RECOMMENDATIONS FOR HEALTH MONITORING OF DYNAMIC CABLES FOR FLOATING OFFSHORE WIND FARMS

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RECOMMENDATIONS FOR HEALTH MONITORING OF DYNAMIC CABLES FOR FLOATING OFFSHORE WIND FARMS

AUTHORS :
Antoine Maison, Mélanie Roulet,
France Energies Marines

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Preface

While the offshore wind energy sector has been developing for the past decades with bottom-fixed turbines at sea, floating offshore wind turbines are a promising solution to increasing electricity production to meet major energy transition challenges. Currently, floating offshore wind represents 0.2% of installed offshore wind capacity worldwide and should increase up to 6% in 2030 (Williams *et al.*, 2022). A major component of floating offshore wind industry is the subsea dynamic cable, required for transporting electrical power from the turbine floater to another floater (supporting another turbine or the substation) or to the shore. Depending on the site conditions and distances, the dynamic cable may be connected to a static cable laid on the seabed (see Figure 1).

Since dynamic cables go through the water column, generally from the seabed to a floating device or between two floating devices without touching the seabed in some cases, they are exposed to external aggressions and loads, such as the movement of the floater or the marine current loads. Hence, unlike static cables, they face dynamic mechanical stresses in addition to thermal and electrical stresses (Thies *et al.*, 2012), which leads to additional kinds of failure modes. The floating offshore wind technology is an emerging sector and the understanding of failure mechanisms is at its early stage. As dynamic cables are one of the most critical components of future floating offshore wind farms, a better knowledge of their failure mechanisms is then needed.

The exposure of the dynamic cable to multiple stresses can contribute to the emergence of degradations and early ageing of the cable and its accessories (France Energies Marines, 2022). Health monitoring can be deployed to detect the appearance and evolution of these phenomena, to prevent cable failure and cable breakdown. Many monitoring solutions already exist or are being developed for offshore applications but are generally not fully adapted to the specific constraints of the dynamic cables for future floating offshore wind farms (France Energies Marines, 2023a). Identifying effective existing solutions and promising solutions under development is essential to select monitoring systems deployable today or in a near future. Also, identifying the best ways to tackle the limitations and initiate developments on the technological barriers as soon as possible will enable efficient monitoring solutions to be available sooner. Installing several monitoring systems on different dynamic cables of a farm requires the definition of an effective monitoring strategy at the wind farm scale, to optimize the deployments and ensure a high level of reliability on this crucial component.

This document is the result of work carried out by the DYNAMO project which is a co-investment by 7 industrial and academic players as well as France Energies Marines over the 2020-2022 period. It was part of a broader framework of research and innovation investments in dynamic cables supported by France Énergies Marines since 2016. The objective was to provide tools to floating wind farm developers and operators to make the appropriate choices regarding dynamic cable monitoring, and to provide evaluation and recommendations on monitoring technologies. The research is based on academic

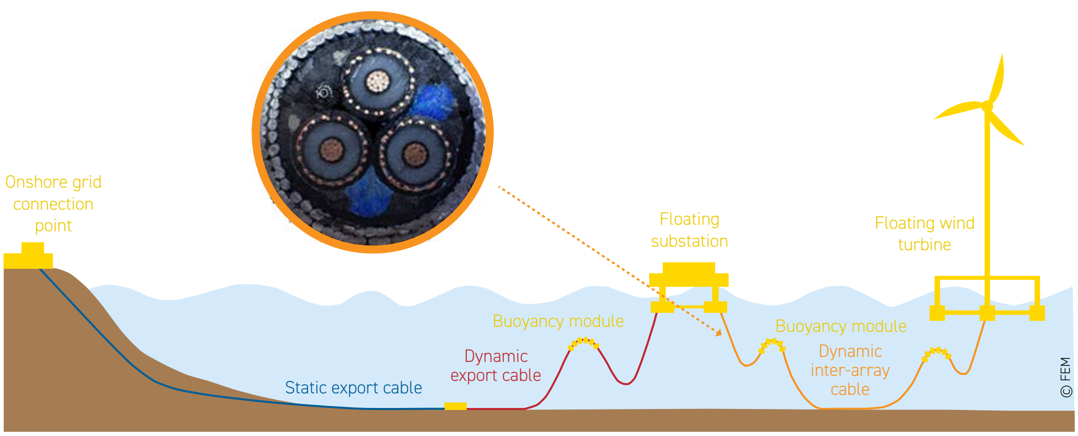

Figure. 1 : Schematic view of a dynamic cable layout in an example of a floating offshore wind farm

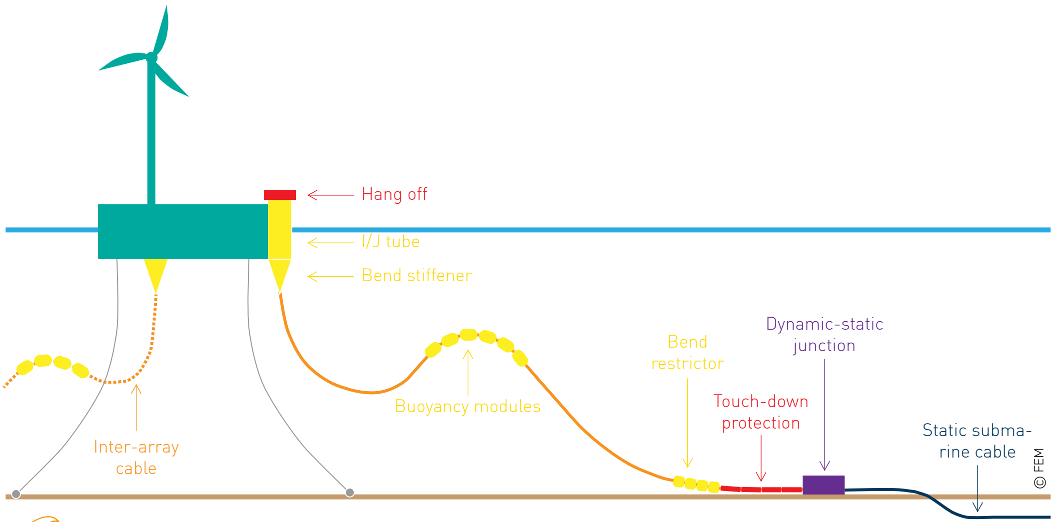

Figure. 2 : Representation of the dynamic cable configuration within this study

& industrial literature review, on feedbacks from the project partners, and on experimental electrical and mechanical tests on samples of a dynamic cable. The dynamic cable configuration (including accessories) considered for the theoretical studies on the deployment of global monitoring solutions is the lazy wave (see Figure 2).

