iWindCr Wireless Sensor System for Corrosion Detection and Monitoring of Offshore Wind Turbine Structures

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Synopsis

The *iWindCr* system, designed and developed to comprise miniaturised corrosion sensors to form a Wireless Sensor Network (WSN), has been piloted in one of the 116 offshore wind turbines located in the south region of the UK. The *iWindCr* system that was equipped with low power-low current sensor interface incorporating the Open Circuit Potential (OCP) and Zero Resistance Ammeter (ZRA) electrochemical technique analysis and the Internet of Things (IoT) was employed to detect and/or monitor electrochemical activities in relation to corrosion on the surface of the M72 stud, part of the monopole (MP) foundation and transition piece (TP) flanged connection of the wind turbine. Through the utilisation of the corrosion threshold database that has been extensively generated also through this project for various materials and environment of wind turbine components, the state of corrosion or damage of the M72 stud can be determined. The provision of the corrosion threshold data could also allow for life prediction.

Keywords— Offshore, wind turbine, corrosion, Wireless sensor network (WSN), Internet of Things (IoT)

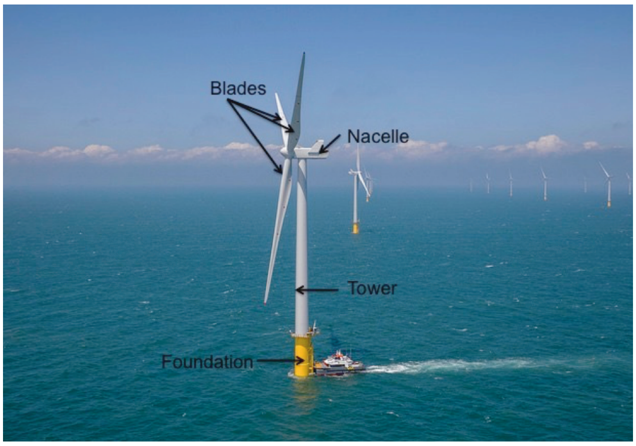
1. Introduction

The UK's geographical location makes it ideal for offshore wind energy, accounting for its status as a world leader in the sector. The UK Wind Energy Database [UKWED, 2019] published by Renewable UK, reported that there are currently 2,016 offshore wind turbines (WT) from 37 offshore operational projects (>100kW projects) that have been producing an operational power capacity of approximately 8.48 GW. These turbines have already powered the equivalent of 4.5 million homes annually and are envisaged to generate over 10% of UK electricity by 2020 [RenewableUK, 2019]. This provision of clean, affordable and secure energy simultaneously would have to consider the integrity, reliability and sustainability in the operation and maintenance of the WT. Particularly when the WT main structures such as the foundation, tower,

http://doi.org/10.24868/icmet.oman.2019.023

nacelle and blades (**Figure 1**) are exposed to harsh conditions generated from the wind, the weather, the ultraviolet radiation (sunlight) and the marine (ocean wave)/maritime environment. This makes corrosion is one of the inevitable and costly issues which has led to the decision of utilising specific corrosion resistance materials and protection in compliance to the industrial standards such as DNVGL-RP-0416 [DNV, 2016]. Nevertheless, corrosion in the foundation structure and its attribute and in the transition piece that connects the foundation and tower has been reported to be one of the main threats of the structural integrity of the offshore WTs. These structures typically comprise external and/or internal components and parts made of steel alloys such as low carbon steels, weathering steels as well as stainless steels [DNV, 2013]. Most parts from the splash zone upwards are coated to prevent corrosion whilst downward of the splash zone would be a combination of coating and sacrificial anodes [Black et al. 2015]. Though the coating could prevent general corrosion, some components/parts are still prone to localised corrosion that may be due to the presence of sulphur in the coating that encourages microbial corrosion, surface or passive film damage from salt spray and impact of foreign object e.g. sands, and from the operation itself e.g. friction between the connected parts [Pawsey, 2016].

