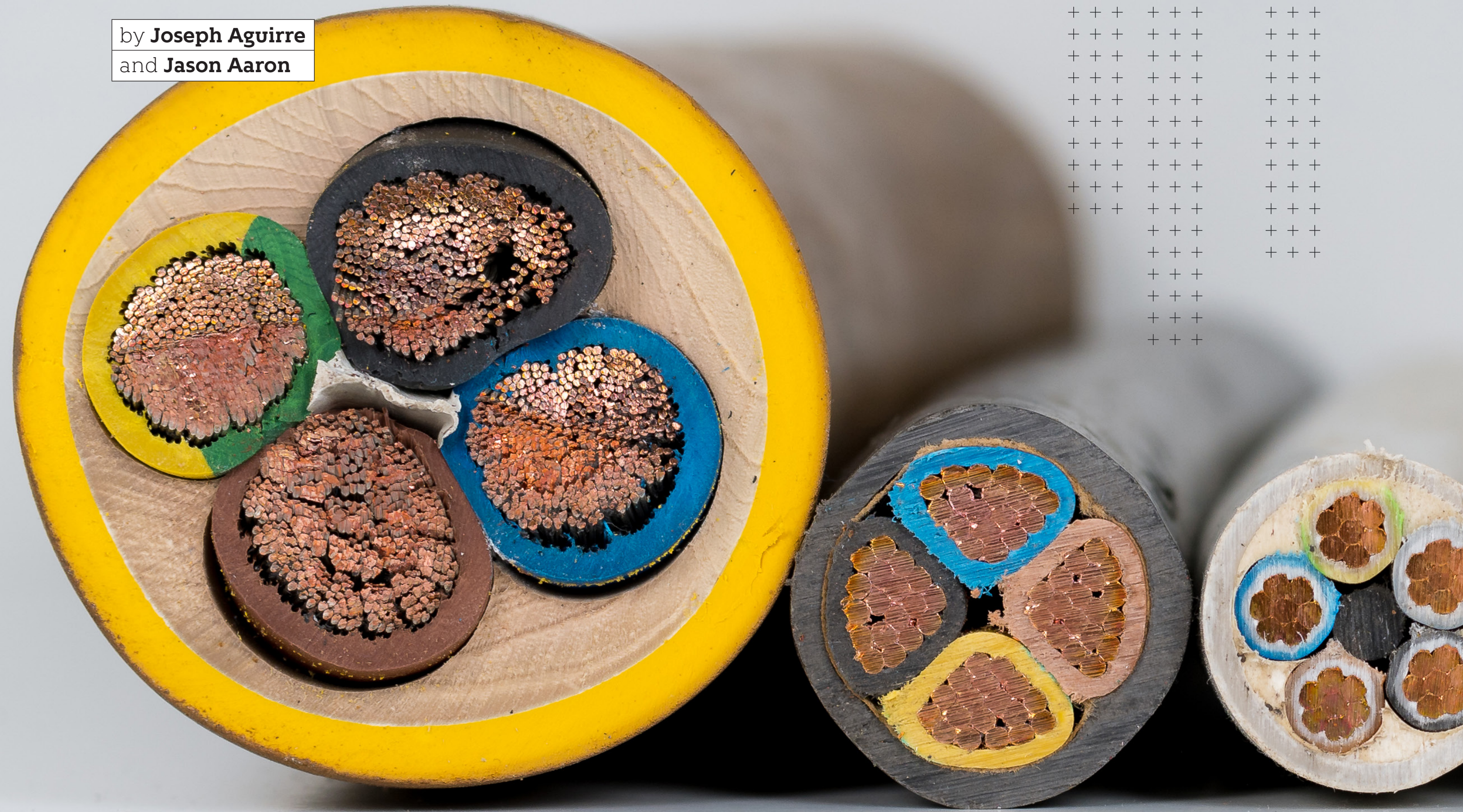
# Enhancing Medium Voltage Power Cable Reliability through Non-Destructive Partial Discharge Measurements

by **Joseph Aguirre**
and **Jason Aaron**



## Introduction

Test equipment using VLF voltage sources was initially available for commercial use in the 1980s, using an AC voltage source in the frequency range of 0.01 to 0.1 hertz. This allowed the use of a smaller power supply to produce the needed voltages for power cable testing that was portable and friendly for field use. Additionally, the non-destructive VLF test signal proved to be more effective at finding hidden insulation defects over the previously used DC test methods.

