Jacket SACP system Design and Optimization using Simulation

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ABSTRACT

Design of sacrificial anode cathodic protection (SACP) systems to achieve uniform anode mass loss rates is desirable, since it helps avoid early installation of costly retrofit systems which may be needed if some anodes are consumed more quickly than others.

Such optimized design is only practically possible through the use of mathematical modeling performed using numerical techniques. A range of numerical methodologies can be applied to simulation of galvanic effects and cathodic protection, and of these it is the boundary element method that is applied in this work. The simulation requires an accurate model of the structure which is to be protected, as well as the anodes, and any other metallic structures which may act as current drains (even though they may not need to be cathodically protected).

The optimization process first involves design and simulation of an initial SACP system design. Performance of the design is assessed against criteria which may include anode mass loss rate, most positive allowed potential and remaining anode mass, not only at start of life, but also throughout the design life of the structure. The results of previous assessments are used to guide the selection of the next trial SACP system design, which usually involves changing the number, position or size of anodes, while adhering to user-defined rules (e.g. “keep-out areas”). The process is repeated until satisfactory results are obtained.

The objective of this paper is to explore such simulation techniques, and show how they can be combined to provide a practical toolset for SACP system design optimization. This provides the user with new and significantly more powerful design capabilities which are based on real physics rather than standardized design rules. The use of these tools both reduces the risk of the CP design not meeting its required life and ensures an economical design.

The paper illustrates performance of the design and optimization processes using a jacket structure for which long-term “sigmoidal” polarization curves provide an appropriate representation of calcareous deposits.

Keywords: SACP, Design, Optimization, Cathodic Protection, Modeling

INTRODUCTION

The use of simulation is well established as a means to determine the potentials and currents on and around an offshore structure, for example caused by current flowing from sacrificial anodes to surfaces.
to be protected. Such simulation allows assessment of performance of a CP system, and therefore allows improvement of a design by use of suitable quantitative measures. In cases where the balance of current changes (for example because of changes in coating breakdown factor with time) design optimization may require use of a measure such as uniformity of anode remaining mass at the end of the design life. The simulation method used in this work is based on the boundary element method\(^1\), which generally requires elements only on the surfaces of the electrolyte. Consequently elements are required only on the polarizing surfaces of the anodes and of the steel structure\(^2\). A commercial modeling system was used for the studies\(^1\).

**Optimization of SACP System**

Since the optimization process involves testing the performance of an initial SACP design, the starting point is a design which includes anode size, shape and offset, anode material performance characteristics, numbers and positions of anodes on the structure, and data regarding any coated areas. In this case study the entire structure is coated, but coating could be restricted to particular areas without changing the basic design-optimization processes (note a mixture of coated and uncoated surfaces makes intuitive design optimization even more difficult).

**Selection of anode size and number**

We used standards (DNV) to design a CP system for the coated steel jacket structure shown in Figure 1. Details of the steel areas are shown in Table 1. Temperate "shallow" conditions were assumed, and a 20 mA/m\(^2\) current drain to buried steel (piles, well casings). The coated surfaces were assumed to have 2% breakdown factor in year 0, rising linearly with time to 38% breakdown factor in year 30. These considerations resulted in total initial current 69 Amps, mid life current 140 Amps, and end of life current 271 Amps.

A long stand-off anode was selected, with height 140mm, width 160mm, and length 1500mm. The end-to-end mounting bar was 50mm in diameter. This resulted in 89.6kg of Al/Zn/In anode material per anode, for which the utilization factor was taken to be 0.9, and assumed 2000 Amp-hours per kg of anode material. A total of 143 (new) anodes would be required to provide the end-of-life current, and although the anodes will be at least partly consumed by then, this number of anodes was selected for use in the case study. The mid-life current was used to determine the total required anode mass, which was 9724 kg. However this was exceeded in the design which provided a total of 12803 kg of anode material.

![Figure 1: The jacket structure, with conductors, piles and well casings, and showing the position of the seabed. Only the part of the structure below the sea surface is shown.](image-url)

\(^{1}\) BEASY

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Table 1:
Areas of steel

<table>
<thead>
<tr>
<th>Location</th>
<th>Surface area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wetted jacket members (coated)</td>
<td>3690</td>
</tr>
<tr>
<td>Wetted conductors (coated)</td>
<td>627</td>
</tr>
<tr>
<td>Buried piles</td>
<td>767</td>
</tr>
<tr>
<td>Well casings (top 50 m only)</td>
<td>731</td>
</tr>
</tbody>
</table>

**Simulation of performance of a CP system**

To assess performance of the CP system, a model of the jacket, conductors, piles and anodes is constructed. Each of the surfaces in the model is discretized into a mesh of elements, with each element associated with one or more degrees of freedom (potential and normal current density). The mesh creation is highly automated, so is not a difficult task.

