POLITECNICO DI MILANO

Scuola di Ingegneria Industriale
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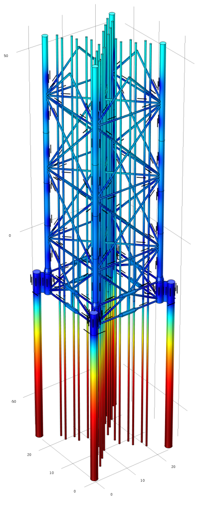
Empirical and Computer Aided Design of Cathodic Protection Systems



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This entire work is dedicated to my parents,
who have always supported me
from my first baby steps towards my greatest ambitions.

Aknowledgement

Sempre avanti

Angelo Veronelli

In achieving this result many thanks are addressed to the entire Tecnomare team who took care of me like a younger brother. A special praise goes to Vittorio for the time and patience he invested on me, Pietro for supporting me from the beginning, Fabio for his sympathy; Filippo and Luigi for sharing their thoughts and life experiences; Raffaele, Antonio, Fabio and Giovanni who lit the gray days in the office with their colourful speeches full of humor.

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> I hear babies cry, I watch them grow They'll learn much more, than I'll never know And I think to myself, what a wonderful world!
>
> Louis Armstrong

Abstract

Cathodic protection is an effective corrosion control technique, which can be applied successfully to protect a metallic structure immersed in an electrolyte. The application of appropriate cathodic protection system design criteria is important to promote safety and energy efficiency. The implementation of computer tools to perform safe, reliable and consistent cathodic protection design for offshore and onshore structures is reported here. Results are shown for the stand off anode geometry optimization process. The application of the Finite Element Method approach to realistic cathodic protection related problems is also presented here. Potential distribution along the surfaces of a cathodically protected platform immersed in sea water, for different conditions, is described in this work. Different conditions are exemplified by what if scenarios such as sea bottom level rising, anodes loss, placing a new riser on the platform leg and ICCP revamping. The procedures and results of time dependent, moving mesh modeling of a jacket node protected by aluminum anodes are also described.

Keywords: Corrosion, Cathodic Protection, Offshore Structures, Platform, Pipelines, FEM
Parole chiave: Corrosione, Protezione Catodica, Strutture Marine, Piattaforma, Tubazione, FEM

Contents

Preface

> A little bit of corrosion is not denied to anyone
>
> Anonymous

The purpose of this work is to give an overview about current practices and state of the art, regarding cathodic protection system design, and to show the potentials and benefits of the application of advanced computer modeling in the oil and gas industry. The idea of coupling two metals, with the intent to protect the surface of the most noble one, has been around for more than two hundred years. Many mechanisms behind corrosion and corrosion prevention has been understood, but many others are still unclear. Working in a natural environment and not in an artificial situation complicates the understanding. The physical modeling have to deal with many unknown parameters and changing variables, which cannot be kept under control. A huge boost to the study of cathodic protection mechanisms has been given by the oil and gas industry which has been working in harsh and hostile environments for more than one hundred years. Nowadays the renewable energy industry, with the construction of humongous offshore wind farm, is also moving toward environments which require the application of cathodic protection.

Corrosion prevention is a matter of safety and efficiency. Many failures occured in the past because of underestimation of corrosion effects. Disasters like the sinking of oil tankers, the spill of toxic fluids from corroded pipelines and many others, happened in the past because of poor corrosion management. Corrosion is a major concern in all those structures working in an electric conductive environment. When a structure is corroded to the point that cannot safely undergo its duties, it has to be placed out of service and a new one has to be built. Most of the steel produced nowadays it is made to replace old strucures that were put out of service. The correct application of cathodic protection can prolong the design life of a structure, saving the energy and the money necessary to build a new one. Therefore, cathodic protection is a tool to achieve energy efficiency.

This report is divided into three main sections, a first general introduction, a second study about current practices used in the industry and a third part showing a new approach using computer modeling. The first two parts, chapters 1, 2 and 3 follow a four months work carried out at Tecnomare SPA, while working as an apprentice in the engineering department. Tecnomare SPA is an engineering company, owned by eni, which works predominantly in the offshore sector and it is currently expanding towards the onshore too, dealing with all the phases of upstream development. The need to design cathodic protection systems, and to verify designs made by other companies, pushed the engineering department to implement a software to carry out these activities. A software based on company and international standards was created and partly validated, to size cathodic protection systems of offshore and onshore structures. The last part of this master thesis, chapters 4 and 5, is dedicated to computer modeling, an approach used to understand cathodic protection systems behaviours, under different working conditions and environments. This section was carried out at Politecnico di Milano, the results achieved during this work were done with the sole purpose of a scientific research and to show the potential of computer modeling approach applied to cathodic protection related problems.

1. Introduction to cathodic protection

Rust never sleeps.

Neil Young

Cathodic protection (CP), is a corrosion control technique, which can be applied successfully to prevent corrosion induced damages on metallic systems immersed in electrolytes. This method consists in coupling the metallic structure, which needs protection, with another system, a galvanic anode or an impressed current setup, to achieve an electric potential lower than the free corrosion potential.

1.1. Costs of corrosion

Corrosion costs in modern society are estimated to be approximately 3 percent of the world GDP [1]. The oil and gas industry, most often working in harsh and hostile environments, has to pay a high toll to the unrelenting struggle with corrosion. The most extreme example can be found in the North Sea oil and gas industry, where 60 percent of maintenance costs are related to corrosion [2]. The application of the well known corrosion protection and prevention techniques could decrease the costs of corrosion related problems by more than 15% [3]. The so called law of five stated by De Sitter can be expressed as follow:

> *"1Euro more spent in the design phase leads to benfits that can be achieved spending 5euro in the building stage, 25Euro when the structure has been completed, 125Euro when corrosion has already started and 625Euro when corrosion is pandemic."*

With the increasing prices of hydrocarbons and improved techniques, it is becoming more and more feasible the exploration and production of reservoirs in extreme conditions such as deep water and arctic climates. To deal with these circumstances will require a more careful and thorough approach to corrosion mitigation practices.

1.2. History

Since the iron age, mankind has had to fight the relentless battle against corrosion. The inevitable destruction of metal objects left unprotected was a challenge, for which a solution was found only in modern time. Some metals, like lead, showed great corrosion resistance characteristics when used in conductive solutions such as water, because of the formation of a thin protective layer on the surface. Other metals needed to be painted, oiled or waxed to keep the moisture away from the metal surface to avoid rust formation. Cathodic protection gave the possibility to widely use cheap metals with great mechanical characteristics but poor corrosion behaviours, like carbon steel, to build structures in highly aggressive environments.

First applications

Corrosion control via cathodic protection in seawater is one of the main challenges that man has been facing since the royal navy introduced copper sheathing on ship hulls in the 18th century. The copper sheathing avoided woodworm attack and prevented marine growth on the hull, enabling fewer drydocks. A corrosion prevention technique was needed to protect the immersed copper in seawater. Sir Humphrey Davy discovered the foundations of modern cathodic protection starting with the work done by Galvani and Volta. Coupling the copper sheathing with iron or zinc resulted in complete corrosion protection of ship hulls. Unfortunately the protected copper lost its anti-fouling properties resulting in severe marine growth, which slowed the ships, decreeing a failure of the first application of cathodic protection. Thomas Edison also experimented impressed current cathodic protection (ICCP) to protect ships, resulting in another complete failure both from a technical and an economical point of view. The production of electricity on a ship in the late 19th century was far more expensive than nowadays. The current required to protect a surface in the open sea was much different from the one calculated from laboratory experiments [4]. It took many decades to recover from these first defeats. The use of cathodic protection on a commercial scale didn't begin until the oil and gas industry started to play an important economic role in modern society.

