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Can a One-Minute PD Test Eliminate the One–Hour Withstand Commissioning Test?

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SUMMARY

To achieve North American electrification and resilience goals, utilities are looking to underground more of the grid than ever before. Data presented in this paper indicates almost 40% of newly installed medium and high voltage cable systems have at least one substandard component. Experience shows that most failures are a result of issues existing at the time of installation [1]. Utilities are planning to use commissioning tests to ensure their investments are installed correctly and will perform reliably for many decades, but what is the current recommended CIGRE protocol, and can we do better? The one-hour AC withstand field tests for extruded insulation cable systems have been part of CIGRE working group recommendations for over twenty-five years. CIGRE Working Group 21.09 in 1997 published Electra 173, indicating an AC withstand test alone may not cause all defects to break down and offered the forward-thinking notion that partial discharge (PD) testing could provide a significant improvement in field testing [2]. A review of CIGRE work [2] [3] [4] [5] yielded several references indicating concerns about PD test effectiveness. In addition to CIGRE recommendations for PD testing, manufacturers' standards generally require PD testing to be performed during various cable system qualification test stages, and during cable system component quality control. However, these manufactures' standards typically specify a PD test lasting only 10 seconds to 60 seconds. This paper provides a cable system failure mechanism overview of extruded cables and establishes a foundational understanding of critical PD testing parameters such as sensitivity, magnitude, and inception voltage. In addition, the supposed link between AC overvoltage withstand/conditioning step and PD test effectiveness is critically reviewed. Cable system field testing data and case studies including both commissioning and aged cable system assessment are provided to substantiate the effectiveness of a factory-comparable PD test (Table I) performed in the field. The authors utilize published references, scientific review, and over twenty years of field and laboratory work experience including performance statistics from hundreds of thousands of field-tested cable systems to provide evidence that: 1) the long-standing PD measurement sensitivity and interpretation goals set by CIGRE have been met and 2) the effectiveness of on-site factory-comparable PD testing surpasses the need for the one-hour withstand test.

KEYWORDS

Partial Discharge (PD), cable test, withstand test, on-site test, field test, reliability, extruded dielectric cable, extruded dielectric behavior, best practices.

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INTRODUCTION

CIGRE has been at the forefront of cable system testing for decades and several publications provide a record of evolving recommendations based on industry experience. Twenty-five years ago, WG 21.09 endorsed a significant improvement to field testing in Electra 173 and recommended to avoid DC voltage testing extruded insulation cable systems in favor of AC voltage withstand testing [2] however, the working group stated their concern that "breakdown does not usually occur in the course of the short duration [60 minute] of the after-laying test"[2]. The publication offered foresight that "partial discharge measurements combined with an AC test could provide a significant improvement in onsite testing" and recommended PD testing experience "should be kept under review and [test recommendation] changes made as appropriate"[2]. Five years later, CIGRE TB 182 stated "PD field testing is a suitable tool to perform useful diagnostic testing," although the brochure highlighted the concern that "improvement of measurement sensitivity and interpretation technology are the most challenging short-term goals"[3]. In 2018, CIGRE TB 728, section "Guidelines for On-site PD Test Procedures," recommended a 60-minute withstand/conditioning step at elevated voltages[4]. Finally, in 2021, CIGRE TB 841 reinforced the purpose of a withstand as a test to "identify weak spots within the [cable] system" but added the caveat "for a healthy, properly installed cable system the withstand test, if kept within recommended voltage and time duration, will not pose a risk to the cable system" [5].

While the referenced CIGRE literature [2] [3] [4] [5] provides an impressive track record of recommendations, there are still a few implied unanswered questions:

1. Does current PD test technology address the measurement sensitivity and interpretation goals set forth by CIGRE 25 years ago?
2. CIGRE acknowledges defects can survive a 60 minute withstand test. Can PD tests detect these issues with sufficient confidence?
3. What if the cable system is improperly installed or is unhealthy as defined by CIGRE? How often do cable systems have improperly installed components and, in such a case, how should one avoid the life-cycle risks posed by a withstand test following the currently recommended voltage and time duration?

In addition to these questions, the authors have assembled a few commonly cited theories supporting the one hour withstand for AC cables, including: comparability to operational transients, fault conditions, and delay caused by an initiatory electron or dielectric heating effects. Can these theories be sufficiently addressed with current experience? Does the industry now have sufficient data to consider the next evolution in testing guidelines?

This paper shares experience gained by the authors over the last two decades and, in cases where overvoltage PD test methods have addressed CIGRE's 25-year-old goals of measurement sensitivity and interpretation, provides evidence indicating cable owners may forgo the one-hour withstand test with confidence.

