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1 SUMMARY

This preliminary report describes the UK’s experience of operating high voltage (≥132kV) offshore wind farm submarine export cables. In the UK all such export links use AC cables with three power cores and at least one fibre optic core packaged together within one armoured cable.

To date the UK offshore wind industry has experienced seven post-commissioning failures (faults or pre-emptive repairs) on its fleet of high voltage export cables. Based on initial details provided to us by the owners of these cables1, we understand that six of these failures would not have occurred had a fibre optic core not been included within the power cable. In most of these cases an initial failure in the fibre optic core appears to have developed so as to affect a power core. There appear to be a variety of possible mechanisms which can cause the initial failure in the fibre optic core, and a variety of mechanisms whereby the damage may possibly spread to power cores.

The author has not been able to undertake a comprehensive survey of cable failures outside the UK offshore wind sector, although two failures on the Guernsey-Jersey cable and one failure on a non-UK offshore wind farm cable are believed to be linked to failures in a fibre optic core.

Up to the end of 2016 the total experience-base represented by the UK’s fleet of high-voltage offshore wind export cables totalled over 4,400km.years. The seven failures that occurred, therefore, represent a mean time between failures of 630km.years. This compares with the mean time between failures of 1,400km.years suggested by Cigre Technical Brochure 379, which has previously been the main source of information on submarine cable reliability2.

An estimate has been made of the cost of the UK’s high voltage export cable failures; this comprises both the cost of repairs and the cost of lost wind farm production. The estimated total cost is about £160m, or nearly £170k for every km of high voltage export cable currently in service.

This high cost emphasises the importance of eliminating cables’ vulnerability to fibre optic core failures in future projects. The report sets out the position of OFTOs and wind farm developers in relation to how best to ensure that the risks faced by future projects are suitably mitigated.

1 As part of a later stage in the examination of these faults, we hope to arrange for the root cause analysis documents prepared after each of these failures to be reviewed by an expert to check for commonalities and to verify the apparent common role of the fibre optic core.

2 Both the number from Cigre and the number calculated from UK export-cable experience suffer from being based on relatively small sample sizes. Although neither number has strong statistical support, the UK number at least has the advantage of being solely based on relevant cable types.
2 EXPORT CABLE FAILURE RATE – UK EXPERIENCE

An investigation has been undertaken into the reliability of the high voltage export cables used to connect UK offshore wind farms to the onshore grid. This has examined cable failures that met the following set of criteria:

i) The failed cable was a three-core AC submarine cable operating at a nominal voltage of 132kV or higher.

ii) The purpose of the failed cable was to connect a UK offshore wind farm to the grid.

iii) The failed cable had been commissioned and was in normal service when the failure occurred. The results presented in this document therefore exclude damage during construction that required the cable to be repaired before it could be put into service. The results also exclude cases where a cable suffered known mechanical damage during installation but, as a matter of convenience, the cable was temporarily put into service pending repair.

iv) The failure that affected the cable might be either a fault (short circuit), or a pre-planned repair to the cable where the owner believes that a fault is likely to develop. In either case the affected cable will be cut, the faulty (or suspect) part removed, and a replacement length of spare cable jointed into place.

The investigation found a total of seven cable failures from November 2011 to date that met the criteria set out above. In addition, at least two situations exist in the UK where an export cable, which remains in service, is exhibiting symptoms that suggest that a fault may develop. Discussions with a limited number of non-UK cable owners suggest that a similar situation may exist on at least one export cable outside of the UK.

Up to the end of 2016 the total experience-base represented by the UK’s fleet of high-voltage offshore wind export cables totalled over 4,400km.years. The seven failures that occurred, therefore, represent a mean time between failures of just under 630km.years.

Readers should note that – like the Cigre data discussed in Section 5 below – this mean time between failures number is based on a limited sample size with the faults being concentrated on a few projects. This means that unusually good or bad results from a handful of projects can easily bias the results up or down.

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3 No attempt has been made to examine the performance of lower voltage three core AC cables such as the 33kV cables widely used within offshore wind farms. Differences in ownership mean that a different organisational approach may be required if it is desired to extend the work described in this report to encompass such cables.

4 The high level of insurance claims arising from submarine cable damage during load-out, laying, burial, or from other wind farm construction activities, has been publicly documented by several insurance companies. Such sources typically show cables representing about three quarters of all claims on a wind farm’s construction all risks (CAR) insurance.
3 CAUSE OF THIS HIGH FAILURE RATE – UK EXPERIENCE

All three-core AC cables used by offshore wind farms contain at least one fibre optic core (see figure 1).

