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Discussion of electrical and thermal aspects of offshore wind farms' power cables reliability☆

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ABSTRACT

The increasing demand for renewable energy worldwide has contributed to a substantial increase of offshore wind farms in recent years. For this type of generation, submarine power cables are of great importance as they transmit power between the turbines and the offshore substation to the land connection. Last 20 years of experience shows that the power cables are the largest contributor to the failures of power supply from the offshore plants. Additionally, the repairs of such a critical infrastructure are extremely challenging and costly. Therefore, several aspects of the design, transportation, installation and operation of power cables at offshore wind farms require special attention.

Based on international experience gathered from various projects over the last few years as well as international references, this paper discusses offshore power cables from the perspective of reducing the risks of failure and increasing supply reliability.

1. Introduction

Vindeby was the world's first offshore wind farm (OWF) (with 11 turbines and 4-Megawatt power generation capacity). It was installed in Denmark in 1991 two kilometers offshore (decommissioned in 2017).

In 2020, an average OWF consists of about 100 wind turbines and provides a generation capacity of about 700 MW or more. Today, about five thousand offshore wind turbines are installed around the world generating about 30 GW of power. For example, in eleven European countries there are more than 100 OWF installations with an installed power of about 23 Gigawatts [GW] [1–4].

In the next ten years, an expected worldwide annual growth of 19 % (Europe 15 %) in offshore facilities will result in about a 177 GW capacity by 2030 [2].

A typical OWF consists of a number of wind turbines each with a generation power of several MW, connected via inter-array cables to an offshore substation (OSS), which is installed with a distance of tens of kilometers to the shore, see Fig. 1.

To deliver the generated power to the onshore grid, the OSS is connected by export cables to the onshore substation which is already integrated to the power transmission network.

It is expected that the maximum turbine power generation will increase from the current average rating of 7.8 MW up to 14 MW in upcoming years (2024) and the average power capacity of newly installed

Abbreviations: OWF, Offshore wind farm; OSS, Offshore substation; WTG, Wind turbine generator; DAC, damped ac; PD, partial discharges; DF, dissipation factor; HVAC, high voltage alternating current; MTTR, mean time to repair: VLF; Very Low Frequency, ACR; Alternating current resonance resting, IEC; International Electrotechnical Commission: IEEE, Institute of Electrical and Electronics Engineers; Cigré, Conseil International des Grands Réseaux Électriques; HVDC, high voltage direct current; XLPE, Cross-linked polyethylene; HDD, horizontal directional drilling; CLV, Cable-Lay Vessel; (E)HV, (Extra) high voltage.

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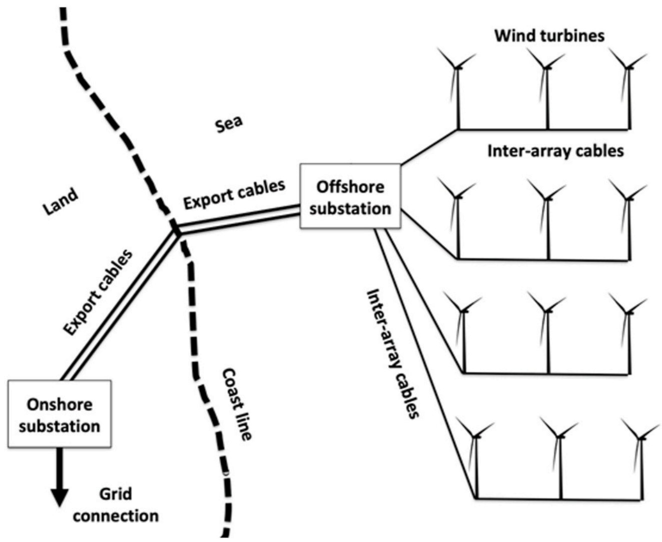

Fig. 1. Schematic layout of an OWF: wind turbines (numbers up to a few hundred) presently up to 7 MW generated power, inter-array cables (lengths between turbines up to 2 km) HVAC up to 66 kV, export cables (sea part lengths up to 90 km) HVAC up to 230 kV, HVDC up to 320 kV.

offshore wind farms in construction will exceed 1 GW. As a result, the export and inter-array cables will require higher power ratings and reliability over long distances as the average distance to the shore will be up to 90 km with water depths of more than 30 m [1].

The growing demands for offshore energy generation will, consequently, increase the demand for delivery of more dedicated technologies for wind turbines, submarine power cables and substation components. This near-doubling of the generated power will result in higher power ratings of the inter-array cables resulting in larger conductor cross-sections and higher operating voltages. It is expected that by 2025, an additional 24,000 km of submarine power cables will be needed [3].

Having in mind that sound cable infrastructure is fundamental to the reliable operation of an OWF, this contribution will discuss such important aspects as: cable design, cable failures and their effects on reliability, risks related to transportation, installation and operation, as well possibilities for quality control improvement.

2. Failures of submarine power cables

Facing the prospect of doubling of the power generation capacity of new OWFs, the lessons learned from the past can be useful. It is important to note that based on the experiences from the last ten years, offshore cable failures are responsible for up to 80 % of total financial losses and insurance claims [3–7].

This situation is much more remarkable and worrisome because when considering the total costs of a windfarm, offshore cables account for less than 10 % of the total capital costs [4,7].

It has been reported that the failure incidents in 2015, resulted in €60 million in insurance claims [6–8].

In the last 7 years, about 90 offshore cable failures have been reported with over €350 million in insurance claims [3]. According to Ref. [3],], the repair costs of an offshore cable can be between €700′000 and €1.5 million.

In the event of a cable failure, one or more WTGs can be out of service. The average mean time to repair (MTTR) such a failure is three days, which is highly dependent on the actual weather conditions, the location of the fault within the inter-array string and, consequently, the number of turbines affected, which in turn depends on the OWF cable string topology. Taking this outage time into account, financial losses easily exceed €100,000 [9]. As a result, depending on the size of a windfarm and the location of the failed turbine, the financial impact of a single inter-array cable (with an operating voltage of 33 kV or 66 kV) can range between €200,000 and €3 million per case [9].

The reasons for offshore failures are manifold and according to Ref. [7] they could be classified into two categories:

- Faults in the open sea, caused by dragging fishing nets, anchor strikes and erosion resulting in the abrasion of the cable due to its lateral movement under the influence of hydrodynamic loading;
- Faults as a result of inadequate preparation, planning and building at the beginning of a OWF project, in combination with insufficient risk identification, the (project specific) subsea cable design and the shortcomings in how specific procedures are implemented.

According to Ref. [5], two-thirds of recorded cable faults can be attributed to contractor errors during installation work, even if these deficiencies are mostly not identified until windfarm operation has started.

References [6,10] have identified the following major problems often resulting in cable failures:

- The most common root causes of failure claims range from contractor error to design defects, mechanical failures and weather influences;
- Technical solutions are constantly under development to target specific problems that occur during installation and operation;
- The managing of human errors is still arguably the greatest challenge;
- The cost and time pressures are the root cause of human errors, resulting in failures occurring during operation;
- The pressure to reduce levelized cost of electricity triggers questionable decisions on both the developers' and contractors' sides;
- The offshore industry is focused on strongly driving down the costs with less room for motivating development and innovations;
- There is no transparency and consistent dialogue between different project teams and suppliers.

According to Ref. [9], the international IEC, IEEE or Cigré regulations for post-installation testing of the submarine cables are deficient in supporting these new developments and do not provide guidelines for the risk management of the offshore cables. The applied regulations, mostly based on the IEC documents, consider the aspects of factory testing (e.g., routine- and sample tests) in detail. However, only the minimum requirements and the basic tests for post-installation are described. Except for occasional evaluation of the past experiences, no concluding recommendations are available for adequate quality control and regarding the maintenance testing of cable circuits, no guidelines are given [11]. This situation, coupled with the expected annual 19 % growth in the OWF installations, might result in dire financial and reliability consequences for all stakeholders.

Therefore, it is of importance to try to answer the following questions:

- Why do the existing offshore wind farms have such a high failure rate caused by cables?
- How can the number of cable failures be reduced at the existing wind farms?
- How to meet the challenges posed by the rapid growth in construction and new technologies entering the market?

As the reasons and timing of the reported failures differ, the following chapters will address different technical and management aspects having an impact on the submarine cable reliability.

3. Offshore wind farm power cables

3.1. Construction of submarine cables

The inter-array and sometimes export AC submarine cables usually have a 3-core construction, see Fig. 2.

In some installations, the single-core design is used for a high voltage AC export cable and all DC cables. The 3-core cables are usually built by twisting three single-core cables and then applying armor reinforcement with several nonconducting layers. These single core constructions currently most often use XLPE insulated cables, but paper-insulated cores are also quite common, especially in older installations.

