Close and Return

THE USE OF AFTER-INSTALLATION COMMISSIONING TESTS TO ASSURE MV POWER CABLE SYSTEMS MEET MANUFACTURERS' STANDARDS

Stefaan **JESPERS** (1), Massimo **VANOSSI** (2), Marco **GREEN** (3), Benjamin **Lanz** (4)
1 – Cegelec, Brussels, B-1200 (Belgium), stefaan.jespers@cegelec.com
2 – Foster Wheeler Italiana, Corsico, Milan, 20094 (Italy), massimo_vanossi@fwceu.com
3 – IMCORP, Rendsburg, 24768 (Germany), marco.green@imcorp.eu
4 – IMCORP, Manchester, CT 06042 (USA), ben.lanz@imcorptech.com

ABSTRACT

Many common solid dielectric 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 decade supported by test experience on over 40,000 cable system tests will demonstrate the significant improvement in cable system reliability performance that can be achieved using this approach in the field.

KEYWORDS

Medium voltage, Cable Commissioning, Partial Discharge (PD); Off-line, Online, Very Low Frequency (VLF); Withstand

INTRODUCTION

Engineers supporting critical facilities, such as power generation plants, data-centers, and petrochemical facilities, are required to provide a safe and reliable cable system infrastructure that will assure maximum uptime at the lowest cost. In order to assure cable system reliability, an after-installation commissioning test is conducted. Field testing standards and guides have been written to include various types of field tests, but most are not comparable with factory tests, and provide little or no certainty of future system performance. One of the most effective dielectric tests performed in the factory on solid dielectric cable system components is the off-line 50/60Hz partial discharge (PD) test. Ideally this quality control test can be performed in the field. However, specific test parameters must be met in order to assure that the field test results are comparable to manufacturer's acceptance standards. This paper will provide examples of applying factory PD standard thresholds on field test results. The case studies will provide examples of the types of defects which a properly implemented PD test can pinpoint, many of which would be missed by other types of commissioning tests. Field test experience and data collected over the last decade will demonstrate the significant improvement in cable system reliability performance that can be achieved using this approach.

Background: Critical Power Cable Systems

Power distribution for critical processes in modern commercial and industrial installations is commonly achieved by power cable systems insulated with extruded materials such as polyethylene (PE), cross-linked polyethylene (XLPE) or ethylene-propylene rubber (EPR). These vital cable systems are installed underground and in above ground cable trays. Experience obtained while conducting predictive diagnostic evaluations of over 40,000 cable tests indicates that cable system deterioration manifests itself through discrete defects. The vast majority of defects in newly installed solid dielectric systems initiate a deterioration process associated with partial discharge (PD). This failure mechanism causes the insulation to erode over time until a fault channel bridges its entire thickness. Cable defects uncovered during commissioning tests include voids, protrusions, delaminations, and physical damage to the cable screen or metal shield due to excessive sidewall pressure at bends. Some examples of accessory installation defects are poor cable preparation involving nicks, cuts, dimensional and alignment errors, poor void filler application, and contamination. Partial discharge testing and its importance to assuring the reliability of critical power cable systems will be thoroughly discussed in the following sections of this paper.

