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Complex cable temperature monitoring within the largest commissioned offshore wind farm

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SUMMARY

Hornsea One (HOW1) is currently the largest commissioned offshore wind farm in the world. It is located 120km off the UK Yorkshire coast and features 174 turbines, each of 7MW, for a total installed capacity of 1.2GW.

The wind farm has three offshore interconnected substations (OSS), each individually connected with a dedicated AC export cable to mainland UK. A first of its kind offshore reactive compensation station (RCS) is located near the middle of the export cables section to compensate for the reactive power along these long links.

The total cable length is around 580km, including three export cables and two interlink cables. Distributed Temperature Sensing (DTS) is deployed over the full cable length in view of ensuring cable integrity and providing uninterrupted energy supply from the production site to the mainland grid.

The DTS are based on Brillouin optical time domain analysers (BOTDA), featuring a fibre pair looped at the far end of the sensing distance. For the longest routes, two interrogators are located on each end of the power cable, with the corresponding loops extending to the opposite end, each BOTDA measuring the temperature up to the middle of the total distance. For the longest sections, optical amplifiers are located at the distal end of the loop, with respect to the interrogator, to handle the propagation loss, to improve performances and to maintain a short measurement time.

Offshore instrumentation is located solely on RCS and OSS2, whilst fibre connections are made on OSS1 and OSS3 to allow for monitoring of all three cable circuits. The full cable length is monitored 4 times per hour with a spatial resolution of 3m.

HOW1 is the most complex and longest AC system which full length is measured using DTS and is a demonstration of fibre-based asset integrity for offshore wind.

KEYWORDS

Distributed Temperature Sensing (DTS), Brillouin, BOTDA, offshore wind, power cable monitoring.

1. INTRODUCTION

The Hornsea project one (HOW1) is currently the largest commissioned offshore wind farm in the world. It is located 120km off the UK Yorkshire coast, covers an area larger than 400 square km and features 174 turbines, each of 7MW for a total installed capacity of 1.2GW (Figure 1). Development consent was granted in December 2014. 2016 saw the construction of the onshore substation, the onshore cable installation, and the cable landfall work began in Q2 2017. The offshore work was conducted from 2018 onwards and the offshore windfarm was commissioned in 2019 [1].

HOW1 has three offshore substations (OSS), each connected to a dedicated AC export cable to mainland UK. A first of its kind offshore reactive compensation station (RCS) is located near the middle of the export cables section to compensate for the reactive power along this long AC transmission line [2].

There are 3 parallel cables for the export, each heading towards one the OSS, whilst 2 interlinks provide electrical connectivity between the OSSes.

All the cables are 3-cores 220kV with XLPE insulation featuring a) 1000 mm^2 Cu conductor, lead sheath and stainless steel/plastic armour wires for the Eastern and Western circuits (see Figure 5), b) 1000 mm^2 Cu conductor, lead sheath and sea grade Al armour wires for parts of the Central circuit, c) 1200 mm^2 Cu conductor, lead sheath and galvanized steel/plastic armour wires for the rest of the Central circuit and d) 950 mm^2 Al conductor, lead sheath and galvanized steel armour wires for the Interlinks. Each export cable is fitted with two Fiber Optic Cable (FOC)

The export route's land section features flat spaced phases with 6m between circuits, within a 30m wide corridor. Land cables are mainly directly buried, with some sections protected by polyethylene (PE) ducts. The cable design features 1600 mm^2 Al conductor, XLPE insulation, welded aluminium screen/water barrier and PE sheath.

A full description of the cable design, the optimisation process, the bonding and the execution can be found in [2].