One of the differences between land and subsea cables will be in the application of a longitudinal water barrier below the jacket of a single-core construction. Most commonly, a thin aluminum foil is used for that purpose. Additionally, submarine cables may have several layers composed of semi-conducting or non-conducting swelling tapes aimed to prevent water ingress into the insulation, see Fig. 2.

Another important difference between land and submarine cables is the application of armor in the latter. Armor, most often built of steel wires in one or two opposite twisted layers, is applied with twisting in the same or an opposite direction with respect to the cores. Armor plays a double role in the submarine cables: it serves as a protective layer but also provides the required strength during the laying process. Armor is also required to achieve the required on-bottom stability to minimize the lateral movement of the cable on the seabed and to ensure that the integrity of the cable is not compromised [61–63].

Magnetic armor has a significant detrimental influence on a cable's current rating; therefore, occasionally non-magnetic materials are used.

Over the armor, as an anti-twist to the steel wires, a layer of polypropylene strings is laid, and such structures are called wet structures, i.e., seawater can penetrate through the roving and armor into the inter-strand space in the cable or the dry structures which have a tight sheath made from high-density polyethylene under and above the armor. However, it should be mentioned that the cable can be covered with the extruded HDPE and still be classified as a wet design. The manufacturers sometimes drill a hole in the extruded outer sheath to make the cable wet design. The holes are made to eliminate the pressure inside the cable. As a consequence, they protect the joints and terminations against a possible damage.

Due to the difficulties in execution and costs, wet cables constitute the vast majority of cables and are used for installations permanently laid on or under the seabed.

Dry cables, usually with two or more layers of armor, are used for mobile applications; that is, for floating wind farms in which cables are suspended from a floating platform and hover in the sea thanks to special floats that keep them in the water, see position 10 in Fig. 3. These have been called dynamic cables.

Technical solutions in wet cables are cheaper compared to dry dynamic cables, however, when designing a cable line, the material used for the production of conductors should also be considered.

The use of aluminum as the cheapest and lightest conductor may entail high service costs in the future directly resulting from its physicochemical properties. The most important are the high coefficient of thermal expansion and the high susceptibility to corrosion in the seawater environment. Cables in wind farms are subject to changes in the diameter of the working conductors. Current loads, wind force, and extreme weather conditions may cause thermal expansion of the conductor, which may result in the change of its diameter. The phenomenon of thermal expansion and contraction of the material harms the insulating layer. The result is microcracks in the insulation system, which usually lead to partial discharges and, consequently, to a cable breakdown.

In the case of a breakdown and water intrusion into the cable, in which there are microcracks, sea water may enter the micropores causing aluminum corrosion. The effect of aluminum oxidation will be porous, large-volume aluminum oxides, which, due to their volume, will damage the insulation, making it impossible to perform local cable repairs and will force the replacement of the entire section. This phenomenon does not occur in cables with copper conductors. Therefore, at the design-stage of submarine cable lines, attention should not only be paid to investment costs, which will be lower for cables with aluminum conductors, but also to the costs of servicing such lines, which will be much higher compared to a cable line with aluminum conductors.

The main technological challenge in the production of submarine cables is to maintain the required long sections of up to 30–50 km in length. For technical reasons, it is often impossible to make the factory section of insulated wires of such lengths, see Fig. 4. Because of the applied technological processes, it is not possible to use (land) joints, commonly used onshore, which significantly increase the diameter of the cable.

Instead, it is necessary to rebuild individual structural elements in such a way that the diameter of the cable is not increased at the connection point. This type of connection is called a "factory joint" and since it is mainly executed by hand, it is always the weakest element of any cable. The technology of manufacturing factory joints is a producer's secret, and tests of its quality are not perfect in terms of consistency and homogeneity of the structure or electrical parameters. The

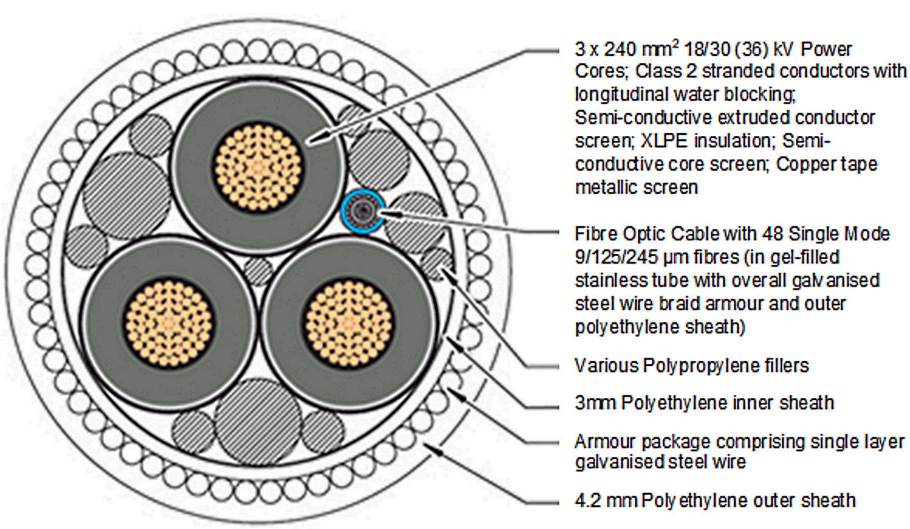

Fig. 1. Schematic cross-section of an inter-array cables 33 kV.

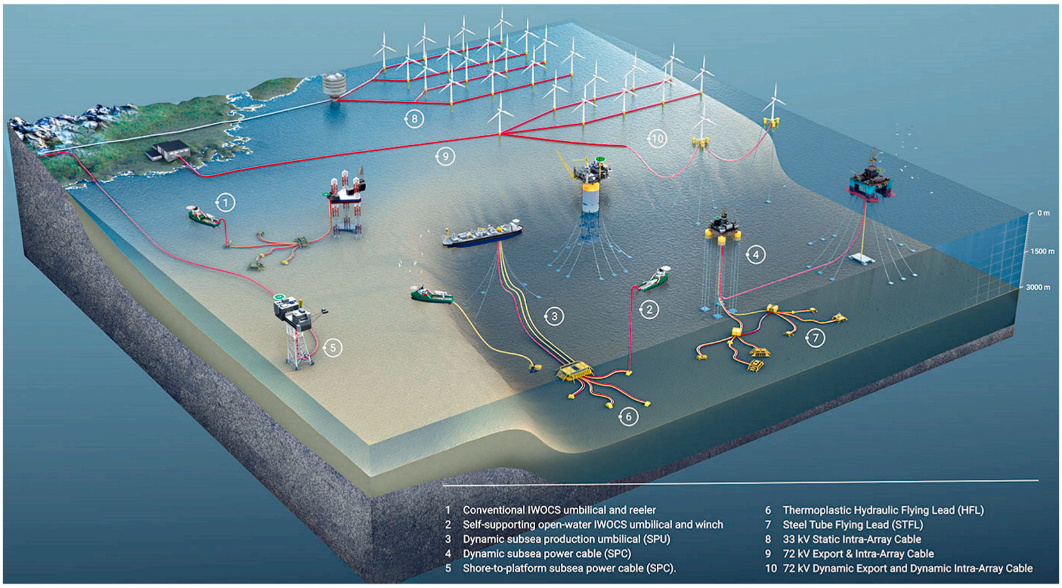

Fig. 3. *Offshore cabling systems for platforms* and *wind towers.*

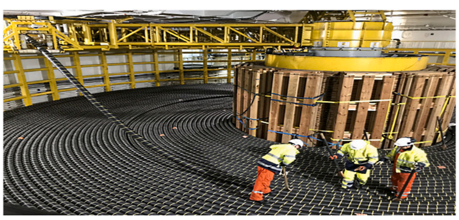

Fig. 4. Winding of a full cable length on a turntable in the factory.

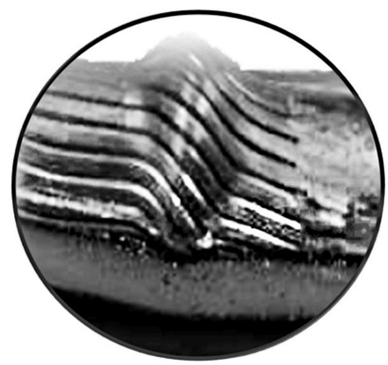

Fig. 5. Example of a bird cage on aluminum conductor close to the factory join core welding.

difference between a factory and the offshore field joint is discussed in Refs. [64,65]. The same references show cases of failure of the offshore field joint.

Testing the structure of the factory joint at the factory floor, apart from visual and X-ray inspections, is practically impossible and one should rely only on the knowledge and experience of the installers making the connection.

Proper construction of the factory joints is also important for further production processes such as twisting, armoring, or making the outer sheath, where the potential for thickening is not accepted and may disturb the above-mentioned processes. Just behind the place where the conductor is connected (welded or brazed), the joints are the most annealed, which is where components are the most plastic (for both aluminum and copper conductors).

