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Corrosion-Protection Design for Floating-Type Offshore Wind Turbines

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ABSTRACT

To overcome installation site drawbacks and noise problems associated with onshore wind turbines, future wind turbines are likely to be installed at offshore sites. However, an offshore environment is highly prone to corrosion and maintenance costs are exorbitantly high. Thus, it is very important to select appropriate corrosion protection systems and to apply them correctly. In this paper, corrosion protection systems applicable for a floating-type offshore wind turbine are summarized based on existing regulations and standards, such as NORSOK M-501, NORSOK M-503, DNV-RP-B101, DNV-RP-B401, and KS M ISO 12944. A floating-type offshore wind turbine undergoes corrosion to different extents in the atmospheric, splash, tidal, and immersed zones, which constitute its corrosion environment. Typical corrosion damage and applicable coating systems for the atmospheric, splash, and tidal zones and cathodic corrosion protection systems for the immersed zone are summarized based on published literatures.

1. INTRODUCTION

Wind turbines are a clean energy source and are the most economical energy source among current technologies. Wind turbines can efficiently use various kinds of territory, including mountainous, remote shore, and offshore regions. However, wind turbines are increasingly being installed offshore instead of onshore owing to public opposition. Offshore steel structures such as wind turbine systems are severely affected by severe corrosion attack unlike those onshore. Steel structures in offshore regions worldwide are being affected by problems related to corrosion damage. For the

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maintenance of offshore steel structures, anti-corrosion management is being conducted very inefficiently owing to a lack of corrosion protection technology and social awareness about corrosion. Moreover, offshore steel structures are difficult to maintain and expensive to manage. In particular, much data are relevant to coating systems of vessel structures domestic and international, and these structures, unlike offshore structures, are designed to have a 5-year service life owing to the ease of recoating the structures when problems occur. On the other hand, offshore steel structures such as wind turbines need to have a 20-year service life. Thus, corrosion protection is required for expanding the design fatigue life by using an appropriate coating system. Data for corrosion protection of wind turbine structures are limited (Black et al. 2011). In this study, an appropriate anti-corrosion method was selected by comparing and analyzing the standards (NORSOK M-501 2004), (NORSOK M-503 2007), (DNV-RP-B101 2007), (DNV-RP-B401 2007), (KS M ISO 12944-5 2008) and a technical report (Karsten 2010).

2. TYPES OF CORROSION

Normally, when metals are placed in electrolytic environments, such as water or soil, a localized potential difference is caused by dissolved oxygen on the metal surface and differences in the surrounding environments (e.g., concentrations or temperatures) and by causes associated with the metals (e.g., impurities contained in the metals, stresses, and dissimilar metal contacts). The potential difference occurs on the surfaces and contact areas of the metals, resulting in anode and cathode formation. Corrosion current then flows from the anode to the cathode through electrolytes and anodic metals in ionic forms are released and dissolved in electrolytes. This electrochemical reaction results in corrosion. Corrosion is largely classified as dry or wet corrosion, and wet corrosion is classified as local or general corrosion. (Lee 2009)

Dry corrosion occurs without water and is caused by reactive gas or oxidation from heating the metal. It appears as mill scale on the surface of the steel. Wet corrosion is oxidation caused by the reaction of water and oxygen on the surface of steel. General corrosion protection is targeted at wet corrosion.

Complete corrosion is also called uniform corrosion and occurs when the complete steel surface exposed to corrosion conditions erodes equally. In most cases, damage results from complete corrosion, but the service life can be easily predicted in this case, owing to which corrosion can be prevented. Local corrosion refers to corrosion of a part of a larger steel structure that, as a whole, has good durability. Local corrosion can cause problems with performance and safety of the entire structure. It can be detected easily and worsen with neglect.

