How Interference Can Impact The Life Of CP Systems. An FPSO Case Study

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ABSTRACT
The design rules used to design CP systems in the main do not take into account the interference between the anodes provided to protect a structure or interactions between the structures themselves. CP systems will always interact with each other to some extent when they are in the same electrolyte even when there is no metallic electrical connection and this can radically affect the protection provided to the structure and the life of the CP system.

A case study is presented involving the design of the CP system of an FPSO (Floating production storage and offloading vessel). The aim of the study was to verify the performance of the CP system to ensure that the structure was protected for the design life and the anodes had sufficient capacity. Computer modelling was used to simulate the performance of the CP system which comprised of an ICCP system and sacrificial anodes. The study identified some interesting and unexpected interactions which required the design of the CP system to be modified.

Key words: Galvanic corrosion, Cathodic Protection, FPSO, ICCP, Interference

INTRODUCTION
Interference can significantly affect the performance of Cathodic Protection (CP) systems designed to protect structures from corrosion. There are many forms of interference which the CP Engineer has to consider and mitigate the effect of, if the CP design is to perform as required over the life of the structure. For example:

- Anode interference can significantly degrade the ability of the anodes to supply the required current
- Interference can occur between structures protected by CP systems
External electrical sources can also cause interference particularly for onshore pipelines and tanks.

This effect of anode interference can be most clearly seen when anodes are closely grouped for example around a monopile or an anode sled where the effective output of the anodes can be radically reduced when compared to the classical anode resistance calculations. For example the effective anode output of an anode sled can be reduced by 80% simply by the way in which the anodes are arranged. In order to accurately determine the anode configuration required to protect the structure, computer modelling is necessary because the classical anode resistance formulas are not applicable.

A similar problem can occur when structures are in close proximity and electrically connected to each other. Even if the individual CP systems are well designed, interference can degrade the performance of the anodes as the current will take the path of least resistance which can result in accelerated depletion of some of the anodes. Therefore later in the life of the structure, the integrity of the structure may be at risk due to poor protection of parts of the structure.

In some cases, the problem of interference may not become apparent until later in the life of the structure when the current demand increases due to degradation of the coatings. Regular surveys and monitoring of the structure are required in order to detect this type of problem and it can lead to urgent unplanned retrofits.

Figure 1 View of the geometry of the FPSO and the related flow lines. All of the metallic components are considered in the model unless they are electrically isolated. (Note. The picture shown is for illustration only and not related to the study presented. Reproduced with permission, See acknowledgments.)

In this paper, an approach based on computer modelling is used to predict the long term performance of the CP system and identify the risk of under protection due to interference. The
methodology can be used during the initial design study and later as an integral part of the regular integrity management of the structure. Modelling used as part of the integrity management of the structure has the benefit that the predictions can be based on the actual degradation rates of the coatings and other structural changes and updated predictions used to plan any remedial activities required. Therefore providing a more accurate understanding of the condition of the “as built” structure and its future protection levels than that based on the design assumptions for example for the rate of coating degradation.

The structure considered in this study is an offshore oil & gas field based on an FPSO with flow lines and subsea systems. The hull is protected by an Impressed Current Cathodic Protection (ICCP) system and certain structures and appendages are protected by sacrificial anodes similar to that shown in Figure 1. In the current study the flow lines and subsea systems were not considered as the aim was to focus on the interference between the ICCP system on the FPSO and the sacrificial anodes on the appendages.

There are many factors which can impact the protection provided by cathodic protection systems for complex structures such as FPSOs. In a previous study it has been demonstrated that significant interaction can occur between the ICCP system and the subsea systems and flow lines if the ICCP system is not designed and operated correctly. These interactions can lead to accelerated depletion of the sacrificial anodes on the subsea systems and lack of protection of the FPSO later in life. The size of the vessel can also have some impact on the interference as for example a larger vessel has a relatively larger surface areas compared with the mooring systems, flow lines and subsea systems. Therefore the larger vessel ICCP system would be required to deliver much high currents which could possibly lead to more damaging interference than shown in this case study.