Fig.1: Offshore Wind Farm in South Region, UK



iWindCr is a technology development project funded by the Innovate UK aims to develop a cost-effective end-to-end Non Destructive Testing (NDT) corrosion detection and monitoring solution for offshore WT. The system comprises miniaturised sensors arranged in a Wireless Sensor Network (WSN) suitable for being affixed to internal and/or external turbine structures. The corrosion detection thus the monitoring is based on measurement of the changes in the electrochemical states employing the Open Circuit Potential (OCP) and Zero Resistance Ammeter (ZRA) techniques. Implementing the concept of an Internet of Things (IoT) on the Sensor Interface system enables the integration of the WSN with a satellite and terrestrial telecommunication that provides guaranteed IP for data backhaul from the *iWindCr* WSN on the wind farm site to the control room for analysis. [Ahuir-Torres et.al 2019] provides the overview of the *iWindCr* design and development. As the *iWindCr* system moves towards its prototyping stage, it shows that the system can be implemented in two possible scenarios, they are:

Scenario 1: Corrosion detection and monitoring system with satellite bandwidth connectivity

> This allows real-time monitoring of corrosion remotely. Depending on the satellite bandwidth plan, any other data can be send/received over the satellite broadband connection thus giving an alternate, high reliability communication channel to the windfarm.

Scenario 2: Corrosion detection and monitoring system without satellite bandwidth connectivity

> Under this option the data from the *iWindCr* system can either be stored locally at the windfarm and retrieved periodically for analysis or accessed remotely via the user interface if connected to the internet using a terrestrial connection.

iWindCr prototype has been trialled in one of the 116 offshore WTs in the UK's south region. The system was used to monitor electrochemical changes in connection to corrosion activities of one of the 84 M72 studs, in the MP-TP flanged connection of the WT. Adapting Scenario 2, an SD card was used to collect and store data over a one-month trial period. This pilot study aims to determine the reliability and stability of *iWindCr* system in the operating/field conditions and environment. The adequacy of data collection in connection to the sensor interface setting i.e. the frequency or number of reading and the quality of the reading needed for the OCP and ZRA analysis could also be assessed. The corrosion threshold database that has been developed extensively through in-house laboratory testing would be used to verify the readings. At the same time, this could be used to analyse the corrosion state/activities of the stud as well as for the life prediction.

2. Pilot Study

2.1 M72 Stud

An offshore wind turbine's MP-TP flanged connection consist of "bolted connection" of 84 studs made of 10.9 grade Galvanised steel alloys. The M72 class studs are used which each has 110mm length across the flat area, 72 mm body diameter and 58mm thickness. As informed by the wind turbine operator, these studs would have Molykote coating [Dow Corning, 2012] for corrosion prevention containing inorganic and organic compounds mixture such as white mineral oil and calcium hydroxide.

2.2 iWindCr sensor system and configuration

iWindCr sensor made of flexible PolyEther Ether Ketone (PEEK) was attached directly to the M72 stud (not on a polished surface) using silver conductive epoxy adhesive. **Table 1** outlines the characteristic of the sensor.

Table 1: Sensor characteristic

Size: width X length X thickness (all in cm)	1.0X1.0X0.15
Exposed Area (cm^2)	1
Molecular Mass (g/Mol)	55.8
Density (g/cm^3)	8.05
Oxidation State (e-)	3
Three electrodes cell system: 1 working, 1 counter, and 1reference electrodes	Silver (Ag) and Copper (Cu) wires inserted in 3 laser grooved sections on PEEK

The electrode wires are connected to the sensor interface system constructed in a squared PCB of 50mm X 50mm X 2.0mm. The PCB hosts the power supply connection pads, switch and regulator; XBee or wireless communication modules; analogue to digital converters; OCP and ZRA modules and mode switches; programming port; microcontroller; and nanotimer. **Figures 2 and 3** show the PCB layout and the *iWindCr* sensor attachment on the M72 stud.

