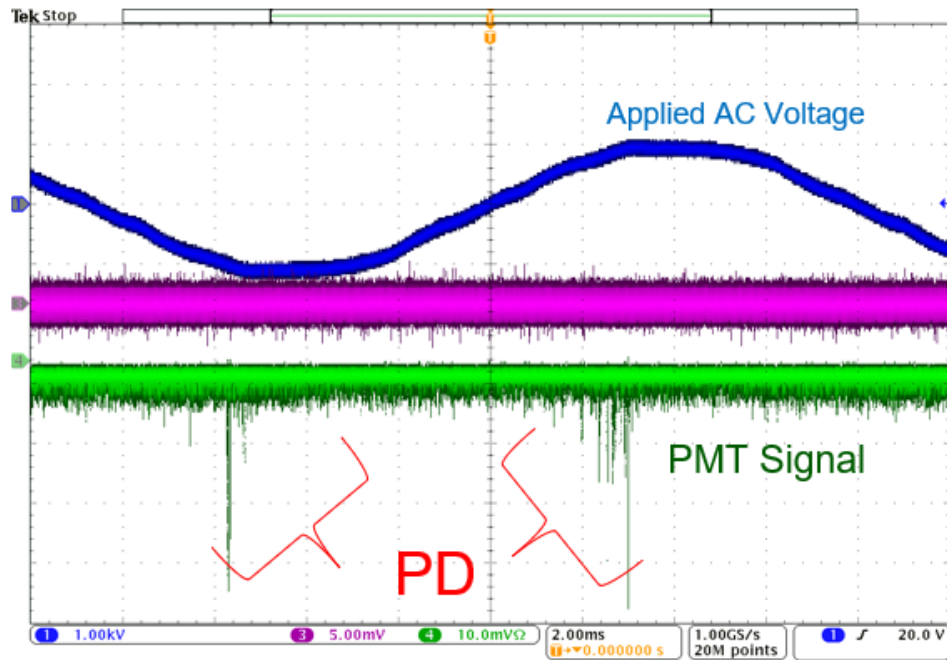


Figure 4.14: AC Partial Discharge Detection - Twisted Pair

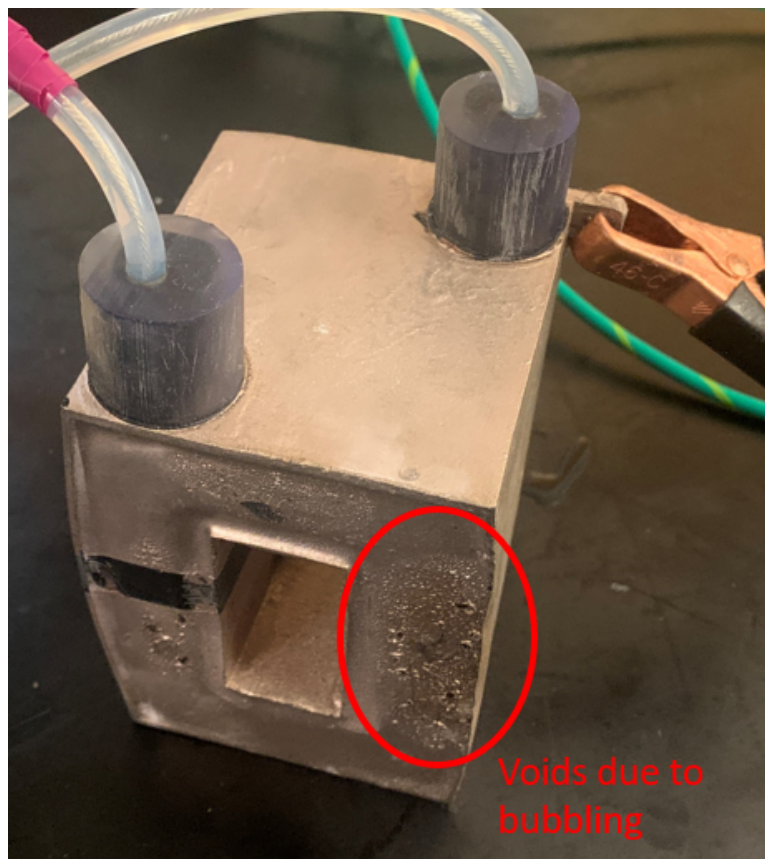


Figure 4.15: Insulated inductor test subject

Figure 4.16 shows the phase resolved partial discharge pattern of the inductor. Similar to the twisted pair, the partial discharge occurs on the rising edge of the applied ac voltage on both the positive and negative half-cycle. In this partial discharge pattern there are some notable differences. The partial discharge signal amplitude is not as large as that seen by the twisted pair. The partial discharge signal does not have a significant disparity in the amplitude of each partial discharge pulse. All of the PDs are of similar size.

4.4.2 Breakdown Protection

Partial discharge testing at very high voltages always runs the risk that the test subject will enter a full breakdown. At this point the test subject could essentially be shorted and the voltage across the device could drop to zero. In the situation of a full breakdown, the converter would be exposed to very high current that could potentially cause damage. The gate drive board does have some form of protection but in the case of a full breakdown the protection would likely not be enough. Large resistance is connected in series with the test subject to limit current draw in the event of a full breakdown. The resistance should be large enough such that the current in case of a full short across the test subject does not exceed the capabilities of the MOSFETs:

$$Resistance > V_{applied}/I_{MOS} \quad (4.10)$$

$$Resistance > 3kV/1.4A > 2.14k\Omega \quad (4.11)$$

The partial discharge test subject and the 10k Ω resistance are connected to the low side device of the 3kV Si converter to meet the current requirement. Two 5 Ω resistors with power ratings of 200W are used in series. These resistors do not have sufficient power rating to withstand breakdown current for long, however in the case of a full breakdown the converter will immediately be shut down.

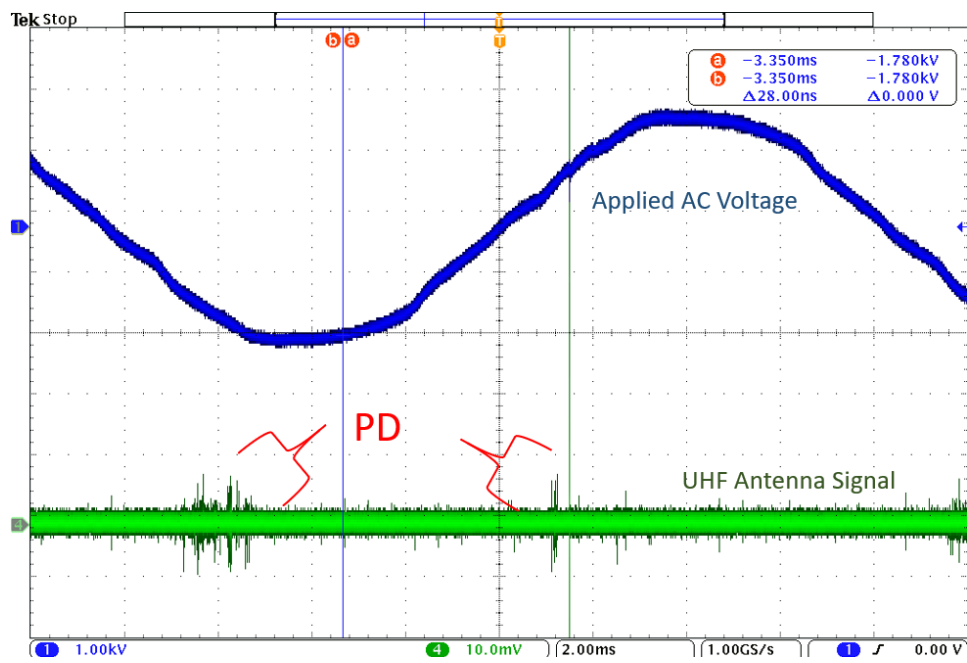


Figure 4.16: AC Partial Discharge Detection - Inductor

4.5 Testing Platform Verification

The converter is designed to operate at a voltage of 3kV with minimal current for short time intervals to do partial discharge testing. In this section the converter is verified to operate at the voltage and switching frequency requirements without excessive heating.

First the gate drive circuit is tested to verify functionality of the control and gate driver IC of each board individually. The deadtime must be configured to ensure that the devices are not accidentally shorted together. With effective gate drive operation, the complete system is constructed and tested to verify operation to desired voltage.

With converter capability proven and several partial discharge test subjects selected, partial discharge testing and behavior analysis can be conducted. The partial discharge test subjects are tested using the 3kV Si converter and the 10kV SiC converter. These test subjects are tested for partial discharge using the detection methods covered in [chapter 3](#). The results of partial discharge testing are covered in [chapter 5](#).

4.6 Chapter Summary

A partial discharge testing platform is designed and built using detection methods found in [chapter 3](#). To complete the partial discharge testing platform, a 3kV half-bridge converter is designed and tested alongside various test subjects. The detection methods were verified effective in the presence of the voltage switching transient noise produced by the converter. Additionally, test subjects are chosen to replicate a void and surface discharge. These test subjects will be used to test analysis methods for partial discharge in [chapter 5](#). A corona discharge test subject was not chosen due to breakdown issues.

Chapter 5

Partial Discharge Classification and Results

Partial discharge detection is the first step to understanding partial discharge behavior in the presence of PWM voltage. To better understand how PWM voltage effects partial discharge, the partial discharge must be classified based on type of partial discharge. For typical partial discharge testing applications, the information that partial discharge is occurring is useful, but only partially useful. It is more useful to be able to determine what type of partial discharge is occurring using detection and classification methods. In this chapter several partial discharge classification methods are studied to determine how to accurately identify what defect is causing the PD. Additionally, partial discharge behavior is studied based on factors that are unique to PWM voltage, such as voltage switching frequency and high voltage dv/dt . First the partial discharge extraction techniques are utilized to remove any remaining noise from the PD signals so that analysis is simpler.

5.1 Partial Discharge Extraction

5.1.1 Wavelet Analysis

Wavelet transform analysis is used to isolate the partial discharge signal from any noise left that was not handled through hardware. The wavelet signal denoiser function in Matlab is

used to remove noise from the signal leaving behind only partial discharge. Trial and error was utilized here to determine the best wavelet analysis method. The 'Sym4' method utilizing universal threshold was found to be consistently successful at removing noise while limiting partial discharge signal loss. A series of high and low pass filters are used in conjunction with down-sampling to decompose the original signal to high-frequency components called details and low-frequency components called approximations. Further down-sampling is performed on the low-pass approximation. Each further decomposition is called a level, and the denoising process for this project utilized 20 levels. In [Figure 5.1](#) the partial discharge signal at several steps of the wavelet analysis process can be seen. At D6, the 6th approximation, the partial discharge coefficients begin to become prominent among the noise. The denoised coefficients or details from each level will be utilized to reconstruct the partial discharge signal without noise.

These denoised coefficients are combined after the 20 levels of decomposition to create an approximation of the partial discharge signal. This approximate signal is shown in [Figure 5.2](#) overlaid over the original signal.

From [Figure 5.2](#) the use of wavelet denoising becomes clear. Wavelet transform analysis provides a useful method of removing any ambient noise from a signal so that the PD signal is easier to work with for partial discharge classification and analysis. The distinction between very small partial discharge and noise is made much clearer through wavelet denoising techniques. In [Figure 5.3](#) several examples of PD signals can be seen. Due to their small size relative to the noise, these PD signals would be very difficult to detect without wavelet denoising. However, wavelet analysis is not foolproof. It cannot consistently detect PD that is smaller than noise recorded. If the voltage switching noise is not addressed through hardware methods of filtering or noise isolation, and the noise is larger than the partial discharge, it is likely that wavelet analysis will be largely useless and most partial discharge information will be lost. For that reason, wavelet denoising is a useful post processing tool to make partial discharge analysis easier, it however is not a solution to noise by itself.

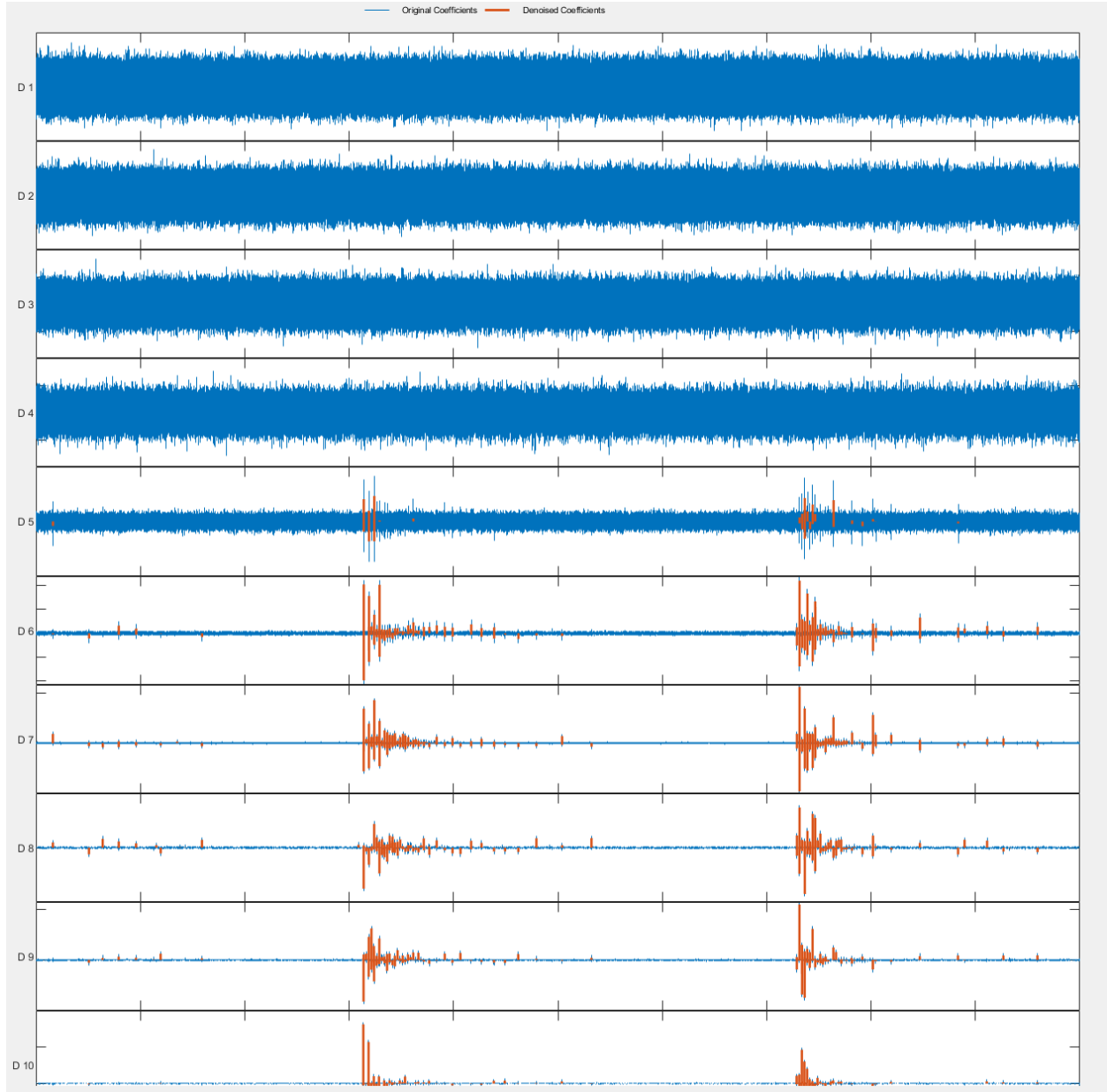


Figure 5.1: Wavelet Signal Denoising - Coefficients D1-D10. At D6, the Pd signal begins to become clearly separated from the noise.