In summary the design and operation of the cathodic protection systems protecting deep water oil & gas assets is a complex problem as there can be interactions which can compromise the protection provided and can shorten the life of the CP systems, or on the contrary, cause overprotection with consequent coating damage.

**COMPUTER MODELING**

Computer modelling has developed over a number of years and is now widely used to verify the performance of CP systems in the maritime environment and onshore. The basis of the techniques used in this study is the BEASY CP software package

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1 Tradename

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A computer model simulates the physics of galvanic corrosion and the features of a cathodic protection system. The model simulates the electrode kinetics on the metallic surfaces, the coating barrier, the electrolyte (seawater) resistivity, the internal resistance paths in the structures and the 3D geometry of the electrolyte and the metallic structure immersed in the electrolyte. The time required to build a model very much depends upon the complexity of the structure but if electronic CAD data is available describing the structure, the time can be significantly reduced.

The starting point for building a model is the geometry of the FPSO, the anchor lines and the internal structures and appendages exposed to the seawater. All the metallic surfaces are defined, including the type of material they are constructed from and the coatings applied to the surfaces. The geometry is preferably created from a CAD system and then imported into the modelling software (Figure 2) with which the computational mesh is created on the surfaces and required data is applied to the model.

The polarization properties of the different metals used in the structure and the seawater resistivity are selected based on the materials and the environment where the vessel is to be located. It is important to select appropriate polarisation data for the temperature, sea water characteristics and flow rates at the location.

The proposed CP system design for the case study FPSO has ICCP anodes located on the bottom and side of the hull as shown in Figure 3. Anodes on the bottom of the vessel may be required to avoid poor protection in this area, but may be subject to gas entrapment if not properly designed. A relatively large number of anodes have been used in the case study, since a typical FPSO may be at sea for 35 years without dry-docking. This means that coating breakdown factors towards end of life may be high, necessitating increased numbers of anodes to avoid over-protection towards end of life. The dielectric shields used in the case study were circular of diameter 3m. In practice bigger shields would normally be used to prevent coating damage close to the shield.
Trial simulations were used to identify locations where the potential was most positive, and in the case study some of these were chosen as positions at which reference electrodes could best be located, as shown in Figure 4. Because of this selection method, these locations are automatically distant from the anodes (and so are not unduly influenced by the intense fields near the anodes), and provide an accurate indication of the most positive hull potential. In the case study the ICCP system was adjusted to achieve most positive potential -950 mV (Ag/AgCl/seawater) at any reference electrode. As the reference electrodes in this case identify the most positive potential on the hull, a more positive target potential could have been used, and this would make it easier to avoid overly negative potentials (which might cause coating damage) near the anodes.

In addition to the ICCP system there are Sacrificial Anodes located on the Chain connectors, Moon pool and Turret as shown in Figure 5.
Electrical Continuity

One of the challenges of the design was that it was not possible to guarantee perfect electrical continuity between the chain connectors and the turret. Therefore an electrical resistance between the chains and the turret had to be considered in the CP design.

The main objective of the modelling study was to predict the protection provided over the design life of the structures to verify that it would meet the design objectives. As part of this study the impact of the internal electrical resistance between the chains and the turret was investigated because of its possible impact on the protection provided and the life of the sacrificial anodes.

Modelling Objectives & Strategy

The most important aspect of any modelling study is the definition of the cases to be investigated. They could be:

- A simple study to verify that the chosen design will protect the structure over its life
- Studies to compare the effectiveness of different designs
- “What if” studies test the robustness of the design by simulating possible damage and failure scenarios the structure may experience over its life

In general, once the model is built it makes sense to use it to test all the design options and the sensitivity of the design to various parameters as it is cost effective to run additional cases.

