Integral sensing of HV cable joints – monitor operation and predict failures early

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ABSTRACT

Due to space restriction and visual appearance, cable systems are becoming an alternative to overhead lines, even in transmission networks. Furthermore, generally speaking, utilities and network operators tend to increase the power transmitted which could be required in regard to overload behaviour. This additional load increases the requirements on cables, as well as the relevant accessories. Nevertheless, safe operation is required and mandatory. This paper discusses the real life pilot installation of three joints equipped with the world's first-time use of complementary sensing technologies: Distributed Acoustic Sensing (DAS) and Distributed Temperature Sensing (DTS).

KEYWORDS

FOC, DAS, DTS, smart joint, hipot test, underground power cable, monitoring, temperature, acoustic

INTRODUCTION AND MOTIVATION

Energy distribution and transmission networks are constantly changing. This change is initiated by several factors, such as changes in energy generation from large power plants to several medium sized power plants.

Another additional aspect is power fluctuation which has become a widely discussed aspect. If there is sun and wind there is a lot of additional power but a few days of cloudy weather without a breeze requires additional backup generation. In this regard the expectation and our common approach in technology is another factor heavily influencing our network setup. There is no acceptance of energy disruption, a 100% continuous coverage of electricity at all time is expected.

These expectations in conjunction with the fluctuating sources, changes the requirement set for energy networks. Utilities need to plan for maximum single source load as well as 100% renewables. Therefore, there is a need to interconnect the distribution and transmission level, as well as to increase the capacity for energy transmission.

But how can this increase be managed? On one hand, one could add additional infrastructure. Interconnecting the mesh. At the same time bigger cross sections could be used to increase capacity.

Nonetheless these are huge investments that need time.

Considering the planning and structuring of existing networks, there are several potential methods to increase energy transmission. Particularly cable systems have been calculated and designed for a specific cause but usually are not run at full capacity. But why aren't these networks not run at full capacity?

A crucial factor limiting transmission power is the maximum permissible temperature of a cable system, usually limited at 90°C for XLPE-insulated cables [1], [2]. In normal operation, operators prefer to have some capacity left in order to handle critical situations. Thermal overload due to excessive currents may lead to critical changes in material properties and therefore shorten the service life.

During the project planning phase, cable transmission lines are designed in accordance with standards and technical guidelines with regard to a maximum limit current resulting from the maximum permissible temperature. Influencing factors such as cable structure, if necessary, accumulation of several cables laid in parallel (often three-phase circuits) as well as soil and ambient conditions are taken into account.

This method of system design is based on relatively roughly categorised calculations and empirical values, which in practice do not always apply completely or are deliberately assumed to be very conservative.

During operation, the network operator intends to operate the cable system within the limits. But future cable systems are designed closer to the limits, so there will be times when the operator will overload the cable for a limited period, e.g. due to high feed-in power from renewables.

Monitoring of decisive parameters (e.g. real thermal conditions) during normal network operation can therefore make a contribution to optimized capacity utilization. In addition, monitoring offers the possibility to detect characteristic changes at an early stage and to react to emerging problems, thus contributes to achieving a high reliability of the entire grid. If a fault occurs in the system, it is also an important tool for fault location and makes it possible to initiate repair measures rapidly and targeted.

If a cable system is in service information about temperatures is only available if an additional measurement system is applied. Often these sensors are optical fibres implemented in the cable's screen or armouring as seen in Figure 1. Additionally, optical fibres can also be used for measuring acoustic strain which can pinpoint cable faults to an exact location.

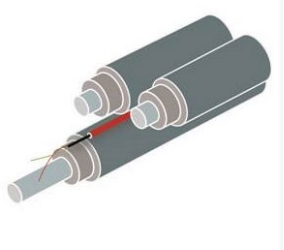

Figure 1: Setup of FOC with power cable

These fibres usually are not implemented in cable joints but in cables only. But cable joints are a crucial point of

Close and Return

information when it comes to temperatures and therefore ageing and load indication. AP Sensing and Pfisterer implemented a pilot installation in the network of Denmarks utility Energinet at which distributed temperature and acoustic sensing has been implemented within the joint as well as along the cable. This paper discusses the applicability and first on-site measurements of such a system.