A Brief History of Cable Testing

During the last century, cable acceptance tests were traditionally carried out by applying a direct current (DC) voltage to a cable at a specific voltage level and for a prescribed duration. The DC high potential withstand test (DC HIPOT), was a reasonable test for paper insulated lead covered (PILC) cables since a significant percentage of defects failed by a process associated with an increase in insulation conductivity. A DC HIPOT was performed in the factory on new PILC cable systems. Thus, repeating the DC HIPOT on PILC in the field was a natural choice. When extruded dielectric cable was introduced in the 1960s, the cable manufacturers were aware that the primary failure mechanism of this type of insulated cable was associated with partial discharge (PD) and not conduction. While the factory PD test (known as a corona test back in the 1960s) was able to detect PD activity in cable and accessories, it involved expensive equipment and required a laboratory with an electromagnetically shielded laboratory. The DC HIPOT is known by manufacturers to be a highly ineffective test with solid dielectric system components and has been removed as a requirement from some of the factory standards for over 10 years. However, the complexities of the PD test all but assured that the field-test industry would continue to use the most widely available and recognized commissioning test (the DC HIPOT). The inability of DC voltage to cause failures in defective extruded insulation during the withstand test led to the introduction of the very low frequency (VLF) or 0.1Hz AC test in the mid 1980s. Unlike DC voltage, VLF voltage was reported to produce sustained PD activity while injecting significantly lower amounts of space charge. However, a major objection to a simple destructive withstand test is the concern that application of elevated voltages for an extended period of time, without any other accompanying diagnostic measurements, can trigger failure mechanisms that will not show during the test but may cause subsequent failures in service. These challenges left a significant void in the industry's ability to effectively test new or existing shielded power cable systems. In the mid-nineties, technology utilizing digital signal processing solved the shielded room/field noise dilemma associated with PD testing in the field. This effort 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 test. This technology, known as off-line 50/60 Hz partial discharge diagnostics, has been used over the past 15 years, and has evolved into a robust condition assessment and predictive diagnostics solution for power cable systems.

PD TESTING

The off-line 50/60 Hz partial discharge [1] diagnostic test offers a major advantage over traditional withstand tests, because it enables the cable owner to non-destructively detect partial discharge and pinpoint the defect location, providing the details necessary to take precise repair action without destroying the cable. During its service life, a cable is subjected to overvoltage conditions caused by switching, lightning, and other transient events. Any test conducted at operating voltage will be unable to simulate transient voltage conditions, which may excite partial discharge activity during operation. Therefore, in order to effectively predict the future performance of the cable system, a partial discharge test accompanied by a short duration overvoltage must be conducted, as stipulated by IEEE ICEA, and IEC. Hence, each cable system component (cable, joint and termination) has precise performance requirements as shown in Table 1 below.

Cable Component Standard	Thresholds
IEEE 48 Terminations	No PD >5pC up to 1.5Uo
IEEE 404 Joints	No PD >3pC up to 1.5Uo
IEEE 386 Separable Connectors	No PD >3pC up to 1.3Uo
ICEA S-97-682 or 94-649 Cable ≤ 46kV	No PD >5pC up to 4Uo
IEC 60502 Cable & Accessories ≤ 30kV	No PD >10pC up to 1.73Uo
IEC 60840 Cable & Accessories 36kV	No PD >10pC up to 1.5Uo

Table 1: Manufacturers' PD Test Standards
Uo is operating line to ground voltage
4Uo is an estimate, actually (7.9kV/mm) or 200V/mil
picoCoulomb (pC)

Since the off-line 50/60 Hz partial discharge diagnostic approach is non-destructive and predictive, it represents a significant breakthrough for critical facility engineers who are required to provide a safe and reliable electrical cable infrastructure. The technology enables engineers to specify and quantify cable system installation quality levels on a component-by-component and meter-by-meter basis. Armed with this system profile information, engineers 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 industry 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.

STANDARDIZED PD TEST REQUIREMENTS

Standards writing organizations such as IEEE, IEC, ICEA and others have developed requirements for factory 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, and (4) PD test voltage level.

Noise Mitigation/Sensitivity Assessment

A 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 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. 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 [2].

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 assessed at the terminals of the measurement 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 50/60Hz voltage source for at least 10 seconds. If, for example, the frequency of the voltage source is changed from 50/60Hz 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% [3]. The manufacturers' standards only support voltage sources which can supply continuous 50/60Hz. 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 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 the cable system's PD response. Without an external 50/60Hz voltage source, a PD test can provide completely inaccurate

Close and Return

measurements of PD inception (PDIV, turn-on) voltage or PD extinction (PDEV, turn-off) voltage [3]. Since standardized PD test pass/fail criteria are based on accurate PDIV and PDEV measurements, the use of a standardized 50/60Hz 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 40,000 tests conducted in the field on medium, 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 2.0Uo. 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 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 10pC sensitivity per IEC 60502 (3 or 5pC for IEEE & ICEA standards)."

