Modeling in selection, design and optimization of cathodic protection retrofit systems of offshore facilities

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Abstract
The paper deals with the retrofit of cathodic protection (CP) systems of in service facilities like offshore platforms and subsea pipelines. The need of CP replacement, or retrofit, can be originated by a number of reasons, the most common one being the depletion of the original galvanic anode system; this is the case of several oil&gas offshore production structures installed in the '70s and in the '80s, still operating and with extended residual life, whose original CP system, mainly of the galvanic anode type, is depleted and approaching its end-of-life.
Design of CP retrofit systems has specific issues which differentiate this type of application from the case of new structures. Installation in fact is carried out with the facility to be retrofitted being at site and operating, and not in the yard as it occurred for the original CP system. This aspect often penalizes the use of galvanic anodes in favour of impressed current systems with non-consumable anodes, typically MMO activated titanium, with a much greater current capacity compared with galvanic anodes. In addition, in-service structures are normally under protection and covered with a calcareous deposit which strongly affects the polarization of the structure.
Modeling of the electrical field, i.e. potential and current distribution over the entire structure to be protected represents an essential tool to select the most adequate and convenient system configuration amongst available options, like tensioned anode strings or remote anodes or suspended anodes in case of platform, or anode pods or anode bracelets in case of subsea pipelines.
The paper presents a number applications of the Finite Element and Boundary Element Method modeling (FEM/BEM), taken from CP retrofit projects.

Keywords Cathodic Protection, Retrofitting, Life extension

Introduction

During the '70s and the '80s several fixed steel offshore platforms have been installed in the word, as a consequence of the increased number of exploited oil and gas offshore fields. These platforms are currently approaching, or have already reached, the end of their design life, and accordingly, a number of them is decommissioned. Other ones, on the contrary are maintained beyond the original design life because production is still of interest; for instance, subsea wells are drilled in close proximity and tied-in to existing production or process platforms. This requires the life extension of the structure and execution of a requalification process. Assessment of the original cathodic protection (CP) system and of its residual life, based on underwater inspections, is typically part of this requalification process.

Cathodic protection for fixed steel offshore platforms is mostly applied by the installation of galvanic slender stand-off anodes in construction yards, before jacket launching. The steel jacket is normally is left bare metal, with coating limited to the splash zone. On the contrary, subsea pipelines are typically protected by the combination of a galvanic cathodic protection system made by bracelet anodes together with organic coatings, often in combination with concrete weighting. For other marine assets, typically coastal structures like peers, jetties, port facilities, different combinations are possible, with bare and coated steel surfaces, and galvanic anode (GA) or impressed current (ICCP) systems, depending on several technical or economic factors.

Apart requalification, the replacement or integration of the original CP system can be required for a number of reasons, such as wrong original design, unexpected performance and failure of CP system due to electrochemical output parameters and/or metallurgy, external cause damages, intentional removal of anodes, being the most common reason the complete or partial natural depletion of galvanic systems.

In order to extend the life of these assets, CP retrofit is required in order to maintain, and sometimes to restore, protection conditions. No specific international standards are currently available for the design of such retrofitting systems[1]. Furthermore, design of CP retrofit systems has specific issues which significantly differentiate this type of application from the case of new structures. Installation in fact is carried out with the facility to be retrofitted being at site and operating, and not in the yard as it occurred for the original CP system. This aspect penalizes the use of galvanic anodes in favour of impressed current systems with non-consumable anodes, typically MMO activated or platinized titanium or niobium, with a much greater current capacity compared with galvanic anodes. The cost saving of ICCP systems with respect to GA ones increases moving from shallow water to deep water platforms, where the installation costs of galvanic anodes becomes prohibitive.

Modeling of the electrical field [1-3], i.e. potential and current distribution over the structure to be protected, like steel jackets, subsea pipelines, SPM, FPSO, etc., represents an essential tool to verify the current demand and protection conditions in the depletion and depolarization phase of the original CP system, and to select the most adequate and convenient protection system configuration amongst available options, like tensioned anode strings or remote anodes or suspended anodes in case of platform, or anode pods or anode bracelets in case of subsea pipelines. In some cases it is also useful in order to identify conditions where no retrofitting is required, with consequent savings for oil companies.

