Ocean Engineering 311 (2024) 118810



Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng



Review

Recent advances in mechanical analysis and design of dynamic power cables for floating offshore wind turbines

Burak Can Cerik *, Luofeng Huang

School of Water, Energy and Environment, Cranfield University, United Kingdom

ARTICLE INFO

Keywords:
Dynamic power cable
Marine renewable energy
Floating offshore wind
Cable local analysis
Export cable
Inter-array cable

ABSTRACT

This review paper presents a comprehensive analysis of the mechanical design and analysis of dynamic power cables for marine renewable energy applications, focusing on research from the last two decades. The review covers key aspects such as mechanical properties, failure mechanisms, fatigue analysis, experimental studies, local cable analysis, and global load analysis. The study aims to provide a concise summary of the state-of-the-art, identifying recent advancements and research gaps in the field. The methodology involves a systematic review of relevant literature, including journal articles, conference papers, and industry reports. The findings are synthesised to provide insights into the current understanding of power cable design and analysis, as well as to highlight areas requiring further research and development. The review is intended to serve as a valuable resource for researchers, engineers, and stakeholders in the marine renewable energy sector, contributing to the development of more reliable and cost-effective dynamic power cable solutions.

Contents

1. Introduction 1
2. Dynamic power cable mechanical design aspects 2
   2.1. Cable internal structure components 2
   2.2. Cable global configuration 4
3. Experimental research 5
   3.1. Full cable mechanical tests 5
   3.2. Component mechanical tests 5
4. Local and global analysis in dynamic power cable design 6
   4.1. FEA-based local analysis 7
   4.2. Fretting and fatigue failure 8
   4.3. Insulation failure 9
   4.4. Biofouling and thermal effects 9
   4.5. Global load analysis and design 9
5. Discussion and research needs 10
6. Conclusions 12
CRediT authorship contribution statement 13
Declaration of competing interest 13
References 13

1. Introduction

Marine renewable energy technologies, such as offshore wind, wave, and tidal energy, are emerging as clean and sustainable alternatives to fossil fuels. These technologies harness the vast resources of the ocean to generate electricity, offering a promising solution to the growing global energy demand. Despite their potential, marine renewable energy technologies face unique technical and logistical challenges that must be addressed to fully realise their capabilities (Karimirad, 2014).

* Corresponding author.
E-mail addresses: burak.cerik@cranfield.ac.uk (B.C. Cerik), luofeng.huang@cranfield.ac.uk (L. Huang).

https://doi.org/10.1016/j.oceaneng.2024.118810
Received 19 June 2024; Received in revised form 8 July 2024; Accepted 23 July 2024
Available online 29 July 2024
0029-8018/© 2024 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

Understanding the unique challenges and design considerations of these dynamic cables is crucial for the successful development and operation of floating offshore wind farms. In the context of marine renewable energy systems, power cables can be categorised as inter-array, inter-platform, or export cables. The term "dynamic cable" has emerged in recent years to describe cables specifically designed to withstand continuous motion and cyclical loading, distinguishing them from static or quasi-static cables. Dynamic sections can be present in any of these cable categories, depending on the specific application and environmental conditions. In floating offshore wind applications, dynamic cables typically experience the most challenging conditions, being subjected to continuous motion due to waves, currents, and platform movements. This review focuses primarily on dynamic power cables designed for floating offshore wind turbines, while also drawing on relevant studies from other marine renewable energy applications where the findings are applicable to floating wind scenarios.

A critical challenge lies in ensuring the reliability and integrity of power cables that transmit electricity to the onshore grid (Thies et al., 2012). In offshore wind farms, subsea cable development focuses on two key technological advancements: the implementation of higher voltage levels in both inter-array and export cables, and the design refinement of dynamic inter-array and export cables for floating offshore wind applications. Unlike static cables, dynamic inter-array and export cables are subjected to increased loadings due to exposure to dynamic tension, bending, and twisting cycles caused by platform's motions, as well as environmental loading to waves, wind and currents, which can lead to fatigue failure (Nasution et al., 2014b). Fatigue is a major concern for dynamic power cables as it can ultimately lead to failure in long term (Kuznecovs et al., 2019; Thies et al., 2012). Additionally, insulation layer failure poses a significant threat as it can compromise the cable's electrical integrity (Tao et al., 2016). Furthermore, the ultimate strength of cables under extreme bending conditions, often characterised by the minimum bending radius (MBR), is crucial for ensuring cable integrity during installation and extreme environmental events (Ehlers et al., 2023).

Power cable failures have substantial financial implications for offshore wind energy projects (Warnock et al., 2019). Approximately 80% of offshore wind-related financial losses and insurance claims are attributed to cable failures, including both static and dynamic cables (de Wild, 2018). With repair-related downtimes averaging 60 days (ORE Catapult, 2021), these failures can result in significant revenue losses and increased maintenance costs. Moreover, dynamic cables for floating offshore wind applications typically incur higher costs compared to traditional static cables due to their more complex design and manufacturing requirements. Therefore, improving the mechanical design and analysis of dynamic power cables is essential to mitigate failure risks and ensure cost-effective operations in the growing floating offshore wind sector.

Advanced mechanical analysis techniques, such as finite element analysis (FEA) and multi-body dynamics simulations, play a crucial role in developing reliable and cost-effective dynamic power cables (Srinil, 2016). These methods enable designers to predict cable behaviour under various loading conditions, optimise cable structure and materials, and assess fatigue life. Integrating these techniques early in the design process allows for the development of cables better suited for the marine environment, reducing failure risks and financial losses (Thies et al., 2012). Furthermore, verifying global cable design, cross-section response, and performance requires robust and validated analysis tools, beside standard type tests for design qualification (Tyrberg et al., 2019).

The increasing demand for reliable and cost-effective dynamic power cables in floating offshore wind applications has driven significant research efforts in recent years. One of the primary objectives is to develop improved mechanical models that can accurately predict the behaviour of these cables under various loading conditions. By reducing the uncertainty in cable performance predictions, designers can optimise cable designs, minimise safety factors, and ultimately decrease the overall cost of floating offshore wind projects (Okpokparoro and Sriramula, 2023). Furthermore, there is a growing recognition that the design standards and practices used in the offshore oil and gas industry may not be directly applicable to dynamic power cables in floating offshore wind applications due to differences in loading regimes, environmental conditions, and operational requirements. This has led to a push for the development of bespoke standards tailored specifically to the needs of the floating offshore wind industry (Carbon Trust, 2023b). Another critical aspect driving research is the need for standardised testing and fatigue modelling methods for dynamic cables. Establishing a standard process for working with dynamic cables, from design to installation and operation, can lead to significant reductions in overall costs and improve the reliability of floating offshore wind projects (Carbon Trust, 2023b). These identified needs serve as key motivators for the ongoing research efforts in the field of dynamic power cable analysis and design for floating offshore wind applications.

This review paper addresses the critical issue of dynamic power cable reliability in marine renewable energy by providing a systematic assessment of research and development efforts mainly over the past two decades. It focuses on studies on power cables that emphasise their application particularly in floating offshore wind technologies. The present review is based on a comprehensive literature survey conducted primarily using Scopus, employing keywords such as "dynamic power cable", "flexible power cable", "inter-array cable", "export cable", "power cable + offshore wind", and "marine power cable", both individually and in combination. The search focused on research from the past two decades, with emphasis on mechanical aspects of dynamic power cables for floating offshore wind applications, including structural design, experimental studies, numerical modelling, and global load analysis. The paper reviews various power cable types used in marine applications along with key design considerations. It also examines experimental studies on power cables, discusses numerical modelling approaches for local and global analysis — including fatigue analysis, mechanical property estimation, and failure assessment — and identifies research gaps and future directions in power cable mechanical design and analysis for marine renewable energy applications.

The rest of this paper is structured as follows: Section 2 provides an overview of dynamic power cable structure and configurations and structural design considerations. Section 3 reviews the recent experimental studies. Section 4 discusses the numerical modelling approaches for local and global analysis of dynamic power cables including design-oriented research work. Section 5 identifies the research gaps and future directions, and finally, Section 6 concludes the paper.

2. Dynamic power cable mechanical design aspects

Before proceeding to the review of the literature, some basic definitions and considerations about dynamic power cables are provided in this section. It should be noted that more detailed descriptions covering design aspects other than mechanical behaviour (among others, manufacturing, installation, inspection and monitoring) are documented in textbooks (Worzyk, 2009; Srinil, 2016) and offshore industry standards (Det Norske Veritas (DNV), 2021c,a,b). In addition, an extensive review of relatively recent industry practices and market analysis is also reported elsewhere (Ikhennicheu et al., 2020).

2.1. Cable internal structure components

Dynamic power cables are heterogeneous, complex structures specifically designed for floating offshore wind farms, while static power cables are sufficient for fixed-bottom wind farms (and some tidal turbine systems). The terms static and dynamic here can be interpreted literally: the former is laid on the seabed and remains still, while the latter is left hanging and subject to frequent dynamic motions caused by turbine movement, wave loading, or sea currents. As shown in Fig. 1,

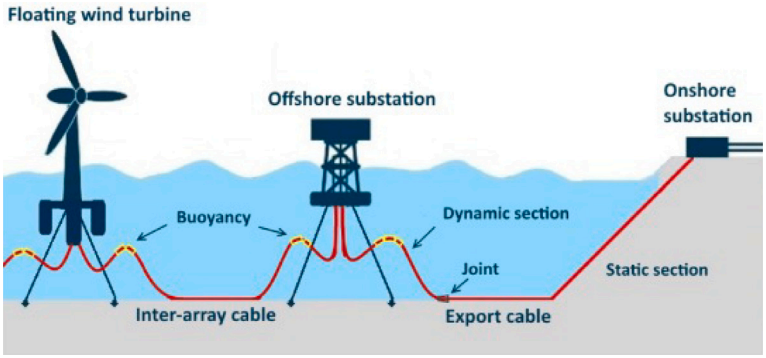


Fig. 1. Typical electrical system of a floating offshore wind farm (Lerch et al., 2021).

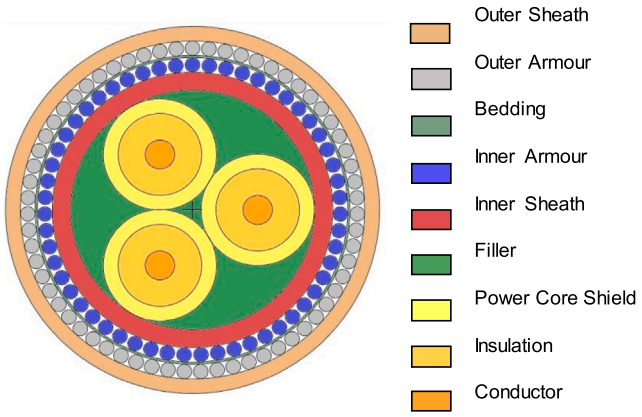


Fig. 2. Typical 3-phase dynamic power cable cross-section.

dynamic power cables are mainly utilised as inter-array/inter-platform or export cables. As evident, array cables are used to deliver power from the wind turbines to the offshore substation, and export cables to deliver power from the offshore substation to the onshore substation.