First applications in the oil and gas industry

In the early 20's, in America, many new pipelines were built to convey liquid fuel and crude oil. After few years, some pipelines laid in highly corrosive soil, started to show signs of severe damage, with leaks that undermined the safety and effectiveness of the pipelines. The first valid applications of cathodic protection were done in the most severely damaged area of pipelines, showing a great capability to decrease the rate of corrosion. As a consequence, it was understood the great potential that cathodic protection could have had on the fast growing Oil and Gas industry and to whichever metallic structure immersed in an electrolyte seeking protection.

Nowadays

Most modern cathodic protection designs are still based on recommended practices, empirical approaches and minimum requirements dictated by previous experiences. Working in an increasingly hostile environment lead to the advent of computer assisted cathodic protection design techniques, which are based on scientific principles. Numerical analysis, applied to the resolution of the electric field, makes possible the comprehension of the electric potential on the surfaces which need protection. These techniques also allow to highlight sites where protection is not achieved and to optimize anodes distribution. The greatest challenge is to get to know the most significant parameters affecting the CP model, which are available from field surveys or from previous experiences. The main concern about the significant parameters is their evolution with time.

1.3. Theoretical basis

In the following chapter corrosion and cathodic protection theoretical backgroung is briefly introduced. This chapter is intended to give some useful hints, to help outsiders coming from different scientific disciplines with a thermodynamic background, to understand the basis of cathodic protection and corrosion prevention.

1.3.1. Corrosion

Corrosion is almost always an electrochemical related process. It can be explained by means of chemical reactions and transport of charged species. Chemical reactions take place on the interface between the metallic structure and the solution. The transport of Charged species consists of ions movement inside the solution (the electrolyte) and electrons mobility inside the conductor (the electrode). Corrosion, to proceed, necessitates of both anodic and cathodic reactions which simoultaneously have to take place on the surface. There are two main questions to answer when talking about corrosion, would the metal corrode? and how long would the process take? The first one has a thermodynamic answer while the second one is a kinetic related problem [5].

Anodic reaction

In a corrosion process the dissolution of the metal in the electrolyte is the anodic reaction. The metal dissolves in the electrolyte in its ionic form discharging electrons in the electrode.

$$M \rightarrow M^{z+} + ze^- \tag{1.1}$$

cathodic reaction

A cathodic reaction which absorbs the electrons released during the anodic process is necessary to develop corrosion on a metallic surface. The two main anodic reactions which are usually involved are oxygen reduction 1.2 and hydrogen evolution 1.3. Oxygen reduction takes place at higher potential than hydrogen evolution. Oxygen reduction is greatly influenced by scale deposits and fluid dynamics conditions as explained in section 2.2.2.

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \; Oxygen\, reduction \tag{1.2}$$

$$2H_2O + 2e^- \quad \rightarrow \quad H_2 + 2OH^- \; Hydrogen\, evolution \tag{1.3}$$

Thermodynamic aspects

The thermodynamic related problem is due to the high energy content stored inside the metal. The inexorable second law of thermodynamic can be stated in many different ways, and from a corrosionistic point of view the most appropriate would be *“corrosion is the act of nature to pursue the lowest energy condition possible”*. Energy is spent to bring metals to a higher energy state, starting from their natural conditions, and energy is dissipated throughout the process of corrosion.

Most of corrosion reactions occur at constant temperature and pressure, consequently Gibbs energy, G, is the state function that needs to be taken into account to explain the thermodynamics of corrosion processes [6]. $\Delta_r G$, related to a reaction, is the parameter that measures the maximum amount of work extractable from the process. The spontaneity of a reaction can be measured by the value of $\Delta_r G$:

- $\Delta_r G < 0$ spontaneous reaction;
- $\Delta_r G = 0$ equilibrium reaction;
- $\Delta_r G > 0$ unspontaneous reaction (spontaneous in the opposit direction).

$\Delta_r G$ can be expressed as:

$$\Delta_r G = \Delta_r G^0 + RT \ln \Pi a_i^{\gamma} \tag{1.4}$$

- $\Delta_r G^0$: $\Delta_r G$ in standard conditions
- R: constant
- T: temperature
- a_i: activity of the i^{th} species
- γ: stoichiometric coefficient

$\Delta_r G$ can be also expressed as:

$$\Delta_r G = -zFE \tag{1.5}$$

- z: number of electrones involved in the reaction
- F: Faraday's constant
- E: Potential

Equation 1.4 and 1.5 can be rearranged and Nernst equation 1.6 can be derived:

$$E = E^0 - \frac{RT}{zF} \ln \Pi a_i^{\gamma} \tag{1.6}$$

In a chemical reaction, involving the dissolution of metal in an electrolyte $M \rightarrow M^{z+} + ze^-$, the equilibrium potential can be calculated:

$$E_{eq} = E^0 - \frac{RT}{zF} \ln a_{M^{z+}}{}^1 \tag{1.7}$$

Depending on the potential E which the metal assumes, compared to the equilibrium potential E_{eq}, the metal dissolution reaction can proceed or not. ΔE is defined as $E - E_{eq}$.

- $E > E_{eq}$ dissolution reaction (anodic)
- $E < E_{eq}$ deposition reaction (cathodic)[2]

When a current is exchanged between the metal surface and the electrolyte, E shifts from E_{eq}, following the mathematical law shown in equation 1.8. A graphical representation of equation 1.8 is shown in figure 1.1, with a semilogarithmic scale representation.

$$E = E_{eq} \pm f(i) \tag{1.8}$$

Kynetic aspects

The kinetic related problem instead infers to the rate at which reactions take place. When a metal is immersed in an electrolyte, and both cathodic and anodic processes are taking place on the surface, the metal corrodes, provided that $E_{cat} > E_{an}$. The electrons partecipating in the anodic and cathodic

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[1] The concentrations of the metal ions in the solution, $a_{M^{z+}}$, is an unknown paramaeter in those situations where CP is applied, and it is therefore assumed equal to $10^{-6} \frac{mol}{l}$ [7].

[2] The thermodynamic relations mentioned above can show that some metals can remain untouched and uncorroded when left in a specific environment. It is the case of gold and platinum, which can be found as element in nature, because the ΔE has a negative value resulting in the so called *thermodynamic immunity*.

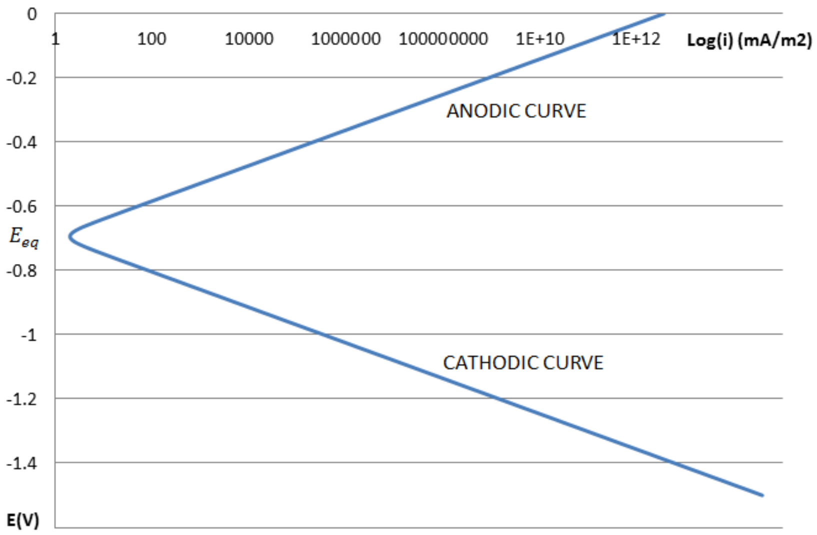

Figure 1.1.: Potential-current logarithm diagram for a metal dissolution-deposition process

reactions must be the same, when no external current source is applied [3], for this reason $i_a = i_c = i_{corr}$ at the free corrosion potential E_{corr}. i_{corr} is the current density exchanged between anodic and cathodic processes and it measures the velocity of the corrosion reaction. To describe corrosion processes Evan introduced potential-current densities diagrams, which show both anodic and cathodic curves, which can be derived from empirical experiments. A potential-current diagram, drawn with a semilogarithm scale, it is shown in figure 1.2. The intersection of the anodic and cathodic curve on Evan's diagram shows the corrosion potential, E_{corr}, and the corrosion current density, i_{corr}. Free corrosion potential, E_{corr}, is the metal potential when both anodic and cathodic reactions are taking place. If the corrosion is thermodynamically possible E_{corr} reaches a value in between the $E_{eq,anodic}$ and $E_{eq,cathodic}$. The mathematical law behind Evan's diagram is used to define the boundary conditions needed in CP computer modelling, as it is stated in section 4.4.

