Commissioning Tests to Assure MV Power Cable Systems meet IEC/IEEE standards

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Abstract - Many common solid-dielectric Medium Voltage cable system commissioning tests are not comparable with factory tests and provide little or no certainty of future performance. One of the most effective dielectric tests performed in the factory and the field on solid-dielectric cable system components is the off-line 50/60Hz Partial Discharge (PD) test. Data collected over the last two decades supported by test experience on over 200,000 cable system tests will demonstrate the significant improvement in cable system reliability performance that can be achieved using this approach in the field.

Index Terms — MV cable, commissioning testing, Partial Discharge, withstand

I. INTRODUCTION

Petrochemical facilities need a safe and reliable cable system infrastructure. Unplanned outages and failing cables involving a flashover can lead to a huge loss of revenue or even catastrophic incidences, depending on the location of such an event in a plant. To assure cable system reliability, commissioning tests are typically conducted after the installation of new components. The industry offers a wide range of tests that can be performed. Field testing guides give some direction on how to use these test systems. However, neither the manufacturer of test equipment nor the authors of field guides provide proper certainty on future system performance. Often it is described how to handle the equipment and how to interpret some of the results. Proper guidance on counter-measures, in cases where results are flawed, are not given and future risks for the cable systems are not discussed.

The “gold standard” on insulation integrity testing for Medium Voltage (MV) power cables and accessories is the off-line 50/60Hz Partial Discharge (PD) test. IEC and IEEE standards demand to perform these off-line 50/60Hz PD tests as factory tests on each cable. Usually, these tests are performed under advantageous laboratory conditions such as shielded rooms / Faraday cages and special power sources with low noise..

Ideally, this quality control test should be performed in the field as well. An off-line 50/60Hz PD test reveals not only issues of the cable insulation and accessories, but also shows possible workmanship issues during installation. Specific test parameters must be met in order to assure that the field test results are comparable to manufacturers’ acceptance standards. Meeting these parameters in the field was difficult to impossible for a long time. Evolving computer science, artificial intelligence and advanced adaptable software algorithms allow the industry to meet these parameters in field now.

This paper will provide examples of applying factory comparable 50/60Hz PD standardized tests the field. Case studies will provide examples of the types of defects which a 50/60Hz PD test, according to manufacturers IEC/IEEE standards, pinpoints in the field. Many of which would be, or were missed by, other types of commissioning tests.

II. GENERAL INFORMATION

The vast majority of power cable systems installed today are insulated with extruded materials that belong to 2 main classes: (a) polyolefins – encompassing polyethylene (PE), cross-linked polyethylene (XLPE), and tree-retardant cross-linked polyethylene (TR-XLPE), and (b) ethylene-propylene rubber (EPR).

In the petrochemical industry, most cable systems are installed underground or in above ground cable trays. Experience of over 200,000 cable tests indicates that cable system deterioration, caused either by operational stresses, manufacturing defects, or workmanship issues during installation, manifests itself through discrete defects. Defects in installed solid dielectric cable systems initiate a deterioration process associated with PD. This failure mechanism causes the process of insulation erosion, beginning with a small part of the insulation only. Over time the heat of PD, 5000°C-7000°C, erodes the insulation further and further, often resulting in a full flashover and/or destruction of the full insulation.

Cable defects uncovered during commissioning tests include voids, protrusions, delaminations, and physical damage. Some examples of workmanship issues with accessories are poor cable preparation involving nicks, cuts, dimensional and alignment errors, poor void filler application, and contamination. 50/60 Hz PD commissioning testing to assure MV power cable systems meet IEC/IEEE standards and its importance to assuring the reliability of critical power cable systems will be thoroughly discussed in the following sections of this paper.

III. CABLE TESTING IN THE PAST

In the beginning and middle of the last century, most cables were paper insulated lead covered (PILC) cables. Most of these cables failed due to localized increase of insulation conductivity, either caused by a lack of oil fill with the presence of air, yielding carbonized paper tapes or the presence of water leading to ionic conduction. For such cables, a direct current (DC) high potential withstand test (DC HIPOT) for a defined duration, was a great tool because it is highly sensitive to conductivity. A DC HIPOT test was required and performed in the factory on new PILC cables. This led to the motivation to repeat the same test in the field as well.

