ON-LINE PARTIAL DISCHARGE DIAGNOSIS FOR POWER DISTRIBUTION AND TRANSMISSION SYSTEMS

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On-line partial discharge (PD) testing is an effective diagnostic approach to evaluate insulation condition in multiple power system assets. Benefits include no power outage, nondestructive, and high accuracy in defect recognition and fault localization. On-line PD testing as a diagnostic tool to improve reliability of power distribution and transmission (T&D) systems has been gradually adopted by many equipment owners. This article provides a brief overview of on-line PD testing technology, including the mechanism of using PD testing in the T&D system, as well as the expectations, challenges, and solutions to performing on-line T&D system diagnosis.

Although various T&D system failures can lead to power outages, most are related to insulation issues. Over 60 percent of major failures in gas-insulated switchgear (GIS) are due to insulation breakdown. The majority of underground cable failures are caused by insulation degradation and aging. About 50–70 percent of transformer failures result from insulation defects in the winding, oil, or accessories. Insulation condition assessment proactively reduces the failure rate of power apparatus, which improves reliability of the entire T&D system.

By definition, PD is an electric discharge that does not bridge two electrodes. Almost all insulation failures exhibit PD activity prior to the fault. In some cases, PD is the symptom of insulation aging/degradation; PD can also cause insulation deterioration. PD as a symptom of early-stage aging further accelerates degradation until insulation breakdown occurs.

PD testing can discriminate defect types, locate defect sites, and recognize defect severity. Therefore, PD testing is an effective and economical diagnostic technology for evaluating insulation condition for power T&D system apparatus. PD diagnosis has been adopted by utilities and industries over the last 20 years.

PD testing can be performed when the equipment under test (EUT) is removed from service, i.e., an offline test. An external power supply energizes the EUT. The offline testing voltage is normally higher than the operating voltage to reach the PD inception voltage (PDIV). The level of over-voltage is determined by the EUT. For example, the PD testing voltage for medium-voltage solid dielectric cables should reach $2.5U_0$ or until PD is initiated; testing voltage for high-voltage cables normally should not exceed $1.7U_0$. The advantage of applying the over-voltage to the EUT is to find dormant defects, which serves as a factory acceptance test or commissioning test when the insulation is brand new. However, the over-voltage test for an aged insulation system must be examined carefully, as aged insulation can be fragile, and over-voltage could reduce the remaining life significantly. Some aged cables fail during the offline test, while others could fail at a higher rate within the first year after the test.

On-line PD testing is truly a non-destructive test, as the PD measurement is performed when the EUT is under normal operating condition. Although performing on-line PD diagnosis has many benefits, its challenges determine the diagnostic effectiveness and accuracy.

ADVANTAGES OF ON-LINE PARTIAL DISCHARGE DIAGNOSIS

PD diagnosis has two major advantages over other testing technologies: defect localization and categorization.

Defect Localization

Defect site localization with PD measurement varies for different types of apparatus, but most technologies use PD pulse propagation in the EUT. Once PD occurs, the PD-induced pulse (electrical pulse, acoustic pulse, electromagnetic pulse, etc.) propagates in the EUT in all directions. Common PD source localization methods include:

- **Time-of-arrival analysis.** Several PD sensors are deployed at separate locations on the EUT to capture PD pulses. The PD source location is calculated by the difference of the PD pulse arrival times at the sensors. This method is popular in PD source locating for power transformers. Several acoustic sensors are placed either in the transformer tank or on the surface of the tank for PD data acquisition. With the known acoustic sensor locations and the model of the transformer, the time difference of the PD pulse arriving at the sensors gives an accurate discharge source location in the transformer.

  In power cables, the time-of-arrival analysis is simpler, as the PD pulse can only propagate in two directions. The PD pulse reflects at the cable joints and terminations during the propagation. One PD sensor is enough to capture the original PD pulse and the reflected pulses. With prior knowledge of the PD pulse propagating velocity in the tested cable, the cable length, and/or the position of the splices, the PD source location can be calculated by the time difference between the original pulse and the reflected pulse.

- **Frequency spectrum analysis.** The original PD pulse has a very sharp rise time in the range of a few nanoseconds (ns), which corresponds to ultra-wide bandwidth (UWB) up to GHz range. The measured PD pulse could have much lower bandwidth, which is determined by the signal propagation path. The PD source location can be estimated with the measured PD bandwidth if the relation between the attenuation and the signal propagation path is known. This method is particularly helpful in PD tests for power cables, where knowledge of the measured PD signal bandwidth as a function of the pulse propagation distance has been established. This method is not as accurate as the time-of-arrival analysis, but has the advantage of simplicity, as the localization only requires one PD sensor and does not rely on the detection of reflections. Using this method, discharges occurring at the sensor placement location can be easily distinguished from discharges propagated from a remote location.