When thermodynamic shows that the anodic corrosion reaction can take place, it does not mean that the reaction rate would suffice to produce any relevant effect. It is the case of active-passive materials such as stainless steel. In a determinate range of potentials the corrosion rate of these metals is so low that it is almost negligible [4]. A corrosion process can be simplified as an electric circuit. This simplification can give a hint to understand which action can be undertaken to stop corrosion. The study of the anodic process leads to the definition of $\Delta E_{anodic\ process}$ as the anodic activation overpotential, which is the driving voltage for the metal dissolution reaction:

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[3] As it is the case of an interference related problem

[4] In the presence of certain species, different forms of corrosion attack like pitting can demage the surface. e.g. the case of austenitic stainless steel in a chlorides rich environment.

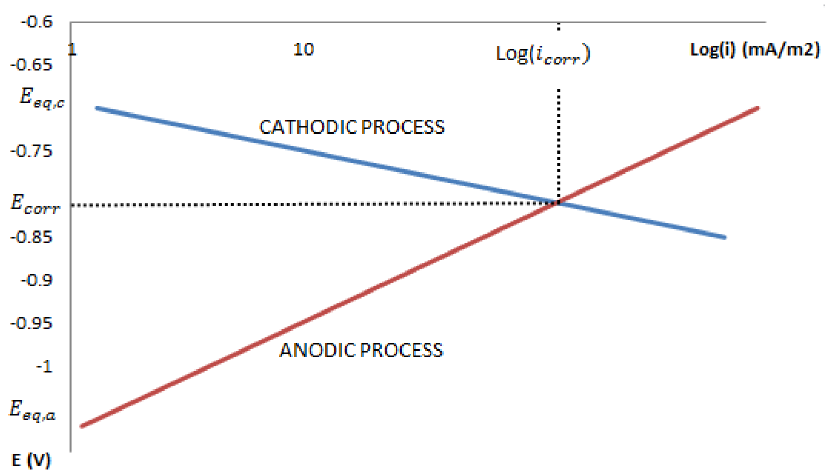

Figure 1.2.: Potential-current logarithm diagram for a typical corrosion process

$$\Delta E_{anodic\ process} = E_{corr} - E_{eq,anodic} \tag{1.9}$$

R_a is defined as the anodic reaction resistance and I the current exchanged. From Ohm's law, it can be consequently stated the following equation:

$$I = \frac{\Delta E_{anodic\ process}}{R_a} \tag{1.10}$$

The higher the R_a, the lower the current exchanged (and consquently the corrosion rate). This is often the case of active-passive materials, where small current densities can change the free corrosion potential significantly.

1.3.2. Cathodic protection

Cathodic protection is the electrochemical technique used to slow, and eventually cease, corrosion processes by means of potential lowering on the metallic surface. It is achieved by circulating a DC current, $i_{external}$, from an external electrode, the anode, to the metallic structure under protection, the cathode. The current can be provided by a galvanic coupling or by an external current generator. A structure can be considered protected when its potential is brought to such a level that corrosion processes can be considered acceptable and consequently i_{corr} is brought to a negligible value. In figure 1.3 and 1.4 it can be seen the effect of the application of $i_{external}$ on metals with different behaviours, active and active-passive. To achieve the potential shift, it is necessary to provide a certain amount of current, referred as the protection current density. Corrosion can be stopped when $i_{external} = i_a$, the structure though can be considered protected when corrosion is brought to a level considered safe, as it might be the case of figure 1.4.

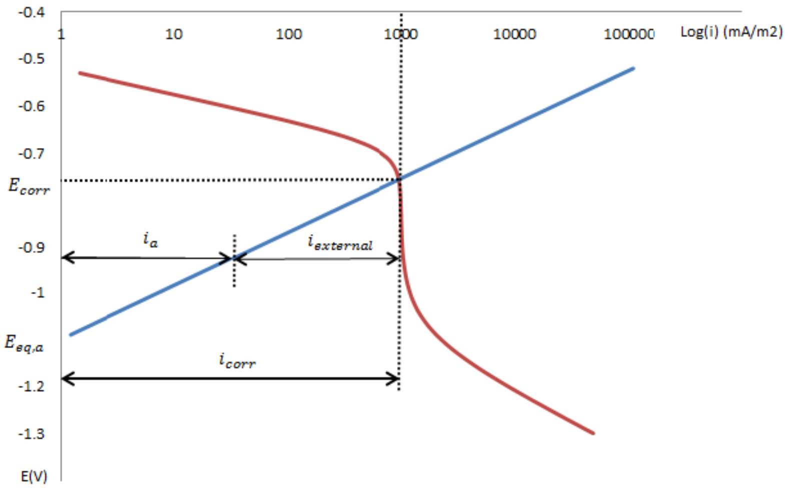

Figure 1.3.: Active material, when an external current is applied

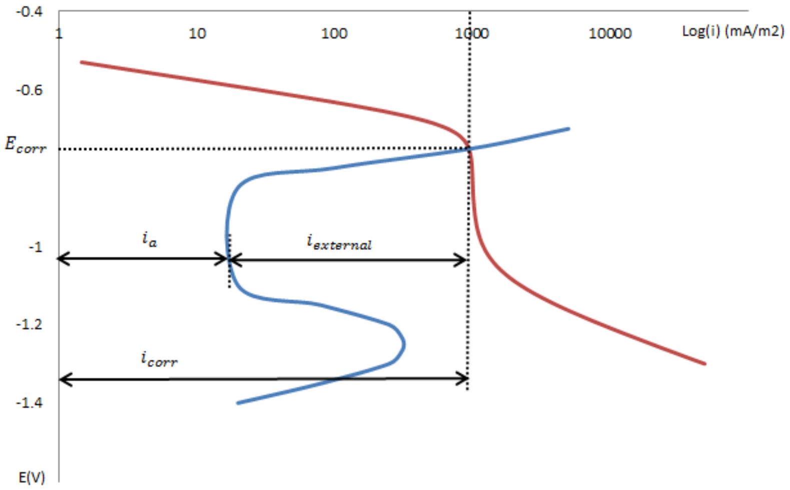

Figure 1.4.: Active-passive material, when an external current is applied

Corrosion can take place in two different forms, localized and generalized, both of them can be stopped by the proper application of CP. Localized corrosion (e.g. pitting and crevice) produces on the surface of the structure a pinpointed attack, due to depassivation of localized spots in which a galvanic cell is initiated. Localized corrosion attack is found on those metals that show active-passive behaviour, stainless steels are the most vulnerable to this type of aggression. General or uniform corrosion attack instead is evenly distributed and spread on the whole surface. Uniform corrosion is typically found on bare carbon steel immersed in seawater.

