



CHAPTER 7

Medium Voltage Cable System Partial Discharge

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7.0 MEDIUM VOLTAGE CABLE SYSTEM PARTIAL DISCHARGE

A large amount of research published over the past 10 to 20 years investigates the phenomenon of partial discharges (PD) in cable systems. Much of this work is meaningful in that it shows how partial discharge testing can be applied to discover and sometimes locate certain types of defects within these systems. Interestingly, the study of partial discharge in cables is largely empirical due to the complexity of the phenomenon [1-25]. In *CDFI Phase II*, NEETRAC explored the complex issues associated with making partial discharge measurements on cable systems and provides a review of what NEETRAC was able to learn about the advantages and disadvantages of this diagnostic technology.

PD measurements are quite different from $\tan \delta$ (dielectric loss) measurements. $\tan \delta$ measurements provide straightforward values that can be readily repeated and analyzed and the measurement method or operator typically does not come into play. On the other hand, the output from a PD measurement is very much a function of the technique/approach used to make the measurement. The output must be highly synthesized and the results provided, particularly for field tests, which are highly customized. This chapter provides a broad overview of the issues associated with making PD measurements on MV cable systems with a primary focus on field measurements though the topic must also be discussed in context with laboratory measurements.

7.1 Test Scope

Partial Discharge diagnostic technologies detect localized “void-type” defects in cables and/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).

It should be noted that cable systems with metallic shields that become ungrounded due to mechanical damage, corrosion or improper ground connections can also experience electrical discharges that may be detected using partial discharge diagnostics, though this is not the primary purpose for deploying this diagnostic technique.

Partial Discharge can occur in all cable system types, although the usefulness of PD diagnostics may be limited when performed on discharge resistant cables (as defined in ICEA S-94-649 and S-97-682) or on fluid impregnated paper insulated cables (PILC or MIND). These cables, which have some resistance to electrical discharges, can experience partial discharges even at operating voltage. However, this is typically not considered a problem because of their discharge resistant characteristics. Mixed (hybrid) cable systems containing both discharge-free and discharge-resistant cable designs can be especially challenging to test using partial discharge diagnostics.

All discharge-free cable and many pre-molded cable accessories are PD tested at the factory prior to shipping. As such, they should be PD free as defined in the appropriate IEC, ICEA, and IEEE standards when received by the customer. Any PD detected in service is likely due to problems caused by installation (new) or defects that develop over time (aged). However, it is important to be aware that there are no industry recognized testing procedures or discharge 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 test procedures are very different.
- 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 such as significant background electrical noise or very long lengths that must be addressed to yield acceptable results.
- Interaction among and impact on PD signals by different cable system components are not completely understood.
- Different PD measurement technologies/approaches generally cannot be correlated.
- PD is often intermittent. It may be present one day and absent the next.

While there are significant complications, PD testing can be useful, but the results are very often not definitive.

7.2 How it Works

During the application of a high voltage on a cable system, sensors pick up electrical discharges that may be from the cable system or external to the system. If conditions are right at a 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, and frequency response of the measurement equipment and the distance between the PD source and the signal detector. Each of these factors alters the shape of the original PD pulse. The PD pulses themselves must then be separated from ambient noise signals. Available PD instruments are classified by bandwidth as they can have bandwidths of hundreds of kilohertz (narrow band and wide band according to IEC 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.

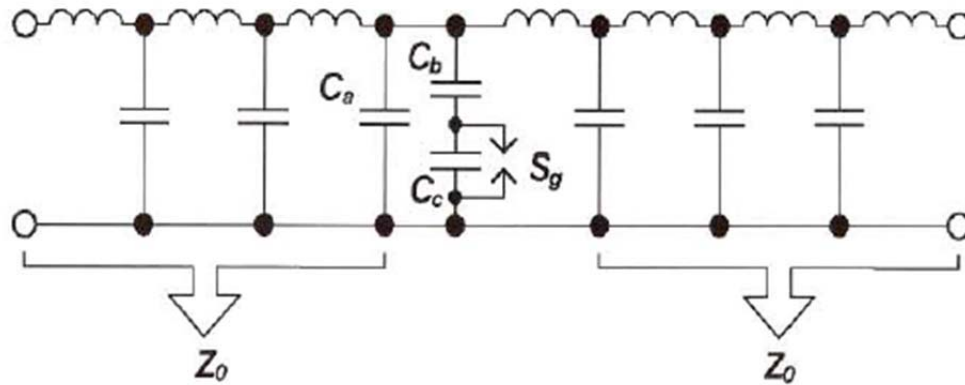


Figure 1: Equivalent Circuit for Power Cable PD [16]

As shown in Figure 1 the capacitances C_b and C_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.

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.

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

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

- 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).

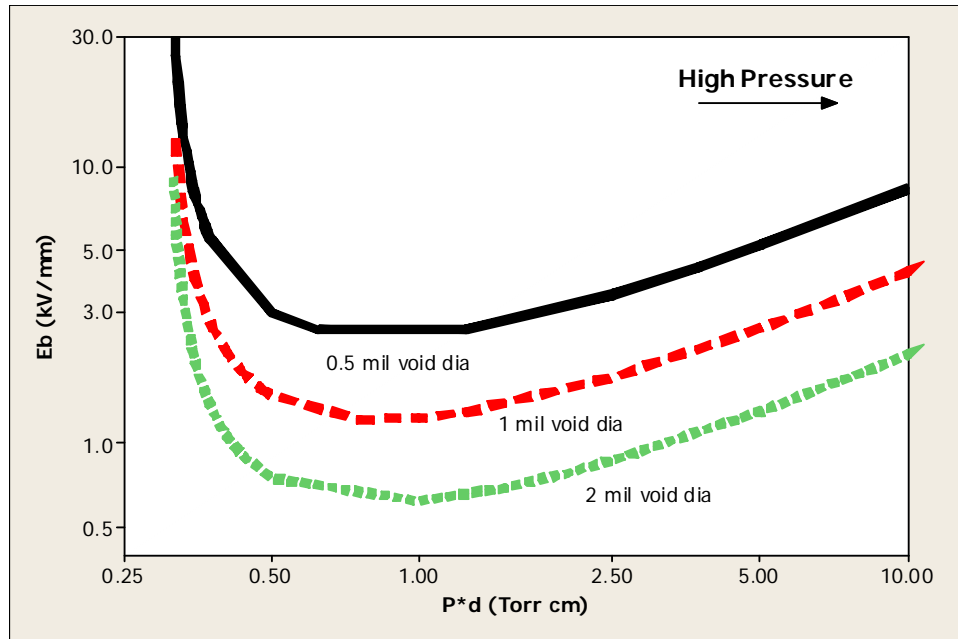


Figure 2: Theoretical Paschen Curves for Air-Filled Voids (Selected Void Sizes)

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).
- The PD signal must reach the detector in a suitably unattenuated, 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 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.

7.3 How it is applied

PD testing can be performed online and offline [11]. 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,

- 30 – 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 but may act as an additional source of noise. Both sinusoidal and cosine-rectangular waveforms can be used.
- Damped AC (DAC): Equipment is relatively light and portable. The applied voltage is a highly 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).

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;
- Extinction voltage (voltage at which the discharge extinguishes as the voltage is lowered);
- 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);
- Estimated PD source location(s).

PD measurements are influenced by the type and location of the defect or defects, operating and testing voltage magnitude, circuit operating conditions, type of insulation material (EPR, XLPE, PILC, etc.), ambient electrical noise, and many other factors discussed earlier. Therefore, accurate interpretation of the PD data requires sound knowledge of temporal (time dependency) PD behavior. Although simplistic PD measurements (discharge magnitude in pC and PD inception voltage) are commonly employed in diagnostic assessments, the true impact of partial discharge on cable system performance is difficult to predict. This happens because different PD techniques/approaches yield different PD measurements, though some PD diagnostic providers claim to have developed proprietary means for interpreting PD measurements to predict cable system performance. Studies performed in the *CDFI* show that a low PD inception voltage or a high picocoulomb value does not necessarily indicate that a cable system will soon fail.

As discussed in the *CDFI* Perspective, the connection between a measured discharge and its impact on the cable system requires many laboratory and field tests to create a database of PD characteristics that indicate “bad” PD and “tolerable” PD. This form of PD testing could enable utility engineers to create their own criteria for evaluating the condition of a cable system. To date, the *CDFI* has not been able to gather a database large enough to establish a correlation between a given PD measurement and cable system performance. However, analyses on a number of PD field test results containing PD based recommendations (*Act* or *Not Act*) are used to establish preliminary accuracy assessments for online and offline PD diagnostic techniques.

The stochastic nature of PD measurements can create considerable variability in the measurements over time and between identical cable systems operating under similar conditions. The best way to overcome this issue is by performing periodic PD tests as part of a power cable testing and replacement program. If data from such tests are analyzed carefully, periodic PD measurements could potentially be correlated, over time, with cable system performance.

Most offline techniques apply a voltage of 1.5 to 2.5 U_0 , where U_0 is the operating phase-to-ground RMS voltage of the circuit. The application of high voltages for a long period (cycles or time) may cause some level of further degradation of an aged cable system. This can potentially occur when performing any diagnostic test requiring the application of voltage above the operating voltage. See a more detailed discussion in Chapter 2. 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. Table 3 shows the overall advantages, disadvantages, and open issues for PD testing.

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

Source Type	Advantages	Disadvantages
<p>60 Hz AC Voltage Supplied by Utility System (De-energizing not needed)</p>	<ul style="list-style-type: none"> • No non-system energization equipment is required. • Testing waveshape and frequency is 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 is performed while the cable system is at normal operating temperature. 	<ul style="list-style-type: none"> • 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 generally must be applied at every cable accessory (either sequentially or simultaneously) and at each end of the tested cable system. • 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. However, changes in frequency spectra can be used to infer proximity to sensors. • 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
30 – 300 Hz AC Power Frequency	<ul style="list-style-type: none"> • Testing waveshape and frequency are close to the operating and factory test voltages. • Sensitivity assessment can establish the lowest detectable PD 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. 	<ul style="list-style-type: none"> • Equipment is large, heavy, and expensive. • Application of elevated voltage ($> U_0$) may cause further degradation. • Short (less than a minute) data acquisition time may not capture some PD. • Results are reported in diagnostic levels, charge, and voltages which specific meaning may be difficult to interpret.
0.01 – 1 Hz AC Very Low Frequency (VLF) Sinusoidal & Cosine-Rectangular Voltage	<ul style="list-style-type: none"> • Equipment is small and easy to handle. • 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. 	<ul style="list-style-type: none"> • Application of elevated voltage ($> U_0$) may cause further degradation. • Short data acquisition time (few cycles) may not allow PD to occur. • Does not replicate operating voltage waveshape or frequency. • PD behavior is not well understood at these frequencies. • Difficulty syncing with voltage waveform when phase-resolved data is needed. • Special filtering and/or gating needed for VLF generators
Damped AC (DAC) (30 Hz to 500 Hz)	<ul style="list-style-type: none"> • Can measure PD inception and extinction voltages (PDEV) in same shot. • Voltage source and PD acquisition are integrated in a single unit. • Straightforward to use. 	<ul style="list-style-type: none"> • Only the first voltage cycle is controlled. • Does not replicate operating voltage waveshape or frequency. • Comparisons between circuits are difficult because the applied voltage frequency and decay rate vary 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.

Table 3: Overall Advantages and Disadvantages of PD Measurement Techniques	
Advantages	<ul style="list-style-type: none"> • Identifies single or multiple localized void-type defects. • Applicable for all cable types. • 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, voids. • Basic results available at end of test. • Test can be stopped if “unacceptable PD” is observed.
Open Issues	<ul style="list-style-type: none"> • 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 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/impossible to compare with each other. • Interpretation of PD signals is very challenging (i.e. the test results can be provided as “Good/Bad”, “Acceptable/Unacceptable”, “Pass/Not Pass”, “Defer/Repair/Replace”, “1/2/3/4/5”, etc.). • Locating and characterizing PD sources can be difficult because of noise, attenuation, dispersion, cable accessories, and cable system complexity. • Not clear which PD features provide information on the severity (i.e. whether or not the defect will lead to failure). • Results for hybrid circuits are difficult to interpret. • Neutral corrosion (wire or tape) can lead to false negatives (i.e. absence of PD). • Voltage exposure (impact of voltage and time on cable system) caused by elevated 60 Hz AC, DAC, and VLF has not been established.
Disadvantages	<ul style="list-style-type: none"> • Cannot detect all possible cable system defects – only those that discharge and are detected by the measurement equipment. • Does not directly detect water trees. • Does not assess global degradation (high density of defects such as water trees or contaminants distributed over a significant portion of the system length). • No uniform Pass / Not Pass criteria established for field testing. • Only a small percentage of PD sites detected actually fail in service.

7.3.1 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 to synchronize the incoming PD signals with the ac waveform.






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. Because it connects with the high voltage terminal, the sensor must be able to withstand test voltages.
- **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 mechanical surges that then 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 limits 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 provides pictures of all the different types of sensors for PD detection (typical images sourced from the Internet).



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 inductive device is the Rogowski coil. The Rogowski 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 Rogowski 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 (typical images sourced from the Internet).

Table 5: Different Types of PD Sensors for Synchronization	
Type	Example
Capacitive – Capacitive Coupler PD and Synch signals	
Inductive – Rogowski Coil Synch signal	

Voltage synchronization can also be accomplished using 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 accomplish meaningful PD measurements.

7.3.2 Partial Discharge Source Location

Before conducting PD measurements in the field, the location of the cable system splices should be determined so that PD signals originating from accessories can be distinguished from those coming from the cable. The splice locations can be determined by the principle of Time-Domain Reflectometry (TDR) presented in Chapter 2.

In most cases, the TDR is performed off-line for terminal and distributed measurements; however, for online PD measurements, the same TDR technique may be employed with the exception that the TDR pulse is injected into the energized cable system using a high frequency current transformer (HFCT).

Upon identifying the splice locations, the PD source location can be performed. There are two approaches used:

- location using PD data in the time-domain;
- location using PD data in the 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.

The following sections elaborate on each of the PD source location approaches.

7.3.2.1 Source Location in Time-Domain

This approach utilizes the same principle as TDR and appears in Figure 3.

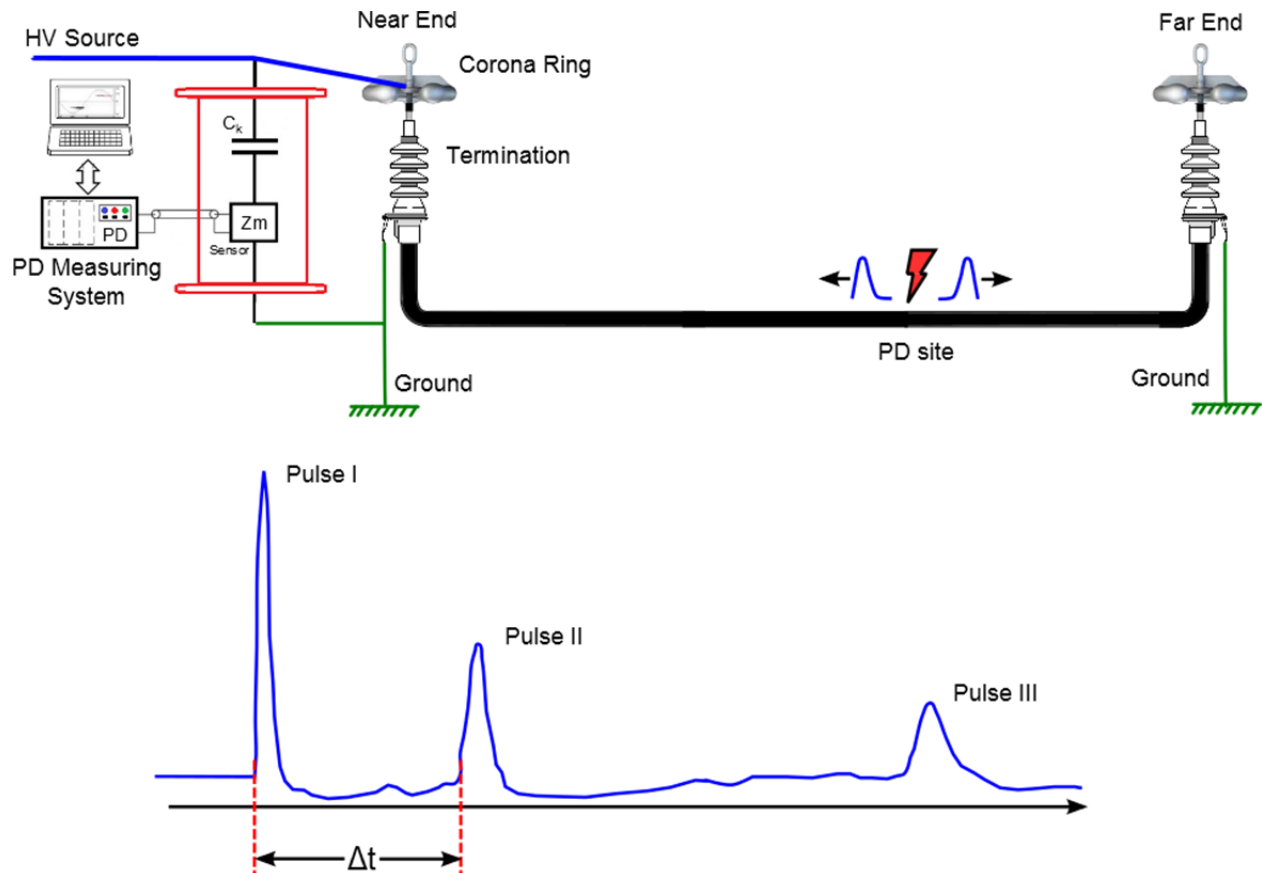


Figure 3: Illustration of PD Location in Time Domain

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. Pulse II is more attenuated and dispersed than Pulse I because of its longer path through the cable system. 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 is applicable 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.

7.3.2.2 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 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 sensor locations near the PD site. By examining the energy signatures measured at each sensor location, an approximate PD source location can be determined.

Two factors can influence the accuracy of this technique:

- 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.

A less commonly used method of location than the time-domain approach, frequency-domain source location has not been verified within *CDFI*.

7.3.3 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 appears in Table 6.

Table 6: Relationship between Test Types and Test Categories for PD Measurements		
Test Type	Laboratory	Field (On site)
		<ul style="list-style-type: none"> • Routine • Qualification • Sample

To better explain Table 6, each test type is detailed below.

- In the laboratory category:
 - **Laboratory Testing:** Tests conducted 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 (typically premolded types) or cable 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), their interfaces, and the cable system as a whole including damage that may have occurred during installation and/or workmanship issues.
 - **Maintenance:** Tests intended to detect deterioration and to verify the serviceability of cable systems in service for some 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 vary significantly. Utility engineers should have a basic understanding of each PD test type. Therefore, Table 7 provides a comparison of the important factors associated with laboratory and field PD tests.

Table 7: Overall Comparison of Laboratory and Field PD Tests

Laboratory Tests
<ul style="list-style-type: none"> • Cable and/or accessories tested together as a <u>short</u> 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 (as defined within IEC 60270) and non-conventional (ultra-wide bandwidth) measurements can be deployed. • Does not replicate operating environment. • Presence of PD on new systems above an accepted threshold can indicate problems with the cable, accessories, or interface between the two.
Factory Tests
<ul style="list-style-type: none"> • Only for new cables and accessories. Each is 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.
Commissioning Tests
<ul style="list-style-type: none"> • Complete cable system that is tested prior to beginning its service life. • Focused on PD detection and PD source location. • Electrical noise, grounding, temperature, accessibility are not readily controllable. • 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. • Rarely deployed at MV except for some utility specific conditions. • Generally performed at test voltages above normal operating voltage.
Maintenance Tests
<ul style="list-style-type: none"> • 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 due to the large differences in the lengths involved - see section 7.6.2 for a detailed discussion of the issues associated with length and measurement bandwidth.

7.4 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 classify the tested cable circuit. In principle, there are two main classes: Pass – no action required and Not Pass – some type of action required. The Not Pass class is often subdivided into finer classes such as “Monitor” or “Repair When Convenient”. Providing the results in the form of classes or rankings provides the customer with a straightforward interpretation of a very complex measurement. However, note that,

- The classification rules are typically proprietary and cannot be compared between PD providers.
- The classification rules often evolve with time.
- The original data may not be readily available for re-analyses or comparison with subsequent test data.

With limited guidance regarding acceptable versus unacceptable PD results, some have suggested using factory test standards as a basis for providing PD results. The basic logic is that if a cable system can meet the current factory test standards for individual new components then it is most likely in good condition. Unfortunately, this only provides guidance for cable systems that are “good” – it says nothing about those cable systems that do not meet the current factory standards. Are the circuits that do not meet these standards really “bad” or are they just “not new”?

There is an additional complication as the factory test standards have changed over time. As a result, an aged cable system could be expected to meet a more stringent test standard than was in effect when the cable system was manufactured. Figure 4 gives the evolution of the maximum permitted factory test PD levels defined in AEIC cable specifications [18] for discharge-free extruded cable only. This figure is helpful in that it shows the level of PD that a cable could possibly have as a function of year of manufacture. To use this information effectively, the cable age must be known. An example can best illustrate this point. The presence today of 20 pC of discharge at $2 U_0$ in a discharge-free cable manufactured in 1975 does not imply that discharge is developing in a worsening void defect or that an electrical tree is growing. That may have simply been the condition of the cable in 1975. However, 20 pC of discharge at $2 U_0$ would be of concern for cables installed in the last 20 years. To help deal with these issues, it is useful to have the basic test data provided in addition to classification information to identify trends over time.

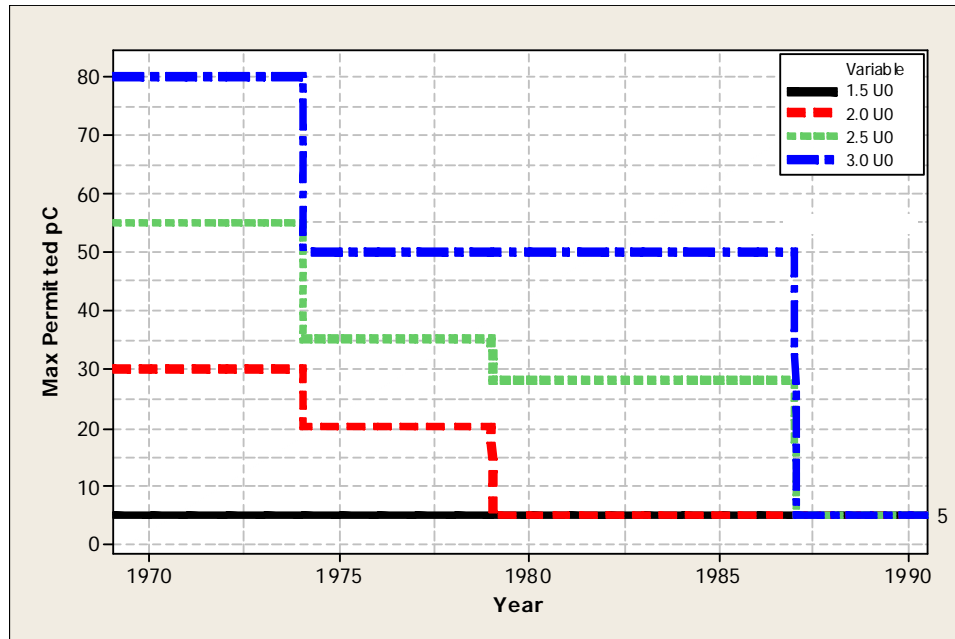


Figure 4: Maximum Permitted Factory Test PD Levels for Discharge-Free Extruded Cable Only (Accessories Excluded and Conventional IEC Std. 60270 – 2000 Style) [18]

The only success criteria for accessory component PD tests in US standards are in IEEE Std. 48 for cable terminations, IEEE Std. 386 for separable connectors (elbows/bushings), and IEEE Std. 404 for cable joints. Note that results for cold shrink and heat shrink accessories that are tested in the factory are not applicable after they are installed.

It is important to note that the PD criteria in these cable and accessory standards and specifications are,

- for design and production tests of new, individual components;
- used as one of a suite of electrical and non-electrical tests;
- Do not address in-service PD tests.

In some cases, partial discharge is allowed, depending on the specific standard/specification, the year of the specification, the type of product, and the test voltage. Partial discharge service providers in the USA do not make their criteria publically available.

7.5 Estimated Accuracy

To estimate the accuracy for the various implementations of PD technologies it is necessary to define common criteria applicable to all technologies. The adopted definitions are:

- “Pass” – Cable System is defined by the PD Providers as either free of partial discharge activity or any measured PD is considered benign. The means by which the providers make this determination is typically proprietary.

because the Pass group tends to be a much larger population. As a result, the Pass group accuracy is more influential in the overall accuracy calculation.

Table 8: Summary of Accuracies for Partial Discharge Techniques			
Accuracy Type	Partial Discharge		
		Raw	Weighted
Overall Accuracy (%)	Upper Quartile	89.2	85.0
	Median	79.8	79.5
	Lower Quartile	64.5	79.0
	Number of Data Sets	18	18
	Length (miles)	669	669
“Pass” Accuracy (%)	Upper Quartile	100	99.1
	Median	98.1	94.0
	Lower Quartile	88.1	88.4
	Number of Data Sets	18	18
	Length (miles)	669	669
“Not Pass” Accuracy (%)	Upper Quartile	4.9	23.0
	Median	0.1	6.0
	Lower Quartile	0.1	0.1
	Number of Data Sets	18	18
	Length (miles)	669	669
Time Span (years)		1998 – 2009	
Cable Systems		Extruded Feeder, Extruded URD, Hybrid Feeder	

7.6 CDFI Perspective

Partial discharge is useful for cable diagnosis because it is able to provide a localized assessment of specific aspects of cable system condition. However, PD tests cannot identify the presence of all defects that can affect the life of a cable system: PD tests are classically focused on “void-type” defects.

At MV, PD technologies are generally deployed on aged assets/systems that have been in service for a number of years. The goal is to diagnose the system health while providing information on the likelihood of future service failures. Medium voltage PD technologies strive to provide a judgment of the severity of any detected signals under the theory that shorter remaining life is associated with more severe signals and hence defects. The basic assumption is - the largest PD signals come from the most severe defects; the most severe defects limit the remaining life; hence, the largest PD signals indicate the shortest remaining life. However, care must be taken when interpreting the PD measurements and the reported classifications that result as the correlation between the PD measurements and remaining life is, to date, weak.

One of the main goals of this section is to help users understand field PD measurement techniques on MV cable systems. The issues are many and diverse; however, during *CDFI Phases I and II* the crucial characteristics and limitations of PD measurements were identified, and are as follows:

1. PD is generally measured on aged assets, i.e. the focus is on maintenance testing. See Section 7.6.4.
2. Field measurements cannot be correlated to laboratory / factory test results. See Sections 7.6.1, 7.6.2, 7.6.3, 7.6.4, 7.6.5, 7.6.6, 7.6.8, 7.6.12, and 7.6.13.
3. PD magnitude does not provide a direct link to estimates of deterioration or likelihood of failure. See Sections 7.6.1, 7.6.4, 7.6.6, 7.6.9, 7.6.10, and 7.6.13.
4. Tests, analysis, and reporting are orientated towards obtaining a diagnosis from a single test (trending or comparison with an identifiable benchmark are rare). See Section 7.6.10.
5. Results from different PD technologies cannot be compared. See Sections 7.6.2, 7.6.3, 7.6.4, 7.6.5, 7.6.6, 7.6.7, 7.6.8, 7.6.10, 7.6.11, and 7.6.13.
6. Complicated test data are commonly processed and reported/recorded as classification data (Thus re-analysis/reconsideration by a user is not possible; only coarse trending (across class boundaries but not within a particular class) is possible by a user). See Section 7.6.10.
7. Measurements and analysis techniques are proprietary, detailed information is not available. See Sections 7.6.2, 7.6.3, 7.6.5, and 7.6.11.
8. Measurements are mostly made from one end of the system (terminal measurements). See Section 7.6.3.
9. Noise and PD signal deterioration are unavoidable and may limit effective PD detection in practice. See Section 7.6.1, 7.6.6, and 7.6.12.
10. Measurement variability is unknown and likely affects making comparisons using criteria and between repeated tests. See Section 7.6.14.

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

During *CDFI Phases I and II*, many laboratory and field PD tests on MV cable systems were conducted in conjunction with analyses of a number of MV PD data sets. These tests and analyses enabled the development of the perspective presented below. The *CDFI* perspective relies on knowledge gained from the following specific hands-on activities:

- Gather and analyze experience (NEETRAC and others) with PD testing of MV cable systems, with respect to test methods, equipment, and results— primarily in the form of maintenance 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 MV systems might bring.

It is useful to begin with a discussion of the frequency content of PD signals as this drives the measurement/detection philosophies and challenges.

7.6.1 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 equal to 50% of the peak amplitude. The amplitude and width of a PD pulse appear in Figure 6.

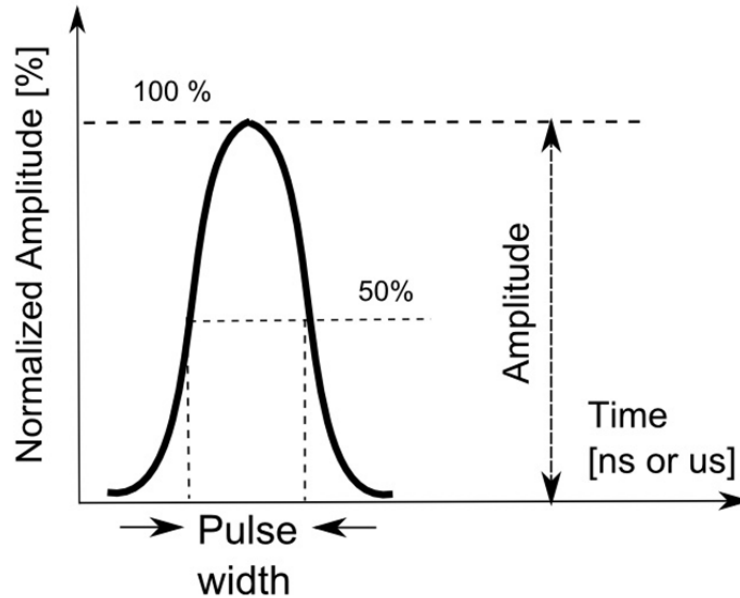


Figure 6: Typical Parameters of PD Pulse

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.