- **Magnitude comparison.** This method is similar to using a stethoscope. The PD sensor(s) are placed at various locations in the EUT, and the measured PD magnitude is strongest when the sensor is closest to the defect. This method is usually employed in testing a pile of switchgear cabinets or testing large, gas-insulated switchgear.

Other non-electrical PD source localization technologies include ultrasonic sniffer, infrared imaging, ultra-violet imaging, etc. Most of these technologies require a clear path between the PD source and the detection equipment, which may not be available in field conditions. Thus, these non-electrical PD testing methods are normally used as additional tools during on-line diagnosis.

Defect Categorization

Categorizing defects is one of the greatest benefits of PD diagnosis, as severity to the insulation system varies among distinct types of defects. Defect categorization is performed with the phase-resolved PD (PRPD) pattern. PD activities can be quantified by magnitude (q, in the unit of pC or mV) and repetition rate (n, number of discharges per a certain time frame, i.e., per cycle or per second). These values can be plotted in one voltage cycle with the phase reference at which the PD pulse occurs, which is the phase resolved PD pattern. The PRPD pattern varies by the nature of defects. Figure 1a, Figure 1b, and Figure 1c show PRPD patterns for three typical defects.

These advantages are generic for all on-line and offline PD diagnosis. On-line PD diagnosis has several unique advantages, as removing the EUT from service is not required. The first benefit is cost savings. Since the EUT remains in service during the test, on-line PD testing does not require switching operations, which saves labor and system downtime. The on-line test is also more economical, as it does not require an

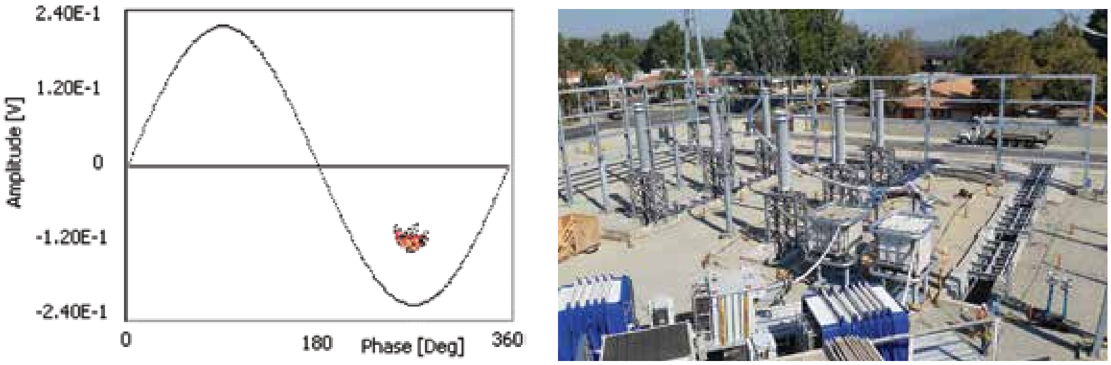

Figure 1a: *Corona discharges are normally caused by a sharp metal edge with high potential. Corona discharge is very common in outdoor substations. The photo on the right shows two 500kV XLPE circuits going through a commissioning test. Strong corona discharge was observed during the PD measurement, but did not raise concern.*

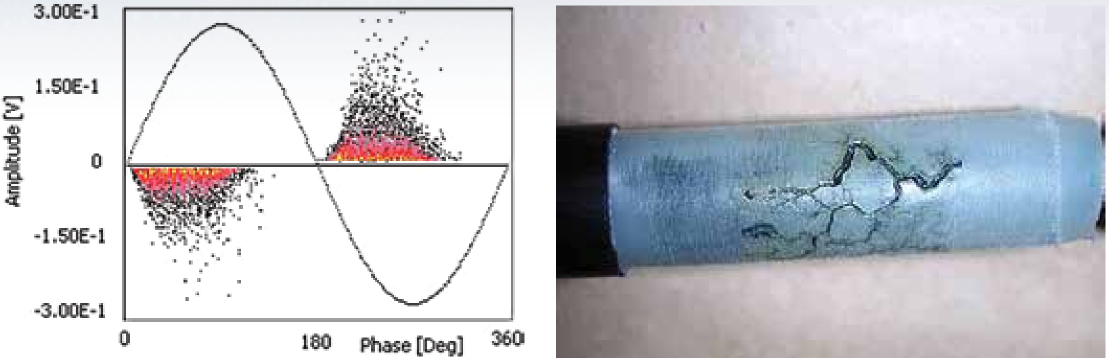

Figure 1b: *Surface discharges could be on the external surface of a component, such as the surface of an insulator, busbar, or arrester. They could also be on the internal surface (interface) of a device, e.g., interfaces within a separable connector, cable termination, cable joint, etc. The photo on the right is the interface in a 15kV splice that showed surface discharges.*

