THE IMPACT OF TRANSMISSION CABLE SYSTEM CONSTRUCTION AND DESIGN ON COMMISSIONING TEST OPTIONS AND RESULTS

Benjamin **LANZ,** IMCORP, Manchester, Connecticut, (USA), ben.lanz@imcorptech.com
Bernard **DHUICQ,** Silec Cable, Montereau, (France), bernard.dhuicq@sileccable.com
Steffen **ZIEGLER,** IMCORP, Manchester, Connecticut, (USA), steffen.ziegler@imcorptech.com

ABSTRACT

To achieve on-site partial discharge (PD) test measurements, which are comparable with factory PD tests, a thorough understanding of how high voltage (HV) and extra high voltage (EHV) cable system design will impact PD test measurements is necessary. Experience indicates that simple modifications early in the design process can greatly simplify the commissioning test process and support a cable test protocol that can provide performance assurance comparable to that provided by manufacturing quality control standards. Test results will be presented that will demonstrate what is achievable on a well designed cable system using an effective and efficient PD commissioning test technique.

KEYWORDS

High Voltage; Extra High Voltage; Cable System Design; Partial Discharge Test; Factory Test Standards; Sensitivity Assessment; Calibration

INTRODUCTION

This paper provides cable system owners with insight into the impact of transmission cable system construction and design on commissioning test options and results. To put the design considerations in context of the industry's experience and need for more effective method to commission HV and EHV cable systems, this paper provides a brief historical review, a discussion of standardized test requirements, an overview of common PD test methods, a review of three case studies, and finally a discussion of design modifications that can greatly simplify the commissioning test process. The final goal of the paper is to present a combination of design considerations and robust PD test specification requirements that can enable test results to readily be compared with factory test standards and provide a credible reliability assurance.

Brief Historical Overview

By many accounts [1-5], well designed and carefully built HV and EHV solid dielectric cable systems rated up to 550kV have been extremely reliable. Since the 1960s, one of the critical methods of assuring dielectric reliability in these cable systems has been a power frequency partial discharge (PD) test performed at a voltage greater than the operating stress. This PD test is used throughout the design and type testing process, and is used routinely on every reel of cable and prefabricated cable accessory prior to being shipped from the factory (See Table 1).

While the factory PD testing standards for cables and accessories have evolved since the 1960s, field test methods have been slow to catch up. Compared to the exacting requirements of the factory quality control tests, many of the early HV and EHV solid dielectric cable systems were energized with little or no additional electrical testing prior to energization. Thus, the authors believe the very high reliability achieved with these systems is not likely a function of the effectiveness of the commissioning test but rather a statement of the quality and diligence associated with the insulation products, shipping and handling, and installation workmanship.

Need for Effective Commissioning Tests

According to CIGRE Working Group B1.22 [6] there is a growing concern about installation workmanship of extruded high voltage cable systems. There are several market forces contributing to the reliability concerns including a general increasing trend in the volume of HV and EHV cable system projects, compressing project timelines, and a shortage of highly qualified technicians. One positive step to meet this market demand is the development of accessories which are easier to install. While the ease of accessory installation can accelerate technician training, compress a project's timeline and reduce costs, the construction of the accessory cannot compensate for poor cable preparation skills. In addition to working group B1.22, CIGRE has constituted Working Group B1.28 which has been tasked with the objective of documenting the technical feasibility and preparing recommendations for standardizing on-site PD tests. The authors' experience indicates that many cable system owners share the concern and interest acknowledged by these CIGRE work groups, and have expressed a need to specify a more meaningful commissioning test.

PD FACTORY TEST STANDARDS

To understand the impact of cable system construction and design on commissioning test options and results, it is necessary to review the basis of PD test standards and how they are used to determine the accuracy, validity, and comparability of PD tests. Standards writing organizations such as IEEE, IEC, ICEA and others have developed requirements for PD tests and pass/fail criteria on the basis of the following four generalized parameters:

1. Noise mitigation/sensitivity assessment
2. Apparent charge magnitude calibration
3. Voltage source frequency
4. PD test voltage level

Table 1 lists factory PD test requirements stipulated by some international standard organizations.