In the 1960s the first solid dielectric cables were introduced. Cable manufactures learned that the primary failure mechanism of this type of insulated cable was associated with PD and not conduction. The factory PD test (back in the 1960s called “corona test”), was able to detect PD activity in cables and accessories. It involved expensive equipment such as oscilloscopes and required laboratories with an electromagnetically shielded room. Over the years, cable manufacturers realized, that the DC HIPOT is an ineffective test for solid dielectric system components. The electric field grading capabilities of most accessories rely on a capacitive field grading under alternating current (AC) loads which behaves very differently under DC conditions. Thus, DC HIPOT testing has been removed as a requirement from some of the factory standards for over 20 years now.

The complexities of the PD test in the field led the industry to continue to use the most widely available and recognized commissioning test (the DC HIPOT). As DC voltage does not cause PD that leads to failures in defective extruded insulation during the commissioning withstand test , very low frequency (VLF) or 0.1Hz AC test was introduced in the mid-1980s. Unlike DC voltage, VLF voltage is able to produce sustained PD activity while injecting significantly lower amounts of space charge when compared to DC. Many standards suggest a testing time at an elevated voltage for 30 minutes or longer. The intention of this overvoltage test is push existing and significant cable issues and defects to failure. The downside of this approach is that without the proper sensitive diagnostic measurement equipment accompanying such tests, VLF can trigger failure mechanisms that will erode the insulation without resulting in an immediate full dielectric failure, potentially leading to subsequent failures in service.

In the mid-1990s, the first generation of digital signal processing equipment was introduced to field testing. Most of these tried to solve the background noise dilemma, in absence of a shielded room, associated with PD testing in the field. Different companies developed different solutions to reduce background noise to offer sufficient sensitivities to on-site tests. The struggle with on-site background noise and the disadvantages of VLF led to the development of a PD test technology that can provide field test results that are comparable with the cable manufacturers’ standardized factory quality control tests. To achieve this, an off-line 50/60 Hz voltage source is used, together with PD diagnostics equipment, which has been used over the past 25 years. This has evolved into a robust condition assessment equipment for commissioning tests and predictive diagnostics solution for power cable systems.

IV. OFFLINE 50/60HZ TESTING

Off-line 50/60 Hz partial discharge [1] diagnostic tests offer a major advantage over traditional withstand tests. It enables the user to perform non-destructive cable assessments while detecting partial discharge, pinpointing the defect location, and providing the details necessary to take precise repair action without destroying the cable.

Cables are subjected to overvoltages caused by switching, lightning and other transient events. Cable systems need to endure thousands of such events over their lifetime. Thus, it is important such transients do not trigger PD. PD triggered by transients will erode the insulation during each event, until the so called partial discharge inception voltage (PDIV, turn-on voltage) is lower than the operating voltage. Once PDs are occurring at the nominal operating voltage of a cable, it is only a matter of time until the cables fail in service.

Therefore, the IEC and IEEE standards demand to test the cable systems with an elevated voltage, well above the operating voltage to ensure there is conservative margin. Different standards from around the world request precise voltage levels for cables and the used accessories, such as end-terminations and joints. The table below gives an overview of the test requirements for IEC and IEEE.

TABLE I

Standard	Test Frequency	Test Sensitivity	Voltage Level
Terminations			
IEC 60502-4	50/60Hz	≤ 10pC	≤ 1.73U_o
IEEE 48	50/60Hz	≤ 5pC	≤ 1.5U_o
Joints			
IEC 60502-4	50/60Hz	≤ 10pC	≤ 1.73U_o
IEEE 404	50/60Hz	≤ 5pC	≤ 1.5U_o
Separable Connectors			
IEC 60502-4	50/60Hz	≤ 10pC	≤ 1.73U_o
IEEE 386	50/60Hz	≤ 5pC	≤ 1.3U_o
Medium Voltage Cables (≤ 36kV)			
IEC 60502-2	50/60Hz	≤ 10pC	≤ 1.73U_o
ANSIICEA S97/94-682/649	50/60Hz	≤ 5pC	≤ 4.0U_o

V. STANDARDIZED PD TEST REQUIREMENTS

Standards writing organizations such as IEC, IEEE, ICEA and others have developed requirements for factory PD tests and pass/fail criteria on the basis of the following four generalized parameters:

1. sensitivity assessment / background noise reduction of the test equipment
2. apparent charge magnitude calibration
3. voltage source frequency
4. PD test voltage level.

