Copyright © 2016, Georgia Tech Research Corporation

CHAPTER 8

Partial Discharge (PD) HV and EHV Power Cable Systems

Jean Carlos Hernandez-Mejia & Joshua Perkel

This chapter represents the state of the art at the time of release. Readers are encouraged to consult the link below for the version of this chapter with the most recent release date:

http://www.neetrac.gatech.edu/cdfi-publications.html

Users are strongly encouraged to consult the link below for the most recent release of Chapter 4:

Chapter 4: How to Start

Copyright © 2016, Georgia Tech Research Corporation

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

This document was prepared by Board of Regents of the University System of Georgia by and on behalf of the Georgia Institute of Technology NEETRAC (NEETRAC) as an account of work supported by the US Department of Energy and Industrial Sponsors through agreements with the Georgia Tech Research Institute (GTRC).

Neither NEETRAC, GTRC, any member of NEETRAC or any cosponsor nor any person acting on behalf of any of them:

a) Makes any warranty or representation whatsoever, express or implied,
   i. With respect to the use of any information, apparatus, method, process, or similar item disclosed in this document, including merchantability and fitness for a particular purpose, or
   ii. That such use does not infringe on or interfere with privately owned rights, including any party’s intellectual property, or
   iii. That this document is suitable to any particular user’s circumstance; or
b) Assumes responsibility for any damages or other liability whatsoever (including any consequential damages, even if NEETRAC or any NEETRAC representative has been advised of the possibility of such damages) resulting from your selection or use of this document or any information, apparatus, method, process or similar item disclosed in this document.

DOE Disclaimer: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

NOTICE

Copyright of this report and title to the evaluation data contained herein shall reside with GTRC.

Reference herein to any specific commercial product, process or service by its trade name, trademark, manufacturer or otherwise does not constitute or imply its endorsement, recommendation or favoring by NEETRAC.

The information contained herein represents a reasonable research effort and is, to our knowledge, accurate and reliable at the date of publication.

It is the user's responsibility to conduct the necessary assessments in order to satisfy themselves as to the suitability of the products or recommendations for the user's particular purpose.

Copyright © 2016, Georgia Tech Research Corporation

TABLE OF CONTENTS

Copyright © 2016, Georgia Tech Research Corporation

LIST OF FIGURES

LIST OF TABLES

Copyright © 2016, Georgia Tech Research Corporation

8.0 PARTIAL DISCHARGE (PD) – HV AND EHV POWER CABLE SYSTEMS

A large amount of research published over the past decade investigates the characterization of partial discharge sources in cable systems. Much of this work was done for aged MV cable systems. There has been growing interest in the application of PD measurement technologies to HV and EHV cable systems. The objectives and thus requirements for tests on these cable systems are quite different to those considered for MV cable systems. The focus at HV and EHV is on commissioning tests (i.e. tests on newly installed systems) rather than maintenance tests on aged systems. This greatly reduces the interpretation side of PD testing as the presence of discharge on these new systems is in itself considered unacceptable. As a result, the focus of PD measurements is on the detection (is it detectable?) and location so the discharge source can be repaired. The remaining sections in this chapter focus on PD measurements on HV and EHV systems and discuss where appropriate the differences between these systems and measurements on MV cable systems.

8.1 Test Scope

Partial Discharge detects localized "void-type" defects, primarily in the form of voids in cable or accessories. Voids in this context can be:

- Quasi-spherical (most often due to manufacturing process problems).
- Dendritic (often due to aging processes that lead to the development of electrical trees resulting from enhanced voltage stresses).
- Interfacial (due to the delamination of components, or a loose fit between the cable and an accessory).
- Irregular (mechanical damage either before or after installation).

PD is applicable to all cable types, although its usefulness may be limited when performed on discharge resistant cables (as defined in ICEA S-94-649 and S-97-682) or on oil impregnated paper insulated cables (PILC or MIND) that also have a significant resistance to partial discharge. These cables may have considerable PD when new. Mixed systems of discharge-free and discharge-resistant cable designs can be especially challenging.

This method is attractive; as all discharge-free cable and many accessories are PD tested at the factory prior to shipping. As such, they are PD free as defined in the appropriate IEC, ICEA, and IEEE standards. Therefore, any additional PD detected in service must be due to problems caused by installation or defects that develop over time. However, it is important to be aware that there are no industry recognized testing procedures or PD limits for PD tests conducted on complete cable systems installed in the field.

Consequently, although appealing, there are some limitations to PD testing in the field, they are as follows:

- Factory and field tests use different approaches.
- In factory tests, components are tested separately (cable, terminations, and joints), while field tests *de facto* involve the complete cable system.

- Different field test environments impose a number of complications that must be addressed in order to yield acceptable results.
- Different cable system length scales (HV and EHV systems can be many miles long with a large number of joints).
- Interaction and impact on PD signals from cable system components are not completely understood.
- Different measurement approaches generally detect the same PD sources but quantify them differently.

8.2 How it Works

A high voltage is applied to the cable system. If conditions are right at the void location, a partial discharge (i.e. a discharge across the void) occurs. The PD measurement equipment detects transient millivolt or microampere level signals generated at the discharge site that travel through the cable to the detection equipment. The exact shape and bandwidth of these pulses depends on the discharge source, frequency response of the cable system, relative locations of the discharge source and detection equipment, and frequency response of the measurement equipment. Each of these elements alters the shape of the original PD pulse. The PD pulses themselves must then be separated from ambient noise signals. The available PD instruments are classified by bandwidth as they can have bandwidths of hundreds of kilohertz (narrow band and wide band according to IEC Std. 60270 – 2000) to up to 100 MHz (ultra-wide bandwidth (UWB)).

Figure 1 shows the commonly used equivalent circuit to describe PD measurements. The capacitances (C) are identified by the subscripts *a*, *b* and *c*. C_a represents the capacitance of an element of power cable that does not contain a defect. C_b and C_c represent an element of cable that contains a void defect, where C_c is the capacitance of the void and C_b represents the remnant cable element capacitance. S_g is the spark gap that represents the discharging defect/void.

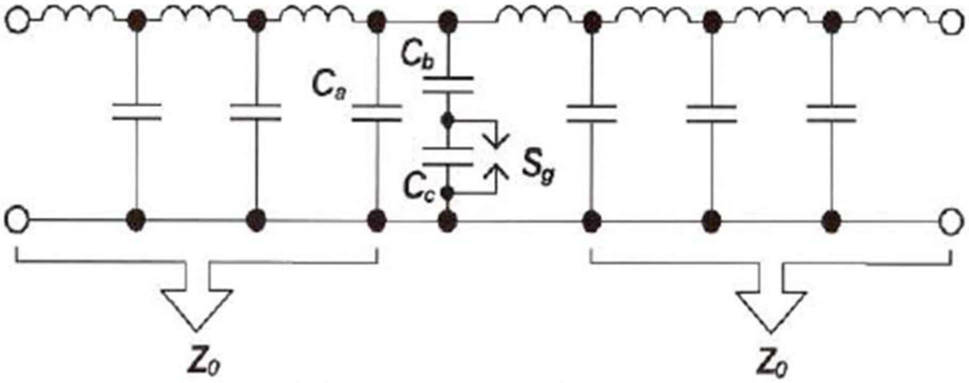


Figure 1: Equivalent Circuit for Power Cable PD [16]

It is important to consider that the capacitances *b* and *c*, and thus the charge generated in the measurement circuit, will depend upon the radial position of the void within the cable. This is because the capacitances depend upon the relative amount of insulation on either side of the defect.

Copyright © 2016, Georgia Tech Research Corporation

Although outside the scope of this project, a brief discussion on the physics of discharges in voids is included to help users better understand the complexity of this test. PD is a Townsend discharge in a small cavity (a gas ionization process where, initially, a small number of free electrons, accelerated by a sufficiently strong electric field, results in electrical conduction through a gas by avalanche multiplication). The stress at which the discharge initiates (V_{PD}) is described by Paschen's Law, where the critical parameter is the product of the void size [diameter *d*] and the internal pressure [*p*]; β and χ are constants related to the gas within the void.

$$V_{PD} = \frac{\beta \cdot p \cdot d}{\chi + \ln(p \cdot d)} \qquad \textbf{Equation 1}$$

The Paschen Equation identifies a number of fundamental issues that the cable system engineer using PD testing must understand:

- Discharges only occur in gaps – PD testing can only find voids, not contaminants unless they subsequently debond from the insulation, thus leaving a void.
- Voids need to satisfy three further conditions to discharge:
  - They must not be completely filled with a liquid.
  - If they are gas filled, then the gas must be at a low enough pressure for the discharge initiation stress to be at or below the test stress. See Figure 2.
  - They must be large enough; small voids require higher initiation stresses (Figure 2).

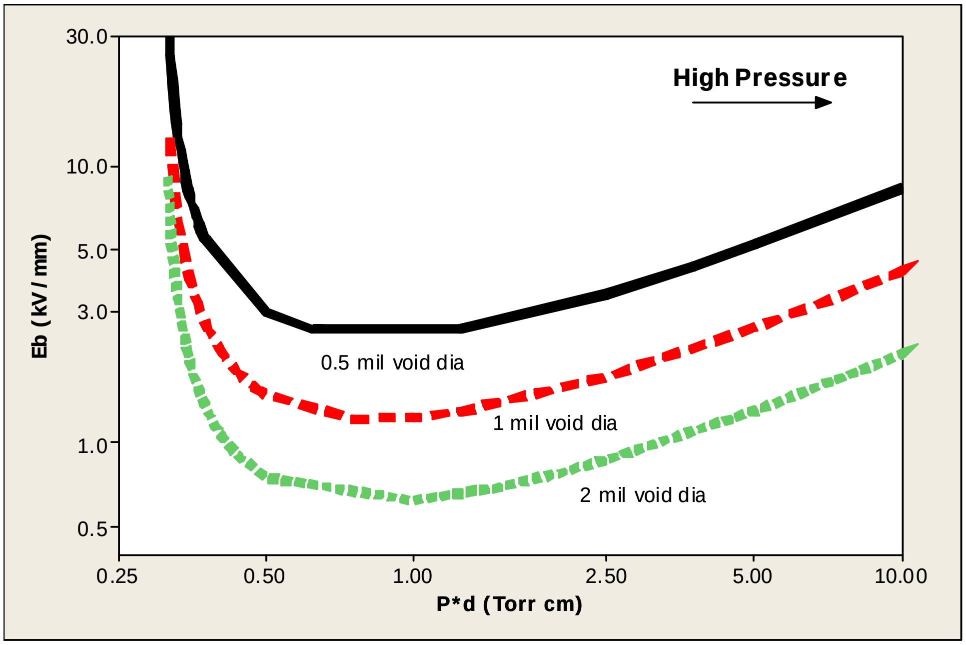


Figure 2: Theoretical Paschen Curves for Air-Filled Voids (Selected Void Sizes)

When measuring PD, three prerequisites must be satisfied during the measurement period:

- The voids must be in a state that allows them to discharge,
- The voltage must be high enough to initiate the discharge (inception voltage), and

- The PD signal must reach the detector in a suitably un-attenuated, undispersed state to be recognizable as PD signals with respect to the background noise.

Addressing the first point, PD is a stochastic (probabilistic) process. It may or may not be present at a void depending on all the parameters and conditions described above. Thus if no PD is detected, it can mean either that no voids are present or that a void is present but that that conditions are not right for it to discharge. This is significant for short measurement times and the risk of "false negative" results should be recognized.

A number of technical articles have described instances where PD pulses (at most a few nanoseconds wide) spread and reduce in magnitude as they propagate away from the PD source as a result of high frequency attenuation in the cable due to dispersion (frequency-dependence of the propagation velocity) [16]. The loss of high frequency energy from the PD pulse reduces its magnitude and distorts its shape. This can make it difficult to acquire the PD pulses and accurately identify the source and type of the PD.

8.3 How it is applied

PD testing can be performed online and offline [2 - 29]. Online techniques typically employ high frequency current transformers (CTs) or capacitively coupled voltage sensors to detect transient signals from discharges.

Offline voltage sources can be:

- 10 – 300 Hz AC: Equipment typically consists of an excitation transformer connected in series or parallel with a variable inductance reactor. The equipment is heavy and requires a truck or van.
- 0.01 – 1 Hz (nominal) ac Offline Very Low Frequency (VLF): Equipment is relatively light and portable compared to ac resonant systems but may act as an additional source of noise. Waveform used is sinusoidal.
- Damped AC (DAC): Equipment is relatively light and portable. The applied voltage is a damped sine wave with a frequency range of 30-500 Hz, though frequency varies with cable length and can, in some cases, be tuned with an external element (capacitor).

Most offline techniques apply $1.3U_0$ to $1.7\ U_0$, where U_0 is the operating phase-to-ground RMS voltage of the circuit.

Field PD results may be reported in terms of:

- Customized indicators (mV or mV·s).
- Scaled charge magnitude (pC) at a given test voltage level.
- Estimated PD source location(s).
- Inception voltage (voltage magnitude at which discharge initiates as the voltage is increased).
- Number of pulses per unit time.

- Frequency content of the PD pulses.
- Phase relationship of the PD pulses to the applied voltage (Phase-Resolved PD Pattern).

PD measurements are influenced by the type and location of the defect or defects, operating and testing voltage magnitude, circuit operating conditions, type and number of joints, ambient noise, and other factors discussed earlier. Therefore, accurate interpretation of the PD data requires sound knowledge of temporal (time dependency) PD behavior.

The application of high voltages for a long period (cycles or time) may cause some level of further degradation of an aged cable system. Consider this potential degradation when performing any diagnostic test requiring the application of voltage above the operating voltage. The precise degree of degradation will depend on the voltage level, frequency, and time of application. Thus, when undertaking elevated voltage PD measurements (or any other elevated voltage test), a utility should consider that a failure might occur and resources may be needed to make repairs. The section on expected outcomes in the *CDFI* Perspective provides insight on the likelihood of failure on test.

The advantages and disadvantages of different approaches to PD testing appear in Table 1 and Table 2 as a function of voltage source used to perform the test. In general, all techniques require skilled personnel for testing and interpretation. Table 3 shows the overall advantages, disadvantages, and open issues for PD testing.

Copyright © 2016, Georgia Tech Research Corporation

Table 1: Advantages and Disadvantages of Online PD Measurements as a Function of Voltage Source

Source Type	Advantages	Disadvantages
60 Hz AC Voltage Supplied by Utility System (De-energizing not needed)	• No non-system energization equipment is required. • Testing wave shape and frequency are the same as the service voltage. • The cable circuit is not de-energized as part of the test. • It is relatively easy to monitor over an extended period (10 to 60 minutes or longer) so that PD sites are more likely to discharge and be detectable. • Test may be performed while the cable system is at normal operating temperature (maintenance tests only).	• Cannot detect PD that would occur at voltages above normal operating voltage. • Sensitivity assessment typically not possible. • Requires a skilled technician to acquire the data and a skilled engineer to interpret the results. • Detailed assessments are not available for several days to weeks. • Sensors must be applied at every cable accessory (either sequentially or simultaneously) and at each end of the tested cable circuit segment. • In most approaches, PD sites in cable are not specifically located. They are only identified as occurring between two sensors or at a sensor on an accessory. • In some approaches, results are reported as levels - the specific meaning of each level is difficult to interpret. • Cannot be combined with other diagnostic tests.

Table 2: Advantages and Disadvantages of Offline PD Measurements as a Function of Voltage Source

Source Type	Advantages	Disadvantages
Power Frequency AC (10 – 300 Hz)	• Testing wave shape and frequency are close to the operating voltage and factory test voltage. • Sensitivity assessment can establish the lowest detectable partial discharge level. • Voltages above U_0 can be applied, allowing for the detection of PD that is typically not present at U_0. • Apparent PD inception voltage may be measured. • Withstand test can be performed simultaneously.	• Equipment is large, heavy, and expensive. • Application of elevated voltage (> U_0) may cause further degradation. • Results are reported in levels or voltages - the specific meaning of each level is difficult to interpret or re-interpret later.
0.01 – 1 Hz AC Very Low Frequency (VLF) Sinusoidal External Voltage (Offline)	• Equipment is smaller than ac resonant systems. • Voltages above U_0 can be applied, allowing for the detection of PD that is typically not present at U_0. • Apparent PD inception voltage may be measured. • Withstand test can be performed simultaneously.	• Application of elevated voltage (> U_0) may cause further degradation. • Does not replicate operating voltage wave shape or frequency. • PD behavior is not well understood at these frequencies. • Difficulty syncing with voltage waveform when phase-resolved data is needed. • Special filtering needed for VLF generators
Damped AC (DAC) (30 Hz to 1 kHz)	• Voltage source and PD acquisition are integrated in a single unit. • Straightforward to use.	• Only the first voltage cycle is controlled. • Does not replicate operating voltage wave shape or frequency. • Comparisons between circuits are difficult because the applied voltage frequency varies as a function of the circuit impedance characteristics. • PD behavior is not well understood when using decaying voltage waveform. • Difficult to define consistent PD test process. • Few cycles during which to detect PD. • Does not included integrated withstand approach.

Table 3: Overall Advantages and Disadvantages of PD Measurement Techniques	
Advantages	• Identifies single or multiple localized void-type defects. • Applicable for all cable and accessory designs. • If PD test interpretation indicates that cable circuit is PD-free then there is a high probability that the circuit will not fail within the next several years. • Offline techniques allow for the detection of PD at voltages above U_0. • Can detect electrical trees, interface tracking, and voids. • Basic results available at end of test. • Test can be stopped if "unacceptable PD" is observed.
Open Issues	• It is unknown whether cycles or time at elevated voltage is the critical parameter in determining the risk of damage to the cable system. • PD results on cable systems are not directly comparable to the factory test results on the individual components. • Different providers perform PD measurements using different measurement methods, sensors, measurement frequencies, bandwidth, metrics, and sensitivity assessment. Results from different PD providers/equipment are difficult to compare. • Locating PD sources can be difficult because of noise, attenuation, dispersion, cable accessories, and cable system complexity. • Voltage exposure (impact of voltage and time on cable system) caused by elevated 60 Hz ac, DAC, and VLF has not been established.
Disadvantages	• Cannot detect all possible cable system defects – only those that discharge and are detected by the measurement equipment.

8.3.1 Partial Discharge Sensors

Two groups of sensors are used for PD measurements, they are as follows:

- **Sensors for PD detection:** transducer that responds to an input PD quantity by generating a functionally related output usually in the form of a mechanical or electrical signal.
- **Sensors for PD synchronization:** transducer that detects the energizing high voltage and provides a low voltage electrical signal.

Partial discharge measurements are most commonly performed using both sensor types.

A variety of PD detection sensors are available:

- **Capacitive:** The PD signal is detected through a capacitive divider (two or more capacitors in series). This type of sensor can be used for both detection and synchronization by using a power separation filter. It is primarily used for offline measurements although it is technically possible to use in online measurements as well in the form of a sheath sensor. Some accessories will include internal capacitive sensors than is accessible from the accessory housing.

Copyright © 2016, Georgia Tech Research Corporation

- **Inductive:** The PD signal is detected through the induction principle most commonly in the form of a high frequency current transformer (HFCT). This type of sensor can also be used for online and offline application. In addition, as no connection is required with the high voltage terminal, the use of inductive sensors is practical and easier to deploy than high voltage capacitive sensors.
- **Piezoelectric:** Partial discharges generate micro explosions that mechanically propagate through the cable system and may be detectable. In this case the sensor is deformed by the wave and the deformation generates an electrical signal.
- **Acoustic:** Similar to the piezoelectric sensor, the acoustic sensor detects the sonic wave that propagates through the surrounding air/soil and converts this to an electrical signal.

Although all four types of PD sensors are applicable, the more commonly used are capacitive and inductive sensors. The reasoning behind this is that detection via electrical measurement (either voltage or current) is the most direct means of quantifying PD. Consequently, electrical measurement is also the only means of providing some estimation of the PD magnitude. The piezoelectric and acoustic sensors can only provide an indication that PD is present and, generally, the sensor must be located near the discharge site to be effective. This in itself causes accessibility issues and would limit applicability to terminations, riser cable sections, and accessories in vaults/manholes. On the other hand, piezoelectric and acoustic sensors may also be combined with capacitive and inductive sensors to improve PD source location.

Table 4 shows illustrative pictures of all the different types of sensors for PD detection.

Table 4: Different Types of Sensors for PD Detection	
Type	**Illustrative Image**
Capacitive – Capacitive Coupler PD and Synch signals	
Capacitive – Direct Coupler PD signal	
Inductive – High Frequency Current Transformer (HFCT) PD signal	
Piezoelectric	
Acoustic	

Two voltage synchronization sensor types are available:

- **Capacitive:** The synchronization signal is detected through a capacitive divider (two or more capacitors in series). This type of sensor can be used for both PD detection and synchronization by using a power separation filter. It is primarily used for offline measurements although it is technically possible to use in online measurements as well. Because it connects with the high voltage terminal, the sensor must be able to withstand test voltages.
- **Inductive:** The PD synchronization signal is obtained by the sensor through the induction principle. The most common device here is the Rogowsky Coil. The Rogowsky coil detects the current flowing in the cable system and generates a corresponding voltage signal. It is necessary, therefore, to adjust the signal phase from the Rogowsky Coil to account for the

phase difference between the current and energizing voltage to provide the correct voltage reference. This type of sensor can be used for online and offline applications.

Table 5 shows examples of all the different types of sensors for PD synchronization.

Table 5: Different Types of PD Sensors for Synchronization

Type	Example
Capacitive – Capacitive Coupler PD and Synch signals	
Inductive – Rogowsky Coil Synch signal	

It is important to mention that PD synchronization can also be accomplished by an external signal if available. For example, the energizing voltage source may include a low voltage output that could be used as a synchronization signal. In the case of online measurements, some PD instruments can use an internal synchronization signal generated from its ac source. However, care must be taken when using this approach because the phase difference between the external synchronization signal and the PD test voltage must be properly determined to allow for noise-PD signal separation.

Copyright © 2016, Georgia Tech Research Corporation

8.3.2 Partial Discharge Source Location

Before conducting PD measurement in the field, the location of the cable system joints should be determined so that PD signals originating from accessories can be distinguished from those coming from the cable. Most HV and EHV cable systems have significantly high attenuation characteristics such that signals from adjoining accessories are not detectable. This causes significant issues in MV cable systems; however, at HV and EHV this is an advantage. In general, a sensor is temporarily installed at each accessory location and so any signals detected at that accessory location are assumed to be only from that accessory or the nearby cable.

In the case of terminal only measurements, the TDR is performed off-line. Once the joint locations are known, the PD source location can be performed. There are two approaches used:

- Location using PD data in time-domain and
- Location using PD data in frequency-domain.

In both approaches, PD instrument bandwidth on the order of several megahertz is necessary to provide a reasonably precise location along the conductor length.

Each of the PD source location approaches is discussed following sections.

8.3.2.1 Source Location in Time-Domain

This approach is based on the same principle as TDR and is illustrated in Figure 3.

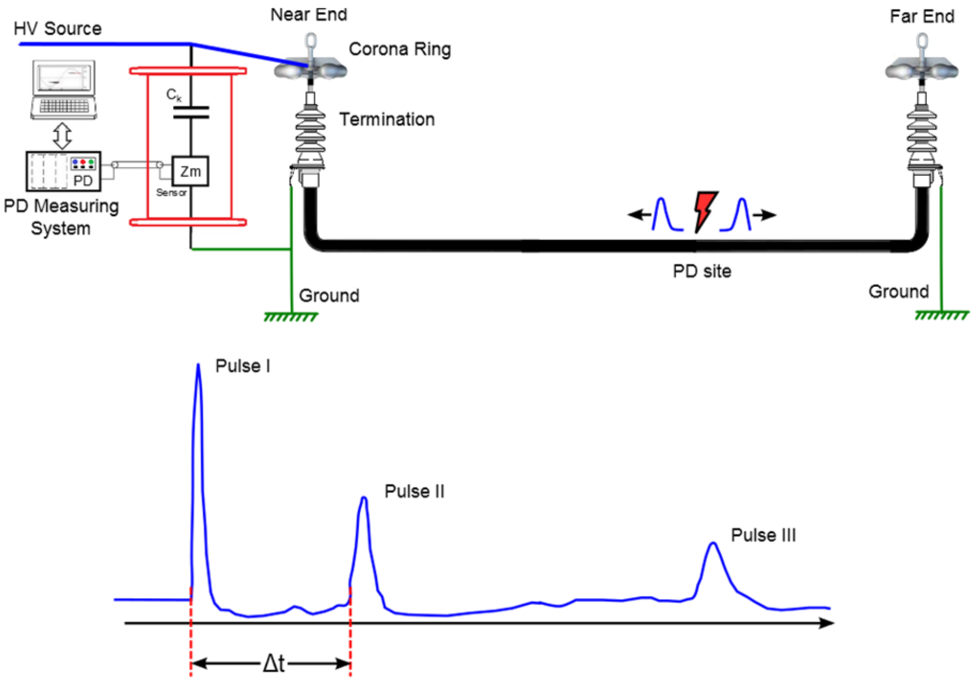


Figure 3: Illustration of PD Location in Time Domain

As shown in Figure 3, the energizing voltage and the PD detection equipment are located at the near end of the cable system. A discharge event occurring at a source located somewhere within the cable system generates a pulse that then splits into two pulses that travel in opposite directions along the circuit. The PD pulse travelling directly to the near end is acquired first as Pulse I. As time passes, the pulse travelling towards the far end is completely reflected at the far end back to the near end where it is acquired as Pulse II. Using the difference between the arrival times of Pulse I and Pulse II (Δt), the total length of the circuit, and the speed of propagation the location of the PD source along the conductor length can be estimated.

Additional reflections may be recorded. Pulse III in Figure 3 represents the round trip (near-far-near ends) Pulse I takes through the cable system after reflecting off the near end.

This method may also be used in cases where multiple synchronized sensors are deployed along the circuit. In this scenario, the PD source location is determined by analyzing the arrival times of the pulses at each sensor. This is particularly useful on branched and extremely long cable systems and it assumes accessibility to the locations of interest where the PD sensors (usually HFCTs) are to be deployed.

8.3.2.2 Source Location in Frequency-Domain

PD source location using frequency domain data can be performed for both offline and online approaches. This method uses the calculated frequency components of the PD pulse and the fact that the energy signature of a PD pulse as a function of its frequency components is highly correlated to the distance from the PD source. The calculated energy is higher at sensors locations near the PD site. By examining the energy signatures measured at each sensor location, an approximate PD source location can be determined.

The accuracy of this technique can be influenced by two factors, they are as follows:

- Distance between two consecutive sensors – shorter distance between sensors improves accuracy because changes in PD pulse energy versus distance can be better estimated.
- PD sensor frequency range – greater bandwidths result in improved accuracies because a wider frequency range is used to estimate the energy and thus its changes with distance can be better observed.

8.3.3 Laboratory and Field Testing

Partial discharge tests are generally classified into two categories: laboratory and field tests. Each category has different objectives and issues. The categories are determined by the location at which tests are performed. Each of the categories covers different test types. The relationship between test types and the test categories is in Table 6.

Table 6: Relationship between Test Types and Test Categories for PD Measurements

	Laboratory	Field (On site)
Test Type	• Routine / Production • Qualification • Sample	• Commissioning • Maintenance

To better explain Table 6, each test type is described in detailed as follows:

- In the laboratory category:
    - **Laboratory Testing:** Tests that are carried out on new or aged accessories and cable together as a cable system to study the interactions between them from a research perspective. The research is commonly focused on investigating design issues and/or estimation of the aging and degradation mechanisms that a cable system as a whole experiences during its service life.
    - **Factory Testing:** Tests carried out on new accessories or cable separately to verify that they comply with industry standards. Tests are performed routinely as part of the production line.
    - **Qualification Testing:** Industry standard tests completed to ensure the effectiveness of the manufacturing processes, equipment, and procedures used to produce cable system components for field use.

- In the field (on site) category:
    - **Commissioning:** Tests deployed to check the integrity of the individual components (cable and accessories) and their interfaces and the cable system as a whole including damage that may had been occurred during installation and/or workmanship issues.
    - **Maintenance:** Tests intended to detect deterioration and to verify the serviceability of cable systems that have been operated in service for some period of time.

The deployment conditions for laboratory and field PD test categories are different; the goal of each test type differs from one another and more importantly the factors that influence PD measurements for each of them may vary significantly. A basic understanding by utility engineers of each PD test type is important. Therefore, Table 7 aids on the understanding by comparing laboratory and field PD tests.

Copyright © 2016, Georgia Tech Research Corporation

Table 7: Overall Comparison of Laboratory and Field PD Tests

Laboratory Tests

- Cable and accessories tested together as a short cable system.
- Focused on investigating design issues and aging and degradation mechanisms.
- Focused on new systems.
- Performed under controlled conditions of noise, grounding, temperature, accessibility, etc.
- Short systems allow for lumped equivalent circuit modeling.
- Conventional and Non-conventional measurements can be deployed.
- Does not replicate operating environment.
- New systems – presence of PD indicates cable, accessories, or interface design/installation issues.

Factory Tests

- Only new cables and accessories tested separately.
- Focused on identifying cable system components that comply with industry standards for maximum discharge magnitude.
- Performed under controlled conditions of noise, grounding, temperature, accessibility, etc.
- Long cable runs are modeled by a lumped equivalent circuit.
- Only conventional measurements are deployed.
- Performed routinely as part of the production line.
- Does not replicate operating environment.
- PD magnitudes that exceed requirements cause components to be examined more thoroughly.