GENERAL SETUP AND FUNCTION OF CABLE JOINTS

Due to transport restrictions, high voltage cables can only be manufactured in limited lengths. For longer cable lengths, this means that cable joints (often installed underground) are necessary for connecting cables. As with the high-voltage cable itself, the cable joints must have a high current carrying capacity on the one hand, and on the other hand the electrical insulation between high-voltage and earth potential must be ensured. It is an essential requirement that cable joints and all other cable accessories need to offer the same performance in regard of transmission performance and service life as the cable itself.

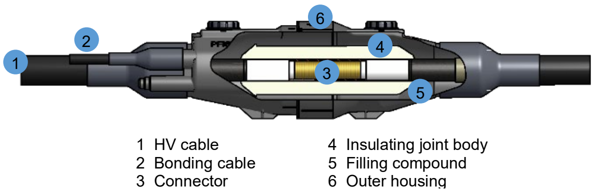

Figure 2: Cable joint for Um = 145 kV

The basic structure of a complete state of the art cable joint is shown in Figure 2. The aluminium or copper cable conductor is contacted by a current-carrying connector. For this purpose, usually screw or press connectors are used. Conductor cross-sections commonly range up to 2500 mm^2. According to the current state of the art, the electrical conductor connections are designed in such a way that no higher temperature occurs at the connector than at the current-carrying cable conductor [3].

The insulating joint body surrounding the connector consists of elastomeric material (usually silicone or EPDM) which has to withstand the electrical field stress not only under normal operating condition but also in the event of circuit faults as well as transient events (e.g. switching operations, lightning strikes). The insulating material contains special conductive contours needed for keeping field stress at non-critical values. This technical principle is often referred to as geometric field control. During installation the elastomeric joint body is temporary placed at one cable end side and pushed back to the final position after conductor connection is assembled.

The advantage of this slip-on technology lies in the fact that the prefabricated joint body can be manufactured under clean production conditions in constant high quality. Electrical pre-tests are performed on each insulating part at the end of production. At installation site, the insulation part of the cable joint only has to be placed onto the prepared and cleaned cable insulation. This procedure minimizes the risk of assembly errors and helps saving installation time compared to wrapping of insulation layers as it was made in former times. The life span of such cable accessories corresponds to service life of XLPE- or EPR-insulated cables.

The outer housing offers protection against moisture and external mechanical forces. The space between the joint body and the outer housing is filled with filling compound additionally leading to an improvement of mechanical stability. The bonding cables (often coaxial bonding cables are used) are connected to the screen of both sides of the HV cable. Thereby the shields of different phases of a circuit can be cross-bonded externally in order to compensate shield voltages and currents. Alternatively, the screens can also be grounded. Generally, treatment of shielding ends is dependent on the earthing concept of the circuit and is determined in its design.

The design of a cable system is intensively proven in type and prequalification tests according to IEC standards [1], [2]. Beside electrical tests such as lightning impulse voltage test, AC voltage test and partial discharge (PD) measurement, heat cycles with temperatures slightly above the maximum permissible conductor temperature as occurring in real field operation are mandatory to ensure functionality also under/after thermal stress.

Nevertheless, cable joints are crucial components in the network, e.g. improper installation may cause partial discharges, accelerated ageing of electrical insulation and finally may lead to a decreased reliability of the whole grid.

PILOT INSTALLATION – SENSOR EQUIPMENT INTEGRATED IN JOINTS

The pilot installation includes three cable joints (installed at different phases of a three-phase circuit), the associated linkbox and a separate box for electronic measurement devices. In this setup some special sensor components were implemented, which are evaluated as basis of a smart system consisting among others of:

- An optical sensor cable that has been routed through all three joints and allows the detection and localization of acoustic signals (DAS)
- Via further optical fibres, the temperature distribution within the cable joints can also be measured (DTS)
- Two electrical temperature sensors each inside the cable joints for reference measurements

The opposite side of the measuring cables, leading to the sensors inside the joints, ends in a manhole where the electronic devices are placed and the linkbox is installed. During the commissioning test (hipot test) of the circuit, a temporary setup was realized in order to check measuring functions and to carry out parameterizations.