This report is directed, among others, towards the research and innovation organisations, the developers and operators of wind farms, and the providers of engineering solutions related to subsea dynamic power cables, to orient the next works and promote the **fastest development possible of reliable and efficient monitoring technologies** dedicated to subsea dynamic power cables. Additionally, this report proposes a monitoring deployment that is a relevant basis package for thoroughly monitoring a dynamic cable.

In a second stage, this report provides **a methodology for deploying a monitoring strategy at the windfarm scale**, for detecting dynamic cable failures. The methodology and tools presented in this report have already been experienced on different theoretical pre-defined internal failure scenarios representative of real-case wind farms (France Energies Marines, 2023b). Finally, this document gathers general **information on the tools developed for selecting and deploying sensors** at the scale of a wind farm depending on the farm layout and the failure modes to monitor and presents improvements applicable to those methodologies.

This document addresses monitoring technologies that are supposed to be already known by the reader: no explanation or information are given on the underlying physical principles.

1 - Developments of existing monitoring techniques and technologies

In this section, the most promising technologies highlighted in the project are discussed and roadmaps for developments are presented. A list of developments that have been identified as relevant for the industry of floating offshore wind energy was established. The development suggestions are based on the literature, discussions with the sensors manufacturers and partners, and on the experimental campaigns on instrumented dynamic cables carried out during this project (Maison *et al.*, 2023 ; Al Ibrahim *et al.*, 2023).

1.1 Optical sensing

Optical technologies (except Raman distributed temperature sensing) need to decorrelate strain and temperature contributions, via, for example, the deployment of an additional technology (either optical or based on another principle) that is sensitive to temperature only. This is inherent to the physics used for the measurements and can be a relatively strong constraint that may be complicated to overcome depending on the characteristics of the deployment of sensors. Post-processing procedures and specific sensors integration plans are under development within some technology providers to overcome this limitation. Efforts should be kept on this topic.

Distributed temperature sensing systems, distributed acoustic sensing and fibre bragg gratings can be made fully sensitive to strains if the interrogated fibres are attached to one component (tight-buffer integration): the fibres will render local strains of the components to which it is attached, in addition to local temperature. Tight-buffer integration is discussed later in the document (see section 2 Modifications in design of cables and accessories for monitoring purpose).

Improving the multiplexing of fibres on a single interrogator is a relevant path for lowering the costs associated with the deployment of fibre optics sensing over a wind farm and is worth pursuing the efforts. In the case of temperature-sensible technologies, fibres could be used to measure temperature of specific points between the interrogator and the entry-point of the fibres inside the cable. For instance, fibres can be laid close to the power cores terminations and connections, as an abnormal temperature rise of these points may indicate an upcoming failure, so avoiding to integrate additional dedicated temperature sensors. For instance, power core terminations and connections are points of interest, as a temperature rise may indicate an upcoming failure.

Distributed Temperature Sensing Systems (DTSS)

DTSS when applied on fibres in a loose tube is sensible to strains to a certain extent, and under hypothesis. However, the presence of the gel inside the loose tube and its role as a strain filter needs to be characterized to make a more proper use of the measured strains. Further developments on DTSS technology for cable applications could be working on the identification of a transfer function associated with a given fibre integration configuration. The hypothesis and the domain of applicability of such a monitoring are yet to be determined, but the transfer function might be dependent, at least, on strain rate, on temperature, and on the type of load (tensile, compressive, or bending). Apart from this processing and integration developments, DTSS technology is already functioning well for the application and does not need specific developments except improvements on spatial resolution, temperature accuracy, and mostly distance range.

Distributed Acoustic Sensing (DAS)

DAS is promising as it offers a wide range of possibilities, however, a consequent amount of R&D has to be conducted on post-processing, to transform raw measurements into exploitable data. Experiments conducted show that the DAS technology is able, under the hypothesis of the experimental campaign, to detect armour wires breakage of high energy (as observed during tensile tests), whereas the low energy ruptures were not identified among the high number of events. Further work is needed to be able to identify the conditions under which DAS can raise a reliable alarm regarding armour wires breakage. A related path for R&D is improving the post-processing algorithm to lower the threshold of energy at which armour wires breakage can be identified. Except from this, DAS technologies are also promising for following human activity around the cables and help prevent or identify third-party damages if the data is used and treated accordingly. A generic path for developing the use of DAS technologies is building databases of signatures of the events that operators want to monitor with DAS, and in parallel, developing methods for identifying and locating the signatures of desired events among the measurements' data. Moreover, procedures for data storage will be needed in a near future to avoid being submerged by data, but this needs post-processing to make steps forward, so that low-value information can be separated from valuable information, thus lowering the volume of data to be stored.

Distributed Temperature Sensing (DTS)

Raman DTS is already functioning well for the application and does not need specific developments except improvements on spatial resolution, temperature accuracy, and mostly distance range.

Fibre Bragg Gratings (FBG)

FBG are interesting for monitoring purpose, as they give the opportunity to measure physical quantities at definite locations. Additionally, from the tight-buffered integration issues discussed later in the document (see section 2 Modifications in design of cables and accessories for monitoring purpose), this concept face two significant limitations, that need to be overcome for FBG to be usable as inner strain sensors. The main challenge is for cable manufacturers to provide manufacturing solutions allowing to control the application of fibres and ensure a correct location of gratings in the final product. Procedures of cable installation are also challenging as the presence of FBG requires a precise laying, so that gratings end up located at their desired position along the dynamic configuration.

1.2 Shape measurement using fibre optics

Fibre optics can be used in configurations allowing to get information on the shape of the cable (see Figure 3) :

- The fibres can be integrated in a loose tube to be sensitive to curvature only or tight buffer to be sensitive to elongation as well. The pros and cons vary with the configuration (multi-core or single core fibres, distributed/FBG measurements, loose tube/tight buffer).
- Multi-core fibres or multiple single-core fibres (either integrated in a dedicated fibre optics cable or distributed over the cable cross-section) can be used. The measurement principle can be based on distributed strain measurements or FBG distributed close one to another.
- Some configurations may be retrofittable in the space between the three cores of the cable over a distance depending on both cables and sensors designs.