Further developments produced the availability of different voltage wave shapes for VLF applications and diagnostic techniques, including partial discharge. Partial discharge testing techniques help to provide a better picture of the overall health of the cable and to detect localized cable defects. These defects are caused by factors such as poor workmanship, manufacturing defects, termination, and voids caused by delaminated surfaces. (Figure 1.) In today's power distribution systems, partial discharge testing is a logical requirement for any commissioning or maintenance program for detecting and localizing cable insulation defects.

## Partial Discharge Measurements in Power Cables

Partial discharge (PD) is defined as a localized electrical discharge that only partially bridges the insulation between conductors [1]. This can occur from the conductor to ground or from a conductor to another adjacent conductor with an existing defect. For partial discharge to occur, the applied voltage must reach a magnitude high enough to initiate the event, this is known as the partial discharge inception voltage (PDIV). Once the event begins, the discharges create a point of concentrated electrical stress causing damage to the insulation until the applied voltage decreases to a point where the PD activity ceases to occur. This voltage magnitude is known as the partial discharge extinction voltage (PDEV).

The discharge behavior typically appears as a short-duration pulse,

Photo: Shutterstock

**The majority of these defects are caused by poor workmanship during cable or termination installation, but other factors include manufacturing errors, electrical stress, thermal stress, or environmental factors. The location of these defects can be determined during the measurement process.**

**Jason Aaron**, a Marine Corps veteran, has worked in the power industry for over 15 years as a field technician and applications engineer. He currently holds the position of Cable Infrastructure Program Manager for North America at Megger. Previously Jason has performed start-up, maintenance and commissioning of electrical power systems and substations while earning a Level IV NETA certification. He is a member of the IEEE Power & Energy Society, a voting member of the IEEE standards society, actively involved with a working group for IEEE 400.2 and an IEEE C37.14 task force for DC circuit breaker traction power applications. In his current role, Jason primarily focuses on the areas of power cable testing, diagnostics, and fault location techniques with emphasis on power system reliability, asset management and proper diagnostic test procedures.

**Joseph Aguirre**, a highly skilled Application Engineer at Megger. With expertise in cable testing, diagnostic and fault location techniques, as well as testing of all substation apparatuses. He has a passion for training end-users on the proper use and theory of various pieces of high-voltage testing equipment. Joseph holds a B.S. in Industrial Technology from the University of Texas of the Permian Basin and is currently pursuing two graduate degrees in Energy Finance and MBA. Before joining Megger, he has worked in various roles such as a maintenance technician, a crew foreman for a utility in substation maintenance/construction, and as a NETA testing technician providing commissioning and maintenance on all substation apparatus and industrial electrical equipment. With his vast experience and knowledge, Joseph is continuously making innovative contributions to the field of cable testing and substation maintenance.

lasting less than 1 microsecond. These voltages or current pulses can be measured and recorded. The quantity for this measurement is referred to as the apparent charge. The system used to perform this measurement typically consists of a voltage source, a coupling device, and a measurement instrument. The coupling device typically includes a coupling capacitor to measure impedance and a PD detector for amplifying, filtering, and processing the decoupled PD signals.

In power cables, partial discharge is generally a result of ionizable, gas-filled voids created by defects in the insulation. The majority of these defects are caused by poor workmanship during cable or termination installation, but other factors include manufacturing errors, electrical stress, thermal stress, or environmental factors. The location of these defects can be determined during the measurement process.

The high-frequency pulses in cables propagate in both directions allowing the measurement system to calculate the position of the partial discharges. (Figure 2.)