DEFINING "UNHEALTY" CABLE SYSTEMS AND HOW THEY FAIL

In general, solid dielectric cable system insulation fails due to an erosion process associated with phenomena called partial discharge (PD). PD can arise from an extreme focus of electric stress, a lack of the appropriate insulation, or a combination of both [6]. A focus of electric stress, or stress enhancement, can be caused by issues such as accessory interface contamination, foreign objects, protrusion of the semiconducting layer, or concentration of moisture (e.g., water tree). Lack of appropriate insulation, or voids, can be caused by issues such as damaged semiconducting layer, overheating of the cable or accessory insulation, insulation cuts, the lack of accessory void filler or an incorrect accessory/cable interface dimension.

PD, and its associated erosion process at a defect site, is rarely active at steady state operating voltage (U_0). PD is initiated when localized electric stress overcomes the local dielectric strength. The voltage at which PD initiates is called the inception voltage (PDIV) [7]. PD activity extinguishes when the localized stress is sufficiently lowered. The voltage at which the PD extinguishes is called the extinction voltage (PDEV) [7]. Voltage transients; fast, short duration electrical transients, are the primary driver of PDIV and insulation failure. The sources of transients include circuit switching, restoration activities (breaker operations and fuse reclosures), fault location and withstand tests, momentary flashovers and grounds (momentary contacts with air insulated components), complete faults elsewhere in the system, sectionalizers, switching power supplies, switching capacitor banks, transformer tap changes, and especially, lightning. Transients reflect and resonate within the power system and can increase in magnitude exponentially [8]. Voltage transients typically occur in the microsecond to millisecond timeframe. This is more than enough time for PD to turn on, erode the insulation, and turn off. Successive transients can cause intermittent growth of an electrical tree (incipient fault channel) [8] [9]. As the electrical tree grows, the PDIV/PDEV continues to drop and eventually, the PDEV is less than or equal to the operating voltage. In this condition, the next transient greater than the PDIV can initiate PD and the associated erosion process usually does not stop until the cable system fails. In most cases, there is very little to no measurable conduction or dielectric loss until the insulation ruptures and a full carbonized fault channel exists.

The root causes of solid dielectric cable system failure mentioned previously all lead to detectable PD activity and given sufficient time and voltage stress, will lead to failure. For this reason, all cable and accessory factory quality control tests on solid dielectric cables and accessories measure PD, and field tests which can measure PD with the same level of confidence are advantageous.

PD IN QUALIFICATION TESTING AND IMPLICATIONS FOR FIELD TESTING

Discussions about PD testing often center on cable system manufacturer and installation quality control, however, it is also an integral part of qualification testing in prevailing international standards and specifications (Table I). PD as a qualification test is used to evaluate new materials and construction and a quality test during the manufacturing processes to establish baseline performance [5]. During a cable component qualification process, international standards such as IEC, IEEE, or ICEA typically include some form of extreme operating condition (AC/impulse voltage, current/temperature, mechanical) followed by a PD test to determine if there are any significant changes to the materials or cable system interfaces that would indicate substandard performance. The following table summarizes how PD tests are used by IEC, IEEE and ICEA and thus are the foundation for insulation quality control. In the standards listed below, PD tests typically require a 45Hz to 65Hz overvoltage application [10] for at least ten seconds but shorter than a minute while measuring the PD response of the component with a calibrated level of sensitivity. For the purposes of this paper the authors will refer to such a test [6] [11]as a factory-comparable PD test. PD tests achieving the standardized requirements of sensitivity and interpretation executed over the past two decades have provided a long-standing precedence of excellent cable system performance.

Table I: Partial Discharge Testing Parameters

Cable Component Standard	Parameters (50/60 Hz only)	PD Testing in Qualification Program
IEEE 48 Terminations IEEE 404 Joints	No PD >5 pC* up to 1.5 U_0	Baseline Performance After Initial ac Withstand and Impulse Tests After Cyclic-Aging (30 cycles) After Post Cyclic-Aging ac Withstand and Impulse Tests
IEEE 386 Separable Connectors	No PD >5 pC up to 1.3 U_0	Baseline Performance After Cyclic-Aging (10 cycles)
ICEA S-97-682 / 94-649 Cable 5 kV-46 kV	No PD >5 pC up to 4 U_0**	Baseline Performance After Cyclic-Aging (14 cycles) After 120-Day Accelerated Water Treeing Tests
ICEA S-108-720 Cable 69 kV-500 kV	No PD >5 pC up to 2 U_0	After Bending Procedure + Cyclic- Aging (20 cycles) + AC Withstand
IEC 60502 Cable & Accessories 1.2 kV-36 kV	No PD >10 pC up to 1.73 U_0	After Bending Test After Cyclic-Aging (20 cycles)
IEC 60840 Cable & Accessories >45 kV-170 kV IEC 62067 Cable & Accessories >170 kV-550 kV	No PD >10 pC up to 1.5 U_0***	