7.6.1.1 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:

$$v_{insulation} = \frac{1}{\sqrt{\epsilon_r \epsilon_0 \mu_r \mu_0}}$$

$$\epsilon_0 \approx 8.854 \text{ E-12 F/m}$$

$$\mu_0 = 4\pi \text{ E-7 H/m}$$

In the case of PE-based insulation materials, ϵ_r is 2.3 and μ_r is 1. Thus, the propagation velocity inside polyethylene material is 1.98E8 m/s. Consequently, a 1 MHz (1 μ s) 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 characteristics such as insulation wall thickness, conductor size, etc., that further reduce the propagation velocity.

A cable system component can affect a pulse when it is similar in size to the pulse wavelength. A splice is unlikely to change the shape of a 1 μ s duration pulse since the pulse is much longer than the splice length. As Chapter 2 described, TDR pulses tend to be less than 100 ns in duration so that they are able to respond when they encounter cable accessories.

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 bands do. As an illustration, simulation results of the relationship between the PD pulse bandwidth and propagation distance from the discharge site appear in Figure 7. These simulation results use a 15 kV 1/0 XLPE cable system with a 175 mil insulation wall.

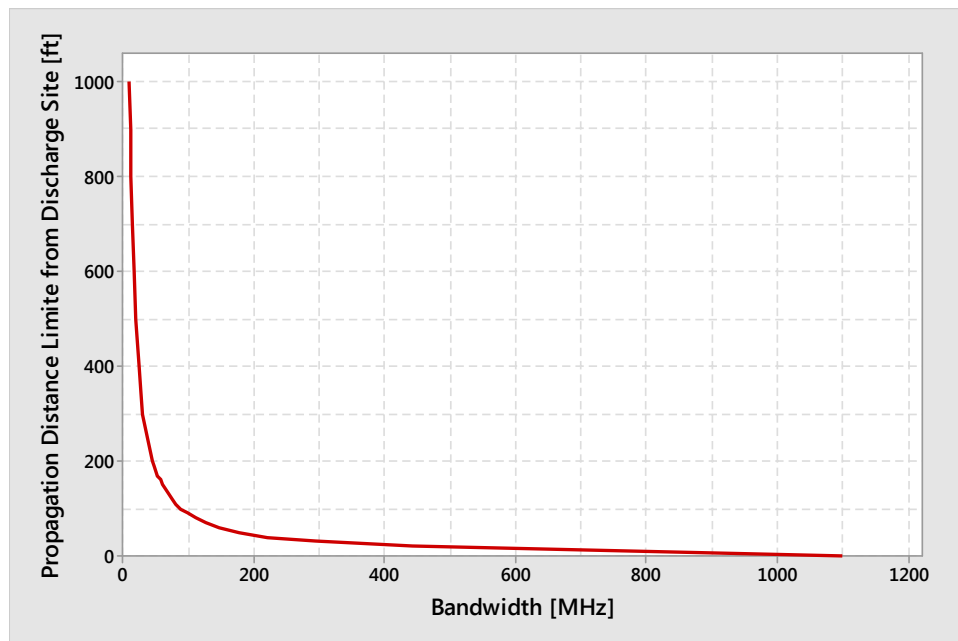


Figure 7: PD Pulse Bandwidth and Propagation Distance from Discharge Site – Linear Scale

As shown in Figure 7, 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 7 may be transformed into a logarithmic scale as shown in Figure 8. The frequency ranges for practical field measurements (yellow rectangle) and IEC 60270 (green rectangle) are included for reference in Figure 8.

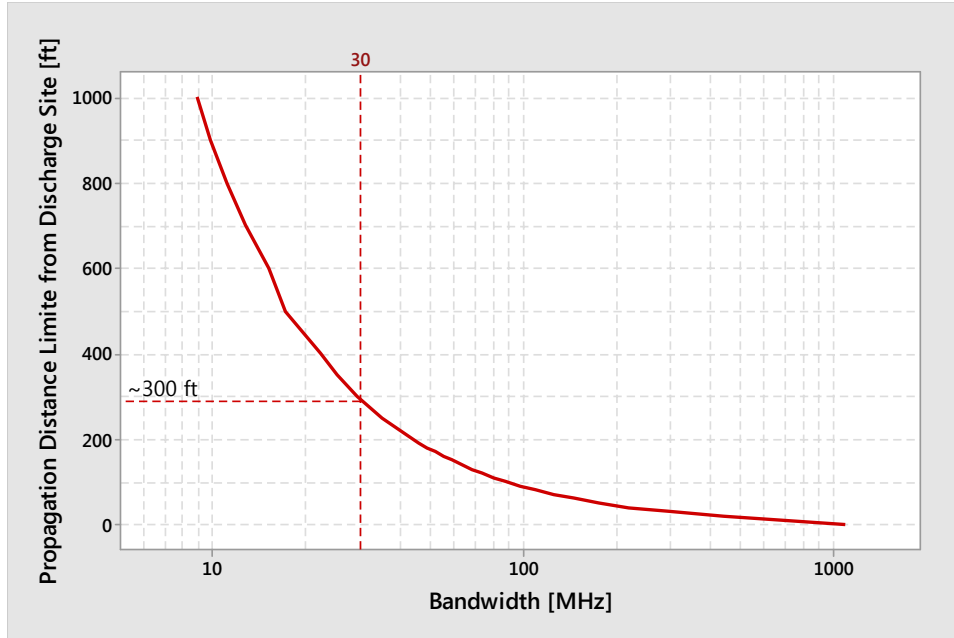


Figure 8: PD Pulse Bandwidth and Propagation Distance from Discharge Site

The most important interpretation of Figure 7 and Figure 8 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. As an example, a typical MV cable system length of 300 ft, the bandwidth of the propagating pulse becomes limited to approximately 30 MHz.

7.6.1.2 Attenuation and Dispersion

As mentioned above, PD pulses distort 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, the greater the distortion [17]. The examples in Figure 7 and Figure 8 show that attenuation can eliminate frequencies present in the original PD pulse once the pulse has traveled short distances from the source location. 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 resulting from reflections of PD pulses at the system ends and at splice locations. Detailed information on attenuation and dispersion follow.

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 semiconductive 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 9 shows the relationship between attenuation per unit length and PD pulse width for a 300 ft cable system of 33 kV, 630 mm² conductor, XLPE cable. Figure 9 shows that faster pulses experience higher attenuation levels as compared to slower/wider pulses.

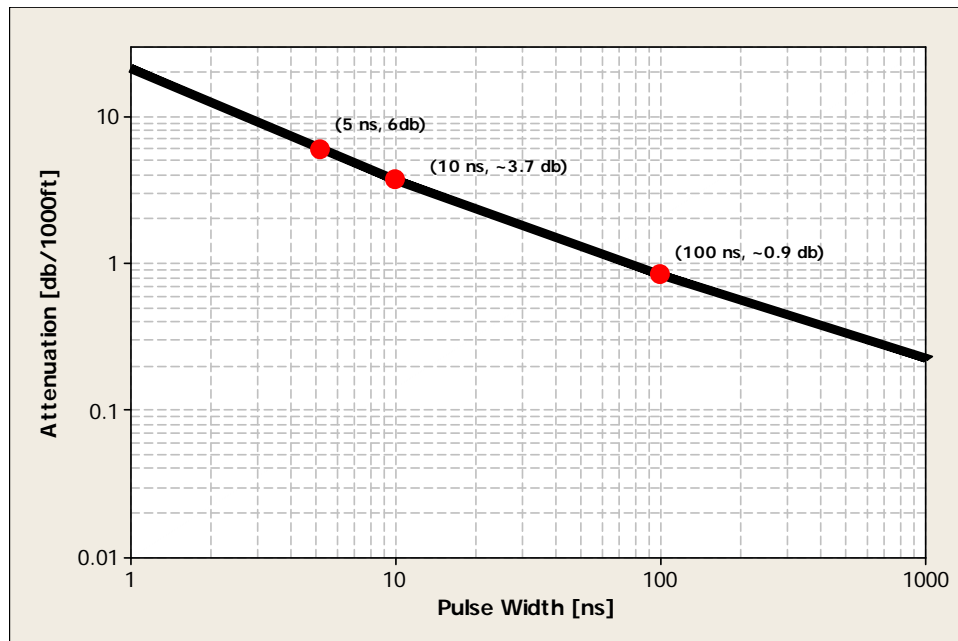


Figure 9: Calculated Attenuation as a Function of PD Pulse Width for 300 ft of 33 kV, 630 mm², XLPE Cable

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 9, several observations follow:

- 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 9 presents the cases on how a PD pulse is distorted by attenuation, dispersion, and both.

Table 9: Attenuation and Dispersion of PD Pulses	
Observations	Case
<p>Attenuation:</p> <ul style="list-style-type: none"> • Reduced amplitude • Constant pulse width • Reduced energy 	<p>Attenuation Pulse width remains constant Pulse energy decreases</p> <p>$A_0 > A_1$</p>
<p>Dispersion:</p> <ul style="list-style-type: none"> • Reduced amplitude • Increased pulse width • Constant energy 	<p>Dispersion Pulse width increases Pulse energy remains constant</p> <p>$A_0 = A_1$</p>
<p>Attenuation & Dispersion:</p> <ul style="list-style-type: none"> • Reduced amplitude • Increased pulse width • Reduced energy 	<p>Attenuation & Dispersion Pulse width increases Pulse energy decreases</p> <p>$A_0 > A_1$</p>

Both attenuation and dispersion of PD pulses have been observed through research in the laboratory. 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 10 and rescaled for comparison in Figure 11.

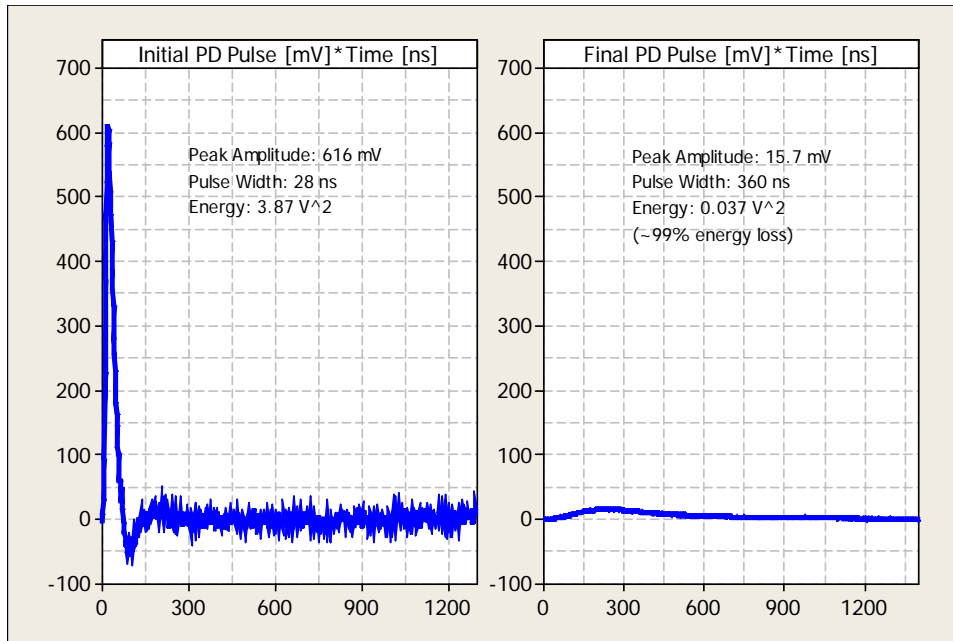


Figure 10: Laboratory Recorded Initial and Final Traces (Equal Axis Scales) of a Fast Voltage Pulse Traveling 2,300 ft along a Cable (WTLPE – 25 kV)

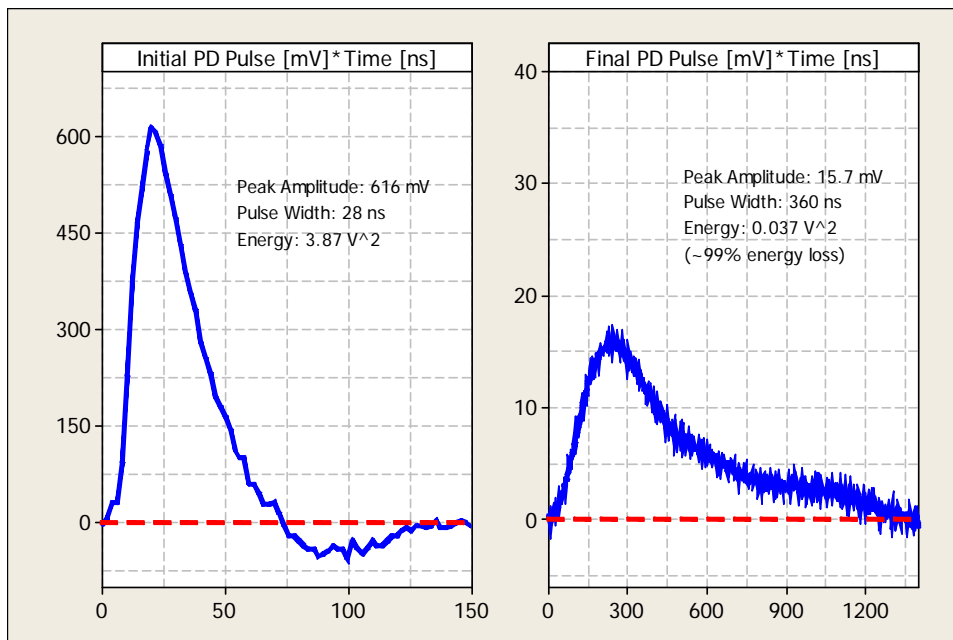


Figure 11: Laboratory Recorded Initial and Final Rescaled Traces of a Fast Voltage Pulse Traveling 2,300 ft along a Cable (WTLPE – 25 kV)

As seen in Figure 11, the attenuation and dispersion phenomena greatly affect the pulse shape parameters; specifically, observe 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 V² while the final pulse has 0.037 V² of energy which represents an energy loss of 99%.

7.6.1.3 Reflections From Cable System Structural Elements

In addition to deterioration from attenuation and dispersion, PD signals are further degraded by the cable system structure (i.e. number of cable sections and accessories that compose the system). This results from 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 splices and between cable and terminations/elbows.

To illustrate the effect of reflections, two different cable system structures appear in Figure 12 and Figure 13. The system in Figure 12 is the least complex system possible in the field: one cable length and two terminations. The second system, shown in Figure 13, adds a splice to the system shown in Figure 12. Both of these systems occur frequently in utility URD systems.

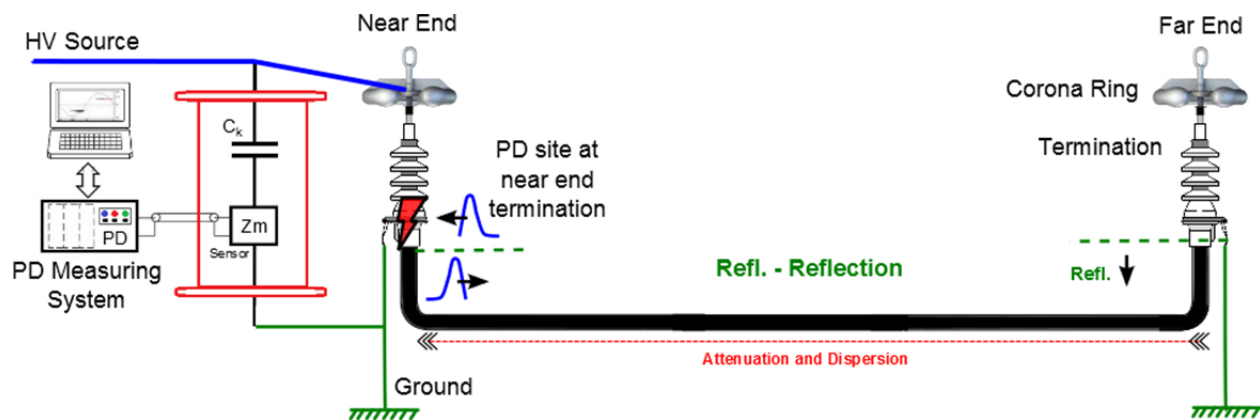


Figure 12: Illustration of PD Signal Degradation by Attenuation and Dispersion

In Figure 12, 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 13, on the other hand, includes attenuation, dispersion, and reflection of the PD pulse at the splice. The mismatch in characteristic impedance between the splice and cable does not allow all the PD pulse energy to transfer from one side of the splice to the other as a portion is reflected. Thus, additional signal degradation occurs and more energy is lost.

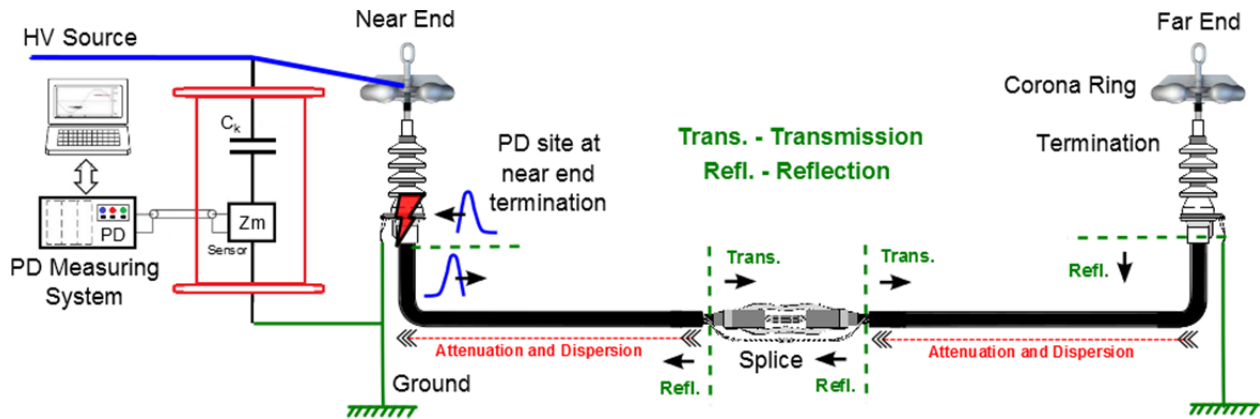


Figure 13: Illustration of PD Signal Degradation by Attenuation, Dispersion, and Cable System Complexity (Structure)

Figure 14 shows the resulting TDR trace for a PD pulse generated at the near end termination for the systems shown in Figure 12 and Figure 13. 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 to quantify and compare the signal degradation.

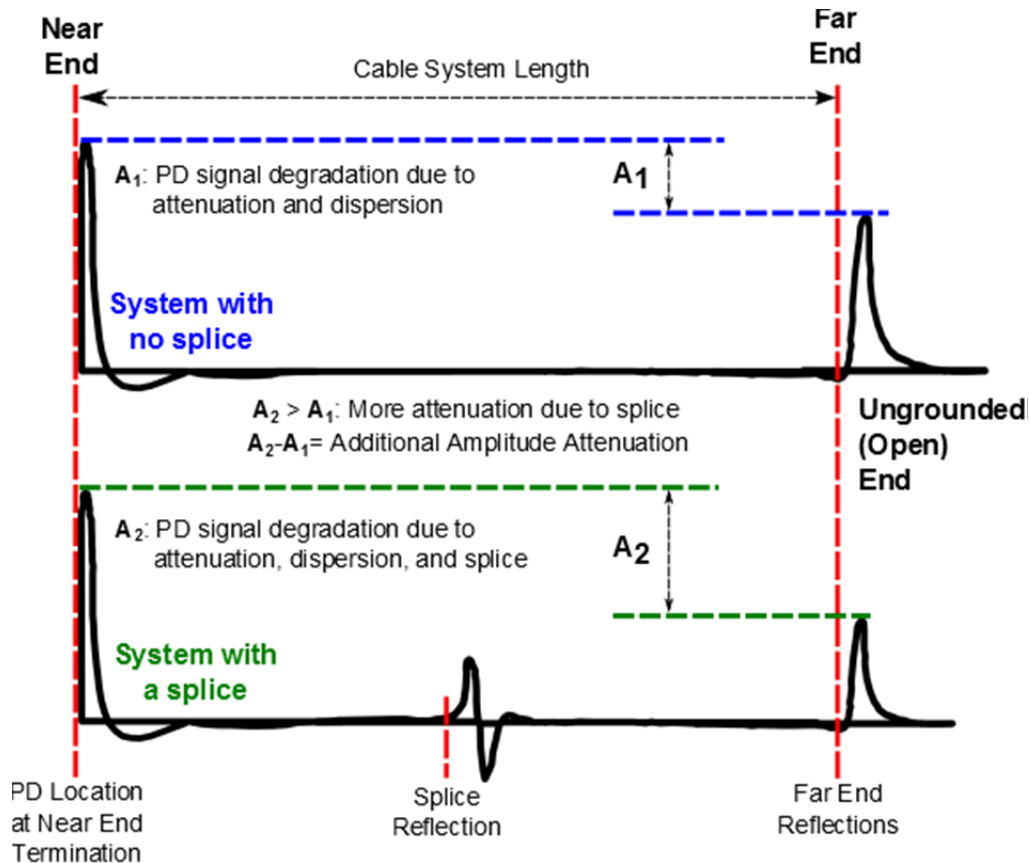


Figure 14: Impact of Cable System Complexity on Additional PD Signals Deterioration

As shown in Figure 14, signal degradation for the cable system with no splices (Figure 12) and for the cable system with a splice (Figure 13) are quantified by A_1 and A_2 , respectively. The signal degradation is worse for the system with the splice as compared to the system with cable and terminations only. Assuming that both systems have the same length, type of cable, and that the splice length is negligible when compared with the total system length, then the signal deterioration from attenuation and dispersion can also be assumed equal on both systems. Therefore, the difference between A_1 and A_2 is the result of the splice.

Users unfamiliar with this issue may tend to think that a good way around this 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. Unfortunately, in field applications the exact circuit composition is generally unknown.

Ultimately, the system composition has a significant effect on the resulting pulse shapes and amplitudes so care must be taken when making assessments based on these features.

7.6.2 Conventional And Non-Conventional PD Measurements

Presently, PD measurements are categorized into 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 by IEC 60270; specifically this document refers to the NB (narrow-band), WB (wide-band), and UWB (ultra-wide-band) bandwidths. Table 10 shows the recommendations for each of these bandwidths within IEC 60270.

Table 10: Recommended Frequency Bandwidths According to IEC 60270		
System Type	Frequency Requirements [kHz]	Observations
Wide Band – WB	$30 \leq f_1 \leq 100$ $f_2 \leq 500$ $100 \leq \Delta f \leq 400$	f_1 – lower limit frequency f_2 – upper limit frequency Δf - bandwidth (BW) $\Delta f = f_2 - f_1$
Narrow Band – NB	$9 \leq \Delta f \leq 30$ $50 \leq f_m \leq 1,000$	f_m – midband frequency $f_m = \frac{f_1 + f_2}{2}$
Ultra Wide Band – UWB	No recommendations given	-

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, appears in Table 11.

Table 11: Comparison between Conventional and Non-Conventional PD Measurement Approaches		
Topic	Category	
	Conventional	Non-Conventional
Typical Deployments	Factory Field Laboratory	Field Laboratory
Standards/Guides	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> Factory – $f_2^{\\$} < 500$ kHz Laboratory – $f_2^{\\$} < 1$ MHz Narrow band (NB) – $\Delta f^{\text{f}} = [9$ kHz, 30 kHz] with $f_2^{\\$} < 1$ MHz Wide band (WB) – $\Delta f^{\text{f}} = [100$ kHz, 400 kHz] with $f_2^{\\$} < 500$ kHz 	1 MHz to 200 MHz (manufacturer dependent)
Calibration	<ul style="list-style-type: none"> Factory – Injection of known charge at one end or ends bonded together, injector must comply with IEC 60885-3 	Not Applicable

Table 11: Comparison between Conventional and Non-Conventional PD Measurement Approaches		
Topic	Category	
	Conventional	Non-Conventional
	<ul style="list-style-type: none"> • Laboratory – Injection of known charge only at the near end, injector must comply with IEC 60270 • Field – Injection of known signal for establishing sensitivity and charge scaling 	
Scale Factor	Not Applicable	Used in some cases
Sensitivity Check	<ul style="list-style-type: none"> • Factory – Capacitive sensors are assumed to have a negligible effect • Laboratory – Capacitive sensors are assumed to have a negligible effect if test set-up conforms to IEC Std. 60270 	Resolve minimum amplitude that can be detected
Performance Check	Included in the calibration procedure	Included in the sensitivity check
Range Check	Not required as it is <u>assumed</u> 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	<ul style="list-style-type: none"> • 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), $\Delta f = f_2 - f_1$		

7.6.2.1 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 model assumption 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 be high at lower frequencies and with longer cable system lengths.

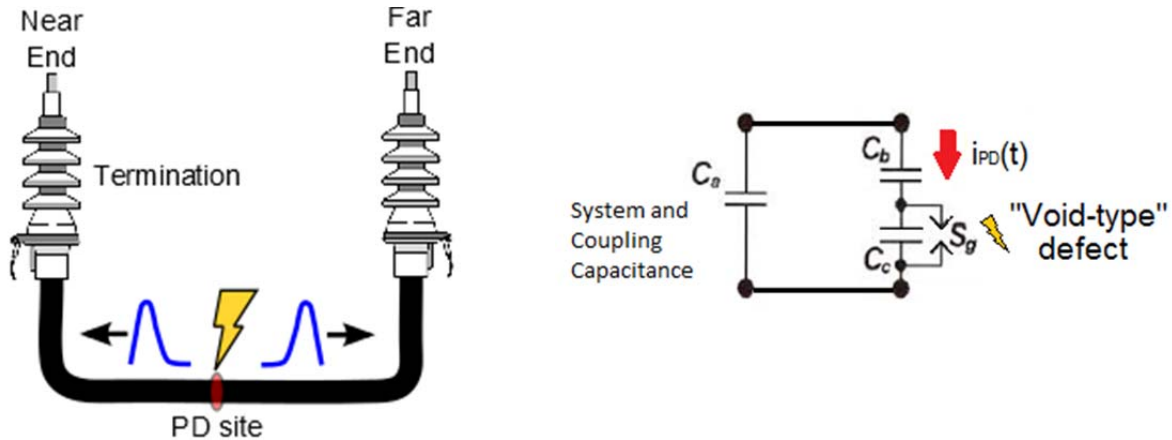


Figure 15: Lumped Capacitive Model

The narrow bandwidths (NB and WB) discussed in IEC essentially define a scaled charge (voltage measurement rescaled to picocoulombs using a calibrator) for PD magnitude. The IEC 60270 approach leads to detection systems that are 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 to perform the localization. In these cases, 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.

As mentioned earlier, the non-conventional category tends to make use of UWB bandwidths, with upper frequency responses in excess of 200 MHz, depending on the equipment manufacturer. These high frequencies, by definition, have shorter wavelengths 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 appears in Figure 16.

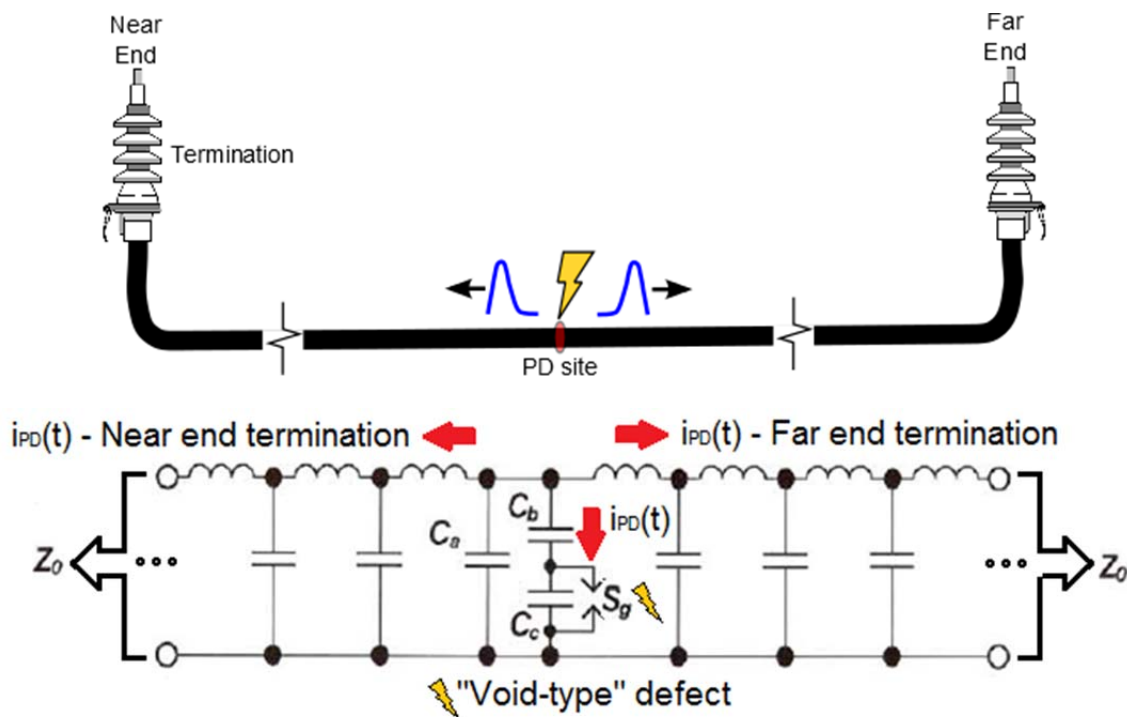


Figure 16: Distributed Impedance Model for Long Cable Systems

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.