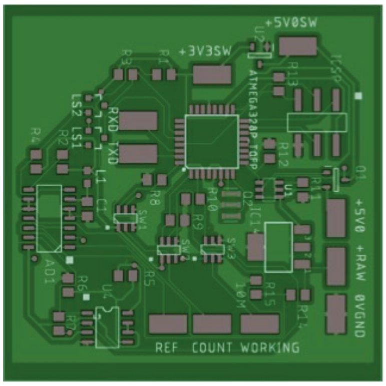


Fig. 2: PCB layout of the sensor interface

Fig.3: *iWindCr* system set-up in the MP-TP flanged connection location with the sensor attached to the M72 stud

From the *iWindCr* in-house performance testing, in order to perform a valid OCP and ZRA electrochemical analysis, it was required to obtain a minimum of 50 data per reading in a period of no less than 120 seconds. Based on this, the sensor data collection time for this field test was set out to be of 200 seconds at every 15 minutes interval of which the nanotimer was set-up. The sensor system outputs will be voltage (V) and current density (A/cm^2), respectively in association with the OCP and ZRA technique analysis that are utilised in the system. **Table 2** highlights the OCP and ZRA electrochemical analysis techniques. The data are collected and stored in an SD card. A battery was used to power the system up to approximately 3-4 weeks.

Table 2: OCP and ZRA technique analysis

OCP	**ZRA**
Non-destructive, passive technique	Non-destructive, passive technique
Provide information of a fresh metal corrosión potential; not suitable for determining the rate of corrosion	Measure directly the stable current density in a corrosion system
$E = E^o + \frac{R\times T}{n\times F}\log\left(\frac{[C_O{}^{no}]}{[C_r{}^{nr}]}\right)$ Equation (1)	$I_{corr} = I_{R.M.S} = \sqrt{\frac{\sum_1^n I_n^2}{n}}$ Equation (2)
Nomenclature:	
E	Potential.
E^o	Standard Potential.
R	Gas Constant (8.314 $J.mol^{-1}.K^{-1}$)
T	Temperature.
n	Number of Electrons transferred in the Corrosion Reaction.
F	Faraday Constant (96485 C/mol).
C_r	The reduced species concentration.
C_o	The oxidised species concentration.
n_o and n_r	Stoichiometric factors of the oxidised species and of the reduced species, respectively
I_{corr}	Corrosion Current Density
I_n	Stable Current Density at certain Number, n of Measurement.
$I_{R.M.S.}$	Root Mean Square of the Current Density

3. In-house Laboratory Testing for Corrosion Threshold Data Generation

3.1 Experimental Procedure

The in-house corrosion laboratory testing has been carried out to determine corrosion threshold values of the 10.9 Galvanised Steel, representing the M72 stud's material in the artificial seawater (SW) environment. The test was performed in accordance to [ASTM D1141 2013] at room temperature and at pH=8.3. **Table 3** outlines further detail on the laboratory testing/experiment.

Table 3: 10.9 Galvanised Steel In-house Laboratory Corrosion Testing

Experimental set-up	
Test samples:	Size: 2.0cmX2.0cmX 0.3cm; Exposed Area: 0.17cm^2
Material:	10.9 Galvanised Steel
Environment & Conditions	Artificial Seawater, pH=8.3, Temperature=298K. Frequencies range: 0.01-30000 Hz. Potential amplitude: 10 mV (r.m.s). Total points: 70. Points/decade: 10.
Standards	ASTM D1141
Equipment	Potentio/Galvanostat: GillAC, ACM Instruments, Software: Gill AC serial no 600.
Electrodes	Reference electrode: Ag/AgCl (KCl Saturated). Counter electrode: Graphite Rod, Working electrode: Test samples.
Samples	1. As-received/Non-corroded sample 2. Artificially corroded sample using the Potentiodynamic Polarisation Curves (PPC) technique 3. Artificially/mechanically damaged (scratched) non-corroded sample 4. Artificially/mechanically damaged (scratched) corroded sample
Method of analysis	Electrochemical Impedance Spectroscopy (EIS)

The Nyquist diagram which is a parametric plot of a frequency, and Bode diagrams that plot gain and phase responses of all the 10.9 Galvanised Steel test samples are shown in **Figures 4 and 5**.