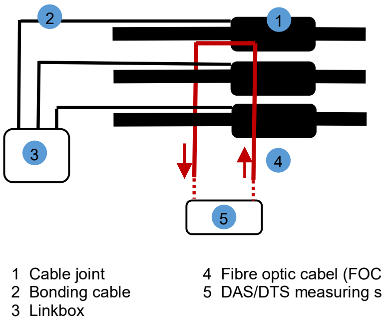

Figure 3: Principle setup of pilot installation

Optical Fibre Sensing Overview

Two types of distributed optical fibre sensing systems were used to measure both the temperature and acoustic/dynamic strain. These two systems are described below.

DAS

Distributed Acoustic Sensing (DAS) systems use a fibre optic cable (FOC), typically buried, to capture acoustic and dynamic strain along the entire fibre's length (Figure 4). The system measures the strain on the FOC using coherent optical time domain reflectometry (c-OTDR) [4]. AP Sensing have developed DAS systems able to use this sensitive technique to acquire measurements up to a range of 70 km, simultaneously recording acoustic signals for every 1.28 meters continuously along the length of the cable. This makes DAS systems very suitable for measurement of large-scale linear assets.

Figure 4: DAS Setup

DAS has been used for many applications, from intrusion detection [5] to cable faults. Recent research has shown that changes in temperature can also be measured using the cOTDR technique, such as the AP Sensing Distributed Acoustic Sensor [6].

DTS

Distributed Temperature Sensing (DTS), based on Raman spectroscopy, is a method of measuring absolute temperature along the length of a FOC. This technique is well established and widely used to monitor the condition of HV and EHV power cables. Like with DAS systems, DTS systems give the potential to simultaneously record the temperature in 1 meter resolution. These measurements can be recorded along the full length of the FOC (up to 70km) without additional wiring or data transmission, providing an accurate picture of the temperature distribution of the power circuit.

Temperature is the most critical physical parameter limiting the operation of XLPE/oil-filled power cables. Consequently, DTS systems are widely used for temperature monitoring of HV and EHV underground power cables, improving the safe operation of power circuits. Abnormal hot spots can be detected, showing serious problems within joints, or indicating critical obstructions caused by environmental or infrastructural conditions (e.g. backfill dry-out, district heat pipes etc.).

DAS and DTS combinations

Combination of DTS and DAS systems provides a novel approach towards integrated monitoring of power cable status. This includes continuous monitoring of the cable conditions with regards to anomalous temperature and acoustic characteristics that are indicative of a cable fault. The use of optical technology also makes DAS and DTS systems robust against electromagnetic interference from power cables.

PROJECT DESCRIPTION

Three separate hipot tests took place on the 26th February 2019 between 11:20 UTC and 16:32 UTC. The tests were carried out on three separate circuit phases (L1, L2, and L3) at a substation in Copenhagen, Denmark. The three phases are shown in Figure 5.

Figure 5: Three circuit phases for power cables (Copenhagen, Denmark)

Data was collected from both a DAS system and a DTS system, each connected to two separate FOCs. Each FOC contained a single mode fibre connected to the DAS system, and a multimode fibre connected to the DTS system. Both FOCs were mounted parallel to the circuits however one FOC travelled outside of the joints as per standard practice whilst the second FOC travelled inside the joints. Using a FOC inside the joints is a novel technique of setting up FOCs with power cables that shows many benefits, as demonstrated in the data analysis section.

Each hipot test reached a full AC voltage of 134kV with a frequency of 22 Hz. In theory this should create a frequency of around 44 Hz in the FOC's. The first test took place on the first phase (L1) between 12:20 UTC and 12:57 UTC. The second test took place on the second phase (L2) starting at 13:38 UTC, reaching half voltage at 13:43 UTC, full voltage at 13:45 UTC, and ending at 14:49 UTC. The final test took place on the third phase (L3), starting at 15:22 UTC, reaching full voltage at 15:32 UTC, finishing at 16:29 UTC. Data was collected for all three tests from both FOCs as well as both the DAS system and the DTS system.