Engineers during the design phase can take actions to prevent corrosion problems, CP and paintings are methods that can further help avoid structural damages due to corrosion. As a first step, material selection and a careful design aimed at reducing unevenness are the basis that every engineer should keep in mind. The next phase involves the painting strategy and coating expected life, taking into consideration any major workover that is forecasted. Inhibitors can be used for internal surfaces of pipelines and vessels to hinder corrosion. CP design is the last step in the process of corrosion protection and it can be applied both for internal and external surfaces, the only requirement is the presence of a suitable electrolyte.

1.4. Fields of application

Cathodic protection can be applied to protect whichever metallic structure immersed in an electrolyte, such as seawater, soil or brackish water. History showed that the first CP applications were done in systems immersed in highly conductive solutions, such as ships sailing the ocean. Afterwards, cathodic protection moved to less conductive media such as soils. Recently, since the late eighties, cathodic prevention has found a wide use in corrosion protection of reinforced steel concrete structures. The application of CP principles to rebars immersed in concrete brings the pH to such a level that maintains the steel surface in its passive conditions. Eventually cathodic protection can be considered as a polyhedric tool to solve many corrosion related issues.

Onshore

The Onshore sector was the first one to benefit, at a commercial scale, from cathodic protection. The O&G sector has always been the main driver of cathodic protection development. O&G industry first development was done onshore, moving offshore only after the 40's, for this reason the first cathodic protection developments were done onshore. Onshore cathodic protection can be more challenging to design, because it has to deal with an heterogeneous electrolyte, such as a stratified soil. Whichever metallic structure, buried in soil, can be protected with a CP system. CP onshore is always combined with protective coatings. The main categories of onshore structure, which are located under the ground, are pipelines and tank bottoms. Pipelines are structures that can stretch for thousands kilometres, and CP is used to protect the area where coating has been damaged, the so called holidays. Tanks instead are bulky structures used to store liquids, which usually require corrosion protection on their bottom. Because soil has a higher resistivity than sea water, onshore structures are usually protected with impressed current systems. Impressed current inert anodes can provide a much higher potential than galvanic anodes.

Offshore

The O&G industry extensively uses humongous offshore structures to exploit hydrocarbons underneath the ocean. These complex constructions have to withstand safely chlorides-rich (e.g. seawater) thus highly corrosive environment for decades. A solution to corrosion related problems would be to build them with expensive corrosion resistant alloys, but talking of systems that weigh several thousand tons this would not be economical. The most pursued way is the extensive use of carbon steel, a material with poor corrosion resistance characteristics but strong, cheap and worldwide available. The combination of carbon steel and cathodic protection proved to be the most cost effective solution for offshore structures. In recent years many subsea developments in deep water have been built. These structures have complicated geometry, they are built with different metals and the design of CP systems to protect them is a challenging task.

1.5. Galvanic anodes

Galvanic anodes are based on the principle of the electrochemical cell, also known as galvanic or voltaic cell. The coupling of two metals which possess different standard equilibrium potentials, E_{eq}, immersed in a conductive solution, leads to the achievement of an equilibrium potential with a value between the two potentials. A steel structure can be protected when it is electrically coupled with an anode made of a less noble metal, such as aluminum, zinc or magnesium alloys. For offshore structure purposes the most widely used anode materials are aluminum alloys, because they show high electrochemical efficiency.

Galvanic series

Two components made of different metallic materials, electrically coupled and immersed in an electrolyte form a galvanic cell. Following a hierarchy, the less noble material corrodes, protecting cathodically the more noble one. This natural effect can be used to protect materials with poor corrosion resistance. The less noble material is referred as the anode and the surface of the more noble metal is called the cathode.

Corrosion can also be intended as metallurgy in reverse [8], nature brings back the element to their natural state. Metals like lithium and aluminum, which are hardly found pure in nature, have a strong tendency to get back to their origins recombining with other elements. Instead, gold and platinum, and the most noble metals have a tendency to remain in a pure state and to resist unchanged when exposed to corrosive environments. The galvanic series shown in figure A.1 found in appendix A is the classification of the previously mentioned principle. Taken two metals from the list, the upper one would galvanically corrode (e.g. Aluminum alloys), leaving the lower one (e.g. low alloy steel) slowing and eventually ceasing the anodic reactions on its surface.

Anode reactions

The reaction taking place on the galvanic anode is the dissolution of the metal in the electrolyte as free ions. Usually the dissolved ions are further transformed in hydroxides, which precipitate, and a consequent acidification is produced on the surface. The acidification is beneficial, because it counteracts the natural properties of some alloys to passivate. As an example a pure aluminum anode[5] shows the following dissolution reaction with consequent hydrolysis:

$$Al \rightarrow Al^{3+} + 3e^{-} \quad \Longrightarrow \quad Al^{3+} + 3H_2O \rightarrow Al(OH)_3 + 3H^{+} \tag{1.11}$$

Electrochemical Capacity

Electrochemical capacity is the energy density stored in the anode material. It is the energy that can be used to accomplish electrochemical reactions and can be calculated, theoretically, with Faraday's relation. It is usually expressed as energy per unit of mass, and most commonly $\frac{Ah}{kg}$. It is strictly material dependent but environmental conditions such as temperature can also influence this parameter. For this reason, practical electrochemical capacity is always lower than the theoretical one, and an efficiency can be defined, usually ranging between 95% to 50%. Aluminum is the material with the highest capacity among metals commonly used to make anodes, and for this reason aluminum alloys are the elected materials for offshore applications where weight-saving is a paramount factor.

1.6. Impressed current

Impressed current cathodic protection, ICCP, is the alternative to galvanic anodes cathodic protection. It consists in an electric power source with the positive pole connected to the anode, which can be active or inert. It is mainly used to protect ships and onshore pipelines, very rarely to protect oil platform jacket structures. This distrust in the oil and gas offshore industry against ICCP is due to failures, occurred in the past, and to the intrinsic greater reliability of galvanic anodes systems. Many failures in ICCP systems were due to undersized anode support structures.

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[5] Practically, because of aluminum passivation properties, such anodes are never made of the pure metal but they are always used in alloys such as Al-Zn-In ternary alloy

Anodes used for ICCP can be of the active or inert type, in section 3.5 a longer description of ICCP anode materials can be found. In onshore applications anodes are placed inside a grounbed, instead offshore the anode surface is placed directly in contact with the electrolyte (seawater). A groundbed is used to decrease anode resistance in soils with high resistivity, a more articulate description about groundbeds can be found in section 3.4.

The reactions produced on the anode surfaces depend on the environment in which the anode is immersed. ICCP systems using iron anodes, though seldom employed nowadays, show a dissolution reactions very much similar to galvanic anodes with iron dissolving in the water in its ionic form. Instead, inert anodes reactions consist usually in oxygen and chlorine evolution:

- $H_2O \rightarrow O_2 + 4H^+ + 4e^-$
- $2Cl^- \rightarrow Cl_2 + 2e^-$ when chlorides are present, such as in seawater application

As it was previously stated for galvanic anodes, the solution surrounding the anodes is acidified as a consequence of anodic reactions. The acidification leads to a more aggressive environment surrounding the anodes, which can cause serious concerns to the anodes integrity. In onshore application a vent has to be placed in the groundbed to dissipate the noxious gases produced.

1.7. Energy efficiency

The steel industry is the largest energy user in the world, steel production is an energy intensive activity. Energy is spent to bring iron to an artificial state much different from its natural form. Energy accounts for 20 percent of the total cost to produce steel. Approximately 5000 kWh are needed to produce one tonne of steel [9]. When steel strucures are left unprotected to the mercy of a natural environment, the whole energy stored in the metal is lost. Cathodic protection is the most energy effective way to avoid this energy loss, giving the opportunity to recycle almost the whole amount of steel used during construction. Offshore oil platforms are usually made of carbon steel, with the section underneath the water line, the jacket, protected via CP. As an example to produce a 2000 tonne jacket structure approximately 10 GWh are used. Most of this energy can be re-used when the structure is brought to the end of its life and decomissioned. ICCP systems are usually more energy efficient than galvanic anodes.

