EXPORT CABLE FAILURE

AXIS RENEWABLES
IN PARTNERSHIP WITH

Renewables Consulting Group

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A WORD FROM AXIS

Dear Broker Partner,

Together with our engineering partner RCG, we have commissioned this report to look at issues of cabling related to Offshore Wind Farms, which unfortunately, are the primary source of claims . According to loss adjuster, Lloyd Warwick, 40% of all claims are cable related, producing 83% of claims costs in Offshore Wind. The aim of this report is to attempt to get a better understanding of this area and what leads to this expense. This report will cover the types of cables used, how the cables used compare to cables in the Oil and Gas industry, the issues that lead to failures, potential defects and how cables are monitored.

I trust that you'll find this report interesting and I look forward to continuing to work with you.

Jamie Fleming
Senior Underwriter

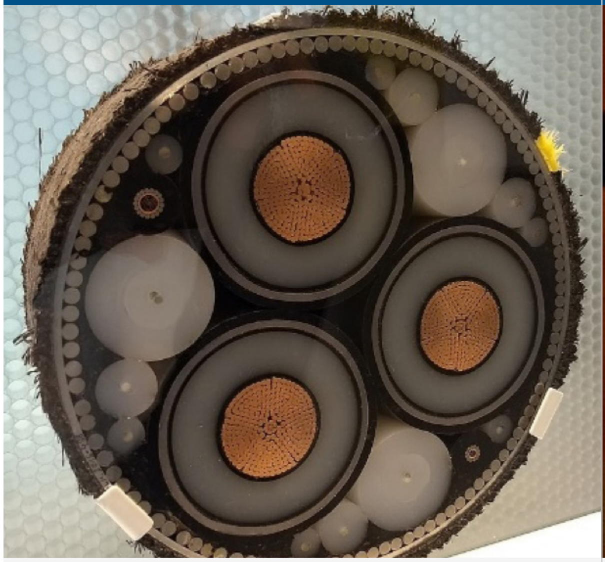
INTRODUCTION

1.1 AC vs. DC, Manufacturing and Market Size

Export cables are the offshore wind farm's connection back to shore, allowing the full power generated by the farm to be transmitted to the local grid. Two general cable technologies exist: alternating current (AC) and direct current (DC). AC is preferred as a grid connection can be made directly into an existing or new substation whereas DC requires an offshore converter station plus an onshore converter station, before connecting into an AC substation. Long distance electrical interconnectors use high voltage DC (HVDC) cables because the higher losses on high voltage AC (HVAC) transmission lines mean long AC systems are not viable, buried cables being more onerous in terms of losses than overhead lines. Early studies [1] calculated that the breakeven point where the additional cost of HVDC outweighed the greater losses incurred by HVAC connections as around 80 km in connection length, below which AC was preferable and above which DC was preferable. However, wind farm owners are incentivised to use longer distance HVAC due to technology and consenting risk, as well as having alternate views on costing. Offshore cable lengths now reach >150 km, and total cable lengths, including offshore and onshore, are approaching 200 km (Hornsea project, as extracted from RCG's GRIPTM database) with AC technology; this however can only be achieved by using intermediate reactor stations along the length. A comparison of AC and DC cables is provided in Exhibit 1 below.

Exhibit 1: Comparison of AC and DC submarine cable systems

AC Submarine Cables



One circuit constitutes a 3-phase cable with three power cores plus optical fibres included.

Range of voltages:

- Low voltage (LV): < 30 kV
- Medium voltage (MV): 30-100 kV
- High voltage (HV): 100-220 kV
- Extra high voltage (EHV): >220 kV

Ethylene and propylene-based insulation is preferred.

DC Submarine Cables

One circuit constitutes a pair of single-core cables (in a 'bipole configuration'), which may also be packaged together with an optical fibre cable.

Two manufactured types, with voltages starting at 100 kV:

1. Single-core mass impregnated (MI) or self-contained fluid-filled (SCFF), up to 500 kV.
2. Ethylene and propylene-based insulation, incl. XLPE , up to 320 kV operational and up to 600 kV planned.

Source: [2], [3]   Data Sources: [4], RCG GRIPTM (2019)

Regardless of the type of cable, submarine power cable manufacture is a slow and delicate process, where a single long piece of cable is produced over an extended period. During this time, it is necessary to perform continual monitoring of the cable and the manufacturing equipment to meet the close tolerances and high degree of accuracy required to ensure a reliable cable product. [5]

RCG's global forecast for export cables installed per annum up to 2023 is shown in Exhibit 2 below. HVAC continues to dominate the current market for offshore wind and while the use of HVDC technology has stalled in recent years, it is expected to pick up again in the early 2020s. LVAC and EHVAC remain small parts of the market. It is seen from Exhibit 2 that the challenge to the industry of maintaining the reliability of cables within the offshore wind sector is exacerbated by the increasing lengths of cable required to service the industry; although this is naturally mitigated by the gain in experience of cable manufacturing and laying over recent years.