DATA ANALYIS

DAS

The results from the experiment highlight three main benefits of installing FOCs inside joints: (i) the internal FOC has lower levels of background noise compared to the external FOC; (ii) it is possible to identify the time and location of the hipot test by examining signal amplitude; and (iii) each hipot test demonstrates similar, expected spectral characteristics for the internal FOC, showing that it is possible to detect hipot tests from frequencies alone.

To obtain the energy from a DAS system, it is standard practice to perform spectral analysis using a Fast Fourier Transform (FFT). The acoustic energy is then calculated by summing the magnitude of the FFT between two frequencies. For this experiment, the energy was taken between 4 and 250 Hz. Usually, when measuring the energy at a joint location there is a lot of background noise. This is due to the fibre traveling away from the joint containing the power cable, resulting in relatively higher levels of various environmental signals that the rest of the FOC does not experience, since it is buried.

Below are distance/time plots of the acoustic data measured by the DAS systems for the FOCs located both internally and externally from the joint. Both plots were taken prior to the hipot test at L2; the two yellow dashed lines represent the joint location in either figure. The external FOC shows a high level of background noise at the location of the joint (Figure).

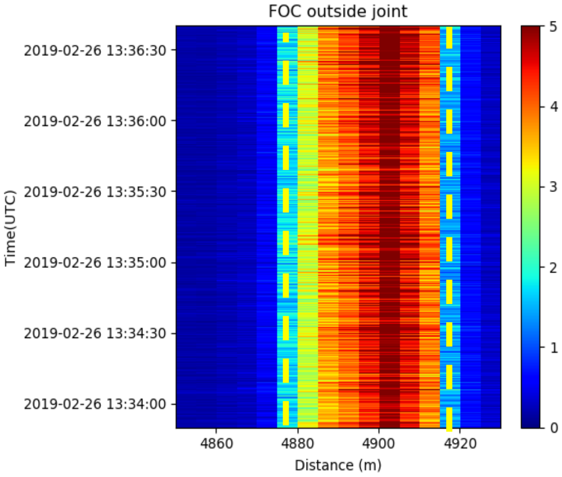

Figure 6: FOC outside of joint at phase L2.

This is a usual result when looking at frequency energies at joint locations. Comparing this to the FOC running through the joint (Figure) the level of background noise is significantly lower. This enables analysis of the acoustic signals emanating from the joint that would otherwise be dominated by background noise.

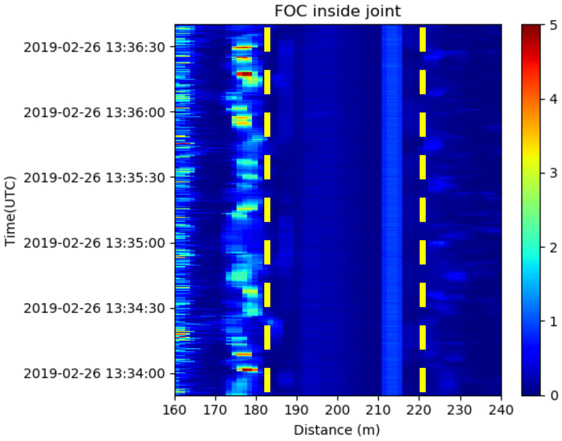

Figure 7: FOC inside joint at phase L2.

The second key result from the data analysis is being able to identify correctly when and where the hipot tests are taking place. Figure shows the start and end times of the hipot test represented by two white horizontal lines.

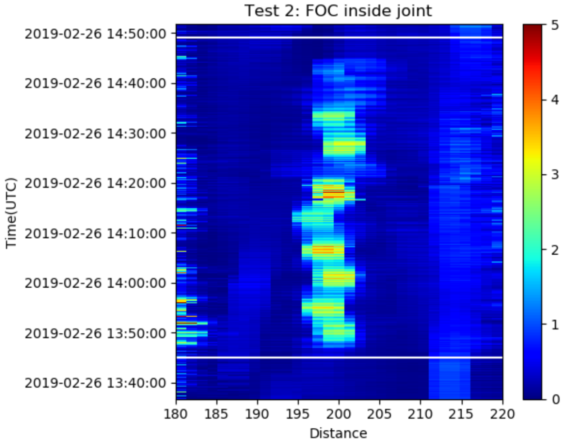

Figure 8: Second hipot test on phase L2 (FOC inside joint).

