Editorial

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Cable Diagnostics Trends

This issue is focused on underground cable diagnostics. Therefore, I thought it would be appropriate to review the latest changes occurring in the cable diagnostics business. Underground cables are an important part of electric power transmission and distribution systems. The global market of the HV power cables is estimated to grow to $14 billion during 2020-2024.

On the other hand, as COVID-19 pandemic has put pressure on every part of each country's economy and society, the need for maintaining reliable, uninterruptable, and sufficient electric power for a sustainable economic recovery is essential. Diagnostics and testing play a critical role to ensuring the reliability and forecasting the life of underground power cables.

The relevant IEC standards for AC cables are IEC 60502-2 for Cables 6kV–30kV, IEC 60502-4 for Cable Accessories 6kV–30kV, IEC 60840 for Cable & Accessories 30kV–150kV, and IEC 62067 for Cable & Accessories 150kV–500kV. These IEC standards provide limited guidance for testing and diagnostics. On the other hand, guides developed by IEEE ICC contain more detailed guidance for traditional and advanced diagnostics of power cables. I will discuss the IEEE documents in other relative sections.

The report published by EPRI in 2014, "Diagnostic Techniques for Underground Cable Systems", provides an overview of existing and developmental diagnostic techniques for both polymeric and oil-impregnated cable systems. The Centre for Energy Advancement through Technological Innovation (CEATI) has recently published a report on "Advanced Cable Diagnostic Test Techniques for XLPE, HPFF and LPFF Cable Systems" that provides a practical guide for HV cable diagnostics.

Oil-Impregnated Paper Systems

There are numerous HV and MV oil-filled cable circuits with an average age of 60 years or older worldwide. These cables are generally reliable and have a long life. The main mechanisms of aging and failure of oil-impregnated cables are leak and corrosion, thermal aging, paper thermomechanical deterioration, metallic sheaths thermomechanical deterioration, and paper electrical aging. One of the challenges is to maintain the integrity of the oil-filled cables such as the pipe for High-Pressure Fluid Filled (HPFF) and the sheath for Self-Contained Fluid Filled (SCFF) cables against corrosion.

IEEE Std. 1425-2001, "Guide for the evaluation of remaining life of impregnated paper-insulated transmission cable systems", is a decent document for diagnostics and condition assessment of oil-filled cables. Furthermore, CEATI developed a guide for "Transmission Underground Cable Reference Manual Maintenance" in 2014. This guide provides detailed procedures for both LPFF and HPFF cable oil leak tests such as PFT. It also covers maintenance testing such as anti-corrosion sheath tests, measurement of sheath bonding currents, cross-bonding check, partial discharge (PD) diagnostic test during the 1-hour AC withstand test, resistance measurement of the conductor, capacitance and dissipation factor, TDR, positive and zero-sequence impedance measurements, Dissolved Gas Analysis (DGA), jacket withstand and insulation resistance, and dielectric insulation resistance measurements.

Extruded Dielectric Cables

In some of the developed countries, XLPE cable installation peaked in the 80s which has resulted in the average age of 40 years or more for the majority of MV XLPE cables. Similar to other MV and HV assets, underground cables and cable accessories are subject to electrical, thermal, mechanical, and environmental stresses during the lifetime. One, or a combination, of the stress factors cause degradation of the cable system that can lead to failure. The main mechanisms of aging and failure modes of extruded cables are moisture ingress, water tree, partial discharge, electrical tree, overheating, thermomechanical stress, and intrinsic breakdown.

Accessories, including splice and termination, have a significant role in the cable system failure for both MV and HV cables. Failure statistics of MV and HV cables are widespread. As a rule of thumb, one can consider almost equal distribution between cable failure, joint failure, and termination failure, each 33%. The CIGRE TB 560 presents a review of the experience of failures in terminations and joints (rated at 60 kV and above), including failure modes, consequences, and corrective actions. Accessory failure was caused by factors such as moisture ingress, insulation degradation, and poor workmanship.

Some of the power utilities and industrial cable owners run the MV cable systems to failure without any testing or maintenance plan after the commissioning. Replacement of cables based on failure or purely on age-based have disadvantages such as lowering the power system reliability and increasing the cost of repair or premature replacement. Aside from Factory Acceptance Tests (FAT), commissioning tests or site acceptance tests (SAT) have become very popular for both MV and HV cables in the past 15 years.

IEEE ICC provides a family of guides for field testing and evaluation of shielded cables.

