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Understanding of XLPE Cable System Commissioning using Partial Discharge Measurements during AC HV Tests

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Abstract

This paper is based on the work done by Altanova Group, India, and describes the process and procedures used in a Partial Discharge (PD) investigation on a cable circuit during the AC withstand test. The paper focuses on the two most common approaches employed, namely, soak tests and resonant tests. In the latter case, the paper describes two approaches to performing the measurements and the relative benefits of each. De-noising the acquired data using T-F map analysis is also described, and real-world examples are given in the two case studies. These detail EHV resonant tests, one performed where all the accessories were monitored simultaneously and another where each accessory was tested in turn before relocating the PD monitoring equipment to the next location. In both cases, the application of T-F maps shows how different PD sources, such as external corona, can be identified and hence segregated.

Keywords: HV AC Tests, Partial Discharge, T-F Map, XLPE Cables

1. Introduction

The high reliability of underground cables is based on many factors, including quality of materials and manufacture, testing at the cable factory, careful transport and installation, and a commissioning test to prove the cable system before entering service. The commissioning test is the last opportunity to detect problems before the system is in operation, after which disruption and/or lost revenue caused by failures is more troublesome. Consequently, performing a high-quality commissioning test is insurance against later complications.

Cables and accessories should all be tested at the factory before shipment, commonly to IEC 60840 and 62067, depending on the voltage level. These tests include a Partial Discharge (PD) test, which is a sensitive way of detecting internal defects, such as fall-in, protrusions, contaminants and voids. Internal PD in solid dielectric cable (e.g., XLPE) at any voltage level degrades the material and ultimately leads to failure.

Damage to the cable during transport or installation or defects introduced by human error during the assembly of accessories are the potential weak links in the cable system. This view is reinforced by CIGRE Technical Brochure 815, "Update of the service experience of HV underground and submarine cable systems", which reported that one-third of cable system failures are associated with the accessories. The commissioning test method should be chosen to uncover these issues allowing them to be rectified.

There are several commissioning tests approaches to prove the performance of the newly installed circuit;

1. Soak test at system voltage (typically for 24 hours)
2. Damped AC or Oscillating Wave test
3. VLF test at higher than the rated voltage
4. Resonant AC test at higher than the rated voltage

These methods have pros and cons, but internationally (1) and (4) are the most common and will focus on this paper: all of these can be combined with PD testing.

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The main advantage of (2) and (3) is the test equipment is relatively small. VLF testing typically energizes the cable system with a sinusoidal or pseudo-square wave at 0.1 Hz. Damped AC subjects the cable to short periods of sinusoidal voltage, which decays with time; each energization may only last one second. However, the drawback of both methods is that the cable system is subjected to a relatively low number of AC cycles during the test period reducing the likelihood of detecting PD.

A soak test is performed in its simplest form by energizing the cables from the connected grid. This test is easy to implement but can create potential problems for the grid in case of failure. Additionally, there is also potentially a lot of energy behind the fault, which can cause a lot of damage to the new cable or accessories depending on the speed of operation of the protection systems. With today's PD monitoring technology, it's possible to enhance the soak test with partial discharge detection. This approach faces sensitivity issues due to high-frequency electrical noise introduced into the test object from the connected power system network. When a high value of noise from the power system network and adjacent phases is superimposed on the signal, it reduces the Signal-to-Noise Ratio (SNR) and reduces the likelihood of detecting any PD in the cable system. Filtering and de-noising can improve the SNR, which is discussed below.

In comparison, an AC resonant test is more complex to undertake and requires additional equipment but has two key advantages compared to a soak test:

1. Asynchronous to the AC power system means a greatly improved signal-to-noise ratio detecting PD.
2. More likely to initiate PD in any defects due to the applied overvoltage, which can range from 1.2 to 1.7U_0 depending on the voltage level of the cable system.

Combining these two factors means the test is highly sensitive to detecting defects in the installed accessories. The location of sensors and different ways the test can be performed are discussed further below.