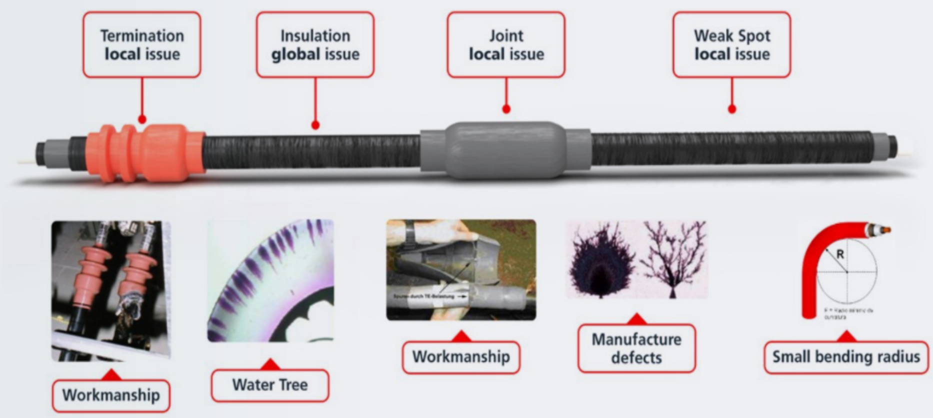



*Figure 1: Types of defects in power cables.*

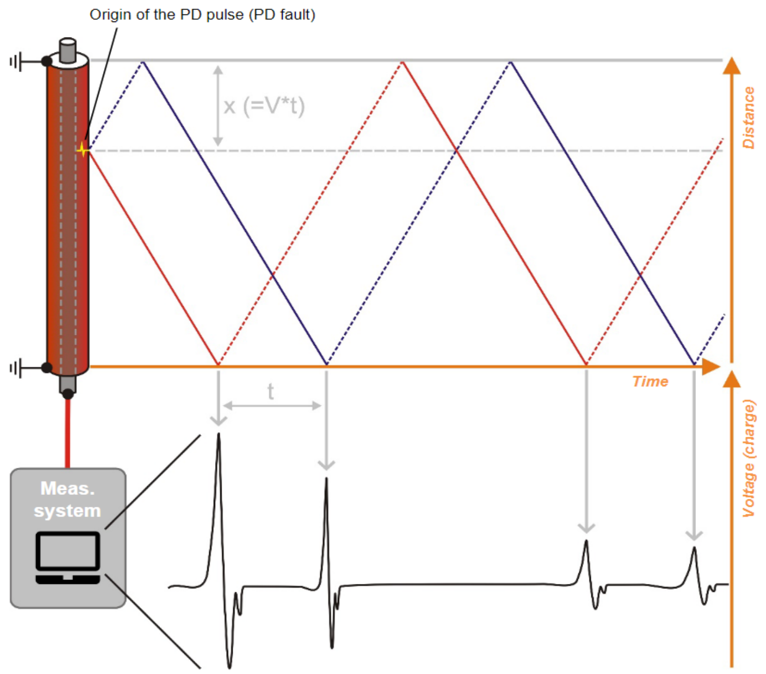



*Figure 2. Partial Discharge Activity Location*

## Using PD as a Part of a Maintenance Program

Periodic PD testing can find defects within the layered construction of a cable system to prevent more significant electrical problems from manifesting later. Diagnosing components quickly, rather than waiting until they suffer complete failure enables users to maintain greater control of equipment performance. By highlighting weak areas, owners stay on top of potential deterioration caused by aging, thus leading to improved reliability and providing more budget-conscious solutions for future reconstruction efforts. This careful monitoring can also extend the lifespan of power cables, as active maintenance can help identify potential problems early in their development cycle to avoid more intrusive repairs. These efforts prevent incurring exorbitant costs due to premature replacements.

Periodic diagnostic tests help guarantee overall safety and peak performance over time. This means nothing falls through the cracks when it is time to replace faulty cables or incorporating new components into existing cables. These preventive steps determine which areas are most prone to failure, allowing for planned repairs to save both money and time.