To predict how the design will perform over the life of the structure, a time dependent simulation is performed where the assumptions regarding the rate of degradation of the coatings with time are input into the model. This data can be based on the design code used or based on damage experienced on similar structures. The simulation starts at year zero and predicts the protection provided to the structure and the current delivered by the individual anodes. The simulation continues step by step, calculating at each step the consumption of the anodes (including the reduction in size) including the assumed degradation of the coatings until the design life is reached. If during the simulation, the anode is consumed, it no longer contributes to the protection of the structure.

The simulation provides data on the protection provided to the structure over time and the consumption of the individual anodes. With this information, areas where protection may not be maintained and imbalances in the anode consumption can be identified and used to improve and optimize the design.
FPSO CASE STUDY

The model was created to simulate the performance of the CP systems and predict the protection potentials achieved at different times over the design life of the structures. In this case the results were predicted for the initial, mean and final life.

The properties of the various coatings on the structures were defined according to the design guidelines including the rate of coating degradation with time. Two cases were considered for the electrical resistance between each chain connector and the turret. Case 1 assumed the resistance was zero and for Case 2 the electrical resistance was assumed to be 0.01 Ohms. All other internal electrical connections were assumed to be perfectly connected. Appropriate values were used to model the internal resistance on the chains.

The ICCP system was simulated in the model to determine the settings required to achieve a protection potential at the hull reference electrodes more negative than -950 mV vs Ag/AgCl (set point). During the time stepping process to simulate the performance of the CP system the ICCP settings were adjusted to maintain the protection potentials at the set point as the structure ages. In this way the model simulates the actual behaviour of the ICCP system.

During the time stepping process the consumption rate of the sacrificial anodes was also predicted and their size adjusted to take into account the metal loss and reduced surface area.

Case 1    Zero Resistance Between The Chain Connectors And The Turret

The predicted protection potentials on the hull at the Initial Life are shown in Figure 6. The most positive potential was predicted to be at RE8 which was used by the ICCP system to maintain the potential more negative than -950 mV vs Ag/AgCl.

![Figure 6 View Of The Protection Potentials On The FPSO Hull At The Initial Life (Time 0)](image)

The current delivered by the ICCP system and the sacrificial anodes, and received by the various component parts of the structures is shown in Table 1. As the structure ages and the coatings degrade, the current required by the ICCP system to maintain the reference electrodes at the set point increases significantly. For example, it is predicted that the current delivered by the ICCP system will increase from its initial value of approximately 98 Amps to 1088 Amps at the end of the design life. These values are very much dependent upon the assumed coating breakdown factors defined in the design rules and may in some circumstances be overly conservative. Initial coating breakdown factor was assumed to be 0.05, changing by 0.02 per year over the first 10 years to midlife and then increased to represent a faster degradation rate.

Note. To improve predictions on the future performance of the CP system some operators provide the monitoring data reported by the ICCP system and other CP surveys to enable the model to be calibrated to determine the actual coating degradation rates over time.
The predicted number of sacrificial anodes that are still active at end of the design life is shown in Table 2.

**Table 1 Case 1. Predicted Anodic & Cathodic Currents at the Initial, Mid and End life conditions**

<table>
<thead>
<tr>
<th>Component</th>
<th>Initial life</th>
<th>Mid life</th>
<th>End of life</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Current</td>
<td>Anodic</td>
<td>Current</td>
</tr>
<tr>
<td>ICCP Anodes</td>
<td>98.9</td>
<td></td>
<td>1087.8</td>
</tr>
<tr>
<td>FPSO</td>
<td>64.4</td>
<td>365.4</td>
<td>1004.0</td>
</tr>
<tr>
<td>Moonpool</td>
<td>10.0</td>
<td>44.5</td>
<td>81.7</td>
</tr>
<tr>
<td>Moonpool Anodes</td>
<td>9.5</td>
<td></td>
<td>46.2</td>
</tr>
<tr>
<td>Turret</td>
<td>10.5</td>
<td>47.3</td>
<td>90.2</td>
</tr>
<tr>
<td>Turret Anodes</td>
<td>13.9</td>
<td></td>
<td>101.3</td>
</tr>
<tr>
<td>Chain Connectors</td>
<td>1.1</td>
<td></td>
<td>11.3</td>
</tr>
<tr>
<td>Chain Connector Anodes</td>
<td>29.2</td>
<td></td>
<td>32.0</td>
</tr>
<tr>
<td>Anchor Chain</td>
<td>66.7</td>
<td>74.5</td>
<td>92.6</td>
</tr>
</tbody>
</table>