Even though a cable system is a relatively simple electrical asset, PD measurements during any commissioning test require experienced operators, calibrated sensitive instrumentation[1] to perform the measurements and, knowledge experts to evaluate the results and determine the status of the insulation system in the field[2–4]. Such an approach provides confidence to both the cable supply/installer and the asset owner that the new cable system is fit for purpose and everything possible has done to avoid early cable system failures in operation.

The following sections briefly consider HV resonant test systems, practical considerations for performing the tests, de-noising the data and identifying PD. The paper also presents the experiences and observations revealed while conducting resonant commissioning tests in India and Italy.

2. Resonant Test Systems and Testing

AC resonant tests are conducted as per IEC60840 and IEC62067 using a Resonant Test System (RTS), wherein capacitive test load of the cable is compensated using an inductor to create resonance the circuit is tuned electronically such that X_c is more or less equal to X_L.

Figures 1 to 3 show a complete Resonating Test System (RTS). This system uses multiple resonating inductors, which can be connected either in series or parallel as per the requirement to boost the voltage and currents. These tests are typically conducted between 20 Hz to 300 Hz depending upon load capacitance.

PD measurements performed as per IEC 60270 in a laboratory setting require a coupling capacitor and a measuring impedance. However, the frequency bandwidth is limited to 1 MHz. Consequently, a wider bandwidth is generally used to have clear and distinct pulses, such as 20 MHz or 30 MHz, using a High-Frequency Current Transformer (HFCT) as the sensor. HFCTs provide

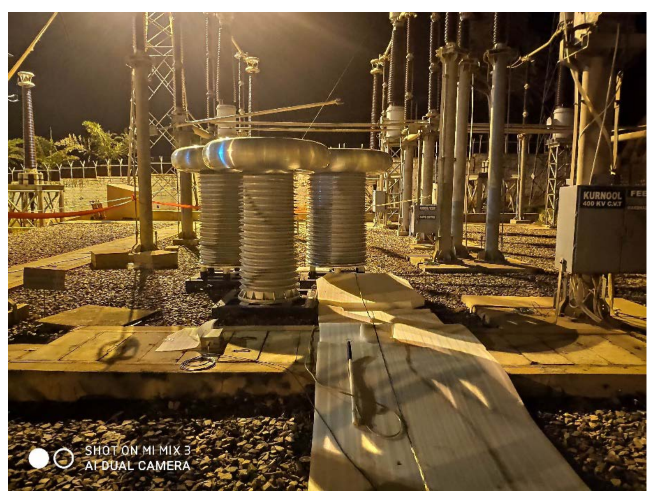


Figure 1. RTS at the site.

high sensitivity across a large bandwidth, which proves advantageous in locating PD sources in a complete cable circuit. In the following, it's briefly explained about the tests conducted using HFCTs connected on the earthing/bonding cables at different joints and terminations. Figure 4 shows a generic cable system complete with the earthing/bonding arrangement.

PD measurements during the commissioning test are either performed simultaneously at all Joint Bays (JB) (i.e., JB1, JB2, …., JB8) and terminations or sequentially at every accessory. The HFCTs must be mounted at every JB for simultaneous measurements, either temporarily or permanently, and individual PD measuring devices must be connected at every JB. In this configuration, the test voltage is applied only once, and measurements are recorded simultaneously at all terminations and joints during the test. Alternatively, sequential measurements can be carried out at each termination and JB by using multiple HV applications. In this situation, the test engineer moves along the circuit, measuring all the cable accessories sequentially, as shown in Figure 5.

If we compare simultaneous versus sequential measurements, the cable system is stressed multiple times at the test overvoltage in the latter case. Additionally, the operator has to move the PD instrumentation along the cable length to take the measurements, and hence, it can be a time-consuming process, especially for a long circuit with many joints. A further consideration is the total length of time the cable system is subjected to the overvoltage during the repeated voltage applications: field experience has nevertheless shown this not to cause problems. Since these tests are pre-commissioning tests, and 1.2 U_o is not considered very high stress.

