PD Testing and Monitoring of HV XLPE Cable Systems

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The correct design and the quality of production of XLPE cable and its accessories, terminations and joints, is checked by various routine tests at the manufacturer’s plant according to relevant standards.

However, installation work on site poses a possible risk of introducing faults, which could negatively impact reliable operation over time. Small particles, dust, and moisture might lead to defects in electrically critical locations of the accessories. Dielectric tests performed on site are therefore highly recommended. These supplementary tests are aimed at checking the dielectric integrity of the fully assembled cable line in order to eliminate defects caused by damages during transportation and lay-out or incorrect assembly of the accessories.

The preferred voltage for on-site tests is ac voltage of industrial frequency, although voltage testing only delivers binary results (withstand or breakdown). Therefore, it is recommended to combine ac voltage testing with sensitive on-site partial discharge (PD) measurements.

Why PD? A major part of all in-service failures in HV XLPE cables can be attributed to the insulation system of accessories, joints and terminations. These failures will normally develop over time. In order to detect these changes at an early stage, detailed information about the actual insulation condition is necessary. With suitable sensors, this information can be derived by monitoring PD activity during the operating life of the equipment.

This article describes the best practice for performing after installation testing and continuous PD monitoring to assess the quality and extend the life of the HV XLPE cable system.

PD Measurements During After-Installation Testing

High-voltage (HV) tests are executed on site for all extruded HV cables. On-site test procedures usually have to be negotiated between the manufacturer and the user on the basis of international and national standards.

Two IEC standards cover after installation tests of extruded cable systems: IEC 60840:2004 for cables of rated voltages from 30 kV ($U_m=36$ kV) up to 150 kV ($U_m=170$ kV) and IEC 62067:2001 for rated voltages above 150 kV up to 500 kV ($U_m=550$ kV). High test power, especially required for long cable lines testing, can only be efficiently generated by
mobile resonant test systems, where the weight-to-power ratio and feeding power demand is relatively low and the transport volume is acceptable (See Figure 1).

The whole dielectric test should be performed as a step test. PD measurements should be taken at every voltage level. By increasing the test voltage in steps of e.g. 20% of the maximum test voltage, critical defects are usually identified before breakdown.

Because HV cables must be tested at the manufacturing facility prior to shipping to the installation site, the on-site PD measurements focus on the field-installed accessories. For this purpose, each accessory has to be equipped with special sensors, such as high frequency current transformers (HFCTs) to pick up the PD signal with high efficiency (See Figure 2).

As an example, during a particular after installation testing of a 220 kV XLPE cable line, fifteen HFCTs were used to pick up the PD signal. They were equipped with an air gap in the core to prevent magnetic saturation.
One MPD 600 unit from OMICRON was connected to the coupling capacitor and calibration was performed according to the IEC 60270 and IEC 60885 standards. A performance check was performed on the other fifteen PD acquisition units, which were mounted into the link boxes close to the terminations and connected in a daisy chain with fiber optics. (See Figure 3). A real calibration is not possible here because impulses cannot be injected directly into the closed and buried joint.

The resonance test set used IGBT’s as switching semiconductors. They produce strong impulses that cause high interference impulses on the MPD 600 instruments, especially to those units which are rather close to the resonance test set. To eliminate this effect, PD
signal gating was performed by one extra MPD 600 unit which was installed close to the IGBT circuit to receive the switching impulses. During the time of the switching impulses, the signals of all other units were blocked by the MPD 600 software. Due to the fact that this is done by software, such gating can be deactivated also for the replay of all recorded streams later on. The result of gating is shown in Figure 4.

Figure 4: PD measurements at joint without gating (left) and with gating (right)

The dielectric withstand test was performed at 180 kV and the corresponding voltage frequency and current were 26 Hz and 68 A respectively. The measurement center frequency for all MPD 600 units was set between 2 MHz and 3 MHz. The selection of lower frequency was not possible due to the high interference.