**Table 2 Case 1. Predicted number of active sacrificial anodes at the end of the design life and the average remaining life of the anodes**

<table>
<thead>
<tr>
<th>Active Anodes</th>
<th>Chain Connector</th>
<th>Moonpool</th>
<th>Turret</th>
<th>Average projected remaining life for active anodes at end of life (years)</th>
<th>Chain Connector</th>
<th>Moonpool</th>
<th>Turret</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Number</td>
<td>144</td>
<td>150</td>
<td>120</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>End of life R=0.0 0hm</td>
<td>124</td>
<td>120</td>
<td>120</td>
<td>R=0.0 0hm</td>
<td>5.5</td>
<td>1.1</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Of the 144 sacrificial anodes on the chain connectors 124 are still active at the end of the design life and the average remaining life of those anodes is approximately 5 years. Note the actual remaining life will be less as it is calculated using the consumption rate at the end life date which does not take into consideration any further degradation of the coatings.

The study also provides interesting information on the distribution of the current from the different anode groups. For example at initial life:

- The sacrificial anodes on the Moonpool are supplying practically all the cathodic current required to protect the Moonpool but at the end of life they are only just providing over 50% of the current and the balance is coming from the ICCP system and from other sacrificial anodes on the Turret.

- There is a similar situation on the chains and chain connectors where the sacrificial anodes are only supplying 30-40% of the cathodic current required by the chains and the balance is coming from the ICCP system.

- For the Turret the sacrificial anodes on the Turret supply the bulk of the cathodic current.

- The ICCP system provides the cathodic current for the FPSO hull.

The overall conclusion from the study is that the ICCP system can maintain the potentials at the reference electrodes at -950 mV vs Ag/AgCl or more negative and the sacrificial anodes have sufficient life to provide protection to the Turret, Moonpool and Chain connectors. There
are also no areas with high negative potentials which would cause concern about damage to the coatings and the size of the dielectric shields was adequate.

**Case 2 0.01 Ohm Resistance Between The Chain Connectors And The Turret**

In the second case study the impact of the electrical continuity between the chain connectors and the turret is considered by imposing a 0.01 Ohm resistance between those structures.

The simulation was performed as before with the model stepping forward in time and the ICCP system maintaining the potentials at the reference electrodes at -950 mV vs Ag/AgCl.

Comparing the anode currents in Table 1 (Case 1) and Table 3 (Case 2) it can be seen that the overall current delivered by the ICCP system is similar but there are major differences in the sacrificial anode currents and currents on the chains and chain connectors. At the end of life the current delivered by the anodes on the chain connector for Case 2 is reduced by 80% compared with Case 1.

The impact can be seen more clearly in Table 4 where the number of active anodes at the end of the design life has been reduced from 124 for Case 1 to 12 for Case 2.

In terms of anode mass consumption the effect is more dramatic with an increase from 75% to 98% on the chain connectors.

<table>
<thead>
<tr>
<th>Component</th>
<th>Current in Amps</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial life</td>
</tr>
<tr>
<td>ICCP Anodes</td>
<td>Cathodic</td>
</tr>
<tr>
<td>FPSO</td>
<td>64.3</td>
</tr>
<tr>
<td>Moonpool</td>
<td>10.0</td>
</tr>
<tr>
<td>Moonpool Anodes</td>
<td>8.7</td>
</tr>
<tr>
<td>Turret</td>
<td>10.6</td>
</tr>
<tr>
<td>Turret Anodes</td>
<td>12.9</td>
</tr>
<tr>
<td>Chain Connectors</td>
<td>1.1</td>
</tr>
<tr>
<td>Chain Connector Anodes</td>
<td>35.5</td>
</tr>
<tr>
<td>Anchor Chain</td>
<td>61.0</td>
</tr>
</tbody>
</table>

**Table 4 Case 2. Comparison Of The Predicted Number Of Active Sacrificial Anodes At The End Of The Design Life And The Average Remaining Life Of The Anodes**

The interference has reduced the life of the anodes even when the individual sacrificial anode systems for the Moonpool and the Turret are well designed.