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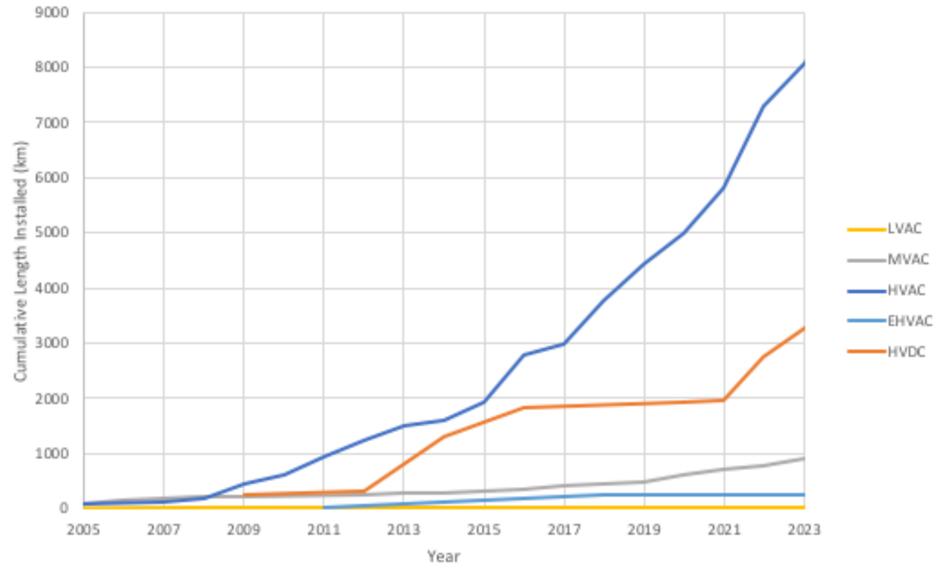
[1] XLPE stands for 'Cross-linked polyethylene' and HPTE stands for 'High Performance Thermoplastic Elastomer', i.e. a polypropylene-based solution

Exhibit 2: Historical and forecasted (to 2023) lengths of offshore wind export cable installed globally (excluding the Chinese market)



Source: RCG GRIPTM (2019)

1.2 Export cable installation

Cable installation methods are similar for both AC and DC submarine cables, with the aim to protect both the cables and the environment, as well as meet the cable install specifications. Man-made risks like anchors and trawler fishing nets mean that cables in shallower water (< 500 m) should be buried in the seabed for protection (though some surface laid cables do exist, safety concerns for the vessels, as well as economic risk through loss of operation, mean most are buried), while cables in deeper water may be laid directly on the seabed as these risks are eliminated by the depth. Cable burial depth is defined through undertaking a cable burial risk assessment, while there have been specialists in this activity for many years, and standards from parallel industries have been used in the past, the recent The Carbon Trust (TCT) guidance forms the basis of wind industry practice [6].

Environmental bodies often seek deeper burial due to concerns from around induced electromagnetic fields, but deeper burial adds significant expense as few cable burial tools exist that can bury deeply, is very dependent on the seabed soil conditions, and results in warmer temperatures around the cable which can result in a larger and more difficult-to-handle cable being required to transmit the same power. Shallow burial, between 0.8 – 2 m, is therefore highly economically incentivised. Deeper burial up to 3 m may be required through sand waves, or if there is a significant risk of large shipping anchoring, although this is unlikely since large shipping is generally passing rather than stopping, and no burial will prevent damage from the largest shipping in an emergency situation. Where burial is not possible, other protection methods such as rock dumping, concrete mattresses or metal structures may be used. All offshore wind farms to date have been installed in < 500 m water depth, making cable burial or other protection a necessity in most cases.

Cable installation requires specialised ships or barges to carry the kilometres of cable and install them according to the specifications, and a dedicated and experienced team is necessary. To simultaneously lay and bury cables, ploughs, remotely operated vehicles (ROVs), water jet trenchers or mechanical trenchers are used depending on the soil composition, as well as other equipment such as excavators. While most of the installation equipment is remotely operated from the cable ship or a support ship, divers may also be necessary (especially when other cable protection methods are employed, such as the laying of frond or concrete mats).