Example International Standard	Threshold*
IEEE 48 Terminations	No PD>5pC up to 1.5Uo
IEEE 404 Joints	No PD>3pC up to 1.5Uo
ICEA S-108-720 69 kV - 345 kV cable	No PD>5pC up to 2 Uo
IEC 60840 30kV to 150kV Cables & Acc.	No PD>10pC up to 1.5Uo
IEC 62067 >150kV to 550kV Cables & Acc.	No PD>10pC up to 1.5Uo

Table 1. Factory PD Test Standards
*Uo is operating voltage (line to ground).
Accessories (Acc.)
picoCoulomb (pC)

Noise Mitigation/Sensitivity Assessment

An effective PD test in the factory or the field must demonstrate effective background noise mitigation through the process of a sensitivity assessment. In order to claim detection sensitivity comparable with factory test standards in the field, a calibrated pulse equal to the maximum allowable charge magnitude (e.g. 10pC per IEC 62067) 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. 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 5pC sensitivity [7].

Apparent Charge Magnitude Calibration

As indicated by the standards listed in Table 1, all PD measurements are intended to assess charge activity, and thus, test results are required to be presented in a unit of charge. By definition, apparent charge is the charge measured at the terminal of the cable system. The apparent charge estimation must take into account the PD measurement system gain and the complex attenuation and dispersion experienced by a PD pulse originating from anywhere in the cable system. This process assures that the apparent magnitude of any PD activity can be displayed in reasonable pC values and the test results are comparable to those obtained according to manufacturers' test standards.

Frequency of Voltage Source

A continuous overvoltage stress needs to be applied with a power frequency voltage source (20 to 300Hz per IEC) for at least 10 seconds. If, for example, the frequency of the voltage source is changed from power frequency to 0.1Hz or to a voltage source which energizes the system with a DC voltage and creates a decaying oscillation, the inception voltage (turn-on threshold) of the PD activity can vary by over 100% [8]. The manufacturers' standards only support voltage sources which can supply continuous power frequency. Failing to follow these guidelines in the field can cause significant changes in the test results and void their comparability.

PD Test Voltage Level

An elevated voltage test is required by all of the manufacturers' standards. For example, IEC 62067 requires the cable system to be energized at power frequency to the test voltage of 1.75Uo for 10 seconds, and then lowered to 1.5Uo before measuring the cable system PD response. Without an external power frequency voltage source, a PD test can provide completely inaccurate measurements of PD inception (PDIV, turn-on) voltage or PD extinction (PDEV, turn-off) voltage [8]. Since standardized PD test pass/fail criteria are based on accurate PDIV and PDEV measurements, the use of a standardized power frequency voltage source to produce a continuous overvoltage is required for comparability to industry standards.

Field PD tests do not always achieve the factory test criteria, but in over 20,000 tests conducted in the field on high and extra high voltage cable systems, more than 95% of the tests achieved better than 5pC sensitivity, and were able to achieve voltage levels of at least 1.75Uo. Although, ideally, a 5 to 10pC field test sensitivity should be specified, the sensitivity which is actually achieved must be documented in order to allow for a reasonable assessment of the PD test reliability. The application of factory PD test standards in the field can be summarized as the "application of a continuous power frequency overvoltage while measuring the cable system's PD response with better than 10pC sensitivity per IEC 62067 (3 or 5pC for IEEE & ICEA standards)."

TWO COMMON FIELD PD TEST METHODS

The PD test methods used in the following case studies can be categorized into two generalized approaches. These approaches are: (a) a segmented test and (b) a terminal test [9]. As the case studies point out, the design of the cable system dictates the type of test which can be used and the relative application efficiency. The following discussion briefly describes the methods and reviews the major tradeoffs of each approach. Table 2 summarizes the comparison.

Segmented Test

Typically, the segmented (segment is the system between two accessories) test approach requires a sensor to be placed at each accessory location. During the overvoltage application, a technician with data recording instrumentation travels to each sensor and records signals that are analyzed to detect PD activity. Presently, the authors are not aware of any effective sensitivity assessment method for a segmented test on a fully assembled cable. Therefore, a sensitivity assessment needs to be performed on one or more segments prior to completing the jointing of the cable system. All other segments are assumed to have a comparable sensitivity. The segmented test can only measure PD activity in one segment of the cable system (unless distributed sensors are networked by means of a wide bandwidth communication system and monitored via a remote PD measurement system). For example, if a PD producing defect is far away from the segment under observation, the segmented test would be blind to it. This scenario may lead to unexpected test failures outside of the monitored segment.