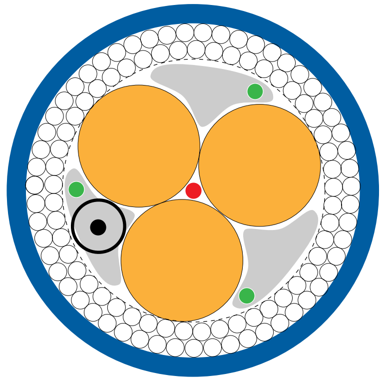

Figure. 3 :
Different configurations of fibre optics for measurements: using fibres among the loose-tube telecommunication fibres (an example of loose-tube location in black), using fibres distributed over the cable cross-section (an example in green), or using fibres in the space between the three cores (in red)

These sensors are interesting for monitoring the shape of the cable, although some configurations only allow to monitor some meters to tens of meters of a cable, sometimes only over the upper part of the cable close to the hang-off. However, they are not very intrusive and do not add hydromechanical loads nor suffer risks of pull-outs like micro-electro-mechanical-based systems or other external systems. Though, they would need developments to reach higher TRL and improve their relevance in being deployed for monitoring dynamic cables.

The main limitations regarding these technologies are:

- the accuracy/durability ratio, linked with the distance between the cores: a short distance means a higher durability but a lower accuracy, whereas a large distance means higher accuracy, but also higher loads transmitted to the fibres and hence a lower durability.
- post-processibility of the results: if the length of fibre optic over one lay length is of the order of magnitude of, or shorter than, distributed measurements' spatial resolution, basic processing algorithm cannot measure curvature. Advanced data processing methods may allow to extract the required information but are not ready for the market yet.
- the spatial resolution/distance range ratio, common with fibre optics-based measurements.
- the measurements give cable curvature (amplitude) but may not be able to give the curvature direction.

- the cost of multi-core fibres, which may be prohibitive.

The R&D efforts can be placed on the development of technologies allowing to monitor curvature amplitude over the first dozen meters of cable, with an accuracy allowing to capture fatigue loads damageable for the cables and the topside accessories. However, technologies whose resolution only allows to monitor curvature amplitudes of extreme events may still be relevant to develop, for estimating remaining lifetime.

1.3 Micro-electro-mechanical based systems

Micro-Electro-Mechanical Systems (MEMS) technology can answer some needs in terms of cable monitoring, but the challenge is to deploy them accordingly to the constraints associated with the dynamic cables. MEMS need a specific casing to be protected from moisture and electromagnetic fields. Some companies provide solutions adapted to offshore applications, and more specifically adapted to shape measurement of the top umbilical sections close to the floater (Morphopipe or Neuron systems for instance). Watertightness and protection from electromagnetic interference are necessary, but robustness is a key factor, that must be balanced with maintainability and minimum dimensions. Minimising the dimensions and the added hydromechanical loads, improving the maintainability and limiting the risks of pull-out (through the management of sensor-cable interfaces and wiring) will be the key factors for providing MEMS based solutions adapted to the monitoring of dynamic cables in floating offshore wind farms.

1.4 Electrical reflectometry

Electrical reflectometry, whether in time-domain or frequency-domain, is widely used in the field of power cables to obtain a footprint of the cable link and to detect or locate faults. This topic undergoes significant continuous research, but it is unclear how the dynamic movements of the cables will affect the measurements. A model-based electrical diagnosis using reflectometry principles was experimentally tested in laboratory and appeared to be very promising (Al Ibrahim *et al.*, 2023). It highlighted the potential benefits that reflectometry methods could offer for the monitoring of dynamic power cables. Reflectometry methods need dedicated experimental campaigns, as well as developments to improve post-processing algorithms to suit the specific needs of dynamic offshore environment and improve fault identification and location in noisy dynamic environments.

1.5 Partial discharge detection

Partial discharge monitoring is widely used for monitoring power cables, and this topic undergoes significant continuous research. However, it is unclear how the dynamic movements of the cables will affect the measurements. Partial discharge measurements through high frequency current transformers require dedicated experimental trials, and developments to improve post-processing methods to meet the specific needs of dynamic offshore environment. This will help to improve partial discharge identification and location in noisy dynamic environments.

1.6 Acoustic emission

Acoustic emission monitoring systems are already at a relatively high TRL, speaking of hardware and processing software. However, the insensitivity to electromagnetic field (of the piezoelectric sensors and of the electrical data transmission wires) should be improved for acoustic emissions devices to be usable on submarine cables. Apart from these electromagnetic compatibility and wiring issues, the main path of improvement for this kind of technologies is building a database of acoustic signatures representative of the failure modes to be observed, which could greatly help in extracting the desired signatures from the ambient noise. Another path of improvement would be to improve the distance range.

Moreover, acoustic emission sensors are generally installed on the outer surface of the monitored asset, which implies high exposure to environmental and external stresses (seawater, hydrodynamics, biofouling and marine mammals) highlighting the need for proper marinization and miniaturization of such exposed sensors. Indeed, the guarantee of a permanent high-quality contact between the sensor and the monitored structure is crucial for acoustic emission sensors. Additionally, acoustic emission method would benefit from an experimental campaigns (in laboratory and in offshore environment) aiming at validating the maximum distance range of one sensor placed on a dynamic cable.

1.7 Generic monitoring configuration

The dynamic cable is exposed to multiple stresses, therefore multi-physical parameters must be measured to have access to its entire structural health, leading to the deployment of various monitoring solutions. The objective of a generic monitoring configuration is to validate in terms of effectiveness and performance, a selection of monitoring solutions working together to give information on the dynamic cable. The following subsections describe a subset of monitoring technologies that would provide a generic monitoring package of interest using technologies available today (see Figure 4). In the case of steep or lazy wave configurations, if the configuration was well designed and installed properly, no loads should be applied to the cable beyond the tether clamp or the touchdown-point. Monitoring that this condition is fulfilled, always guarantees the avoidance of most failures at this location, and would be beneficial, but is not treated in this document.

