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VGB/BAW Standard

Corrosion Protection for Offshore Wind Structures

Part 4: Cathodic Protection (CP)

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Corrosion Protection for Offshore Wind Structures

Part 4: Cathodic Protection (CP)

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Preface

The growing number of wind turbines in Europe and the world raise new challenges to operators. To reduce the cost of installation and operation and to increase operating reliability, a coordinated and joint analysis of operating experience is an absolute necessity. Apart from exchanging information and experience, the participating companies mainly strive to promote standardisation (best practice). To this end, VGB PowerTech e.V. and Bundesanstalt für Wasserbau (BAW – Federal Waterways Engineering and Research Institute) have decided jointly to draw up a VGB/BAW Standard on corrosion protection for offshore structures (e.g. offshore stations).

The aim of this standard is to ensure that the considerable investments in offshore structures are safeguarded by appropriate corrosion protection systems. In this context, coating systems, for instance, are to protect the steel structures of offshore units from corrosion damage during their entire service life – which is normally at least 25 years – and without requiring any expensive repair work. Robust systems are therefore required which, while involving calculable manufacturing costs (CAPEX), can keep the operating costs (OPEX) at a predictable and low level in the long term. Repair work at sea is to be avoided, as the cost of such offshore repair work can exceed the cost of onshore repairs by a factor of as much as 100.

In this Part 4, “Cathodic Protection” the planning, design, operation and monitoring of galvanic and impressed-current protection systems are described. In the previously published Parts 1 to 3, corrosion protection in general is discussed and stress zones are defined in Part 1. Part 2 focusses on the requirements of coating systems, and Part 3 on the proper application of the initial coating. Parts 5 and 6 are currently in preparation and will be concerned with the topics of coating system repair and in-service inspection and monitoring.

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Proposed changes can be sent to the e-mail addresses **vgb.standard@vgb.org** and **info@baw.de**. To enable unambiguous allocation of the contents, the subject line should contain a brief designation of the document concerned.

The following institutions and associations submitted comments on topics addressed by this standard, which were adopted in the process of editing this standard:

- Bundesamt für Seeschifffahrt und Hydrographie (BSH – German Maritime and Hydrographic Agency), authority responsible for approving offshore structures in Germany within the exclusive economic zone
- TenneT TSO GmbH
- 50Hertz Transmission GmbH
- Arbeitsgemeinschaft Offshore-Wind e.V. (AGOW – Offshore Wind Power Consortium)
- Fachausschuss für Korrosionsfragen (Committee for Corrosion Issues) of Hafentechnischen Gesellschaft (HTG-FAKOR)
- Fachverband Kathodischer Korrosionsschutz e.V. (fkks – Cathodic Protection Association)
- DNV GL SE
- Gesellschaft für Korrosionsschutz e.V. (GfKORR – Society for Corrosion Protection)

and other interested parties.

Essen, July 2018

Karlsruhe, July 2018

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Part 4 – Cathodic Protection (CP)

Contents

1 General

Unprotected steel corrodes in the atmosphere, in water and in moist soil, possibly giving rise to damage. To avoid such corrosion damage, steel structures are protected so that they can withstand corrosion stresses during the required service life, usually at least 25 years.

Offshore structures are exposed to strong corrosive influences over a long period, while the conditions for maintenance and repair are poor. Along with corrosion protection systems that must meet the highest demands, the idea of a corrosion protection strategy must be taken into consideration. This means, among other things, that the specific stresses in the various areas of offshore structures, but also the cooperation of several methods of protection, e.g. coatings, duplex systems (passive corrosion protection), cathodic protection (active corrosion protection) and corrosion allowance (see DIN 50929-3 Supplement 1) in submerged areas, must also be taken into consideration.

This standard is concerned with offshore structures made of steel. In its various parts it takes into account all essential factors having significance for appropriate corrosion protection.

To protect steel structures effectively against corrosion, project owners, ordering parties, planners, advisors, firms carrying out corrosion protection measures, supervisory personnel for corrosion protection work and manufacturers of coating systems require state-of-the-art information on corrosion protection by corrosion protection systems, in condensed form. Such information must be as complete as possible, unambiguous, and easy to understand as well so that complications and misunderstandings are avoided between the parties involved in carrying out the protective measures.

In regard to the minimum requirements for corrosion protection concepts, reference is made to the BSH Standard “Mindestanforderungen an die konstruktive Ausführung von Offshore-Bauwerken in der ausschließlichen Wirtschaftszone (AWZ)” (Minimum requirements for the design of offshore structures within the exclusive economic zone) as amended from time to time.

This standard defines additional requirements supplementing the standards and codes of practice cited in Chapter 7 hereinafter.

In addition to this standard, the minimum requirements, rules and regulations applicable on the federal state level to the locations of wind turbines, wind farm components and other offshore wind structures must also be considered for the design of the corrosion protection. For the area of the German exclusive economic zone, the minimum requirements and regulations stipulated by the BSH are applicable.

2 Scope

This standard, “Corrosion Protection for Offshore Wind Structures – Part 4: Cathodic Protection (CP)”, specifies the requirements applying to cathodic corrosion protection by means of galvanic and impressed-current protection systems for offshore structures exposed to water and mud, as defined in Part 1, “General”, Chapter 2, Scope.

3 Cathodic protection

In the part of offshore structures that comes into contact with water, cathodic protection (CP) is an essential factor for ensuring structural stability.

Basically, all parts of the steel structure to be protected must be permanently connected to one another by electrically conductive means in order to ensure effective CP. To this end, all structural parts must be connected by sufficiently dimensioned welds. The CP can be applied alone, or in combination with a suitable coating, in this area. The protective current necessary for cathodic protection depends on

- the nature of the surrounding medium,
- the object being protected and
- the surface.

Through the supply of current, a permanent reduction in potential is achieved to protect the structure. There are several ways to generate the protective current:

- by using impressed current,
- with galvanic anodes (sacrificial anodes) or
- a combination of these (hybrid system).

In the case of metallically conductive plant components connected to one another, mutual interference between galvanic protection systems and impressed current systems must be avoided.

Chapter 7 deals with the fundamentals of functional design and the measurement techniques required for cathodic protection as well as with their practical applications.

3.1 Notes on planning

Already during the first phase of the planning of an offshore structure, the necessity for and type of corrosion protection must be determined, as this has a decisive influence not only on the structural design, but also on the service life. Because of the fundamental importance of corrosion protection for the design and construction of offshore structures, as well as for their service life and economic efficiency, all basic investigations and field measurements must be completed early on, but at the latest upon the start of detailed design work. See BSH Standard

> “Mindestanforderungen an die konstruktive Ausführung von Offshore-Bauwerken in der ausschließlichen Wirtschaftszone”

Near the seabed, there is always the danger of microbiologically influenced corrosion (MIC) on the inside and outside of offshore structures. This corrosion can be effectively countered by a CP system insofar as a more negative potential than -900 mV versus Ag/AgCl electrode is applied.