Resistivity of the seawater and seabed are required, in this case values of 30 Ohm-cm resistivity for the water and 130 Ohm-cm for the seabed were selected.

Polarization characteristics of the steel and anode surfaces must be defined, using polarization curves. In this case study the anode closed circuit potential was taken to be -1050mV (Ag/AgCl/seawater - the reference used throughout this paper), and the anode surface was assumed to polarize through 2.5mV for every 1000mA/m² change of current density. If advantage is to be taken of the more negative open circuit potential of such an anode material (at low current density the potential is more negative than the "closed circuit potential" recommended by standards), then a more complex curve is required to reflect the more rapid change of potential at low current densities. Similar considerations apply at very high current density.

The long-term polarization behavior of bare steel surfaces in seawater has been shown by Hartt and Chen⁴ to follow a sigmoidal curve which relates potential and current density. Similarly Strommen³, using data obtained from several surveys of existing structures, observed that in North Sea waters the long-term behavior fell into a band, for which the upper bound is shown in Figure 2. This curve can be regarded as a "worst-case" long-term curve for North Sea waters, and should therefore provide a conservative solution.

![Figure 2: Sigmoidal curve at upper limit of observed measurements for structures in North Sea waters (data from Strommen³)](image)
For a coated surface, the approach used in the case study is to assume that a 50% coating breakdown factor equates to 50% of the surface completely bare of coating. Thus current densities in the curve in Figure 2 are scaled to correspond to any required coating breakdown factor.

Behavior of buried steel surfaces can also be characterized by a polarization curve, a method preferable to simply applying the "standard" current drain of 20mA/m² to the buried surfaces because the latter approach artificially distorts the electric fields and makes them unrealistic close to the seabed. In this case study we used a polarization curve for which potential is -677mV at zero current density and potential is -950mV at 20 mA/m² current density.

Assessment of CP system performance

In order to assess performance of a CP system over the lifetime of a structure, it is necessary to perform time stepping, so as to take account of:

- loss of anode mass and corresponding change of anode size
- change of breakdown factor

Solution at start of life provides anode current, which is used to determine mass lost during a time-step. At the new time, the anode size is automatically adjusted to correspond to the remaining mass, or if consumption has reached the utilization factor, the anode is effectively removed from the model.

The reduced anode sizes and possible consumption of some anodes, combined with changes of breakdown of any coating, are all used during simulation at the new time.

Thus the time-stepping provides results, at all stages of life, which include:

- Potentials
- Current density
- Anode current
- Anode remaining mass
- Projected anode remaining life

Clearly at the end of the design life, the projected remaining anode life is determined using the potentials and condition of the coatings on the structure, the remaining mass of the anodes, and the anode current in year 30 (the design life in this case), subsequent changes of breakdown factor, loss of anodes and so on are not considered.

Other quantities which can be displayed graphically for the anodes include:

- whether/not the anode has reached its utilization factor (in which case it will have been automatically switched-off)
- the consumption factor
- anode current
- mass loss rate
- remaining mass

Assessment is made of performance of the CP system at end of life as follows:

- First and foremost this assessment focuses on extremes of magnitude of potential, since potential more positive than some value may be judged to not provide the required protection.
- Secondly, the uniformity of potential is assessed, since greater spread of potential implies greater risk that variation of conditions (from those assumed) would cause corrosion.
Finally, in addition to these protection-based criteria, the uniformity of anode consumption is assessed, since greatest efficiency of the design is implied when all anodes reach the utilization factor at the same time.

In the case study shown here, the selected design changes were based solely on moving anodes from one position to another, i.e. the number and size of anodes was not changed. In general it may be more appropriate to additionally modify the number of anodes on the structure.

Assessment can of course be made of protection achieved at start of life, and at intermediate times, and could be used to guide modifications to the design, but this has not been done in this case study.

The remainder of this paper shows results for a series of designs which were incrementally improved using the process described above.

**SACP Design Optimization applied to the Case Study**

The anodes were roughly uniformly distributed in the initial design, as shown in Figure 3. The structural potentials obtained after time stepping through the 30 year design life are shown in Figure 4. Anode remaining mass in year 30 is shown pictorially in Figure 5, and projected anode remaining life in year 30 is shown in Figure 6.

Positions of the anodes in design 2 were adjusted to move those which in design 1 had longest remaining life to positions close to those which had short remaining life. This is a relatively easy operation, during which use is made of the graphical display of anode remaining life. Anode positions for design 2 are shown in Figure 7, with structural potentials, anode remaining mass and projected remaining life in year 30 shown in Figure 8, Figure 9 and Figure 10.