Terminal Test

A terminal test typically uses capacitive sensors that are directly coupled to one or both terminations. The authors' experience indicates that in a well designed and implemented cable system, a terminal test should be able to achieve 5 to 10pC sensitivity on a 3 to 4 kilometer cable with a single sensor, and on a 6 to 8 kilometer cable with two sensors. Since the terminal test has a visibility over the entire cable system, only one short voltage application is needed. The test's visibility allows for a well documented sensitivity assessment and magnitude calibration. Generally, where the issue of shield interruption and signal attenuation is adequately addressed in the design process, the terminal test approach can readily provide accurate and reliable PD test results that are comparable to factory standards.

Parameter	Segmented Test	Terminal Test
Sensitivity assessment	Test one segment then assume typical	Entire cable system – no assumption
Location capability	No, detection within segment only	Yes, meter by meter profile
Visibility	1 segment / sensor	Entire cable system
Observation Time	Measurements at ea. Accessory at 1 voltage	Measurements during withstand, ramp up & down
PD parameters measured	Detection, PD mag. & Phase pattern	Detection, Location APDIV/EV, ApC Mag. & Phase pattern

Table 2. Test Method Comparison
Apparent pC (ApC)
Apparent inception voltage /extinction voltage (APDIV/EV)

CASE STUDIES

The following case studies describe the application of the PD test requirements discussed above in the context of three different cable system design configurations. These design configurations were specifically chosen as case studies for this paper to provide variety to the application discussion. The first two case studies involve cable systems designed by the manufacturer represented by one of the authors. The third case study involves another anonymous cable manufacturer.

Parameter	System A	System B	System C
Voltage Class	230 kV	230 kV	400 kV
Insulation	23,4 mm XLPE	23,4 mm XLPE	27,9 mm XLPE
Conductor	1773 mm^2 Cu	1773 mm^2 Cu	800 mm^2 Al
Metal Shield	Al wires & LA tape	Al wires & LA tape	Cu wires & LA Al tape
Length	9371 m	1153 m	86 m
Termination	Open air, Oil filled	Open air, Oil filed	Open air, Oil filled & GIS
Joint	16 pre-molded EPDM with shield interrupt	1 pre-molded EPDM no shield interrupt	No joints
Gnd. Scheme	Single point bonding at each joint	Single point bonding at one termination	Single point bonding at one termination
Recommendation	Segmented test	Terminal test	Terminal test

Table 3. PD Test Method Comparison
Longitudinally applied (LA)

Case Study I, System A

The design of System A included 16 joints with shield interrupts. In general, a shield interrupt acts as a high impedance to PD pulses propagating within the cable system and causes most of the signal energy to be reflected. The cable system did not have provisions to by-pass the shield interrupts. Thus, a segmented PD test using a specially designed high frequency current transformer (HFCT) to measure PD activity at the joint locations was selected. This type of test is capable of detecting PD activity, and providing an accurate phase resolved diagram, but is not likely to locate the PD activity.

In order to assess how PD pulses interact with the interrupts and determine the level of sensitivity that could be expected during the commissioning test, a preliminary assessment was performed before the cable system installation was complete. To accomplish this task, a calibrated 10pC signal was injected into a yet-to-be-jointed cable at a neighboring manhole approximately 600 meters away. Once the background noise was mitigated, a single 10pC pulse could be readily detected on either side of the joint interrupt. Assuming that the cable system construction was consistent throughout the system and the HFCTs could be placed at the same location at other joints, these measurements indicated that the sensitivity of the PD test would likely be better than 10pC for signals originating from within the cable system from either side of the joint out to about 600 meters. In addition, calibrated pulses of known magnitude were injected at the termination point (over 4 shield interrupts/cable segments away from the measurement point). This procedure verified that signals with a magnitude of 100pC or larger could potentially couple in from other cable segments, joints or terminations and potentially cause the test to mistakenly attribute PD to the monitored segment. Thus additional efforts would be necessary to isolate the source in the event that PD activity was detected.

The cable system owner's specification required the commission test to include a traditional one-hour withstand at 1.7Uo. Since the preliminary sensitivity assessment indicated that each HFCT was likely to achieve better than 10pC sensitivity over two adjacent cable segments, PD response measurements were accelerated by taking measurements on one joint, which effectively covered two segments and three joints. All of the cable system passed the withstand voltage test and no PD activity was detected at any of the joint locations indicating that the system passed the requirements of IEC 62067 factory test. IEC 62067 requires that the cable system have less than 10pC of PD activity from any location at 1.5Uo.