This paper illustrates a few case histories of applications of the Finite Element Method (FEM) and Boundary Element Method (BEM) modeling, taken from CP retrofit projects:

- Case A Offshore platform protected by galvanic anodes
- Case B Offshore platform retrofitted by impressed current system
- Case C Subsea pipeline retrofitted by galvanic anode sleds
- Case D Single Point Mooring retrofitted by galvanic anodes clamp and pods

The geometry and main environmental parameters were modelled. Boundary conditions included the corrosion electrochemical processes.

Methodology

All cases described in the following paragraphs were modelled by using the commercial software Comsol® Multiphysics 5.2 and previous versions. The domain was modelled by considering the electrolyte i.e. seawater resistivity, data. Boundary Element Method (BEM) modelling was applied for platform jackets, whereas Finite Element Method (FEM) modelling was used for subsea pipeline and Single Point Mooring (SPM). Galvanic anode systems were modelled using the geometry of original protection system (case A) after consumption, approximated as cylinder, or the real geometry of anodes proposed for retrofitting (case C and D). Impressed current systems were modelled with the real geometry of applied activated

[1] At the time of this paper, NACE TG 168 is working on a draft of State of the Art Report for cathodic protection retrofitting.

titanium anodes, typically 1” tubular ones. Cathode geometry was described as cylinders with the same diameter as the legs of platform jackets, by importing wireframe model of jacket and associating bracing and relevant diameter. Pipeline was also modelled as a cylinder. The geometry of SPM was draught in a 3D CAD software and then imported in the modelling software. Domains were meshed with tetrahedral elements (FEM) with number in the order of 10^6 or with edge elements (BEM) with number in the order of $10^4 \div 10^5$. As far as boundary conditions are concerned, constant potential equal to the measured potential was applied to anodic surfaces of galvanic anode systems (case A, C and D) or the output current by impressed current cathodic protection systems (case B).

At the cathodic surfaces, the Butler-Volmer equation was applied:

$$i = i_{corr} \cdot e^{\frac{-2.303 \cdot (E - E_{corr})}{b_a}} - i_L - i_{H_2} \cdot e^{\frac{-2.303 \cdot (E - E_{H_2})}{b_{H_2}}} \qquad \text{(Eq. 1)}$$

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 [4-6].

Case Hystories

Case A. Offshore platform protected by galvanic anodes

The first case (A) is related with an offshore platform jacket installed in late ’80s.

Due to underwater installation works, a number of anodes, less than 1% of the total, but concentrated in a limited zone, were removed in order to allow the installation of new supporting steel frames and structures. In order to identify the need of a local retrofit intervention, typically with installation of additional galvanic anodes supported by clamps, to be fixed on bracing elements, a study assisted by modeling was started.

The platform jacket has been created as three-dimensional wireframe drawing in 3D CAD software and imported in the model. A three-dimensional domain was modelled with Boundary Elements Method (BEM). At each tubular element the relevant radius has been associated. Galvanic anodes assembled on the jacket have been modelled as cylinders with 90% of original length. End-life size, i.e. residual mass equal to 10% of original mass, was considered as worst case scenario (anode at end life and repolarization current required). The current radius was also considered for the present-day scenario, based on real subsea inspection measurements. Two scenarios were considered:

- Present-day scenario: expected maintenance current density of 25 mA/m^2; this value is based on real data as described in [8]; current density value is very low due to the formation of a protective calcareous deposit on cathodic surface at potentials lower than -0.90 V vs AAC.
- Worst case scenario: anodes at end life and repolarization required; expected current density of 50 mA/m^2 according to [7]. In repolarization conditions, the cathodic surface is

assumed to have lost or damaged protective layer of calcareous deposit and the potential approaches -0.80 mV vs AAC owing to depolarization (corresponding to the maximum current density at -0.80 mV vs AAC in Figure 1). Current density increases by two times, from the expected realistic value of 25 mA/m^2 up to 50 mA/m^2, i.e. the expected repolarization current density. Additional sensitivity case with 100 mA/m^2 has also been performed (being the average value for subtropical region in DNV RP B401 standard and considering the platform depth).

