Interpretation of galvanic anode inspection data through Finite Element Method (FEM) Modelling

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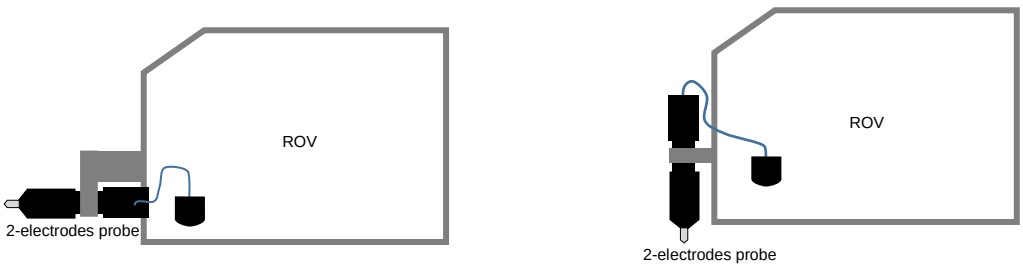
Abstract

Offshore oil and gas structures are generally protected from seawater corrosion through a combination of coatings and Cathodic Protection (CP) by galvanic anodes. In order to monitor the integrity of these assets during their design life, CP systems are periodically inspected. In the case of stand-off anodes attached to jackets, CP inspection is typically based upon potential contact measurements carried out by divers with 'gun' probes or by ROVs fitted with CP probes. In the case of subsea pipelines, potential profile and potential (field) gradient, from which current density can be calculated, are usually collected through ROV-based methods, incorporating multi-celled probes.
Anode potential provides only basic information about the status of the anode itself and can be compared with basic design value. On cathode side, potential measurements are necessary to determine if the structure is within the correct protection range. Current (density) output value is useful to determine relative anode activity and for evaluation of anode residual life.
However, the correct interpretation of potential gradient data and estimation of current output requires knowledge of the electrical field near the anode, which depends on several factors. Historically, this has been achieved using simple approximate linear equations. In this paper the traditional approach and the use of Finite Element Method (FEM) modelling have been compared and discussed.

Keywords: cathodic protection, inspections, offshore structures, galvanic anodes, FEM modelling

Introduction

Cathodic protection (CP) monitoring and inspection of submerged structures, such as offshore steel platforms, subsea pipelines, marine terminals, etc., is mainly based on potential measurement of the protected structures, i.e. the cathode, with respect to a reference electrode, which, in seawater, is normally the silver-silver chloride (Ag/AgCl) reference electrode. The measurement is simple and provides direct information on the protection status of the steel. A second type of measurements used in underwater CP inspections is based upon the measurement of the potential difference, namely the ohmic drop, between two reference electrodes at a fixed distance apart. This measurement, normally reported as *electrical potential gradient* (or *electrical field gradient*), provides information on the local current circulating in the electrolyte. The method was introduced and developed in the 1980s, in combination with the close-to-remote potential measurement, for CP inspection of subsea pipelines where continuous direct potential measurements of the cathode are impossible to perform because of the presence of organic coating and sometimes of concrete weight coating; or because the pipeline is buried [1,2]. Electrical gradient measurements were also used to assess the cathodic protection current density on the cathode side of protected steel structures [1,3]. For more than 30 years electrical potential gradient measurements have been performed routinely as part of CP underwater inspections and pipelines integrity assessments [3], aimed to identify and localize coating defects on subsea pipelines, recorded as positive peaks in the gradient profile; to localize anodes on buried pipelines, recorded as negative peaks in the gradient profile, and to assess the current output of galvanic anodes – either bracelets or slender standoff type. The estimated anode current output is then used, in combination with the original anode mass, to predict the anodes' residual life. The electrical field gradient measurements are performed using a probe consisting of two accurately balanced and calibrated reference electrodes at a fixed distance apart. The probe is normally assembled on Remotely Operated Vehicles (ROV), or on Autonomous Underwater Vehicles (AUV), and interfaced with dedicated electronics also installed on same vehicle (see Figure 1). The potential difference is then continuously recorded by a data acquisition system – hardware and software, suitable to measure potential differences as low as a few microvolts.