Following preparatory works and cable load-out onto the cable ship, a 'shore-pull' is carried out, where the landfall end of the sea cable is landed on the shore and installed with horizontal directional drilling (HDD) or trenching methods, depending on the shore's physical and environmental requirements. The cable is then laid on the seabed, as described above, out to the wind farm, whereupon the cable must be cut to the correct length to allow it to lie properly on the seabed. Finally, a 'pull-in' operation is performed to bring the cable end into the offshore substation or wind turbine. At all times during installation, the cables' mechanical properties such as pulling tensions and bend radii are monitored and recorded.

After cable installation is completed, post-installation verification is carried out to ensure that the cable was installed correctly, which is necessary from a project due diligence perspective, as well as for prospective OFTOs. This process will include electrical testing, usually according to IEC and CIGRE standards, as well as surveys assessing the cable burial/protection. If issues are identified in the subsequent risk assessment, remedial works may be needed.

Individual cables must be separated on the sea-bed by a sufficient distance, which distance depends upon the water depth. Cables are often laid slightly snaking rather than straight, to accommodate sea-bed movement. This also means that should a cable repair be required, the cable can be lifted to the surface, an additional length added, and the cable re-laid without overlaying any neighbouring cables.

Exhibit 3: *Cable ship Stemat Spirit performing a shore-pull using a plough*

Source: *wikimedia*[7]

Exhibit 4:
Cable ship Nexans Skagerrak in port, with a large central cable tank and specialised handling equipment visible

Source: *wikimedia* [8]

Exhibit 5:
Cable installation barge BoDo Installer under tow

Source: *wikimedia* [9]

EXPORT CABLE FAILURES

Export cables can experience full or partial failures during the manufacture, construction and operations phases of the project, leading to delays that are likely to affect the project timeline and result in significant capital costs for repairs or replacements, and loss of revenue for an operating wind farm. The export cable is a critical component and a failure will delay commissioning or interrupt operations unless an alternative cable connection is available.

Repair or replacement work is often carried out by a different specialised vessel than the installation cable ships and involves the following steps: de-burial and/or removing cable protections, lifting the cable onto the vessel, repairing or replacing the damaged cable section and finally re-burying the cable; with all of these operations being highly weather sensitive. To ensure confidence that the issue has been fixed and that water ingress into the cable conductors is not a problem, it is often necessary to remove a section around 1 km in length around the damage using the bespoke spare repair joints and clean cuts to the cable and jointing on a replacement piece.

Export cable replacement work can have time implications of around 6 months with capital and loss of revenue costs of multiple millions of GBP (not counting any additional spare joint or spare cable manufacture).[10]

This section lists some of these failure modes and assesses their impacts and associated costs and delays.

2.1 Installation: Failure to meet cable install specifications

Cables are difficult to handle and during installation; the cable must be managed according to the mechanical handling and physical specifications given by the manufacturer, which includes requirements such as keeping the cable tension within the correct range, preventing the cable from bending past the minimum bend radius, and others. Installers do monitor the cable's condition carefully during installation by use of subsea video and continuously running 'OTDR' testing of the fibres (see later section) but a momentary lapse in the continuous laying operations can lead to the failure by the installer to meet these specifications and can result in significant damage to the cable that may or may not be detectable during installation or commissioning and could cause the cable to fail prematurely.

It is also critical that the geotechnical data for the seabed soils is accurate and comprehensive enough to ensure that the cable installer uses the appropriate methods and equipment, both to ensure thermal properties around the cable and to avoid physical damage due to hazards such as sharp rocks. This geotechnical data is typically provided to the installer by the developer and can thus be the cause of significant contractual disputes.

Damage from cable installation will typically require at least a section of the cable to be replaced, although the entire cable could be affected. The resulting delay may be a few months depending on whether there is enough spare cable, or if a new installation contractor is needed, available weather windows for installation[2], etc. In addition to the delay costs, there will be capital costs on the repair/replacement works and the extra spare cable/joints manufacture (if needed). These costs are not typically covered by the installation contractors and often the risk remains to be assumed by the project developer.

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[2] In addition to requiring the appropriate specialist equipment, offshore works are very dependent on a good weather being available, since high winds and large waves can present unacceptable risks to components, vessels and crew.

2.2 Installation & Operations: Significant cable burial issue

Difficulties in cable burial are common, often due to insufficiencies and/or inaccuracies in the marine geophysical and geotechnical surveys conducted during the project planning phase. Unexpected cable burial difficulties result in installation cost overruns and delays, although these themselves will not cause cable damage. If a cable is left unburied and unprotected, it would be more susceptible for damage from maritime activities (trawler fishing and ships' anchors) and potential liability for damage to such vessels, but again would not necessarily fail, especially if other mitigation is performed such as communicating the risks to mariners.