Dynamic power cables are composed of conductive metal cores, surrounded by insulation and armouring material, all bound by a sheath. Fibre optic cables can also be incorporated into the cable to facilitate communications and data transfer between the shore, the wind farm, and for cable condition monitoring. Fig. 2 illustrates the design structure and sub-components of a typical three-phase dynamic power cable. The term 'three-phase' refers to the number of cores/conductors the cable has; a cable with one core would be referred to as a single-phase power cable. Three-phase cables are normally used for floating offshore wind turbines to maintain the high voltage - alternating current being transmitted and avoid any transmission losses. At the moment, 33 and 66 kV cables are well-established technology with three-phase semi-wet and wet designs as inter-array/platform cables, which are based on the use of XLPE-WTR (water tree retardant) materials for insulation - cross-linked polyethylene (XLPE) with additives retarding the formation of the water tree phenomenon that leads to degradation of insulation and cable failure.

The conductors, located at the centre of each core, are the principal components of the power cable. They conduct and transmit the electricity generated from the floating renewable energy platforms to the onshore/offshore substation. They comprise a group of helically stranded wires, compacted together through an extrusion process. This way, the cable has better flexibility properties, which is essential for dynamic cables. Additionally, current is also distributed uniformly over the cross-section, improving the conductor's current-carrying capacity. Copper and aluminium are commonly used as conductor materials, with aluminium cores and cables needing to be larger to transmit the same power. However, in general copper is more expensive than aluminium and its price is volatile (Marcollo and Efthimiou, 2024).

Each conductor is protected by an insulator, with a screen placed on both the inner and outer sides of each insulator. These two screens, combined with the insulator, make up the dielectric system of the cable. The dielectric system prevents electrical failures or leakage of currents during transmission and, together with the conductor and conductor sheath, forms a single core. However, the insulation material in the dielectric system of dynamic power cables for floating offshore wind turbines is susceptible to the formation of electrical trees and water trees. Electrical trees are microscopic, tree-like structures that grow within the insulation material when subjected to high electrical stress, while water trees are similar structures that form due to the presence of moisture and electric fields (Li et al., 2022). Both types of trees can lead to the degradation of the insulation material over time, compromising the integrity of the dielectric system and potentially causing premature failure of the power cable. The growth of electrical and water trees is particularly concerning in dynamic power cables for floating offshore wind turbines, as these cables are exposed to harsh marine environments and subjected to mechanical stresses such as bending, twisting, and stretching. These mechanical stresses can accelerate the growth of trees and increase the risk of insulation breakdown. Therefore, it is crucial to select appropriate insulation materials and design the dielectric system to minimise the formation and growth of electrical and water trees, ensuring the long-term reliability of dynamic power cables in floating offshore wind applications. Finally, a filler is added to act as a shield and also gives a cylindrical shape to the three cores, which are helically wrapped around each other.

Armour, arguably the most essential part of dynamic cables, provides mechanical protection against external loadings and carries the axial and bending forces acting on the cable. The presence of this armour is crucial as it directly affects the cable's mechanical properties, which in turn determine the cable's dynamic performance and fatigue life. The armour consists of multiple steel wires (stainless steel or non-magnetic galvanised steel), which are wrapped around the cable at a specific lay angle (determined by the lay length). Dynamic power cables have two layers of armour laid in opposite directions, as shown in Fig. 3. This enhances the torsional stability of the cable. The outer sheath, commonly made of HDPE, represents the outermost layer of the cable and is technically the cable's first layer of protection against abrasion, corrosion, and external loading.

When the dynamic power cable undergoes bending, the steel armour layers exhibit a unique stick–slip behaviour that significantly influences the cable's bending response. Initially, as the cable starts to bend, the armour wires maintain their relative positions, exhibiting a "stick" state. In this state, the cable demonstrates a higher bending stiffness, as the armour wires effectively contribute to the cable's resistance to bending. However, as the curvature of the cable increases, the armour wires experience increasing lateral pressure and friction forces. At a certain threshold, the friction forces are overcome, and the armor

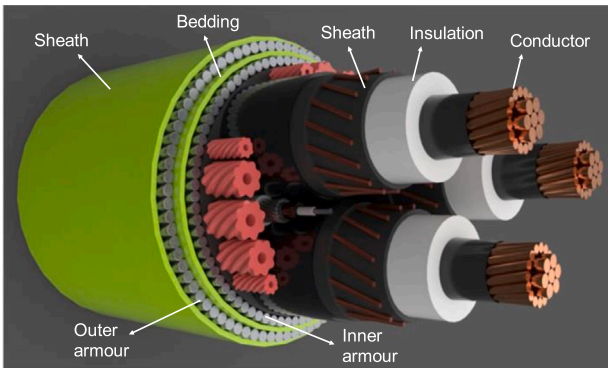


Fig. 3. Breakdown of components inside a 66 kV dynamic power cable. *Source:* 2H Offshore/ORE Catapult (2022), annotated by the authors.

wires begin to slip against each other, transitioning from the "stick" state to the "slip" state. This transition is not instantaneous but occurs gradually over a range of curvatures, representing a transition phase between the two states. During this transition phase, the cable's bending stiffness decreases, as the slipping armour wires contribute less to the cable's resistance to bending. As a result, the cable becomes more flexible in bending, exhibiting a non-linear bending response. This stick–slip behaviour and the associated transition phase have important implications for the cable's performance and long-term reliability, as the repeated sliding and friction between the armour wires can lead to fretting wear, fatigue damage accumulation, and potential challenges in accurately predicting the cable's behaviour and loads.

A significant modification in dynamic cables, as opposed to static ones, is the incorporation of a sturdier external protective layer (such as PE, Nylon, or another type of solid extruded coating) rather than the lightweight protective rovings (spiral-wound strings of polypropylene rope with a bitumen coating) found in static cables. Additionally, dynamic cables are characterised by an increased number of armouring layers which serve to shield the cable from physical harm and ensure it remains torsionally balanced.

As mentioned earlier, dynamic power cables in floating offshore wind applications are subjected to a variety of mechanical loads that can lead to potential failure modes. These cables experience dynamic loading conditions such as bending and axial tension, and possibly torsion, due to the motion of the floating platform, wave and current action. The cable's armour layer, typically made of steel wires, is designed to withstand these mechanical loads and protect the internal components. However, the repeated cyclic loading can lead to fatigue damage accumulation mainly in the armour wires over time (particularly in the segments experiencing large curvature, such as hog and sag segments in a lazy wave profile), potentially resulting in wire breakage or corrosion. This can compromise the cable's structural integrity and lead to failure. Another area of concern is the cable's terminations and connectors, which are subjected to concentrated stresses and can be prone to fatigue damage. The insulation material and conductor are also susceptible to mechanical damage, such as abrasion, indentation, or crushing, which can occur due to the cable's movement and contact with the seabed or other structures. Additionally, the cable's internal components (particularly conductor) may experience relative movement and friction, leading to fretting and wear. The mechanical design of dynamic power cables for floating offshore wind applications must take into account these complex loading conditions and potential failure modes to ensure the cable's long-term reliability and performance. This requires a thorough understanding of the cable's mechanical behaviour, as well as the use of advanced modelling and simulation techniques to predict the cable's response under various loading scenarios. Furthermore, careful selection of materials, design optimisation, and robust manufacturing processes are essential to minimise the risk of mechanical failure in dynamic power cables.

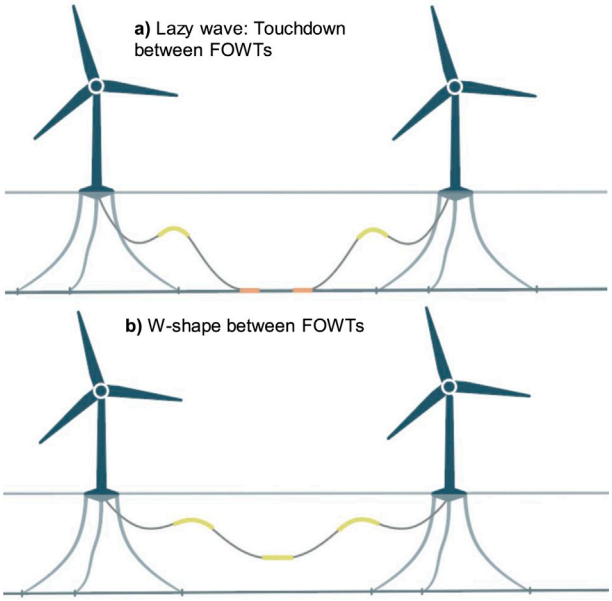


Fig. 4. Cable global configurations: (a) lazy wave and (b) W-shape (Srinil, 2016).

2.2. Cable global configuration

When it comes to floating offshore wind farms, the array cables' dynamic sections are significantly longer compared to their counterparts in fixed-bottom installations. This is because these cables are suspended in the water column, extending from the floater or the floating substation, often assuming a lazy-wave configuration (Fig. 4(a)). The primary purpose of this shape is to accommodate the floating substructure's dynamic motion, including its horizontal movement, known as lateral excursion. However, this configuration also exposes the dynamic section to the challenges of withstanding the loads imposed by the entire water column and the abrasion caused by the seabed.

To ensure the cable maintains its shape, the connection points are protected, and the installation process is carried out smoothly, a variety of ancillary components are employed. These include bend stiffeners, buoyancy and ballast modules, tether and anchor systems, touch down and abrasion protection, and bend restrictors. Once the cable reaches the seabed, it is either buried or anchored using rocks or protective matting. However, in most existing installations, the cable is left unburied.

There are three primary ways to incorporate the dynamic section of array cables in floating offshore wind farms. The first approach involves using a single length of dynamic cable to connect the turbines directly. The second method utilises dynamic cable lengths at each turbine, which are then connected to a static length in between using either field joints or connectors. The third option is to create a single cable assembly that features dynamic cable at each end, with a length of static cable in between, all joined together using factory joints. The decision to choose one configuration over another is influenced by several factors, such as the relative costs of static and dynamic cables, the additional expenses associated with using field joints or connectors, and the potential risks of introducing additional points of failure at these joints or connectors.

For installations in very deep waters, engineers are exploring the use of W-shaped configurations to minimise the cost of running the cable all the way to the seabed and back up again (Fig. 4(b)). In this setup, the cable is suspended between the floating offshore wind turbines (FOWTs) at a higher position in the water column, which is made possible by using clamped buoyancy and ballast modules.

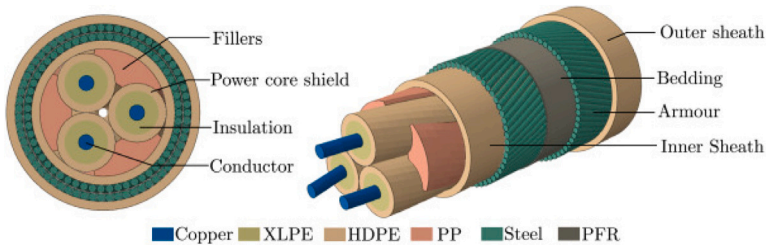


Fig. 5. Components of the dynamic power cable tested by Ménard and Cartraud (2023).

Another approach that is being considered for deep water applications is to suspend the array cables across their entire length. While this method could potentially reduce the overall cable length required, it would also subject the cables to increased loading due to the movement induced by water currents. Although this approach has not been implemented in any floating projects thus far, it is believed to become an attractive option for water depths of around 500 m or more.

3. Experimental research

Given the intricate structure of dynamic power cables, which comprise multiple layers with varying dimensions, materials, and complex contact and friction conditions, the development of analytical or numerical methods for assessing cable stiffness and capacity, as well as models for stress analysis and fatigue life prediction, requires validation against reliable experimental test data. However, cable mechanical tests are often conducted for design verification purposes (CIGRE, 2022) rather than basic research, and due to commercial interests, these test data are not readily available for reproduction and reuse. It should also be noted that experimental tests on offshore umbilical cables are more widely available. However, several recent papers targeting marine renewable energy applications have reported tests in considerable detail, and these are reviewed in this section.

