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ASSURING THE RELIABILITY OF CRITICAL POWER CABLE SYSTEMS AT THE LOWEST COST

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Critical facility engineers are required to provide a safe and reliable electrical cable infrastructure that will assure maximum uptime at the lowest cost. Engineers assigned this responsibility are able to make better power cable system reliability decisions when effective predictive diagnostic tools are applied. Many in the industry are not aware that the IEEE no longer fully supports high potential withstand tests as an acceptance test for shielded power cable systems, and are unknowingly putting their systems at risk. This paper is an overview covering the latest IEEE standards and best practices for specifying modern cable systems and applying predictive diagnostics to industrial shielded extruded dielectric cable systems rated 5kV and higher. Case studies from actual critical facilities will demonstrate the ability of modern defect specific diagnostics (DSD) to repeat the manufacturers test in the field, pinpoint defects, and avoid future unplanned service outages.

According to recent industry discussions, there is an increased demand for critical facilities to operate reliably and safely while cutting costs by extending the traditional maintenance cycle. The forces of higher reliability and longer maintenance cycles are diametrically opposed and thus, cost reductions require asset managers to have access to better, more predictive information to facilitate cost effective actions. The vital links of shielded power cable infrastructure are no exception.

BACKGROUND ON CABLE SYSTEMS

Medium voltage power systems most widely used in commercial and industrial installations are composed of cables with extruded insulation, such as crosslinked polyethylene (XLPE) and ethylene-propylene rubber (EPR), and cables with laminated insulation, i.e. fluid-impregnated paper-insulated lead-covered (PILC). These cables, which power vital processes, are installed underground and in cable trays throughout commercial and industrial facilities. The cable systems range from 5kV to 35kV. As cables and their accessories age, their propensity to fail in service increases. Experience obtained while conducting predictive diagnostic evaluations of over 12,000 miles of cable demonstrates that cable deterioration manifests itself through discrete defects. Some examples of discrete cable insulation defects are electrical trees, water trees eventually leading to electrical trees, impurities, delamination of semi-conducting screens, protrusions in extruded insulation, and carbonized tracking in laminated insulation. Accessories, on the other hand, typically fail because of poor workmanship, contamination, or moisture ingress along interfaces within the cable insulation. Many in the industry are surprised to learn that modern extruded cable systems are not likely (less than 1% of time) to fail due to conduction, otherwise known as the proverbial electrical "leakage". Although there are many scenarios which can initiate the process that will eventually cause the insulation of modern extruded cable systems to fail, there is one common symptom. The vast majority of failure mechanisms (>95%) are associated with a process known as partial discharge (PD). This failure mechanism causes the insulation to be eroded over time until a fault channel bridges its entire thickness. Partial discharge and its importance to leading edge defect specific diagnostic technology will be thoroughly discussed in the following sections of this paper.

HISTORY OF CABLE TESTING

During the last century, cable acceptance tests have traditionally been 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, or DC HIPOT (an IEEE Type 1 Destructive Withstand Test), was a reasonable test for paper insulated lead covered (PILC) cables due to the significant percentage of defects associated with an increase in insulation conductivity (approximately 40%). The DC test can only detect the types of defects which are associated with conduction and present themselves in the form of power loss or "leakage current." Today we know that as much as 70 to 80% of defects in these older type cable systems fail in association with the aforementioned electrical phenomenon known as partial discharge. Thus, partial discharge measurements are very useful for aged paper insulated systems. When extruded dielectric cable (i.e.HMWPE, XLPE, EPR) was introduced in the 1960s, the cable manufacturers were aware that the primary failure mechanism of this type of insulated cable was partial discharge (over 95%). While the factory partial discharge test (known as a corona test back in the '60s) was able to detect partial discharge in cable, it involved expensive equipment and required a fabricated electromagnetically shielded environment to conduct the test. Even though the DC HIPOT was known to manufacturers to be highly ineffective, the complexity of the PD test all but assured that the field test industry would continue to use the widely available and most recognized DC test. In fact, "from the work of Bach (TU Berlin), we know that even massive insulation defects in extruded dielectric insulation cannot be detected with DC at the recommended voltage levels." (IEEE 400, section 4.2) For some time the industry experimented portable alternatives to the DC test such as very low frequency (VLF) AC, however "a major objection to Type 1 field tests is the concern that application of elevated voltages without any other accompanying diagnostic measurements trigger failure mechanisms that will not show during the test but which may cause subsequent failures in service." (IEEE 400, Section 4.3) These challenges left a significant void in the industry's ability to effectively test new or existing shielded power cable systems until the mid-nineties when Dr. Matthew Mashikian, an innovative engineering professor at the University of Connecticut, was able to utilize evolving digital signal processing technologies to solve the shielded room/field noise dilemma and develop a PD test technology to replicate the cable manufacturers' factory test in practical field applications. This technology, known as off-line 50/60 Hz partial discharge diagnostics, has been developed over the past 12 years in the utility industry and has evolved into a robust condition assessment and predictive diagnostics solution for power cable systems.