The predicted potentials on the FPSO at Initial, Mid and End Life are shown in Figure 7 and Figure 8. The addition of the resistance between the chain connector and the turret has also
resulted in the protection potentials being reduced to approximately -845 mV in some areas on the chain connectors (Figure 7 right hand side) and 98% of the anode mass consumed at the end of life. This can be clearly seen in Figure 9 which shows the depleted anodes. This is further evidenced by the 50% reduction in the cathodic currents supplied to the chain connector at the end of life.

Near the end of life when the ICCP system was delivering the highest currents, overprotection (excessive negative potentials) on the hull near the edge of the dielectric shields was predicted. Therefore one of the conclusions of the study was that larger shields were required.
The accelerated anode consumption on the chain connectors is caused by interference currents from the ICCP system. For Case 1 current from the ICCP system delivered to the chains and the chain connectors returns back to the power supply through the structures without any IR drop. However for Case 2 there is a resistance to this current caused by the resistance between the chain connector and the Turret and hence an IR drop. This has two effects:

- The current flowing to the chains from the ICCP system is reduced because of the increased resistance in the return path through the structure
- Some current takes the path of least resistance and passes between the sacrificial anodes on the chain connector to the Turret/FPSO through the seawater therefore accelerating their consumption.

Figure 8 Comparison of the protection potentials on the Moon Pool/Turret/Chain Connectors/Chains for Case 1 and Case 2 at End Of Life.

Figure 9 View of the active anodes on the chain connector at the end of life for Case 1 (R=0) and Case 2 (R=0.01). A colour indicates the anode is active and the grey indicates it is fully consumed

Discussion

The accelerated anode consumption on the chain connectors is caused by interference currents from the ICCP system. For Case 1 current from the ICCP system delivered to the chains and the chain connectors returns back to the power supply through the structures without any IR drop. However for Case 2 there is a resistance to this current caused by the resistance between the chain connector and the Turret and hence an IR drop. This has two effects:

- The current flowing to the chains from the ICCP system is reduced because of the increased resistance in the return path through the structure
- Some current takes the path of least resistance and passes between the sacrificial anodes on the chain connector to the Turret/FPSO through the seawater therefore accelerating their consumption.
For the operator of the vessel relying on CP surveys the accelerated anode consumption may not become apparent until later in the life of the vessel when the anode depletion can be clearly observed. At this point what would be the appropriate remedial action?

The simplest action would be to make the set point of the ICCP system more negative so the system delivers more current with the aim to reduce the current being delivered by the sacrificial anodes. However, the design of any remedial action is complex as the interactions can cause unexpected results. For example if the solution adopted is to increase the current delivered by the ICCP system how much should it be increased by and what should the set points be to provide protection while at the same time not causing damage to the coatings?

To answer these questions, a study was performed where the ICCP anode current was increased by 10 Amps to determine what effect this had on the consumption rates of the sacrificial anodes. In Table 5 the results are shown where it is clear that for Case 1 ($R=0$) the additional ICCP current results in a reduction of the current delivered by the Chain Connector sacrificial anodes. For Case 2 ($R=0.01$) there is a smaller reduction but if the resistance is increased further the effect on the sacrificial anode consumption rate becomes negligible.