Nevertheless, sequential testing is often called simultaneous testing since it saves set-up costs requiring fewer measuring devices and no communications network. One key advantage of the simultaneous measurement is the continuous application of the test voltage gives the maximum amount of time for any voids in the accessories to charge sufficiently to start discharging during the test period.

Figure 2. Connection of RTS with the cable at the site.

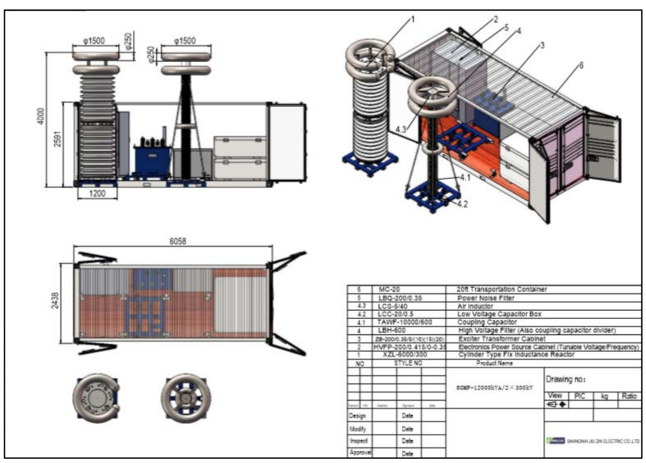


Figure 3. System outlook drawing used in the field.

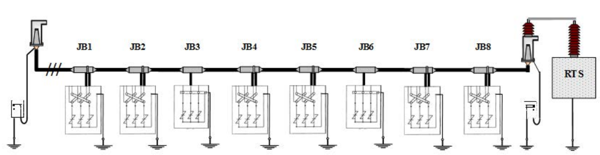


Figure 4. Generic cable system installation with JBs and RTS connection.

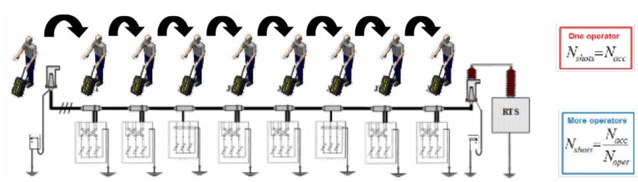


Figure 5. Sequential measurements at all JBs one by one.

2.1 Noise Rejection

The Time-Frequency (T-F) map algorithm is a useful de-noising technique for several reasons, including:

1. Noise rejection
2. Segregation of PD signals from noise
3. Separation and identification of multiple PD sources from within the same test object

A key advantage of the T-F map algorithm is that the filtering can be applied during data acquisition, allowing PD phenomena to be identified as quickly as possible, i.e., while the test is still running, thereby not stopping the test if PD is detected. Post-processing of the data allows the different segregated clusters to be reformed into Phase-Resolved Partial Discharge (PRPD) patterns, making it easier to identify the particular PD phenomenon from its PRPD pattern (e.g., internal PD, surface PD, corona discharge, etc.).

Field-captured PD data do not resemble the classic PD patterns captured in a laboratory under controlled conditions with minimal noise and ideal defects. In the real world, the actual PD signals are sometimes masked within the noise level or overlapped with other types of discharge phenomena. Under such circumstances, it is difficult to assess the severity of the internal discharges as they do not appear in entire PRPD patterns. This problem can be resolved by utilizing the T-F Map algorithm.

Eq. Frequency $$F = \sqrt{\int_0^{\infty} f^2 \left|\tilde{S}(f)\right|^2 \, \mathrm{d}f}$$

Eq. Timelength $$T = \sqrt{\int_0^{L} (t - t_0)^2 \tilde{s}(t)^2 \, \mathrm{d}t}$$

Figure 6. Fast Fourier transformation equations for T-F map.