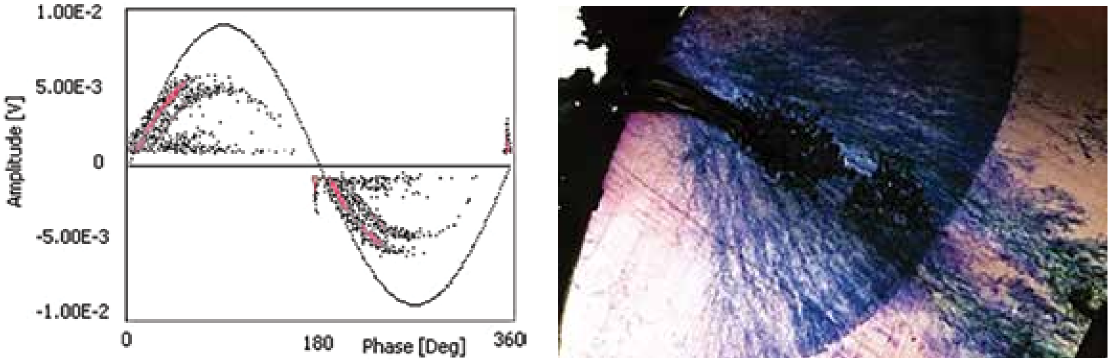

Figure 1c: *These internal discharges were caused by voids or cavities in an insulation system. Internal discharge is the most dangerous defect in the organic insulation system, as the discharge activities further deteriorate the polymer chains and accelerate the aging process. The photo on the right shows electrical tree (black traces) going into the water-tree region (blue traces) in a medium-voltage XLPE-insulated cable.*

expensive external power supply and testing productivity is much higher than an offline test.

On-line PD testing can reveal all active defects in an operating condition, including load- and temperature-dependent defects. IEEE 400.3-2006 standard describes load- and temperature-dependent defects as:

> *In a complex cable system…the voltage built up in the ground system is induced by the current being conducted and is therefore a strong function of the cable loading… For this type of discharge, testing under heavily loaded conditions is essential.”*

> *[In] an XLPE insulated cable…the size of some defects varies with cable loading so that the PD magnitude varies with the cable loading. PD in some cases might disappear (extinguish) as load conditions change. For a laminated cable, long-term operation at high temperatures may cause the insulating fluid to migrate. The extent of this depends on the viscosity of the impregnating fluid. This can affect the PD producing defect.*

Since the EUT is connected to other components in the T&D system, an on-line PD test also assesses insulation condition for all connected components. At the same time, the interconnection poses a challenge for on-line

PD diagnosis, as the measured signals could come from any of the connected components or even be cross-talked from nearby devices, creating difficulties in PD data interpretation.

CHALLENGES IN ON-LINE PD DIAGNOSIS — DATA INTERPRETATION

Commercially available equipment can be used for on-line PD measurement. However, PD diagnosis is difficult: How can we derive insulation condition from the measured data, and what action shall we take after PD measurement? Unlike other testing technologies, PD diagnosis does not have standard numerical values to categorize the condition of the EUTs. Questions arise, such as "Why did Device A work properly with 100mV measured PD, but Device B failed with only 2mV of measured PD?" or "The measured PD value for Device C is 12 mV; what should I do?" The objective of PD data interpretation is to answer those questions, which is considered the most challenging process in the on-line PD diagnosis.

To properly evaluate insulation condition with on-line PD diagnosis, assess the following:

- **Noise separation.** The first question when analyzing measured PD data is whether the data contains PD signals from the EUT. Noise separation is the first step for PD data interpretation, and it is a critical step in on-line diagnosis. Various interferences could occur during on-line PD measurement, including switching noise, interference from stationary broadcasting, communication noise, and irrelevant PD signals such as coronas from overhead lines. All noises must be identified and removed before further analysis.