High Frequency Current Transformers (HFCT)

Deploying HFCT on the three cores of the cables at the terminations provides valuable continuous information on the electrical health of a certain cable length, at relatively low costs. Fault identification is accessible, but fault location may be challenging. Quality of fault identification and location highly depends on the post-processing algorithm applied to the data. HFCT are widespread in the field of cable monitoring and can be purchased from many different providers.

Distributed Temperature Sensing (DTS)

Connecting one communication fibre embedded in the cross-section of one or several cables to a DTS interrogator is valuable, since it requires little installation time and gives a lot of information in return. It may however become a significant investment if all cables are to be connected, so the number of cables to be connected need to be chosen carefully as a ratio between coverage exhaustivity, inital investment, and expected return on investment. The amount of engineering and processing time depends on the type of processing applied to the data: basic processing is available from different providers and requires little time, while specific requirements may need substantial R&D developments for advanced processing. It provides highly valuable information (including location) on the development of hotspots or cold spots along cables and their accessories and may help to locate faults detected by other techniques when those faults locally impact temperature. Many providers of DTS systems are available on the market.

Inertial Measurement Unit (IMU)

Although not giving direct information on cable health or integrity, an IMU provides information on the position and movements of the cable topside. This is a crucial information for assessing instantaneous theoretical cable configurations, and eventually for feeding a digital twin of the cable. Lots of companies can provide different types of IMU dedicated to this application, at relatively low costs.

Acoustic Emission (AE)

Acoustic emission devices are relatively low cost and can easily be deployed over the cable topside when a risk of armour wires breaks exists, but it needs some engineering time for a proper, efficient, and safe integration and wiring. Some companies can provide offshore-ready solutions to be deployed over cable sheath to follow acoustic activity over relatively short distances and can identify and locate some high energy acoustic events whose acoustic signatures are known.

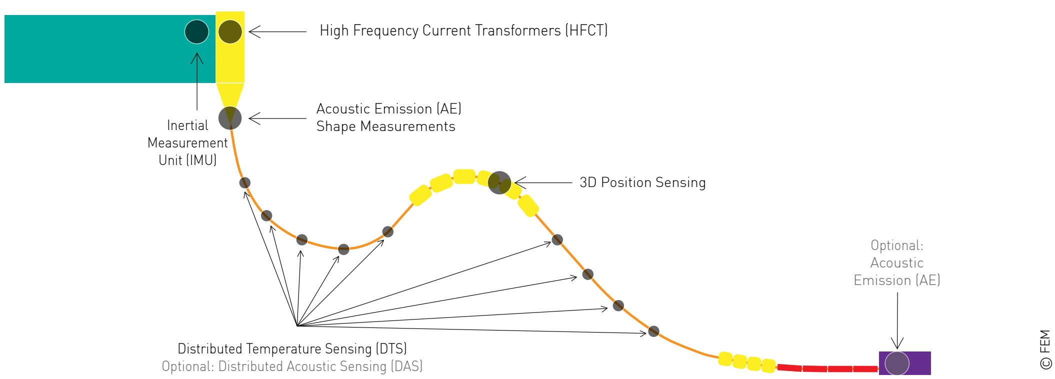

Figure. 4 : Schematic view of a generic monitoring configuration for dynamic cable

Shape measurement of the upper part of the cable

Measuring the shape of the upper part of the dynamic cable is very interesting for monitoring purpose, as the bend stiffener area concentrates a significant part of the possible failures. Events impacting the global configuration of the cable may have an impact on the shape inside, or near of the bend stiffener. Fibre optics or MEMS based systems can be considered to monitor the shape of the upper parts of cables. Coupled with the IMU and fed into a digital twin model including the dynamic cable, the information of the deformed shape of the upper part of the dynamic cable will give inputs and may rise alerts on an abnormal behaviour of the cable. It may also help to discriminate between different failures having similar signatures using a given technology but generating different impacts on the deformed shape. These technologies are relatively expensive and still present low TRL and return of experience is relatively low yet. Some companies provide such solutions, but resolutions and accuracy need to be carefully looked at, depending on the targeted signals.

Intermediate position detection along the dynamic cable

Technologies for monitoring the 3D position of specific points along the cable (hog and sag, for instance) relatively to the floater in space and wirelessly from the floater, on the principle of Ultra-Short Baseline (USBL) systems, would be of high interest for dynamic cables monitoring. It would bring the possibility to follow position of specific points and assess the global shape. It is an additional information complementing data from the IMU and the shape measurement of the upper part of the cable.

Distributed Acoustic Sensing (DAS)

Connecting some fibre optic to a DAS system is relevant, rather on an experimental R&D basis than on a systematic deployment on all dynamic cables. Indeed, this technology relies on mature measurement principles and offers a wide range of possibilities without modifying the design nor adding devices on the cable. However, the processing of DAS data for monitoring subsea dynamic power cables is not yet reliable enough for DAS technology to be deployed as a standalone monitoring solution. Deploying a limited number of DAS on a limited number of cables is a way to learn faster how to exploit this rich and promising information, without investing excessively and generating an unreasonable amount of data.

2 - Modifications in design of cables and accessories for monitoring purpose

Cables and bend stiffener would benefit in being designed considering the objective of facilitating the use of post-installation retrofittable sensors for monitoring their shape over the first tens of meters. For instance, letting space for inserting an FBG-shape sensor or installing MEMS sensors.

Tight-buffered fibre optic would open the door to the use of strain and eventually shape measurements using fibre optics distributed technologies (DTSS, DAS), but also to the use of FBG-based technologies, integrated during manufacturing. The two main limitations preventing tight-buffered fibres from being commonly used are:

- breaking elongation of fibres is much smaller than that of the polymeric components inside the cable: tight-buffered fibres are exposed to high risks of rupture during cable transport, installation, and operation. This risk needs to be overcome by a proper integration of the fibres in the cross-section design, in terms of lay-length and distance to the cross-section centre. These two integration parameters play a significant role in system sensitivity and imply requirements regarding spatial sampling resolution.
- integrating tight-buffered fibres in the manufacturing process is challenging, as manufacturers need to modify their production lines, manipulation of fibres before and during integration put them at high risks of rupture, and the physical bond between the tight-buffered fibre and its substrate needs to be of good quality and durable.

Moreover, tight-buffered fibres need to be redundant to a certain extent, as repairing is not possible. Tight-buffered fibres would be highly valuable if these limitations were overcome and a solution offering an interesting spatial resolution were to become available (see Figure 5).