Figure 1:
(Left) cross section of a typical 3-core submarine cable showing two power cores and the fibre optic core. (Right) close up of the fibre optic core. This shows optical fibres (brightly coloured stands emerging from cable), the metal tube enclosing the fibres (the silver circle around the fibres), armouring (the thicker silver stands around the metal tube – not present in all fibre optics cores), and the anti-corrosion sheath (thick black plastic around the armour layer). In this design the fibre optic core is held in place by a moulded plastic insert which fills the interstices between the power cores and the armouring.

According to information provided by the cable owners, six of the seven cable failures referred to in Section 2 involved failures within the fibre optic core. These failures in the fibre optic core either developed to affect a power core (the more common situation), or an outage of the power cores was required to repair the fibres (less common).

Where failures in the fibre optic core have developed and affected a power core, the damage to the cable caused by the eventual short circuit may make it difficult to establish any root cause, and the root causes of the failures in the fibre optic cores appear to vary between cases. Nevertheless, a few points about the fibre optic core are relevant:

i) The fibre optic core is much smaller and lighter than the power cores within the same cable. It is therefore more vulnerable to being damaged during the assembly of the cable where larger and heavier cable elements are in motion around it.
ii) The fibre optic core is exposed to a 50Hz magnetic field from the adjacent power cores. The fibre optic cores used in submarine cable always include a metallic tube to prevent seawater from reaching the optical fibres themselves, and the magnetic fields that the fibre optic core is exposed to can cause currents and voltages to be induced on this metallic tube, especially if faults or transients cause the magnetic fields to be unusually strong. (For the cable design shown in figure 1 above, the tube is made from stainless steel and is surrounded by armour wires; these increase mechanical strength but can also carry an induced electrical current).

iii) Despite the fact that it may be exposed to significant currents and voltages, the design and testing of the fibre optic core is focussed on the optical characteristics of the optical fibres that it contains – not on its ability to withstand its electrical service conditions. Indeed with some designs the electrical condition of the fibre optic core is inherently difficult to measure, even while the cable is still in the factory.

Although the level of damage from short circuits often makes diagnosis difficult, analysis by cable owners suggests that the mechanisms by which a failure in a fibre optic core could affect the adjacent power core(s) also vary between cases. Mechanisms involving electrical discharge, overheating and electrochemical effects (corrosion) have been suggested in various cases and all need to be further investigated and understood.

There are several types of fibre optic core present across the UK export cable fleet. The faults that have occurred have affected more than one type of fibre optic core. Although some types of fibre core have not yet been affected, the limited amount of data available means that it is not possible to be confident that these types do not share some or all of the same vulnerabilities as those types that have already experienced failures.

While there is much uncertainty about the exact mechanisms and risks, the analysis undertaken by the cable owners highlight one key point: **if the fibre optic core had not been present inside the power cable then the failure would not have occurred.** This analysis suggests that the fibre optic core may be a weak point for the whole power cable: relative to the power cores it is smaller, lighter, has limited electrical withstand capabilities, and is subject to little or no electrical testing. Yet the presence of the fibre optic core may increase the vulnerability of the whole cable to full electrical failure.

### 4 OTHER RELEVANT EXPERIENCE

The authors are aware of a few failures of similar high voltage three core AC cables outside of the UK offshore wind industry, though we do not have access to a comprehensive list of failures or their causes.
Export Cable Reliability – Description of Concerns

The Guernsey-Jersey 90kV cable has suffered two failures which the owner has publicly stated\(^5\) were related to an issue within the fibre optic core. These are:

i) A fault on the cable in 2012

ii) A pre-emptive repair in 2015. In this case forensic analysis of the replaced section of cable showed that “the power cable would inevitably have failed within a very short period of time” had the pre-emptive repair not been undertaken.

The authors are also aware of at least one non-UK offshore wind farm export cable where a fault has been linked to an issue with the fibre optic core.

5 EXPECTED EXPORT CABLE FAILURE RATE

Prior to the work undertaken for this report, estimates of the reliability of submarine cables typically referenced Cigre Technical Brochure 379 (TB-379): “Update of Service Experience of HV Underground and Submarine Cable Systems”. The part of this report that deals with submarine cables made use of submarine cable failure data from 32 sources, covering the period from 1990 to 2005.

