Corrosion Protection of Offshore Wind Energy Constructions in Germany: Challenges and Approaches

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***Abstract*—The significant increase in the share of renewable energies within the next decades has high political relevance in Germany. Due to the high availability and rate of yield for wind, offshore wind energy plants are of particular interest. Currently, wind energy plants with power ratings up to 8 MW and rotor blade diameters up to 150 m are raised near the German coast. To operate these devices economically, service lives of 25 years or more are required. Here, corrosion is an important limiting factor, as the devices are constantly exposed to a highly corrosive environment (sea water, saline air). In this paper, general conditions and specific technical challenges to protect offshore wind energy plants from corrosion are described, and some examples of technical solutions are presented. Some of the reported solutions have been developed in nationally funded joint research projects between research institutions and industrial companies, representing the full supply chain for offshore wind energy plants.**

***Index Terms*—Corrosion Failure; Offshore Wind Energy Plants; Protective Coatings; Repair Concepts.**

I. Introduction

In Germany, renewable energies should cover 80% of the electricity supply by 2050. Actually, in 2016, this was about 29%, with a share of the offshore wind energy of only 1.9% [1]. Therefore, on the basis of the initiative “Wind Energy” by the German Government and the Federal States of Germany, the sites in the North Sea and the Baltic Sea shall now be substantially expanded in addition to the existing onshore wind power plants. Corrosion is one of the dominating limiting factors for the operation of offshore wind turbines. Offshore environment provides extreme conditions concerning the corrosion of metals. The utilized materials - mainly non-alloyed steel for the structure - do not have the durability to ensure the required operating times of 25 years or more. Not only chemical impact by highly saline seawater and humidity has to be considered regarding materials durability. Also, mechanical impact during service (floating bodies, boat landing, erection of the structure, etc.) can affect protective coatings and decrease their protection performance. Furthermore, biological growth may affect the corrosion behavior. Formation of a microbiologically grown film or fouling by barnacles, mussels and other immobilized species may deliver a completely different chemical environment on a metal surface and, therefore, affect the corrosion behavior. The critical consideration of all influencing factors, both the environment and the materials of the structure, and their interaction is of decisive importance for sustainable utilization over a long operating period.

II. Regulations

For the approval of the construction of offshore wind power plants in the German territory (the North Sea and Baltic Sea), the Federal Maritime and Hydrographic Agency (*Bundesamt für Seeschifffahrt und Hydrographie* BSH) is responsible. It is a higher federal authority in Germany under the jurisdiction of the Federal Ministry of Transport and Digital Infrastructure. The Agency is editor of standards concerning the technical requirements for the design of offshore wind energy plants. For minimal requirements for corrosion protection, the BSH refers in its standards to guidelines of classification societies like DNV Gl [2]. Furthermore, the German Society for Corrosion Protection GfKORR (*Gesellschaft für Korrosionsschutz e.V.*) published recommendations for the best practice of corrosion protection which are published only in the German language so far [3].

These standards, guidelines and recommendations refer to each other and are defined as state of the art by intensive discussion and collaboration between the companies involved in the value-added process as well as the authorities and scientific institutions. For this, the GfKORR provides platforms such as conferences, workshops and regular work meetings.

III. Technology of Corrosion Protection

Offshore wind turbines are divided into various zones with regard to the corrosive load and the performance of the corrosion protection as shown in Figure 1.

According to offshore experience, for most materials of the structure, in particular for non-alloyed steel, the corrosive load is highest in the splash zone and the tidal zone. This is due to the fact that under wet conditions the oxygen access to the metallic surface is the limiting factor for corrosion progress. Shortly below the surface, the water is intensively mixed by waves and therefore enriched with oxygen from the air. In addition, a thin liquid film occurs on the surface in the splash zone and tidal zone for most of the time, through which oxygen can diffuse to the metal surface relatively quickly. For deeper zones, the oxygen transport is limited.

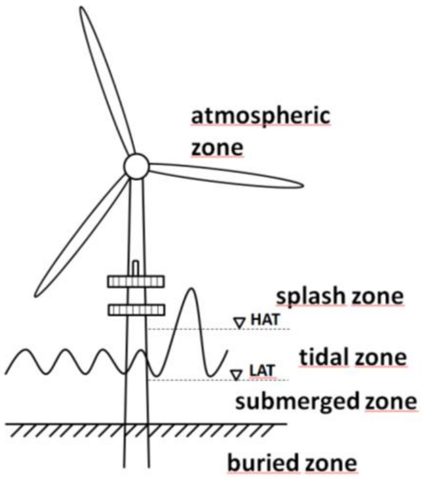

Figure 1: Definition of different corrosion impact zones (HAT: highest astronomical tide, LAT: lowest astronomical tide)

For increasing height of the tower, the so-called „time-of-wetness“, which is defined as the time when a water film covers the metal surface and metal dissolution can proceed, is decreasing. An additional role plays the increasing concentration of salts from the sea water in those areas of the surface where splash water and aerosol deposition evaporate due to heat and sunlight. This is problematic for passivating materials like stainless steel or aluminium alloys, which are used on platforms for operational purposes. These materials form a very thin (< 1 µm) but dense oxide layer, which provides protection from corrosion. Higher chloride concentrations may interfere with this oxide layer formation, provoke critical corrosion effects like pitting corrosion, and therefore abolish the durability of the material. Therefore, more stable alloys are often required compared to the submerged zone.

