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Recent experiences with after-laying tests of solid dielectric transmission class cables

Streszczenie. (Najnowsze doświadczenia z prób pomontażowych kabli przesyłowych z izolacją stałą). *W okresie ostatnich dwóch lat pewna liczba kabli XLPE przesyłowych i rozdzielczych – rozlokowanych głównie na środkowym wschodzie – została poddana próbom pomontażowym obejmującym: test napięciem przemiennym podwyższonym oraz próbie na obecność wyładowań niezupełnych (wnz). Badania te były częścią pakietu prób odbiorczych kabli. Próby napięciem podwyższonym wykonano zgodnie z normami IEC 62067 [1] oraz IEC 60840 [2], a próby wyładowań niezupełnych wykonano przy użyciu dostępnego komercyjnie rejestratora wnz. Artykuł przedstawia otrzymane wyniki oraz zebrane doświadczenia.*

Abstract*. Over the past two years, a number of transmission and distribution class XLPE cable circuits - located primarily the Middle East - have been subjected to after-laying tests consisting of ac high potential over voltage tests and partial discharge tests as part of a commissioning test package. The hi-potential tests were performed in accordance with IEC 62067 [1] and IEC 60840 [2] and the partial discharge tests were performed using commercially available partial discharge monitoring technology. The results obtained and experience gained are presented in this paper.*

Słowa kluczowe: kable XLPE, próby pomontażowe, wyładowania niezupełne.
Keywords: XLPE cables, after-laying tests, partial discharges.

Introduction

Over the past past decade the use of solid extruded polymer cables in high voltage transmission systems has steadily increased throughout the world. The reason for the rapid increase in such cable installations is due to opposition, especially in urban areas, to overhead lines. Further, environmental concerns severely limit the possibility of employing self-contained or high pressure fluid-filled systems, thus the overwhelming majority of new underground infrastructure projects utilize high voltage cross-linked polyethylene (XLPE) insulated cables.

Typically, these circuits are of significant importance in the power system. Further, their installation in often congested urban environments requires that these cables and the associated accessories are highly reliable. Utilities in some jurisdictions are requiring warranties of twenty years and upwards. Consequently, afterlaying tests capable of identifying life limiting defects in the cables or accessories are specified by utilities in many parts of the world.

Traditionally, due to the lack of ac high voltage power supplies capable of energizing cable lengths in the range of several kilometers, dc overpotential tests were applied similar to those employed for fluid-filled cables. However, concerns with respect to problems caused by space charge injection resulting from high voltage dc testing resulted in dc tests being abandoned for cables insulated with solid extruded polymers. The lack of alternative forms of external energization lead to the use of the so-called soak test in which the newly installed cable is put on potential at the relevant system voltage, but not loaded, for a period of up to 24 hours. However, there have been a number of cable and accessory failures that occurred within a short time following connection of the cable being placed in service.

Fortunately, the availability of variable frequency ac power supplies has enabled afterlaying high voltage testing of XLPE-insulated transmission cables of up to 20 km in length at the 400 kV level. The purpose of this contribution is to discuss the application of ac overpotential testing in conjunction with partial discharge (PD) testing to aid in assuring the reliability of the cable installation.

Test Equipment

High voltage power supply

The high voltage power supply employed in the work described below is a 260 kV, 83 A variable frequency resonant test set. This power supply is compliant with IEC standards 60840 and 62067 and operates within the frequency range of 20 – 300 Hz. A schematic of the test setup is illustrated in Figure 1 and a photograph of a typical set up in the field is shown in Figure 2. As can be seen from Figures 1 and 2 a blocking impedance is placed between the power supply and the high voltage connection to the cable under test. The purpose of the blocking impedance is two fold: Firstly, the blocking impedance protects the RTS in the unlikely event of a cable failure and, secondly, the blocking impedance effectively filters any high frequency noise originating from the RTS thus improving the signal-to-noise ratio of the power supply for the purpose of performing PD measurements.

A capacitive voltage divider provides for a voltage reference for the control unit of the power supply. Though not seen in either Figure 1 or 2, the common point grounding of the entire test circuit is connected to station ground for the circuit under test. A 6” wide copper foil provides for a high frequency ground path whereas a stranded, insulated aluminium conductor positioned directly on top of the copper sheath constitutes the power frequency ground.

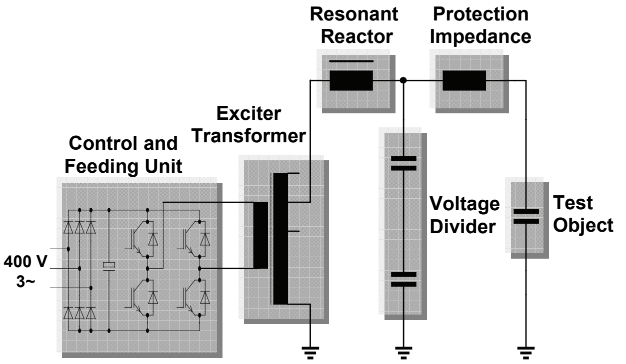

Fig. 1. Schematic of high voltage power supply

Fig. 2. Typical test set up

Signal detection

Signal coupling is provided by attaching a High Frequency Current Transformer (HFCT sensor) around the ground link from the cable joint towards the link-box. High frequency currents induced as a result of any partial discharge activity occurring in the joint or in the cable section will be coupled to the HFCT sensor and measured by a conventional partial discharge monitor. Figure 3 shows a HFCT sensor placed around the ground link of a joint in a typical configuration.