Qualification Tests

- Only new cables and accessories tested as part of a cable system.
- Generally performed before full-scale production begins.
- Ensures the effectiveness of the manufacturing process, equipment, and procedures.
- Allows independent evaluation against industry standards.
- Focused on PD detection and location.
- Performed under controlled conditions of noise, grounding, temperature, accessibility, etc.
- Short cable length allows for lumped circuit modeling.
- Only conventional measurements are deployed.
- Does not replicate operating environment.
- Presence of PD can indicate design, compatibility, or installation issues.

Commissioning Tests

- Complete cable system that is tested prior to beginning its service life.
- Focused on PD detection and PD source location.
- Performed under uncontrolled test conditions of noise, grounding, temperature, accessibility, etc.
- Long systems require distributed impedance circuit modeling.
- Attenuation, dispersion and reflections cause PD signal degradation that affects the measurements.
- Conventional and Non-conventional measurements can be deployed.
- Presence of PD could indicate design, after-laying, and/or workmanship issues.

Copyright © 2016, Georgia Tech Research Corporation

Table 7: Overall Comparison of Laboratory and Field PD Tests
• Generally performed at test voltages above normal operating voltage.
Maintenance Tests
• Complete cable system that is tested at some point during its service life. • Focused on detecting and localizing PD sources with some assessment of severity. • Done under uncontrolled test conditions of noise, grounding, temperature, accessibility, etc. • Long systems require distributed impedance equivalent circuit modeling. • Attenuation, dispersion and reflections cause signal degradation affecting measurements. • Conventional and Non-conventional measurements can be deployed. • Presence of PD could indicate design, degradation, or installation issues.

As factory and laboratory testing are familiar to many engineers involved in cable system diagnosis the tendency has been to try and transfer criteria for factory and laboratory tests to field testing. However, these criteria cannot be directly applied to field tests as the underlying assumptions used in factory and laboratory tests are no longer valid.

8.4 Success Criteria

As mentioned above, PD results may be reported in a number of ways. However, many providers of PD testing services prefer not to supply detailed PD data. They suggest that interpretation of the test results requires analysis of charges, voltages, pulse shapes, pulse frequencies, etc. that is best undertaken by the provider. Instead, they process the data to identify any discharge activity and to locate its source within the cable system. In principle, there are two main classes: Pass – no action required and Not Pass – action required. As most of the HV and EHV partial discharge tests are performed as commissioning tests, the presence of discharge activity is in itself sufficient to classify the circuit as Not Pass. The industry as a whole has been able to reach this level of agreement while specific severity levels for discharge activity remains proprietary.

Criteria for PD levels are available in standards for use during qualification and design tests as well as production tests. However, these criteria are intended to be used under specific conditions that are rarely achievable under field conditions. Furthermore, the measurement equipment used in field tests are designed with wider signal bandwidths and advanced signal processing algorithms that are simply beyond the scope of the available standards documents.

8.5 Estimated Accuracy

As discharge activity is generally eliminated after detection as part of the commissioning / recommissioning process, accuracy data cannot be estimated for PD tests on HV and EHV cable systems.

8.6 *CDFI* Perspective

Partial discharge is useful for cable system commissioning because it is the technique that has the most potential to provide a localized assessment of the cable system. Although PD tests cannot identify the presence of all defects that can impact the life of a cable system, they can detect "void-type" defects that are most likely to put at risk the life of an HV or EHV cable system.

As a consequence, at HV, PD technologies are generally deployed on new or recently installed assets/systems as part of a commissioning test prior to entering service. The PD at commissioning test is generally undertaken as a Monitored Withstand test (i.e. simple withstand and PD combined). The goal is to provide assurance to the installer and the user that the system does not contain defects or installation errors. Hence, PD technologies implemented at HV/EHV strive to identify the presence and likely location of PD. Little effort is made to make a judgment of the severity of any detected signals. The basic assumption is that HV and EHV cable systems should be PD free at the start of their service lives.

One of the main goals of this section is to help users understand field PD measurements techniques on HV and EHV cable systems. The issues are many and diverse, during *CDFI Phase II* we identified the most crucial characteristics and limitations of PD measurements; the most important of which are listed below:

1. Technologies are generally deployed on new assets, i.e. oriented to commissioning testing. See section 8.6.4, 8.6.5, & 8.6.8.
2. Field measurements cannot be correlated to laboratory / factory test results. See sections 8.6.1, 8.6.2, 8.6.3, 8.6.5, & 8.6.6.
3. Measurements are carried out as part of an ac Monitored Withstand protocol (i.e. simple withstand and PD combined). a) ac withstand {$1.7U_0$ for 60 min} combined with b) PD tests {PD checks at 0.5 U_0, U_0, and 1.5 U_0 on ramp up and monitoring throughout the withstand portion} are commonly deployed and effectiveness is supported by international data. See sections 8.6.4 & 8.6.5.
4. The aim is to detect the presence and location of PD – the magnitude is generally not of interest. See section 8.6.4, 8.6.5, & 8.6.8.
5. Systems are long and have complicated architectures (laboratory/factory tests assume short lengths and a simple architecture). See section 8.6.1 & 8.6.2.
6. Calibration commonly found in laboratory/factory tests is not valid for field tests. See section 8.6.1, 8.6.2, 8.6.6, & 8.6.11.
7. PD signal deterioration is significant and unavoidable, this imposes limitations on the range of detection (i.e. how far can be seen into the cable system). Hence, only terminal (tests from one end) are rare while distributed measurements (measurements at each accessory – joint hopping) are most commonly used. See sections 8.6.1, 8.6.7, 8.6.9, and 8.6.10.
8. Tests, analysis and reporting are orientated towards establishing the absence of PD from a single test, though multiple PD technologies may be used (trending or comparison with an identifiable benchmark are rare). See section 8.6.4 & 8.6.5.
9. Results showing the absence of PD obtained from different PD technologies can be collated. See section 8.6.3, 8.6.5, & 8.6.8.
10. Trending/repeat tests are rarely carried out. See section 8.6.4, 8.6.5, & 8.6.8.

Due to the issues and limitations above, the information in this Chapter provides the user with an increased awareness of PD measurements on HV and EHV cable systems rather than a detailed explanation of how to conduct tests or analyze data.

During *CDFI Phase II*, a number of laboratory PD tests on HV and EHV cable systems were conducted in conjunction with analyses of a number of HV/EHV PD (Monitored Withstand) data sets. These tests and analyses have enabled the development of the perspective presented here. The *CDFI* perspective is based on knowledge gained from specific hands-on activities that are listed as follows:

- Gather and analyze experience (NEETRAC & others) with PD testing of HV/EHV cable systems, with respect to test methods, equipment, and results– primarily in the form of commissioning tests.
- Conduct laboratory tests to assess and support field test processes and procedures.
- Recommend practices to enhance field PD measurements (calibration, sensitivity, and range checks).
- Provide general guidelines for PD test procedures on site (voltage levels, measuring time, measuring conditions, and pass criteria).
- Understand the impact of generally acceptable requirements on the value that field PD testing on HV and EHV systems might add to a user.

8.6.1 PD Signal Characteristics and Behavior in Cable Systems

A PD current signal or pulse constitutes a displacement of electrons and positively charged ions parallel to the direction of the local electrical field. For a “void-type” defect inside the bulk dielectric insulation of a cable system, the PD current generates a time varying electro-magnetic field which permeates the bulk dielectric insulation and induces current flows on both the conductor and the metallic shield of the cable system [17].

Partial discharge pulses can be described in terms of their shapes. The typical parameters of a PD pulse are its amplitude and width. The amplitude is defined as the peak amplitude of the PD pulse; in other words, it is the maximum magnitude that the PD pulse reaches independently of its shape. On the other hand, the pulse width is generally defined as the difference in time between those points in the PD pulse that have amplitude of 50% the peak amplitude. The amplitude and width of a PD pulse are illustrated in Figure 4.

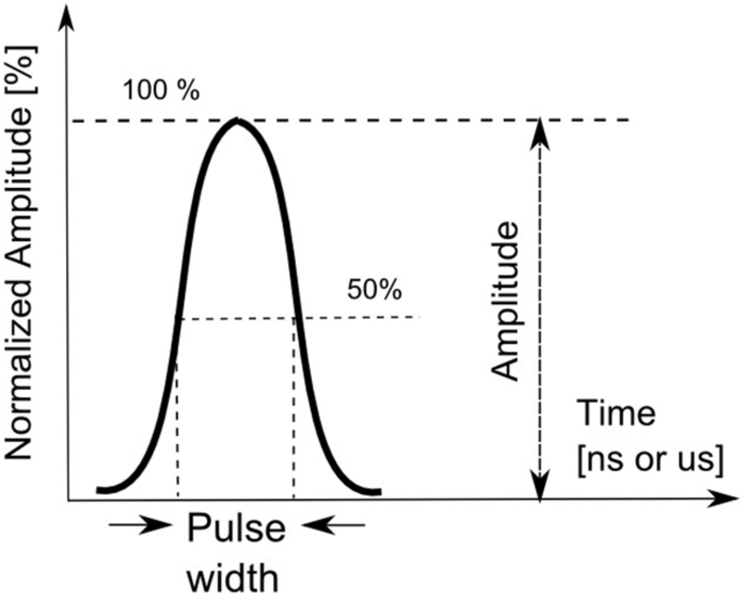


Figure 4: Typical Parameters of PD Pulse

The time-domain waveform of a PD pulse occurring within a cable system depends on the nature of the "void-type" defect and its location. However, the typical pulse width is on the order of fractions to tens of nanoseconds. Therefore, the frequency content of an actual PD pulse (at the discharge site) would be on the order of tens to several hundreds of megahertz [17]. The magnitude of the induced current depends on the strength and direction of the electromagnetic field generated by the discharge itself at the conductor and metallic shield. Thus, the magnitude of the induced PD signal on both conductors also depends upon the location of the "void-type" defect relative to the insulation and conductor screens.

8.6.1.1 Pulse Propagation

Partial discharge pulses are electromagnetic waves that propagate along the cable system. According to Maxwell's Equations, the propagation velocity is a constant and is the product of the frequency (*f*) and wavelength (λ) as shown below:

$$v = f\lambda$$

Where:

v is the speed of light within the cable system as defined by the permittivity and permeability of the insulation:

$$v_{insulation} = \frac{1}{\sqrt{\varepsilon_r \varepsilon_0 \mu_r \mu_0}}$$

$\varepsilon_0 \approx 8.854$ E-12 F/m
$\mu_0 = 4\pi$ E-7 H/m

Copyright © 2016, Georgia Tech Research Corporation

PE-Based insulation materials have permittivity and permeability ratios of 2.3 and 1, respectively. Thus, the theoretical propagation velocity inside polyethylene material is 1.98E8 m/s. Consequently, a 1 MHz (1 µs) pulse would have a wavelength of 198 m while a 1 GHz (1 ns) pulse is 0.2 m in length. The wavelength represents the physical space within the material that the pulse occupies. Cable systems include other parameters that further reduce the propagation velocity.

A cable system component can affect a pulse, the component must be similar in size to the pulse wavelength. A joint is unlikely to change the shape of a 1 µs duration pulse since the pulse is much longer than the joint length. As Chapter 5 describes, TDR pulses tend to be less than 100 ns in duration so that they are short enough in wavelength to be affected by a joint.

Unfortunately, cable systems cause a number of changes in the characteristics of propagating pulses. Suffice it to say, as the pulse propagates, its high frequency components degrade faster than those in the lower frequency ranges. For illustration, simulation results of the relationship between the PD pulse bandwidth and propagation distance from the discharge site are shown in Figure 5. These simulation results use a 15 kV 1/0 XLPE cable system with a 175 mil insulation wall.

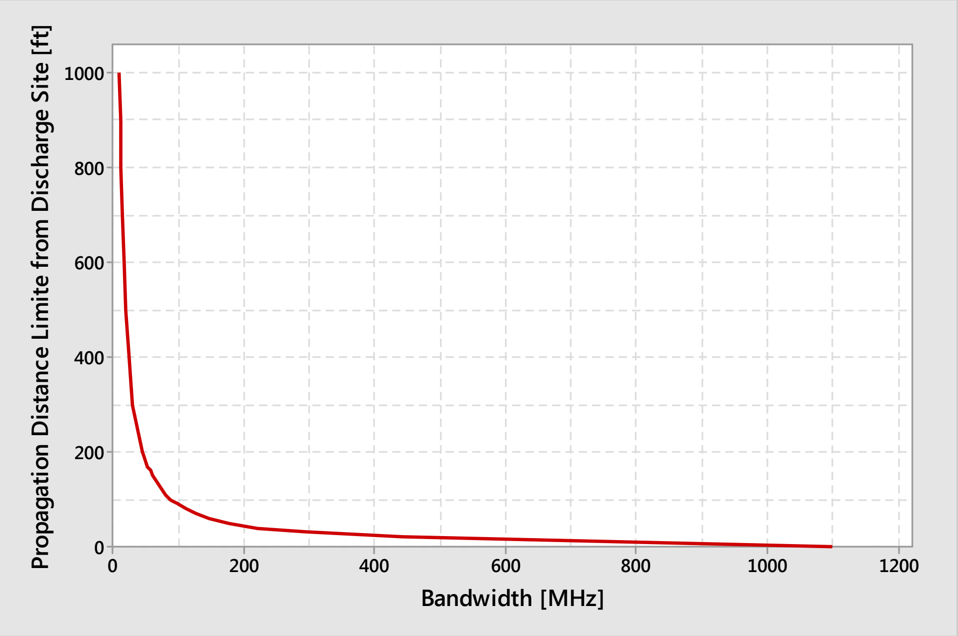


Figure 5: PD Pulse Bandwidth and Propagation Distance from Discharge Site – Linear Scale

As shown in Figure 5, the bandwidth of the propagating pulse decreases rapidly as the pulse moves away from the discharge site; as the propagation distance increases, the bandwidth seems to reach an asymptote. However, to better visualize the bandwidth behavior over all frequencies, the bandwidth axis in Figure 5 may be transformed into a logarithmic scale as shown in Figure 6. The frequency ranges for practical field measurements (yellow rectangle) and IEC 60270 (green rectangle) are included for reference in Figure 6.

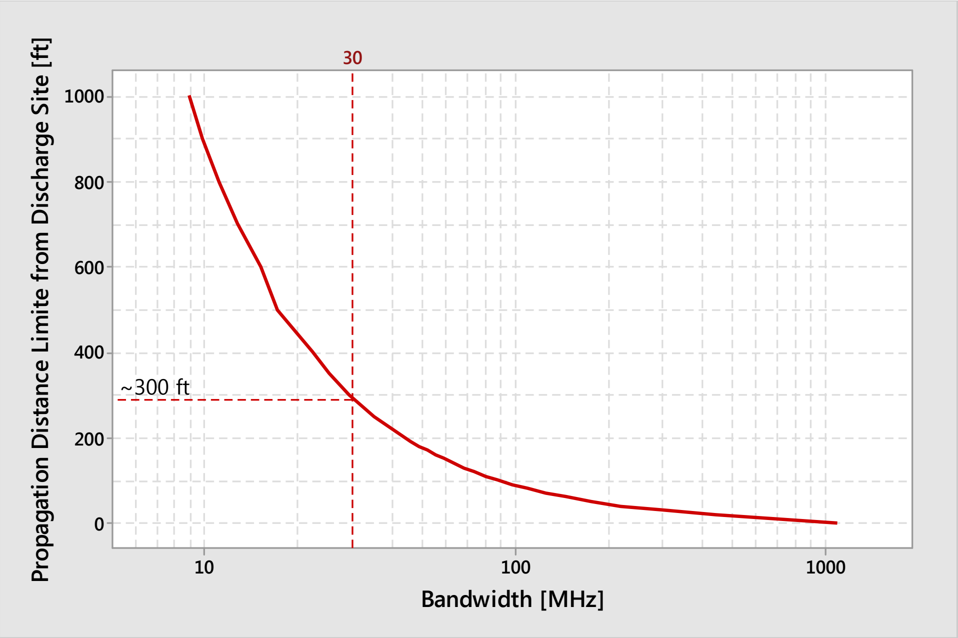


Figure 6: PD Pulse Bandwidth and Propagation Distance from Discharge Site

The most important interpretation of Figure 5 and Figure 6 is that they clearly show that the bandwidth of a PD pulse propagating along the cable system becomes limited as the PD pulse moves farther away from the discharge source.

8.6.1.2 Attenuation and Dispersion

As mentioned above, PD pulses are distorted as they propagate away from their sources. The distortion is caused by several types of cable system losses which are frequency dependent. The longer the cable system is, the greater the distortion [17]. The example in Figure 5 and Figure 6 shows that attenuation can eliminate frequencies present in the original PD pulse once the pulse has traveled short distances from the source location. This fact is used as an advantage in HV and EHV systems as the joints can be spaced far enough apart so as not to allow much signal to pass from one all the way to the next. The physical processes that characterize the changes are well known and defined: skin effect, dielectric loss, reflection and radiation [17]. These physical processes can be represented by two major sources of PD pulse distortion: attenuation and dispersion.

As PD pulses travel along a cable system, the system behaves as a “lossy” transmission line. The various physical sources for these losses can be categorized into two primary mechanisms:

1. Loss of energy (attenuation) and
2. Different propagation velocities for different frequencies (dispersion).

In addition, spurious pulses will appear that are introduced by reflections of PD pulses at the system ends and at joint locations. Attenuation and dispersion are discussed in more detail in the next paragraphs.

Copyright © 2016, Georgia Tech Research Corporation

Attenuation: Energy lost as a function of the distance traveled by the pulse and its frequency spectrum. In a cable system, attenuation is due to losses in the bulk insulation and propagation through the resistance of the conductor, neutral, and semi-conductive screens. Normally, attenuation increases with frequency; energy losses may be quite high for frequencies on the order of a few megahertz. As a consequence, fast PD pulses can only travel limited distances (because of their high frequency components) before they are attenuated to a level at which they may be hidden by the induced background noise. Figure 7 shows the relationship between attenuation per unit length and PD pulse width for a 300 ft cable system of 33 kV, 630 mm^2 conductor, XLPE cable. Note in Figure 7 that faster pulses show higher attenuation levels.

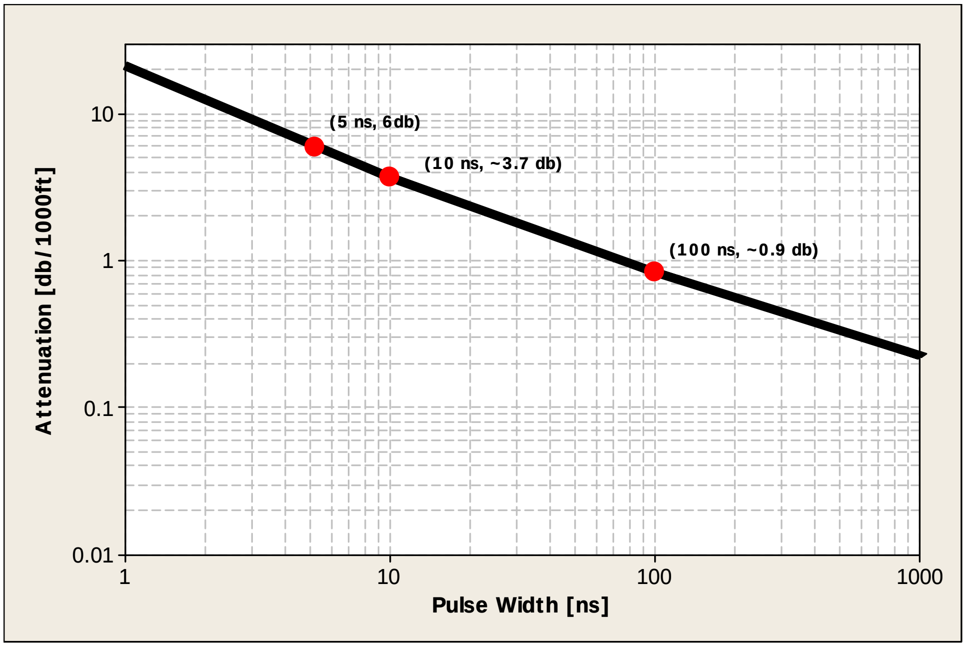


Figure 7: Calculated Attenuation as a Function of PD Pulse Width for 300 ft of 33 kV, 630 mm^2, XLPE Cable

The attenuation per unit length provides useful information regarding how far a PD pulse could theoretically travel through a cable system before being attenuated by a specified amount. For example, by analyzing the attenuation function shown in Figure 7, several observations can be made:

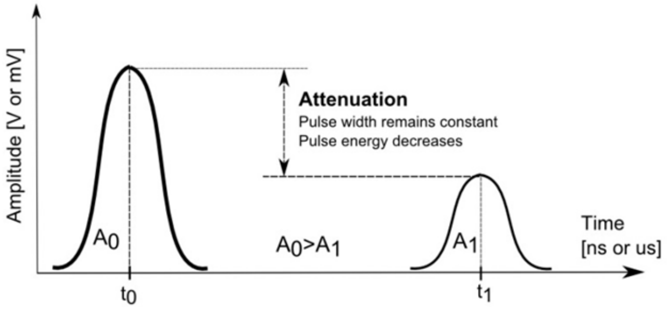
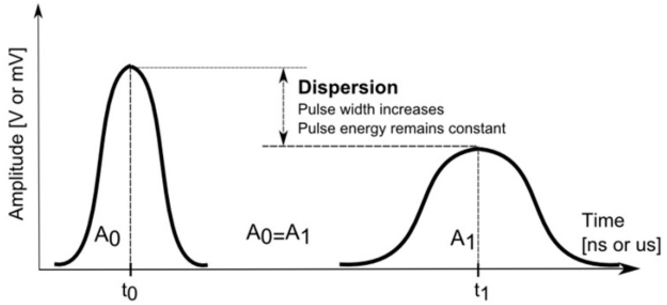
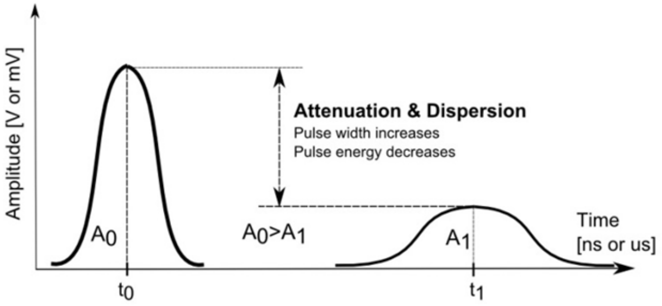
- A 5 ns PD pulse has an attenuation of 6 dB/1,000 ft; consequently, the pulse only travels 1,000 ft before losing 50% of its initial amplitude.
- A 10 ns PD pulse has an attenuation of approximately 3.5 dB/1,000 ft; consequently, the pulse travels 1,700 ft before losing 50% of its initial amplitude.
- A 100 ns PD pulse has an attenuation of approximately 0.9 dB/1,000 ft; consequently, the pulse travels 6,700 ft before losing 50% of its initial amplitude.

Even though the attenuation information is useful; generally, it cannot be considered alone. PD pulse distortion is always due to both attenuation and dispersion.

Dispersion: The velocity of a pulse through a medium generally depends on the frequency and wavelength of that pulse. As a result, different pulses will travel at different velocities and different components of a pulse will travel at different velocities as well. Since a PD pulse is composed of different frequency components, these components travel at different velocities along the cable system. This difference causes the distortion known as dispersion. The distortion can be seen as a phase shift of each of the individual frequency components of the PD pulse and generally results in lower amplitude, longer duration pulses as compared to pulse shapes at their sources. Dispersion distorts PD pulses without loss of energy.

As a rule of thumb, it can be understood that attenuation causes the loss of frequency content of the PD pulses while they are distorted and spread out in time due to the dispersion effect. Table 8 presents the cases on how a PD pulse is distorted by attenuation, dispersion, and both.

Table 8: Attenuation and Dispersion of PD Pulses

Observations	Case
Attenuation: • Reduced amplitude • Constant pulse width • Reduced energy	
Dispersion: • Reduced amplitude • Increased pulse width • Constant energy	
Attenuation & Dispersion: • Reduced amplitude • Increased pulse width • Reduced energy	

Both attenuation and dispersion of PD pulses have been observed through laboratory measurements. The observation is possible by injecting a fast voltage pulse into a non-aged 25 kV WTRXLPE cable. The pulse travels approximately 2,300 ft and its initial and final traces at the near and far ends, respectively, are shown in Figure 8 and rescaled for comparison in Figure 9.

Copyright © 2016, Georgia Tech Research Corporation

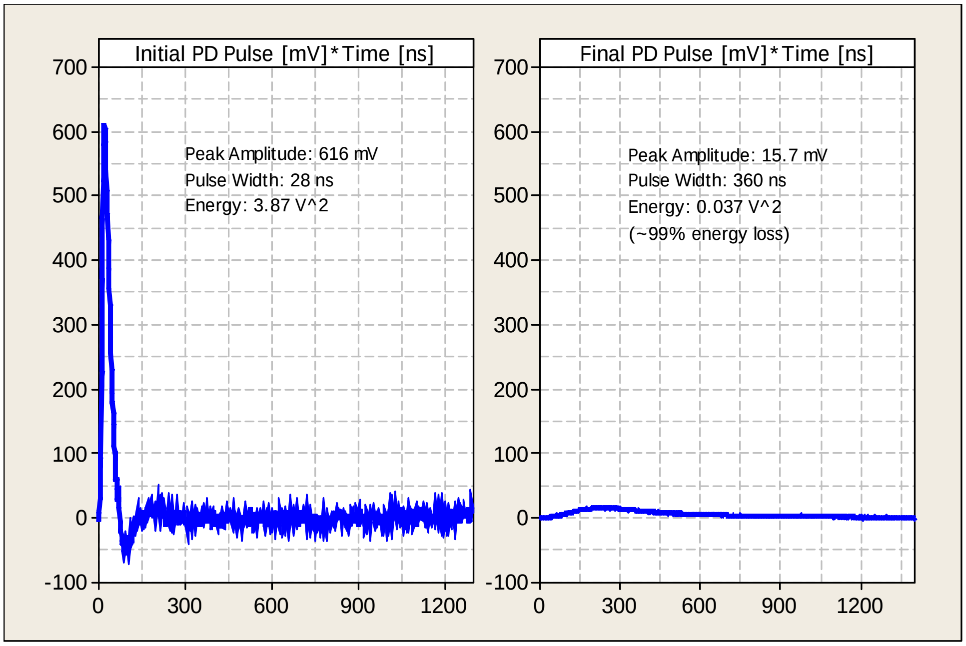


Figure 8: Laboratory Recorded Initial and Final Traces (Equal Axis Scales) of a Fast Voltage Pulse Traveling 2,300 ft along a Cable (WTXLPE – 25 kV)

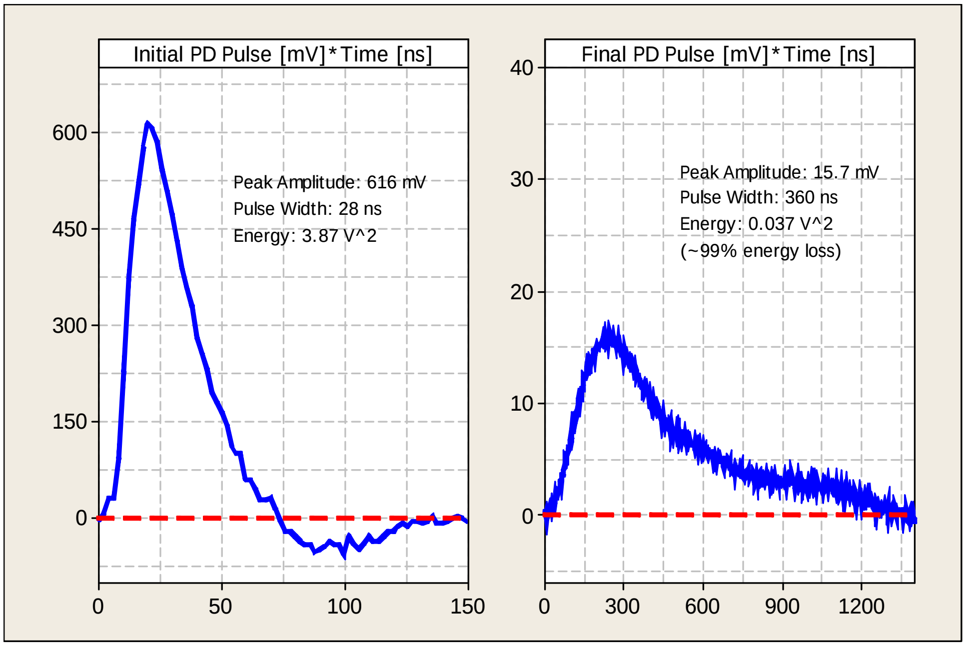


Figure 9: Laboratory Recorded Initial and Final Rescaled Traces of a Fast Voltage Pulse Traveling 2,300 ft along a Cable (WTXLPE – 25 kV)

As seen in Figure 9, the attenuation and dispersion phenomena greatly affect the pulse shape parameters; specifically, it is observed that the peak amplitude decreases from 616 mV to 15.7 mV, which represents a reduction in amplitude of approximately 30 dB over the 2,300 ft of cable length. Similarly, the pulse width increases from 28 ns to 360 ns. Regarding the change in energy, the initial pulse shows an initial energy of 3.87 V^2 while the final pulse has 0.037 V^2 of energy which represents an energy loss of 99%.

Copyright © 2016, Georgia Tech Research Corporation

8.6.1.3 Reflections from Cable System Structural Elements

In addition to deterioration from attenuation and dispersion, PD signals are further degraded as a consequence of the cable system structure (i.e. number of cable sections and accessories that compose the system). This is caused by characteristic impedance changes between cable sections and accessories that cause portions of the pulses to be reflected. These impedance mismatches occur at all transitions between cable and joints and between cable and terminations/elbows.