However, it always must be taken into account that the CP system can lead to the formation and accumulation of hydrogen and chlorine gas inside the foundation elements. With regard to the hazards for personnel and offshore structures, it must be ensured that suitable monitoring measures and any necessary ventilation equipment are provided in closed spaces (e.g. monopiles), inter alia for reasons of explosion protection. This equipment must be adapted to the special conditions (acidic, saline and moist air as well as hydrogen and chlorine gas).

To enable dispensing entirely with corrosion protection inside foundation elements, the entry of oxygen would have to be completely prevented. This is a design requirement that can hardly be met. During inspections beneath the airtight deck, there is the possibility that oxygen will enter the closed space. Also, in the case of cable lead-in tubes in a foundation element (e.g. monopile) it must be borne in mind that these do not have permanent, secure seals. Moreover, even in an oxygen-free environment the occurrence of MIC cannot be ruled out.

CP systems can be used for the outside and inside of monopiles also in combination with a coating.

The use of aluminium anodes in the interior always must be viewed critically on account of the possible environment changes (including pH reduction). Alternatively, an impressed current system can be employed.

For a guide to the applicability of the two CP systems (galvanic anodes, impressed current), see Annex 1.

3.2 Planning and protective current calculation

The design and calculation of the CP system of offshore structures usually take place in an iterative process. Annex 2 contains a list of the minimum data required to design a cathodic protection system.

Design and calculation are to be carried out by a certified specialist firm based on the codes of practice DVGW GW 11 or fkks-Richtlinie Güteüberwachung (Quality Surveillance Guideline) or a comparable code.

The generally accepted criterion for adequate corrosion protection is a potential range between -800 mV and -1,100 mV versus Ag/AgCl electrode. To avoid cathodic blistering or disbonding of the coating, it must be ensured that a cathodic protection system is limited to a potential of -1,100 mV versus Ag/AgCl electrode. In addition, this ensures that no harmful formation of hydrogen takes place on the surface of the steel (hydrogen embrittlement). In the presence of microbiologically influenced corrosion (MIC) the potential must be reduced to at least -900 mV versus Ag/AgCl electrode.

Depending on location and environmental influences, on offshore structures there are three corrosion zones (A-C) requiring cathodic protection. They are shown taking a monopile as example. See Table 1 and Figure 1.

Table 1: Cathodic corrosion protection zones with possible defects

Zone	Area	Coating discontinuities/repair/CP
A	TZ, LWZ and UWZ	Discontinuities caused by mechanical influences; coating repair possible only in tidal zone Specific protective current requirement of CP **high**
B	Loosely packed seabed/mud	Discontinuities subsequent to installation of offshore structures; coating repair unrealistic Specific protective current requirement of CP **very high**
C	Densely packed seabed	Discontinuities subsequent to installation of offshore structures; coating repair not feasible Specific protective current requirement of CP **moderate**

TZ = tidal zone
LWZ = low water zone
UWZ = underwater zone

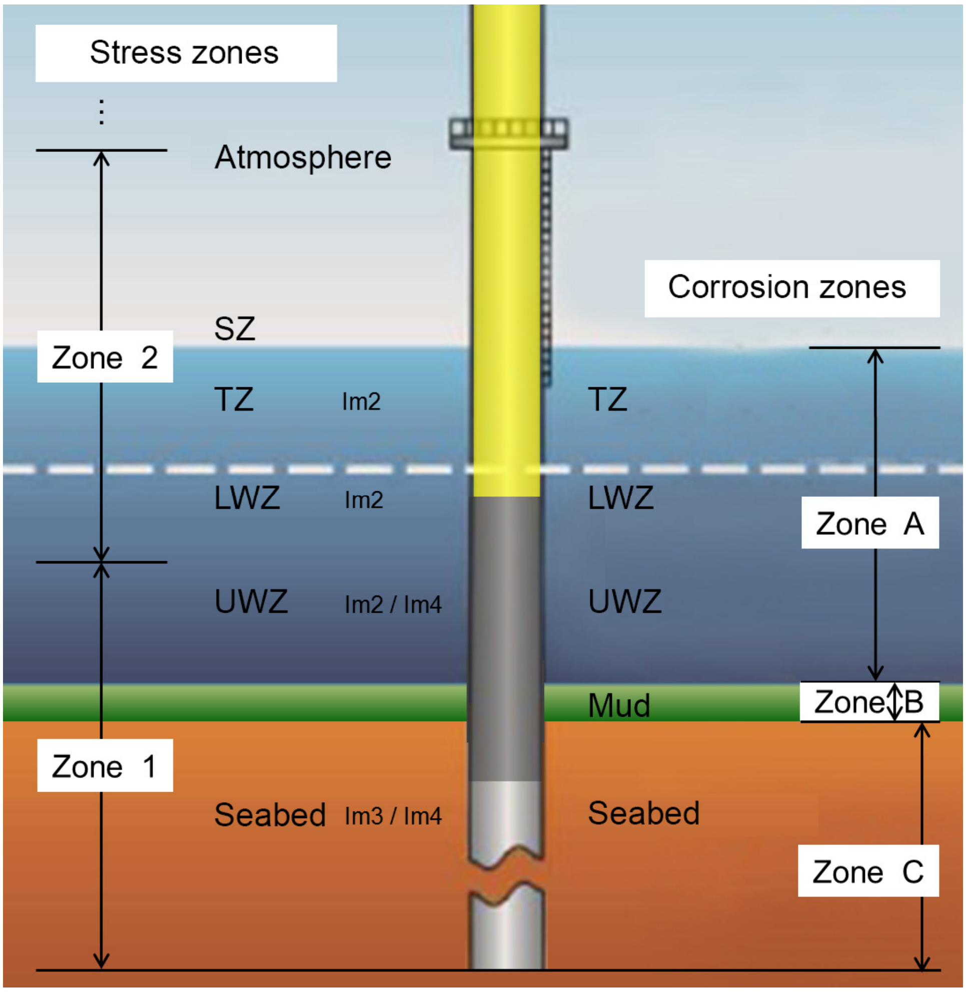

Figure 1: Corrosion zones of offshore structures (e.g. monopile) requiring cathodic protection

Stress zones (Belstungszonen), Atmosphere, splash zone (SZ), tidal zone (TZ), low water zone (LWZ), underwater zone (UWZ), Seabed

Corrosion zones (Korrosionszonen), TZ, LWZ, UWZ, Mud, Seabed

Guide values for the electrical conductivity of water bodies in Germany are shown in Table 2. The values must be verified by the project owner for making precise calculations (e.g. based on measurements of the project owner's own).

Table 2: Guide values for specific electrical conductivity and electrical resistance of the following bodies of water

Body of water	κ [µS/cm]	ρ [Ω ·c m]
North Sea	approx. 33,333	approx. 30
Baltic Sea	approx. 9,100	approx. 110

The values for the required protective current follow from, among other things, the discontinuities in the coating and the required current density at the point of application. The discontinuities have a decisive influence on the design of the CP system.

Annex 3 contains a model CP calculation for exterior protection of a coated monopile. Taking into account in particular the requirements for coatings set out in VGB/BAW Standard VGB-S-021, Parts 1 to 3, the initial, mean and final discontinuities are to be determined jointly by contractor and principal/owner. Indications of discontinuities can be found in Annex 3, in the pertinent regulations, standards, codes and directives, or can be taken from the experience of neighbouring offshore structures.