To improve strain detection using the pre-integrated loose-tube fibres, additional efforts, in collaboration with the cable manufacturers to integrate their constraints, should be investigated to find the optimal position and number of fibres inside the cable, to optimise their sensitivity without putting the fibres at risk in case of excessive bending. The choice of the lubricant inside the loose tube will be key in determining the transfer function of the strains between the tube and the fibres, and in ensuring a low drift of this transfer function along cable lifespan.

Development of specific joints (for the transitions between dynamic and static cables, for instance) featuring integrated partial discharge detection devices, either wired or wireless or autonomous, could be interesting as junctions are considered as weak points. This represents high challenges regarding data and eventually power transmission, as junctions are in general far from both ends. Moreover, joints are critical zones, and their instrumentation shall not become a source of failure.

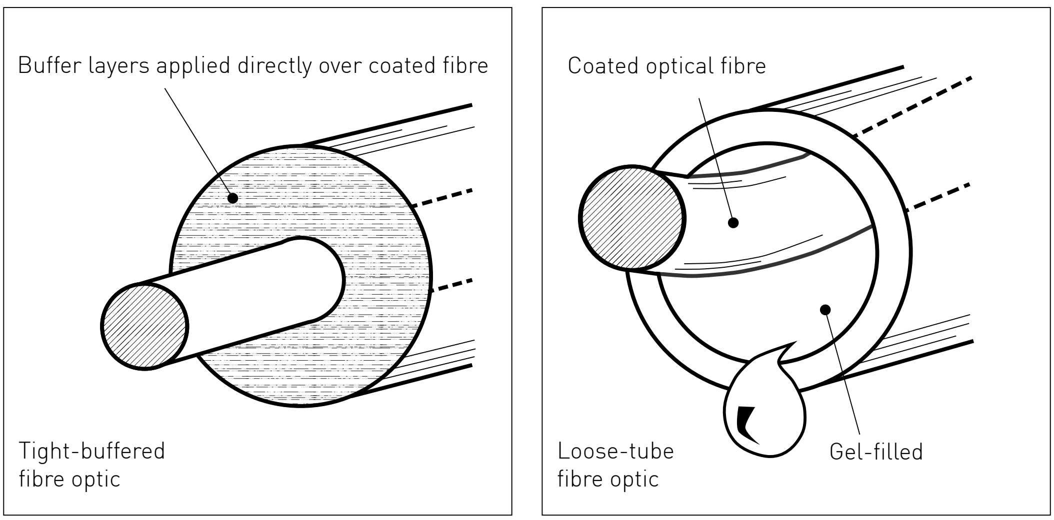

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Figure. 5 : Illustration of loose-tube fibre optic compared to tight-buffered fibre optic

3 - Experimental campaigns on components in laboratory

Experimental campaigns on full scale cables or specific cable components will be essential for better understanding the degradation mechanisms and their detection. It also allows to benchmark different monitoring technologies and suppliers, and gives practical information on the performances and reliability.

3.1 Amour wires breakage

For benchmarking the technologies dedicated to detecting armour wires breaks, an experimental plan aiming at generating breakages of armour wires with different levels of rupture energies would permit to gather information on the sensibility and the distance range of the technologies. Highest level of rupture energy is obtained via monotonic tensile tests, while lowest level of rupture energy is obtained via bending fatigue tests at low amplitude. Intermediate levels of rupture energy can be obtained by placing the cursor in between these two protocols. Full scale cables are required for this kind of experimental campaigns, as the environment of the armour wires plays a significant role in wave propagation. This work could also be conducted on screen wires breakage but would be more complicated to specify and realise.

3.2 Bird caging

Bird caging has been identified as a potential failure mode of dynamic cables, especially in shallow waters. However, experience shows that choosing experimental boundary conditions reproducing the physics of the failure mode in laboratory is challenging, as the phenomenon, based on dynamic compression, is very unstable. To move forward on the detection of bird caging on a cable in service, effort should be put on the definition of a protocol for generating the conditions necessary for a bird caging phenomenon to develop. Specifications of such a test would need to face two successive challenges: properly understanding the physics at the origin of the failure, before building an experimental protocol allowing a cable sample to develop a local bird caging pattern at some point, preferentially in laboratory. However, the bird caging phenomenon has been extensively studied by the O&G community: the context generating bird caging phenomenon on floating wind farms dynamic cables must be proven to be different from O&G return of experience for the work described in this paragraph to have legitimacy.

3.3 Strain measurement using loose-tube fibres

The bending tests conducted during the project showed that communication fibres embedded in a loose tube may be sensitive to strains, to a certain extent and under specific hypothesis. A dedicated experimental campaign could help to better understand the hypothesis under which monitoring the strains using the communication fibres embedded in a loose tube gives information on local loads applied to the cable (frequency of oscillating loads, or amplitude of extreme events, for instance). The position of the optical fibre inside the loose tube also influences the measure during a deformation of the loose tube (see Figure 6). The ultimate result of such a campaign could be the identification of a typical transfer function for translating cable deformation into fibre deformation and inversely. Such tests should be considered at two scales:

- at the full power cable scale to maximise representativity,
- at the fibre optic cable scale (the tube containing the fibres bundle and the lubricant) to simplify the processing of results.

The experimental protocol shall test different kinds of mechanical loads, as preliminary experimental results obtained show that the transfer coefficient is different in the tensile and bending tests. Due to the presence of a lubricant bringing a viscous behaviour, transfer coefficients are likely to depend on strain rates, so the tests should be conducted at a variety of speeds. The properties of the lubricant are likely to depend on temperature as well. Ultimately, transfer coefficients are likely to evolve along cable lifespan with lubricant ageing.