***picoCoulomb (pC); **4U_0 is an estimate, actually 200V/mil or 7.9 kV/mm**
*****IEC 60840/62067 Accessories have a 5 pC requirement**

Proper Measurement Sensitivity and Interpretation

Aside from onsite PD test set up and analysis described in [6] [11], one of the most common misinterpretations for PD measurement is the comparison of apparent charge or pC (picocoulomb) to defect severity. Picocoulomb magnitude presented in a test report from a calibrated measurement system is the size of a PD pulse apparent to testing equipment. The amount of charge released during a PD event is dependent on several factors but is strongly correlated with the defect size and shape [12]. Cable and accessory manufacturers' standards use pC magnitude as a measurement of test sensitivity or visibility (signal or defect size observable). However, pC magnitude is often misunderstood as a measurement of severity. Consider the defects in Figure 1 and Figure 2.

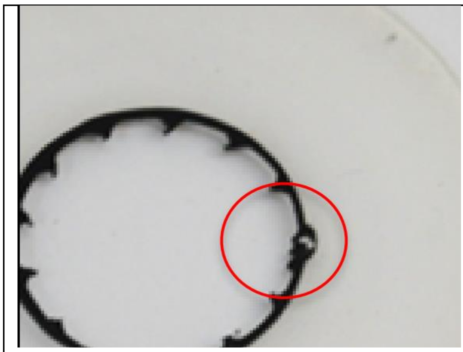

Figure 1: 9pC round void defect

Figure 2: 10pC sharp elec. tree defect

Both defects are insulation voids, air- or gas-filled gaps in insulation. An electrical tree is a special type of void associated with a growing carbonized fault channel. The rounded void defect and the electrical tree have similar pC magnitudes, yet their respective shapes and severity are significantly different. The electrical tree is something similar to a very sharp needle in the insulation whereas the round void is a blunt shape. The charge per unit area (energy density), at the electrical tree tip is much higher than the rounded void making the electrical tree defect more severe as it is likely to erode the remaining material faster. In addition to the defect shape, the surrounding material can make a difference in severity. For example, some rubber-based materials (e.g., EPR, EPDM, Silicone) are significantly more resistant to the erosion process associated with PD as compared to some plastics (e.g., XLPE, HMWPE). In summary, pC magnitude is a useful measure of test visibility but is not typically useful for measuring defect severity. Thus, small PD signals missed by the measurement system could easily account for complete insulation failures detected during the withstand test with no apparent precursor of PD activity.

Measurement Sensitivity

A PD test in the factory or the field must demonstrate effective background noise mitigation through the process of a sensitivity assessment [6] [11]. In order to claim detection sensitivity comparable with the standards listed in Table I, a calibrated pulse equal to the maximum allowable charge magnitude (e.g., 10pC per IEC 60502) must be able to travel from anywhere in the cable system and reach the PD measurement system with a signal to noise ratio (SNR) of 2 or greater. For reflectometry measurements, location sensitivity requires the same 10pC pulse to make a complete round trip in the cable system and still have a SNR of 2 or greater. The sensitivity assessment is a critical step in the test process. The authors have access to a database including over 250,000 factory-comparable PD tests in the field in 17 countries and 49 US states on cable systems rated 5kV to 500kV. Using the 95% of tests achieving 5pC to 10pC sensitivity, the data indicates that if a PD test cannot detect a pulse 50pC in magnitude, the test could be missing 60% of PD activity that would be evident in the cable if the test had a verifiable 5-10pC sensitivity. The same data set indicates a test with only 100pC sensitivity will overlook over 80% of PD activity that would be evident in the cable if the test had a verifiable 5-10pC sensitivity. This data reinforces the importance of using a field test comparable to the international standards such as IEC, IEEE and ICEA (Table I). Generally, without proper calibration, any test is likely to produce results which may be unknowingly blind to defects.

ONE-HOUR AC WITHSTAND TESTING RATIONALE

The ten-second overvoltage step for factory-comparable PD testing is well established for qualification testing and quality control. However, the field test recommendation for one-hour AC withstand/pre-conditioning testing remains despite better understanding of PD and cable system failure mechanisms. The reservations to forgo the legacy one-hour withstand in favor of a factory-comparable PD test solution is based on the belief that it somehow provides additional value that might be missed with a factory-comparable PD test solution alone. Engaging in numerous discussions over the last few decades with industry colleagues, the authors have recognized four common theories, beyond the reason of historical positive experience, when justifying continued use of the one-hour withstand.

The first two theories express concerns in the delay of PD ignition due to 1) availability of an initiatory electron, and 2) dielectric heating. These theories are seemingly supported by CIGRE TB 728 Figure 5.1., shown in Figure 3 below. The final two theories express concerns with operational performance in response to 3) typical voltage transients, and 4) delta system configured faults.

