CARBON TRUST

Offshore Wind Accelerator

Fibre Optic Cable Protection Assessment

Design and testing recommendations

EnBW equinor Ørsted RWE SCOTTISHPOWER RENEWABLES sse Renewables VATTENFALL

Contents

The Offshore Wind Accelerator

The Offshore Wind Accelerator (OWA) is the Carbon Trust's flagship collaborative research, development and deployment programme. The joint initiative was set up between the Carbon Trust and nine offshore wind developers in 2008, with the aim to reduce the cost of offshore wind to be competitive with conventional energy generation, as well as provide insights regarding industry standard (and best practice) health and safety requirements.

The current phase involves participation and funding from eight international energy companies: EnBW, Equinor, Ørsted, RWE, ScottishPower Renewables, Shell, SSE Renewables, and Vattenfall Wind Power, who collectively represent 75% of Europe's installed offshore wind capacity. This project also received partial funding from the Scottish Government.

Acknowledgements

This document was produced on behalf of the Offshore Wind Accelerator by RINA Tech UK Ltd, with technical review by the Offshore Wind Accelerator Cables Technical Working Group.

With a history going back 150 years, the RINA Group is a global corporation that provides engineering and consultancy services, as well as testing, inspection and certification.

Executive summary

Since 2014, more than six faults on three-core submarine cables have been reported where the root cause of a fault has been assigned to the interaction between the power cable and the metallic part of an integrated fibre optic cable (FOC). This has led to some concern in industries designing, installing and operating offshore cable assets.

The Carbon Trust Offshore Wind Accelerator has launched the Fibre Optic Cable Protection Assessment project with the key aim to confirm or dismiss the reports that the faults have been caused by an interaction between the power cores and the FOC.

This report aims to propose specifications for cable designs that would minimise the risk of failures due to interaction between the power cores and the fibre optic elements of the cable.

The results of the modelling carried out in the induced voltage modelling report concluded that an FOC can be designed to eliminate the type of fault that has been attributed to an interaction between the induced voltage on the FOC and the sheaths of the power cores.

The recommended design features for an FOC in an export or array cable are summarised below:

1. FOC to have stainless steel tube and stainless steel wire armour with a combined resistance of no less than 30Ω/km.
2. The sheath of the FOC is to be semi-conductive having dimensions such that the radial resistance through the sheath is no more than 75Ω·m. For the design described in 1 above it is considered that this can be achieved using semi-conductive material having a resistivity of no more than 1000Ω·m.
3. There are to be no insulating binder tapes, adhesives or other insulating material between the armour wires and sheath of the FOC.
4. The preference is for the export or array cable to have extruded fillers where either the complete filler or the channel holding the FOC is made from semi-conductive material.
5. The position of the FOC within the three-core cable remains unchanged from present practice.

The testing that can be carried out to demonstrate the continuity of the stainless steel tube and the armour is limited to tests before installation. No tests have been identified that will confirm the integrity of the semi-conducting sheath. However, it is concluded that a design that eliminates a known fault mechanism is preferable to a design that has a known weakness but can be tested.

The feasibility of developing an FOC with no metallic components has been considered. It has been concluded that such an FOC could be developed but the depth at which it could be installed is likely to be limited.

It is recommended that installation specifications/contracts make it clear which party is responsible for the earthing of the FOC. It is also recommended that inspection of the earthing of the FOC is a specific item on any commissioning check list.

It is also recommended that all fibres in all FOCs in export cables are monitored for continuity over the life of the cable. Actions in the event of the loss of a fibre have been recommended.

1. Cable design

1.1 FOC specification

The cables considered in this report are three-core, high voltage (HV), cables incorporating one or more FOC, Figure 1.

