State of the art: Corrosion protection for offshore wind turbines

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Abstract

This review paper provides an initial overview of the state of the art of common corrosion protection methods for offshore wind turbines. The functions of the individual corrosion protection methods and their interaction are explained. In addition, the specific corrosion protection of different zones and components of an offshore wind turbine will be discussed. Finally, some information is given on current and possible future developments in this subject area.

Keywords: corrosion protection, offshore wind turbines

1 Introduction

In recent decades, the use of offshore wind turbines to generate electricity has significantly increased as they present a sustainable and environmentally friendly energy source. A major expansion of renewable energy is required in all sectors to meet the German government's ambitious target of making German electricity generation 80 % climate-neutral by 2030 and completely climate-neutral by 2045. In the first half of 2023, renewable energy sources only provided around 52 % of the electricity consumed in Germany [1]. Offshore wind can therefore represent an important component for climate-neutral electricity generation in the coming years. Offshore installations are exposed to extreme environmental conditions such as salt water, wind and waves, which leads to an increased risk of corrosion. Corrosion can not only significantly shorten the service life of the turbines, but also lead to significant economic losses. As a rule, these structures are designed to last more than 25 years. It is therefore of great importance to develop and apply effective corrosion protection measures to ensure the long-term performance and reliability of these systems.

2 Corrosion mechanisms at sea

The environmental conditions at sea demand much greater resistance and durability from wind turbines. The turbines are exposed to various, sometimes extreme stresses at sea:

- Extreme weather conditions
- Mechanical stresses
- Biological stresses

Extreme weather conditions at sea are characterised by wind, waves, extreme temperatures, UV exposure and especially increased exposure to salty seawater [2, 3]. Compared to drinking water, seawater can be characterised as corrosive due to its salt content. Corrosion effects increase with rising salt content [4].

Offshore wind turbines are exposed to additional mechanical stresses due to currents and waves, floating objects, the landing of boats and the installation of the structure [2, 5].

Furthermore, marine growth, e.g. by mussels, barnacles or algae, can have an additional influence on the chemical conditions of the metal surface of the structure and negatively affect the corrosion behaviour [2, 5].

When considering corrosion-promoting stresses at sea, it is therefore a complex combination of different influencing factors. Careful analysis of all factors and their interaction is necessary to ensure sustainable utilisation of the systems over a long life cycle. Due to their high susceptibility to corrosion, offshore structures are categorised in the most critical category CX "extreme corrosiveness" [6].

Corrosion and fatigue are the main causes of the primary loss of strength of steel in offshore wind turbines [3]. Corrosion can reduce the thickness of steel components and thus increase the risk of fatigue cracking and buckling. Information on corrosion appearances and failures on offshore wind turbines is generally rare, as systematic analyses were or are often not part of the maintenance and repair activities and information on damage is kept secret for intellectual property reasons [5].

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Plagemann and Momber [5] provide an overview of the causes of corrosion in the first years of operation of a plant:

- Mechanical damage (30 %)
- Wrong design (30 %)
- Insufficient coating (24 %)
- Welding (11 %)
- Environment (5 %)

The causes of corrosion can often be traced back to defects or damage to the protective coatings during the installation of the plant or the manufacture of the components [2, 3, 5]. Flange connections, in particular, can be critical structural parts due to corrosion in gaps (crevice corrosion) resulting from moisture and inadequate coating adhesion during installation [2, 7]. For corrosion protection reasons, welded connections are generally preferable to flanged connections.

Wind turbines at sea are usually categorised into different zones, which are exposed to different conditions, show varying degrees of corrosion and therefore require different corrosion protection. Figure 1, based on [5], provides an overview.