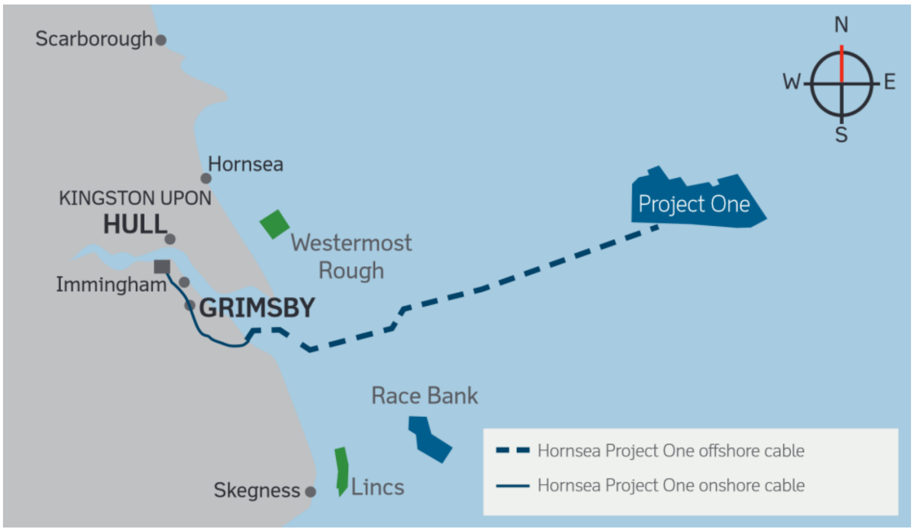

Figure 1: Hornsea Project one (HOW1) offshore UK, by Hull ([1], [2])

With about 438km offshore cable length, 117km land section as well as 27.5km interlink connectors, HOW01 is the longest AC offshore wind export cable systems ever commissioned. The more than 580km are totally monitored by a distributed temperature sensing system (DTS), making it one of the most complex and longest fully monitored offshore wind assets worldwide. The Cluster Westlich Adlergrund project is similar in complexity with slightly shorter measurement distances [3] whilst the Crete-Peloponnese interconnector is currently the longest single fully monitored cable with a 180km long sensing distance [4].

Given the length and the number of cable routes linking the three OSSes, the RCS and the onshore substation, Brillouin optical time domain analysers (BOTDA) based DTS were chosen. This is a field proven approach providing long distance absolute measurement with good accuracy and reliable and stable long-term calibration. In addition, using optical amplification to manage the optical budget of the longest sections, it allows a full cable route coverage with a minimum number of interrogators and a short measurement time.

2. DISTRIBUTED TEMPERATURE SENSING

2.1. Backscattering

Distributed Fibre Optic Sensing (DFOS) is based on the measurement of backscattered light from optical fibres [5], [6]. A powerful light pulse, known as Pump, at wavelength λ_0 is launched in an optical fibre. A small amount of the incident power is scattered in all directions due to local non-homogeneities, of which a fraction is guided in the backward direction (towards the pump laser) where it can be analysed. The scattering signal has three components originating from material impurities (Raleigh scattering), thermally excited acoustic waves (Brillouin scattering) and atomic or molecular vibrations (Raman scattering) as shown in Figure 2.

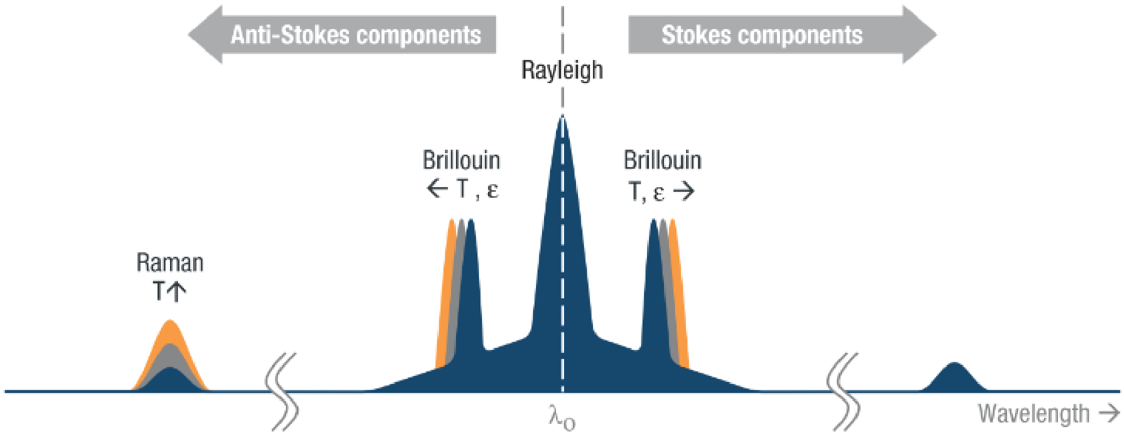

Figure 2: Backscattered light components of a single mode laser (single wavelength λo) light launched in a single mode optical fibre