FEM results pointed out that the platform structure is currently in good protection conditions (-0.88÷1.05 V vs AAC), with potential values in perfect accordance with the results of the inspection campaign performed one year before anode removal and new structures installation.

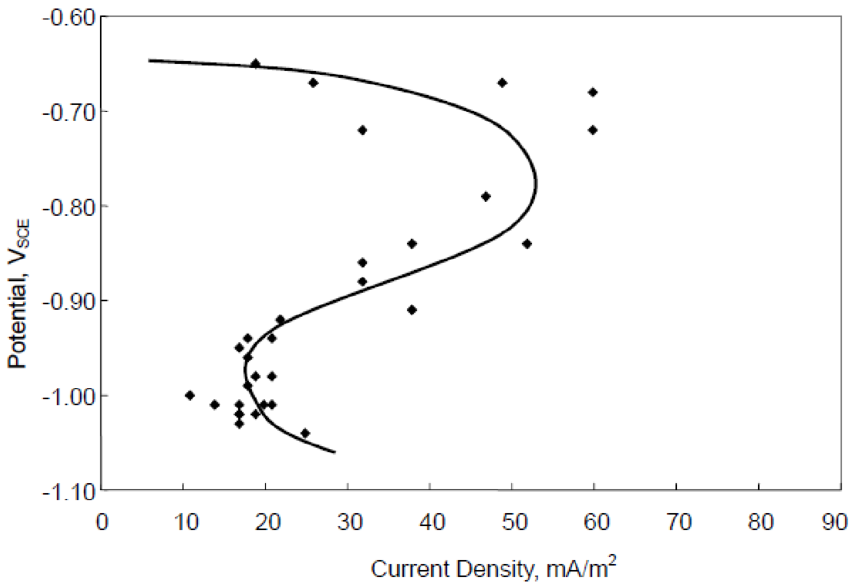

Figure 1 – Long-term potential versus current density data according to Hartt et al (Ref.).

Under the worst case scenario, i.e. with original anodes depleted at 90% at the end of their operating life and expected repolarization current of 50 mA/m^2 required, the jacket still remains in correct protection conditions, even if the nodes are close to the limit for full protection (see Figure 2).

The installation of new structures on the jacket with consequent removal of anodes, does not have significant impact on the overall and local protection conditions of the platform, and therefore a retrofit intervention was unnecessary.

Additional local measurements confirmed the potential values predicted by model. Also the current density value at cathode has been therefore confirmed and validated.

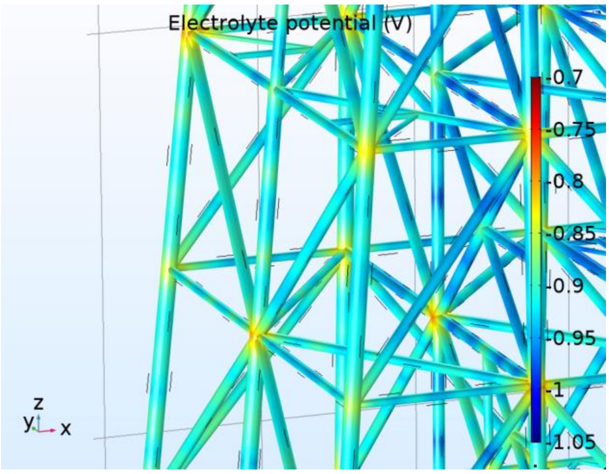

Figure 2 – BEM modeling results for potential distribution (V vs AAC) of platform jacket under worst case conditions (anodes at 90% depletion and repolarization current required).

<u>Case B. Offshore platform retrofitted by impressed current system</u>

The second case (B) is related with an offshore platform jacket installed in middle ’80s. This platform reached the end of the original design life, however the cathodic protection system, based on galvanic anodes, was not depleted yet and structure was still in good protection conditions. In order to achieve requalification and life extension, retrofitting system design and installation were foreseen.