Figure 1. Case I, Power Frequency Voltage Source Setup

Case Study II, System B

The design of System B included two open-air terminations and one joint with no mid-span shield interrupt. This system was ideally configured for a single ended termination test using a capacitive sensor directly coupled to the termination. This type of test is capable of detecting and locating PD activity, and providing accurate location specific phase resolved information during the ramp up and ramp down and the withstand portions of the overvoltage.

In order to assess the PD test sensitivity and signal magnitude calibration, a preliminary assessment was made before the cable system installation was complete. To accomplish this task, a calibrated 5pC signal was injected into one termination while measuring the system response at the other termination over one kilometer away. Once the background noise was mitigated, the sensitivity assessment process, as described above, indicated that a single 5pC pulse could be detected and located. This process verified that the test results would most likely be comparable to the factory test as per standard IEC 62067.

As with Case Study I, the owner of System B specified that the commissioning test include a traditional one-hour withstand test at 1.7Uo. The sensitivity assessment, including the completed cable system and the test setup, indicated that the single ended terminal test could detect and locate PD activity from anywhere in the cable system with better than 5pC sensitivity. PD was detected at the near end terminations on A & B phases. The phase resolved PD pattern at 1.5Uo was typical of corona external to the termination. The termination clearances were inspected and a few sharp metal points from neighboring substation structures were mitigated with corona rings. The PD test was repeated and the corona did not appear until 1.7Uo, which indicated that the PD activity was accurately located and characterized by the test. On C-phase, PD activity appeared at the far end termination at approximately Uo. While nothing unusual was spotted from the ground, upon closer inspection of the far end C phase termination, a small postage stamp sized (approximately 2x3cm) inventory identification tag was found on a corona ring (Figure 2). Once the tag was removed, the C phase cable system exhibited no PD activity up to 1.7Uo. Thus, the field test confirmed the cable compliance with the routine IEC 62067 PD performance requirements, which stipulate that any PD activity in the cable system is not to exceed 10pC at 1.5Uo.

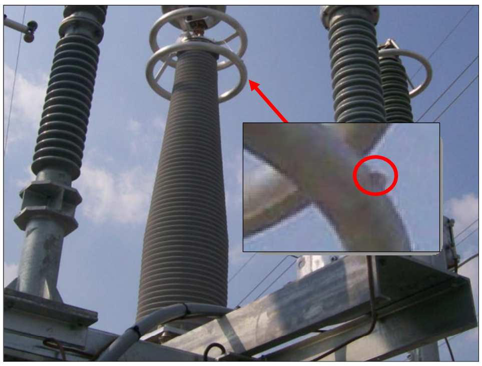

Figure 2. Postage Stamp Sized Identification Tag Source of Corona at Uo

Case Study III, System C

The design of System C included open-air and GIS (gas insulated) terminations. The short length of this 86 meter system was ideally configured for a single ended termination test using a capacitive sensor directly coupled to one termination. As in the previous two case studies, a preliminary PD test sensitivity and signal magnitude calibration assessment was performed before mobilizing to test the cable system. Using the same procedure as with Case II, the PD test sensitivity achieved ranged from better than 5pC to 10 -20pC. The range of sensitivity was most likely due to the different lengths of GIS bus connected to the cable system. Ideally, GIS terminations should be removed from the GIS bus and installed in a pressurized test fixture. While the authors have some experience with testing cable systems with GIS test fixtures, they are not always practical. In this case study, the test fixture was not available and thus the PD measurements had to cope with high signal attenuation and lower sensitivity.

The original commissioning test requirements for this cable system included a DC jacket test, a DC insulation resistance test and a no-load energization for 24 hours (“soak test”). None of these tests exhibited anything unusual and the cable system was energized. One phase experienced a cable insulation failure 3 weeks after energization. The failure was determined to be caused by an insulation defect. The owner of the cable system requested that a PD test comparable to the IEC 62067 factory test be performed after the repair to assure performance. The owner also requested that the cables be tested with a traditional one-hour withstand test at approximately 1.3Uo. The withstand test was performed and the cable systems passed with no failures.