To illustrate the effect of reflections, two different cable system structures are shown in Figure 10 and Figure 11. The system in Figure 10 is the least complex system possible in the field: one cable length and two terminations. The second system, shown in Figure 11, adds a joint to the system shown in Figure 10.

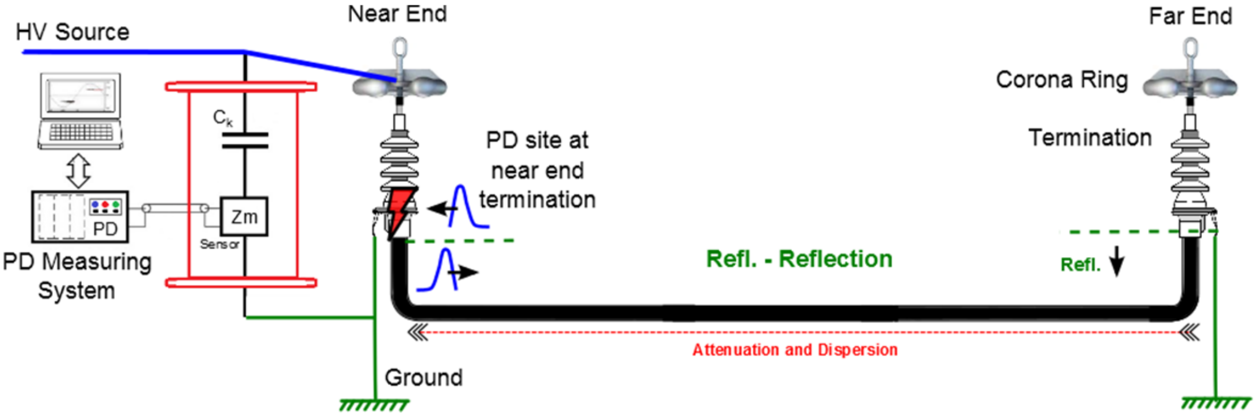


Figure 10: Illustration of PD Signal Degradation by Attenuation and Dispersion

In Figure 10, PD signal degradation results only from attenuation and dispersion (ignoring reflections off the far end termination) of PD pulses traveling from their source site along the cable system length to the detection equipment.

The signal degradation that occurs in Figure 11, on the other hand, includes attenuation, dispersion, and reflection of the PD pulse at the joint. The mismatch in characteristic impedance between the joint and cable does not allow all the PD pulse energy to transfer from one side of the joint to the other as a portion is reflected. Thus, additional signal degradation occurs and more energy is lost.

Copyright © 2016, Georgia Tech Research Corporation

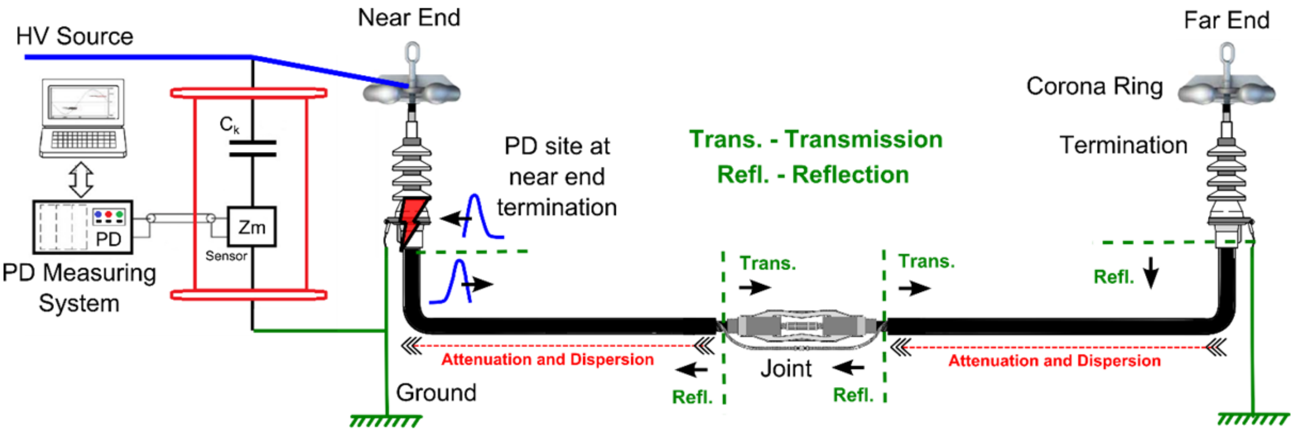


Figure 11: Illustration of PD Signal Degradation by Attenuation, Dispersion, and Cable System Complexity (Structure)

Figure 12 shows the resulting TDR trace for a PD pulse generated at the near end termination for the systems shown in Figure 10 and Figure 11. In both cases, the most important feature to consider is the amplitude of the far end reflection with respect to the initial PD pulse amplitude at the near end termination; the difference between these two amplitudes can be used as a metric to quantify and compare the signal degradation.

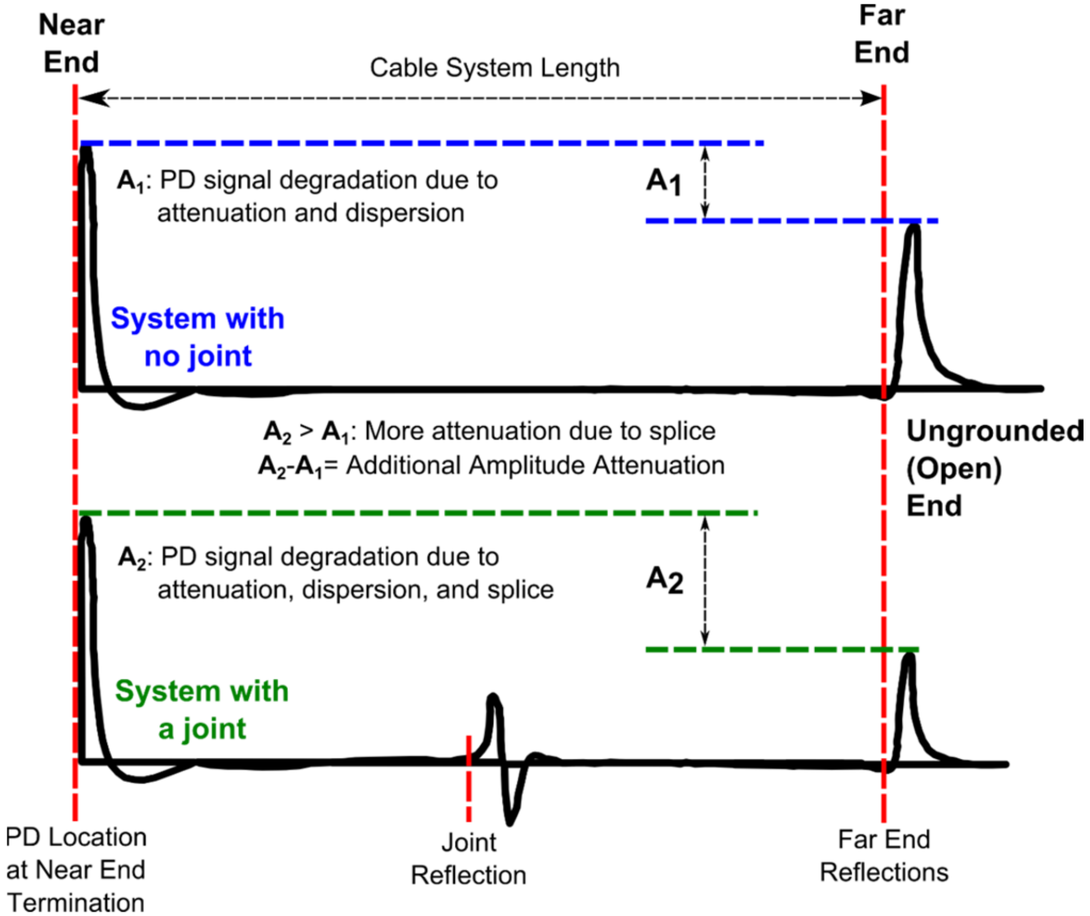


Figure 12: Impact of Cable System Complexity on Additional PD Signals Deterioration

As shown in Figure 12, signal degradation for the cable system with no joints (top Figure 12) and for the cable system with a joint (Figure 12) are quantified by A_1 and A_2, respectively. The signal degradation is worse for the system with the joint as compared to the system with cable and terminations only. Assuming that both systems have the same length, type of cable, and that the joint length is negligible when compared with the total system length, then the signal deterioration as result of attenuation and dispersion can be also assumed to be equal on both systems. Therefore, the difference between A_1 and A_2 is the result of the joint.

Users that are not familiar with this issue may tend to think that a good way around this issue would be to characterize, in some consistent way, the interactions between characteristic impedances of all different cable system components. While this approach may work, its application is only possible if all the information about cable and components is known. This process has a higher chance of success at HV and EHV than at MV. A manufacturer tends to utilize a limited number of joint and termination designs and so undertaking this process would be theoretically possible.

Ultimately, the system composition has a significant effect on the resulting pulse shapes and amplitudes so care must be taken when determining the presence or absence of PD.

8.6.2 Conventional and Non-conventional PD Measurements

At present, PD measurements are categorized as Conventional and Non-Conventional approaches. The categorization is done with respect to the frequency bandwidth of the measurement equipment used to detect and quantify the PD activity. The frequency bandwidth is typically defined by users from recommendations given in IEC 60270; specifically the standard refers to the NB (narrow-band), WB (wide-band), and UWB (ultra-wide-band) bandwidths. Conventional and Non-conventional measurement approaches relate to the bandwidths as follows:

- **Conventional PD Measurement:** Measurement methodology outlined in IEC 60270 and makes use of either NB or WB bandwidths. Results are typically reported in terms of charge magnitude (pC).
- **Non-Conventional PD measurement:** Measurement methodology that utilizes UWB equipment that is outside the scope of IEC 60270. Results can take a variety of formats but are not provided as charge magnitude. UWB is understood to be 1 MHz to 200 MHz and above. The lack of standard recommendations has consequentially led to a diverse group of commercially available equipment from multiple manufacturers and service providers.

A comparison between Conventional and Non-Conventional PD measurements categories, considering a set of important topics, is presented in Table 9.

Copyright © 2016, Georgia Tech Research Corporation

Table 9: Comparison between Conventional and Non-conventional PD Measurement Approaches

Topic	Category	
	Conventional	**Non-Conventional**
Typical Deployments	Factory Field Laboratory	Field Laboratory
Standards / Guides	• Factory – IEC 60885-3 • Laboratory – IEC 60270	IEEE Std. 400.3
Typical Approach for Measurements	Single-ended terminal measurement	
Sensor	Coupling Capacitor	Coupling Capacitor HFCT LFCT
Typical Cable or Cable System Length	• Factory – Less than 3,000 ft (~1,000 m) • Field – 50 ft to 10,000 ft (16 m to 3,300 m) with average of 300 ft (100 m) • Laboratory – Less than 300 ft (~100 m)	50 ft to 10,000 ft (16 m to 3,300 m) Average of 300 ft (100 m)
Metric for Reporting on PD Magnitude	Scaled charge – apparent charge by quasi-integration (usually in pC)	Multi-featured – amplitude of pulse in mV or area under pulse waveform (mV·s)
Measurement System Bandwidth	• Factory – $f_2^{\S} < 500$ kHz • Laboratory – $f_2^{\S} < 1$ MHz	1 MHz to 200 MHz (manufacturer dependent)
	• Narrow band (NB) – $\Delta f^{\pounds}$ =[9 kHz, 30 kHz] with $f_2^{\S} < 1$ MHz • Wide band (WB) – $\Delta f^{\pounds}$ =[100 kHz, 400 kHz] with $f_2^{\S} < 500$ kHz	
Calibration	• Factory – Injection of known charge at one end or both ends bonded together, injector must comply with IEC 60885-3 • Laboratory – Injection of known charge only at the near end, injector must comply with IEC 60270	Not Applicable
Scale Factor	Not Applicable	Used in some cases
Sensitivity Check	• Factory – Capacitive sensors are assumed to have a negligible effect • Laboratory – Capacitive sensors	Resolve minimum amplitude that can be detected

Table 9: Comparison between Conventional and Non-conventional PD Measurement Approaches

Topic	**Category**	
	Conventional	**Non-Conventional**
	are assumed to have a negligible effect if test set-up conforms IEC Std. 60270	
Performance Check	Included in the calibration procedure	Included in the sensitivity check
Range Check	Not required as it is assumed that if the requirements of the standards are met, all PD signals can be measured at the ends	Generally ignored
Background Noise	< 5 pC	No established criteria
Loss of Charge	• Factory – Loss is assumed to be insignificant • Laboratory – Conservation of charge is assumed	Not relevant

§: f_2 – upper limit frequency and f_1 – lower limit frequency
£: Δf – bandwidth (BW), $\Delta f = f_2 - f_1$

8.6.2.1 Filtering Approaches Compliant with IEC Std. 60270 – 2000

One important point to mention for conventional PD measurements is the way the required bandwidths are met. The required bandwidths can be accomplished in two different ways through filtering:

- **Analog:** The filtering is deployed as analog hardware before the signals are digitally processed (see Figure 13).
- **Digital:** The filtering is deployed in digital signal processing software (see Figure 14).

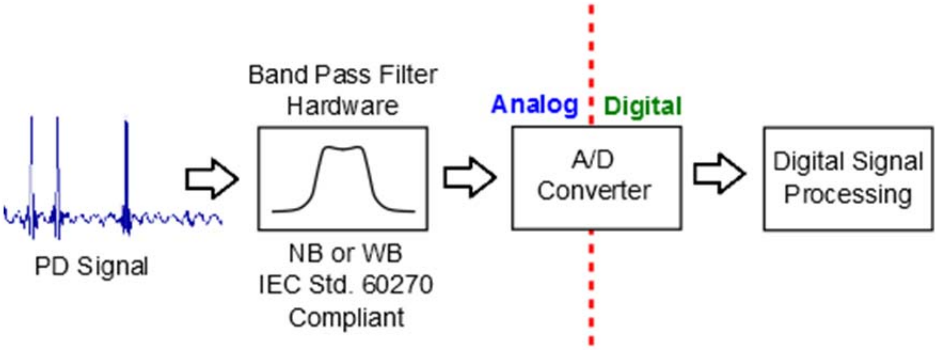


Figure 13: Conventional PD Measurements Using Analog IEC Std. 60270 – 2000 Compliant Bandpass Filter

Copyright © 2016, Georgia Tech Research Corporation

Both filtering deployments are valid and compliant with IEC Std. 60270 – 2000. However, the digital filtering deployment provides more flexibility because higher frequency components and thus sharper/faster PD pulses are captured and they may be used for an eventual PD location. PD location using NB and WB bandwidths is not possible due to the large width of the captured PD pulses; the large width directly translates to poor location resolution. It must be also recognized that the capturing of sharper/faster PD pulses requires faster A/D converters and related hardware and software, which can impact equipment cost.

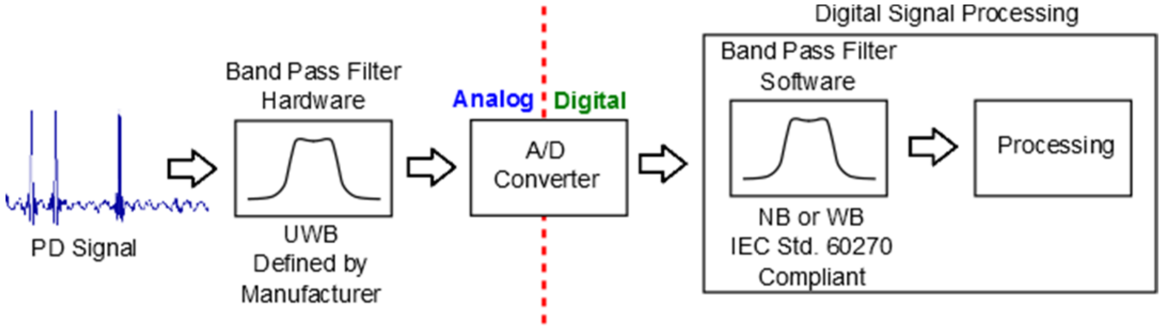


Figure 14: Conventional PD Measurements Using Digital IEC Std. 60270 – 2000 Compliant Bandpass Filter

8.6.2.2 Cable System Modeling

Partial discharge signals at their sources can include frequency components in excess of 1 GHz. In Conventional PD measurements, the calibration and interpretation procedures are based on a simplified lumped capacitive model of the cable system as shown in Figure 15. This is generally a reasonable modeling assumption at MV since the low frequencies considered by the NB and WB bandwidths have wavelengths longer than the typical tested cable system lengths. Longer lengths may be achieved with lower frequencies. Unfortunately, the electrical noise tends to increase at lower frequencies and longer cable system lengths.

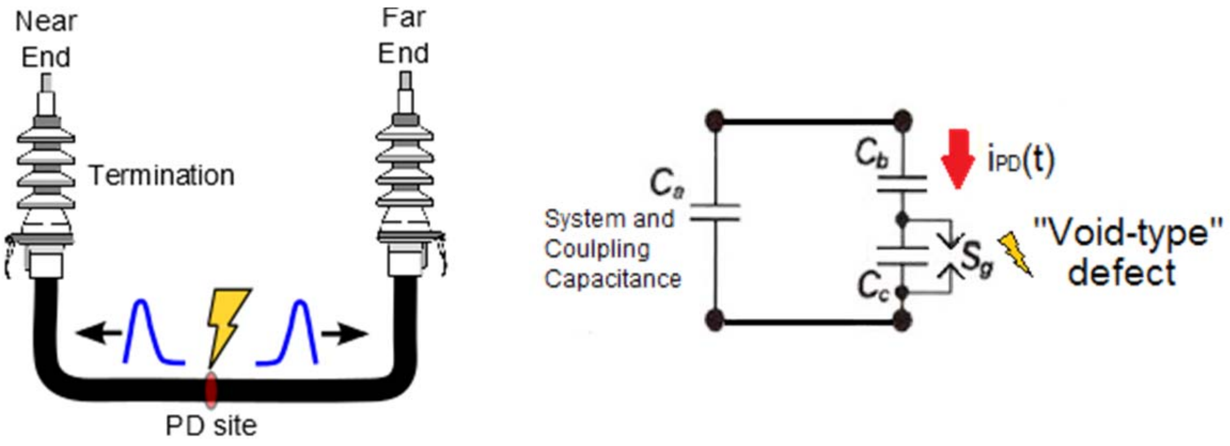


Figure 15: Lumped Capacitive Model

Copyright © 2016, Georgia Tech Research Corporation

The narrow bandwidths (NB and WB) focus on scaled charge for PD magnitude. IEC 60270 makes compliant detection systems relatively insensitive to variations in the PD pulse wave shape and duration, so long as the PD pulse is fast relative to the detection equipment. Thus, conventional PD measurements are insensitive to high frequency attenuation, dispersion, and other signal deterioration factors caused by the cable system structure and internal configuration as previously discussed. The primary disadvantage of low bandwidths and long cable systems is that multiple pulses can be captured at the same time resulting in an error in the estimated charge magnitude. A further complication is that the location function of a PD system requires a travelling pulse in order to perform the localization. As deployed for HV and EHV, the location function of PD measurement systems is critical for users. As a result, the cable system must be modeled as distributed impedance and not as a lumped capacitance.

In recent years, users have tended to move away from the conventions of IEC 60270 to avail themselves of more advanced electronics, digital signal processing, and lower noise levels to perform the diagnosis using higher frequency measurements; i.e. measurements in the non-conventional category. Such measurements tend to use UWB bandwidths, with upper frequency responses in excess of 200 MHz, depending on equipment manufacturer. These high frequencies by definition have shorter wavelengths (as compared to frequencies in either the IEC NB or WB) and so they become comparable in size to the cable system and even the components within that cable system. Thus, the non-conventional category is based on the more general distributed impedance model that is shown in Figure 16.

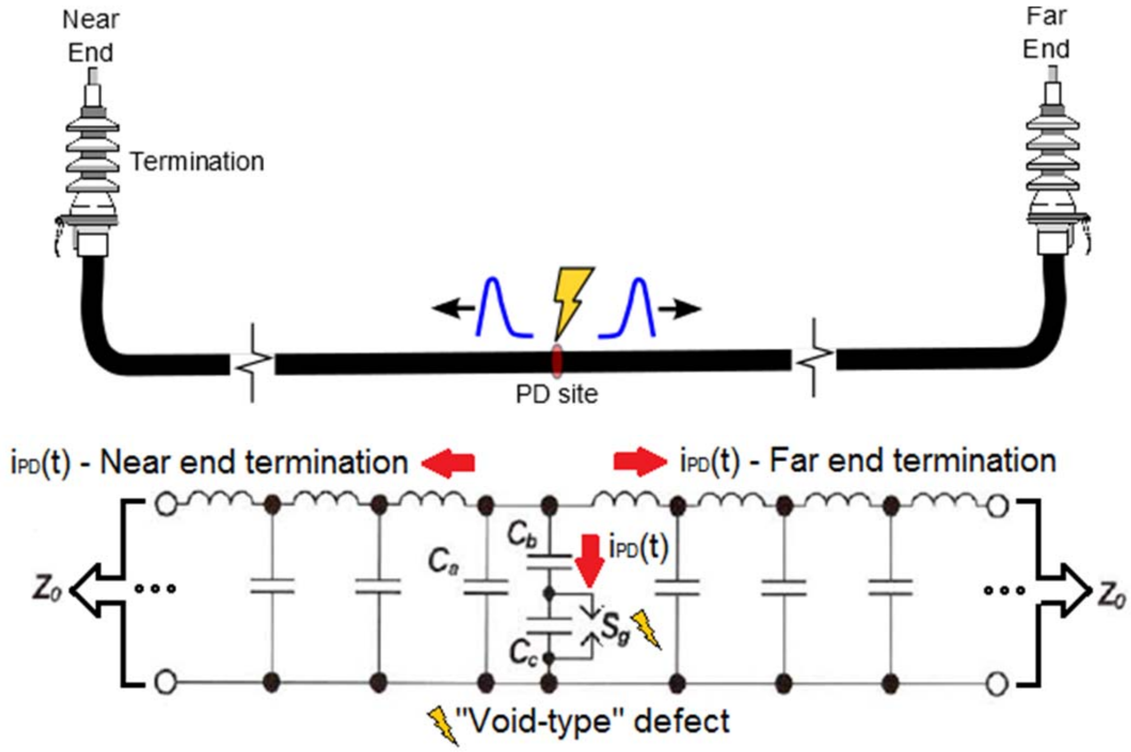


Figure 16: Distributed Impedance Model for Long Cable Systems

Copyright © 2016, Georgia Tech Research Corporation

There is a complicated relationship between conventional and non-conventional PD measurements, measurement bandwidth, cable system length, and modeling. The following sections attempt to unravel some of this complexity.

8.6.2.3 The "Bandwidth-Length" Relationship

The challenge of which cable system model to use may be addressed by considering frequency wavelengths and comparing them with the cable system length. Well established guidelines from signal theory exist for demarking the boundary between lumped and distributed modeling. This threshold is illustrated in Figure 17.

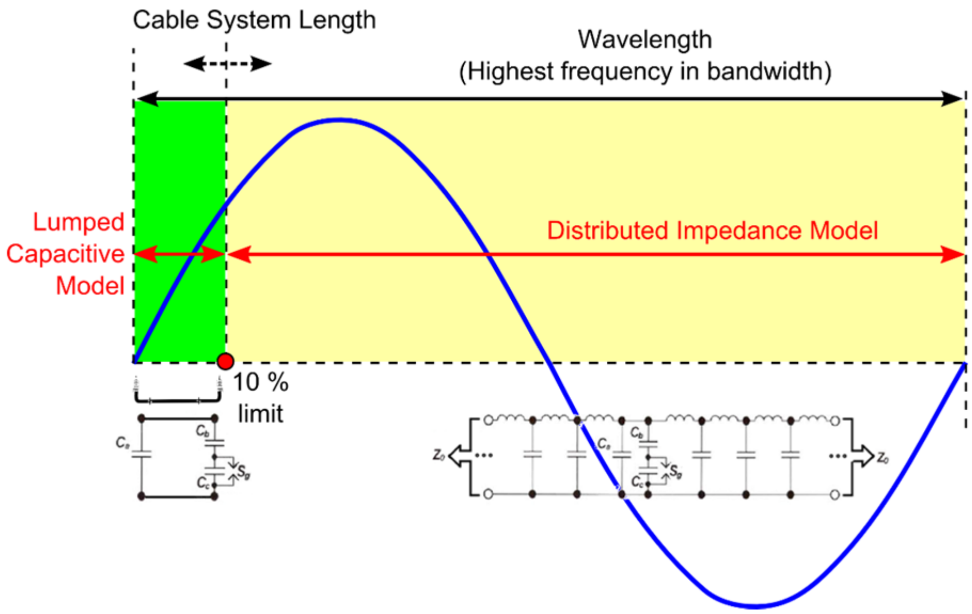


Figure 17: Illustration of Criteria for Lumped or Distributed Modeling

As seen in Figure 17, the accepted criterion indicates that if the cable system length is less than 10% of the wavelength corresponding to the highest frequency under evaluation (i.e. the shortest wavelength) then the cable system model may be simplified to the lumped capacitance approach. On the other hand, cable systems which are longer than this threshold should only be modeled using the distributed impedance approach. It should be noted that the distributed impedance approach is valid for *any* cable system length.

IEC 60270 limits the bandwidth so that cable systems can be tested using the lumped capacitance approach. The recommended frequency bands from IEC 60270 are shown in Table 10 and are illustrated in Figure 18.

Copyright © 2016, Georgia Tech Research Corporation

Table 10: Recommended Frequency Bandwidths According to IEC 60270

System Type	Frequency Requirements [kHz]	Observations
Wide Band – WB	$30 \le f_1 \le 100$ $f_2 \le 500$ $100 \le \Delta f \le 400$	f_1 – lower limit frequency f_2 – upper limit frequency Δf - bandwidth (BW) $\Delta f = f_2 - f_1$
Narrow Band – NB	$9 \le \Delta f \le 30$ $50 \le f_m \le 1{,}000$	f_m – midband frequency $f_m = \frac{f_1 + f_2}{2}$
Ultra Wide Band – UWB	No recommendations given	-

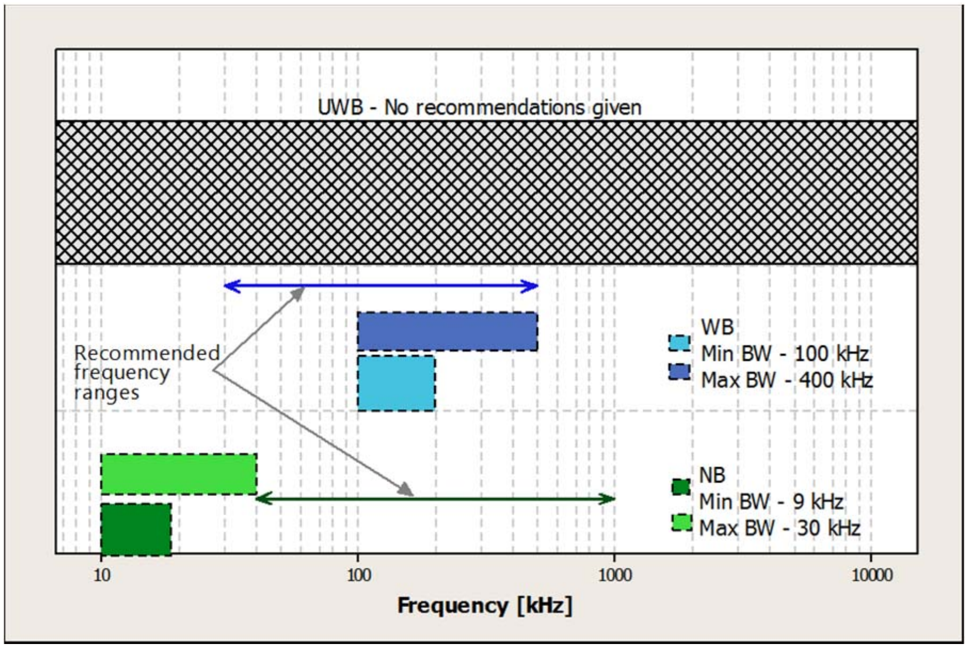


Figure 18: Illustration of Frequency Recommendations According to IEC 60270

The “10%” wavelength guideline can then be applied to the recommendations shown in Figure 17 and Figure 18 and a “map” may be constructed for the appropriate modeling conditions (see Figure 19).