- IEEE 400- Guide for Field Testing and Evaluation of Shielded Cables
- IEEE 400.1- Guide for Field Testing of Laminated Dielectric Shielded Power Cable Systems with HVDC Voltage
- IEEE 400.2- Guide for Field Testing of Shielded Power Cable Systems Using VLF
- IEEE 400.3- Guide for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment
- IEEE 400.4- Damped AC Voltage Testing
- IEEE 400.5- DC Field Testing of Extruded Cable Systems
- IEEE 1234- Guide for Fault Locating on Shielded Power Cables

DGA

DGA is one of the most efficient tests for oil-filled cable diagnostics. IEEE Std. 1406-1998 is an old guide for the use of DGA analysis of electric power cable systems. The updated version of this guide is in its final stages of publication by the corresponding ICC working group.

Low dissolved gas concentrations are observed in cables operating in a reasonable manner. On the other hand, elevated dissolved gas levels indicate electrical and/or thermal abnormalities in the cable. Similar to power transformers, for cables, C_2H_2 is the most important dissolved gas, and its value should be close to zero for normal operation. It is imperative that the fluid extracted during sampling represents the cable system as opposed to the fittings. Fluid sampling is to cover both the cable system and accessories (splices and terminations) alongside the pressurizing unit. The cable accessories (terminations and splices) are typically equipped with sampling ports.

Oil Leak Detection

Oil leaks can threaten the performance of fluid-filled cables and harm the environment. Typical causes of oil leaks are pipe/sheath lead corrosion, external damage due to excavation, poor workmanship and laying techniques, DC and stray current, mechanical stress, vibration, and compression from road construction work.

Injecting dyes, radioactive material, tracer gases, odorants, acoustic emission, radar, infrared, and even dogs are classic methods to detect oil leaks. Perfluorocarbon tracer (PFT) technique is a relatively new method for finding leaks in oil-filled high voltage cables. This method is based on finding the locations at which the pressure drops continuously after the cable oil is frozen at multiple spots. It can aggravate the state of the jacket, causing water ingress and corrosion. CIGRE TB 652, "Guide for Operation of SCFF Cable Systems-2016", proposed three techniques pertaining to the leak detection of SCFF cables: freezing, hydraulic bridge technique, and PFT injection.

Withstand VLF-Tan Delta

In the past 15 years, very low frequency (VLF) voltage testing in the frequency range from 0.01 to 0.1 Hz has increasingly been used for Hi-Pot acceptance for MV extruded cables. At present, the maximum voltage of the available VLF (0.1 Hz) test set is 200 kV peak. Therefore, the present VLF testing is limited to lower voltage HV cables.

VLF has also been used to perform VLF Tan-Delta for service aged MV polymeric cables. Based on more than 16,000 km of cable testing, IEEE 400.2-2013 was developed to provide a detailed guide to test and analyze the results. The main advantage of such a test is that a small reactive power is needed compared to 50/60 Hz Hi-Pot testing. This IEEE guide provides recommendations to evaluate VLF Tan-Delta for PE-based (XLPE, TRXLPE), EPR (black, pink, discharge resistance) and PILC MV cables. One of the practical challenges with this guide is that it does not provide a clear direction for the intervention of decision making. This guide offers three condition assessment categories: 1- "No Action Required", 2- "Further Study Advised", 3- "Action Required", of which categories 2 and 3 do not offer a clear action outcome. The future revision of IEEE 400.2 may provide a better recommendation and possibly include more than three assessment categories to help the industry for better cable fleet management.

Partial Discharge Tests

In the past 15 years, most of AC Hi-Pot commissioning has been conducted in conjunction with PD measurement. The onsite PD test is more popular for HV and EHV cables. However, some of the utilities have been doing PD testing for newly installed MV cables or service aged MV cables. IEEE 400.3-2007, which provides a guide for onsite PD testing of shielded power cables, is under revision. It is expected that the revised IEEE 400.3 document will include the requirement of PD extinction voltage (PDEV) for different cable voltage classes and cable accessories.

One of the challenges of onsite PD measurement is that most of the existing guides refer to the conventional IEC 60270 method which assumes a lumped capacitance test object. This works well in the factory where the cable reel is lump. For cables with a length of a few kilometers or more, this is not a correct assumption. Background noise is also another challenge. For these reasons, unconventional onsite PD measurement is common, which allows a wideband PD measurement with a higher center frequency (1 MHz or higher). In order to reduce the effect of attenuation for long cables with multiple joints, it is common to perform a distributed PD measurement to monitor all the accessories. In such a setup, unconventional PD sensors such as HFCT, sheath sensor, differential field sensor, ultrasonic probe, or TEV can be used.

Over the last 15 years, as PD measuring instruments have become more sophisticated with the application of digital technology to reduce external noise and improve high-frequency electronics, many utilities, consultants, and testing service companies have added PD monitoring to the Hi-Pot test.