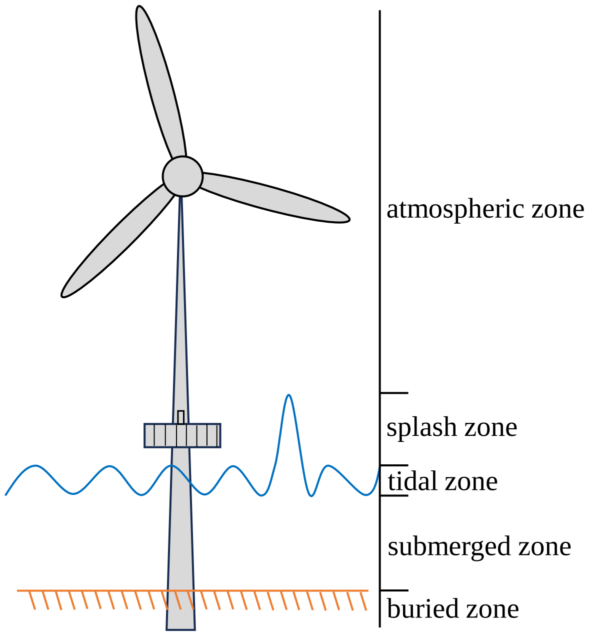

Fig. 1: Stresszones offshore wind turbines

Different corrosion rates are assumed for each zone. According to DIN EN ISO 12944 [6], the maximum corrosion rate for heavily loaded components is 0.7 mm/a, whereas Momber et al. [2, 3] report maximum corrosion rates of up to 2.5 mm/a under extreme conditions. Components located in the tidal and splash zones experience the highest levels of stress because they are subject to alternating wet/dry cycles and the surface is often permanently covered with a thin film of moisture through which oxygen can easily diffuse to the metal surface, allowing corrosion to progress most rapidly. The rate of corrosion is reduced underwater (submerged zone) because oxygen can hardly reach the metal surface. The impact of marine growth has not been clearly investigated in the literature, although it is known that microbiologically induced corrosion (MIC) can lead to serious and rapid corrosion failures [2, 3, 5]. In addition, the corrosion rate is lower when in the atmospheric zone, where salt has a reduced influence, and infrequent wet/dry cycles occur.

3 Corrosion protection

Corrosion protection at sea is not a fundamentally new issue that has come up with the construction of wind turbines at sea. The majority of measures to protect against maritime corrosion originate from shipping, harbours, and oil and gas extraction at sea [2–4]. Nevertheless, offshore wind turbines differ from oil and gas extraction in that they mostly remain unmanned structures with very limited access. On oil and gas platforms, corrosion protection systems are usually subject to permanent inspections, which is often not the case with offshore wind energy. Therefore, reliable corrosion protection is all the more important to guarantee a long, reliable service life. To achieve this, several guidelines and standards provide reliable guidance, such as [8–12].

It is generally split into active and passive corrosion protection. However, it is important to note that corrosion allowance, a corrosion-friendly design, as well as maintenance and inspection also have important roles to play.

3.1 Passive corrosion protection

Passive corrosion protection describes the application of a barrier layer to prevent the material from coming into contact with the corrosive environment. This creates an artificial barrier on the material surface and represents the most used form of corrosion protection on offshore structures [3].

The most important criteria when choosing a coating system are [3]:

- Type of building
- Importance of the structure
- Environmental condition
- Required durability
- Performance

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- Costs
- Surface preparation
- Application

Several layers of coating with different properties can be applied to structures. The compatibility and adhesion between individual layers is of great importance. These layers can be metallic, non-metallic or a combination of both [2, 3]. Metallic layers protect the structure through galvanic protection and by acting as a barrier layer. As a rule, non-ferrous metals such as

- Aluminium
- Zinc
- Alloys of both metals

can be used because they are more corrosion-resistant than ferrous metals. Non-metallic coatings are mainly organic based. Developments are focused on [2, 3]:

- Antifouling coatings
- Composite materials
- Nanocoatings
- Self-healing coatings
- Sol-gel coatings

As mentioned by Price and Figueira [3], there are only a limited number of studies and field reports on self-healing and sol-gel coatings, as these coating systems are not yet established on the market and are still in the development and optimisation phase. Organic protective coatings are commonly used in combination with metallic coatings [3, 5]. It is also important to note that the use of only metallic coatings is not allowed [10]. The most corrosion-resistant protective coating is currently considered to be the duplex system, as reported in [2, 3, 5]. This includes applying a metal coating (ZnAl15 base layer that is thermally sprayed) along with an intermediate layer made of particles-reinforced epoxy resin and a top layer made of polyurethane.

This coating system is used on all metallic components of the offshore structure, including the submerged zone. It is important to note that repairs cannot be made in these underwater areas after installation. To effectively prevent corrosion, active corrosion protection must be used in addition.