As a result of thermal expansion, compensated stresses accumulate in the place where the metal has the lowest mechanical strength. This is just behind the weld of the cable core, forming the so-called bird cage (see Fig. 5). As the thermal expansion coefficient for aluminum is 73 % higher than for copper, the risk of this phenomenon resulting in cable line damage is much higher. After twisting, a very long finished cable section is usually placed on a large turntable (see Fig. 4). The extensive length makes it impossible to perform classic partial discharge tests; hence, there is a need to use alternative methods for assessing the quality of the connection, as described later in this paper.

3.2. *Installation of subsea cables*

Finalized cables, after completing the necessary acceptance tests (usually voltage tests), are rewound onto specialized vessels for laying on the seabed. The process of laying is preceded by conducting detailed analyses of the soil, its thermal properties, shape, and occurrence of rocks, in order to determine the required processes for laying the cable. For inter-array cables, installation procedures can be simplified because the sections between wind turbines are relatively short. As a rule, when installing specialized equipment, the cables are buried, usually between 1 and 3 m below the seabed. Burial under the seabed is a preferred method of installing the submarine power cables. Of course, this is not always possible, and hence, other methods of laying may be used.

When submarine cables are laid on the bottom of the sea floor or just before they enter the wind turbine tower, it may be necessary to use special protection systems (CPS) for protection against the strong sea currents, shifting sandbanks, or rocky ground. For cables with aluminum conductors, the diameter of which is about 20 % greater than that of copper cables and their weight two or even three times smaller while maintaining the same load capacity, the application of the CPS is more common. The use of this type of security system can double the cost of cable installation due to the significantly reduced laying speed, the cost of cast iron elements, the use of specialized assembly technologies, and, at the same time, it can eliminate the advantage of cables with aluminum conductors, that is, the price. Fig. 6 shows an example of a cast-iron cable protection system against unfavorable sea conditions.

When there is no need to use cable protection systems (CPS) to secure the cable line, it may be necessary to bury cables with aluminum conductors deeper under the seabed. This is not necessary in the case of

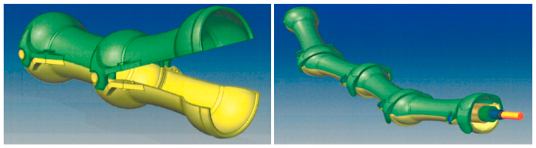

Fig. 6. Example of specialized cable protection systems (CPS).

cables with copper conductors due to their compact nature and larger weight. The consequence of deeper cable burying may be a significant reduction in the load capacity of the cables, which in turn may cause a further increase in the cross-section of the working conductors, with all its consequences.

The majority of the cable-laying vessels currently in operation were designed to lay cables with copper conductors, meaning heavy cables with a compact outer diameter. The use of aluminum cables sets another limit, namely the limit of the maximum volume of the turntable on vessels, but not the problem of weight capacity. Such a situation may significantly affect the cost of installation because an additional course for the second section of the cable may be required. The additional cost related to the vessel's course to the port, loading the cable, and returning to the installation can be between € 100′000 and € 250′000 for each day. Due to shorter factory sections, the number of factory joints in lines with aluminum conductors is higher at the assumed line length, which means that the probability of damage is higher. This underscores the advantage of cables with copper conductors.

3.3. Reducing possible damage during transportation and installation as well as failures during operation

Submarine power cables are subjected to high mechanical stresses even before they are energized. They are rewound several times and laid at significant depths subjected to bending and torsional forces. These are particularly hard on the more delicate components of the cable like, aluminum foil or concentric neutral wires. Considering the processes of transportation and installation where mechanical -stresses might be too excessive to the cable, surface damages must be considered. Fig. 7 shows an example of mechanical damage (probably due to transportation) on the armor of the cable; a close visual inspection has shown that at least from the outer side the cable, the surface inside was not damaged. Nevertheless, it is impossible to say what the long-term effect of this damage on the electrical- and mechanical integrity of the cable would be.

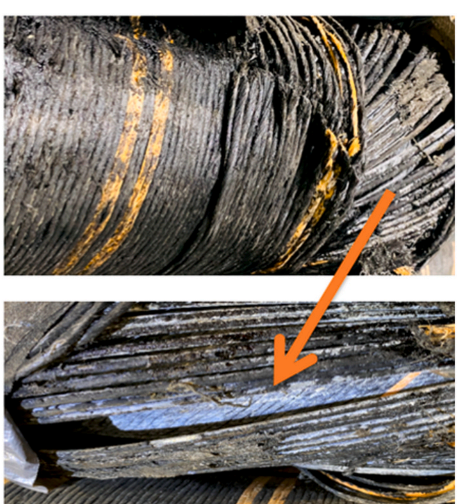

Fig. 7. Example of mechanical damage (due to transportation) on the armor of the cable; a closed visual inspection has shown that at least from the outer side the cable surface inside was not damaged.

In practice, maintaining proper tension and bending radius during rewinding is relatively simple. However, when laying cables and routing their ends to wind turbine towers, special attention should be paid so that there are no micro-damages that could affect the integrity of its components.

With the above in mind, special attention is paid to the combination of the twist of the conductor wires, a selection of the fillers and construction, size and twisting of the steel armor wires to create a self-compensating system preserving the integrity of the cable under the influence of the longitudinal stress occurring during laying, as well as subsequent operation.

Additionally, when developing cable structures, especially for long sections, special attention should be paid to the occurrence of the cyclical stresses and the resulting phenomenon of thermal expansion of the conductors.

The key parameter when laying cables is to maintain the longitudinal stresses and bending radius required for a given structure in such a way that no micro-damages are introduced into the cable. The risks involved in the installation of a submarine cable are discussed in Refs. [65,66].

It is very important to carry out post-installation tests to make sure that the cable installation did not deteriorate its technical parameters. A preferred solution is to perform factory tests before the cable is passed onto the vessel and then perform post-installation tests and compare the results. The examinations should not be limited to the voltage test or the tightness of the jacket only, but also the level of partial discharges should be tested to show, among other things, the micro-damage of the insulation system. There are three well-known systems for carrying these tests, namely the Very Low Frequency (VLF), AC Resonance Testing (ACR) and Damped AC (DAC).

The first method was practically excluded by the new IEC 63026 standard due to the high test voltage; that is 3 times Uo. For practical reasons, the ACR method is difficult to perform at sea due to the size and weight of the device, see Ref. [12] for more details. The most practical seems to be the DAC method because of the device's compactness (see Refs. [9,12] for more details), ease of use and comparable results to the ACR and VLF procedures. The methodology will be discussed in detail in later chapters.

3.4. Possible bottlenecks, pressures, limitations influencing design, manufacturing, testing, transportation, and installation of the offshore cables

Inter-array and export submarine cables are produced from several sections to long lengths. This makes it impossible to perform traditional tests such as partial discharges (PD) using the standard AC 50 Hz method due to their dimensions and cable capacity. Currently, full cable lengths are PD tested at the beginning and the end of the cable, however, this method of testing does not give 100 % certainty about the quality of the whole section, which often includes one or more factory joints. As an alternative, the DAC method can be applied for partial discharges testing and an examination of the dissipation factor. The information about the specific cable parameters before loading and installation, can be compared to similar tests after installation. This will provide answers about the quality of the installed cable line. This is extremely important because in the process of rewinding to the vessel, laying on the seabed, and assembly in the towers, there can be many factors that can damage the cable.

The cable must be designed to withstand all mechanical stresses in all phases of its intended lifetime, including manufacturing, transportation, testing, and also the installation. The key process for transporting submarine cables is their loading on the vessel. The vessel's structure must be compatible with the system of trays on which the cables are laid. If the manufacturer of the cables has introduced appropriate torsional stress during the laying on the basket stage, the transport vessel should be adapted to compensate for this stress. In the case of turntables, the vessel should also be equipped with a winding system so that no additional torsional stresses are introduced in the cable. The key parameter is to synchronize the cable tension and to maintain the required cable bending radii [13].

The occurrence of strong currents, wind pressure on the vessel, and drift associated with waves have a significant impact on the tension forces that can affect the insulation structure of the cable and, consequently, lead to the formation of partial discharges and punctures. Therefore, another important parameter is to maintain the proper speed and direction of the vessel concerning the designated cable laying track on the seabed in correlation with the speed of cable release (unwinding) from the vessel. The equations that can be used to estimate the maximum tensile force occurring in the cable during installation can be found in Ref. [14]. Failure to observe this basic principle results in either excessive cable tension, lifting of the burial kit (if applicable), or the formation of a cable loop on the seabed.