3.4 Insulation material ageing

In order to benchmark sensing technologies dedicated to monitor insulation material ageing, protocols for ageing the materials of a cable in representative ways (mechanical, electrical, thermal, seawater) will be needed. A first step can be achieved at the scale of power cores, as the critical phenomena involved will take place within this

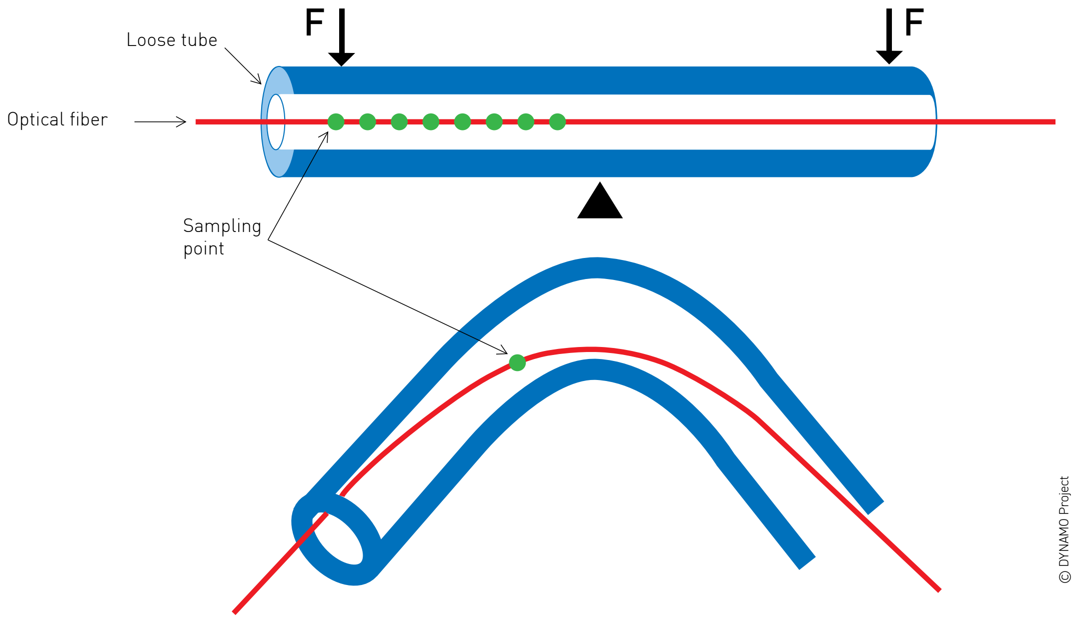

Figure. 6 : Illustration of fibre shape in the loose tube before and after bending

component. Controlling the application of the four types of stresses coupled may be highly challenging even at the core scale. Coupling three types of loads are challenging as well but should be achievable with some effort on protocols definition and may bring the opportunity to accelerate ageing mechanisms. Such results would be highly valuable, as only few results are available yet on this topic at this scale. Electrical ageing in water and thermo-electrical ageing are already well documented, even though some questions remain unanswered, but conducting mechanical fatigue tests in seawater or under electrical load could be an interesting step forward that has not been widely studied yet. The following step would be benchmarking the insulation ageing monitoring technologies, which can be executed at different scales. This step is possible at different levels of complexity, from laboratory experiments on power cores or on a three-core assembly to the real full-scale load case at sea. Coupling the four types of stresses or most of them is essential for representativeness but may not be needed if the benchmark aims at comparing a specific feature or measurement principle.

3.5 Sensors durability

The sensors that will be deployed on dynamic cables for monitoring purpose will face harsh environments (high levels of loads and movements, in seawater) and will not be easy to inspect and replace: a maximum durability with a minimum frequency of maintenance is key for a valuable monitoring. Sensor qualifications methods exist for guaranteeing that sensors can operate subsea (the O&G industry provides plenty of examples), but specific protocols will need to be developed and experimented for testing sensors durability in highly dynamic solicitations for long-term subsea deployments at moderate depths (order of magnitude of 100 m).

3.6 Full-scale experimental campaign at sea

A full-scale campaign, involving the deployment of a cable at sea in a representative depth, hanging from a floating structure imposing uncontrolled movements that are close to that of a real turbine floater, would be the opportunity to test monitoring techniques in a representative environment. An example of generic monitoring configuration that could be deployed was previously presented in this document (see subsection 1.7 Generic monitoring configuration). This setup, for which loads are imposed by waves and current, will not give the opportunity to reproduce long-term fatigue or ageing failure modes but would give the opportunity to challenge shape and strains sensors, that show great potential but still need R&D and applicability tests in real conditions. In case the deployed cable already presents faults or significant partial discharge activity, the experimental campaign could bring the opportunity to challenge reflectometry and partial discharge measurements robustness in presence of representative dynamic movements and environmental noise, which are complex to reproduce in laboratory. The full-scale campaign could be used as a validation case for global modelling of cables as well. Besides, heating the conductors to generate a thermal field inside and in the vicinity of the cable would be highly beneficial, as it would improve representativity (introducing thermo-mechanical loads and reducing stiffnesses) and would open the door to the use of thermal monitoring techniques. However, it represents a challenge and adds strong constraints on the protocol.

Assuming that the timeline is coherent with that of monitoring technology developers, a full-scale experimental campaign at sea could be the opportunity for technology developers to challenge their solutions regarding operability, watertightness, durability (to an extent depending on the total duration of the deployment at sea), and sensitivity to external stresses. Such a campaign can also be an opportunity for testing the data recovery and the data management associated with the monitoring solutions.

4 - Method and improvements for the monitoring deployment at the wind farm scale

The procedure for deploying a complete monitoring solution has been divided into three stages (see Figure 7). In the first stage, a list of the failure modes the operator wants to detect is established. In a second stage the sensors technologies are selected based on the list of failure modes to be monitored. In the third stage the sensors system is deployed across the farm and integrated in the SCADA system.

The method has been experienced within the project on different theoretical case studies that include different farm architectures and lists of failure scenarios to monitor (France Energies Marines, 2023b). Strategic sensor deployments have been produced for each case study using the selection method presented here. In the following sections, the method's stages are detailed, and improvements to optimise the global monitoring deployment strategy are provided.

4.1 Failure modes analysis

Scenarios of failure mechanisms (chains of events leading to a cable failure) have been detailed at a macro scale and a micro scale. This work allows to identify the physical parameters that vary during the different stages of each failure mode. The operator can select a degradation at the macro scale and retrieve the physical parameters to monitor, in the objective to select the relevant sensors.

Listing the possible failure modes linked with the chosen dynamic configuration is the starting point of the monitoring strategy, since it will directly impact the sensors selection. Establishing the list of possible failure modes is not trivial and will depend on many factors like the cable design, the cable configuration, the farm location, or platform movements, among others. The possible failure modes then need to be ranked according to the requirements and priorities of the responsible party, to identify the most critical failure modes to follow, and target the most relevant sensors.

