Fault Localisation with Distributed Acoustic Sensing (DAS) – Service Experience

Rasmus **OLSEN**; Ørsted Wind Power, (Denmark), raaol@orsted.dk
Simon **STEFFANSEN**, Kristian **OLESEN;** Energinet Transmission, (Denmark), ssv@energinet.dk, koe@energinet.dk
Rosalie **ROGERS**, Gareth **LEES**; AP Sensing, (Germany), rosalie.rogers@apsensing.com, gareth.lees@apsensing.com

ABSTRACT

Installing cables with direct cross-bonding, in ducts, without link box access, etc. it becomes difficult to perform fault localisation with traditional methods. Therefore, other methods were investigated for the Danish transmission grid. Distributed Acoustic Sensing (DAS) was found to be a viable option however limited experience worldwide is freely available. The paper presents the use of DAS for fault localisation on three different cables where both successful and less successful cases are presented so that the combined cable community can become wiser and more efficient in the future.

KEYWORDS

Distributed Acoustic Sensing (DAS), Distributed Vibration Sensing (DVS), Distributed Temperature Sensing (DTS), Fault Localisation, Fault Pinpointing, Cable, HV, EHV, Real Time, Online.

INTRODUCTION

With the introduction of cross bonded cable systems, the design engineers introduced problems for asset departments as fault localization with standard methods became much more difficult. TDR and bridge measurements does, in most cases, not give reliable data for fault localization. Therefore, many asset departments have relied on the use of applying voltage to the screen (over the cable jacket) to pinpoint faults. However, this requires access to the screen at every cross-bonding point, i.e. a link box. Link boxes though require regular maintenance and are therefore expensive in operation, and it has on that background become common practice in the Danish transmission system to use direct cross bonding which means that screen access is not possible and all standard fault localization methods have thus become ineffective. A totally different approach therefore had to be implemented to find and pinpoint faults on cable systems in the Danish transmission grid.

DESIGN OF CABLE SYSTEM AND TRENCH

Cables installed in rural areas cable systems are installed in flat configuration in a trench with a design as shown in Fig. 1. The three cables are separated by 400 mm and to the centre cable is taped a tube wherein an optical fibre cable is installed. The fibre cable is mainly used for communication between substations, however a number of fibres are dedicated for monitoring of the HV cable system.

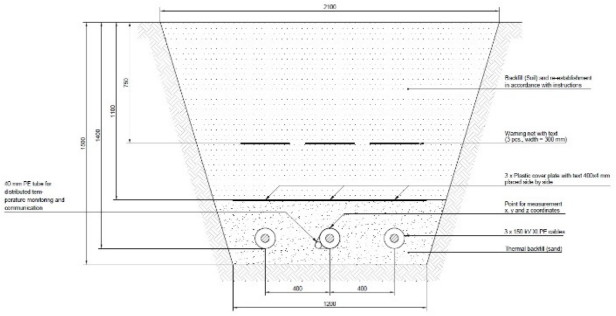

Fig. 1: Cross sectional sketch of a trench for installing cables in rural areas in the Danish transmission grid

This trench design has shown to be the optimal balance between cable performance, installation costs and operational (including maintenance) costs for installation in rural areas.

For cables in urban areas, problems with other utility lines, etc. may force the TSO to install the cables in ducts which makes it more difficult to perform fault localisation

Cable systems are, similar to the cable trench, designed to reach an optimum between cable performance, installation costs and operational (including maintenance) costs. Therefore, new cable systems in rural areas are designed with direct cross-bonding to the furthest possible extend, however to protect the bonding system (including screen separation, cable jacket, etc.) the first major section at each end from a substation is protected with SVLs in link boxes, Fig. 2.

