ABSTRACT

Computer based modeling tools have developed in recent years to the stage where they are routinely used to assess the performance of corrosion control measures for naval ships and boats and critical parts of the infrastructure. They are also used to predict the important associated electric and magnetic fields induced by the corrosion related currents. Computer modeling enables the designer to build a virtual prototype of the ship or structure and predict how the corrosion control measures will perform over under various operational conditions. Thus reducing the need for frequent post commissioning design changes and surveys.

Since cathodic protection (CP) systems were first applied, engineers have used experience and intensive monitoring to optimize their design to prevent corrosion. The use of sacrificial and impressed anodes on ship’s hull, offshore structures, pipelines storage tanks etc has become standard practice in order to preserve the structure and to protect coatings. However, the correct position and current of the anodes is a subject, which has recently been studied by the scientific community, since its adequacy is of vital importance to the performance of the CP system as a whole. Wrong currents and positions would lead to unprotected or overprotected areas.

In this paper, optimization methods combined with the computer models of the corrosion processes will be presented which enable the optimum system design to be achieved both in terms of the location and current output of the anode but also in the location of reference electrodes for active CP systems. Examples will be presented for a frigate.

In typical CP systems, the designer knows the source of current (the anodes) but does not have a clear knowledge of where the current goes (the cathode) as this depends upon the condition of the metallic surfaces and location of any damage, etc. In this paper, a method will also be presented to determine where the current goes from the anodes and hence predict the general condition of the vessel and possible areas of damage. The method involves using a mathematical model of the CP system, the ship and its environment and solving an inverse problem to predict the hull condition given information from reference cells, the CP system or sensor readings of the electric fields surrounding the ship. Example applications are presented showing how areas of damage can be predicted as well as the associated signatures of the ship.

The final section will describe how these techniques can be applied to pipelines, storage tanks and other general corrosion application areas.

KEY WORDS: boundary element method; cathodic protection; coating; inverse problem; optimization; objective function; electric field.
Cathodic protection can reduce the roughness of the hull provided that a uniform potential distribution is supplied throughout the structure. Hull roughness has a dramatic effect on efficiency. The shape or form drag will be a factor which relates the speed of the vessel to the ship’s length, see optimum design of a planning boat’s hull form Yoshida (1997) [1], while the surface drag will relate the drag to the under water surface area of the vessel. A British study, based on 400 ships, revealed that a new-build typically has a paint roughness that is about 125 microns. [2].

Computer modeling based on the boundary element method [5] [6] [7] has been widely used to predict the effectiveness of corrosion control measures and provide quantitative data on the protection potentials achieved by a CP system. Numerical methods have been successfully compared with physical scale modeling experimental results and data obtained from tests performed on full size ships [8]. Physical scale model testing provides the computer analyst with a well defined set of conditions to model. In addition, DeGiorgi, Kee and Thomas studied a 3D model of a U S Navy CG class ship [9] using boundary elements.

In order to find the best design the computational model representing the electrochemical reactions and the electrical fields in the electrolyte have been combined with a optimization technique which is capable of searching for the best design to achieve the objectives while at the same time satisfying the constraints imposed. This fundamentally changes the way engineers can use computer models. Not only can predictions be made under a set of conditions defined by the user but also the user can define the objectives of the simulation and the design variables and the constraints on the design.

In the example described below, the current at the anodes are varied in such a way that the potential is matched to a target value. Thus, the surface will have a homogeneous potential value which could avoid the roughness of the metal surfaces or detachment of the painting.

The least squares of the current potential on the elements on the surfaces with respect to a potential target value are used as objective function to achieve a uniform potential.

\[
\text{Obj} = \sum_{i=1}^{n_s} \sum_{j=1}^{n_e} |f_{ij} - f_{(\text{target},i)}|^2
\]

Subject to the following constraints on the surface of the cathode:

\[
g_i = \frac{f_{i} - f_{\text{Max},i}}{f_{\text{Min},i}} \leq 0 \text{ on } G_C \quad i = 1,\ldots,m
\]

\[
g_j = \frac{f_{\text{Min},j} - f_{j}}{f_{\text{Min},j}} \leq 0 \text{ on } G_C \quad j = 1,\ldots,m
\]

Where:

- \(n_s \) and \(n_e \) is the number of surfaces and elements per surface.
- \(f_{\text{target}}, f_{\text{min}}, f_{\text{Max}} \) is the target potential, the minimum and maximum potential per surface.
- \(m \) is the number of elements on the surface.
- \(G_C \) is the surface of the cathode.