The Mistaken Assumption of PD Ignition Delay

CIGRE TB 728 Figure 5.1 [4] combined with the stated assertion that “This [TB 728 Figure 5.1 or Figure 3 below] emphasizes the necessity for the 60 minute withstand/conditioning at voltages higher than $1.5U_0$ prior to performing the PD test,” seems to support the PD ignition delay theory. From this data one could conclude detectable PD inception could take up to one hour of energization at $1.7U_0$, but the theory is based on flawed assumptions. The first is the assumption that a test performed yielding no detectable PD concludes no PD existed. The data provided by CIGRE TB 728 does not establish a baseline PD test sensitivity. This can create scenarios, as stated previously, where evaluations are unknowingly blind to defects. The other flaw to the one-hour delay theory stems from a misunderstanding that PD magnitude is a function of degradation and severity as opposed to a combination of factors, including defect geometry as previously described in the Proper Measurement Sensitivity and Interpretation section above. Since no test sensitivity data exists, there is no proof PD producing defects detected throughout the duration did not exist at time zero and thus, this graph cannot be used to justify continued use of the one-hour withstand.

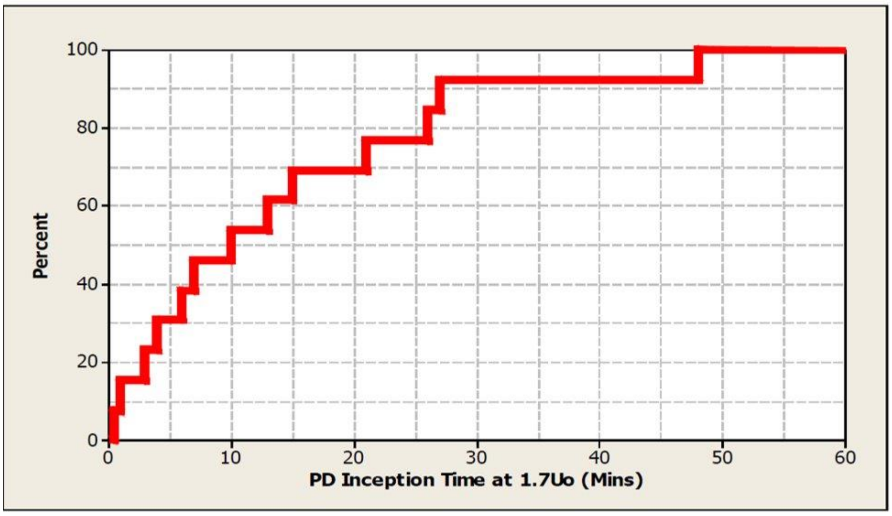

Figure 3: CIGRE TB 728 Figure 5.1
Flawed Graph: Percent of PD sites detected vs. Time at $1.7U_0$

Delay in PD Ignition Due to Initiatory Electron

One common theory for PD ignition delay is that a long withstand duration is required to assure the existence of an initiatory electron and the start of insulation deterioration [13]. This theory does not hold up to critical scientific review. According to Boggs [13], cosmic rays generate about 3 electrons/cm^3-s in air. For a 1 mm^3 cavity, the waiting time for a free electron would be in the range of 5 minutes. This is far shorter than a one-hour withstand and far longer than any power system transients. If a PD site cannot be activated during a transient in the microsecond or millisecond time frame, it will likely never activate in service. However, even this 5-minute theoretical limitation does not hold up in practice since materials are not perfectly devoid of free electrons as any existing carbonization (electrical treeing), conductive contamination, or neighboring semicon screen material provides a local source of free electrons. If localized stresses are sufficiently high due to elevated test voltages, free electrons can be generated from the insulating material directly, especially in voids. In addition, many standardized qualification PD tests for cable accessories, arguably the most vulnerable part of the cable system due to on-site workmanship, do not require a withstand test and specify an overvoltage duration of less than one minute (Table I). If PD tests with a duration less than one minute have been sufficient to determine the quality of solid dielectric accessories for multiple decades, it is a reasonable approach for on-site tests. Finally, if PD cannot be initiated by an overvoltage test lasting multiple seconds, the defect poses little to no risk to cable system performance as most transients only last micro- to milliseconds. Therefore, the initiatory electron theory is not a solid base to recommend the one-hour AC withstand test.

Delay in PD Ignition Due to Dielectric Heating

Another theory for the delay in PD ignition reasons the one-hour withstand provides sufficient duration for evaluating molecular-level dielectric heating. Molecular-level heating can be an issue with paper-insulated cable systems due to higher insulation conductivity and with HVDC cable systems due to space charge accumulation effects. However, AC systems have virtually no measurable dielectric heating effect during an AC one-hour withstand. For example, using the approximate dimensions of typical power cable design with a 2,000 mm^2 conductor in the 220kV - 230kV family, a simple model for temperature increase due to dielectric heating can be built [14].