3.1. Full cable mechanical tests

Full-scale mechanical testing of dynamic power cables is essential for understanding their behaviour under various loading conditions and validating numerical models used in the design process. Several research papers in the literature have reported experimental studies on dynamic power cables, providing valuable insights and data for the development of reliable cable designs for floating offshore wind applications.

Ménard and Cartraud (2023) conducted a series of experimental tests on a three-phase dynamic power cable with a diameter of 101 mm, which was assumed to be connected to an 8 MW floating offshore wind turbine (FOWT). The cable structure is shown in Fig. 5. Cyclic bending tests were performed on a four-point bending test rig, and bending moment–curvature curves were obtained, as shown in Fig. 6. The results exhibited stick–slip transition behaviour, which is typical in helically stranded wire-type structures. While the geometrical data of the cable were reported in detail, material parameters were taken from material databases or other studies dedicated to dynamic submarine power cables. Friction coefficients and the initial stress state due to the cable manufacturing process were estimated by tuning the numerical model with the test data. Despite these limitations, the reported test data are considered complete and valuable for validation purposes.

A comprehensive experimental test campaign was conducted by Ringsberg et al. (2023) on three dynamic power cables (1 kV, 3.6 kV, and 24 kV) without metallic armours, which were considered suitable for application in wave or tidal energy converters. The cables featured mechanically strong synthetic aramid fibre ropes integrated into the cable's helically wound structure to provide the required mechanical stiffness and flexibility. Axial tension, bending, torsion, and fatigue tests

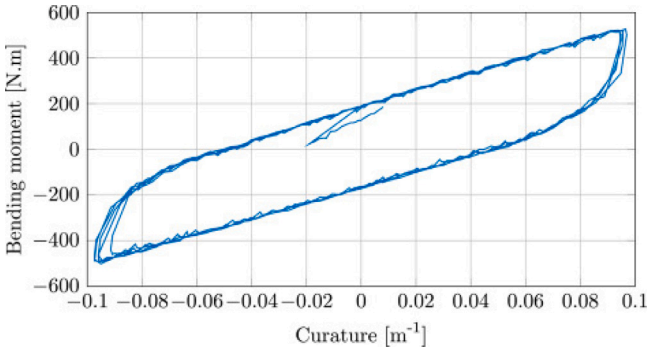


Fig. 6. Sample bending-curvature curve reported by Ménard and Cartraud (2023).

were performed on the target cables, and the repeatability of the tests was demonstrated. The study highlighted challenges in fatigue testing of power cables, particularly the unsuitability of the combined traction-three-point bending fatigue test setup. Although the tested cables differ from those used in FOWTs, the experimental procedures and reported insights are still relevant to the FOWT dynamic power cables.

Ehlers et al. (2023) investigated the ultimate strength of power transmission cables under excessive axial straining, representing a scenario of trawler anchor damage. Full-scale three-phase HVAC (high voltage alternating current) and single-core HVDC (high voltage direct current) cables were tested. Standard tension tests were also performed to obtain basic material data for the cable components, such as copper conductor, galvanised steel wire, PE sheath, insulation material, lead sheath, and shaped filler material. These data can be used in non-linear finite element analysis (FEA) of the tests or taken as a reference. Fig. 7 shows the post-mortem cable specimens. Force–displacement curves for both tests, as well as material test curves, were provided. Ehlers et al. (2023) conducted numerical simulations of the tests and obtained relatively good agreement with the experimental results.

Lastly, Guo and Ye (2020) reported full-scale axial tension and fatigue tests on a typical dynamic power cable and compared their finite element simulation estimates with the test results. The test data included the cable cross-section and dimensions of the components, as well as nominal material parameters. The static axial tension test result was used to verify the axial stiffness estimate using the FEA software UFLEX.

These experimental studies provide a solid foundation for understanding the mechanical behaviour of dynamic power cables under various loading conditions. The reported data and insights can be used to validate and improve numerical models, optimise cable designs, and develop reliable testing procedures.

3.2. Component mechanical tests

The cable conductor is one of the most widely analysed components in terms of experimental research. Karlsen (2010) conducted fatigue tests on power cores (power phases) with copper conductors and reported strain range to cycle curves. Nasution et al. (2013, 2014b,a)

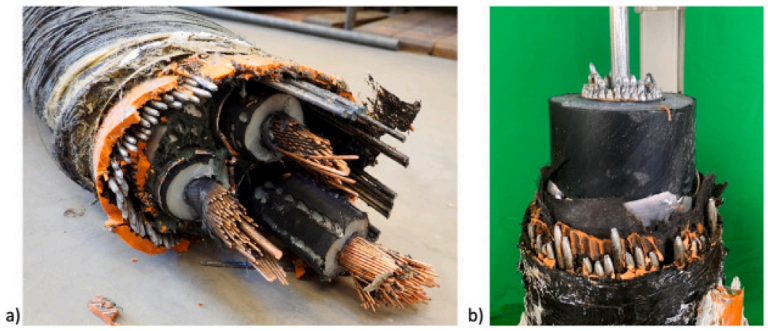


Fig. 7. Post-mortem HVAC and HVDC specimens after being subjected axial tension (Ehlers et al., 2023).

tested individual copper wires and copper strands under different cyclic loading regimes (tension-tension for individual wires and constant tension-bending for full-section conductors) and reported S-N curves for individual wires. Their research also included comparisons with FEA, which considered trellis (point) contact and inline contact within each layer, as well as surface irregularities in wires. In the FEA, the properties of individual wires were employed to predict the fatigue life of the whole conductor.

Hu et al. (2022) conducted a study on the non-linear bending hysteresis behaviour of copper conductors used in dynamic power cables. The research involved both experimental and numerical approaches to investigate the bending properties of copper conductors and the influence of various structural parameters on their behaviour. The authors first carried out a cyclic bending experiment on copper conductors to obtain non-linear bending hysteresis curves. These curves provide valuable information about the conductor's response to cyclic bending loads, which is crucial for understanding its fatigue performance in dynamic power cable applications. To complement the experimental study, Hu et al. (2022) also developed a three-dimensional finite element model to simulate the bending behaviour of copper conductors. The numerical results from this model were compared with the experimental data to validate the accuracy of the finite element approach. Finally, the authors performed a sensitivity analysis to investigate the influence of structural parameters on the non-linear bending properties of copper conductors. They found that the friction coefficient and radial extrusion pressure from the conductor's outer sheath layer significantly affect the critical sliding curvature and bending hysteresis properties.

Jiang et al. (2023b) investigated the influence of compaction degrees on the fatigue performance of stranded copper conductors. They conducted fatigue tests under tension-tension loading on conductors with two different compaction degrees and observed that the fatigue data did not fall within the same scatter band. The authors attributed this difference to the deformation of conductor wires caused by the compaction procedure during fabrication. By adjusting the fatigue data to account for stress concentrations due to the deformation, the data fell within the same scatter band. The study also included simulations of the compaction procedure using the finite element method, and the results were compared with real conductors. The authors proposed a simplified fitting formula to quantitatively describe the relationship between fatigue life and compaction degrees of copper conductors and provided a predicted fatigue life table to aid in cable design.

The literature on dielectric system failure in electric cables through tree-like defects is vast (an extensive review was provided by Danikas et al. (2019)) but specific interest in water tree issue in dynamic power cables for marine renewable energy can be traced only recently with a growing demand for wet or semi-wet larger capacity cables. In this context, Hu et al. (2024) investigated the effects of compressive and tensile strains on the growth of electrical trees in cross-linked polyethylene (XLPE) samples from power cables. Fig. 8 shows some sample microscopy images of the electrical grown in XLPE specimens tested by Hu et al. (2024). They found that compressive strain widened electrical trees along the direction of the applied strain, while tensile strain led to narrower trees and distorted their rotational symmetry. The distortion was linear with strain magnitude, and the likelihood of increased tree branch bending or bifurcation angles was linearly related to the applied strain. Strain did not significantly influence the growth rate of trees until a value of 5% was reached, at which point compressive strain reduced the growth rate by a factor of approximately 2, while tensile strain showed no influence. The authors also observed that increasing compressive strain linearly delayed tree initiation, and that time-to-failure was decreased by a factor of 1.8 at 5.7% tensile strain, which could have implications for the in-service usage of high voltage cables under dynamic forces found in floating wind applications.

4. Local and global analysis in dynamic power cable design

The design and analysis of dynamic power cables for floating offshore wind applications require a comprehensive understanding of the cable's mechanical behaviour under various loading conditions. This process involves a combination of local and global analysis techniques to assess the cable's performance and ensure its long-term reliability. In addition to fatigue analysis, estimating the cable's axial and bending stiffnesses is crucial for accurate global analysis and design optimisation. Analytical methods, such as the ones proposed by Costello (1978), Fang et al. (2021) and Papailiou (1997) for less complex stranded wires, can be used to calculate the cable's stiffness properties based on its cross-sectional geometry and material properties and by homogenising cable internal components. These methods provide quick estimates and are particularly useful in the early stages of design. Numerical techniques, such as finite element analysis (FEA) (Ménard and Cartraud, 2023), offer more detailed and accurate estimations of the cable's stiffness, considering the complex interactions between the cable components. The stiffness values obtained from these analyses serve as input for global dynamic simulations, ensuring reliable predictions of the cable's response to environmental loads and floating platform motions. Another critical aspect of dynamic power cable analysis is assessing the cable's capacity or strength under combined loading scenarios, such as simultaneous bending and axial tension It is important to note that the strength of dynamic power cables is often characterised by their MBR due to the cables' relatively low flexural stiffness. The combined effects of tension and bending loads on the cable's strength are depicted in capacity curves, which illustrate the interaction between these two types of loads.

The workflow for fatigue analysis of dynamic power cables typically consists of several steps. First, a global load analysis is performed using software such as OrcaFlex (Orcina Ltd., 2023) to determine the cable's response to environmental loads, such as waves and currents, and the motions of the floating platform, which may excited also due to wind. The results from the global analysis are then used as input for local analysis, which focuses on the stress distribution within the cable's cross-section. Software tools like Helica (Skeie et al., 2012; DNV GL, 2024) or UFLEX (SINTEF, 2023) are commonly employed for

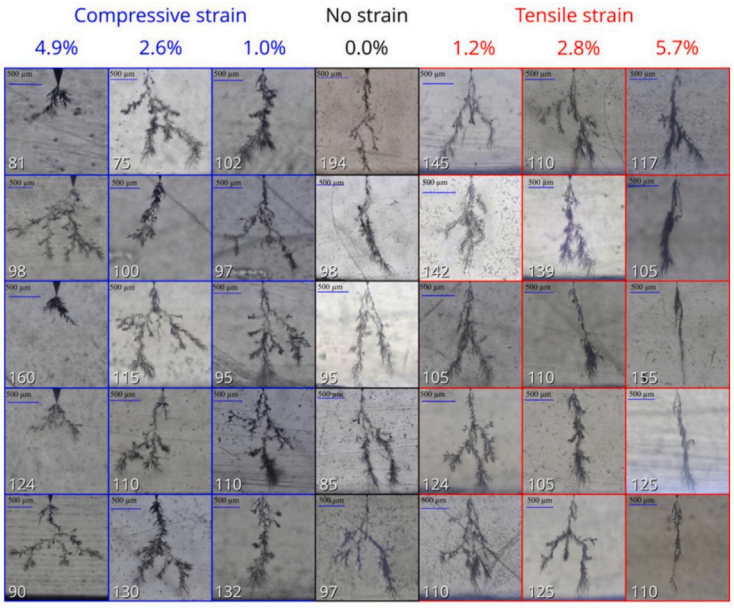


Fig. 8. Microscopy images of 35 electrical trees grown in XLPE samples tested by Hu et al. (2024).

this purpose. The local stress time-series obtained from the analysis are then processed using rainflow counting to extract the stress cycle information. Finally, the fatigue damage is assessed using a cumulative damage model, such as the Palmgren-Miner's rule, to estimate the cable's fatigue life.