Since constraints are considered, the final solution is guaranteed to be within the required potential range. A frigate model was analyzed.
Frigate model, description

The frigate was considered fully coated apart from some specific damaged areas. The propeller was set made of nickel-aluminum-bronze.

The dimensions of the frigate are:
- Waterline length: 34.0m.
- Draft: 2.3m.
- Waterline beam: 6.4m.

To speed up the solution and since the model is symmetric only half of it was modeled.

The electrolyte considered was seawater with a resistivity of 20ohm cm [3], what implies a conductive of about 5S/m.

The frigate was modeled with 2000 elements. A refined mesh was created at the stern of the vessel since it is the most critical area of the frigate due to the propeller and the location of the main anodes.

Numerical examples, frigate model

In order to ensure that the structure is protected the potential of the damaged surfaces were required to be within a certain potential range –850mV and –1100mV. In addition, in order to ensure the smoothness of the surface a potential of –900mV was set as a target value. The damaged areas, physical properties and anodes location are shown below (FIGURE 1).

The propeller was set made of Nickel-Aluminum-Bronze with an area of 1.84m².

Achieve a uniform protection potential. Initial currents were applied to each one of the anodes. After the optimization, the current at the anodes were increased to reach the potential range required. The current of the anode at the stern shows a larger value since is placed in the area which requires more current, propeller and damaged area at the stern.

At the end of the optimization process all the surfaces are within the required potential range (-850mV, -1100mV). In addition, the potentials have approached as much as possible to the target value –900mV (FIGURE 2). To achieve these results with the standard modeling approach (ie without optimization) would require the user to perform many simulations and would be time consuming.

Achieve a uniform protection potential by varying the anode current and position. In the first application an active CP system was used and the design variables were the anode currents. In this case both the position of the anodes and also the currents were varied in order to improve the solutions previously obtained. The anodes are moved on a surface, search surface which enables the user to restrict the position of the anode to a specific region (FIGURE 3).

Three anodes were initially located shown in FIGURE 2 and the currents obtained the previous optimization were taken as initial values.

The evolution of the positions of the anodes on the surfaces is shown in FIGURE 3. The final position of the anode at the stern almost coincides with the initial one. However, the anodes at the bow and at the keel will be moved towards the bow to distribute homogeneously the potential on the damaged area at the keel.

The objective function was reduced from 286000mV² achieved in the fixed anode positions to 254700mV² when the anodes were moved to the optimum position, achieving a reduction of about 10%. The results are summarized in Table 2. The total current supplied by the anodes was reduced from -7958.5mA to -7528.9mA in about 5%. The anodes were placed at the bow and at the stern of the hull. Thus, the anode could evenly distribute the current along the keel, and also protect the stern and the bow.

The FIGURE 4 shows how the potential distribution on the hull surface at the end of the optimization is within the required range and it has moved towards the target value.
Summary

The two examples demonstrate that the optimization approach provides a clear insight into the way ICCP systems work and how they can be designed to achieve specific results. In this case the optimum location of the anodes has been identified as well as the optimum anode currents under the specified operating conditions.

MINIMISE THE ELECTRIC FIELD GENERATED BY THE ICCP SYSTEM OF A VESSEL

The corrosion related magnetic and static electric field signatures arise from the corrosion currents generated by the metals from which the vessel is constructed or from the cathodic protection system used to prevent corrosion, which provides an alternative current flow. This current flow creates a characteristic static electric field or Underwater Electric Potential (electric field) and an alternating electric and magnetic fields (ELFE) [4].