The measurement of the backscattered signal is made over time. Thus, knowing the speed of light in the fibre and the time at which a backscattered signal was measured, it becomes possible to define at which distance this backscattered signal originates from. Such a method is known as time domain reflectometry (TDR), sometime referred to as time-of-flight measurement or light radar.
The measurement of Rayleigh backscattering intensity and phase is used for the measurement of vibration, known as Distributed Acoustic Sensing (DAS). Raman is solely dedicated to the measurement of temperature (Distributed Temperature Sensing, DTS) through changes in the intensity of the backscattering signal whilst Brillouin is used for the measurement of both temperature (DTS) and strain (Distributed Strain Sensing, DSS) by measuring frequency shifts of the backscattered light. Classically, Raman DTS are single-ended multimode fibre (MMF) based system with a 30km sensing distance whilst Brillouin DTS are using a single-mode fibre (SMF) loop to stimulate the signals (Brillouin Optical Time Domain Analyser, BOTDA). Both Raman and Brillouin DTS are deployed within the offshore wind industry, as demonstrated for the measurement of the Cluster Westlich Adlergrund in the Baltic Sea [3].

2.2. Brillouin Optical Time Domain Analyser with optical amplification

Brillouin DTS [5], [7] are based on SMF, like those used for telecommunication purposes. In the loop configuration (BOTDA), a probe signal (continuous wave) is sent to the distal end of the sensing fibre and is looped back towards the interrogator. As it crosses the pump signal traveling in the forward direction, it stimulates the Brillouin interaction. This loop configuration provides much better performances over long distances or short acquisition time as required by dynamic monitoring than its single end counterpart (BOTDR).
BOTDA can be efficiently combined with optical amplification, either by using Erbium Doped Fibre Amplifier (EDFAs) or distributed Raman amplification, to increase their accessible optical budget, thus providing unmatched measuring distance, or to improve their performances for a given measurement distance. Different schemes have been tested, featuring simple probe power management with a single amplifier at the distal end [8], distributed amplification [9] or a more complex management of both pump and probe signals using in field amplification similarly to the long haul telecommunication links [10].

To investigate performances and to push the concept, a test setup was built (Figure 3), with a distance from the interrogator to the opposite end of 180km and a total loss of 37.1dB, featuring an equivalent 0.21dB/km fibre loss. In the middle, a 100m long fibre section was laid in a water bath to allow for stable temperature and repeatability measurement.

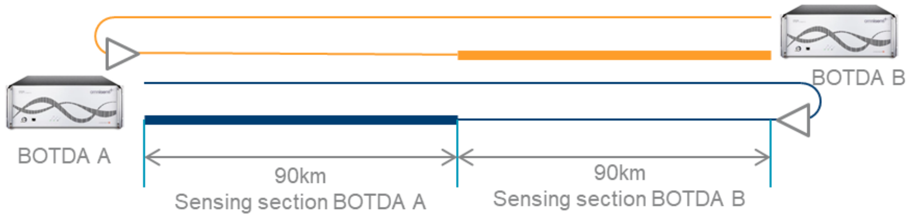

Figure 3. *180km sensing featuring two BOTDA and two optical amplifiers at the respective opposite end.*

With this setup, using a spatial resolution of 5m and a measurement time of 15 minutes, five measurements were acquired over the full distance. The 100m section in water bath was calibrated (from 90.6 to 90.7km) and a repeatability of less than 3°C (2σ) was achieved in the middle of the (Figure 4) and corresponds to the Crete-Peloponnese interconnector performances [4]. Within HOW1, the longest links are based on this architecture.