Figure , shows the same hipot test for the external FOC. From this, the start and end times for the hipot test cannot be distinguished from the high level of background noise, whereas this is very clear for FOC running inside the joints (Figure).

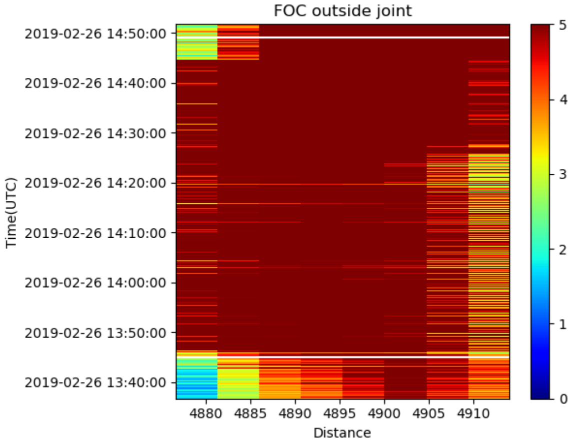

Figure 9: Second hipot test on phase L2 (FOC outside joint).

Another plot that supports this finding is a strain-frequency plot for both FOCs before and during the same hipot test, shown in Figure 10.

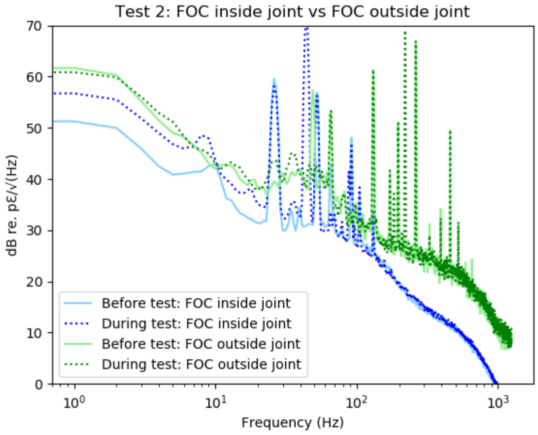

Figure 10: Strain-frequency for Test 2.

From this figure, the FOC outside the joint shows higher levels of noise in frequencies of 80 Hz and above compared to the internal FOC. Additionally, the external FOC shows no clear difference between the strain-frequency response before and during the hipot test.

Comparatively, the FOC inside the joint demonstrates notably less noise compared to the external FOC at both low and high frequencies. Secondly, there is a clear spectral difference between the strain-frequency response before and during the hipot test, as during the test the signal was approximately 5 dB higher at low frequencies and showed a sharp increase of approximately 30–40 dB at 40–45 Hz.

The final finding from the DAS data analysis is that all successful hipot tests produced the same frequency levels which are only present during the hipot test. Figure 1 below illustrates this by showing strain-frequency data for the FOC running inside the second joint (L2) and the third joint (L3). Data for both before and during the hipot tests for both circuit phases were analysed to enable a direct comparison between the different frequencies produced. Both hipot tests on either circuit phase showed an increase to 70 dB around 40-45 Hz. This frequency is not present when there is no hipot test happening for either joint, concluding that this is due to the hipot tests. Additionally, this is very similar to the expected frequency to be produced which is 44 Hz. Figure 12 shows the same graph but zoomed in to the area of interest, showing that the DAS detects frequencies of 44 Hz which was expected.