Very often, the voltage and a coating leak tightness are the only tests performed after installation of the cables. If these two tests were positive, the assembly was considered to have been done correctly. This approach is not always appropriate, as there could have been degrading stresses associated with excessive cable tension or bending. This could result in future breaks and would not be detected during the voltage test. A separate topic for discussion is the value of the voltage that should be applied for the voltage test. The question of whether a voltage of 3 times U_0 (as applied with the VLF testing) after installation is not too high, should be kept in mind as it could be destructive for the cable insulation. A discussion of other possible field joint tests on a submarine power cable is offered in Ref. [67].

4. Technical aspects of submarine cables design

4.1. Introduction

This section briefly describes the methodology which should be followed in the dimensioning of HV and EHV submarine power cable systems.

The IEC standards [15–19] contain the most extensive current rating calculation methods within the cable industry. However, these standards do not fully describe the calculations for some specific cable designs and complex topologies encountered in the offshore industry. The following sections are, therefore, meant to fill the voids, where the IEC standards [15–19] are unclear or inadequate.

Most modern power cables are rated for continuous operation at manufacturer specified conductor temperature, which is dictated by the insulation material in contact with the conductor. The maximum continuous current, which each phase can carry, without exceeding this temperature, is dependent on the cable construction and detailed thermal conditions of the external environment surrounding the cable. Hence, each section of the cable route must be considered individually to determine the portion which will dictate the most onerous thermal conditions, and therefore, the maximum continuous current rating for the cable. For submarine cables, this aspect is particularly important because there are several design interfaces not encountered in land installations. Therefore, cable system rating calculations must be performed for each of its individual sections, including for example: direct buried, horizontal directional drilling (HDD), in troughs, J-tubes, and so on. These relevant sections are defined by the applicable cable design and installation conditions.

When considering the buried portion of the submarine cable it is important to take into account the possible settlement of the cable into soft sediment as well as silting and sediment deposition. Both may result in much greater soil coverage than the design value leading to an unacceptable rise in the conductor temperature. Additionally, sediments often have higher thermal resistivity than the values assumed in the rating calculations.

One more aspect of cable rating may be important for designing submarine cable systems. In some jurisdictions, it is required that the temperature rise at the so-called ecological point (usually 20–30 cm below seabed) does not exceed 2 K in comparison with the situation prior to cable energization. This so called 2 K-criterion may either severely limit the current carrying capacity of the cable or may force the application of a larger cable conductor compared to similar land cable installations.

During the initial design of the cable system, the cable crossings and HDDs are assumed to have a current rating equal to that of normal installation, e.g., buried in a trench, buried in ducts and so on.

4.2. Limiting parameters of cable system current ratings

Different companies would specify different limiting temperatures and durations for emergency operations. For a steady state, almost uniformly the same limitations are used throughout the industry. The following paragraphs list the most important limiting parameters but the values quoted should be taken with care and examined for each installation situation separately.

For a steady state and dynamic operation, the conductor temperature should not exceed 90 °C. The jacket/duct outer temperatures can occasionally be also listed as the limiting parameter. If this is the case, it can be expected that the allowable steady state current will be lower than the one computed with the insulation temperature limit. The jacket temperature would not be considered a limiting factor for short (say less than 40 h) dynamic and emergency operations.

There is no widely accepted approach to limit the conductor temperature during an emergency operation; however, the value of 105 °C (for up to 1 h) is often specified. It should be remembered that these suggested temperatures are applicable unless test reports from the cable manufacturer prove that another (higher or lower) value must be used.

4.3. Load conditions

Submarine power cables serving OWF are a subject to variable loading. Normally, the load variations cannot be defined as a daily cycle load curve, which is a standard practice for land cables. Nevertheless, rating calculations should consider both the steady state and transient/emergency loadings with the following stipulations.

- Operational voltage (U_n) rather than the design voltage should be taken from the specific cable system and must be used for all calculations performed to obtain the current rating;
- Continuous load current is the maximum constant current with a unity load factor that is required to reach the maximum allowed conductor temperatures throughout its entire lifetime, assuming the surrounding conditions are constant;
- Transient overload currents are currents lasting for a limited period of time, e.g., 1 h, 40 h, etc., sufficient to produce the maximum allowed temperatures asymptotically after the duration of the transient, assuming the surrounding conditions are constant. In general, the initial conditions of these calculations are steady state, or a fraction of the steady state cable rating. This fraction is usually taken in the range of 0.5–1.0.

4.4. Parameters for calculation of current ratings

Current rating calculations require a fairly large number of parameters. Some of them are specified by the cable manufacturer, others can be measured and some other have to be assumed. All rating calculations are composed of two steps:

- Obtaining the heat losses generated by the cable;
- Analysis of how the heat is dissipated into the environment.

The following sections briefly describe the required information.

4.4.1. Thermal parameters

The thermal parameters include thermal resistivities and specific heat value of each cable component. It is a common practice to assume that the metallic components of the cable have negligible thermal resistance. Hence, this parameter is usually not required for the calculations. The values of the thermal resistivities and specific heat for each cable component are usually taken from Refs. [15,16]. For the insulation thermal resistivity, the manufacturer is allowed to present alternative values based on the test reports.

In order to calculate the heat irradiated by the cable surface, it is normally assumed that it is a black body with an emissivity coefficient equal to one. A typical solar radiation intensity is around 1000 W/m^2. However, it could be computed quite precisely for each geographical location. It should be remembered that peak solar radiation occurs at different times of the day for horizontal and vertical installations. This value is required for the un-shaded cables installed in air.

4.4.2. Electrical parameters

Electrical parameters include electrical resistances and loss factors for the sheath and armor. These depend on the component material properties and its temperature. Therefore, the values used in the calculations should be adjusted as the temperature of the component changes.

For all the possible conductor topologies, the conductor's DC resistance values should be taken from Ref. [17]. Other relevant electric parameters, such as (but not limited to) the screen's DC resistance, loss angle (tan δ) or relative permittivity (ε), should be taken from the IEC 60287-series of standards [15], unless valid tests prove them to be different. When computing the electrical resistances of concentric neutral and armor wires, the lay factor of the wires should be taken into account. For calculation of the armor losses, it would be advisable to consider not only the lay factor but also whether the cable is uni- or contra lay. The material properties could include complex magnetic permeability of the type of steel used.

For three core submarine cables, which usually have a metallic screen around each core, the bonding of the screens should be considered. If the core of a 3-core submarine cable has more than one metallic component; e.g., wire screen and aluminum foil, the presence of the aluminum foil could be neglected in loss calculations. However, if the computer program used can handle such constructions, both layers should be considered. When calculating the electrical resistance of the core screen wires, two lay factors should be considered: one for the wires and one for the cores. The latter is usually much smaller than the former. The lay factor of the cores should also be considered when computing insulation capacitance.

4.5. Dynamic rating for the export cables

Many submarine cable operators have developed some preliminary load current profile along the cable route based on the planned output of the wind farm in order to obtain dynamic rating values.

The full current load profile includes the two ends of the route (HDD and OSS) and several intermediate points separated approximately by 10.0 km. It is usually represented as a yearly load curve by the percentage of the full load current that should be applied with respect to the values indicated for each location. Fig. 8 shows a sample load profile that was used in dynamic loading studies in one of the offshore wind farm projects [20].

Usually, the contractor should develop a detailed design of the cable according to the most updated installation conditions for steady-state loading and additionally, a dynamic rating-based design is required. The thermal design of the cable aims to avoid any overheating of the insulation under the loading and installation conditions of the project, taking into account the thermal limits of the XLPE insulation.

Additionally, offshore export cables should be designed to withstand maximum short-circuit currents without exceeding the maximum

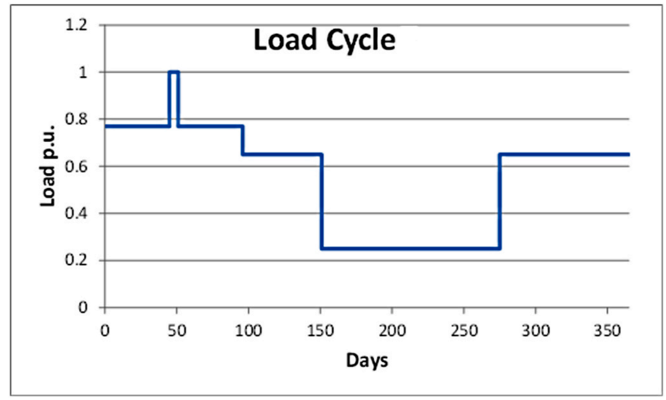

Fig. 8. Dynamic Load current profile showing level and duration of each load step.

temperatures of the conductor and the rest of the cable components. The calculation of the permissible short-circuit currents of the offshore export cable is normally performed according to the IEC standard [18]. The short-circuit temperature limit for cable components are specified in Ref. [19].

In the majority of cases, HDDs are generally assumed not to pose a hot spot for the cable system. Due to the dynamic behavior of the load, it can generally be shown that the normal trench is the limiting part. However, as mentioned above, it is difficult to state off-hand which section of the cable route will be limiting. This is important because submarine cables exhibit several installation interfaces that are not present in land cable designs as outlined in the next section.