The following procedure must be followed to plan active corrosion protection by means of a CP system:

- Compiling of the data required for planning (see Annex 2)
- CP-adapted design of steel components
- Minimising of galvanic elements (e.g. avoidance of CrNi steel)
- CP-compatible coating
- Inclusion of secondary steel structures
- Allowance for anode to earth resistance
- Arrangement of anode attachment points and holders

Welded joints take precedence over bolted connections and are made by welding during manufacture of the structure. If possible, junctions of the CP system (e.g. anodes, electrodes, holders, cable runs) preferably should be installed before applying the coating.

As part of the planning an inspection and test plan (ITP) is to be drawn up by the contractor and approved by the principal/owner.

3.3 Overpotentials and coatings

Damage to coatings suitable for CP caused by overpotentials (protection potentials that have been lowered too much) normally is not possible in the case of galvanic anodes, with the exception of magnesium anodes.

Near the anode the potential is appreciably more negative than the general protection potential. Consequently, a plastic insulating shield or a thicker coating layer must be provided in the immediate vicinity of the anode. The intended protection potential should be maintained at the edge of this so-called protective shield. Overpotentials must be avoided since basically they can damage organic coatings due to hydroxyl formation. If the distance of the anodes from the object being protected is adequate, an insulating shield or thicker coating layer can be dispensed with. One should strive to make the distance between the anodes and the object being protected as large as possible, taking into account the mechanical stresses. Indications can be found in DNV-RP-B401.

4 Galvanic protection systems

4.1 Anodes

On offshore structures, as a rule it is possible to use anodes made of aluminium whose material properties are described in DIN EN 12496.

For good anode current output, the distance between anode and surface should not be less than 0.3 m. If the distance is smaller, appropriate allowance must be made for the anode resistance to earth and the consequently reduced current output.

Low-resistance current transfer is achieved in particular by welding the cast-in holders onto a steel plate welded onto the object. This makes subsequent re-welding possible without damaging the structure. Welded joints always are to be preferred to bolted connections at this point. If bolted connections nevertheless are to be used, they must be secured against loosening, e.g. by means of a spot weld (screw locking device).

The use of galvanic anode chains is not permitted, since the current output of the anode chain is appreciably reduced by the increasing drop in voltage towards the end of the chain.

In closed interior areas or in interior areas where only partial flow occurs, galvanic anodes made of aluminium result in a pronounced environment change and in pH reduction of the trapped seawater. This leads to premature failure of the protection and can cause corrosion damage. Galvanic anodes made of aluminium must not be used in these areas.

4.2 Measuring the protection potential of galvanic anodes

If not specified otherwise, for exterior protection with galvanic anodes it is recommended to equip at least ten percent of the structures in an offshore wind farm with a remote monitoring system. The CP remote monitoring system has the purpose to ascertain and transmit measurement values for the protection potentials in exterior areas (see 5.4).

The values must be measured, recorded and transmitted in time cycles (e.g. 12 h) specified by the principal/owner.

5 Impressed current systems

Components of a CP system are:

- impressed current anodes
- protective current unit with power source
- reference electrodes
- protective tubes, holders
- cable junction boxes
- connecting cables

Detailed information about the individual components is provided in the HTG handbook *Kathodischer Korrosionsschutz im Wasserbau* (2009) and *Handbook of Cathodic Corrosion Protection* (1996) as well as in standards and other codes and regulations.

5.1 Temporary protection systems

As long as external current is unavailable (e.g. during field erection), temporary protection systems as shown in Table 3 are recommended. Crucial to the choice of a temporary protection system are possible corrosion risks such as discontinuities and MIC.

Table 3: Temporary protection systems

<table>
<tr><th rowspan="2">Primary protection system</th><th colspan="2">Temporary protection system</th></tr>
<tr><th>Exterior</th><th>Interior</th></tr>
<tr><td>Fully coated and with impressed current system</td><td rowspan="3">Rust allowance
and/or
galvanic anodes made of aluminium (removable or as hybrid system[1])</td><td>No temporary protection needed</td></tr>
<tr><td>Partially coated and with impressed current system</td><td rowspan="2">Rust allowance
and/or
galvanic anodes made of zinc[2]</td></tr>
<tr><td>Uncoated and with impressed current system</td></tr>
</table>

1 If hybrid system, any interaction between galvanic anodes (for protection during the time of erection) and the impressed current system (for subsequent protection) must be taken into account.

2 Zn anodes to avoid negative pH reduction versus Al anodes.

The temporary protection inclusive of the interaction between the single protection systems is to be planned by an external specialist in collaboration with the structural analyst (fatigue check).

Location-based individual planning is indispensable and a part of the corrosion protection concept (see VGB/BAW Standard VGB-S-021-01, Part 1, Chapter 4).

Documents suitable for the planning, tendering and construction of cathodic protection systems can be found in the literature list and the list of standards, codes and regulations.

5.2 Impressed current anodes

Impressed current anodes must be resistant to seawater. The following impressed current anodes have proved themselves in seawater:

- Metal oxide coated titanium (MOX), high specific current density.
- Magnetite anodes, can be used with high driving voltages; resistant to acid and chlorine gas.
- Platinum-coated titanium/niobium/tantalum, high specific current density.

Overvoltages must be avoided by all means (heavy material erosion). Table 4 shows the characteristics of common anode materials.

Table 4: Comparison of different impressed current anode types

Impressed current anode	Erosion rate [g/A•a]	Utilisation rate [%]	Max. current density [A/m^2]	Voltage limit [V]
Metal oxide coated titanium (MOX)	0.04	90	600	12
Magnetite	20	90	70	none
Platinum-coated titanium/niobium/tantalum	0.08	90	600	12/40/80

The coating thickness of MOX anodes must be designed for the operational lifetime of the anodes and be at least 12 g/m^2. Preferably, Ir mixed oxides or Ir/Ru mixed oxides are to be used.

Through the use of Ru mixed oxides in seawater, considerably more chlorine gas is produced at the anode. Use of these anodes thus is not recommended.

Magnetite anodes require no additional coating and generally can be used in all areas as impressed current anodes with no voltage limitation. In combination with cable connection components and cables made of PVDF they are resistant to chlorine gas, which is formed at the anode in seawater containing chloride.

The platinum layer of platinum-coated anodes must be at least 5 µm thick.

The decision on the anodes to be used can be made with the aid of ZTV-W, LB 220 taking into account practical experience and the explanations of the HTG handbook *Kathodischer Korrosionsschutz im Wasserbau* (2009).

To avoid damage to coatings due to the influence of anode to earth resistance in the immediate vicinity of the anode, the distance between anode and surface should be made so large that the surface is outside the anode/earth resistance area. This distance must be at least 1.5 m. If this distance is not achievable, an insulating shield in the form of plastic interlayers is to be mounted under the anodes; at the edges of this shield the potential must not attain a value more negative than -1,100 mV Ag/AgCl (calculation of resistance of anode to earth).