The division into zones is also relevant with respect to the applied protection methods. Inside the nacelle, which contains sensitive electrical and mechanical components, it is important to avoid the occurrence of high humidity and salt ingress by seawater aerosols. Here, the air inside the nacelle is conditioned (aerosol separation and air drying). Due to the application of a slight overpressure, no salt containing aerosols will ingress. According to experience, this is a very effective method to avoid corrosion.

Outside, for atmospheric, splash, and tidal zone, organic coatings are applied most often. An actual trend to increase protection performance is to apply duplex coatings with thermally sprayed ZnAl15 base coat, organic mid coats and an organic top coat.

DIN EN ISO 12944 is the reference standard for corrosion protective coatings on thick steel structures [4]. Important aspects, such as definitions of corrosion categories, coating relevant design of the structure, surface preparation, application, recommendation of coating systems and their estimated protection time, are defined. The DIN EN ISO 12944 is under revision as new aspects for offshore structures are implemented [5]. For instance, part 9 is added, that comprises specific protective paint systems and their test procedures. Here, the ISO 20340 test procedure is implemented [6]. The test procedure includes cyclic changes between salt spray test and weathering under UV radiation as well as condensation and low temperature (-20°C) impact to address more strongly the durability of polymeric protective coatings, and therefore the offshore corrosion conditions, more adequately (Figure 2). Furthermore, new corrosion categories CX and IM4 are implemented.

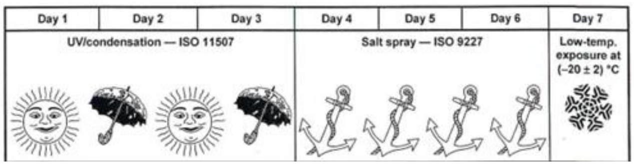

Figure 2: Cyclic exposure procedure of ISO 20340 test

Another and more specified standard for protective coatings for offshore-application is the Norsok M501 [7], which are strongly related to [4].

Principally, protective coatings can also be applied in the submerged zone and the buried zone. But due to the fact that coatings cannot be repaired in these zones, the regulations demand additional measures, like corrosion allowances and cathodic protection (CP).

The principle of both methods of cathodic protection, impressed current and galvanic anodes, is to provide electrons to inhibit the electrochemical reaction of metal dissolution, which means to impress a protective electrochemical potential onto the metal surface. For galvanic anodes, this will be achieved by dissolution of metals with a lower electrochemical potential than steel. For technical applications, zinc, magnesium and aluminium are commonly used as anode materials. In the case of offshore wind turbines, aluminium anodes are usually used because of their protection efficiency and low weight. Galvanic anodes have to be frequently replaced. An impressed current cathodic protection system (ICCP) uses inert electrodes, which do not have to be replaced. However, ICCP requires a current supply and a potential control which requires more elaborative devices.

IV. Specific Corrosion Damages and Their Causes

There is little information published concerning corrosion damages on offshore wind power plants. Systematic analyses of the causes of corrosion were often not part of service and maintenance concepts or were withheld for reasons of intellectual property.

Figure 3 shows the results of a study conducted in Germany, where the causes of corrosion damages on offshore wind energy plants are classified by their origin and occurred in the first years of service.

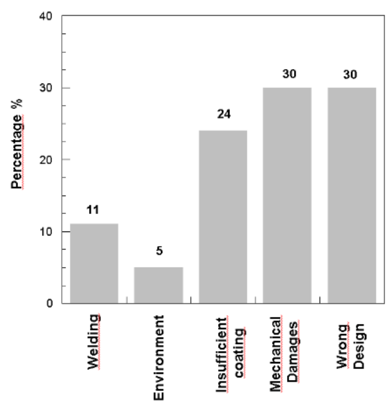

Figure 3: Classification of observed corrosion damages of wind energy plants in the first years of service [8]

The causes are mostly attributed to defects in the protective coatings. Weld seams are discontinuities in the surfaces. Due to their geometry and the surface tension of the uncured varnish, they lead to a retraction of the liquid varnish and thus to a reduced layer thickness in the cured state. This effect is also known as "edge retention". Therefore, a proper mechanical post-treatment of weld seams is essential for the efficiency of protective coatings. The execution of this post-treatment is specified in DIN EN ISO 8501-3 [9]. It is surprising that most causes of corrosion already occur during assembly and erection of the wind power plant. An insufficient coating is synonymous with a wrong coating, e.g. not in accordance to [4], and it includes faulty manufacture and wrong design, too. Mechanical damages very often occur during the erection process. Bumping, improper erection attachments and other reasons lead to local damages of the organic coating. Hence, to accomplish a long service life, strict quality control during fabrication, erection and in service in combination with an efficient maintenance concept, e.g. for the repair case, is essential.