In more extreme cases however, cable burial and protection issues can directly lead to cable failure: if a section of the cable is left unsupported underneath as a result of these issues, known as a 'free span', the increased tensional load and/or fatigue-inducing vibrations on the cable can damage it. Hydrodynamic scour, where supporting sediment is carried away from an object (cable in this case) by water currents and results in 'scour pits' forming around/underneath it, can lead to these free spans. If the risk of free spans is not properly mitigated during installation, they will often only become evident later (e.g. during the commissioning or post-installation surveys). In the worst cases, cable re-burial remedial works, such as by the application of rock-dumping, concrete mattresses, frond mats or by water-jetting, are always expensive, can pose further risk to the cable (and potentially during diving operations), plus may only be done during full cable outages resulting in further lost revenue.

2.3 Installation: Electrical connection fault

Interfacing of the export cable with the electrical infrastructure in both the onshore and offshore substations (or converter station for HVDC) is generally done as the last main installation step before testing and commissioning. The termination operations (i.e. making the final electrical connections) of all the power cables has all the typical high voltage electrical risks (compounded by the nature of working offshore where the environment is not as clean and controllable as, say, an onshore substation building) meaning that faults and subsequent damage to either the cable or substation infrastructure is possible. However, if cable termination damage does occur, the repair/replacement works are generally not as complex as for a subsea electrical fault, resulting in lower associated costs and delays. With good electrical safety practices, the damage from any incidents can typically be limited and the risks to the electricians themselves will be minimised. Again, loss of revenue will occur if any cable terminations do show faults.

Export cables are typically long and may exceed the length of cable that can be carried by a single vessel, preventing it from being laid in a single piece. Such export cables will require in-field cable joints to be included, which are inherently vulnerable compared to the un-cut lengths of cable and constitute potential weak points. Because the joints must be made offshore, they will be especially susceptible as it is impossible to achieve the engineering control standards possible within an onshore cable facility, although experienced offshore installers will have acceptable results.

2.4 Manufacture: Manufacturing defect or testing error

Manufacturing defects are relatively common for long length power cables, since they are made in long continuous sections in a time-consuming and precise process, where even the smallest process errors can produce defects that could lead to electrical faults with catastrophic implications if they are not rectified before the cable is put into service. The main way that a project owner can mitigate manufacturing defects is by ensuring the highest standards of experience, quality control and assurance processes are maintained by the manufacturer. Many owners require that the cable delivered does not include any factory joints, which may not be possible if the total length required exceeds the physical length capacity of the factory. This means that new or bespoke cable types should also be avoided where possible. As a general point, 'quality is king' when manufacturing power cables of the lengths used in offshore wind.[3]

2.5 Operations: Man-made or natural damage

The trend for offshore wind cables (inter-array and export) is that most cable damage is caused by manufacturing and installation issues. The cable burial report issued by the Carbon Trust's Offshore Wind Accelerator (OWA) programme stated that 80% of European offshore wind farm insurance claims were cable related [6] – of these 62% related to cable damage during construction, although not all attributable to cable burial operations. In addition, to the knowledge of the OWA partners there is no evidence of anchor strikes and/or dragging, either to export or inter array cables, on offshore wind farms operating in UK waters. The fibre-optic manufacturing fault (section 3.2) was not known at the time of this report's publication, and wider European experience was not documented, however cable failure examples presented by industry participants appear to follow this trend. The more recent OREC report [11] includes more recent UK cable failures, which again are as a result of manufacturing issues, not third-party damage. The CIGRE working group (B1.57) is expected to publish an update to TB 379 [12] shortly, which will update this knowledge base.

It is, however, interesting to note that for fibre-optic cables globally, the greatest risk to operational submarine cables is physical damage from human activities, including from ships' anchors and fishing trawler nets. For these submarine cables worldwide, 80-90% of all faults can be attributed to human activities , which predominantly occur in water depths shallower than 1,000 m and mostly in less than 200 m water depth [13]. The risks from human activities are lower in countries where better risk communication practices are established, such as through the KIS-ORCA project in Europe [14]. Thus, it may be that when the wind industry's teething problems are resolved, human damage may become the primary cause of damage, if protections are compromised.

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[3] It should be noted that the total conductor length for 3-phase AC cables is triple the length of the cable itself.