Conservatively, design did not take into account the presence of the galvanic anode system, however the design approach was based on maintenance and repolarization current density only, due to the structure is still well polarized and does not require initial polarization stage.

This platform is installed in water depth of more than 100 m. For platforms with this size and depth, the installation of galvanic type retrofit system is not viable due to low anode capacity and installation costs, involving also saturation diving and subsea welding or other operations.

Impressed current retrofit system is then required. Among the possible options, sleds laid on sea bottom and tensioned anode strings have been considered. The first one provide quite uniform protection distribution, thanks to installation in remote location, but effectiveness could be limited due to internal bracing elements are shielded by surrounding external elements and furthermore the upper portion of the structure would receive less protection current with respect to the lower zone. Moreover, from the installation point of view, even if the laying of sleds is relatively easy and safe, cables and conduits shall be positioned and fixed on the structure with more complex and expensive operations.

The selected solution was then tensioned string of anodes (TSA). This system is based on activated titanium tubular anode strings supported by a galvanized steel supporting rope, coated with high thickness polyurethane sheet. Anodes are evenly distributed along the string, avoiding possible mechanical interferences and impact with the structure. Strings are connected to T/Rs and it is then possible to adjust and manage output current zone by zone, depending on specific cathode current demand.

Analogous system (TSRE) is provided with zinc reference electrodes in order to provide also retrofitting of original monitoring system.

All strings are fixed on the structure above water, and the opposite end at sea bottom is connected to a dead weight. The installation of such a system is relatively easier due to string can be laid together with dead weight, a limited number of divers are required for assistance in seawater, cable routing is completely performed above water.

For this project and platform, the installation of strings within the jacket was foreseen. This option creates issues both with respect to the structural point of view and under/overprotection. In fact, owing to actions of waves, marine current and wind, TSAs and TSRE are suffering deformation, even with significant displacement, in particular in the middle zone. For this reason, the system was investigated from the structural point of view, with assistance of modeling, taking into account the applied tension, extreme environmental conditions and available space and constraints, in order to verify mechanical resistance and compatibility of horizontal displacement with respect to potential impacts with bracings.

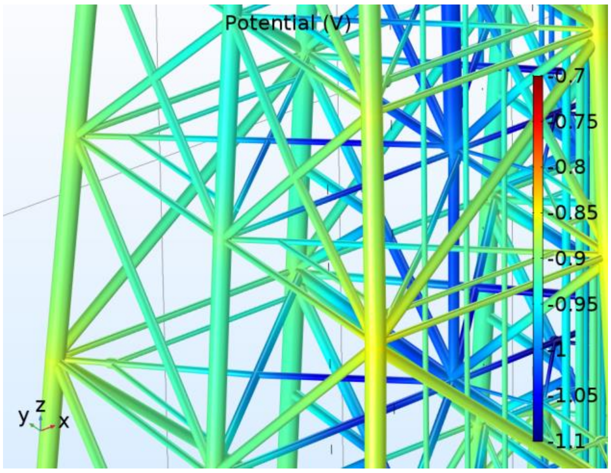

Figure 3 – BEM modeling results for potential distribution (V vs Zn) of platform retrofitted with tensioned anode strings installed within the jacket, 30 mA/m^2 current density demand at cathode.

From cathodic protection point of view, impressed current systems, in case of excessive current output, can produce very low potentials, lower that the hydrogen evolution potential, with consequent risks of overprotection and hydrogen embrittlement (HE) phenomena, in particular for susceptible steels. In this regard, it has been verified that bracing and other elements near titanium anodes have negligible and acceptable overprotection values, also considering that no high strength steels susceptible to HE have been used for this platform and appurtenances.

Modeling has been performed considering 30 mA/m^2 current density at cathode, i.e. the real current density absorbed by a similar platform (see previous paragraph and 0), conservatively increased up by 20%. Protection conditions are reached on all the platform elements, and output current was predicted and balanced on the T/Rs in order to achieve similar potential distribution in the upper and lower zone of the jacket. Also the potentials measured in correspondence with the zinc reference electrodes have been simulated, in order to provide a reference of interpretation of future measurements data and in order to extrapolate the conditions near the TSRE to the overall platform.