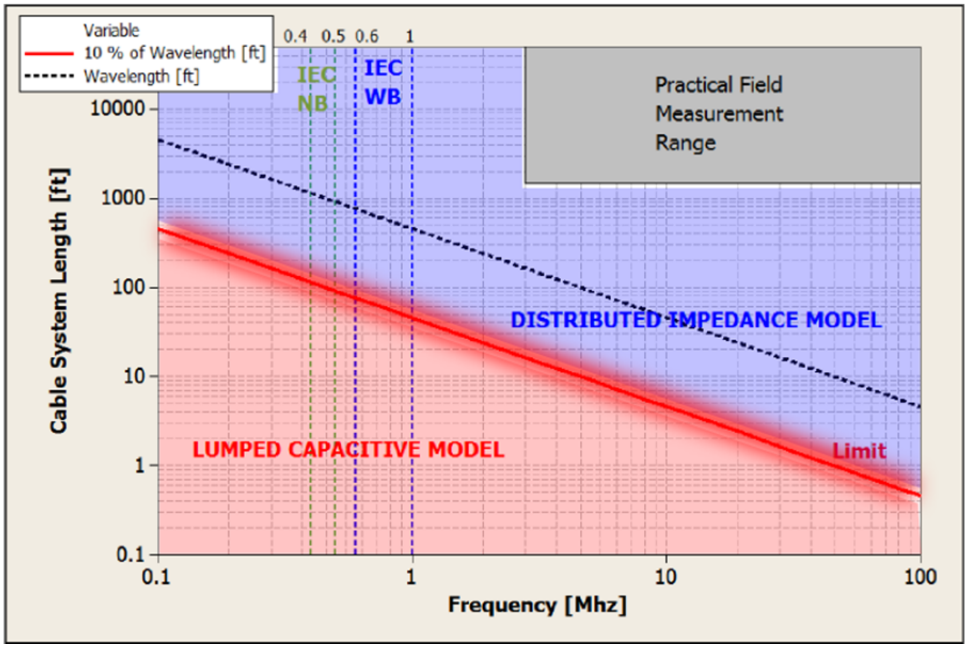


Figure 19: Relationship between PD Measurements Highest Frequency on Bandwidth and Applicability of the Cable system Modeling Categories (Figure 15 and Figure 16).

Figure 19 can be interpreted as follows:

- Within the frequency and bandwidth range specified by IEC Std. 60270 – 2000, the assumption that the cable system predominantly behaves like a lumped capacitance is not valid for lengths encountered in the field. As a consequence, calibration of the measured PD magnitude as per by IEC Std. 60270 – 2000 is not a valid concept.
- All HV and EHV cable systems should be modeled by the distributed impedance model and should be tested as such for all practically deployed PD measurements. In this case, the assumptions that are made in IEC Std. 60270 – 2000 for system modeling and calibration are no longer valid.

In addition, Figure 19 serves to demonstrate the reason why it is not possible to directly compare measured PD magnitude data between factory (conventional) PD tests and field PD tests. Although other PD metrics such as occurrence, PDIV, PDEV, and pulse repetition rate may still be performed on cable systems with lengths and frequencies above the black line in Figure 19, the calibration of measured PD magnitude for these cases as per IEC Std. 60270 – 2000 is no longer valid. The practical field measurement range in terms of frequency and cable system length is represented in Figure 19 by the gray box centered positioned above 1,200 ft, which is the typical minimum expected length of HV and EHV power cable system in the field.

Finally, PD technology users need to be aware that most non-conventional partial discharge measurement equipment offer advantages over the conventional category and they are as follows:

- Allows the use different types of sensors.
- Generates high resolution phase-resolved PD patterns.
- Measures and/or stores acquired PD pulse shapes.

- Classifies measured signals into groups including the ability to separate noise from PD signals using advanced data processing techniques.
- Uses digital filtering improving signal to noise ratios.

8.6.3 Measurement Approaches

The underlying principles of PD measurements are common to all approaches to PD detection. However, there are many ways to de-noise and quantify these discharge signals. This large number of approaches makes comparisons between test results from different PD diagnostic technologies so difficult that utilities are cautioned against making such comparisons.

8.6.3.1 Capturing PD Signals

Data acquisition systems are the interface between the sensors and computers. Through the data acquisition systems, the signal data that comes to the sensors gets converted, from its physical form, into an analog electrical signal that the acquisition system transforms a digital form to be processed and analyzed by computers. The signal is then run through a series of algorithms and results can be sent to other computers to be presented to the user. For PD measurements, there are two main data acquisition philosophies, they are as follows:

- Triggered Instruments
- Continuous Acquisition Instruments

Each of the PD measurement philosophies is discussed below.

Triggered Instruments

The first instrument type is the "triggered" class. The decision by a PD acquisition unit as to whether or not to record a signal is determined by, as its name states, an amplitude trigger. In other words, the instrument records a signal whose instantaneous amplitude exceeds a user selected value. Once the trigger level is reached, the instrument records the signal for a preset length of time. The instrument typically maintains a "pre-trigger" buffer that allows for the portions of signals that occur before the trigger level is reached to be captured as well. To assist in demonstrating the concept, its illustration in time domain is shown in Figure 20.

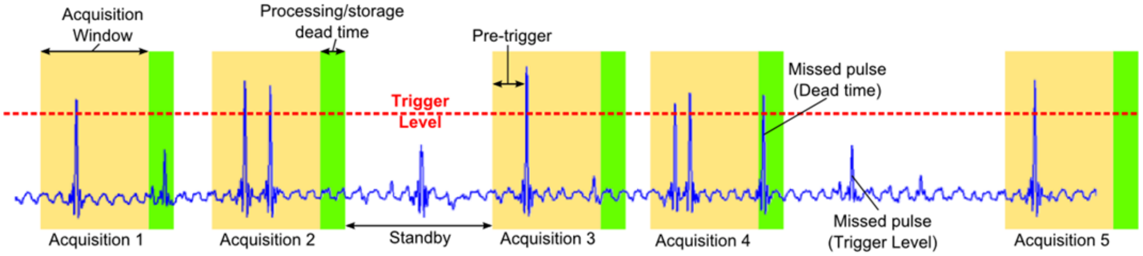


Figure 20: Time Domain Illustration for Trigger Level Based PD Measurement Philosophy

In Figure 20, the set trigger level is represented by the red dashed line and the incoming signal (waveform) by the blue solid line. With these settings, only five pulses reach the trigger level and thus only five acquisition windows are recorded. Note that for each acquisition window, there is a pre-trigger time (time before triggering instant) and a processing/storage dead time (time after the acquisition window has ended). The pre-triggering time is used to capture the waveform before the trigger instant while the processing/storage dead time is time required to run the acquired data through a series of algorithms that characterize and store the acquired signals to memory. After an acquisition window and its corresponding dead time, the acquisition system goes to standby mode waiting on the next pulse to reach the trigger level and thus repeat the process.

Also note in Figure 20 that some pulses can be missed. This occurs for two reasons:

- **Pulses that do not meet the trigger level:** The missed pulses that do not meet the trigger level can be captured by decreasing the trigger level to an adequate value. The *CDFI* perspective considers that the best practice is to have the trigger level just above the average background noise level; in this case, all pulses having a higher peak amplitude than the average background noise level are captured and more importantly the acquisition system would not get continuously triggered ("stuck") on the noise.
- **Pulses that meet the trigger level but come during the processing/storage dead time:** There is no clear solution around the issue of missed pulses that meet the trigger level but come during the processing/storage dead time. However, continuing improvements in computer processing and communication times have resulted in small dead times such there is not much concern.

As mentioned earlier, once the data are acquired, it must be stored to memory and analyzed. The typical analysis and storage process scenario (i.e. data processing) for a trigger level based PD instrument is illustrated in Figure 21. The synchronization signal in Figure 21 provides information about the phase of the test voltage.

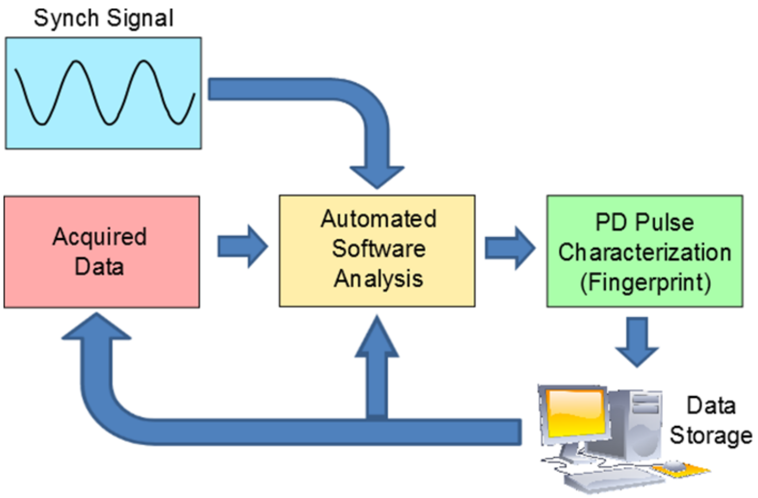


Figure 21: Typical Data Processing Scenario for Trigger Level Based PD Measurement Philosophy

As seen in Figure 21, the acquired PD and synchronization signals are automatically analyzed by software providing a basic characterization or fingerprint of the acquired pulse. After the automated analysis, all the information can then be communicated and stored to memory in a remote computer. The remote computer is generally used as the operator interface. Based on the information, the operator may take control actions on the acquired data or automated software analysis process, adapting the acquisition system to his/her needs.

Continuous Acquisition Based PD Measurement

The second philosophy is the continuous acquisition based PD measurement. In this case, the measurement is based on a single acquisition window in which all signals that come from the sensor are continuously acquired. The start and end times for the acquisition window define the acquisition time and are not trigger driven; they are selected by the operator of the PD measuring equipment. Typical predefined acquisition times are one cycle of the test voltage (typically 30 - 300 Hz). It is also possible to have alternative operator specified acquisition times. For ease in understanding the concept of continuous acquisition based PD measurement, its illustration in time domain is shown Figure 22. The incoming signal in Figure 22 is represented by the blue solid line.

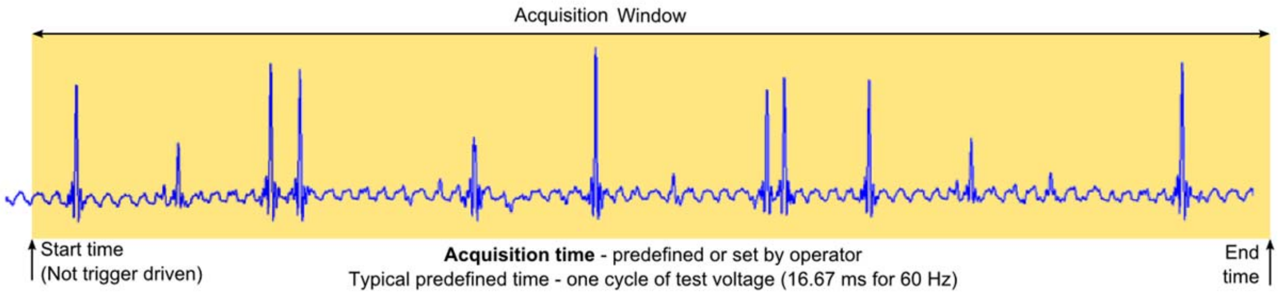


Figure 22: Time Domain Illustration for Continuous Acquisition Based PD Measurement Philosophy

Because of its nature, no pre-triggering or dead time issues exist for the continuous acquisition based PD measurement philosophy. The extraction, analysis, and characterization (i.e. data processing) of the PD signals are generally done offline, i.e. after all the data have been acquired over a range of test conditions. A typical data processing scenario for this approach is shown in Figure 23. As before, the synchronization signal in Figure 23 provides information about the phase of the test voltage.

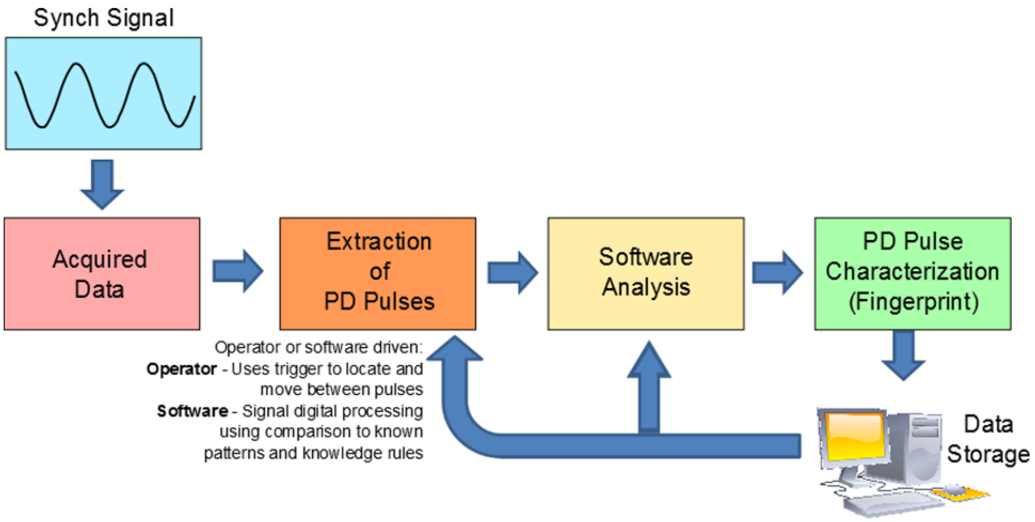


Figure 23: Typical Data Processing Scenario for Continuous Acquisition Based PD Measurement Philosophy

In Figure 23, the extraction of PD pulses can be operator or software driven. When the operator extracts the PD pulses, he/she uses experience and knowledge rules to recognize PD pulses. Various software tools may be used by the operator to extract PD pulses of interest.

Once the PD pulses have been extracted from the raw data, the analysis, characterization, and storage of data is done in a similar manner as the trigger level based instruments.

8.6.3.2 Locating Sensors and Quantifying PD Signals

The two PD instrument types described above can be used for acquiring PD signals at a number of cable system locations including one or both terminations as well as any accessible joint location. This yields three primary deployment types:

- **Single-ended Terminal Measurement:** PD measurements are performed with a PD sensor located at one of the cable ends (typically designated as the “near” end) – see Figure 24.
- **Dual-ended Terminal Measurement:** PD Measurements are performed simultaneously at both cable ends (near and far ends) – see Figure 25.
- **Distributed Measurement:** PD measurements are performed with sensors located at terminations and joints, the measurements can be done sequentially or simultaneously. When a PD sensor is moved from joint to joint and PD measurements are made sequentially, the deployment is often termed “joint hopping” – see Figure 26 and Figure 27.

Copyright © 2016, Georgia Tech Research Corporation

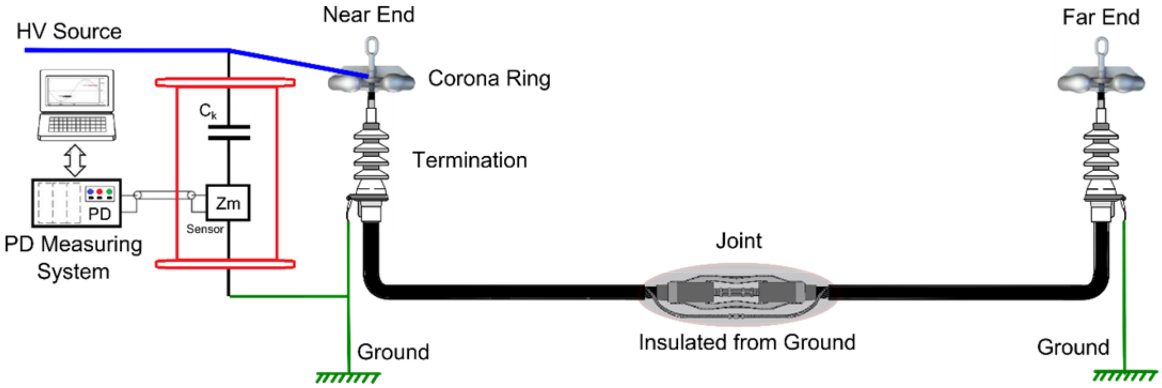


Figure 24: Single-ended Terminal Measurement

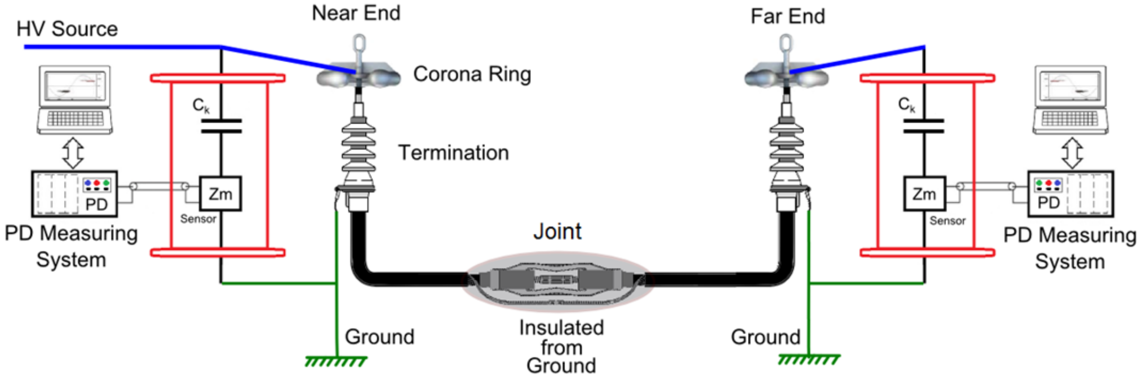


Figure 25: Dual-ended Sequential Terminal Measurement

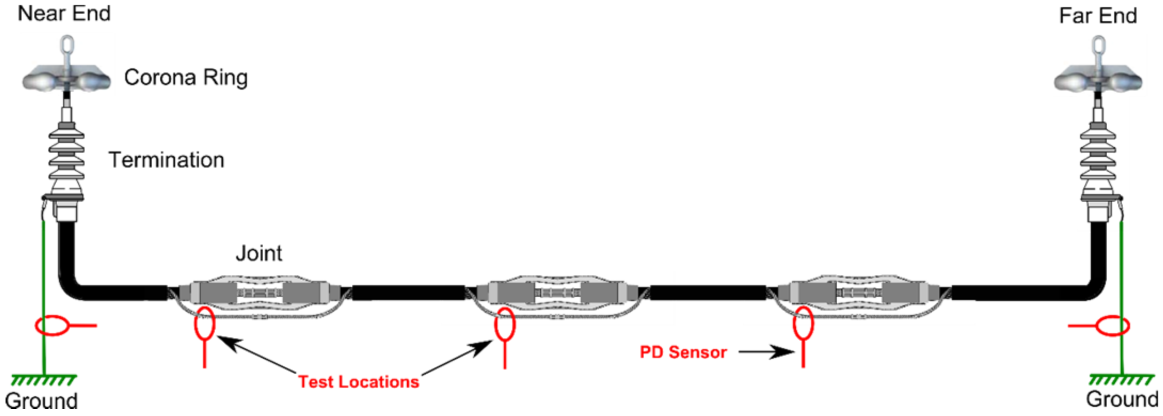


Figure 26: Illustration of PD Distributed Measurement on HV Power Cable Systems

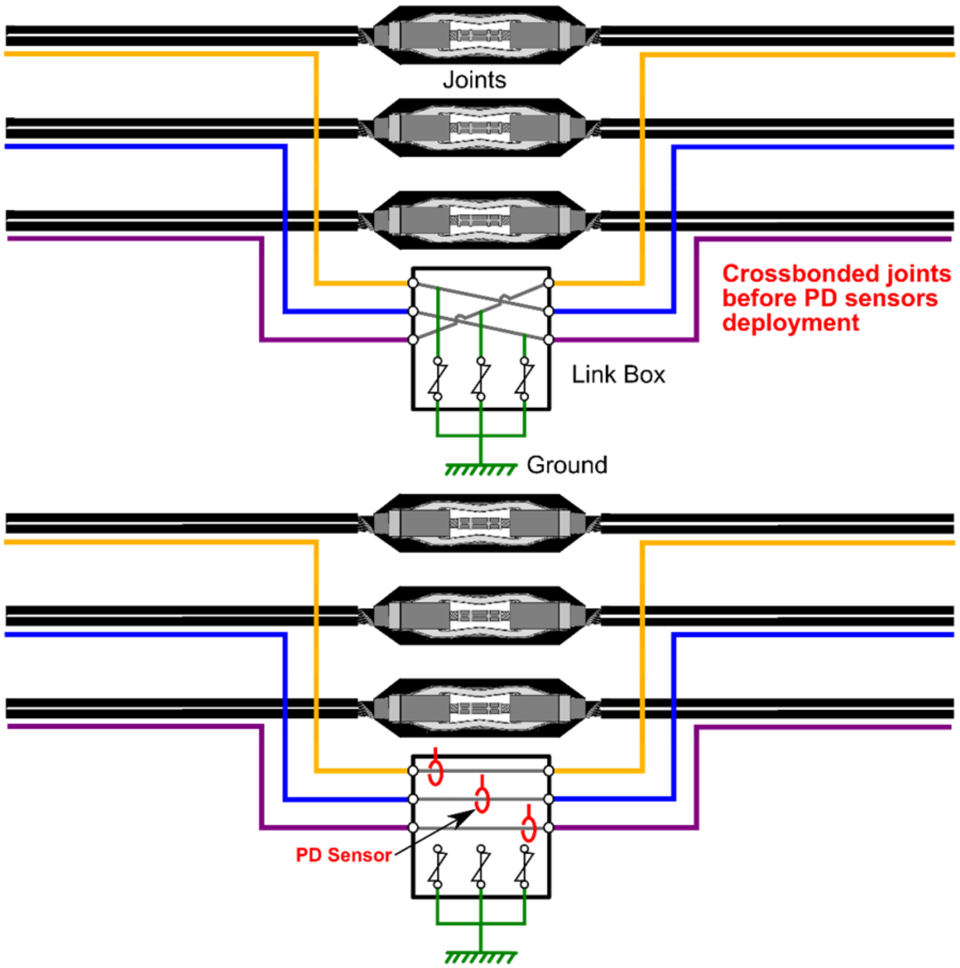


Figure 27: Illustration of PD Measurement on HV Power Cable Systems at Cross-bonded Joints

The measurements approaches shown above can use different methods to estimate the size of the discharge; however, the size of the charge is not typically used in the decision-making. Most users are interested only in the presence or absence of detectable discharge and so its severity is not as important as in MV PD tests. In cases where discharge size is of interest, the following two methods may be used:

- **Scaled Charge (pC):** The apparent charge, expressed in pC, can be estimated using a pre-derived scale factor or integration of PD current waveforms (as captured by the sensor-acquisition equipment). This method is related to the wide-band and narrow-band test setups presented on the IEC 60270 – 2000 and IEC 60885 – 1988. In addition to the PD magnitude, other PD diagnostic indicators can be used to further characterize the measurements.
- **Multi Featured (mV):** PD magnitude is estimated from measurement results using any relevant/convenient metric – typically PD magnitudes are referenced to the peak magnitude of PD waveforms (as captured by the sensor-acquisition equipment) in millivolts. Other metrics such as the area under the pulse curve in mV-μs could also be used. This method is related to the ultra-wide-band test described on the IEC Std. 60270 – 2000. In addition to the

Copyright © 2016, Georgia Tech Research Corporation

PD magnitude, other PD diagnostic indicators can be used to further characterize the measurements.

Table 11 shows the relationship between the voltage source type and the measurement approaches for on-site PD testing of HV and EHV cable systems.

Table 11: Usage of source type for On-site PD Testing of MV Power Cable Systems

Source Type	**Approach to Measurement**	**Scaled Charge**	**Multi-Featured**
Power Frequency AC (30-300 Hz)	Terminal (Single and Dual-ended)	Yes	Yes
	Distributed	No	Yes
Very Low Frequency AC (≤ 0.1 Hz)	Terminal (Single and Dual-ended)	Yes	Yes
	Distributed	No	No
Damped AC Voltage (20 Hz to 1 kHz)	Terminal (Single and Dual-ended)	Yes	No
	Distributed	No	No

Regardless of the voltage source type, there are several issues that need to be considered:

- Time and test voltage magnitude above U_0.
- PD diagnostic features (e.g. PD magnitude, PDIV, PDEV, or PD Patterns) cannot be compared between voltage source types.

As seen in Table 11, PD tests performed in HV and EHV power cable systems typically fall into one of two configurations:

1. Terminal single and double-ended PD measurements for all source types.
2. Distributed sensors in scaled charge or multi featured PD measurements.

Terminal PD measurements somewhat mimic a conventional PD test like those performed in the laboratory. However, due to the attenuation and dispersion effects, terminal PD measurements are often constrained to short lengths of cable – typically a section containing only a length of cable and two terminations.

Since accessories are often the source of PD in HV and EHV cable systems and these systems have significant attenuation and dispersion effects PD measurements are often performed in a distributed sensor approach. The test can be performed sequentially or simultaneously at each accessory during the test. The latter method requires a PD sensor for each accessory with a communications link between testing locations. The advantage of this approach is that accessories are locally monitored during the test and therefore periodically or cyclically occurring PD sources may be detected. When measurements cannot be performed simultaneously, the joint hopping approach mentioned above is used. PD sensors are moved from accessory to accessory with short acquisition times at each location.

Table 12 outlines the three different field approaches and relevant features here off for PD tests at HV and EHV.

Copyright © 2016, Georgia Tech Research Corporation

Table 12: Overview of Field PD Approaches to Measurement [30]

Test Category	Terminal Scaled Charge	Terminal Multi Feature	Distributed Scaled Charge	Distributed Multi Feature
Location of Measurement	Single or Dual-ended		Distributed PD Measurement with sensors at accessories (joints and / or terminations)	
Sensor	Any internal or external sensor (capacitive or inductive)			
Typical Power Cable System Length	• 6,000 ft from each terminal sensor used. • No joints or few straight metal clad joints. • Limited by cable system propagation characteristics maximum lengths often lower due to attenuation and dispersion effects – see Range Check.		Any length	
Upper Cut-off Frequency	< 1MHz Typically	< 30MHz Typically	< 1MHz Typically	< 750MHz Typically
	Or any other specified bandwidth within allowed range			
Calibration	• Any well documented form of either classic calibration or double sensors. • Calibration voltage pulse with a rise time typically 10 times faster than circuit response – see Calibration.		Not applicable.	
Scale Factor	Not applicable		• Any well documented form of either double sensor methods and/or sensitivity by construction. • Includes evaluation of wave propagation in the cable adjacent to sensors.	
Sensitivity Check	• Required across the frequency range of the bandwidth of the measurement. • Includes evaluation of wave propagation in the cable adjacent to sensors – see Sensitivity Check.			
Performance Check	Required to check PD System Operability – see Range Check			
Range Check	Required to establish the length that a PD pulse can travel down a cable at selected levels of amplitude and dispersion – see Range Check			
Noise	Noise mitigation is essential		Noise mitigation may not be essential due to sensor location at accessories and propagation (filter) characteristics of cable	
Loss of charge	Loss assumed to be small enough not to perturb measurement	Recognizes loss of charge / current, especially at bonding of cable systems	Recognizes loss of charge / current, especially at bonding of cable systems	
Reporting on PD magnitude	Apparent charge by suitable (typically digital) integration technique. Any suitable metric (pC, mV, i_{PD})		Induced apparent charge by suitable (typically digital) integration technique.	Any suitable metric (pC, mV, i_{PD})
Location	Location by time of flight from terminals		Location by sensor position and time of flight	

Copyright © 2016, Georgia Tech Research Corporation

8.6.4 Commissioning versus Maintenance Tests

CDFI Phase II has had the unique opportunity to collaborate with the CIGRE B1.28 Working Group to generate a publication regarding on-site PD assessment of HV and EHV able systems. The CIGRE HV and EHV voltage classifications are based on those in IEC 60840 – 2004 and IEC 62067 – 2011, respectively. One consequence of such designations is that 35 kV and above cable systems are classified as HV while some users, especially in North America, would consider these voltages as MV voltage classes. However, the voltage designations considered here follow the following convention:

- MV – 15 through 35 kV
- HV – 46 through 161 kV
- EHV – greater than 161 kV

One of the more important efforts than the CIGRE B1.28 Working Group has already accomplished is a survey that has been carried out among CIGRE membership countries. In total, 60 survey responses were obtained from 13 different countries. The participation by country is shown in Figure 28.

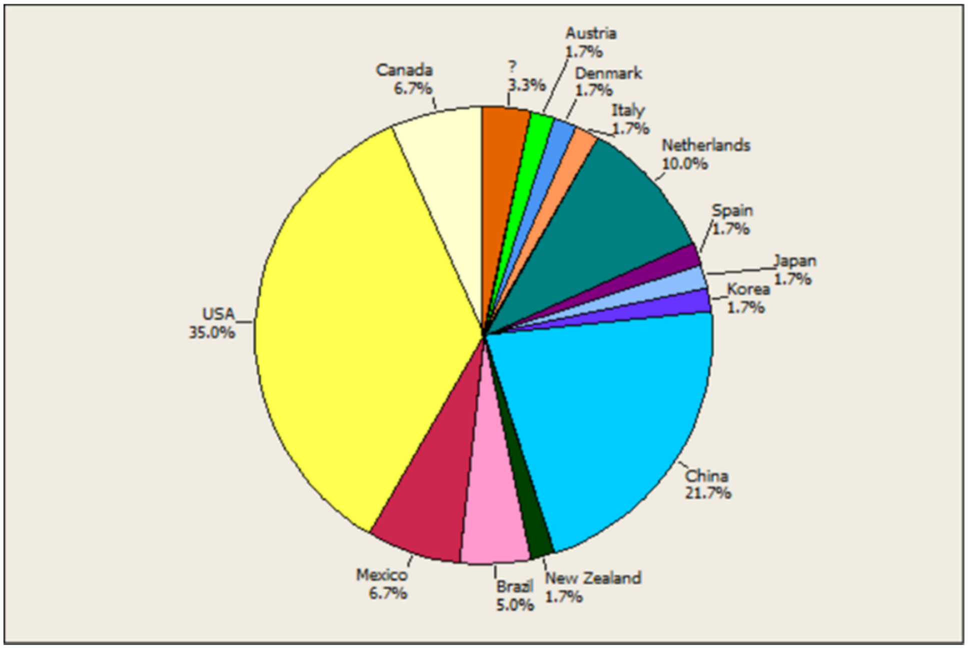


Figure 28: Global Participation of the Survey Conducted by CIGRE B1.28 Working Group

Utilities, manufacturers, and diagnostic service providers had participation levels of 58%, 22%, and 20%, respectively. Survey respondents were requested to describe their normal practice regarding the use of PD measurements as part of testing for HV and EHV cable systems. Results indicated that 27% of respondents do not perform any PD tests on these systems. The remaining 63% of respondents indicate that they do perform PD measurements primarily on new cable systems in the form of commissioning tests.