The main source of natural damage to submarine cables is seabed movement from moving sand-waves, subsea landslides, tidal movement or even tectonic shifts. These can result in direct physical damage to the cable or can cause it to become de-buried (see Section 2.2 above). Abrasion from water-borne materials also poses a physical risk, and together these hazards account for 10-15% of all (global) submarine cable faults [13].

Condition monitoring, which is covered in more detail in Section 4 below, is critical for effective responses to cable failures during operations. If cable damage can be pre-empted, repair/replacement work can be planned in advance for significantly reduced capital and downtime costs, but quick responses to unexpected cable failures will also reduce the downtime costs; some cable owners are pooling their resources into a 'club' which can then offer a much faster time of response than if procured via a single cable owner.

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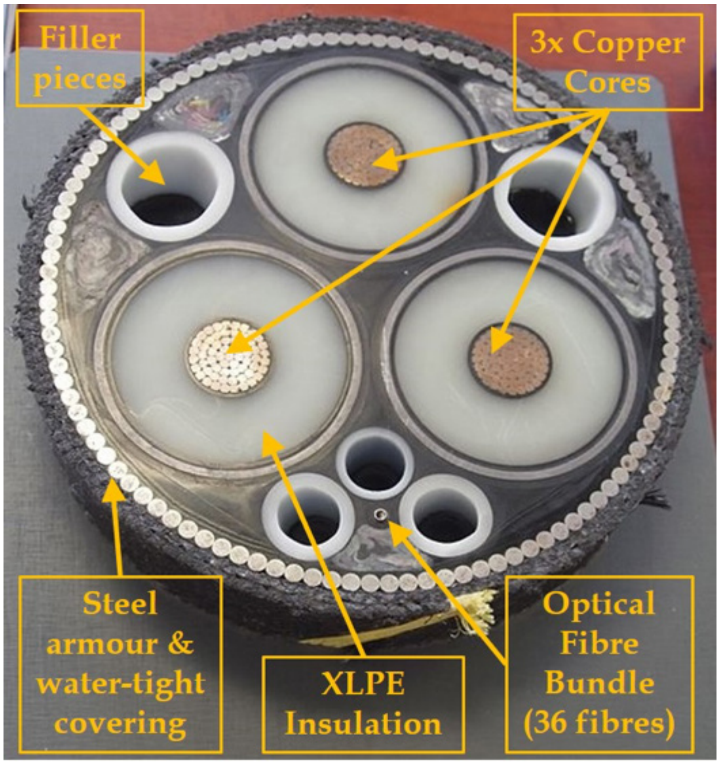
[4] This figure does include optical fibres, which are installed more globally in communications cables and often have less protection than submarine power cables.

DEFECTS IN OPTICAL FIBRE CABLING

Optical fibres in power cables

Exhibit 6 below shows a 245 kV HVAC submarine cable with a bundle of optical fibres packed into the cable. The fibres are included separately outside the three XLPE insulated conducting cores and typically are within their own metal tube, which may be surrounded by further plastic or metal armouring (similar to the armouring around the outside of the cable). Stainless steel is the most commonly used metal for these parts.

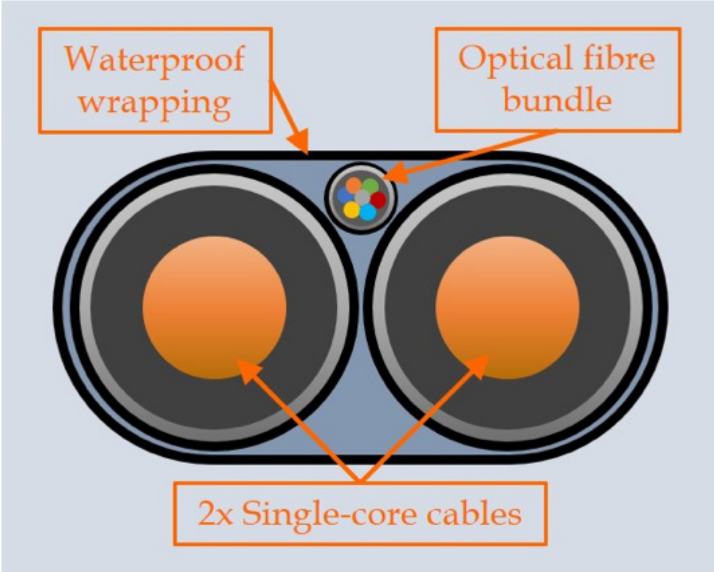
Exhibit 6: Annotated photograph of a (E) HVAC submarine cable



Source: wikimedia [15] *& Canadian Copper & Brass Development Association* [16]

HVDC uses two single-core power cables and the optical fibres are generally included as a separate cable, which is commonly wrapped together with the power cables to simplify installation, as shown in Exhibit 7 below.