7.6.2.2 The “Bandwidth-Length” Relationship

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

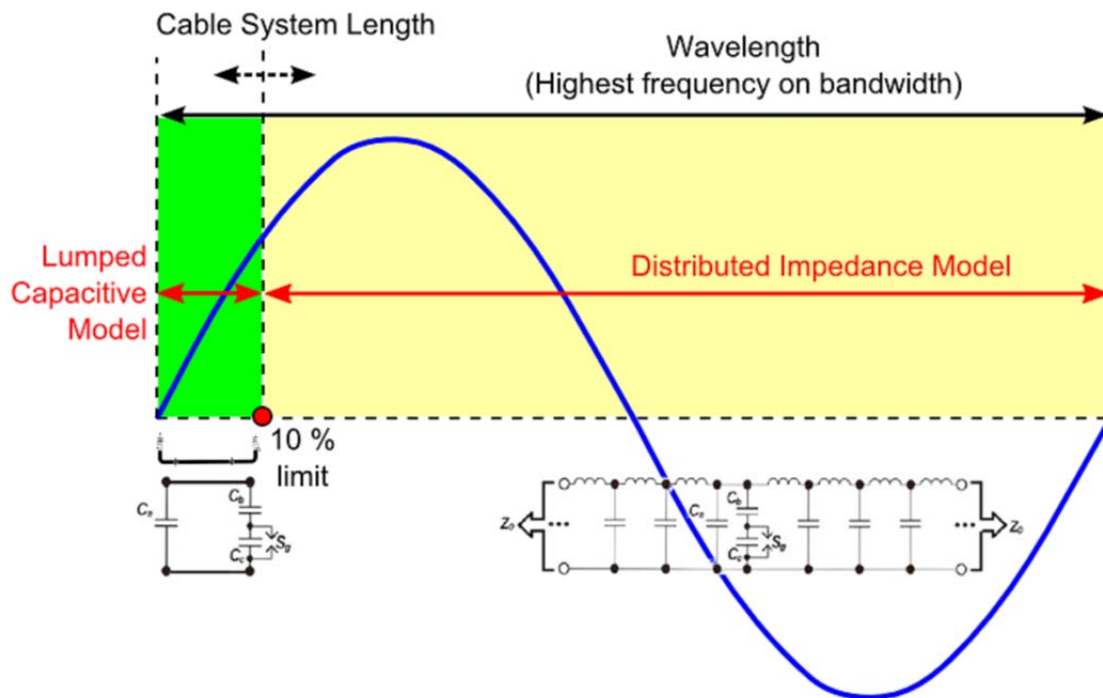


Figure 17: Illustration of Criteria for Lumped or Distributed Modeling

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 may only be modeled using the distributed impedance approach. Note 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 shown earlier are repeated here for convenience in Table 12. An illustration appears in Figure 18.

Table 12: Recommended Frequency Bandwidths According to IEC 60270		
System Type	Frequency Requirements [kHz]	Observations
Wide Band – WB	$30 \leq f_1 \leq 100$ $f_2 \leq 500$ $100 \leq \Delta f \leq 400$	f_1 – lower limit frequency f_2 – upper limit frequency Δf - bandwidth (BW) $\Delta f = f_2 - f_1$
Narrow Band – NB	$9 \leq \Delta f \leq 30$ $50 \leq f_m \leq 1,000$	f_m – midband frequency $f_m = \frac{f_1 + f_2}{2}$
Ultra Wide Band – UWB	No recommendations given	-

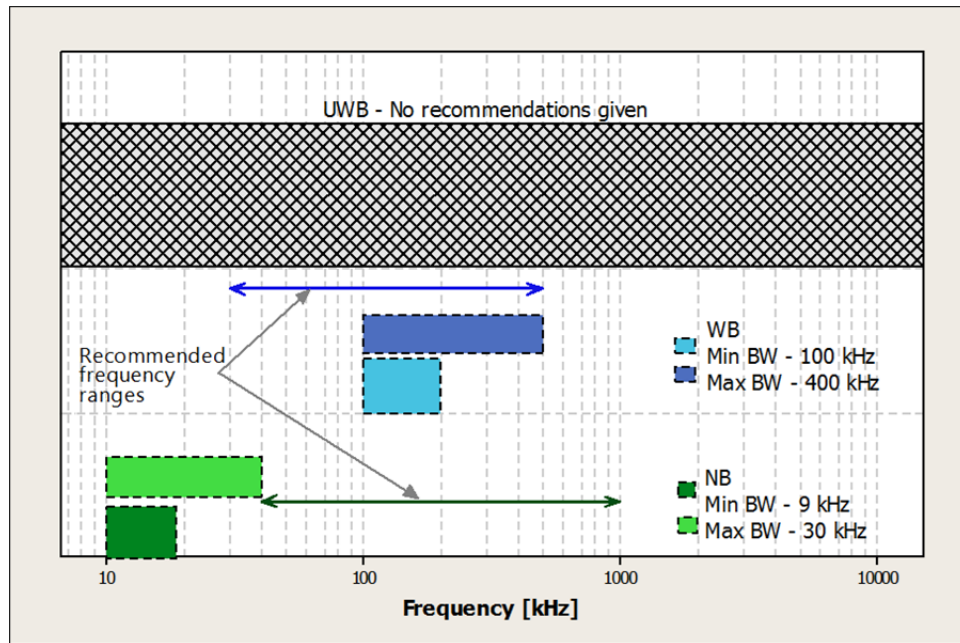


Figure 18: Illustration of Frequency Recommendations According to IEC 60270

The “10%” wavelength guideline can then be applied to the recommendations shown in Table 12 and Figure 18 and a “map” may be constructed for the appropriate modeling conditions (see Figure 19).

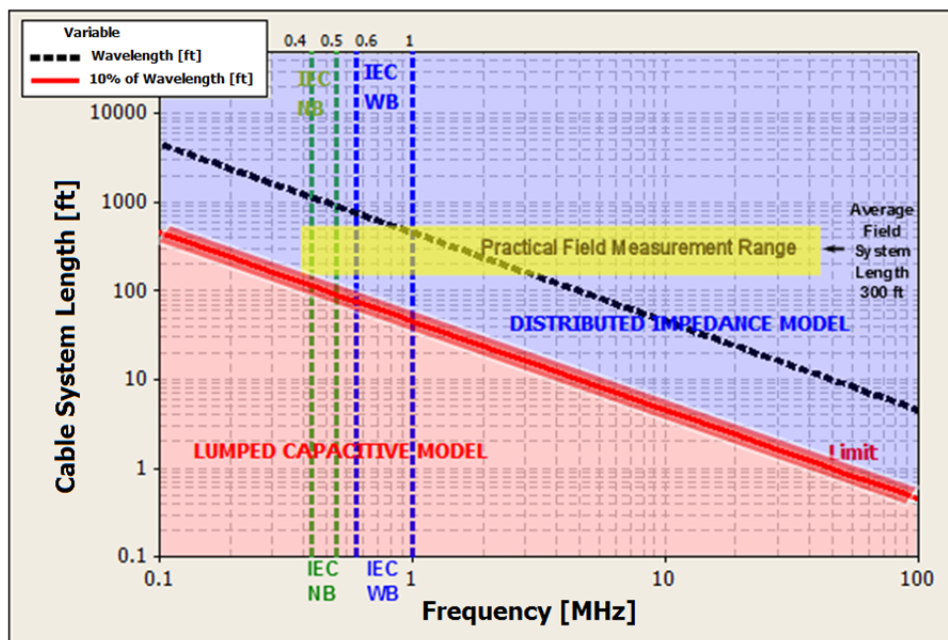


Figure 19: Relationship between PD Measurements Highest Frequency on Bandwidth and Applicability of the Cable system Modeling Categories (Figure 15 and Figure 16).

In Figure 19, the red line represents the recommended maximum cable system length (i.e. 10% of the frequency wavelength) and the black line represents a full frequency wavelength. In this analysis, the signal propagation speed required to compute the wavelength is assumed to be 50% the

speed of light. This speed value corresponds to the average of most real PE-based insulation cable designs. Note that this is less than the theoretical value for pure polyethylene.

Figure 19 can be interpreted as follows:

- Within the frequency and bandwidth range specified by IEC 60270, the assumption that the cable system predominantly behaves like a lumped capacitance is likely to be valid for lengths less than 40 ft (as high as 100 ft if using narrow bandwidth). For these lengths, calibration of the measured PD magnitude is a valid concept.
- A cable system with a length exceeding 500 ft is more likely to behave as distributed impedance and should be tested as such for all practically deployed PD measurements. In this case, the assumptions that are made in IEC 60270 for system modeling and calibration are no longer valid.

In addition, Figure 19 serves to demonstrate the reason why it is impossible to directly compare measured PD magnitude data between factory (Conventional) PD tests and field PD tests. Although other PD metrics (e.g. PDIV, PDEV, pulse repetition rate, etc.) may still be estimated for cable systems with lengths and frequencies in the blue region in Figure 19, calibration per IEC 60270 is no longer valid. The practical field measurement range in terms of frequency and cable system length is represented in Figure 19 by the yellow box centered at 300 ft, which is the average length of MV cable systems in the field. This indicates that most field test lengths fall outside of the region where a lumped parameter is applicable.

7.6.3 Measurement Approaches

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

7.6.3.1 Energizing Cable Systems In The Field

There are two basic approaches for energizing cable systems for PD measurement:

Online

This approach uses PD signals captured under operating conditions of voltage and temperature. There are at least four different methods of online technology each of which takes a different approach to quantification and interpretation of the test results.

The ability to test without disconnecting the system is often cited as an advantage. However, no less effort is required as some form of sensor needs to be attached at multiple locations along the cable system. This may be much easier for conduit systems than for direct buried systems. This entails risks, including safety risks for line crews.

In one form of this approach, the technique cannot pinpoint discharge locations between sensors. Discharges that are active only above operating voltage go undetected. The inability to locate discharges distant from the sensor may not be a serious handicap as many utilities replace cable sections or accessories rather than repair a specific location. In these cases, the ability to locate PD within a few feet is insignificant.

Providers' different approaches make it difficult to compare quantitative measurements. Most of the online data reported within the *CDFI* has come from one service provider/technology, which provides the results in the form of numerical ranking.

Offline

This approach uses PD signals captured at voltages that are typically above operating voltages. When adopting this method, there might be some risk to the cable system from elevated voltage, but the risk to personnel and the customer are minimal. The ability to conduct a sensitivity assessment (i.e. assessment of the measurement system's ability to detect low magnitude signals), locate discharges, and probe for defects that discharge only above operating voltages are seen as advantageous. When making these measurements, defects that are prevalent at operating temperatures may be missed. The stochastic nature of PD can mean that the defects are inactive during the short times typically employed for the measurements.

The approaches to interpretation of offline PD are complex and fluid. However, all approaches typically employ procedures that should maximize the measurement sensitivity. Unfortunately, sensitivity assessments in the field are complex and conducted in many different ways. Practical comparisons of the quantitative measurements made by the different approaches are difficult and generally impossible to make.

Most of the data reported within the *CDFI* has come from two excitation technologies: 60 Hz AC and 0.1 Hz VLF AC.

7.6.3.2 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 is converted from its physical form into an analog electrical signal that the acquisition system transforms into 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:

- Triggered Instruments
- Continuous Acquisition Instruments.

A description of each of the PD measurement philosophies follows.

Triggered Instruments

The first instrument type is commonly known as “triggered” instruments. The decision by a PD measurement as to whether to record a signal or not 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 appears in Figure 20.

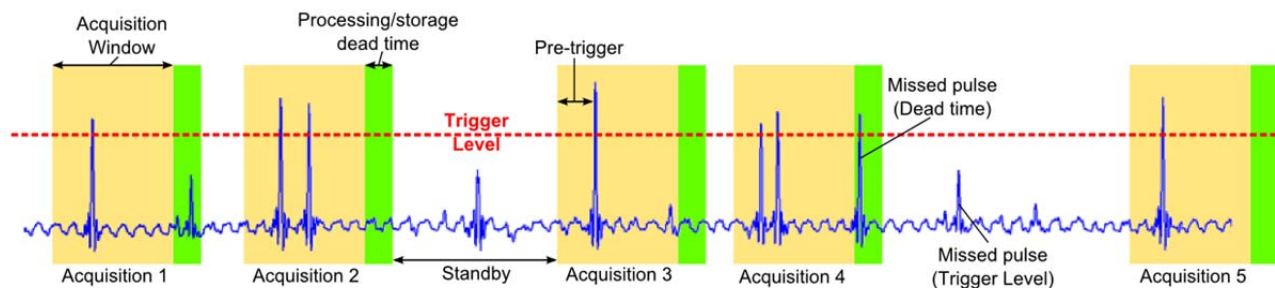


Figure 20: Time Domain Illustration for Trigger Level Based PD Measurement Philosophy

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. In 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, as noted in Figure 20, two reasons explain whyt some pulses are missed:

- **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 for handling missed pulses that meet the trigger level but occur during the processing/storage dead time. However, concerns have abated as continuing improvements in computer processing and communication times have reduced the significance of dead times.

As mentioned earlier, after data acquisition, 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 appears in Figure 21. The synchronization signal in Figure 21 provides information about the phase of the test voltage.

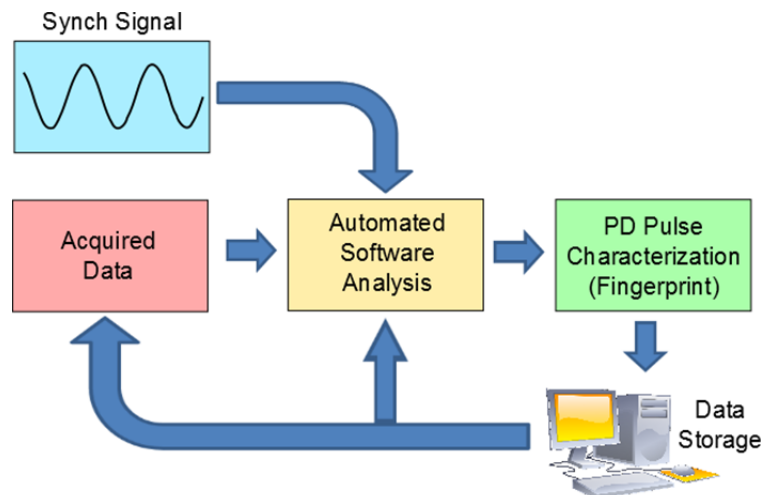


Figure 21: Data Processing Scenario for Trigger Level-based PD Measurement Philosophy

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 generally serves 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 50 or 60 Hz). It is also possible to have alternative operator specified acquisition times. Figure 22 illustrates the concept of continuous acquisition based PD measurement. In this figure the blue solid line represents the incoming signal.

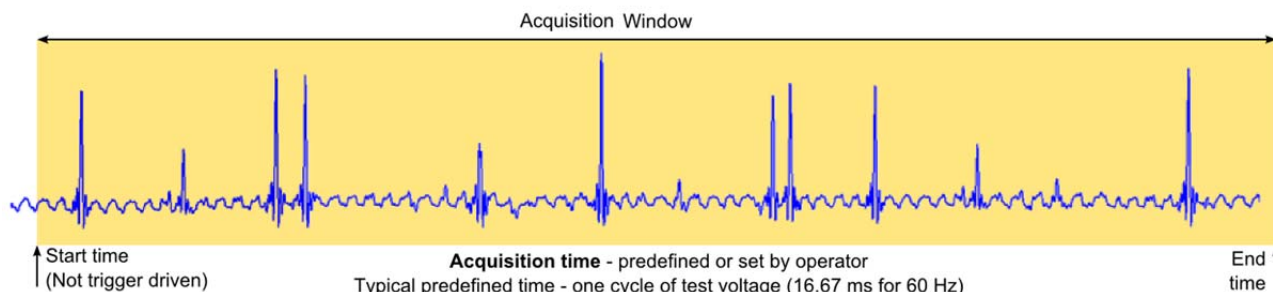


Figure 22: Time Domain Illustration for Continuous Acquisition-based PD Measurement Philosophy

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 performed offline, i.e. after all the data are acquired over a range of test conditions. A typical data processing scenario for this approach appears in Figure 23. As before, the synchronization signal in Figure 23 provides information about the phase of the test voltage.

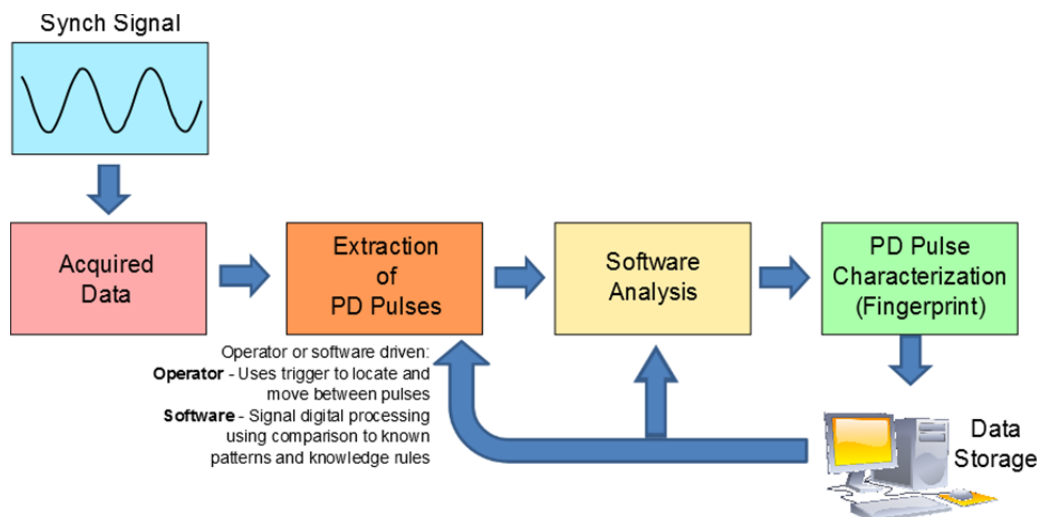


Figure 23: Typical Data Processing Scenario for Continuous Acquisition-based PD Measurement Philosophy

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. The operator can use a variety of software tools 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 accomplished in a similar manner as the trigger level based instruments.

7.6.3.3 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 splice 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 splices, the measurements can be done sequentially or simultaneously. When a PD sensor is moved from splice to splice and PD measurements are made sequentially, the deployment is often termed “splice” or “joint hopping” – see Figure 26.

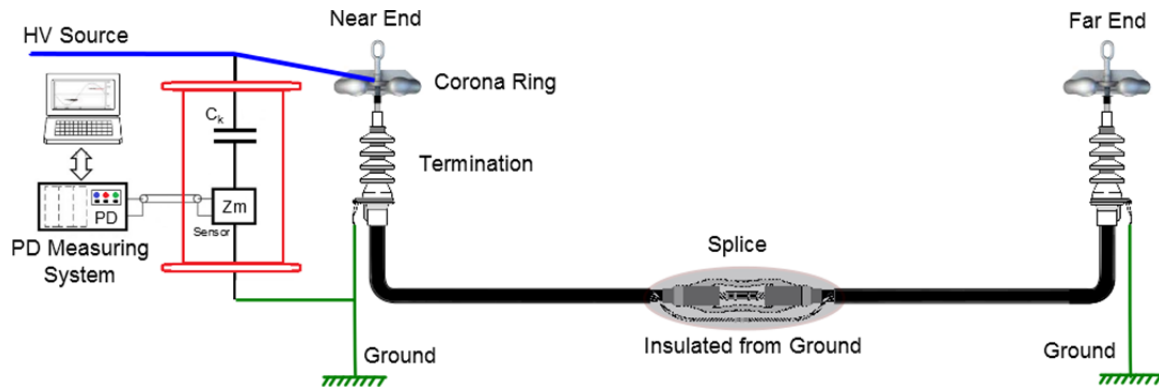


Figure 24: Single-ended Terminal Measurement

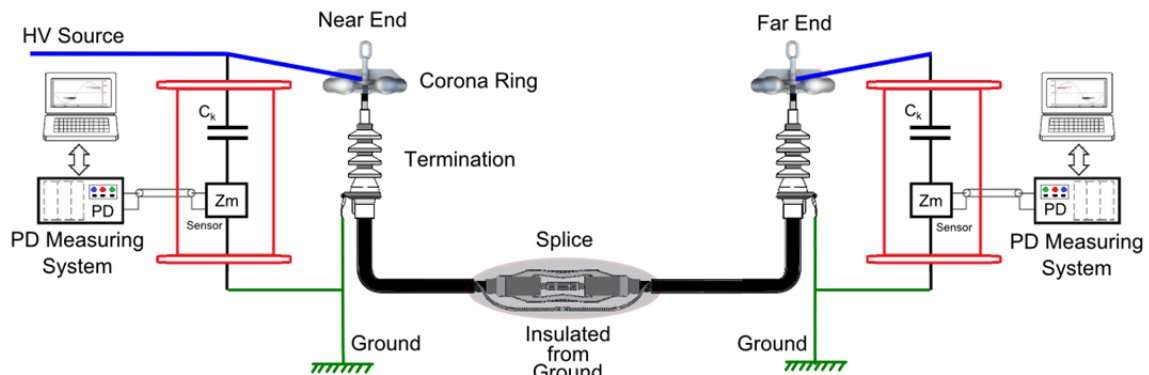


Figure 25: Dual-ended Sequential Terminal Measurement

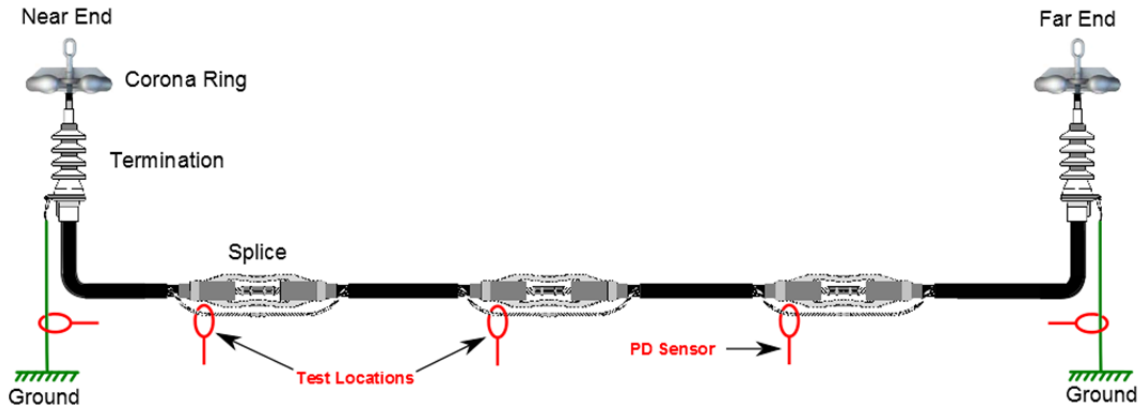


Figure 26: Illustration of PD Distributed Measurement on MV Power Cable Systems

The measurement approaches shown above can use different methods to estimate the size of the discharge. The following two methods are typically 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- μ s 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 PD magnitude, other PD diagnostic indicators can be used to further characterize the measurements.

Table 13 shows the relationship between the voltage source type and the measurement approaches for on-site PD testing of MV cable systems.

Table 13: Source Type Usage for On-site PD Testing of MV 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 to consider:

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

In the previous measuring scheme, Table 14 outlines the four different field approaches to PD measurement and their relevant features.

Table 14: Overview of Field PD Measurement Approaches [26]

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 (splices and/or terminations)	
Sensor	Any internal or external sensor (capacitive or inductive)			
Typical Power Cable System Length	<ul style="list-style-type: none"> <5,000 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	<ul style="list-style-type: none"> 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		<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> 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 <u>assumed</u> 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 integration technique (typically digital).	Any suitable metric (pC, mV, i_{PD})
Location	Location by time of flight from terminals		Location by sensor position and time of flight	

7.6.4 Commissioning and Maintenance Tests

During *CDFI Phases I and II*, the utility participants were asked to provide locations where the various diagnostic technologies could be deployed in a field setting. A number of utilities volunteered for this opportunity and a number of sites were chosen for PD testing. Both commissioning tests on new systems and maintenance or condition-assessment tests on aged systems were performed. Table 15 summarizes the PD tests completed during the *CDFI*.

Table 15: PD Field Tests Performed During <i>CDFI Phase II</i>				
Utility	Date	Length [ft]	Voltage Source Types	Test Type
Hydro Quebec	April 2011	35,000	VLF	Maintenance
Duke Energy	June 2011	5,700	VLF	Maintenance
Alabama Power	July 2011	9,000	VLF Online Damped AC	Maintenance
Alabama Power	August 2011	60,000	VLF Damped AC	Maintenance
Industrial Plant	December 2011	9,300	Damped AC	Maintenance
Georgia Power	December 2011	11,700	VLF	Maintenance
AEP	February 2012	7,900	VLF	Maintenance
Snopud/EPRI	March 2012	12,400	VLF	Maintenance
Hydro Quebec	March 2012	35,400	VLF Damped AC	Maintenance
Georgia Power	March 2012	16,500	VLF	Maintenance
We Energies	November 2012	31,000	60 Hz VLF Damped AC	Maintenance
Ameren	April 2013	79,100	Damped AC	Commissioning
Georgia Power	April 2013	5,000	VLF Damped AC	Maintenance
Ameren	August 2013	14,000	Damped AC	Commissioning
Snopud/EPRI	February 2014	38,400	VLF Damped AC	Maintenance
Duke Energy Franklin	March 2014	4,600	VLF Damped AC	Maintenance.
Duke Energy	March 2014	2,800	VLF Damped AC	Maintenance.
Duke Energy	March 2014	13,200	VLF Damped AC	Maintenance
Maximum Length Tested: 457,602 ft or 87 mi or 139 km in over a 41-month period (Actual Tested Cable System Length is a Subset of Total)				

The results shown in Table 15 consider a time span of 41 months that started in April 2011 and ended in March 2014, a significant total length of 457,602 ft (87 mi or 139 km) of cable systems have been tested using different PD source types and this approach to measurement deployment. The PD sources were made available by the diagnostic testing providers, most of whom were participants in the *CDFI*. The PD source types include online PD and VLF, Damped AC, and 60 Hz for off-line PD. More importantly, Table 15 also shows the type of test deployed; i.e. maintenance or commissioning tests. Additional tests are known to have been completed by utilities not directly involved in *CDFI*. These tests are included in Figure 27.

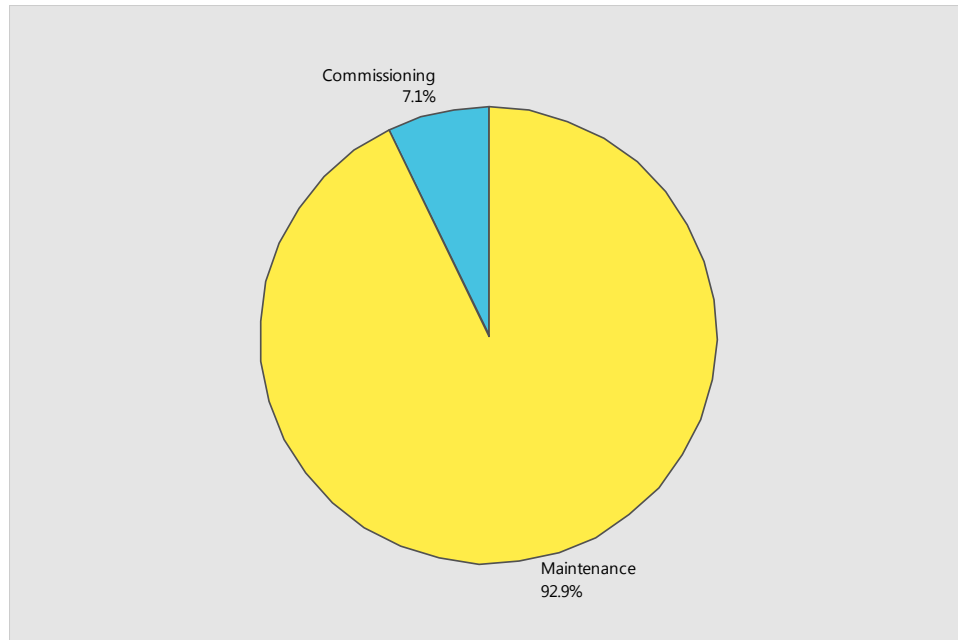


Figure 27: Distribution of PD Tests for MV Cable System between Commissioning and Maintenance Tests

Based on Figure 27, it is straightforward to conclude that MV PD field measurements are mainly used in the maintenance mode.

7.6.5 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.

7.6.5.1 IEC 60270 Calibration Method

The calibration of PD measuring systems serves to verify that the measuring system is able to measure a predetermined PD magnitude in picocoulomb correctly. Calibration is performed for the complete test configuration including,

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

Each cable system tested requires calibration unless tests are conducted on a group of similar cable systems. In this case, “similar” means the same cable type, length, and terminations.

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 or both terminals 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 28.

The pulse injection uses a calibrator (pulse injector) designed and 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 included.