This section will delve into recent advancements in the local analysis of cables using FEA, as well as global analysis techniques and their applications in dynamic power cable design. Additionally, the integration of FEA and global analysis in the design process will be discussed, highlighting their contributions to the optimisation of dynamic power cable systems.

4.1. FEA-based local analysis

Advanced FEA models have the potential to become an indispensable tool for the local analysis of dynamic power cables, providing valuable insights into the cable's mechanical behaviour and stress distribution under various loading conditions. However, the complexity of dynamic power cable structures poses several challenges in FEA modelling. The cable's cross-section consists of multiple components with different materials and complex contact conditions, leading to a high degree of non-linearity in the analysis. The use of solid elements to model each component accurately can result in an extremely large number of elements, increasing computational costs and potentially causing solver convergence issues (Tjahjanto et al., 2017; Chang and Chen, 2019). Moreover, the helical geometry of the cable components further complicates the modelling process, requiring careful consideration of the pitch angles and contact definitions.

A review of the literature on FEA-based local analysis of stranded wires, umbilicals and power cables reveals three main trends in modelling techniques aimed at addressing these challenges. The first trend is the employment of periodic boundary conditions to reduce the model size and computational effort (Jiang, 2012; Jiang et al., 1999; Leroy et al., 2017; Smith et al., 2024; Ménard and Cartraud, 2023; Fang et al., 2023). By exploiting the cable's helical symmetry, a representative segment of the cable can be modelled, and the results can be extrapolated to the entire cable length. Fig. 9 illustrates this concept on a single-layer strand, where p denotes the helix period and l is cable length considered for analysis.

Li et al. (2024b) developed a three-dimensional Representative Volume Element (RVE) model for predicting the non-linear bending

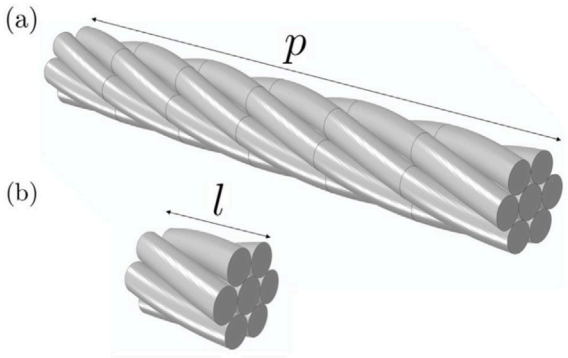


Fig. 9. (a) A single-layered helical strand cable with length equal to the helix period and (b) the repeated unit cell (RUC) of the cable (Smith et al., 2024).

stiffness of three-core submarine power cables. Their approach uses dashpot-enhanced periodic boundary conditions to address the stick–slip challenges associated with cable bending. The model incorporates thermal effects on material and contact properties, allowing for thermal-mechanical coupled flexural analysis. Validation against bending tests and comparison with a 3D full-scale finite element model demonstrated the RVE model's efficiency and accuracy. This work addresses the need for computationally efficient models that can capture complex cable behaviour.

The second trend is the adoption of beam elements whenever possible to simplify the model and improve computational efficiency. Beam elements can be used to model the global response of the cable, while solid elements are used only in critical regions or for detailed local analysis. In this context, Kim and Lee (2017) presented a novel approach for modelling helically stranded cables using multiple beam finite elements. Their method aimed to achieve accurate results comparable to those obtained from full solid FE models while significantly reducing the computational cost. The proposed beam FE model considers wire-to-wire contacts and elasto-plastic material behaviour, which are essential factors in capturing the complex mechanical behaviour of helically stranded cables. By incorporating these aspects, the model could accurately represent the cable's response under various loading conditions. To validate the accuracy of their beam FE model, Kim and

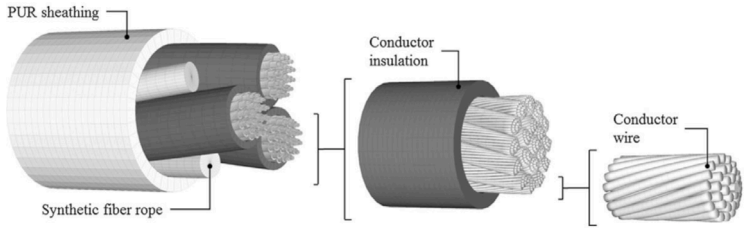


Fig. 10. Hierarchical modelling approach of power cable (Kuznecovs et al., 2019).

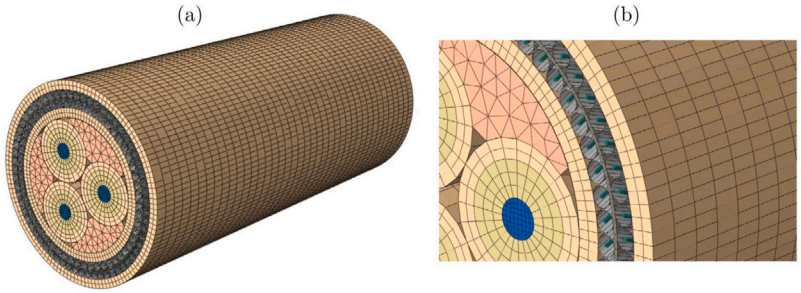


Fig. 11. (a) Global and (b) close-up view of cable FE model by Ménard and Cartraud (2023).

Lee (2017) analysed the mechanical behaviour of helically stranded cables under axial and transverse loadings. They compared the numerical results obtained from their model with those from full solid FE models and available experimental data. The comparison demonstrated that their proposed beam FE model could achieve a level of accuracy similar to that of the solid FE models, confirming its reliability in predicting the cable's response. The present authors noted that this approach can be extended to more complicated helically stranded structures, such as dynamic power cables, demonstrating its broad applicability and potential for improving modelling accuracy and efficiency.

The third trend is the use of homogenisation techniques and hierarchical modelling approaches. Homogenisation involves replacing the complex cable cross-section with an equivalent homogeneous material, reducing the number of elements and contact definitions required (Cartraud and Messager, 2006; Ménard and Cartraud, 2021; Treyssède and Cartraud, 2022). Hierarchical modelling, on the other hand, employs a multi-scale approach, where the results from a detailed local model are used to inform a simplified global model, enabling efficient analysis of the entire cable length (Kuznecovs et al., 2019).

Kuznecovs et al. (2019) presented a cable design model and simulation models for the design and fatigue analysis of dynamic cables, with a specific focus on dynamic power cables for floating point-absorbing wave energy converters (WECs). One of the key aspects of their work was the development of a cable design model that incorporates a detailed design and dimensioning methodology for cables with multi-order helical structures Note that conductor, power core and wire armour are helically stranded structures on their own. This hierarchical modelling approach considers the cable at different levels: conductor, power core, and full cable. By addressing the structural response at each level, which informs the next higher level, the analysis of the full cable's mechanical properties was enabled. Fig. 10 shows the concept proposed by Kuznecovs et al. (2019).

Considering all these three aspects, Ménard and Cartraud (2023) proposed a 3D FE numerical approach to calculate the global mechanical behaviour and local stress state of dynamic submarine power cables. The method was applied to a three-core dynamic submarine power cable subjected to cyclic bending load. To reduce the computational domain and mesh size, the authors employed the homogenisation theory of periodic structures and beam element modelling of the armour components, respectively. This approach allowed them to fully consider the geometrical complexity and contact interactions between the cable components while maintaining computational efficiency. The study also investigated the sensitivity of the cable's bending behaviour to frictional interactions and manufacturing residual stresses. The numerical model was validated by comparing the results with experimental data discussed earlier and analytical results, focusing on the overall cable behaviour under cyclic bending load and local quantities such as displacement and stresses. Fig. 11 shows the mesh of the cable FE model by Ménard and Cartraud (2023). Note that some components were either ignored or simplified, particularly in the power core, based on some reasonable assumptions. However, the sensitivity of the model to these simplifications were not discussed in detail.

One last crucial aspect of FEA modelling of power cables is determining whether some components can be neglected or simplified without compromising the model's integrity. Additionally, optimal mesh size ranges for all components must be identified based on parametric studies to ensure a balance between computational efficiency and accuracy. Ye and Yuan (2020) conducted a systematic investigation of modelling alternatives for non-critical components in dynamic offshore power cables using the software UFLEX. The study aimed to clarify the extent to which these components should be considered in finite element modelling depending on the purpose of the analysis. The authors examined the effects of key parameters such as the level of simplification, choice of element type, and determination of contact stiffness on the physical properties of the cross-section, stick and slip characteristics of helical components, and axial stress in the tensile armour wires. They found that computing efficiency can be greatly improved by simplifying or omitting irregular-shaped filled bodies, with little influence on the estimation of the cable's axial and bending stiffness. However, such simplifications may lead to slightly higher stress ranges in the tensile armour wires, making the analysis more conservative. The study also highlighted the importance of proper mesh size selection for sheath layers and tensile armour wires in stress analysis, while the structural behaviour of the power cable was found to be independent of the mesh size of the irregular filled bodies.

4.2. Fretting and fatigue failure

Fretting-related damage in multi-strand copper wire conductors within power cables (SPCs) for floating offshore wind turbines is a relatively under-explored issue. Recent papers by Poon et al. (2022a,b, 2023, 2024) addressed the fretting-related damage in cable conductors

extensively. Their work introduced a comprehensive finite element methodology encompassing global-local analysis to identify critical inter-wire fretting conditions under dynamic loading. This included a three-dimensional global multi-wire model that captures complex contact interactions, local 2D and 3D representative models for micro-scale fretting resolution, and a critical-plane, multiaxial fretting-fatigue life methodology. They characterised fretting wear behaviour through laboratory-scale testing and validate their models against experimental data. Their findings highlighted the significant impact of factors such as lay angle, contact size, wire diameter, friction, and slip on fretting fatigue life, revealing that increased values generally reduce the lifespan of the cables. Their novel contributions included linking local and global modelling approaches and rationalising the effects of transverse and longitudinal contact sizes, ultimately enhancing the understanding and predictive capabilities for SPC durability in offshore wind applications.

Jiang et al. (2023a) extended their experimental work (Jiang et al., 2023b) and employed a fatigue life estimation method based on a fatigue damage evolution model to assess conductors with varying degrees of compaction. The researchers developed macroscopic and mesoscopic elastic–plastic constitutive models for copper using mixed hardening theory and two-scale theory, and implemented these models through user-defined material subroutines (UMAT). The estimated fatigue lives are validated against experimental results, demonstrating the method's accuracy and applicability for tensile fatigue life prediction in stranded copper conductors.

