Iterative Electric Potential Adjustment of Damaged Naval Vessels using the onboard ICCP System

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Abstract

In this work, we present an iterative approach to adjust the *Impressed Current Cathodic Protection* (ICCP) system to maintain the electric potential of a ship's hull in a corrosion protective state. Therefore, the *Underwater Electric Potential* (UEP) signature and the potential distribution of a generic ship model provided by the COMSOL Multiphysics® tutorial section are simulated using the *Electric Currents* (ec) module within the AC/DC physics. As a reference scenario — in which the ship is protected against corrosion — additional coating damages are added in order to change the electric potential distribution of the hull. The ICCP currents are adjusted in an iterative manner through a simple mathematical formulation with a Matlab–based script connected to the model via the LiveLink for Matlab™ which further ensures the protective state of the hull as well as of the newly placed coating damages.

1. Introduction

Navel vessels passively communicate with their surrounding environment via electric signatures. These signatures are known as *Underwater Electric Potential* (UEP) signatures and are mainly generated through a corrosion process that occurs when two different metallic materials are connected galvanically. In this case, the material with a lower equilibrium potential or (in case both materials have a negative equilibrium potential) less negative equilibrium potential acts as the anode and the material with a higher equilibrium potential acts as the cathode. The surrounding seawater functions as the electrolyte, thus granting a current flow through the seawater from anode to cathode leading to anodic currents from the vessel's hull to the propellers. To prevent hull corrosion processes, active and passive corrosion protection systems can be implemented on the vessel. In this paper, a combination of passiv and activ corrosion protection systems are proposed encompassing a protective coating (passive) along with the *Impressed Current Cathodic Protection* (ICCP) system that actively impresses cathodic currents and consequently enforce the hull in the cathodic regime. In ship monitoring systems the potential distribution over the hull is measured using reference electrodes placed at different positions of the hull and ICCP currents are adjusted in a way to match the protection potential definition. However, when new damages appear at the hull due to e.g. collision with objects at or near the water surface, higher ICCP–currents are needed to be impressed to keep the hull in a protective state, which simultaniously lead to higher UEP signatures. The drawback of such high signatures is that they can impose a possible threat for the ship, since sea mines use — in addition to other signatures — the UEP signature as an indicator for activation. Conclusively, the evaluation of UEP signatures with existing coating damages is vital and hence, the simulation scenario of UEP signatures using real polarization data is presented and furthermore, the impact on the UEP signature is investigated.

2. Simulation Setup and governing equations

In order to accurately simulate the UEP signature, a modified version of a generic ship model provided by the COMSOL Multiphysics® [1] tutorial section [2] is used, where the total ship length and width is assumed to be 50 m and 8 m, respectively. A schematic of the underlying model is depicted in Figure 1. As illustrated, a total number of 4 circular ICCP anodes with 15 cm radius and surrounding circular dielectric shielding with 50 cm radius are defined. The dielectric shielding is applied to prevent overproetction close to the ICCP anode due to high gradients in the electric potential distribution near the anodes. Additionally, a *Sacrificial Anode Cathodic Protection* (SACP) system represented by several circular zinc anodes with 10 cm radius is positioned along the ship's hull, to ensure a more homogeneous electric potential distribution on the hull. In order to achieve more realistic simulation