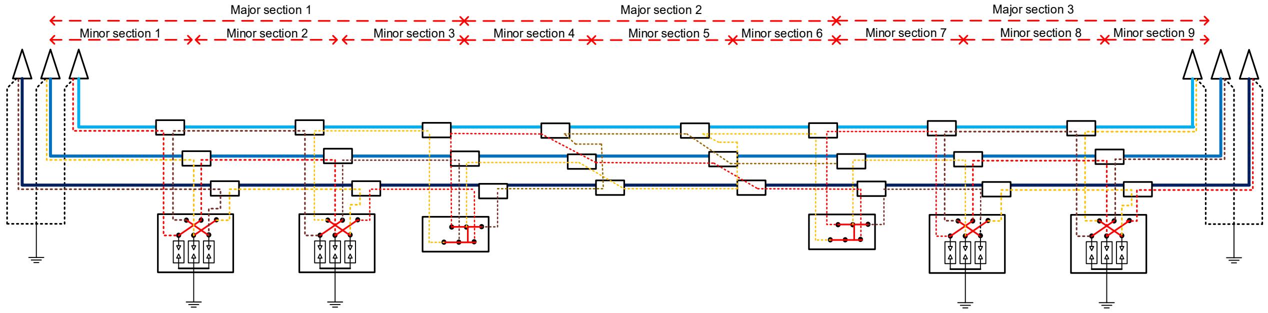

Fig. 2: Principal sketch of a typical cable system design for installation in the Danish transmission system. Together with the trench design this cable system design makes fault localisation difficult when using traditional methods.

MONITORING THE CABLE SYSTEM THROUGH OPTIC FIBRES

As there is always installed optical fibres , in the cable trench, for communication between the substations, it was investigated what kind of optical monitoring techniques could be utilised for fault localisation and pinpointing.

Distributed Temperature Sensing (DTS) equipment is always installed for new cable systems in order to identify possible faulty cross bondings and to enable dynamic line rating. It was investigated how others have utilised DTS systems to locate faults and it was found that the optical fibre should be very close (preferably embedded in the cable) to the faulty core. Traditionally the fault has been located by thumbing the fault repeatable with high voltages which makes the fault location hotter than the rest of the cable. As this in its nature is a very localised heating, it is evident that a fault on one of the two outer phases in a trench design as shown in Fig. 1 would not be caught by monitoring the temperature only on the centre phase.

This led to search for other methods where Distributed Acoustic Sensing (DAS) was presented.

It was found that DAS had a lot of positive references; however, most fault localisations were on already failed cables and thus not on live cables enabling real time fault localisation.

Using DAS in fault localisation is based on the principle that an electrical fault in the cable will generate a large sound which the DAS system simply will pick up as a distributed microphone. The place on the optical fibre where the electrical fault appears first and with the largest amplitude is the location where the fault is. By walking along the cable and following the footsteps on the DAS it is possible to correlate the geographical position of the fault when the footsteps overlay the electrical fault on the DAS.

The following sections shows how this has worked for finding 3 different faults in the Danish transmission grid.

CASE STUDY 1 – PARTIALLY UNSUCCESSFULL BUT FULL OF LEARNINGS

Site Acceptance Tests (SATs) of HV cables in the Danish grid includes that the cables, to the furthest possible extend, shall be subjected to 1.7xU_0 for an hour at 50 Hz (but minimum 1 hour). For a SAT performed at 25 Hz the test duration is therefore 2 hours, and it so happened that a cable failed after approximately 1.5 hours.

As stated, directly cross bonded cable systems are difficult to perform fault localisation on, and therefore the cable system was equipped with a DAS before the SAT.

By consulting the DAS after this failure, nothing of obvious interest was visible at the time of the fault, as shown in Fig. 3.

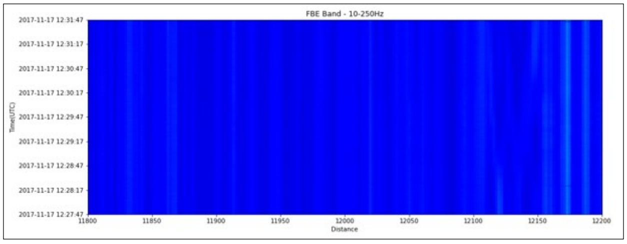

Fig. 3: "Waterfall diagram" showing the intensity of the acoustical signal along the cable as a function of time. Unfortunately and unexpectedly, no distinguishable noise is seen at the time of the fault.