There are several HV power supplies that can be used for (monitored) withstand and PD testing, including 50/60 Hz power frequency, variable frequency resonance, VLF, and damped AC voltage.

Power Frequency or Near Power Frequency PD

This test requires a variable reactor or variable frequency convertor to create a resonance circuit with the cable capacitance. Such a setup can build a power frequency or a frequency in the range of 20 Hz to 300 Hz depending on the cable capacitance. CIGRE TB 728-2018, provides the latest international guide for the onsite withstand and partial discharge assessment of HV and EHV cable systems. According to this CIGRE guide, commissioning tests with PD monitoring should be carried out at 2 U0 for voltage ratings between 69 kV and 115 kV, 1.7 U0 for all voltage ratings between 132 kV and 400 kV, and 1.5 U0 for 500 kV rated and that there should be no detectable PD at 1.5 U0.

IEEE 400 has an active working group: "Constant Voltage AC Testing of Cable Systems (Resonant Testing)" to develop a guide for MV and HV cable onsite withstand testing with power frequency or near power frequency resonance circuit. This guide is expected to be published in 2021-2022.

VLF PD

A recent study commissioned by CIGRE, WG D1.48 found that the risk of space charge accumulation is very low, and the electric field distribution of VLF is similar to that at power frequency. However, the rate of electric treeing at VLF voltage is lower than power frequency primarily due to the lower number of partial discharges per time unit and reduced voltage drop across voids and electrical tree channels. On the other hand, using cosine rectangular VLF, it is possible to perform PD testing during the period of polarity reversal. The PD parameters, such as partial discharge inception voltage (PDIV) and PD magnitudes measured during the period of polarity reversal, are expected to be comparable to that at power frequency.

Damped AC PD

The Damped AC (DAC) test set uses high voltage DC to charge up the cable circuit under test to a specified voltage. Once this voltage is reached, the cable is discharged into an inductor to set up a decaying high voltage oscillatory waveform on the cable circuit (20 Hz to 500 Hz). IEEE Std. 400.4-2015, specifies the magnitude of the charging voltage for each rated voltage, up to 230 kV. The number of shots at each voltage level is 50, and the test levels for new cable systems (peak voltage to ground) vary between 2 U0 and 3 U0. An advantage of using the DAC test is that both the PD inception and extinction voltages (PDIV/PDEV) can be measured during any shot if PD exist.

DAC AC withstand and PD test is more popular in Europe than North America. There is limited data available comparing the PD characteristics (magnitudes, inception, extinction, etc.) between the power frequency and DAC tests.

Time Domain Reflectometry (TDR)

TDR can characterize changes in the cable impedance caused by splice, faults such as open or short, and deteriorated metallic shield. There are no unified success criteria for TDR testing. Another difficulty with TDR test is that there should be a balance between the injected pulse "amplitude resolution" and "time resolution". TDR looks like a straightforward test; however, proper interpretation of the TDR test data requires the skill of the operator.

TDR can be used to assess the metallic shield. Cable shield corrosion, splice shield crimp corrosion, or splice thermal defects can change the resistance or the TDR waveform reflection. IEEE Std. 1617-2007 is a technical guide for condition assessment of the metallic shield. It provides corrosion categories of concentric neutral wires. This standard provides a four-level neutral corrosion condition based on the TDR pulse compared with the cable splice reflection. This guide is currently under revision by IEEE ICC.

NEETRAC Cable Diagnostic Focused Initiative-2016 - Chapter 11 is also a reliable practical guide for metallic shield assessment. CIGRE WG B1.55, "Recommendations for additional testing for submarine cables from 6 kV up to 60 kV". recommends adding extra commissioning tests of TDR, OTDR, and sheath insulation resistance to SAT.

Dielectric Spectroscopy

Dielectric spectroscopy including Frequency domain spectroscopy (FDS) or time-domain spectroscopy (TDS) has been used for more than 3 decades for diagnostics of MV and HV cables, especially PILC cables. For oil-filled cables, there is a direct relation between the paper insulation moisture percentage and FDS curve behavior. The preferred method for measuring the moisture in cellulose is FDS. FDS/TDS test technique has also been applied to polymeric cables. Unlike oil-filled equipment that do not require high voltage, polymeric cables require high voltage variable frequency source that can generate output voltage equal or higher than the cable rated voltage in a wide frequency range (0.001 Hz to 100 Hz). This is a practical challenge as the reactive power required for generating high voltage at 10 Hz to 100 Hz is high.

FDS can indicate the extent of the water treeing effect in XLPE cables and moisture ingress in oil-filled cables. Some recent studies show promising results to employ FDS for thermal aging of XLPE cables at voltages equal to or lower than the rated voltage. There is a newly published IEEE guide C57.161-2018 for power transformers diagnostics. There is no IEEE or IEC guide for FDS testing of underground cables. It is likely that IEEE ICC develops a guide for cable DS testing in the future.