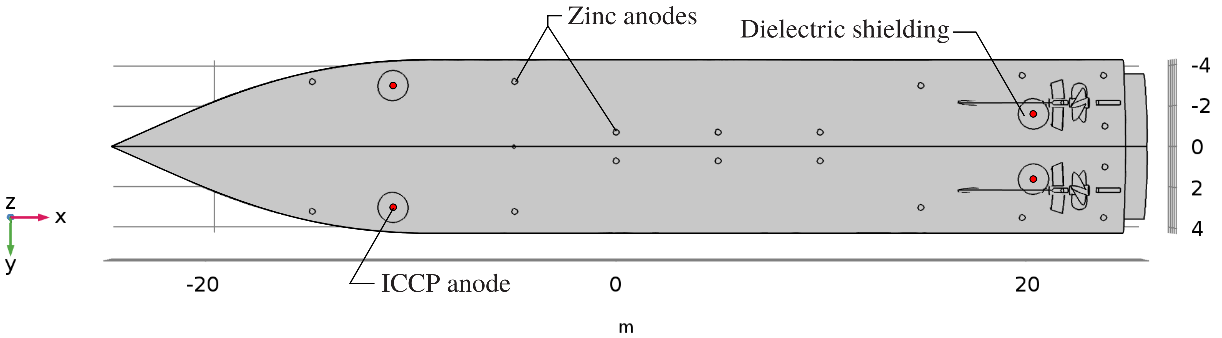

Figure 1: Modified generic ship model provided by COMSOL Multiphysics® tutorial section. In addition to the ICCP anodes, several zinc anodes are positioned along the hull to ensure a more homogeneous electric potential distribution.

results of the electrochemical behaviour of the ship, realistic polarization curve data are implemented in COMSOL Multiphysics® as shown in Figure 2. For the ship's hull the polarization curve of steel [3] is chosen, while the material of the propellers is defined as Nickle Aluminum Bronze (NAB) [4]. In the case of the SACP system the polarization data of grade zinc [4, 5] is used. It should be mentioned that all polarization curves are measured versus an Ag/AgCl reference electrode. The simulation setup for the analysis of the UEP signatures is illustrated in Figure 3, while width, depth and height are 100 m, 35 m and 30 m, respectively. At a depth of 20 m a UEP signature line is defined to extract the UEP signature for all three vector components. Furthermore, the outer domains are defined as Infinite elements to ensure open water conditions and the electrical conductivity of the seawater is set to $\sigma_{\mathrm{w}} = 2.8\,\mathrm{S/m}$. For the numerical calculations the *Electric Currents* (ec) module within the AC/DC physics is used which covers the following equations:

$$\nabla \cdot \boldsymbol{J} = Q \tag{1}$$

$$\boldsymbol{J} = \sigma \boldsymbol{E} + \boldsymbol{J}_{\mathrm{e}} \tag{2}$$

$$\boldsymbol{E} = -\nabla V \tag{3}$$

To model the passive protection system of the ship, or more precisely a minor damaged coating of the ship, only a fraction of the polarization data is taken into account as corresponding boundary condition. In case of the hull only 5 % of the orazem steel polarization curve's total current density is defined as the inward current density which represents a total damage of 5 % that is equally distributed over the hull. For the propellers 10 % and 15 % of the NAB polarization data is defined at port and starboard side, respectively. While for the zinc anodes 100 % of the grad zinc polarization data is taken into account indicating a perfectly working sacrificial anode. It's worth mentioning that for all ICCP anodes, an inward current density, via the

