Condition monitoring of 88km long Offshore HVDC Power Cable: comparison of DTS and as built data

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Abstract. Distributed temperature sensing (DTS) has been deployed for a field trial on a high voltage direct current (HVDC) cable in the North Sea. Temperature measurements using a fibre optic sensing cable bundled onto the HVDC cables are compared with both the cable characteristics and the cable route demonstrating an excellent agreement. Horizontal Directional Drilling (HDD), land and offshore cable joints, transitions as well as hot spots and excess burial are clearly visible. Thermal data thus helps in assessing the cable condition.

1. Introduction
Over recent years, distributed temperature sensing (DTS) systems have been installed on many wind farm export and inter-array cables, as well as on some on-shore buried cables [1]. DTS was originally used as a hot spot detection tool to identify known and unknown thermal bottlenecks; it is now increasingly used as a data input to a dynamic cable rating tool in order to optimize the cable load [2].

In this paper, we report on a DTS measurement campaign of an operational 88km long HVDC submarine export cable in the North Sea. The purpose of the test was to investigate performances over the full cable length. For this reason, two Brillouin optical time-domain analyzers (BOTDA) known as DITEST [3], (one on each side of the cable), were deployed. The required loop configuration was installed on the far end with respect to each DITEST. Both instruments could measure the full cable length, but only half of the sensing distance per instrument was considered, in order to have better performance over the full length. (Note that temperature measurement performance decreases with distance when using any fibre optic based DTS instrument.)

Temperature data are compared with the cable characteristics and the cable laying conditions. Land cable sections with their junction boxes, horizontal directional drilling (HDD) sections and cable transitions are clearly identified through their respective thermal response, as it was also the case for the variation in burial depth and transition in covering material. Separately, and in order to push the technology to its current limits, the sensing scheme is repeated and extended using optical amplifiers in separate laboratory conditions to reach a 180km total sensing distance.

2. Monitoring concept
The HVDC power cable is the concatenation of a 17.5km section (of which a 1.5km long land section), with a cross-section of 1200mm² and a 70.5km section, with a cross-section of 875mm².
A fibre optic cable (FOC) for telecommunication purposes was laid bundled with the two DC power cables. The fibre loss was measured at approximately 18dB with a total loop optical budget of 36dB, which corresponds to the upper limit of the commercially available BOTDA.

Two commercially available BOTDA-DTS, known as DITEST, based on the so-called double-sidebands configuration [3] were used for full cable length temperature measurement (Figure 1). The optical power of each system was tuned such as to remain below non-linearity thresholds, as discussed in [4]. Using 5m spatial resolution and a 20min measurement time, each interrogator produced a full temperature profile over the full distance. Repeatability at the far end from the interrogator was around 8°C. Note that the repeatability is computed according to IEC 61757-2-2 standard [5]. Repeatability is a statistical measurement of the “precision of temperature data based on repeated temperature traces at a given location, expressed by twice the standard deviation of corresponding temperature sample points in each temperature trace, with the fibre optic sensor held at constant temperature [5].” By definition, the repeatability is given at twice the standard deviation (2σ) although commercial documentation often provides results at one standard deviation (1σ), which makes the result look twice better…

![Figure 1](image1.png)

Figure 1. Monitoring scheme featuring two DITEST at each side with a fibre loop at the opposite end of the cable.

To meet the project requirement, only half of the FOC was measured by each interrogator, in 15min, with a spatial resolution of 4m. Using this configuration with post processing, the temperature repeatability in the middle of the cable was below 0.6°C (at 2σ) as shown in Figure 2.

![Figure 2](image2.png)

Figure 2. Temperature repeatability (2sigma, 4m spatial resolution, 15min measurement time) along the distance (left) and repeatability variation over 1 month in the middle position (right).

Note that long term repeatability graph (Figure 2-right) is made on a live cable with significant thermal fluctuations related to load variations, hence some spikes.

Taking into account the difference between the required repeatability (2°C at 2σ) and the achieved repeatability (0.6°C at 2σ), there is some margin for improvement on the spatial resolution. Reducing it from 4m to 2m would result in a repeatability of 1.5°C (at 2σ), still well within the required performance, but with much finer granularity when it comes to hot spot localization, burial depth variation or scouring localization.
No cable absolute temperature calibration was performed prior to installation. Field calibration consisted in a reference temperature point in the substation, together with a standard Brillouin to temperature coefficient of 1MHz/°C.

3. Measurement results

3.1. Full length temperature measurement

Full temperature measurement is shown in Figure 3. The profile may look fairly inhomogeneous, but represents accurately the cable conditions; some features are related to the cable itself and some to its installation and sea bed conditions. They are discussed in the following paragraphs.

![Figure 3. Temperature profile along the 88km-long subsea power cable](image)

3.2. Land sections, junction box and horizontal directional drilling

When looking over the first 1500m (Figure 4) in relative temperature (one measurement was used arbitrarily selected as a base line), one notices clearly 4 dips (450m, 650m, 950m, 1250m) with little temperature variation. In between are 5 sections of around 200m each, showing homogenous temperature changes due to load variations. Between 1500m and 1900m, a long and homogenous section can be observed with similar thermal variations.

Dips correspond to junction boxes between short land sections; the FOC is further away from the power cable than the rest of the power cable route, hence smaller influence from the power cable.

A horizontal directional drilling section (HDD) is clearly identified between 1500m and 1900m, thanks to a very homogenous temperature zone with large variations (Figure 4, right) attributed to a deeper burial depth than the remaining part of the long section together with a poor heat exchange with the environment.