Sensitivity Assessment / Background Noise Reduction

PD tests, according to the standards, must demonstrate effective background noise reduction through the process of a sensitivity assessment. To ensure all possible PD pulses can be detected in a cable system, a calibrated pulse must be injected anywhere in the cable and must be detectable with the testing equipment. Due to the lowpass characteristic of the cable and the signal dampening process, the injection point usually is chosen to be the far end of the cable. By doing so, it can be assured, that even pulses from the far end can be detected properly.

IEC 60502 demands that the calibration pulse must be equal to the maximum allowable charge of 10pC. Furthermore, the signal to noise ratio SNR (calibration pulse to background noise) shall be 2 or greater. This concludes that the background noise shall not be bigger than 5pC.

This sensitivity assessment process allows the specifying engineer to assure that there is no PD activity above the allowable charge (IEC 60502: ≤10pC). In order to localize a possible PD in the cable, the process of reflectometry is used. In such a process, the original pulse from anywhere in the cable and its reflection from the far end of the cable must be detectable. To make certain all PD above the allowed value can be localized, a 10pC calibration pulse must be able to do a full round trip, travel from the near end of the cable to the far end of the cable and back again. Still, the SNR should be equal or greater than 2.

Such sensitivity assessment is a crucial step in the test process. If a PD test cannot detect a signal of 50pC in magnitude, the test could be missing 60% of PD activity in the cable when compared to a test with 5pC sensitivity [2].

Apparent Charge Magnitude Calibration

All calibration and PD signals must be presented in a unit of charge, as required in the standards listed in Table 1. Due to losses, attenuation and dispersion in the cable system, the real charge of a PD pulse cannot be determined. Therefore, the term "apparent charge" was introduced. It describes the measurable charge at the terminals of the measurement system. Injecting a known calibration pulse anywhere in the cable and recording it at the intended test measurement point, allows the PD testing system to display all results in reasonable pC values. This is crucial to obtain test results that are comparable with manufactures' standards.

Frequency of Voltage Source

To perform a PD test, the cable under test must be excited with an overvoltage at 50/60Hz, as required in the IEC and IEEE standards. If a voltage waveform other than 50/60Hz is used, e.g. 0.1Hz or a system that charges the cable with DC voltage to create a decaying oscillation, the PD inception voltage (turn-on voltage for PD) can vary over 100% [3]. This could lead to damaging a cable with PD activity which would normally not occur at 50/60Hz, or result in missing PD activity that will happen while in service at normal power frequency. More and more cable and accessory manufacturers deny claims from clients that test with different voltage waveforms than 50/60Hz. Some even deny any warranty, if the accessories have been tested with some form of DC or 0.1Hz (VLF), as the capacitive field grading are designed for 50/60 Hz and not DC or VLF.

PD Test Voltage Level

An elevated voltage is required by all international standards (Table 1). IEC 60502 requires the cable system to be energized at 50/60Hz to the test voltage of 2.0Uo for 10 seconds, and then lowered to 1.73Uo before measuring PD. Without an external elevated 50/60Hz voltage, a PD test can provide completely inaccurate measurements of PD inception (PDIV, turn-on) voltage or PD extinction (PDEV, turn-off) voltage [3]. Standardized PD test pass/fail criteria are based on accurate PDIV and PDEV measurements and the use of a standardized 50/60Hz voltage source to produce a continuous overvoltage, to assure comparability to industry standards.

On-site PD tests do not always achieve the factory test criteria, but in over 200,000 performed tests in the field on medium, high and extra high voltage cable systems, more than 95% of tests achieved better than 5pC sensitivity and were able to achieve voltage levels as required in the IEC/IEEE standards. According to the standards, the sensitivity which is actually achieved must be documented and should be part of the report, in order to allow for a reasonable assessment of the PD test reliability. The application of Medium Voltage factory PD test standards in the field can be summarized as the "application of a continuous 50/60Hz overvoltage while measuring the cable system's PD response with better than a calibrated 10pC sensitivity per IEC 60502 (5pC for IEEE & ICEA standards)."