- **PD source classification.** PRPD pattern is the most common tool employed in defect categorization. However, discharge signals from various sources and interferences are always mixed together in on-line PD testing. To accurately recognize the type of defect, the acquired PD data must be categorized by the discharge sources. The five illustrations in Figure 2 show the signal categorization method based on T-F Map analysis. The entire acquired data (Figure 2a) contains strong interferences from variable speed drives, and the possible PD signals are all overwhelmed by the noise. To separate the PD signals from the noise as well as categorize PD signals from various sources, each acquired pulse in Figure 2a is plotted in the T-F Map (Figure 2b) by its equivalent pulse width (T) and pulse bandwidth (F). Signals from the same sources tend to cluster in the T-F map, as they have similar waveform features.

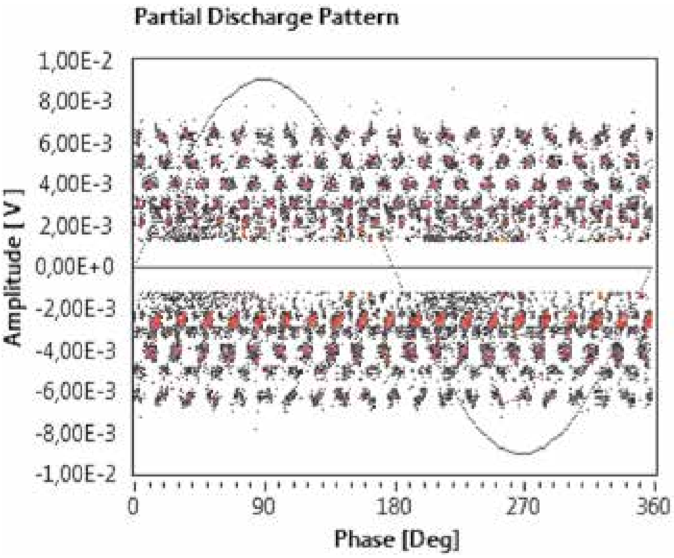

Figure 2a: *PRPD Pattern for Entire Acquired Data*

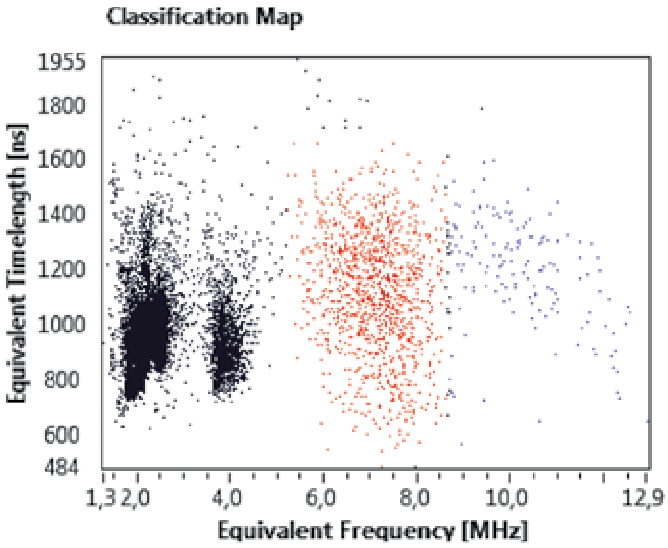

Figure 2b: *PD Data Plotted in T-F Map*

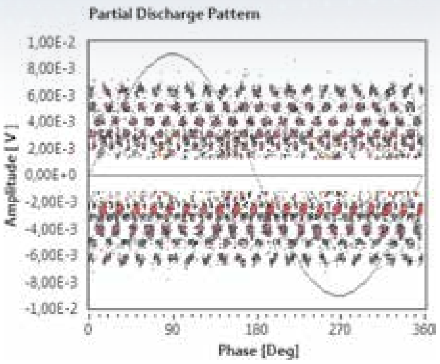

Figure 2c: *Black Cluster, Noise From VFD*

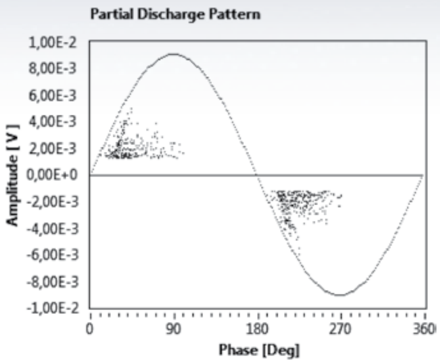

Figure 2d: *Red Cluster, Surface Discharges*

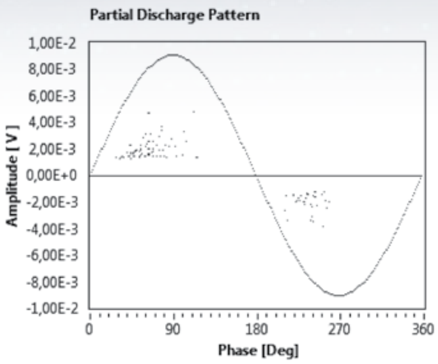

Figure 2e: *Blue Cluster, Internal Discharges*

Each cluster in the T-F Map can be separated for further analysis, as shown in Figure 2c, Figure 2d, and Figure 2e. Weak PD signals can be extracted from strong interferences with T-F Map analysis, and each type of discharge signal can be categorized for further evaluation.