5.3 Protective current unit

The protective current unit is the heart of an impressed current system. The system should feature automatic control. An essential component is the rectifier set, which is why the protective current unit frequently also is referred to as a rectifier. If possible, the protective current units should be installed in dry, ventilated spaces inside the offshore structures. The choice of units depends on conductivity fluctuations, operation and other constraints and conditions. The features and functions are described taking into consideration ZTV-W, LB 220 and in BAW Leaflet "Kathodischer Korrosionsschutz im Stahlwasserbau (MKKS), 2015". The necessity of data transmission to the control centre especially must be emphasised. To avoid lengthier downtimes, automatic systems must be provided with interfaces so that alarms can be forwarded to control centres and corrections can be initiated before lengthier depolarisation phases occur. Owing to the exposed location of offshore structures, the harsh ambient conditions, the limited accessibility of the offshore structures and the large number of offshore structures, it is recommended to at least design the impressed current CP systems as redundant systems in order to avoid depolarisation phases altogether.

5.4 Reference electrodes

Reference electrodes (RE), also called measuring or reference electrodes/probes, serve monitoring purposes and, in the case of protective current units with automatic potential regulation, the control of impressed current systems. The results of measurement permit detecting changes in passive or active corrosion protection systems. Table 5 contains information about reference electrodes and permanent reference electrodes.

Table 5: Reference electrode potentials and areas of use

Reference electrode	Electrolyte	Potential U_H* [mV]**	Use
$Cu/CuSO_4$ saturated [mV Cu]	Saturated copper sulphate solution	+320	Mobile measurements; cannot be used as permanent reference electrode, as contamination is possible
Ag/AgCl saturated [mV Ag]	Saturated potassium chloride solution	+200 ±10	Mobile measurements; not as permanent reference electrode
Zinc rod [mV Zn]	Water in structure	-770 ±25	Permanent reference electrode and mobile measurements

* Symbol used in DIN EN 13509: E_H

** U_H is the potential difference of the reference electrode versus the normal hydrogen electrode

For the in situ inspection of CP systems the reference electrodes must be checked in regard to their potential stability (variance of up to 25 mV possible) with the very accurate mobile $Cu/CuSO_4$ or saturated Ag/AgCl half cells. Possible passivation/contaminations are to be taken into account as they can result in erroneous potential measurements.

The permanent reference electrodes are to be installed where the lowest and highest potentials can be expected. With an eye in particular to future expensive and dangerous underwater work, a redundant design at least should be provided for.

5.5 Equipment parts – Accessories

5.5.1 Cables and wires

The demands on the quality of the cable sheathing and the manner of installation are very high in offshore structures. For the cables and wires from the protective current unit to the anodes, the cable cross-sections must be dimensioned so that the driving voltages are maintained also at the anode itself.

Attention generally must be paid to protection against mechanical and chemical stresses. The anode head is to be designed particularly tight and mechanically robust. Cable kink protection is necessary, also at the local transitions from any planned protective anode cages into the cable conduits, and especially at edges. Depending on the stresses, the materials listed in Table 6 can be used.

Table 6: Characteristics of cables and wiring for CP systems

Environment	Cable type	Material	Properties/notes
Seawater or brackish water	NSSHÖU, H01N2-D (old designation NSLFFÖÜ)	Heavy rubber-sheathed cable	Mechanically very robust, oil-resistant and temperature-resistant mining or arc welding/battery cable Routing above water in UV-resistant cable conduits
Mud – with no water exchange	PVDF	Chlorine gas-resistant PVDF	Mechanically robust, thermally and chemically resistant; specifically for use in extremely aggressive environments

5.5.2 Anode and electrode holders, conduits

The configuration of the anodes and permanent reference electrodes as well as their safe installation already begins in the planning and design phase of the foundations for the offshore structures. Niches in the structure or the installation of cofferdam boxes are advantageous, but difficult in offshore structures or only feasible at considerably greater effort. It is better to install anodes and electrodes in protective tubes or special holders. Cable conduits must be dimensioned and installed in such a way that subsequent insertion of cables by divers is safe and easy. Materials for anode and electrode holders as well as protective tubes are described in Annex 4. Cables are to be adequately protected against mechanical influences for their intended useful life.

Chlorine-, chloride- and acid-resistant materials, along with UV exposure, must always be taken into account when making the selection. Due to galvanic cell formation, one should abstain from the use of CrNi steels, e.g. for clamps and bolts (higher corrosion risk). In internal areas under atmosphere, for health reasons only halogen-free materials should be used; if necessary, a hazard assessment is to be made.

6 Operation and monitoring

CP systems, impressed current systems in particular, fulfil their function in the long term only if they are continually in operation and the proper equipment settings are constantly monitored (e.g. online), and if the components used are continually looked after or monitored within the scope of system and structure inspections. An inspection and maintenance plan must be developed in advance and handed over to the future operator.

6.1 Measuring the protection potential

For optimum protection of offshore structures, a potential of -800 mV measured against a saturated silver-silver chloride (Ag/AgCl) measuring electrode must be achieved (-900 mV under anaerobic conditions [danger of MIC]). Mobile measurements with a copper/copper sulphate ($Cu/CuSO_4$) measuring electrode also are possible.

Note:

– The zinc electrode changes polarity at -1,036 mV, referenced to Ag/AgCl.

– The protection potential is determined usually by measuring the instant-off potential. In the case of galvanic anodes, determination of the instant-off potential requires great effort. Alternatively, the protection potential can be determined by measuring a reference electrode directly on the structure using a potential measuring gun (Figure 2).

Figure 2: Potential measuring gun

6.2 Assessment of protection potential

Assessment of the measured potential values is not entirely free of problems. The evaluation must be made by the plant operator (or more specifically by a person with special expertise). To avoid confusion, the measured potential values always must be recorded in millivolts [mV] Ag/AgCl.

Note:

- The reference electrode and the sign of the potential value must be documented as well, since interpretation is impossible without this information.
- Table 7 shows the potentials and potential ranges with the greatest practical relevance for the most common reference electrodes (Ag/AgCl and Zn) in comparison with the standard hydrogen electrode (SHE).

Table 7: Potential ranges of structural steels versus the most common reference electrodes

Measuring electrode limit potentials	[mV Ag/AgCl]	[mV Zn]	[mV Cu/ $CuSO_4$] °	[mV SHE]
Range of free corrosion potential of structural steel in seawater	-500 to -700	+536 to +336	-550 to -750	-236 to -434
Protection potential limit value 1	**-800**	**+236**	**-850**	**-534**
Protection potential limit value 2 *	-900	+136	-950	-636
Max. reduction for coated components	**-1,100**	**-64**	**-1,150**	**-834**
Hydrogen development	-1,200	-164	-1,250	-934

* Mud, anaerobic conditions – e.g. for microbiologically influenced corrosion (MIC)
° Exclusively for mobile measurements

If mobile reference measurements are performed at intervals on offshore structures, they must be compared with the continuous measurements in order to make corrections to the controls of the impressed current system if necessary.

Details of measurements for the monitoring of CP systems in operation are separately discussed in the section “Regular checks/monitoring”.

6.3 Requirements for personnel operating a CP system

The cathodic protection system must be continually looked after by experienced operating personnel (trained personnel or qualified persons according to DIN EN 15257 Level 2, Offshore).