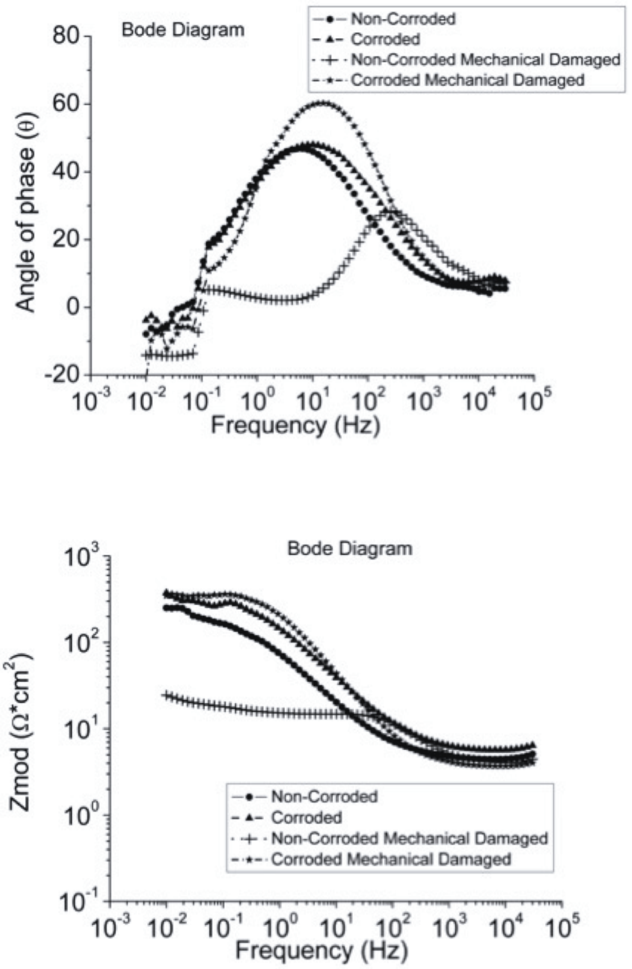


Fig.4: Bode Diagrams of the 10.9 Galvanised Steel Samples from the EIS analysis following the artificial seawater (SW) immersion testing

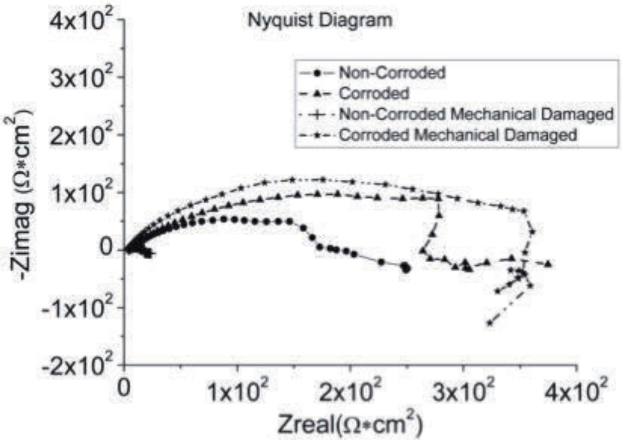


Fig.5: Nyquist Diagram of the 10.9 Galvanised Steel Samples from the EIS analysis following the artificial seawater (SW) immersion testing

4. Field Test Data Analysis and Verification

The field data shows that the *iWindCr* system was piloted for a more and less 30-day period (March to April). From the understanding of the position where the MP-TP flanged connection is within the offshore WT and the local tidal wave data during the field study period, the studs would have not experienced a full seawater immersion. The observation at the field test location suggests that the studs would have more likely been exposed to saltwater spray or moisture.

Table 4 outlines the summary of the sensor interface system (nanotimer) field test performance. Included in **Table 4** are the outcomes of the OCP and ZRA analysis, showing the calculated average potential and average current density that were derived from the raw data recorded during the field test period. The average standard deviation current density indicates the error tolerance of the system. The raw recorded data are represented in **Figures 6 to 8**.

Table 4: Summary of the Field Test Performances and Outcomes of the OCP and ZRA analysis

Field test performances and data	Value
Nanotimer wake interval (average, second)	886 (at 15 minutes interval)
Sensor interface uptime (minimum, second)	250
Total time between reading (second)	1136
Average Potential (V)	2.6966E-02
Standard Deviation Potential (V)	3.7040E-03
Average Current Density (A/cm^2)	1.7195E-10
Standard Deviation Current Density (A/cm^2)	1.4854E-09
Corrosion Rate (cm/s)	4.1401E-15

The corrosion threshold values (*iWindCr* database) obtained from the in-house laboratory corrosion tests for the 10.9 Galvanised Steel alloy are used to verify the electrochemical or corrosion state of the stud. The average voltages and current densities from the database are compared with the OCP and ZRA data from the field test.