The survey also explored how the respondents viewed the following common reasons for undertaking PD measurements:

- **Test the quality of the installation:** To verify the installation was done properly.
- **Test the quality of the accessories:** To reduce the likelihood of an accessory failure during the system service life.
- **Test the quality of the cable:** To reduce the likelihood of a cable failure during the system service life.
- **Increase assurance:** To increase confidence in the installation especially where the utility's public perception and quality assessment (QA) program are important.

Within the survey, the respondents were asked to rank the above reasons according to their relative importance (see Figure 29). According to the responses, the most important reason was to test the quality of the installation while the least important was to increase assurance.

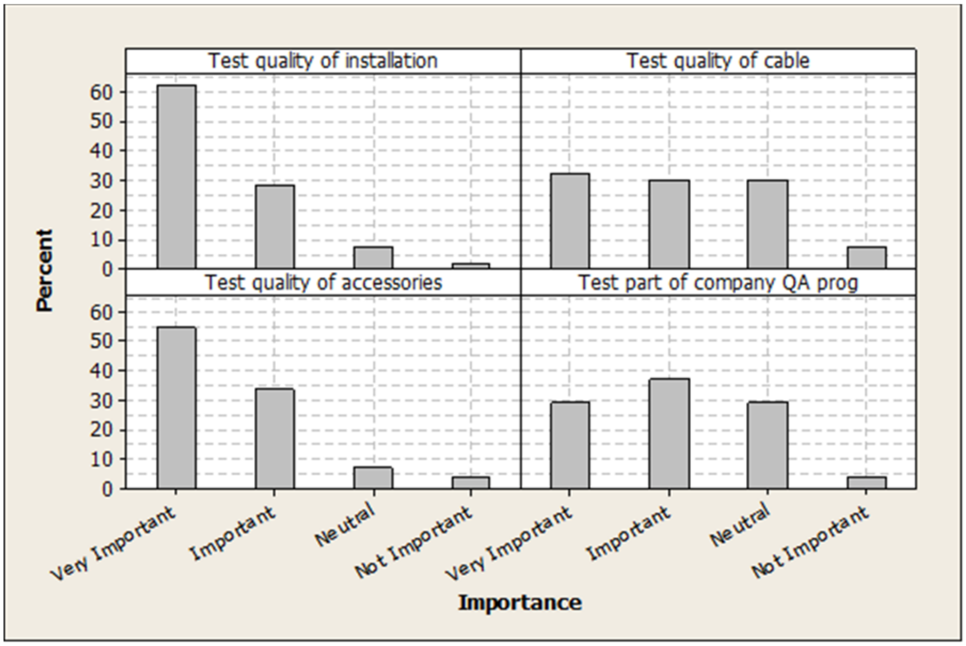


Figure 29: Relative Importance of PD Measurements – Common Reasons

A complimentary study was conducted from survey results to look at the type of PD measurements that have been used and on what voltages and lengths of systems they were employed. A summary of the complimentary study is presented in Table 13. In Table 13 table, PD measurements fall into two groups in terms of deployment (i.e. terminal or distributed) and two groups in terms of data reporting (i.e. scaled charge or multi-feature). In this context a distributed deployment is when sensors are located close to the accessories (terminations or joints) under PD evaluation to avoid as much as possible background noise, signal deterioration, and/or any other issue that may negatively influence successful PD detection. When the sensors are deployed simultaneously or sequentially on the accessories, the deployment is typically known as "Joint Hopping".

The data provided by respondents was also used to estimate typical system lengths upon which the PD measurements were deployed. To provide information about length variability, the typical

Copyright © 2016, Georgia Tech Research Corporation

system lengths are expressed in terms of interquartile ranges; i.e. the low range (25th percentile of the data), median (50th percentile of the data), and high range (75th percentile of the data) as shown in Table 13. Thus, for HV systems approximately 5% of tests were conducted using a distributed sensor/scaled charge approach for lengths between 10 mile (16 km) and 34 mile (55 km) with a median of 22 mile (35 km), whereas for EHV systems between 65% and 80% of tests were conducted using a distributed sensor/multi-featured approach for lengths between 0.6 mile (1 km) and 8.7 mile (14 km) with a median of 3.6 mile (6 km).

Table 13: Common Practices for Field PD Measurements of HV and EHV Cable Systems

Standards	Field PD measurements are not required to conform to IEC Std. 60270 - 2000 and IEC Std. 60885-3 - 1988		
Deployment	Single or Double Terminal Measurement	Distributed PD Measurement with Sensors at Accessories (i.e. joints and/or terminations)	
Reporting (See Table 12 for further explanation)	Scaled charge with a reference to laboratory calibration procedures according to IEC Std. 60270 - 2000	Scaled charge usually from integration of current vs. time traces of captured pulses	Convenient multiple metrics or features
Sensor	Any internal or external sensor		
HV Cables Systems			
Global Experience (to 2010)	< 50% of tests	<5% of tests	50 to 80% of tests
Length [mile] (Low Range Median High Range)	0.1 0.6 1.2	10 22 34	0.6 3 12.4
EHV Cables Systems			
Global Experience (to 2010)	< 35% of tests	<5% of tests	65 to 80% of tests
Length [mile] (Low Range Median High Range)	0.1 1.8 3.6	8.7 8.7 19.8	0.6 3.7 8.7

As seen in Table 13, the most common practice for field PD measurements on HV and EHV cable systems is distributed measurements with sensors deployed at accessories and using multiple features. This style of field measurement accounts for 50% - 80% of tests for HV systems and 65% - 80% for EHV systems. The data represent tests conducted through 2010.

Copyright © 2016, Georgia Tech Research Corporation

Therefore, based on survey results, two observations are apparent:

- PD measurements on HV and EHV cable systems are mainly deployed as commissioning tests.
- With the focus on commissioning tests, the interpretation of PD is not as important as for MV systems and so PD diagnostic criteria should not be based on PD severity but rather on its presence/location in the system.

It should be recognized that some cases, e.g. maintenance tests, would require some kind condition assessment. However, the fact that these systems should be PD free leads to the conclusion that any new PD detected during the system service life must be due either to installation problems not detected during commissioning or defects in the system that developed since installation. The latter case is more concerning as these systems have historically performed with very high reliability.

Unfortunately, it is important to be aware that no industry diagnostic criteria for PD condition assessment exist for maintenance tests conducted on HV or EHV cable systems. Criteria do exist for laboratory qualification tests; however, as discussed earlier these cannot be applied to systems installed in the field.

8.6.5 Energizing Cable Systems

To perform a PD test, the cable system must be energized from either the transmission grid or an external voltage source. This section discusses the energization options available for HV and EHV cable system PD tests.

8.6.5.1 Online Testing – Maintenance Tests

On-line monitoring maintenance testing is conducted with the cable system as is normalized energized and connected to the power system. An on-line PD monitoring an assessment can be deployed periodically with PD data acquisitions predetermined intervals or it can be continuous for an extended period which can range from days to years.

While on-line PD measurements are not performed at elevated test voltage levels, several case studies have documented their applicability; in particular, solid dielectric field aged cable systems [11]. In the case of terminations, PD activity can be present for a significant amount of time prior to failure and, thus, on-line PD measurements could potentially be used to identify a defect in a termination with enough warning to allow some action to be taken.

The B1.28 Working Group has developed recommended test procedures for on-line monitoring as shown in Table 14. Similar to elevated voltage tests, these procedures are the result of extensive discussions within the B1.28 Working Group. Since the *CDFI* has participated in these discussions, the test procedures and success criteria in Table 14 also reflect the views within *CDFI*.

Table 14: Recommended Maintenance Test Procedures and Success Criteria for PD On-line Monitoring Maintenance Testing

Voltage Class [kV]	Test Level [U_0]	Frequency [Hz]	Monitoring Duration [min]	PD Pass/Fail Criterion
66-72	1.0	60	10	Guiding criterion is no detectable PD §
110/115				
132/138				
220/230				
345/400				

§: However, experience shows that in some cases utility specific criteria exists depending on the particular application

8.6.5.2 ac Resonant Testing – Commissioning and Maintenance Tests

The primary purposes of a commissioning test are:

- To verify that the cable system is free of life limiting defects caused by damage during transportation and/or installation.
- To provide a clear contractual hand over to the asset owner. A secondary benefit is that a commissioning test provides a base line measurement for any future PD measurements.

As mentioned earlier, the most common practice for commissioning tests for extruded HV and EHV cable systems is a combination of AC Withstand Testing (performed according to IEC 60840 – 2004 or IEC 62067 – 2011) with PD measurement (this combination can also be seen as a monitored withstand).

Feedback from cable owners of HV and EHV cable systems within the *CDFI* and discussions with the B1.28 Working Group indicate that commissioning tests performed at voltage test levels less than 1.7 U_0 do not adequately identify life-limiting defects via PD measurements. In addition, evidence from test experiences indicate a higher rate of in-service failures is observed on cable systems that have been commissioning tested at voltages lower than 1.7U_0.

Figure 30 and Figure 31 show recent data provided by the B1.28 Working Group to the *CDFI* in which PD activity was continuously monitored during a 60 min withstand tests. Specifically, Figure 30 shows the cumulative distribution function of PD inception time and Figure 31 shows the cumulative distribution function for the PD inception voltage for commissioning test performed at 1.7U_0.

Copyright © 2016, Georgia Tech Research Corporation

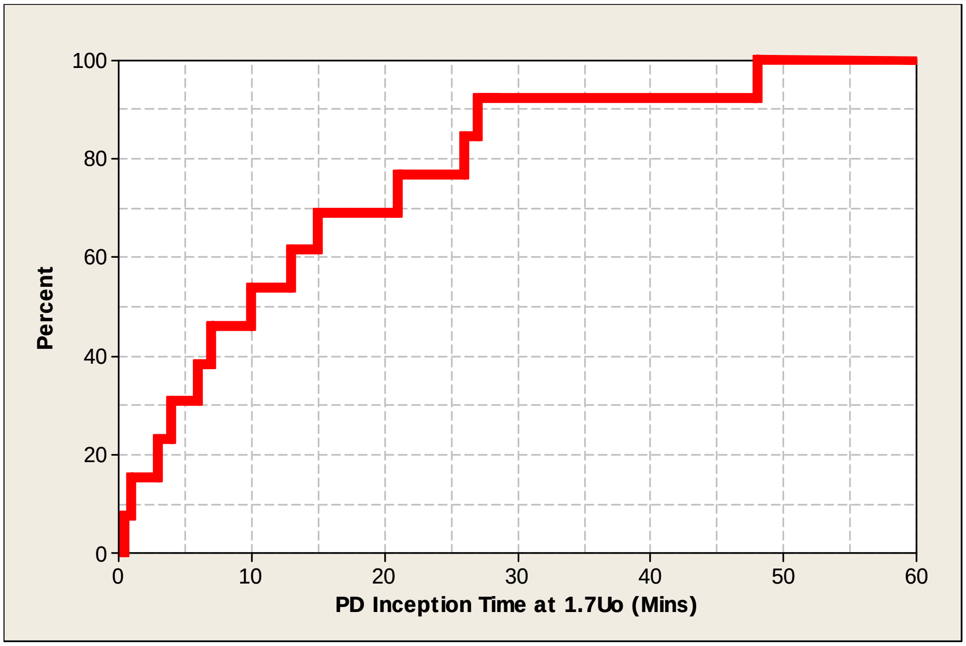


Figure 30: Cumulative Distribution Function of PD Inception Time for Commissioning Tests Performed for 60 min at 1.7U$_0$ on HV and EHV Cable Systems

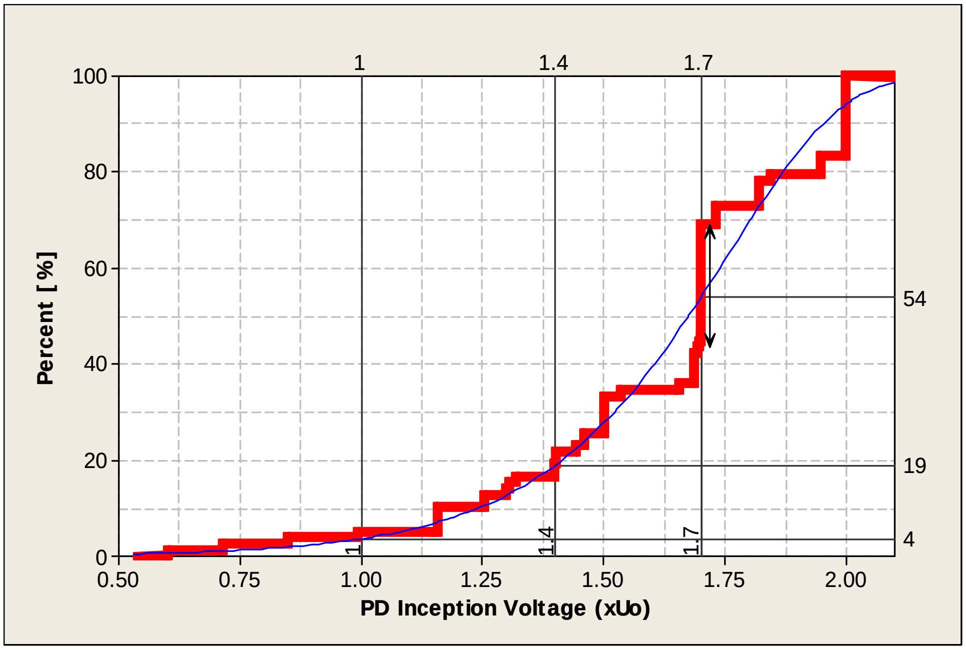


Figure 31: Cumulative Distribution Function of PDIV for Commissioning Tests Performed for 60 min at 1.7U$_0$ on HV and EHV Cable Systems

As can be seen from Figure 30 some PD sources require some time to become active after the withstand test has started. More importantly, however, Figure 31 shows that the majority of PD sources require at least 1.5U$_0$ to incept. This implies that test voltages below 1.5U$_0$ will likely allow a significant number of defects to go undetected.

Consequently, the B1.28 Working Group has recommended the test procedure and success criteria shown in Table 15.

Table 15: Recommended Commissioning Test Procedures and Success Criteria

Voltage Class [kV]	Test Level [U_0]	Frequency Range [Hz]	Duration [min]	PD Pass/Fail Criterion
66-72	1.7	10-300	60	No Detectable PD
110/115				
132/138				
150/160				
220/230				
275/285				
345/400				
500				

The test voltage is a trade-off between (a) using a high enough voltage to initiate PD from defects (during a one hour test) that would result in an in-service failure during the normal service life of the system and (b) using voltage that is too high and might cause PD around defects in the system which would otherwise not have resulted in an in-service failure. The test voltage recommended in IEC 60840 – 2004 and IEC 62067 – 2011 are 1.9 U_0 and 1.7 U_0, respectively. IEC 62067 – 2011 allows testing lower than 1.7 U_0 if 1.7 U_0 is not technically feasible as a result of long cable lengths.

AC resonant test sets typically have a working frequency range of 20 Hz to 300 Hz. It may be necessary to extend the lower limit to 10 Hz to allow the testing of very long cable systems. Research has shown that when subjected to electrical stresses in the frequency range of 20 Hz to 300 Hz PD inception and electrical tree growth do not vary significantly and, therefore, from a PD point of view, the cable system dielectric behaves similarly as it does at 60 Hz.

A typical test voltage profile for commissioning and re-commissioning tests for HV and EHV power cable systems is shown in Figure 32. The re-commissioning tests are defined here as tests performed within the first 5 years of service life (including before initial energization) or at the end of the warranty period; whichever is longer. The profile shown in Figure 32 holds for single-ended, double-ended, simultaneously distributed, or sequentially distributed PD measurements. In the case of sequentially distributed PD measurements, it is assumed that all joints can be visited and PD tested for a reasonable period of time of 5 min with continuous PD assessment.

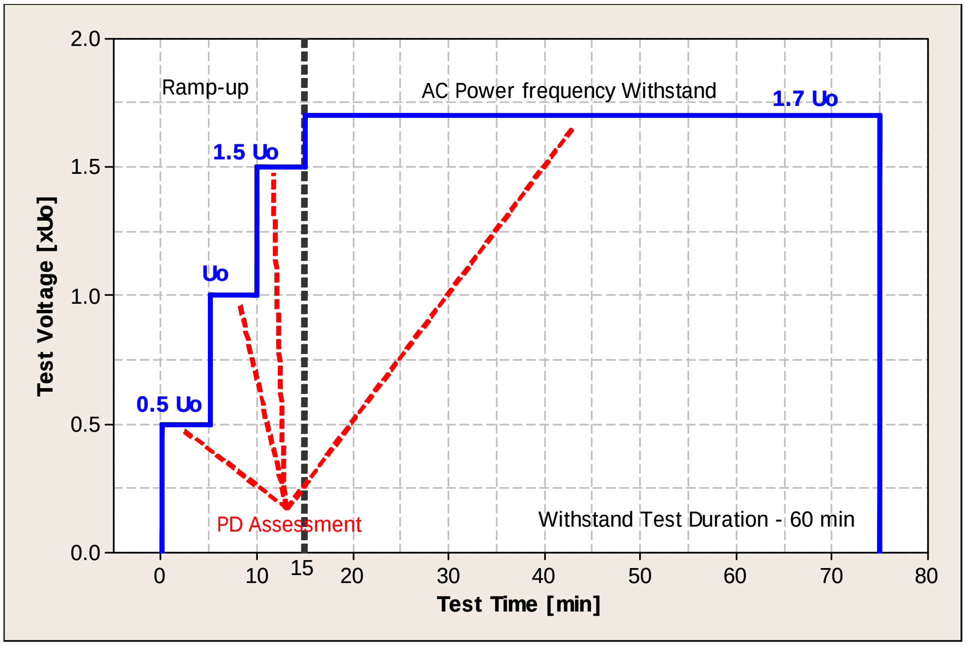


Figure 32: Typical Test Voltage Profile for Commissioning and Re-commissioning (less than 5 years) Tests for HV and EHV Power Cable Systems

For the cases in which all joints cannot be visited during the AC withstand test 60 min period, a "Joint Hopping" or "Daisy Chain" measurement approach must be followed. In this case, the test voltage is maintained for short periods of time and then taken down so that the PD equipment can be relocated to the next joint location. In very long cable systems, the total time at the withstand voltage level may exceed the 60 min minimum. Such a profile is shown in Figure 33 and includes the periods where voltage is reduced to at least operating voltage during the position change.

Copyright © 2016, Georgia Tech Research Corporation

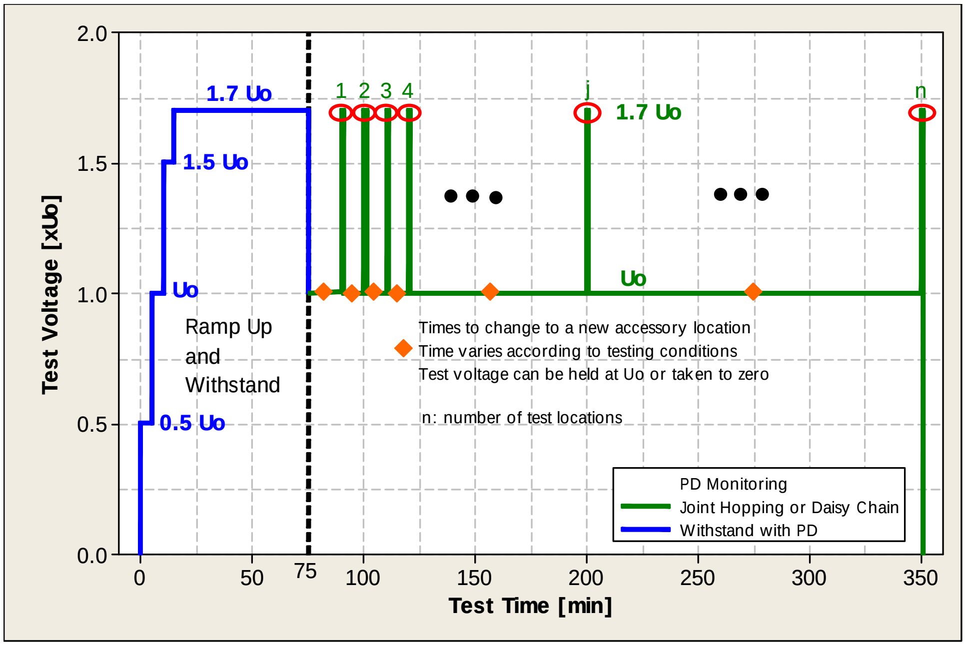


Figure 33: Typical Test Voltage Profile for Commissioning and Re-commissioning Tests for HV and EHV Power Cable Systems using "Joint Hopping" or "Daisy Chain" PD Measurement Approach

Maintenance Tests

The primary purpose of a maintenance test is to check that the cable system is free of life limiting defects caused by aging mechanisms acting on the main insulation system. As mentioned above, the Cigre survey showed that few cable owners in general perform maintenance tests on HV & EHV cable systems. There are, however, some maintenance tests conducted after a system is repaired as the result of a service failure or when reworking an existing cable system (re-routing the cable or adding extra sections). In a few cases, maintenance tests are also performed when a PD source was detected in an accessory but the utility chose to accept the accessory anyway. Each of these cases is handled slightly differently and depend on the cable system age.

In maintenance tests after a repair on systems less than 5 years old the cable system is subjected to a full AC withstand and PD assessment test with withstand voltage levels and durations as indicated in Table 15 (1.7 U_0 for 60 min).

For systems older than 5 years or after the warranty period (whichever is longer), ac withstand and PD testing is performed at a reduced test voltage level and/or duration (Table 16). There are very few data on such tests. Thus, the B1.28 Working Group was guided by the levels used for commissioning with the application of appropriate reduction factor (i.e. in general the test voltages lay mid-way between the commissioning test voltages (Table 15) and the maximum voltage for the cable system (U_m)). It is possible that these levels may be too low and that future experience will reveal more appropriate levels. It has also been suggested that an additional reduction factor should be considered when the cable system is older than 15 years.

Copyright © 2016, Georgia Tech Research Corporation

In light of the above discussion, Table 16 shows the compiled recommendations from Cigre B1.28. These test voltages and durations also represent the suggested practice within *CDFI*.

Table 16: Recommended Maintenance Test Procedures and Success Criteria for Off-line PD Measurements at Overvoltage

Voltage Class [kV]	Frequency Range [Hz]	Duration [min]	Service Life			
			5 Years[§] to 15 Years		More Than 15 Years	
			Test Level [xU_0]	PD Pass/Fail Criterion	Test Level [xU_0]	PD Pass/Fail Criterion
66-72	10-300	60	1.5	No Detectable PD	1.1	No Detectable PD
110/115						
132/138			1.4			
150/160						
220/230						
275/285						
345/400						
500						

§: Or end of warranty period whichever is the longer

It is also important to mention that field experience has shown that if the PD tests are performed at voltages less than 1.7 U_0 then the cable system is often preconditioned at 1.7 U_0 for 10 – 15 s after which the test voltage level is lowered to the level at which the PD assessment is to be performed. Unfortunately, the risk and impact of this preconditioning have yet to be evaluated. From the *CDFI* perspective, the decision to raise the test voltage to 1.7 U_0 must be made by the cable system owner.

8.6.5.3 Very Low Frequency (VLF) Testing – Commissioning Tests

The Cigre B1.28 survey shows that AC voltage testing (20-300 Hz) is more commonly deployed in the field than other voltage sources. However, there have been some tests where the voltage source was sinusoidal VLF. The limited reported experience with VLF is insufficient to make recommendations on test parameters (voltage levels or durations). Using experience at MV, it is possible to provide some suggestions for how one might proceed to utilize VLF for HV and EHV systems. These suggestions are shown in Table 17.

Copyright © 2016, Georgia Tech Research Corporation

Table 17: Recommended Commissioning Test Procedures and Success Criteria for VLF Test Voltages

Voltage Class [kV]	**Test Level [U_0]**	**Frequency Range [Hz]**	**Duration [min]**	**PD Pass/Fail Criterion**
66-72	1.9	0.05 – 0.1	60§ min for 0.1 Hz	No Detectable PD
110/115				
132/138	1.7			
150/160				
220/230	Some reported experiences but insufficient to provide test guidance			
275/285				
345/400	No reported experiences to provide test guidance			
500				

§: Minimum time requirement is currently unknown; however, but for experimental purposes a time of greater or equal to 60 min is suggested, it might be appropriate to use an increased time if the frequency is significantly reduced so that to have the same number of test voltage cycles as 0.1 Hz for 60 min

There remain a number of issues/unknowns with the use of VLF voltage sources on HV and EHV cable systems, which include:

- The electrical tree initiation and growth dynamics are largely unknown for VLF frequencies and the electrical stresses for HV and EHV cable systems.
- The appropriate initial test voltage levels to initiate PD at life limiting defects in typical HV and EHV cable systems are largely unknown.
- The duration of VLF required to initiate PD at life limiting defects otherwise requiring local losses (some time with constant voltage AC) to be detectable.
- The duration of VLF required to cause insulation failure for life limiting defects which do not give rise to PD during constant voltage resonant tests but do cause insulation failure.

8.6.5.4 Damped AC Testing – Commissioning Tests

Similar to VLF voltage sources, there is some reported usage of Damped AC (DAC) voltage sources for PD measurements on HV and EHV cable systems. The amount and scope of this usage is insufficient to make recommendations on test parameters. However, there may be users who wish to undertake experimentation and gather information on PD under DAC voltage. To this end, Table 18 contains test guidelines for using DAC voltage sources.

Copyright © 2016, Georgia Tech Research Corporation

Table 18: Recommended Commissioning Test Procedures and Success Criteria for Damped AC Test Voltages

Voltage Class [kV]	Test Level [U_0]	Frequency Range [Hz]	Number of Shots [#]	PD Pass/Fail Criterion
66-72	1.9	10-500	> 50[§]	No Detectable PD
110/115				
132/138	1.7			
150/160				
220/230	Some reported experiences but insufficient to provide test guidance			
275/285				
345/400	No reported experiences to provide test guidance			
500				

§: The number of shots required is currently unknown but for experimental purposes a number greater than 50 is suggested

There remain a number of issues/unknowns associated with the use of DAC voltage sources, including:

- The damped nature of the voltage waveform thereby making specification of test duration challenging.
- The non-constant nature of the applied test voltage.
- The electrical tree initiation and growth dynamics are largely unknown for repetitive applications of DAC waveforms.
- The appropriate initial voltage test levels to initiate PD at life limiting defects in typical HV and EHV cable systems are largely unknown.
- The appropriate number of shots of Damped AC required to initiate PD at life limiting defects otherwise requiring local losses (some time with constant voltage AC) to be detectable.
- The number of shots required to cause insulation failure for life limiting defects which do not give rise to PD during constant voltage resonant tests but rather cause insulation failure.
- The voltage exposure resulting from long dc charging times relative to the DAC waveform period (minutes versus milliseconds).

8.6.6 Calibration Principles

In the context of cable system PD measurements, the term "calibration" is strictly defined as the process presented in IEC 60270 for relating measurement data to charge magnitudes. Originally, the calibration process was developed for laboratory use; the goal was to develop a practical framework that enabled results between laboratories to be compared. However, there are a number of explicit conditions that must be fulfilled in the field for calibration to be meaningful. The following sections discuss these conditions and the resulting limitations.

Copyright © 2016, Georgia Tech Research Corporation

8.6.6.1 IEC 60270 Calibration Method

The calibration of PD measuring systems is intended to verify that the measuring system is able to measure a predetermined PD magnitude in pico-coulomb correctly. Calibration is done for the complete test configuration including:

- Cable system under test,
- Coupling capacitor, and
- Measurement hardware.

Calibration must be made for each cable system to be tested unless tests are made on a group of similar cable systems. In this case, "similar" means the same cable type, length, and accessories.

Calibrating a PD measuring system is done by repetitively injecting a short duration current pulse of known charge magnitude (known current and integration time) into one termination of the cable system under test (with all required measuring and source equipment connected). The resulting configuration puts the pulse injector in parallel with the coupling capacitor and high voltage source as shown in Figure 34.

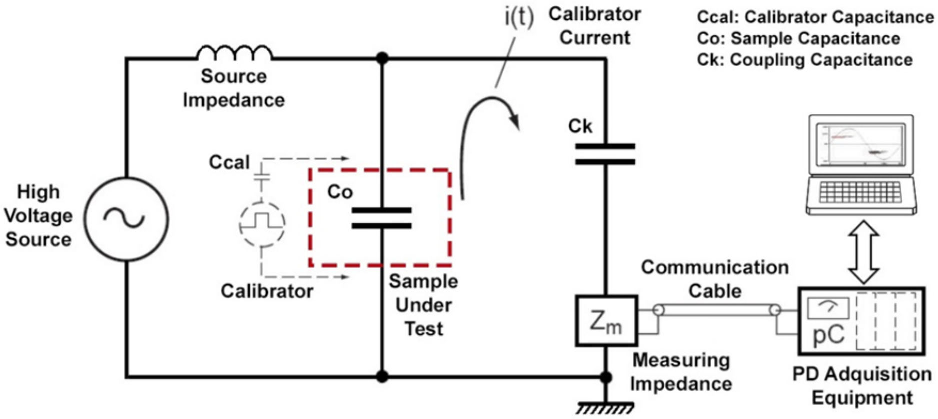


Figure 34: Calibration Test Set-up for PD Measurements

The pulse injection is done using a calibrator (pulse injector) that is designed and is itself calibrated to provide a consistent known charge magnitude. IEC 62070 specifies a number of requirements for the calibrator device. Unfortunately, no specific requirements for the pulse wave shape (i.e. amplitude and pulse width) are specified.