## Waveforms

### VLF Sinusoidal

VLF sinusoidal emulates the same wave shape as line frequency (50 Hz, 60 Hz), but it is slowed down to 0.1 Hz or lower to detect smaller signals among the stronger ones present at regular frequencies. This waveform is recognized for testing per IEEE 400.2 standards, since its prolonged changing nature takes 10 seconds to complete one entire cycle or polarity crossover every 5 seconds, for partial discharge detection on the power cable. By using this technology, repairs can be made selectively on cables before complete failures take place, leading to extensive and costly repairs or replacements.

### VLF Cosine Rectangular

Historically, the European VPP and DERM market is mainly driven by the requirement for integration of increasing share of supply-side renewable generation. The expansion in wind power from 94 GW to 197 GW and solar power from 18 GW to 120 GW in the last decade has paved way for grid flexibility services.

Cosine rectangular utilizes the cable's capacitance and a fixed inductor within the test equipment, creating a resonance circuit when polarity transitions occur. The diode stops this polarity switch and produces a closer transition to line frequency than VLF sinusoidal waveforms, which are 1,000 times longer in duration. Moreover, this test type does not damage the cable's insulation due to its brief intervals between DC polarities. The range for CR polarity reversal (Figure 5) falls from 16ms -1.6ms, being close in value compared to 60hz 8.3ms or 50hz 10ms test frequencies.

## Damped AC

A particularly useful technique in PD diagnostic is Damped AC (DAC). DAC utilizes a resonance circuit, similar to Cosine Rectangular (CR), that allows voltages to decay exponentially through resistive losses in the circuit. The properties of this waveform make it particularly suitable as a non-destructive method, especially for service-aged cables. DAC resonates at frequencies closer to the line frequency range, around 20-500 Hz, but with much lower peak voltages than CR and VLF Sinusoidal techniques. This increases the probability that PD can be measured while providing gentler measurements as opposed to more traditional methods such as switching surges or impulse crosses, lasting only a few hundred milliseconds, and producing voltage on cable for a short duration. DAC has polarity changes closer to line frequency, increasing the likelihood of finding PD on cable.