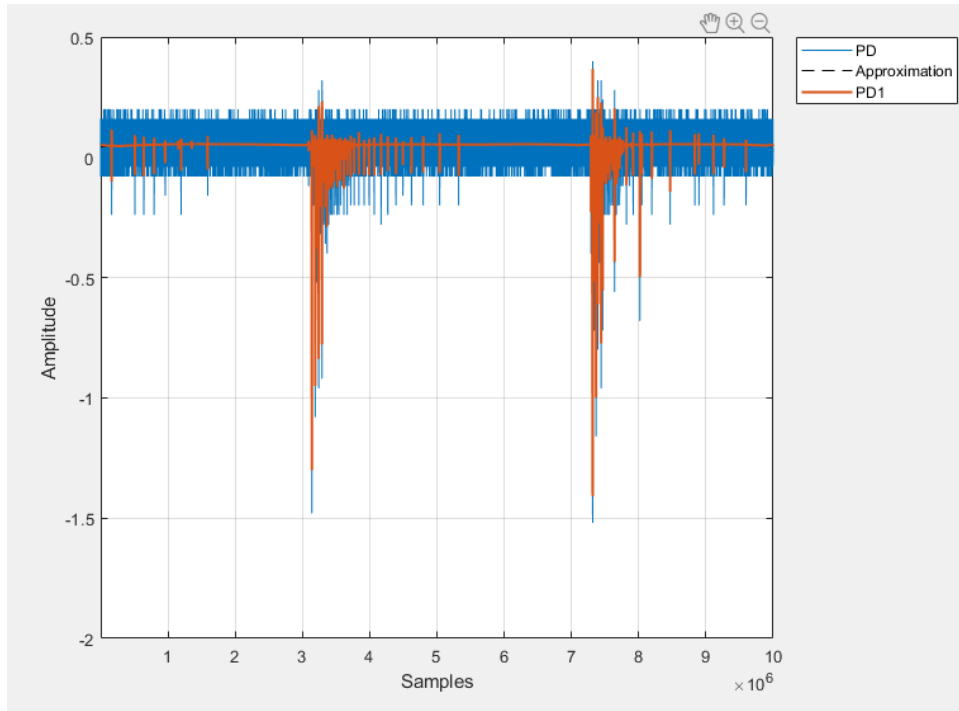


Figure 5.2: Approximate Denoised Partial Discharge Signal overlaid atop the original signal

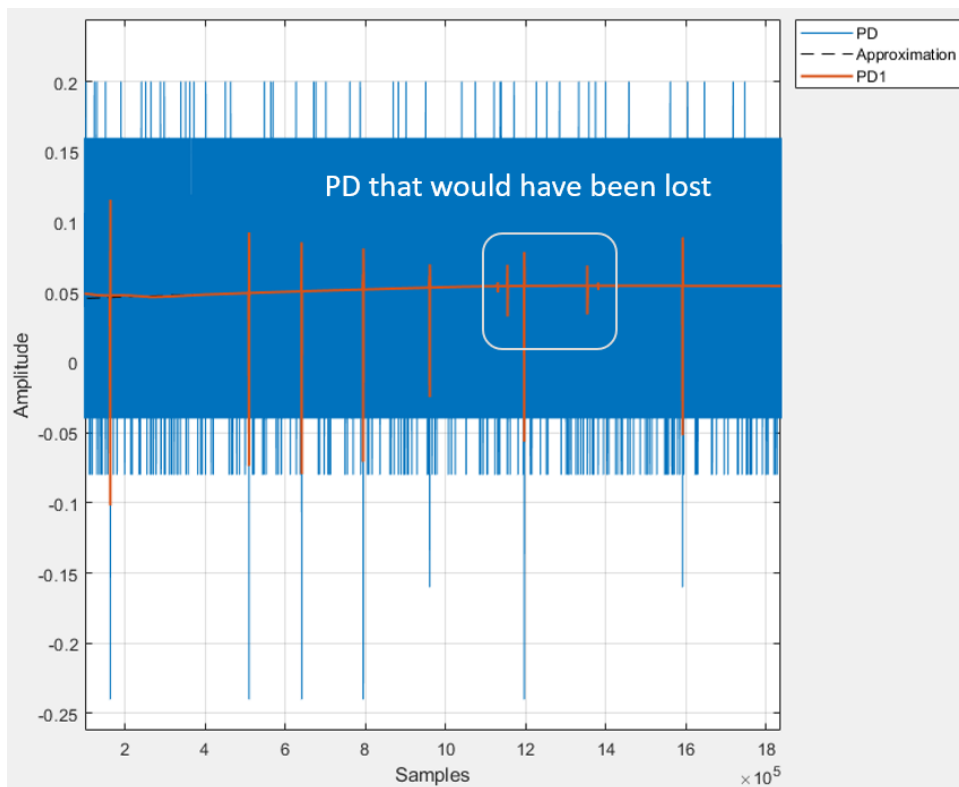


Figure 5.3: Approximate Denoised Partial Discharge Signal (Zoomed in)

5.1.2 Filtering

In certain cases, post process filtering can be utilized alongside wavelet denoising to improve the the signal to noise ratio of the original signal prior to applying wavelet denosing techniques. This improves the likelihood of retrieving an accurate partial discharge approximation. [Figure 5.4](#) shows a potential example where a partial discharge signal could be recovered from an original signal in which the partial discharge is completely hidden with the assistance of a bandpass filter. This bandpass filter has corner frequencies of 150kHz and 350kHz. The noise was simulated to test whether or not partial discharge could be effectively 'pulled' from an acoustic signal in which the acoustic voltage switching noise was larger than partial discharge that is occurring. The corner frequencies reflect the operating range of the acoustic sensor utilized for this testing. The filtering method proved successful in sufficiently improving the signal to noise ratio of the signal such that partial discharge could be effectively decoupled from the noise using wavelet denoising techniques. However, a few false partial discharge signals were added to the signal due to the filtering process, shown in [Figure 5.5](#). Although, post-processing filtering in conjunction with wavelet denoising appears to be an effective method of recovering partial discharge signals from acoustic noise, this method of software noise suppression was not pursued further due to the additional partial discharge testing issues of acoustic emissions testing. As mentioned previously, acoustic detection detection is not an effective method of addressing voltage switching noise because the sensor becomes quickly saturated. With optical detection and electromagnetic detection, hardware filtering and inherent voltage switching noise immunity of these detection methods was enough to get a reasonably high signal to noise ratio from recorded signals. From that point, wavelet denoising is enough already to clean up partial discharge signals, and further filtering is not needed.

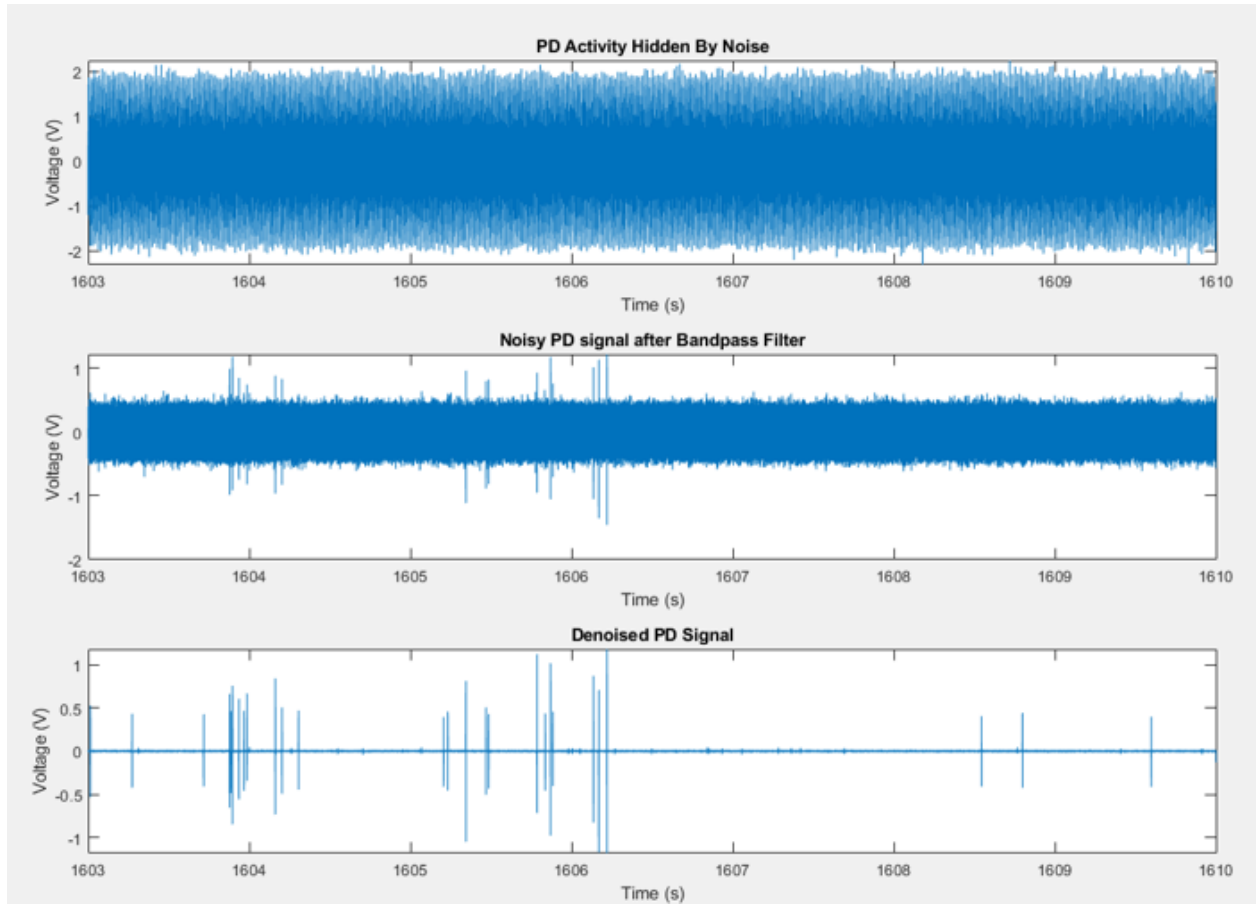


Figure 5.4: Partial Discharge signal before and after filtering and wavelet denoising.

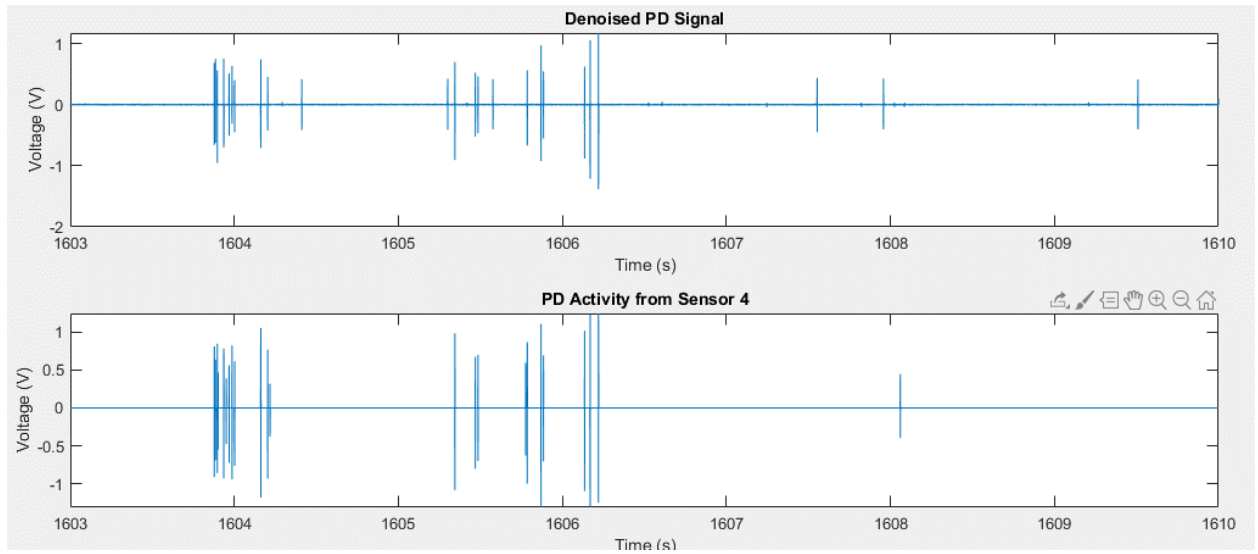


Figure 5.5: Denoised Partial Discharge signal with additional false PD signals

5.2 Partial Discharge Classification

5.2.1 Phase Resolved Analysis

Phase resolved analysis for partial discharge (PRPD) is a technique in which partial discharge pulses are plotted over one complete cycle of a voltage waveform. For 60Hz AC sinusoidal voltage this is the prevailing method of partial discharge classification and analysis. The magnitude of partial discharge and the location of the partial discharge relative to the voltage cycle make PRPD patterns ideal for determining the type of partial discharge as well as the severity of the PD. Phase resolved analysis can be applied to PWM voltage in one of two ways: across one switching cycle in converters with a constant duty cycle and across one fundamental cycle for more complex converters with a modulated duty cycle. Both methods of phase resolved analysis will be explored here. The 3kV Si half-bridge converter has a constant duty cycle. The 10kV SiC full-bridge converter has a variable duty cycle, with a 60Hz sinusoidal output.

An example of a PRPD pattern by the switching cycle is shown in [Figure 5.6](#). Phase resolved analysis at the switching cycle has limited usefulness. Partial discharge in the presence of PWM voltage typically occurs at the switching event or very close to it. This PRPD pattern is useful to determine the magnitude of partial discharge that is occurring. In terms of partial discharge classification switching cycle, PRPD analysis is very difficult. Partial discharge that occurs with a PWM voltage like this is very consistent with very little variance in behavior. Partial discharge occurs at or near the switching cycle no matter the type of partial discharge that is occurring. Once partial discharge begins, it tends to occur at every switching cycle after ([Figure 3.25](#)). The quantity and magnitude of partial discharge does not appear to be overly effected by whether the switching is the rising or falling edge. Phase resolved partial discharge analysis becomes much more useful when looking at PWM voltage where the duty cycle is modulated. This type of voltage aims to produce a sinusoidal output, and therefore the duty cycle is modulated based on a carrier waveform. For this project the carrier waveform has a 60Hz fundamental frequency. Partial discharge behavior that occurs due to this type of PWM voltage behaves much more similarly to partial discharge that is occurring due to AC sinusoidal voltage.