- **Condition assessment.** When noise signals are removed from the PD signals and the PD signals are separated by discharge sources, the PD activity for each defect type can be quantified by PD features such as discharge magnitude and repetition rate. Most on-line PD tests stop at this step. However, those PD values cannot answer the initial questions: What is the status of the tested apparatus, and what should we do with it?

There are no easy answers. Condition assessment depends on many factors, and damage to the insulation system varies from different types of PD activities. Corona discharge normally does not cause much damage to the insulation system; therefore, corona discharge might be considered acceptable in many applications. Internal discharge occurs within the dielectric and accelerates insulation aging significantly; this is considered the most dangerous defect in a dielectric. The severity of surface discharge falls between the corona discharge and internal discharge. Moreover, different insulation materials have different tolerances on PD activities. Oil-paper insulation can survive with PD for a long time, so even if oil-paper insulation has intensive PD activities, the insulation system may hold for years. However, once PD starts in a medium-voltage XLPE cable, organic insulation would quickly degrade and electrical treeing could be initiated, quickly leading to failure.

To properly assess insulation condition, consider the following factors:

- Type of insulation materials
- Knowledge of the aging and failure mechanism for the tested insulation system
- Operating condition of the apparatus
- Type of defects from PD measurement
- Measured PD magnitude
- Measured PD repetition rate
- Comparison of historical PD data for trending analysis

Note that the absolute value of PD magnitude does not carry much weight in condition assessment, which is quite different from other diagnostic technologies that have defined threshold values for good or bad. First, damage to insulation varies by defect type. Comparing PD magnitude without mentioning defect type does not make sense. Second, the measured PD magnitude is not the defect's real discharge. Measured PD magnitude is strongly affected by the propagating path and position of the defect in the insulation. Therefore, the measured PD magnitude has no direct relation to the size or severity of the defect.

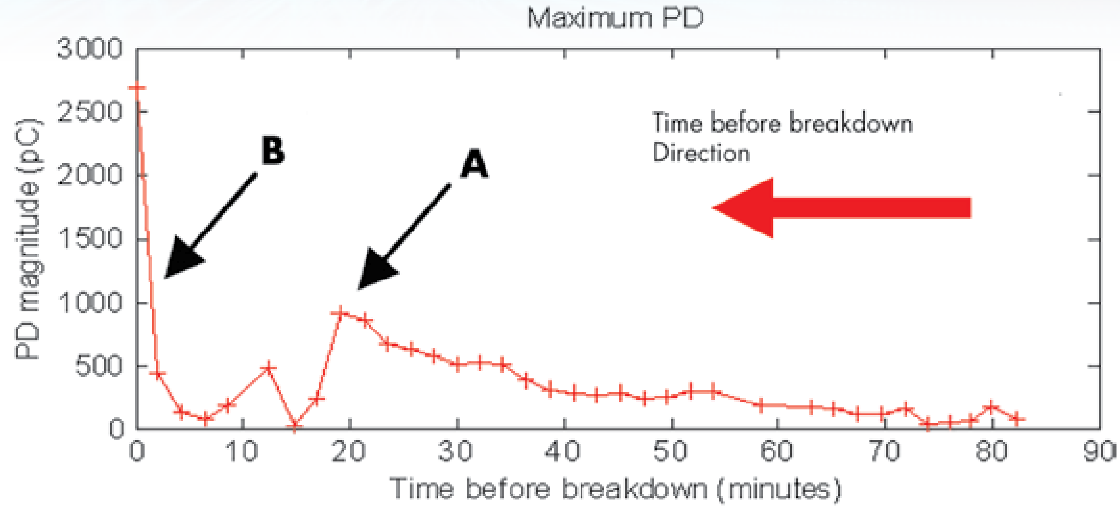

Figure 3: *PD magnitude varies prior to breakdown. Discharge magntiude decreases from Point A and surges in Stage B until fault. 09/20/17* (SOURCE: LAI, LOHRASBY, PHUNG, AND BLACKBURN)

Moreover, PD magnitude may fluctuate during the insulation aging process. PD magnitude increases with the aging process until a certain point prior to breakdown. PD magnitude may drop for a while and then surge until breakdown occurs, as shown in Figure 3. Hence, one cannot determine the aging stage with only the PD magnitude from a spot measurement. Instead, trending analysis of PD magnitude and repetition rate gives a more precise indication of the aging process. Trending data can be obtained by comparing a series of historical spot measurements or from the PD monitoring system.