The energy lost through the real resistive heating is:

$$(1) \qquad Q[Joules] = t\omega CV^2 \cdot tan\delta$$

where $t = time\ [s]$
$\omega = angular\ speed$
$C = capacitance\ [F]$
$V = electric\ potential\ [V]$

The equation for the joule heating of a given material is:

$$(2) \qquad Q\ [Joules[= m\Delta T C_p$$

where $m = mass\ [g]$
$\Delta T = change\ in\ temperature\ [\ ^oC]$
$C_p = material\ specific\ heat\ capacity\ [\frac{J}{g\ ^oC}]$

By setting the equations equal and solving for the change in temperature, ΔT, we reach a simple model for dielectric heating:

$$(3) \qquad \Delta T = \frac{\omega C V^2 \tan\delta}{m C_p} * t$$

Utilizing assumed values for XLPE of $tan\delta$ = 0.0003, ε_r = 2.3 to determine capacitance, C_p = 2.1 J / g^{o}C for specific heat capacity, and a density of 0.941 g / cm^3 to determine mass, a one-hour (3,600s test) at 2.5U_0 for 220kV-230kV cables would only expect to experience a temperature increase of approximately 1^{o}C. Factors affecting cable behavior, such as thermal expansion, are not significantly impacted by this small fluctuation of temperature, therefore dielectric heating is not a reasonable basis to recommend a one-hour withstand.

Voltage Transient Performance Comparison

With respect to operational performance, a common theory is that the withstand test evaluates the cable performance during transient overvoltage conditions. While the authors agree with the overvoltage principle, simple physics theory does not support a one-hour withstand comparison to transients. A typical power system transient duration is in the micro to millisecond range. If we assume that a cable system can see ten, 5ms, 1.7U_0 transients per day, a one-hour withstand would be the equivalent duration of over 100 years' worth of transients. The purpose of a commissioning test is to determine the reliability of the new asset, not to put the asset through a lifetime's worth of stress which could potentially damage insulation. Thus, the theory that a one-hour withstand simulates realistic voltage transient conditions without potentially harming the cable system is extreme on its premise and does not substantiate the one hour withstand test recommendation [6].

Test comparability to delta-configured system fault

Another theory commonly cited states withstand tests need to simulate a delta configured power system fault. In the case of a delta system, the failure of one phase causes the other two phases to rise up to 1.73U_0. If there is no partial discharge at 1.73U_0, then the stress on the remaining serviceable cable systems will not be detrimental. Thus, if a commissioning test is performed on a delta-configured cable system with a factory-comparable PD commissioning test in accordance with the appropriate standard in Table I, and is shown to be PD free, then this situation is not of concern. If the system has been operated in a manner that is routinely outside of normal design parameters such as extreme voltage or load, there is always a risk that new defects could be created. If an extreme event occurs, the system operator could easily request another PD test after the fault is repaired to assess the cable system's reliability degradation in comparison to applicable industry standards and repair accordingly. This process can eliminate the risk of consequential and unknown insulation damage due to an overvoltage during a fault. Since a PD test can negate the risks of insulation defects at 1.73U_0 during the commissioning test and after any extreme operational events, the specification of a one-hour AC withstand test is not necessary.

Ultimately, ensuring long-term reliability at the quality control stage is a matter of evaluating the insulation for the root cause of cable failure under reasonable conditions (voltage level and time) that will likely be experienced in-service. For example, in service, a cable system with adequate surge arresters will not likely see deterioration due to voltage above the level of protection. Additionally, by not pushing anomalies to complete failure as illustrated in Figures 4 and 5, which represent a typical

XLPE-insulation dielectric failure, defect sites can be preserved for further analysis as illustrated in Figure 6, aiding tremendously in root cause analysis activities and its associated knowledge gain.

Figure 4: Dielectric failure of XLPE cable with electrical puncture through outer semicon screen. Much or all of the root cause evidence is destroyed by the withstand test fault.

Figure 5: Hot-oil bath showing fault channel created by dielectric failure event. Specific root cause evidence most likely consumed by the withstand test fault.

Figure 6: 10 µm void in XLPE insulation at the inner semicon screen of an installed cable found using a factory-comparable PD commissioning test with better than 5pC sensitivity. A withstand test would have destroyed this evidence.

PROBABILITY OF IMPROPERLY INSTALLED CABLE SYSTEMS

As stated in the introduction, CIGRE TB 841 reinforces the purpose of a withstand test is to “identify weak spots within the [cable] system” with the caveat “for a healthy, properly installed cable system the withstand test, if kept within recommended voltage and time duration, will not pose a risk to the cable system” [5]. But what if a new cable system is improperly installed or is unhealthy as defined by a factory-comparable PD test? How often does this happen and how should one avoid the risks posed by a withstand test following currently recommended voltage and time duration? As previously stated, the authors have access to a database including over 250,000 factory-comparable PD tests in the field in 17 countries and 49 US states on cable systems rated 5kV to 500kV. These tests achieved calibrated test sensitivities in the range of 5pC to 10pC sensitivity in over 95% of cases and thus can be used as evidence indicating the likelihood of a substandard or improperly installed cable system.