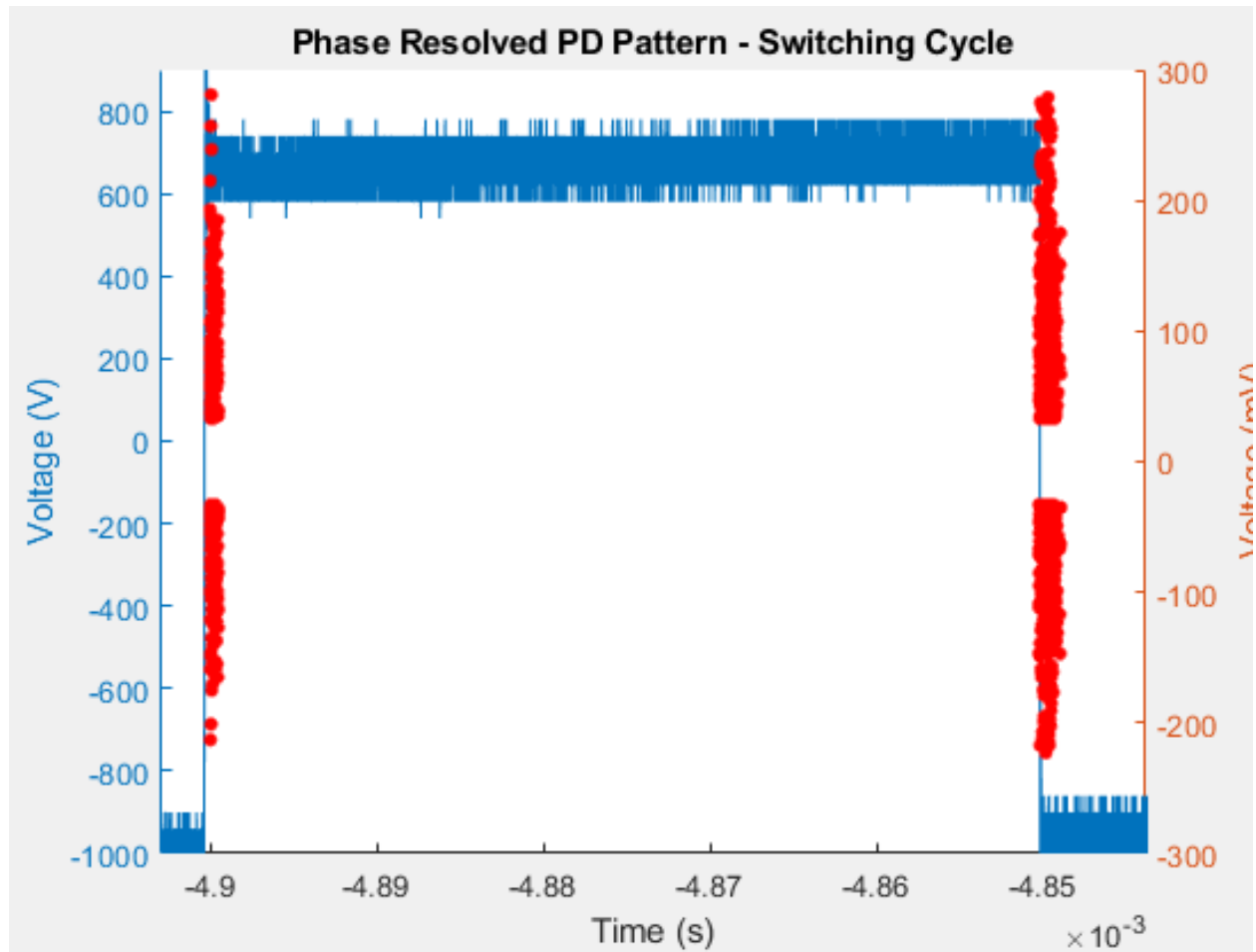


Figure 5.6: Phase Resolved Partial Discharge - Twisted pair

The PRPD pattern of partial discharge at the fundamental cycle gives more insight into how the PD behaves and potentially what type of PD is occurring. Examples of PRPD patterns at the fundamental cycle are shown in [Figure 5.7](#), [Figure 5.8](#) for the surface discharge due to a twisted pair. Additionally, PRPD patterns of an internal discharge due to the inductor are shown in [Figure 5.9](#) and [Figure 5.10](#).

The twisted pair surface discharge PRPD pattern shows many similarities to the 60Hz AC sinusoidal PRPD pattern shown in [Figure 4.14](#). The partial discharge signal has 1-2 large spikes in PD magnitude compared to the other PD pulses. The partial discharge occurs on the rising edge of the fundamental waveform. As the applied voltage is increased, the amplitude of the largest PD spike increases very slightly, but partial discharge begins to occur across more of the cycle until it eventually occurs across both rising and falling edges of both half cycles. There are notable differences as well. The peak partial discharge pulse occurs first chronologically with the PWM voltage, occurring very near the zero-crossing. With AC voltage applied, this peak pulse occurs as the voltage waveform approaches its own peak. The most significant difference is the fact that partial discharge tends to occur first at the zero-crossing of the PWM voltage, this trend shows in both test subjects tested.

For the inductor again the partial discharge behavior of the PWM voltage at fundamental cycle is very similar to the behavior of a 60Hz AC sinusoidal voltage. The partial discharge is tightly clumped. All of the PD pulses within the clump are of similar magnitude. Partial discharge tends to occur in greater quantity on the rising edge but with greater magnitude potential on the falling edge. The differences are similar as with the twisted pair, in that the partial discharge typically occurs very near the zero-crossing, not near the peak of the voltage waveform. This distinct difference may be the most important observation from the phase resolved analysis of PWM voltage partial discharge. With AC sinusoidal voltage, the zero-crossing is typically the last place that partial discharge will occur. However for PWM voltage it is exactly the opposite. The reason is not immediately clear but the gradual change in voltage from positive to negative cycle with AC sinusoidal voltage allows for the local electrical field to decrease before polarity is flipped. However with PWM voltage, the polarity slips very quickly, without a local electric field reduction first. This leads to a dramatic electric field change that very quickly increases the partial discharge.

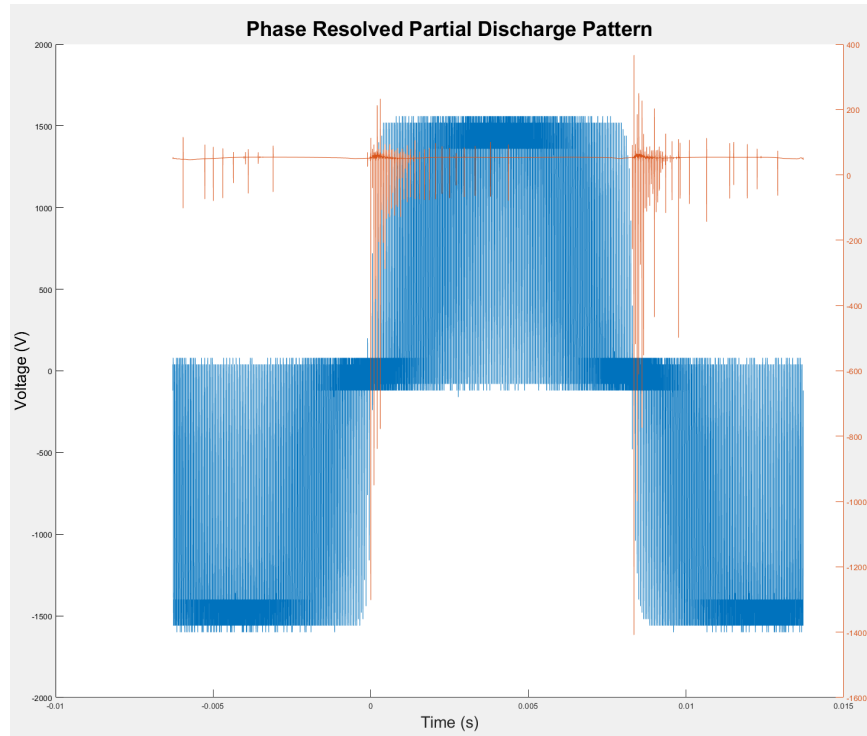


Figure 5.7: PRPD pattern - surface discharge on twisted pair at 1500V

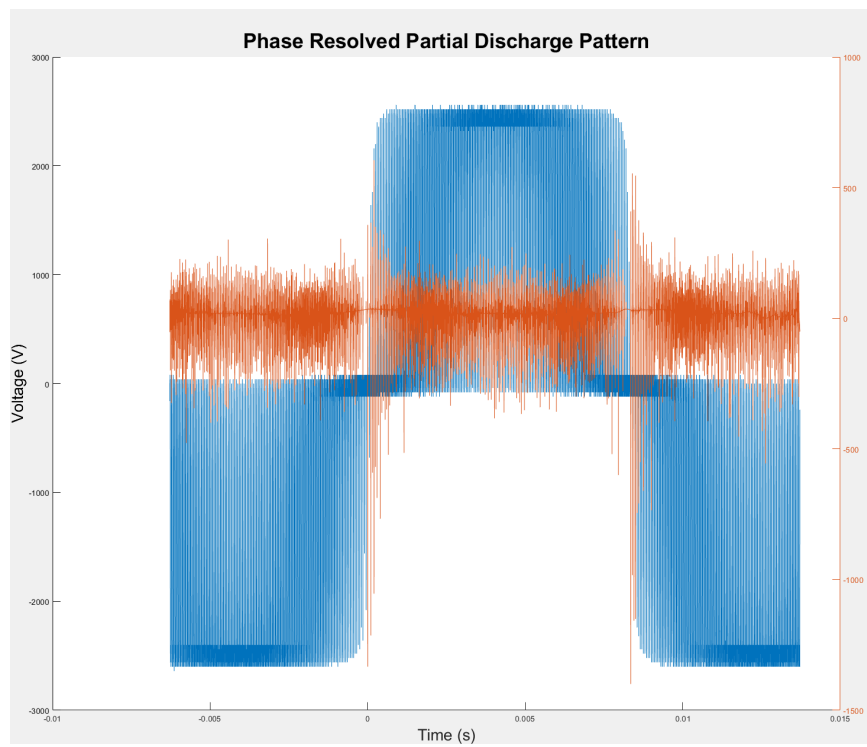


Figure 5.8: PRPD pattern - surface discharge on twisted pair at 2500V

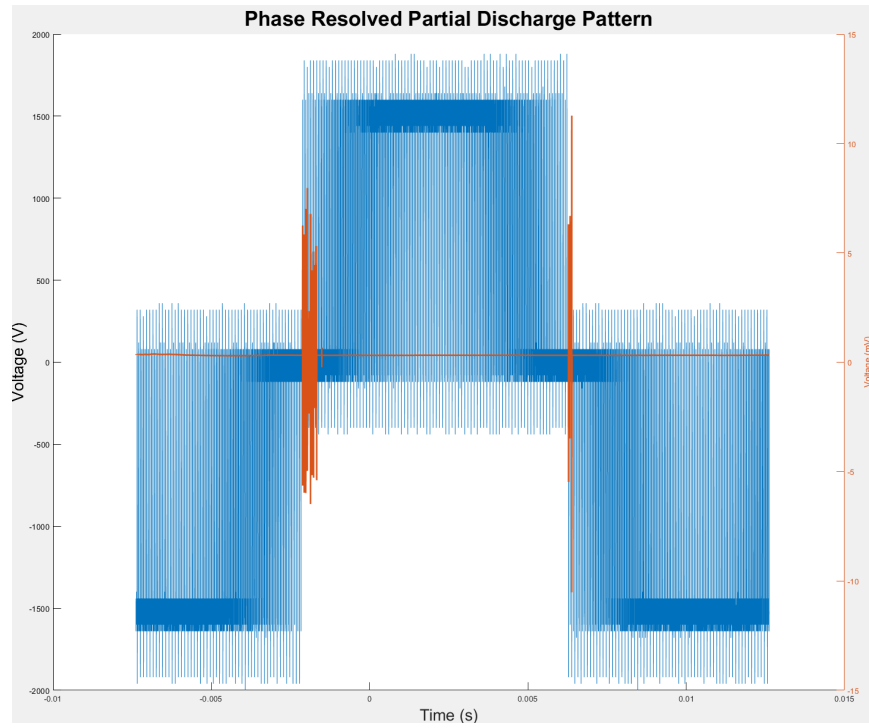


Figure 5.9: PRPD pattern - internal discharge of inductor at 1500V

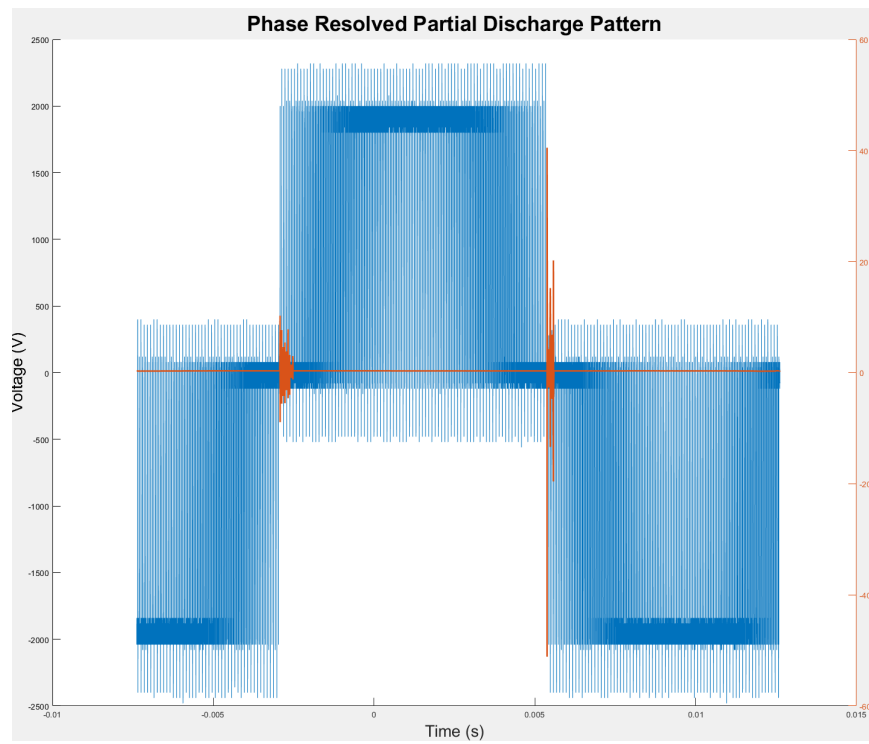


Figure 5.10: PRPD pattern - internal discharge of inductor at 1900V

Comparing the PRPD patterns of the surface discharge (twisted pair) and the internal discharge (inductor) show that the two types of partial discharge could be easily distinguished with a modulated PWM voltage. Phase resolved partial discharge analysis has mixed usefulness for partial discharge analysis due to PWM voltage. For PWM voltage with a fixed duty cycle, where analysis occurs at the switching cycle, PRPD is not useful other than to determine that partial discharge is occurring and to what magnitude. For PWM voltage with a carrier waveform, however, PRPD analysis is more useful. In this project the converter output voltage had a fundamental frequency of 60 Hz, closely matching a AC sinusoidal voltage. In this application the PRPD patterns are very similar to what would be expected from an AC voltage. This indicates that much of PRPD patterns used with AC sinusoidal voltage to determine the type of partial discharge could be transferred to this type of PWM voltage with relative ease. More test subjects of different insulation and partial discharge type will need to be tested to see if this pattern of partial discharge behavior continues.