Photo: Shutterstock

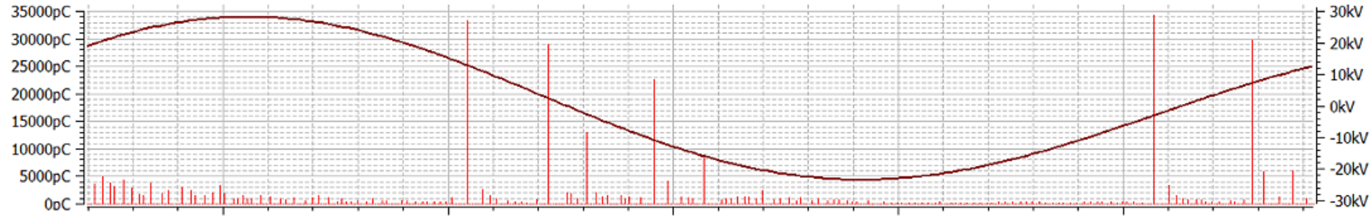



*Figure 3: VLF Sine Wave Voltage*

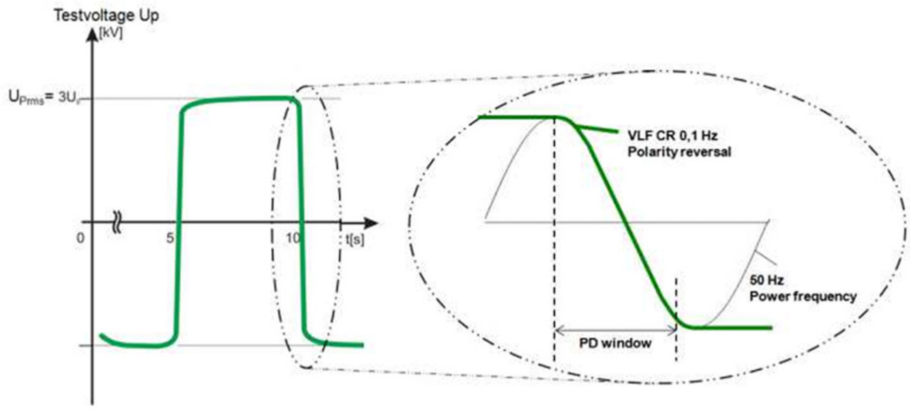
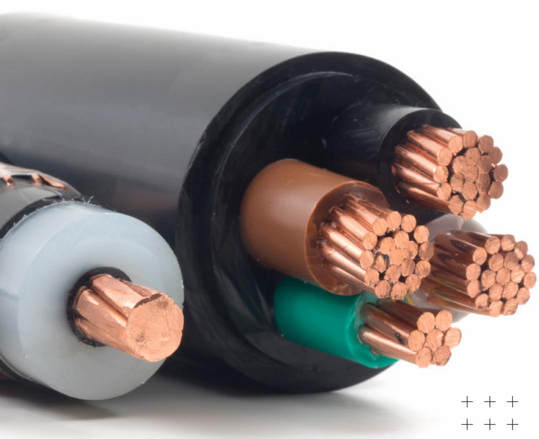



*Figure 4: VLF Cosine Rectangular Voltage measurement window at polarity reversal*

## Advantages/Disadvantages and When to Use Each Waveform

VLF sinusoidal is considered a preliminary waveform for PD testing. When using this waveform, it is recommended to modify the voltage output after ten full waveforms. Relying solely on VLF sinusoidal could represent an inaccurate account of actual condition of cables when being tested. DAC or CR should be used depending on the circumstances. DAC is the best solution regarding service-aged cables and maintenance tests. However, for commissioning and acceptance testing, CR would be the optimal choice for capturing any defects. The utilization of Partial Discharge proves as an advantageous instrument providing an efficient solution to a technical problem - decreases costs from breakdown due to increased confidence during testing without risk of damaging cables and causing slowdowns on costly repairs.



**Periodic PD testing can find defects within the layered construction of a cable system to prevent more significant electrical problems from manifesting later. Diagnosing components quickly, rather than waiting until they suffer complete failure enables users to maintain greater control of equipment performance.**

## 60HZ Power Frequency vs Alternative Waveforms

A commonly utilized technique for offline partial discharge testing of power cables is applying VLF or DAC waveforms. The equipment that produces these waveforms is more portable, less expensive, and more friendly for field testing.
These include the options of 0.1 Hz very low frequency voltage, sinusoidal or cosine rectangular, and damped AC. The applications of CR and DAC are comparable to power frequency power sources. This is due to the gradient of the applied voltage, which is the rate of change in the applied voltage with respect to time. Partial discharge activity is strongly dependent upon the gradient of the applied voltage.

## Evaluating Test Measurements and Decision Making for Reliability

The following are several pieces of key information to evaluate when analyzing PD test results:

### Localization

As previously discussed, a significant benefit of performing partial discharge measurements is the ability to localize defects in a power cable. This allows the user to identify, isolate and repair damage to a cable system. Some cable systems consist of long cable runs with several splices, so having the ability to identify a single splice, termination or span of cable as problematic can help to increase cable maintenance efficiency and reduce downtime.