2. Empirical design - offshore structures

> There's no such thing as bad weather, only unsuitable equipment.
>
> Sir Robert Baden Powell

Due to the many failures of early applications of cathodic protection it was understood the importance of proper CP design criteria. The very first CP practical use done by Davy was a failure itself, and many problems also aroused when applying to new environments commonly used CP design practices. The first oil platforms launched in the North Sea had a CP system based on the experience acquired in the gulf of Mexico, without taking into account the harsher conditions that can be found at a such northern latitude. Cold water and rough seas, leading to poor calcareous deposits and high oxygen concentration, brought CP systems to premature failures, with severe economical consequences. Industry, collecting data from field experiences, introduced guidelines, standards and recommended practices to help engineers to design safe CP setups. Different companies can have different standards based on their own experiences and feedbacks from past enterprises.

It might appear to outsiders that since the fluid, seawater, in which the structure is immersed is the same all around the world, identical CP designs can be applied everywhere without distinctions. In practice, many different parameters influence the specifications that need to be taken into consideration to plan a safe CP system.

Engineers need tools to perform reliable, safe and consistent CP design, for this reason a computer software was created to implement and guide technicians through the process of CP system design. A first version of the software was created in Tecnomare two years ago, part of the work of this thesis consisted in a further development of this software, testing its reliability and performing trouble shooting on the problems which aroused.

2.1. Rules and Standards regarding offshore CP system design

Nowadays most of CP design is based upon technical documents set by classification societies and company standards. The three main international classification societies which emit standards and recommended practices regarding CP are NACE, DNV and ISO. In Europe CP design is also regulated by CEN and in Italy UNI define Standards concerning offshore structures CP systems. Often oil companies, such as eni, set their own standards which are usually based upon documents emitted by classification societies and their own experiences. Usually company standards tend to be more conservative than International Rules. The most important Rules and Standards regarding Offshore CP systems are:

- DNV RP-B401 Recommended Practice Cathodic Protection Design [10].
- EN 12954 Cathodic Protection of Buried or Immersed Metallic Structures, Principles and Applications for Pipelines [11].
- NACE SP0176-2007, Corrosion Control of Submerged Areas of Permanently Installed Steel Offshore Structures Associated With Petroleum Production [12].
- ENI 27589.VAR.COR.PRG, Linee Guida per la Progettazione e l′Attuazione di Sistemi di Protezione Catodica, in italian [13].

The standards listed above are the results of the work carried out by technical committees and working groups of expert, set by classification societies to produce CP design. The resulting documents are published after a long process, which is driven by the necessity to conform the different practices present in the industry.

2.2. Main parameters involved

To design a reliable CP system many site related parameters have to be taken into account. These parameters influence greatly the electrochemical reactions, primarily oxygen reduction, taking place on the surface of the structure. Most of the parameters listed below are interrelated with each other, leading to a difficult modeling approach.

2.2.1. Geographical location

Geographical location is the main parameter that has to be taken into account, it gives a first sight about the environment which the CP system have to withstand. The knowledge acquired during the exertion of nearby existing structures is a treasure to seek. When designing a CP system, the experience of close-by structures is the best solution to minimize engineering flaws. Most often the individual parameters influencing CP are not measured directly on site but taken from a region related database.

2.2.2. Calcareous deposits

Calcareous deposits accumulate on the structure when CP is applied. The formation of scale on the cathodic surface is beneficial, it decreases the oxygen diffusion and the amount of oxygen reaching the steel surface is also decreased, as a result the current requirements are lowered. The application of CP on a structure sparks a pH increase on the cathodic surface, which veers the carbonate-bicarbonate equilibrium towards the precipitation of a scale deposit. Because of the many affecting variables, the prediction of calcareous deposits formation is probably the most influencing and yet unknown parameter in cathodic protection design. The main reactions taking place under cathodic protection conditions are listed here below.

- Oxidation of iron, it is inhibited after CP is applied and a potential below free corrosion potential is achieved

$$Fe \quad \rightarrow \quad Fe^{2+} + 2e^- \tag{2.1}$$

- Oxygen reduction, it is usually the main cathodic reaction taking place on the surface when polarization is achieved

$$O_2 + 2H_2O + 4e^- \quad \rightarrow \quad 4OH^- \tag{2.2}$$

- Hydrogen evolution, it is the dominant reaction when the surface is brought to low potential level. Hydrogen formation is a major concern, when CP is applied and overprotection is reached on high strength steel structures causing hydrogen embrittlement [14]

$$2H_2O + 2e^- \quad \rightarrow \quad H_2 + 2OH^- \tag{2.3}$$

- $Mg(OH)_2$ precipitation, it is a reaction that occurs mainly at high pH level

$$Mg^{2+} + 2OH^- \quad \rightarrow \quad Mg(OH)_2\downarrow \tag{2.4}$$

- Carbonate/bicarbonate equilibrium, it is changed by the pH increase at the structure surface, pushing the reaction towards the product

$$OH^- + HCO_3^- \quad \rightarrow \quad H_2O + CO_3^{2-} \tag{2.5}$$

- Calcium carbonate precipitation, it is the final reaction causing scale deposition

$$Ca^{2+} + CO_3^{2-} \quad \rightarrow \quad CaCO_3\downarrow \tag{2.6}$$

Many studies were carried out to determine the conditions necessary for the formation and composition of calcareous deposits. Different numerical models can be found in literature to determine the most influencing parameters, based on thermodynamics and kinetics expression [15]. The most impacting factors that determine the quality of scale deposits are applied potential, temperature and seawater velocity. The lower the potential the faster the deposition rate of calcareous deposits, and as a consequence a higher $Mg(OH)_2$ concentration can be found in the scale. As the temperature approaches zero, calcareous deposits are increasingly hard to form, leading to high current density to polarize the structure. High flow velocity at the interface cathode-electrolyte inhibit scale formation, due to the increased mass transfer that leads to a lower concentration on the surface of the products formed during the reactions.

2.2.3. Temperature

Temperature influences the current required to polarize a structure with a lower incidence than flow velocity and turbolence. The effect of temperature is diversified since it impacts reaction kinetics, oxygen concentration and scaling tendency. Electrochemical reactions follow a faster kinetic as temperature increases, due to the fact that a greater number of molecules possess a sufficient energy to react. Oxygen diffusion is enhanced by high temperatures, conversely oxygen solubility follows an opposite trend. In warmer seas calcareous deposits are more protective and form more quickly than in colder water. Living organisms are also influenced by water temperature and are temperature related in the same manner as the calcareous deposits. As a rule of thumb it can be stated that cold water leads to higher current requirements than warm water. An extreme example is the Ormen Lange subsea development, out of the coast of Norway, where water temperature reaches value below zero and its CP system design posed some major challenges.

2.2.4. Storms and sea currents

Storms can damage the calcareous deposits that have formed on the surface to protect. Also, rough and stormy circumstances can lead to oxygen supersaturating conditions, which increase the current requirements due to higher cathodic reaction rates. Due to mass transfer, a higher water flow around the structure can decrease the pH in the proximity of the cathodic surface. With a pH lower than 10 the calcareous deposits cannot form and a higher protection current density is required. For the same reason, sea currents also prevent calcareous deposition.