T-F map comes from the fast Fourier transformation of each and every pulse appearing in the PRPD pattern and gives the result in equivalent frequency and equivalent time length. Different PD sources and noise are different when comparing their location, occurrence and repetition rate. Hence, every PD defect in the insulation has different T-F characteristics and helps analyze and identify each PD phenomenon.

3. Brief Understanding of XLPE Cable and Possible Defects

Considering these types of defects, it becomes essential to perform an HV AC test to detect early defects and avoid any sudden failure of the insulation system.

The experience and observations during on-site HV tests are shared in the following sections.

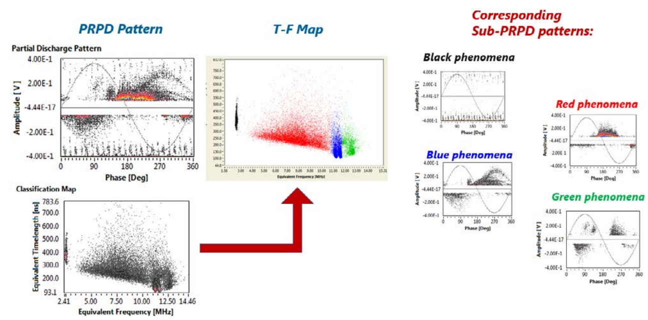


Figure 7. Advantages of T-F map in the segregation of different PD phenomena.

4. Case Studies

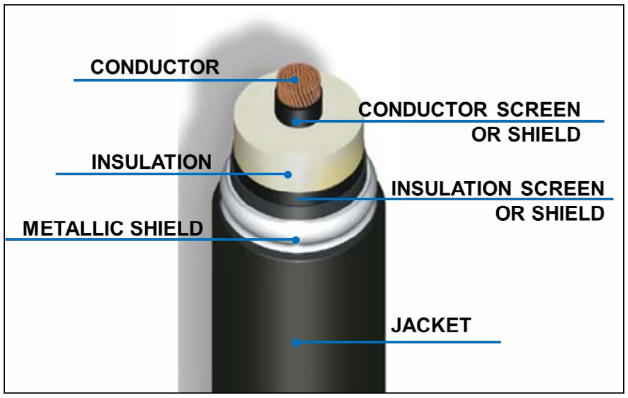
4.1 Commissioning Test on a 230 kV, 50 Hz Cable of 16.1 km Length (Italy)

230 kV, 16.1 km long cable with 31 joints was tested in Italy for HV AC voltage test by monitoring PD at all the accessories and joints[5]. The two cable circuits constituting the cable system are identical, and both were commissioned employing the same procedures and testing. The single cable circuit is depicted in Figure 9. At both Sides 1 and 2, the cable is terminated through outdoor terminations, and then the joints are installed at about every 500 to 600 m. Table 1 provides the main characteristics of the tested cable circuit.

Figure 10 shows the installation of the PD measurement system in the field on (A) the outdoor terminations and in (B) the joint bays (JB). The acquisition boxes, temporarily installed at the termination and inside the manholes close to the joints, contained the PD instrument and the communication means. In this example, the PD measurements were carried out at all locations simultaneously and to achieve this, and the acquisition units were connected through a fiber optic communication network in a daisy chain arrangement. Each acquisition unit had six channels connected to a PD sensor at the same detection point.

Figure 11 shows the original PRPD pattern from a signal sensor location and how T-F map filters can classify the detected signals. No PD phenomena emanating from inside the cable occurred during the resonant AC withstand test even at maximum test voltage applied, namely, 1.6Un in this case. Nevertheless, other PD signals were captured, and three clusters were identified in the T-F map. The point in the T-F map clusters can subsequently be reconstructed back to PRPD patterns to aid identification. In this case:

1. The black cluster shows noise from the RTS IGBTs (vertical lines) and other background noise
2. The blue cluster is probably surface discharge at the RTS connection



(a) Typical cable cross-section.