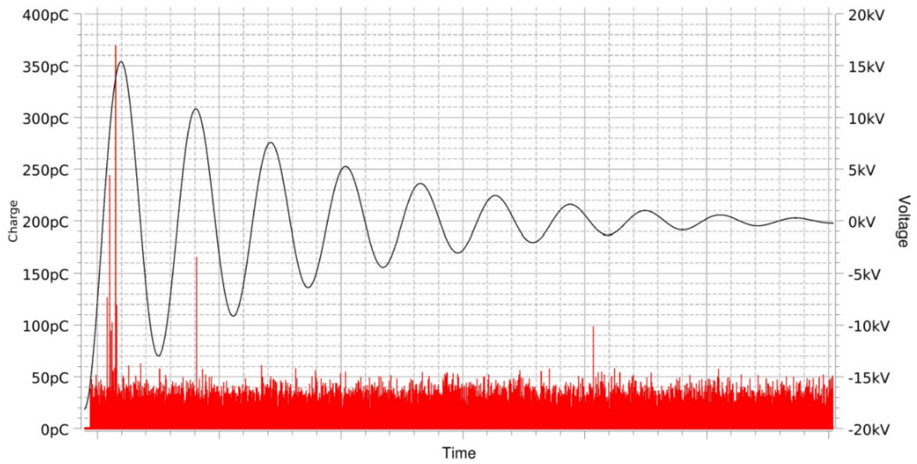



*Figure 5: Typical Damped AC Voltage*

This is accomplished through partial discharge mapping using the instrument software (Figure 5).

## PDIV/PDEV

The PDIV/PDEV relative to the rated voltage of the cable (Uo) is another characteristic to evaluate. Generally, PDIV values exceeding 1.7 times the voltage rating of the cable is acceptable. This establishes the voltage magnitude where PD would initiate and answers the question of; if PD activity is present. PDIV found at or near the 1.0 times Uo is a cause for alarm, and a deeper investigation is required. If partial discharge activity is not present, this is considered to be a successful test. In the instance that PDIV is discovered, PDEV is then established. There are different sets of criteria depending on what is being evaluated in the cable system.

For the cable itself, any detection of partial discharge is a concern and should be followed with further investigation. Although, PDEV should be measured to determine the severity of the deterioration for making decisions involving the cable in question. For cable accessories, such as splices and terminations, there are acceptable tolerances for PDEV. The localization ability allows for the determination of the specific source of PD to identify whether it is an accessory. In these cases, each type of accessory has different criteria. The minimum acceptable PDEV is 1.5 Uo for cable joints (IEEE 404) [2] and terminations (IEEE 48) [3], while separable connectors (IEEE 386) [4] are 1.3 Uo. For cases where cable accessories fail to meet the minimum PDEV values, the severity of the activity and criticality of the circuit should be taken into consideration for cable maintenance decisions. Additionally, other diagnostic methods and testing may be necessary.

## Discharge Magnitude

The coulomb is used for the measurement of PD activity. Generally, on the scale of Pico coulombs (10-12) or Nano coulombs (10-9). For PD testing, any measurement above 5 pC is above acceptable thresholds for lab testing. However, this value was established for lab environments on new cable systems. Measurements in the field have other aspects to consider, such as background noise, grounding conditions, and the age of the cable, as previously mentioned. Therefore, the background noise value must be considered when grading the quality of a cable exhibiting low levels of PD activity. For example, if the noise floor measurement was 50 pC, a measurement beginning at 60 or 70 pC should be noted and recorded.  Decisions can be made for appropriate follow-up actions based on the PDIV and PDEV values in relation to established tolerances (seen above) and whether it is a critical circuit to operations.

## PRPD, phase-resolved partial discharge

The type of discharge should be determined based on the PRPD pattern. PRPD has been previously discussed in this paper and can be applied as a useful tool for determining if PD being detected is a concern. In some cases, it may be corona discharges created by a poor test setup. This can be alleviated by adjusting the setup and retesting. In other cases, surface and/or void discharges are produced internally