The following list, compiled in a database over the past 16 years, provides the percent of new cable systems or components not passing a factory-comparable PD test:

1. 5kV- to 500kV cable systems 37.1%
2. HV and EHV cable systems only 45.1%
3. 5kV-500kV class components

    a. Terminations 3.0%
    b. Joints 4.4%
    c. Cables 1.6%
4. HV and EHV components only
    a. Terminations 13.8%
    b. Joints 3.1%
    c. Cables 1.1%

This data indicates there is a high likelihood of encountering an improperly installed cable system in the field and thus, according to CIGRE's recommendation [5], a withstand test may pose a life-cycle risk to the cable system. On this basis the authors conclude that where a factory-comparable PD test is possible, the one-hour withstand/condition system should be avoided.

Case Study 1 – Field Comparison
A utility was trying to decide whether to use a one hour withstand test or a factory-comparable PD test to commission new cable systems. The utility installed 2,771 km (1,722 miles) of cable systems. They used a factory-comparable PD test on 2,601 km (1,616 miles, population A) and a withstand test on 169 km (105 miles, population B). All detected defects were repaired and retested. Over a 4-year observation window the utility experienced two failures in population A in total. Over a 3-year observation window the utility experienced 8 failures in population B. Calculating failures/100km/year, population A (0.019 failures/100km/year) experienced 80 times better performance than population B (1.58 failures/100km/year). In conclusion, this data validates the concern brought forth by CIGRE TB 841 [5] that the one-hour withstand test can miss defects and that adding a PD test can improve the results. In addition, the data indicates that a factory-comparable PD test (using less than a one-minute overvoltage) is much more effective than a one-hour withstand and the one-hour conditioning step is not needed to achieve very high reliability.

Case Study 2 - Laboratory Comparison
In the Electric Power Research Institute report on the "Estimation of the Future Performance of Solid Dielectric Cable Accessories" in 2002 [15], withstand testing and PD testing were compared. Samples with substandard PD activity were extracted from the field and some were created in the laboratory. Samples had issues including a lack of void filler at the outer semicon layer cutback, a knife cut 30% through the cable insulation wall, semicon contamination wiped across the insulating surface, and a joint housing misplaced off center by a few centimeters. Using a factory-comparable PD test, all joints exhibited substandard performance. Voltage was applied exceeding the inception voltage of the defects to ensure continuous PD activity. The continuous PD activity was monitored during the withstand for 3 months with no failures. If only a one-hour withstand test (or even a three-month withstand test) had been performed, all of the cable samples would have passed with gross defects left to fail in service. This study once again reinforces CIGRE's concern that withstand tests can miss defects and yet clearly shows that a factory-comparable PD test confidently identified all the defects after a 10 second overvoltage. This case study also demonstrates that a factory-comparable PD test is sufficient to assure the reliability of field-aged cables without the use of a withstand conditioning step.

Case Study 3 - Aged Cable System Experience
A large utility in eastern USA had concerns with high failure rates on its aging underground system. The utility developed a program to maximize system reliability while limiting asset management costs by using a factory-comparable PD test to assess the cable condition and repair or replace sections or accessories as necessary. At the beginning of the program, the utility had over 25,000 km (16,000 miles) of in-service underground medium voltage power cable. A subset of this population (approximately 1,750 km (1,000 miles), or 7% of the total) was mostly installed before 1986 and failing at a significantly elevated rate of 20 failures/100 kilometers/year. For a few years, the utility systematically replaced cable systems based on legacy metrics of vintage, frequency of failure, age, and construction type until program costs increased by 200% and were beyond their budget of approximately 20 million dollars. The utility had the option to perform a withstand test with or without a PD test but based on previous experience with unexpected post-withstand test failures, they opted for

a factory-comparable PD test to guide the 8-year program. The factory-comparable PD test pinpointed defects which were repaired and retested to confirm standards compliance. The failure rate dropped by 98% (0.4 failures/100km/year) while leaving 94% of the 24,000 cable systems in the ground. This case study demonstrates that a factory-comparable PD test is sufficient to assure the reliability of field aged cable without the use of a withstand conditioning step.