VI. CASE STUDIES

Case Study 1

During a planned outage, a petrochemical facility installed twelve MV cable systems linking a critical plant process to a substation. The plant owner was especially concerned about this installation as a failure in one of these cables could potentially cost over €1million. The cable systems were installed by a reputable contractor who had been installing cable systems at the plant for over 25 years. The plant owner requested that the installation contractor perform a DC HIPOT test. Each cable passed the DC HIPOT test without a problem, indicating that all the cable systems were fit for energization. Following the DC test, the cable owner requested an off-line 50/60Hz PD test according to the standards indicated in Table 1. The off-line 50/60Hz PD test located a termination that showed severe PD well below the IEC 60502 requirements on a 791m long cable span. Further investigation revealed that the contractor had difficulty installing a cold shrink termination and had accidentally displaced the stress control mastic, which created an electric stress enhancement at the end of the outer semi-conducting layer cutback. (See Figure 4). According to the manufacturer of this termination, this error is very serious and the termination would likely have failed in service after a short time. The termination was replaced and a retest demonstrated that the repair passed the manufacturer's PD test criteria (IEC 60502).

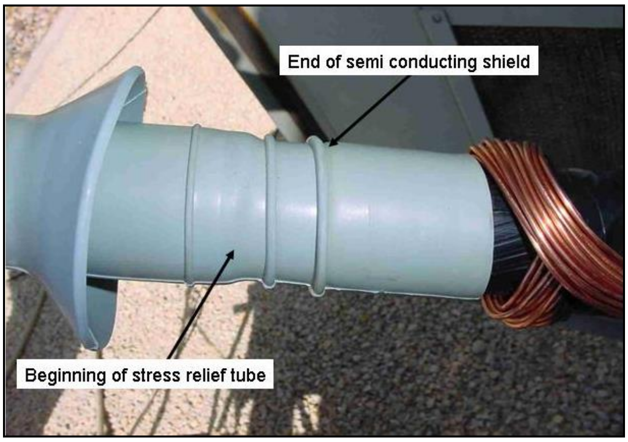


Fig. 1 Semi conductive shield and stress relief tube are not aligned in an open air termination

Case Study 2

In a power generation plant, critical cables to a substation were commissioned using an off-line 50/60Hz PD diagnostic test. All the terminations of four cables (3-phase) were found to be performing well below the IEC 60502 requirements. Despite the results, the contractor insisted that the terminations were installed correctly. Being unfamiliar with the latest diagnostic technology and industry standards, the contractor performed a 0.1Hz VLF withstand test on all of the cable systems in question. None of the cables failed during the VLF withstand test. Under the assumption such a test is sufficient, the cables were put into service. Within one month, one of the terminations recommended for repair by the off-line 50/60Hz PD test failed (see Figure 2). This led to a downtime of the power generation plant, as all substandard terminations had to be repaired. This is only one instance, but it is typical of many others which have been documented by the authors.

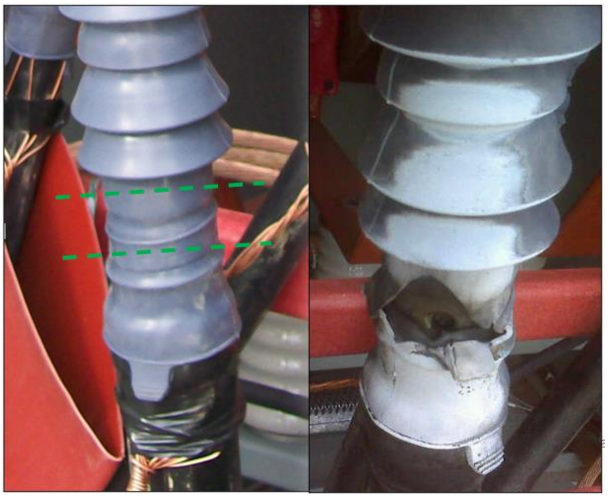


Fig. 2 Cable Termination with Substandard Installation (left); Same Cable Termination with Failure Less Than 1 Month Later (right)

Case Study 3

A petrochemical plant was experiencing an average of one failure every three years for a total of three failures over a 10-year period. On a regular basis, all 44 of the plant's 3-phase EPR-insulated cables were subjected to a traditional DC HIPOT maintenance test. The cables routinely passed the DC test but continued to fail in service. Fault records and subsequent off-line 50/60Hz PD diagnostic tests confirmed that the terminations were the weakest points on the system and causing most of the failures. After performing the off-line 50/60Hz PD diagnostic test, the results were used to make specific repairs to approximately 10% of the terminations, 5% of the splices and 2% of the cable segments. Since the PD test and repairs, the site has not experienced a single failure. If the failure rate prior to the PD test and repair activities had continued, this plant would have experienced three more costly unplanned outages during the subsequent 10-years.