An important aspect which is actually under discussion, as it is not clearly investigated, is the impact of biological growth on the corrosion. It is well known that microbiologically induced corrosion (MIC) may lead to very severe and fast corrosion failures. On the other hand, the experience on mass loss rates of substrate material and protection performance of coatings was gained under outdoor conditions and therefore under the biological influence. But there is still no method available to quantify reliably the biological influence, and it is speculated that changes in the biological diversity due to globalization may also exceed the assessment thresholds, such as the supposed maximum corrosion rates.

V. Maintenance and Repair of Protective Coatings

As on-site repair of coatings has to be performed under totally different and also more difficult conditions, it is important not only to develop a repair coating system but a holistic concept including inspection, assessment, access and logistics, surface preparation and coating material application. Such a holistic concept was developed in a German joint project [10], in which companies of the entire supply chain and a research institute were involved.

A key aspect was to develop a specific repair coating material, because so far standard coating systems, which are optimized for application under workshop conditions, have been used for repair. In a 500 µm thick coating layer, the developed coating material shows comparable protection performance like original coatings, even if the surface preparation and application conditions are not ideal. A higher salt residual on the pretreated surface (up to 50 µg/m²), a damp but not wet surface, and varying surface conditions concerning preparation and substrate materials, such as coating residuals, are acceptable. Anyhow, proper surface preparation is a key for the performance of protective coatings. Blast cleaning, which is the standard procedure, is not always applicable on-site due to handling (tools have to be "single-handing usable") and emission of grit in the environment. Different manual surface treatment procedures have been investigated, like grinding, impact brush, needle hammer, etc. Grinding and impact brush showed an acceptable performance with the developed repair coating system but still cannot reach the performance of grit blasting. Therefore, there is significant potential to increase the protection performance of repair coatings by developing improved manual techniques for pre-treatment.

For inspection and repair, the service personnel have to climb on the structures of the wind energy plant. This is critical concerning personnel safety and requires extensive expenditures for logistics. Therefore, at least for inspection, new technology was developed. It consists of a quadrocopter as unmanned aerial vehicle, which is equipped with a suitable camera system, image stabilization, and a laser scaling system. This system is deployable up to wind speeds of force 6 on the Beaufort scale and can be started from a service ship. Local repair spots will be still assessed manually, but digital image evaluation is already in use and may lead to an automated inspection system in the future.

A temporary surface protection, which avoids new contaminations in the time between surface preparation and application of the coating material, was also developed. It consists of a fluid which hardens elastically and which can be removed almost residue free.

Completing the concept, a test procedure specifically for repair coating systems was developed. For this procedure, the cyclic exposure was adopted from ISO 20340 (Figure 2), but a specific test sample is used to implement specific surface preparation of a repair scenario. Standard steel panels for corrosion testing were masked locally in some spots and were coated subsequently. The masks were removed so that the sample obtained areas without coating. After that, the samples were exposed to salt spray test conditions with a fog of 5% sodium chloride solution at 35°C [12] for two weeks. As a result, the uncovered areas showed intense rusting and represented reproducible areas for repair.

VI. Conclusion

Offshore wind energy will be of high relevance to reach Germany's targets in power supply for the next centuries. However, from the view of corrosion resistance, it is not yet possible to reliably ensure that the offshore wind energy plants will reach the targeted service time of 25 years, and high maintenance efforts will be required. Therefore, there is an urgent need for further efforts in research and development in collaboration with companies and research institutions.

In principle, if the state-of-the-art protection methods are used in a professional manner, many problems in the further operation of the plants can be avoided. This is why substantial personnel qualification and quality assurance concept are of paramount importance. Results of research and development must be integrated into training and teaching, e.g. at the universities, in a timely manner in order to ensure a substantiated personnel qualification.

Further research is needed to refine maintenance and repair concepts. The digitization of engineering processes can be particularly innovative. The digital documentation of the surfaces of the structure during the inspection procedure with the unmanned aerial vehicle also delivers valuable information for the development of service life forecast models and, therefore, for "maintenance-on-demand" concepts. Automated repair procedures, which are controlled from service shops or even totally autonomous, may reduce service costs and therefore gain the profitable efficiency significantly.

Technological progress in the field of this energy generation technology will be of particular importance for national economies. Its sustainability legitimates the special research needs in the coming years or even decades where collaboration is the key aspect.

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