(b) Internal PD in the form of treeing.

(c) PD defect in termination.

(d) Surface discharge at the interface.

(e) Corroded shield.

(f) Broken jacket.

Figure 8. **(a)** to **(f)** shows the cross-section of a typical cable, possible defects due to poor workmanship or improper care of the installation, and defects due to operation and ageing of the main insulation of the cables.

Table 1. Main characteristics of the cable system under evaluation.

Rated voltage	230kV
Rated frequency	50Hz
Cables under test	3 × 2 circuits
Insulation technology	extruded XLPE
Embedded capacitive sensor	RFCT permanently installed
Sectionalized or straight	Both
Total number of accessories	198(12 OT + 186 Joints)
Total length	16.1 km

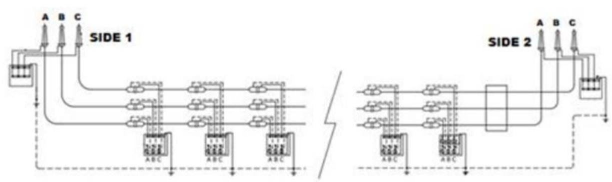


Figure 9. Schematic of a 3-phase 230 kV, 16.1 km long cable installation. Side 1 was used to inject the high voltage.

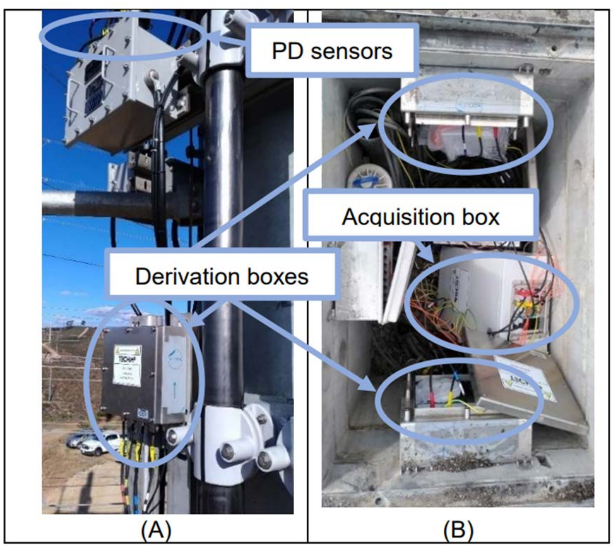


Figure 10. Installation of the measuring system **(A)** On the outdoor terminations and **(B)** In the joint bays.

3. The red cluster shows corona at the outdoor termination

Each phase of the two circuits was tested in turn from Side 1, and with PD acquisition units at each joint bay and the remote termination (simultaneous test arrangement), all the data could also be accessed and analyzed from the same location. If PD was detected during the test in any accessory (or the cable), the test voltage could immediately be reduced, and the source investigated. In this case, all six phases successfully passed the test.

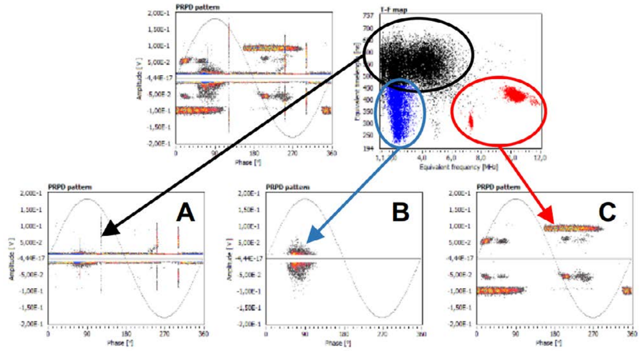


Figure 11. Separation of signals employing the T-F map.