4.3. Insulation failure

Some studies also considered mechanical analysis of water tree problem by considering it as insulation fatigue cracking. Young (2020) and Young et al. (2018a,b) presented a methodology for modelling the propagation of water trees in dynamic cables, aimed at predicting the time until failure. His work accounted for both mechanical and electrical stresses experienced by the cable. A global model of a floating wind platform was used to derive a local model of the cable's cross-section, thereby determining the mechanical stresses from environmental forces on the insulation. Subsequently, the distortions in the electric field due to the presence of a water tree are modelled to calculate the resulting stresses. By combining these mechanical and electrical stresses, his method employed fatigue damage and crack propagation methods to model the micro-scale breaking of insulation chemical bonds, predicting water tree propagation. However, this methodology was not backed up by experiments and lacked validation.

Researchers from Chalmers University of Technology also visited this problem. Li et al. (2022) presented a comprehensive study on the degradation mechanisms of dynamic power cables due to water treeing. The research employed advanced simulations using COMSOL (multi-physics software), SIMA (global load analysis software), and ABAQUS (FEA software) to analyse the growth of vented water tree defects in XLPE insulation under varying environmental conditions. Key findings highlight that while electric field-induced stresses play a predominant role in water tree propagation, cyclic mechanical stresses from cable motions do not significantly contribute to crack growth under the investigated load scenarios. This study underscored the importance of accurately modelling electric field strengths and cyclic Maxwell stresses for predicting the operational life and failure risks of dynamic power cables affected by water treeing. An electro-mechanical model has been utilised to analyse the influences of various factors on mechanical stresses in the PE insulation. In addition, Serdyuk et al. (2023) performed computer simulations implementing an electro-mechanical model, which indicated strong effects of the test voltage and temperature. It was found that increased applied voltage generates stronger stress, whereas increasing temperature leads to its weakening. This behaviour was attributed to variations in the densities of the interfacial charges, defined by the field and temperature dependencies of material conductivity. The impact of the frequency of the applied test voltage was observed as an enhancement of mechanical stress at higher frequencies, which was more pronounced at elevated temperatures and almost negligible at room temperature.

Building upon these works, Ringsberg et al. (2024) presented a comprehensive methodology for predicting the failure of dynamic subsea power cables, with a focus on water tree growth in the insulation material. Their study combined global mechanical stress analysis, local finite element modelling, and electric stress analysis to assess both fatigue damage in conductors and insulation breakdown. The authors applied their method to a case study of a cable connected to a wave energy converter, demonstrating how the combination of mechanical and electrical stresses can significantly reduce the predicted service life of the cable compared to considering electrical stresses alone. Their work highlighted the importance of considering multi-physics approaches in dynamic cable analysis (possibly for floating offshore wind applications), addressing the complex interactions between mechanical fatigue, fretting/wear, and water tree growth.

4.4. Biofouling and thermal effects

Biofouling, particularly by mussels, can significantly impact the thermal behaviour and fatigue performance of dynamic power cables used in floating offshore wind turbines. Recent studies have shed light on the complex thermal interactions between mussel colonisation and cable performance.

Maksassi et al. (2022) conducted a comprehensive thermal characterisation of mussels, revealing that their effective thermal conductivity varies with age and porosity. Juvenile mussels (3–6 months) exhibited the lowest thermal conductivity, while adult mussels (12–18 months) showed the highest. This variation was attributed to differences in porosity, which increases with mussel age, enhancing natural convection within the mussel cluster. The study also found that living mussels have a higher effective thermal conductivity than dead ones, due to the metabolic process of water filtering. This filtering action creates micro-movements within the mussel cluster, improving heat transfer. Furthermore, the temperature difference across the mussel layer significantly influences its effective thermal conductivity, with higher temperature differences leading to increased conductivity.

In a follow-up study, Maksassi et al. (2024) further investigated the thermal impact of mussels on dynamic power cables. They found that mussel colonisation can cause the copper conductor temperature to exceed its maximum operating temperature of 90 °C. Juvenile mussels had the most significant impact, potentially raising the conductor temperature to 95.18 °C, while adult mussels increased it to 90.8 °C. This temperature increase could significantly reduce the lifetime of the cable's cross-linked polyethylene (XLPE) insulation and overall fatigue life, potentially increasing maintenance costs.

These findings highlight the importance of considering biofouling in the design and maintenance of dynamic power cables for FOWTs. Beyond thermal effects, biofouling also influences the fatigue life of dynamic power cables. Yang et al. (2017) investigated the impact of biofouling on the energy performance and fatigue life of mooring lines and power cables in a wave energy converter (WEC) system. Their study considered different mooring configurations, biofouling conditions, sea states, and wave/current directions. The results showed that biofouling was found to decrease the fatigue life of mooring lines by approximately 20%. The study highlighted that the impact of biofouling is more pronounced under moderate sea states, where it can reduce the fatigue life of moorings by up to 68%. These findings emphasise the importance of considering biofouling effects in the design and maintenance strategies for dynamic power cables and mooring systems in floating offshore renewable energy installations.

4.5. Global load analysis and design

Global load analysis and design is a crucial aspect of dynamic power cable development for floating offshore wind applications. It

involves assessing the cable's response to environmental loads, such as waves and currents, and the motions of the floating platform to which it is connected. Research work on global analysis of different cable configurations, linking global analysis load results to fatigue analysis, and assessing cable fatigue performance from global analysis has appeared in the last five years.

Sobhaniasl et al. (2020) proposed a procedure to determine the fatigue life of power cables connected to a 5 MW floating offshore wind turbine supported by a spar-buoy at a depth of 320 m. The study investigated the effects of wave and wind intensity, as well as their simultaneous actions, on specific cable configurations, and evaluates the fatigue life of the cables. The authors utilised Ansys AQWA computational code and FAST NREL code (now known as OpenFAST) through one-way coupling. The study estimated the fatigue life of the cable's copper conductor at the FOWT site through a detailed procedure that included computing total strain time histories in the cable cross-section using fully non-linear time histories and numerical analyses of the entire turbine system. Simple beam models were used for calculating strains and stresses in the cable, while strain versus number of cycles curve ($\varepsilon - N$) was utilised for fatigue damage calculation.

Hall et al. (2021) addressed the enhancement of the MoorDyn module within OpenFAST (NREL, 2024), an open-source software widely used for fully-coupled simulations in FOWTs. Previously focused on mooring line modelling with axial stiffness, MoorDyn has integrated bending stiffness capabilities to simulate dynamic power cables. The study validated this enhancement through static conditions against analytical solutions and dynamic scenarios using prescribed motions and wave loadings, comparing results with the aforementioned commercial software OrcaFlex. Findings confirmed the effective implementation of bending stiffness, demonstrating close agreement with OrcaFlex and enhancing MoorDyn's utility in simulating dynamic power cables for both offshore wind turbines, as well as wave energy converters.

Beier et al. (2023, 2024a) presented fatigue analysis of inter-array power cables in two different papers. In the first paper (Beier et al., 2023) focus was given on investigating the fatigue life of a suspended power cable with attached buoys that connect two spar-type FOWTs, using typical North Sea environmental conditions. The analysis considered the non-linear bending behaviour of the power cable (stick–slip transition). Fatigue assessment was conducted within the global analysis software OrcaFlex, which utilised stress factors derived from cross-section analysis. The study proposed a method for early engineering design stages to obtain stress factors, comparing results with those from the finite element software UFLEX simulation. The second paper (Beier et al., 2024a) adopted a similar approach and considered inter-array cables for semi-submersible floaters and spar floaters. Critical insights include confirming curvature-induced stresses as the primary contributor to fatigue damage and demonstrating the advantages of alternative configurations using semi-submersible floaters. A recent follow-up study on the same topic has been reported by Beier et al. (2024b), where the behaviour of power cables in different offshore wind farm layouts has been systematically analysed. A similar study was conducted by Schnepf et al. (2023a), focusing on suspended inter-array power cables with various configurations, including buoyancy modules and subsea buoys, and also included a cost analysis. An optimisation methodology for suspended inter-array power cables was also presented by the same research group (Ahmad et al., 2023). The most recent work by the same research group, Liu et al. (2024), investigated the effect of failure of a buoy element in a suspended inter-array power cable between two spar-type floating wind turbines through numerical simulations using OrcaFlex.

While the previously cited works on suspended inter-array cables were based entirely on fully-coupled numerical simulations of FOWTs, including mooring lines and power cables, a comparison with tests was lacking. Li et al. (2024a) addressed this gap by assessing the feasibility of using a fully suspended inter-array cable system for offshore wind farms through both numerical simulations and a 1:49 scale experiment. Their study focused on a 15 MW floating offshore wind turbine and a floating offshore substation, using data from the Taiwan Hsinchu offshore area to validate platform motion and mooring line tension under 50-year return period conditions. It examined the dynamic cable system's tension, curvature, and fatigue damage using OrcaFlex (Li et al., 2024a), addressing challenges posed by extreme sea conditions and the implications for vessel navigation due to the cable's spatial requirements. The research integrated long-term environmental data to evaluate cumulative fatigue damage and used fitness parameters to determine the feasibility of various cable configurations.

Parametric studies on finding the optimal lazy-wave configuration have also been reported in the literature (Rentschler et al., 2019). Building on this, Rentschler et al. (2020) proposed a design approach for dynamic inter-array cables that combines fatigue analysis and performance assessment under extreme weather conditions. Their study optimised lazy wave configurations using a genetic algorithm, which adjusts the position of buoyancy elements to lower the wave shape and reduce the cumulative length of buoyancy sections to 18%–23% of the total cable length. Additionally, the study highlighted the significant impact of the cable's orientation relative to the platform on the cable's motion, suggesting that lateral oscillations may necessitate a pliant wave configuration or additional bend stiffeners at the touchdown, balanced against the extra costs. Lastly, Schnepf et al. (2023b) proposed a gradient-based optimisation approach for dynamic power cable configurations in floating offshore wind turbines. Using Sequential Least Squares Programming (SLSQP), they optimised a tethered lazy-wave cable configuration for a spar-type FOWT. Their optimised configurations demonstrated reduced cable length compared to initial designs, with dynamic analyses confirming compliance with design limits.

Abrahamsen et al. (2024) proposed a conceptual reference dynamic power cable for a 15 MW NREL reference turbine on a UMaine floater in 82 m water depth. The study combined electromagnetic-thermal finite element simulations to determine cable current capacity with aeroelastic simulations to assess key failure modes. The thermal analysis established a maximum current rating of 730 A for the 66 kV cable. Mechanical simulations revealed that the cable sections near the floating turbine were overloaded, highlighting the need for a cable bend stiffener in future designs. The authors also identified fatigue hotspots in the lazy-wave configuration, suggesting areas for focused fatigue evaluation in future studies.

Lastly, Janocha et al. (2024) contributed significantly to dynamic power cable design for large floating wind turbines by developing and validating three baseline designs rated at 33 kV, 66 kV, and 132 kV. Fig. 12 shows the dimensions of these three designs. Janocha et al. (2024) also provided the material data, total number of helical elements and their lay angles for all components in the proposed cable designs. Their study established a comprehensive structural and mechanical property database through FEM modelling in UFLEX, with rigorous mesh sensitivity analyses ensuring data accuracy. Utilising global response simulations (as in previous studies, OrcaFlex was used) integrating an OC3 5MW reference wind turbine with dynamic cables in a lazy wave configuration, they effectively demonstrated cable-turbine interaction under operational conditions. While their simplified fatigue life and structural integrity analyses under extreme environmental loads offer valuable insights, further validation of the proposed reference designs against test data and exploration of long-term maintenance implications would enhance the study's applicability in floating offshore wind energy.