3. CORROSION FACTORS IN SEAWATER

Offshore vessels and wind turbine systems can be severely damaged by corrosion. Several factors can lead to corrosion of offshore structures (Kim 1994). For example, dissolved oxygen might affect structures depending on the water level and temperature may generate cathode reactions and subsequent electrochemical corrosion. Thus, corrosion speed increases with an increased amount of dissolved oxygen. Moreover, corrosion speed increases with increased flow velocity in offshore environments because the flow provides oxygen to the steel surface, thereby damaging the surface film. In addition, microorganisms that adhere to the material in water are another factor that can cause corrosion; in addition, temperature, pH, and sodium chloride may also influence corrosion speed. The relationship between the corrosion factors and corrosion rate is shown in Fig. 1.

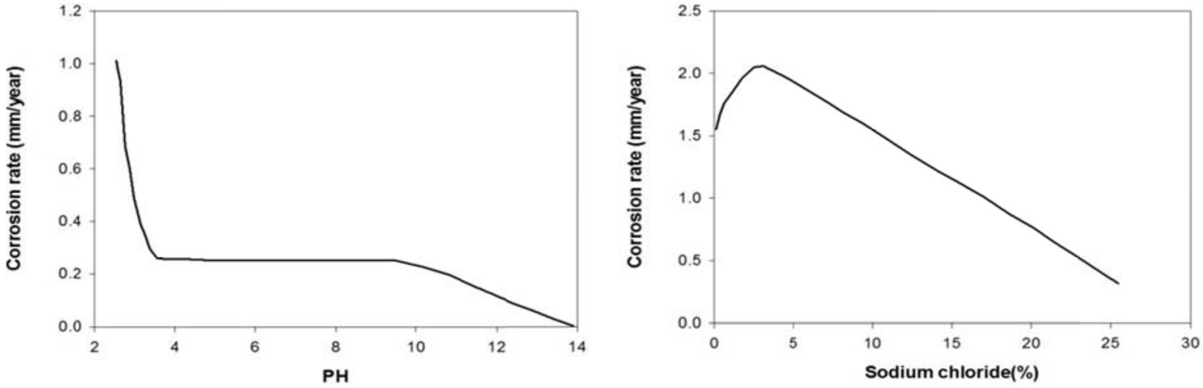

Fig. 1 Relationship between corrosion rate and sodium chloride or pH (DOE-HDBK 1993), (Kim 1994)

In general, the corrosion rate increases at a sodium chloride of 3%. Since the sodium chloride in offshore environments is 3.3–3.5%, severe corrosion occurs. The corrosion rate sharply increases when the pH drops below 4. This is due an increase in the dissolved oxygen at a pH less than 4. The pH in offshore environments is 8.1; therefore, the effect of pH on corrosion is negligible.

4. CORROSION RATE ACCORDING TO ENVIRONMENT OF WIND TURBINE STRUCTURE

The oceanic environment is conducive to severe corrosion and is influenced by factors such as ultraviolet (UV) radiation exposure, salt concentration, and wetness/immersion time. The corrosion-prone areas that are affected by these factors can roughly be divided into three kinds in accordance with standards ISO 12944-5 (2008) and NORSOK-M 501 (2004): atmospheric zones, splash zones, and immersed zones (the latter two being kinds of underwater zones). Because the corrosion rates differ in the corrosion-prone areas, classifications are made to select the most appropriate corrosion protection method. The corrosion environment comprising the three zones is shown in Fig. 2 and the corrosion rates according to these zones are listed in Table 1 (Momber et al. 2008), (KS M ISO 12944-2 2008).

The atmospheric zone is the area above the water level. The structure above the water, which is C5-M according to ISO 12944 (2008), is highly prone to corrosion. The offshore atmospheric zone is more prone to corrosion than the onshore atmospheric zone. The main factors causing corrosion in the atmospheric zone are UV rays, temperature, and sodium chloride. Paint with zinc is mainly used as a protective coating, since it will protect the material by corroding itself on account of the galvanic effect of zinc; however, the primer is damaged in this process.

The splash zone is the transition area around the water line between high and low levels of water. This is the area undergoing the most severe corrosion in the offshore environment. The materials used in the splash zone are constantly exposed to moisture with high dissolved oxygen. Owing to the power of water in waves, even a thick protective film can be easily damaged. Thus, it is better to use passive steels, such as stainless steel and titanium, despite their higher costs than paint coatings. Because the corrosion rate is two times that of other parts, the coating needs to be thicker for a long service life.

The immersed zone is the part under the water line under the lowest tidal current condition. In this zone, pitting corrosion and crevice corrosion are the main problems. Material in the sea undergoes fatigue corrosion from repeated stress, and both fatigue corrosion and repeated force are constant problems. Another important factor causing corrosion in this zone is extraneous matter such as barnacles. Micro-fouling can occur owing to barnacles and shellfish. For this reason, paint with good antifouling and cathodic protection is mainly used for the immersed zone. In this zone, careful attention should be paid to the use of resin with zinc, since zinc will generate salt by reacting with water.

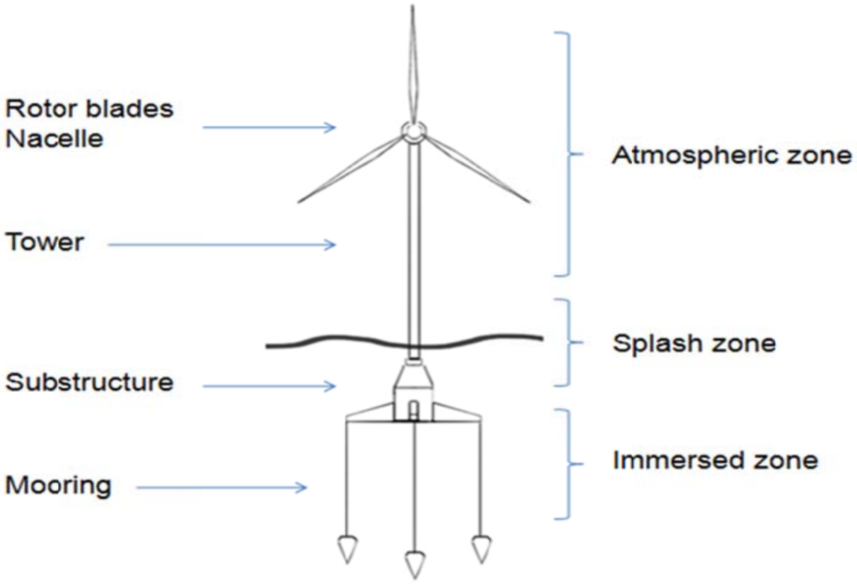

Fig. 2 Corrosion environment

Table. 1 Corrosion rates according to the corrosion environment (Momber et al. 2008), (KS M ISO 12944-2 2008)

Corrosion environment	**Corrosion rate**
Atmospheric zone	0.08~0.2mm
Splash zone	0.4 mm
Immersed zone	0.2 mm

5. CORROSION PROTECTION

The goal of corrosion protection is to prevent corrosion caused by chemical reaction between steel and corrosive material, including gases and liquids. Since the quantitatively identical anode and cathode reactions always occur simultaneously during the corrosion phenomenon, preventing all of the following is necessary: action of the anode, action of the cathode, and migration of ions into the electrolyte. The major factors to be considered for achieving corrosion protection are listed below.

- Correct selection of materials
- Appropriate construction design
- Use of paints and coatings
- Cathodic protection
- Conditioning of the environment

For appropriate construction design for corrosion protection, blowholes and pores generated by welding should be removed from the steel surface and sharp edges of the used materials should be rounded with a minimum radius of 2 mm (NORSOK Standard M-501 2004).

6. DEFECTS IN CORROSION PROTECTION

Currently, Paints for corrosion protection are categorized as vessel and heavy duty coatings. In the case of vessels, since recoating is easy and maintenance is feasible, a 5-year design life is usually required for vessel coating. However, structures for which maintenance is difficult, such as oil and gas and wind turbine structures, need a design life of over 20 years, which requires heavy-duty coatings, unlike vessel coatings. The coating needs to be thick, i.e. heavy duty, to prevent severe corrosion. Selection of improper paint and thickness can lead to sagging, blushing, blistering, and peeling. The major coating defects are shown in Fig. 3.

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Fig. 3 Coating defects (International paint Korea 2010)

7. CURRENTLY USED COATING SYSTEMS FOR CORROSION PROTECTION

Paints for offshore steel structures should be selected in consideration of waterproofing and chemical resistance. The standards EN ISO 12944-5 (2008), NORSOK M-501 (2004), and DNV RP B-401 (2010), technical data (International paint Korea (2010) and theoretical considerations (Black et al. 2011), (Brown 2004) of corrosion protection of wind turbine structures can be referred to for selecting an appropriate paint. In the case of NORSOK M-501, distinction is made between shipping and other general marine structures. The standard ISO 12944-5 provides a better classification of paints appropriate for the maritime and land-based structures than other standards do. However, for the fixed offshore structures, both these standards fail to distinguish the paint for individual sections of the splash zone and immersed zone. In the case of the DNV RP B-401 standard, which is known to be a standard for vessel painting, corrosion protection methods are depending on the vessel corrosion environment. Previous studies on offshore structures have a limitation in that the selection range of paints is too broad, despite the fact that the environments are classified on the basis of the standards. (Black et al. 2011), (EN ISO 12944-5 2008), (NORSOK M-501 2004), (DNV RP B-401 2010)

The paints and dry film thicknesses are listed in Tables 2 and 3 for standard and theoretical coating systems, respectively. Appropriate paints and dry film thicknesses for wind turbine systems are listed in Table 4. In reference to standards and theoretical coating systems, in the atmospheric zone, zinc silicate is considered an appropriate method owing to a reduction in corrosion by the galvanic action of zinc; furthermore, epoxy and polysiloxane are also considered feasible options. Owing to the higher severity of corrosion in the splash zone, ultrahigh-build epoxy paint is required to have a dry film thickness greater than 1000 μm. In the immersed zone, a combination of cathodic protection and epoxy coating is found to be a suitable method to extend design life, according to DNV RP-B401 and NORSOK M-503.

Table 2. Coating systems according to standards
(NORSOK M-501 2004),(KS M ISO 12944-5 2008)

Corrosion environment	**Standard**			
	NORSOK M-501		**ISO 12944-5**	
	Coating	**DFT**	**Coating**	**DFT**
Atmospheric zone	ZP	60 μm	EP	40 μm
	EP	280 μm	PUR	280 μm
Splash zone	EP	350 μm	CE	1000 μm
Immersed zone	CP			

ZP : Zinc Rich Primer, EP : Epoxy, PUR : Polyurethane, CP : Cathodic Protection, CE : Coar Tar Epoxy, (DFT : Dry Film Thickness)

Table 3. Coating systems according to theory and technical report
(Black et al. 2011),(Brown 2004)

Corrosion environment	**Theory**			
	wind farm structure		**offshore structure**	
	Coating	**DFT**	**Coating**	**DFT**
Atmospheric zone	EZ EP PUR	60 ㎛ 200 ㎛ 60 ㎛	ZP EP UV	320 ㎛
Splash zone	EP	1000 ㎛	EP or PES	600 ㎛
Immersed zone	PUR	50~70 ㎛	EP	450 ㎛
ZP : Zinc Rich Primer, EP : Epoxy, PUR : Polyurethane, EZ : Epoxy Zinc Dust Primer, PES : Polyester				

Table 4. Selected coating systems according to corrosion environment in this study

Corrosion environment	**Typical coating system**	**Dry film thickness**
Atmospheric zone	Zinc silicate primer Epoxy 2coat Polysiloxane topcoat	70 ㎛ 200 ㎛ 80 ㎛
Splash zone	Ultra high build epoxy Polyurethane top coat	1400 ㎛ 60 ㎛
Immersed zone	Epoxy 2coat Cathodic protection	320 ㎛