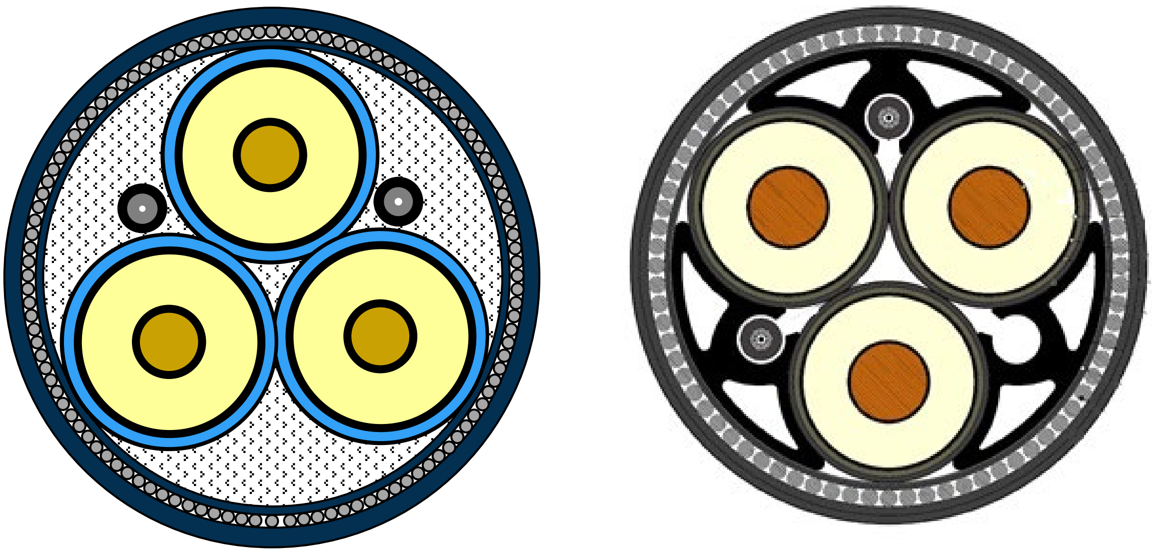

Figure 1: Cable designs

The work carried out in the induced voltage modelling report considered a number of aspects of the cable design that could influence any interaction between the power cores and the metallic parts of the fibre optic cable (FOC). These aspects are discussed below.

The FOC is usually positioned in the interstices of the cable close to the power cores. In this position, electrical activity and heating at the FOC can readily transfer to the sheath of the power cores. Consideration was given to locating the FOC closer to the armour of the three-core cables. The calculations showed that this would not have a significant effect on the induced voltage in the FOC and hence the risk of damage to the FOC due to induced voltages across any break would not be reduced. However, in this position any heating or electrical activity at the FOC is less likely to affect the power cores. Moving the FOC out to near the armour wires will increase the mechanical stress on the FOC when the cable is bent. This would increase the risk of damage to the FOC during handling and installation. On balance it was considered that the position of the FOC should not be changed provided that the recommendations discussed below are incorporated in the design of the FOC.

The calculations carried out as part of the induced voltage modelling report showed that if the metallic parts of the FOC have a relatively high resistance the current induced in the FOC will be reduced and hence the heating at any break in the FOC is reduced. The calculations demonstrated that if the FOC has only a stainless steel tube and no armour, giving a resistance of 300Ω/km, heating at a break in the FOC would be negligible. However, such a design is relatively weak mechanically. The author is aware of one instance where the stainless steel tube in an unarmoured FOC in an export cable was found to have parted at multiple points. Hence the inclusion of stainless steel armouring is recommended. Calculations have shown that if the combined resistance of the stainless steel tube and stainless steel armour is in the order of 30Ω/km there will be some heating at a break in the FOC but the temperature rise will not be sufficient to damage the power cores. A review of AC corrosion of aluminium in water has shown that corrosion rates will be high. Because of this it is recommended that aluminium armour is not used on FOCs incorporated into export cables. It is therefore recommended that the FOC has a stainless steel tube and stainless steel armour with a combined resistance of no less than 30Ω/km.