<u>Case C. Subsea pipeline retrofitted by galvanic anode sleds</u>

This case has been presented and discussed in a previous paper [5], where additional details and results are shown. For this project the Cathodic Protection retrofitting of a subsea pipeline with the use of galvanic anode sleds have been considered.

FEM modelling has been applied in order to minimize the number of anode sleds and to optimize their locations, ensuring a reliable but easier installation on-site. The interference between anodes was also investigated by varying the distance between the sleds and the pipelines and by varying the sled to sled distance. Coating breakdown was also considered. Furthermore, the effect of presence of a localized coating holiday was introduced and assessed.

The subsea pipeline, installed in late ‘80s and located in the Mediterranean Sea, has 16” diameter and a total length of about 3 km. It is protected against external corrosion by coal tar enamel coating plus concrete weight and by cathodic protection with bracelet aluminum alloy galvanic anodes.

This pipeline, during last CP inspection campaign, evidenced high consumption of the installed bracelet anodes. Anode consumption was found to be in the range 50÷100%, particularly in the second quarter. Severe anode depletion could lead to under-protection conditions and thus the retrofitting of the existing cathodic protection system was investigated to extent operating life.

Selected CP retrofitting system was based on 8 sleds, each one with 2 anodes.

FEM analysis has been carried out in order to verify that the installation of n. 4 sleds at each end, riser side and SPM side, provide cathodic protection of the whole pipeline. In fact, the best protection current distribution could be achieved by evenly distributing the anodes along the pipeline. However the installation of a number of sleds in several positions produces complicated and expensive offshore operations. The installation of the sleds near the starting and ending points represents a simpler solution, providing adequate cathodic protection conditions are verified, in particular in the central zone. Both small evenly distributed defects and large defects localized in middle zone, with area corresponding to that exposed after total depletion of anode, i.e. the worst case, were modelled.

Results showed that the pipeline potentials are always in the protection range -0.90 to -1.05 V vs Ag/AgCl (anaerobic conditions). Also in this case, modeling results were found to be in line with subsea CP inspection data.

Support of FEM was essential in order to define the locations of anode sleds near the ends of this pipeline, at platform and near the single point mooring, resulting in optimization of foreseen installation activities and reduction of relevant costs. Furthermore, the evaluation of the effect of distance between the sleds and pipeline and the distance between the sleds allowed to optimize the positions of sleds themselves and to define target area for laying.

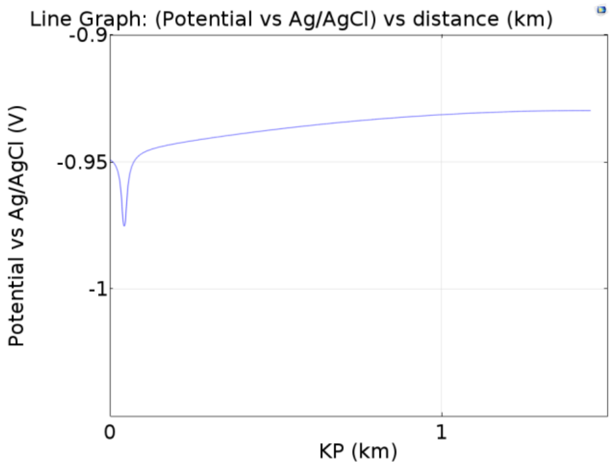

Figure 5: potential (V vs AAC) along the pipeline, at the bottom line, in case of presence of a depleted anode in the middle of pipeline (note: only half pipeline shown)

Case D. Single Point Mooring retrofitted by galvanic anodes clamp and pods

Last case is related with retrofitting of a Single Point Mooring (SPM) installed in late ‘80s. The structure has more than 100 m height, it is coated only for a few meters in the splash zone and showed different original galvanic anodes consumption along the water depth.