Ships may try to conceal themselves by varying the current at the anodes, changing the performance of their ICCP systems. On the other hand, a minesweeping system must be able to accurately emulate these signatures in shape, intensity and spatial relationship.

The minimization of the signature of the vessel is of vital importance to conceal the vessel from the enemy.

Minimizing the electric field process

When the electric field generated by the ICCP of a vessel is minimized the ship is concealed against electric field sensors.

The objective function below will be utilized to minimize the electric field:

- Minimize the least squares of the current at the sensors beneath the vessel.

\[
\text{Obj} = \sum (I_x^2 + I_y^2 + I_z^2)
\]  

Where:

\( I_x, I_y, I_z \) is the current density in the x, y and z component.

Subject to constraints on the surface of the cathode, equations (2) and (3).

The minimization of the electric field and also the protection of the damaged areas was studied on the frigate model by using the previous equation (4). The current and position of the anodes will be automatically modified until the best solution is found [10][11][12].

Numerical examples, minimize the electric field

The same damaged areas, physical properties and anodes location used to minimize the current at the anodes were employed in this experiment (FIGURE 1). The propeller was set made of Nickel-Aluminum-Bronze with an area of 1.84m².

The electric field was studied at 30 meters below the sea surface and underneath the keel (FIGURE 5). Sixty measurements were registered and their values were employed to computed the objective function (4). (Note that the motion of the ship relative to the sensor is simulated by moving the sensor relative to the stationary ship).

The electric field was minimized using the equation (4), constraining the potential of the damaged areas to the potential between –850mV and –1100mV. This will ensure that the design is sufficient to protect the structure. The electric field is minimized by varying the anodes current but no the position.
In this first case, the electric field was minimized using the equation (4), which minimizes the maximum measured value of the current at the sensors beneath the vessel. After the optimization, the current at the anodes are adjusted to reach the potential range required while at the same time minimizing the electric field (Table 3). The current of the anode at the keel takes a significant value, while the current of the anodes at the stern and at the bow are reduced.

The initial value of the objective function is 8.2 mA²/m⁴ and more than 60% of the damaged area is within the range of protection. During the optimization process, the number of elements in the required potential range is increased until all the areas are protected as the electric field is, in addition, reduced. The final value of the objective function was 0.0624 mA²/m⁴ which implies a reduction of 99%.

The FIGURE 6 show that the final maximum and minimum potentials for the surfaces are in the required range; therefore, the surfaces have become protected.

The FIGURE 7 shows the final signature obtained after achieving the minimization of the electric field. The athwartships component (X) is not shown because its value is negligible due to the symmetry of the model.

Summary

The minimization of the electric field reduced the initial signature of this frigate in 99% compared with the initial design.

CATHODIC PROTECTION IN UNDERGROUND STRUCTURES

The protection of pipelines from external corrosion is commonly accomplished by the combination of pipeline coatings with cathodic protection, to protect those portions of the pipeline that are inadequately coated or where the coating contains defects.

When designing or operating a CP system, it is important to ensure that foreign structures are not damaged by the system. Stray currents effects and how the optimization software could help to achieve a correct design will be studied in this section. The optimization software will attempt to achieve uniform potential protection on the pipelines by varying the position and current of the anodes in order to reduce the harmful effects of the stray currents.

Achieving a uniform protection potential

The least squares of the current potential on the element of the pipes with respect to the potential target value of the pipes are employed as objective function to achieve a uniform potential (1), (2) and (3). The variables are the current at the anodes, the longitudinal coordinate along the pipeline and the vertical coordinate or depth of the anodes (vertical distance with respect to the pipeline).

Modeling the Underground Infrastructure

The application focuses on the region where two pipelines cross. A series of remote groundbeds anodes were allocated to each separate pipe CP system and staggered at intervals along the length of the pipes.

The impressed anodes selected were High Silicon Cast Iron Anodes with a length of 2.133m, a diameter of 0.67m, area of 0.46m² and a Nominal Discharge (Amps) of 3.5-5.0 A.

Tube elements were utilized which assume a uniform radial current density distribution.