**Table 5 Impact of additional current supplied by the ICCP system on the current delivered by the anodes and the cathodic currents received by the structures for various values of the resistance between the chain connectors and the turret.**

<table>
<thead>
<tr>
<th>Component</th>
<th>Total Current in Amps</th>
<th>Total Current delivered by anodes shown as negative values</th>
<th>Total Current flowing to surfaces shown as positive values</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICCP output</td>
<td>90A</td>
<td>100A</td>
<td>90A</td>
</tr>
<tr>
<td>Most Positive Potential on RE</td>
<td>-948</td>
<td>-957</td>
<td>-959</td>
</tr>
<tr>
<td>Component</td>
<td>ICCP Anodes</td>
<td>FPSO</td>
<td>Moonpool</td>
</tr>
<tr>
<td>R=0 Ohm</td>
<td>-89.0</td>
<td>-98.9</td>
<td>-89.0</td>
</tr>
<tr>
<td>R=0.01 Ohm</td>
<td>60.3</td>
<td>64.4</td>
<td>64.3</td>
</tr>
<tr>
<td>R=0.05 Ohm</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>R=0.1 Ohm</td>
<td>10.5</td>
<td>10.5</td>
<td>10.6</td>
</tr>
<tr>
<td>R=0.1 Ohm</td>
<td>-14.2</td>
<td>-13.9</td>
<td>-12.9</td>
</tr>
<tr>
<td>R=0.1 Ohm</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>R=0.1 Ohm</td>
<td>-31.5</td>
<td>-29.2</td>
<td>-35.5</td>
</tr>
<tr>
<td>R=0.1 Ohm</td>
<td>63.7</td>
<td>66.7</td>
<td>61.0</td>
</tr>
</tbody>
</table>

The impact of the resistance becomes clearer if the behaviour of individual anodes is considered. In Figure 10, the change in the individual sacrificial anode current is shown when the ICCP system current is increased from 90 Amps to 100 Amps. On the right ($R=0$) all the anodes show a decrease in their output as the ICCP system current is increased. However, on the left for the case with $R=0.1$ Ohm, the anodes on the first and second row show a smaller decrease than the case with $R=0$ Ohm but the anodes on the third and fourth row (nearest the...
turret) show an increase in their current output and so they would be consumed faster. Therefore increasing the ICCP current will not always solve the problem of accelerated anode depletion and in some cases it will make the problem worse.

The increased ICCP current could also have other consequences such as excessively negative protection potentials and damage to coatings which would then lead to a greater current requirement followed by additional coating damage.

The connection resistance between the chain connectors and the Turret is also difficult to estimate. The benefit of the model is that these possible scenarios can be simulated to predict the outcomes over the life of the structure so the possible problems can be mitigated during the initial design process.

However the design variables such as the coating breakdown factors and the internal resistances of the chains, flow lines, connections are based on the design rules and in practice their actual values can be significantly different. By updating the model with the data from the ICCP system and the CP survey data during the operation of the vessel it can be calibrated to the actual performance of the coatings and the electrical resistances. In this way, issues related to interference and accelerated anode depletion can be predicted in sufficient time to allow remedial measures to be planned efficiently. The model predictions can be used to verify the effectiveness of the proposed measures and CP survey plans can be optimized to monitor critical areas.

**CONCLUSIONS**

The modelling study has demonstrated how the protection over the life of the structure can be predicted for complex structures including ICCP and sacrificial anodes.

There are many causes of interference which can prevent the correct operation of CP systems and can lead to premature failure of the system. These can include anodes very close to each other or poorly designed or imbalanced systems.

In this study interference issues related to the electrical continuity have been highlighted which cause similar problems which can be difficult to detect as they sometimes only become significant later in the life of the structure. The choice of remedial actions has to be carefully made as without the use of simulation models it is difficult to be sure of the outcomes as the
effects can be complex and subtle. Finally it is important to be able to predict and mitigate these phenomena as they can reduce the life of the CP system and increase the risk to the structural integrity even when the individual sacrificial anode systems are well designed.

Although the FPSO presented in this study was a relatively small vessel, similar phenomena have been observed in previous studies by the authors on much larger vessels.

ACKNOWLEDGEMENTS

Figure 1 reproduced with permission from Bluewater.

REFERENCES