(a) (b)

Figure 1: 2-electrode probe for electrical field measurements assembled on ROV: (a) horizontal assembly for measurements on offshore platforms and risers; (b) vertical assembly for measurements on subsea pipelines.

In this paper, the specific case considered is of electrical field gradient measurements performed in close proximity to galvanic anodes for CP of offshore structures or pipelines, and of their interpretation using Finite Element Methods (FEM) modelling. The paper, in particular, shows

that significant errors can be generated using the overly-simplified earliest approach of converting the field gradient measurements into anode current output, which can lead to an overestimation of the anode residual life.

Evaluation of current density and anode residual life

The current density, *i*, flowing in seawater surrounding a galvanic anode connected to a (cathode) metallic structure is directly proportional to the measured ohmic drop between two electrodes, ΔE, and inversely proportional to seawater resistivity, ρ, and to distance between the two electrodes, *d*:

$$i \propto \frac{\Delta E}{\rho \cdot d} \qquad \text{(Eq. 1)}$$

The above relationship derives from the Laplace equation describing the electrical field in the electrolyte between anode and cathode:

$$\nabla^2 E = 0 \qquad \text{(Eq. 2)}$$

Which gives the Ohm's law:

$$i = -\frac{1}{\rho}\nabla E \qquad \text{(Eq. 3)}$$

If linear variation of potential in close proximity to the anode is assumed, Eq. 1 can be written as:

$$i = \frac{\Delta E}{\rho \cdot d} \qquad \text{(Eq. 4)}$$

where *i* is expressed in mA/m^2, ΔE in mV, ρ in Ωm and *d* in m. However, it is well known in cathodic protection theory and state-of-the-art design that a significant ohmic drop adjacent to the anode and a strong, non-linear, potential gradient in the electrical field surrounding the anode, are produced. An improvement to this considers, instead of a linear relationship, a parabolic variation of the current density with the distance from anode. Under this assumption, the Eq. 4 changes to the following:

$$i = \frac{3}{2}\frac{\Delta E}{\rho \cdot d} \qquad \text{(Eq. 5)}$$

In all of the above cases, the anode current, *I*, is determined by multiplying the current density, *i*, by the actual anode surface, S_{ACTUAL} (this step introduces a further simplification assuming the current density is uniform all over the anode surface):

$$I = i \cdot S_{ACTUAL} \qquad \text{(Eq. 6)}$$

Equation 5 and 6 are the most commonly used for converting potential gradient measurements into anode current output.
The residual life of anode is then calculated, in accordance with Faraday's Law, as:

$$t = \frac{M_R}{C \cdot I} \qquad \text{(Eq. 7)}$$

where

- *t* is the residual life in years [y]
- *C* is the practical consumption rate of the anode alloy [kg/(A·y)]
- M_R is the residual anode mass

An appropriate utilization factor can be introduced (depending upon the anode geometry) to reduce the residual anode mass actually available before anode depletion. This calculation is obviously simplified because it assumes a constant protection current density demand and

consequently a constant anode current output during its working life. Actually, the progressive depolarization of the cathode leads to an increase of the anode-cathode driving voltage and to a progressive increase of the anode current output with an associated accelerated consumption. The important point considered here, however, is that the residual life is inversely proportional to the anode current, and that an under-estimation of the anode current implies a corresponding over-estimation of the anode residual life.
Results that are more reliable than the traditional equation for conversion of current density into field gradient should be obtained by applying analytical solutions of the electrical field.
An analytical solution is available for the case of cylindrical anode, even if this considers coaxial cathodic surface. By assuming that the cathode in the real structure is far from the anode, and simplifying the geometry of the anode with a cylinder, the variation of the electrical potential E as a function of the distance from anode axis r is given by the equation [5]:

$$E(r) = \frac{\rho \cdot I}{2 \cdot \pi \cdot L} \ln \frac{r}{r_a} \qquad \text{(Eq. 8)}$$

Where r_a is the radius and L the length of the anode.
Then it can be easily derived, by also applying the properties of logarithms:

$$\Delta E = \frac{\rho \cdot I}{2 \cdot \pi \cdot L} \ln \frac{r_{upper}}{r_{lower}} \qquad \text{(Eq. 9)}$$

where

- r_{upper} is the sum of anode radius and distance of upper reference electrode from anode surface and
- r_{lower} is the sum of anode radius and distance of lower reference electrode from anode surface.