5.2.2 Pulse Sequence Analysis

Pulse sequence analysis (PSA) is a partial discharge classification technique that utilizes the voltage difference between partial discharge occurrences to identify different types of partial discharge. This type of classification is different from PRPD analysis in that it does not rely on the phase or magnitude of a partial discharge in relation to applied voltage; this information is lost. Pulse sequence analysis is typically utilized for the insight into the sequence of partial discharge and as a method of distinguishing different types of partial discharge from each other. For the purposes of this project, pulse sequence analysis is potentially useful as a method of distinguishing different types of partial discharge from each other, whether that be a void, corona or surface discharge for example. PSA patterns for the twisted pair are shown in [Figure 5.11](#) and [Figure 5.12](#). PSA patterns for the inductor are shown in [Figure 5.13](#) and [Figure 5.14](#). The pulse sequence analysis is defined by comparing the voltage of a partial discharge to the voltage of the next partial discharge and the voltage of the previous discharge:

$$\Delta V(n) = V(n + 1) - V(n) \quad (5.1)$$

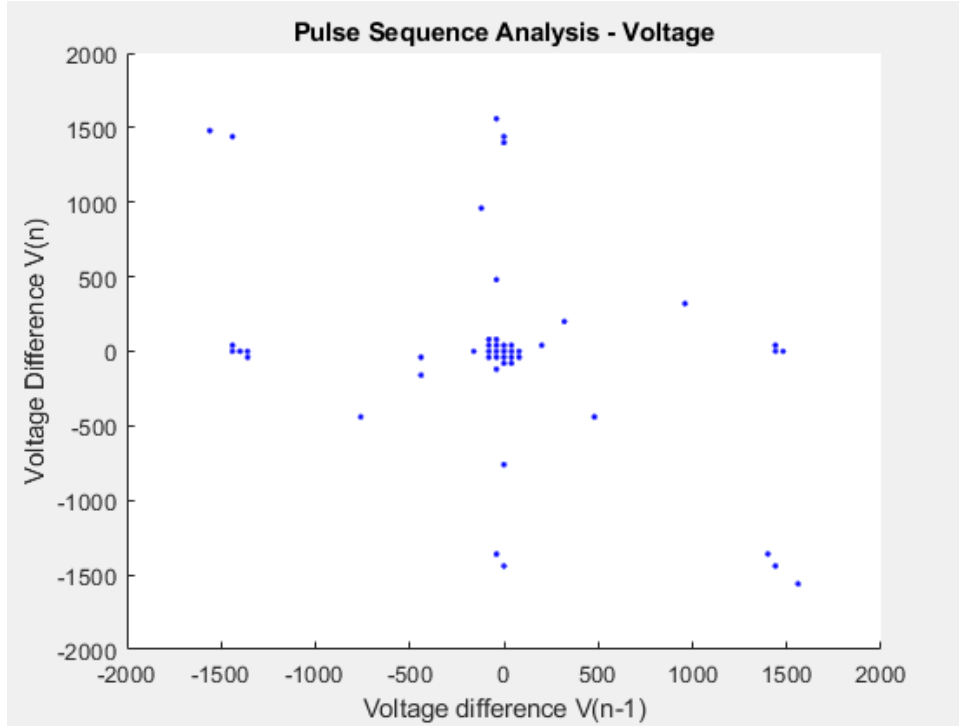


Figure 5.11: PSA pattern (Voltage) - surface discharge on twisted pair at 1500V

$$\Delta V(n-1) = V(n) - V(n-1) \quad (5.2)$$

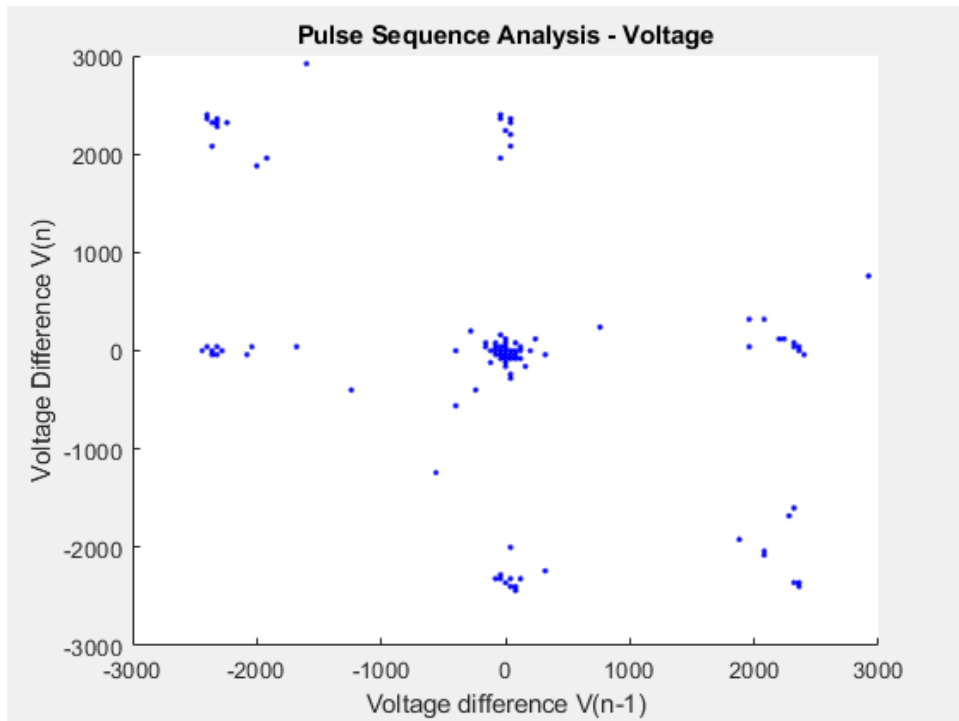


Figure 5.12: PSA pattern (Voltage) - surface discharge on twisted pair at 2500V

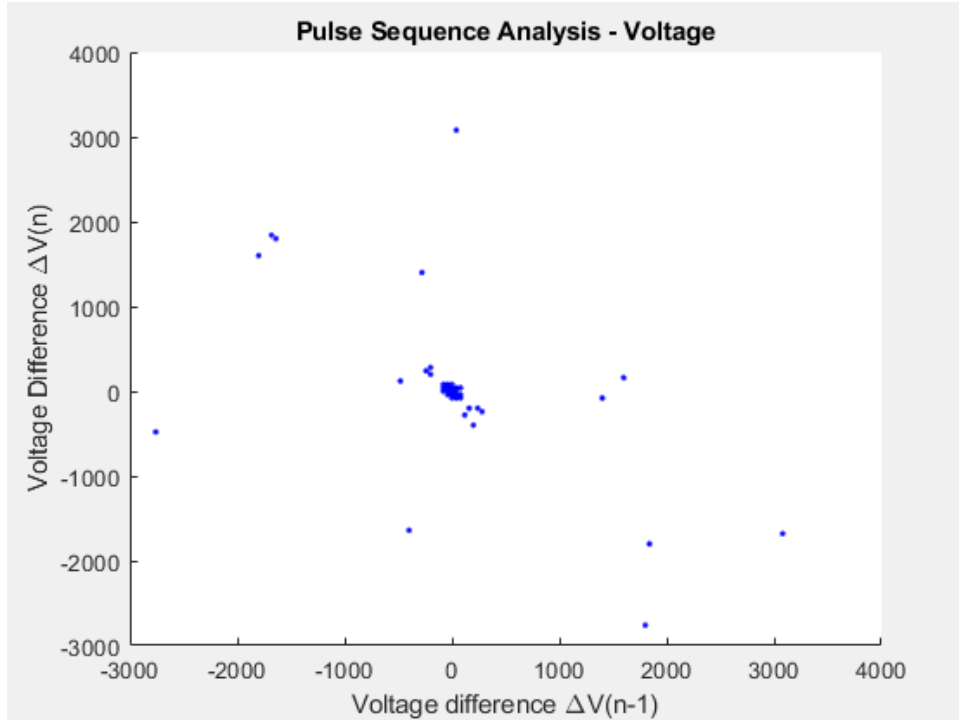


Figure 5.13: PSA pattern (Voltage) - internal discharge of inductor at 19500V

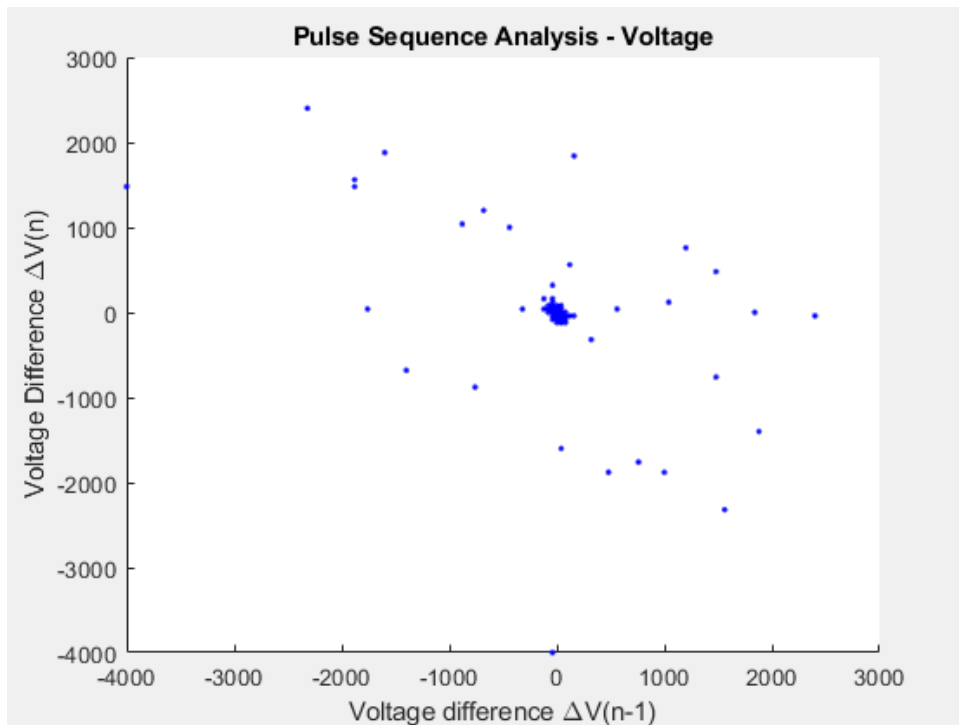


Figure 5.14: PSA pattern (Voltage) - internal discharge of inductor at 19000V

Pulse sequence analysis serves to make partial discharge type easily detectable by representing the sequence of partial discharge in accordance to the applied voltage waveform. If the partial discharge is densely packed at for example the peak of the applied voltage waveform, the PSA will show that as the pattern will be tightly packed with very little voltage difference between pulses. At the peak of a sinusoidal AC voltage, for example, voltage does not change rapidly. However if the PD occurs on rising edge of the voltage waveform, where voltage is more rapidly changing, the PSA pattern will reflect that. However, pulse sequence analysis is less effective with PWM voltage. This is due to the fact that the PWM voltage output of the SiC full-bridge converter is typically one of three values: applied bus voltage, zero and the negative of the applied bus voltage. In between these times the voltage is rapidly changing states with high dv/dt . Therefore, the PSA pattern will show clumps at X and Y values of applied bus voltage, zero and the negative of the applied bus voltage. This pattern will show through with slight variation no matter what type of partial discharge is occurring with slight variation. This behavior can be seen in [Figure 5.12](#) and less clearly in [Figure 5.14](#) though the trend is there. Although these patterns are different, the difference is not very distinct and pulse sequence analysis with voltage difference as the sequencing measurement is not very robust for classification of partial discharge due to PWM voltage.

The pulse sequence analysis technique can be modified in a simple way to improve its usefulness for partial discharge classification in the presence of PWM voltage. With the SiC full-bridge converter, the duty cycle is modulated in order to create a 60 Hz sinusoidal voltage and current at the output as a representation of a fairly standard application shown in [Figure 5.15](#). The duty cycle is recreated by recording the area of each switching cycle with respect to the area of a possible duty cycle of 1, shown in [Figure 5.16](#).

With the duty cycle modulation recreated, the partial discharge classification based on pulse sequence analysis could prove more useful.

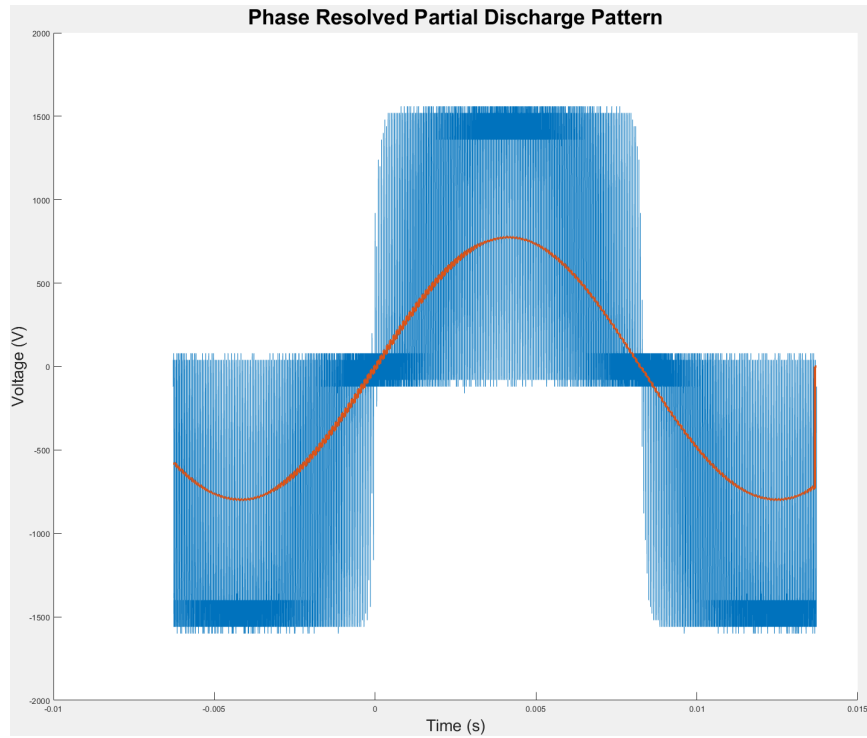


Figure 5.15: Duty Cycle Modulation Waveform

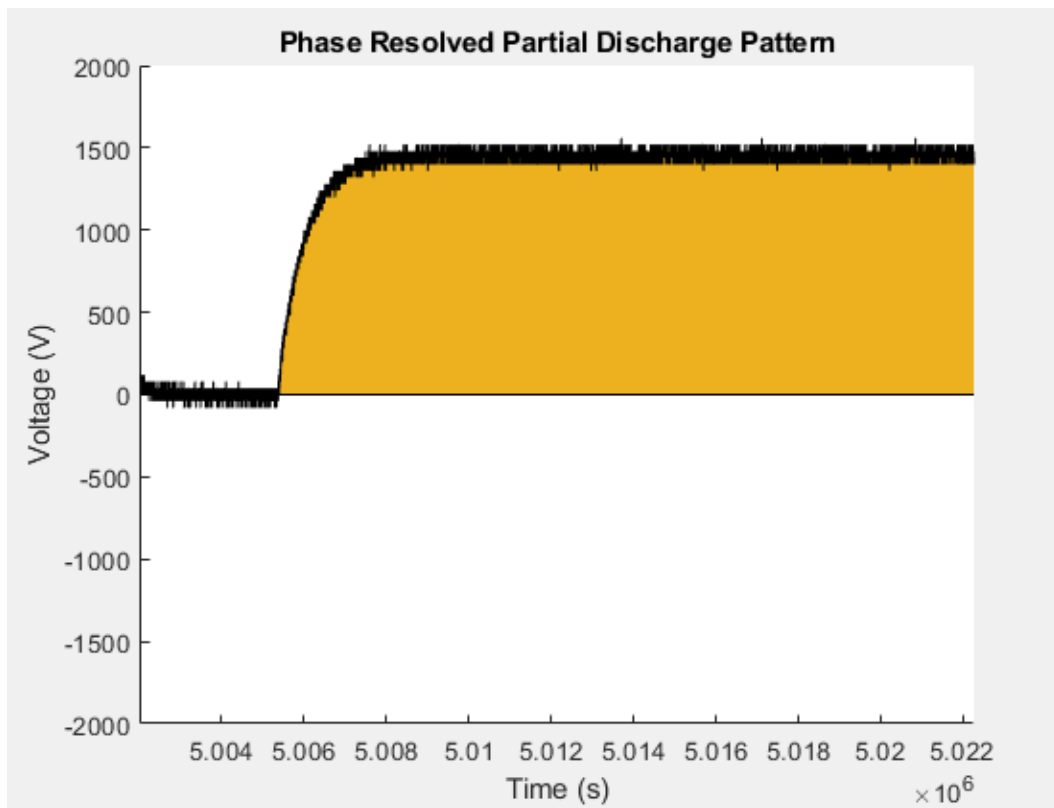


Figure 5.16: Duty cycle detected from switching cycle area

The sequencing on the X-axis and Y-axis is defined just as before, but looking at duty cycle modulation instead of voltage:

$$\Delta D(n) = D(n + 1) - D(n) \quad (5.3)$$

$$\Delta D(n - 1) = D(n) - D(n - 1) \quad (5.4)$$

This change creates potential for more variation in sequencing, as partial discharge occurring at any point along the PWM voltage waveform can be more uniquely identified using the duty cycle as a reference. The duty cycle PSA patterns for the twisted pair are shown in [Figure 5.17](#) and [Figure 5.18](#). The duty cycle PSA patterns for the twisted pair are shown in [Figure 5.19](#) and [Figure 5.20](#). Utilizing the duty cycle based pulse sequence analysis, the classification of a surface discharge with the twisted pair and an internal discharge with the inductor becomes more clear. With the twisted pair the partial discharge occurs across the entire rising edge of the voltage waveform, especially as voltage increases. This is reflected in the PSA pattern, as the partial discharges are evenly sequenced. Partial discharge duty cycle difference is typically the same between a partial discharge and the next and that same partial discharge and the previous. This leads to a more linear PSA pattern from the bottom left of the graph towards the top right, especially as voltage increases and partial discharge occurs more frequently.

The internal discharge on the inductor is more consistent across tested voltage ranges. The PD occurs near each zero-crossing. The PD is very 'tightly-packed' long the X-axis which leads to a large clumping in the PSA pattern. Because all of the partial discharge occurs close together in a 'small part' of the voltage waveform, the PSA pattern shows very small changes in duty cycle between partial discharges, leading to the clump near zero. At the higher voltages, the same pattern remains as partial discharge does not start to occur over a larger part of the voltage waveform, but occurs with larger amplitude and quantity.

The duty cycle modification to pulse sequence analysis makes partial discharge classification more useful for PWM voltage. These patterns could be used to identify an internal or void discharge for these types of insulation; twisted pair and insulated inductor.

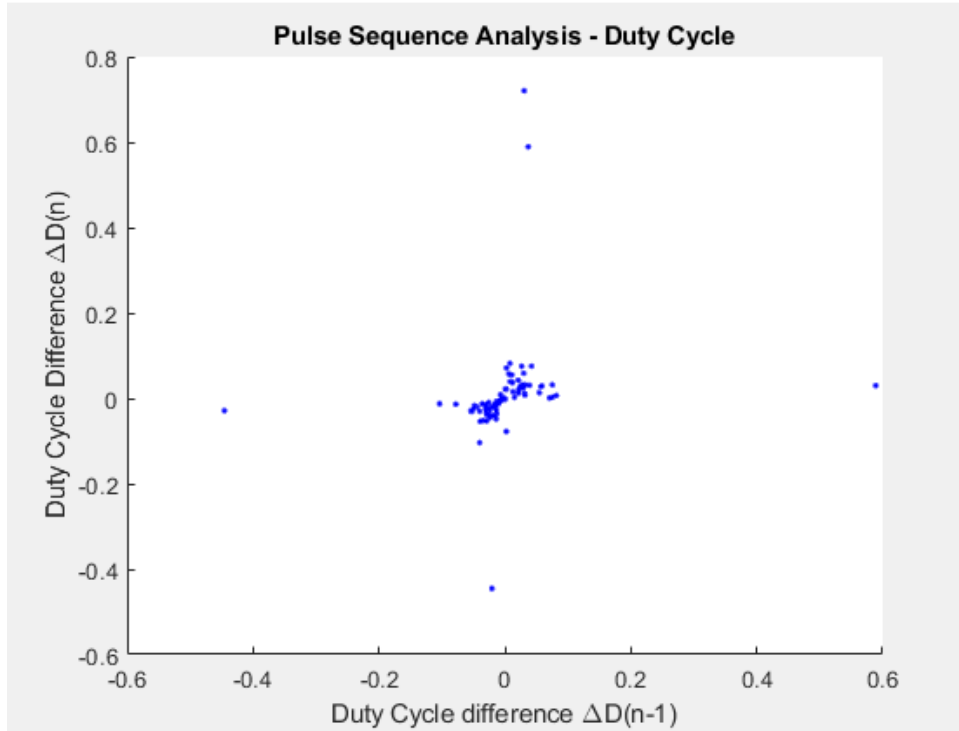


Figure 5.17: PSA pattern (Duty Cycle) - surface discharge on twisted pair at 1500V

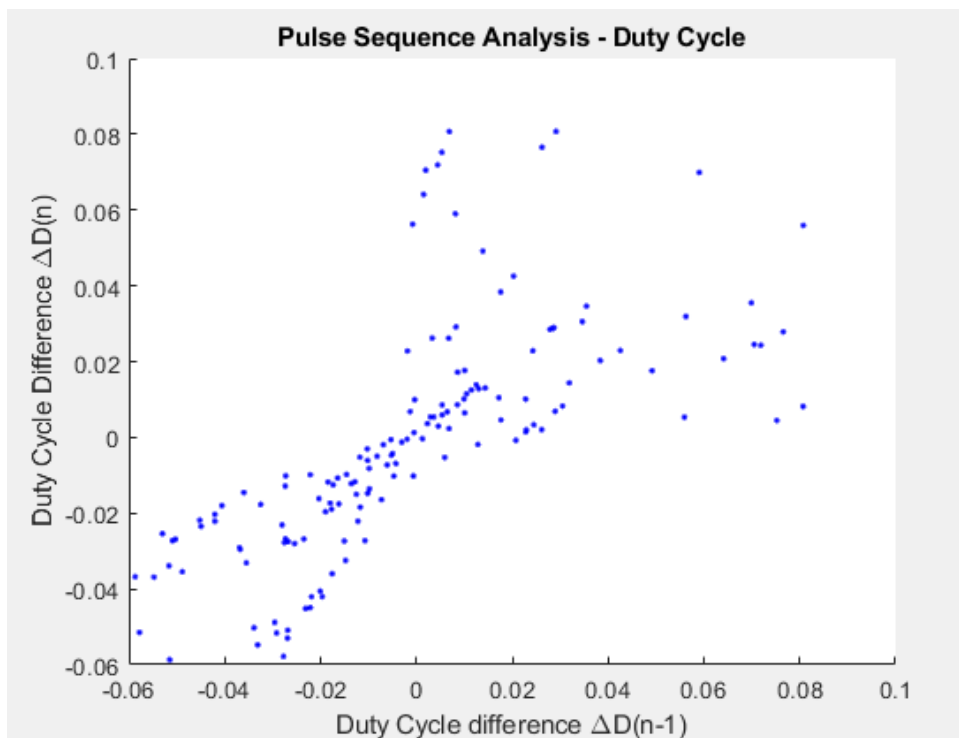


Figure 5.18: PSA pattern (Duty Cycle) - surface discharge on twisted pair at 2500V

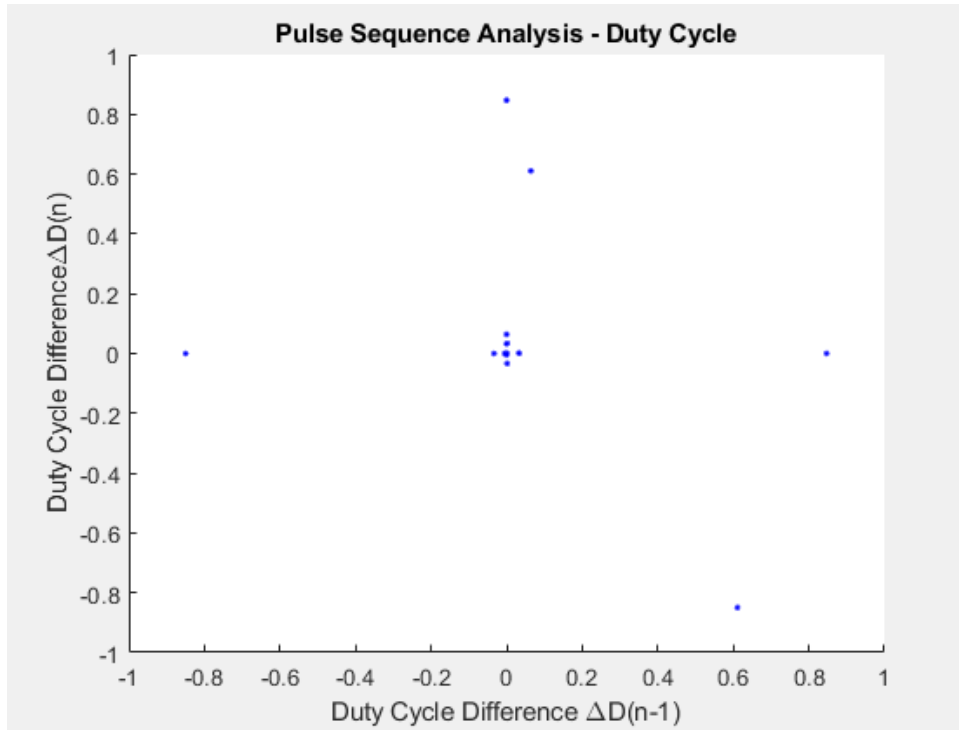


Figure 5.19: PSA pattern (Duty Cycle) - internal discharge of inductor at 1500V

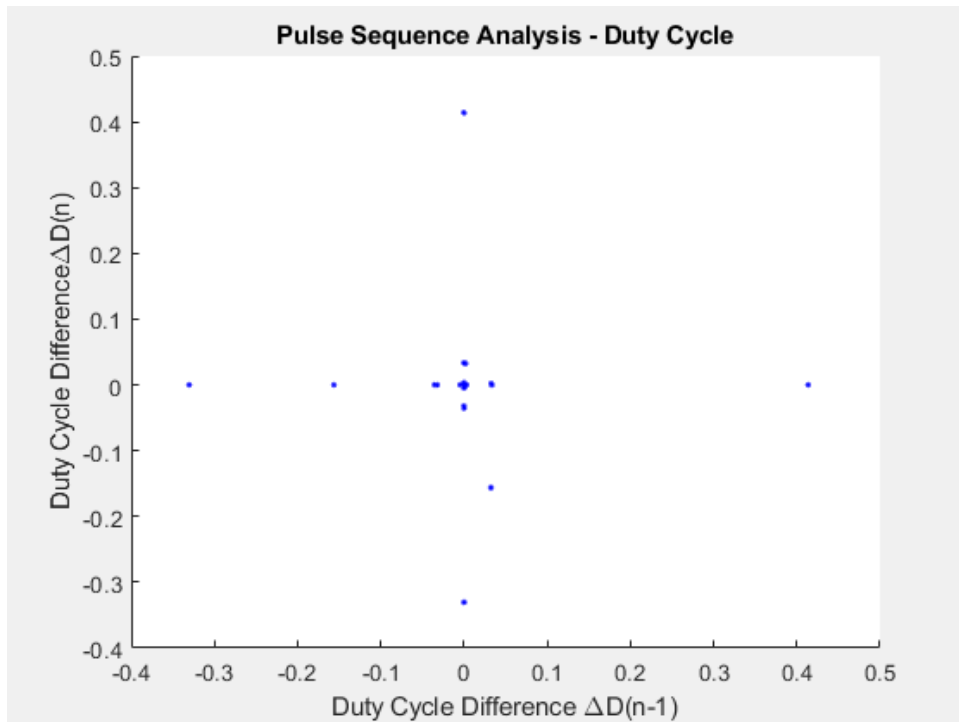


Figure 5.20: PSA pattern (Duty Cycle) - internal discharge of inductor at 1900V

However, these are not definitive partial discharge patterns for surface and void discharge, as partial discharge of the same type may behave differently in different environments, and would need to be explored further to verify.

5.3 Partial Discharge Behavior Analysis

5.3.1 Switching Frequency

A distinct difference between 60Hz sinusoidal voltage systems and power electronic based systems is the presence of voltage waveforms, PWM voltage, with fast rise times and fast switching frequencies. In high voltage applications, both of these characteristics can have a potentially harmful impact on the behavior of insulation. The switching frequency of a power electronic converter refers to the frequency at which the power semiconductors turn on and off to create PWM voltage. Every time a power semiconductor is turned on or off, it is switched between an open or closed state, ideally acting like a switch. This provides a lot of potential applications but for the purpose of partial discharge testing, it is essentially a change in the voltage that insulation or a test subject will be exposed to. For the purposes of this project, the voltage applied to the test subject is switched between positive or negative bus voltage and zero volts. This means that each time the semiconductors switch states, the test subject is exposed to a potentially large change in voltage over a short period of time. The switching frequency will indicate how frequently a test subject must undergo this voltage change during converter operation. Switching frequency can be very high in high voltage power applications, typically as high as 10-100kHz. In order to test the effects that high switching frequencies have on partial discharge, the twisted pair test subject is tested at 2kV applied voltage with varying frequency over a 10ms period. During this time all partial discharge signals are recorded and counted to determine the effect that switching frequency has on partial discharge. [Figure 5.21](#) shows the phase resolved PD patterns of the PWM voltage at four different switching frequencies ranging from 5-60kHz.