PARTIAL DISCHARGE DIAGNOSTICS

The IEEE Type 2 off-line 50/60 Hz partial discharge diagnostic test, otherwise known as defect specific diagnostics (DSD), offers a major advantage over traditional IEEE Type 1 DC and AC destructive withstand test, because it enables the cable owner to predictively pinpoint the exact defect location, providing the details necessary to take precise 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 in the cable system the conditions which may produce partial discharge during operation. Therefore, in order to effectively predict the future performance of the cable system, a partial discharge test at a reasonably elevated voltage must be conducted, as stipulated by IEEE ICEA, and IEC. Hence, each component of the system, the cable, joints and terminations have their own acceptable level of discharge (see Table 1 below) defined by IEEE and ICEA. 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 basis. Armed with this foot by foot profile, engineers can now hold contractors to task for substandard workmanship prior to the end of the warranty period. The baseline profile provided by this technology is also a powerful tool for asset managers. Once a system is installed and each system component is proven to meet industry standards, the baseline profile can be compared to subsequent diagnostic tests. Asset managers can use trending information as a factual condition basis to optimize and extend the period between maintenance cycles.

IEEE 400 section 7.4 states that "if the cable system can be tested in the field to show that its partial discharge level is comparable with that obtained in the factory [off-line 50/60 Hz PD diagnostics test on the cable and accessories], it is the most convincing evidence that the cable system is in excellent condition."

TABLE 1
STANDARDS AND SPECIFICATIONS

STANDARD	SPECIFICATION*
IEEE 400.3	pC Calibration/Sensitivity Assessment Procedure
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
ANSIICEA S-97-682-2007 MV Cable	No PD ≥ 5pC up to 4Uo**

**Uo is the cable system's operating voltage, **200V/mil*

CASE STUDY I

A petrochemical plant was experiencing an average of 1 failure every 3 years leading up to a off-line 50/60Hz PD diagnostic test. On a regular basis, all of the plant cables were subjected to an IEEE Type 1 destructive DC HIPOT maintenance test. These tests were performed according to IEEE recommendations prior to the latest revision in 2001. The cables routinely passed the DC test but continued to fail in service. Fault records and subsequent off-line 50/60Hz PD diagnostics confirmed that the terminations were the weakest points on the system. After performing the off-line PD diagnostic test, the results were then used to make specific repairs to the 40 defective terminations, 9 defective splices and 3 defective cable spans. If the failure rate prior to the off-line PD diagnostic tests and repairs had continued, this plant would have experienced 2 more costly unplanned outages to date. Since the off-line 50/60Hz PD diagnostic test in 2000, the site has not experienced a single failure and the maintenance test cycle was stretched from once per year to once in nine years. This case study illustrates how a plant owner can maximize reliability while significantly lowering maintenance costs.