From the previous equation, current density at the anode is then:

$$i = \frac{2 \cdot \pi \cdot L \cdot \Delta E}{\rho \cdot \ln \frac{r_{upper}}{r_{lower}}} \cdot \frac{1}{2 \cdot \pi \cdot L \cdot r_a} \qquad \text{(Eq. 10)}$$

$$i = \frac{\Delta E}{\rho \cdot r_a \cdot \ln \frac{r_{upper}}{r_{lower}}} \qquad \text{(Eq. 11)}$$

All of the above equations still represent an approximation of the complex electrical field in real structures and their cathodic protection systems. Furthermore, it is evident that, for instance, the same equation may apply consistently for the case of slender stand-off anode on a platform jacket, but not for the case of galvanic bracelet anodes on a subsea pipeline. Analytical solutions of the electrical field between galvanic anodes and cathodic surfaces, i.e. solutions of the Laplace equation, are very limited and apply to simple geometries not corresponding to the real, complex geometries. A more accurate description of the electrical field around anodes in cathodic protection systems, leading to more reliable predictions, can be achieved with a combination of survey data and FEM (Finite Elements Method) modelling [6]. In the next paragraphs some applications of FEM modelling to interpretation of field gradient data, available from real-case underwater CP inspections, and estimation of current output and anode residual life, will be presented. In particular:

- Case A Loading terminals (bare cathode and slender stand-off anode)
- Case B Offshore platform (bare cathode and slender stand-off anode)
- Case C Subsea pipeline (coated cathode and bracelet anode)

Methodology

All cases described in the following paragraphs were modelled by using the commercial software, Comsol® Multiphysics 5.2. The domain was modelled by considering the electrolyte i.e. seawater resistivity, data. In the case of slender stand-off anodes, geometry was approximated as a block with a shape similar to the original if the anode was slightly consumed, or as a cylinder in the case of heavily consumed anodes. Cathode geometry was described as cylinders with the same diameter as the legs of terminals and platform jackets, and having a surface area approximately equal to the total surface divided by the number of anodes. Pipelines were modelled on both sides of the bracelet anode up to a length equal to half of anode spacing (owing to symmetry and modularity of the pipeline structure). For the sake of simplicity of meshing, the same diameter was used for bracelet anode, adjacent bare surfaces and coated surfaces. All domains were meshed with tetrahedral elements, with number in the order of 10^6. As far as boundary conditions are concerned, a constant potential equal to the measured potential was applied to anodic surfaces. On the cathodic surfaces, the Butler-Volmer equation was applied:

$$i = i_{corr} \cdot e^{\frac{-2.303(E-E_{corr})}{b_a}} - i_L - i_{H_2} \cdot e^{\frac{-2.303(E-E_{H_2})}{b_{H_2}}} \qquad \text{(Eq. 12)}$$

where

- i_{corr} corrosion current density (= i_L due to the oxygen reduction as dominant cathodic process)
- b_a anodic Tafel slope
- i_L is the oxygen limiting current density
- i_{H2} hydrogen exchange current density on steel
- E_{H2} hydrogen equilibrium potential
- b_{H2} hydrogen Tafel slope

Details of above boundary conditions and parameters are described in previous works [7-9]. As a consistency check, measured field gradient was then compared with the difference in potential between the two points of the model corresponding to the theoretical positions of upper and lower reference electrodes on the probe. Calculated cathode potential values were also compared with the corresponding measured data.

Case A – Loading terminals

Underwater CP inspection was performed on two (2) terminals originally protected with aluminium galvanic anodes. The structure consisted of a number of bare steel piles with galvanic anodes clamped on each pile. Terminal A was found under free corrosion potential conditions, with its galvanic anode system almost depleted. One of the few residual anodes had a reported size of 120 x 45 x 60 mm, and the measured gradient on it was 127 mV (0.5 m upper to lower electrodes distance).