2.2.5. Depth

Depth is linearly related to pressure, though this is not per se a very influencing parameter. Pressure influences the equilibrium constants of some of the reactions taking part in the carbon dioxide-carbonate scheme but the resulting pH is also function of the dissolved carbon dioxide which is exchanged in the upper surface layers. The overall result is a pH lowering as function of depth which implies a less favorable calcareous deposition. Many studies have demonstrated the relation between depth and calcareous composition. Greater depth leads to a higher concentration of Magnesium hydroxide in the scale, much less protective than Calcium carbonate. Water depth has a very high impact when taking into consideration variations in: temperature, chemical species concentration and current velocity. Because nowadays many new developments are done subsea in deep water, the depth factor is an increasingly important parameter in CP design.

2.2.6. Salinity

Salinity is the main parameter influencing electrolyte (sea-water) resistivity. Salinity is the concentration of dissolved salts in seawater. Calcium and magnesium concentration are also directly related to salinity, because the proportion of elements in the water is almost constant all across the oceans. Therefore salinity is not really a variable when talking about offshore structures in the open sea. Only for few exceptions like structures in fjords, adjacent to river estuaries or in enclosed lagoons, salinity is an influencing paramater that has to be taken into account.

2.2.7. Fouling

Fouling, acting as a diffusion barrier, can be beneficial, lowering the oxygen flux reaching the surface of the structure. In the meantime this oxygen concentration lowering on the cathodic surface can bring ideal conditions for the proliferation of anaerobic bacteria colonies, enhancing corrosion risks. Also dead macro-organisms on the steel surface can leave part of the surface bare. Bare spots of metals can also be favorable places for differential aeration corrosion. Fouling is a major concern for those structures which have to sail across the seas, because of severe drag issues. Anti fouling paint can be applied with an effect which is limited to very few years.

2.2.8. Mud

Most of the offshore structures are laid upon mud. Offshore pipelines are often buried in mud or trenched, and offshore platforms foundations have long poles inserted in mud, in order to give stability. Well conductors too are immersed in mud. Cathodic surfaces laying underneath the mud-line require less current density to reach full protection due to lower oxygen concentration in the mud. As mentioned above for fouling, anoxic conditions can cause problems related to microbiologic induced corrosion. For this reason surfaces buried in mud require lower protection potentials than structures immersed in seawater.

Due to the higher resistivity of mud, compared to the one of water, anodes buried in mud are less efficient and possess a lower throwing power compared to the ones exposed to sea water. Anode capacity decreases when anodes are surrounded by mud, due to the fact that their corrosion products cannot diffuse easily, changing the thermodynamic characteristics of the metal dissolution reactions.

2.3. Protection potential

Depending on the material and the environment under study, different protection potentials need to be achieved. Protection potential is the potential at which the structure has to be brought to slow corrosion processes to an accettable level. Overprotection conditions, with potentials well under the necessary protection potential, enables a faster formation of scale deposits on the surface. The main drawback of overprotection is hydrogen formation on the surface, consequently rising an inherent danger of hydrogen embrittlement. The electric potential is directly related with the exchanged current density.

Galvanic anodes usually create calcareous deposits more quickly than ICCP systems because the potential distribution on the surface is generally less uniform, higher current densities can be usually delivered in specific area. The surfaces directly facing the anodes are immediatly brought to low potentials and a calcareous layer is rapidly formed, the current required to keep protected these surfaces decreases sharply. Consequently, higher current densities can be delivered to neighbouring surfaces and the scale deposits is formed gradually on the cathodic surface. ICCP systems instead produce a more uniform current density distribution, and possibly the calcareous deposits are formed more slowly than with a galvanic CP system.

2.4. Protection current required

The current required to protect the structure depends on the cathodic processes taking place at the protection potential, which are influenced by the many variables listed above, though in the standards and best practices regarding offshore structure CP only the most significant parameters are taken into consideration. The most influencing parameters taken into consideration to calculate current density are geographical location and temperature, both of them are directly related to calcareous deposit formation. The protection current required is also strongly dependent on the type of coating and coating breakdown which is function of the design life. The current required to polarize the structure changes with time and this change has to be predicted.

2.5. CP system dimensioning Jacket

Jackets are steel lattice structures, they are built to support all the equipments necessary to process the reservoir fluids and sometimes the drilling equipment. Jackets are usually designed with a minimum design life of twenty years, consequently their CP system is usually concepted to be able to provide protection for a longer period (usually five years longer than the structure design life). Even though the oil and gas industry is following a trend that is moving away from jacket structures, towards FPSOs and subsea development, a great number of jackets are still built and an even greater number was built in the past and they require now retrofitting.

To provide the correct CP system is not an easy task, the decision made in the design stage have a great impact on the overall life profitability and safety of the project. A mass of anodes greater than needed poses greater stress on the structure, longer time to build the jacket and larger barges and cranes to launch it. When the CP system is highly over-dimensioned more problems arise during the decomissioning phase, when the structure needs to be removed, again larger machineries are needed to dismiss the structure. Though, an underdimensioned CP system can lead to dangerous structural failure due to underprotection conditions, such as corrosion fatigue. When underprotection conditions are detected a very costly CP retrofitting is required. The problems are not only limited to the design phase, but also the anodes casting stage and the welding at the building site have to be done following procedures and standards. Many failure in the industry were due to poorly managed production practices, a clear example is shown in figure 2.1.

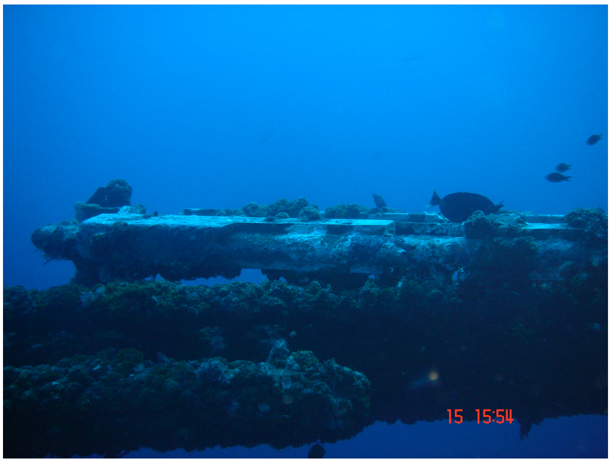

Figure 2.1.: Damaged anode, loss of active material.

On average a first rough estimation of the anodes weight needed to protect a jacket can be evaluated as a fraction of the structure weight. From previous experience of offshore CP design undertaken by Tecnomare SPA, following rules and standards, it was estimated that the anodes weight is usually in the range of 7-10% of the total structure weight. A low anodes weight is needed for structures placed in warm seas with short design life, whereas higher anodes weight is needed for structures placed in cold seas with long design life. Usually it can be stated that the galvanic anodes CP system placed to protect a structure, following recomended practices, is highly overdimensioned.

2.6. Wind Turbine Platform

The offshore wind industry has benefited a lot from the experience acquired by the O&G activities in the past few decades. Wind turbine platforms are placed in the same hostile environment where structures serving the O&G business are located. The offshore wind industry is moving from shallow water to deep water with semisubmersible platforms, following a path already taken by the petroleum industry. The same CP systems approaches used for exploration and production jacket structures can be used to design CP systems for wind turbine platforms. Corrosion control techniques have to take into account a longer design life[1], giving the opportunity to experiment ICCP systems and coated surfaces. Tests are nowadays carried out to study the best coating modus operandi to apply, a recent example is the WindFloat Structure shown in figure 2.2 [16]. In a near future large fixed offshore structures will probabily be commissioned more for the wind industry rather than for the O&G business.

Figure 2.2.: WindFloat semisubmersible structure and 2MW wind turbine.

2.7. Software

A software was implemented to provide galvanic anodes CP dimensioning for jacket structures. The software was developed in Microsoft Excel VBA in order to run on all computers in Tecnomare SPA. It was also conceived to be user friendly, in order to guide newcomers in CP design to easily undertake CP systems dimensioning. Help buttons were placed to aid users in the design process. The main drivers that pushed towards the idea of making a software were time saving in the design phase and producing a standardized output for different projects.