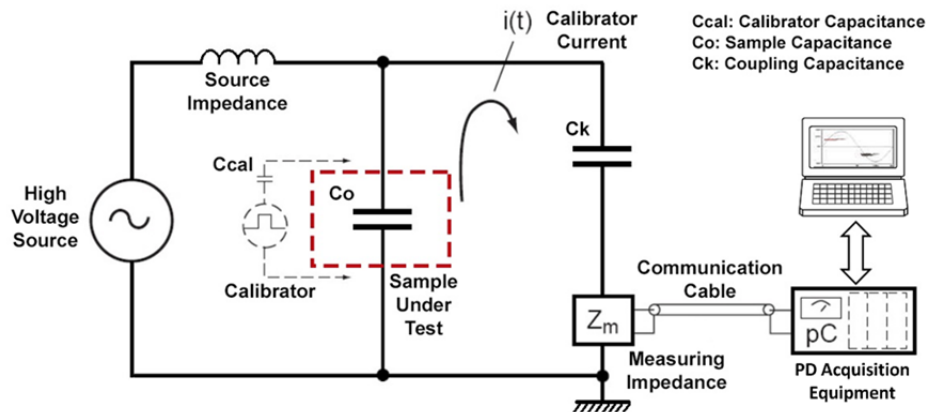


Figure 28: Calibration Test Set-up for PD Measurements

The standard PD measuring test method presented in the 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 28 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 the 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 peak magnitudes of pulses in the PD detector. Peaks of pulses 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 charges of 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 appear in Table 16. 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 16: IEC 60270 Requirements for PD Calibrators		
Attribute	Requirement	Comments
Calibrator Charge (q_0)	Tolerance $\pm 5\%$ of set charge and ≤ 1 pC	Clause 7.2.3 whichever is greater
Pulse Rise Time (tr)	Tolerance $\pm 10\%$ of set time and ≤ 60 ns	Clause 7.2.3 $tr - 10\%$ to 90% of peak value
Pulse Repetition Rate (N)	Tolerance $\pm 1\%$ of set rate	Clause 7.2.3
Linearity of Calibrator	Tolerance $\pm 5\%$ 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 $\pm 10\%$ of C_0 allowed	No recalibration required for similar cable systems Clause 5.2

7.6.5.2 Pulse Injectors

Pulse injectors (otherwise known as calibrators) are used in the calibration procedure described above. As Table 16 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 because 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 research appear in Figure 29.



Figure 29: Commercially Available Pulse Injectors

Figure 30 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.

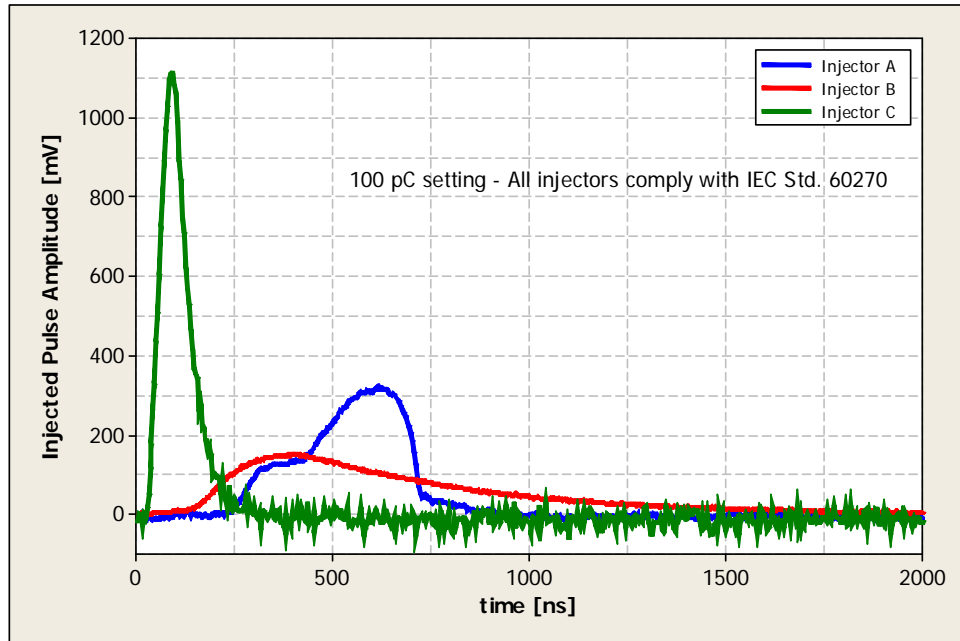


Figure 30: Comparison Between Pulse Injectors – 100 pC Setting into a 50 Ω Impedance

As seen in Figure 30, the waveforms between pulse injectors are different; however, they should be compared in terms of their charge setting, which can be estimated by the area under the pulse. This comparison appears in Figure 31.

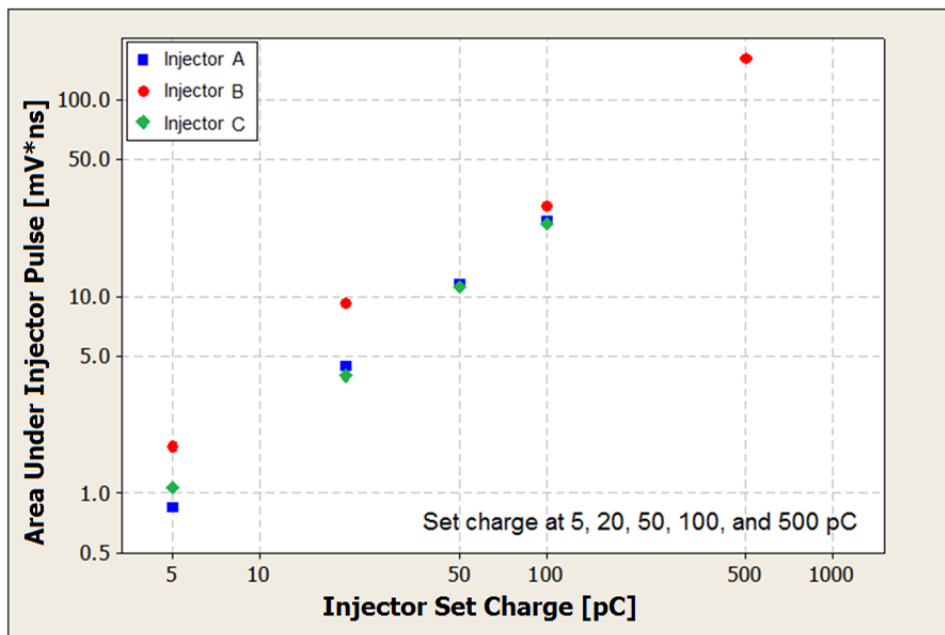


Figure 31: Comparison of Calculated and Actual Charge Settings for Different Injectors

As seen in Figure 31, 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 are apparent between the injected pulse waveforms in Figure 30. 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 appears in Figure 32.

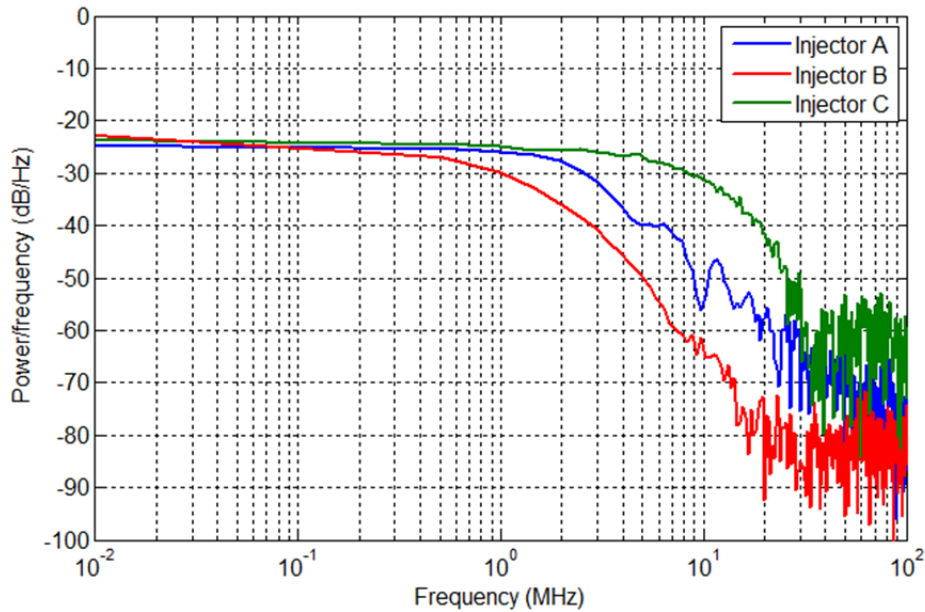


Figure 32: Power Spectral Density of Different Injector Pulses

As shown in Figure 32, 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. Figure 32 also indicates 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 identical 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 very important and should be considered if measurements are to be deployed in this frequency range.

While the above two observations are clearly shown in Figure 32, 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 often defines the frequency threshold value 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 32 and the results appear in Figure 33.

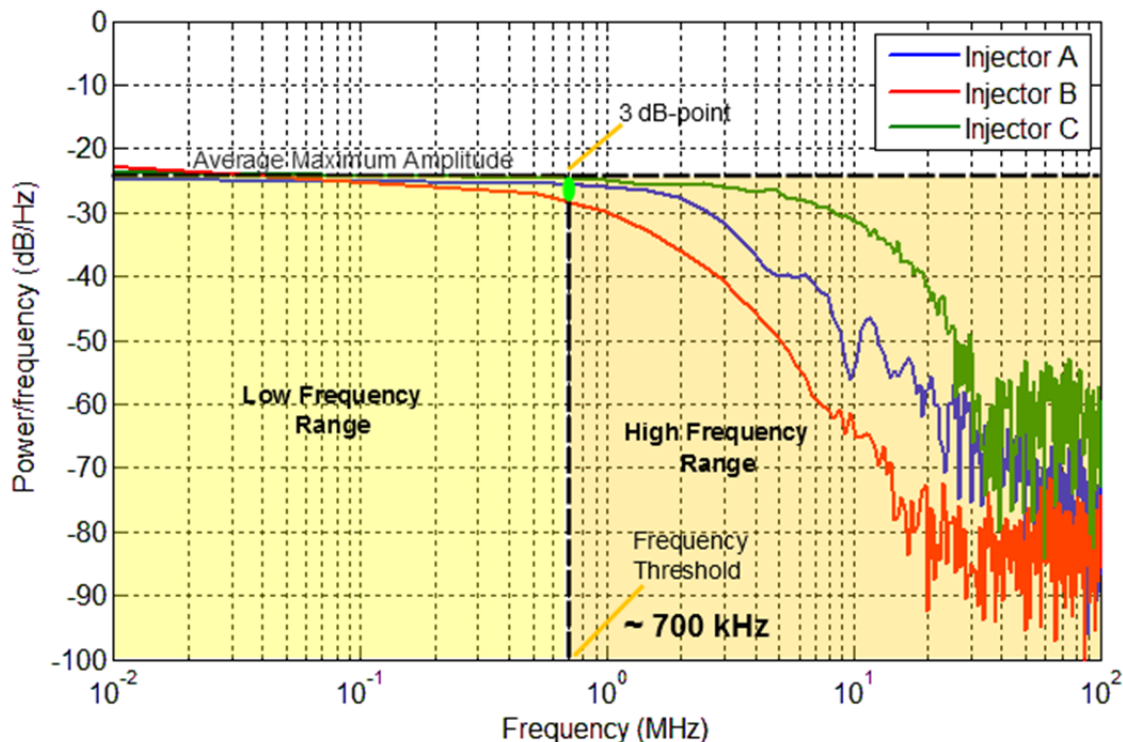


Figure 33: 3 dB-point Criterion to Determine Frequency Threshold

As seen in Figure 33, the threshold for differentiating the low and the high frequency ranges is approximately 700 kHz.

Once the threshold frequency between the low and the high frequency ranges has been established, a comparison between IEC Std. 60270 – 2000 bandwidth requirements and the power spectrum density functions, of the different injector pulses corresponding to Figure 30, is shown in Figure 34.

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 34 could consider frequencies that are below and above the threshold level of 700 kHz; therefore, the injector pulse results using different injectors cannot be compared. Under these conditions the energy of the injected pulse is an extra factor to consider e.g., the energy of the pulse from Injector C has more energy when compared to the pulse from Injector B. The bigger energy of Injector C comes from the fact that its power spectrum density function has higher frequency components; the energy of the injector pulse is related to the area under the curve of its power spectrum density function.

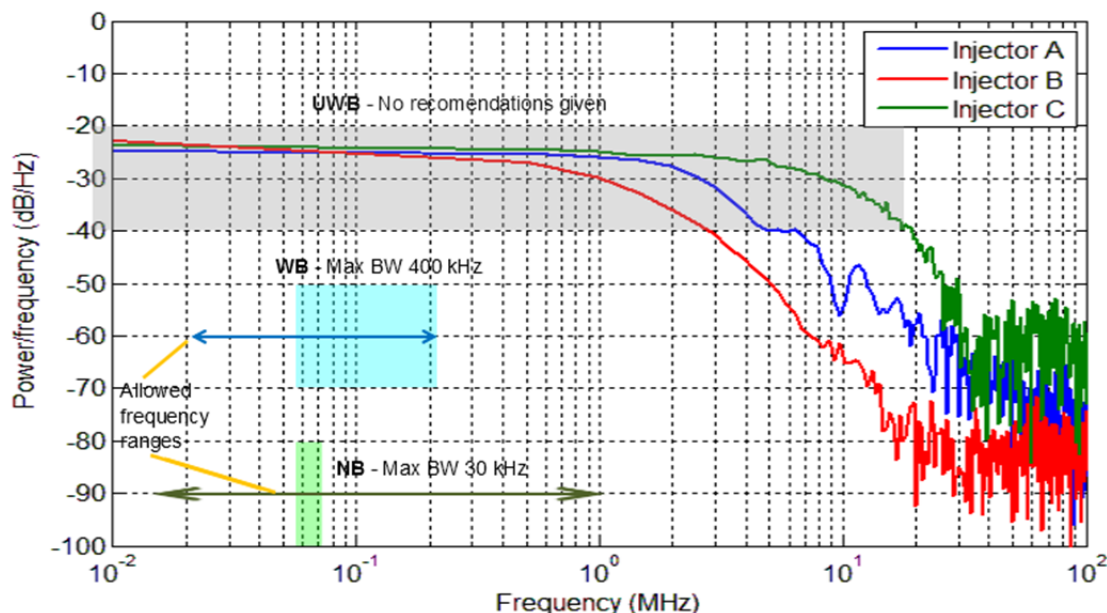


Figure 34: Comparison between IEC Std. 60270 – 2000 Bandwidth Requirements and the Power Spectral Density Function of Different Injector Pulses Corresponding to Figure 30

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.

7.6.6 Performance Assessment

The current thinking for field PD measurements is that performance checks should be made before the actual PD test to provide a measure of the “goodness” of the test. 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 the measurement was performed.

Two performance checks have been proposed:

- Sensitivity Check; and
- Range Check.

These checks are covered in the following sections.

7.6.6.1 Sensitivity Check

The sensitivity of a measuring system is defined as the capacity it has to respond to changes in the variable that it is measuring. The sensitivity is an absolute quantity and can be also understood as the smallest absolute amount of change in the measured variable that can be detected by the measuring equipment. The main goal of this check is to establish the smallest pulse amplitude and

width that can be detected from the injection location (either near end, far end, or both) by the PD measuring system.

In the context of cable systems, the sensitivity check is a complex topic to handle and characterize, which is due to all the factors that can affect the sensitivity of a PD measuring system. These factors directly affect the amplitude of PD pulses:

- Background noise;
- Type and performance of PD sensors;
- Grounding practices; and
- Frequency response of PD measuring system.

The sensitivity check tries to establish the relationship between the amplitude of “PD-like” injected pulses (A_i) and the amplitude of the resulting measured pulses (A_m) as detected by the measuring equipment. This is illustrated in Figure 35. Measurements that will be made according to IEC are performed in terms of charge while UWB measurements are made in terms of voltage.

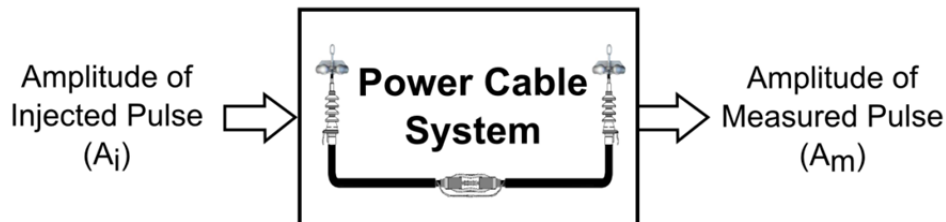


Figure 35: Sensitivity Check of PD Measurements on MV Power Cable Systems

The concept of the sensitivity check is illustrated in Figure 36. The pulse injection can be performed from either end of the cable system. However, it is useful to start at the near end first as the minimum pulse width and amplitude for the near end will be lower than would be observed from the far end. The benefit of this approach is that the user is able to confirm the PD detection equipment and associated connections are installed/operating correctly.

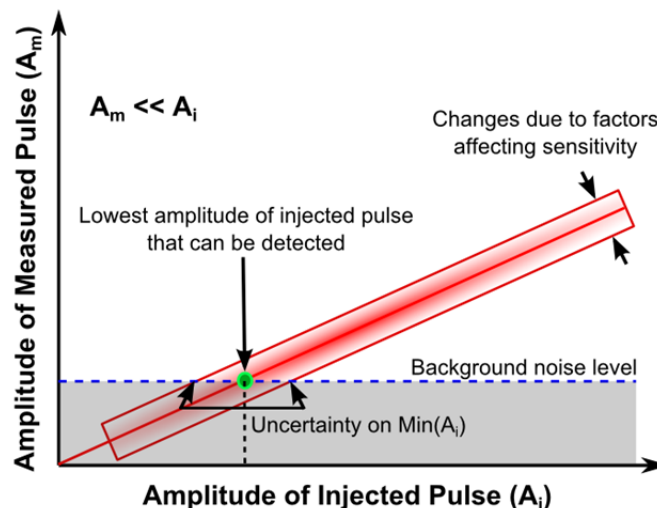


Figure 36: Sensitivity Check Concept (Near or Far End Injection)

There are fundamentally two ways of approaching the Sensitivity Check:

- For a given pulse width, the lowest amplitude of the injected “PD-like” pulse is determined. The injection starts with the highest possible amplitude and is reduced until the measured pulse amplitude falls beneath the background noise level. This amplitude and the fixed pulse width represent the sensitivity of the PD measuring system under these particular test conditions.
- For a given pulse amplitude, the narrowest pulse width of the injected “PD-like” pulse is determined. The injection starts with the widest possible pulse and the width is then decreased until the measured pulse amplitude falls beneath the background noise level. This value and the pulse width represent the sensitivity of the PD measuring system under these particular test conditions.

In addition, Figure 36 depicts a linear relationship between A_i and A_m . Under ideal conditions, this would be the case. However, the linearity is influenced by a multitude of factors and interactions that are beyond the scope of this document. Suffice it to say, there is inherent uncertainty in the $\min(A_i)$, i.e. tests performed at different times may give different sensitivity check results.

There are several ways to deploy the sensitivity check for laboratory and field PD measurements, including terminal (single-ended and double-ended) and distributed measurements. The details of the sensor placement and connections for the various options appear in Table 17.

Care must be taken when interpreting the approaches to Sensitivity Check in comparison to the PD approaches to measurements. The approaches to Sensitivity Check consider only the relationship between the “PD-like” pulse injection location and one PD sensor at a time. If more than one PD sensor is used simultaneously during the test (e.g. for dual-ended or distributed deployment), then the sensitivity check should be performed from the injection location to each of the PD measuring systems present in the cable system during the simultaneous acquisitions of the PD signals by using the approaches presented in Table 17.

Table 17: Illustration of the Approaches for Sensitivity Check Deployment for PD Measurements on MV Power Cable Systems

Deployment	
Injector and PD Measuring Equipment Located at the Same End with Coupling Capacitor	
	<ul style="list-style-type: none"> • Not affected by attenuation or dispersion • Capacitive or inductive sensors • Highest sensitivity
Injector and PD Measuring Equipment Located at the Same End without Coupling Capacitor	
	<ul style="list-style-type: none"> • Inductive sensor • Not affected by attenuation or dispersion • Reduced sensitivity (enhanced noise rejection)
Injector and PD Measuring Equipment Located at Different Ends with Coupling Capacitor	
	<ul style="list-style-type: none"> • Attenuation and dispersion effects observed • Capacitive or inductive sensors • Quantifies ability to detect PD from far-end
Injector and PD Measuring Equipment Located at Different Ends without Coupling Capacitor	
	<ul style="list-style-type: none"> • Inductive sensor only • Attenuation and dispersion effects observed • Reduced sensitivity (enhanced noise rejection)

Table 17: Illustration of the Approaches for Sensitivity Check Deployment for PD Measurements on MV Power Cable Systems	
Deployment	
Injector Located at One End and PD Measuring System Located at a Splice	
	<ul style="list-style-type: none"> • Distributed measurement • Inductive sensor • Attenuation and dispersion effects observed • May require injection from both ends if splice is not centrally located

As mentioned above, the presence of the coupling capacitor is always advisable to ensure a low impedance path for the PD current to flow and thus increase the sensitivity. However, there are situations in which it is not possible to use a coupling capacitor. In such cases, the sensitivity check could still be performed as shown in Table 17 using an inductive PD sensor. Unfortunately, the expected sensitivity would not be as high as those approaches that use a coupling capacitor.

7.6.6.2 Range Check

As mentioned above, as PD pulses propagate from a source or sources towards the cable system ends, they are subjected to attenuation and dispersion that then degrade the signal that could be detected. This affects the sensitivity of PD measurements. In particular, the peak amplitude and energy of the traveling PD pulses decrease with the increasing travel length. As a consequence of this length effect, the sensitivity changes as a result of the relative positions of the PD source(s) and sensors. So for short cable systems, PD activity may be readily detected by a terminal measurement using capacitive or inductive sensors. For long cable systems, the attenuation, dispersion, and other factors affecting the sensitivity may degrade the signal to the point where pulses occurring at the far end would no longer be detectable. Range check is a procedure that establishes the distance that a “PD-like” pulse can travel along a cable system and still be measured. Similar to the Sensitivity Check, the Range Check is accomplished by injecting “PD-like” pulses into the cable system from either end. The concept of range check appears in Figure 37.

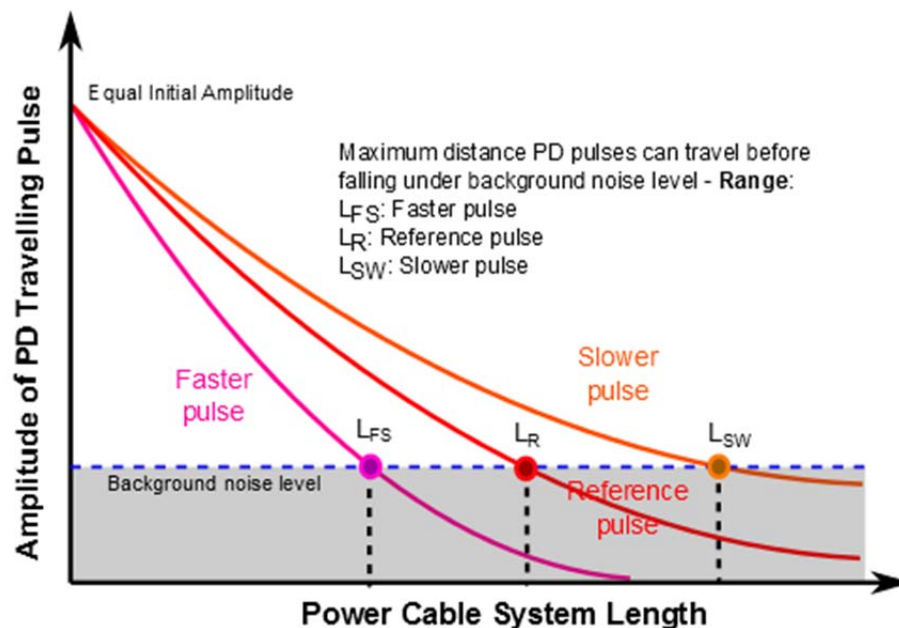


Figure 37: Range Check Concept for MV Cable Systems

Figure 37 illustrates how the peak amplitude of a PD pulse changes as it travels along the cable system. Initially, three PD pulses with the same peak amplitude are considered, the difference between them is their width with the “Faster Pulse” having a narrower width than the “Reference Pulse” and with the “Slower Pulse” having a wider width than the “Reference Pulse”. The dashed blue line represents the background noise level. If the peak amplitude of the traveling PD pulse drops below this value then it is assumed that the pulse cannot be detected. Under this scenario, it is observed in Figure 37 that the “Faster Pulse”, “Reference Pulse”, and “Slower Pulse” are able to travel distances L_{FS} , L_R , and L_{SW} , respectively. The distances L_{FS} , L_R , and L_{SW} represent the “ranges” that their respective PD pulses can travel down the cable system and still be detected. It is also important to note that the faster the pulse, the shorter the range and *vice versa*.

The comparison between pulses in Figure 37 is possible because all the PD pulses were assumed to have the same initial peak amplitude. This assumption is rarely true (if ever) for commercially available pulse injectors. Therefore, care is required when comparing range check results for different pulses/pulse injectors on the same cable system. In the ideal case, the peak amplitude and width of the injected pulses could be adjusted to different values thus allowing the Range Check to be performed over a range of different conditions. However, in reality, conventional calibrators or portable TDR units are used as sources for the “PD-like” pulses. Unfortunately, these devices are limited in their flexibility as they generally only allow changes of one of the pulse parameters. For example, PD calibrators utilize a fixed pulse shape where only the initial amplitude (charge magnitude setting) may be adjusted by the user. TDR units, on the other hand, generally only allow the alteration of the pulse width. The ideal “PD-like” pulse injector should have the option of independently setting the amplitude, pulse width, and its characteristic input/output impedance. The typical connection of a pulse injector appears in Figure 38.

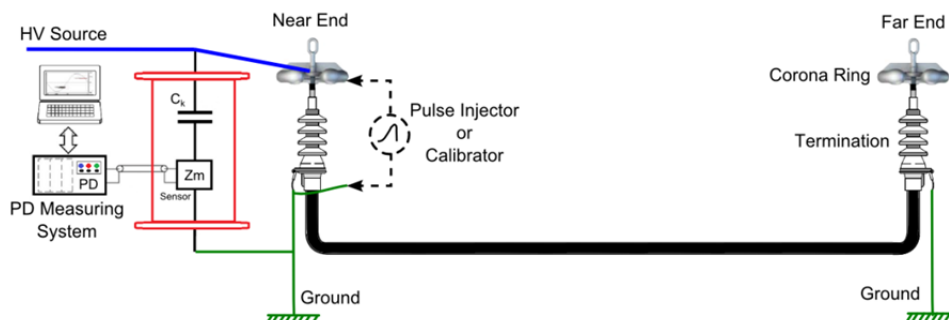


Figure 38: Typical Test Setup for Range Check Procedure

The Range Check procedure begins by injecting a “PD-like” of known width and amplitude into a power cable system as shown in Figure 38. The PD acquisition system should be able to provide the TDR trace of the injected “PD-like” pulse as it travels through the cable system. An illustration of this TDR trace for a power cable system without splices appears in Figure 39.

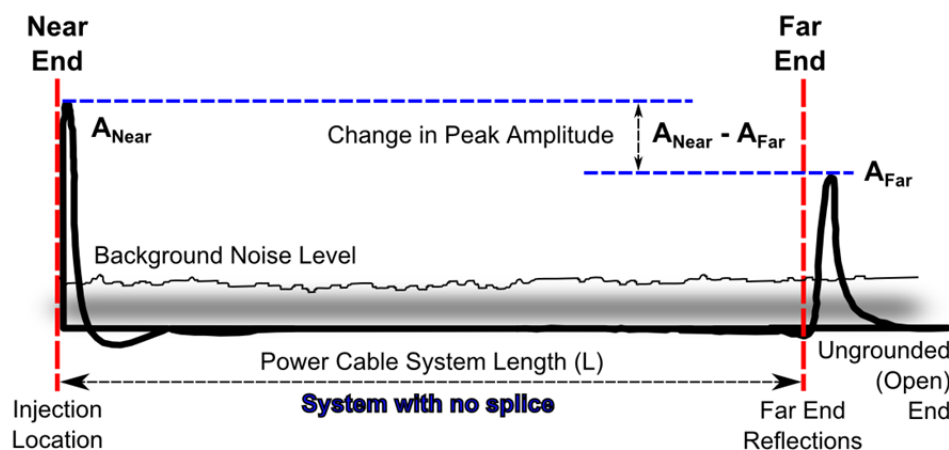


Figure 39: Illustration of Range Check Trace for a Cable System without Splices

The text below describes the Range Check procedure for a power cable system with no splices. In this example this procedure is conducted on a 34 ft long XLPE, 15 kV, 1/0, jacketed cable system for demonstration.

1. Use the following established pulse time widths: 5 ns, 10 ns, 20 ns and 30 ns. If these exact pulse time width numbers cannot be met, use approximate values. For faster pulses, if necessary, adjust the amplitude of the injected pulse at the near end until a good reflection from the far end above the background noise level is observed on the TDR trace (as shown in Figure 39). Each TDR trace represents the cable system response to the different pulse widths – see example traces in Figure 40.