A lead-in section (up to 200m) shows a slow but constant varying temperature (no load pattern, see Figure 4, right). This section is not in contact with the power cable, and is therefore not influenced by the load. The small temperature increase is likely due to seasonal soil temperature variation (daily oscillation pattern is filtered out at this FOC depth).

These findings agree well with the as built information.
3.3. Cable transition

Further away, the cable joint between the two cross-sections is clearly visible (Figure 5). Larger variations are seen on the smaller cross section cable, which make sense; the smaller the cable the larger the loss, at constant current. In addition, the smaller cross section cable’s burial depth is shallower than for the larger cross section cable, thus resulting in larger thermal variation as well.

3.4. Depth of burial

DTS measurement can also provide very interesting information on burial depth, as shown in Figure 6. Based on concatenated survey data (bottom lines), one sees a large change in burial depth at 4.5km; the additional depth directly results in a temperature increase along the cable. Similarly, dips in the seabed (post-installation) are identified at KP7, KP10 and KP15; they correspond exactly to temperature peaks and the logical conclusion is that those dips have now been filled up by adjacent sea bed material, resulting in a deeper burial depth.
Figure 6. Comparison between temperature profile and the cable depth at the beginning of the cable.

3.5. Change of seabed material
Another fascinating example is illustrated in Figure 7; around 38.5km, a noticeable ~100m long 2.5°C cooling effect is measured. Such a smooth transition can only be related to a variation of the cable environment. It matches sand / organic silt / silty spots to sand transition in the seabed survey. As expected, with finer material, the water induced cooling effect is smaller and the temperature is higher [6].

Figure 7. Thermal change due to a change in the cover material.

3.6. Distance between FOC and power cable
When looking at the minimum and maximum temperature over distance, a well localized dip was observed around 70.2km (Figure 8-left). Its temperature variation does not follow the load pattern (Figure 8-right). This is only possible when the FOC is not influenced by the cable anymore, that is, when is it located further away from the cable than at other positions. With the FOC being bundled to the HVDC, it is likely that the FOC came loose over a few meters.
4. Strain compensation

BOTDA are intrinsically sensitive to both temperature and strain. This is often criticised as being a show stopper for using Brillouin DTS in the field, albeit the only option for longer cables such as this one. 

Having deployed almost 2500 kilometres of Brillouin based DTS in the power market, much experience has been gained on the presence or the absence of strain and the means of correcting it. In particular, comparison between the cable’s “as built” and measured Brillouin profile, as well as large and sharp temperature fluctuations are potential signatures of strain coupling. Figure 9 shows a temperature profile (red) with obvious variation of a couple of degrees that are related to sharp transition of the burial depth (bottom black curve). For such strained sections, temperature before and after can be assumed to be nearly identical so that strain is the difference between the measured Brillouin profile and a constant temperature. The strain component is then simply subtracted from the temperature profile to provide a clean signal (blue). Note that the strain-compensated temperature follows the load pattern, as expected.

Figure 8. Loose FOC in the bundle.

Figure 9. Example of strain cross-sensitivity related to large burial depth variation with strain-compensated temperature.
5. DTS and optical amplification

DTS based on stimulated Brillouin scattering can be combined with optical amplification in order to improve their performances and their sensing range [7]. In an attempt to extend the sensing range beyond current field deployments, a laboratory experiment was built using an “as simple as possible” amplification scheme: both DITEST were combined with an optical amplifier located at their respective opposite side’s of the sensing loop. The distance from the interrogator to the opposite end was 180km with a total loss of 37.1dB, featuring an equivalent 0.21dB/km fibre loss (Figure 10). In the middle, a 100m long fibre section was laid in a water bath to allow for stable temperature measurement and repeatability evaluation.

![Figure 10](image)

**Figure 10.** 180km sensing featuring two DITEST and two optical amplifiers at the respective opposite end.

Using a spatial resolution of 5m and a measurement time of 15 minutes, a repeatability of less than 3°C (2σ) was achieved in the middle of the cable, as can be seen in Figure 11.

![Figure 11](image)

**Figure 11.** 180km sensing featuring 3°C repeatability (5m spatial resolution, 15min measurement time, 2σ) at the middle of the cable.

Without amplification, a BOTDA scheme would require a loop in the middle of the cable; for instance in a subsea joint as already demonstrated in the field [8]. Alternative schemes using single end interrogation either cannot match the distance [9] or cannot achieve the short spatial resolution required by the application [10].

6. Conclusion

DTS measurement was performed on an 88km-long wind farm HVDC submarine power cable using two commercially available BOTDA known as DITEST, one at each end of the cable. A loop was made at the respective other side.
Single side measurement was possible, thanks to the interrogator optical budget matching the 18dB (one way) loss, however by combining data from each interrogator up to the middle of the cable, a repeatability of 0.6°C (at 2sigma) with 4m spatial resolution was achieved in 15 minutes; this is well below the 2°C target. In retrospect it was seen that spatial resolution could have been set to 2m, providing a better granularity and hence higher probability of detecting small events without exceeding the temperature repeatability target.

Beyond simple temperature monitoring, the DTS measurement allowed clear identification of cable features such as junction boxes within the land sections, HDD’s, transition between land and offshore section as well as cable joints

In addition to cable characteristics, the DTS measurement was used to identify burial depth variation and sea bed material accumulation, as well as material transition. This demonstrates a clear link between the as built and survey data and the temperature data, that is key to assess the cable condition.

Finally, and separate to this actual cable measurement, the use of an optical amplifier with the DITEST BOTDA, demonstrated effective monitoring over 180km long sensing distance was in the laboratory. This configuration is currently commercially deployed over shorter distances.

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