The performance of FOCs having a semi-conducting sheath rather than an insulating sheath has been investigated. Using a semi-conducting sheath reduces the standing voltage on metallic parts of the FOC in the event of a break. The calculations demonstrated that utilising a semi-conducting sheath with a resistivity of no more than 1000Ω·m reduced the voltage across a break in the metallic parts of the FOC to a level that is not expected to lead to damage, when combined with metallic parts having a resistance of no less than 30Ω/km. The calculations were based on an FOC with an outside diameter of 16mm and a sheath thickness of 3mm. If the sheath is significantly thicker the resistivity of the sheath material should be reduced so that the resistance across the sheath is no more than 75Ω·m.

There have been unarmoured designs of FOC where there has been a layer of adhesive between the metallic tube and the semi-conducting sheath. This will clearly reduce the effectiveness of the semi-conductive sheath in reducing any standing voltage. Thus, it is recommended that no binders, adhesives or other insulating material are introduced between the armour and sheath of the FOC.

The calculations that were carried out to derive the recommendations given above assumed that the outside surface of the FOC could be treated as an earth plane. There are several different designs of export cables that use different fillers between the cores. Some designs use polypropylene rope or similar fillers (left in Figure 1). In these designs, seawater is expected to percolate between the fillers. However, the density of the fillers is likely to be such that the effective resistance of the material surrounding the fillers is higher than that of seawater. This will reduce the effectiveness of the semi-conducting sheath in reducing the standing voltage at any break in the metallic parts of the FOC. Because of this, tightly packed rope fillers are not recommended.

Other designs of export cable use extruded fillers (right in Figure 1). The author has seen several variations in the material used for these fillers. In some cases it is insulating material and in others it is semi-conducting material. A further design used insulating material with a semi-conducting material around the part holding the FOC. The extent to which insulating extruded fillers reduce the integrity of the earth plane around the FOC will depend on whether the FOC is a tight fit in its channel in the filler. However, in order to minimise any reduction in the effectiveness of the semi-conducting sheath of the FOC it is recommended that extruded fillers are made from semi-conducting material or have a semi-conducting section around the channel for the FOC.

The recommended design features for an FOC in an export or array cable are summarised below:

1. FOC to have stainless steel tube and stainless steel wire armour having a combined resistance of no less than 30Ω/km.
2. The sheath of the FOC is to be semi-conductive having dimensions such that the resistance through the sheath is no more than 75Ω·m. For the design described in 1 above it is considered that this can be achieved using semi-conductive material having a resistivity of no more than 1000Ω·m.
3. There are to be no insulating binder tapes, adhesives or other insulating material between the armour wires and sheath of the FOC.
4. The preference is for the export or array cable to have extruded fillers where either the complete filler or the channel holding the FOC is made from semi-conductive material.
5. The position of the FOC within the three-core cable remains unchanged from present practice.

For the mitigation measures to be effective, the metallic components must be reliably bonded to earth at both ends. This applies to both the stainless steel tube and the stainless steel armour wires.

1.2 Applicability

The specification described above has been developed based on consideration of a 50km long export cable carrying a load of 1000A and operating at up to 250kV. The induced voltage that would appear across a break in the metallic parts of an FOC is a function of the load current and length of the circuit. The operating voltage has very little effect on the magnitude of the induced voltage. Failures, due to an interaction between the FOC and the power cores, are known to have occurred in export cables approximately 20km long with load currents of less than 1000A. Thus, it is considered that the specification given above should be adopted for all export cables and other cables having similar lengths and loads.

Array cables are substantially shorter than export cables and, apart from the sections of cable close to the offshore substations, the load is expected to be lower than that on the export cables. Because of this, the type of failure seen in export cables is not expected to occur in array cables. However, it is considered that it would be appropriate to adopt the specification given above for any inter-array cables that are more than 5km long.

It is also recommended that aluminium wire armour is not used on any FOC incorporated into an inter-array cable or other sub-sea cable power cable incorporating an FOC.