The most relevant reliability data provided by TB-379 is a mean time between failures of over 1400km.years for the category of “AC XLPE\(^6\) cables”, with the bulk of these failures being external (i.e. the cable being hit by an anchor, trawl board or similar). Unfortunately the AC XLPE cables category used by Cigre is extremely broad, encompassing many types of cable that are irrelevant for UK offshore wind applications:

i) Nearly half of the cables in this category are at voltages between 60kV and 110kV, making their relevance for the UK fleet of cables at 132kV and above questionable.

ii) A third of all the cables in the category are single-core, and so immune to the problems described in Section 3, which are unique to three core cables. All wind farm AC cables are of the three core type.

iii) No information is provided regarding whether the three core cables in Cigre’s data set include fibre optic cores or not (showing how this issue was not considered relevant for reliability until recently).

iv) No information is provided regarding whether the cable is buried or not. It seems likely that most of the external faults indicated by Cigre originate from unburied cable sections, and that Cigre’s mean time between failures would be much higher if all of the cables in their data set were buried, as UK wind farm cables are.

\(^5\) See the annual report of Guernsey Electricity, March 2015.
\(^6\) Cross Linked Polyethylene
Despite the “AC XLPE” category being extremely broad, the data set available to Cigre was not particularly large: even in 2005, when the fleet studied by Cigre would have been at its largest, the data set for “AC XLPE” cables was not significantly larger than the current UK offshore wind high voltage export cable fleet. This, presumably, is why the writers of TB-379 were unable to provide more detailed breakdowns.

Cigre has recently established a working group (B1.57) which aims to update TB-379, and UK cable owners are urged to contribute to its work. This group is not expected to issue its final report until 2018: in the meantime parties seeking statistical data on export cable reliability will still need to reference TB-379, but should consider combining this with newer data known to be directly relevant to wind farm export cables – such as the UK export cable experience set out in Section 2 above.

6 COST OF CABLE FAILURES

The economic impact of a wind farm export cable failure can be examined under the following categories:

i) The cost of repairing the cable.

ii) The cost of lost wind farm production over a period that can range from several weeks (for a pre-emptive repair) to 3-5 months\(^7\). for an unexpected fault.

iii) In cases where there is only a single cable connecting an offshore substation, the failure of this cable will result in the loss of all auxiliary power to the wind turbines. This in turn will lead to costs for the provision of temporary emergency generators and/or extra maintenance costs where turbines are left without power for an extended period.

The cost of cable repair includes precise location of the fault; mobilisation of a suitable repair vessel, equipment and personnel; deburial of the failed cable; removal of a length of cable – often several hundred meters long – that includes the fault location; jointing in a length of spare cable to replace the removed section; and reburying or otherwise protecting the repaired cable. Costs will depend on market conditions and weather conditions during the repair, but can be extremely high. Table 1 shows a selection of publicly disclosed cable repair costs:

\(^7\) The repair times for the four submarine cable faults indicated by the NGET C17 document are 106 days (3.5 months), 133 days (4.4 months), 153 days (5.0 months) and 105 days (3.5 months)
Table 1: Publicly disclosed cable repair costs

<table>
<thead>
<tr>
<th>Repair</th>
<th>Cost</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guernsey-Jersey (2012)</td>
<td>£8m</td>
<td>BBC News</td>
</tr>
<tr>
<td>Guernsey-Jersey (2015, pre-emptive)</td>
<td>£5.3m</td>
<td>Owners’ annual reports</td>
</tr>
<tr>
<td>Moyle (2011-12), 2 repairs</td>
<td>£15.5m average per repair</td>
<td>Owner’s annual report</td>
</tr>
<tr>
<td>Gwynt y Mor (summer 2015)</td>
<td>£10.2m</td>
<td>Ofgem (income adjustment claim)</td>
</tr>
<tr>
<td>Gwynt y Mor (2015-16)</td>
<td>£14.2m</td>
<td>Ofgem (income adjustment claim)</td>
</tr>
<tr>
<td>Thanet (2015)</td>
<td>£11.7m</td>
<td>Ofgem (income adjustment claim)</td>
</tr>
</tbody>
</table>

Excluding the single pre-emptive repair, the average repair cost from this data set is £12.5m.

The cost of a pre-emptive repair is substantially less than the cost of an unplanned repair\(^8\). In practice, however, pre-emptive repairs are frequently impossible: either because the cable gives little or no warning of failure, or because – given that the failure mechanism(s) are still poorly understood – the risk of unnecessarily repairing a healthy cable is judged to be too high.

As noted above, following an unplanned failure on a UK high voltage export cable the typical time required to repair the cable and return it to service is 3-5 months. During this time the output of the wind farm will be curtailed:

- i) If the failed cable is the only connection to an offshore substation then all of the output from the turbines served by this substation will be lost until the repair is complete.
- ii) If there are two (or more) cables connecting an offshore substation then the turbines served by the substation can continue to operate while the failed cable is repaired, but their output will be restricted at times of high wind.