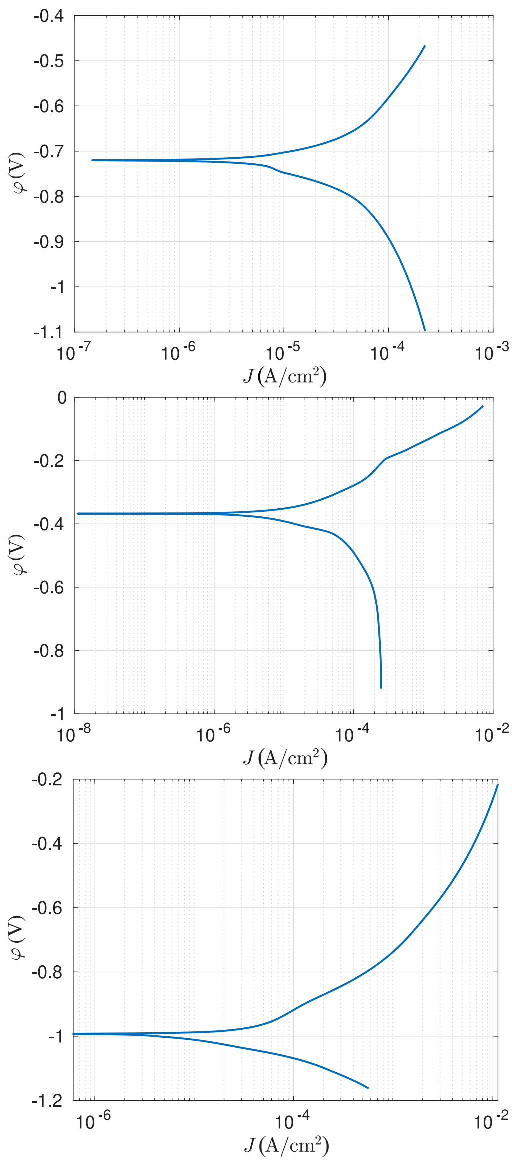

Figure 2: Implemented polarization curves from top to bottom: Steel, Nickle-Aluminum-Bronze (NAB) and grade zinc. All presented data are measured versus an Ag/AgCl reference electrode.

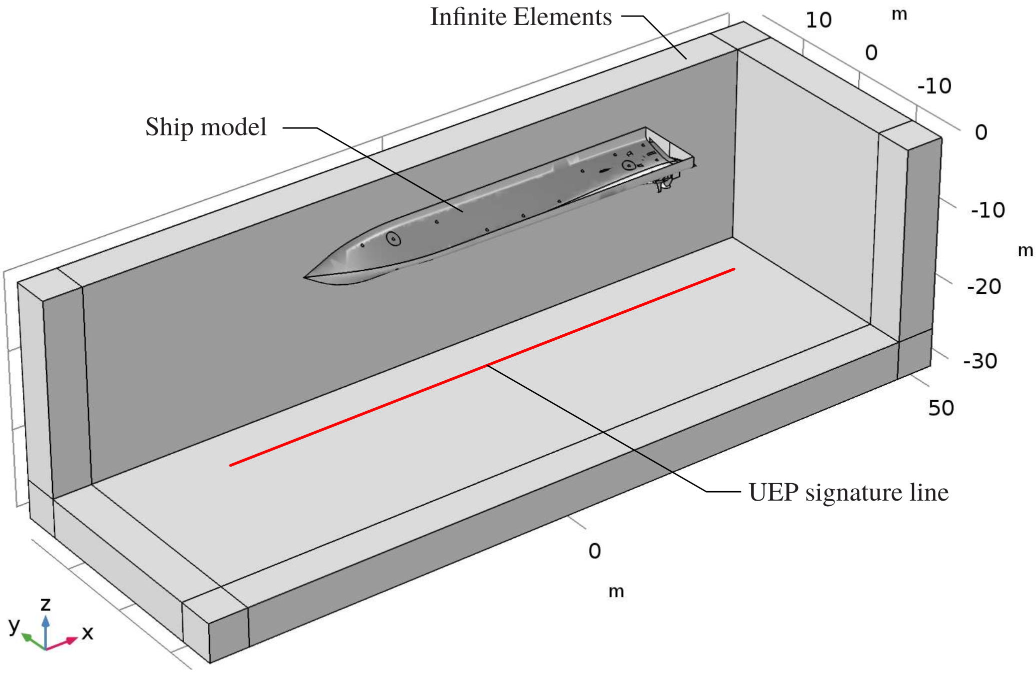

Figure 3: Simulation setup of the UEP signature calculation at a depth of 20 m and the electric potential distribution over the ship's hull. The outer domains of the simulation environment are defined as infinte elements to realise open water condition. For a better visualsation some domains are hidden.

follwing formulation, is considered.

$$J_n = \frac{I_{\mathrm{ICCP,anode}}}{A_{\mathrm{anode}}} \tag{4}$$

In order to just have the tangential components of the electric current density near the ICCP anodes the shielding surrounding the ICCP anodes is defined as a dielectric shielding boundary condition. Finally, a stationary analysis is selected using the stationary solver *Pardiso* for fast and efficient simulation results.