The cable fault was located within two major sections, by using the access to the screens which, in this case, was available after every second major section. However as each minor section was 1500 meters on average this only limited the search to 9 km. With a ground microphone the fault was, after several days of searching, located to be at a joint. However; on the outside the joint did not show any signs of a fault, and an immediate visual inspection was therefore not possible. After dissection is was evident that the localisation was correct, as shown in Fig. 4.

Fig. 4: Fault location inside the joint. It is clearly seen that the fault was located correctly even though it was not possible to visually confirm on the outside of the joint.

As stated, the DAS was procured and installed for online fault localisation, and it was therefore not satisfactory that the fault was not seen on the DAS. However; after the fault had been located, the data from the DAS, at the fault site, was analysed, and an unusual pattern was found in the frequency as seen in Fig. 5.

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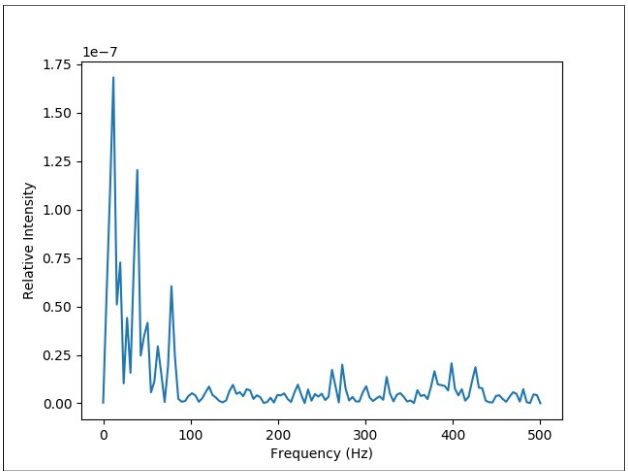

Fig. 5: Frequency content of the DAS signal from the fault location. It is here seen that there is a distinct pattern which could be used for automatic detection of future faults.

Main learnings from case study 1

First learning is that even though the sound from the flashover in the cable was not distinguishable from the waterfall diagram, it would be possible to perform automatic detection of flashovers by filtering the data in the proper way. Based on this case study, and case study 2, such a feature can thus be implemented in the software package.

Second learning from this case study, supported by discussions with several suppliers, is that DAS equipment is not a simple plug and play solution which enable fault localization without significant calibration and adaption to the site conditions. Skilled personnel both from DAS manufacturer and cable owner should therefore set aside a couple of days for tuning of equipment to ensure optimal performance.

Third learning is that it shall be ensured that the fibre optic cable shall go through the entire joint bay and not be pulled out of the joint bay for splicing without ensuring that a fibre loop runs close by the joints.

Fourth learning is that proper performance requirements should be agreed before commissioning to ensure that the cable operator will instantly get info about a fault location. Because the DAS equipment is not plug-and-play, it is difficult to set strict requirements to magnitude of background noise, what should be distinguishable on the waterfall diagram, etc. and therefore other more practical performance requirements should be enforced. The fourth learning is therefore that the cable operator should create an artificial flashover close to the cable at a certain length from the DAS. This could be done e.g. by burying a spark gap 0.5 meters from the cable and energize the spark gap with an impulse generator.

CASE STUDY 2 – SUCCESS

At a 150 kV cable project, which was started up before DAS became standard on all cable projects in Denmark, a fault was encountered during the HiPot test. The fault turned out to be very difficult to locate by traditional methods and after a week a DAS equipment was brought to the site together with a heavy 90 kV impulse generator capable of supplying around 50 kJ.

By thumbing the cable with the impulse generator, it was found that it required 28 kV before a flashover could be generated, however at that point the fault location was also clearly shown on the DAS, as seen in Fig. 6.