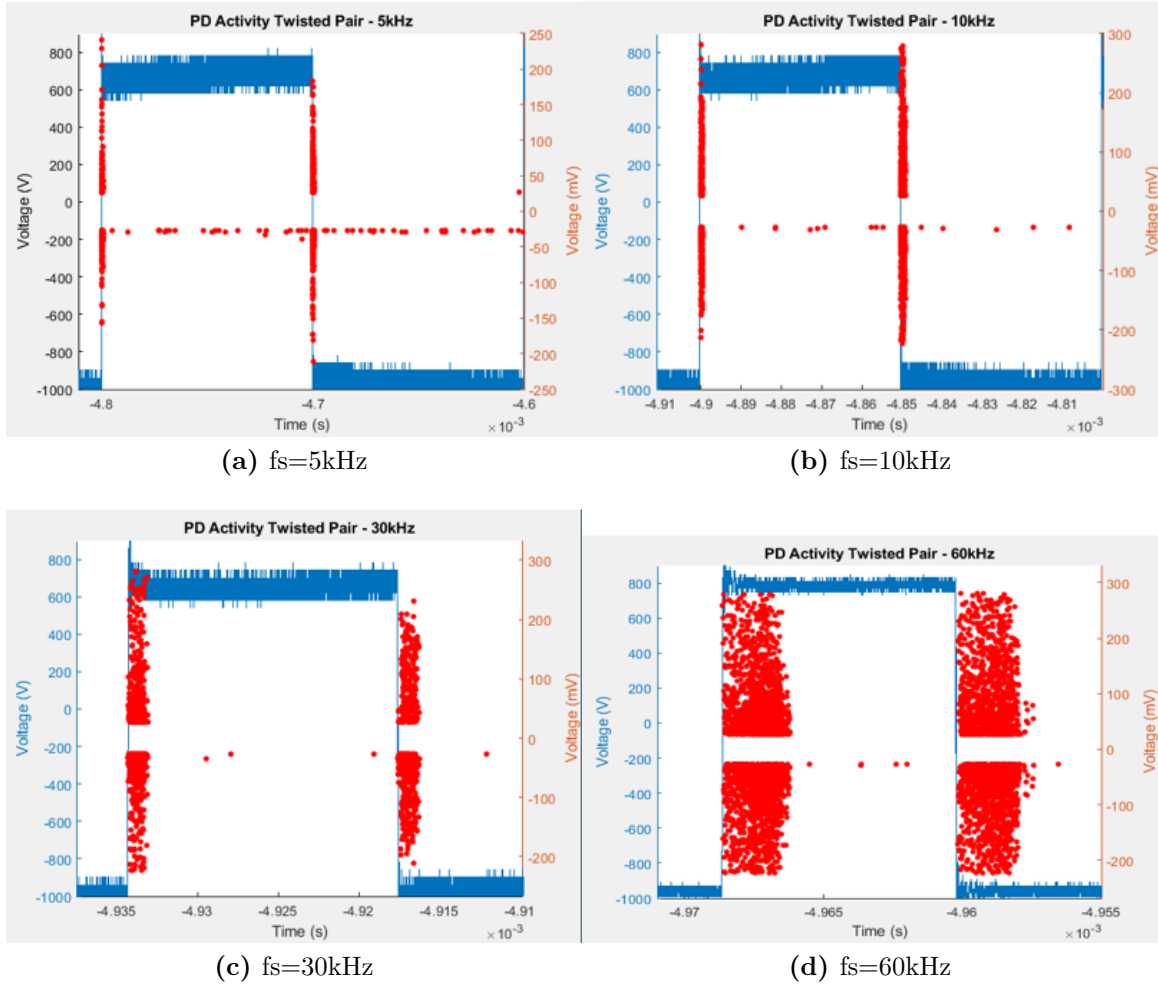


Figure 5.21: PRPD for PWM Voltage at several switching frequencies

The ambient noise was filtered out somewhat imperfectly as an alternative to wavelet denoising here as wavelet denoising can effect the amplitude of the partial discharge signals. However, the prevailing partial discharge behaviors are apparent despite minor noise, because the test was preformed approximately 400V above inception voltage, at which point partial discharge is suitably large and easily distinguishable from noise. From these results it can be seen the switching frequency primarily effects the quantity of partial discharge that insulation will see over a certain period of time. The amplitude of partial discharge is not noticeably affected by the switching frequency as maximum PD pulses occurred consistently between 250mV and 300mV as observed from the UHF antenna. Additionally partial discharge appears to occur over a larger percentage of the switching cycle however this is due to the smaller time period of the higher switching speed voltages. The partial discharge pulses consistently occur within $50\mu\text{s}$ of the switching event across all switching frequencies. The one effect that switching frequency does have on partial discharge behavior is the quantity of partial discharge that will occur over a constant period of time. [Figure 5.22](#) shows that as switching frequency increases, so does the quantity of partial discharge proportionally. Although this behavior is not exactly surprising, it is worth noting. The increase in partial discharge is across all amplitudes not just partial discharge of small size. Insulation exposed to partial discharge at higher frequency will experience a greater number of partial discharge, a greater amount of electrical stress. At higher switching frequencies, once partial discharge begins to occur, insulation can be expected to fail more quickly. To determine the long term effect that switching frequency has on insulation performance, lifetime partial discharge testing of insulation will need to be performed.

5.3.2 Dv/dt

The dv/dt of the Full-bridge converter was varied by increasing or decreasing the turn on gate resistance. This only effected the turn on time of the PWM voltage but allowed dv/dt from 11-16 V/ns with this SiC converter. With the change of dv/dt the twisted pair is tested at 5 voltage levels ranging from 1-3kV to determine whether or not dv/dt affects partial discharge behavior.

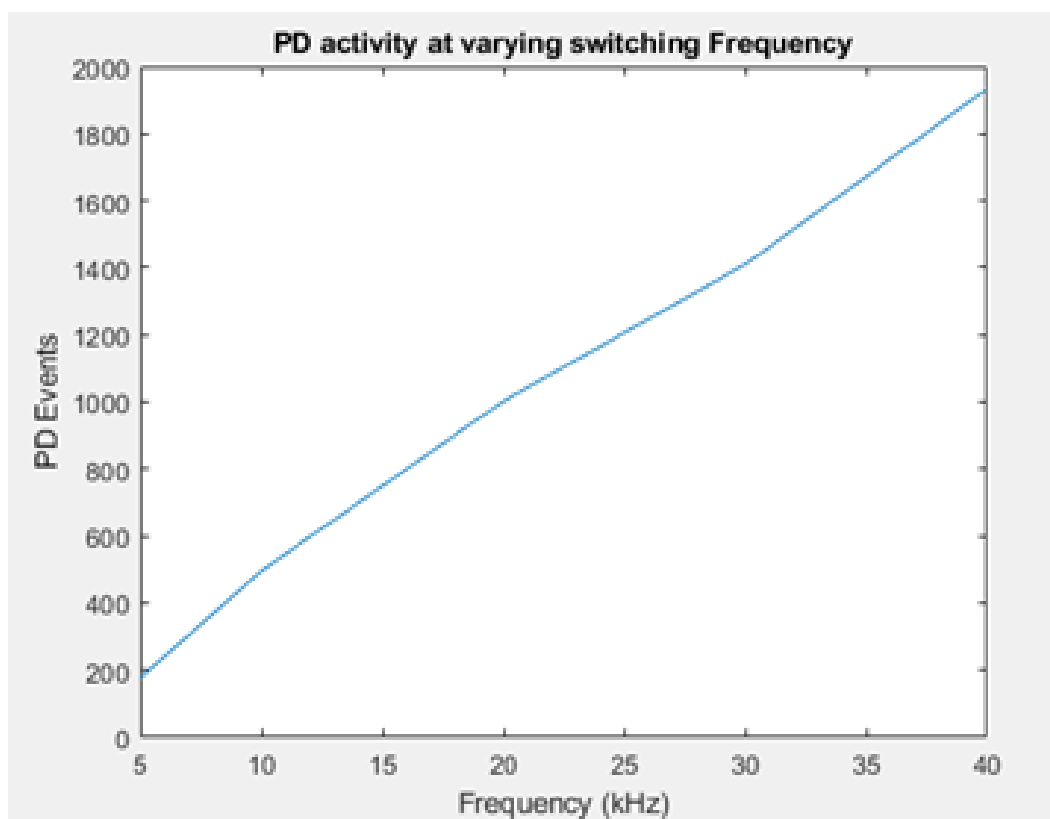


Figure 5.22: Partial Discharge Quantity due to Switching Frequency

An increase in the dv/dt of the PWM voltage leads to a slight increase of partial discharge events occurring over once cycle of the PWM inverter voltage ([Figure 5.23](#)). The increase of partial discharge events can be seen more prominently at the peaks of the voltage waveform. The increase of partial discharge events is slight and falsely appears to stabilize and at higher voltages due to sensor saturation. This increase of partial discharge is over the course of one voltage cycle, and could contribute to increased insulation degradation. In order to confirm this proper lifetime testing would need to be performed.

5.4 Chapter Summary

In this chapter methods of partial discharge classification and analysis are analyzed. An important use of partial discharge testing is identifying the type of partial discharge occurring in an insulation system. Partial discharge analysis methods are dependent on the type of PWM voltage waveform applied. For fixed duty cycle square wave voltage, analysis methods are very limited in usefulness. Phase resolved methods cannot distinguish between types of partial discharge occurring. However, when the duty cycle is modulated, such as with unipolar PWM voltage, analysis methods prove more useful. Phase resolved analysis is proven as potential methods to identify partial discharge types. A modification of pulse sequence analysis that utilizes duty cycle can also be used to identify PD types. Additionally, the effect of dv/dt and switching frequency on PD likelihood is briefly explored. As both characteristics are increased, more PD will occur leading to shorter insulation lifetime.

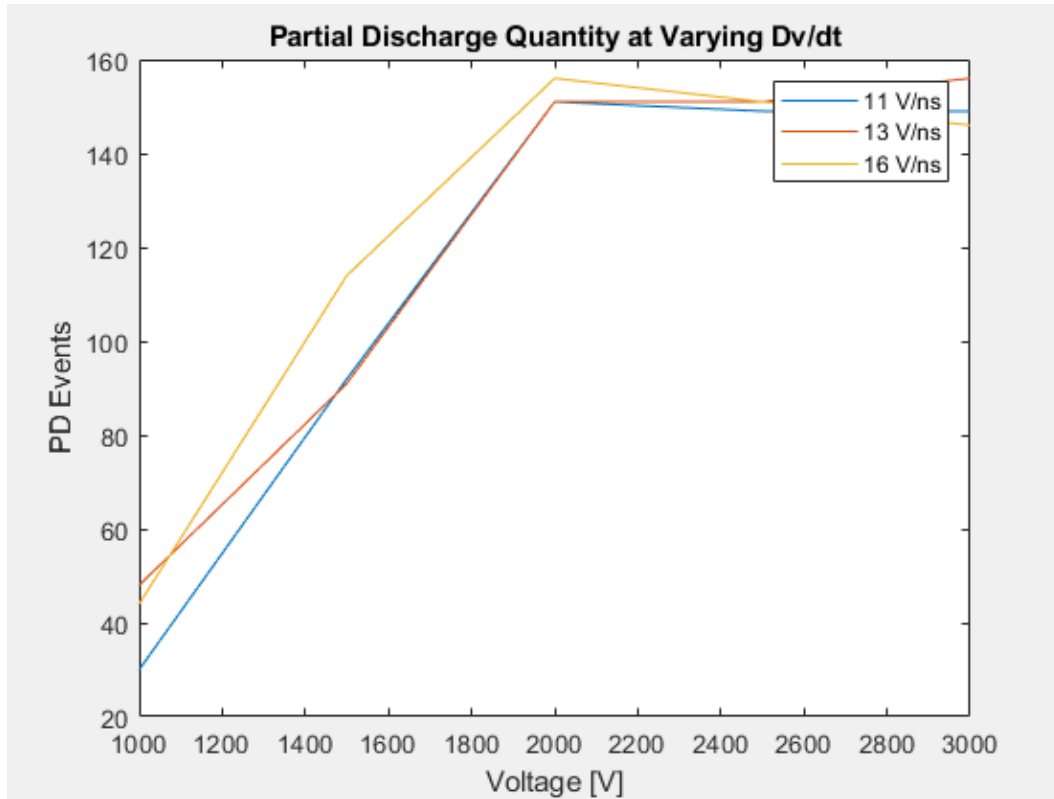


Figure 5.23: Partial Discharge Events due to dv/dt of PWM Voltage Inverter - twisted pair

Chapter 6

Conclusions

Partial discharge detection and testing is an important part of high voltage electrical applications both in design and long term maintenance. Partial discharge detection and behavior study will become more important to power electronic applications as power electronic converters are utilized at higher voltages.

The first step in partial discharge testing is addressing the noise caused by fast voltage switching transients. Electrically isolated methods for partial discharge testing will be vital to testing in such a noise heavy environment. Optical and electromagnetic detection methods are the best at partial discharge detection of the tested methods. However, optical detection via a photo multiplier tube requires significant setup to be suitable for partial discharge detection. The testing environment must be mostly free of ambient light. This can be arranged in a lab, but for practical application, optical detection is difficult. Additionally, optical detection is not suitable for every type of partial discharge. Partial discharge that occurs internal to the insulation or test subject cannot be seen by the optical detection as light cannot escape the void. For these reasons, electromagnetic detection is the recommended method for partial discharge testing. Although the ultra-high-frequency antenna utilized for this project had limited sensitivity, it was not an antenna designed for these applications. Electromagnetic detection of partial discharge utilizing an antenna and high pass filter design for the specific purpose would prove the most effective and versatile partial discharge testing technique.

Partial discharge behaves differently when in the presence of PWM voltage as opposed to

60Hz AC sinusoidal voltage. How partial discharge behaves as a result of PWM voltage is highly dependent on the PWM voltage however. Partial discharge as a result of PWM voltage with a constant duty cycle occurs at each switching cycle. The partial discharge will begin at the first switching event at inception voltage, and partial discharge will occur every switching cycle after that. This type of square-wave PWM voltage is the most difficult to analyze for partial discharge classification because the partial discharge behavior gives no clues that indicate what type of defect is causing the PD.

Partial discharge as a result of PWM voltage with a modulating duty cycle shows much greater similarity to partial discharge behavior of 60Hz AC sinusoidal voltage. This type of PWM voltage is more similar to a likely power electronic inverter application. The PRPD patterns utilized for defect identification with AC voltage could be fairly easily used to determine the type of defect occurring in insulation exposed to this type of PWM voltage. The most distinct difference is that partial discharge tends to occur close to the zero-crossing with unipolar PWM voltage due to the polarity flip, causing an enhanced local electric field at the defect. The discrepancy of partial discharge behavior due to what type of PWM voltage is applied to the test subject demonstrates that the only way to accurately determine how insulation will perform in the presence of a certain type of PWM voltage is to apply that specific type of PWM voltage to it. This will be difficult as power electronic penetration in high voltage electrical systems increases unless there are standard types of PWM voltage utilized. However, if the PWM voltage output is designed to reflect AC sinusoidal voltage, the partial discharge behavior can be expected to behave similarly.

Additional methods of classifying partial discharge were explored, and utilizing pulse sequence analysis based on duty cycle is an effective method for partial discharge classifications, where it is applicable. The modulated duty cycle provides a constantly changing variable for pulse sequence analysis that is missing with PSA methods based on voltage. These PSA methods can clearly distinguish different types of partial discharge from each other such as the type of surface and internal discharge tested in this project. PWM voltage will likely lead to faster insulation degradation, however, with all else being equal. Switching frequency and higher dv/dt lead to a greater quantity of partial discharge over the same time period. This increase in partial discharge pulses will ultimately lead to a reduction in insulation

lifetime. Each partial discharge pulse refers to a partial localized micro-explosion in the insulation, each of which damages then insulation. The switching voltage and high dv/dt does not lead to larger magnitude of partial discharge however. If insulation can perform to expectations with any partial discharge under 60Hz AC sinusoidal voltage, the insulation can be expected to perform similarly with PWM voltage, the partial discharge will not be of greater magnitude.