5. Discussion and research needs

The review of recent advancements in the mechanical analysis and design of dynamic power cables for floating offshore wind turbines reveals significant progress in understanding the complex behaviour of these critical components. However, several challenges and research gaps remain, which need to be addressed to ensure the reliable and

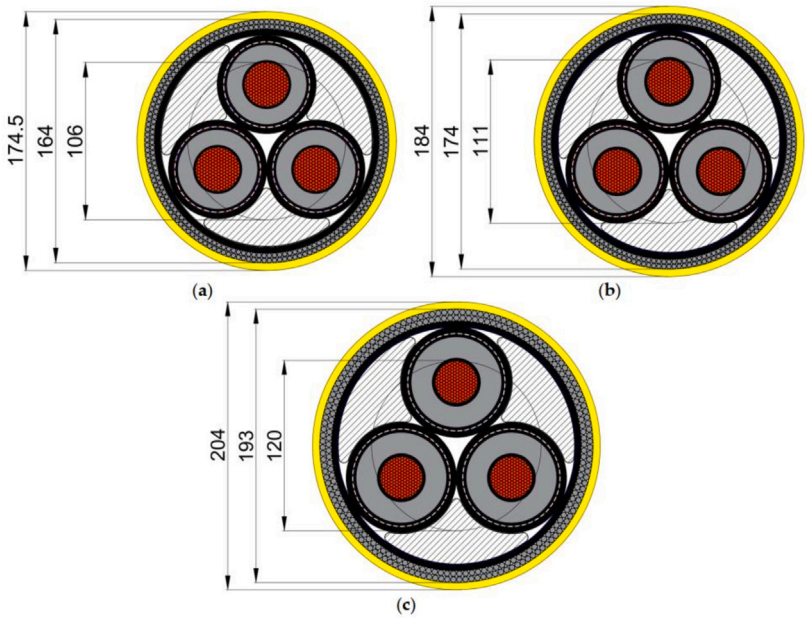


Fig. 12. Overall dimensions for (a) 33 kV, (b) 66 kV, and (c) 132 kV cable cross sections designed by Janocha et al. (2024) (unit: mm).

Table 1
Ongoing research status and future research topics.

Ongoing research status	Suggested future research topics
Full-scale mechanical testing of cables	Standardised testing protocols; public data sharing
FEA-based local analysis of cable cross-sections	Validate and improve cross-sectional analysis tools
Global load analysis for fatigue prediction	Refine methods linking global and local analyses
Fretting and fatigue failure in conductors	Develop advanced fatigue models including fretting
Water tree growth modelling in insulation	Integrate mechanical, thermal, and electrical effects
Lazy-wave configuration optimisation	Research novel configurations for deep water
High-voltage dynamic cable development	Investigate corrugated armour cable mechanics
Suspended inter-array cable studies	Optimise designs for various floater types
Project-specific cable designs	Develop industry-wide standards and guidelines
Cable-floater interaction analysis	Improve coupled simulation techniques

cost-effective deployment of dynamic power cables in the rapidly growing offshore wind industry. Table 1 summarises the ongoing research status and suggested future research topics for dynamic power cables in floating offshore wind applications, which are discussed below.

One of the primary limitations identified in this review is the scarcity of publicly available experimental data for validating mechanical models used in cable stiffness and capacity assessment. While some recent studies have reported valuable test data on full-scale cables and individual components, there is a need for more comprehensive and standardised experimental campaigns. Future research should focus on conducting extensive testing programs that cover a wide range of cable designs, materials, and loading scenarios. The availability of reliable and well-documented experimental data will be crucial for the development and validation of accurate analytical and numerical models, enabling more confident predictions of cable behaviour and performance.

Fatigue failure of dynamic power cables, particularly in the core conductors and insulation layers, has been a topic of increasing interest in recent years. However, current testing approaches that rely on S-N curves of material coupons may lead to overly conservative estimates of the fatigue life of complete cable assemblies. To address this issue, future research should explore alternative testing methods, such as full-scale cable fatigue tests under representative loading conditions. These tests would allow for a more accurate determination of the fatigue life of the entire cable assembly, considering the complex interactions between the various cable components. Moreover, the development of advanced fatigue models that account for the specific failure mechanisms in dynamic power cables, such as fretting and wear in conductors and water treeing in insulation, could lead to more reliable fatigue life predictions and optimised cable designs.

The design and testing of dynamic power cables are highly dependent on project-specific factors, such as environmental conditions, installation methods, cable configurations, and floater types. As a result, current cable designs and test programs are often tailored to individual projects, hindering the development of standardised solutions. To facilitate the large-scale deployment of floating offshore wind turbines, there is a pressing need for the development of standardised design and testing protocols for dynamic power cables. This standardisation effort should aim to establish representative design load cases, testing procedures, and acceptance criteria that are applicable across a wide range of projects. The development of industry-wide standards would streamline the design process, reduce costs, and ensure the consistency and comparability of cable performance, ultimately boosting the confidence of investors and stakeholders in the offshore wind industry.

The validation of software tools used for the cross-sectional analysis of dynamic power cables is another area that requires further attention. While widely used software packages like Helica and UFLEX have been employed in numerous studies, comprehensive validation studies comparing their predictions with experimental data and other validated models are still limited. Future research should prioritise the systematic validation of these tools, considering various cable designs, loading scenarios, and material properties. The availability of validated and reliable software tools will be essential for the efficient and accurate design and analysis of dynamic power cables, reducing the reliance on conservative assumptions and enabling more optimised cable designs.

As the offshore wind industry expands into deeper waters, the importance of understanding the behaviour and performance of dynamic power cables in various water depths and configurations becomes

increasingly evident. While recent research has focused on suspended inter-array cables, future studies should extend this work to cover a broader range of water depths and cable configurations, such as lazy-wave and W-shaped configurations. The investigation of the influence of water depth on cable dynamics, fatigue, and failure mechanisms will be crucial for the successful deployment of floating offshore wind turbines in deeper waters. Moreover, the development of optimised cable configurations and installation methods that minimise the risk of failure and reduce the overall cost of the system should be a priority for future research. The auxiliaries of dynamic power cables, such as bend stiffeners and restrictors, play a critical role in ensuring the cable's integrity and longevity by reducing the stresses and fatigue damage at the cable's termination points. Despite their importance, research on the design and testing of these components is relatively limited. Future studies should focus on developing standardised design guidelines and testing procedures for bend stiffeners and restrictors, considering their compatibility with various cable designs and environmental conditions. The optimisation of these auxiliaries, in terms of materials, geometry, and manufacturing processes, could lead to more efficient and reliable cable protection systems, ultimately reducing the risk of cable failure and extending the service life of dynamic power cables.

The exploration of new materials, structures, and designs for dynamic power cables presents an exciting opportunity for future research. Non-metallic designs, such as those incorporating fibre reinforcements or thermoplastic composites, may offer advantages in terms of weight reduction, corrosion resistance, and cost-effectiveness. The development of advanced insulation materials with improved resistance to water treeing and electrical degradation could significantly enhance the reliability and longevity of dynamic power cables. Moreover, the investigation of innovative cable structures, such as those with built-in sensor networks for real-time monitoring of cable health and performance, could enable predictive maintenance strategies and reduce the risk of unexpected failures. Research efforts in these areas could lead to the development of next-generation dynamic power cable solutions that are more reliable, cost-effective, and sustainable.

The development of high-voltage dynamic cables (>132 kV) for floating offshore wind applications presents unique challenges and research opportunities. While current research largely focuses on cables rated up to 66 kV, the industry is moving towards higher voltage systems. A recent Carbon Trust report (Carbon Trust, 2023a) on 132 kV array cables highlights the industry's prioritisation of long-term technical performance reliability in cable design decisions. The report emphasised the need for standardised testing protocols, particularly for wet designs, which are of strong interest to offshore wind farm developers. Future research should address the mechanical properties and fatigue behaviour of high-voltage dynamic cables, with particular attention to wet designs and their long-term performance under combined mechanical, thermal, and electrical stresses. Additionally, the behaviour of cables with corrugated sheath armours, which may exhibit different mechanical characteristics compared to traditional helical wire armours, requires further investigation. The development of industry-wide standards and improved testing methods for 132 kV array cables, especially for wet and dynamic designs, will be crucial for the successful implementation of these advanced cable systems in future floating offshore wind projects.

Another critical research gap identified in this review is the lack of studies that combine mechanical, thermal, and electrical effects in the analysis and design of dynamic power cables (Dobson, 2023; Gulski et al., 2021). The complex interactions between these phenomena can significantly influence the cable's performance and long-term reliability. Future research should focus on developing comprehensive multi-physics simulation frameworks that integrate mechanical, thermal, and electrical effects, enabling a more holistic understanding of cable behaviour under realistic operating conditions. These multi-physics models should be validated against experimental data and benchmarked against existing single-physics models to assess their accuracy and computational efficiency. The incorporation of multi-physics analysis in the design process could lead to more optimised cable designs that account for the coupled effects of mechanical loads, temperature variations, and electrical stresses, ultimately improving the reliability and longevity of dynamic power cables.

Lastly, the link between global response analysis results and local analysis models in FEA requires further clarification and development. The current approach of obtaining unit-load stress response from local analysis models and mapping the time series of loads to obtain stress time series for fatigue damage calculation using Miner's rule is a simplified method that may not fully capture the complexities of cable behaviour. Future research should explore more refined approaches that consider the non-linear effects and the influence of model extents on the accuracy of stress predictions. Sensitivity analyses should be performed to assess the impact of various modelling assumptions and parameters on the fatigue life estimates. The development of robust and efficient methods for linking global and local analysis results will be crucial for the accurate prediction of cable fatigue performance and the optimisation of cable designs for specific project requirements.

6. Conclusions

This review paper has provided a comprehensive overview of the recent advances in the mechanical analysis and design of dynamic power cables for floating offshore wind turbines. The study has highlighted the critical role of dynamic power cables in ensuring the reliability and cost-effectiveness of floating offshore wind energy systems, as well as the unique challenges associated with their design and operation in the harsh marine environment.

The review of experimental studies has shown the importance of full-scale cable testing and component-level investigations in understanding the mechanical behaviour and failure mechanisms of dynamic power cables. The advancements in FEA techniques, particularly in modelling the complex cross-sectional structure and non-linear behaviour of cables, have been discussed, emphasising the need for further validation and standardisation of these tools.

The integration of global load analysis and local stress analysis has been identified as a crucial aspect of the dynamic cable design process, with recent studies demonstrating the effectiveness of this approach in predicting cable fatigue life and optimising cable configurations. The review has also highlighted the potential of new materials, designs, and high-voltage cable systems in improving the performance and reliability of dynamic power cables.

However, several critical research gaps and challenges have been identified, including the need for more comprehensive experimental data, the development of standardised design and testing protocols, the validation of cross-sectional analysis software tools, the investigation of cable behaviour in deeper waters and various configurations, the optimisation of cable auxiliaries, the exploration of multi-physics simulation frameworks, and the refinement of methods for linking global and local analysis results.

Addressing these research needs will require collaborative efforts between academia, industry, and regulatory bodies, as well as continued investment in research and development activities. By tackling these challenges head-on, the offshore wind community can accelerate the development and deployment of reliable, cost-effective, and sustainable dynamic power cable solutions, ultimately contributing to the large-scale adoption of floating offshore wind energy worldwide. As the global demand for clean energy continues to grow, the importance of dynamic power cables in enabling the expansion of floating offshore wind cannot be overstated. The insights and recommendations provided in this review paper aim to guide future research efforts and inform the development of next-generation dynamic power cable technologies, ensuring the success and long-term viability of the floating offshore wind industry.