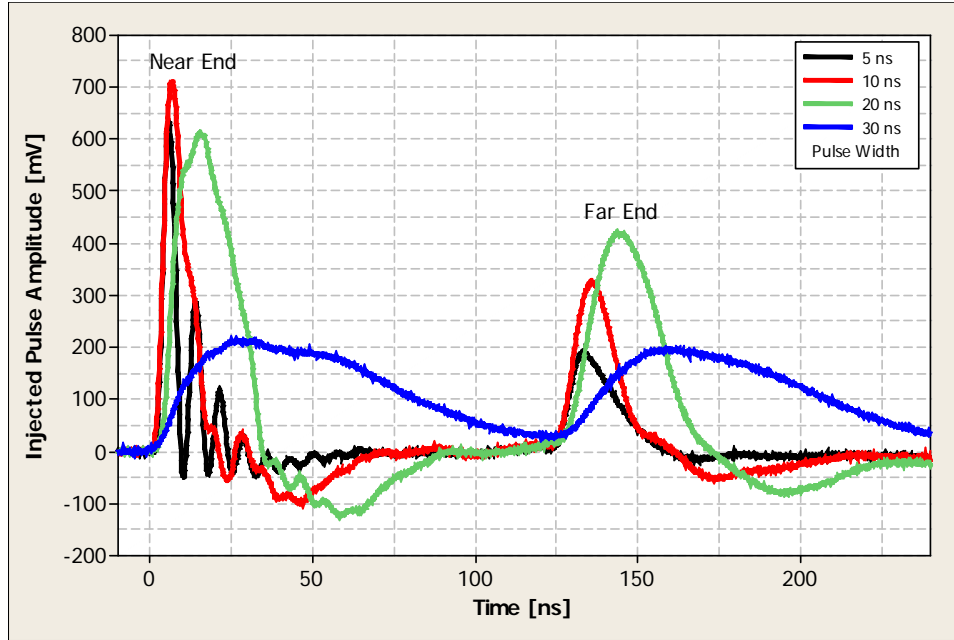


Figure 40: Example Range Check Traces

- For each of the traces, identify and quantify the peak amplitudes of the injected pulses at the near end and far end reflection and compute the change in amplitude per unit length according to:

$$\Delta A = \frac{1}{2L} \ln \left(\frac{A_{Near}}{A_{Far}} \right) \quad \text{Equation 2}$$

Where,

ΔA : Change in peak pulse amplitude per unit length in [ft^{-1}],

L : Cable system length in [ft],

A_{Near} : Peak amplitude of the injected “PD-like” pulse at the near end in [mV],

A_{Far} : Peak amplitude of the reflected pulse corresponding to the far end in [mV].

Figure 41 shows the normalized (to initial peak value) Range Check traces for the traces shown in Figure 40.

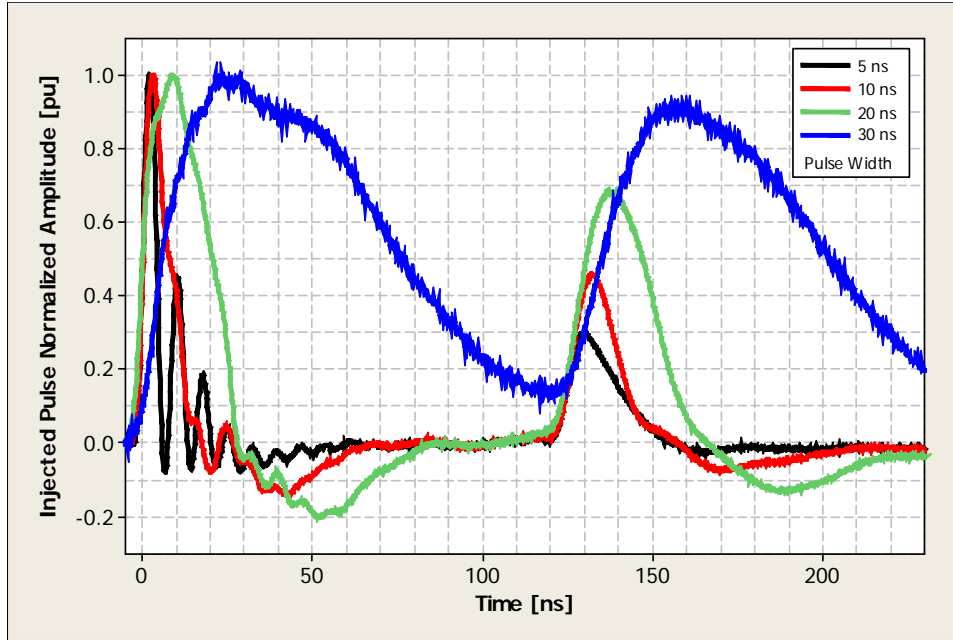


Figure 41: Normalized (to Initial Peak) Range Check Traces

- Estimate distance needed to attenuate each initial peak to the measured noise floor (wider pulses will yield longer distances) using (3).

$$Range\ Check|_{Amplitude}^{Pulse\ Width} = \frac{1}{\Delta A} \ln \left(\frac{Amplitude}{A_{Noise}} \right) \quad \text{Equation 3}$$

Where,

Range Check: Distance, for a given pulse width and amplitude, that a PD pulse can travel along the cable system and still be detectable above the background noise level in [ft],

Amplitude: Peak amplitude of a PD pulse at its source location in [mV],

A_{Noise}: Estimated metric for the amplitude of the background noise level in [mV].

Figure 42 shows the resulting distance calculations for the 5 ns, 10 ns, 20 ns, and 30 ns pulses used in this example. The background noise for these measurements was 2 mV and so the 30 ns pulse would be able to travel 4,000 ft before the return pulse would too low to distinguish above the noise floor. The 5 ns pulse, on the other hand, can only travel 264 ft before it is lost in the noise.

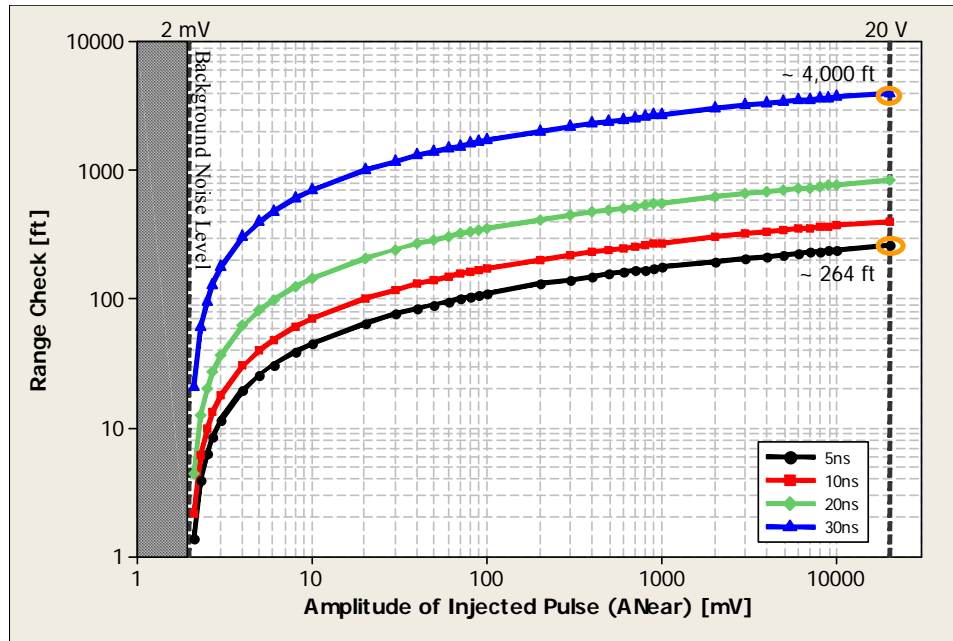


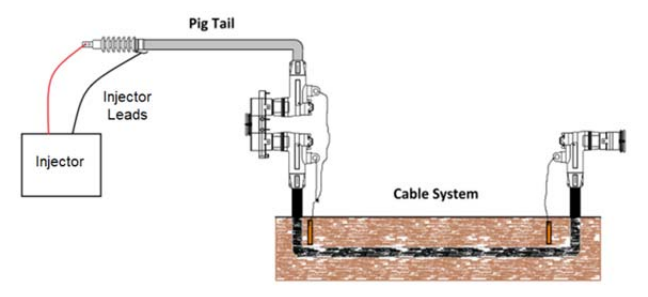
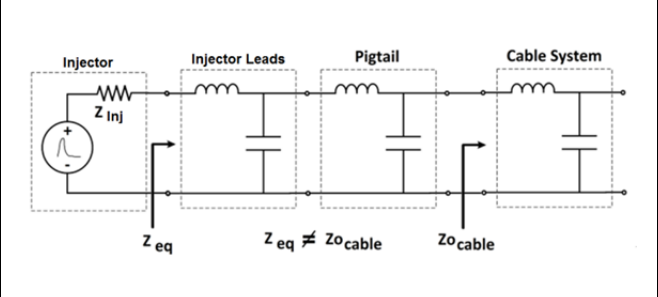
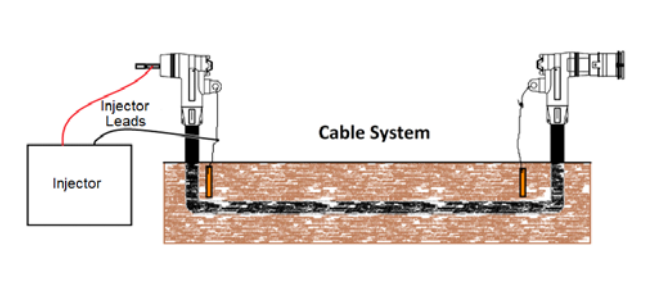
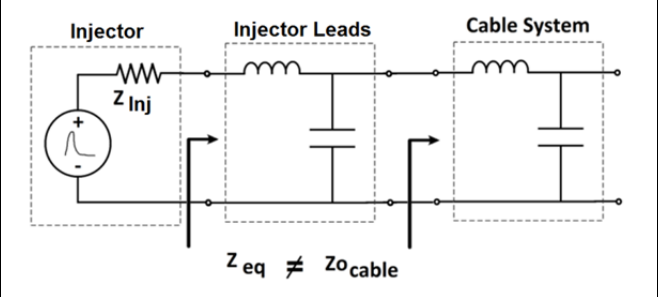
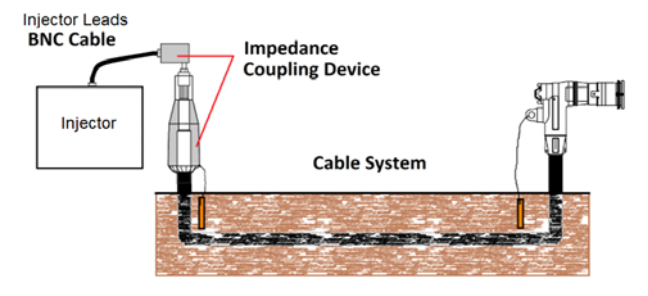
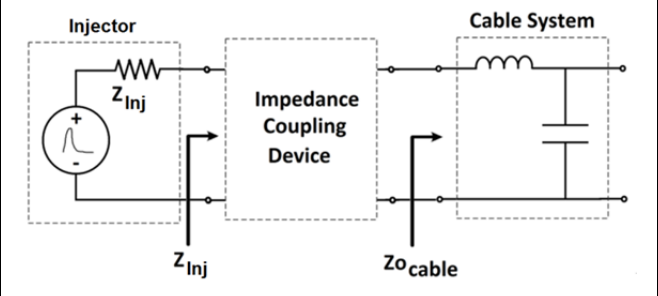
Figure 42: Results for Range Check Example

In summary, the Range Check procedure described above can estimate the distance that a “PD-like” pulse, of known characteristics, could travel along a cable system and still be distinguishable above the noise floor. This method, while imperfect, does provide enhanced information on the attenuation, dispersion, and other factors that cause PD signals to deteriorate as they travel to the detection equipment. The information can then be used to evaluate whether a PD signal, coming from a particular site of the cable system, can be successfully detected at the location of the measuring equipment location and thus determining whether distributed PD measurements should be deployed or not.

7.6.7 Practices For “PD-like” Pulse Injection

Pulse injection units are not built to connect directly onto the various cable system sizes in use on utility systems. The injectors utilize a set of test leads for making the actual connection which have a difference characteristic from that of the cable system. The resulting impedance mismatch causes a reflection at the transition point from the connection leads to the cable system. The severity of this reflection is determined by the degree of mismatch. This reduces the energy the pulse injector is able to transfer into the cable system and can limit the user’s ability to perform Sensitivity or Range Checks on longer length systems.

Table 18 shows the known practices for “PD-like” pulse injection, the typical deployment and equivalent circuit showing the transition points and characteristic impedance changes are also presented.

Table 18: Known Practices for “PD-like” Pulse Injection	
Typical Deployment	Equivalent Circuit
Multiple Impedance Mismatches – No Correction	
	
Single Impedance Mismatch – No Correction	
	
Single Impedance Mismatch – Impedance Coupling Device	
	

As Table 18 shows, the three primary means of pulse injection include at least one impedance mismatch and may or may not utilize an impedance coupling device (ICD). The ICD can utilize geometric grading, a resistive matching circuit, or a combination of both. Use of an ICD can allow a pulse injector to be used on longer length cable systems than would have otherwise been possible. The least efficient method utilizes a “pig tail” to connect the pulse injector to the cable system while the most efficient method makes a direct connection to the cable system via an ICD. The latter method may require the user to remove the existing termination or elbow to install the ICD.

It is important to mention that in most cases a perfect impedance coupling is not possible nor is it needed. In most MV cable systems, a high level of matching is unnecessary to successfully complete both Sensitivity and Range Checks. This is more of an issue on longer length systems or those that exhibit high dielectric loss.

7.6.8 Grounding Effects

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 (some HV and EHV installations) 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. This is primarily an issue in the field where cable systems are often grounded in at least two locations (such as MV cable systems). Laboratory tests can utilize the single ground approach and are thus better able to capture the PD pulses that might occur in a cable system in the field.

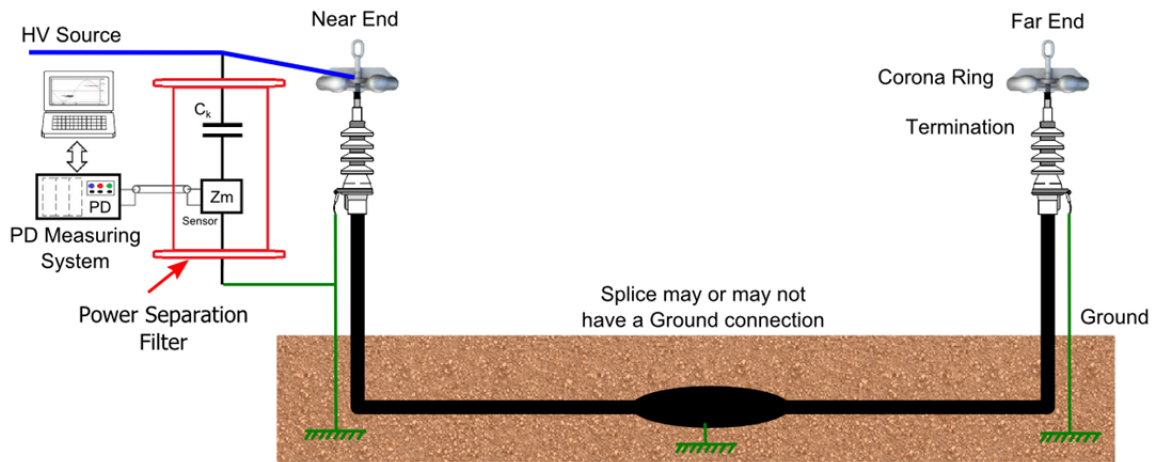
Grounding affects the signals that are able to flow through the sensors and so sensor placement is a key component to the effect grounding has on PD measurements. Three primary sensor configurations are considered:

- **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 an 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 coupled to the grounding connection of the cable system under test at the near end.

The various sensor connections and their field and laboratory deployments appear in Table 19 through Table 21.

Table 19: Capacitive Divider with Built-In Sensor Connections

Field Deployment



Laboratory Deployment

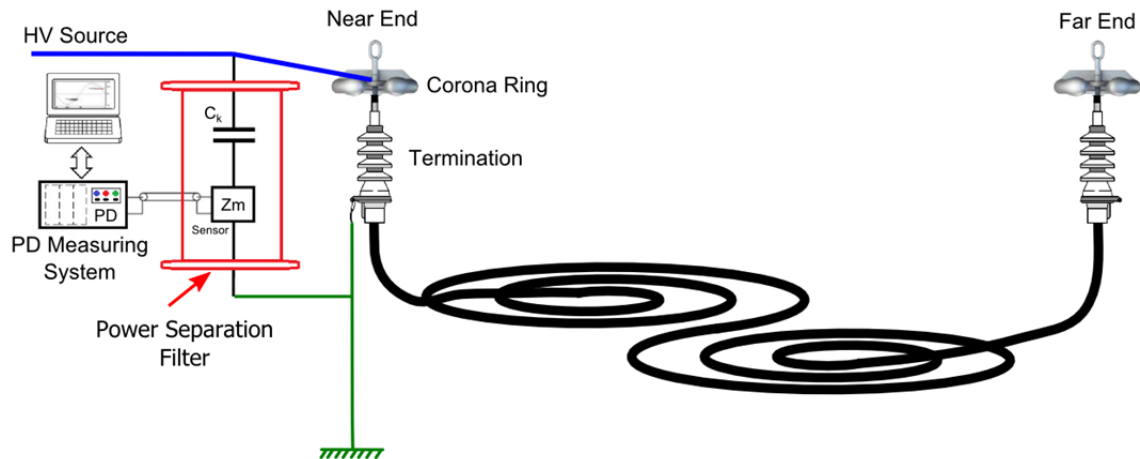
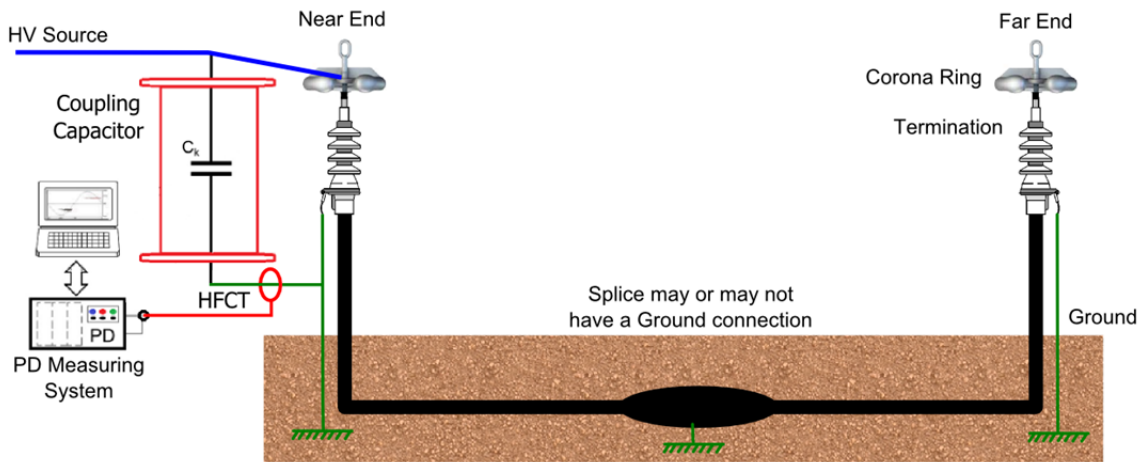


Table 20: Capacitive Divider with Separate Sensor Connections

Field Deployment



Laboratory Deployment

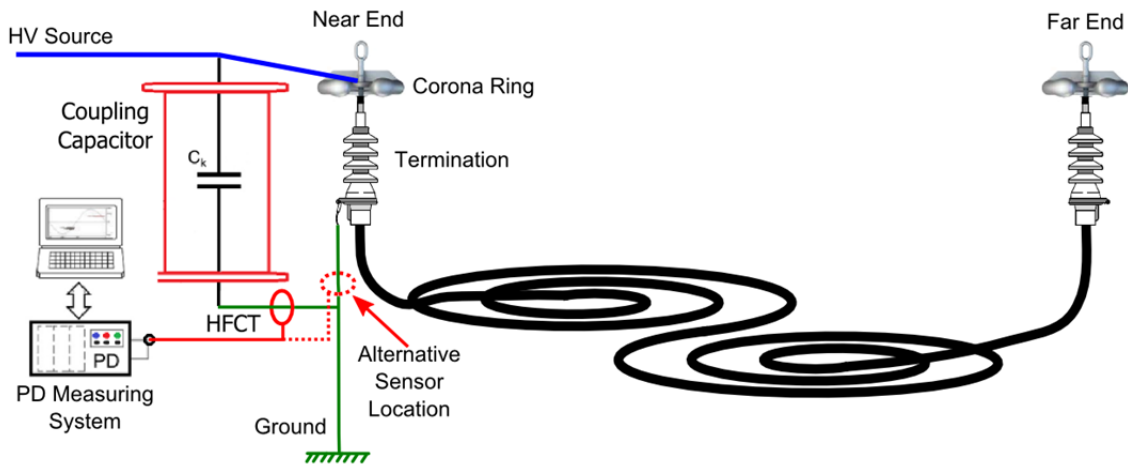
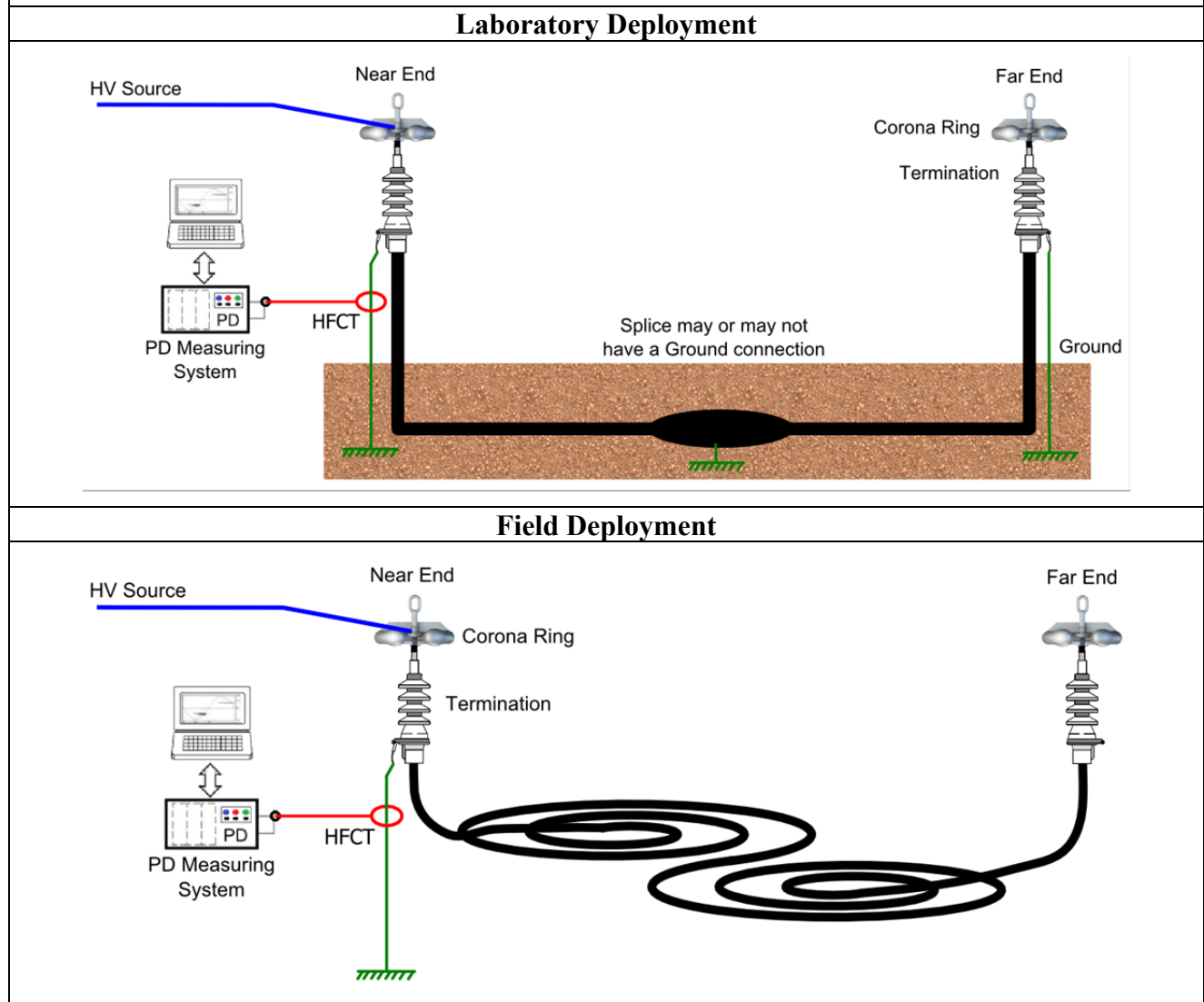


Table 21: Standalone Sensor Connections



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

7.6.9 PD Inception Voltage And Magnitude For Classification

Traditionally, the magnitude and inception voltage of PD signals were used to determine whether discharge sites would cause a failure in service. Analytical work on pilot studies have shown that, even if advanced classification tools are used, PD magnitude and inception voltage cannot be used to accurately identify the defects that cause cables or accessories to fail.

The objective of any classifier used in this fashion is to correctly predict a cable system's performance based solely on the available diagnostic feature data. This amounts to assigning a

“Pass” or “Not Pass” assessment to each tested cable system. The most critical performance metric for any classifier is the success rate of its classification, in other words, whether it correctly assesses each cable system. There are fundamentally two forms of success rates for classifiers:

- **Overall Success Rate** – For a complete set of cable systems, this success rate is based on the percentage of the systems that performed as predicted by the classifier (i.e. the number of “Good” systems that did not fail plus the number of “Bad” circuits that did fail) when tested using a training dataset.
- **Group Success Rate** – For each group (“Pass” and “Not Pass”), this success rate is based on the percentage of the systems that perform as predicted by the classifier, but separated by the assessment class. In other words, what percentage of “Pass” systems did not fail and what percentage of “Not Pass” did fail. These tend to be very different figures.

Because of the above definitions, three classifier success rates must be considered in examining a technique’s performance with different diagnostic features. It is important to understand, however, that different classification techniques are more efficient in emphasizing elements of the diagnostic features. Unfortunately, classifiers are only successful if the diagnostic features they use are the right ones to make the classification. For example, one cannot use the sound of a car engine to classify the color of its body. Engine sound simply has little or no connection to the color of the car. This analogy is also true in classification using diagnostic features.

Figure 43 shows an example of the accuracies of one classifier, k-Nearest Neighbor (k-NN), when used with PD magnitude and inception voltage data to classify sites as those that will fail (“Not Pass”) and those that will not (“Pass”). This classifier has one adjustable parameter that might improve the classification success rate: the number of neighbors to use in the classification. The objective is to choose the number of neighbors (neighborhood size) that achieves the best balance between the group success rates. In this example, 13 neighbors represent the best balance between the two groups.

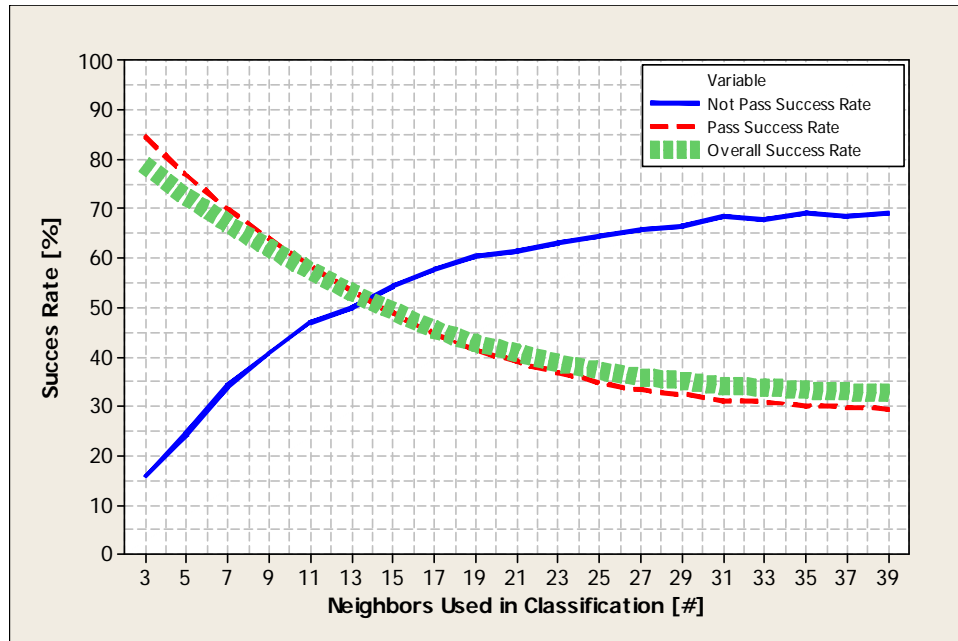


Figure 43: k-NN Success Rates for Different Sized Neighborhoods

For 13 neighbors, the overall success rate for this classifier is only 52%. This implies that PD magnitude and inception voltage are unsuitable for classification since the accuracy is only slightly better than flipping a coin.

The k-NN analysis raises a number of rarely addressed issues:

- What are the appropriate diagnostic features to use for classification? (If not PD magnitude and inception voltage, then what?)
- How many diagnostic features are required?
- What is the best way to use these features?

These questions are addressed for both laboratory and field measurements in the *CDFI*. The approach was to use a multivariate clustering algorithm that combines similar variables into groups or clusters. These clusters indicate, in principle, the number of features required and what features might be chosen. Figure 44 shows the analysis of laboratory data that initially contains 56 different PD diagnostic features. The goal of this graph is to identify how dissimilar different features are – the more dissimilar the better, since dissimilar features provide unique information on the PD signal. Lower values of similarity indicate high dissimilarity (Figure 44). Successive use of clustering reduces the original 56 features down to 15.