Positions of the anodes in design 3 are shown in Figure 11. Again the anode positions have been adjusted to move those which in design 2 had longest remaining life to positions close to those which had short remaining life. Other anodes were simply moved along the member to which they were attached. Resulting structural potentials, anode mass and projected remaining life in year 30 are shown in Figure 12, Figure 13 and Figure 14.

Finally, positions of the anodes in design 4 are shown in Figure 15. Again the anode positions have been adjusted to move those, which in design 3 had longest remaining life, to positions close to those which had short remaining life. Thus for example the bottom horizontal members which in design 3 (Figure 11) had two attached anodes now have 4 attached anodes in design 4 (Figure 15). The total number of anodes has remained at 143 in all the designs.

Comparison of projected anode remaining life in year 30 for the four designs is shown in Figure 19 and Figure 20.
Figure 3: Design 1 Anode Positions

Figure 4: Design 1: Potential (mV) in year 30
Figure 5: Design 1: Anode mass (kg) in year 30

Figure 6: Design 1: Projected Anode Remaining Life (years) in year 30
Figure 7: Design 2 Anode Positions

Figure 8: Design 2: Potential (mV) in year 30
Figure 9: Design 2: Anode mass (kg) in year 30

Figure 10: Design 2: Projected Anode Remaining Life (years) in year 30
Figure 11: Design 3 Anode Positions

Figure 12: Design 3: Potential (mV) in year 30

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Figure 13: Design 3: Anode mass (kg) in year 30

Figure 14: Design 3: Projected Anode Remaining Life (years) in year 30
Figure 17: Design 4: Anode mass (kg) in year 30

Figure 18: Design 4: Projected Anode Remaining Life (years) in year 30
Discussion of results

The ranges of total anode current, structural potential, anode remaining mass and projected anode remaining life observed for the different designs are tabulated in Table 2 to Table 5.

It is clear from Table 2 that the design changes have not significantly altered the total anode current delivered.

The extremes of structural potential, shown in Table 3, show that as the designs are improved, the most positive potential steadily becomes more negative.

From the table it can be seen that this is accompanied by a general reduction in the range of structural potentials observed, from 99mV in design 1 to 66.4mV in design 4.

Although the improvement of protection potentials are clear, they are not as striking as the improvement of uniformity of anode consumption, which from Table 3 shows a ratio of greatest to smallest anode mass in year 30 of:

- 8.7 for design 1
- 2.9 for design 2
- 2.2 for design 3
- and finally 1.6 for design 4.

The same is reflected in the projected anode remaining life (Table 5) which shows that for design 1 some anodes are close to being fully consumed in year 30, whereas others have 8 years of remaining life. By contrast in year 30 design 4 has a range of projected anode remaining life from 3.1 to 6.3 years.
The greater spread of projected remaining life in design 1 compared with design 4 can be clearly visualized in Figure 19 and Figure 20.

Clearly optimization of the SACP system has produced a better design, but there is a law of diminishing returns. In this case study, we chose to stop the optimization process at the fourth design.

Table 2:
Total current delivered by the SACP system at start, mid and end of life, for the four designs

<table>
<thead>
<tr>
<th>Design</th>
<th>Total anode current in year 0 (Amps)</th>
<th>Total anode current in year 15 (Amps)</th>
<th>Total anode current in year 30 (Amps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>34.9</td>
<td>93.4</td>
<td>146</td>
</tr>
<tr>
<td>2</td>
<td>34.9</td>
<td>93.6</td>
<td>146.3</td>
</tr>
<tr>
<td>3</td>
<td>35</td>
<td>93.7</td>
<td>145.9</td>
</tr>
<tr>
<td>4</td>
<td>35</td>
<td>93.4</td>
<td>146.4</td>
</tr>
</tbody>
</table>

Table 3:
Most positive and most negative structural potentials at end of life, for the four designs

<table>
<thead>
<tr>
<th>Design</th>
<th>Most positive potential in year 30 (mV)</th>
<th>Most negative potential in year 30 (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-900.9</td>
<td>-999.8</td>
</tr>
<tr>
<td>2</td>
<td>-914.4</td>
<td>-997.8</td>
</tr>
<tr>
<td>3</td>
<td>-931.3</td>
<td>-996.1</td>
</tr>
<tr>
<td>4</td>
<td>-934.1</td>
<td>-1000.5</td>
</tr>
</tbody>
</table>

Table 4:
Smallest and largest anode remaining mass at end of life, for the four designs (original anode mass was 89.6 kg)