Occurrence probabilities and criticality of the failure modes are not considered as a quantitative criterion for sensors selection, at this stage, but is embedded qualitatively in the requirements and priorities of the responsible party. Introducing a quantitative level of risk based on a limited number of noted parameters (for instance: failure rates, direct and undirect economic impact, environmental impact, etc.) weighted in a single criticality indicator would be valuable.

At the light of current knowledge, it is difficult to discriminate criticality of failure modes one from another, due to a lack of return of experience. First, there is a need to collect data on dynamic cable failure modes to compute the failure occurrence. Second, there is a need to evaluate the economic impact of each failure mode based on the O&M needs and possible shutdown.

Having this information will allow to rank the failure modes objectively with respect to the operator requirements, and thus highlight the most critical failures to monitor preferentially. The level of risk is defined by the operator on what is acceptable regarding his own criteria.

4.2 Sensors selection

The primary input of the sensor's selection is the list of physical parameters to monitor, corresponding to the list of failure modes of interest. A first selection of sensors is then produced with all the monitoring technologies capable of measuring the corresponding physical quantities. Then, sensors are filtered

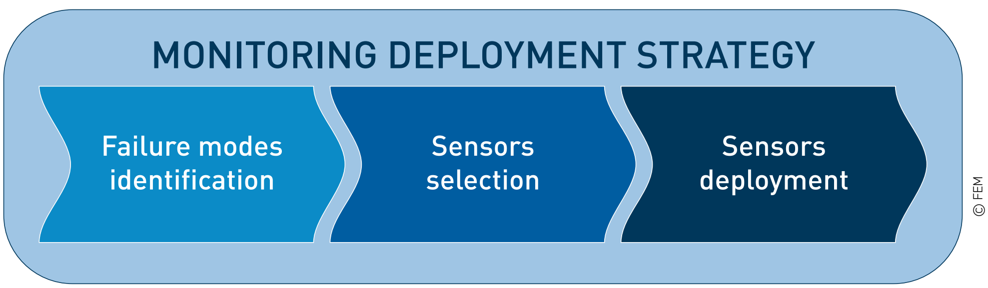

Figure. 7 : Representation of the different stages of the monitoring deployment strategy away based on successive selection criteria, to reduce the number of technologies down to several technologies acceptable by the operator (see Figure 8).

Below are some examples of the criteria definition:

- Price of the technologies (sensor(s), hardware, software, installation, O&M costs).
- Retrofitting possibility.
- Sensitivity to external and environmental disturbances (i.e., offshore environment and presence of electromagnetic field).
- Data retrieval (regarding presence of wires, real-time accessibility, or recovery frequency).
- Redundancy of the detection for one or more physical parameter(s).

Two specific issues are interesting to consider when it comes to the choice of selecting a criterion. They are developed in the following subsections.

Redundancy on event detection

Redundancy, meaning "multiple ways of detecting the same event", appears to be valuable for the most important physical parameters. Indeed, on the one hand, even the most reliable technologies may drift or raise false alerts due to sensor issues, and, on the other hand, unexpected events could generate signatures like another expected event and lead to misinterpretation of a signal. In both cases, having a secondary technology allowing to double-check and validate the interpretation of the signal ensures a high quality and reliability of the global monitoring system.

Ultimately, if this criterion is integrated as a primary selection criterion in the process (see Figure 8), it does not necessarily increase the total monitoring price or the amount of data dramatically, as sensing technologies can be chosen for their ability to be a lead-instrumentation for following one failure mode while serving as a verification medium for another critical failure mode already monitored by another dedicated technology.

The value of information

In this context, the value of information is defined as the difference of the maximum cost saved on cable O&M actions between the cases and without information. It is an indicator of the economical added value on OPEX of the monitoring technologies and strategies deployed over the wind farm. When this information is available, it is a relevant basis for comparing the monitoring technologies and thus improve sensors selection. It can serve as an optimisation parameter for the monitoring deployment strategy.

In the case of dynamic cable monitoring, the value of information depends on two main aspects:

- The impact of a failure mode on the farm costs regarding maintenance operation, repairs and shut down. This would be part of the failure ranking (see subsection 4.1 Failure mode analysis).
- The reliability of the selected sensors (through statistics on the false silences, the false alarms, and sensor lifetime).

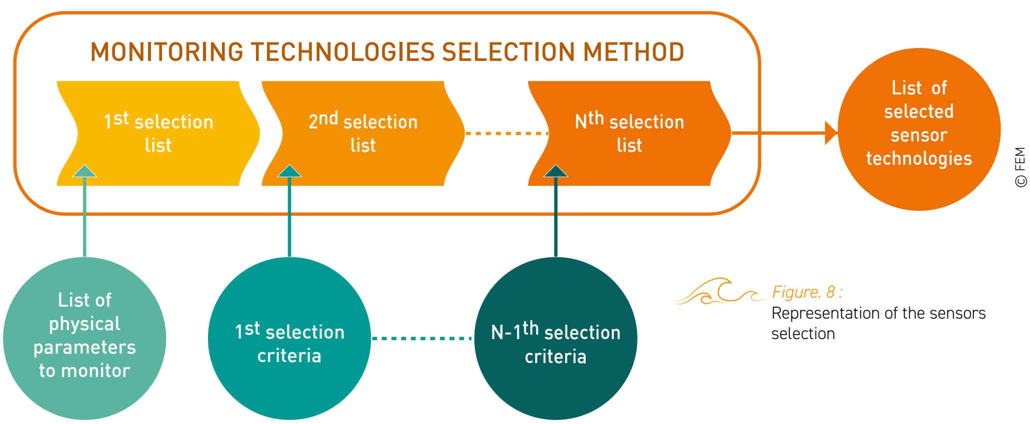

Figure. 8 :
Representation of the sensors selection

4.3 Sensors deployment

In this stage, the sensor deployment over the wind farm scale is considered through two main axes: the number and position of sensors to deploy, and data governance issues.