CRediT authorship contribution statement

Burak Can Cerik: Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Conceptualization. **Luofeng Huang:** Writing – review & editing, Writing – original draft, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

2H Offshore/ORE Catapult, 2022. Dynamic Cable Technology Qualification Review and Mapping Report. Technical Report Report No PN000486-RPT-009.

Abrahamsen, A.B., Faria, B.R., Lund, R.S., Verelst, D.R., Roques, J., Hochet, M., Dykes, K., 2024. Reference dynamic power cable of floating offshore wind turbine for thermal and simple fatigue evaluation. J. Phys. Conf. Ser. 2767 (6), 062036. http://dx.doi.org/10.1088/1742-6596/2767/6/062036.

Ahmad, I.B., Schnepf, A., Ong, M.C., 2023. An optimisation methodology for suspended inter-array power cable configurations between two floating offshore wind turbines. Ocean Eng. 278, 114406. http://dx.doi.org/10.1016/j.oceaneng.2023.114406.

Beier, D., Janocha, M.J., Ye, N., Ong, M.C., 2024a. Fatigue assessment of suspended inter-array power cables for floating offshore wind turbines. Eng. Struct. 308, 118007. http://dx.doi.org/10.1016/j.engstruct.2024.118007.

Beier, D., Ong, M.C., Janocha, M.J., Ye, N., 2024b. Application of suspended inter-array power cables in floating offshore wind farms. Appl. Ocean Res. 147, 103991. http://dx.doi.org/10.1016/j.apor.2024.103991.

Beier, D., Schnepf, A., Van Steel, S., Ye, N., Ong, M.C., 2023. Fatigue analysis of inter-array power cables between two floating offshore wind turbines including a simplified method to estimate stress factors. J. Mar. Sci. Eng. 11 (6), http://dx.doi.org/10.3390/jmse11061254.

Carbon Trust, 2023a. 132 kV Array Cable Requirements and the Need for Improved Testing Standards. Technical Report.

Carbon Trust, 2023b. Dynamic Cable Failure Rates. Technical Report.

Cartraud, P., Messager, T., 2006. Computational homogenization of periodic beam-like structures. Int. J. Solids Struct. 43 (3), 686–696. http://dx.doi.org/10.1016/j.ijsolstr.2005.03.063.

Chang, H.-C., Chen, B.-F., 2019. Mechanical behavior of submarine cable under coupled tension, torsion and compressive loads. Ocean Eng. 189, 106272. http://dx.doi.org/10.1016/j.oceaneng.2019.106272.

CIGRE, 2022. Recommendations for Mechanical Testing of Submarine Cables for Dynamic Applications. Technical Report TB 862.

Costello, G.A., 1978. Analytical investigation of wire rope. Appl. Mech. Rev. 31 (7).

Danikas, M., Papadopoulos, D., Morsalin, S., 2019. Propagation of electrical trees under the influence of mechanical stresses: A short review. Eng. Technol. Appl. Sci. Res. 9 (1), 3750–3756. http://dx.doi.org/10.48084/etasr.2483.

de Wild, F., 2018. Offshore wind industry joins forces to reduce costs of cable failures. Available online: https://www.dnv.com/news/offshore-wind-industry-joins-forces-to-reduce-costs-of-cable-failures-117811. Det Norske Veritas (DNV).

Det Norske Veritas (DNV), 2021a. Electrical Power Cables in Subsea Applications, DNV-RP-F401. Technical Report, DNV, Recommended Practice.

Det Norske Veritas (DNV), 2021b. Subsea Power Cables for Wind Power Plants, DNV-ST-0359, Technical Report, 2016-06 - Amended 2021-11 DNV, Standard.

Det Norske Veritas (DNV), 2021c. Subsea Power Cables in Shallow Water, DNV-RP-0360. Technical Report, DNV, Recommended Practice.

DNV GL, 2024. Helica. URL https://www.dnv.com/Publications/helica-69612. Available online.

Dobson, A., 2023. Challenges associated with high voltage dynamic inter array cables. In: Proceedings of the ASME 2023 42nd International Conference on Ocean, Offshore and Arctic Engineering. OMAE 2023, In: International Conference on Offshore Mechanics and Arctic Engineering, Volume 3: Materials Technology; Pipelines, Risers, and Subsea Systems, V003T04A024. http://dx.doi.org/10.1115/OMAE2023-107668.

Ehlers, S., Biglu, M., von Bock und Polach, F., Thießen, W., 2023. Experimental and numerical investigations of the ultimate strength of two subsea power-transmission cables. Mar. Struct. 88, 103346. http://dx.doi.org/10.1016/j.marstruc.2022.103346.

Fang, P., Jiang, X., Hopman, H., Bai, Y., 2021. Mechanical responses of submarine power cables subject to axisymmetric loadings. Ocean Eng. 239, 109847. http://dx.doi.org/10.1016/j.oceaneng.2021.109847.

Fang, P., Li, X., Jiang, X., Hopman, H., Bai, Y., 2023. Bending study of submarine power cables based on a repeated unit cell model. Eng. Struct. 293, 116606. http://dx.doi.org/10.1016/j.engstruct.2023.116606.

Gulski, E., Anders, G., Jongen, R., Parciak, J., Siemiński, J., Piesowicz, E., Paszkiewicz, S., Irska, I., 2021. Discussion of electrical and thermal aspects of offshore wind farms' power cables reliability. Renew. Sustain. Energy Rev. 151, 111580. http://dx.doi.org/10.1016/j.rser.2021.111580.

Guo, Y., Ye, N., 2020. Numerical and experimental study on full-scale test of typical offshore dynamic power cable. In: Proceedings of the 30th International Ocean and Polar Engineering Conference. ISOPE2020, International Society of Offshore and Polar Engineers, Virtual.

Hall, M., Sirnivas, S., Yu, Y.-H., 2021. Implementation and verification of cable bending stiffness in MoorDyn. In: Proceedings of the ASME 2021 3rd International Offshore Wind Technical Conference. ASME 2021 3rd International Offshore Wind Technical Conference, p. V001T01A011. http://dx.doi.org/10.1115/IOWTC2021-3565.

Hu, F., Emersic, C., Smith, D., Chen, T., Rowland, S., Cunningham, L., 2024. The effect of mechanical strain on electrical tree development in XLPE. IEEE Trans. Dielectr. Electr. Insul. 31 (1), http://dx.doi.org/10.1109/TDEI.2023.3337765.

Hu, H., Yan, J., Sævik, S., Ye, N., Lu, Q., Bu, Y., 2022. Nonlinear bending behavior of a multilayer copper conductor in a dynamic power cable. Ocean Eng. 250, 110831. http://dx.doi.org/10.1016/j.oceaneng.2022.110831.

Ikhennicheu, M., Lynch, M., Doole, S., Borisade, F., Wendt, F., Schwarzkopf, M.-A., Matha, D., Vicente, R.D., Tim, H., Ramirez, L., et al., 2020. Review of the State of the Art of Dynamic Cable System Design. Technical Report, COREWIND, Brussels, Belgium.

Janocha, M.J., Ong, M.C., Lee, C.F., Chen, K., Ye, N., 2024. Reference power cable models for floating offshore wind applications. Sustainability 16 (7), http://dx.doi.org/10.3390/su16072899.

Jiang, W.-G., 2012. A concise finite element model for pure bending analysis of simple wire strand. Int. J. Mech. Sci. 54 (1), 69–73. http://dx.doi.org/10.1016/j.ijmecsci.2011.09.008.

Jiang, K., Bai, Y., Cheng, P., 2023a. Fatigue life estimation of stranded copper conductors using the method based on the fatigue damage evolution model. Ships Offshore Struct. 1–13. http://dx.doi.org/10.1080/17445302.2023.2225941.

Jiang, K., Bai, Y., Cheng, P., 2023b. Influence analysis of different compaction degrees on the fatigue performance for stranded copper power conductors. Ships Offshore Struct. 18 (11), 1547–1558. http://dx.doi.org/10.1080/17445302.2022.2129912.

Jiang, W., Yao, M., Walton, J., 1999. A concise finite element model for simple straight wire rope strand. Int. J. Mech. Sci. 41 (2), 143–161. http://dx.doi.org/10.1016/S0020-7403(98)00039-3.

Karimirad, M., 2014. Offshore Energy Structures: For Wind Power, Wave Energy and Hybrid Marine Platforms. Springer, http://dx.doi.org/10.1007/978-3-319-12175-8.

Karlsen, S., 2010. Fatigue of copper conductors for dynamic subsea power cables. In: Proceedings of the ASME 2010 29th International Conference on Ocean, Offshore and Arctic Engineering. OMAE 2010, 29th International Conference on Ocean, Offshore and Arctic Engineering: Volume 6, pp. 275–281. http://dx.doi.org/10.1115/OMAE2010-21017.

Kim, S.-Y., Lee, P.-S., 2017. Modeling of helically stranded cables using multiple beam finite elements and its application to torque balance design. Constr. Build. Mater. 151, 591–606. http://dx.doi.org/10.1016/j.conbuildmat.2017.06.052.

Kuznecovs, A., Ringsberg, J.W., Yang, S.-H., Johnson, E., Anderson, A., 2019. A methodology for design and fatigue analysis of power cables for wave energy converters. Int. J. Fatigue 122, 61–71. http://dx.doi.org/10.1016/j.ijfatigue.2019.01.011.

Lerch, M., De-Prada-Gil, M., Molins, C., 2021. A metaheuristic optimization model for the inter-array layout planning of floating offshore wind farms. Int. J. Electr. Power Energy Syst. 131, 107128. http://dx.doi.org/10.1016/j.ijepes.2021.107128.

Leroy, J.-M., Poirette, Y., Brusselle Dupend, N., Caleyron, F., 2017. Assessing mechanical stresses in dynamic power cables for floating offshore wind farms. In: Proceedings of the ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering. OMAE 2017, Volume 10: Ocean Renewable Energy, p. V010T09A050. http://dx.doi.org/10.1115/OMAE2017-61630.

Li, X., Liu, Z., Jiang, X., Hopman, H., 2024b. RVE model development for bending analysis of three-core submarine power cables with dashpot-enhanced periodic boundary conditions. Ocean Eng. 309, 118588. http://dx.doi.org/10.1016/j.oceaneng.2024.118588.

Li, Z., Ringsberg, J.W., Johnson, E., Serdyuk, Y., 2022. Crack propagation in dynamic power cables. In: Proceedings of the ASME 2022 41st International Conference on Ocean, Offshore and Arctic Engineering. OMAE 2022, Volume 2: Structures, Safety, and Reliability, http://dx.doi.org/10.1115/OMAE2022-79467.

Li, D.-R., Su, Y.-S., Yang, R.-Y., 2024a. Experimental and numerical study of suspended inter-array cable configurations for floating offshore wind farm. J. Mar. Sci. Eng. 12 (6), http://dx.doi.org/10.3390/jmse12060853.

Liu, D., Janocha, M.J., Ahmad, I.B., Ong, M.C., 2024. Failure analysis of a suspended inter-array power cable between two spar-type floating wind turbines: Evaluating the influence of buoy element failure on the cable. J. Mar. Sci. Eng. 12 (6), http://dx.doi.org/10.3390/jmse12061001.