The long-term impact of coating systems in terms of emissions and impact on the marine environment is still unclear [4].

3.2 Active corrosion protection

Active corrosion protection aims to minimise the rate of corrosion if the protective barrier has been damaged, and corrosive substances have come into contact with the metal surface. This protection is electrochemical in method.

The aim is to supply electrons that prevent the metal from dissolving through an electrochemical reaction. This is done by providing the metal surface with a protective electrochemical potential. To achieve this, an electric direct current (DC) is passed through the corrosive medium into the object to be protected. The direct current causes cathodic polarisation, which shifts the metal potential to more negative values and simultaneously reduces the corrosion rate [4, 5, 13, 14]. Effective corrosion protection occurs when the current density on the surface is strong enough to decrease the potential to an acceptable level, resulting in an acceptable corrosion rate for the structure [14].

This type of corrosion protection is known as "cathodic corrosion protection" and is mainly applied to the components of an offshore structure that come into contact with water, making it a key factor in the stability of the system [11]. There are two widely-used techniques to implement cathodic corrosion protection. These include employing either galvanic anodes (GACP) or inert anodes (ICCP), also known as impressed current system. These two options provide a protective current for the polarization of the metal surface, either through the galvanic reaction of a metal that is less noble than the metal structure (GACP) or through an active current (ICCP) [4]. It is regardless for the protective effect of the structure which method is used to supply the protective current, be it from a galvanic anode or a DC power source [13].

Even a hybrid system consisting of GACP and ICCP can be used. This is especially useful during the installation phase of the offshore plant, when the structure will be without power for an extended period of time. During this phase, the galvanic anode serves as the primary cathodic corrosion protection; once the power supply is connected, the galvanic anode can support the impressed current system [10].

3.2.1 Galvanic Anodes Cathodic Protection (GACP)

Galvanic anodes represent the most basic form of cathodic corrosion protection. Their function is to dissolve a metal with a lower electrochemical potential than steel (colloquially known as a less noble metal). The typically used materials for technical applications are zinc, magnesium or aluminium as the anode material [5]. Aluminium anodes are mainly used for offshore wind turbines due to their protective effect and light weight [4, 5]. Aluminium has a high electrochemical capacity in seawater (2000 Ah/kg)

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compared to zinc (780 Ah/kg) or magnesium [4]. Galvanic anodes vary in the amount of required anode material per year from a few kilograms (e.g. monopile structures) to several tonnes (e.g. jacket structures) [4]. The quantity of anodes material required depends on:

- Type of foundation (different surface)
- Desired service life
- Seawater conditions
- Combination with other corrosion protection methods

Galvanic anodes are generally not provided with a monitoring system, even though this would be beneficial for early detection of increased wear. Only about 10 % of offshore structures with GACP are equipped with remote monitoring [11].

Due to the high rate of anode wear, this method of corrosion protection is considered to be the most emission generating. Annual emissions from a system range from kilograms to tonnes [4].

3.2.2 Impressed Current Cathodic Protection (ICCP)

Unlike galvanic anodes, where protection is achieved by the difference in electrochemical potential of the materials, impressed current systems provide direct current (DC) from an external power source to the steel surface of the structure [4]. Inert anodes are used which typically consist of [4]:

- Titanium
- Iridium
- Iridium/ruthenium MOX coatings
- Magnetite
- Platinum with titanium, niobium and tantalum coatings

These do not need to be replaced and have low annual emissions in the range of milligrams to grams [4, 5].

Unlike GACP systems, impressed current systems must be equipped with measurement, monitoring and control systems to monitor and control key system parameters. The output current of the protective device can be controlled by [14]:

- Constant output voltage: Current is controlled by the resistance of the circuit, external influences lead to changes in the values of the current fed in.
- Potential control: The system potential is measured at one point and signalled to the protection device. The DC current fed is then controlled according to the set target value of the system potential.
- Current control: The protective current device supplies a predefined current.

The correct device settings must be permanently secured [10, 11]. The height of the required protective current depends on:

- Type of surrounding medium
- Type of protected object
- Type of surface
- Combination with other corrosion protection methods

Bette and Büchler [13] specify a required protective current density of approximately 120 to 160 mA/m^2 for the North Sea.