3. Results

To examine the influence of newly occuring damages at the hull, an intact reference scenario needs to be simulated in which the ship model is protected against corrosion. To achieve such reference scenario, the required ICCP currents are extracted and the protection potential distribution is visualised in Figure 4. All provided values for matching corrosion protection condition for orazem steel are calculated using a german standard [6]. In the mentioned case which was simulated with an imposed current of 12.5 A for each ICCP anode is needed to ensure a protection potential along the hull. However, the emergence of new damaged sites will change the ICCP currents as a result of the modification of the electric potential distribution. In actual ICCP systems, reference electrodes measure the hull potential at specific locations of the ship and correspondingly, the ICCP currents are adjusted if the

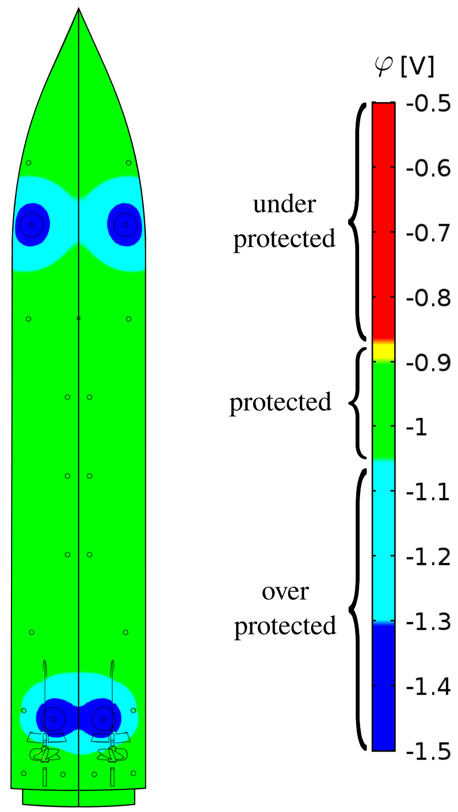

Figure 4: Electric potential distribution for a reference scenario with a homogeneous coating damage of 5 %. The needed protection potential for the defined material is calculated using a german standard [6].

corrosion protection conditions are no longer met. In order to account for ICCP system changes within the simulation setup, an iterative ICCP current adjustment is implemented using LiveLink for Matlab to achieve a simple current adjustment formulation. As a consequence of strong gradients in the electric potential distribution near ICCP anodes the ICCP current modification is more significant in close vicinity of the anodes. Due to stronger gradients in the electric potential distribution near ICCP anodes ICCP currents will change more significant when coating damages are close to the anodes. Therefore, it seems reasonable to consider a formulation which takes the distance of the applied coating damage into account, which is shown in equation (5) when calculating the new ICCP currents within the iteration.

$$I_{\mathrm{ICCP,new}} = I_{\mathrm{ICCP,pre}} + \frac{C}{d_{\mathrm{norm}}}\left(\frac{\varphi_{\mathrm{ref}} - \varphi_{\mathrm{new}}}{\varphi_{\mathrm{ref}}}\right) \tag{5}$$

Here, the previous value of each ICCP current is considered plus an additional term consisting a factor C which represents the iteration step size and is further multiplied by the term $\varphi_{\mathrm{ref}} - \varphi_{\mathrm{new}}$ that allows the new ICCP current to be smaller than the previous ICCP current which prevent overprotection of the damaged region and supports the convergence towards the reference electric potential. The variable φ_{ref} represents the corrosion protection potential while φ_{new} describes the electric potential of the coating damage. Moreover, the variable d_{norm} stands for the normalized distance between ICCP anode and damaged region and is calculated using the following equation:

$$d_{\mathrm{norm}} = \frac{d_{\mathrm{abs}}}{\min(d_{\mathrm{abs}})} \tag{6}$$

with

$$d_{\mathrm{abs}} = \Big[\left(d_{\mathrm{x,anode}} - d_{\mathrm{x,damage}}\right)^2 + \left(d_{\mathrm{y,anode}} - d_{\mathrm{y,damage}}\right)^2 + \left(d_{\mathrm{z,anode}} - d_{\mathrm{z,damage}}\right)^2\Big]^{1/2} \tag{7}$$