As shown in **Table 5**, the database from the in-house corrosion test of the 10.9 Galvanised Steel showed different average voltage and current density levels (different order of magnitude) to the data obtained from the field test. This would be expected as the 10.9 Galvanised Steel's threshold values obtained from the in-house laboratory testing conditioned the full surface immersion in seawater. This was not the case during the field test where the surface of the stud was mainly exposed to saltwater spray or moisture. The salt spray corrosion threshold values of the 10.9 Galvanised Steel was not currently available.

The average voltage and current density values from the field test appeared to be more comparable with the threshold values of the alloys that have a type of protective film. This film could be resulted from oil or grease covering the surface of the alloy. In conjunction with the presence of the thin passive film on the surface of the stainless steel, the 316 stainless steel threshold values derived from the salt spray corrosion testing showed similarities in the average voltage and current density values from the field test. This seems to support the information given by the WT operator with regards to the used of (Molykote) coating on the M72 stud. However, a chemical compositional analysis would be needed to confirm it. Because of the stud was made of low carbon steel (10.9), the corrosion threshold values of the S235, a low carbon steel alloy (a weathering steel) were also referred to and compared with the field test data. For the references, **Table 6** lists the conditions and the experimental standards used to generate the in-house corrosion threshold values i.e. the *iWindCr* database.

By referring to similar conditions and type of materials, the voltages and current density evaluated from the field test suggested that there is no general corrosion as well as localised corrosion detected on the M72 stud during this pilot study period.

The field test average current density and sensor characteristic values given in **Table 3** could also be used to estimate the corrosion rate, *CR* (cm/s). The *CR* is derived using Equation (3).

$$CR = \frac{I_{Ave}*M}{F*n_e*\rho} \qquad \text{Equation (3)}$$

where: M=molecular mass (g/mol), F=constant of Faraday (96,485 C/mol), n_e=number of transferred electrons in redox reaction, and ρ=density of the material (g/cm^2). The pilot study estimated a very low corrosion rate, indicating that there was no accelerated corrosion monitored in this trial period.