Case Study 4

Critical power plant cables consisting of over 20 km of MV cable systems were tested using a DC HIPOT test. All cable systems passed the test and were put in service. Within the first 3 years, the cable system experienced 9 failures. Each failure cost the owner of the plant approximately €15k to €35k. After a loss of over €200k caused by failures, the operator performed an online PD test with the hope of exposing the remaining issues. The online PD test did not detect any PD in the cable system. Thus the cable owner believed, the cable system was in good condition and no action was needed. In the following year 3 more failures happened. With total outage costs of about €300k, the operator decided to perform an off-line 50/60Hz PD tests.

The off-line 50/60Hz PD test pinpointed 15 defects and recommended the necessary actions to correct each issue. The cable owner used the meter-by-meter profile produced by the test to identify 6 cable insulation, 4 joint, and 5 termination issues that did not meet the IEC/IEEE standards and were likely to fail significantly short of the system's design life. This proactive approach prevented as many as 15 failures. This site did not report any failures for 15 years after implementing the recommended actions and commission testing the repair work.

Fig. 3 Cable failure after DC HIPOT and prior to off-line 50/60Hz PD test

Case Study 5

A 150MW wind farm commissioned the newly installed Medium Voltage cables using a VLF AC withstand test. All cables passed. Within the first few years of operation, several MV cables failed. On one such occasion, the wind farm experienced a failure on a circuit supporting 16 turbines, 1.5MW each. The average wind speed during the failure was 8.4 m/s. According to an internal report, the nine-day production loss cumulated to €109k. Additional costs of €31k for the emergency fault location and €9k for the emergency repair cost, added up to around €149k. The wind farm owner requested the system be tested using an off-line 50/60Hz PD test. The PD test located 5 terminations, 3 joints, and 12 sites in the cable insulation which did not meet international standards.

Case Study 6

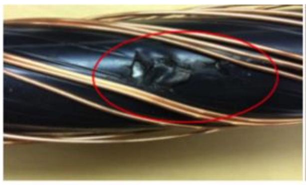
Two cable systems supporting a critical plant were installed under the ground in a fluidized backfill for the purpose of enhancing ampacity. After installation, the cables passed a VLF withstand test. An off-line 50/60Hz

PD test was performed and 7 PD sites not meeting the international standards were located in the cable system (see example in Figure 3). The damaged is believed to have been caused by the aggregate of the backfill getting in between a mechanical guide and the cable jacket during the installation process. The pressure from the guide caused the aggregate to puncture the jacket and outer insulation screen.

Fig. 4 Cable Damage passing VLF test but pinpointed within 10cm by 50/60Hz PD test

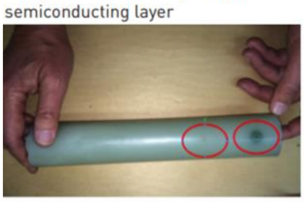
Case Study 7

A power plant owner specified an off-line 50/60Hz PD test with 5pC sensitivity as part of its newly-built site commissioning process. After several cable defects were identified, the site contractor questioned the validity of the 50/60Hz PD assessment and retested the substandard cable segments using a VLF PD test. A formal investigation at an independent laboratory through a dissection and root cause analysis confirmed that all identified defects were manufacturing defects that did not meet the international standards. In contrast, the VLF PD method failed to locate any of the defects in the same analyzed segments.



Sample 1: Discontinuity in outer semiconducting layer

Sample 2: Installation damage



Sample 3: Contaminants introduced during manufacturing

Sample 4: Protrusion in outer semiconducting layer

Fig. 5 Samples of found issues in cables

VII. DISCUSSION

Above case studies provide a small glimpse into the 100s of documented cases which demonstrate that many widely used cable system commissioning tests, that are not meeting the international standards concerning voltage waveform and PD sensitivity, cannot be used to ensure reliable MV cable systems.

Some readers who are familiar with DC and AC withstand tests for commissioning may notice that this paper did not discuss withstand test maximum durations or voltages. This subject has been a continuous source of discussion in the industry for over two decades. Based on the authors' experience, this discussion may be somewhat misleading. Estimating the time to failure for most defects under specific voltage withstand conditions is a fundamentally flawed approach.

The time-to-failure in solid dielectric defects under withstand conditions depends on many parameters which are unknown variables. These include the defect geometry, the materials involved, the local stress distribution, and space charge effects. Since these parameters are unknown, it is nearly impossible to determine how much of the insulation has been eroded during the withstand test.