There were two types of PD tests performed by separate parties. Vendor A used a HFCT clamped around the grounding lead of the termination and Vendor B used a single ended termination test using a capacitive sensor directly coupled to the open-air termination. Vendor B also installed a HFCT, with a bandwidth similar to that of Vendor A, on the termination ground lead. Vendor B performed a sensitivity assessment on the HFCT setup and the sensitivity was determined to be in the range of 100 to 200pC. PD measurements were recorded on the ramp up at 1.0, 1.1, 1.2, and 1.3 Uo, and on the ramp down, at 1.2 and 1.0Uo. Vendor A detected a phase resolved pattern of PD activity that appeared to suggest corona coming from outside the cable system. Vendor B detected nothing but noise with the HFCT sensor. However, using the directly coupled capacitive sensor (terminal test), Vendor B detected a PD site in the cable insulation at 1.3Uo. The PD site was located 64 meters from the open-air termination in the cable insulation. The PD activity at this site had an average pC magnitude of approximately 30pC. According to the factory test requirements of IEC 62067, cable systems are required to have less than 10pC of PD activity at 1.5Uo. On this basis, the cable system was recommended for repair and was replaced.

DISCUSSION

The case studies above provide an opportunity to consider the impact of transmission cable system construction and design on commission test options and results. On the basis of the authors’ experience and these case studies, the following section lists some features of the cable system designs and test techniques and describes how the test results can be impacted. This information is provided to enable cable owners to consider a cable system design and test specification that will maximize test efficiency, assure factory test performance comparability, and assure the reliability of their cable systems.

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Type of Metallic Shielding

A combination of longitudinally applied aluminum sheath and concentric wires provide excellent PD signal propagation characteristics. In Case Study II, a 5pC pulse was resolvable with a signal to noise ratio of greater than 2 after traveling the round trip distance of over 2.2 kilometers. As previously mentioned, the authors' experience indicates that in a well designed and implemented cable system, a terminal test should be able to achieve 5 to 10pC sensitivity on a 3 to 4 kilometer cable with a single sensor, and on a 6 to 8 kilometer cable with two sensors. This type of shielding enables relatively long cable system lengths to be tested by means of the preferred terminal test method and obtain factory level sensitivity.

Construction of Joints

The joints used in the first two case studies have significant capacitive signal coupling across the built-in shield interrupt. This provides significantly better high frequency coupling across interrupts than other joint designs. Case Study I demonstrates that this is an advantage, since the HFCT could detect PD coming from either direction with better than 10pC sensitivity. In a practical sense, the joint construction enabled the number of joints that needed to be accessed during the test to be cut in half. The reduction in test points provided significant time and labor savings. Additionally, joints with good signal transfer characteristics enabled longer lengths to be tested with the preferred single-ended terminal test and obtain factory level sensitivity.

Accessories with Built-in Sensors

None of the accessories included in the above case studies included built-in sensors. Built-in sensors can simplify the segmented PD test method but are not necessary for the terminal test method. If built-in sensors are used they need to be built so they do not affect the reliability of normal operation. They also need to have sufficient bandwidth and coupling efficiency so accurate sensitivity assessment and apparent charge magnitude calibration tests can be performed.

Shield Interrupts

Shield interrupts are common in EHV cable system designs. If the interrupts are left in place, the PD method is generally limited to the segmented PD test. To perform the preferred single ended terminal test, shield interrupts must be temporarily by-passed to allow the high frequency of the PD signal to propagate through the joint with minimal reflection and signal attenuation. If jumpers for the shield interrupts are considered early in the design and the project planning, provisions can be made to simplify the jumper connection. The installation of the jumpers might be possible at the same time as the joint installation with little extra effort. This will accelerate the testing process and enable the system to be tested with the preferred single-ended terminal test method and achieve test results compatible with factory test standards. As a secondary benefit, if the shield interrupts are by-passed and an insulation failure occurs during the overvoltage test, a reflectometry method can be used to quickly locate the fault.

Substation Structures

In Case II the substation structures were designed and supplied by the owner. Some of these structures, which were in close proximity to the open-air terminations, had sharp corners. The sharp corners created challenges and delays in the testing process as clearance adjustments needed to be made in order to mitigate external corona PD activity. Working with the owner early on in the project can assure that good high voltage engineering principles are applied to all structures near open-air terminations. This will not only accelerate the testing process, it will assure that high stress points are eliminated from around the open-air terminations and assure reliable performance.