CASE STUDY I

Critical shielded power cable systems linking a substation with a power generation plant were commissioned using an off-line 50/60Hz PD diagnostic test. All of the terminations on the substation end of four, 3-phase circuits where found to be performing well below the IEC 60502 requirements. The electrical contractor, being unfamiliar with the latest diagnostic technology and industry standards, insisted that the terminations were installed correctly. In an attempt to prove a point, the electrical contractor performed a very low frequency AC withstand test on all of the cable systems in question. All cable systems passed the VLF AC withstand. Within one month, one of the terminations recommended for repair by the off-line 50/60Hz PD diagnostic test failed (see Figure 1). The contractor was required by the plant owner to repair all the substandard terminations. This case study is only one instance, but it is typical of many others which have been documented by the authors.

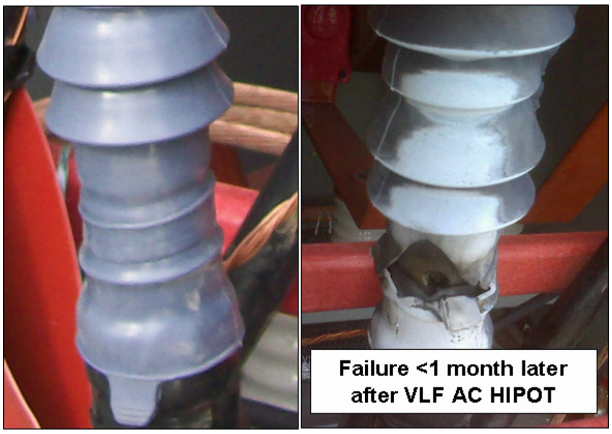

Figure 1. Cable Termination with Substandard Performance (left) Cable Termination with Failure Less Than 1 Month Later (right)

CASE STUDY II

A critical power plant cable system comprised of over 20 kilometers of medium voltage cable systems, was tested using a DC high potential test. All cable systems passed the test. Subsequently, the cable system experienced 9 failures over a 3-year period. Each failure cost the owner of the plant approximately €15k to €35k. After spending over €200k on failures, the operator implemented an on-line PD test with the hope of exposing the remaining issues. The on-line PD test indicated the cable system was in good condition and no action was needed. The following year, the cable system had another 3 failures. With the total outage cost nearing €300k, the operator turned to an off-line 50/60Hz PD test. The off-line 50/60Hz PD test pinpointed each defect 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 splice, and 5 termination defects that did not meet industry 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 has had no failures for 5 years after implementing the recommendations and successfully passing all the retests.

Figure 2. Cable failure prior to off-line 50/60Hz PD test

CASE STUDY III

The medium voltage cable system on a 150MW wind farm was commissioned using a VLF AC withstand test. Within the first few years of operation, there were several failure events. On one such occasion, the wind farm experienced a failure on a circuit supporting 16, 1.5MW turbines. The average wind speed during the failure was 8.4 m/s. According to an internal report, the nine-day production loss was €109k. Adding €31k for the emergency fault location and €9k for the emergency repair cost, the total failure cost came to approximately €149k. The wind farm owner requested the system 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 manufacturers' PD specifications.

CASE STUDY IV

Two, 3-phase cable systems supporting a critical plant were installed under the ground in a fluidized backfill for the purpose of enhancing ampacity. The cable systems were commissioned using a VLF AC withstand test. All the cables passed the test without failing. An offline 50/60Hz PD test was performed and 7 PD sites not meeting the manufacturers' specifications 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.

Figure 3. Cable damage missed by a VLF AC withstand and pinpointed with off-line 50/60Hz PD test

CASE STUDY V

During a planned outage, a petrochemical facility installed twelve, 3-phase medium voltage cable systems linking a substation to a critical plant process. 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 high potential test. Each cable passed the DC 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 diagnostic test according to the standards indicated in Table I above. The off-line 50/60Hz PD diagnostic test located a termination that had severe partial discharge activity well below the IEC 60502 requirements on one of the cables, approximately 791m in length. Further investigation revealed that the contractor had difficulty installing a cold shrink termination, and had accidentally displaced the stress control mastic, which created at electric stress enhancement at the end outer semi-conducting layer cutback. (See Figure 4) According to manufacturer of this termination, this error is very serious and the termination would likely have failed in service. The termination was replaced and a retest demonstrated that the termination passed the manufacturer's PD test criteria (IEC 60502).