ON-LINE PD DIAGNOSIS FOR T&D SYSTEMS – APPLICATION AND CASE STUDY

Since different devices under test are energized, non-galvanic sensors are required for PD detection. Figure 4 shows possible sensor placement in a medium-voltage distribution system. Using a hot-stick, a capacitive sensor was connected to the shielded part of the cable close to the termination or the joint. The PD sensor is connected to the data acquisition system via coaxial cable. A laptop controller connects to the acquisition system through fiber optic cable or Wi-Fi to isolate the operator

Figure 4: *Non-galvanic capacitive sensor is placed on the shielded part of medium-voltage cables for PD measurment.*

Table 1: *Five-Level Condition Assessment for Apparatus in a T&D System*

LEVELS	INSULATION CONDITION	RECOMMENDATIONS
Level 1	The insulation in the EUT is not degraded.	No action needed.
Level 2	EUT is aged but not in danger. The probability of failure within 2 years is negligible.	Retest is recommended within 2 years for trending analysis.
Level 3	EUT has low to moderate deterioration and low probability of failure within the next 2 years.	Retest is recommended within 1 year.
Level 4	EUT has medium probability of failure within the next 2 years.	Further discussion is required to determine repair or replacement.
Level 5	EUT is at the end of economic life and has a high probability of failure within 1 year.	Recommend immediate attention.

and the energized testing equipment. During the data acquisition, the technician determines the type of apparatus, vintage, installation, operating and environmental condition, etc. The controller stores the acquired PD data for further analysis.

After onsite data acquisition, stored PD data is transferred to a PD expert for interpretation. The assessment is presented by levels to indicate the insulation condition or the probability of failure, with recommended actions. Table 1 shows a five-level condition assessment that categorizes EUTs by the probability of failure in a certain timeframe. The probability of failure is analyzed by an independent research institute, as shown in Figure 5. The five-level result helps equipment owners prioritize the maintenance plan.

Figure 6 summarizes testing performed for a utility in the northwestern United States. A total of 97 circuit segments were diagnosed in a five-day on-line PD test. The testing was