<table>
<thead>
<tr>
<th>Design</th>
<th>Smallest anode remaining mass (kg)</th>
<th>Biggest anode remaining mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.9</td>
<td>42.7</td>
</tr>
<tr>
<td>2</td>
<td>14.2</td>
<td>41.7</td>
</tr>
<tr>
<td>3</td>
<td>17.6</td>
<td>38.9</td>
</tr>
<tr>
<td>4</td>
<td>23.4</td>
<td>36.8</td>
</tr>
</tbody>
</table>

Table 5:
Smallest and largest projected anode remaining life in year 30, for the four designs

<table>
<thead>
<tr>
<th>Design</th>
<th>Shortest projected remaining life (years)</th>
<th>Longest projected remaining life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1</td>
<td>8.0</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>7.6</td>
</tr>
<tr>
<td>3</td>
<td>1.9</td>
<td>6.9</td>
</tr>
<tr>
<td>4</td>
<td>3.1</td>
<td>6.3</td>
</tr>
</tbody>
</table>
Additional features of SACP system performance

The variation of structural potential during the life of the structure can be displayed as shown in Figure 21. This type of display, combined with appropriate choice of contour display (e.g., red = likely to corrode, green = protected) can provide rapid visual assessment of performance. Similar tabulated data, extracted from simulation report files, is shown in Table 6.

Table 7 shows data (again extracted from simulation report files) identifying current flowing to buried and to wetted steel at start, middle, and end of life of the structure, for design 4.

The change of anode size with consumption is shown in Figure 22 for design 4 on a small part of the structure.

The state of polarization of the structure at end-of-life for design 4 can be seen in Figure 23, which shows the long-term curve as a solid green line, with polarization of each part of the structure shown as red dots. It is clear that the structure is well polarized, with low maintenance currents.

If a CP system was inadequately designed, so that the anodes could not deliver enough current to polarize the structure, the simulation would reflect this fact. In such a case, potentials would be more positive, and current densities bigger. The structure would be above the "nose" of the sigmoidal curve at around -650 to -800 mV in Figure 23.

Because the simulation method used has in this case allowed acquired calcareous deposits to dissipate if the CP system cannot maintain them, it can be concluded that for Design 4 the remains of the anodes at year 30 would be able to re-polarize the structure in the event that calcareous deposits were lost as a result of a storm.

Figure 21: Protection potentials at years 0, 15 and 30 for Design 4
Figure 22: Showing anode remaining life in year 0, year 15, and year 30, for a small part of the structure and SACP design 4

Table 6:
Range of protection potential on wetted steel in years 0, 15 and 30 for SACP system design 4

<table>
<thead>
<tr>
<th>Year</th>
<th>Most positive potential on wetted steel (mV)</th>
<th>Most negative potential on wetted steel (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-1010</td>
<td>-1042</td>
</tr>
<tr>
<td>15</td>
<td>-980</td>
<td>-1022</td>
</tr>
<tr>
<td>30</td>
<td>-934</td>
<td>-1000</td>
</tr>
</tbody>
</table>

Table 7:
Total current flowing to buried and wetted steel at start, middle, and end of life, for SACP system design 4

<table>
<thead>
<tr>
<th>Year</th>
<th>Current flowing to buried steel (Amps)</th>
<th>Current flowing to wetted steel (Amps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>28</td>
<td>7</td>
</tr>
<tr>
<td>15</td>
<td>27</td>
<td>67</td>
</tr>
<tr>
<td>30</td>
<td>25</td>
<td>121</td>
</tr>
</tbody>
</table>
Discussion

In the early years of the life of a coated structure, when the coating breakdown factor is small, the wetted steel surfaces do not require significant current for adequate protection, but the buried steel is a continuous drain on the CP system, as shown by the data in Table 7.

This continuous drain of current to the buried steel combined with the large variation through time of current to the coated wetted steel makes it more difficult to achieve a balanced design in which all anodes reach consumption factor at about the same time. It is in situations like this, as well as when only some parts of a structure are coated, that simulation can provide the insight and understanding required for an effective design to be achieved.

An optimal design based on a single state of the coating will not be so optimal at other stages of life, so whole-of-life assessment is important.

Conclusions

This paper has demonstrated how simulation can be used to assist optimization of the design of a SACP system on a jacket structure, and has shown that whole-of-life assessment of system performance is important, in particular for coated structures.

The methods demonstrated in this paper provide insight into the real physical effects which influence CP system performance, and allow the CP designer to adjust the system accordingly.

The use of sigmoidal long-term curves has been demonstrated, with discussion of the benefits of using such a curve.
References