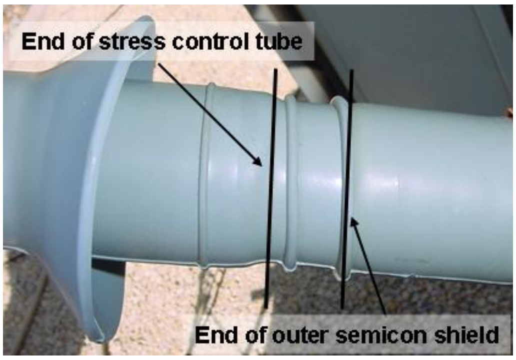

Figure 4. Example of cold shrink stress control tube not overlapping the outer semi-conductive shield

CASE STUDY VI

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 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 in 2000, 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 to date.

DISCUSSION

The case studies presented in this paper provide a small glimpse into the hundreds of documented cases which demonstrate that common solid dielectric cable system commissioning tests are not comparable with factory tests and provide little or no certainty of future performance.

Some engineers who are more familiar with DC and AC withstand tests may notice that this paper purposely avoids the discussion of withstand test maximum durations and voltages. This subject has been a continuous source of discussion in the industry. However, based on the authors' experience, this discussion maybe somewhat misguided. The authors' experience indicates that estimating the time to failure for most defects under specific voltage withstand conditions is fundamentally a flawed approach. The time to failure in solid dielectric defect under withstand conditions depends on many parameters which are unknown variables including 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. This point is substantiated by a 3-year research effort by the Electric Power Research Institute (EPRI) in the Technical Report 1001725 "Estimation of Future Performance of Solid Dielectric Cable Accessories." [4]. In this study, EPRI created typical 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 requirement. 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. 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 withstand period.

This paper is based on experience which encompasses tens of thousands of off-line 50/60Hz PD tests performed insitu on solid dielectric cable systems in Europe, North America and Asia. While the case studies may seem to some engineers as statistical anomalies, the authors' experience indicates that the majority of cable systems are likely to have a few percent of components which are not built to manufacturers' expectations. For example, in a recent survey of 13,000 off-line 50/60Hz PD commissioning tests on critical power cable systems 4.29% of terminations, 4.02% of splices, and 1.23% of cable segments did not meet manufacturers' specifications.

Another useful statistical comparison can be derived by comparing the off-line 50/60Hz results to other types of tests. This analysis provides a test-by-test comparison estimating the percentage of substandard components (components not meeting manufacturers' standards) that would likely be detected. In general the comparison case on cable defects show that VLF AC withstand detects (fails) less than 5%, a DC withstand detects (fails) less than 1% and an online PD test detects less than 5% of defects which manufacturers would consider substandard and a design life issue. 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 cable systems since their dielectric properties are still intact.

CONCLUSION

This paper presents an off-line 50/60Hz PD test specification that can provide an after-installation commissioning test which can assure medium voltage power cable systems meet manufactures' performance standards. In general, to assure reliability, cable owners should consider a test which supports the application of a continuous 50/60Hz overvoltage while measuring the cable system's PD response with better than 10pC sensitivity per IEC 60502 (3 or 5pC for IEEE & ICEA standards)." The following are bulleted list of summarizing conclusions

- One of the most effective dielectric tests performed in the factory on solid dielectric cable system components is the off-line 50/60Hz partial discharge (PD) test.
- The vast majority of failures in newly installed solid dielectric systems are initiated by a discrete deterioration process associated with partial discharge (PD) and not conduction.
- Failures on critical power cable system are very costly and thus an effective commissioning test method is needed
- 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
- A continuous 50 or 60Hz voltage source is necessary in order for a test to be comparable to factory standards.
- An overvoltage of at least 1.7Uo is necessary in order for PD test result 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 manufacturers' test standards

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