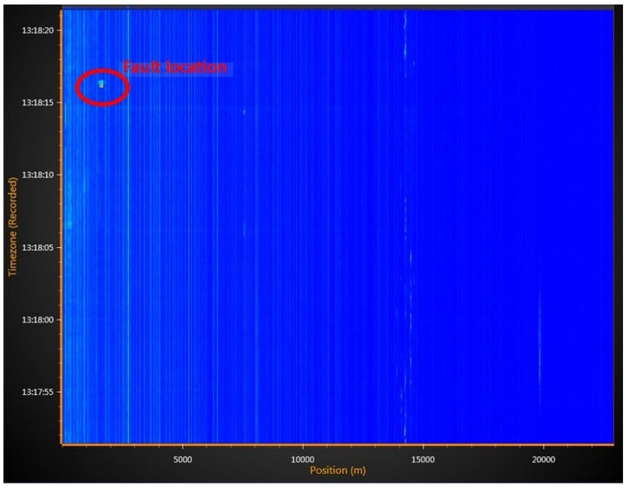

Fig. 6: Waterfall diagram showing the intensity of the acoustical signal along the cable as a function of time. The fault location is clearly seen, and the geographical position was identified by walking along the cable which could be followed on the DAS system.

By sending a man walking along the cable, it was possible to get a geographical pinpointing of the fault, to perform the excavation at the correct location and, as shown in Fig. 7, it was correct that the joint was faulted, and a flashover had occurred. Also for this fault, the personnel had to rely on the DAS data for fault localization as no visual signs were noticeable on the outside of the joint.

Fig. 7: Fault location inside the joint. It is clearly seen that the fault was located correctly even though it was not possible to visually confirm on the outside of the joint.

As for case study 1, the frequency content of the acoustical signal was analysed, and it is clearly seen that the pattern of that fault has similar frequency characteristics as this fault, see Fig. 8.

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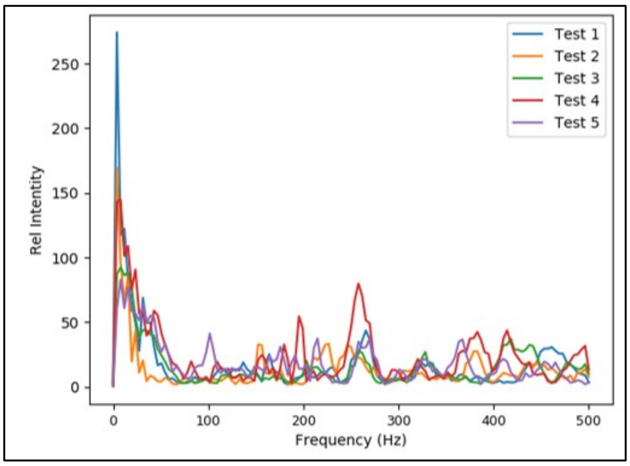

Fig. 8: Frequency content of the DAS signal from the fault location. It is here seen that there is a distinct pattern which could be used for automatic detection of future faults.

This knowledge can be used to create automatic fault detection algorithms in order to ease the fault finding even more.

Main learning from case study 2

This case study proves that by proper calibration and adjustment of the equipment, easy fault pinpointing is possible by using DAS. Furthermore, it is shown that even a fault with a limited fault energy of 5 kJ, as in this case, is very noticeable in the DAS waterfall diagram if properly setup. A real fault where an entire transmission grid is delivering energy to the fault will be even more noticeable, and it will therefore not be problematic to locate faults even in the phases furthest away from the fibre optic cable.

Furthermore, this case study and case study 1 combined has shown that there are recognisable patterns in the DAS data which enables automatic fault detection, which eases even further the fault pinpointing.

CASE STUDY 3 – BUSINESS AS USUAL

Even though cable faults are not something the cable operator is hoping for, proper preparations can make damages and outage time less painful. Case study 1 and 2 proved to be perfect preparations for the third fault which was pin pointed with DAS. The cable is very long, and the capabilities of the DAS were therefore stretched to the fullest, as just the fibre was more than 90 km long.