Based on the repair costs indicated above, the actual repair times and substation configurations, and assuming that existing UK offshore wind farms have an average load factor of 40% and a typical income of £140/MWhr, a rough estimate of the total cost to the industry of the seven cable failures described in Section 2 above can be calculated. The author estimates that this total cost is on the order of £160m, roughly equally split between repair costs and the costs of lost offshore wind production.

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\(^8\) Since Table 1 shows a cost for only one pre-emptive repair, we do not know if this £3.5m cost is typical or not. Nevertheless, it is so much lower than the costs for the unplanned repairs that it is safe to state that the cost of a pre-emptive repair will be much lower than that of an unplanned repair.
7 SUGGESTED ACTIONS FOR COMPANIES ORDERING NEW CABLES

From the calculation described in Section 6 above, the seven faults that have occurred to date have resulted in costs that have already reached nearly £170k per km of export cable.

Such a cost is a significant percentage of the capital cost of these cables, implying that significant actions and expenditures may be justified on new projects in order to ensure that newly procured cables do not suffer from the same issues.

This report is not intended to be instructional, and does not make any recommendations to the procurers of new high voltage export cables. However we have summarised below the two main opinions expressed by members of the Export Cable Reliability Project, the industry group created by the OWPB to aid in discussions on this issue. Whether to follow either of these opinions is a decision for the reader.

OFTOs’ Opinion

The Offshore Transmission Owners (OFTOs), acting through their representative body, the Electricity Networks Association OFTO Forum, have provided the following statement:

*Integral FOC presents an inherent weakness where any single/ minor defect caused during manufacture, load out, or installation leads to a power core failure. This failure mode was not foreseen and is not identified in publicly available failure statistics. No FAT or SAT regime is in place at present to identify the presence of defects impacting the FOC.*

*In the opinion of the ENA OFTO Forum it is essential that FAT and SAT tests are in place to verify the integrity of 3-core AC transmission submarine cables with integral fibre optic cable(s). Until such tests are in place there is a risk of future failures related to the FOC, and this risk should be recognised by all stakeholders.*

FOC = fibre optic core  
FAT = factory acceptance test  
SAT = site acceptance test

Generators’ Opinions

While there is no equivalent “official” view held by generators, several persons involved in the development of generator connections have expressed the view that it is premature to consider removing fibre optic cores from power cables. In particular, there were concerns that moving the fibre core from the export cable to a cable of its own would result in unnecessary costs and could introduce new risks – both known risks (e.g. fibre damage during installation) and unanticipated risks. Furthermore removing fibre optic cores from power cables may reduce developers’ ability to apply dynamic ratings, a technique which can offer overall cost reductions – particularly as distances increase – and which can allow increased wind farm output during outages.
If a decision is made to retain a fibre core inside the export cable, however, great care will be required in order to minimise the risk of a failure in the fibre core. It has been suggested that some types of fibre optic core may be inherently less vulnerable, or their integration into the overall cable design may be improved, and it may be possible for buyers to assess or improve the vulnerability of cable designs by:

i) Suitably adding to their technical requirements. For instance, cable buyers could specify maximum currents/voltages allowed on the fibre core’s metallic tube under normal and fault/transient conditions.

ii) Explicitly specifying designs that should reduce fibre core vulnerability. For instance, we understand that consideration has been given to specifying an optimised location for the fibre core within the power cable in order to minimise its exposure to electromagnetic fields, and to specifying a balanced set of fibres with periodic phase rotation with respect to the power cores.

iii) Questioning manufacturers (including requests for information and validation tests) on relevant issues (for instance the magnitude of induced currents and voltages under various circumstances) before placing an order.

iv) Suitably monitoring the manufacturing (and/or installation) processes (i.e. enhanced quality assurance).

8 NEXT STEPS

The Export Cable Reliability project has developed a plan which would produce advice that offshore wind developers could use when procuring new export cables for future projects. This could include, for instance:

i) Advice on questions that should be raised with cable manufacturers.

ii) Advice on calculation methodologies that cable manufacturers would be asked to use when responding to such questions.

iii) Advice on additions to developers’ technical requirements.

iv) Advice on tests of the fibre optic cores that developers, OFTO’s and generators should ask cable manufacturers to undertake.

At any early stage within such future work, it will be necessary to collect information on each fault (through questionnaires and/or review of root cause analysis reports) for review by a single expert team to check for commonalities and to verify the role of the fibre optic core.

Work is ongoing on refining this plan and obtaining funding for its execution.
Export Cable Reliability – Description of Concerns