According to Hartt et al [10], an actual protection current density of 60 mA/m^2 was assumed because of the loss of polarization and of calcareous deposit; the measured anode potential was –0.940 V vs. Ag/AgCl. FEM results showed a potential on the cathode of approximately –0.670 V vs Ag/AgCl, coherent with survey data, which was found to be in the range –0.640 ÷ –0.680 V vs Ag/AgCl.

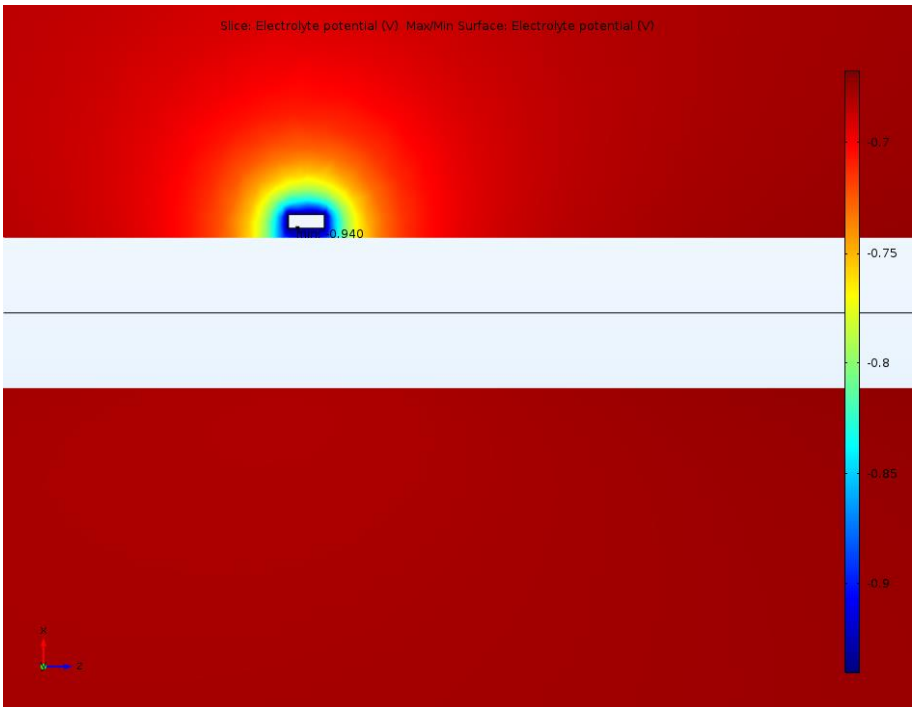


Figure 2: Electrical field near anode (V vs. Ag/AgCl) for Terminal A.