4.6. Cable route interfaces

When analyzing submarine installations, detailed cable continuous current rating calculations for several cable route interfaces are usually required. Typical interfaces would include:

- Interfaces A: Substation Installation (Internal Platform Cables (IPC))
  Interface A1: Connectors on single core IPC cables in switchgear
  Interface A2: Single core IPC cables in/below switchgear
  Interface A3: Single cores in cable ladders on cable deck (in open air)
  Interface A2.3: Single cores from switchgear to main transformer
  Interface A4: Parallel single-core circuits in cable ladders (in open air)
- Interfaces B: Substation Installation (Platform Connection Cables (PCC))
  Interface B1: Subsea cable free hanging in hang-off support
  Interface B2: Subsea cable free hanging below hang-off support
  Interface B3: Subsea cable free hanging in J-tube (in air)
  Interface B4: Subsea cable free hanging in J-tube (in water)
- Interfaces C: Subsea cables in Cable Protection System (PCCs and ICCs)
- Interfaces D: Cables Buried Directly in Sea Bed (PCCs and ICCs). Since the depth of cable burial is often unknown and/or it changes during exploitation, these calculations are usually performed for a range of cable depths.

When possible, calculations should be based on the methods described in the IEC standards [15–19]. However, for some interfaces listed above no standard recommendations exist. In such cases, numerical methods, like for example the Finite Element Method (FEM) can be used. When FEM is applied, great care should be taken in constructing the model and defining boundary conditions. Since such calculations are usually very complex, experts with extensive experience in these types of studies should be employed. As a review of several failures of submarine cables has shown, this part of the analysis is often taken lightly to save costs but, as mentioned above, the consequences can be severe.

5. Historical perspective for submarine cable failures

The reasons for an OWF cable failure could be divided in to five categories as illustrated in Fig. 9. We will discuss each category in more detail focusing on the time of their occurrence during the life cycle of an offshore power cable.

During the manufacturing process, factory joints are installed to produce long lengths of power cables. Cables with lengths up to few tens of kilometers have to be wound on a turntable for storage prior to transport. It is known that the manufacturing imperfections caused, for example, by wrong design, inappropriate materials, lack of compliance with the standards or due to the application of only the minimum required routine testing, could result in:

- voids, cavities and delamination
- contaminations in the cable insulation
- inadequate implementation of the shield materials
- protrusions on the cable shields
- inadequate application of the jackets

To prevent the occurrence of such defects during the production of long lengths of submarine power cables, quality control involving dedicated sensitive electrical tests is needed. It is up to the cable manufacturers and the developers to set the requirements for factory routine testing and the delivery conditions. As each OWF project requires its own solution, a gap might occur between quality control and the product soundness.

During transportation from the factory to the offshore installation site, the long lengths of cables are rewound on another turntable for transport with weights of 2500 tones and more followed by storage of cables and accessories at the quayside in a port. Finally, after rewinding on a vessel, the cables and accessories are transported to the site. As the cables are rewound several times for storage and transportation, excessive bending and pulling forces might occur to the complete cable batch with the consequence of creating mechanical weak spots. Such mechanical over-stresses can result in a (local) reduction of the dielectric strength. If the mechanical stress is localized, the impact can be restricted to short lengths of cable.

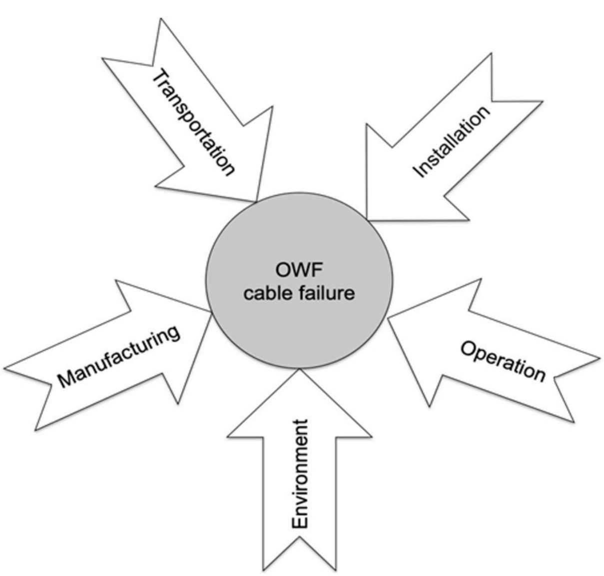

Fig. 9. Basic risk elements of a cable system failure at the OWF.

Installation of offshore cables involves different aspects of laying, with the main route requiring the application of various burial methods depending on the type of the seabed. Here, temporary facilities on the offshore structures for cable pull-in (e.g., through the J-tubes) are used. During the construction of crossings or entrances to the wind turbine generator, rock or other materials are placed for cable protection. Furthermore, the installation covers the adjustment of the cable lengths, the cutting of cables, sealing and securing of the cable ends by permanent hang-offs at the wind turbines and offshore platforms. Finally, the installation of the cable terminations and installation in the switchgear ends this process.

Considering the complexity of the installation process in an offshore environment, as well as all risks coming from the manufacturing and transportation phases, dedicated testing of the installed cables is crucial for the verification of the integrity of the complete cable system and to exclude such defects as:

- cuts in polymeric materials
- contaminations on interfaces
- missing or wrongly applied components or connections or incorrect dimensions
- misalignment of accessories

All that potentially leads to an increase of the local stress and can eventually lead to early failure or a higher aging rate during operation.

During the operation, the submarine power cable circuits are subjected to high fluctuation of the power load. These changing loads might result in high operating stresses on the cable and accessories (joints, terminations). Also, the inter-array cable circuits are mostly not redundant and in a string configuration, which means that, in the case of a cable failure, high losses might occur, as multiple wind turbines cannot deliver energy, (see Fig. 10 a).

There is usually no redundancy in export cable installations. In case of a cable failure, the complete power of the wind farm cannot be delivered to the grid, resulting in high financial losses, (see Fig. 10 b).

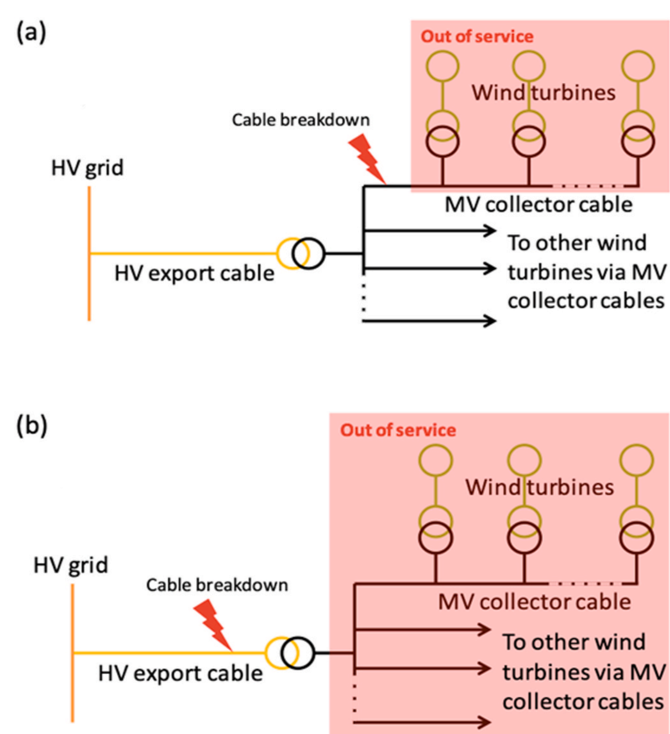

Fig. 10. Example of failure consequences: a) in case of a failure in the MV inter-array cable a part or the complete string of wind turbines is out of service and cannot deliver power to the grid; b) in case of a failure in the HV export cable.

Furthermore, the operation effects that can result in a (local) reduction of the dielectric strength, where the impact can be restricted to short lengths of cable if the unfavorable thermal environment is localized. Such stresses are caused by:

- overheating
- mechanical stress
- water ingress
- operational stresses under the environmental and operating conditions, which can be related to the excessive current through the cable conductor (global),
- the proximity for a short distance to other infrastructure, e.g., other cable circuits (local).

The environmental aspects could be divided into fishing activities and ambient influences. The first ones are due to trawling and damages caused by anchors. Those rank as the highest cause of subsea power cable failures (export cables). The ambient influences could have a mechanical or chemical impact on the export and the inter-array cable system integrities.

In particular an aggressive and/or wet environment means:

- chemical attack e.g. transformer oil leaks or petrochemical spills
- floods
- neutral corrosions.

The wet environment (can increase the local stress which can reduce the dielectric strength):

- bowtie or vented water trees
- high rates of corrosion
- damage from dig-ins (local).