The standard PD measuring test method presented in IEC 60270 is the coupling capacitor method (i.e. independent of the type of electrical sensor used (capacitive or inductive) the presence of the coupling capacitor is always required). Figure 34 illustrates the reasoning behind this. As PD pulses contain high frequency components, these frequency components do not flow through the high voltage source as it is largely inductive and represents high impedance. The coupling capacitor provides a low impedance path for these frequencies allowing PD current pulses to be measured by the sensor (Z_m – measuring impedance).

In this method, the charges of PD pulses are usually determined from the peak magnitudes of the pulses in the detector. These peaks as seen by the PD detector depend on the capacitances of the sample under test and the measuring circuit (coupling capacitance). When the detected PD pulses are compared with the calibration pulses, the apparent charge magnitudes of the PD pulses can be estimated.

The PD calibrator needs to comply with standard requirements and so its characteristics are checked periodically. IEC 60270 regulates the specification to estimate the calibrator performance, and this specification and others related to the calibration procedure are shown in Table 19. This standard specification regulates the type test, routine test, performance test, and performance check of the PD calibrator. Charge, rise time, and pulse repetition rate must be measured and calibrated in these tests, except for the performance check.

Table 19: IEC 60270 Requirements for PD Calibrators

Attribute	**Requirement**	**Comments**
Calibrator Charge (q_0)	Tolerance ±5% of set charge and ≤ 1 pC	Clause 7.2.3 whichever is greater
Pulse Rise Time (tr)	Tolerance ±10% of set time and ≤ 60 ns	Clause 7.2.3 tr – 10% to 90% of peak value
Pulse Repetition Rate (**N**)	Tolerance ±1% of set rate	Clause 7.2.3
Linearity of Calibrator	Tolerance ±5% or ±1 pC	Clause 6.3 whichever is greater
PD Measured Metric (Scaled Charge)	50% to 200% of Calibration	Clause 5.2
Calibrator Capacitance (C_{cal})	≤ 0.1 Sample Capacitance (C_0)	Clause 5.2
Coupling Capacitor (C_k)	Always to be present	Regardless sensor type (capacitive or inductive)
Recalibration Sample Capacitance (C_0)	In the range of ± 10% of C_0 allowed	No recalibration required for similar cable systems Clause 5.2

8.6.6.2 Pulse Injectors

Pulse injectors (otherwise known as calibrators) are used in the calibration procedure described above. As Table 19 shows, the waveform the pulse injector generates is not defined and so the bandwidth of the pulse is equally ill-defined. It is, therefore, difficult to reconcile the "calibration" aspect of these devices with the recommended bandwidths for PD instruments when the pulses used in calibration are not specified.

The issue is important since the signal deterioration of high frequency components of PD pulses travelling through a cable system is significant. Pulse injectors themselves are believed to produce pulses that resemble actual PD pulses and so should have quite wide bandwidths. The relationship between the injected pulses and the bandwidth can be analyzed by comparing the power spectrum density functions of the pulses with the recommended bandwidths. A study was conducted with three different pulse injectors to determine what differences exist between devices and their effect on the results a PD instrument would report had these injectors been used for calibration.

The pulse injectors used in this experiment are shown in Figure 35.

Figure 35: Commercially Available Pulse Injectors

Figure 36 shows a comparison between pulse waveforms of the different injectors for a setting of 100 pC and into an impedance of 50 Ω. The value of 50 Ω is selected because cable characteristic impedances are usually near this value.

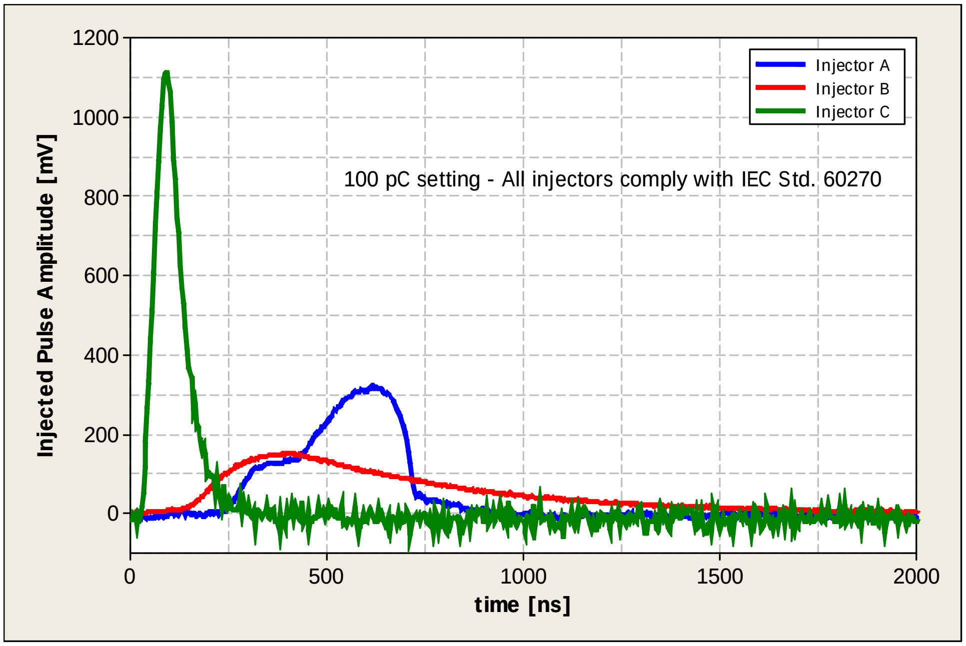


Figure 36: Comparison between Pulse Injectors – 100 pC Setting into a 50 Ω Impedance

As seen in Figure 36, the waveforms between pulse injectors are different; however, they should be compared in terms of their charge settings, which can be estimated by the area under the pulse. This comparison is shown in Figure 37.

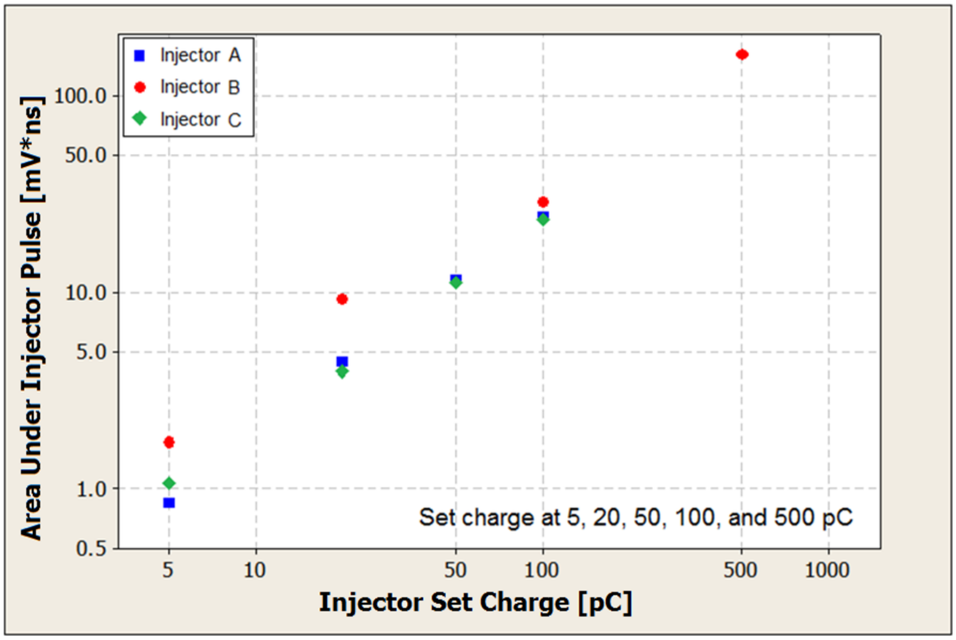


Figure 37: Comparison of Calculated and Actual Charge Settings for Different Injectors

As seen in Figure 37, there is a linear correlation between the charge setting and the area under the pulse for all three injectors. However, the difference between pulse waveform shapes is significant even though they produce similar charge magnitudes. Considerable differences may be observed between the injected pulse waveforms in Figure 36. These differences do not impose limitations on the applicability of pulse injectors because all of them comply with the required scale charge magnitude and other IEC 60270 requirements. However, differences in pulse waveforms directly translate to different frequency spectra. The comparison of these spectra is shown in Figure 38.

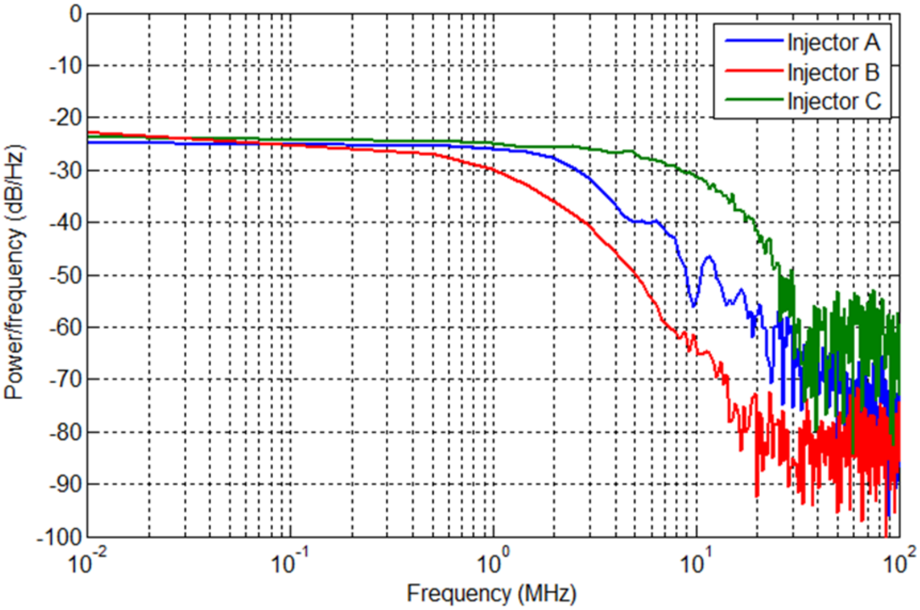


Figure 38: Power Spectral Density of Different Injector Pulses

As shown in Figure 38, at low frequencies (< 300 kHz) all three pulses have virtually the same spectrum. This is expected since the zero frequency component of the spectrum is directly related to the area under the pulse in time domain and thus the charge setting. However, significant differences are observed between spectra at high frequencies (>1 MHz). For example, the fastest pulse (Injector C) has higher frequency content as compared with the slowest pulse (Injector B) which has the lowest frequency content. It can be also seen in Figure 38 that at high frequencies the pulse from Injector A lies between Injector B and Injector C. This leads to two observations:

- At low frequencies and for the same charge setting, all injector pulses and, thus, devices can be assumed to be the same as long as they comply with IEC requirements.
- At high frequencies and for the same charge setting, all injector pulses and, thus, devices behave differently. Therefore, injected pulse waveform is imperative and should be considered if measurements are to be deployed in this frequency range.

While the above two observations are clearly shown in Figure 38, it is still difficult to define the boundary that should be used for distinguishing the low and the high frequency ranges. This can be overcome by considering the approach adopted in filter design. When designing different filters (low, high, and band pass) the 3 dB-point criterion by which the frequency threshold value is often defined relative to the maximum value of the power spectrum density function. The 3 dB-point corresponds to the frequency where the power spectrum density function is half its maximum value. The 3 dB-point criterion has been applied to the power spectrum density functions of Figure 38 and the results are shown in Figure 39.

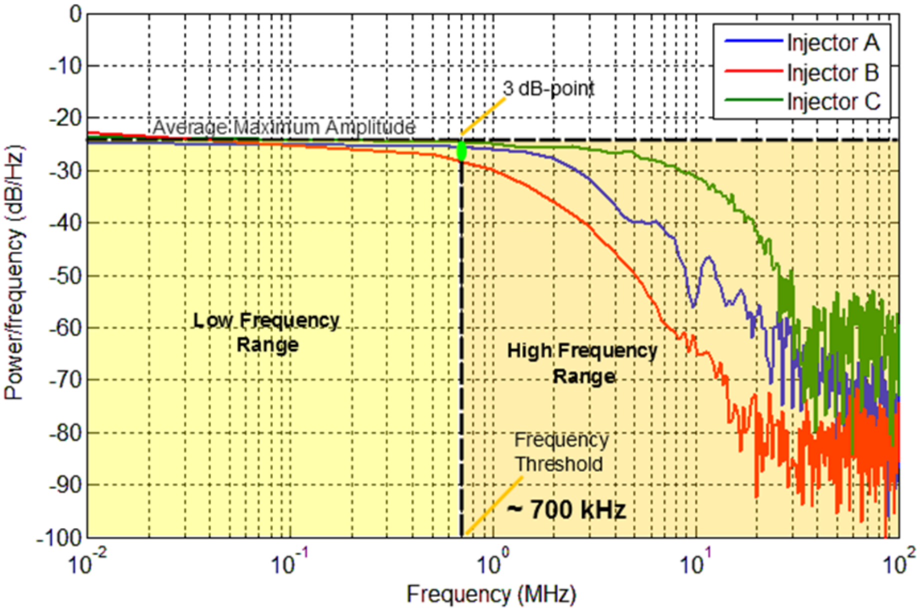


Figure 39: 3 dB-point Criterion to Determine Frequency Threshold

Figure 39 shows the threshold for differentiating the low and the high frequency ranges is approximately 700 kHz using the criterion discussed above.

Copyright © 2016, Georgia Tech Research Corporation

Once the threshold frequency between the low and the high frequency ranges is established, a comparison between IEC Std. 60270 – 2000 bandwidth requirements and the power spectrum density functions, of the different injector pulses corresponding to Figure 36, is shown in Figure 40.

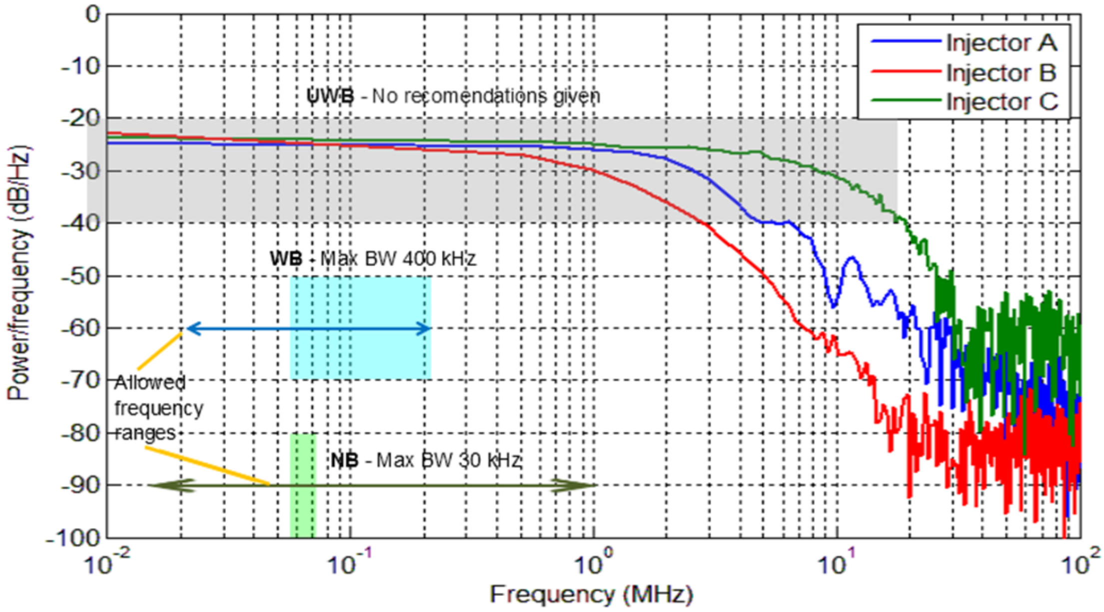


Figure 40: Comparison between IEC Std. 60270 – 2000 Bandwidth Requirements and the Power Spectral Density Function of Different Injector Pulses Corresponding to Figure 36

Considering the frequency threshold level of 700 kHz, then the narrow-band (NB) and wide-band (WB) allowed bandwidths fall in the low frequency range of the spectral density function of the injector pulses; therefore, it can be concluded that if NB or WB frequency ranges as specified by IEC Std. 60270 – 2000 are used for PD measurements, then there are no issues or limitations regarding the waveform of the injector pulses. Under this scenario, different injectors may be used and results can be compared in terms of scale charge through the calibration procedure as specified by the standard.

In contrast, the ultra-wide-band (UWB) as seen in Figure 40 considers frequencies that are below and above the threshold level of 700 kHz. Therefore, the injector pulse waveshape is relevant and results using different injectors cannot be compared. It is also important to note that under these conditions the energy of the injected pulse could be an additional factor to consider since the energy in the Injector C pulse is greater than that from Injector B. The higher energy of Injector C comes from the fact that its power spectrum density function has higher frequency components.

All issues and limitations described here that emerge when using UWB could be diminished by defining the characteristics of pulse injectors such that they produce the same standardized waveform.

8.6.7 Performance Assessment

The current thinking for field PD measurements is that there should be performance checks made before the actual PD test to provide a measure of the "goodness" of the test. This would include quantifying background noise levels, sensitivity, etc. In declaring cable systems to be PD free it is important to understand the detection limitations for the particular circuit, equipment, and noise environment at the time of the test. HV and EHV cable systems are exceedingly good at attenuating PD signals either through the cable or accessories. It is, therefore, difficult to define performance metrics given the nature of these systems and the wide variety of designs in service. At a minimum, the PD provider should provide an indication of the background noise level and confidence level when declaring a cable system to be "PD free". Discussions within the industry continue on this topic.

8.6.8 Expected Outcomes

The effort expended by the Cigre B1.28 Working Group in conjunction with the *CDFI* led to the collation of the world's most extensive HV and EHV testing outcome database. This database was used to extract the expected outcomes for tests on these types of cable systems. As explained above, the focus on commissioning style tests is also evident in the testing database and so the outcomes reported below are for commissioning tests only. When considering these results it is important to be aware of the effect of "confirmation bias" where respondents are more likely to report tests in which PD presence is confirmed rather than its absence. As a consequence, the analysis reported here should be regarded as representing the upper limits for the expected outcomes.

The occurrence of PD within commissioning tests was segregated for HV and EHV cable systems and the percentages are calculated considering the following approaches:

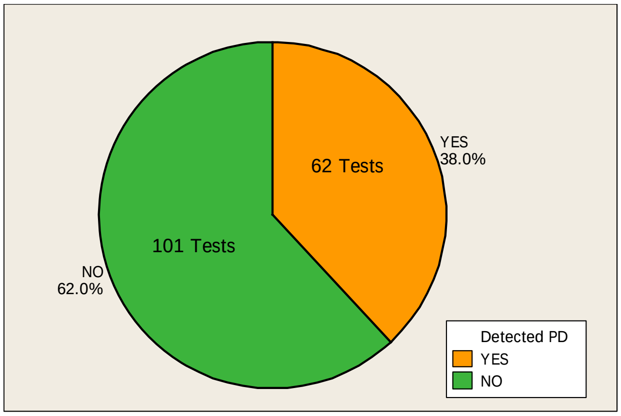
- In terms of total number of PD tests conducted and irrespective of cable system length and
- In terms of total PD tested length.

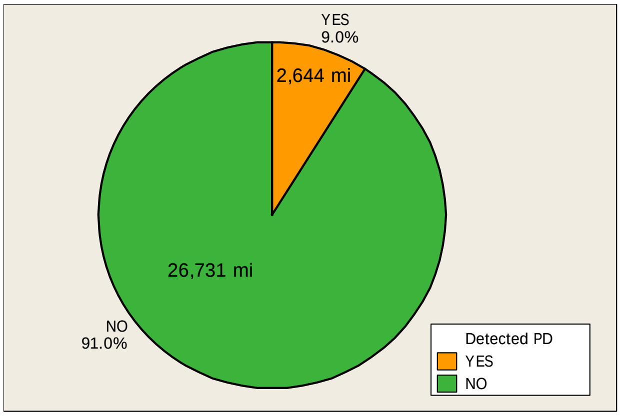
Considering these alternative approaches, the expected outcomes for PD measurements deployed on HV and EHV cable systems from survey results are shown in Table 20.

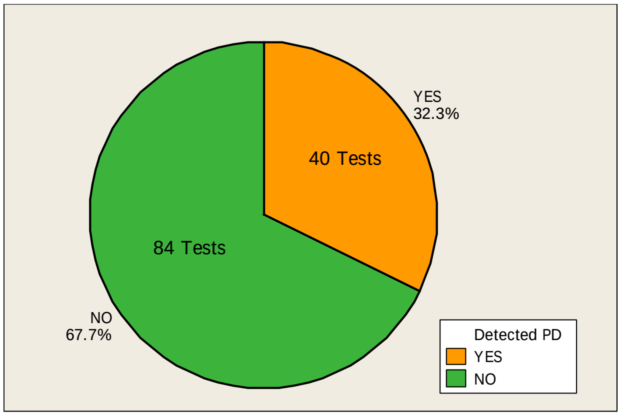
The results for HV cable systems are based on a total of 163 tests with a total tested length of 29,375 mi (~ 47,378 km) over 19 years (1990 through 2008). Meanwhile, the results for EHV cable systems are based on 124 tests with a total tested length of 14,955 mi (~ 23,934 km) over the same time period as HV.

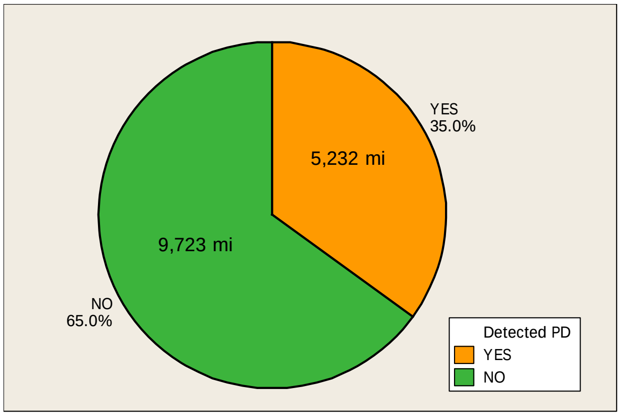
Copyright © 2016, Georgia Tech Research Corporation

Table 20: Expected Outcomes for PD Measurements Deployed in HV and EHV Cable Systems

<table>
<tr><th>In terms of Total Number of PD Tests</th><th>In terms of Total of PD Length Tested</th></tr>
<tr><td colspan="2">HV Cable Systems</td></tr>
<tr><td>


</td><td>


</td></tr>
<tr><td colspan="2">EHV Cable Systems</td></tr>
<tr><td>


</td><td>


</td></tr>
</table>

One of the benefits of PD testing as part of commissioning is that the detection of PD provides the opportunity for the test to be ended early before an actual failure occurs. This can potentially reduce the costs and time associated with a repair. A number of respondents provided information on whether dielectric failures occurred when PD was detected. In these cases, failure occurred in only 3 – 4% of the tests where PD was detected. Data to determine the failure rate for a non-PD monitored withstand commissioning test (Simple Withstand) to IEC Std. 60840 – 2004 and IEC Std. 62067 – 2011 were not available.

8.6.8.1 Cable System Information

As mentioned earlier, the voltage ranges for the Cigre B1.28 study were determined according to the ranges specified in IEC 60840 and IEC 62067. The distribution of test entries (regardless of whether or not PD assessment was performed) was determined. These data are shown in histogram format in Figure 41. The figures represent the cable system length tested.

Copyright © 2016, Georgia Tech Research Corporation

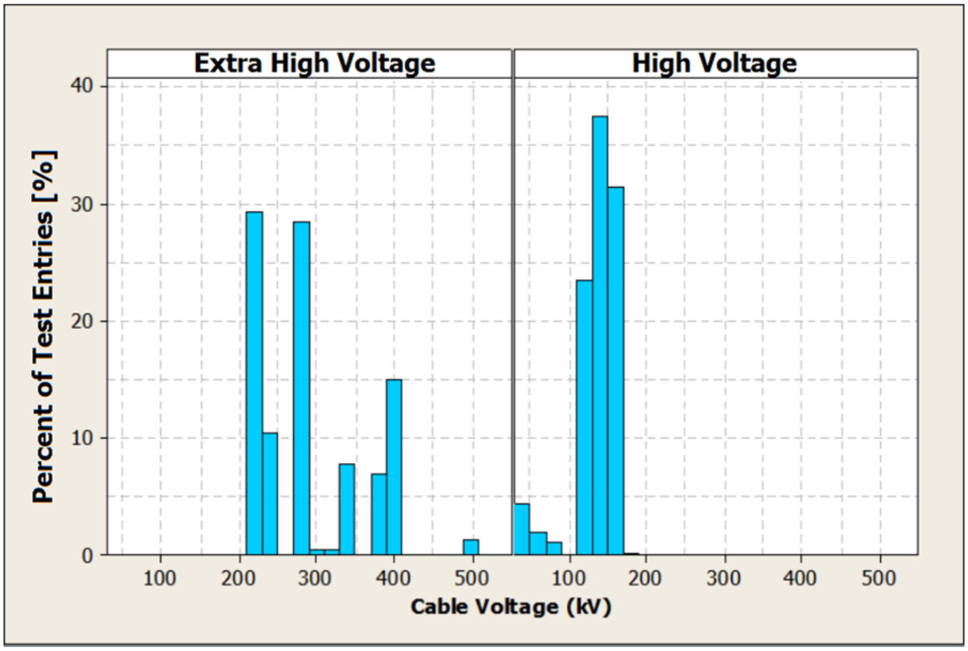


Figure 41: Distribution of Tests within the HV and EHV Voltage Classes (the lengths refer to the cumulative length of the cable systems)

Survey respondents, in general, also provided an indication of the year in which tests were carried out. Thus, it is instructive to examine the evolution of testing in terms of both number of tests and their inclusion of a PD measurement. These data are shown in Figure 42.

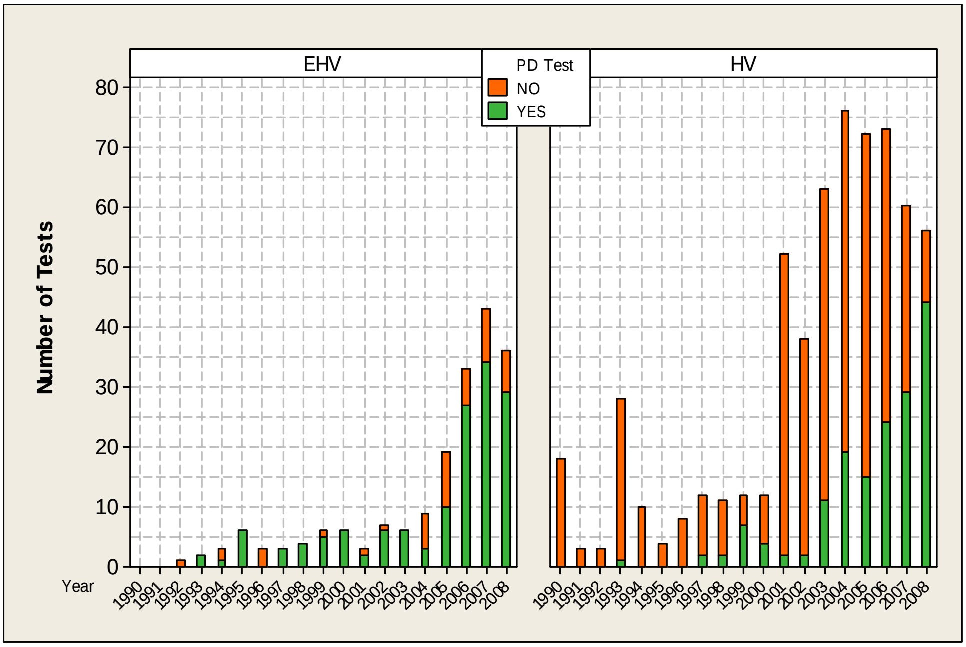


Figure 42: Evolution of Reported Commissioning Tests – Voltage Withstand Tests both with (YES) and without (NO) PD Assessment

As Figure 42 shows, the number of commissioning tests has increased considerably for both HV and EHV systems. It is also evident that the fraction of tests that make use of PD measurements has also increased. By the end of the 2008, the inclusion of PD measurement during commissioning has become essentially standard practice. However, the results presented in Figure 42 must be viewed as upper limits resulting from the potential "confirmation bias" mentioned earlier.

8.6.9 Influence of Noise

As PD measurement constitutes the detection of induced high frequency, very high frequency and/or ultra-high frequency signals on cable systems, rejection of similar non-PD related signals is imperative. These signals are generally termed as noise. Unfortunately, noise is always present when performing PD measurements.

The noise can be a critical impediment to successfully detecting discharge. Magnitudes of the PD pulses as seen by the measuring equipment are in the order of fractions of a millivolt to several tens of millivolts. In addition, when PD pulses reach the detection equipment, they generally have a bandwidth of several tens of megahertz. Unfortunately, this frequency range includes most of the amplitude and frequency modulated communication signals and, in some cases, these signals can have a higher magnitude than the partial discharge signals that are of interest.