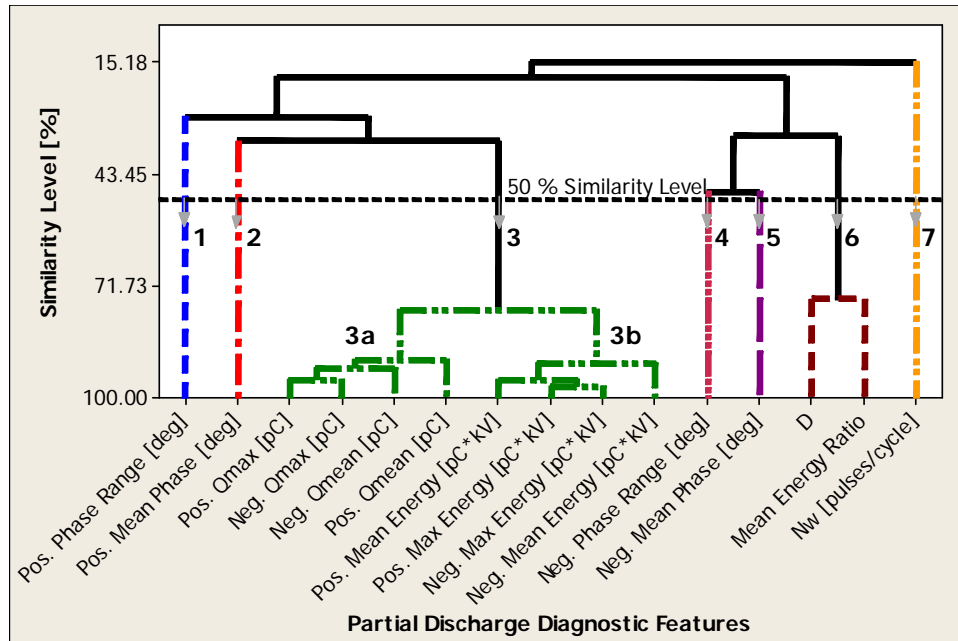


Figure 44: Dendrogram Representation of PD Features

These remaining 15 features naturally arrange themselves into 7 clusters. Clusters 1, 2, and 7 each have a single member while Cluster 3, for example, contains 8 features. This means that a single diagnostic feature from within Cluster 3 can represent the information contained in all the features in Cluster 3. This is important since adding more features from Cluster 3 will not improve the classifier’s ability to make the classification, as these additional features do not contain additional information.

Table 22 shows the resulting seven clusters and the features contained within each cluster. In theory, these features could be used for classification.

Table 22: Feature Clusters Based on Dendrogram		
Cluster [#]	Feature [#]	Feature Name
1	1	Positive Phase Range [deg]
2	2	Positive Mean Phase [deg]
3	3	Positive Qmax [pC]
	4	Negative Qmax [pC]
	5	Negative Qmean [pC]
	6	Positive Qmean [pC]
	7	Positive Mean Energy [pC*V]
	8	Positive Max Energy [pC*V]
	9	Negative Max Energy [pC*V]
	10	Negative Mean Energy [pC*V]
4	11	Negative Phase Range [deg]
5	12	Negative Mean Phase [deg]
6	13	D - Symmetry Factor
	14	Mean Energy Ratio
7	15	Nw [pulses/cycle]

As mentioned above, the key to any classification problem is to choose the right features. The dendrogram approach shown in Figure 44 represents one approach to solving this problem.

7.6.10 Reporting and Interpretation

It is widely acknowledged that signal interpretation and classification are major challenges in field testing. PD tests on new cables or accessories in the factory are made on,

- one device at a time with known characteristics;
- inside shielded rooms where ambient electrical noise is minimized;
- with special laboratory type terminations and grounding arrangements; and
- no component to component interfaces.

Interpretation of the PD data is relatively straightforward in these cases as there should be no PD present. PD tests in the field, on the other hand, are made on circuits with,

- multiple unknown aged components (with possibly different factory PD requirements);
- standard cable system field grounding; and
- located in unique ambient noise environments.

The signals of interest must first be captured and then separated from the extraneous noise. This separation process is challenging as the cable system acts as an antenna for all types of electrical noise. Interpreting the PD signals (if present) is also a challenge because the circuit under test is

often a hybrid mix of cable types and cable accessories that are of different vintages with different amounts of aging. Thus, PD measurements in the field are generally more difficult to interpret than factory or laboratory measurements.

The basic goals of PD interpretation are to,

- distinguish true PD signals from background noise;
- establish that the PD signals are located within the devices being tested; and
- confirm whether the PD poses a risk to the cable system.

Partial discharge data are reported in a variety of forms. They may be a simple report of one PD parameter such as PD magnitude as a function of applied voltage or may include an analysis of multiple parameters that are embedded in PD signals (e.g. phase, density, inception voltage, etc.). Some practitioners believe that a detailed analysis provides little benefit to the customer. They benefit most by indicating that PD is present, often by quoting a discharge magnitude (pC) and/or an inception voltage and an approximate location. Others consider that the traditional PD metrics are insufficient indicators and have developed customized and, thus, proprietary indicators. Both approaches are effective; however, they each have advantages and disadvantages.

Traditional Indicators (PD magnitude and inception voltage)

The advantages of this approach are:

- This type of data is familiar and available from providers.
- Performance criteria based on these indicators may be uniformly established and updated as new performance information becomes available.

The disadvantages of this approach are:

- Although familiar underlying assumptions are well understood, misinterpretations of PD data can occur.
- PD magnitude and inception voltage are generally insufficient to classify accurately the severity of the discharge. In fact, highly detailed analyses within the *CDFI* show this is the case (Figure 43 and Figure 44).
- Traditional parameters do not provide the user with actionable information.
- Without an indication of severity, it is impossible to know if the presence of PD is a problem.
- PD magnitude is highly dependent on calibration and service providers have not standardized calibration procedures.

Customized Indicators (recommended actions or level codes)

The advantages of this approach are:

- They have the potential to consider more information in their classification of discharges than magnitude and inception voltage alone.
- The more detailed analysis of the PD has the potential to highlight the impact of the discharge on performance.
- The recommended actions or level codes derived from the detailed analysis provide a user with actionable information.

The disadvantages of this approach are:

- It is difficult to verify that the more detailed classification is accurate as the algorithms and knowledge used to make the classifications are proprietary.
- When classes are updated, it is difficult to establish the relationship between the old and new classes. This is particularly challenging when the number of classification levels change.
- Level indicators are essentially ranks (e.g. “1, 2, or 3,” “a, b, or c,” or “replace, repair, or OK”) and, thus, do not convey the relative differences between levels. In other words, we can say (a) is more severe than (b) but not by how much.

7.6.11 Expected Outcomes

During the *CDFI*, several PD data sets were collected and analyzed from both lab and field PD tests. The distribution of the data between lab and field data appears in Table 23. Figure 45 shows the individual lengths of cable systems tested using PD measurement techniques.

Table 23: PD Measurement Lengths		
Technique	Laboratory [Conductor miles]	Field [Conductor miles]
PD Offline	2	490
PD Online	-	262

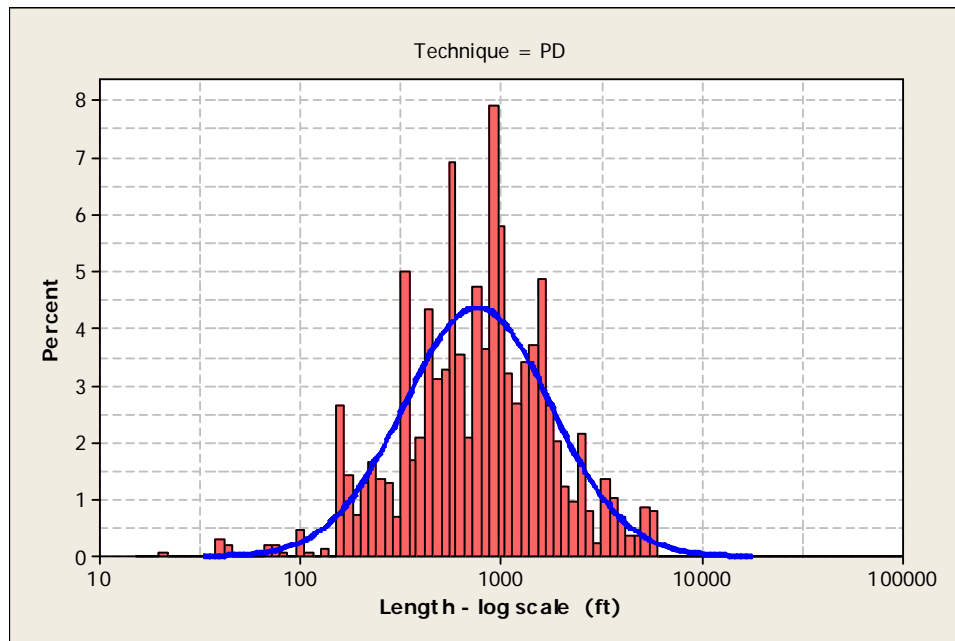


Figure 45: Tested Cable System Lengths – PD

Analyzing the reported data is useful in two ways:

- to estimate potential scenarios that would result from the use of different PD measurement techniques; and
- to establish trends and to identify uncharacteristically high or low test results.

Analyses were compiled for field data from the two main PD approaches:

- online – one of four techniques were analyzed;
- offline – two of four techniques were analyzed.

The use of customized indicators in some of the offline and online measurement techniques makes it difficult to compare results. However, they are useful in analyzing general outcomes/scenarios.

Offline

Figure 46 shows how all of the Offline PD data analyzed in the *CDFI* are distributed as a whole among the custom indicators. For example, 62.2% of the total populations of systems tested were classified as “Defer” by the diagnostic provider. The data are from one Offline PD technique. The diagnostic provider has verified that the custom indicators have evolved over time, but the extremes appear to be consistent (“Replace” and “Defer”). The “Repair” category consolidates a number of generational steps (indicators).

Figure 47 shows how the individual data sets are distributed among the custom indicators (used in Figure 46): each solid symbol represents a single dataset. For example, for the “Replace” indicators one data set had 25% its tested circuits classified as “Replace” while another data set had only 2.5% of circuits classified as “Replace”.

Figure 48 shows how all of the detected PD site data analyzed in the *CDFI* were distributed as a whole among the cable system components. As an example, approximately 39% of the PD sites were found in the cable portions of the tested circuits.

Figure 49 shows how detected PD sites from the individual data sets were distributed among the cable system components: each solid symbol represents a single dataset. As an illustration, this figures shows that 5% – 44% of all PD sites identified within a particular dataset were located in splices.

Figure 50 relates the occurrence of PD sites to the length of the cable system tested: based on the mean and median, respectively, we would expect 19 and 8 PD sites per 10,000 ft of system tested.

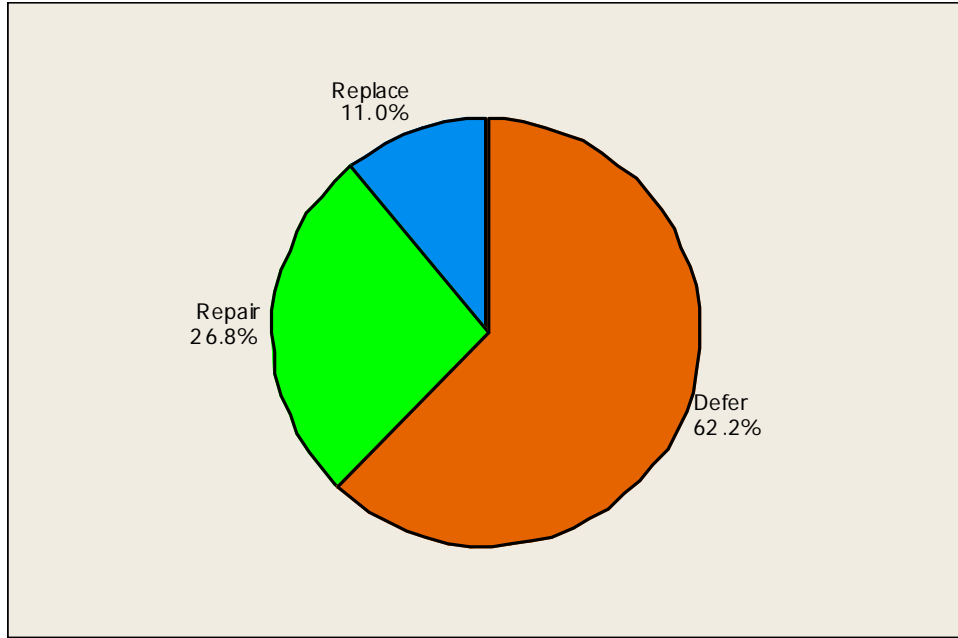


Figure 46: Split between Action Classes – Offline

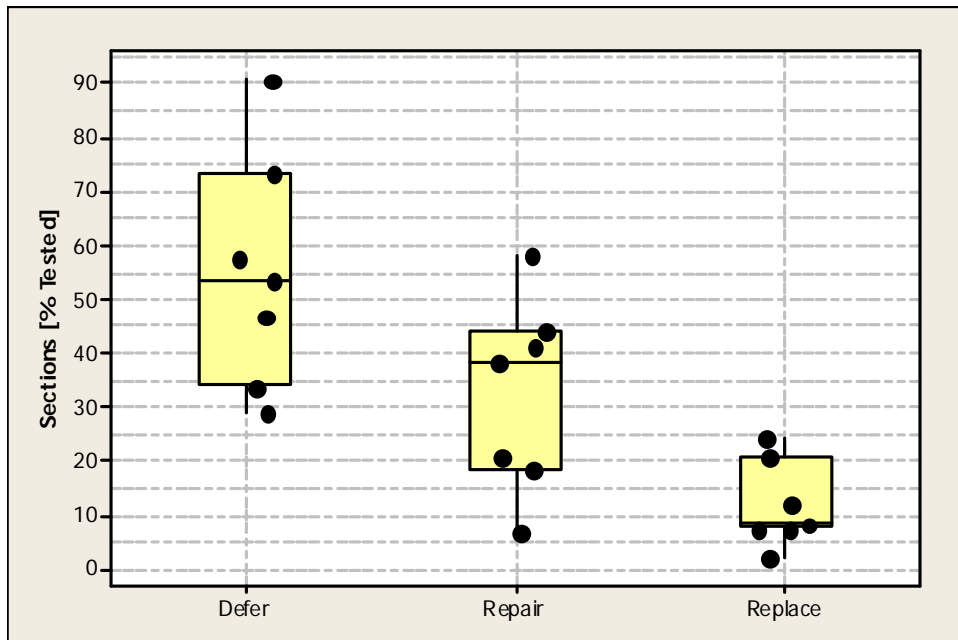


Figure 47: Range within Classes - Offline

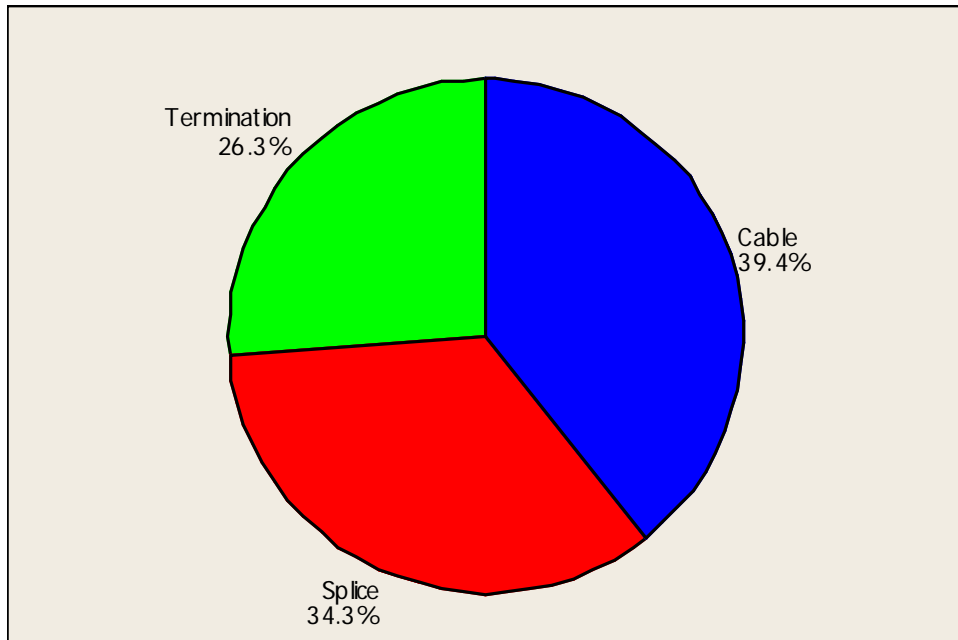


Figure 48: Split between PD Sources – Offline

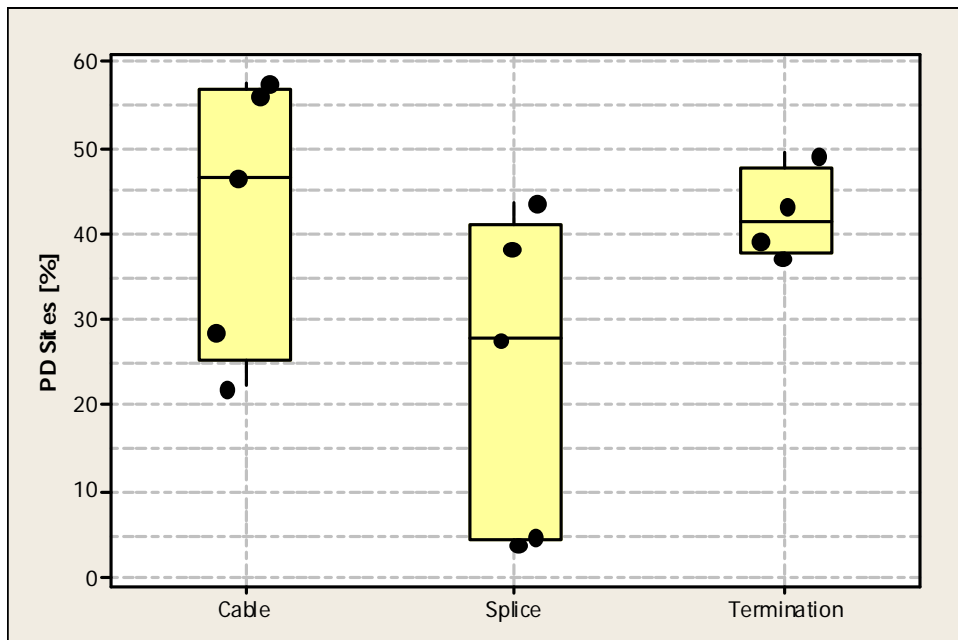


Figure 49: Range within PD Sources – Offline

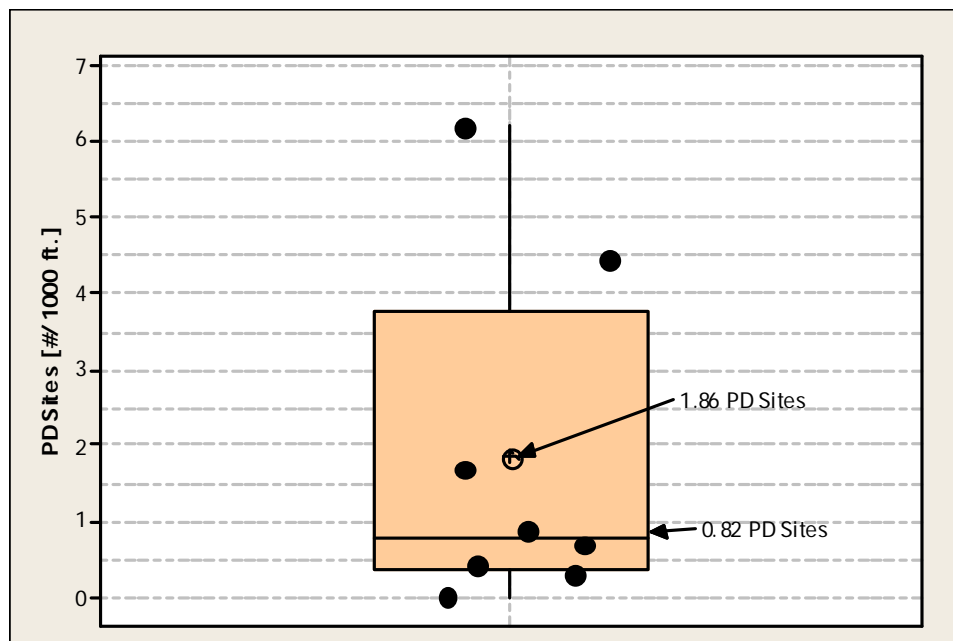


Figure 50: Range of PD Occurrence per 1,000 ft - Offline

Online

Figure 51 shows how all of the Online PD data analyzed in the *CDFI* are distributed as a whole among the custom indicators. The data are from a single method of the Online PD technique. The diagnostic provider has reported that the custom indicators have not evolved over time. For example, 62.2% of accessories and 68% of cable sections tested are classified as Level 2 by the diagnostic provider.

Figure 52 shows how the individual data sets are distributed among the custom indicators (used in Figure 51): each solid symbol represents the dispersion for a single dataset. For example, the individual datasets indicate that 45% – 90% of tested accessories were classified as Level 2.

Figure 53 shows how all of the Level 4 and Level 5 (indicating presence of PD) data analyzed in the *CDFI* were distributed as a whole among the cable system components. This technology embodiment does not permit the separation of joints and terminations, thus the data only pertain to accessories.

Figure 54 shows how the Level 4 and Level 5 data from the individual data sets were distributed among the cable system components: each solid symbol represents the dispersion for a single dataset. For example, 0% – 80% of tested cable sections within a particular dataset were classified as Level 4 or Level 5 by the diagnostic provider.

Figure 55 relates the occurrence of Level 4 and Level 5 to the length of cable system tested, these data are segregated for cables and accessories as well as the grouped approach for all - based on the median we would expect 1 PD site per 4,000 ft of system tested.

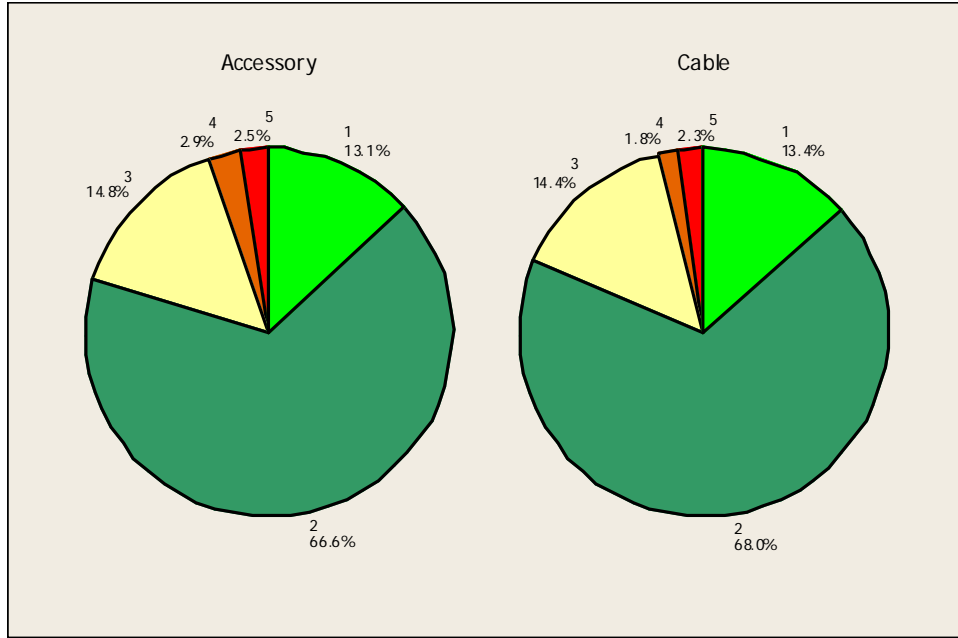


Figure 51: Split between Assessment Classes – Online

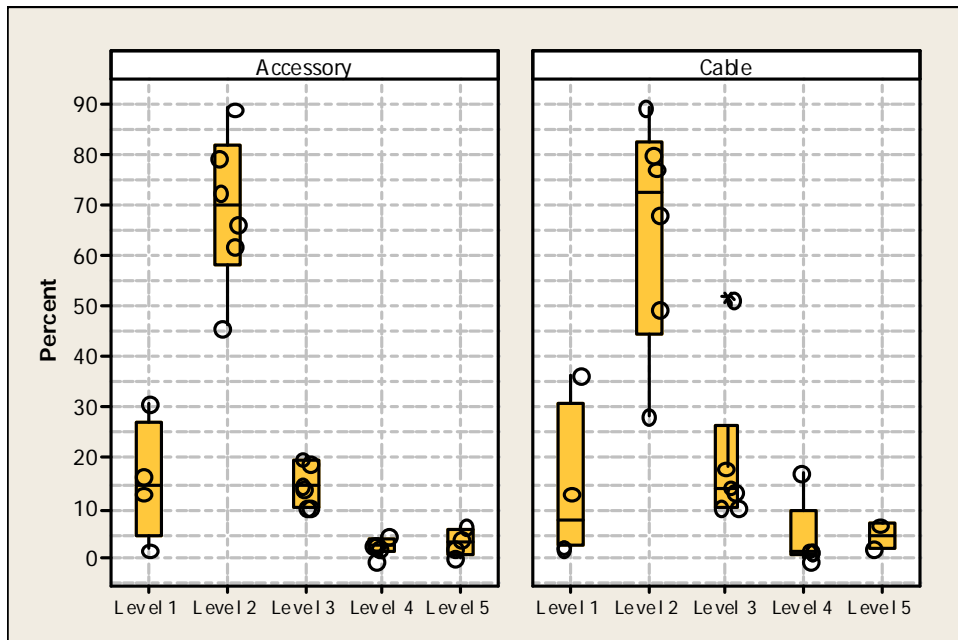


Figure 52: Range within Classes - Online

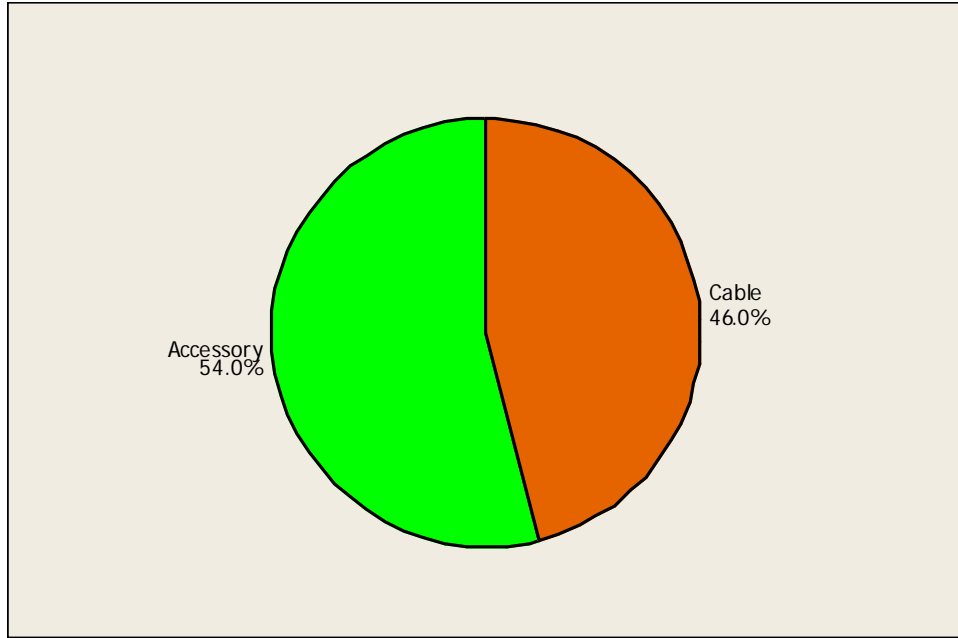


Figure 53: Split between PD Sources – Online

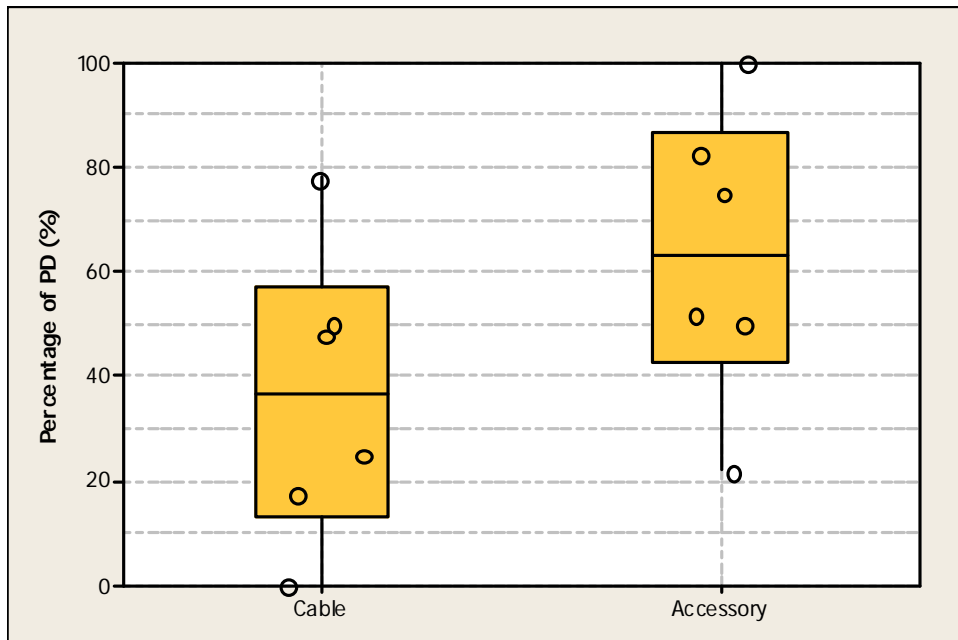


Figure 54: Range of within PD Sources – Online

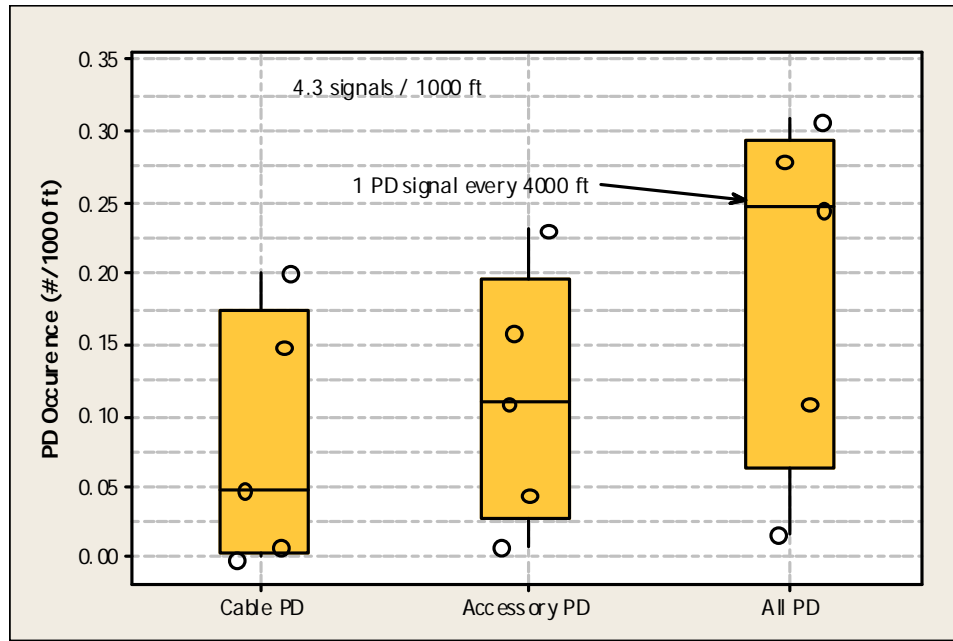


Figure 55: Range of PD Occurrence per 1,000 ft – Online

When pilot studies were undertaken (with the diagnosed cable systems left in service) and the post-test service performance was followed, it was possible to determine Diagnostic Performance Curves. These curves show how failures have accumulated within circuits in the same classification group. Figure 56 shows diagnostic performance curves for one of the Online PD technologies from data supplied by a diagnostic provider. This approach uses the provider’s custom classifications for discharges (1 to 5, Levels 4 and 5 refer to “discharge” signals while it is not clear what Levels 1, 2, and 3 represent). The collated service failures recorded after the test enable the probabilities of failure (shown as percent on the y-axis) for Levels 3, 4, and 5 to be estimated since the systems were left untreated. Interpreting these curves entails estimating the probability of service failure for selected times. As an example, systems classified as Level 5 have a failure probability of 40% within one year after the test and greater than 99% within 2.5 years after the test.