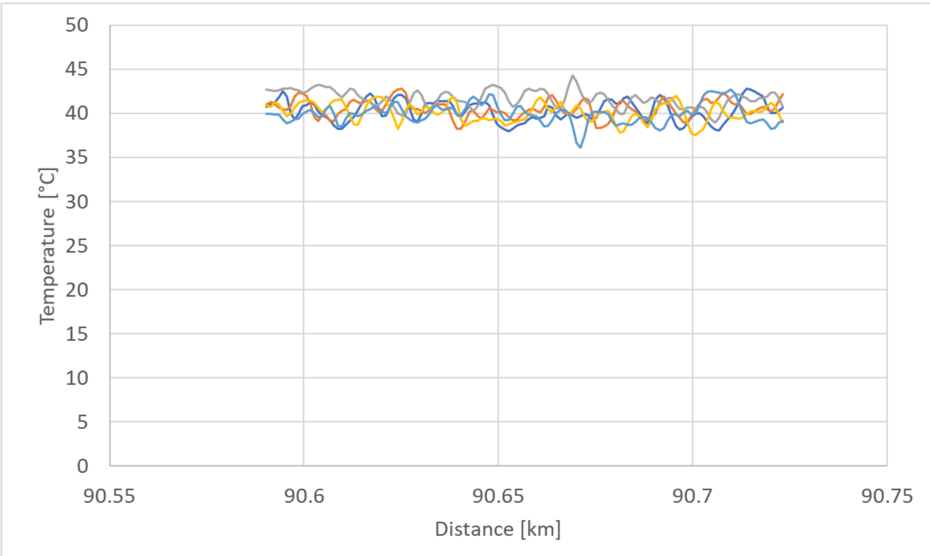

Figure 4. 180km sensing featuring 3°C repeatability (5m spatial resolution, 15min measurement time, 2σ) at the middle of the cable.

3. HOW1 MONITORING SCHEME

3.1. Cable route, BOTDA and amplification

From the Onshore substation (OnSS), three export cables are running in parallel, first to the transition joint beach (TJB, ~39km each) and then to the reactive compensation station (RCS, ~68km each). From the RCS, the 3 export cables continue in parallel to the beginning of the wind farm area where they split and eventually head towards the three Offshore substations (OSS1, OSS2 and OSS3) with 70km, 76km and 88km long link respectively. In addition to the export cables, two short interconnectors of 13.5km and 14km provide electrical connection between OSS1/OSS2 and OSS2/OSS3 respectively (Figure 5).
To monitor the entire cable length, one BOTDA is located onshore; it features 3 channels, one for each of the land sections, and provides temperature monitoring up to the TJB.
The shore area is monitored by one BOTDA located on the RCS.
The main lay area is monitored by combining measurement from one BOTDA on the RCS and one BOTDA on the OSS2. Each instrument is measuring half of the cable distance with the optical loops located at the distal end of the fibre section. From the RCS, the West and Central circuit have optical loops on the OSS1 and OSS2 respectively; for the East circuit, the measurement path goes through OSS3to OSS2 where an optical amplifier is located. Similarly, from OSS2, the West circuit is measured

through OSS1, with an optical amplifier on RCS whilst the East circuit is measured through OSS3, again with an optical amplifier on RCS. The central circuit is measured without amplification.
With this specific interrogator layout, instrumentation (BOTDA and amplifiers) is located on the RCS and on OSS2, as well as on shore, whilst OSS1 and OSS3 only have spliced fibres (Figure 5).