The partial discharge monitor used is commercially available and has a bandwidth of 350 kHz to 800 MHz and measures the amplitude (in mV) and phase angle of any signal detected. As measurements are performed in time intervals of up to 5 minutes, a pulse count rate for various categories of magnitudes and phase-angles is generated.

The phase angle reference is provided by a low-frequency winding embedded in the HFCT sensor it self. In addition, the operator would check the waveform of the signal activity measured via an oscilloscope to confirm the signal strength as well as confirm the presence of PD or noise.

Fig. 3. Photo of HFCT sensor in MH #2

Test Method

While IEC standards 60840 and 62067 provide basic guidance on the waveform, frequency and prescribed voltage to be employed during the overvoltage test, there is no standard procedure laid down for PD measurements. Consequently, there is some variation in the measurement procedures employed by the various service providers in this field. The basic measurement protocol followed in the tests to be discussed below consisted of,

1. Upon tuning of the high voltage power supply to the appropriate resonant frequency, a relatively low voltage of the order of 30 - 40 kV is applied for two minutes. During this time various diagnostic parameters are checked to ensure that the system is functioning correctly.
2. The voltage is increased to the nominal line-to-ground potential (U_0) and held for a further two minutes while the diagnostic parameters are confirmed as normal.
3. The voltage is raised to the prescribed level specified in the IEC standards for one hour.

During the one hour high voltage test, PD measurements are performed at as many of the sensor locations as possible within the restricted time frame. However, the complete PD test for the entire circuit is usually performed at U_0 because the often significant numbers of joints mitigate against completing the measurements in one hour. Ideally, the PD testing should take place during the overvoltage test, however, on longer circuits with significant numbers of accessories there are limitations on how many

Field Experience

The following discussion of field experience is based on numerous tests performed in various locations in the Middle East and North America. All of the cables were XLPE-insulated spanning the voltage range of 66 through 380 kV with circuit lengths ranging from 3 to 15 km. Typically, those circuits rated at 220 kV and above required the use of two resonant test systems operating in parallel. Figure 4 shows two parallel connected resonant test systems set up for testing a 380-kV and a 220-kV cable installation.

The majority of circuits subject to overpotential testing successfully withstood application of the prescribed voltage for one hour. However, in a small number of cases dielectric breakdowns have occurred. The times-to-failure range from just over one minute to 21 minutes. One of the failures was located in the cable itself and the remainder were found either in, or in close proximity to, a joint or termination. Typically, defects in the joints were attributable to problems with installation procedures rather than resulting from design or materials deficiencies. Regarding the one incident in which the failure occurred in the cable, mechanical damage to the cable during transportation or storage may have played a role. However, the root cause of that breakdown is still under investigation. The failure that occurred after one minute was located in the immediate vicinity of the joint but not in the joint itself.

Fig. 4a. Parallel setup of two resonant test systems for testing an 11-km 380-kV cable installation

Fig. 4b. Parallel setup of two resonant test systems for testing a 10-km 220-kV cable installation

Fig. 5. Example of treeing in failed cable

Microscopic examination of the cable demonstrated that the failure had resulted from electrical treeing (Fig. 5). However, the treeing had not resulted from the inclusion of a void or contaminant but rather from mechanical damage inflicted on the cable during preparation of the cable for splicing.

Evidence from the post-failure analysis showed that significant electrical treeing had occurred prior to failure, even in the short time that the cable was at the test voltage. In principle, this type of defect should have been amenable to detection using PD measurements. However, the short time-to-failure rendered the probability of detection prior to breakdown remote. The methodology used to facilitate PD tests on these cable installations requires that a measurement be made at each joint and termination. Presently, two sets of PD test operators are deployed and these two teams leapfrog each other down the cable route. This method has the advantage that if one team considers that signals consistent with a PD source are present in an accessory, the second set of operators at the next joint can aid in confirmation using the assumption that a component of these signals will propagate to that location. However, there are obvious limitations in this strategy and, in most practical cases involving large numbers of accessories the PD test cannot be completed within the one hour time frame of the overvoltage test.