2. Testing

2.1 Background

Failure examinations carried out have identified a number of different factors that contributed to the failures of export cables that were attributed to interactions with the FOC. The primary factor in all cases was the loss of continuity of the metallic parts. In some cases, this was due to mechanical failure of the FOC and in others it was due to corrosion of the aluminium wire armour of the FOC. Where corrosion had occurred, it was concluded that it had been due to a loss of integrity of the sheath of the FOC, either due to damage or a manufacturing defect.

It is also known that there have been several instances where the resistivity of the semi-conducting sheath of an FOC appeared to vary along the length of the cable.

Ideally, tests should be developed for the following:

1. Confirm the continuity of the metallic parts after manufacture of the FOC, after assembly of the complete cable, after load out and at commissioning after installation.
2. Confirm the integrity of the semi-conducting sheath after manufacture of the FOC and after assembly of the complete cable.
3. Confirm the resistivity of the semi-conducting material over the whole length of the FOC during or after manufacture of the FOC.

2.2 Continuity measurements

In dry conditions the resistance of the metallic parts of an FOC with a semi-conducting sheath can be measured and the result compared with the design value. If both the tube and the armour have parted, the measured resistance will include the resistance of the semi-conducting sheath which will act as a shunt across the break. For a 50km cable where the metallic elements of the FOC have a resistance of 30Ω/km, the resistance of those elements is expected to be 1500Ω. For a 1mm gap across a break in the metallic parts of the FOC the resistance of the tube of semi-conducting sheath over the break will be in the order of 8kΩ. Thus, the increase in resistance can readily be measured.

If there is a break in the steel tube but not the armour it is considered unlikely that it would be detected by a resistance measurement because the armour would provide a low resistance path across the break.

Time domain reflectometry (TDR) is used to detect breaks or other faults in power cables. This technique would not be effective on the metallic elements of an FOC with a semi-conducting sheath because of the signal loss via the sheath.

After the cable is installed the FOC will be surrounded by water. The water will provide an additional path where the test current can bypass a break in the metallic elements of the FOC by flowing out through the sheath, through the water and back in at the other side of the break. This assumes that the test source and FOC are not bonded to earth for the test. Where the radial resistance of the sheath is in the order of 75Ω·m the parallel path through the sheath and the seawater will be low resistance, relative to the resistance of the complete length of the FOC. Hence it is very unlikely that a break in the metallic parts of the FOC would be detected by resistance measurements after installation. Measuring the resistance of the metallic elements of the FOC with one end of the FOC earthed is expected to result in a low resistance being measured because of the parallel paths through the sheath and the seawater.

2.3 Sheath integrity

On-line spark testing is used in the manufacture of cables to detect pinhole defects in the insulation of low voltage cables and the outer sheaths of other cables. This technique is well developed for LV conductor insulation and non-conducting sheaths. The technique is not known to be used to detect pinholes in semi-conducting materials. The voltage required to produce a flashover at a defect in the sheath would result in a high continuous leakage current through a semi-conducting sheath. Existing spark testers are not designed to operate with a relatively high continuous leakage current. Also, the leakage current may be high enough to burn through, or degrade, an intact semi-conducting sheath. RINA has previously carried out tests that demonstrated that applying approximately 35V across the semi-conducting sheath of a power core was sufficient to cause immediate melting of the sheath at the point where the voltage was applied.

The author is not aware of other test methods that would detect pinholes or other defects in a semi-conducting sheath during manufacture.

For installed conventional cables a sheath withstand test or sheath insulation resistance measurement can be carried out after installation to test the integrity of the sheath. Where the cable sheath is semi-conducting such tests could not be used to detect a sheath defect. For a 50km FOC where the radial resistance of the sheath is in the order of 75Ω·m the 'insulation resistance' of the whole length of the FOC will be a fraction of an ohm. Hence any defect in the sheath would not make a measurable difference to the overall 'insulation resistance'.

The author considers that there are no suitable tests available to detect a sheath defect in an FOC with a semi-conductive sheath, either during manufacture or after installation.