The resolution of the DAS therefore had to be set to the maximum of 50 meters and careful monitoring of the waterfall diagram was done by skilled personnel from the TSO. The results were clear and a zoom on the 500 meters closest to the acoustical signal is shown in Fig. 9.

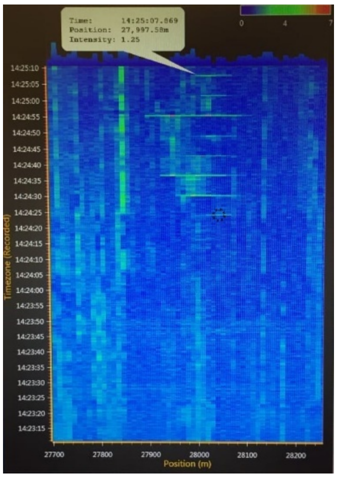

Fig. 9: Waterfall diagram showing the intensity of the acoustical signal along the cable as a function of time. The fault location is seen at 28040 m even though it is not so explicit as case study 2, Fig. 6. The resolution is not as high as elsewhere in this paper as the cable length was 90 km.

It is clear from this that the cable fault should be found around 28020 meters from the measurement unit.

It is important to remember that Fig. 9 shows that even on a 90 km cable it is possible to get very close to pin pointing the fault, as the fault indication is within 50 meters and that this can be geographically coordinated by walking along the cable and making noise.

In this case study a further pinpointing was done, to get even closer to the location, by measuring the step potential. During this step potential measurement, the DAS unit was optimised to a 20 meters resolution around the fault location which was also a success, and it was possible to correlate the movement around 28000-28020 meters on the ground with the flashover site, as shown in Fig. 10.

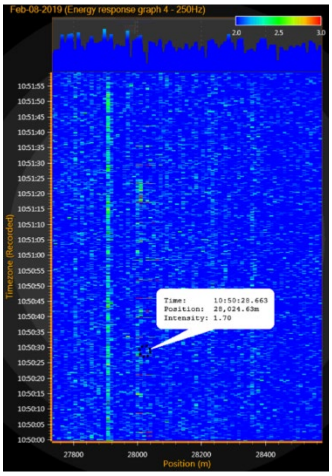

Fig. 10: Waterfall diagram showing the intensity of the acoustical signal along the cable as a function of time. The data presents someone walking on the cable around the fault location. This served as geographical correlation between the DAS fault data and the geographical position of the fault.

As seen in Fig. 11 the DAS pinpointing was also correct in this case.

Fig. 11: Fault location. It is clearly seen that the fault was located correctly.

Main learnings from case study 3

The first learning is that having a proper repair response prepared for fault localisation it is possible to perform pinpointing with DAS and an impulse generator very easily. This is however an offline method and it will result in longer outage times than an online pinpointing where DAS equipment locates the fault immediately during the initial flashover.

The second learning is that even though the given equipment is only rated to cover 50 km in range, it is possible to locate faults on longer cables by adjusting the measurement parameters in the equipment. If it would be possible to locate the fault further away, e.g. 60-70 km from the end is to be tested at a later stage, however for this case where the fault was only around 28 km from the end, it was easily noticeable on the waterfall diagram.

ONLINE FAULT LOCALISATION

As it is not possible to predict where a failure will occur in the future in an entire transmission grid of cables in operation, it is not possible to choose just one cable for monitoring with DAS, if the desired outcome is to gain experience with fault localisation with DAS. In the Danish transmission grid all new cables are therefore equipped with online DAS equipment which is installed with the sole purpose of fault online localisation. However as this regime, of systematic DAS installation, has only been applied for a few years, and none of these cables have failed yet during operation it is not possible to report here on any online faults and therefore not possible to show results from such faults, however the Danish transmission grid is prepared for the future and it is certain that significant time and economical savings will be gained during each future breakdown of these cable systems.

Presently the DAS data that is created on the cables in the Danish transmission grid is used to optimise algorithms and used for machine learning so that future cable failures can be located online to ensure a fast repair and recommissioning of the cables.