The operating personnel must at least have basic skills in the following areas:

- Pertinent standards, codes, regulations on cathodic corrosion protection
- Electrochemical corrosion
- Active corrosion protection
- Passive corrosion protection
- Electrical measurement technology

7 Standards and codes of practice

This standard defines additional requirements supplementing the following series of technical rules, some of which are cited in this standard:

Standards:

DIN EN 10204	Metallic products – Types of inspection documents
DIN EN 12068	Cathodic protection - External organic coatings for the corrosion protection of buried or immersed steel pipelines used in conjunction with cathodic protection - Tapes and shrinkable materials
DIN EN 12473	General principles of cathodic protection in seawater
DIN EN 12474	Cathodic protection for submarine pipelines
DIN EN 12495	Cathodic protection for fixed steel offshore structures
DIN EN 12496	Galvanic anodes for cathodic protection in seawater and saline mud
DIN EN 12499	Internal cathodic protection of metallic structures
DIN EN 13173	Cathodic protection for steel offshore floating structures
DIN EN 13509	Cathodic protection measurement techniques
DIN EN 15257	Cathodic protection – Competence levels and certification of cathodic protection personnel
DIN EN 61400-3	Wind turbines – Part 3: Design requirements for offshore wind turbines
DIN EN ISO 12944	Paints and varnishes – Corrosion protection of steel structures by protective paint systems
DIN EN ISO 12944-9	Protective paint systems and laboratory performance test methods for offshore and related structures, 2018 replaces ISO 20340
DIN EN ISO 13174	Cathodic protection of harbour installations

Codes of practice, leaflets and lists:

BAW	BAW-Merkblatt – Einsatz von nichtrostendem Stahl im Stahlwasserbau (MNIS), 2012
BAW	Liste der zugelassenen Systeme II (für Meerwasser und Böden, Im 2/3), 2016
BAW	BAW-Merkblatt Kathodischer Korrosionsschutz im Stahlwasserbau (MKKS), 2015
BAW	Guidelines for the testing of coating systems for the corrosion protection of hydraulic steel structures, 2011
BSH	Standard Konstruktion – Mindestanforderungen an die konstruktive Ausführung von Offshore-Bauwerken in der ausschließlichen Wirtschaftszone (AWZ); Bundesamt für Seeschifffahrt und Hydrographie, 2015
DNVGL	DNV-OS-J101: Design of Offshore Wind Turbine Structures (DNV, 2014)
DNVGL	DNV-RP-B401: Cathodic Protection Design, 2017
DNVGL	DNVGL-RP-0416 Corrosion protection for wind turbines, 2016
DNVGL	Guideline for the Certification of Offshore Wind Turbines, GL, Edition, 2012
FKKS-Richtlinie	Güteüberwachung – Qualifikationsanforderungen für die Zertifizierung von Fachunternehmen des kathodischen Korrosionsschutzes
GfKORR	Richtlinie für die Zertifizierung von Personal und Akkreditierung von Zertifizierungsstellen auf dem Gebiet der Korrosion und des Korrosionsschutzes
HTG	Kathodischer Korrosionsschutz im Wasserbau, 2009
NORSOK M-501	Surface preparation and protective coating, 2012
NORSOK M-503	Cathodic protection, Edition 4, 2016
STKL-W	STKL, LB 218: Standardleistungskatalog – Korrosionsschutz im Stahlwasserbau (2011)
STKL-W	STKL, LB 220: Standardleistungskatalog – Kathodischer Korrosionsschutz im Stahlwasserbau (2015)

TL/TP-KOR-Stahlbauten	Technische Lieferbedingungen und Technische Prüfvorschriften für Beschichtungsstoffe für den Korrosionsschutz von Stahlbauten
VG 81259	Verteidigungs-Geräte, vom deutschen Bundesamt für Wehrtechnik und Beschaffung – Kathodischer Korrosionsschutz von Schiffen; Außenschutz durch Fremdstrom
VGB/BAW Standard VGB-S-021	Corrosion Protection for Offshore Wind Structures
ZTV-Ing 4/3	Zusätzliche Technische Vertragsbedingungen und Richtlinien für Ingenieurbauten, Teil 4 Stahlbau, Stahlverbundbau, Abschnitt 3 Korrosionsschutz von Stahlbauten
ZTV-W	Zusätzliche Technische Vertragsbedingungen – Wasserbau (ZTV-W) für Korrosionsschutz im Stahlwasserbau (Leistungsbereich 218)
ZTV-W	Zusätzliche Technische Vertragsbedingungen – Wasserbau (ZTV-W) für Korrosionsschutz im Stahlwasserbau (Leistungsbereich 220)

8 Literature

von Baeckmann, W.: Taschenbuch für den Kathodischen Korrosionsschutz, Vulkan Verlag Essen, 6. Auflage 1996

von Baeckmann, W.: Handbook of Cathodic Corrosion Protection, Gulf Professional Publishing, 1997

Karge, C. & Graff, M.: Zum Risiko für und die verschiedenen Arten von mikrobieller Korrosion in Monopiles; HTG-Workshop 2013; www.htg-online.de

Krebs, T.: KKS für OWEA; HTG-Workshop 2014

9 Annexes

Annex 1: Comparison of galvanic anodes and impressed current systems

Criterion	Galvanic anodes	Impressed current system
Seawater	High metals input	Very small metals input
Internal spaces	Danger of environment change and insufficient protection	Take H_2 and Cl_2 development into account
Flexible design of protection period	No subsequent extension of planned design possible	Replacement of anodes after end of planned useful life possible with relatively small effort
Construction	Robust, limited to sub-areas	System parts such as protective current unit must be taken into account; cables and anode holders are susceptible to damage
Installation effort	Technically simple	Technically complex
Effort for retrofitting	Transport and mounting of anode material – very high	Medium to high depending on scope and design of original equipment
Anode mass, number of anodes	(Very) high	Small
Current output [dimension]	Limited per anode ([mA]/anode)	Anodes are controllable ([A]/anode)
Driving voltage	Small, determined by material	High, variable, but dependent on base material of anode
Harmful influence on directly adjacent structures	Generally none	Control measurements required
Possible harmful effects on the protected structure	Generally none, locally limited overprotection possible	Coating damage caused by overprotection and unsuitable coating
Operational checks	Short circuiting connection, visual check during inspection of structure, regular control measurements (protection potential) required	With measuring instruments no problem; remote monitoring possible, regular control measurements required since in the case of a monopile, for example, the installation of reference electrodes towards the seabed is hardly technically feasible.
Servicing and maintenance effort	Small	Medium (constant monitoring – remote monitoring required)
Planner	DIN EN 15257 Level 2, Offshore	DIN EN 15257 Level 2, Offshore
Implementer	GW 11, Offshore, or equivalent standard	GW 11, Offshore, or equivalent standard
Monitor/inspector	DIN EN 15257 Level 2, Offshore	DIN EN 15257 Level 2, Offshore