3.3 Corrosion allowance

Corrosion allowance implies the use of thicker steel than required for the construction of the system to withstand corrosion effects in a marine environment. Its use is only considered as a backup solution when conventional protection systems do not work or when damage to coatings needs to be covered. In addition, a corrosion allowance covers the period until a cathodic protection system is installed.

The thickness of the corrosion allowance is estimated based on the expected corrosion rate of the structure and is between 0.2 and 1.2 cm [4].

The emission potential of this corrosion protection method is classified as low [4].

3.4 Corrosion protection of individual zones

The offshore wind turbine zones are subject to different loads and conditions and must be individually protected against corrosion. Table 1 relates the corrosion protection methods to different zones of the wind turbine.

3.5 Maintenance and inspection

Maintenance, inspection and repair work in an offshore environment is associated with difficult conditions. In order to inspect the system, personnel have had to climb the system in most cases. The same applies to

Tab. 1: Corrosion protection from different turbine zones

Zone	Corrosion protection method	Reference
Submerged zone	Combination of coating systems with cathodic protection and corrosion allowance for corrosion losses. Mainly protected thru cathodic protection. Coating systems cannot be repaired here.	[3–5]
Tidal & splash zone	Area affected by oscillations, subject to wet and dry cycles, highest corrosive loads. Corrosion protection primarily through coating systems, additional use of cathodic protection and corrosion allowance for critical components.	[3]
Atmospheric zone	Low corrosive load. Corrosion protection mainly through coating systems and corrosion allowances. Critical components made of resistant material, e.g. stainless steel.	[3]
Indoor area/ gondola	Sensitive electrical and mechanical components indoors must be protected from high humidity. Aerosol and air separators are used for this purpose. Mild overpressure inside prevents penetration of salty aerosols. Coating of coatable components. Critical components made of resistant material, e.g. stainless steel.	[3, 5]

maintenance and repair work, especially on the outside of the turbine. This is not only time consuming, but can also be dangerous.

The coating systems should be inspected every 4200 hours, which represents an enormous amount of work with approximately two inspections per year [8].

Repairing the coating system on site is difficult. Salt and moisture residues and difficult surface preparation make application difficult and expensive. The cost of on-site coating can be up to 1000 €/m², a huge increase compared to factory coating costs of 15-20 €/m² [3].

The latest developments in this field have resulted in a repair paint that is better able to handle the conditions it is exposed to and can therefore guarantee a good protective performance despite poor surface preparation (moisture, salt) [5]. In addition, inspections of protective systems are increasingly being carried out using drones or quadrocopters [5]. These are unmanned flying objects equipped with camera systems with image stabilisation systems and laser scaling systems. The flying objects and digital image analysis ensure that only identified repair areas need to be inspected and repaired by hand. Furthermore, the use of the quadrocopter is more flexible, as it can also be used in higher wind situations, compared to manual inspection, for example.

The additional integration of camera and sensor monitoring systems and the connection to existing plant monitoring systems (e.g. SCADA) could significantly reduce on-site inspection work in the future.

4 Conclusion and outlook

The protection against corrosion for offshore wind turbines is of utmost importance and should not be underestimated. The harsh conditions at sea can result in increased corrosion rates and significant wear and tear on the structures of an offshore turbine.

The adoption of known standards, regulations and procedures from the oil and gas industry for the extraction of fossil fuels provides a good basis for providing reliable corrosion protection for offshore structures. For the protection of steel structures in the marine environment, active and passive corrosion protection methods are generally suitable, as long as the protection devices are not damaged or worn.

Intensive inspection and maintenance are necessary for offshore wind turbines to detect and repair damage in a timely manner, as these turbines are not typically monitored continuously. Currently, personnel must climb the turbines to conduct these tasks manually, resulting in significant time, potential shutdowns, and costs.

However, there is a trend towards increased digital monitoring and a reduced use of manpower for specific fault analysis and repair only. Furthermore, the development of dependable and uncomplicated repair processes is of significant importance. These developments need to be followed and driven forward.

Only by combining active and passive corrosion protection, with a reliable digital monitoring system and sophisticated repair procedures, can the demands to ensure the strength of each turbine over a lifetime of more than 25 years be met while the number of offshore wind turbines rises and their distance from the coast increases.

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