Ideally, a PD test conducted at the terminals of the cable circuit would solve the time constraint issue. However, well known problems due to signal attenuation and dispersion in cables place a limitation on the lengths of cable upon which such a measurement method could be applied successfully. Detection of PD-related phenomena occurring several kilometres from the detection point requires that the bandwidth of the measurement be relatively low. Consequently, such techniques will suffer problems due to the relatively high background electrical interference associated with field measurements. Further, although mitigating steps are taken to minimize the effect of switching noise from the high voltage power supply, these signals will also be present to add to the difficulty of the task of separating PD signals from noise.

Alternatively, schemes have been implemented in which a PD measurement system is installed at each of the accessories in the circuit. Signals from these devices are fed back to a remote test operator for display and analysis. These installations although expensive have significant advantages in that each sensor point can be observed simultaneously in real-time.

A critical question of concern when making PD measurements relates to the establishment of pass/fail criteria for PD magnitudes. While the simplest, and most conservative, answer is that any detectable level of PD is too high, there are many practical issues that need to be address among them the costs and delays introduced by replacing a section of cable or an accessory. One practical example of attempting to define PD-based acceptance criteria for commissioning testing is illustrated in Figure 6. The left side of Figure 6 displays the data acquired during the off-line test whereas the right side of the figure displays the data acquired during the on-line test. The applied voltage for both tests was U_0. The PD activity measured during the off-line test has a frequency content ranging from 7 MHz to 8 MHz. The minimum, mean and maximum PD magnitudes for the off-line data are 5 mV, 7 mV and 24 mV respectively. In addition, the phase resolved PD plot for the off-line data shows clusters of negative and positive polarity pulses centered near 45° and 225° phase angle with reference to the phase to ground voltage which are classic phase locations for phase-to-ground dependent partial discharge data. However, during the on-line tests, the signal activity measured is quite different: As can be seen, the frequency content of the signals measured range from approximately 800 kHz to approximately 2 MHz. In addition, the phase resolved PD plot show the pulses measured to be located through out the AC cycle. Consequently, the data acquired during the on-line test relates to electrical noise.

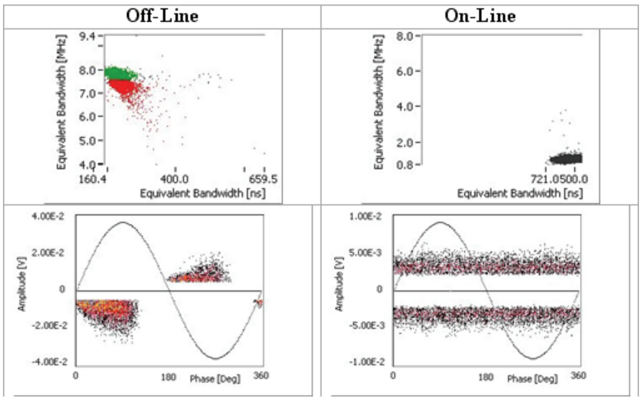

Fig. 6. Comparison of off and on-line PD test results

The figure demonstrates that no PD signals were present during on-line tests. Had PD been present, it would have been detected simultaneously with the noise signals and would have been identifiable in the frequency domain plot of Figure 6. While there are a number of factors that may account for the differences observed above, the decision was made to put the cable in-service notwithstanding the presence of detectable PD during the off-line test. This circuit is currently operating without incident.

One key point emerging from the testing performed to date is that all of the circuits that successfully withstood the high voltage tests and on which no PD was detected at U_0 have operated without incident since commissioning. Those failures that have occurred did so either very rapidly thus lowering the probability of successful detection or, in the case of the longest time-to-failure and others, where no PD test was specified. Consequently, the combination of overvoltage and PD testing appears to provide the highest level of confidence in the reliability of the cable, accessories and installation method.

Conclusions

Numerous transmission cable circuits in the Middle East and North America have been subject to high voltage and PD testing as part of the commissioning process following installation. The majority of the cables tested successfully met the test criteria. However, a small number of cables suffered dielectric breakdown during the overvoltage test. The failures were generally located in, or in close proximity to, the accessories. Only one of the breakdown sites was located in the cable itself.

Times-to-failure ranged from just over one minute to 21 minutes. These time frames were insufficient to permit detection of PD prior to failure. Where post-failure analysis has been performed the results are consistent with installation issues or damage to the cable during transportation or storage. None of the breakdowns has been attributed to design, materials or processing issues.

While there is significant ongoing debate regarding the technical and cost issues associated with optimizing PD test procedures for on-site transmission cable testing, experience from this and other contributions shows that the combination of high voltage and PD testing of transmission cables is necessary to satisfy the needs of the industry for high reliability.

The comparison between off- and on-line PD testing described in this contribution demonstrates that there is still significant work to be done to establish reliable pass/fail criteria based for PD testing.

REFERENCES

[1] IEC Standard 62067, Power Cables With Extruded Insulation and Their Accessories for Rated Voltages Above 150 kV up to 500 kV – Test Methods and Requirements

[2] IEC Standard 60840, Power Cables With Extruded Insulation and Their Accessories for Rated Voltages Above 30 kV up to 150 kV – Test Methods and Requirements

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