Exhibit 7:
Annotated cross-section of a HVDC bipole system showing optical fibre cable



Source: *RCG*

In both cases, the steel tube armouring on the optical fibre cable provides stiffness to protect the fibres from mechanical damage (including during manufacture), as well as further protection in case of water ingress. To minimise the impact of any individual fibre having a fault, many levels of redundancy are often in-built to the fibre package by it containing double or triple the numbers of fibres actually required for the safe control and operation of the windfarm. A failure in enough of the fibres would, however, mean the replacement running of a new fibre cable along the length of the cable, regardless of whether the power cores themselves are affected.

3.2 Risks to power cables due to optical fibres

It is not practical to provide a statement on the overall reliability of optical fibres used within submarine power cables, as they do not experience the same exposure as standalone fibre-optic cables.

'Export Cable Reliability: Description of Concerns', a May 2017 report by Transmission Excellence Ltd on behalf of the Offshore Wind Programme Board (OWPB), stated that there have been seven post-commissioning failures in UK offshore wind AC export cables, and based on data from the cable's owners, at least six of the failures would not have occurred "had a fibre optic core not been included within the power cable". [11] The report proposes three possible contributing factors:

1. The optical fibre cables, which are small and light, are prone to accidental damage during cable manufacture;
2. The design and testing of the optical fibres is focused on their optical performance, without enough consideration of the effects of exposure to high voltages and currents, which may happen under some fault conditions;
3. The fibre may be exposed to large magnetic fields from the adjacent power cores which could induce damaging electrical currents and voltages in the metal tube armour used around the fibres. These would be more likely if an electrical fault caused the magnetic fields to be higher than expected.

The first and second points are manufacturing practice issues that may be reduced through careful auditing of manufacturers, while the third is a potential design issue. In both AC and DC configurations, design symmetry helps ensure that the magnetic fields generated during normal operation will be minimised, reducing the potential impact of the issue (also for DC the magnetic fields are static). An approximate calculation for a standard HVAC cable suggested that during normal operation, the induced voltages and currents would be far too small to result in any significant damage to the fibres[5] and is only likely to cause a little heating in the fibre area of the cable.

The above conclusion is supported by an inquiry submitted by RCG to a large power cable manufacturer. The response stated that designers do consider the voltages and currents induced in the stainless-steel tubing, but that the associated losses in transmitted power are very low, so that designers do not seek to mitigate them by introducing alternative designs. The small power loss suggests little heating due to this mechanism, and the cables are already designed to manage the heat from the conducting cores themselves which will be much larger sources of heat. Although damage to the fibres from this mechanism is very unlikely during normal operation, it possibly could result in a significant electrical fault which subsequently affects the fibres as well.

We do not believe there is enough information on export cable failures overall to determine how prevalent each of the above three failure modes is, with the available data being limited by the small number of cases and the commercially sensitive nature of the failures. If the third issue were significant (although this is unlikely as explained previously), the planned move towards HVDC cables in the UK and other markets could slightly reduce the failure rate[6], although other factors such as the differences in testing and maintenance practices are likely to have a larger impact.

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5 Induced voltages ~mV per metre of cable, producing ~mA of current.

6 The mean 'time' between failures for HVAC cables is thought to be around 600 km years. Definition: for a length of cable installed L [km], the time expected before a failure would be given by T [years]≈ (600 [km years])/(L [km]) based on the empirical studies performed by CIGRE (2009) and Transmission Excellence Ltd. (2017). [11] [12]

CABLE CONDITION MONITORING SYSTEMS

4.1 Testing offshore power cables

'Condition Monitoring' refers to the continued testing of the export cable system after it has been commissioned and is fully operational, which can include manual or automated testing of electrical, optical and other physical conditions, as well as physical subsea surveys.

During commissioning, typically, a full set of cable testing is carried out to demonstrate continuity and insultation integrity, which can only be repeated later by taking the cable fully out of service, something that all operators would wish to avoid. These include high voltage AC 'pressure' tests (either at very low frequency 'VLF', or at the resonant frequency of the system), line resonance analysis and other partial discharge (PD), continuity and resistance tests. VLF tests are often the subject of negotiation with the cable manufacturer and supplier, because some consider that they can cause damage whereas others contest they do not; they merely exacerbate a developing problem and bring the failure forward. VLF is generally accepted as preferable to DC testing, which is seen as invasive, meaning that such tests are often accepted once only. For DC cable systems, high voltage DC tests will constitute direct proof-of-function tests, although PD and other electrical tests will also be performed. During operation it is not possible to perform these controlled tests (which would require downtime) and an alternative approach must be adopted: an operating system that demonstrates performance, and an electrical protection system that identifies insulation degradation-related faults as and when they occur/escalate.