Optimization of the pipelines

The potential of both pipelines are to be smoothed around the target value by varying the currents and positions of the anodes. The potential distribution along the pipeline 1 and pipeline 2 before and after the optimization has the plot shown in the FIGURE 8.
The initial and final position of the anodes over the pipelines are shown in FIGURE 9.

Summary

A methodology for automating the design of cathodic protection systems of pipelines through the use of computer modeling has been presented. The techniques can predict the optimum location of anodes and their output given guidelines on the target potential to be achieved on the pipelines.

The models and techniques can predict the level of interference between CP system (and other equipment) and optimize the CP system design to minimize the interference.

PREDICTION OF THE STATE OF THE COATING

The condition of coatings on the metallic surface of the hull of a vessel changes over its lifetime due to the action of the sea, deterioration of the paint itself and damage caused by impacts, etc., [13]. Although increased current demand from an ICCP system can indicate the presence of damage, the location and extent is unknown. A method for the prediction of the state of the coating [14] is shown in the next sections.

The prediction of the state of the coating is based in what is known as Inverse Problem. Some information about the conditions of the vessel is assumed and the optimization process will attempt to match them. Two approaches can be used:

- Knowledge of the potential of the reference electrodes.
- Knowledge of the UEP, under electric potential surrounding the vessel.

Apart from this data, also the position and current of the anodes must be known in the approach explained below.

Prediction of the coating from reference cells measurements, Objective Function

The optimization process requires that the problem is posed in the form of an objective function, design variables and constraints. In order to match the measured reference cell potentials the objective function was defined as the least squares of the difference between the target potentials at the reference cells and the potentials predicted by the model (equation (1)) subject to constraints on the surface of the cathode (equations (2) (3)).

The process. The coating of the surface is interpolated among the values of a number of locations (coating sensor positions) on the surface of the vessel. Therefore the coating values used for individual elements are derived from the values at the coating sensor positions. These sensors are the variables of the optimization software. The boundary elements equations are then solved. The objective function, equation (1), and the constraints, equation (2) and (3), are computed. The optimization method evaluates the objective function and constraints and decides whether this solution is the optimum or not. If not, a new search direction and step size are computed.

Damaged areas. Three damaged were initially placed on the surface of the frigate. The FIGURE 10 shows the position and size of the damaged areas. Two impressed anodes were placed on the surface of the model.

Coating sensors arrays. The damaged are assumed to be unknown. The coating of the vessel will be predicted. An array of 7 coating sensors (FIGURE 11).

Reference cells. The number of reference cells will be the target value of the optimization. It will try to match them by varying thickness of the coating. The number of reference cells, target values, was increased to determine how much data was required to detect the damage. Tight constraints (+- 5mV) were set around the target value to make the optimization software reach the target with more accuracy.
Results. FIGURE 12 shows the damaged that the damaged areas were found after the optimization process:

CONCLUSIONS

In this work, a general method for predicting the performance of cathodic protection systems and determining the best ICCP system design has been presented.

The approach has been demonstrated on the ICCP system design of a frigate and an underground structure. The optimum anodes currents and positions have been predicted to protect a vessel and an underground pipeline. In addition, the electric field was minimized by varying the currents of the anodes. Not only can the current of the anodes be optimized but also their positions. Thus automating many of the tasks associated with designing a cathodic protection systems.

The modeling paradigm has been changed so that the corrosion engineer can define the objectives and requirements of the design for which the model will find a solution. Replacing the typical modeling approach where the user defines all the conditions for which the model predicts the behavior, thus requiring the user through a process of trial and error to iterate towards satisfying the design objectives.

The optimization approach can be applied to many engineering cases, such as minimize currents, minimize electric fields, match target values of potential, predict the state of the coating, etc., [ 15 ][ 16 ][ 17 ][ 18 ].

The methodology can be utilized in a wide range of corrosion control applications to predict corrosion damage and compare alternative designs.

The approach has also been developed to apply the technology to the control of the associated corrosion related electric fields. This can be used to provide quantitative data on stray current interference for example.