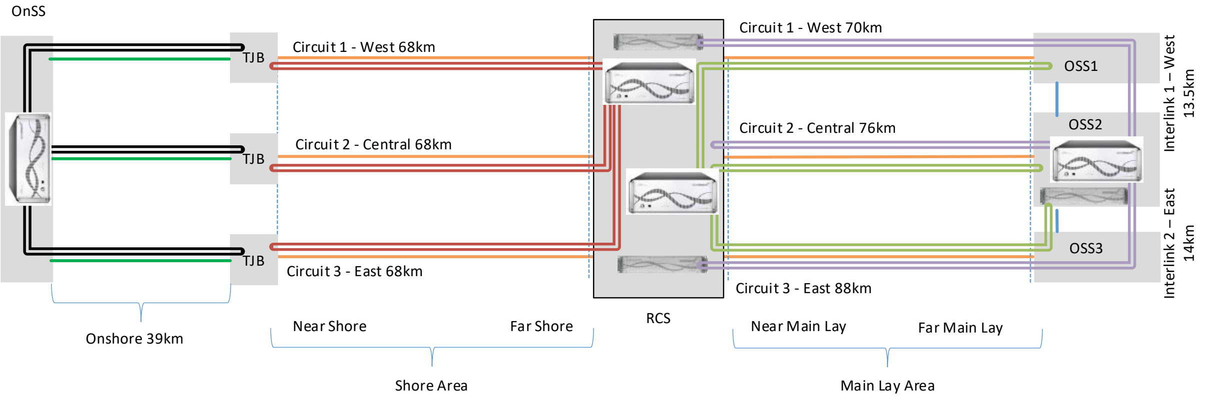

Figure 5: Cable route and length, BOTDA and amplifier location.

3.2. PERFORMANCES

Initial optical budget was computed per circuit, assuming a conservative 0.25dB/km loss for the fibre, with 0.1dB loss per splice and 0.25dBloss per offshore joint. Under these assumptions, the optical budget for the longest link, namely RCS-OSS3-OSS2 was 26.2dB, for a total loop budget of 52.6dB. This is beyond the budget of the available interrogator and requires amplification to handle the propagation of the probe signal through the loop. By adding a 20dB gain, the loss budget goes down to 32.6dB (total loop), which is well within the range of the longest BOTDA interrogator.
Repeatability, as measured in the field, is shown in Figure 6; all cable sections are measured with 3m spatial resolution. The measurement time is 9min for OnSS-TJB, 15min for RCS-TJB as well as for RCS mi-point towards OSS2 and 16min for OSS2 mi-point towards RCS. Thus, the complete cable system is measured four times per hour.

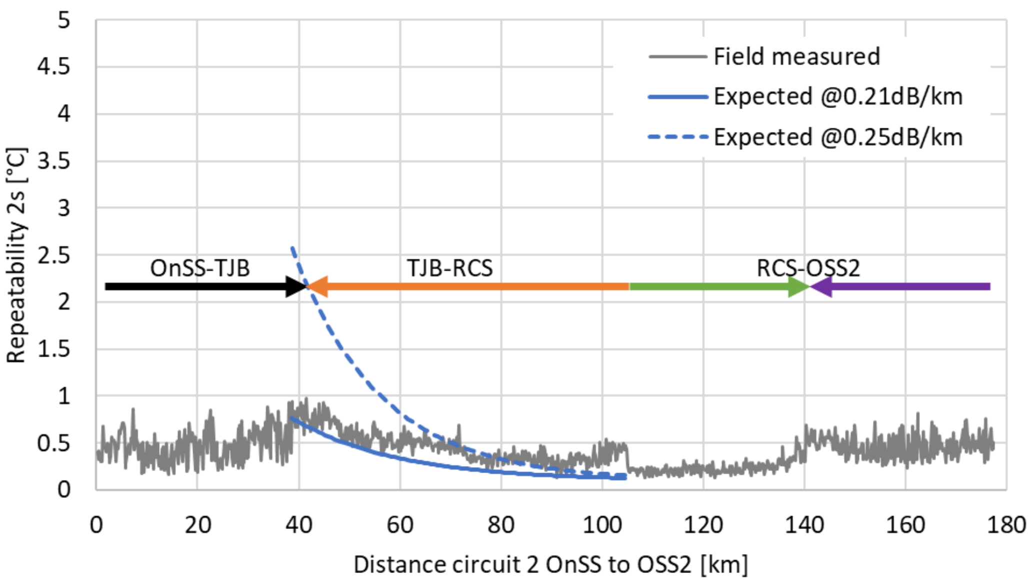

Figure 6: Field measured repeatability (2σ) along circuit 2, from OnSS to OSS2, 3m spatial resolution, and expected repeatability over RCS to TJB assuming 0.21dB/km and 0.25dB/km respectively.