The variable d_{abs} represents the absolute value of the distance and is normalized to the minimum distance insuring that higher currents are to be imposed if the damage is closer to the hull and vice versa. Therefore, the variable d_{norm} acts as a weighting factor. To clarify the role of the iterative process, an example of ICCP current adjustment using LiveLink for Matlab$^{\mathrm{TM}}$ is provided in Figure 5. Within the reference scenario a circular coating damage with a 50 cm radius is considered at the ship's bow while 100 % of the polarization data of steel is applied to the new damage in order to capture a perfectly damaged coating. In case of a stepsize $C = 50$ and a reference electric potential $\varphi_{\mathrm{ref}} = -900\,\mathrm{mV}$, the corrosion protection condition can be achieved after 4 iterations. However, due to the new ICCP currents — that are close to 20 A at the ship's bow — higher UEP signatures will occur which can lead to unwanted ship signatures. The corresponding UEP signatures for the example provided in Figure 4, are ilustrated in Figure 6. The left picture a) represents the UEP signature for the reference scenario without adjusting the ICCP currents to force the new coating damage in the protective regime while the right picture b) clarifies the influence of the ICCP currents on the UEP signature for corrosion protection condition of the new coating damage. As the ICCP current changes to nearly a maximum value of 20 A the UEP signature is approximately doubled. Such high UEP signatures might be strong enough to trigger underwater seamines and hence cause serious damages to the naval vessel which can ultimately lead to a total loss. As a result, a full understanding of UEP signature modification in correlation with the ICCP system is key for accurately estimateing the detection risk along with the ship damage protection. The provided examples can also be adapted for multiple coating damages and alter the ICCP currents in an iterative manner for each individual ICCP anode and additionally, be adapted for real–time control scheme in e.g. ship models and in existing ICCP system configurations.

4. Conclusion

In this study we proposed an iterative approach for adjusting ICCP currents of an ICCP system, which ensures corrosion protection condition of a naval vessel's hull. To achieve a successful methodology, a reference scenario of a generic ship model was created and simulated using the *Electric Currents* (ec) physics within COMSOL Multiphysics® AC/DC module along with a stationary solver (Pardiso). To capture the electrochemical corrosion effects, realistically nonlinear polarization curves were implemented. Since changes of the hull conditions would lead to adjustments in the ICCP currents due to the shift of the operating point within the polarization curves, a simple mathematical formulation was presented to successfully adjust ICCP current using COMSOL Multiphysics® and LiveLink for Matlab$^{\mathrm{TM}}$ to match the protection potential conditions. As a result of additionally introduced defect sites, major changes in UEP signature strength were depicted and an approximately doubling of the UEP signature was shown for a coating damage at the hull's bow. Using such iterative approach a noval adaption scheme for real–time control of corrosion protection levels is proposed in this framework of existing ICCP system configurations. The overall system is also ideally suited to impart deeper understanding of UEP signatures in correlation with ICCP current adjustments.