Computer modeling can also be used to identify the position of damaged areas on the surface of a pipeline, structure or ship using the potential measurements at reference cells on the structure and by using the electric field measurements in the electrolyte. A minimum number of potential measurements are necessary to predict the position of the damaged areas otherwise the prediction will not be accurate enough and only some of the damaged areas will be revealed. However, an increment in the number of coating sensors can improve the prediction from the same data.

No precise polarization data is necessary since a curve, which roughly represents the behavior of the underlying materials, can be used.

The methods presented could form the basis of a condition monitoring system or improved control system for CP systems.

REFERENCES


FIGURE 1 - Propeller and damaged areas on the ship hull.

1.- Damaged surface at the bow of the ship, bare steel. [c$p_{\text{opt}}$ metal surface bow, 4.34m$^2$]
2.- Damaged surface at the keel of the ship, bare steel. [c$p_{\text{opt}}$ metal surface keel, 7.96m$^2$]
3.- Damaged surface at the stern, bare steel. [c$p_{\text{opt}}$ metal surface stern, 8.01m$^2$]
4.- Propeller, nickel aluminum bronze. [c$p_{\text{opt}}$ metal surface propeller, 1.84m$^2$]

TABLE 1
INITIAL AND FINAL CURRENTS APPLIED TO THE ANODES.

<table>
<thead>
<tr>
<th>Name</th>
<th>Initial Current (mA)</th>
<th>Final Current (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C$p_{\text{opt}}$ anode bow</td>
<td>-315.3</td>
<td>-1818.6</td>
</tr>
<tr>
<td>C$p_{\text{opt}}$ anode keel</td>
<td>-300.1</td>
<td>-1079.2</td>
</tr>
<tr>
<td>C$p_{\text{opt}}$ anode stern</td>
<td>-159.4</td>
<td>-5060.7</td>
</tr>
</tbody>
</table>
FIGURE 2 - Potential distribution over the hull after the optimization of the process of smoothing the potential.

FIGURE 3 - Movement of the anode initially placed at the keel.

TABLE 2
FINAL CURRENTS, MOVING THE ANODES

<table>
<thead>
<tr>
<th>Name</th>
<th>Final Current (movement)(mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cpopt anode bow</td>
<td>-1833.0</td>
</tr>
<tr>
<td>cpopt anode keel</td>
<td>-826.4</td>
</tr>
<tr>
<td>cpopt anode stern</td>
<td>-4869.5</td>
</tr>
<tr>
<td>TOTAL</td>
<td>-7528.9</td>
</tr>
</tbody>
</table>
FIGURE 4 - Potential distribution of the hull after the optimization of the currents and positions of the anodes.

FIGURE 5 - Internal points placed at 30m from the frigate.

TABLE 3
INITIAL, FINAL CURRENTS APPLIED TO THE ANODES.

<table>
<thead>
<tr>
<th>Name</th>
<th>Initial Current (mA)</th>
<th>Final Current (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cpopt anode bow</td>
<td>-5000</td>
<td>-1300</td>
</tr>
<tr>
<td>cpopt anode keel</td>
<td>-5000</td>
<td>-4755</td>
</tr>
<tr>
<td>cpopt anode stern</td>
<td>-5000</td>
<td>-2010</td>
</tr>
<tr>
<td>Total Current</td>
<td>-15000</td>
<td>-8065</td>
</tr>
</tbody>
</table>

FIGURE 6 - Potential distribution after minimizing the electric field by varying only the current of the anodes.
Comparison vertical (Y) component of current density, 30m depth

Comparison vertical (Z) component of current density, 30m depth

FIGURE 7 - Comparison of the components of the current density of the initial design and the final design achieved by the optimization when the minimization of the electric field was carried out.

Potential Distribution along the first pipeline

Potential Distribution along the second pipeline

FIGURE 8 - Potential distribution along the pipeline 1.
FIGURE 9 - Initial and final position of the anodes over the pipelines.

FIGURE 10 - Damaged areas placed on the surface of the frigate.
FIGURE 11 - Twelve coating sensors distribution on the surface of the frigate.

FIGURE 12 - Damaged prediction.