The expected repeatability for the RCS-TJB link, assuming 0.25dB/km fibre loss as used for the optical budget validation was around 2.6°C. Assuming a more typical 0.21dB/km loss, the corresponding repeatability would be improved to 0.8°C, which is matching the measured value (Figure 6). This confirms that it is important to have a realistic estimation of the fibre loss to accurately predict the performances. In some cases, a proper assumption on the loss allows to measure a long link with good performances without amplification at the loop end, whilst a conservative assumption does not allow it.

4. Temperature measurements

The concatenated temperature profile measured by the DTS for the west circuit is shown in Figure 7 for variable load conditions (the magnitude of the load is not relevant for the discussion). As demonstrated in previous publication [8], all variations in the thermal profile can be traced back to some cable properties, either in the cross-section, or the laying depth, or in the seabed parameters. For instance, the peaks seen within the land section corresponds to multiple road crossings with the temperature increase simply reflecting changes in the heat dissipation properties of the soil/HDD/tubing around the cable. Along the full cable length, the temperature profiles are moving in a very homogenous way when the load varies.

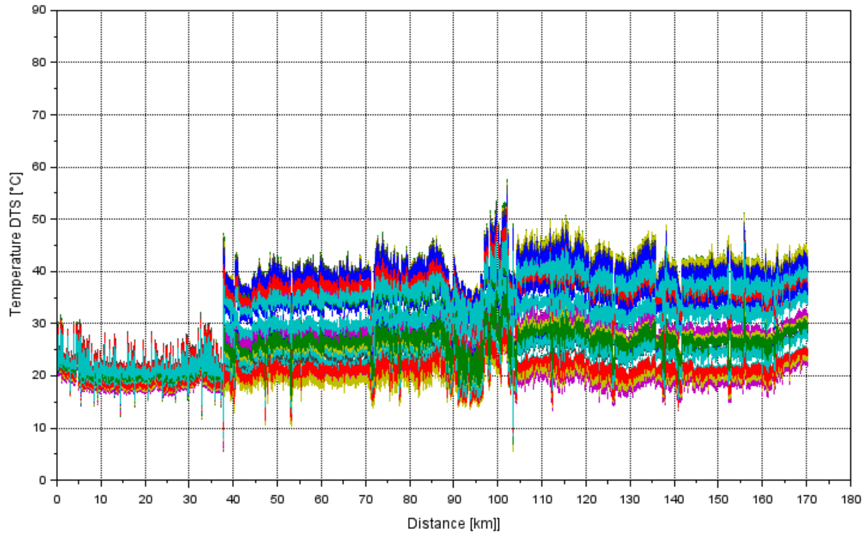

Figure 7:Temperature along circuit 1, at two different loads

Looking over time at a specific location, here on the second half of the RCS to OSS2 cable (Figure 8 arbitrary selected point), the temperature dependence on the load is clearly seen. In addition, it shows the delayed thermal response of the cable with respect to the fast load variations which can be considered when computing the conductor temperature using a Real Time Thermal Rating computation system.