Owing to the lack of availability of electrical power sources, and the needing of achieve protection system totally independent from those of connected Floating Storage Off-loading unit and pipeline and nearby submarine structures, retrofitting with galvanic anode systems has been considered and developed.

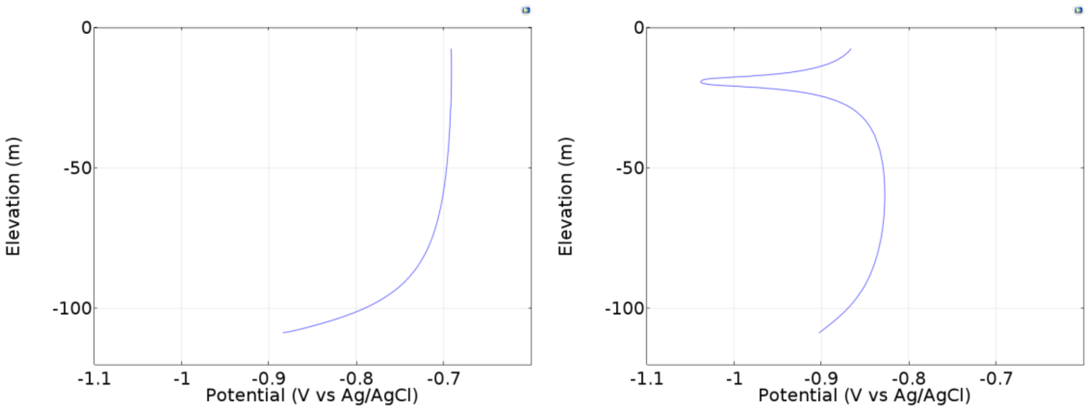

Figure 6: potential (V vs AAC) distribution along the SPM: left, in case of presence of anode pods only; right, with installation of both anode pods and anode clamp.

At first, the possibility to protect the entire structure only with anode pods laid on sea bottom was analysed, although, based on CP engineering expertise, and the concept of throwing power of galvanic anodes, it was likely that protection would not be achieved on top of structure. However modeling provided a better and precise estimation taking into account the real geometry, the presence of bare metal surface and relevant current density demand, as well as the seawater conductivity and boundary conditions at anodes and cathode.

Under this scenario, protection was achieved for about 25 m at the bottom, whereas protection current could not reach the middle and upper portions of the SPM column (Figure 6, left). In order to provide protection for overall structure, an integration of anode pods with a clamp supporting anodes, fixed in the upper zone, has been developed. With this mixed solution, modeling showed that protection is achieved even in the middle zone of the column (Figure 6, right).

FEM model was also applied in order to minimize the interference between anode pods, adjusting their positions and distance each other, and defining the correct distance from the structure in order to provide maximum throwing power in the middle zone, respecting client’s constraints in terms of available and permitted laying area surrounding the structure.

Summary and conclusions

In this paper a number of application cases of FEM/BEM modeling to design of cathodic protection retrofit systems have been discussed.

No standards are currently available for the design of CP retrofit systems, and a different approach and design bases, taking into account the actual polarization of structures, shall be considered. In such a frame, modeling can provide an important tool for CP engineer in order to select and later optimize protection system.

The use of modeling provides a realistic picture of the conditions of the structure, and help with the decision of apply CP retrofit actions or not.

When conditions require to start with retrofit, in particular when it is possible to rely on galvanic systems not totally depleted yet and structures well polarized and covered by calcareous deposit, FEM/BEM modeling assists in the selection of most effective solution, together with considerations related with installation and economic issues.

Configuration of the protection system is optimized with respect to layout, verifying throwing power of anodes and absence of under-protected areas, considering presence of coating, such as for pipelines, or bare metal surface conditions typical of platform jacket, SPMs, and other structures.

For impressed current systems, risk of overprotection with consequent possible hydrogen embrittlement of susceptible steels and coating disbonding, if any, are avoided by ensuring that optimal protection range is not exceeded.

Also the interpretation of monitoring system measurements is enhanced by comparison and extrapolation with data provided by the model of protection and current density distribution.

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