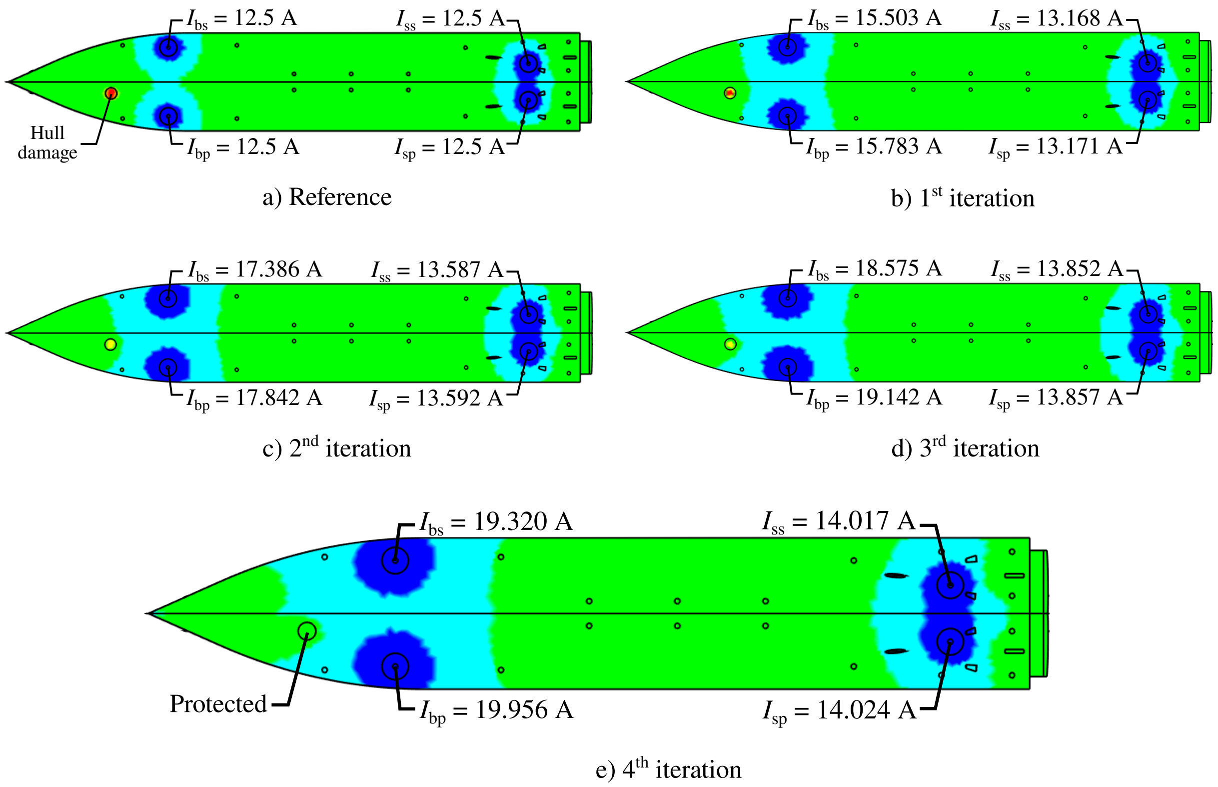

Figure 5: Iterative numerical ICCP–current adjustment to restore the protection potential of the damaged hull. Within four iteration steps b)–e) the protection conditions are met for the applied coating damage.

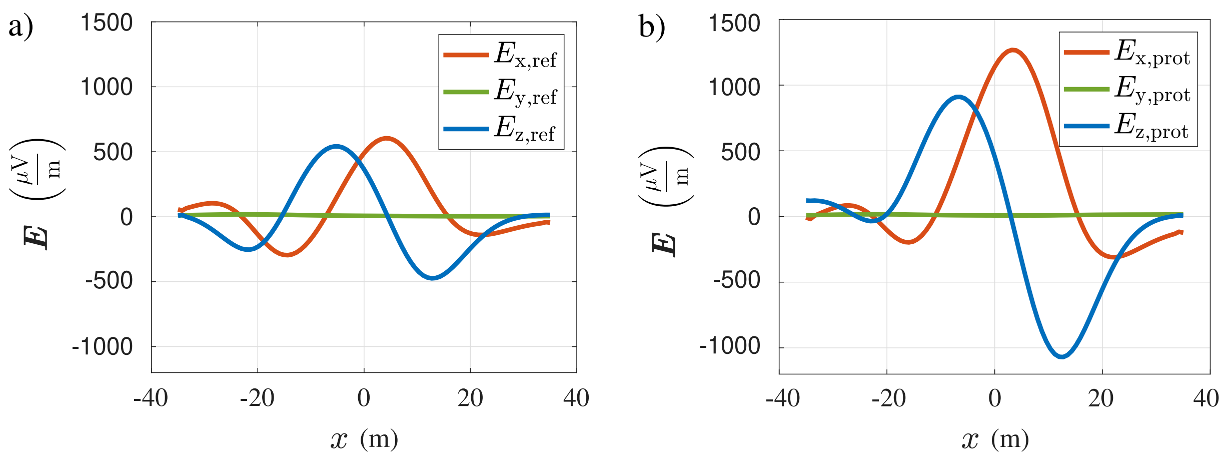

Figure 6: Simulated UEP signature for the reference scenario with an imposed current at each ICCP anode of 12.5 A a) and stronger UEP signature due to ICCP current adjustment to ensure corrosion protection condition with an additional coating damage b). Due to newly adjusted ICCP currents the UEP signature after protection is nearly doubled.

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