2.4 Consistency

It has been noted, in two failures, that the resistivity of the semi-conducting sheath of FOC appeared to vary along the length of the cable. In one case this may have been due to an uneven layer of adhesive on the inside surface of the sheath rather than a variation in the sheath material. If the variation was due to inconsistencies in the sheath it suggests that quality control checks on the material used may not have been sufficient. The simple approach to this issue is to carry out routine tests on multiple samples of each batch of incoming raw material.

A more complex approach would be to develop on-line testing to monitor the resistance of the cable sheath. The author is not aware of any existing test equipment or methodology for such testing. It is considered that such a test would involve applying a voltage between the outer surface of the sheath and the armour of the FOC and monitoring the leakage current. If the leakage current fell below a predetermined level it would indicate that the sheath resistance was higher than intended. The leakage current would have to be of sufficient magnitude to allow it to be readily monitored. The magnitude of the test voltage and length over which it is applied, to achieve a suitable leakage current, would have to be determined. Because the sheath is semi-conducting the test voltage could appear on the cable sheath outside the test area. Thus, the test voltage would have to be low enough so as not to be a safety risk.

Because of the above factors it is considered that on-line testing of the resistance of the sheath would not be practicable.

2.5 Overview

The recommendation for a semi-conductive sheath combined with high resistance metallic paths is intended to eliminate the risk of failures due to interaction between the FOC and the power cores. However, the use of a semi-conducting sheath removes the possibility of testing for continuity of the metallic elements and testing for integrity of the FOC sheath.

On balance it is preferable to adopt a design that is intended to eliminate the failure mode rather using a design where a known failure mode could occur but tests could be carried out to detect whether conditions exist that could result in a failure.

3. Specification, commissioning and monitoring

3.1 Earthing

In several of the failures examined there had been some uncertainty regarding the earthing of the metallic elements of the FOC after installation. To minimise the risk of any interaction between the FOC and the power cores, for any design of FOC, the metallic parts should be reliably earthed at both ends of the cable. Uncertainty over the earthing may have arisen because it had not been made clear whether the earthing of the FOC was the responsibility of the team carrying out the fibre installation or that of the team responsible for the installation of the power cable.

To minimise the possibility of uncertainty over the earth of the FOC the appropriate contract documentation should make it clear who is responsible for this earthing. Commissioning inspection schedules should also include inspection of the earthing of the FOC as a specific item.

Where the FOC contains two metallic layers, armour and stainless steel tube, both the armour and the tube should be independently bonded to earth. This will cover the situation where the FOC is manufactured with a semi-conducting bedding between the tube and the armour. In addition to bonding both the tube and the armour at terminations, continuity of both parts must be ensured at any sub-sea joints.

3.2 Monitoring

In two of the failures examined there were failures of the optical fibres prior to the failure of the power cores. In one case the failures were progressive over a number of years before the final failure, and in the other the failures were noted weeks before the final failure. In another failure the cable had two FOCs and the fault was associated with the ‘spare’ FOC, hence it was not known whether any fibre failures occurred prior to the main fault.

In other failures where loss of fibres was not noted prior to the fault there may have been loss of fibres but if they were not being used it would not have been noted.

Because loss of fibres may give some advanced warning of degradation of the cable it is recommended that all fibres in the cable are continuously monitored for continuity. Details of such a monitoring system are outside the scope of this report but the system only needs to be able to detect a break in a fibre.

The loss of one fibre in a cable does not necessarily indicate that a fault is developing that could affect the power cores. However, if several fibres are lost at the same location it would be indicative of a localised issue. Thus, OTDR measurements should be made if more than one fibre is lost to determine whether the breaks are at the same location.

When a fault is developing due to interaction between an FOC and the power cores, heat will be generated. A localised temperature rise at a location where fibres have broken would be a strong indication that a fault was developing. Thus, if a number of fibres have broken at the same location, temperature measurements made using a distributed temperature sensing system would provide further evidence as to the nature of the fault. Such a system would not need to be permanently connected to the cables.