The level of noise depends on several factors that include system parameters such as length, location, design, structure, and signal degradation mechanisms, as well as the particular nature of the discharge itself. From the perspective of noise, the cable acts as an antenna that picks up the communication signals, additional noise may be present due to noisy grounding. Therefore, it is unavoidable for these communication signals or ground noise to be present in the cable system and thus get detected together with the PD signals. Several techniques have been used to reduce the background noise level. Analog and digital filters are typically applied. Most recently the application of powerful digital signal processing techniques such as wavelet transforms have been used to address this issue.

One of the more important improvements for signal classification has been the development and application of the classification map. The basis of the classification map is the fact that PD pulse waveform characteristics depend on the nature of the defect, as well as the signal deterioration they experience while travelling from their source to the measurement equipment. Thus, the main assumption / premise is that pulses having similar waveforms should come from the same source. The classification map is realized by computing features that provide a compact and meaningful representation of the acquired pulses. Several features are possible. Within *CDFI*, the instruments available for HV and EHV PD tests have typically used temporal and frequency content information.

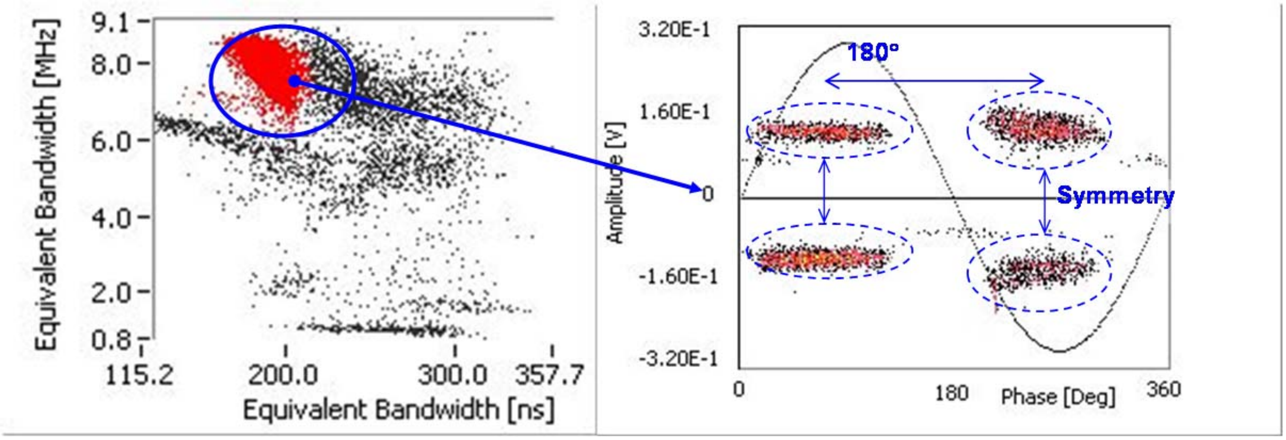
Various approaches to this technique have been implemented by manufactures and providers of PD test equipment. The processing and generation of a classification map relies upon the acquisition of a large number of pulses and can only be applied to acquired data. Unfortunately, in many cases such classification mapping does not significantly improve the true signal-to-noise ratio of a field PD measurement in the presence of high levels of noise. In other cases, there is a noticeable improvement in less intense noise environments as the classification map was shown to provide an improvement in the qualitative signal-to-noise ratio of the test.

Copyright © 2016, Georgia Tech Research Corporation

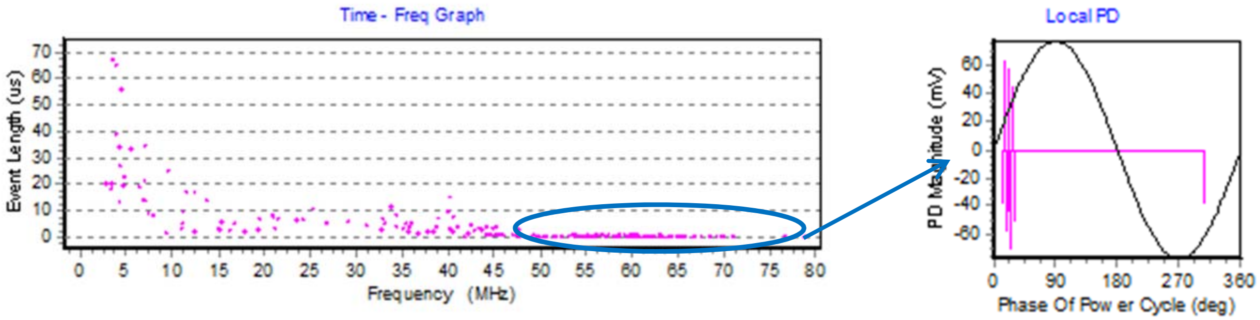
The most powerful capability of classification maps are their ability to separate pulses from multiple sources be they discharge or noise. This allows the operator to focus on the pulse classes that are most likely to affect the performance of the cable system. Figure 43 shows some examples of classification maps from different PD providers.

Classification Map **Phase-Resolved PD Pattern**

Provider A



Provider B



Provider C

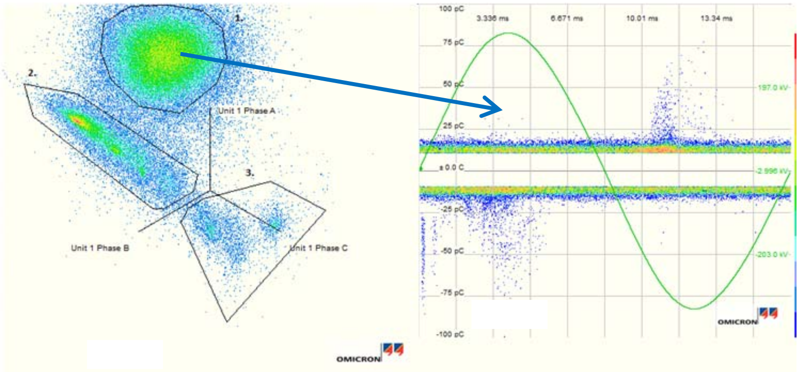


Figure 43: Example Classification Maps from Different PD Providers

8.6.10 Conundrum between PD Apparent Charge and Energy

The idea of signal "size" is crucial to many applications. For example, it would be nice to know how much electricity can be used in a defibrillator without causing permanent damage to the patient, or if the signal driving a set of headphones is enough to create a sound. While both of these examples deal with electrical signals, they are clearly very different cases. For this reason, it is imperative to quantify this idea of "size" of a signal in its specific context. The quantification of the "size" of a signal then leads to the ideas of area under the curve and energy.

Since a signal is generally thought of as a function of varying amplitude through time, it seems to reason that a good measurement of the strength of a signal would be the area under the time curve. However, this area may have the opposite polarity of another portion and could thus cancel each other out. The negative polarity part does not have less strength than the equivalent positive signal. A better approach to estimate the signal strength would then be either squaring the signal magnitude or taking its absolute value, and then finding the area under that curve. As a matter of fact, it turns out that the energy of a signal is defined as the area under the curve of the squared signal. An illustration of the area under the curve and energy for a signal as a function of time ($f_{(t)}$) is shown in Figure 44.

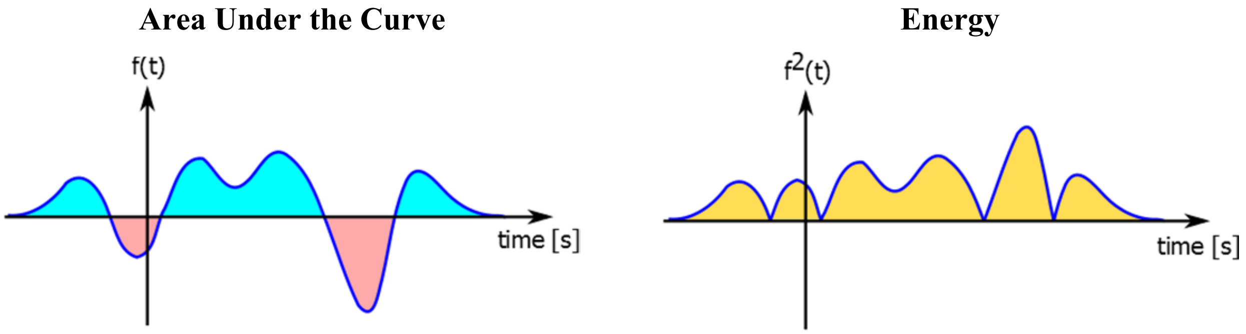


Figure 44: Illustration of the Area Under the Curve and Energy for a Signal as a Function of Time ($f_{(t)}$)

In the case of PD, the relationship between the area under the curve (scaled charge) and energy is rather important to understand. Traditionally, PD activity has been quantified by the scaled charge. The use of scaled charge as a metric for PD and low frequency bandwidths make measurements insensitive to PD pulse shape and other signal aberrations. However, this assumption only holds valid by assuming that the cable system acts as a low-pass filter and thus the scaled charge (dc component of the PD signal) is completely transferred from the PD site to the location of the PD measuring equipment. Under this scenario, another issue that is generally overlooked even for an ideal (lossless) cable system is the fact that the peak amplitude of the traveling PD pulse could decrease to a point at which it is comparable to the background noise level and thus no triggering/detection are possible.

In real cases, both the scaled charge and signal energy change as the PD signal propagates through the cable system. This situation is unavoidable and is a consequence of the very high frequency components of PD signals and the non-linear frequency response of the cable system that results in interactions between frequencies components. In order to understand the conundrum between PD scaled charge and energy, two studies are presented:

- Cable system simulation based on simple filtering and
- Cable system simulation based on frequency dependent and distributed model.

The two studies are presented in detailed in the next sections.

8.6.10.1 Simple Filtering Model

In the simple filtering case, the cable system is modeled as low-pass filter, the input PD pulse is run through the filter and the output PD pulse is recorded. The basis for cable system simulation based on simple filtering is shown in Figure 45.

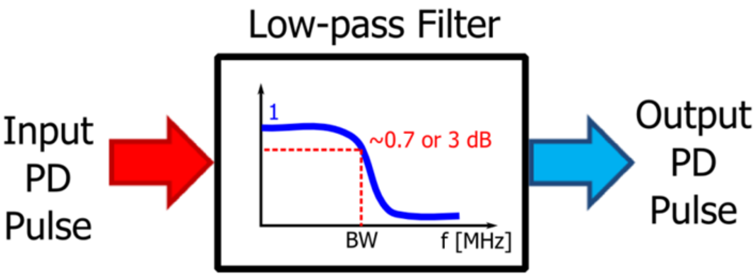


Figure 45: Illustration of Cable System Simulation Based on Simple Filtering

The idea of this example is to consider changes in the filter bandwidth and then study its impact on the PD pulse scaled charge and energy of the output PD pulse referenced to the scaled charge and energy of the input PD pulse. For this example, the input pulse will be a Gaussian pulse of 5 pC and 20 ns (time width). Its time domain waveform and frequency domain spectrum are shown in Figure 46.

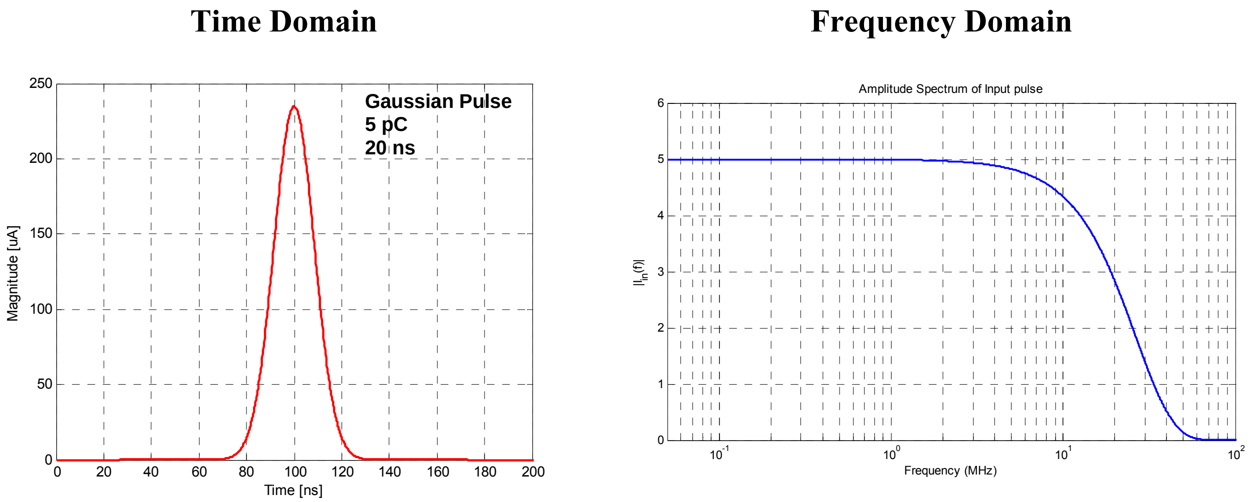
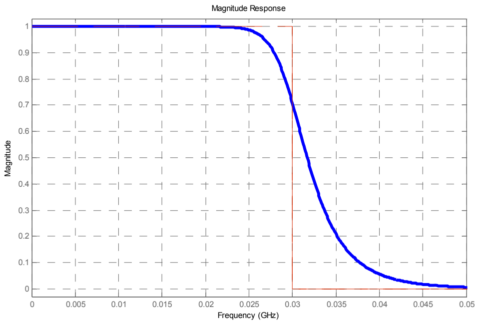
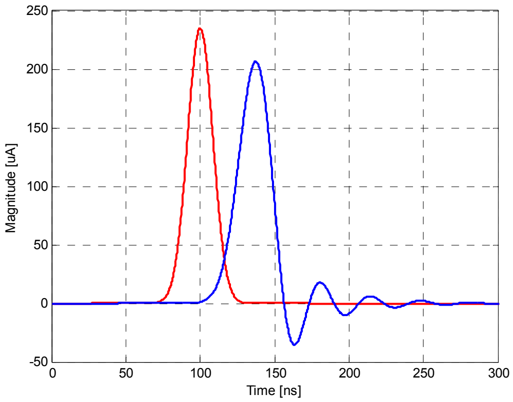
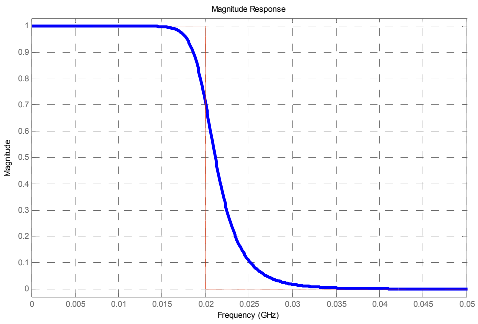
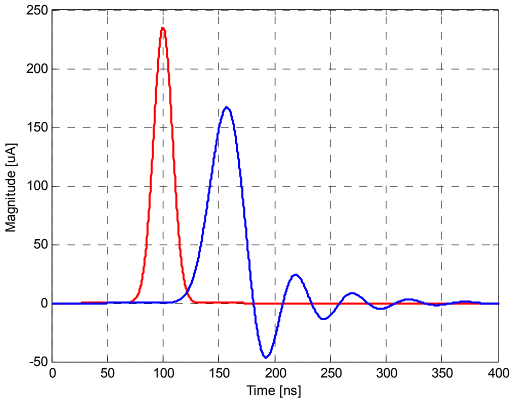
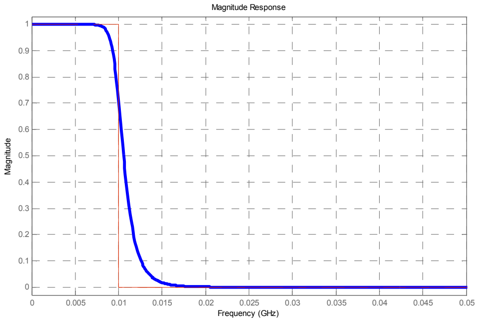
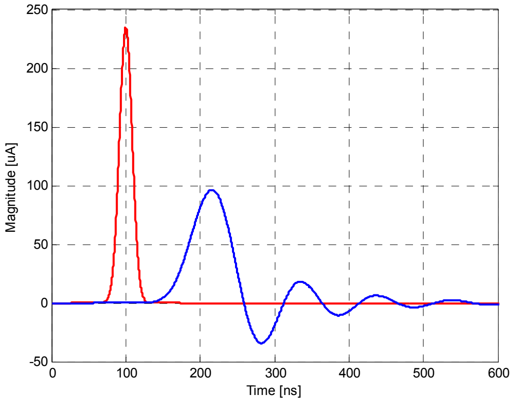


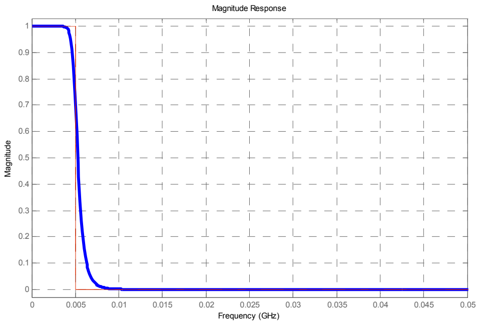
Figure 46: Waveform and Frequency Spectrum of the Input PD Pulse

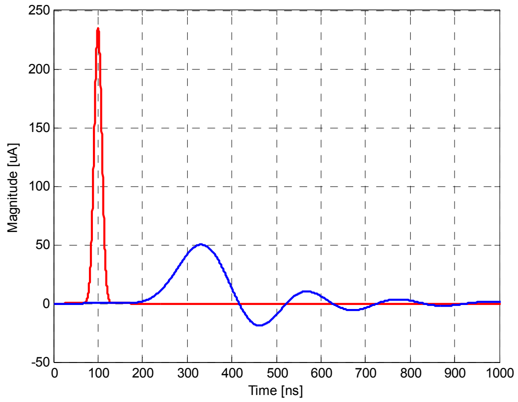
Copyright © 2016, Georgia Tech Research Corporation

The simulation results considering filter bandwidths of 30, 20, 10, 5, and 1 MHz are shown in Table 21. The resulting effects on the output pulse are shown in blue while the input pulses are shown in red. Note the changes in the pulse heights and shape.

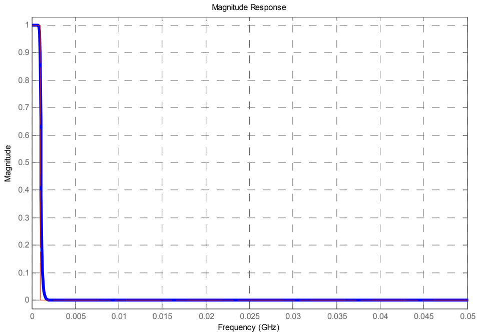
<table>
<tr><th colspan="2">Table 21: Results for Cable System Simulation Based on Simple Filtering</th></tr>
<tr><th>Filter Frequency Response</th><th>Input (Red) and Output (Blue) PD Pulses</th></tr>
<tr><td colspan="2">30 MHz Bandwidth</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">20 MHz Bandwidth</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">10 MHz Bandwidth</td></tr>
<tr><td>
</td><td>
</td></tr>
</table>

5 MHz Bandwidth





1 MHz Bandwidth



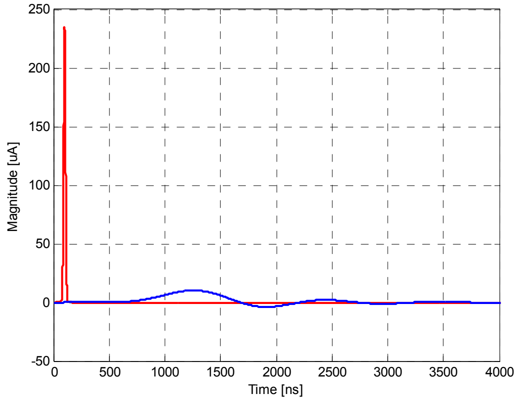


Table 22 shows the scaled charge results for the cable system simulation based on simple filtering.

Table 22: Scaled Charge Results for Cable System Simulation Based on Simple Filtering

Filter Bandwidth [MHz]	Input Scaled Charge [pC]	Output Scaled Charge [pC]	Scaled Charge Ratio [%]
30	5.0	5.0	100
20		5.0	100
10		5.0	100
5		5.0	100
1		5.0	100

As seen in Table 22, the output scaled charge is independent of the bandwidth; in other words, it remains unaltered over changes in bandwidth. The independence of the scaled charge with respect to bandwidth is due to the low-pass characteristics of the filtering, as mentioned earlier, the scaled charge represents the dc (zero frequency) component of the input PD pulse that is always transferred to the output without change. This helps explain why when PD was first used that the scaled charge was selected as the most attractive metric for quantifying PD magnitudes. Unfortunately, the use in PD on long cable systems in the field has made the above assumptions inaccurate.

Copyright © 2016, Georgia Tech Research Corporation

Simulation results for the PD output pulse energy are shown in Table 23 and are also plotted in Figure 47. However, Figure 47 shows the energy loss in percent relative to the energy of the input pulse as a function of bandwidth. The energy loss shown in Figure 47 is obtained by subtracting from 100% the energy ratio in percent column shown in Table 23.

Table 23: PD Energy Results for Cable System Simulation Based on Simple Filtering

Filter Bandwidth [MHz]	Input Energy [μA^2*ns]	Output Energy [μA^2*ns]	Energy Ratio [%]
30	4.15	4.04	97.4
20		3.60	86.7
10		2.28	55.0
5		1.23	29.5
1		0.25	6.0

As seen in Table 23 and Figure 47, the output PD pulse energy loss increases as the filter bandwidth decreases (i.e. more energy is rejected by the filter). For example, the energy losses are 2.6% and 94% for filter bandwidths of 100 MHz and 1 MHz, respectively. Thus, for a bandwidth of 100 MHz, the energy loss is negligible, while the 1 MHz bandwidth energy loss is high. The relationship between energy loss and filter bandwidth is highly dependent on the energy content of the input PD pulse. In this case, the input pulse has a bandwidth of approximately 15 MHz. Therefore, the 30 MHz bandwidth filter allows most of the input PD pulse energy through to the output. On the other hand, the 1 MHz filter only allows a small fraction of the pulse energy though.

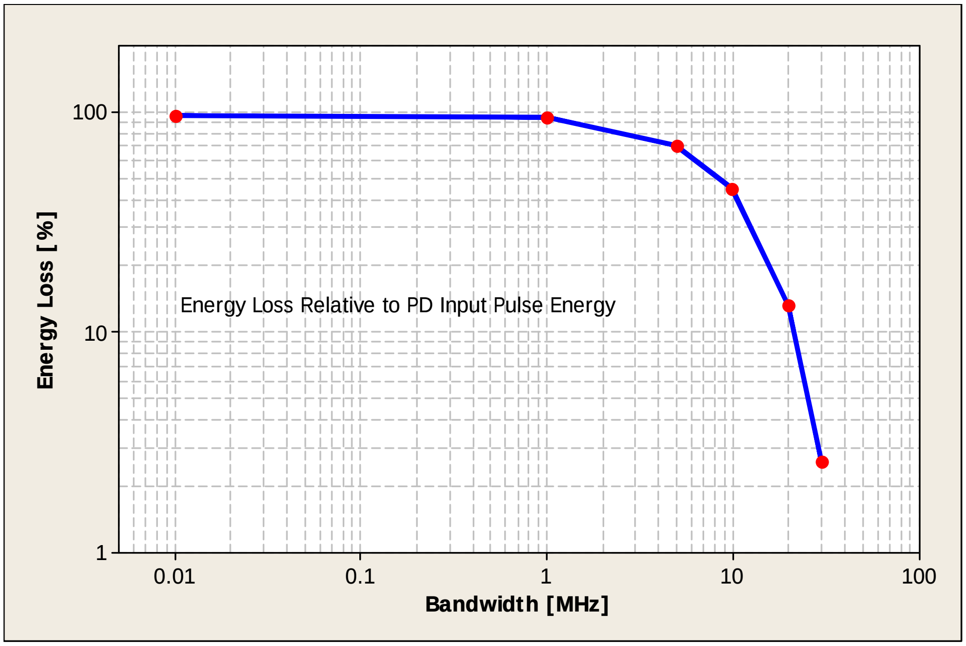


Figure 47: PD Signal Energy Loss versus Filter Bandwidth

As mentioned earlier, another issue to consider is how the peak amplitude of the PD output pulse changes with bandwidth and this is shown in Figure 48.

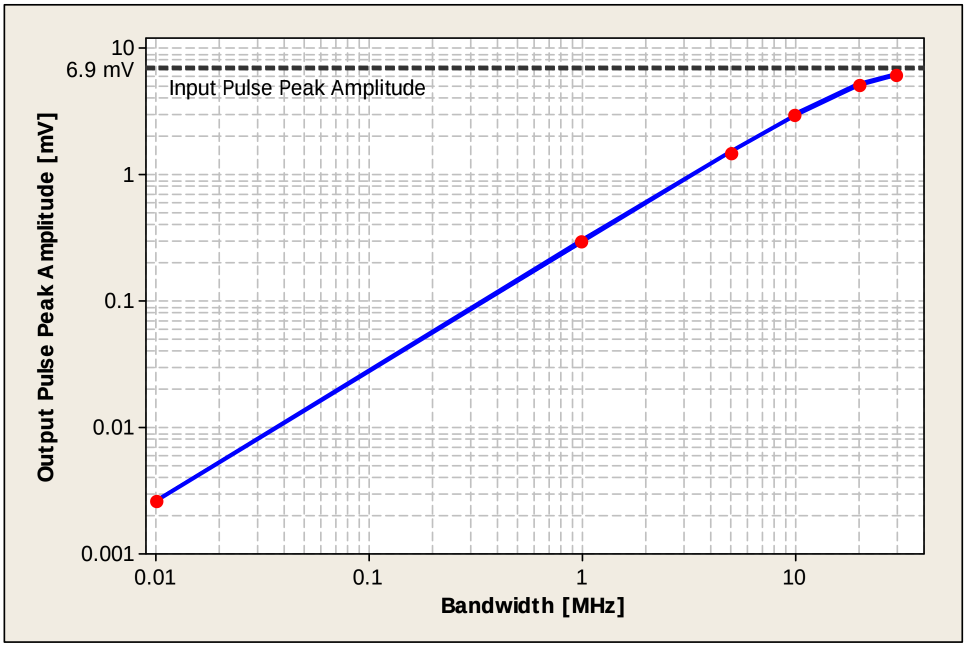


Figure 48: Output PD Pulse Peak Amplitude versus Filter Bandwidth

As observed in Figure 48, the peak amplitude of the output PD pulse increases with increasing filter bandwidth. Since the peak amplitude of the output PD pulse is often used to trigger the detection equipment, care must be taken when selecting the bandwidth of the detection equipment (as well as any noise filters) to avoid reducing the amplitude below the background noise level. Equipment that does not utilize a triggering approach would be more immune to this issue.

8.6.10.2 Frequency Dependent and Distributed Model

The second study is the cable system simulation based on a frequency dependent and distributed model. An illustration of the simulation block diagram is shown in Figure 49.

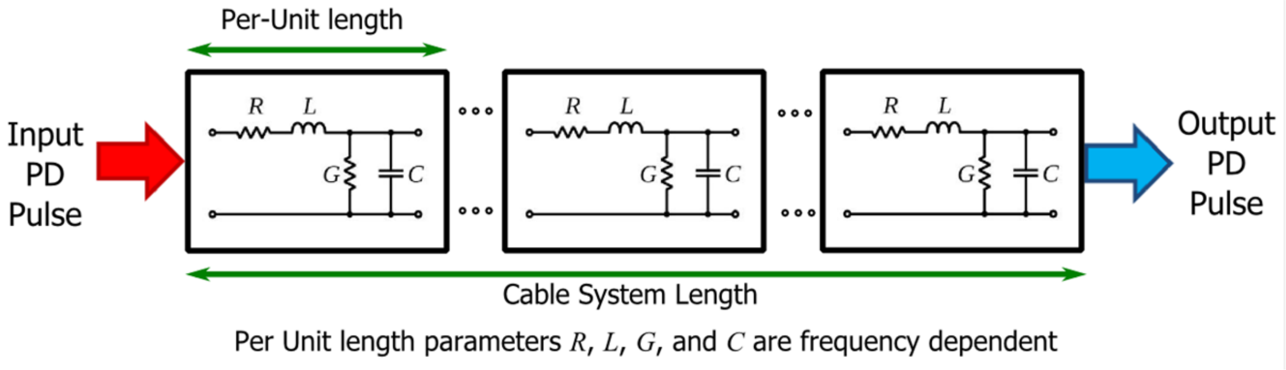


Figure 49: Frequency Dependent Simulation Model

According to Figure 49, the simulation process is as follows: a Gaussian PD input pulse of specified charge and time width enters the cable system model, which consists of a series of equivalent circuits of per-unit length connected in series. The output of the last equivalent circuit represents the

PD output pulse that would be received by the PD sensor. Using this model, changes in the charge can be observed as functions of pulse parameters and distance travelled along the cable system. A set of five input PD pulses with different time widths and the same charge magnitude (50 pC) were used in the simulation. The resulting pulses are shown in Figure 50.