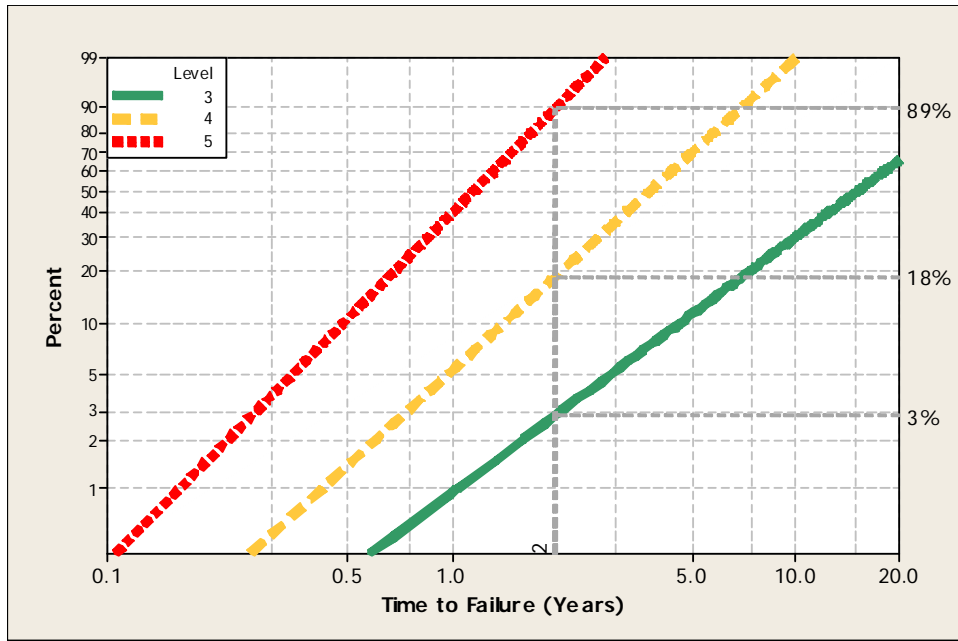


Figure 56: Diagnostic Performance Curves for One Online PD Test Technique

Figure 57 shows the diagnostic performance curves for PD sites detected using one Offline PD technique. The curves originate from failure data supplied by a participating utility. Note that these curves are for individual PD sites located in cables and splices.

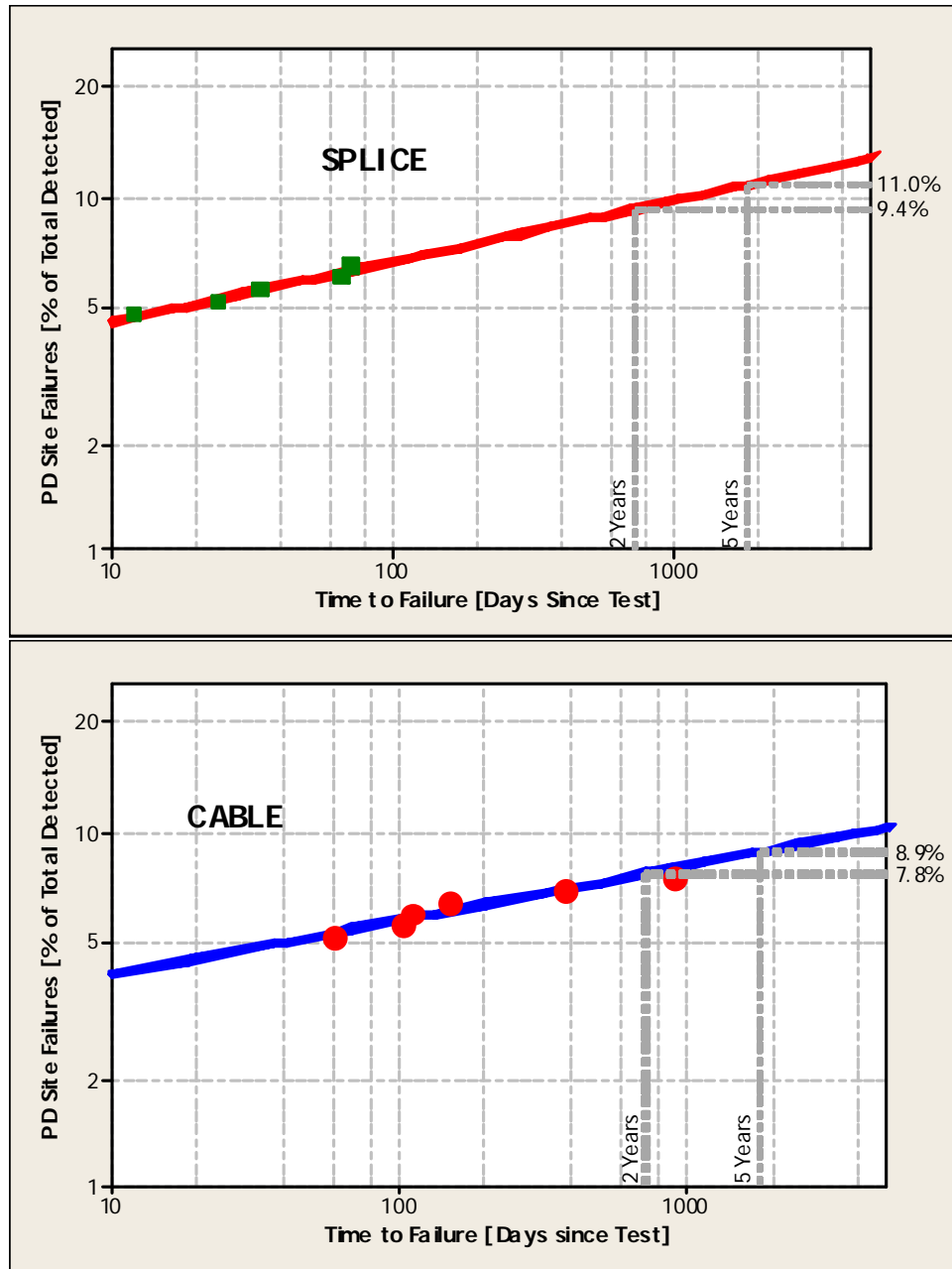


Figure 57: Diagnostic Performance Curves from a Cable System in Service for One Offline PD Test Technique, Separated by Cable (bottom) and Splices (top)

The Diagnostic Performance Curves of the type shown in Figure 56 and Figure 57 are useful as they help utilities interpret diagnostic test results by indicating expected results. A number of these benefits appear below:

As noted previously, one of the aspects of custom indicators is that the level codes are ranks that do not convey the relative differences between levels. Performance curves enable level interpretation or renaming as shown in Table 24. Levels are based on the probability of failure for circuits classified at each level shown in Figure 56 within two years after the test. The alternate codes show

that the separations between Level 3 and Level 4 are different as compared to the difference between Level 4 and Level 5. The available data in Figure 56 do not include information on Level 1 or Level 2. Thus, these levels only indicate a lower probability of failure than Level 3.

PD Level Code	Alternate Code
Level 1	<< 3
Level 2	< 3
Level 3	3
Level 4	18
Level 5	90

The Diagnostic Performance Curves also enable utilities to estimate the potential number of failures over time and, thus, make an informed economic evaluation of potential actions to take based on the test results. Table 25 shows a computation for a 14-mile MV cable system segregated into 100 systems (the dispersion of PD sites is shown in Figure 48 and the occurrence of PD appears in Figure 50). The estimates show that approximately 12% of the defects will have led to failure within 5 years. It is important to recognize that all defects need to be treated, repaired, or replaced to improve reliability because which ones will fail first is unknown.

PD Location	Sites [#]	Predicted Failures	
		After 2 Years	After 5 Years
Cable	31	3	3
Accessories	47	5	6
TOTAL	78	8 [10.2%]	9 [11.5%]

7.6.12 Noise

As PD measurements constitute the detection of an induced high frequency (HF), very high frequency (VHF) and/or ultra-high frequency (UHF) electric signals on cable systems, rejection of similar non-PD related signals is imperative. Such signals are commonly referred to as noise. Noise is always present and different for each test when performing PD measurements in the field. It can come from radio stations, television stations, electronic switching devices operating nearby, stray currents in the earth or on the cable metallic shield and a wide variety of other sources.

Noise can be a critical impediment to successfully detecting PD. Both Sensitivity and Range Checks are affected by external noise. Magnitudes of the PD pulses registered by the measuring equipment are in the order of fractions of millivolts 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.

The level of noise depends on several factors that include system parameters such as length, location, design, structure, signal degradation mechanisms, and neutral condition, as well as on the particular nature of the PD present in the cable system. From the perspective of noise, the cable acts as an antenna that picks up the communication signals as well as other noise that may be related to the grounding. In reality, it is impossible to avoid these signals in the field.

Several techniques have been used to reduce background noise levels. Analog and digital filters are typically applied; however, other digital signal processing techniques such as wavelet transforms have recently been used as well. Improvements over the past decade in signal classification have greatly improved the value and interpretation of acquired PD data. One of the more important improvements was the development and application of the time-frequency classification map. This map is based on the fact that PD pulse waveforms depend on the nature of the defect and its location within the cable system. Thus, pulses having similar waveforms should be from the same source.

Manufacturers and providers of PD test equipment have implemented various approaches to this technique. The technique involves classifying individual measured pulses on the basis on their frequency content, duration, and other characteristics associated with the pulse shape. The processing and generation of a classification map relies upon the acquisition of a large number of pulses. This technique is particularly useful for on-line PD measurements where, very often, multiple PD sources are present. Classification of different categories of measured pulses can help separate multiple PD sources from one another and thus produce individual pulse phase analysis plots for each source. Different examples for the application of the classification map from different providers appear in Figure 58.

There is no doubt that noise will continue to be a challenge for PD measurements even though the effectiveness and sophistication of noise mitigation techniques continues to advance.

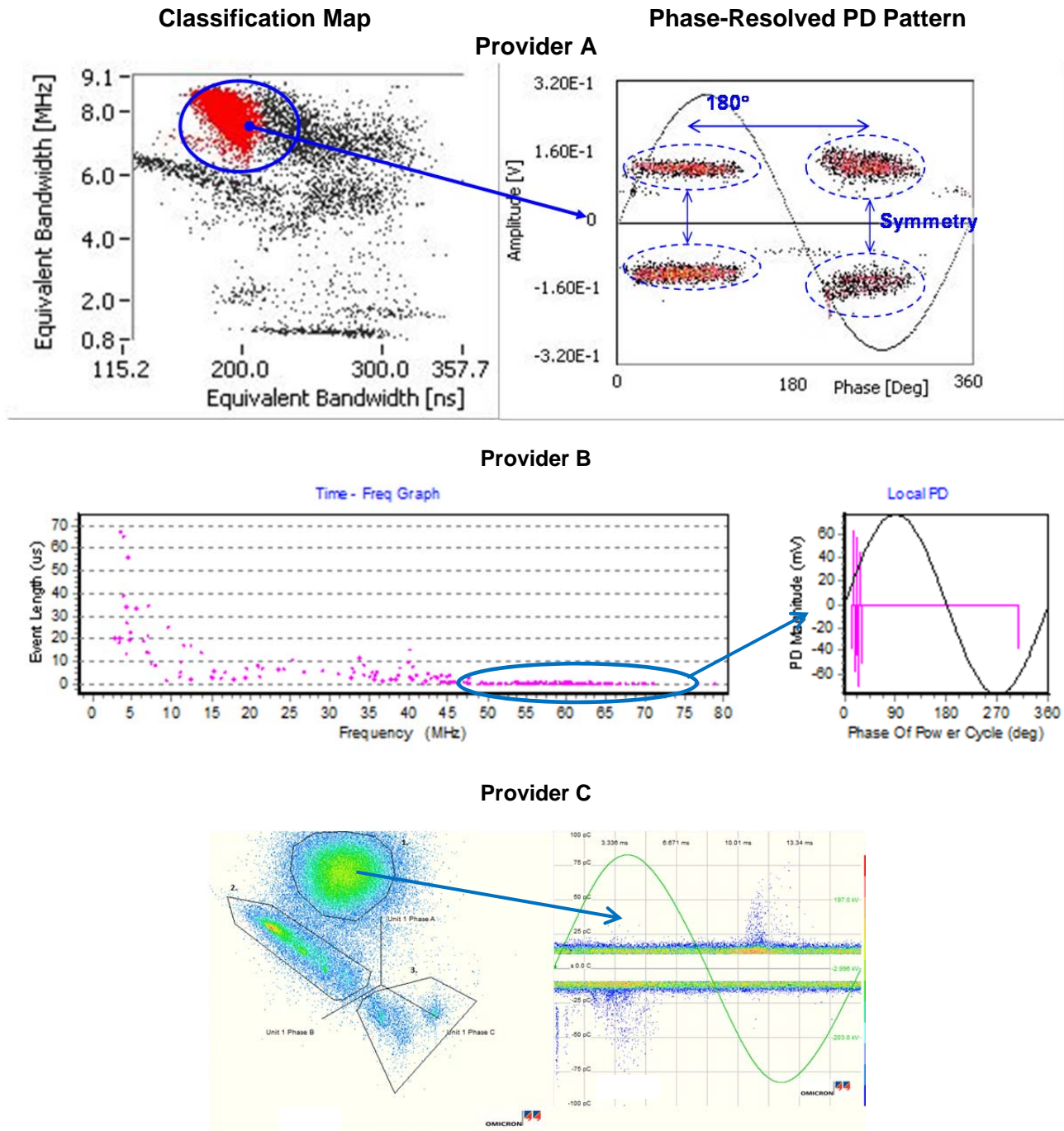


Figure 58: Different Examples for the Application of the Classification Map from Different Providers

7.6.13 Conundrum between PD Scaled Charge and Energy

The idea of signal "size" is crucial to many applications. Examples of such applications might include knowing how much electricity can be used in a defibrillator without causing permanent damage to the patient, or it would be also nice to know if the signal driving a set of headphones is enough to create a sound. While both of these examples deal with electric signals, they are clearly very different dealing with signals of significantly different scale from those seen in PD measurements. 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 is reasonable to assume that a good measurement of the strength of a signal would be the area under the curve. However, this area may have a negative portion. This negative portion does not have less strength than a positive signal of the same size; however, by taking the area encompassed by the curve the areas below the time axis cancel with the areas above it. A better approach to estimating the signal strength would be to either square the signal or take its absolute value, and then find the area under that curve. In fact, 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 ($f(t)$) appears in Figure 59.

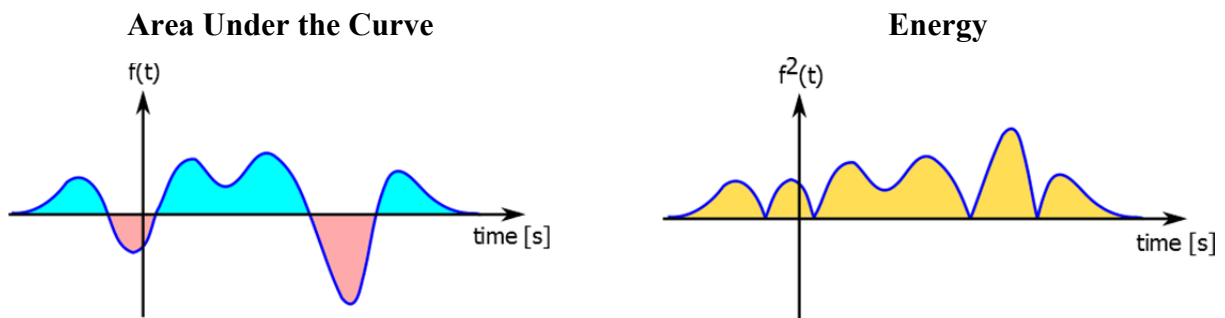


Figure 59: Illustration of the Area Under the Curve and Energy for a Signal as a Function of Time ($f(t)$)

In the case of PD, the relationship between the area under the curve (scaled charge) and energy is important. Traditionally, PD activity was simply 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 is only valid if it is assumed 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 frequently overlooked issue, even for an ideal (lossless) cable system, is that the peak amplitude of the traveling PD pulse can decrease to the point that it is comparable to the background noise level and thus no triggering/detection is possible.

In reality, 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. Therefore, 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 a frequency dependent, distributed model.

The two studies are presented in detail in the next subsections.

7.6.13.1 Simple Filtering Model

In this case, the cable system is modeled as a simple low-pass filter, the input PD pulse is run through the filter and output PD pulse is recorded. The origin for this cable system simulation is based on simple filtering as is shown in Figure 60.

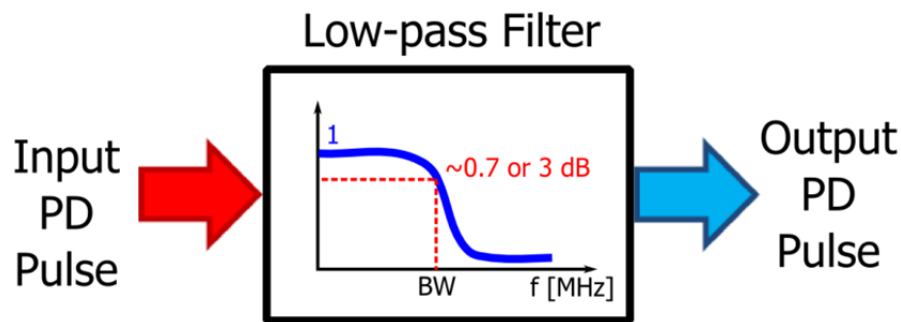


Figure 60: Illustration of Cable System Simulation Based on Simple Filtering

The purpose of this simulation using simple filtering is to demonstrate the effect of filter bandwidth on a PD pulse’s scaled charge and energy as a function of the input PD pulse. As the input pulse, a Gaussian pulse of 5 pC and 20 ns (time width) is considered, its time domain waveform and frequency domain spectrum are shown in Figure 61.

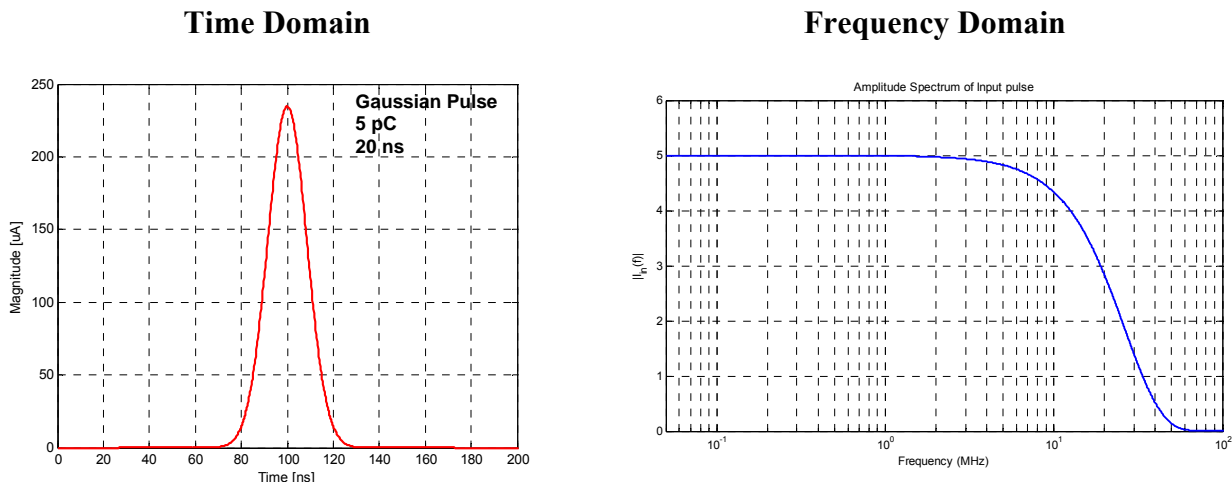


Figure 61: Waveform and Frequency Spectrum of the Input PD Pulse

The simulation results considering filter bandwidths of 30, 20, 10, 5, and 1 MHz are shown in Table 26.

Table 26: Results for Cable System Simulation Based on Simple Filtering	
Filter Frequency Response	Input (Red) and Output (Blue) PD Pulses
30 MHz Bandwidth	
20 MHz Bandwidth	
10 MHz Bandwidth	

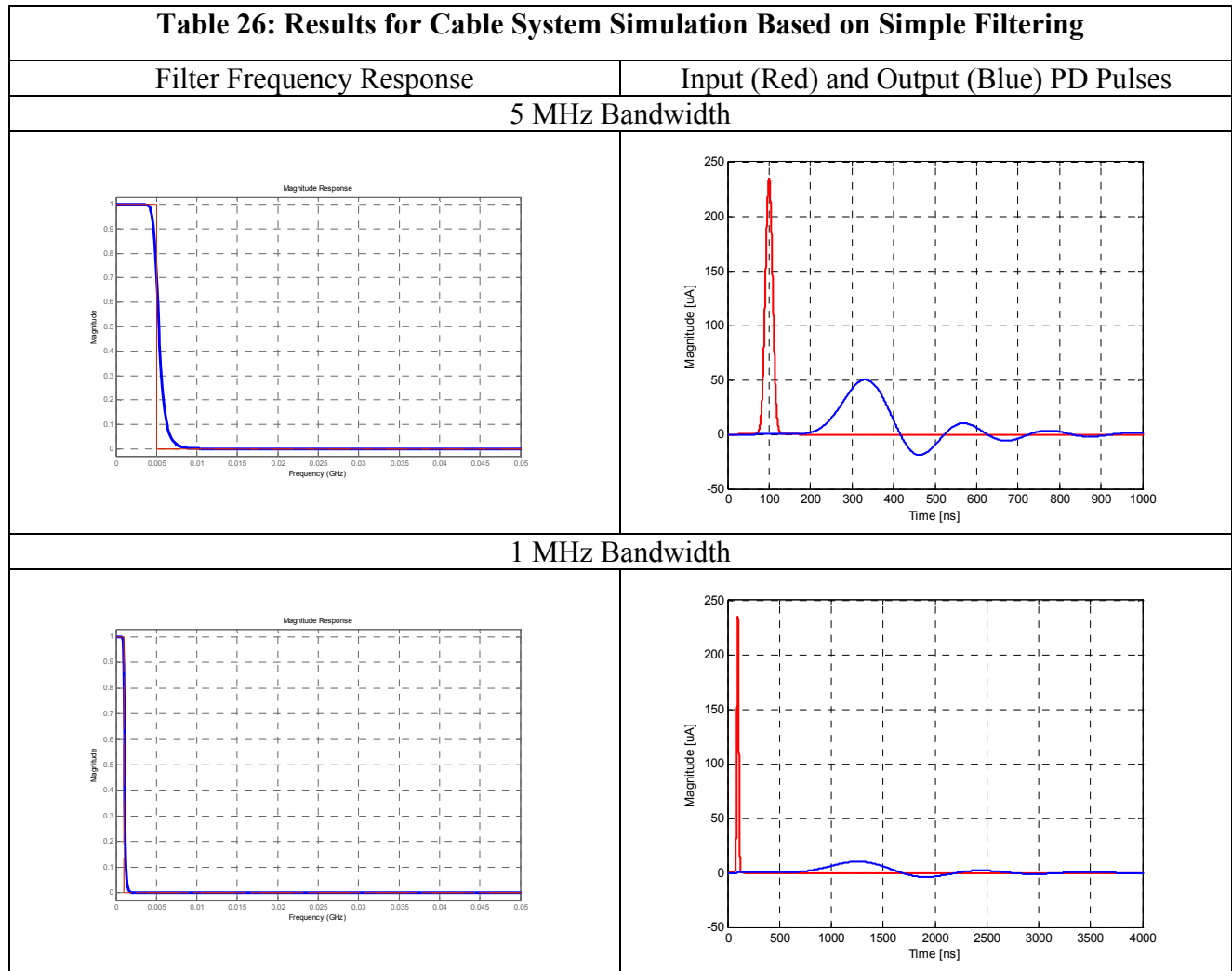


Table 27 shows the scaled charge results for the cable system simulation based on simple filtering.

Table 27: 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 27, 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. The main contribution of the results shown in Table 27 is

that they help in understanding why, when PD first appeared, the scaled charge was selected as the most attractive metric for quantifying PD measurements. As the detection equipment and associated understanding have evolved, it is apparent that alternative metrics to quantify PD activity could be used for diagnosis.

Simulation results for the PD output pulse energy appear in Table 28 and are plotted in Figure 62. However, Figure 62 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 62 is obtained by subtracting from 100% the energy ratio in percent column shown in Table 28.

Filter Bandwidth [MHz]	Input Energy [$\mu\text{A}^2*\text{ns}$]	Output Energy [$\mu\text{A}^2*\text{ns}$]	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 28 and Figure 62, the output PD pulse energy loss dramatically 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. Specifically, note that for a bandwidth of 100 MHz, the energy loss can be considered negligible, while for 1 MHz bandwidth the energy loss is high. The relationship between energy loss and filter bandwidth is highly dependent on the energy content 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 through.

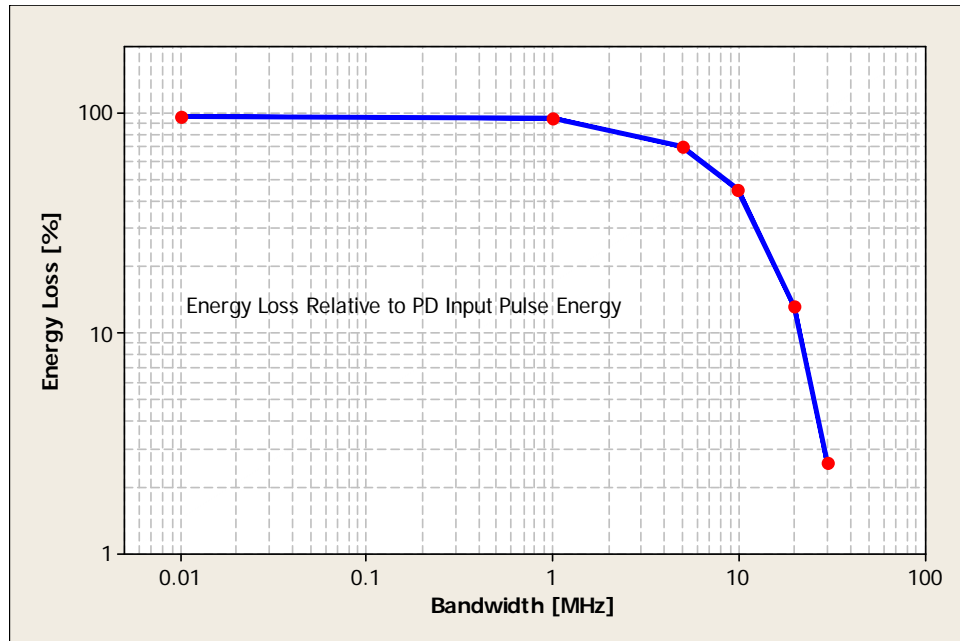


Figure 62: PD Signal Energy Loss versus Filter Bandwidth

As mentioned earlier, another issue to consider is how the peak amplitude of the PD output pulse changes with bandwidth; this is shown in Figure 63.