If OTDR and temperature sensing indicate that there is interaction taking place between the metallic parts of the FOC and the power cores there may be sufficient time for a pre-emptive repair to be carried out before the failure occurs. The rate of degradation due to this type of fault is a function of the induced voltage across a break. This is proportional to the load current in the cable. Thus, if a developing fault is detected, reducing the load on the cable will reduce the rate of degradation. This will extend the time available for a pre-emptive repair to be carried out. The amount of extra time available cannot be predicted because it will depend on how far the fault had developed before it was detected.

4. Alternative designs

Any interaction between the metallic layers in the FOC and the power cores would be eliminated if the metallic components of the FOC could be eliminated. The stainless steel or copper tube enclosing the fibres forms an impermeable barrier to prevent water reaching the fibres. Moisture around the fibres in an FOC can lead to an increase in attenuation due to absorption of hydroxide ions into the glass. This effect is commonly known as hydrogen darkening and it can progressively increase the attenuation in a fibre to the extent that it becomes unusable.

Moisture will permeate through a polymer sheath or tube surrounding optical fibres. The rate of permeation will be a function of the material chosen, its thickness and the water depth. Fibre optic cables without a metallic water barrier are used in some buried applications where moisture will be present in the surrounding soil. These cables have a high density polyethylene, HDPE, sheath, which has a low permeability in water. The permeability coefficient of HDPE is approximately 30 times less than that of PVC but approximately twice that of Teflon. Cables buried in the ground will also be subjected to a much lower head of water than sub-sea cables. Buried cables are also unlikely to be continuously immersed in water. Thus FOCs, without a metallic moisture barrier, intended for burial in the ground may not be suitable for use in sub-sea cables.

The rate at which hydrogen darkening progresses is also a function of the type of glass used and the type of coating. The author considers that an FOC without a metallic tube could be developed for use in sub-sea cables, given the selection of a suitable sheath and tube together with the appropriate selection of fibre type. As the rate of moisture permeation into the cable is a function of the water pressure, such designs may not be appropriate for all water depths.

The second metallic layer in the specification that has been recommended is the stainless steel armour. This provides mechanical support for the tube and fibres. The author is aware of instances, in a sub-sea cable having an unarmoured FOC, where the stainless steel tube had parted without a break in the fibres or the sheath of the FOC. This demonstrated that in the loose tube design there was sufficient ‘slack’ in the fibres and elasticity in the sheath to withstand the extension that caused the tube to part.

Thus, it is considered that an FOC without a metallic tube or armour could be designed for use in a sub-sea cable. This would require a change in design philosophy whereby instead of designing the FOC with sufficient strength to withstand the stresses imposed on it during installation, it would be designed with sufficient ‘elasticity’ to withstand the strain imposed on it.

5. Conclusions and recommendations

From the results of the modelling carried out it is concluded that an FOC can be designed to eliminate the type of fault that has been attributed to an interaction between the induced voltage on the FOC and the sheaths of the power cores.

The recommended design features for an FOC in an export or array cable are summarised below:

1. FOC to have stainless steel tube and stainless steel wire armour having a combined resistance of no less than 30Ω/km.
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5. The position of the FOC within the three-core cable remains unchanged from present practice.

The testing that can be carried out to demonstrate the continuity of the stainless steel tube and the armour is limited to tests before installation. No tests have been identified that will confirm the integrity of the semi-conducting sheath. However, it is concluded that a design that eliminates a known fault mechanism is preferable to a design that has a known weakness but can be tested.

The feasibility of developing an FOC with no metallic components has been considered. It has been concluded that such an FOC could be developed, but the depth at which it could be installed is likely to be limited.

It is recommended that installation specifications/contracts make it clear which party is responsible for the earthing of the FOC. It is also recommended that inspection of the earthing of the FOC is a specific item on any commissioning check lists.

It is also recommended that all fibres in all FOCs in export cables are monitored for continuity over the life of the cable. Actions in the event of the loss of a fibre have been recommended.

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