All of the findings of this project were made with limited test subjects and testing environments relative to all the potential types of insulation and types of PWM voltage that could be paired. Partial discharge behavior is heavily dependent on the insulation of which it is occurring and the type of PWM voltage begin applied. To truly understand partial discharge behavior as a result of PWM voltage, many more insulation types need to be tested to ensure that the classification and behavior patterns found in this project are consistent across all types of surface or void discharges for example. The detection methods proven here will need to be tested at faster voltage rise times, where the voltage switching noise will have higher frequency content. This consideration will be of even greater importance with wide bandgap semiconductors that are capable of very fast switching times. The very high dv/dt and resulting high frequency noise could potentially make high pass filters such as the 300MHz filter used in this project less effective. As the noise is of higher frequency, more of the noise will pass this type of filter and new solutions may be needed. Additionally, extended duration testing will be needed to demonstrate whether the increase in partial discharge quantity due to switching frequency or dv/dt is enough to appreciably effect the lifetime of insulation.

6.1 Future Work

This project focused on developing a partial discharge testing platform for PWM voltage with a focus on electrically isolated detection methods that effectively detect partial discharge in the presence of voltage switching transient noise. Some study into the effects of PWM voltage on partial discharge behavior are explored as well. Additionally methods of identifying insulation defects by partial discharge detection, such as phase resolved and modified pulse

sequence analysis are explored for two test subjects of surface and void discharge. For future work, more test subjects will need to be studied to gain a better understanding of the PRPD and PSA patterns of several examples of surface and void discharge. Additionally, effective test subjects to model corona discharge can be established. Additional test subjects would validate the effectiveness of phase resolved analysis and pulse sequence analysis methods. More PWM voltage waveforms should be tested as well. While a few potential classification methods are tested here primarily for a unipolar PWM voltage, no effective classification solutions were found for partial discharge with a PWM voltage and fixed duty cycle. Finally, to fully understand the effect of PWM voltage on insulation, lifetime durability testing will need to be conducted. Test subjects will need to be exposed to partial discharge until failure. Through this lifetime testing, the true effect of PWM voltage could be found. The increased quantity of partial discharge due to either switching frequency or higher dv/dt can be tested to verify that these factors will lead to faster degradation. The effect of high switching frequency and dv/dt will need to be studied further as wide bandgap devices such as silicon-carbide and gallium nitride are capable of much higher dv/dt and switching frequency than silicon devices like the one used in the designed converter. Any negative effect on partial discharge likelihood or severity due to switching frequency and dv/dt will effect wide bandgap devices to a greater degree. Further testing of partial discharge behavior and the long term effects of PWM voltage on insulation systems is needed at varying converter voltage configurations as partial discharge is shown to be dramatically effected by applied voltage waveform, even when comparing different types of converter PWM voltage.

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Appendices

A Matlab Code

A.1 SiC Converter PD Data Processing

```
% PD testing
% SiC Converter
% comparison of PD testing on twisted pair or inductor at various dv/dt
% Going to look at 20kHz
5 clear; clc; close all;
PD_count = zeros(1,15);
MPD = 50e3;
%% 50 ohm

10 % 1.0kV
clearvars -except PD_count MPD;
Applied_Voltage = 1000;
waveform1 = readtable('50ohm/1_04_Ch3.csv');
waveform2 = readtable('50ohm/1_04_Ch2.csv');
15 PD = waveform2.Var5;
PD_denoised = wdenoise(PD,20, ...
    'Wavelet', 'sym4', ...
    'DenoisingMethod', 'UniversalThreshold', ...
    'ThresholdRule', 'Soft', ...
20    'NoiseEstimate', 'LevelDependent');

offset =1/20e3;
PD_count(1) = 0;
25 dy = gradient(PD_denoised, mean(diff(waveform2.Var4)));
[dypks,ix] = findpeaks(dy, 'MinPeakDistance',MPD, 'MinPeakHeight',1);
PD_count(1) = length(ix);
%%
```

```

% 1.5kV
30 clearvars -except PD_count MPD;
    Applied_Voltage = 1500;
    waveform1 = readtable('50ohm/1_50_Ch3.csv');
    waveform2 = readtable('50ohm/1_50_Ch2.csv');
    PD = waveform2.Var5;
35 PD_denoised = wdenoise(PD,20, ...
        'Wavelet', 'sym4', ...
        'DenoisingMethod', 'UniversalThreshold', ...
        'ThresholdRule', 'Soft', ...
        'NoiseEstimate', 'LevelDependent');
40 offset =1/20e3;
    PD_count(2) = 0;
    % PD events of test
    dy = gradient(PD_denoised, mean(diff(waveform2.Var4)));
    [dypks,ix] = findpeaks(dy, 'MinPeakDistance',MPD, 'MinPeakHeight',1);
45 PD_count(2) = length(ix);
    %%
    % 2.0kV
    clearvars -except PD_count MPD;
    Applied_Voltage = 2000;
50 waveform1 = readtable('50ohm/2_0_Ch3.csv');
    waveform2 = readtable('50ohm/2_0_Ch2.csv');
    PD = waveform2.Var5;
    PD_denoised = wdenoise(PD,20, ...
        'Wavelet', 'sym4', ...
55     'DenoisingMethod', 'UniversalThreshold', ...
        'ThresholdRule', 'Soft', ...
        'NoiseEstimate', 'LevelDependent');
    offset =1/20e3;
    PD_count(3) = 0;
60 % PD events of test

```

```

    dy = gradient(PD_denoised, mean(diff(waveform2.Var4)));
[dypks,ix] = findpeaks(dy, 'MinPeakDistance',MPD, 'MinPeakHeight',1);
PD_count(3) = length(ix);
%%
65 % 2.5kV
clearvars -except PD_count MPD;
Applied_Voltage = 2500;
waveform1 = readtable('50ohm/2_52_Ch3.csv');
waveform2 = readtable('50ohm/2_52_Ch2.csv');
70 PD = waveform2.Var5;
PD_denoised = wdenoise(PD,20, ...
    'Wavelet', 'sym4', ...
    'DenoisingMethod', 'UniversalThreshold', ...
    'ThresholdRule', 'Soft', ...
75    'NoiseEstimate', 'LevelDependent');
offset =1/20e3;
PD_count(4) = 0;
% PD events of test
    dy = gradient(PD_denoised, mean(diff(waveform2.Var4)));
80 [dypks,ix] = findpeaks(dy, 'MinPeakDistance',MPD, 'MinPeakHeight',1);
PD_count(4) = length(ix);
%%
% 3kV
clearvars -except PD_count MPD;
85 Applied_Voltage = 3000;
waveform1 = readtable('50ohm/3_03_Ch3.csv');
waveform2 = readtable('50ohm/3_03_Ch2.csv');
PD = waveform2.Var5;
PD_denoised = wdenoise(PD,20, ...
90    'Wavelet', 'sym4', ...
    'DenoisingMethod', 'UniversalThreshold', ...
    'ThresholdRule', 'Soft', ...

```

```

        'NoiseEstimate', 'LevelDependent');
offset =1/20e3;
95 PD_count(5) = 0;
% PD events of test
dy = gradient(PD_denoised, mean(diff(waveform2.Var4)));
[dypks,ix] = findpeaks(dy, 'MinPeakDistance',MPD, 'MinPeakHeight',1);
PD_count(5) = length(ix);
100 %%
%%
%% 25 ohm

% 1.0kV
105 clearvars -except PD_count MPD;
waveform1 = readtable('25ohm/1_05_Ch3.csv');
waveform2 = readtable('25ohm/1_05_Ch2.csv');
PD = waveform2.Var5;
PD_denoised = wdenoise(PD,20, ...
110     'Wavelet', 'sym4', ...
        'DenoisingMethod', 'UniversalThreshold', ...
        'ThresholdRule', 'Soft', ...
        'NoiseEstimate', 'LevelDependent');
offset =1/20e3;
115 PD_count(6) = 0;
% PD events of test
dy = gradient(PD_denoised, mean(diff(waveform2.Var4)));
[dypks,ix] = findpeaks(dy, 'MinPeakDistance',MPD, 'MinPeakHeight',1);
PD_count(6) = length(ix);
120 %%
% 1.5kV
clearvars -except PD_count MPD;
Applied_Voltage = 1500;
waveform1 = readtable('25ohm/1_51_Ch3.csv');

```

```

125 waveform2 = readtable('25ohm/1_51_Ch2.csv');
    PD = waveform2.Var5;
    PD_denoised = wdenoise(PD,20, ...
        'Wavelet', 'sym4', ...
        'DenoisingMethod', 'UniversalThreshold', ...
130     'ThresholdRule', 'Soft', ...
        'NoiseEstimate', 'LevelDependent');
    offset =1/20e3;
    % PD events of test
    PD_count(7) = 0;
135     dy = gradient(PD_denoised, mean(diff(waveform2.Var4)));
    [dypks,ix] = findpeaks(dy, 'MinPeakDistance',MPD, 'MinPeakHeight',1);
    PD_count(7) = length(ix);
    %%
    % 2.0kV
140     clearvars -except PD_count MPD;
    waveform1 = readtable('25ohm/2_01_Ch3.csv');
    waveform2 = readtable('25ohm/2_01_Ch2.csv');
    PD = waveform2.Var5;
    PD_denoised = wdenoise(PD,20, ...
145     'Wavelet', 'sym4', ...
        'DenoisingMethod', 'UniversalThreshold', ...
        'ThresholdRule', 'Soft', ...
        'NoiseEstimate', 'LevelDependent');
    offset =1/20e3;
150     PD_count(8) = 0;
    % PD events of test
    dy = gradient(PD_denoised, mean(diff(waveform2.Var4)));
    [dypks,ix] = findpeaks(dy, 'MinPeakDistance',MPD, 'MinPeakHeight',1);
    PD_count(8) = length(ix);
155
    % 2.5kV

```

```

clearvars -except PD_count MPD;
waveform1 = readtable('25ohm/2_52_Ch3.csv');
waveform2 = readtable('25ohm/2_52_Ch2.csv');
160 PD = waveform2.Var5;
PD_denoised = wdenoise(PD,20, ...
    'Wavelet', 'sym4', ...
    'DenoisingMethod', 'UniversalThreshold', ...
    'ThresholdRule', 'Soft', ...
165    'NoiseEstimate', 'LevelDependent');
offset =1/20e3;
PD_count(9) = 0;
% PD events of test
dy = gradient(PD_denoised, mean(diff(waveform2.Var4)));
170 [dypks,ix] = findpeaks(dy, 'MinPeakDistance',MPD, 'MinPeakHeight',1);
PD_count(9) = length(ix);

% 3kV
clearvars -except PD_count MPD;
175 waveform1 = readtable('25ohm/2_99_Ch3.csv');
waveform2 = readtable('25ohm/2_99_Ch2.csv');
PD = waveform2.Var5;
PD_denoised = wdenoise(PD,20, ...
    'Wavelet', 'sym4', ...
180    'DenoisingMethod', 'UniversalThreshold', ...
    'ThresholdRule', 'Soft', ...
    'NoiseEstimate', 'LevelDependent');
offset =1/20e3;
PD_count(10) = 0;
185 % PD events of test
dy = gradient(PD_denoised, mean(diff(waveform2.Var4)));
[dypks,ix] = findpeaks(dy, 'MinPeakDistance',MPD, 'MinPeakHeight',1);
PD_count(10) = length(ix);

```

```

%%
190 %%
    %% 15 ohm

    % 1.0kV
    clearvars -except PD_count MPD;
195 waveform1 = readtable('15ohm/1_0_Ch3.csv');
    waveform2 = readtable('15ohm/1_0_Ch2.csv');
    PD = waveform2.Var5;
    PD_denoised = wdenoise(PD,20, ...
        'Wavelet', 'sym4', ...
200 'DenoisingMethod', 'UniversalThreshold', ...
        'ThresholdRule', 'Soft', ...
        'NoiseEstimate', 'LevelDependent');
    offset =1/20e3;
    PD_count(11) = 0;
205 % PD events of test
    dy = gradient(PD_denoised, mean(diff(waveform2.Var4)));
    [dypks,ix] = findpeaks(dy, 'MinPeakDistance',MPD, 'MinPeakHeight',1);
    PD_count(11) = length(ix);
    %%
210 % 1.5kV
    clearvars -except PD_count MPD;
    Applied_Voltage = 1500;
    waveform1 = readtable('15ohm/1_52_Ch3.csv');
    waveform2 = readtable('15ohm/1_52_Ch2.csv');
215 PD = waveform2.Var5;
    PD_denoised = wdenoise(PD,20, ...
        'Wavelet', 'sym4', ...
        'DenoisingMethod', 'UniversalThreshold', ...
        'ThresholdRule', 'Soft', ...
220 'NoiseEstimate', 'LevelDependent');

```

```

    offset =1/20e3;
% PD events of test
    PD_count(12) = 0;
    dy = gradient(PD_denoised, mean(diff(waveform2.Var4)));
225 [dypks,ix] = findpeaks(dy, 'MinPeakDistance',MPD, 'MinPeakHeight',1);
    PD_count(12) = length(ix);
%%
% 2.0kV
clearvars -except PD_count MPD;
230 waveform1 = readtable('15ohm/2_03_Ch3.csv');
    waveform2 = readtable('15ohm/2_03_Ch2.csv');
    PD = waveform2.Var5;
    PD_denoised = wdenoise(PD,20, ...
        'Wavelet', 'sym4', ...
235 'DenoisingMethod', 'UniversalThreshold', ...
        'ThresholdRule', 'Soft', ...
        'NoiseEstimate', 'LevelDependent');
    offset =1/20e3;
    PD_count(13) = 0;
240 % PD events of test
    dy = gradient(PD_denoised, mean(diff(waveform2.Var4)));
    [dypks,ix] = findpeaks(dy, 'MinPeakDistance',MPD, 'MinPeakHeight',1);
    PD_count(13) = length(ix);
%%
245 % 2.5kV
clearvars -except PD_count MPD;
    waveform1 = readtable('15ohm/2_53_Ch3.csv');
    waveform2 = readtable('15ohm/2_53_Ch2.csv');
    PD = waveform2.Var5;
250 PD_denoised = wdenoise(PD,20, ...
        'Wavelet', 'sym4', ...
        'DenoisingMethod', 'UniversalThreshold', ...