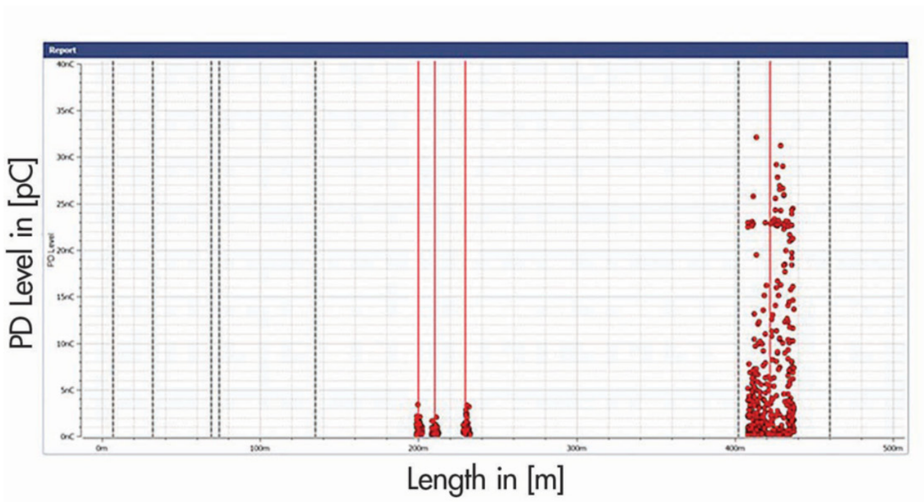



*Figure 6. Partial Discharge Mapping*

**A particularly useful technique in PD diagnostic is Damped AC (DAC). DAC utilizes a resonance circuit, similar to Cosine Rectangular (CR), that allows voltages to decay exponentially through resistive losses in the circuit.**

*Photo: Shutterstock*

**The applications of CR and DAC are comparable to power frequency power sources. This is due to the gradient of the applied voltage, which is the rate of change in the applied voltage with respect to time.**

with serious defects that will need to be addressed with further testing and investigation of the cable defects. Identification of the types of PD being measured can help avoid lost downtime due to the investigation of a phantom defect caused by an inadequate test setup. On the other hand, it can also validate the presence of PD activity needing immediate attention.

## Conclusion

Partial discharge (PD) diagnosis of medium voltage power cables is essential in the successful and safe operation of any modern energy system. PD testing enables engineers to detect defects in power cables before they become dangerous or cause irreparable damage, safeguarding both people and components. Through PD diagnosis, engineers can also accurately measure leakage levels, allowing them to identify elements that may fail without sacrificing the cable's integrity.

PD testing involves applying varying waveforms and voltages on power cables, which detect any irregular behavior of the cable's insulation system that may indicate the presence of a fault. PD provides engineers with the essential information required to ensure the efficiency of modern energy systems. As such, it can serve as a cost-effective alternative to replacement or repair through its ability to address issues quickly and safely. All with minimal disruption or downtime for the energy system. In addition to providing an effective means of detecting faults, PD diagnosis plays a crucial role in catching potential problems before they escalate and become more hazardous or damaging. PD diagnosis is also invaluable for predicting future cable performance and getting the maximum life out of medium-voltage power cables.

To conclude, PD Diagnosis serves various purposes that justify its implementation into energy systems, from cable-related issues to improving overall reliability and longevity by identifying potentially faulty cable sections. Also, amongst other equipment where predetermined electrical tolerances are not met. Partial discharge should rightly be considered integral to commission and maintenance test procedures when dealing with medium-voltage power cables.

**References**

[1] IEC 60270 3.1 Page 15
[2] "IEEE Standard for Extruded and Laminated Dielectric Shielded Cable Joints Rated 2.5 kV to 500 kV," in IEEE Std 404-2022, vol., no., pp.1-46, 21 March 2023, doi: 10.1109/IEEESTD.2023.10077511.
[3] "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," in IEEE Std 48-2020 (Revision of IEEE Std 48-2009), vol., no., pp.1-49, 12 Oct. 2020, doi: 10.1109/IEEESTD.2020.9222616.
[4] "IEEE Standard for Separable Insulated Connector Systems for Power Distribution Systems Rated 2.5 kV through 35 kV," in IEEE Std 386-2016 (Revision of IEEE Std 386-2006), vol., no., pp.1-81, 14 Oct. 2016, doi: 10.1109/IEEESTD.2016.7592838.