CASE STUDY II

The critical shielded power cable systems linking a substation with a power generation plant were commissioned using an off-line 50/60Hz PD diagnostic test. Twelve cable terminations on the substation end of the circuits were found to be performing well below the industry specifications in Table 1. The contractor, being unfamiliar with the latest diagnostic technology and industry standards, insisted that the terminations were installed correctly. In an ill-fated attempt to prove a point, the contractor performed an IEEE Type 1 VLF 0.1Hz Destructive AC HIPOT on all of the cable systems in question. All cable systems passed the VLF AC HIPOT. 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 forced by the plant owner to concede and repair all the substandard terminations. This case study is only one instance but, it is typical of many others which are playing out across the industry in which the off-line 50/60 Hz PD diagnostic technology is putting plant engineers in the driver's seat of the quality assurance process.

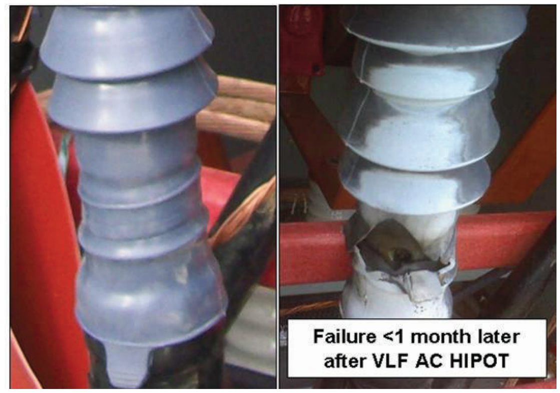

Figure 1 Cable Termination with Substandard Performance (left) Cable Termination with Failure Less Than 1 Month Later

CASE STUDY III

A cable owner was interested in comparing off-line PD diagnostics with on-line PD diagnostics on a 35 year-old critical circuit. The on-line test had the advantage of not having to take the line out of service. The owner first requested an off-line 50/60Hz, PD diagnostic test to be performed on the 630ft long, 15kV class, extruded cable. According to the PD diagnostic test results and the industry specifications in Table 1, there were 13 defects in the cable insulation and one defect in a joint. The defect in the joint was found to have PD at only 80% of the operating voltage stress level which means that it was most likely under continuous PD conditions. Refer the PD test results in Figure 2 below. Even though the cable system was recommended for replacement, for experimental purposes, the cable system was temporarily put back in service.

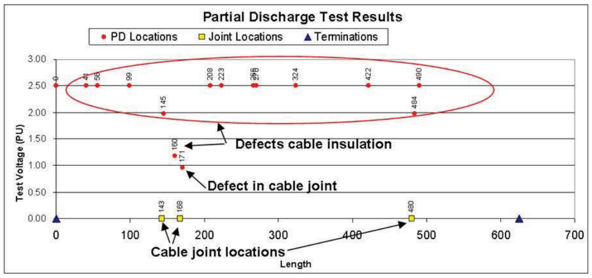

Figure 2 Off-line 50/60Hz PD Diagnostic Test Results

The on-line PD test technician was not given the off-line test results. The on-line test technician applied the sensors at the terminations of the cable. Using proprietary sensors, a spectrum analyzer, and a special noise filtering process, the mobile on-line testing unit was not able to detect any PD activity in the cable system. The on-line PD test report stated that the cable was free from defect and should be left in service. In this case study, the superior accuracy and value of the off-line 50/60Hz PD diagnostic test clearly illustrates how engineers responsible for critical cable systems can use advanced technology and the latest industry standards to make condition based strategic decisions and maximize the reliability of aged assets.

CONCLUSION

In order to assure the reliability of critical power cable systems at the lowest cost, engineers need a predictive technology which gives complete and factual condition based information. This paper has provided an overview of the latest IEEE standards and applying predictive diagnostic industrial shielded extruded dielectric cable systems rated 5kV and higher. Case studies from actual critical facilities have demonstrated off-line 50/60Hz PD defect specific diagnostics have the ability to repeat the manufacturers test in the field, pinpoint defects, avoid future unplanned service outages and assure liability while extending the maintenance cycles and saving precious operating and maintenance dollars.

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