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► **To cite this version:**

Michaël Nale, Olivier Chadebec, Jean-Michel Guichon, Olivier Pinaud, Brahim Ramdane, et al..
Transient Modelling of Corrosion Protection Systems with BEM-Electrical Circuit Hybrid Model.
20th Biennial IEEE Conference on Electromagnetic Field Computation (IEEE-CEFC'2022), Oct 2022,
Denver, United States. hal-03808761

HAL Id: hal-03808761

<https://hal.science/hal-03808761>

Submitted on 10 Oct 2022

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Transient Modelling of Corrosion Protection Systems with BEM-Electrical Circuit Hybrid Model

Michaël Nale
Univ. Grenoble Alpes, CNRS,
Grenoble INP, G2Elab
38000 Grenoble, France

Olivier Chadebec
Univ. Grenoble Alpes, CNRS,
Grenoble INP, G2Elab
38000 Grenoble, France

Jean-Michel Guichon
Univ. Grenoble Alpes, CNRS,
Grenoble INP, G2Elab
38000 Grenoble, France

Olivier Pinaud
Univ. Grenoble Alpes, CNRS,
Grenoble INP, G2Elab
38000 Grenoble, France

Brahim Ramdane
Univ. Grenoble Alpes, CNRS,
Grenoble INP, G2Elab
38000 Grenoble, France

Virginie Roche
Univ. Grenoble Alpes, CNRS,
Grenoble INP, LEPMI
38000 Grenoble, France

Marie Minola
Univ. Grenoble Alpes, CNRS,
Grenoble INP, LEPMI
38000 Grenoble, France

Cedric Göeau
DGA Techniques navales
29240 Brest, France

Abstract—Modelling of corrosion protection systems in seawater is classically based on Boundary Element Method (BEM) with a limitation to static studies. This paper presents an original transient approach hybridizing BEM and circuit solving, enabling the modelling of more complex system and interface phenomena.

Keywords—Corrosion protection system, Boundary Element Method (BEM), Equivalent circuit modelling

I. INTRODUCTION

Usually, to prevent corrosion, ships are protected by imposing currents thanks to active anodes. This current flow from the anodes through seawater to damaged hull areas putting them in their electrochemical inactive domain. This corrosion protection system is known as ICCP (Impressed Current Cathodic Protection). The flow of currents in the seawater (Fig.1) induces a measurable electrical field around the ship which can endanger it, knowing that mine sensors can exploit this indiscretion.

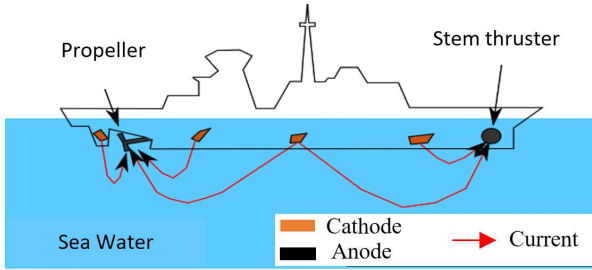


Fig. 1: Corrosion phenomena on ship hull

To model dynamic effects due to the ICCP when the system is triggered or the influence of the moving propeller on the signature, a transient approach has to be developed. In this paper, we propose an original approach based on the coupling of Boundary Element Method (BEM) with an equivalent electric circuit. The BEM is used in order to model the water and is associated to a resistance network. The equivalent electrical circuit approach is used in order to model the dynamic behaviour associated to the corrosion and the control of the ICCP.