The PD results at 180 kV at all MPD 600 units are shown in Figure 5. No PD activity was detected and the tests were successfully finished within 3 ½ days.

Figure 5: PD measurement at 180kV with 15 MPD units
1.1 = coupling capacitor, 1.3 = joint 1-2, 1.4 = joint 2-3, 1.5 = joint 3-4, 1.6 = joint 4-5, 1.7 = joint 5-6, 1.8 = joint 6-7, 1.9 = joint 7-8, 1.10 = joint 8-9, 1.11 = joint 9-10, 1.12 = joint 10-11, 1.13 = joint 11-12, 1.14 = joint 12-13, 1.15 = end terminal of GIS.
Monitoring of 420 kV XLPE Cable System in an Underground Tunnel

A. Continuous Monitoring System Concept

An underground tunnel having a length of 10 km and a 3-meter inner diameter connects the substations at Beddington and Rowdown in London. The tunnel houses a new 400 kV, 2500 mm² XLPE cable circuit. The longest cable sections are approximately 1176 m in length, which is currently the record for this type of voltage in the UK.

A continuous monitoring system was applied to the cable system. Partial discharges (PD) are continuously monitored at all joints and terminations, and at the same time the system performs measurement of oil pressure in terminations and checks the condition of all sheath voltage limiters (SVLs) located in the joint bays (See Figure 6).

Figure 6: Schematic diagram of monitoring system

The concept of an applied continuous monitoring system is presented in Figure 7. The signals from different sensors measuring partial discharges, distributed temperature, oil pressure in terminations and sheath voltage limiters are acquired by multi-channel data acquisition units.
In case of PD signals, the acquisition unit performs advanced pre-processing of the raw data. The disturbances are removed and main characteristics of the PD signal are determined. The output of the data pre-processing is transferred to a server, which enables long-term data storage. Advanced intelligent pre-processing reduces the amount of data to adequate levels for transmission over a communication network.

The separation of PD sources and the effective suppression of external noise is achieved by the application of synchronous multi-channel (3PARD) evaluation techniques. The 3PARD diagram visualizes the relation among amplitudes of a single PD pulse in one phase and its crosstalk generated signals in the other two phases.

**B. PD Acquisition System and Inductive Power Supply**

Inductive high frequency current transformer (HFCT) sensors are mounted on cross-bonding (CB) links and are used to detect PD directly at the accessories. The PD monitoring system consists of one four-channel, high-precision and modular acquisition unit for each accessory. The acquisition unit is connected to a data concentrator. One data concentrator collects monitoring data from two or three acquisition units via fiber optic cables, and it routes the data to a server. Pre-processing functions, such as band pass integration, gating, denoising and multi-source separation, are already performed in the data concentrator.

The active components of the monitoring system require electrical power for several processes. In addition to the computer and communications devices, pre-amplifiers or signal converters (for example electrical to optical) located close to the sensors also have to be supplied with power.

The Inductive Power Supply (IPS) provides the necessary electronics to supervise and manage the dc current delivered at its output, depending on the various HV cable current.
load situations (See Figure 8). The PCBs and electronics elements are filtered and optimized to avoid any disturbances of the PD measurements close by.

Figure 8: Inductive Power Supply

C. Sheath Voltage Limiters Monitoring

Sheath Voltage Limiters (SVL) minimize the transient voltage across the screen separation of cross-bonding joints during switching or lightning transients and they reduce the risk of damage. The access to the SVLs is limited, so there is a requirement to continuously monitor their status, such as:

- Normal operation (below inception voltage);
- SVL is short circuited when the conductive flashover trace is generated through the SVL varistors;
- SVL is in open loop – totally damaged (active elements destroyed-exploded).