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[1] An offshore wind structure doesn't have any constraint regarding hydrocarbons time of production from a reservoir.

VBA

The computer program used to create the software was Visual Basic for Application,VBA, a software implementation inserted in the office package. VBA is a high-level programming language, meaning that the user has to deal with a language that is more similar to human's logic than machine code. VBA is a programing language remarkably easy to learn from every day computer users. VBA is not made to work as a stand alone software but it requires another program, for this work Microsoft Excel was used. Excel work sheets can be used as a database to store input and output data. VBA allows engineers to create a GUI, Graphical User Interface, producing a user friendly software. VBA can also communicate with a Microsoft word document to create reports. The automatic creation of a report, even though it is a long task to implement via VBA, is a very usefull tool in a company such as Tecnomare SPA where the commodities produced are electronic documents.

The Algorithm

The algorithm follows the design procedures and standards listed in the beginning of the chapter. The algorithm is translated into a software, which is a list of procedures that the computer executes, processing a given input to return an output. In figure B.1 found in appendix B is shown the flow chart of the software.

The main input parameters that the user has to insert to produce the output are:

- **Structure and environment**
    - Surface requiring protection for each different trunk $[m^2]$
    - Polarization, average and repolarization current density, related to geographical location $\left[\frac{mA}{m^2}\right]$
    - Design life $[years]$
    - Sea water resistivity $[\Omega m]$
- **Anode**
    - Anode resistance, function of geometry and sea water resistivity $[\Omega]$
    - Anode net weight $[kg]$
    - Electrochemical capacity $\left[\frac{Ah}{kg}\right]$
    - Available driving voltage $[V]$

The input parameters are checked, to make sure that they are included in a specified range. The ouput from the program consists of:

- dimensions and mass of the anode after optimization
- number of anodes to be installed

- anode distributions per each trunk

The software can produce a Microsoft Word report with all the input and output data. The last step for CP design is to decide the specific positioning of each single anode in the required zone (this task couldn't be implemented automatically in a software).

Hypothesis

Some hypothesis are made, dictated by norms and recommended practices:

- For corrosion protection of structural elements located within the splash zone, 6 mm of corrosion allowance and a protective coating are foreseen;
- Risers are not considered part of the CP system because they are electrically isolated from the jacket;
- All surfaces in contact with sea mud have to be cathodically protected with galvanic anodes installed in the lower part of the jacket and in contact with sea water;
- The design of cathodic protection system shall be based on aluminum-zinc-indium alloy galvanic anodes, which proved the best properties in sea water environment;
- Long-slender stand-off type anodes have to be used to guarantee Cathodic protection of external surfaces of steel jacket and relevant related appurtenances;
- To assess the local protection current demand, the structure is divided into different trunks, which are depth related;
- Each trunk includes the vertical and oblique structural elements between the relevant elevations and, if any, the horizontal elements in the lower plan of the trunk;
- The external surface area of the buried part of piles has been included in the calculations only to 30 m depth below the seabottm, because it is assumed that the oxygen concentration near the piling, below the mud line, is normally low and, therefore the corrosion rate is negligible;
- To account for minor metal surfaces not explicitly considered, safety factors have been adopted for each surface;
- During the life of the structure the protection current density changes, this is due to calcareous deposit formation which causes a decrease in current demand. Accordingly, in the design of the CP system, the following protection current densities are used:
  - Initial: it is the current density required to achieve the initial structure polarization and to start forming the calcareous deposit;
  - Maintenance: it is the current density required to maintain the structure polarization;

  - Repolarization: it is the current density required to regain structure polarization conditions after severe storms or cleaning operations.

- As specified in eni Company Standard 27604-VAR-COR-SPC [13], all splash zone steel surfaces shall be coated. The coating breakdown criterion is used to quantify the deterioration of coating efficiency during the life of the structure. The coating efficiency is defined as the ratio between the current density required to protect a coated surface, in presence of coating defects, and the current density to protect the same surface when uncoated.

Procedure

The total number of galvanic anodes required is determined with the following procedure:

1. Calculation of Surface to be protected
2. Calculation of the total current demand to protect each zone, exposed to sea water and mud, based on the corresponding values of the protection current density[2]. The total protection current required is determined by means of the following formula:

$$I = F_{sw} i_{sw} (S_{b,sw} + S_c C_b) + F_m S_{b,m} i_m + N_w I_w \tag{2.7}$$

   - I: protection current $[A]$;
   - F_{sw}: safety factor for surfaces exposed to sea water;
   - F_m: safety factor for surfaces exposed to sea mud;
   - $S_{b,sw}$: total uncoated surface area to be protected exposed to sea water $\left[m^2\right]$;
   - S_c: total coated surface area to be protected exposed to sea water $\left[m^2\right]$;
   - $S_{b,m}$: total uncoated surface area to be protected exposed to sea mud $\left[m^2\right]$;
   - C_b: coating breakdown [%];
   - i_{sw}: required current density to protect surfaces exposed to sea water $\left[\frac{A}{m^2}\right]$;
   - i_m: required current density to protect surfaces exposed to sea mud $\left[\frac{A}{m^2}\right]$;
   - N_w : number of wells;
   - I_w : current demand per well $[A]$;.

3. Calculation of initial and final anode resistance R_a, using the Dwight's formula for slender anodes,

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[2] The mud mats and the piles surfaces exposed to the sea mud are protected by anodes exposed to seawater and located on the lower part of the steel jacket; the splash zone is protected by anodes located on the uncoated steel jacket.

based on sea water resistivity and anodes dimensions. The anode resistance, (R_a), for slender stand-off type anodes, is given by the following formulae:

- $\frac{L}{r} \geq 4$

$$R_a = \frac{\rho}{2\pi L}\left[ln\left(\frac{4L}{r}\right) - 1\right] \tag{2.8}$$

- $\frac{L}{r} \leq 4$

$$R_a = \frac{\rho}{2\pi L}\left\{ln\left(\frac{2L}{r}\right)\left[1+\sqrt{1+\left(\frac{r}{2L}\right)^2}\right]\right\} + \left(\frac{r}{2L}\right) - \sqrt{1+\left(\frac{r}{2L}\right)^2} \tag{2.9}$$

- ρ: seawater resistivity $[\Omega m]$
- L: anode length $[m]$
- r: anode equivalent radius $[m]$

4. Calculation of anode current output, in the initial and final phase. The current output of each anode is determined by the ratio between the driving voltage[3] ΔE and the anode resistance R_a.

$$I_a = \frac{\Delta E}{R_a} \tag{2.10}$$

5. Calculation of required number of anodes for each section, from initial and final anode current output viewpoint.

$$N_{a,i} = \frac{I_i}{I_a} \quad ; \quad N_{a,r} = \frac{I_r}{I_a} \tag{2.11}$$

- $N_{a,i}$: number of anodes required to polarize the structure
- $N_{a,r}$: number of anodes required to repolarize the structure
- I_i: polarization protection current $[A]$
- I_r: repolarization protection current $[A]$
- I_a: current provided by a single anode $\left[\frac{A}{anode}\right]$

6. Calculation of required number of anodes for each section, from a mass demand point of view, to maintain polarization on the structure surface.

$$N_{a,m} = \frac{I_m \, t \, 8760}{u \, \epsilon \, M_a} \tag{2.12}$$

- $N_{a,m}$: number of anodes required to mantain polarized the structure
- u: anode utilization factor, it is the ratio between the volume of the anode which is used to protect the structure, "lost" during the design life, and the volume at the initial stage.