Continuous monitoring of the health of the optical fibres is often carried out during installation, although the current techniques tend to yield limited information. The take-up of condition monitoring of cables during operations is also limited, largely due to the increased OpEx costs that are often seen as financially unattractive. Of course, a lot of continuous testing is present during manufacturing as part of the cable manufacturer's quality control process, although this is not considered condition monitoring from the perspective of the project.

4.2 Distributed sensing for online monitoring

The general approach is to use remotely operated sensing equipment distributed along the length of the cable to observe it during operations and provide continuous and non-invasive data collection.

The optical fibres included inside, or along with, the export cables enable various types of distributed optical fibre sensing to measure temperature and strain along the cable (with spatial resolutions ~1 m). 'Optical time domain reflectometry' (OTDR) is the industry standard technique for these measurements, although frequency domain reflectometry is also used (OFDR), and both methods allow for faults to be located along the length of the cable.

Distributed temperature or strain sensing with optical fibres has been implemented in offshore wind to characterise and test export cable during commissioning, to monitor them during operations and to diagnose faults when they occur.

Organisations such as The Carbon Trust and the US DoE are known to be interested in distributed sensing for condition monitoring:

- The Carbon Trust has an offshore wind cable condition monitoring work stream as part of their industry-collaboration Offshore Wind Accelerator programme. A cable monitoring competition to develop real-time mechanical cable monitoring was launched in January 2017. OTDR methods were expected to prove successful, but the results have yet to be announced. [17] [18]
- The Carbon Trust also launched a research project ITT for 'Fault Location and Condition Monitoring in Long Offshore Cables' in December 2018, with a focus on 'online' solutions to be used while a wind farm is operational. The closing date was 25th January 2019. [19]
- The US DoE has recently awarded several million USD of funds to research projects addressing other issues faced by offshore wind (ecological protection, etc.) and RCG is aware of interest within the department to fund cable condition monitoring research as well. [20]

Optical fibre-based distributed sensing is not able to directly sense electrical problems within the cable conducting cores/insulation, such as any partial discharge (PD). However, any fault issues will eventually become apparent via an increased temperature, or strain, which may be detected through OTDR/OFDR methods, allowing the location of the fault to be identified along the length of the cable.

It is also possible to detect such faults with electromagnetic methods, allowing for pre-emptive repair/replacement at allegedly significantly lower costs. Cable manufacturer Prysmian Group has commercialised one of the only implementations of this technology under the trade name 'PRY-CAM', which has been developed since 2008 [21] and announced its first sale for an offshore wind project – a full cable monitoring system included with the export and array cable supply – to EDF Renewables for the Provence Grand Large floating offshore wind project in southern France. [22] The technology uses individual battery-powered sensors (shown in Exhibit 8 below) each with a wireless electromagnetic sensor to detect local PD occurrences.

It is not known how robust the system is or whether Prysmian's main competitors, such as Nexans and NKT, are working on similar systems, however with more and more potential monitoring solutions coming into the market, it is our view that both CapEx and OpEx costs will be tending to decrease, with the systems' effectiveness tending to increase.

Exhibit 8:
A Prysmian Group PRY-CAM PD sensor; multiple networked sensors are attached to the cable to form a distributed monitoring system

Source: Prysmian [21]

4.3 Future development in export cable condition monitoring

As downtime in an offshore wind farm cable is extremely financially damaging, project owners and operators aim to create maintenance and repair infrastructure (including technicians, vessels, crew, spare components) that can rapidly respond to failures and other issues. For the power cables, this will involve electrical contractors specialised in high voltage work, cable manufacturers and cable ship owners/operators, and is typically established separately and specifically for each project. However, as shown with Prysmian's full-scope offering for the Provence Grand Large project, cable manufacturers are increasingly looking to provide their own condition monitoring and O&M services, in a similar way to those offered by turbine manufacturers; it does however remain uncertain how cost-effective these solutions are, and whether project owners are willing to invest in what can be seen as an unestablished design.