	Galvanic anodes	Impressed current system
Ad-vantage	• Very small effort for maintenance, only occasional control measurements • Mainly used for structures with small protective current requirements and low specific soil and water resistances • Suitable especially for smaller, labyrinthine, distributed structures • Shadow areas can be compensated with additional anodes • Special protective layers in anode/earth resistance area not necessary • Immediately effective after installation • Not tied to certain structural shapes • Anodes can have any shape imaginable • No electric safety problems thanks to low voltages	• High driving voltage possible • System is constantly monitored by means of installed reference electrodes • Automatic potential regulation by means of reference electrodes possible • Remote operation possible • Subsequent installation offshore possible
Disad-vantage	• Special active alloy required • Large anode mass • Large number of anodes • Low driving voltage • Limited current output • Protection ends at the latest upon complete dissolution of the anode material • Exact duration of protection depends on an adapted design of the CP system and on the ageing process of an existing coating • Retrofitting with new anodes offshore is time-consuming and cost-intensive • Instant-off potentials cannot be measured	• Great effort for maintenance and, where necessary, repair, since at least the incoming measured values have to be continuously evaluated • Repair at least in submerged areas difficult, e.g. if holders are destroyed • Anodes can be destroyed by excessive driving voltages; does not, however, apply if magnetite anodes are used • Continuous supply of energy required • Robust protective structures required • Ongoing operating expense • Cable runs must be designed robustly and for subsequent replacement of anodes if defects occur • Plastic insulating shield in the immediate area of the anode possibly required • Overprotection possible if systems are poorly regulated • Possible hydrogen and chlorine gas development • On failure of a component (protective current unit, cable, power connection, anode) the cathodic protective current is interrupted

Annex 2: Data for design of a cathodic protection system

1. Geographic location
   - Specific electrical resistance [Ωcm]
   - Specific polarisation current density (water and soil) [mA/m^2]
   - Specific mean current density (water and soil) [mA/m^2]
   - Specific repolarisation current density (water and soil) [mA/m^2]
2. Specification of component surface requiring protection [m^2]
3. Surface uncoated [m^2]
4. Surface coated [m^2]
   Condition of coating
5. Stainless steel surface uncoated [m^2]
6. Discontinuities
   - Initial discontinuity [%]
   - Average discontinuity [%]
   - Maximum discontinuity during the useful life of the system [%]
7. Anode parameters
   - Practical current carrying capacity [Ah/kg]
   - Assumed current carrying capacity [Ah/kg]
   - Erosion rate [kg/Aa]
   - Utilisation factor
   - Driving voltage [mV]
   - Size/length [m]
   - Mass [kg]
8. Drawings of the offshore structure that is to be protected
   (e.g. monopile, tripile, jacket, tripod, reinforced concrete foundations)
9. Foreign objects nearby
   (e.g. pipework, cables, other offshore structures)
10. Water analysis at the protected object, possibly at different depths (annual average)
    - Flow velocity [m/s]
    - Oxygen concentration [mg/l]

Optional

- Sulphide (S^{2-}); seabed area [mg/l]
- Sulphate (SO_4^{2-}) [mg/l]
- Chloride (Cl^-) [mg/l]
- Phosphate (PO_4^{3-}) [mg/l]
- Calcium (Ca^{2+}) [mg/l]
- Magnesium (Mg^{2+}) [mg/l]
- Manganese (Mn^{4+}) [mg/l]
- Iron (Fe_{total}) [mg/l]
- pH

Annex 3: Exemplary calculation of cathodic protection systems

Exemplary calculation
of
cathodic protection systems
(impressed current system and galvanic system)
for
external protection of a coated monopole

Contents

1. Design parameters

The exemplary calculation of cathodic protection systems (impressed current system and galvanic system) for the external protection of a coated monopile takes into account Zone A (TZ/LWZ/UWZ) and Zone C (seabed). Zone B is included in Zone A (mud).

1.1 Project data of a North Sea monopile

Material:	Steel
External diameter:	6 m
Max. length underwater:	26 m
Length in soil:	25 m
Surface (TZ, LWZ, UWZ):	490 m^2
Surface (seabed):	471 m^2
Coating:	Organic coating with 600 µm total film thickness in area coming into contact with water
Planned useful life:	25 years
Planned protection period:	27 years

1.2 Specific water resistance

Specific water resistance (North Sea): 30 Ωcm

1.3 Specific protective current densities

The protective current densities required for each zone can be taken from the pertinent standards and codes of practice (e.g. DIN EN 12495, DNV RP-B401).

The current density data for the initial phase serve to design the system capacity for the initial polarisation, while the data of the final phase are for repolarisation. The mean value serves to design the overall capacity.

For coated components, for design purposes the following specific protective current densities are assumed (reference value for bare steel):

Table 8: Example of protective current densities for each zone and design phase (referenced standard)

Zone	Initial phase	Mean value	Final phase
A: TZ/LWZ/UWZ	200 mA/m^2 *(DNV)*	100 mA/m^2 *(DNV)*	130 mA/m^2 *(DNV)*
C: Seabed	25 mA/m^2 *(DIN)*	20 mA/m^2 *(DIN)*	20 mA/m^2 *(DIN)*

If necessary, the mud zone/sedimentation zone can be considered as a separate zone with a much higher protective current density.

1.4 Discontinuities (coating reduction)

The starting point for calculating the protective current requirements is the protective current density required for bare structural steel in seawater (see e.g. Table 8 for this calculation). For this purpose the product of the zone- and phase-specific protective current density ($i_{p,z}$, p= i: initial, m: mean, f: final; z=A: Zone A, C: Zone C) and the corresponding coating reduction factor ($f_{c,p}$, Table 9) is taken.

In the part of the structure covered by water, the protective current density is strongly reduced by a coating, so that for the calculation only uncoated parts of the structure are taken into account. The reason for the increase in the coating reduction factor over time is the breakdown of the coating over the period of use. This factor generally depends on the quality of the coating.

Normally the coating reduction factor is formed by addition of an initial value and an annually evenly progressing degradation. If no testable values for the coating reduction factor are available, by way of substitution the values contained in the relevant standards and codes of practice (e.g. DIN EN 12495, DNV RP-B401) can be used. This initial value (a = 0.02) normally takes into account the assumed damage to the coated components during transport and installation. The annually evenly progressing degradation (b = 0.012) starts from the time of the completed installation. The annual (t) degradation is calculated as follows:

$$f = a + b * t$$

Possible coating reduction factors at the beginning, at half-time, and at the end of life of a plant with a planned useful life of 27 years are shown in Table 9.

Table 9: Possible coating reduction factors for up to 27 years (annual degradation: 0.012; to water depth of 30 m):

Situation	***Period of use (t)***	***Symbol***	***Value***
Initial value	0 years	$f_{i,z}$	0.020 *(DNV)*
Mean value	13.5 years	$f_{m,z}$	0.182 *(DNV)*
Final value	27 years	$f_{f,z}$	0.344 *(DNV)*

2. Calculation of protective current requirements

In this example, the specific protective current densities defined in the design parameters (Table 8) and the coating reduction factors stated in Table 9 are used. This calculation is made based on the usual three criteria for beginning, end, and total period of use. For this purpose the initial polarisation capability, the repolarisation capability with a damaged coating at the end of the useful life, and the total current requirements over the entire useful life are established.