In a 3-year study [4], the Electric Power Research Institute created typical cable workmanship errors including misplaced stress elements, knife cuts to 30% of the extruded insulation, and conducting residue left along the cable insulation shield cutback. All of the samples included in the study did not meet IEC 60502 PD performance requirements Although it is highly likely that these errors would have caused a service failure, all of the workmanship defects survived a 4-month AC withstand at 2 times the operating voltage ($2U_0$), while showing continuous PD activity. One of the conclusions of this study is that while AC withstand tests are intentionally designed to be destructive, one cannot rely on these tests to break down many serious insulation defects during the short withstand period.

Since the off-line 50/60 Hz PD test is non-destructive and predictive, it represents a significant breakthrough for critical facility engineers who are required to assure safe and reliable MV cable systems. The technology enables engineers to specify and quantify cable system installation quality levels on a component-by-component and meter-by-meter basis. With this system profile information, owners can now hold contractors accountable for substandard workmanship prior to the end of the warranty period. Once performance of each component of an installed cable system meets or exceeds IEC/IEEE standards, the baseline profile can be compared to future diagnostic tests for trending purposes. This information can be used as a factual condition basis to optimize and extend the period between future maintenance cycles.

This paper is based on experience gained during over 200.000 off-line 50/60Hz PD tests performed on MV cable systems in Europe, Middle East, North America and Asia. Some readers may believe above case studies are statistical anomalies, the authors' experience indicates that the majority of MV cable systems are likely to have a few percent of components which are not built to manufacturers' expectations. In a recent survey of over 100,000 off-line 50/60Hz PD commissioning tests on critical MV cable systems 3.0% of terminations, 4.4% of joints, and 1.6% of cable segments did not meet IEC/IEEE standards.

Another useful statistical comparison can be derived by comparing off-line 50/60Hz results to other types of commissioning tests. This analysis provides a test-by-test comparison estimating the percentage of substandard components that would likely be detected. The comparison case on MV cable defects show that VLF AC withstand detects (fails) less than 2%, a DC withstand detects (fails) less than 1% and an online PD test detects less than 2% of defects which do not meet IEC/IEEE standards and are considered to shorten cable life. General condition assessment tests such as dissipation factor (or tangent delta) at a single frequency or a spectrum of frequencies (dielectric spectroscopy), polarization voltage (or return voltage), relaxation current, and others have not been included in this paper. While these tests can provide an overall assessment of the deterioration of certain dielectric properties, they cannot pinpoint the location of defects responsible for this deterioration, and are generally not recommended for commissioning new MV cable systems since their dielectric properties are still intact.

VIII. CONCLUSIONS

This paper shows that only few commissioning tests systems are useful to assure MV power cable systems meet the IEC/IEEE standards. As demanded in the standards, only off-line 50/60Hz PD test meeting the strict IEC/IEEE specification can provide an after-installation commissioning test which can ensure MV power cable systems meet manufactures' performance standards.

In general, to assure reliability, cable owners should consider testing cables and accessories, that are designed for 50/60Hz usage, with continuous 50/60Hz overvoltage while measuring PD with better than 10pC sensitivity per IEC 60502 (5pC for IEEE & ICEA standards).

In summary:

• Failures on critical power cable system are very costly and thus an effective commissioning test method is needed

• One of the most effective dielectric tests performed in the factory on solid-dielectric MV cable system components is the off-line 50/60Hz partial discharge (PD) test.

• Nowadays, it is possible to obtain the same quality of results in the field as well.

• The vast majority of failures in newly installed solid dielectric MV systems are initiated by a discrete deterioration process associated with partial discharge (PD) and not conduction.

• Traditional DC or VLF AC withstand tests are not likely to detect (fail) the majority of significant defects

• Momentary PD tests performed at the operating voltage (online PD tests) are not comparable to factory standards and are not likely to detect the majority of significant defects shorting the cables' life

• A continuous 50 or 60Hz voltage source is necessary in order for a test to be comparable to international standards (IEC/IEEE).

• An overvoltage of at least $1.7U_0$ is necessary in order for PD test results to be comparable with a factory test.

• A sensitivity assessment is critical to assure the test equipment is working properly and that results can be compared to factory test requirements.

• A pC magnitude calibration is necessary to assure 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 IEC/IEEE standards

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IX. VITA

This section provides a short biographical or autobiographical account of the author(s). Please add also a photo of the author(s). Examples:

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