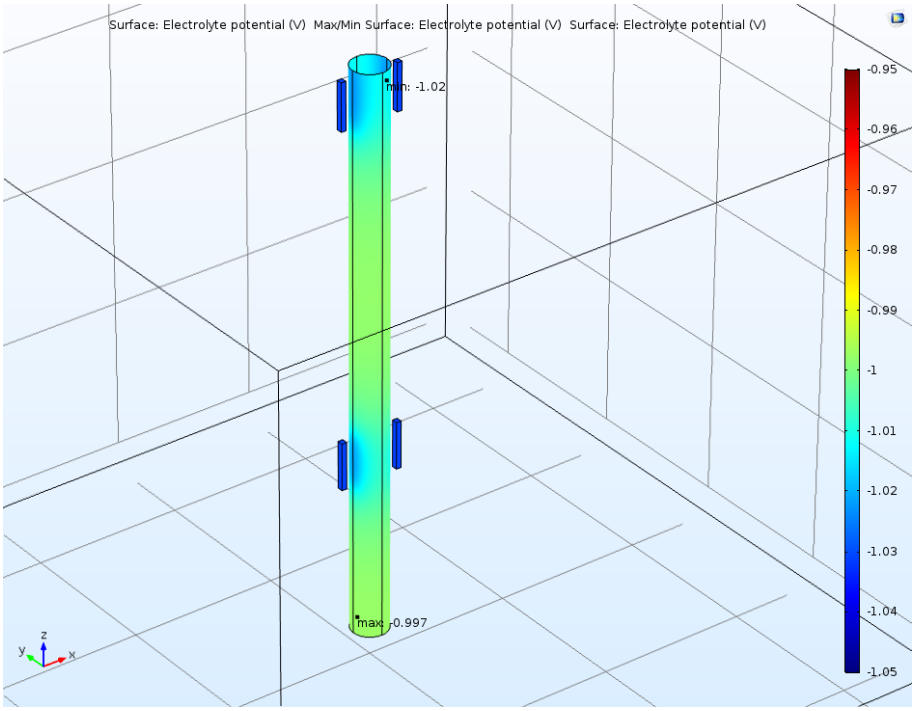


Figure 3: Potential distribution (V vs. Ag/AgCl) for Terminal B.

Terminal B, protected by clamps fitted with two anodes each, showed low anode consumption and optimal protection conditions (measured –1.02 to –1.03 V vs. Ag/AgCl). In this case the structure was covered by calcareous deposits and expected protection current density is very low; a value of 25 mA/m^2 was considered, based on experimental results in the Mediterranean Sea [11]. FEM potential results are in the range –1.00 to –1.02 V vs. Ag/AgCl. Table 1 summarize the results of FEM modelling in comparison to traditional formulae and approach.

i is calculated starting from Eq. 4 or 11, or FEM results. *I* is calculated by multiplying *i* by the surface of anode; whereas the FEM value was calculated through integration by the software. The residual life, t, is calculated in all cases through Eq. 7. It can be noted that, for Terminal A, gradient measurement and FEM results are quite similar. Current density is similar for the FEM model and the formula based on cylindrical shape (Eq. 11), whereas the traditional formula (Eq. 4) underestimated *i* by one order of magnitude, with consequent overestimation of residual life of anode. In the case of Terminal B, where anodes still retain the original ingot shape, formula based on cylindrical shape (Eq. 11) seems to overestimate *i* and FEM results are more similar to the traditional Eq. 4.

Table 1: Summary of FEM modelling results for anodes on offshore terminals and comparison with traditional and analytical equations.

Terminal	ΔE [mV] measured	ΔE [mV] FEM	i [A/m^2] Eq. 4	i [A/m^2] Eq. 11	i [A/m^2] FEM*	I [mA] Eq. 4	I [mA] Eq. 11	I [mA] FEM
A	127	159	1.0	18.8	25.8	24	439	607
B	15.0	14.4	0.12	0.73	0.07	110	668	81

* Average value on anode surface

Case B – Offshore platform

It is the case of an offshore platform, in service from several years, protected with trapezoidal, slender stand-off aluminium alloys galvanic anodes. Original anode sizes were:

- Length: 2300/2400 mm
- Section: 160/260 x 260 mm
- Insert: tubular, 4” dia. Sch. 80

A value of 25 mA/m^2 was adopted for oxygen limiting current density, owing to the structure having environmental conditions similar to those in Ref. [11]. Data for two anodes are reported here as examples: anode I is situated near the sea bottom and has low consumption (size has been approximately modelled by 80% residual mass, keeping ingot shape), anode II is situated at about –10 m elevation vs sea level and its residual mass is in the order of 20%. In order to simulate anode consumption, length was reduced by 10% and an equivalent radius calculated by considering the estimated residual mass. The potential at the cathode were found to be in good agreement with survey data for the first simulation (–1.03 to –1.01 V vs. Ag/AgCl in FEM model, –1.025 V average survey value), whereas in the second one potentials are about +40 mV higher than measured -1.017 V vs. Ag/AgCl). Results of potential gradient in FEM simulation were practically coincident with cathodic protection inspection data (Table 2), with a difference in the order of 1 mV or less. Once again, the traditional Eq. 4 seemed to underestimate by one order of magnitude the current density with respect to new proposed formula (Eq. 11) and FEM model results for both simulations. Contrary to expectations, results from Eq. 11 (i.e. from formula for cylindrical shaped anodes) were more similar to FEM results in the first case, anode with ingot shape, and slightly different in the second case, where consumed anode was, in fact, modelled as cylinder.