```

```

        'ThresholdRule', 'Soft', ...
        'NoiseEstimate', 'LevelDependent');

255 offset =1/20e3;
    PD_count(14) = 0;
    % PD events of test
    dy = gradient(PD_denoised, mean(diff(waveform2.Var4)));
    [dypks,ix] = findpeaks(dy, 'MinPeakDistance',MPD, 'MinPeakHeight',1);
260 PD_count(14) = length(ix);
    %%
    % 3kV
    clearvars -except PD_count MPD;
    waveform1 = readtable('15ohm/2_98_Ch3.csv');
265 waveform2 = readtable('15ohm/2_98_Ch2.csv');
    PD = waveform2.Var5;
    PD_denoised = wdenoise(PD,20, ...
        'Wavelet', 'sym4', ...
        'DenoisingMethod', 'UniversalThreshold', ...
270 'ThresholdRule', 'Soft', ...
        'NoiseEstimate', 'LevelDependent');
    offset =1/20e3;
    PD_count(15) = 0;
    % PD events of test
275 dy = gradient(PD_denoised, mean(diff(waveform2.Var4)));
    [dypks,ix] = findpeaks(dy, 'MinPeakDistance',MPD, 'MinPeakHeight',1);
    PD_count(15) = length(ix);
    %%
    %% Dv/dt
280 clearvars -except PD_count
    close all;
    % Plot dv/dt comparisons
    Voltages = [1000, 1500, 2000, 2500, 3000];
    figure(1)

```

```

285 plot(Voltages, PD_count(1:5));
    hold on;
    plot(Voltages, PD_count(6:10));
    plot(Voltages, PD_count(11:15));
    title('Partial Discharge Quantity at Varying Dv/dt');
290 xlabel('Voltage [V]');
    ylabel('PD Events');
    legend('11 V/ns', '13 V/ns', '16 V/ns');
    %%
    %% Phase resolved partial discharge
295 close all;
    figure(1)
    hold on
    plot(waveform1.Var4, waveform1.Var5);
    % plot(waveform1.Var4, waveform_duty*1000, 'linewidth', 3);
300 title('Phase Resolved Partial Discharge Pattern', 'FontSize', 26)
    xlabel('Time (s)', 'FontSize', 20);
    ylabel('Voltage (V)', 'FontSize', 20);
    figure(1)
    hold on
305 yyaxis right;
    ylabel('Voltage (mV)')
    plot(waveform1.Var4, PD_denoised*1000);

310
    %% Pulse Sequence Analysis
    % Plot PD by seperation of pulses
    % Volt_PD = zeros(5000000,1);
    before = 0;
315 now = 0;
    after = 0;

```

```

figure(2)
hold on;
title('Pulse Sequence Analysis - Voltage');
320 xlabel('Voltage difference V(n-1)');
ylabel('Voltage Difference V(n)');
for i = 2:1:length(ix)-1
    before = waveform1.Var5(ix(i-1));
    now = waveform1.Var5(ix(i));
325 after = waveform1.Var5(ix(i+1));
    x = now-before;
    y = after-now;
    plot(x,y,'b. ');
    hold on;
330 %     offset = offset + 2/20e3;
end
% Pulse Sequence Analysis - Duty Cycle Version
% Plot PD by separation of pulses - Duty cycle version
% Volt_PD = zeros(5000000,1);
335 % close all;
cycle_length = 25000;
fullD = cycle_length*Applied_Voltage*cycle_length;
waveform_duty = zeros(10e6,1);
% Determine duty cycle first
340 x = 5e6:1:5e6+cycle_length;
y = waveform1.Var5(5e6:5e6+cycle_length)';
test = polyarea(x,y);
for i = 1:cycle_length:10e6-25000
    x = 1:1:cycle_length+1;
345 y = waveform1.Var5(i:i+cycle_length);
    duty = cycle_length.*sum(y)'./fullD;
    waveform_duty(i:1:i+cycle_length) = duty;
end

```

```

350 before = 0;
    now = 0;
    after = 0;
    figure(3)
    hold on;
355 title('Pulse Sequence Analysis - Duty Cycle');
    xlabel('Duty Cycle difference \Delta D(n-1)');
    ylabel('Duty Cycle Difference \Delta D(n)');
    for i = 2:1:length(ix)-1
        before = waveform_duty(ix(i-1));
360        now = waveform_duty(ix(i));
        after = waveform_duty(ix(i+1));
        x = now-before;
        y = after-now;
        plot(x,y,'b.');
```

365

```

        hold on;
    %     offset = offset + 2/20e3;
end

```

A.2 Si Converter PD Data Processing

```

% UHF antenna PD testing
% Twisted Pair - switching frequency

5 %% 5kHz
clear; clc; close all;
waveform1 = readtable('twisted_pair-5kHz.csv');
    offset = 1/5e3;
% figure(1)
10 % hold on

```

```

% plot (waveform1.TIME, waveform1.CH2);
% title('PD Activity UHF antenna - 5kHz')
% xlabel('Time (s)');
% ylabel('Voltage (V)');
15 figure(1)
hold on
plot(waveform1.TIME, waveform1.CH1);
%plot (waveform1.TIME, waveform1.CH2.*50000);
axis([(-5.01e-3+offset-1e-6) (-5e-3+2*offset) -1000 900])
20 title('PD Activity Twisted Pair - 5kHz')
xlabel('Time (s)');
ylabel('Voltage (V)');

% calculating max point of each spike and plotting on graph
25 for i = 1:1:height(waveform1)
    if abs(waveform1.CH2(i)*50000) > 130
        x_loc = rem(waveform1.TIME(i), 0.5*offset)+-5e-3+1.5*offset;
        hold on;
        yyaxis right
30 plot(x_loc, waveform1.CH2(i)*10000, 'r.', 'Markersize', 14);
    else
        ;
    end
% offset = offset + 2/20e3;
35 end
ylabel('Voltage (mV)')
%%
% Plot PD by seperation of pulses
for i = 1:1:height(waveform1)
40 if abs(waveform1.CH4(i)*50000) > 130
        Volt_PD(i) = waveform1.CH1(i);
        Time_PD(i) = waveform1.TIME(i);
    end
end

```

```

        else
            ;
45    end
%    offset = offset + 2/20e3;
end

figure(2)
50 title('Pulse Sequence Analysis - Voltage');
xlabel('Voltage difference V(n-1)');
ylabel('Voltage Difference V(n)');
for i = 2:1:length(Volt_PD)-1
    x = Volt_PD(i)-Volt_PD(i-1);
55    y = Volt_PD(i+1)-Volt_PD(i);
    plot(x,y,'.');
    hold on;
end

60 %% 10kHz
clear; clc; close all;
waveform1 = readtable('twisted_pair-10kHz.csv');
    offset =1/10e3;
% figure(1)
65 % hold on
% plot(waveform1.TIME, waveform1.CH2);
% title('PD Activity UHF antenna - 5kHz')
% xlabel('Time (s)');
% ylabel('Voltage (V)');
70 figure(1)
hold on
yyaxis left
plot(waveform1.TIME, waveform1.CH1);
%plot(waveform1.TIME, waveform1.CH2.*50000);

```

```

75 axis([(-5.01e-3+offset-1e-6) (-5e-3+2*offset) -1000 900])
   title('Phase Resolved PD Pattern - Switching Cycle')
   xlabel('Time (s)');
   ylabel('Voltage (V)');

80 % calculating max point of each spike and plotting on graph
   for i = 1:1:height(waveform1)
       if abs(waveform1.CH2(i)*50000) > 155
           x_loc = rem(waveform1.TIME(i),0.5*offset)+-5e-3+1.5*offset;
           hold on;
85         yyaxis right
           plot(x_loc, waveform1.CH2(i)*10000,'r.','Markersize', 14);
           else
               ;
           end
90 %     offset = offset + 2/20e3;
   end
   ylabel('Voltage (mV)')
   %% 30kHz
   clear; clc; close all;
95 waveform1 = readtable('twisted_pair-30kHz.csv');
   offset =2/30e3;
   % figure(1)
   % hold on
   % plot(waveform1.TIME, waveform1.CH2);
100 % title('PD Activity UHF antenna - 5kHz')
   % xlabel('Time (s)');
   % ylabel('Voltage (V)');
   figure(1)
   hold on
105 yyaxis left
   plot(waveform1.TIME, waveform1.CH1);

```

```

%plot (waveform1.TIME, waveform1.CH2.*50000);
axis([(-5.01e-3+1.25*offset-1e-6) (-5e-3+1.5*offset) -1000 900])
title('PD Activity Twisted Pair - 30kHz')
110 xlabel('Time (s)');
ylabel('Voltage (V)');

% calculating max point of each spike and plotting on graph
for i = 1:1:height(waveform1)
115     if abs(waveform1.CH2(i)*50000) > 130
        x_loc = rem(waveform1.TIME(i), offset/2)+-5e-3+1.5*offset;
        hold on;
        yyaxis right
        plot(x_loc, waveform1.CH2(i)*10000, 'r.', 'Markersize', 14);
120     else
        ;
    end
    %     offset = offset + 2/20e3;
end
125 ylabel('Voltage (mV)')
%% 40kHz
clear; clc; close all;
waveform1 = readtable('twisted_pair-40kHz.csv');
    offset =2/40e3;
130 % figure(1)
% hold on
% plot (waveform1.TIME, waveform1.CH2);
% title('PD Activity UHF antenna - 5kHz')
% xlabel('Time (s)');
135 % ylabel('Voltage (V)');
figure(1)
hold on
yyaxis left

```

```

plot(waveform1.TIME, waveform1.CH1);
140 %plot(waveform1.TIME, waveform1.CH2.*50000);
axis([(-5.01e-3+1.25*offset-1e-6) (-5e-3+1.5*offset) -1000 900])
title('PD Activity Twisted Pair - 40kHz')
xlabel('Time (s)');
ylabel('Voltage (V)');

145 % calculating max point of each spike and plotting on graph
for i = 1:1:height(waveform1)
    if abs(waveform1.CH2(i)*50000) > 130
        x_loc = rem(waveform1.TIME(i), offset)+-5e-3+1.5*offset;
150 hold on;
        yyaxis right
        plot(x_loc, waveform1.CH2(i)*10000, 'r.', 'Markersize', 14);
    else
        ;
155 end
% offset = offset + 2/20e3;
end
ylabel('Voltage (mV)')
%% 60kHz
160 clear; clc; close all;
waveform1 = readtable('twisted_pair-60kHz.csv');
offset =2/60e3;
% figure(1)
% hold on
165 % plot(waveform1.TIME, waveform1.CH2);
% title('PD Activity UHF antenna - 5kHz')
% xlabel('Time (s)');
% ylabel('Voltage (V)');
figure(1)
170 hold on

```

```

yyaxis left
plot(waveform1.TIME, waveform1.CH1);
%plot(waveform1.TIME, waveform1.CH2.*50000);
axis([(-5.01e-3+1.2*offset-1e-6) (-5e-3+1.35*offset) -1000 900])
175 title('PD Activity Twisted Pair - 60kHz')
xlabel('Time (s)');
ylabel('Voltage (V)');

% calculating max point of each spike and plotting on graph
180 for i = 1:1:height(waveform1)
    if abs(waveform1.CH2(i)*50000) > 130
        x_loc = rem(waveform1.TIME(i), offset)+-5e-3+1.5*offset;
        hold on;
        yyaxis right
185 plot(x_loc, waveform1.CH2(i)*10000, 'r.', 'Markersize', 14);
    else
        ;
    end
% offset = offset + 2/20e3;
190 end
ylabel('Voltage (mV)')

```

A.3 Acoustic PD Localization

```

% acoustic location solver
% research
clear; clc; close all;

5 T0000 = readtable('test0006.xlsx');
coords = [26.24 10.16 0; 78.232 82.424 0; 186.944 167.259 0; ...
        152.273 107.823 0;];
vs = 3600000;

```

```

10 %intial avg values
    AvgX = 0;
    AvgY = 0;
    n = 0;

15 x = coords(1:4,1);
    y = coords(1:4,2);
    z = coords(1:4,3);
    figure(1)
    plot(x,y,'Rd', 'MarkerSize', 24)
20 xlabel('x');
    ylabel('y');
    zlabel('z');
    xlim([0 217.424]);
    ylim([0 185.801]);

25
    grid on
    hold on

    %board measurements - 217.424x185.801 mm

30
    img = imread('pcb.png');      % Load a sample image
    xImage = [0 217.424;0 217.424 ]; % The x data for the image corners
    yImage = [185.801 185.801;0 0]; % The y data for the image corners
    zImage = [-100 -100; -100 -100]; % The z data for the image corners
35 surf(xImage,yImage,zImage,... % Plot the surface
        'CData',img,...
        'FaceColor','texturemap');

40 for i=1:5:height(T0000)

```

```

A = T0000.HH_MM_SS(i);
a = str2double(A{:});
Achan = T0000.mmmuuun(i);
45 achan = str2double(Achan{:})
B = T0000.HH_MM_SS(i+1);
b = str2double(B{:});
Bchan = T0000.mmmuuun(i+1);
bchan = str2double(Bchan{:})
50 C = T0000.HH_MM_SS(i+2);
c = str2double(C{:});
Cchan = T0000.mmmuuun(i+2);
cchan = str2double(Cchan{:})
D = T0000.HH_MM_SS(i+3);
55 d = str2double(D{:});
Dchan = T0000.mmmuuun(i+3);
dchan = str2double(Dchan{:})
t0 = a;
t1 = (b-a)/1e7;
60 t2 = (c-a)/1e7;
t3 = (d-a)/1e7;

syms x y z T
eqns = [(x-coords(achan,1))^2+(y-coords(achan,2))^2+...
65 (z-coords(achan,3))^2==(vs*T)^2,...
(x-coords(bchan,1))^2+(y-coords(bchan,2))^2+...
(z-coords(bchan,3))^2==(vs*(T+t1))^2,...
(x-coords(cchan,1))^2+(y-coords(cchan,2))^2+...
(z-coords(cchan,3))^2==(vs*(T+t2))^2,...
70 (x-coords(dchan,1))^2+(y-coords(dchan,2))^2+...
(z-coords(dchan,3))^2==(vs*(T+t3))^2];
S = solve(eqns,[x, y, z, T]);

```

```

75      fprintf("PD coordinates (%0.4f,%0.4f,%0.4f)", S.x, S.y, S.z)
      S.x;
      S.y;
      S.z;
      S.T;
80      %
      PD = [S.x(1) S.y(1) S.z(1)];
      fprintf("Coordinates = (%.5f, %.5f, %.5f)\n Time Delay = %.5f\n", ...
              S.x(1), S.y(1), S.z(2), S.T(1))

85      %plotting
      plot(PD(1),PD(2),'r*', 'MarkerSize', 24);

      %solving for average value
      if PD(1) > 0 && PD(2) > 0
90          if PD(1) < 4032 && PD(2) < 3024
              AvgX = PD(1) + AvgX;
              AvgY = PD(2) + AvgY;
              n = n+1;
          end
95      end
      end

      AvgX = AvgX / n;
      AvgY = AvgY / n;
100 plot(AvgX,AvgY,'b*', 'MarkerSize', 24);

```

Vita

John Paschal Meadors Jr. was born in Columbia, South Carolina to John Paschal Meadors Sr. and Patricia Rogers Meadors on February 13, 1996. He attended Satchel Ford Elementary School in Columbia SC from 2002-2007, Crayton Middle School from 2007 – 2010 , and AC Flora High School from 2010 – 2014. He then went on to attend Clemson University and graduated with a bachelor's of science in Electrical Engineering in 2019. During his time at Clemson University, John participated in undergraduate research with the Department of Electrical and Computer Engineering for one year. He completed internships with South Carolina Electric Gas. John then accepted a graduate research fellowship through the Department of Energy Wide Bandgap Traineeship at University of Tennessee, Knoxville, in the Department of Electrical and Computer Engineering in August of 2019. During graduate school his main responsibilities were to carry out research regarding the effects of partial discharge on high voltage power electronic converters and associated systems. John will graduate in August 2021 with his degree in Electrical Engineering with an emphasis in power electronics from The University of Tennessee, Knoxville.