II. BEM-ELECTRICAL CIRCUIT HYBRIDIZATION

Let us consider a conductive media Ω with a linear isotropic and homogeneous conductivity σ ($S \cdot m^{-1}$) and delimited by its boundary S . The electric field derives from an electric scalar

potential U (V) and is linked to the current density \mathbf{J} (A/m^2) by the Ohm's law. Considering the free-divergence of the current, we get the Laplace equation for the scalar electric potential:

$$\Delta U = 0 \quad (1)$$

completed by boundary conditions on S . Using the third Green's Identity combined with a Galerkin projection method, we get a linear matrix system linking both potential and its normal derivative on S . Surface S is meshed with p elements associated to 0-order piecewise shape functions that are used to interpolate both quantities. Thus, we have [1]:

$$\mathbf{H}U_{BEM} + \mathbf{T} \frac{\partial U_{BEM}}{\partial n} = 0 \quad (2)$$

with

$$H_{ij} = \int_{S_i} \int_{S_j} \frac{\partial G}{\partial n} dS_j dS_i \quad (i \neq j), \quad H_{ii} = \int_{S_i} (2\pi + \int_{S_i} \frac{\partial G}{\partial n} dS_i) dS_i$$

$$T_{ij} = \int_{S_i} \int_{S_j} G dS_j dS_i$$

where \mathbf{n} is the outward normal to Ω , $G = 1/4\pi r$ is the so-called Green's function. Since the normal derivative of the potential on S is proportional to the current, a matrix admittance \mathbf{Y} , which links the currents to the boundary potentials, can be defined :

$$\mathbf{Y} = -\sigma_s \mathbf{T}^{-1} \mathbf{H} \quad (3)$$

where s is a vector containing the surface of the elements of the mesh. This admittance ($p \times p$) full matrix can be seen as a circuit network in which each element of the mesh is linked to the others by static resistances.

Additionally, the corrosion occurring at the interface between the steel hull and the water can be represented as an electric dipole ruled by a differential equation that expresses the dynamic behaviour between the water and the corroded material. It is classical to assume that the dipole has the following topology (Fig. 2, left) [2].

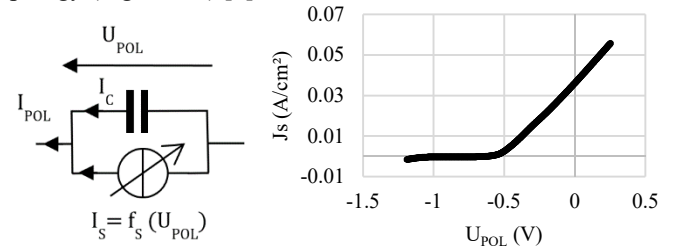


Fig. 2. Electric component representing the corrosion at the interface between water and hull (left) and static polarization law (right).

Let us define I_{POL} as the total current flowing through the interface and U_{POL} as the voltage between the water and the hull. We have:

$$I_{POL} = C \frac{\partial U_{POL}}{\partial t} + f_s(U_{POL}) \quad (4)$$

where C is a linear capacitance (constant and not depending on the polarization point), $f_s(U_{POL})$ is the static polarization law which is nonlinear (Fig.2, right) and t is the time.

The BEM model and the element associated to corrosion are merged in a global electric circuit (Fig. 3). Let us notice that the region associated to Neumann boundary condition (imposed currents) can be seen as a current source with an unknown voltage U_1 .

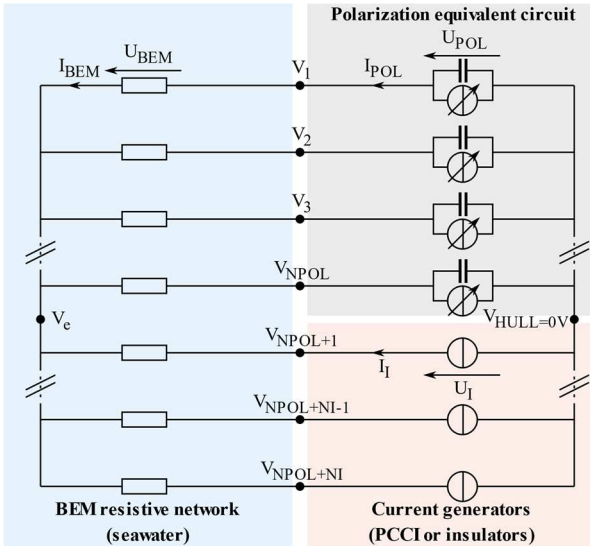


Fig. 3. Global equivalent electric circuit of the problem including polarized element and imposed current elements.