Figure 4: Anode I (left) and anode II (right).

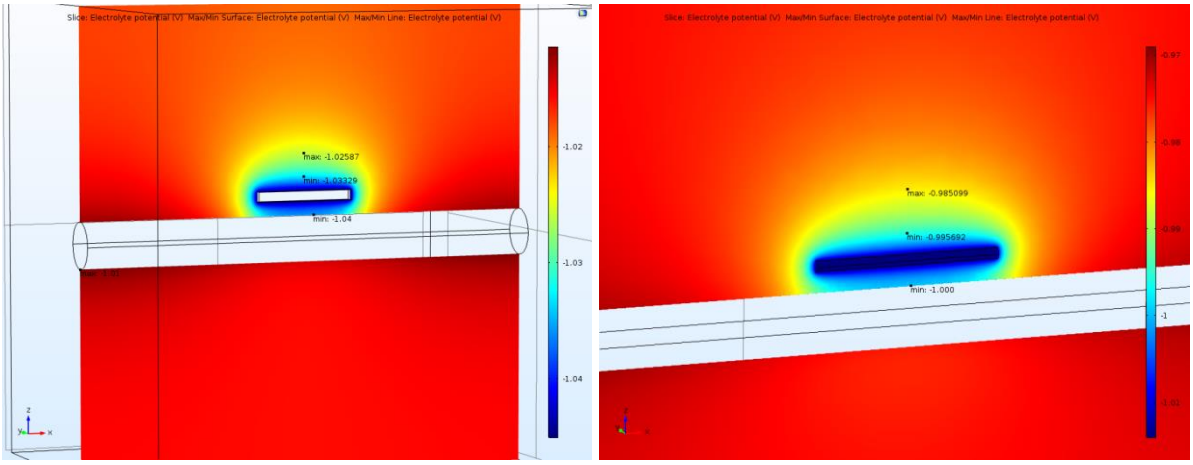


Figure 5: Potential gradient near anode I (left) and anode II (right).

Table 2: Summary of FEM modelling results for anodes on offshore platform and comparison with traditional and analytical equations.

Anode	ΔE [mV] measured	ΔE [mV] FEM	i [A/m^2] Eq. 4	i [A/m^2] Eq. 11	i [A/m^2] FEM*	I [mA] Eq. 4	I [mA] Eq. 11	I [mA] FEM
I	7.8	7.4	0.071	0.367	0.420	139	718	822
II	9.0	10.6	0.082	0.761	0.498	67	627	420

* Average value on anode surface

Case C – Subsea pipeline

This considers the case of a subsea pipeline conveying hot fluid and cathodically protected by aluminium alloy bracelet galvanic anodes, about 600 mm long and 40 mm thick. In the model, bare surfaces were considered at the two sides of anode, for considering metal exposed after reduction in length of the anode (90% of original size). Current density demand on the remaining cathodic surface was reduced to take into account the presence of a coating and estimated coating breakdown factor (0.045 after 30 years life). By considering an oxygen limiting current of 125 mA/m^2 due to the high temperature of the pipeline, an anode potential of approximately –1.00 V vs Ag/AgCl according to survey data and a resistivity of 23 ohm·cm, potentials on the cathode in the range –0.93 to –0.95 V vs. Ag/AgCl were obtained, in good accordance with survey results, showing potential in a similar range, up to –0.92 mV vs Ag/AgCl.