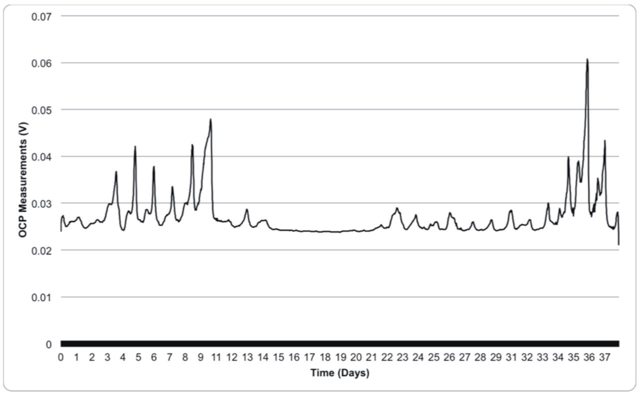


Fig.6: OCP (raw data) measurement plot

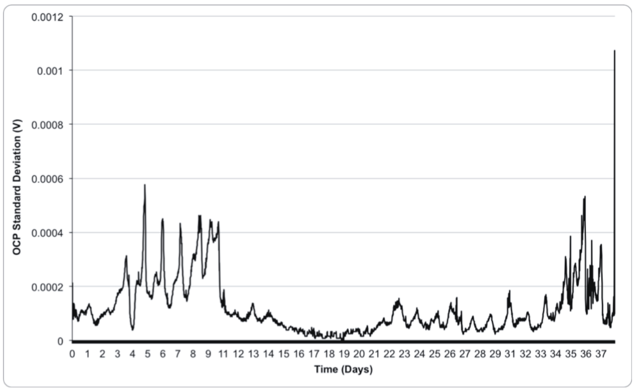


Fig.7: OCP (raw data) Standard Deviation Plot

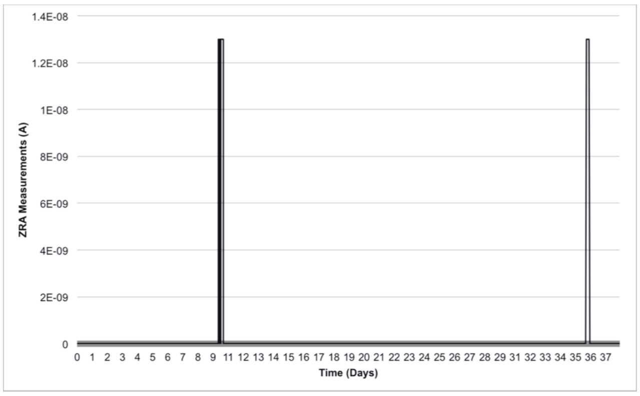


Fig.8: ZRA (raw data) Measurement plot

5. Conclusion

A pilot study (a field test) on the *iWindCr* WSN system on one of the offshore WT structures has been conducted. Albeit the system was only installed on one of the MP-TP flanged connection studs for only a limited period of time, this field test has demonstrated the full functionality of the design and the stability of the prototype system with regards to corrosion detection and monitoring. This gives the confidence to further develop the system towards commercialization.

Table 5: Potential and Current Density values of selected steel alloys

Alloy	Environment	Potential (V)	Current density (A/cm^2)
M72 stud	Salt Spray (SS) or Moisture	0.0270	1.7E-10
10.9 Galvanised Steel	Seawater (SW)	≤-1.000,	≥8E-05
SS316L	SS	≤0.030, ≥0.050	≥2E-09
S235	Grease Lubricant (GL)	≤-0.120, ≥3.000 ¥	≥2E-09
	SW	≤-0.720, ≥-0.600	≥1E-05
	GL+SW at 298K	≤-0.150 ≥3.000	≥3E-08
	Oil Lubricant (OL) at 298K	≤1.180, ≥3.000	≥2E-10
	SS	≤-0.390 ≥-0.120	≥2E-07

There are of course some improvements needed especially with regards to lowering the system's power and current consumptions and perhaps scaling down the system. A follow-up trial would be needed to test the stability and reliability of the sensor for example with regards to the WSN communication between turbines. Although the current *iWindCr* corrosion database has been developed for the offshore WT structures however its usage can be adapted for other applications such as for marine structures or vessels. It needs to be further expanded to include more materials including coated ones since the threshold values are strongly dependence on the materials and the environments/conditions. The media or environments that the materials are exposed to, such as seawater, oil, moisture or salt spray would result in a different electrochemical or corrosion activities and types.

Although, it has been shown in this paper that *iWindCr* system could be used to estimate the corrosion rate hence predict the life of the component, this work was performed for the purpose of *iWindCr* system pilot study only and should not be used for a structural judgment of the relevant WT.

Table 6: Conditions and Standards for the *iWindCr* database

Environment	Conditions	Standard
Artificial SW	Immersion 40mL/cm^2	[ASTM D1141, 2013]
	pH=8.2 at T=298K	
OL	Immersion	[ASTM D6547, 2016]
	Poly-Alpha-Olephine	
	pH=8.8 at T=298K	
	pH=8.6 at T=328K	
GL:SW (30:70) in (Wt/Wt)	Immersion	[ASTM D665, 2014]
	pH=4.3 at T=298K	
	pH=6.8 at T=328K	
SS	Dissolution; Salt Water mass 5%	[ASTM B117, 2018]
	Pressure; 83KPa	
	Fog Volume: 80cm^3	
	pH = 7 at T=308K	
	Mode: Continuous (for 96 hours)	

6. Acknowledgments

This work was supported by the Innovate UK *iWindCr* Project (Grant Number 103504) and co-funded by our industrial partners Avonwood Development Ltd (Co. No. 02570711) and Avanti Communication Plc (Co. No. 03101607). The authors would also like to acknowledge the Faculty of Technology and the School of Engineering, University of Portsmouth for their support in this work.

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