Case Study 4 – 230kV Commissioning Test Experience
Xcel Energy is an American utility holding company based in Minneapolis, Minnesota, serving more than 3.7 million electric customers and 2.1 million natural gas customers in Minnesota, Michigan, Wisconsin, North Dakota, South Dakota, Colorado, Texas, and New Mexico. As part of a transmission resiliency upgrade project including two, 1.9km (1.2 mile), 4,000 kcmil 230 kV circuits, the utility chose to confirm correct installation by employing a factory-comparable PD test. The test was performed by applying a continuous 50/60Hz overvoltage a short overvoltage for less than 1 minute and measuring the PD performance from one end. The target overvoltage duration for the PD measurement was less than one minute. The initial profile assessment confirmed the performance of all components except for a substandard joint (>5pC at $1.5U_0$ per IEEE 404, U_0 = 133 kV) at 1,381 meters (4,533ft) from one end. The test was repeated for confirmation with identical results. Since there was no observable evidence of a defect on the outside of the joint, there was doubt on the part of some stakeholders and an additional voltage test was requested. After the joint failed under test, there was no longer doubt from any stakeholders.

A dissection confirmed the initial test results on the substandard joint. The installation of a shear bolt conductor connector was not properly completed, and a small burr created at one of threaded holes remained. When the pre-molded joint was slid into place, this burr sliced through the interior surface of the joint, resulting in substandard PD activity, electrical/carbon treeing, and subsequent failure. The cable ends at the joint were cleaned, sanded, and the repair joint was installed within 24 hours. The new 230 kV cable systems are initially operating in service at the 115kV level and will be for several years until the future upgrades are completed. Had this cable only been tested to the 115kV levels (such as during a U_0 test), no issues would have been detected and it most likely would have survived in service until energization at the full 230kV level, years after the warranty expired. Ultimately, the factory-comparable PD test saved Xcel Energy a future outage and enabled immediate root cause investigation and corrective actions for future installations without the need for a one-hour withstand condition step.

Case Study 5 – 69kV Commissioning Test Experience
Public Service Electric and Gas (PSE&G) is the largest investor-owned electric public utility in New Jersey, USA, servicing over 2.2 million electric customers. The utility identified the need to upgrade their aging infrastructure to accommodate future capacity needs, including an upgrade from 26kV to 69kV at their substations. The upgrades necessitated upgrading the cable systems and PSE&G chose a 69kV 1500kcmil copper conductor with 650mils of EPR insulation with heat shrink joints and cold shrink terminations.

PSE&G initially opted to conduct VLF (very low frequency (0.1Hz) withstand commissioning tests to confirm proper installation of the high voltage cable system, but shortly after the circuits were tested and energized, they began to experience joint failures. Dissection and root cause analysis of the failed joints revealed multiple workmanship issues, including insufficient heating of layers, improper cable preparation, improper application of conductive paint, and lack of insulation void filling grease.

Through this root cause analysis, the team identified the need for more in-depth onsite training and better tools. After these corrective actions PSE&G was still experiencing sporadic failures up to 5 years after a passing VLF withstand test. As a result, and by the recommendations of the accessory manufacturer, they opted to conduct a factory-comparable PD test to pinpoint defects and direct repair and training activities. The PD test specified included a continuous 50/60Hz overvoltage application with a 5pC sensitivity PD measurement for less than one minute. Results after testing over 300 cable systems revealed that nearly 5%, or 32 out of 717 joints, and many terminations did not meet minimum performance expectations (>5pC at $1.5U_0$ per IEEE 404 and IEEE 48, U_0 = 40 kV). After all defects identified by the factory-comparable PD tests were repaired, PSE&G has experienced no in-service failures during the 3-year program and has achieved this milestone without the need for a one-hour withstand.

DISCUSSION

Factory-comparable PD testing has been utilized as the foundation for extruded insulation cable system qualification and quality control. Field PD testing technology has evolved significantly over the last twenty-five years. The data presented, based on hundreds of thousands of field cable tests, demonstrates not only is 5 to 10pC sensitivity achievable in over 95% of tests, but also indicates the high probability of missing defects when this sensitivity level is not achieved. Additionally, field application of factory-comparable PD tests has enabled the localization of thousands of defects before failure and provided the industry a better understanding of failure mechanisms and severity interpretation beyond PD magnitude alone.

The data presented in CIGRE TB 728 Figure 5.1 [4] appears to support the theory a one-hour AC overvoltage pre-conditioning step prior to PD detection is necessary but the underlying assumption of sufficient test sensitivity is flawed [4]. The data only contains a few hundred data sets and has no declared assumptions related to the magnitude of measured PD, or the sensitivity of the measurement system during evaluation. The authors' experience presented in the data above suggests there is a high likelihood PD signals existed at time zero but were not detected due to insufficient background noise reduction. One possible explanation for the delay in detection is the potential for defect growth during the withstand, creating a larger void, and yielding a larger PD magnitude, as described by Boggs and Densley [12]. Establishing a baseline sensitivity measurement can provide a quantitative risk assessment of PD signal detectability. Based on the authors' experience, sensitivity in the 5pC to 10pC range provides a high degree of confidence that defects can be detected and eliminate the risk of existing defect growth or new defects caused by one hour withstand tests.