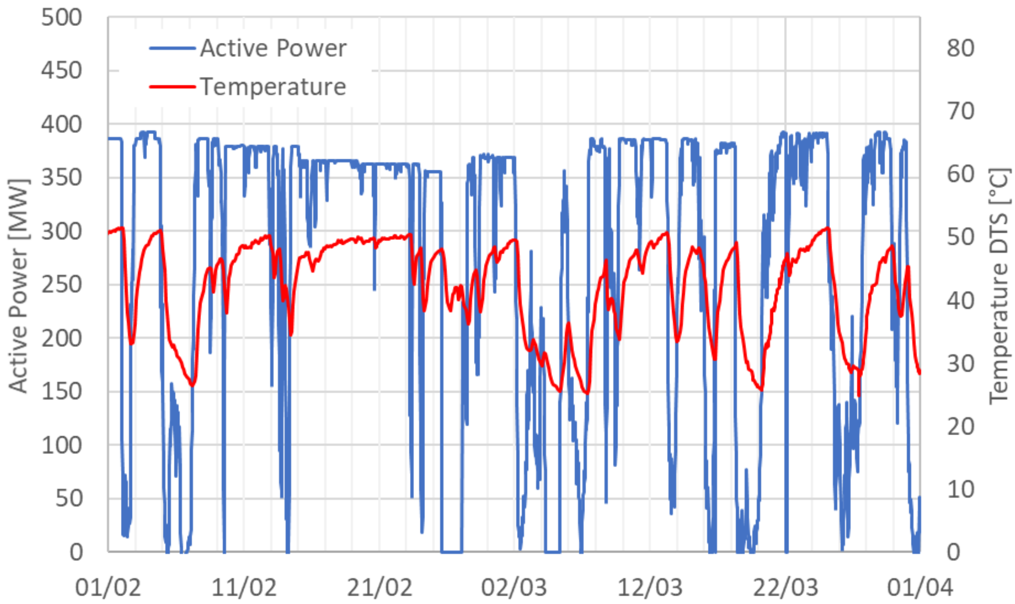

Figure 8: Fibre temperature and cable load over time.

One interesting position to look at is the J-tube vicinity. Figure 9 shows the temperature evolution as measured by the DTS over distance at the RCS, for different load conditions (lowest temperature profiles corresponding to lowest load, highest temperature profiles corresponding to highest load condition within the randomly selected time period). A clear and stable temperature is seen on both side of the platform, with a colder position where the cable is exposed to water, either at the seabed/J-tube transition, or in the J-tube itself; cable protection system (CPS) is also in this area, although not seen on the thermal data. Temperature is significantly warmer where the cable is in the air section of the tube and at the hang off; in these locations, the cable is influenced both by the load and the ambient condition (exposure to sun, ambient temperature). The dynamic variation at these locations shows (Figure 10) up to 40°C differences between the unloaded and the loaded periods. In addition, the in-air section can be colder than the water when the cable is unloaded during cold season.