GIS components

GIS components provide many design advantages but they can provide some challenges to performing effective PD testing on the associated cable system. In Case Study III, the GIS terminations were already connected to the GIS bus. As previously mentioned, this configuration caused challenges for the PD test. Fortunately, there was a grounding/test point and a GIS disconnect switch a few meters away from the cable terminations. The grounding point was used to inject calibration signals and the disconnect switch allowed for the cable system to be energized with a minimum amount of GIS bus connected. Prior to the cable system test, a separate field test demonstrated that the GIS disconnect and bus had less than 2pC of PD at 500kVAC. This provided assurance that the GIS system would not introduce PD signals into the cable system during the off-line PD test. While the ground point and disconnect switch enabled the test to proceed, this design negatively impacted the PD test results. The sensitivity of the test would have likely been better than 5pC, but in some cases the test only achieved 10 to 20pC sensitivity. As mentioned before, the reason for the range of sensitivity was most likely due to the different lengths of GIS bus connected to the cable system. Ideally, GIS terminations should be removed from the GIS bus and installed in a pressurized test fixture. This would assure that the GIS bus will not impact the PD test results.

Calibration and Sensitivity Assessment

Throughout this paper, calibration and sensitivity assessment tests are referenced repeatedly as one of the critical steps in determining the impact that a particular cable system design will have on the PD test results and their comparability to standardized factory tests. The high frequency current transformer (HFCT) used in Case Study III only achieved the very poor sensitivity of 100 to 200pC, which according to [7] means, there could be over an 80% likelihood of missing PD activity in the cable that would be evident if the test had 5pC sensitivity. Thus using a HFCT at the termination with this particular design is not useful. Conversely, a terminal PD test demonstrated the ability to achieve better than 10pC sensitivity, which meets the requirements of IEC 62067, and was instrumental in detecting the defect in the cable insulation.

Terminal Test vs. HFCT

While a terminal test requires more initial equipment set up time than a HFCT and is typically limited to cable shorter systems with by-passed shield interruptions, there are several advantages regarding test sensitivity,

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overvoltage duration, and comparability to factory PD test standards. As mentioned above, the sensitivity of a terminal test can be more than 10 times better than an HFCT based test. Since a terminal test can monitor the entire cable system with a documented 10pC sensitivity during the overvoltage sequence, cable owners can take advantage of the IEC 62067 factory test standard which does not require an extended withstand time to establish the absence or presence of substandard PD activity (less than 10 seconds is required). For example, the substandard PD activity located in the cable insulation in Case III required less than one minute of voltage application to record the PD response data for the entire cable system at 1.3Uo. After recording the data on such a terminal test, the voltage can be turned off. Shortening the overvoltage time minimizes the risk of a test failure, and perhaps more importantly, minimizes the risk to test technicians who commonly need to take PD measurements at each accessory when implementing the HFCT test method.

CONCLUSION

The case studies presented in this paper demonstrate that PD test measurements made in the field can be comparable with factory PD test on a variety of HV and EHV cable system designs and installation configurations. The following is a bulleted list of summarizing conclusions

- Cable system owners are concerned about the quality of cable system workmanship and need to be able to specify an effective commissioning test.
- Traditional jacket or DC resistance test are not likely to detect many significant insulation defects.
- Traditional withstand tests at operating voltage (Uo) are not likely to detect (fail) significant defects
- Traditional overvoltage withstand tests are not likely to detect (fail) all incipient defects/faults.
- Momentary PD tests performed at the operating voltage are not likely to detect all significant defects
- A directly coupled capacitive sensor can achieve over 10 times the sensitivity of an HFCT configured on the bonding lead of a termination.
- Some cable system designs enhance test options while others limit the capability and increase time and effort (thus cost and risk).
- Planning for a temporary shield interrupt by-pass enables terminal testing of longer cable systems.
- Terminal tests with directly coupled capacitive sensors are preferred to segmented test using HFCTs as they can provide visibility over the entire cable system, shorten withstand times, and provide documented sensitivity assessment.
- A continuous power frequency (20–300Hz) overvoltage is necessary in order for a test to be comparable to factory standards. An overvoltage equal to 1.5Uo is required IEC 62067. However, in some cases 1.25Uo may be all that is practical.
- A sensitivity assessment is a critical step in determining the impact that a particular cable system design will have on the PD test results and their comparability to standardized factory tests.

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