An SVL is a non-linear resistor and, together with the parallel cable screen at a cross-bonding link, creates characteristic loop impedance. This impedance will change according to the status of the SVL, and the operation of the SVL monitoring system is based on these changes. In the monitoring system, the PD acquisition units located at the joint bay periodically “inject” signal pulses using their internal test generators. These signals propagate through the HFCT sensors to the SVL impedance loop and are collected by the acquisition unit. The Fourier transforms of injected and returned signals are calculated, averaged and compared. No special sensors are required for the scope and a major part of evaluation of SVL monitoring data is performed within the monitoring server. Differences can be easily analyzed and distinguished by a spectral processing algorithm implemented in the monitoring server software (See Figure 9).
D. Server and Software Architecture

The monitoring server receives data for analysis, display, and storage. The acquisition units are configured and remote-controlled by the monitoring system software. The software supports remote access over TCP/IP. This allows operators to quickly react to detected problems and access the stored data from any remote location. The software is a highly modular, scalable distributed system. Its system architecture consists of the Windows-based core part and the web-based control part. The core part of the monitoring software is realized as windows services and runs continuously without any direct user interactions. The core system implements: Collection and persistence of measurement; data post-processing and analysis; security tasks for data access and system operations; and external interfaces for data exchange over Ethernet or field bus.

E. Trend Analysis

The monitoring system provides data from each of the acquisition units and oil pressure sensors in permanent and periodic time intervals (See Table I).

<table>
<thead>
<tr>
<th>Value</th>
<th>Mode</th>
<th>Permanent</th>
<th>Periodic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial Discharge</td>
<td>every 2-3 sec</td>
<td>for 1 every 1 h</td>
<td></td>
</tr>
<tr>
<td>Oil pressure at terminations</td>
<td>every 2-3 sec</td>
<td>once every 1 h</td>
<td></td>
</tr>
<tr>
<td>SVL status</td>
<td>--</td>
<td>once every 8 h</td>
<td></td>
</tr>
</tbody>
</table>

During the permanent mode, the data is acquired every 2-3 seconds, compared with
threshold values and displayed in real-time in the graphical user interface. If this data is within normal margins, it will be colored in green. If the values exceed thresholds for "warning" or "alarm", they are colored in yellow or red accordingly.

Periodic measurements are initiated in equidistant time spans, such as every hour. The duration of the periodic measurement is normally 1 minute. During this time span, all mentioned scalar values are calculated and PRPD (phase resolved PD) and 3PARD diagrams are acquired. This data is saved for later post-processing and trend visualization. Unscheduled periodic measurements are triggered in case one or more measured quantities exceed the threshold level.

PD activity is displayed as PRPD for each phase/sensor and for each separated PD source, respectively. Trend diagrams of statistical parameters such as PD magnitude, frequency of occurrence of PD pulses, etc. are available. Suitable filter options enable the user to select the data display according to his specific interest. The user can set limits that cause warning or alarm messages to be generated when exceeded. The measured values are continuously compared with signal levels (See Figure 10).

The measured quantities are color-coded based on their value related to pre-set warning or alarm threshold levels. For example, if the detected PD level on any channel on one asset exceeds a configurable threshold, the corresponding value will be drawn in red.

Figure 10: Graphic user interface

The SVL status is verified within the Server Software by FFT-based spectral analysis of the signal injected to the XB link loop impedance from PD acquisition unit. A statistical model of “normal” SVL behavior is used for reference. The model is constructed based on the SVL data collected during starting limited time period of cable system operation with different load...
conditions. SVL status analysis is based on statistical comparison parameters between the model and current SVL measurements which clearly distinguish normal operation of SVL from short circuited and open loop SVL.

F. Acceptance of the Monitoring System on site

The monitoring system was routinely tested in the factory and later installed on-site (See Figure 11).

![Installation of the system on site](image)

**Figure 11:** Installation of the system on site

The site check of monitoring system performance was performed according to the following steps:

- **Step 1:** Verification of the functional readiness of the measuring system and of the monitoring server
- **Step 2:** Verification of the synchronous behaviour of the PD measuring system
- **Step 3:** Determination of PD impulse attenuation, damping and dispersion along the cable system.