Marine surveys play some role in post-commissioning condition monitoring but they are relatively expensive to carry out and are generally only used when further information is needed about a strongly suspected problem, such as a significant cable burial issue having developed since commissioning. Similar to the post-lay survey carried out during commissioning, these surveys can measure the cable's exact position, the depth-of-burial/depth-of-cover, the physical conditions of the cable and cable protection, whether the cable is supported well or if free span sections have formed, etc. Survey data should be independently validated, and repeated to ensure honest and consistent reporting.

While best practices have largely been established for pre-installation testing and electrical & optical commissioning, there are several technology gaps for condition monitoring during installation and operations which the industry is currently seeking to address. Furthermore, where condition monitoring has been implemented, it has largely been done on a very bespoke basis and the range of commercially available 'off-the-shelf' solutions remains limited. The continued commercialisation and development of submarine power cable condition monitoring systems is expected to result in cost reductions for these services, although it is difficult to anticipate timescales for these changes as new sensing technologies must first be developed before being brought to market.

COMPARISON TO OIL & GAS POWER CABLES

Submarine cables are used in the oil & gas industry in multiple different applications, and the types of cables vary greatly as a result. A large portion of these cables are referred to as 'umbilicals', which link surface and seafloor equipment to transmit communications signals (for sensing and control), power, hydraulic and chemical injection fluids, as well as heating. Umbilical cables do have uses in offshore wind farm construction, such as for remote controlling submarine installation equipment, but they are not very relevant to operational wind farms. Power umbilicals are typically medium voltage (up to 36 kV).

Offshore oil & gas platforms have energy-intensive operations, with power requirements of up to several hundred megawatts (MW) on the largest installations. The traditional solution has been to use diesel engines or gas turbines fuelled by the petroleum or gas extracted and processed by the platform, however the industry is increasingly considering this approach to be inefficient and environmentally damaging. The main alternative is referred to as 'power-from-shore', where a dedicated submarine power cable is used to transmit power from the onshore grid to the platform.

A pioneer in this approach was Statoil, whose Gjøa floating oil & gas platform located in the North Sea is powered by a 100 km-long 115 kV HVAC XLPE cable, manufactured and installed by ABB in 2010. [23] ABB have since provided AC and DC power-from-shore solutions to several oil & gas platforms, as have other cable manufacturers such as Prysmian Group. Shorter LV, MV and HVAC submarine cables have also been used for power distribution between different sections in oil & gas installations, e.g. as an inter-link between two nearby platforms, although this application remains significantly smaller than HVAC cable use in offshore wind.

Additionally, floating offshore wind demonstrators have been used on offshore oil and gas, to provide power instead of on-platform diesel generation. This provides the mutual benefit of demonstrating the floating wind technology, whilst providing needed power to get the remaining deposits out of the field.

Although the power loads generated by an offshore wind farm will be different to those required by an offshore oil & gas platform, the cable technologies will be relatively similar, and the installations will have similar associated risks. However, one of the main notable differences is the water depths in which the cables are installed. Oil & gas platforms will be located wherever oil/gas fields can be found and may operate in water depths of hundreds to thousands of metres, whereas almost all offshore wind farms (except for the newer floating designs) are in water depths less than 60 m. The risks to submarine cables are known to vary with water depth as man-made activities such as ships dropping anchors or trawling nets are only present up to around 200 m below the surface and in water depths greater than 1,000 m almost all damage to (fibre optic) cables is due to natural causes such as abrasion, underwater landslides and seismic activity. As a result, a greater portion of submarine power cables in the offshore wind industry can be expected to be exposed to the man-made shallow water risks compared to those in the oil & gas industry, which would instead experience more damage from seismic activity and other natural causes, although a full study would be necessary to confirm this. Manufacturing and installation damage would be equally applicable to both industries.

CONCLUSION

- Reliable cable systems are essential to maintain the revenue being generated in offshore windfarms; and it is this loss of revenue which is a key driver in prompt reinstatement of faulted systems (for both the developers and their insurers).
- The offshore wind industry has gained more experience and competition in the manufacturing and laying of cables, and mistakes of the recent past are being learnt.
- However, the increasing volume of cables in this industry tends to indicate the number of faults occurring will remain steady.
- There is some (limited) new evidence that the metal tubing within which fibres are placed may be the cause of particular faults; although the manufacturers themselves doubt this.
- Maintaining the highest quality of manufacturing, handling and installation of marine cables is essential in the reduction of faults.
- Cable condition monitoring systems are being developed which should tend to drive costs downwards, although there is not one clear technology winner.
- The relatively shallow water installation of offshore wind cables may become a factor in their reliability, something which O&G cables tend to avoid.

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