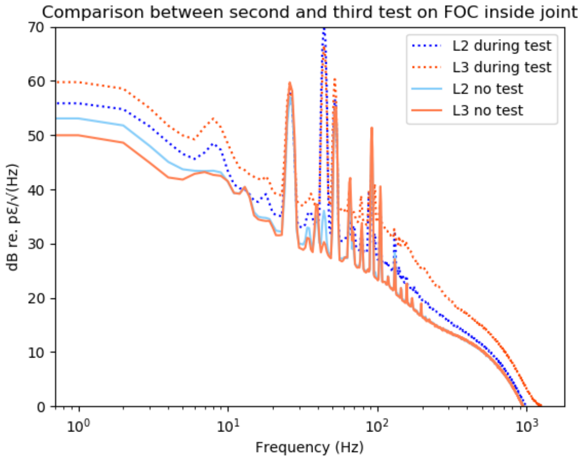

Figure 11: Strain-frequency for FOC inside joints.

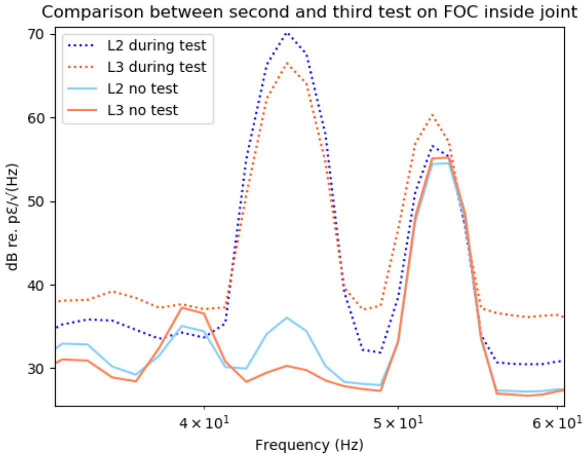

Figure 12: Strain-frequency for FOC inside joints.

DTS

The temperature measurements by the DTS didn't show any temperature variations during the hipot tests, neither on the fibre running in parallel to the power cable nor on the fibre installed directly in the three Smart Joints. This was more or less expected as a hipot test applies only voltage on a power cable, no load. Below, Figure 3 shows the measurement results from the fibre directly installed inside the Smart Joints. The variations at the beginning and at the end are from the feeding fibre lengths and coming from changing ambient temperatures. There is no temperature change due to no load. In real operation temperature increase are to be expected in relation to the load condition. At the point of the hipot tests, the cable was not in operation.

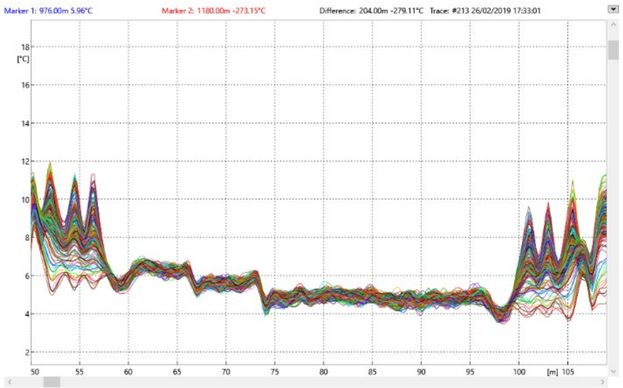

Figure 13: DTS measurements from FOC inside joints.

CONCLUSIONS

Usually FOCs for acoustic and thermal measurements are laid parallel to cables, but cable accessories are not included. In a pilot project now some cable joints were included. During the commissioning test several measurements and comparisons were carried out, which show promising results. Since the main purpose of the commissioning test is to prove a certain withstand level of the electrical insulation, high AC voltage is applied but no power is transmitted. Therefore no significant current flows and no significant thermal effects are to be expected. Thus, further investigations of the DAS and DTS measuring system must be carried out under different (including extreme) load conditions.

The value of injoint monitoring have been proven by comparing external FOC and internal FOC both during hipot testing and without test voltages. There is a clear advantage in having the FOC inside the joint from a data analysis point of view, as temperatures and cable faults can be more accurately located. Additionally, it is possible to detect hipot tests from frequencies alone, as they are expected to produce a frequency of around 44 Hz which is evident from the data analysis. We have sensitive detection means as well as potential to create an early warning system for degrading joints, this is to be proven and will be completed in future projects.

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