The following parameters were determined: PD impulse attenuation; damping and dispersion along the cable; velocity of the calibration signal in the cable; best frequency ranges for PD measurements at all PD units (with highest signal to noise ratio); and PD detection path division factor for every chosen frequency range.

G. Maintenance of the system and customer support

The monitoring system service and maintenance scheme is presented in Table II. The installed system elements, such as sensors, acquisition units, power supplies, batteries and
fiber optic data transmission network elements are periodically inspected and checked. These visual inspections and functional checks include adjustments, repair or minor maintenance activities. Such visual inspections are planned once every three years in coordination with the scheduled maintenance activity of the cable system. This requires access to the system installations, including the cable tunnel, manhole, shafts and other related substation facilities. It may also necessitate an eventual outage of the cable system, which requires respective scheduling efforts. Software updates include periodic modifications, bug fixes, and enhancements with new features. If requested by the system owner, regular checks and evaluation of data values as well as trending of the acquired partial discharges stored in the monitoring system database can be performed on a per cable system accessory basis. In the case of repeatedly reported trending alerts or alarms, or specific PD events detected by the monitoring system, outside PD expert consultancy and support can be requested by the system owner.

Table II: Maintenance scheme of a monitoring system

<table>
<thead>
<tr>
<th>System element</th>
<th>Activity to be performed</th>
<th>Periodicity</th>
<th>Responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardware</td>
<td>visual check</td>
<td>yearly</td>
<td>owner</td>
</tr>
<tr>
<td></td>
<td>functionality check</td>
<td>every 3 years</td>
<td>owner &amp; system provider</td>
</tr>
<tr>
<td>Software</td>
<td>updates</td>
<td>every 3 years</td>
<td>system provider</td>
</tr>
<tr>
<td></td>
<td>data evaluation</td>
<td>periodic reports</td>
<td>system provider</td>
</tr>
<tr>
<td></td>
<td>expert consultancy</td>
<td>in case of PD event</td>
<td>system provider</td>
</tr>
</tbody>
</table>

Conclusions

- The combination of resonance AC voltage testing and distributed, synchronous PD measurements at all cable accessories has proven highly effective for after installation testing of HV XLPE cable systems.

- A continuous PD monitoring system provides actionable data to support maintenance on a condition-based rather than time-based plan to extend the life of the HV asset.

- Separation of PD sources and suppression of external noise is effectively performed by the multi-channel evaluation techniques of the monitoring system.

- The Inductive Power Supply provides the necessary power to the monitoring equipment to supervise the 400 kV cable system. The dc current delivered is
depending on the HV cable load situations, but even at very low load the power is sufficient to run the monitoring system;

- To verify the status of SVL, the system can utilize the CB link loop impedance;

- A modular, distributed monitoring software system allows reliable long term storage of monitoring data and provides access via web interface.

- The monitoring system provider supports the asset owner in all stages of the monitoring project, from system design, installation and periodic mainenance, to training and data evaluation support.

About the Authors

Dr.hab. Wojciech Koltunowicz received the M.S., PhD and Dr. hab. degrees in electrical engineering from the Warsaw University of Technology in 1980, 1985 and 2004, respectively. From 1984 to 1987, he was with Institute of Power in Poland, as a research scientist in the High Voltage Department. From 1987 to 2007 he was with CESI, Italy, where he was mainly involved in HV testing and diagnostics of HV equipment. In 2007, he joined OMICRON, where he is involved in monitoring of HV equipment. He is Secretary of CIGRE Advisory Group D1.03 “Insulating Gases”, WG D1.25 and Member of AG D1.02 “High Voltage and High Current Test and Measuring Technique and Diagnostic” and WGs D1.28, D1.37 and D1.51. He is also member of IEC TC42 WG14. He is author of dozens of international reports.

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