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Quantitative performance assessment of corrosion protection systems for offshore wind power transmission platforms

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ABSTRACT

The paper reports about the assessment of deteriorated protective coatings and exposed steel surfaces on offshore wind power platforms in the North Sea and the Baltic Sea. A simple procedure for the assessment of coating deterioration and metal loss on exposed steel surfaces is developed. The procedure delivers a protection number $N_P{=}N_C + N_S$, whereby the term N_C characterizes coating deterioration, and the term N_S characterizes metal loss at exposed surfaces. For $N_P = 0$, the structure is fully protected, and for $N_P = 2$, the capacity of the corrosion protection system (protective coating combined with corrosion allowance) is completely exhausted. This number is linked to maintenance procedures. A total of 750 inspection results are reviewed and categorized. The majority of coating damages can be attributed to unsuitable constructive design and to mechanical loading. Design specifications and testing scenarios for coating assessment may be updated in order to account for special stresses in addition to corrosive stresses. Color-based digital image processing is applied for the quantitative recording and rating of coating deterioration processes and for the estimation of N_C-values. Preliminary investigations reveal that color-based digital image processing opens the opportunity to evaluate fouling, top coat color changes, and early iron corrosion products.

1. Introduction and objective

Future offshore wind farms will be further off the coast and in deeper waters due to the higher wind speeds and better landscape protection. In order to explore the offshore wind potential, good power transmission systems are of the utmost importance. Today's installed offshore wind farms have relatively small rated capacities and are placed closer to shore, and High Voltage Alternating Current (HVAC) technology has been used as the power transmission technology. However, future offshore wind farms will be located further off the coast, which means that efficient and cost effective power transmission systems at this distance will be required. High Voltage Direct Current (HVDC) technology has a proven record of efficient power transmission. Offshore wind power transmission platforms are demanding engineering steel constructions. A typical basic structure is provided in Fig. 1. A major concern to all offshore wind constructions, including transmission stations, is corrosion [1–4]. Fundamental corrosion protection measures for offshore wind substations include the following [3]: protective coatings and/or cathodic protection; use of a corrosion allowance; inspection/monitoring of corrosion; corrosion-protection-friendly design; control of environment (internal zones only). Cathodic protection is of concern for submerged and tidal zone sections (Fig. 1). Coating application, however, applies to the majority of the structures. The total coated area of a large platform can exceed 200,000 m^2. This paper is concerned with corrosion protection coating systems.

A modern and increasingly considered maintenance strategy is risk-based inspection and maintenance [5]. This methodology concerns particularly stability and function of the steel structures of offshore wind constructions [3,6,7]. A holistic approach would consider protective coatings being part of the steel structure, and it would include the performance of protective coating systems into the risk assessment. A number of approaches have been developed for the assessment of protective coating systems for offshore oil and

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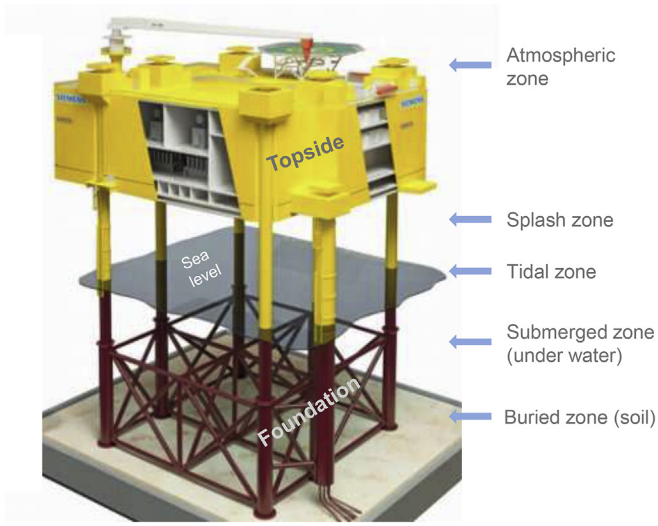

Fig. 1. Structure and corrosion zones of an offshore wind transmission platform (The graph is adapted from "4c-Offshore.com" and is modified by the author).

gas platforms [8–10], but not for OWEA power transmission platforms. Risk for structural failure is defined as the product of probability of failure and consequence of failure [11]:

$$RS = P_F \cdot C_F \quad (1)$$

The consequence of failure (C_F) of OWEA is dependent on the local situation, the function of the parts, and the corresponding mechanical and corrosive loads. It is known, that the splash zone of offshore structures is particularly vulnerable to corrosive loads [12,13]. The consequence of failure is higher for primary, load carrying structural parts compared with secondary parts [11]. These topics are not the objectives of this paper. The probability of failure (P_F) is assumed to include coating failure (coating deterioration) and corrosion (metal loss). These topics are the objectives of this paper. The procedures in Refs. [7,8] basically combine criteria for coating deterioration and for steel corrosion in order to derive maintenance periods or maintenance strategies in general. Examples for steel corrosion (metal loss) criteria are provided in Tables 1 and 2. Examples for coating deterioration criteria are provided in Table 3. It shall be noted that these coating conditions are not in accordance with the degrees of rusting specified in Ref. [16]. A major issue in due of the development of the risk-based assessment is coating condition, or coating damages, quantified in degrees (%). These approaches, however, basically lack in an objective estimation of coating damages and in a more detailed specification of the sizes of reference areas the coating damages are related to. This paper is concerned (i) with the development of a simple condition assessment model for corrosion protection systems for offshore wind power transmission platforms; and (ii) with the

Table 2
Corrosion rates (mild steel) for different zones in an offshore environment [13].

Zone	Corrosion rate of unprotected steel in μm/year
Atmospheric	50 to 75
Splash zone	230 to 400
Tidal zone	50 to 230
Immersed (seawater)	130 to 200
Seaground (soil)	60 to 130

systematization and quantification of coating deterioration mechanisms. The systematization is based on the discussion and interpretation of 750 inspection points on offshore wind power transmission platforms in the North Sea and the Baltic Sea. The quantification is based on the utilization of a digital image processing scheme developed in a previous paper [17] for the objective assessment of coating deterioration degrees. All photographs discussed and processed in this paper were taken with standard digital cameras under natural light under offshore conditions without any modifications.

2. Assessment procedure

A schematic representation of corrosion progress for marine steels is provided in Fig. 2. It is assumed that the structure is protected against corrosion through a protective coating and corrosion allowance. The protection performance of the coating is characterized through R_i, and the protection performance of the corrosion allowance is characterized through h_S. If the coating performance deteriorates ($R_i > 0$), the (locally or totally) exposed steel surface starts to corrode ($h_S > 0$). The protection capacity of the coating is completely exhausted at $R_i = 100\%$. The protection capacity of the corrosion allowance is completely exhausted at $h_S = CA$. The metal loss of maritime structures due to uniform corrosion can be described as follows [18]:

$$h_S = C_1 \cdot T_E^{C_2} \quad (2)$$

Here, h_S is the metal loss, and T_E is the exposure time after coating breakdown. The coefficients C_1 and C_2 are empirical parameters, and they depend on the particular corrosive conditions (time of wetness, relative humidity, temperature, chloride concentration in the environment, etc.). The linear coefficient is indicative of the annual corrosion rate. The power exponent can have values between $C_2 = 0.3$ and 1.5 [18]. The metal loss can either follow a convex function ($C_2 > 1$), a linear function ($C_2 = 1$), or a concave function ($R_2 < 1$); see curves 1A to 1C in Fig 2. For rather short exposure periods ($T_E < 3$ years), the linear condition, $C_2 = 1$, can be assumed for steel structures under atmospheric maritime exposure [19–21]. This condition also holds for splash zone and tidal zone conditions [21]. The case $C_2 = 1$ is also taken into account for the calculation of corrosion allowances for OWEA structures [22]. The parameter T_E in Eq. (2) is the exposure time after coating

Table 1
Corrosiveness classification [8]; based on [14].

Category	Corrosion rate of low-carbon steel in μm/year[a]	Suggested classification
C1	≤1.3	1
C2	>1.3 to 25	
C3	>25 to 50	
C4	>50 to 80	
C5-I	>80 to 200	2
C5-M		
CX	>200	3

[a] Based on thickness loss measurements after the first year of exposure [14].