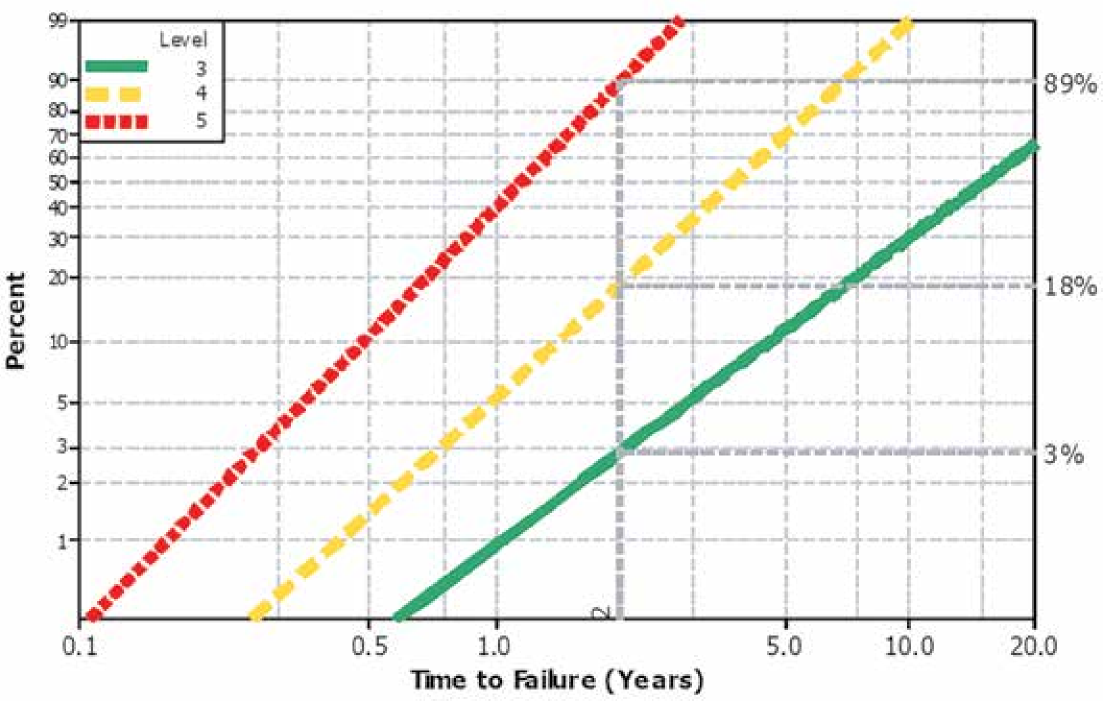

Figure 5: *Diagnostic Performance Curve for an On-Line PD Test Technology* (SOURCE: NEETRAC CDFI REPORT)

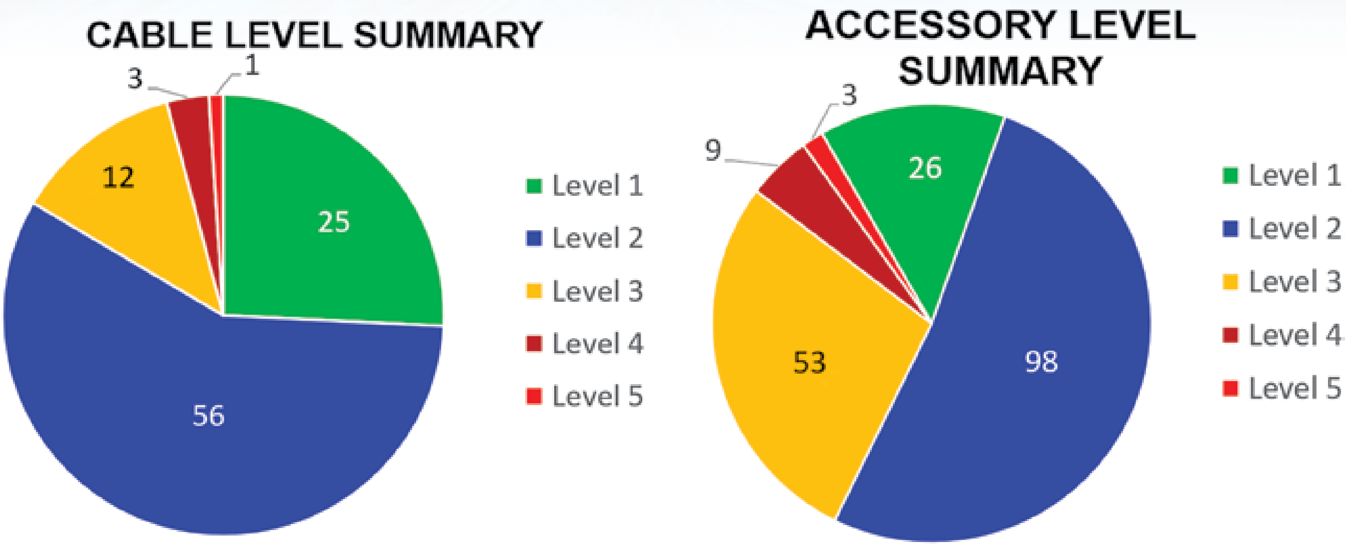

Figure 6: *Pie graphs summarize assessment levels for tested cables, cable termanations, and splices, as well as connected apparatus such as switchgears, riser pole components, transformers, etc.*