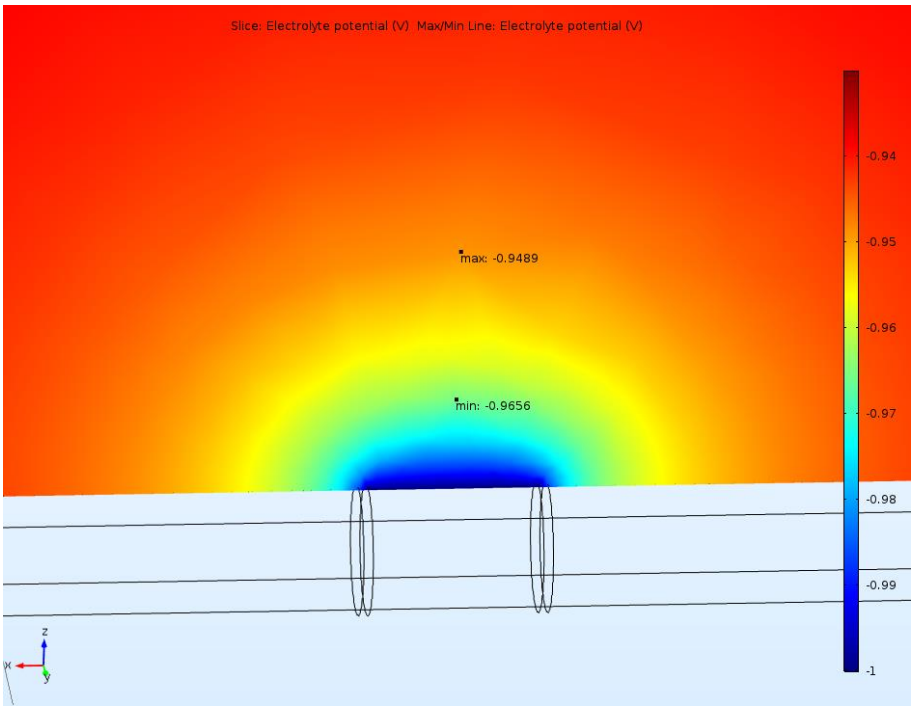


Figure 6: Potential gradient above bracelet anode of pipeline laid on seabed (slice view, xz plane)

Potential gradient obtained with modelling is, for two anodes (n. 2 e n. 3), very close to the measured value (Table 3). However, a great variability of anode residual masses, cathode conditions, and the influence of cathodic protection systems of other structures, influenced the high dispersion of survey data. By comparing FEM modelling potential gradient results with values obtained by traditional approaches (Eq. 4 and 11), it can be noted that current density values are underestimated from 1/2 to 1/10 by analytic formulae. The current values obtained by multiplying current density by the anode surface area and those derived by integration of *i* on anode surface within the FEM modelling software are consequently different by about 1/3 (for anodes n. 1, 4 and 5 they are apparently similar, but gradient data are not comparable).
Values obtained with Eq. 4 are very similar in this case to those obtained with the new Eq. 11. This can be attributed to the fact that the bracelet anode has a radius much larger than a consumed stand-off anode (see previous paragraph), thus the effect of curvature on the potential distribution near anode is less significant.

Table 3: Summary of FEM modelling results for bracelet anode of a pipeline laid on seabed and comparison with linear and analytical equations

Anode	ΔE [mV] measured	ΔE [mV] FEM	i [A/m^2] Eq. 4	i [A/m^2] Eq. 11	i [A/m^2] FEM*	I [mA] Eq. 4	I [mA] Eq. 11	I [mA] FEM
1	42.5	16.7	0.370	0.303	0.919	610	501	615
2	**16.3**	**16.7**	**0.142**	**0.116**	**0.919**	**234**	**192**	**615**
3	**12.1**	**16.7**	**0.105**	**0.086**	**0.919**	**173**	**142**	**615**
4	37.7	16.7	0.328	0.269	0.919	542	444	615
5	58.6	16.7	0.510	0.418	0.919	842	691	615
Aver.	33.4	16.7	0.291	0.239	0.919	480	394	615

* Average value on anode surface

Summary and conclusions

A number of cases have been presented with respect to underwater cathodic protection inspection of offshore structures complete with recording of electrical field gradient in close proximity to galvanic anodes. Both bare structures (marine terminals and an offshore platform) and coated structures (a subsea pipeline) have been considered.