The ingress of water (can lead to the reduction of the dielectric strength and an increase of the stress in the area around the moisture), as a result of:

- normal migration through the polymeric materials
- breaks/damages in seals or metallic sheaths.

Summarizing the above factors, stresses can be divided in to five categories, indicating the specific mechanisms that can result in the excessive mechanical, electrical or chemical over-stresses or bulk deterioration of an offshore cable.

The complexity and the wide range of factors having influence on a reliable offshore cable operation, are not comparable to the situation with the land power cables. This might explain the fact that presently about 80 % of the OWF problems are connected to submarine power cables.

Based on the above discussion, it can be concluded that the quality and the reliability of submarine cables are closely linked. Keeping quality means reducing teething problems, avoiding manufacturing defects and transportation and installation mistakes. High reliability means preventing failures during the complete operational life, from the commissioning until decommissioning. The challenge is to develop an approach that includes all the risk factors discussed in this section that will also increase the reliability of the offshore cables and reduce the number of failures.

6. Reliability and the cost of failure

To determine the cost-effectiveness of power generation systems and in the field of electrical systems, the reliability approach is frequently used [21,22].

For an OWF, reliability means the probability that the given installation is able to operate under the electrical, thermal, mechanical and environmental circumstances, as defined for the service lifetime of a windfarm. As a result, the reliability can be considered as a percentage-indicator of an operational success. E.g., an 80 % reliability of an OWF means that installation will operate without a failure 80 % of the time.

Reliability engineering frequently uses additional parameters such as availability which describes the probability that the power generation can operate when it is needed; Availability = Uptime/(Uptime + Downtime) and maintainability, which describes the probability that an installation can be repaired in a given amount of time [22]. In general, availability will be highest when the uptime will be large and downtime will be small and to achieve this goal a high reliability is needed. For example, with conventional power generation with an active, controlled supply of fuel, the reliability is about 99.9 % and the availability factors are ranging from 80 % to 99 % [23]. Although an OWF cannot operate in wind speeds below or above certain limits, modern wind turbines, have availability factors of up to 98 %, with very little maintenance [23].

Since power cables are the major contributor to OWF failures, an increase of the reliability of an OWF means increasing the reliability of these distribution/transmission components. This is a serious concern for manufacturers of the electrical equipment and the OWF operators [21]. With the IEC-based insulation coordination rules for type and routine testing of submarine power cables [11,24,25], the majority of design, materials and manufacturing problems can be overcome. Unfortunately, as discussed in the previous section, most problems contributing to the reduction of quality of the submarine power cables come from the process of transportation, installation and operation.

Assessment of the reliability of submarine power cables is not as well established as it is for land installations. There are several reasons for this. One is the complexity of a typical OWF often with hundreds of kilometers of cable infrastructure. Table 1 serves to illustrate this problem. It can be observed that the total length of the inter-array cables is much higher than the export cables and as a consequence, their failure rate is usually higher. In addition, due to confidentiality restrictions and shareholders' interests, the service providers of the OWF facilities are very reluctant to provide failure statistics [26]. Systematized information about failure data can be found in Ref. [27] and in some other publications [28,29] for export cables only. Despite contributing about 80 % of the cost to the offshore installation failures, there are neither systematic studies of failure causes nor discussions of the possible measures to improve the reliability of offshore cables.

References [27–29] provide failure rates of the XLPE insulated offshore cables. However, there is a significant difference between the published failure rates and this, in turn, has an impact on the estimated supply reliability, as illustrated in Table 2.

The failure rate in Ref. [26] is mainly based on external causes. On the other hand, the category of AC XLPE cables used in Ref. [27] is extremely broad, and includes cables that are irrelevant for offshore wind applications. The failure rates provided in Refs. [28,29] are more realistic as they are based on the actual failures of the submarine cables used in the OWFs.

It can be found that 10 %–20 % are a result of internal failures of cables and their accessories (18% in Ref. [27]). If the number of those failures can be reduced by applying a selective after-laying testing, the supply reliability would increase significantly.

Table
1*Example of the cable assets complexity of a typical midsize OWF* e.g., 600 MW.

	Export Cables 150 kV/ 220 kV	Inter-array Cables 33 kV/ 66 kV
Number of cable circuits	2	100
Number of cable terminations	12	600
Cable joints	Factory/site	Factory
Accessories installed offshore	6–12	600
After installation test	Onshore	Offshore

Table
2 *Overview of the reliability of offshore cables based on different studies and the effect of lowering the failure rate with selective after-laying testing.*

	According to [27]	According to [28]	According to [29]
Failure rate λ (failures/km/year)	0.000705	0.00299	0.008
Repair time (days)	90		
Export cable length (e.g., 1 GW OWF) (km)	210		
Reliability (%)	96.3	84.3	58.0
Reliability with a 10 % improvement (%)	96.7	85.9	62.2
Reliability with a 20 % improvement (%)	97.0	87.4	66.4

It follows from Table 2 that reliability calculations results based on different data may show large differences in the range of 58 %–96.3 %. We can also observe that those values are low compared with the conventional power generation reliability standard value of 99.9 %. When we also consider the annual wind availability of about 40 % and dependence on the wind strength fluctuations and the aging process of the windfarm installation [30] it appears that much improvement is needed in OWF reliability.

To illustrate the financial consequences of submarine cable failures, let us consider an example of a mid-sized OWF [9] with 48 turbines and 48 inter-array cables (divided in 8 strings) where in 3.7 % of them enhanced risks of potential annual failures have been observed. The reliability and cost indices reported in Table 3 are computed assuming a failure rate of 1.78 failures/per year with respect to the OWF total inter-array cable grid and considering 1, 2- and 3-months stoppage periods. The above failure rate and having an incident with a 1-month duration results in 86 % reliability.

The longer the incident, the lower the reliability is. Considering the costs for non-delivered energy (based on the average capacity factor and the price per MWh), it can be seen that the costs increase significantly depending on the location of the failed cable within the string.

Combining the inter-array cable indicators with the 58 %–84 % reliability of the export cables shown in Table 2, we can conclude that this performance cannot be accepted for an OWF with e.g., 800 MW installed power.

As discussed earlier, the financial losses due to turbines out of operation can easily reach over € 100′000 within three days. Taking into account the failure rates for terminations and other relevant factors, a post-installation test can have a positive financial effect, especially if it can prevent e.g., a cable termination fault. The costs, as shown in Table 3, are several orders of magnitude higher than the costs of a more careful one (more time and/or more skilled installers) during the installation or more dedicated testing. The additional installer and testing costs are approximately € 10′000 to € 15′000 per turbine subject to the scope of the testing. Furthermore, these costs reduce with volume.

Table
3 *Reliability and financial losses of inter-array cable failures. Approximate failure costs for a* 48 WTG (295 MW) *OWF (With a price of € 52/MWh, assuming a wind farm efficiency capacity factor of 40 %* [31]*).*

Outage	Reliability	1 WTG (6.2 MW) affected (End of String)	6 WTG (37.2 MW) affected (Start of String)
1 month stop	85.8%	€ 92′900	€ 557′100
2 months stop	71.7%	€ 185′700	€ 1′114′200
3 months stop	57.5%	€ 278′600	€ 1′671′300
Repair costs of one cable accessory		€ 100′000–300′000[a]	€ 100′000–300′000[a]

[a] Depending on the complexity of the repair.

According to Ref. [9], there are two main categories of an export cable failure that have an economic impact: the cost related to the repair of the cable and the cost related to the unsupplied electric power for the duration of the failure. This can range from several weeks (for a pre-emptive repair) up to 3–9 months for an unexpected fault. The cost of a cable repair includes:

- Fault location: the precise fault location has to be determined
- Vessel mobilization: a suitable repair vessel needs to be arranged including equipment and personnel
- Cable de-burial: the failed cable part needs to be recovered
- Cable removal: removing the length of cable that includes the fault (often several hundred meters long)
- Cable jointing: installing a length of spare cable to replace the removed section
- Cable re-burying: placement of the cable on the seabed with suitable protection.

The export cable repair costs will further depend on market and weather conditions and can be extremely high. Based on several reported export cable failures in the past years, the average repair costs are defined as € 14 million (ranging from € 6 million to € 17 million) [9].

The cost of a pre-emptive repair (estimated at € 4 million) is projected to be substantially smaller than the cost of an unplanned one.

The above-mentioned costs for a failure repair can quickly be doubled if the financial loss of the undelivered energy is also taken into consideration [9]. An estimate of the total cost to the industry due to cable failures can be estimated taking into account the repair costs, the actual repair times, and the typical price of a loss of supplied energy (€/MWh).

The total power rating of a wind turbine also plays a significant role. In the future, 14 MW wind turbines will be installed requiring higher power and voltage ratings for cables with higher electric fields and consecutively higher electric-stresses. Without any principal changes in the cable supply chain, the cable installation deficiencies would lead more quickly to a failure during operation and to even higher financial losses as a result of the increased loss of energy. Therefore, to prevent costly failures during operation and to verify cable system quality, higher quality of transportation, installation and a more dedicated post-installation testing program would be beneficial.