Based on the authors' experience most cable systems are less than 2 miles. For most cable systems less than 3 km (2 miles), a factory-comparable PD test can be applied directly by coupling a test system to one end. Longer cable system tests are still possible, but they are much more complex multi-sensor options and often result in a compromise in PD test sensitivity and confidence level. For examples of single ended, double ended, and multi-sensor test options and more in-depth capability comparisons, one can reference [16].

A factory-comparable PD test in the field has extended usefulness beyond after-laying tests. CIGRE TB 841 states that an AC overvoltage withstand test does not pose a risk to healthy and properly installed extruded insulation cable systems. The data presented shows that nearly 40% of new cable systems have at least one substandard component and thus presents a risk to long term performance after a passing withstand test alone. The case studies above have demonstrated how the factory-comparable PD test has successfully ensured the reliability of thousands of kilometers of new and aged cable systems observed over multiple years without the need for a 60-minute withstand/conditioning test.

CONCLUSION

The one-hour AC withstand test has long been established as a standard test method for extruded insulation cable systems. In 1997 CIGRE predicted the addition of a PD test to an AC withstand test would offer significant improvement to field testing. Over the past twenty-five years several CIGRE Working Groups have predicted that PD testing would evolve to be considered a value-added diagnostic to field testing. PD testing has always been a fundamental method to establish the health of extruded insulation cable systems in response to extreme conditions presented during factory qualification and quality control steps. As PD testing experience has increased, so has the understanding of cable system failure mechanisms. Theories have been critically reviewed and data presented indicating a factory-comparable PD test can detect defects with a high degree of confidence regardless of severity, without the need for a one-hour withstand test. Therefore, when achievable in the field, the factory-comparable PD test can provide significant benefit by ensuring reliability without the delays or the life-cycle risks caused by a one-hour withstand test.

BIBLIOGRAPHY

[1] M. Joseph, B. Lanz, R. Hummel and D. Byrne "Can Cables Last 100 Years?" (Jicable, Versailles, 2019).

[2] Working Group 21.09. "After Laying Tests On High Voltage Extruded Insulation Cable Systems" (ELECTRA, 1997).

[3] Working Group 21.16. "Partial Discharge Detection in Installed HV Extruded Cable Systems" (CIGRE 182, 2001).

[4] Working Group B1.28. "On-Site Partial Discharge Assessment of HV and EHV Cable Systems" (CIGRE 728, 2018).

[5] Working Group B1.38. "After Laying Tests on AC and DC Cable Systems with New Technologies" (CIGRE 841, 2021).

[6] A. Szatkowski and M. Mashikian "Medium Voltage Cable Defect Revealed by Off-line Partial Discharge Testing at Power Frequency" (IEEE Electrical Insulation Magazine, volume 22, number 4, July/August 2006).

[7] IEC 60270, High-Voltage Test Techniques – Partial Discharge Measurements, IEC, 2000.

[8] S. Boggs, J. Densely and J. Kuang "Mechanism for Conversion of Water Trees to Electrical Trees Under Impulse Conditions" (IEEE Transactions on Power Delivery, volume PD-13, issue 2, April 1998, pages 310-315).

[9] J. Densley "Ageing Mechanisms and Diagnostics for Power Cables – An Overview" (IEEE Electrical Insulation Magazine, volume 17, number 1, January/February 2001, pages 14-22).

[10] IEC 60885-3, Electrical Test Methods for Electric Cables - Part 3: Test Methods for Partial Discharge Measurements on Lengths of Extruded Power Cables, IEC, 2015.

[11] S. Jespers, M. Vanossi and B. Lanz "The Use of After-Installation Commissioning Tests to Assure MV Power Cable Systems Meet Manufacturers’ Standards" (Jicable, Versailles, June 2011).

[12] J. D. S. Boggs "Fundamentals of Partial Discharge in the Context of Field Cable Testing" (IEEE Electrical Insulation Magazine, September/October 2000, page 15).

[13] S. Boggs "The Case for Frequency Domain PD Testing" (IEEE Electrical Insulation Magazine volume 19 number 4 July/August 2003 pages 15-19).

[14] Q. Xiaoguang and S. Boggs "Thermal and Mechanical Properties of EPR and XLPE Cable Compounds" (IEEE Electrical Insulation Magazine, volume 22 number 3, May/June 2006, pages 19-24).

[15] EPRI, "Estimation of the Future Performance of Solid Dielectric Cable Accessories," (EPRI, Palo Alto, CA, 2002).

[16] B. Dhuciq, B. Lanz and S. Ziegler "The Impact of Transmission Cable System Construction and Design on Commissioning Test Options and Results" (Jicable, Versailles, June 2011).