Maksassi, Z., Garnier, B., Moctar, A.O.E., Schoefs, F., Schaeffer, E., 2022. Thermal characterization and thermal effect assessment of biofouling around a dynamic submarine electrical cable. Energies 15 (9), http://dx.doi.org/10.3390/en15093087.

Maksassi, Z., Moctar, A.O.E., Garnier, B., Schoefs, F., Schaeffer, E., 2024. For better comprehension of mussel's thermal characteristics and their thermal effect on dynamic submarine electrical cables. Appl. Ocean Res. 144, 103900. http://dx.doi.org/10.1016/j.apor.2024.103900.

Marcollo, H., Efthimiou, L., 2024. WFO – floating offshore wind dynamic cables: overview of design and risks. Available online: https://wfo-global.org/wp-content/uploads/2024/02/WFO-Cables-and-FOSS-White-Paper.pdf.

Ménard, F., Cartraud, P., 2021. Solid and 3D beam finite element models for the nonlinear elastic analysis of helical strands within a computational homogenization framework. Comput. Struct. 257, 106675. http://dx.doi.org/10.1016/j.compstruc.2021.106675.

Ménard, F., Cartraud, P., 2023. A computationally efficient finite element model for the analysis of the non-linear bending behaviour of a dynamic submarine power cable. Mar. Struct. 91, 103465. http://dx.doi.org/10.1016/j.marstruc.2023.103465.

Nasution, F.P., Sævik, S., Berge, S., 2014a. Experimental and finite element analysis of fatigue strength for 300 mm2 copper power conductor. Mar. Struct. 39, 225–254. http://dx.doi.org/10.1016/j.marstruc.2014.07.005.

Nasution, F.P., Sævik, S., Gjøsteen, J.K., 2014b. Finite element analysis of the fatigue strength of copper power conductors exposed to tension and bending loads. Int. J. Fatigue 59, 114–128. http://dx.doi.org/10.1016/j.ijfatigue.2013.09.009.

Nasution, F.P., Sævik, S., Gjøsteen, J.K., Berge, S., 2013. Experimental and finite element analysis of fatigue performance of copper power conductors. Int. J. Fatigue 47, 244–258. http://dx.doi.org/10.1016/j.ijfatigue.2012.09.006.

NREL, 2024. OpenFAST. URL https://github.com/OpenFAST.

Okpokparoro, S., Sriramula, S., 2023. Reliability analysis of floating wind turbine dynamic cables under realistic environmental loads. Ocean Eng. 278, 114594. http://dx.doi.org/10.1016/j.oceaneng.2023.114594.

Orcina Ltd., 2023. OrcaFlex manual. URL https://www.orcina.com/SoftwareProducts/OrcaFlex/Documentation/index.php.

ORE Catapult, 2021. Offshore Substations: Fixed or Floating? – Technoeconomic Analysis. Technical Report.

Papailiou, K., 1997. On the bending stiffness of transmission line conductors. IEEE Trans. Power Deliv. 12 (4), 1576–1588. http://dx.doi.org/10.1109/61.634178.

Poon, C.T., Barrett, R.A., Leen, S.B., 2022a. Global and local modeling for inter-wire fretting in multi-wire copper conductors. Fatigue Fract. Eng. Mater. Struct. 45 (6), 1618–1634. http://dx.doi.org/10.1111/ffe.13683.

Poon, C., Mhurchadha, S.U., Barrett, R., Leen, S., 2024. Three-dimensional representative modelling for fretting wear and fatigue of submarine power cable conductors. Int. J. Fatigue 184, 108302. http://dx.doi.org/10.1016/j.ijfatigue.2024.108302.

Poon, C.T., Mullins, C., Radziunas, L., O'Connell, E., Connolly, A., Leen, S., 2022b. Finite element design study of dynamics in submarine power cables for offshore renewable wind energy. In: ASME 2022 4th International Offshore Wind Technical Conference. In: Proceedings of the ASME 2022 41st International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2022), V001T01A023. http://dx.doi.org/10.1115/IOWTC2022-98245.

Poon, C., O'Halloran, S., Connolly, A., Barrett, R., Leen, S., 2023. Fretting wear and fatigue in submarine power cable conductors for floating offshore wind energy. Tribol. Int. 186, 108598. http://dx.doi.org/10.1016/j.triboint.2023.108598.

Rentschler, M.U., Adam, F., Chainho, P., 2019. Design optimization of dynamic inter-array cable systems for floating offshore wind turbines. Renew. Sustain. Energy Rev. 111, 622–635. http://dx.doi.org/10.1016/j.rser.2019.05.024.

Rentschler, M.U.T., Adam, F., Chainho, P., Krügel, K., Vicente, P.C., 2020. Parametric study of dynamic inter-array cable systems for floating offshore wind turbines. Mar. Syst. Ocean Technol. 15 (1), 16–25. http://dx.doi.org/10.1007/s40868-020-00071-7.

Ringsberg, J.W., Dieng, L., Li, Z., Hagman, I., 2023. Characterization of the mechanical properties of low stiffness marine power cables through tension, bending, torsion, and fatigue testing. J. Mar. Sci. Eng. 11 (9), http://dx.doi.org/10.3390/jmse11091791.

Ringsberg, J.W., Li, Z., McCormick, R., Fagan, N., Stewart, G., Marwood, T., 2024. Structural integrity analysis of marine dynamic cables: Water trees and fatigue. J. Offshore Mech. Arct. Eng. 1–57. http://dx.doi.org/10.1115/1.4065816.

Schnepf, A., Giljarhus, K.E.T., Johnsen, Ø., Lopez-Pavon, C., 2023b. Dynamic power cable configuration design for floating offshore wind turbines using gradient-based optimization. In: Proceedings of the ASME 2023 42nd International Conference on Ocean, Offshore and Arctic Engineering. OMAE 2023, In: International Conference on Offshore Mechanics and Arctic Engineering, Volume 8: Ocean Renewable Energy, V008T09A037. http://dx.doi.org/10.1115/OMAE2023-102788.

Schnepf, A., Lopez-Pavon, C., Ong, M.C., Yin, G., Johnsen, Ø., 2023a. Feasibility study on suspended inter-array power cables between two spar-type offshore wind turbines. Ocean Eng. 277, 114215. http://dx.doi.org/10.1016/j.oceaneng.2023.114215.

Serdyuk, Y.V., Li, Z., Ringsberg, J.W., Johnson, E., 2023. Evaluation of an electro-mechanical model of vented water tree inception in polyethylene insulation. In: 2023 IEEE Conference on Electrical Insulation and Dielectric Phenomena. CEIDP, pp. 1–4. http://dx.doi.org/10.1109/CEIDP51414.2023.10410544.

SINTEF, 2023. UFLEX: Stress analysis of power cables and umbilicals. URL https://www.sintef.no/en/software/uflex-stress-analysis-of-power-cables-and-umbilicals/. Available online.

Skeie, G., Sødahl, N., Steinkjer, O., 2012. Efficient fatigue analysis of helix elements in umbilicals and flexible risers: Theory and applications. J. Appl. Math. 2012 (1), 246812. http://dx.doi.org/10.1155/2012/246812.

Smith, D.M., Cunningham, L.S., Chen, L., 2024. Efficient finite element modelling of helical strand cables utilising periodicity. Int. J. Mech. Sci. 263, 108792. http://dx.doi.org/10.1016/j.ijmecsci.2023.108792.

Sobhaniasl, M., Petrini, F., Karimirad, M., Bontempi, F., 2020. Fatigue life assessment for power cables in floating offshore wind turbines. Energies 13 (12), http://dx.doi.org/10.3390/en13123096.

Srinil, N., 2016. Cabling to connect offshore wind turbines to onshore facilities. In: Ng, C., Ran, L. (Eds.), Offshore Wind Farms. Woodhead Publishing, pp. 419–440. http://dx.doi.org/10.1016/B978-0-08-100779-2.00013-1.

Tao, W., Ma, Z., Wang, W., Liu, J., Zhou, K., Li, T., Huang, M., 2016. The mechanism of water tree growth in XLPE cables based on the finite element method. In: 2016 IEEE International Conference on High Voltage Engineering and Application. ICHVE, pp. 1–4. http://dx.doi.org/10.1109/ICHVE.2016.7800764.

Thies, P.R., Johanning, L., Smith, G.H., 2012. Assessing mechanical loading regimes and fatigue life of marine power cables in marine energy applications. Proc. Inst. Mech. Eng. O: J. Risk Reliab. 226 (1), 18–32. http://dx.doi.org/10.1177/1748006X11413533.

Tjahjanto, D.D., Tyrberg, A., Mullins, J., 2017. Bending mechanics of cable cores and fillers in a dynamic submarine cable. In: Proceedings of the ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering. OMAE 2017, Volume 5A: Pipelines, Risers, and Subsea Systems, p. V05AT04A038. http://dx.doi.org/10.1115/OMAE2017-62553.

Treyssède, F., Cartraud, P., 2022. A two-dimensional formulation for the homogenization of helical beam-like structures under bending loads. Int. J. Solids Struct. 234–235, 111270. http://dx.doi.org/10.1016/j.ijsolstr.2021.111270.

Tyrberg, A., Eriksson, E., Persberg, A., 2019. Importance of mechanical design and testing of cable systems for floating offshore wind. CIGRE Sci. Eng. 2019 (15), 5–13.

Warnock, J., McMillan, D., Pilgrim, J., Shenton, S., 2019. Failure rates of offshore wind transmission systems. Energies 12 (14), http://dx.doi.org/10.3390/en12142682.

Worzyk, T., 2009. Submarine Power Cables: Design, Installation, Repair, Environmental Aspects. Springer Berlin Heidelberg, http://dx.doi.org/10.1007/978-3-642-01270-9.

Yang, S.-H., Ringsberg, J.W., Johnson, E., Hu, Z., 2017. Biofouling on mooring lines and power cables used in wave energy converter systems—Analysis of fatigue life and energy performance. Appl. Ocean Res. 65, 166–177. http://dx.doi.org/10.1016/j.apor.2017.04.002.

Ye, N., Yuan, Z., 2020. On modelling alternatives of non-critical components in dynamic offshore power cables. In: Proceedings of the 39th International Ocean and Polar Engineering Conference. ISOPE2020, pp. ISOPE–I–20–2176.

Young, D.G., 2020. Predicting Failure of Dynamic Offshore Cables by Insulation Breakdown Due to Water Treeing (Ph.D. thesis). University of Edinburgh, http://dx.doi.org/10.7488/era/190.

Young, D.G., Ng, C., Oterkus, S., Li, Q., Johanning, L., 2018a. Assessing the mechanical stresses of dynamic cables for floating offshore wind applications. In: Journal of Physics: Conference Series. Vol. 1102, IOP Publishing, 012016. http://dx.doi.org/10.1088/1742-6596/1102/1/012016.

Young, D.G., Ng, C., Oterkus, S., Li, Q., Johanning, L., 2018b. Predicting failure of dynamic cables for floating offshore wind. In: Proceedings 3rd International Conference on Renewable Energies Offshore. RENEW2018, Lisbon.



https://dspace.org/

Recent advances in mechanical analysis and design of dynamic power cables for floating offshore wind turbines

Cerik, Burak Can; Huang, Luofeng

2024-11-01
Elsevier
https://doi.org/10.1016/j.oceaneng.2024.118810
Cerik BC, Huang L. (2024) Recent advances in mechanical analysis and design of dynamic power cables for floating offshore wind turbines. Ocean Engineering, Volume 311, Part 1, November 2024, Article number 118810

Downloaded from a DSpace repository. https://dspace.org/