Compared to land cable installations, offshore cables are often manufactured in long lengths. From manufacturing up to the offshore installation, a lot of handling takes place. This results in higher risks of cable damages compared to the land cables [9]. Therefore, it is necessary to implement an integral approach, where the actual condition of the cables will be verified. With the obtained quality fingerprints, a comparison could be made to verify the cable quality during the complete supply chain [9]. Moreover, considering the reliability expectations over its lifetime, the fingerprint information could also be utilized for cable maintenance activity later during its service life, as illustrated in Fig. 11.

7. Quality control OF OWF power cables

Considering that reliable energy transport and distribution are fundamental for an OWF, various facets of the quality control for newly installed and in-service offshore cables are important for asset management, as illustrated in Fig. 11.

As a result, for maintaining/updating internal procedures for a reliable offshore cable network operation, manufacturers, developers, contractors and system operators should ask some important questions:

1. Are the quality tests in the factory sufficient to exclude possibilities of a defect?
2. How to perform a sensitive detection of transportation over-stresses leading to hidden damages?

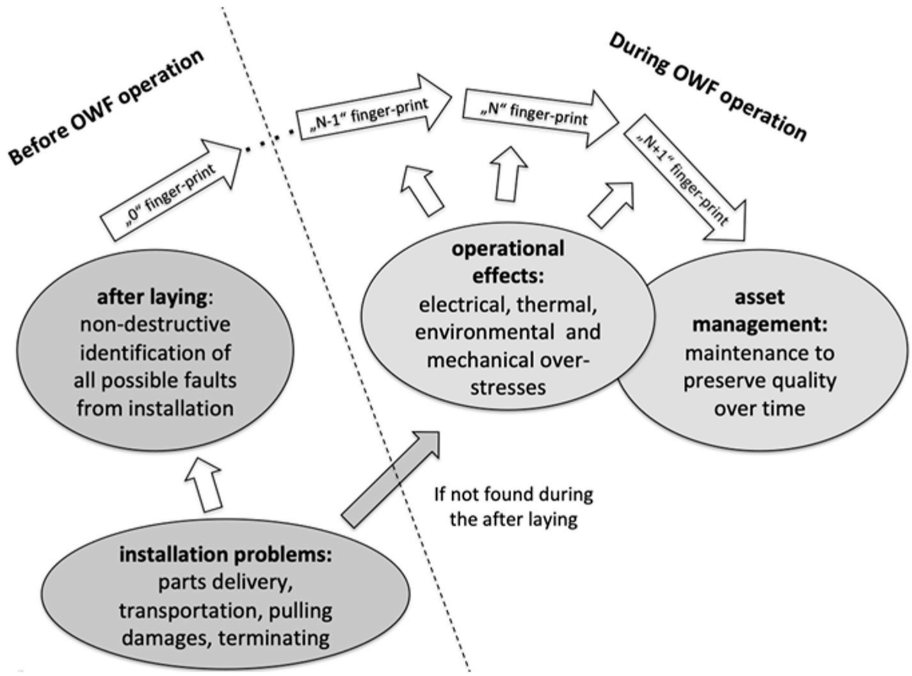

Fig. 11. Basic asset management factors determining a safe and reliable grid operation for OWF power cables. The "finger-print" approach means a cable system quality determination over the overall life-time by evaluation of diagnostic parameters e.g., partial discharges, dissipation factor (Tan δ), etc.

3. How to detect poor workmanship defects of newly installed offshore cable circuits in a sensitive and non-destructive way?
4. How to determine the actual condition of offshore cable circuits in service by means of non-destructive diagnostics?

It is known that IEC standards [11,24,25] are mainly addressed to cable manufacturers and therefore, the majority of the content relates to various aspects of factory testing. In most standards, no up-to-date guidelines are provided regarding recent field experiences related to the after-laying and maintenance testing of the submarine cable circuits. The traditionally recommended over-voltage testing with the binary test result outcome" break-down" (rejected) or "no break-down" (accepted) can exclude only major defects, but has not much added value to provide a safe and reliable grid operation for the OWF export and inter-array cable connections.

Therefore, some countries or developers and contractors are developing their own more dedicated procedures [32–37] to test newly installed inter-array cables that are based on their own experiences and international standards. These regulations represent a more current state-of-the-art of non-destructive methods for both post-installation and maintenance testing and diagnosis [38–40].

According to Ref. [41], using simple on-site voltage tests with maximum voltages of up to 1.7 x Uo (nominal operating voltage between cable conductor and earth), the number of breakdowns as

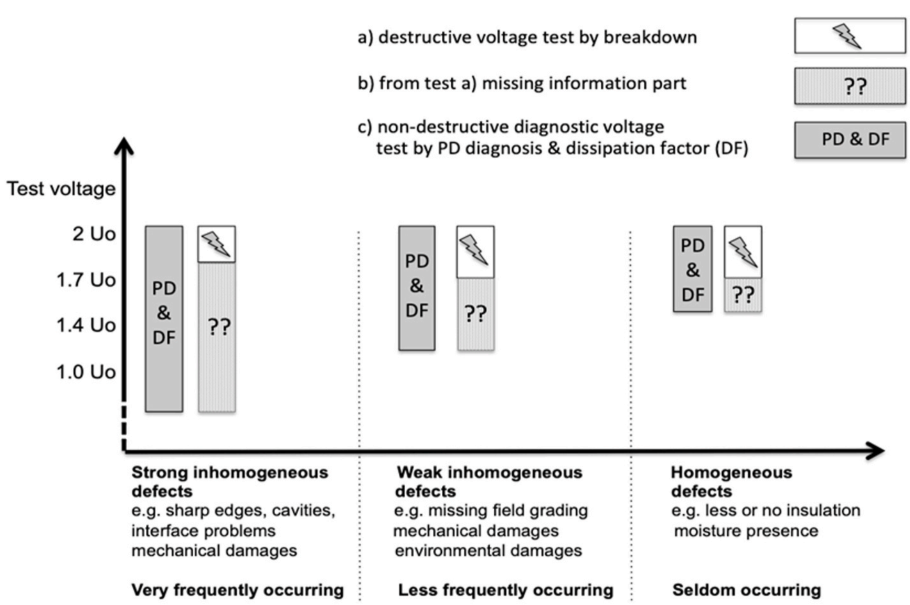

Fig. 12. Schematic effectiveness to detect insulation defects in an offshore power cable system using PD diagnosis and dissipation factor DF (tan δ) versus simple voltage breakdown testing.

observed by newly installed onshore cable circuits might reach up to 8 incidents per 100 km. The reasons of those failures are believed to be caused by incorrect cable jointing due to time pressure to finish the project and due to poor workmanship by the installers [41].

It is known, that during a simple over-voltage test, an insulation breakdown occurrence depends mostly on the homogeneity of a defect, as illustrated in Fig. 12.

However, in reality the number of installation defects per 100 km cable length might be much higher as only serious defects can be detected using the voltage breakdown testing and because potential strong and weak – as well as inhomogeneous – defects are not discovered, see Fig. 12. This has been confirmed in Ref. [39] by reporting that only 42 % of the defects produce breakdown during testing whereas 72 % of defects produces PDs that might be considered pre-breakdown phenomena. Consequently, a responsible operation and asset management of offshore power cables has to consider a number of aspects [42–44], as illustrated in Table 4.

A safe and reliable OWF cable grid operation already starts at the moment of commissioning a newly installed cable circuit. Considering the fact that the number of installation defects might be more than 10 per 100 km cable length and that the on and offshore HV cable links are getting longer and longer, we can conclude that [36]:

- Destructive over-voltage testing only is not technically optimal and sufficient for the detection of all possible installation defects;
- PD diagnosis is more sensitive to detect all defects.

As a result, a sensitive PD-monitored withstand test can be more effective in the identification of faults originating from poor installation and for providing the so-called "0"-fingerprint for further condition evaluation of a cable circuit, e.g., to be compared just before the end of the warranty period, (see Fig. 11).

In the last 30 years, different testing methods have been introduced and are currently in use: continues AC resonant (ACR), damped AC (DAC) and very low frequency (VLF) [38]. Consequently, from the beginning of the OWF installations, these methods have also been used for testing offshore power cables. Unfortunately, considering higher demand on quality control for these cables as compared to the land cables, not all of these methods are providing good results, as illustrated in Table 5.