Inspection data, including anode and cathode potential values and electrical field gradient values, have been used to feed FEM models of the electrical field around the anode for the specific geometry of each case under study. For each case, FEM models provided realistic representations of the electrical field of the galvanic anode system, with calculated potential distribution at cathode surfaces fitting with the measured potential values.

For each considered case, anode current has been calculated in accordance with FEM models as well as using the traditional approaches, in particular the most-used one based on linearization of the electrical gradient and an improved one based on analytical calculation of electrical field around the anode. Results are summarised in Table 4.

FEM results confirmed that the traditional formulae (Eq. 4 and Eq. 6), by which the anode current is calculated by simply dividing the measured potential gradient by seawater resistivity and then multiplying it by the anode surface, sometimes leads to under-estimated output current up to one order of magnitude, with consequent over-estimation of the residual anode life.

Analytical formula, available for simple geometries such as a cylinder, provide uncertain results. This formula appears to be mostly applicable to slender stand-off anodes near to the end of their life.

In conclusion, modelling of the electrical field by numerical methods looks the unique approach for correct interpretation of cathodic inspection results and in particular for the calculation of the anode current from electrical potential gradient measurements to be further used for the assessment of the anode residual life.

Table 4: Comparison of FEM, traditional (linear) and analytical results for anode current prediction for the presented cases.

CASE	Structure	Anode	I (mA)			Remarks
			Linear	Analytical	FEM	
A	Terminal A	Slender clamped (I)	24	439	**607**	Large under-estimation of the linear model
	Terminal B	Slender clamped (II)	110	668	**81**	Large over-estimation of the analytical model
B	Offshore Platform	Slender stand-off (I)	139	718	**822**	Large under-estimation of the linear model
		Slender stand-off (II)	67	627	**420**	
C	Subsea Pipeline	Bracelet (II)	234	192	**615**	Under-estimation of both linear and analytical models
		Bracelet (III)	173	142	**615**	

References

1. R. Strommen, A. Rodland, Corrosion Surveillance of Submarine Pipelines by Electric Field-Strength Monitoring, Material Performance, Vol. 22, October 1981, p. 47.
2. T. Sydberger, Evaluation of Inspection Methods for Offshore Pipeline Cathodic Protection Systems, Material Performance, Vol. 22, May 1983, p. 56.
3. ASTM. STP1154. Roe Strommen. Computer Modelling of Offshore Cathodic Protection Systems: Method and Experience. Published: Jan 1992.
4. DNV-RP-F116. Integrity management of submarine pipeline systems. October 2009.
5. L. Lazzari, P. Pedeferri, Cathodic Protection, Polipress, Milano, 2006.
6. P.O. Gartland, R.D. Strommen, H. Osvoll, R. Johnsen, Offshore Cathodic Protection Design, Inspection, and Computer Modelling, Innovations from the 1980s, Materials Performance, December 1993.
7. P. Marcassoli, A. Bonetti, L. Lazzari, M. Ormellese Modelling of Potential Distribution of Subsea pipeline Under CP by Finite Element Method, NACE Corrosion 2013, paper 2333, NACE International, Houston, Texas.
8. P. Marcassoli, M. Ginocchio, B. Bazzoni, A. Msallem, A. Ibrahim, "Design of Cathodic Protection retrofitting of subsea pipelines assisted by Finite Element Method (FEM) Modelling", Eurocorr 2014, September 2014, Pisa, Italy.
9. P. Marcassoli, A. Bonetti, L. Lazzari and M. Ormellese, Modelling of potential distribution of subsea pipeline under cathodic protection by finite element method, Materials and Corrosion 2015, 66, No. 7, DOI: 10.1002/maco.201407738.
10. W.H. Hartt, S. Chen and D.W. Townley, Sacrificial anode cathodic polarization of steel in sea water", NACE Corrosion 1994, paper 502, NACE International, Houston, Texas.
11. B. Bazzoni, F. Belloni, P. Cavassi, S. P. Dubini, A. Msallem, I. Romeo, NACE Corrosion 2011, paper N. 11051, NACE International, Houston, Texas.