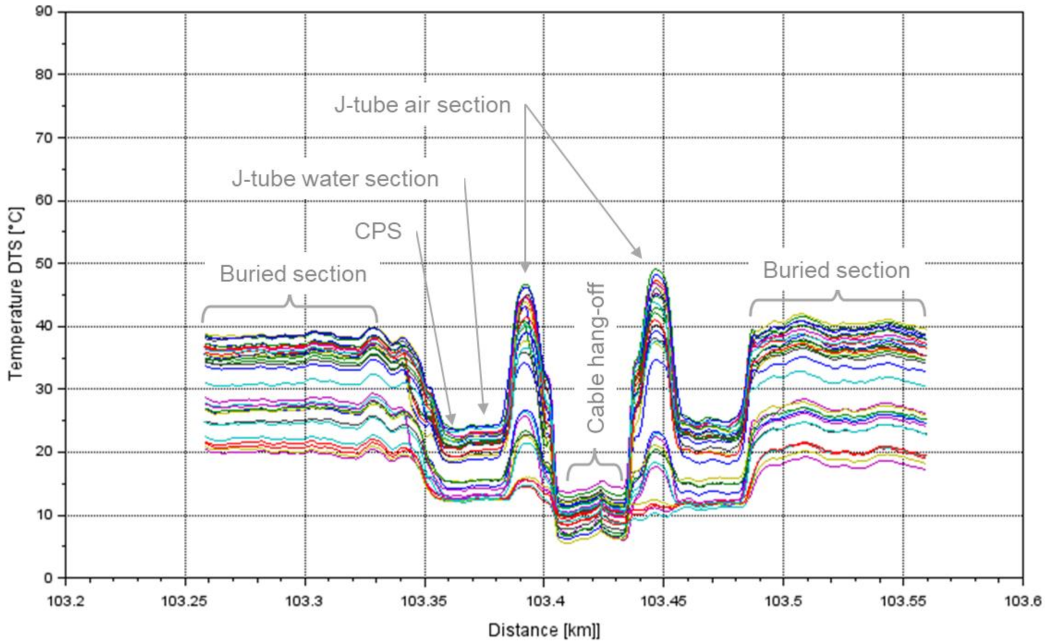

Figure 9: DTS measurement on both side of RCS, featuring buried cable section, CPS, cable length in flooded J-tube and cable in unflooded J-tube/hang off section

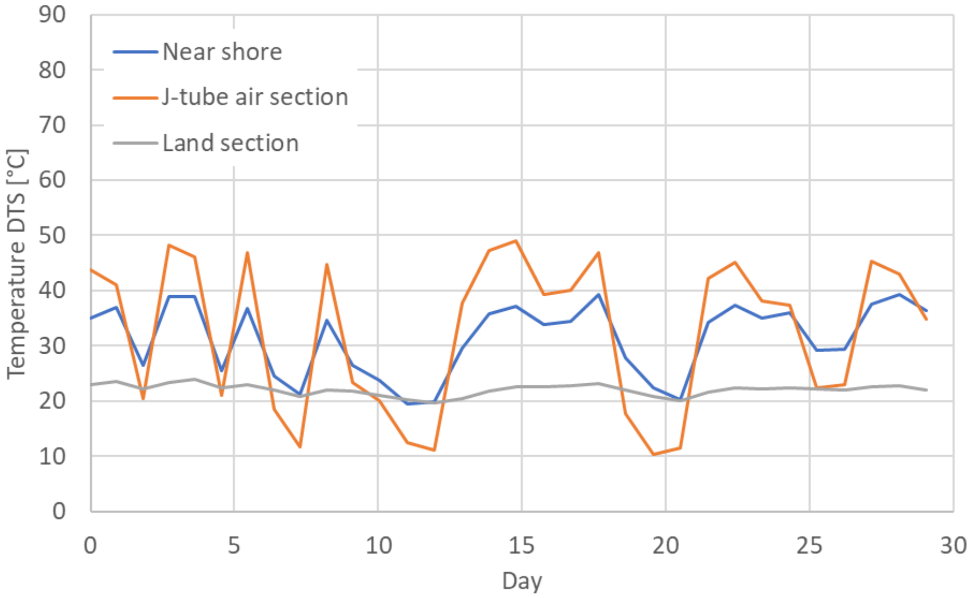

Figure 10: Measured DTS temperature variations as a function of load.

The cable route is split in multiple zones with corresponding alarms. The alarming level is configured on zone basis independently, and alarms are forwarded to the operator over a Supervisory Control and Data Acquisition system (SCADA).

5. CONCLUSION

HOW1 is currently the largest commissioned offshore windfarm with its 1.2GW installed capacity. The complex cable route, featuring three export cables, a reactor compensation platform mid-way to the farm and three offshore interconnected substations is monitored with DTS over the entirety of the more than 580km cable length.

Instrumentation was installed onshore, on the RCS and on one of the OSS, in view of centralising as much as possible the sensing infrastructure whilst providing measurement of all cable sections. Due to the long lengths, BOTDA were selected for the temperature measurement, with, for the longest routes, the assistance of optical amplification at the loop end to guarantee sufficient performances.

The systems are configured with a 3m spatial resolution and a measurement time around 15min so that the entire cable route is measured 4 times per hour. The temperature repeatability is always below 1°C (at 1σ).

Temperature profile over distance is a signature of the cable cross-section, depth of burial and surrounding conditions. When analysed as a function of the load, one can see the thermo-dynamic behaviour of the cable.

Looking more specifically at the J-tube, the difference between the in-water and the in-air sections are clearly visible, with large variations in temperature for the latter case.Ø

HOW1, together with the Cluster Westlich Adlergrund [3] belongs to the most complex installation worldwide so far.

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