In order to determine the total cathodic protective current requirements I of phase p, as already described the surfaces of the protected areas with their specific protective current requirements and coating reduction factors are ascertained and added up using the following formula:

$$I_p = \sum_{z=1}^{n} (A_z \cdot f_{p,z} \cdot i_{p,z})$$

2.1 Calculation of protective current requirements at the beginning of the protection period

Current requirement calculation for Zone A (TZ/LWZ/UWZ)

$$I_{i,A} = A_A \cdot f_{i,A} \cdot i_{i,A}$$

A_A	= Cathode surface	490	m^2
$f_{i,A}$	= Coating reduction factor	0.020	
i_{iA}	= Specific protective current reqt.	0.200	A/m^2
<u>$I_{i,A}$</u>	<u>= Initial protective current reqt.</u>	<u>1.96</u>	<u>A</u>

Current requirement calculation for Zone C (seabed)

$$I_{i,C} = A_C \cdot f_{i,C} \cdot i_{i,C}$$

A_C	= Cathode surface	471	m^2
$f_{i,C}$	= Coating reduction factor	1	
$i_{i,C}$	= Specific protective current reqt.	0.025	A/m^2
<u>$I_{i,C}$</u>	<u>= Initial protective current reqt.</u>	<u>11.8</u>	<u>A</u>

Total current requirements of all zones

$$I_i = I_{i,A} + I_{i,C}$$

$I_{m,A}$	= Current requirements Zone A	1.96	A
$I_{m,C}$	= Current requirements Zone C	11.8	A
<u>I_m</u>	<u>= Initial total current requirements</u>	<u>13.8</u>	<u>A</u>

2.2 Calculation of mean protective current requirements

Current requirement calculation for Zone A (TZ/LWZ/UWZ)

$$I_{m,A} = A_A \cdot f_{m,A} \cdot i_{m,A}$$

A_A = Cathode surface	490	m^2
$f_{m,A}$ = Coating reduction factor	0.182	
i_{mA} = Specific protective current reqt.	0.100	A/m^2
$I_{m,A}$ = Mean protective current reqt.	8.92	A

Current requirement calculation for Zone C (seabed)

$$I_{m,C} = A_C \cdot f_{m,C} \cdot i_{m,C}$$

A_C = Cathode surface	471	m^2
$f_{m,C}$ = Coating reduction factor	1	
$i_{m,C}$ = Specific protective current reqt.	0.020	A/m^2
$I_{m,C}$ = Mean protective current reqt.	9.42	A

Total current requirements of all zones

$$I_m = I_{m,A} + I_{m,C}$$

$I_{m,A}$ = Current requirements Zone A	8.92	A
$I_{m,C}$ = Current requirements Zone C	9.42	A
I_m = Mean total current requirements	18.3	A

2.3 Calculation of protective current requirements at end of useful life

Current requirement calculation for Zone A (TZ/LWZ/UWZ)

$$I_{f,A} = A_A \cdot f_{f,A} \cdot i_{fi,A}$$

A_A = Cathode surface	490	m^2
$f_{f,A}$ = Coating reduction factor	0.344	
i_{fA} = Specific protective current reqt.	0.130	A/m^2
$I_{f,A}$ = Final protective current reqt.	21.9	A

Current requirement calculation for Zone C (seabed)

$$I_{f,C} = A_C \cdot f_{f,C} \cdot i_{f,C}$$

A_C = Cathode surface	471	m^2
$f_{f,C}$ = Coating reduction factor	1	
$i_{f,C}$ = Specific protective current reqt.	0.020	A/m^2
$I_{f,C}$ = Final protective current reqt.	9.42	A

Total current requirements of all zones

$$I_f = I_{f,A} + I_{f,C}$$

$I_{f,A}$ = Current requirements Zone A	21.9	A
$I_{f,C}$ = Current requirements Zone C	9.42	A
I_f = Final total current requirements	31.3	A

2.4 Overview of protective current requirements

In Table 10 the results after erection (initial value) and after a protection period of 13.5 and 27 years, based on the above calculations, are summed up:

Table 10: Protective current requirements

Current	Initial value	Mean value	Final value
$I_{p,A}$	1.96 A	8.92 A	21.9 A
$I_{p,C}$	11.8 A	9.42 A	9.42 A
I_p	**13.8 A**	**18.3 A**	**31.3 A**

The values computed above are the basis of the further calculations for an impressed current system and a galvanic CP system.

3. Design calculations for cathodic corrosion protection by an impressed current system

3.1 Design current

An impressed current system must be able to provide the maximum current indicated by the results of Table 10 (protective current requirements).

$$I_{max} \approx 32\ A$$

If necessary the maximum current can be multiplied by a safety factor of 1.25 to 1.5 in order to make allowance for a poor distribution of potential (see DIN EN 12495).

3.2 Material parameters

For this sample calculation the following essential components are selected:

Anode:	Magnetite anode	
	Max. current output:	8 A
	Anode weight (net):	4.7 kg
	Anode length:	0.67 m
	Anode diameter:	0.06 m
	Consumption rate:	0.02 kg/Aa (kg/ampere year)
	Polarisation voltage:	2 V
Cathode cable:	Copper cable, 16 m^2 cross-section, 50 m length	
	Resistance: 0.056 Ohm	
Anode cable:	Copper cable, 16 m^2 cross-section, 30 m length	
	Resistance: 0.033 Ohm	

3.3 Calculation of anode life

Useful life of an anode:

$$t = \frac{m \cdot u}{I \cdot C}$$

m = Anode mass [kg]

u = Utilisation factor

I = Anode current [A]

C = Anode consumption rate [kg/ampere year]
0.02 kg/Aa (for magnetite anode)

t = Anode life [years]

$$t = \frac{4.7\ kg \cdot 0.9}{8\ A \cdot 0.02\ kg/A\ a} = 26.4\ years$$

If the impressed current anode is not put into operation until some time after installation, the anode life must be longer than the remaining useful life of the structure (in this case 25 to 26 years). However, the time until the system is put into service must be bridged with temporary corrosion protection.

3.4 Anode resistance to earth

Resistance to earth of a bar anode (magnetite anode):

$$R_a = \frac{\rho}{2\pi \cdot L} \cdot \left(ln \frac{8 \cdot L}{D} - 1 \right)$$

ρ = Specific electrolyte resistance [Ohm · m]

L = Anode length [m]

D = Anode diameter [m]

R_a = Resistance to earth

$$R_a = \frac{0.3\ Ohm \cdot\ m}{2 \cdot \pi \cdot 0.67m} \cdot \left(ln \frac{8 \cdot 0.67m}{0.06\ m} - 1 \right) = 0.249\ Ohm$$

3.5 Total circuit resistance

The total circuit resistance is the sum of all individual resistances in the circuit between the positive pole and the negative pole of a protective current unit. It consists essentially of:

$$R_{total} = R_{ac} + R_a + R_c + R_{cc}$$

Anode cable resistance (R_{ac}):	0.033 Ohm
Anode resistance to earth (R_a):	0.249 Ohm
Cathode resistance to earth (R_c):	0 Ohm
Cathode cable resistance (R_{cc}):	0.056 Ohm

$$R_{total} = 0.033\ Ohm + 0.249\ Ohm + 0\ Ohm + 0.056\ Ohm = 0.338\ Ohm$$

3.6 Output voltage of the protective current unit

$$U_{TR} = R_{total} \cdot I + U_{pol}$$

Circuit resistance (R_{total}):	0.338 Ohm
Anode current (I):	8 A
Polarisation voltage (U_{pol}):	2 V
Output voltage (U_{Tr}):	

$$U_{TR} = 0.338\ Ohm \cdot 8\ A + 2\ V = 4.7\ V$$

3.7 Number of anodes

$$N_{anodes} \geq \frac{I_{max}}{I_{anode}} = \frac{32\ A}{8\ A} = 4$$

Accordingly, the minimum number is 4 anodes.