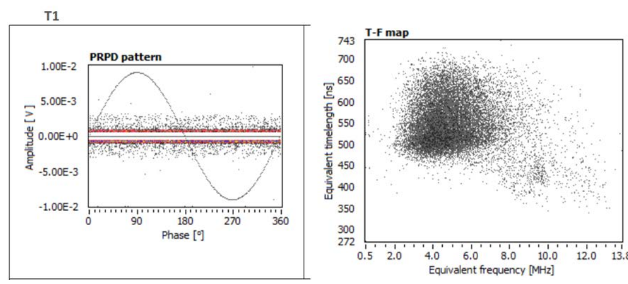


Figure 12. Results of termination 1, T1.

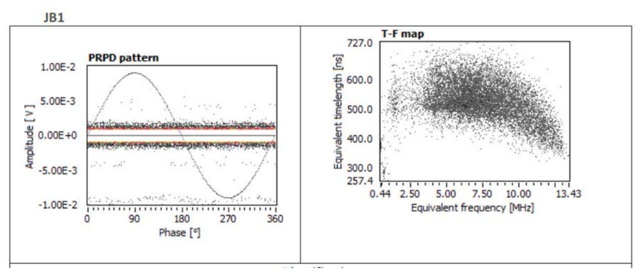


Figure 13. Results of joint 1, JB1.

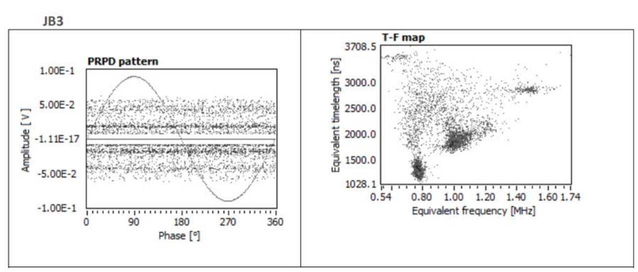


Figure 14. Results of joint 3, JB3.

4.2 Commissioning Test on 220 kV, 50 Hz Cable Circuits of 5.8 km Length (BPCL Kochi, India)

An offline HV and PD test was carried out in Oct 2021 on a 220 kV, 5.8 km long cable circuit at the BPCL Refinery, Kochi in India. The resonant test system used could deliver 300 kV, 60A AC RTS to apply sinusoidal single-phase HV to the XLPE cable system through an outdoor air-XLPE bushing. In this example, the AC resonant test was performed sequentially at both the end-terminations, T1 & T2 and the 11 joint bays, JB1 to JB11. Using portable PD monitoring equipment (Model: AQUILA), this was achieved sequentially to each joint bay and termination. The test was carried out at a $1.4U_0$ rated voltage, and the frequency was 40 Hz.

The T-F map and the PRPD patterns shown in Figure 12 to 14 show only background noise at a few test locations. Note that the equivalent frequency and time-length of the patterns changes as the distance from the termination are increased (i.e., each successive joint bay) due to attenuation and dispersion of extraneous signals entering at the termination.

At the time of the commissioning test, the cables were found to be PD free within the measurement sensitivity. The measurements can be repeated after six months or a year to detect any possible PD phenomenon which may arise due to thermo-mechanical movement and electrical stresses.

5. Conclusion

HV resonant tests with PD measurements effectively screen defects introduced into the cable system during installation. In the two examples performed on 230 kV and 220 kV cable systems, the test was completed successfully on all the cable circuits in 4-5 days. Although this is longer than a 24-hour soak test, it provides a higher degree of quality assurance before switching the cable circuit into operation.

The discussed case studies show the effectiveness of the PD measurement carried out during the AC withstand test and help reduce the infant failure of newly commissioned cables. The PD measurement system worked very well despite external disturbances in the form of corona discharges, external discharges or disturbances emanating from the HV test system. The use of T-F map technology helps in the separation and identification of multiple discharge sources, which in these case studies were diagnosed as external discharges originating from outside the cable and avoided giving a false negative result. This way has helped in achieving a good Signal-to-Noise Ratio (SNR), essential to detect PD phenomena harmful to the insulation system.

6. References

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