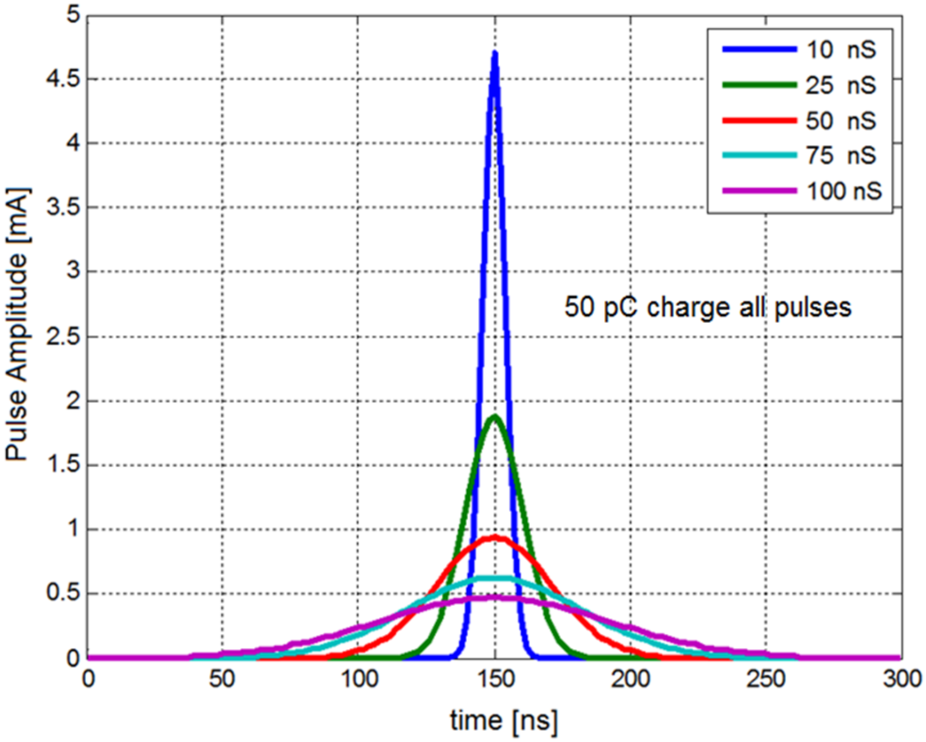


Figure 50: Gaussian PD Pulses for Simulation of Loss of Charge using Frequency Dependent and Distibuted Modeling.

The cable system modeled in these simulations was a 1/0 AWG, XLPE, 15 kV, and 175 mil wall cable system. The simulation results for the PD input pulses of Figure 50 are shown in Figure 51. This figure shows PD pulse charge loss as a function of the distance traveled from the discharge site.

Copyright © 2016, Georgia Tech Research Corporation

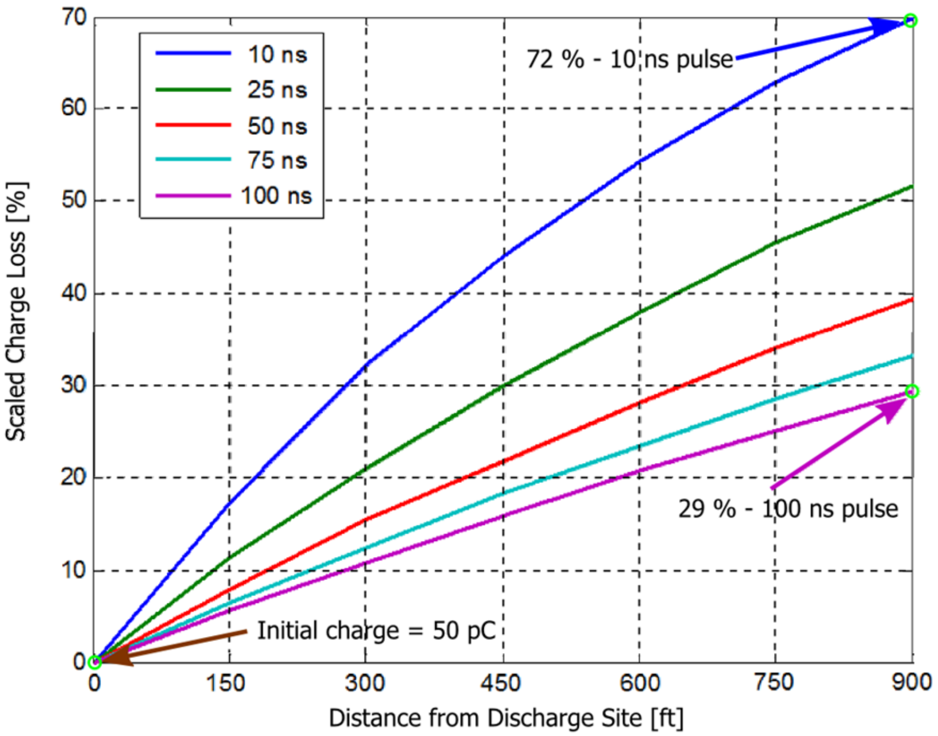


Figure 51: PD Pulse Scaled Charge Loss as a Function of Distance from Discharge Site

The results presented in Figure 51 should be interpreted as follows: the PD pulse originating at the discharge site has an initial charge magnitude of 50 pC and charge is lost as the pulse travels away from the discharge site. For example, consider the 100 ns and 10 ns pulses after they have propagated 900 ft from the source. According to the results in Figure 51, the 100 ns PD pulse would be expected to exhibit 29% charge loss. Similarly, the 10 ns pulse exhibits a charge loss of 72%. Therefore, the corresponding scaled charge magnitudes at 900 ft are would be 36 pC for the 100 ns pulse and 14 pC for the 10 ns pulse.

The results shown in Figure 51 are relevant because they show that the scaled charge loss for a PD pulse is a function of three main factors:

- **PD Pulse Waveform:** Different PD pulse waveforms would have different frequency spectra and thus different charge loss profiles. Since the PD pulse waveform depends upon the nature of the "void-type" defects responsible for the PD then the scaled charge loss profile also depends on the nature of the defect.
- **Distance from PD Source:** The PD pulse scaled charge that is typically thought to be independent of cable system length actually is not. In reality, this phenomenon is always present and the lack of awareness of its existence may cause additional confusion in the interpretation.
- **Other Factors:** Other factors affecting scaled charge loss of a PD pulse are cable system design, structure, aging, and degradation conditions.

Copyright © 2016, Georgia Tech Research Corporation

8.6.11 Grounding Practices

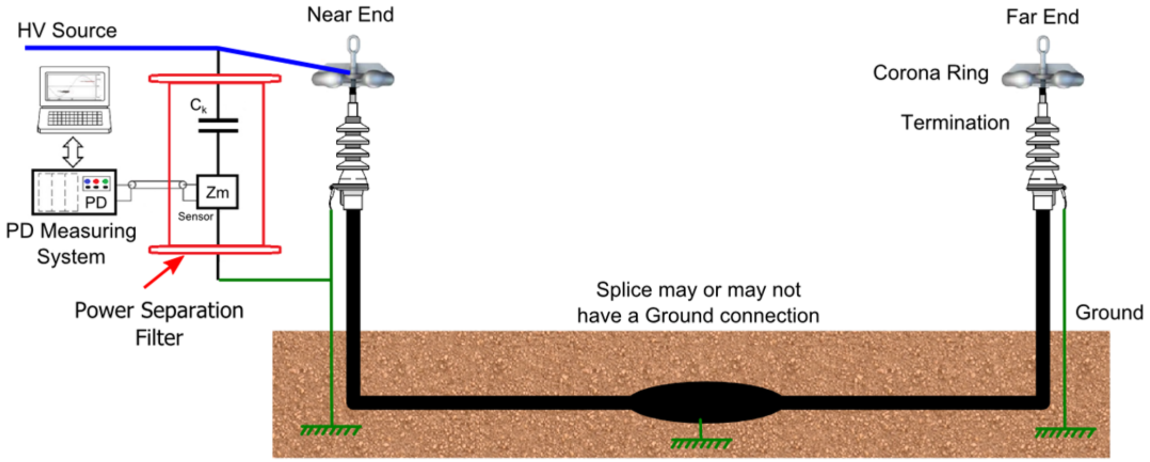
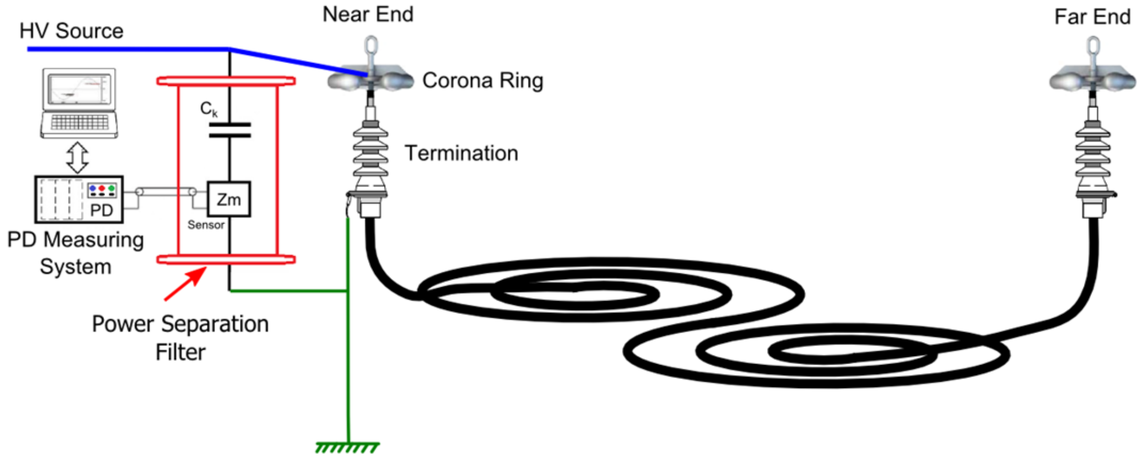
The main goal of grounding is to provide a low impedance path for fault current to return so that protective equipment can detect the fault and act accordingly. This protects users from equipment that could become energized if the fault were not interrupted. Within the context of PD measurements, the cable system grounding has a large effect on how PD signals propagate within the system. Systems with a single grounding point allow PD detection equipment to capture more signals as there is but one path to ground. Multiple grounds allow signals to exit the cable system where there may not be detection equipment set up. Cross bonding causes signals to travel on different phases while Surge Voltage Limiters (SVLs) prevent PD pulses from reaching ground in the first place. These issues all arise with HV and EHV systems installed in the field.

Grounding impacts the signals that are able to flow through the sensors and so sensor placement is a key component to the effect grounding has on PD measurements. Three primary sensor configurations are considered:

- **Capacitive Divider with Built-In Sensor:** This configuration considers the coupling capacitor and the sensor together in the same unit. The PD signal may be detected using either a capacitive or inductive (HFCT) sensor.
- **Coupling Capacitor and Sensor:** This configuration considers the coupling capacitor and sensor as separate units; typically the sensor is an HFCT that can be coupled to the grounding connection of the coupling capacitor or the grounding connection of the cable system under test.
- **Standalone Sensor:** This configuration only considers the presence of the sensor because there are situations in which the use of a coupling capacitor is not possible. Typically the sensor is a HFCT that is coupled to the grounding connection of cable system under test at the near end. Another option is a capacitively coupled sheath sensors.

The various sensor connections and their field and laboratory deployments are shown in Table 24 through Table 26.

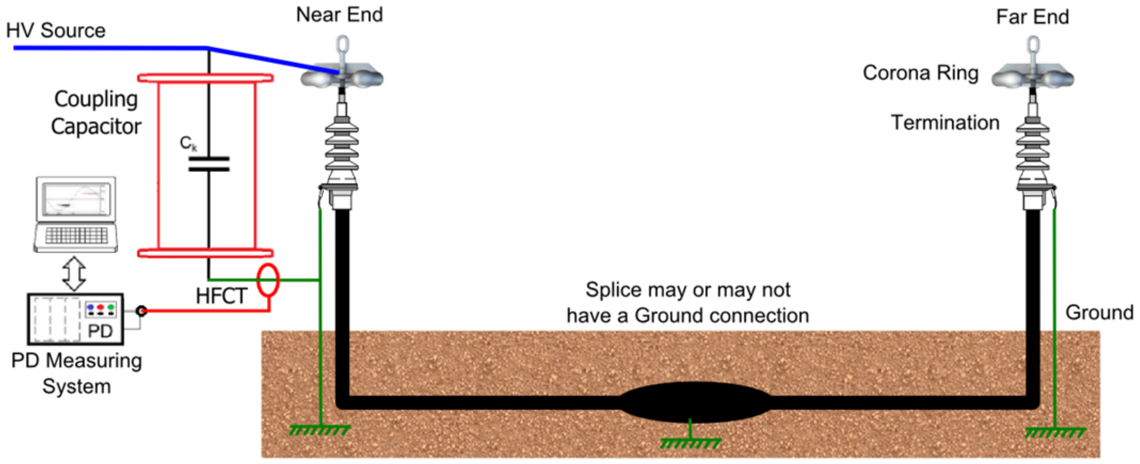
Copyright © 2016, Georgia Tech Research Corporation

Table 24: Capacitive Divider with Built-In Sensor Connections
Field Deployment

Laboratory Deployment


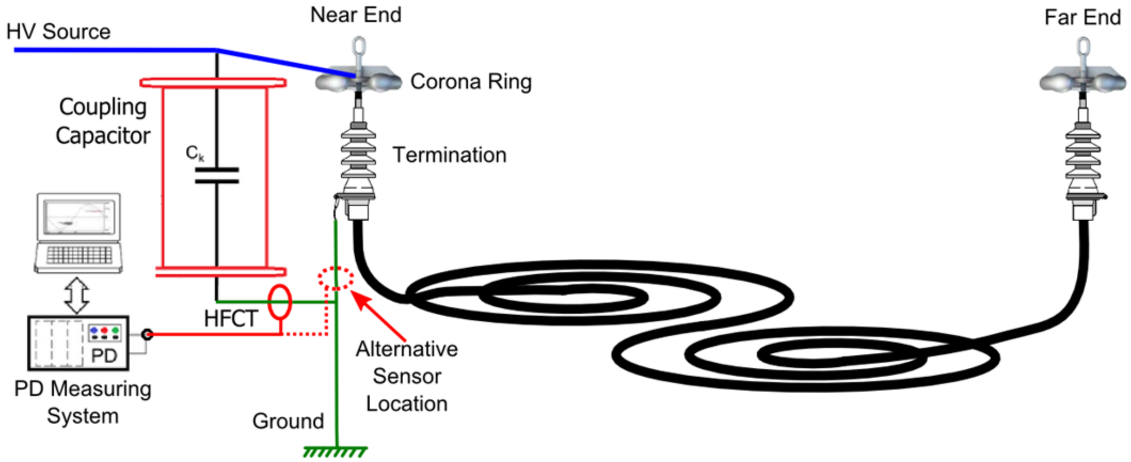
Copyright © 2016, Georgia Tech Research Corporation

Table 25: Capacitive Divider with Separate Sensor Connections

Field Deployment



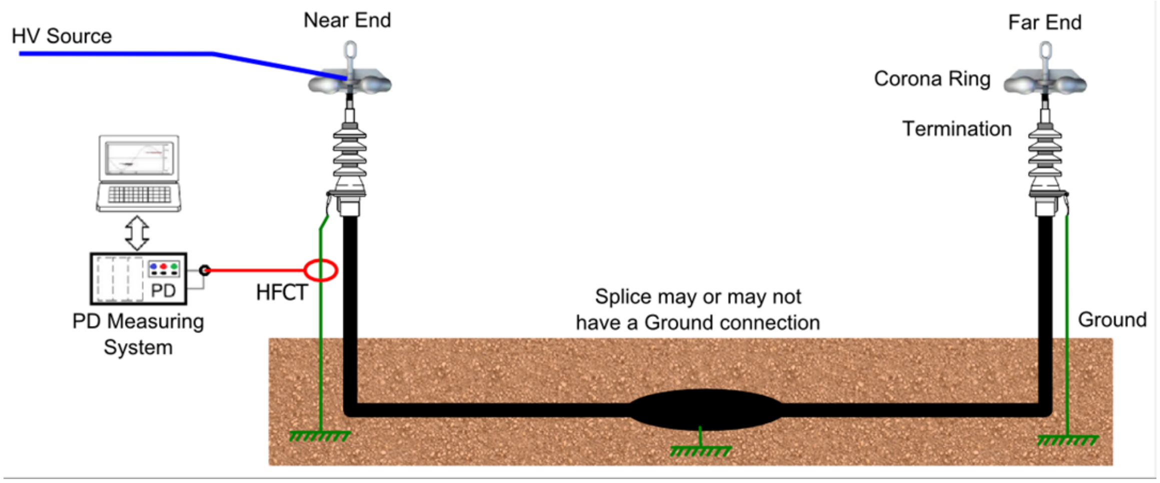
Laboratory Deployment



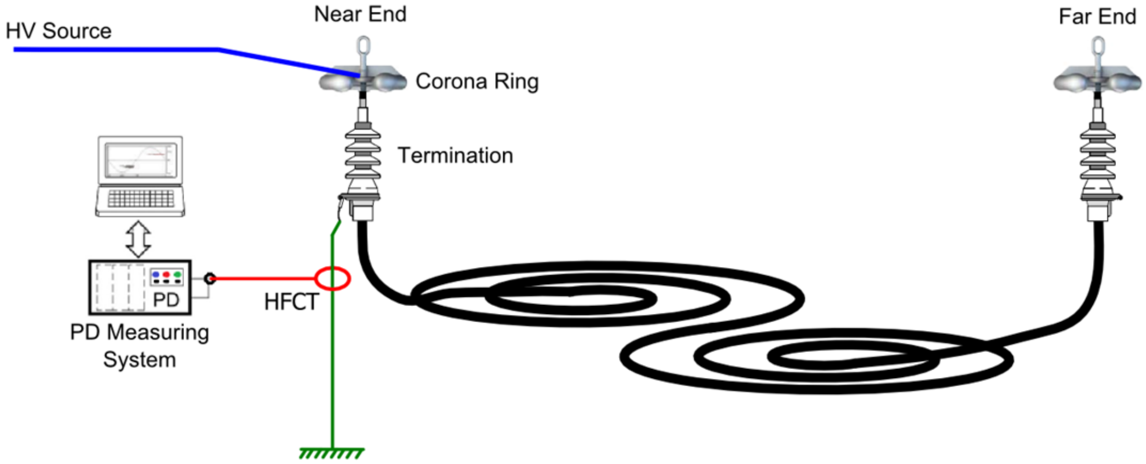
Copyright © 2016, Georgia Tech Research Corporation

Table 26: Standalone Sensor Connections

Laboratory Deployment



Field Deployment



It is important to note than each of the field connection examples utilize a more complicated grounding arrangement than those employed under laboratory conditions. Care must be taken when trying to employ laboratory techniques and guidance in field situations.

Copyright © 2016, Georgia Tech Research Corporation

8.7 Outstanding Issues

As seen in Section 8.6, issues that affect PD measurements on HV and EHV power cable systems are many and diverse; they have been identified and analyzed by the *CDFI*. The identification and analysis have been based focused on crucial characteristics and limitations of PD measurements. Therefore, the outstanding issues, regarding the use of PD measurements as a mean for condition assessment of HV and EHV power cable systems, are as follows:

1. Technologies are generally deployed on new assets, i.e. oriented to commissioning testing. See section 8.6.4, 8.6.5, & 8.6.8.
2. Field measurements cannot be correlated to laboratory / factory test results. See sections 8.6.1, 8.6.2, 8.6.3, 8.6.5, & 8.6.6.
3. Measurements are carried out as part of an ac Monitored Withstand protocol (i.e. simple withstand and PD combined). a) ac withstand {1.7U_0 for 60 min} combined with b) PD tests {PD checks at 0.5 U_0, U_0, and 1.5 U_0 on ramp up and monitoring throughout the withstand portion} are commonly deployed and effectiveness is supported by international data. See sections 8.6.4 & 8.6.5.
4. The aim is to detect the presence and location of PD – the magnitude is generally not of interest. See section 8.6.4, 8.6.5, & 8.6.8.
5. Systems are long and have complicated architectures (laboratory/factory tests assume short lengths and a simple architecture). See section 8.6.1 & 8.6.2.
6. Calibration commonly found in laboratory/factory tests is not valid for field tests. See section 8.6.1, 8.6.2, 8.6.6, & 8.6.11.
7. PD signal deterioration is significant and unavoidable, this imposes limitations on the range of detection (i.e. how far can be seen into the cable system). Hence, only terminal (tests from one end) are rare while distributed measurements (measurements at each accessory – joint hopping) are most commonly used. See sections 8.6.1, 8.6.7, 8.6.9, and 8.6.10.
8. Tests, analysis and reporting are orientated towards establishing the absence of PD from a single test, though multiple PD technologies may be used (trending or comparison with an identifiable benchmark are rare). See section 8.6.4 & 8.6.5.
9. Results showing the absence of PD obtained from different PD technologies can be collated. See section 8.6.3, 8.6.5, & 8.6.8.
10. Trending/repeat tests are rarely carried out. See section 8.6.4, 8.6.5, & 8.6.8.

Due to the issues and limitations listed above, the information in this Chapter provides the user with an increased awareness of PD measurements on HV and EHV cable systems with a somewhat detailed explanation of how to conduct tests and analyze their results.

8.8 References

1. L.A. Dissado, and J.C. Fothergill, "Electrical degradation and breakdown in polymers," IEE Materials and devices series 9, Peter Peregrinus Ltd., London, 1992.
2. E. Gulski, J. Smit, and F. Wester, "PD knowledge rules for insulation condition assessment of distribution power cables," IEEE Trans. on Dielectrics and Electrical Insulation, vol. 12, no. 2, pp. 223-239, Apr. 2005.
3. J. Densley, "Aging Mechanisms and Diagnostics for Power Cables-An Overview," IEEE Electrical Insulation Magazine, vol. 17, no. 1, pp. 14-22, Jan. /Feb. 2001.
4. R. Bartnikas and K. D. Srivastava, "Power and Communication Cables: Theory and Applications," IEEE Series on Power Engineering, New York, 1999.
5. M. S. Mashikian, "Preventive Maintenance Testing of Shielded Power Cable Systems," IEEE Transactions on Industry Applications, Vol. 38, No. 3, May/June 2002, pp. 736-743.
6. T. Toshikatsu and A. Greenwood, "Advanced power cable technology: present and future," CRC Press Inc., Boca Raton, vol. II, 1983, pp. 57-94.
7. B. Fruth and L. Niemeyer, "The importance of statistical characteristics of partial discharge data," IEEE Trans. on Dielectrics and Electrical Insulation, vol. 27, no. 1, pp. 60-69, Feb. 1992.
8. R. Bartnikas, "Editorial - Partial Discharge Measurements," IEEE Trans. on Dielectrics and Electrical Insulation, vol. 12, no. 2, pp. 195, Apr. 2005.
9. N. C. Sahoo, M. M. A. Salama, and R. Bartnikas, "Trends in partial discharge pattern classification: a survey," IEEE Trans. on Dielectrics and Electrical Insulation, vol. 12, no. 2, pp. 248-264, Apr. 2005.
10. A. Contin, A. Cavallini, G. C. Montanari, G. Pasini, and F. Puletti, "Artificial intelligence methodology for separation and classification of partial discharge signals," Proc. of the Conference on Electrical Insulation and Dielectric Phenomena 2000, 2000, pp. 522-526.
11. N. H. Ahmed and N. N. Srinivas, "On-line partial discharge detection in cables," IEEE Trans. on Dielectrics and Electrical Insulation, vol. 5, no. 2, pp. 181-188, Apr. 1998.
12. O. E. Morel, N. N. Srinivas, "Phase Resolved Online PD Detection for Cable Systems," IEEE Insulated Conductors Committee, Subcommittee F Fall 2009.
13. F. H. Kreuger, M. G. Wezelenburg, A. G. Wiemer, and W. A. Sonneveld, "Partial discharge part XVIII: errors in the location of partial discharges in high voltage solid dielectric cables," IEEE Electrical Insulation Magazine, vol. 9, no. 6, pp. 15-22, Nov.-Dec. 1993.
14. Y. Tian, P. L. Lewin, A.E. Davies, and Z. Richardson, "Acoustic emission detection of partial discharges in polymeric insulation," Proc. of the IEE High Voltage Engineering Symposium, 1999.
15. L.E. Lundgaard, "Partial discharge part XIV: acoustic partial discharge detection - practical application," IEEE Electrical Insulation Magazine, vol. 8, no. 5, pp. 34-43, Sep.-Oct. 1992.
16. CIGRE TF D1.02.05, "Practical aspects of the detection and location of partial discharges in power cables," Electra 297.
17. S. Boggs, A. Pathak, P. Walker, "Partial Discharge XXII: High Frequency Attenuation in Shielded Solid Dielectric Power Cable and Implications Thereof for PD location," IEEE Electrical Insulation Magazine January/February 1996 -Vol. 12, No. 1.
18. E. Walcott, "Partial Discharge Factory Test Requirements and In Field Partial Discharge Testing of Medium Voltage Cables," IEEE Electrical Insulation Magazine September/October 2005 – Vol 21 No 5.

19. L. Renforth and R. Mackinlay, "An Introduction to On-Line Partial Discharge (PD) Testing & PD Site Location (Mapping) Of Medium Voltage (MV) Cables," IPEC High Voltage Ltd. <http://www.ipechv.co.uk>, 17th October 2006, Appendix 1.
20. J. C. Hernández-Mejía, J. Perkel, R. Harley, M. Begovic, R. N. Hampton, and R. Hartlein, "Determining Routes for the Analysis of Partial Discharge Signals Derived from the Field," IEEE Trans. on Dielectrics and Electrical Insulation, December 2008, pp. 1517-1525.
21. A. Cavallini, G. C. Montanari, and F. Puletti, "A Novel Method to Locate PD in Polymeric Cable Systems Based on Amplitude-frequency (AF) Map," IEEE Transactions on Dielectrics and Electrical Insulation Vol. 14, No. 3, pp. 726-734, June 2007.
22. C. Buccella, M. Feliziani, and G. Manzi, "Detection and Localization of Defects in Shielded Cables by Time-Domain Measurements With UWB Pulse Injection and Clean Algorithm Postprocessing," IEEE Transactions on Electromagnetic Compatibility, Vol. 46, No. 4, pp. 597-605, Nov. 2004.
23. F. Kreuger, E. Gulski, and A. Krivda, "Classification of PDs," IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 28, No.6, pp. 917-931, Dec. 1993.
24. H. Kranz, "PD pulse sequence analysis and its relevance for on-site PD defect identification and evaluation," IEEE Transactions on Dielectrics and Electrical Insulation*,* Vol. 12, No. 2, pp. 276-284, Apr. 2005.
25. R. J. Van Brunt, "Stochastic Properties of Partial-discharge Phenomena," IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 16, No. 5, pp. 902-948, Oct. 1991.
26. F. Puletti, F. Ombello, M. Albertini, A. Cavallini, G.C. Montanari, "Improved Diagnostic Tools for Cable Accessories by Digital PD Detection Systems," Conference on High Voltage Plant Life Extension, pp. 2.2.1-2.2.9, Linkebeek, Belgique, November 2000.
27. M. Fenger, J. Levine "Sensitivity Assessment for HV & EHV Field Partial Discharge Measurements via Laboratory Testing," Conference Record of the 2012 IEEE International Symposium on Electrical Insulation (ISEI), June 2012.
28. M. Fenger, "Test Procedure and Acceptance Criteria for PD Commissioning Testing of Transmission Class Cables," Conference Record of the 2010 IEEE International Symposium on Electrical Insulation (ISEI), June 2010.
29. M. Fenger, "Experiences with Commissioning Testing of HV & EHV Cable Systems: The Influence of Voltage Level and Duration for Identifying Life Limiting Defects," Conference Record of the 2012 IEEE International Symposium on Electrical Insulation (ISEI), June 2012.
30. CIGRE TB B1.28 – 2014, "On Site PD Measurements", 2014,

Copyright © 2016, Georgia Tech Research Corporation

8.9 Relevant Standards

- IEC Std. 60183 – 1984: *Guide to the Selection of High Voltage Cables*
- IEC Std. 60270 – 2000: *High-Voltage Test Techniques – Partial Discharge Measurements*
- IEC Std. 6084 – 2004 : *Power Cables with Extruded Insulation and Their Accessories for Rated Voltages Above 30 kV (Um = 36 kV) up to 150 kV (Um = 170 kV) – Test Methods and Requirements*
- IEC Std. 60885-2 - 1987: *Electrical Test Methods for Electric Cables. Part 2: Partial Discharge Tests*
- IEC Std. 60885-3 - 1988: *Electrical Test Methods for Electric Cables. Part 3: Test Methods for Partial Discharge Measurements on Lengths of Extruded Power Cables*
- IEC Std. 62067 – 2011: *Power Cables Above 150 kV and their Accessories for Rated Voltages Above 150 kV (Um = 170 kV) up to 500 kV (Um = 550 kV) – Test methods and requirements*
- CIGRE TB B1.28 – 2014 Omnibus: *On-Site PD Assessment (Working Group B1.28)*
- CIGRE TB 21.09 – 1997: *After Laying Tests on High Voltage Extruded Insulation Cable Systems (Working Group 21.09, Std. also typically known as Electra 173, pp. 33- 41)*
- CIGRE TB 182 – 2001: *Partial Discharge Detection in Installed HV Extruded Cable Systems*
- IEEE Std. 48 – 2009: *IEEE Standard for Test Procedures and Requirements for Alternating-Current Cable Terminations Used on Shielded Cables Having Laminated Insulation Rated 2.5 kV through 765 kV or Extruded Insulation Rated 2.5 kV through 500 kV*
- IEEE Std. 404– 2006: *IEEE Standard for Extruded and Laminated Dielectric Shielded Cable Joints Rated 2500 V to 500 000 V*
- IEEE Std. 400– 2012: *IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems Rated 5 kV and Above*
- IEEE Std. 400.3 – 2006: *IEEE Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment*