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Unification of corrosion protection for offshore wind farms - collaboration in partnerships

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ABSTRACT

The offshore wind energy industry is focused on reducing the total cost of energy. Industrialized production and standardization are considered increasingly important elements in the pursuit of this. The intention of this paper is therefore to illustrate how this challenge, which is faced across the industry, can be dealt with in cooperation. The key words within the industry right now are doing it better, doing it smarter and doing it together. One way is to create new standards and guidelines within the industry, while other projects attempt to avoid previous times' mistakes through participation and elaboration on observations, by improving guidelines etc. Common for many of the attempts is that they are often carried out by more than one partner and often in the form of Joint Industry Projects (JIPs).

Some of the projects dealt with over the past years, by the authors, have been with regard to corrosion protection of monopiles, manufacturing of industrialized jackets, work on more accurate cathodic protection guidelines and standardization and verification of new design curves for welded substructures. Some of these elements account for a large share of the investment and maintenance costs as regards offshore wind energy. The hope is that ultimately an as accurate data basis as possible combined with experience and knowledge, will lead to more standardized structures and hence reduction of cost. But to be more successful, more cooperation is needed.

Key words: Offshore Wind, Marine Corrosion, Fatigue, Protective Coatings, Cathodic Protection, Standards

INTRODUCTION

The offshore wind industry is evolving rapidly. Approximately 400 new offshore wind turbines were installed in 2016, mainly in the North European seas[1]. In the future, the installed capacity is likely to increase significantly when others are coming along too. As an emerging industry that eventually has proven itself sustainable, there is now much focus on optimizing design and cutting costs to reduce the cost of energy (CoE). The hope is that ultimately only few modifications should be made from site to site. Until now, the major focus from wind turbine manufacturers has been directed at cost reductions of the turbine itself. Currently an offshore turbine is only responsible for approximately ¼ of the service lifetime cost. Costs associated with other elements such as foundations, installation and maintenance of offshore farms, are responsible for nearly half the service lifetime cost. Thus, by optimising corrosion protection and design, large cost savings are expected from longer service life-times and less maintenance.

The current stage of offshore wind may be compared with the early days of car and aircraft manufacturing or ship building. Yet, there is no straight forward way of doing things smarter. This is something which has to be learned. Some details will remain protected for commercial reasons by the companies, while standardisation and shared supplier networks may be sought for other parts. The foundation is an obvious part, for which unification may be sought across companies. Maintenance and repair of unmanned offshore wind structures are extremely expensive and design variations are indeed trickier to deal with in an offshore environment. The cost is typically a factor of 100 times greater than that of similar repair onshore.

Several initiatives are currently seen to approach the common challenges of corrosion protection. Specific industry standards are available today, such as the DNV GL recommended practices[2-4], the VGB/BAW standard[5] and the NACE TG476 committee work[6]. However, much of the content refers to standards initially made for other offshore structures, such as oil & gas platforms. Since the challenges are different for wind structures, there is still room for improvement.

Another approach to solve these problems is through Joint Industry Projects (JIPs). Some of the known international JIPs on corrosion and materials include the SLIC project[7] about fatigue design, the DNV GL project[8] on subsea bolts or the OWA projects offered by Carbon Trust[9] in UK. Similar efforts are initiated at a more local level in Denmark where some projects – which are referred to as Fast Tracks[10] explore more unification in relation to corrosion protection of substructures. These Fast Tracks constitute a cooperation between several technological partners in Denmark and academia, and the projects are hosted in a societal partnership founded by Innovation Fund Denmark.

The current paper presents examples of on-going activities in various joint industry projects, of which the authors of this paper take part in one way or another.

NEXT GENERATION OFFSHORE COATINGS

The first offshore wind farm in the North Sea was implemented in 2002. The coating specifiers were inspired from the oil and gas industry and the selected paint system (two-coat, ceramic reinforced epoxy, 350 µm DFT) was approved by the testing regime of ISO 20340/NORSOK M-501[11-12]. After 14 years of exposure, the foundations painted with the 350 µm two-coat epoxy system showed pronounced corrosion and almost complete loss of coating (Figure 1)[13]. As a test, 5 of the 80 transition pieces (TPs) were painted with a two-coat solvent-free epoxy system (1000 µm DFT). The two-coat solvent-free epoxy system with 1000 µm DFT appears intact, apart from minor damages made by impacts from supply boats, with no visible corrosion, after the 14 years of exposure (Figure 2).


Photo credit: Hempel A/S

Figure 1: Two-coat system, 350 µm (DFT). Passed test protocol according to NORSOK M-501[12].


Photo credit: Hempel A/S

Figure 2: Two-coat epoxy system in 1000 µm (DFT) – no NORSOK approval.

Even though the thin 350 µm paint system passed the tough testing regime of ISO 20340/NORSOK M-501[11-12] it did not pass the real-life service. The learning from this case is that pre-qualification tests alone do not necessarily point out the right coating systems for real service.

Since the commissioning of the first windfarm in 2002, the coating systems have undergone many developments and, mostly, the experiences have been positive. Indeed, provided the application was filled in correctly. Based on the perceptual search for reduced costs, the paint systems have gradually been modified to become thinner, with fewer layers. So far with predominant success. However, the constant search for optimization remains.

New offshore wind projects are designed with a service lifetime of at least 25 years, and ideally no need for future refurbishment. To meet such tough demands for the coating systems, we need trustworthy pre-qualitification tests. Furthermore, we need to combine them with experience from existing offshore structures in similar environments. It could be field failure analyses or it could be from forensic analyses after decommissioning. It will provide valuable information for future projects, accelerated testing regimes as well as standards and guidelines, which to a degree are based on experience from the field. Such work is seldom included in the decommissioning program. This would be a very valuable initiative.

Our previous JIP together with a range of paint manufacturers, had the aim of testing coatings for a novel jacket foundation concept, based on steel pipes from the line pipe industry[14]. The testing was aimed at supporting the goal of 25 years' service lifetime. 15 coatings were tested with a range of mechanical and environmental tests. The mechanical tests included impact test (IMP), thermal cycling (TCT) and flexibility test (FLEX), after NACE TM 0404[15]. The employed environmental tests counted immersion test (IMS), ageing test (AGE) and cathodic disbondment (CBT) following ISO 20340[12]. Special attention was on fusion bonded epoxy technology in comparison with conventional coating systems. The tested coating systems include various wet epoxy systems (EP), of which some were solvent-free (SF) and some standard (STD), fusion bonded epoxy coating systems (FBE) and glass flake polyesters (GF). Polyurethane top coats were also included on some coating systems but this is not evident from the sample names. An overview of samples and results is provided in Table 1[14].

Table 1
Summary of results on the 15 tested coating systems. Green color means "pass", red means "fail" and yellow means "limited" performance[14].

System #	Code	IMP (in.lb)	TCT (crack)	FLEX (%)	IMS (mm)	Age (mm)	CBT (mm)
1	SF_EP1	>126	No cracks	1.6	0.1	15.5	0
2	SF_EP2	110	No cracks	2.0	0.4	6.4	19
3	FBE3	>126	No cracks	>8	2.7	14.1	0
4	FBE4	>126	No cracks	1.8	0.1	24.7	35.3
5	FBE5	>126	No cracks	1.7	0.2	23.4	29.3
6	GF6	40	(Corner)	0.8	0.5	7.8	4
7	SF_EP7	40	No cracks	2.1	0	10.5	12
8	STD_EP8	40	No cracks	1.3	0.1	23.2	21.3
9	SF_EP9	65	NA	NA	0.2	NA	6.7
10	SF_EP10	35	NA	NA	0.8	NA	20
11	FBE11	>126	NA	NA	4.4	NA	13
12	FBE12	>126	NA	NA	0.9	NA	27.7
13	FBE_Zinc13	123	No cracks	1.8	1.2	0.1	6.7
14	GF14	81-90	(Corner)	<0.5	0.2	2.9	0
15	FBE15	>126	No cracks	2.6	1.5	7.5	0

The FBE systems generally performed better in the impact test than the wet epoxy and the glass flake systems. Exceptions were the wet epoxy systems top coated with a polyurethane (systems 1 and 2), which showed performance on par with the FBE systems.

In general, no cracks were observed on any system in the thermal cycling test except the glass flake systems. In this respect, it should be noted that cracks were only detected in the corner and due to the difficult geometry of the panels (L-shape) and difficulties associated with the spray application, giving rise to excessive DFT in the critical areas.

Regarding the flexibility testing, the wet epoxy and the FBE systems showed an expected flexibility of about 2 %. One exception was system 3 (FBE) with a very high elongation, >8%. The glass flake systems showed slightly lower flexibility (< 1 %) compared to the other systems.

All systems pass the immersion test showing no blistering and no rust, and the rust creep from the scribe is well below 8 mm (3 mm for zinc primed systems).

In ageing testing approximately half of the systems pass the ISO 20340 requirements[12]. There is a strong indication that zinc primer improves rust creep resistance (system 13).

In cathodic disbondment testing 12 systems pass the ISO 20340 requirements (≤ 20 mm) and 3 systems show a disbondment > 20 mm. The 3 systems failing the cathodic disbondment test are all FBE systems.

The overall summary of all tests is that good candidates for offshore wind foundations were found among all three technologies. Glass flake polyester seems to be the safe choice, since the results were good and there is a lot of experience and thereby predictability associated with the coating. The drawback of the coating is the lack of flexibility. Fusion bonded epoxy (FBE) is a very promising candidate as it showed some good results in the tests. Future experiments are planned to get more experience with the new coating system.

It should be mentioned that ISO 20340 requires 6-months exposure, which refers to >15 years' service lifetime. In the end of the project, it was decided to extent and add a 9 months' evaluation also, in order to simulate a longer service lifetime. The results presented in Table 1 are from the 6-months exposure.

RISK OF HISC IN NEW FOUNDATION DESIGNS

As mentioned in the previous section, a new jacket foundation concept has been developed, using coated standard pipe sections from the line pipe production, see figure 3.

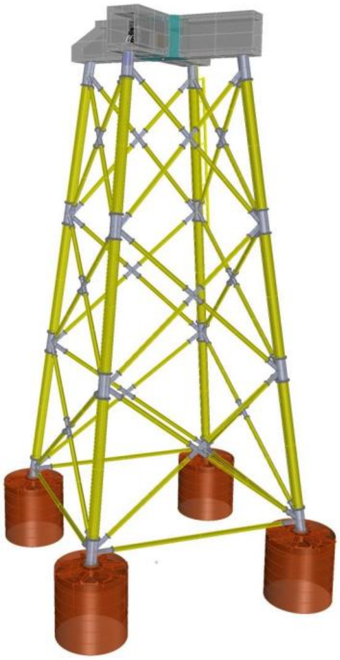

Figure 3: The new jacket design.


Photo credit: FORCE Technology

Figure 4: Full scale mechanical testing of critical parts of the new jacket design.

The jacket structure will enable a considerably reduced CoE applying an industrialized concept, taking advantage of mass produced line pipes with well-proven coating systems for corrosion protection. The pipes can be pre-fabricated into the desired jacket structure components that may be joined to comprise the jacket foundation. Assembly of components can be executed at quayside in the port of wind turbine shipment just before shipping to offshore locations. This enables a more flexible and cheaper production of the foundations.

CeJacket is a large ongoing project involving many partners, including the authors of the present paper. The goal is to promote a cost-effective jacket foundation, which, at best, should be the primary choice for all future offshore wind turbine installations. Full scale testing of critical parts is being conducted as part of the project, cf. Figure 4. One unique initiative within the project is that certifying bodies are approached early in the project, with the aim of reducing the acceptance time of the new solutions. We believe that this is a clever choice in a project constellation within this field. The CeJacket project consists of several work packages, one of which deals with loss of structural integrity in bolts and welds caused by corrosion related failures such as hydrogen induced stress cracking (HISC). This presentation focuses on the HISC issues by virtue of two case-stories on bolt failure respectively weld heat affected zone cracking.

It has long since been recognized that there is a risk of HISC in high strength steel (i.e. quench and tempered) bolts used in subsea structures. In 2016, BSEE published an alert regarding numerous failures of bolts in subsea structures due to HISC[16]. The alert indicates the lack of sufficient requirements for the qualification, production and documentation of alloy and carbon steel bolting used in the petroleum and natural gas industries, which led to the issue of API 20E covering these issues[17]. This problem disperses throughout all types of subsea installations, such as the new jacket foundation structure. It is often conceived that ISO class 8.8 bolts are immune to HISC. As presented below, however, the case of a subsea joint indicates that there is also a risk in ISO 8.8 class materials in special conditions. This underlines that the BSEE alert is not only appropriate for high strength bolts ISO class 10.9 or higher.

An M20 bolt was exposed to 2 years of subsea service, in close proximity to cathodic protection provided by sacrificial aluminum anodes. The bolt fractured just inside a threaded hole, see a picture of the fractured bolt in figure 5.

Figure 5: Fractured M20 bolt exposed to 2 years of subsea service.

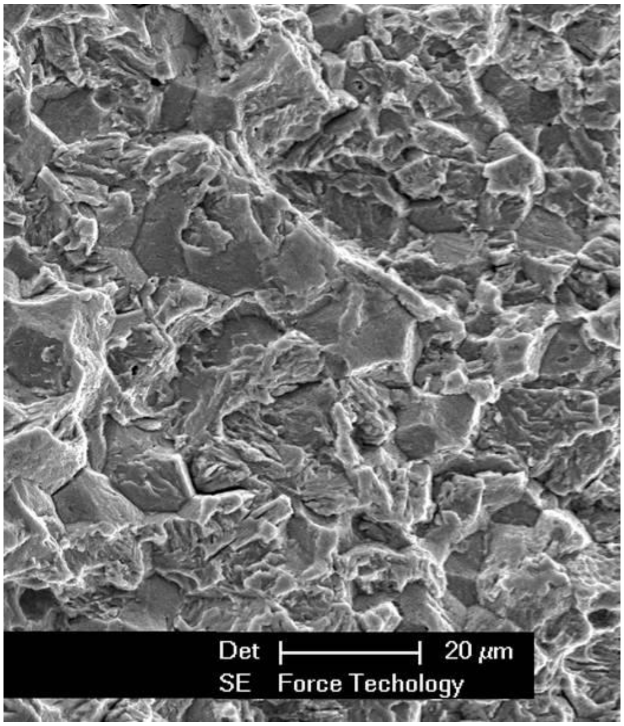

Figure 6: Fracture surface of bolt showing a mixed intergranular and quasi cleavage morphology.

Investigations of the bolt showed that the ISO 8.8 requirements were met, with respect to composition, microstructure and hardness. The maximum hardness was < 320 HV10 with average hardness of 313 HV10, which is just within the ISO 8.8 requirement of 285-320 HV. The failure analysis concluded the failure mode to be HISC, resulting in mainly intergranular cracking mixed with patches of quasi-cleavage, as seen on the fracture surface in Figure 6. The hydrogen source comes from the cathodic protection system, which in combination with the oxygen-depleted conditions inside the threaded hole, promotes absorption of hydrogen in the steel. The hardness of the present 8.8. bolt corresponds to a UTS just above 1000 MPa, hence close to the specification of a 10.9 bolt.

This example underlines the necessity of enforcing strict requirements also of lower strength bolts to avoid HISC. An 8.8. bolt with a HISC sensitive microstructure may not be applicable in cathodically protected structures while a 10.9 bolt of high quality may work in environments of cathodic protection without a risk of HISC, if properly heat treated, despite its inherently higher strength and hardness. Work on implementing sufficient demands on the bolting quality for the jackets structures is ongoing, to avoid future failures due to HISC. Steps to be taken to avoid HISC of bolts and fasteners include stricter specification on microstructure and hardness. Adoption of the experience from the petroleum industry, which is collected in the API 20E[17], could be an option to ensure sufficient quality of bolts used for offshore wind. However, while many bolted joints and structures within the petroleum industry will be periodically retrieved and cleaned and inspected above water, the wind turbine foundations will be submerged for >20 years. The implication is that the effects of sulphate reducing bacteria in an anaerobic sea bed and local anoxic conditions that may develop beneath heavy layers of decaying marine growth will aggravate the risk of HISC by promoting hydrogen uptake in the steel. It may be necessary to define safe borderlines of acceptance by use of test methods to determine if a material is fit for service. The HISC work package in Cejacket includes works on establishing procurement tests for such bolts for critical joints.

HISC failures may also occur in connection with welds of submerged marine structures as illustrated by a case story of a bulkhead to chord weld cracking. The hardness varied from 247 HV10 in the base metal to peak values of >370 HV10 in the high temperature heat affected zone, close to the fusion line. The weld surface was initially coated with a high-quality epoxy system and cathodic protection was supplied by aluminum anodes. Preexisting under bead cracks and toe cracks were not detected due to insufficient quality control. Examples of such cracks are shown in Figure 7. When subjected to the loads during service the cracks opened. The hydrogen developed from the cathodic protection system migrates to sites of triaxial stresses at the tips of the pre-existing cracks, which in combination lead to HISC, see Figure 8. The pre-existing cracks could have been eliminated by proper welding procedures or detected by sufficient inspection before installation. This once again emphasizes the importance of quality control during the entire process.

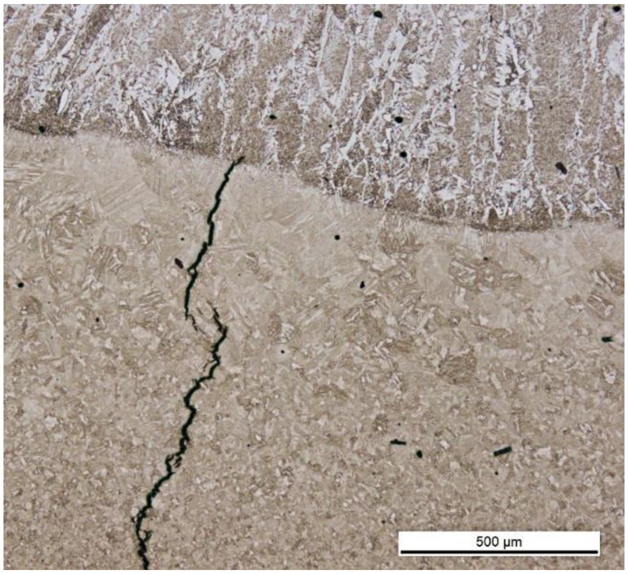

Figure 7: Preexisting crack from welding.

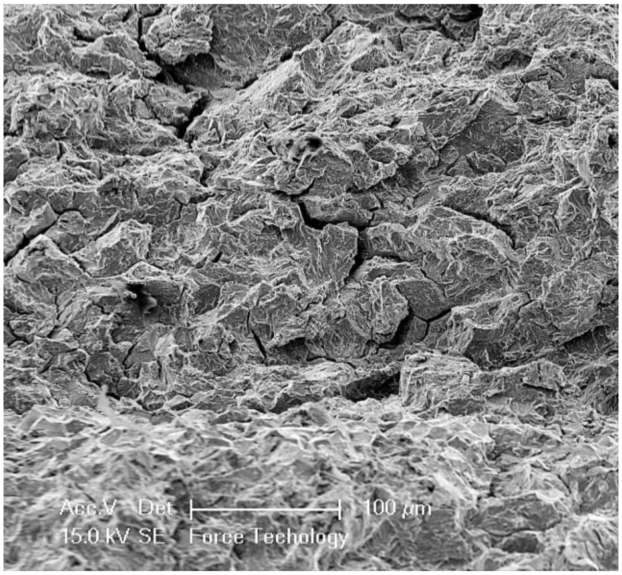

Figure 8: HISC fracture in welded structure.

The above described examples are presented to indicate the risk of HISC in the new jacket design, which can be overcome by proper initiatives and guidelines. Cooperation in the industry is necessary to develop and implement the relevant requirements for the new jacket structure.

SLIC – STRUCTURAL LIFECYCLE INDUSTRY COLLABORATION

SLIC is another example of a JIP with participation of a wide variety of wind operators including authoring companies of this paper[7,18,19]. The SLIC project was aimed at improving the data basis for construction of new offshore wind farms and has thoroughly investigated fatigue crack initiation and growth behavior in welded steel structures for multi-pass butt welds exposed to different relevant environments. SLIC was initiated because currently available S/N-curves in standards and guidelines to a wide extend are based on old experiments. Some stakeholders believe that these are outdated and, hence, lead to over-engineered structures. The overall goal with the SLIC project was therefore, through standardization, to reduce the CoE of future offshore wind projects by creating a more accurate design basis.

It is obvious that standardization of new design data is a too large a task for one partner alone. A number of partners (including some of the authors of this paper) engaged in this attempt. Also two offshore certification agencies, DNV-GL and Lloyds Register, were involved as well as 3 independent test centers in order to validate results. Figure 9 illustrates how the S-N design curve in air compares to the present design basis for free corrosion – the fatigue life is one third under corrosion fatigue conditions. The prediction of the corrosion fatigue conditions, when tested, is expected to be less conservative than the current design for free corrosion.

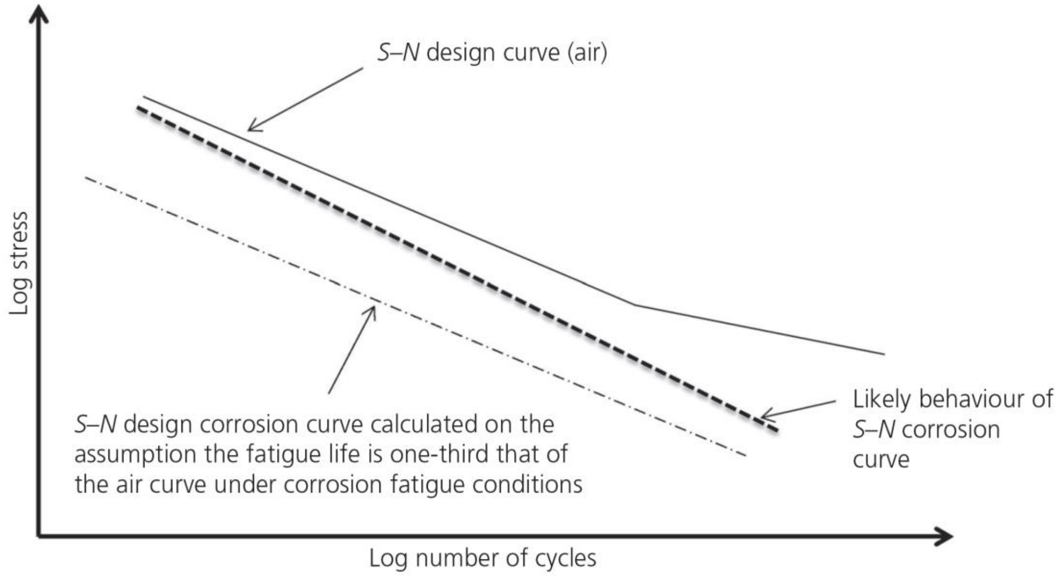

Figure 9: Illustration of how S–N fatigue behavior in air compares with that of free corrosion. The curve in the middle is the predicted outcome of the SLIC test programme[18].

Through the last decades, the offshore industry has evolved significantly towards more industrialized manufacturing processes. New materials, new welding technologies and a different application of the structures are just some of the changes when comparing structures to those of oil and gas. At the same time, design savings are becoming more and more attractive due to the quantity of substructures being designed. It is increasingly relevant to make sure that the applied data is as accurate and as close to reality as possible. To ensure this, testing is needed to reflect the actual environment. The samples were therefore characterized in-air and in simulated seawater environment.

Even in a consortium such as the above, there are some limitations to what is feasible. It is also, from a practical point of view, simply not realistic to test a sufficient quantity of full-scale welded circular sections. The SLIC team hence faced the requirement that fatigue tests had to be accurate and small enough to be handled in the various laboratories. Testing was therefore downscaled and Figure 9 shows an example of how testing in a seawater simulating environment was carried out.

Figure 9: Example of corrosion fatigue testing performed during the SLIC project.

In order to represent the actual manufacturing details, sub-suppliers of steel and fabricators were also asked to deliver the relevant materials for testing. Published findings from the SLIC study can be found in [19].

Overall, the project demonstrated why JIPs in the offshore industry are becoming increasingly attractive. The project is a perfect example of how involvement of an entire industry can lead to mutual benefit. The results generated throughout the project led to work on new design standards for offshore support structures[20].

REFINING AND OPTIMIZING THE CP DESIGN

The CP design of offshore wind foundations is based on well-established guidelines, such as DNVGL RP-B401[21]. However, the monopile foundations are often installed in difficult locations with limited long-term experience about CP performance, such as shallow water having high sea currents and tidal activity or brackish waters with low conductivity. Cathodic protection of the internal compartment also presents special challenges, such as acidification and gas evolution[22]. At the same time, the CP system must be designed to provide protection for the entire service lifetime (>25 years) without need for costly offshore retrofitting or maintenance work. To be on the safe side, this could potentially lead to a too conservative design.

In order to verify the CP design in offshore wind farms, the Field Gradient Sensor (FIGS) has been applied for detailed CP surveys, Figure 10. The field gradient sensor is a rotating dual electrode, which measures the potential gradients around the structure in very high resolution (0.1 µV/cm). By combining this technique with mathematical modeling and contact probe (stab) measurements, a detailed 2D or 3D model of the cathodic protection system can be established, providing both anode output and current density, Figure 11.

By using this technique on monopile foundations in brackish water, it was possible to calculate the anode output and the remaining anode lifetime, which turned out to be 70-85 years, and thus, by far on the safe side[23]. Thus, the field gradient sensor may be a strong tool for optimizing CP design and saving costs. Apart from those of the external side, options for CP-design of the internal water flooded compartment are being debated extensively. There are currently no guidelines or standards that address this issue in detail. Some concerns include the current drain to the seabed and its effect on anode lifetime. To establish new guidelines on this item, a study using the field gradient sensor might be an obvious candidate for future research collaboration or JIPs.

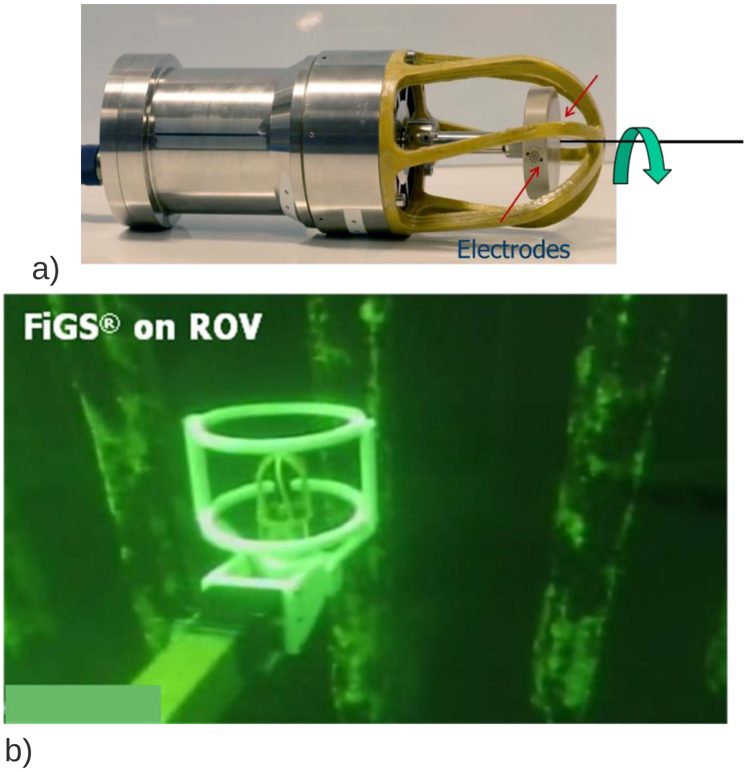

FIGURE 10: (a) Field gradient sensor. (b) Field gradient sensor mounted on a remotely operated vehicle (ROV) measuring output from anode.

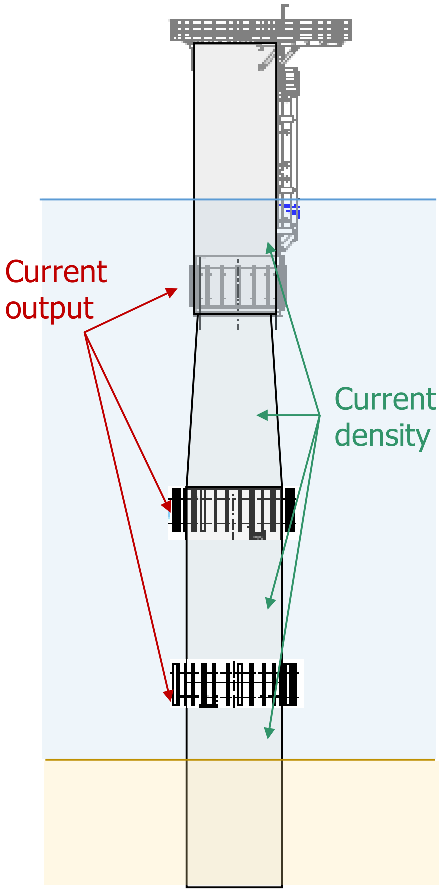

FIGURE 11: Example of CP design on monopile foundation.

JOINT INDUSTRY PROJECTS

All stakeholders involved in offshore wind farm activities are faced with the requirement that the industry has to break free from subsidy links. It is realized that governmental support is declining around the world. Large efforts are therefore put into reaching the cost reductions, often described as a reduction of CoE, needed for the offshore wind to become competitive with other renewable technologies as well as fossil powered energy production. The industry is however well on its way and 2017 was the year that first bids on subsidy-free wind were given by the world's largest wind farm company[24].

Unfortunately, faith is seldom enough to move mountains, and cooperation is necessary in order to continuously improve the industry. The increasing focus on cost reductions has, therefore, led to renewed awareness of JIPs in which complex challenges – often too complex for one to solve alone – are faced by a series of interested participants. These participants recognize that new data, methods, guidelines and standards are not generated without the knowledge and involvement of the entire supply chain. A myriad of such projects has been launched in recent years and they have generated exclusive partner knowledge. The results could not have been generated individually because they rely on the experiences of the entire consortium. Some of these activities are described below.

REALIZING COST REDUCTIONS IN THE OFFSHORE BUSINESS

Options for potential cost reductions are being analyzed extensively throughout the industry. In order to meet future goals, several initiatives have been launched. DNV-GL, an important partner in the offshore industry, even published a manifesto for cost reduction[25]. This document aimed at quantifying cost reduction opportunities. The document contains 3 basic cost reduction strategies namely; doing it right, doing it better and doing it differently[25]. On a more local level, similar initiatives are also sprouting. The Danish Wind Industry Association has through a project – financed in the Danish Industry Foundation – also put up different work groups consisting of various stakeholders focusing on cost optimization in relation to future wind turbines. The aim of much of the ongoing work is to identify areas with cost saving potential.

As for the typically initiated JIPs, the downside of these is that planning is far from executing. In order to increase the agility of such collaboration, a societal partnership was launched in 2016 in cooperation between Siemens Gamesa, FORCE Technology, Hempel, Elplatek and Danish universities. In this partnership, a small fraction of the overall budget has been allocated to a so-called Fast Track setup. This setup allows the partners of the consortium, as well as external partners interested in solving the same problems, to join forces in a fast and non-bureaucratic way within the framework of the overall project. An expert panel approves funding of the Fast Track projects. The fast track projects have a duration from a few months to six months. Common for the projects are that the interests are in some ways shared between the participants.

One of the Fast Track projects focused on unification of monopile corrosion protection. The Fast Track was basically initiated based on failed internal corrosion protection observed at several wind farms. This led to retrofit solutions and unplanned inspections. In order not to repeat this at new wind farms, it was the project goal to obtain some consensus among the partners, on what would be a suitable and holistic corrosion protection strategy for monopile substructures. The result was some overall recommendations on how to avoid future mistakes in order to ultimately reduce the cost. Among the recommendations were to design open monopile foundations (no more oxygen starvation), include coating in initial design on entire structure, apply CP system internally and externally, and include monitoring in the form of reference electrodes. The outcome from this Fast Track is now being discussed with other interested companies and the hope is that a more shared strategy may lead to more standardization and hence a reduction of cost.

Another Fast Track focused on how to reduce steel consumption for substructures. In this project it was discussed whether the S/N-design curves applied for welds today can actually be replaced with more precise ones in the event where welds are mechanically treated to improve fatigue properties. The project was initiated in the slipstream of the SLIC project, which is described in a previous section of this paper. Instead of focusing on the crack itself, the Fast Track was focused on the effect of surface modifications on the crack initiation. The project led to an application for continued research involving several new partners, thus allowing treatment parameters of the welds to be studied in detail. It is the consortium partners' view that such Fast Tracks are eminent at promoting shared goals in a continuously cost oriented market.

CONCLUSIONS

The paper has reviewed some challenges for corrosion protection of wind offshore farms that are addressed in JIPs:

- A coating service lifetime of >25 years for the next generation of wind farms requires customised qualification testing
- A new industrialized jacket design could imply large cost-savings and the related activities focus on FBE coatings, fatigue strength, subsea bolting and HISC
- Better corrosion fatigue design data adapted to wind structures is needed to optimize design
- Cathodic protection of offshore wind farms may be refined and optimized, using new techniques such as the field gradient sensor
- The above-mentioned projects are examples of JIPs in the offshore wind industry. This paper demonstrates how fruitful collaboration is and how involvement of the entire supply chain can be used to generate new data, methods, guidelines and standards. Hopefully, more unification in offshore wind energy will lead to more a more cost-effective energy source.

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