BUSINESS CASE CONSIDERATIONS

Installing DAS equipment on a cable system obviously increases the Capital Expenditure (CAPEX), and therefore the installation of DAS must be justified.

For export cables to an offshore wind farm, grid connection cable to a power plant and other cable radials the cost of an outage might be easily calculated as the price of not delivered kWh is known by the TSO. The Mean Time Between Failures (MTBF) can be based on statistics and is presently the same whether DAS is installed or not. However; the Mean Time To Repair (MTTR) can be reduced with the quicker fault pin pointing and thus the business case can be easily done for installing DAS for such cables.

For a cable in a meshed transmission grid, the calculation making the economic justification of installing DAS is more difficult to perform as there might not be a direct cost related to unserved customers or unserved producers. Instead a holistic approach to justification may be used as the MTTR can be lowered and therefore grid reinforcements, ensuring N-1 grid security, may be less important.

Furthermore, several ideas are on the table where DAS data is used to increase the MTBF, and this will create even better business cases for the installation of DAS.
For example, it has been suggested that it, by proper calibration and machine learning, may be possible to foresee (and thereby hopefully prevent) damages to cables such as anchors hitting submarine cables, excavators hitting underground cables, locating exposed (unburied zones) of submarine cables, etc. Work is ongoing in creating proper machine learning of DAS data to enable the cable operators to prevent failures and thereby increase reliability of the grid. Even for cables in the meshed grid, these properties will assist in justifying the use of DAS. However, it should be realised that also for the purpose of increasing the MTBF, a significant amount of data is necessary, and therefore it is vital that many DAS units are installed to gather enough events in the databases to perform serious machine learning and thereby automatic warning systems e.g. for preventing excavation damages to the cables.

Moreover, it should be remembered that DAS suppliers and DTS suppliers generally overlap, and that installing DAS on top of DTS (which many cable operators already installs as standard) is possible as a cost-effective combination. The cost of several items can be shared between the DTS and DAS, if both are installed, where the cost would be born solely by the DTS if this is installed alone. This applies to rack cabinets, servers, UPS systems, shipment, testing, commissioning, connection to SCADA systems (and other networks), etc. and therefore the DAS equipment is not costly to implement even though it seems to come at a high price.

WHY ARE SOME CABLE OPERATORS SCHEPTICAL ABOUT IMPLEMENTING DAS

Transmission grid components are in general procured and installed with an intended lifetime of 40-50 years, and cable operators therefore has a general perception that auxiliary equipment, such as DAS, DTS, etc. will be an expensive component as the IT equipment (such as servers, etc.) will need maintenance and partially exchange after e.g. 10-15 years. Furthermore, the DAS equipment is still at a stage where many operators see it more as a development project than a commercially available component, and therefore the operators do not trust it to be stable enough to rely on in a transmission grid that has to serve energy to the consumers 99.999% of the time.

With the cases presented in this paper it is evident that there is room for improvement as not all case studies were successful at first, however the cases also clearly show the potential of DAS, and that it is ready for online fault localisation if proper attention is paid to setup, calibration and performance testing before commissioning.

CONCLUSION

This paper has presented the practical use of Distributed Acoustic Sensing (DAS) for fault pin pointing of three different cable faults. It was proven that the DAS equipment was capable of finding faults instantly where other methods had had difficulty over several days.

The three cases showed that proper calibration of the DAS is necessary, and that careful adjustment of measurement parameters is necessary as part of the commissioning, as the DAS monitoring system otherwise may not detect faults right-away.

The paper has shown that even though some people still sees DAS equipment as a development project, the cases clearly shows that it is now a product that is able to reliably monitor cable systems and detect fault online.

The paper also outlines the future possibilities for DAS utilisation that are worked on, concerning advanced data analysis and machine learning. However automatic warning of excavation damages, anchor damages, exposed submarine cables, etc. are not yet fully developed, partially because the databases do not contain enough events to intelligently train the machine learning algorithms. Even though, the authors perceive this as being a matter of time before such algorithms can be sufficiently equipped.