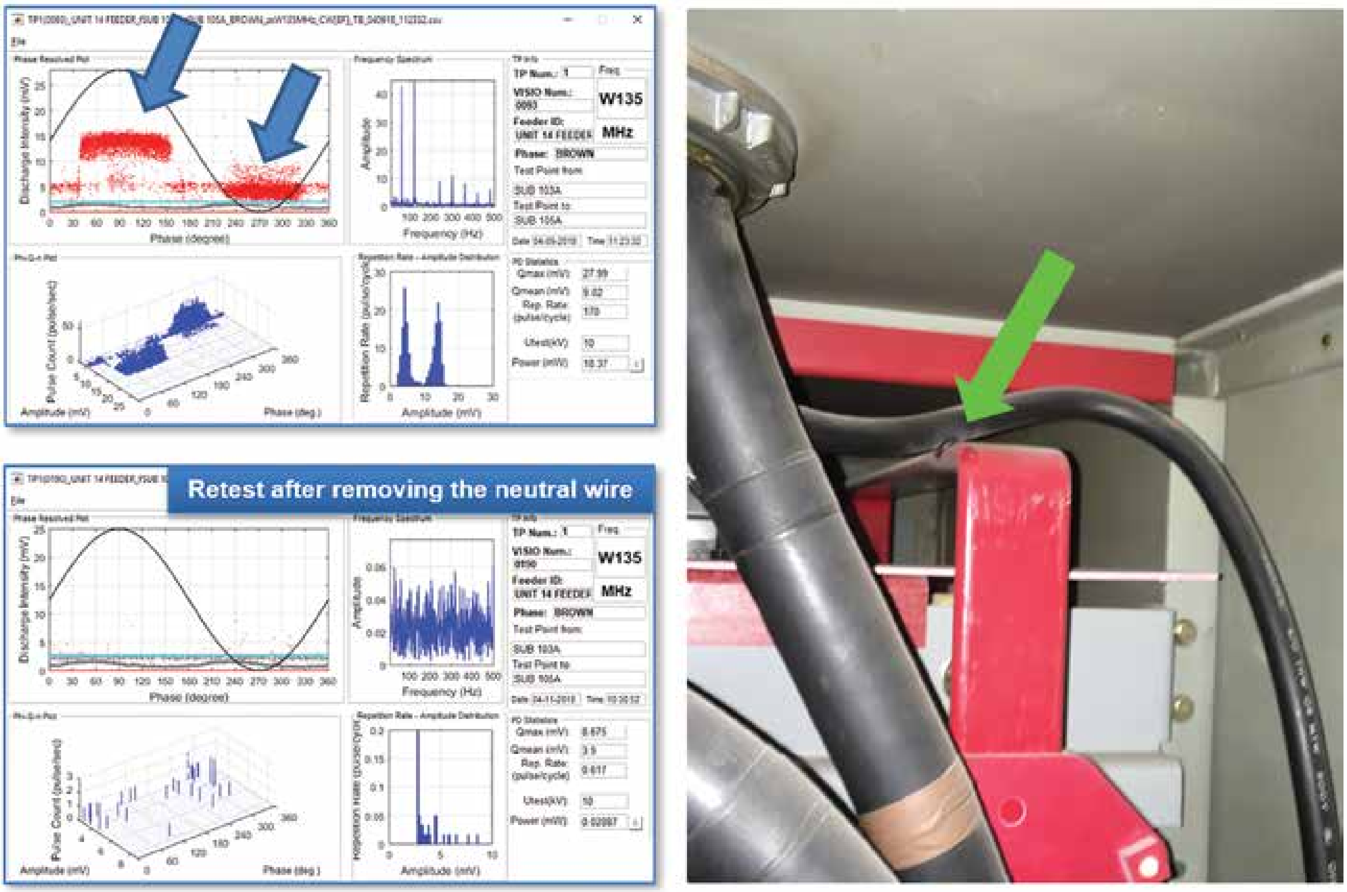

Figure 7: *A Level 4 defect was pinpointed during the on-line testing. The neutral wire was touching the energized bus-bar in a switchgear cabinet and created intensive tracking discharges. Discharge was eliminated once the wire was repositioned.*

performed for the medium-voltage distribution network in a metropolitan downtown area. The PD data were acquired at each cable termination and splice if accessible.

The data pinpointed one Level 4 defect that was repaired immediately (Figure 7). Such discharges erode the insulation and eventually lead to a flashover. This defect was pinpointed during the test, and the neutral wire was re-positioned immediately. The retest of the circuit confirmed the correction.

The final assessment results helped the circuit owner prioritize the maintenance schedule. In general, the Level 5 cables and accessories needed immediate replacement. The Level 4 circuits could wait 6–12 months for repair or replacement. Normally, Level 3 circuits do not require immediate action, although some circuit owners replace Level 3 cables in 2–5 years depending on budget. Retesting for the Level 3 component in 1–2 years is recommended to monitor the degradation process and to determine the best actions based on economy and reliability. The acquired PD data was safely saved in cloud storage for future trending analysis.

CONCLUSION

It is not difficult to perform PD testing and generate good data with the available technology. However, the data needs to be analyzed by experts to assess the health of an individual EUT and to help in prioritizing asset management decisions.

In the modern T&D system, an aging North American infrastructure is a key concern. The investment to address aging infrastructures is significant. Often, an asset manager is not only deciding whether to replace equipment or cables, but also prioritizing among aging system components.

On-line PD measurement is a widely accepted diagnostic tool for T&D systems and is an economic, effective, and flexible diagnostic technology for evaluating power apparatus insulation condition. Those benefits make on-line PD diagnosis a good choice for asset managers in prioritizing their T&D system maintenance plans.

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