8. CATHODIC PROTECTION

The corrosion of steel structures occurs because of anode and cathode reactions in the presence of electrolytes such as soil or water. Such corrosions can be prevented in three ways. The first is to prevent contact between the metal surface and electrolytes. The second is to inhibit the progression of the anode reaction. The third is to separate the anode and cathode areas. Inhibiting the progression of the anode reaction is a common cathodic protection method, whereas the other two methods have been considered impractical. The system of using the cathodic protection method can be further classified as the sacrificial anode system and the impressed current cathodic protection system (Kim 1993). The sacrificial anode system is addressed in standards NORSOK M-503 (2007) and DNV RP B-401 (2010). This system inhibits corrosion by using an anode (with higher electro-negativity than iron); therefore, when the anodes are corroded, the generated electrons are supplied to the iron inhibiting the corrosion. Three types of anodes are known to exist but the present standard NORSOK M-503 and DNV RP B-401 considers aluminum and zinc anodes. The most appropriate current range for such anodes is –0.8 to 1.10 V Ag/AgCl/seawater. Moreover, this cathodic protection method can extend design life by using a combination of coating systems. The result of comparisons between the present standard NORSOK M-503 and DNV RP B-401 and other studies showed that epoxy could be used for electrolyte corrosion protection, but polyurethane, vinyl, and rubbers with high alkali-resistance can also be used as alternative paints. A combination of such cathodic protection methods and coating would extend the design life by approximately 20 years, and the standards (NORSOK M-503 2007), (DNV RP B-401 2010) related to electrolytic protection are similar.

9. CONCLUSIONS

Currently, the classification of high-performance paint and marine paint is unclear in some standards (DNV standard, NORSOK standard, and ISO 12944 standard) and theory. In the case of marine paints, it is difficult to meet design life requirements in fixed offshore structures such as wind turbines.

The offshore corrosion environment is divided into the atmospheric zone, splash zone, and immersed zone. Some standards specify the same coating method for the splash zone and immersed zone. However, the different corrosion rates in these environments indicate that they need dissimilar coating methods.

A combination of cathodic protection and coating systems has proved to be useful in immersed zones. The paints that can be used for cathodic protection are epoxy, polyurethane, vinyl and rubber such as alkali resistant rubber. The over-protection is generated, if a primer containing aluminum and zinc is used.

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REFERENCES

A.R. Black, P.K. Nielsen (2011), "Corrosion protection of offshore wind farm structures present understanding and future challenges".
Dae Kyung Kim (1993), "Standard and application of the cathodic protection".
DNV-RP-B101 (2007), “Corrosion protection of floating production and storage units”.
DNV-RP-B401 (2010), “Cathodic protection design”.
International paint Korea (2010), “Vessel coating technical data”.
KS M ISO 12944-2 (2008), “Paints and varnishes-Corrosion protection of steel structures protective paint systems-part 2: Classification of environments”.
KS M ISO 12944-5 (2008), “Paints and varnishes-Corrosion protection of steel structures by protective paint systems-part 3: Protective paint systems”.
Karsten Muhlberg (2010), “CORROSION PROTECTION OF OFFSHORE WIND TURBINES”.
NORSOK Standard M-501 (2004), “Surface preparation and protective coating”.
NORSOK Standard M-503 (2007), “Cathodic protection”.

U.S. Department of Energy Washington, D.C. 20585 (1993), “DOE-FUNDAMENTALS HANDBOOK CHEMISTRY Volume 1 of 2”.

Thomas H. Brown, JR (2004), “Designing Protective Coating Systems for Offshore Oil and Gas Platforms”.

Young Sik Kim (1994), “On the Effects of Sea water on the Corrosion Behavior of Metallic Materials”.

Youn Hee, Lee(2009), “Study on Corrosion Characteristics in the Water Distribution Pipeline depending on Water Quality”.