Recovery Voltage Measurement (RVM)

RVM is a method where the cable circuit is charged using a DC voltage for a given time. This concept is based on applying DC voltage until a short circuit condition is produced and measuring the open-circuit voltage. The circuit is usually charged for 15 minutes, with voltages ranging from 1 to 2 kV. The charged circuit then discharges through a ground resistor within a short period of time. The open-circuit voltage is recorded versus time during the test.

The RVM test was introduced in the 1990s for power transformer testing and gained some popularity in the 2000s but experienced a decline in the 2010s. Limited experiments show that the

RVM can be used for oil-filled cables. NEETRAC Cable Diagnostic Focused Initiative (2016) introduced a diagnostic factor D which is the ratio of recovery voltage at 2 U0 over U0. Clearly, this does not work for service aged polymeric cables as applying HVDC to XLPE cables over a suggested period of 15 min can introduce trapped charge and accelerate the cable aging.

Polarization/Depolarization Current (PDC)

PDC involves applying a DC voltage in the range of 100 V to 5 kV for a period of 5 to 30 minutes and discharge the cable in a few seconds through a resistor. The depolarization current is recorded. PDC identifies conduction and polarization effects in the insulation of the cable. An increase in the absorption current happens due to various effects inclusive of interfacial polarization and the presence of by-products due to PD, oxidation, and thermal degradation. On the other hand, the formation of voids in extruded cables can cause a reduction in the absorption current. Since the current measurement is in the range of nano or even pico ampere, reproducibility and overcoming noise are issues for onsite measurement. The interpretation of the results could be complicated. This technique may be sensitive to water trees. However, more onsite testing and validation is needed to accept this technique for practical diagnostics.

Metallic Shield Testing

Practically, I found the metallic shield integrity is one of the major causes of MV cables loss of life. The end-users and testing companies do not usually take this seriously. The industry focus is the insulation diagnostics by PD or VLF-Tan Delta. At the same time, it is essential to ensure concentric neutral integrity, especially for old and longer cables. Jacket integrity test, DC resistance of the shield, and TDR for corrosion investigation are the most important tests related to the metallic shield.

During the SAT commissioning, it is possible to measure the resistance of both the main conductor and the metallic shield (including the splice). However, it is a challenge to measure the metallic shield of a service aged cable unless one side of the grounded shield crimp is open or disconnected from the ground. There are test devices such as Ohm-Check that can be used to do an online neutral resistance measurement.

Broadband Impedance Spectroscopy

Cable impedance spectroscopy, often called line resonance analysis (LIRA) is based on frequency domain reflectometry. A very low voltage (3V to 5V) is applied to a cable system over a range of frequencies up to hundreds of MHz. The complex impedance of the cable is measured and the amplitude and phase at different resonance frequencies are measured. The analogy for this test is the power transformers SFRA test.

Based on the manufacturer's claim, LIRA has greater advantages over TDR, including less influenced by noise, therefore more sensitive and accurate, greater possibility to focus on blind zone spots at the near end and measure on long cables, and global aging assessment. Theoretically, this technique can be applied to all LV, MV, and HV cables. LIRA is relatively new and needs additional work to verify its associated claims, e.g., in terms of the ability to detect oxidation, moisture ingress, and the influence of external noise, especially for long cables with such a very low voltage (3V to 5V).

In summary, there are various advanced cable test techniques available for the diagnostics of MV and HV cables. The most popular test based on industry practice is withstand Hi-Pot and PD for commissioning test and VLF Tan-Delta for maintenance test. The interpretation of advanced cable test diagnostics is a crucial component that determines the relative success of the testing and maintenance program. It is a common practice to engage a third party with field experience to perform advanced diagnostics and subsequent interpretation. There are several challenges and open issues specific to each advanced cable test diagnostic that remain to be addressed in the industry, such as:

- Onsite PD testing, including criteria of PDEV for different MV and HV cables, PD sensitivity, background noise, measurement frequency, proper calibration, signal attenuation, and PRPD interpretation. The revised IEEE 400.3 is expected to cover some of the concerns.
- Lack of field data and test equipment for HV transmission class cables using VLF Hi-Pot and PD and VLF Tan-Delta testing.
- Lack of available guidelines for FDS, RVM, and PDC.

Thus, diagnostics of underground cable is still in high demand and requires innovative ideas to improve the existing techniques, bring new ideas, and help the industry for a better condition assessment.

Research organizations and industry will have to cooperate more efficiently to improve the existing diagnostic techniques and offer new technologies toward a better practice and extending the life of the aged population of the cable fleet.