This calculation does not take into account the distribution of potential on the structure, which depends on the number, position and potential of the anodes. This has to be considered separately. The use of the full current output of 8 A may not be possible, as otherwise this may result in an overrun of the maximum permissible negative potential on the structure. This applies especially to distributed structures (e.g. jacket foundations). It may therefore be necessary to use more electrodes than called for by the calculation.

3.8 Dimensioning of the protective current unit

$$P = I_{max} \cdot U_{TR} = 32\ A\ \cdot 4.7\ V = 150.4\ W$$

The protective current unit must be able to deliver at least a direct current output of 150.4 W.

4. Design calculations for cathodic corrosion protection by galvanic anodes

The calculation of a CP system with galvanic anodes is not a straightforward calculation, but requires an iterative procedure to achieve a technically and economically optimum solution. Among other things, the number and dimensions of the anodes are changed during this procedure.

This calculation is performed using the following anode data:

Anode material:	Aluminium alloy
Anode mass:	65 kg
Anode width:	0.122 m
Anode height:	0.110 m
Anode length:	2.5 m
Diameter of steel beam:	0.06032 m
Driving voltage:	0.25 V
Current capacity:	2,000 Ah/kg

The effectively usable current capacity of aluminium anodes in most cases is estimated by the manufacturer to be 2,400 to 2,500 Ah/kg. This figure must be understood merely as an indication. For the calculation, however, only 2,000 Ah/kg should be used. For use in soils, this value is to be reduced to 1,500 Ah/kg (refer also to DNV RP-B401).

In the following calculation, 40 anodes were estimated in the first step, but this is not necessarily the best solution.

This calculation can be followed by further calculations varying the anode data in order to find the optimum solution for the particular application.

4.1 Required anode mass

Calculation of anode mass consumed in 27 years

$$M_{av} = \frac{I_m \cdot t \cdot 8{,}760}{\varepsilon}$$

I_m	= Mean protective current reqt.	18.3 A
t	= Anode useful life	27 years
Hours per year		8,760 h
ε	= Current capacity	2,000 Ah/kg
M_{av}	= Consumed anode mass	2,164 kg

Calculation of required anode mass after 27 years

$$M_{ab} = \frac{M_{av}}{u}$$

M_{av}	= Consumed anode mass	2,164 kg
u	= Utilisation factor	0.9
M_{ab}	= Required anode mass	2,405 kg

The utilisation factor u depends on the anode type and can be found in the relevant standards and codes of practice.

4.2 Remaining total anode mass

The remaining anode mass at the end of the useful life serves as basis for calculation of the then existing anode dimensions.

Calculation of the remaining anode mass after 27 years

$$M_{ar} = M_{ai} - M_{av}$$

M_{ai}	= Installed anode mass	2,600 kg
M_{av}	= Consumed anode mass	2,164 kg
M_{ar}	= Remaining anode mass	436 kg

Calculation of the remaining anode mass after 27 years in percent

$$M_{arp} = 100 - \frac{M_{ar} \cdot 100}{M_{ai}}$$

M_{arp}	= Percentage of a. remaining	16.8 %
M_{ai}	= Installed anode mass	2,600 kg
M_{ar}	= Consumed anode mass	2,164 kg

From the remaining anode mass, among other things the remaining length and the remaining radius of the anode must be calculated. These then serve to estimate the resulting anode resistance to earth and thus the maximum current output at the end of the useful life. This calculation step is not explicitly demonstrated in the example in hand.

4.3 Anode current calculation (initial)

Calculation of the resistance to earth of a bar anode

Initial resistance to earth of a single anode

$$R_a = \frac{\rho}{2 \cdot \pi \cdot L}\left(\ln \frac{4 \cdot L}{r} - 1\right)$$

ρ	= Spec. water resistance (North Sea)	0.3 Ohm m
L	= Anode length	2.5 m
r	= Anode radius	0.0738 m
R_a	= Anode resistance to earth	0.075 Ohm

For non-cylindrical anodes, r is derived from the cross-sectional circumference

Calculation of the current output of a bar anode

Initial current output of a single anode

$$I_a = \frac{\Delta E}{R_a}$$

ΔE	= Driving voltage	0.25 V
R_a	= Anode resistance to earth	0.075 Ohm
I_a	= Current from single anode	3.33 A

Calculation of the current output of 40 bar anodes

Initial current output of 40 anodes

$$I_{atot} = I_a \cdot N$$

I_a	= Current from single anode	3.33 A
N	= Number of anodes	40
I_{atot}	= Total anode current	133 A

4.4 Anode current calculation (final)

When calculating the resistance to earth at the end of the protection period, it must be taken into account that the length and radius of the anode have been reduced by the consumption of material.

Calculation of the resistance to earth of a bar anode

Initial resistance to earth of a single anode after 27 years

$$R_a = \frac{\rho}{2 \cdot \pi \cdot L}\left(\ln\frac{4 \cdot L}{r} - 1\right)$$

ρ	= Spec. water resistance (North Sea)	0.3 Ohm m
L	= Anode length	2.25 m
r	= Anode radius	0.0377 m
R_a	= Anode resistance to earth	0.095 Ohm

Calculation of the current output of a bar anode

Current output of a single anode after 27 years

$$I_a = \frac{\Delta E}{R_a}$$

ΔE	= Driving voltage	0.25 V
R_a	= Anode resistance to earth	0.095 Ohm
I_a	= Anode current	2.63 A

Calculation of the current output of 40 bar anodes

Current output of 40 anodes after 27 years

$$I_{atot} = I_a \cdot N$$

I_a	= Anode current	2.63 A
N	= Number of anodes	40
I_{atot}	= Total anode current	105 A

4.5 Criteria check

1. Total mass

$$M_{ai} \geq M_{ab}$$

$$2{,}600 \text{ kg} \geq 2{,}405 \text{ kg}$$

2. Polarisation current

$$I_{atot}(\text{initial}) \geq I_i$$

$$133 \text{ A} \geq 13.8 \text{ A}$$

3. Repolarisation current

$$I_{atot}(\text{final}) \geq I_f$$

$$105 \text{ A} \geq 31.3 \text{ A}$$

4.6 Result

The installation of 40 aluminium anodes, each weighing 65 kg, as described above, suffices to satisfy the mean protective current requirements over a useful life of 27 years, as well as to provide the initial current (polarisation current) of 13.8 A and the final current (repolarisation current) after 27 years of 31.3 A.

However, the calculations do not yet take into account that the anodes may influence each other in the installed configuration, possibly resulting in a reduction of the usable protective current.

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