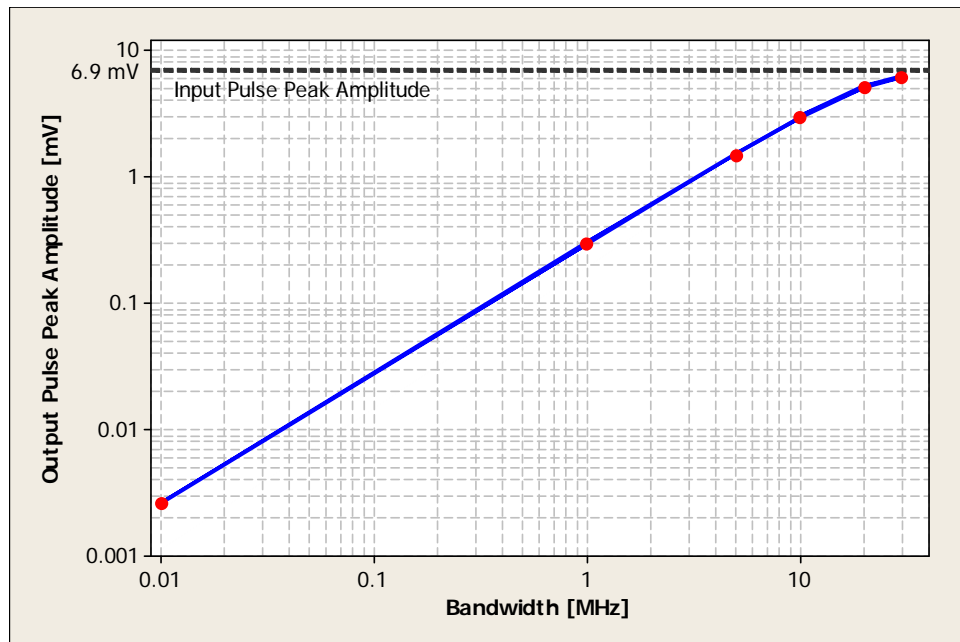


Figure 63: Output PD Pulse Peak Amplitude versus Filter Bandwidth

As observed in Figure 63, 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.

7.6.13.2 Frequency Dependent and Distributed Model

Another approach is to simulate the cable system simulation using a frequency dependent, distributed model. An illustration of the simulation appears in Figure 64.

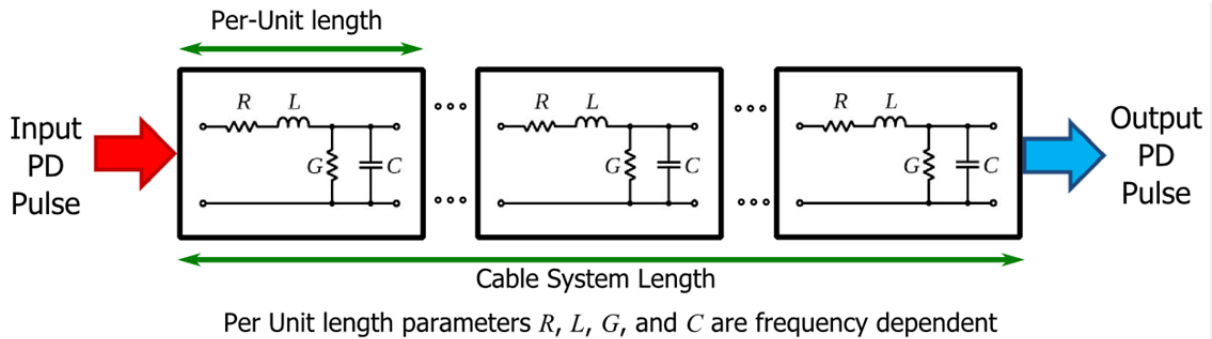


Figure 64: Frequency Dependent Simulation Model

As illustrated in Figure 64, 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 appear in Figure 65.

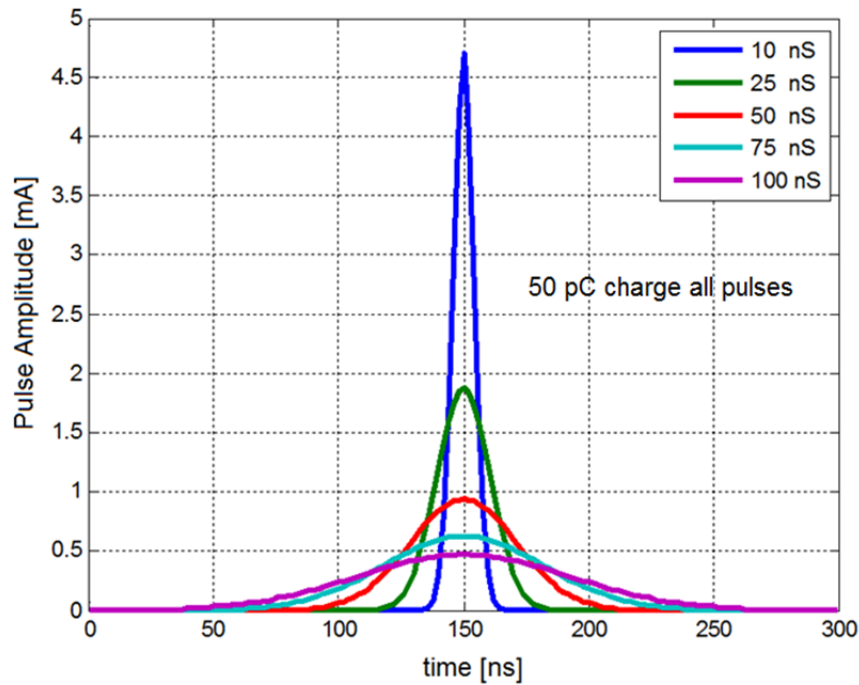


Figure 65: Gaussian PD Pulses for Simulation of Loss of Charge using Frequency Dependent and Distubted Modeling.

The cable system modeling 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 65 are shown in Figure 66. This figure shows PD pulse charge loss as a function of the distance traveled from the discharge site.

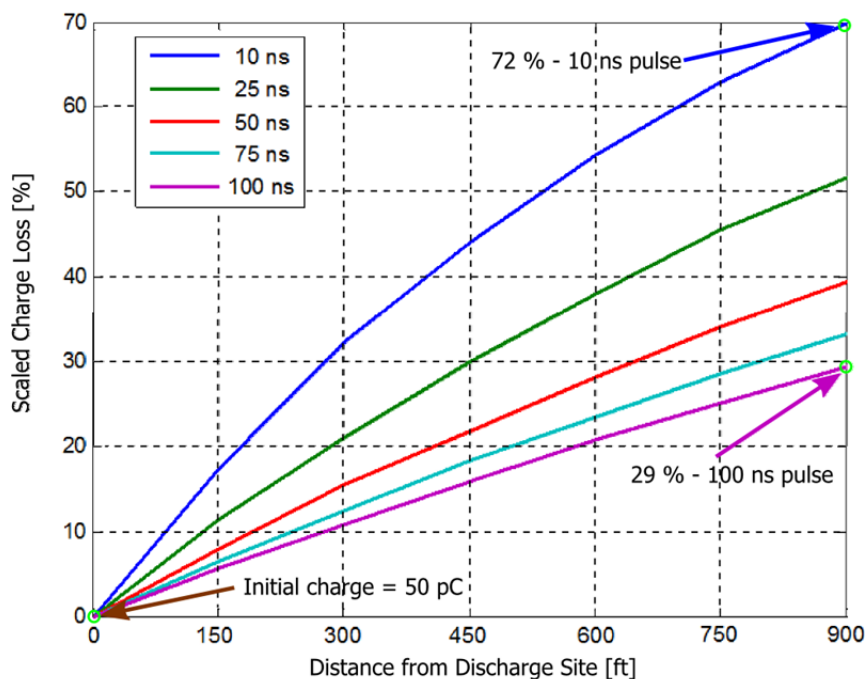


Figure 66: PD Pulse Scaled Charge Loss as a Function of Distance from Discharge Site

The results presented in Figure 66 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 66, 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 would be 36 pC for the 100 ns pulse and 14 pC for the 10 ns pulse.

The results shown in Figure 66 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 typically thought to be independent of cable system length, actually is not. In reality, this phenomenon is always present and unawareness of its existence may lead to a confused interpretation.

- **Other Factors:** Other factors affecting scaled charge loss of a PD pulse are cable system design, structure, aging, and degradation conditions.

7.6.14 Limitations Of Repeat Tests

Early approaches for characterization of PD phenomena in cable systems required determining a metric for the PD level or mean PD value usually expressed in the units of picocoulomb. There is no question that these approaches are convenient because of their simplicity in as much as only a single number is reported for a given set of system parameters and operating conditions. The inception and extinction voltages were also used in conjunction with the PD magnitude as metrics for condition assessment. Early efforts also considered attempts to estimate the mean PD magnitude from field-theoretical considerations on different types of voids within the bulk volume of the insulation material [25].

Although there is much that can be learned from a deterministic approach to PD theory and measurement, the fact remains that PD phenomena are fundamentally stochastic processes in which there can be significant statistical variability (e.g. pulse peak amplitude, pulse waveform, and time of occurrence). However, it can be argued that some of the individual interactions or steps that take place in the creation of a PD event can be considered as deterministic. Unfortunately, this oversimplifies the nature of PD so an accurate characterization can never be accomplished using a deterministic approach [25].

Consequently, PD phenomena are characterized by adopting a stochastic description in which their properties are described in terms of time-dependent random variables. The random variables such as pulse amplitude and time of occurrence that describe the PD process can be specified in terms of probability distribution functions. The stochastic behavior of PD phenomena can also be revealed by appropriate measurements and analyses. A complete explanation of the factors that determine the statistical behavior of PD is beyond the scope of this document. One of the main consequences from this stochastic nature is that PD measurements from repeated tests cannot be compared beyond the simple question of “Is PD still present?”.

To provide experimental evidence of the stochastic nature of PD phenomena, a laboratory test program was implemented. The program considered sequential and repeat PD tests on a cable sample that was removed from the field after testing showed that it had had PD. The sequential measurements were performed the same day with a two-hour difference between measurements while the repeat tests were performed a few days apart. In this case, two sequential measurements are considered a measurement set. The test program timing is illustrated in Figure 67.

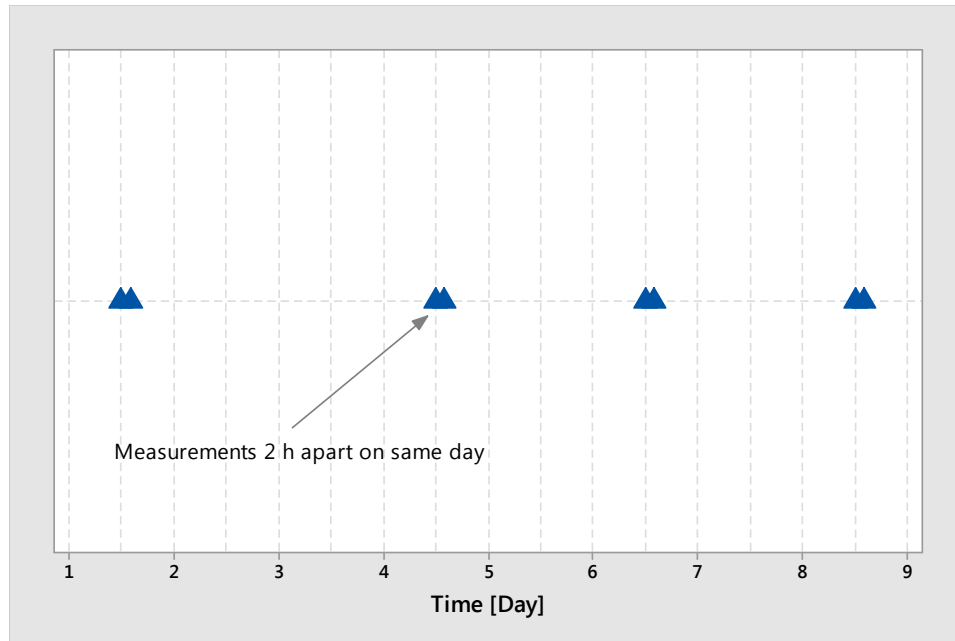


Figure 67: Measurement Timing (Two Measurements per Day)

Table 29 shows the cable sample used during the test program.

Table 29: Sample Description for Experimental Evidence of PD Stochastic Nature					
Condition	Length [ft]	Year of Manufacture	Voltage Class	AWG	Insulation Material
Field-aged cable	17	1968 Phelps Dodge	15 kV $U_0 = 7.2$ kV	1/0 Unjacketed Concentric Neutrals	XLPE

Since this field-aged cable sample was stored in a de-energized state, a preconditioning procedure was conducted before each PD measurement by applying $0.5 U_0$ (3.6 kV) for 15 minutes. The inception voltage after preconditioning was then determined and recorded for each measurement. Before recording, each termination was checked for discharge to ensure they were PD free. Details of the test program appear in Table 30.

Table 30: Laboratory Test Program Measurement Details		
Preconditioning	PD Measurements [#]	Details for each data capture
15 min At 0.5 U ₀ (3.6 kV)	8	Inception voltage after preconditioning Two sequential PD measurements at 1.25 the measured inception voltage after preconditioning Each acquisition lasts 30 sec or until 5000 pulses are acquired, whichever happens first

The test program shown in Figure 67 and Table 30 includes PD measurements at one test voltage level of 1.25, the inception voltage after preconditioning.

The schematic of the test set-up appears in Figure 68. The sample was an unjacketed cable and was submerged in a water tank to guarantee good electrical contact between the cable metallic shield and insulation shield. This avoids any potential external arcing that could result from a poor contact.

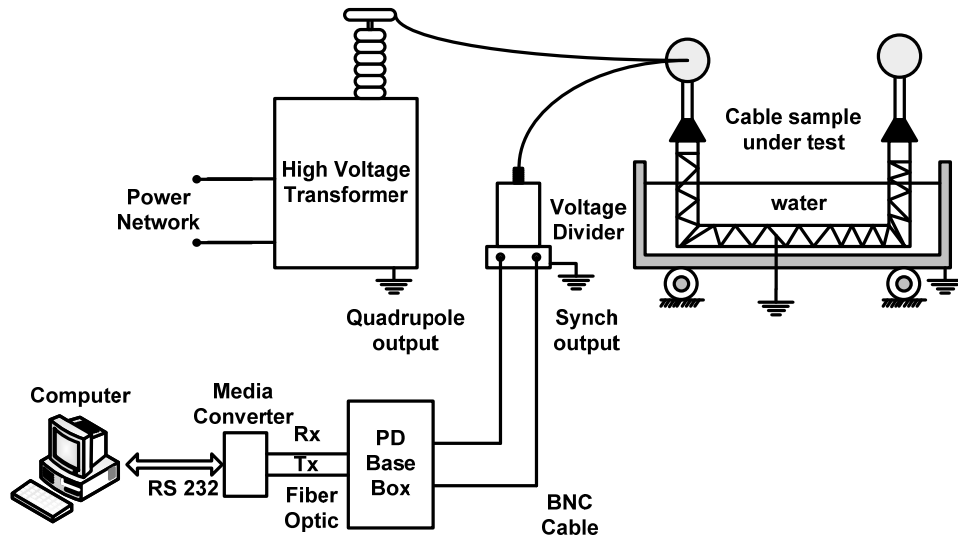


Figure 68: Test Set-up for Laboratory PD Test Program

Figure 69 shows the actual test set-up; the water tank, the voltage divider and the transformer can be observed in the figure.



Figure 69: Test Set-up with Water Tank, Transformer, and Capacitive Divider

The PD measurement results presented below are based on the phase-resolved PD pattern (PRPD). There is no question that a considerable number of PD diagnostic features can be obtained from each pattern using statistical tools. However, for a simpler analysis, nine PD diagnostic features were used to quantify the results. The features are as follows:

1. **Inception Voltage:** Inception voltage after preconditioning, measured in kV;
2. **Pos. Max Amp:** Maximum PD amplitude for the positive polarity of the test voltage, measured in mV;
3. **Pos. Mean Amp:** Mean PD amplitude for the positive polarity of the test voltage, measured in mV;
4. **Pos. Mean Phase:** Mean phase for the positive polarity of the test voltage, measured in degrees;
5. **Neg. Max Amp:** Maximum PD amplitude for the negative polarity of the test voltage, measured in mV;
6. **Neg. Mean Amp:** Mean PD amplitude for the negative polarity of the test voltage, measured in mV;
7. **Neg. Mean Phase:** Mean phase for the negative polarity of the test voltage, measured in degrees;
8. **Symmetry Factor – D:** Symmetry factor, positive over negative number of pulses;
9. **Mean No. Pulses per Cycle – Nw:** Average number of pulses per period of the test voltage, i.e. number of acquired pulses in 16.7 ms for a 60 Hz test voltage.

Since each PD measurement is characterized by a set of nine diagnostic features, a total of eight sets are considered and their results appear in Table 31.

Table 31: PD Measurement Results for Experimental Evidence of PD Stochastic Nature								
Feature	PD Measurement Sequence							
	1	2	3	4	5	6	7	8
1 - Inception Voltage [kV]	5.7	5.6	5.2	5.6	5.9	5.5	5.7	4.7
2 - Pos. Max Amp [mV]	232	222	191	246	225	210	102	90
3 - Pos. Mean Amp [mV]	97	101	101	122	55	73	10	11
4 - Pos. Mean Phase [Deg]	48	58	41	61	52	52	53	55
5 - Neg. Max Amp [mV]	238	193	229	240	227	216	156	113
6 - Neg. Mean Amp [mV]	77	82	113	140	67	132	19	17
7 - Neg. Mean Phase [Deg]	33	32	63	48	46	37	50	53
8 - Symmetry Factor - D	0.45	0.45	0.52	0.54	0.55	0.63	0.65	0.62
9 - Mean No. Pulses per Cycle - Nw	1.96	1.27	0.83	0.48	5.79	0.56	38.30	41.20

As seen in Table 31, each PD measurement set is different from all the others. Every diagnostic feature has a different, non-repeating value. This illustrates the stochastic nature of PD as these tests were conducted in a highly controlled manner. A comparison between maximum and mean amplitudes segregated by the polarity of the test voltage and as a function of the PD measurement number is presented in Figure 70.

In Figure 70, note that larger changes are observed for the mean amplitudes on both polarities; specifically, for the PD measurements numbers 7 and 8 when they are compared to PD measurements numbers 1 through 6, the observed changes are approximately one order of magnitude.

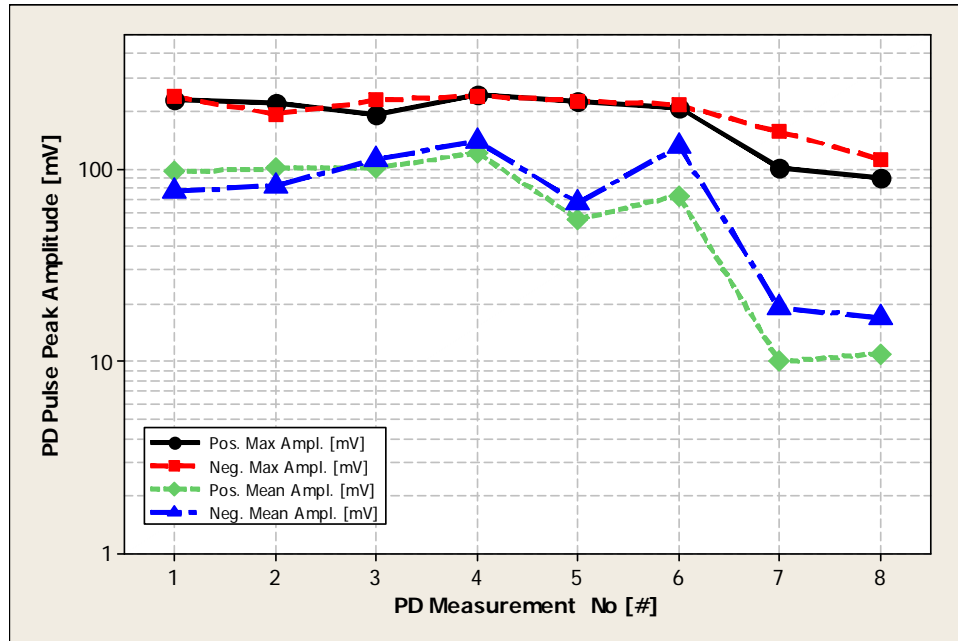


Figure 70: Mean and Maximum PD Amplitudes by Polarity

To further understand PD variability and thus its stochastic nature, Figure 71 shows the inception voltage and the average number of captured PD pulses per cycle of the test voltage as a function of the PD measurement number.

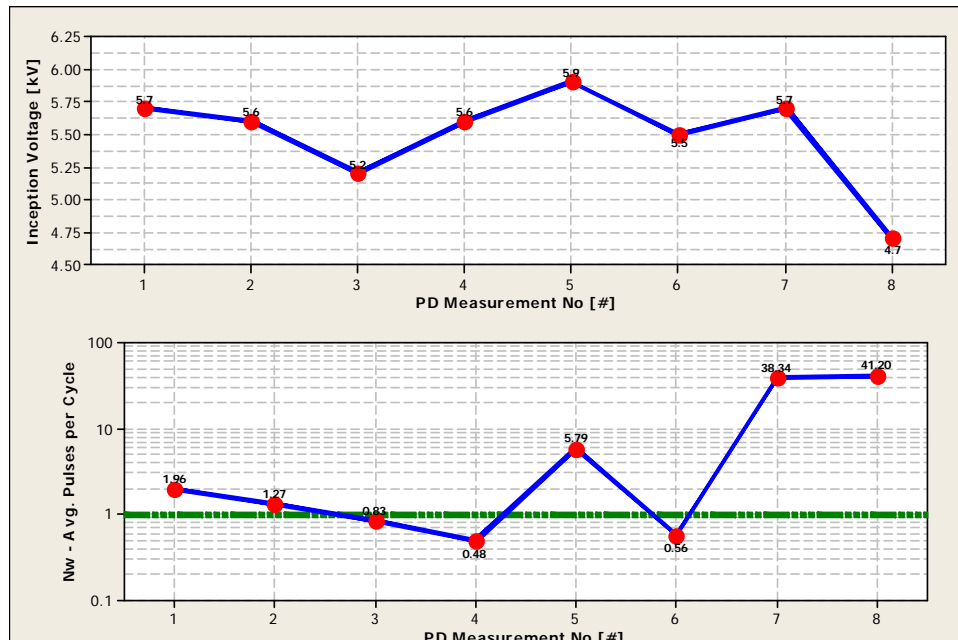


Figure 71: Inception Voltage and PD Repetition Rates for each Measurement

According to Figure 71, the maximum and minimum inception voltages were 5.9 kV and 4.7 kV. The range of inception voltages, therefore, is 1.2 kV or 20% - 26% of the measured inception

voltages. In the case of PD pulses per cycle (N_w), the variability is the highest with a range of 0.48 PD pulses per cycle to 41.20 PD pulses per cycle. Complete phase-resolved patterns for all eight PD measurements appear in Figure 72 using the same amplitude scale so that differences between them are clearer.

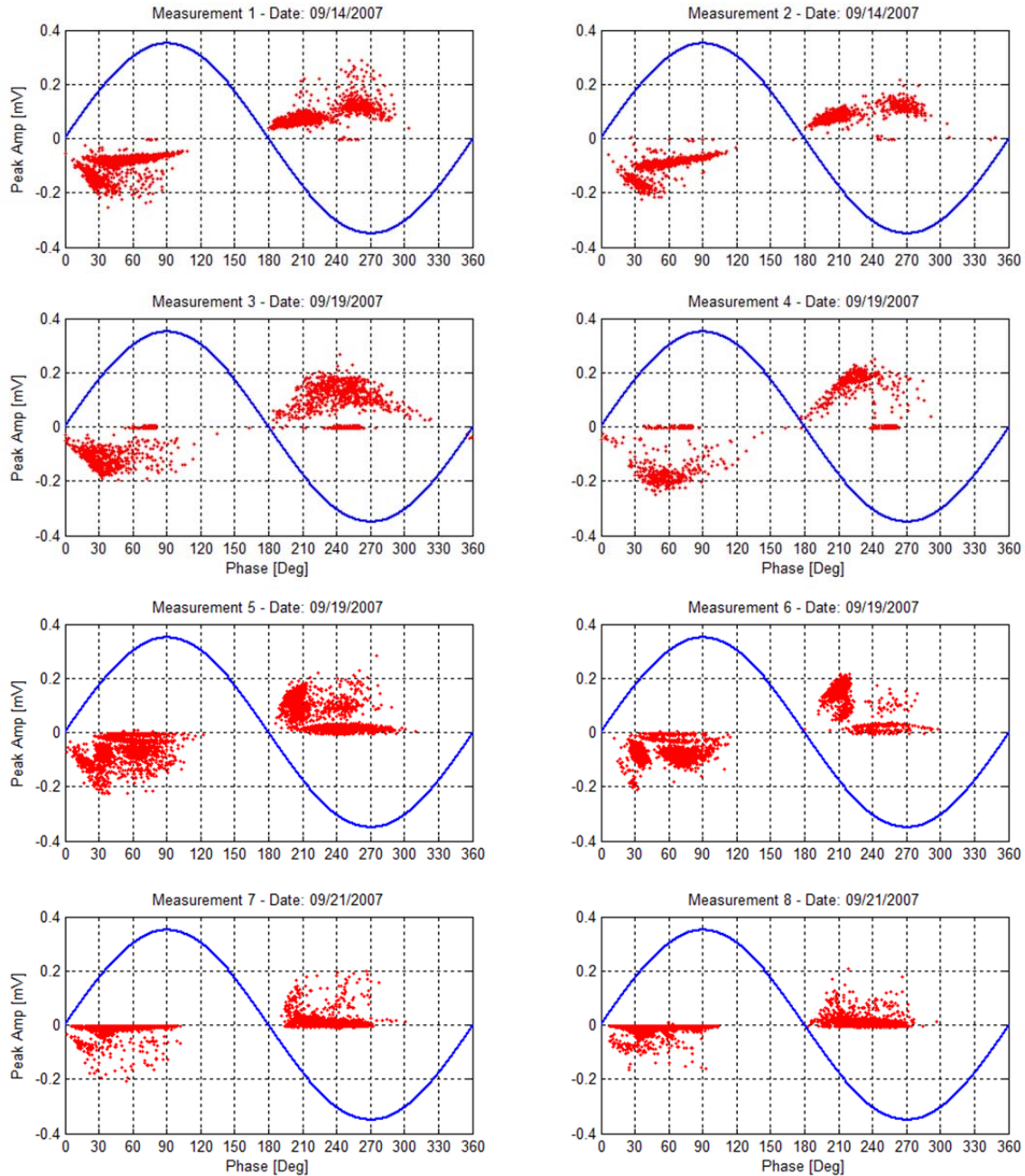


Figure 72: Phase-resolved Patterns for all PD Measurements

Given the dramatic differences in the PD measurements observed over an eight-day period, it is important to recognize that PD is a stochastic process that by definition changes over time. Awareness of this issue helps the user better understand PD measurements.

7.7 Outstanding Issues

As seen in Section 7.6, issues that affect PD measurements on MV power cable systems are numerous and diverse. They have been identified and analyzed in the *CDFI* during both phases. The analysis focused on crucial characteristics and limitations of PD measurements. According to this research, the following outstanding issues for PD measurement as a condition assessment diagnostic for MV power cable systems are identified:

1. When used as a field diagnostic, PD is generally measured on aged assets (maintenance testing). See Section 7.6.4.
2. Field measurements cannot be correlated to laboratory/factory test results. See Sections 7.6.1, 7.6.2, 7.6.3, 7.6.4, 7.6.5, 7.6.6, 7.6.8, 7.6.12, and 7.6.13.
3. PD magnitude does not provide a direct link to estimates of deterioration or likelihood of failure. See Sections 7.6.1, 7.6.4, 7.6.6, 7.6.9, 7.6.10, and 7.6.13.
4. Tests, analysis, and reporting are used to obtain a diagnosis from a single test. Trending or comparison with an identifiable benchmark are rare and difficult to interpret. See Section 7.6.10.
5. Results from different PD measurement approaches/technologies cannot be compared. See Sections 7.6.2, 7.6.3, 7.6.4, 7.6.5, 7.6.6, 7.6.7, 7.6.8, 7.6.10, 7.6.11, and 7.6.13.
6. Complicated test data are commonly processed and reported/recorded as a classification category. Re-analysis/reconsideration by a user is not possible and only coarse trending (across class boundaries but not within a class) is possible by a user. See Section 7.6.10.
7. Measurements and analysis techniques are proprietary so that detailed information about the measurement is unavailable. See Sections 7.6.2, 7.6.3, 7.6.5, and 7.6.11.
8. Measurements are mostly made from one end of the system (terminal measurements). See Section 7.6.3.
9. Noise and PD signal deterioration are unavoidable and can limit effective PD detection. See Section 7.6.1, 7.6.6, and 7.6.12.
10. Variability in measurement results makes it difficult to compare results with specific criteria and to compare results when the tests are repeated. See Section 7.6.14.

Due to the issues listed above, the information in this chapter provides the user an increased awareness of PD measurements on MV cable systems rather than a detailed explanation of how to conduct tests or analyze data.

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7.9 Relevant Industry Standards and Guides

- ICEA S-94-649 – 2004: *Standard for Concentric Neutral Cables Rated 5 Through 46 kV*
- ICEA S-97-682 – 2007: *Standards for Utility Shielded Power Cables Rated 5 Through 46 kV*
- IEC 60270 - 2000: *High-Voltage Test Techniques – Partial Discharge Measurements*
- IEC 60840 – 2011: *Power Cables with Extruded Insulation and their Accessories for Rated Voltages Above 30 kV ($U_m = 36$ kV) up to 150 kV ($U_m = 170$ kV) – Test Methods and Requirements*
- IEC 60885-2 - 1987: *Electrical Test Methods for Electric Cables. Part 2: Partial Discharge Tests*
- IEC 60885-3 - 1988: *Electrical Test Methods for Electric Cables. Part 3: Test Methods for Partial Discharge Measurements on Lengths of Extruded Power Cables*
- IEC 62067 – 2011: *Power Cables with Extruded Insulation and their Accessories for Rated Voltages Above 150 kV ($U_m = 170$ kV) up to 500 kV ($U_m = 550$ kV) – Test Methods and Requirements*
- CIGRE TB B1.28 – 2014 Omnibus: *On-Site PD Measurements*
- 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. 386 – 2006: *IEEE Standard for Separable Insulated Connector Systems for Power Distribution Systems Above 600 V*
- 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*