Table
4 *Basic aspects of a responsible operation and asset management of OWF power cables.*

Goals of after installation testing of newly installed export and inter-array cable systems		Goals of maintenance and diagnostic testing of export and inter-array cable systems in service	
Source of problems	Probability to find	Source of problems	Importance
Manufacturing related defects	Low due to high level of manufacturing quality control	Operational damages and electrical, thermal and mechanical over-stresses	High, cannot be neglected e.g., transients, over-voltages, over-loading, etc.
Accessories parts delivery problems	Medium due to diversification in the supply chains	Assess aging processes	Medium, depends on various operational and local factors e.g., presence of installation defects, constructions work, etc.
Installation related defects	High due to diversification in the installation supply chains, poor workmanship, etc.	Lack of knowledge about the remaining life	High, keeping CAPEX and OPEX on an optimal level is the objective of most asset managers

Several studies performed by different parties during the last 20 years have shown that when considering voltage stresses, partial discharge (PD) occurrence and the dissipation factor measurement (tan δ), there are no significant differences between traditional ACR and modern DAC methods [44–48]. Compared to other methods, DAC technology allows more sensitive PD detection [49–51] and localization of the problematic areas in a complete cable system (terminations, all types of joints, cable sections). This method has been used extensively for land cables and also for a few years for offshore power cables [37,52,53]. Considering the use of PD as a criterion for accepting/rejecting a newly installed cable circuits, the ongoing discussions concern the establishment of suitable acceptance criteria.

Due to reasons of liability, no international organizations like Cigré, IEEE or IEC will be able to define exact acceptance criteria for on-site testing. The above situation is fully understandable as a PD detection should be considered on a case-per-case basis including factors like calibration uncertainty, detection sensitivity and to the local electromagnetic interferences occurring on-site.

The introduction 20 years ago of the damped AC technology for the onsite testing of power cables [38,54,55] opened the possibility of reproducible testing conditions for PD detection [56,57] as illustrated in Table 6.

As a result of scientific research projects [9,37,53,54] and about 20 years of worldwide testing of MV and HV power cables at more than hundred different installations, the parameters summarized in Table 7 could be recommended as general criteria to determine if a cable has passed the test and if it is sound for operation.

Reference [36] reports that using DAC testing with PD mapping helps in faster pinpointing the fault locations after breakdown of a HV cable with accuracy of several meters. Whereas the use of the continuous test voltages may create extra damage at the fault location with the consequence of more difficult fault investigation as well as more difficult and costly repair.

In this section, the emphasis was on high voltage after-laying test of OWF submarine cables. This is one of many tests that can be performed on cables to verify their condition. Although the combination of a high voltage DAC after-laying test with partial discharge measurement will result in finding defects at an early stage, it will not find all possible cable-related defects. In particular, as long mechanical, environmental or thermal defects do not result in local electrical degradation of the cable system e.g., by local electric field over-stresses or in a breakdown during the test, they will remain undetected, which can lead to a future failure during operation.

Because almost all cable failures are sooner or later of an electric kind, when considering different testing methods timing needs to be found on what is technically and economically feasible on the one hand and the effect it has on the reliability on the other.

8. Recommendations and conclusions

Based on the discussion in this contribution, supported by extensive references, the following conclusions may be drawn:

1. In the upcoming years, a 19 % worldwide growth of new offshore wind farms (OWF) is expected. This process will be accompanied by an increase of the OWF generation capacity to more than 1 GW per farm, by almost doubling of the wind turbine power generation capacity up to 14 MW, by longer distances to the shore e.g., 90 km and by demand on higher power ratings for power cables and substations components.
2. The experiences from last decennia of OWF generation have indicated, that offshore cable failures are responsible for up to 80 % of total financial losses. These facts are worrisome as cable investment accounts for less than 10 % of the total OWF capital costs.

Table
5 *Overall evaluation of test technologies for PD monitored withstand test of offshore power cables* [9].

Test Technology	Technical Acceptance (Meets Recognized International Standards, e. g., IEC, IEEE)	Capability of Testing High Capacitive Load (Long and Multiple Cables)	Off-shore Application (Size, Weight)	Sensitive PD Detection (System PD level, PD Characteristics)	Price-Performance Factor
ACR + PD	++	±[a]	–	-[c]	–
VLF + PD	±[d]	±[b]	+/−	-[c]	+/−
DAC + PD	+	++	++	++	++

[a] When connecting multiple resonance reactors.
[b] When lowering the VLF test frequency to e.g., 0.01 Hz.
[c] Voltage source produces high electromagnetic interferences during the PD measurement.
[d] Only accepted up to 69 kV for onshore, up to 33 kV for offshore.

Table
6 Testing and diagnostic parameters for offshore power cables.

Voltage withstand test	Partial Discharges	Dielectric losses
YES/NO breakdown during min. 50 DAC excitations voltage withstand test at max. selected test voltage conform [11,24,25,38,39]	PD inception/extinction voltage (PDIV/PDEV) PD magnitude in pC [39,40,56,57] qV- characteristics	Dissipation factor Tan δ
	Phase-resolved PD pattern PD localization in a complete cable circuit	The ration of tip-up Tan δ

Nowadays, DAC technology provides the possibility of energizing high capacitances, i.e., long lengths of power cables, with a low input power demand combined with a sensitive PD detection and localization [55,58–60]. Submarine cables with the length of up to 60 km of have been tested in Europe with this technology [37].

Table
7 General testing and evaluation general criteria for OWF power cables.

General criteria	Cable voltage class up to 230 kV
Maximum test voltage	IEC 60840, IEC 62067, IEEE 400.4, IEEE 400 After-laying test: 1.4–2.0 x Uo (depending on the cable voltage class)
Background noise level PD measurement (IEC 60270)	≤25 pC with tolerance of ±20 %
Withstand test criterion	No breakdown during the withstand test (50 DAC excitations) respectively (1 h using ACRT) at the maximum test voltage level
PD criterion	No concentrated PD activity (>6 PD events per cycle) above the background noise level on the maximum test voltage level
Dissipation factor criterion	Tan δ ≤ 0.4 %/Δ Tan δ ≤ 0.2 % with tolerance of ±20 % up to the maximum test voltage level (values depending on the insulation material)

3. Several of the reported cable failures were the result of poor design practices. Therefore, there is a need for establishing sound submarine cable design criteria including proper handling of calculations of various interfaces not present in land installations.
4. Technical solutions in wet cables are cheaper compared to dry dynamic cables, however, when designing a cable line, the material used for the production of conductors should also be considered.
5. In contrast to the use of copper, the use of aluminum as the cheapest conductor may entail high service costs in the future resulting directly from its physicochemical properties.
6. The final tests of factory joints' quality are not perfect in terms of consistency and homogeneity of the structure or electrical parameters. Checking the correctness of the factory joint at the factory floor, apart from visual and X-ray inspection, has to be improved e.g., by standardized and IEC calibrated PD detection.
7. Most of the vessels that are currently in operation were designed to lay cables with copper conductors, meaning heavy cables with a compact outer diameter. The use of aluminum cables sets another limit, namely the limit of the maximum volume of the turntable on vessels, but not the problem of weight capacity.
8. Submarine power cables are subjected to high mechanical stresses even before they are energized. They are rewound several times and laid at significant depths subjected to bending and torsional forces. The long-term effect of this damage to the electrical and mechanical integrity of a cable cannot be determined.
9. When designing submarine cable systems particular attention should be paid to the methodologies that are different from the land cable procedures, to which the majority of cable designers are applied.
10. There are several cable interfaces in the submarine installations for which current rating should be computed and which do not appear in land systems. In particular, cable protection systems, J-tube or HDD sections for landing the cables onshore should be investigated.
11. Since during laying of a submarine cable very large mechanical stresses can be present, the design stages of the various cable components require special tools and techniques to ascertain whether the cable will not be damaged during installation.
12. Reasons of offshore cable failures have been identified and classified into five categories: manufacturing, transportation, installation, operation and environment. The impacts of failures on reliability, availability and costs are discussed and the urgency to eliminate those reasons has been pointed out. Since in the future OWF cables with higher capacity will be needed, this will increase the already present over-stresses, and hence enhancing the probability of a failure.
13. As the present international regulations for quality-control after installation of power cables are deficient, sensitive and non-destructive methods have been discussed and a proposal has been made regarding how to generate an integral fingerprint for a cable for the time of the installation and also for the time of operation of an OWF.
14. Using these dedicated methods better quality control of newly installed offshore power cable circuits and approaches to preserve power cable quality over the OWF operation time will be possible, resulting in a higher reliability and consequently, lower costs of outages.

Author contributions

Edward Gulski: Conceptualization, Investigation, Writing - Original Draft, Visualization, Supervision. George Anders: Conceptualization, Writing - Original Draft, Validation. Rogier Jongen: Writing - Original Draft, Writing - Review & Editing, Visualization. Jaroslaw Parciak: Writing - Original Draft, Investigation. Jakub Siemiński: Writing - Original Draft, Elżbieta Piesowicz: Writing - Original Draft. Sandra Paszkiewicz: Writing - Original Draft. Izabela Irska: Writing - Original Draft.

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.

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