Number and position of sensors

Once sensors are selected, they need to be appropriately distributed over the windfarm, in terms of number and positioning. Apart from the probabilities of failure detection, it will impact the price and the amount of collected data. For a given technology, the number of sensors may be dependent on the farm architecture, the number of turbines, the distance between the turbines, the depth, and the percentage of coverage (whether all cables/floaters are instrumented or only a part of it). In the case of partial coverage, the covered items need to be chosen carefully to maximise the chances of detection while controlling the costs. For instance, in the case of a radial farm architecture, the operator can choose to instrument all the turbines of half the strings, or half the turbines of all the strings. Similarly, in some cases, monitoring the beginning of a string may be sufficient for getting enough information on the whole string.

Data governance during operational monitoring

The operational aspect of the monitoring has not been investigated during the project. However, it is important to consider it at the stage of choosing a strategy for monitoring deployment. Three aspects are presented in the following paragraphs to introduce the needs and issues in terms of operational monitoring.

The **data management**, including data transmission and storage, needs to be addressed early in the strategy definition. Conversion of measurements into transportable signals may be considered as being part of data management when it is not embedded with the sensor. Conversion of signals is not treated in this section. Data retrieval is much more complex in the offshore environment, particularly for sensors installed under water and exposed. Subsea communication is a real challenge, as the use of communication cables has major drawbacks for such dynamic problematics in an electromagnetic environment. Besides, radio waves, commonly used for wireless communication in air, cannot propagate far in water. Acoustic waves and more recently light communication are very promising, but still suffer from some limitations that need to be overcome, mostly regarding the distance range and dependence to the environment (salinity, turbidity, external noise, etc.). An effort should be placed on the improvement of subsea communication. In a general way, the technologies that need a wired connection could be improved by integrating local storage devices and data recovery techniques or developing wireless communication abilities.

At the scale of a wind farm, **data storage** can become a real challenge as some technologies can generate huge amounts of data (DAS, for instance), and as the number of monitored assets can increase rapidly over an entire farm. The strategy for data management needs to be anticipated as much as possible with regards to this amount of data, before starting to record outputs and ideally before installation and construction of the farm. The most proper way of dealing with data storage is to minimise the volume to be stored, but this means being able to sort valuable information from unvaluable information. This requires a lot of return of experience, and a full confidence in the processing algorithms.

Different levels of **data processing** may be applied to the data collected:

- The first level consists in processing raw data to harmonise all data coming from the different sensors. Data can then be displayed in a dashboard as absolute values, figures and diagrams, showing the most important parameters at a glance. This dashboard can be watched over by an operator to rise alerts when parameters show values or behaviours that could be signs of failures.
- Instead of being implemented in a dashboard and visually analysed, additional processing can use advanced data processing algorithms to derive health parameters or calculate failure probabilities. This advanced processing can consist of conventional data processing algorithms or artificial intelligence use but can also lay on the numerical modelling of the monitored assets (digital twin) or on the comparison with databases of failures signatures.

These different types of processing will rise alerts, show indicators, and may help to choose between different alternatives, but the final processing of the data, leading to the choice of conducting any action (additional inspection, increased vigilance period, repair, etc.) will still need human intervention.

The objective of monitoring is to provide information on the structural health of the dynamic cables. The output of the system is an information that is transmitted to the operator. Depending on this information, the operator has the choice to start or not O&M actions. To help this choice, database of O&M actions linked to the potential output signals from monitoring systems could be established. Such database will considerably feed the value of information parameters (see subsection 4.2 Sensors selection).

4.4 Case-by-case and additional inspection methods

Other technologies, not described in this report, can be deployed for occasional monitoring on a case-by-case basis, e.g., profiting from maintenance downtimes, such as reflectometry or very low frequency methods. Moreover, still on a case-by-case basis, additional inspection methods can be deployed occasionally using specifically equipped Remotely Operated Vehicles (ROV) or Autonomous Underwater Vehicles (AUV), depending on the specific needs of a situation. Inspection plans that could be carried out in parallel of the monitoring strategy installed on the floating offshore wind farms have not been investigated but should be treated in the future to evaluate its advantages and cost effectiveness.

5. General conclusion

Numerous ways for further R&D investigations are identified in this report, targeted at different contributors (providers of monitoring solutions, cable manufacturers, R&D institutes, and industrials), with different levels of complexity and different levels of benefits.

This report also includes a proposition of monitoring devices fitting well together for equipping a floating windfarm and monitoring most of the main failures expected to happen in the dynamic sections of inter-array and export cables. Ideas of experimental campaigns for further benchmarking the technologies and gathering failure signals database are proposed, as well as more general concepts such as the level of acceptable risk, the value of information, and the construction of O&M actions database. The information included in this report provides some orientations for further works in the short-term to mid-term future, with the aim of making the industry provide better solutions for cable monitoring and lifetime assessment.

A proper monitoring of the cable network in the floating windfarm is key to enable the trust needed in these critical components, for bankability and insurability as well as for reducing the costs of operation and maintenance. This report provides matter and arguments for enhancing reliability of the dynamic cables and reducing the LCOE of floating offshore wind energy.

Acronyms

AE = Acoustic Emission
AUV = Autonomous Underwater Vehicles
DAS = Distributed Acoustic Sensing
DTS = Distributed Temperature Sensing
DTSS = Distributed Temperature Sensing Systems
FBG = Fibre Bragg Grating
HFCT = High Frequency Current Transformers
IMU = Inertial Measurement Unit
LCOE = Levelized Cost of Energy
MEMS = Micro-Electro-Mechanical System
O&G = Oil & Gas
O&M = Operation & Maintenance
OPEX = Operational Expenditure
R&D = Research & Development
ROV = Remotely Operated Vehicle
SCADA = Supervisory Control and Data Acquisition
TRL = Technology Readiness Level
USBL = Ultra-Short Baseline

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The monitoring of dynamic cables is a crucial topic for the development of the floating offshore wind farm sector since developers and insurances require high reliability of the dynamic cable. It is therefore important to provide tools and methodologies to make the appropriate choices regarding dynamic cable monitoring. This report is directed, among others, towards the R&D institutes, the developers and operators of wind farms, and the providers of engineering solutions related to dynamic subsea power cables, to orient the next works and promote the fastest development possible of reliable and efficient monitoring technologies dedicated to dynamic subsea power cables. Additionally, this report proposes a monitoring deployment that is a relevant basis package for thoroughly monitoring a dynamic cable.

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Bâtiment Cap Océan
Technopôle Brest Iroise
525, avenue Alexis de Rochon
29280 **PLOUZANÉ**
02 98 49 98 69
www.france-energies-marines.org

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