The global circuit is solved in the time-domain with a nodal approach [3]. It consists in writing an equation at each node and requiring that the incident branch currents at a node must be equal to zero. The backward Euler method is used and coupled to an internal Newton-Raphson method in order to deal with the non-linearity of the polarisation law. A special care is taken in order to increase the efficiency of the computing performances. As the \mathbf{H} and \mathbf{T} come from integral formulations, they are fully dense and need to be compressed if problems with a large number of degrees of freedom has to be solved. The full paper will discuss deeply the global solving process including two levels imbricated linear solvers with appropriated preconditioning techniques in order to ensure a fast convergence.

III. RESULTS

We have tested our implementation on the following problem: We consider a 1m side cube filled with water (5S/m). The cube surface is meshed with 384 quadrangles. The cube is fed by two opposite faces. The interest of such a geometry is that the resistance can be calculated analytically (0.2Ω) and the current path is perfectly straight. One electrode is associated to a static polarization curve of steel (Fig. 2) and a capacitance $C =$

20 F. The other electrode is associated to a current generator. Others faces of the cube are insulating. As all the electric parameters are known, it is also possible to simulate the problem with the circuit solver LTSpice. The study focuses on the characteristic time allowing the system to reach a stationary equilibrium following the injection then the protection current due to an ICCP is stopped. To do this, we inject a current of 250 μA after 1 second for a total simulation time of 30s. Comparison between LTSpice and the hybrid BEM solver are presented in Fig. 4. validating the model.

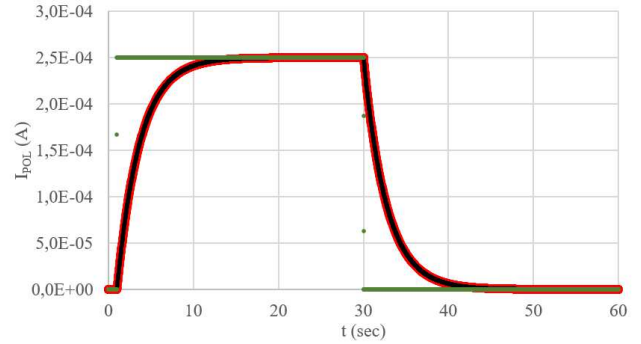


Fig. 4. Comparison of hybrid BEM and LTSpice models. Imposed current by the PCCI (green). Current I_s flowing in the other electrode computed by LTSpice (red) and hybrid-BEM (black)

Finally, the model can be used to evaluate the electrical signature. A transient simulation is carried out with two different steps. The initial state consists in a galvanic coupling between the two materials (bronze and steel) through seawater. At a given time, the ICCP is switched-on in order to protect the steel. The simulation aims to compute the modification of the electrical anomaly generated by the corrosion protection system. Results are presented on Fig. 5.

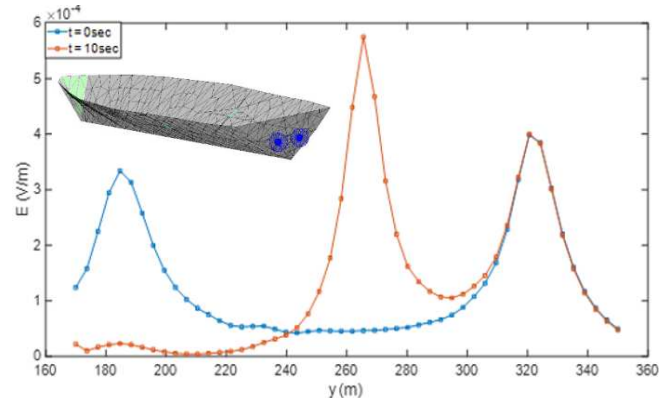


Fig. 5. BEM mesh of the ship hull and electric field computed above the hull (blue ICCP off – $t=0\text{s}$, red ICCP on – $t=10\text{s}$).

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