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[3] $\Delta E = E_{prot} - E_a$, typical values of ΔE for carbon steel are $0.25V$ for surfaces immersed in sea water and $0.15V$ for structures buried in mud.

- ϵ: anode capacity $\left[\frac{Ah}{kg}\right]$
- I_m: maintenance protection current $[A]$
- t: design life $[years]$
- M_a: single anode mass $[kg]$

7. Determination of required number of anodes for each section, maximum between calculated anodes number based on current demand and mass demand

$$N_a = \max\left(N_{a,i}; N_{a,m}; N_{a,r}\right) \tag{2.13}$$

8. Anode optimization based on: protection current demand, durability, anode distribution requirements. An optimization process is performed changing the anodes geometrical dimensions.
9. Distribution of the anodes on the steel jacket to provide current distribution and achieve uniform protection. Galvanic anodes installation shall be performed in accordance with the requirements in Section 9 of the reference Recommended Practice DNV-RP-B401 [10]. Anodes shall be welded via steel insert to jacket. The anodes requested for cathodic protection of the splash zone shall be located below the lower limit of the splash zone. The anodes requested for cathodic protection of the mud zone shall be located in the lower part of the steel jacket and in contact with sea water. The anode positions are usually reported in relevant drawings.

Optimization process

An additional tool to perform an automatic geometrical optimization of the anode dimensions was created. It was noticed that during the process of CP design, in previous project undertaken by Tecnomare SPA, a manual optimization was always done. In the previous designs, after the creation of the Excel file, different anode geometries were tried to check the best solution. The optimization was always carried out using commercial size anodes. Because the optimization was done manually only few solutions were tried, usually not more than 20 different geometries were processed. It was felt the need to create a tool that could process many more different geometrical solutions automatically.

Anode geometry influences mainly two output parameters, total gross weight and number of anodes. The cost of the galvanic anode CP system is directly influenced by the above mentioned parameters. The number of anodes influences the costs of welding, while the total gross weight influences the material costs supply. Other important parameters are directly influenced to total gross weight, such as structure bearing capacity and launching machinery dimensions, but they were not taken into account in the optimization algorithm.

Beside the normal input parameters needed to design a CP system for a jacket, welding cost per anode and cost per kilogram of anode are needed to perform the optimization process. These two values were found in literature [17], but they were also confirmed by the data about CP design costs of a steel jacket recently designed by Tecnomare SPA and built in northern Africa. Welding is a labour intensive process, for this reason the cost of welding per anode is strongly influenced by the geographical location where the jacket is built. Conversely, the material cost of an anode is only slightly related to the construction site location.

Table 2.1.: Anode welding and material costs

Parameter	**Cost**
Anode welding $\left[\frac{USD}{anode}\right]$	500-714
Anode material $\left[\frac{USD}{kg}\right]$	4

Optimization algorithm

The algorithm followed to perform the optimization process was also implemented in VBA. The automatic optimization process undertakes the same procedure that a CP designer would perform, keeping track of the results obtained in an Excel sheet. While the program is processing a loading bar was created to inform the user about the iteration progress. The algorithm procedure can be summarized as follow:

1. All the data needed to perform CP anode dimensioning are stored in an excel sheet (e.g. protection current density, surfaces). They were previously inserted by the user in other userforms.
2. The userform, via textboxes, requires to the user to insert the cost regarding the welding of the anodes and the cost of anodic material.
3. By clicking a button the user can start the iteration program.
4. Automatically the program enters different loops in which the anode geometrical dimensions are changed, and for each dimension it is calculated the number of anodes to protect the structure and the total gross weight of the anode system, these data are stored in an Excel sheet. At each iteration step the anode dimensions are changed, the support dimensions are calculated following a trend evaluated from commercial size anodes.
5. Once all the different geometrical solutions have been studied the program exits the loops and it calculates the best solution under a cost, weight and number of anodes installed point of view.

6. The results regarding the optimized solution are shown to the user.
7. The user can decide to utilize one of the optimized anode geometrical solution to protect the structure[4].

Optimization results

The output from the optimization process showed interesting results and trends. During the testing phase of the software, it was estimated that a considerable amount of money (approximatly 10% of the overall costs) can be saved if the automatically optimized anode dimensions are chosen instead of the manually optimized ones. It has to be said that the savings are very much dependent from the input paramaters: welding and material costs. The overall costs, for a typical jacket structure CP system, range between 300 kUSD and 1MUSD, the result is that an optimized anode geometry can provide savings in the 10kUSD order of magnitude. An interesting trend can be seen in figure 2.3, where it is shown the graph with the output cost-number of anodes-total gross weight for a typical jacket structure. Each point on the graph represents a precise geometrical set (anode length and cross section). From a cost point of view, it can be noted that keeping constant the anode length and changing the cross section dimensions a minimum is reached. It can be said the same when the cross section is kept constant and the length is kept as a variable, it is also visible a parabolic trend with a minimum.

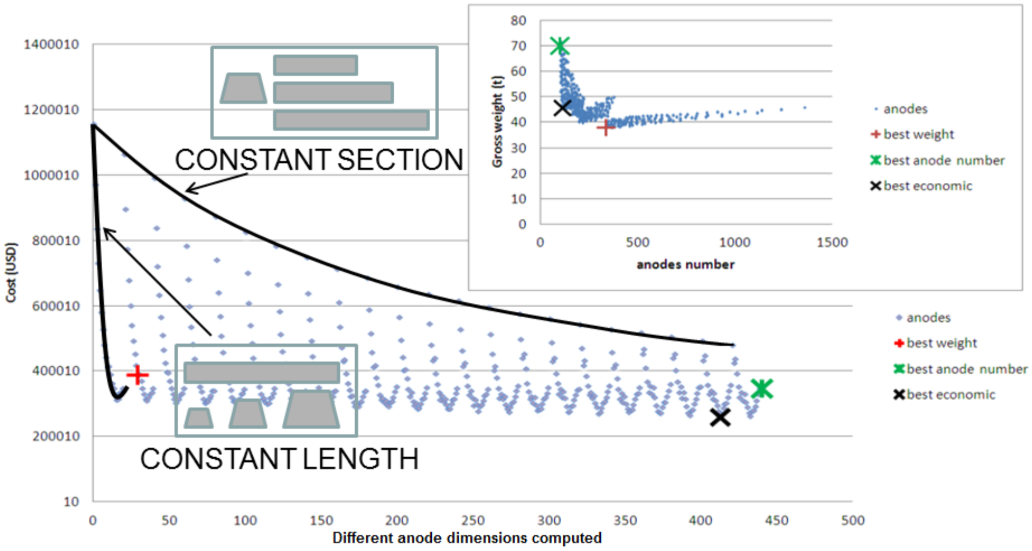

Figure 2.3.: Optimization process output of a typical structure, cost trend.

Three important anodes geometry dimensions are highlited in figure 2.3, representing:

- best weight: solution with the lowest total gross weight;

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[4] Most often the user checks on a catalogue the commercial anode dimensions more similar to the optimized solution.

- best anode number: solution with the lowest number of anodes installed;
- best economic: solution with the lowest installation costs.

As it was previously said a trade off exists between minimization of total gross weight and number of anodes minimization. A plot representing the number of anodes required to protect the structure and the total gross weight for each calculated solution is shown in figure 2.4. On the right side of the graph the solutions with smaller anodes are plotted, which necessitate a high number of anodes to protect the structure (more than 500 anodes). It can be clearly seen a linear relation between anodes number and gross weight in this region of the plot. This is because the constraint is the required anode mass to maintain the structure polarized, as it is given in equation 2.12. The slight increase in weight with increasing anodes number is due to the higher ratio $\frac{gross\ anode\ mass}{net\ anode\ mass}$. On the left side the solutions with bigger anodes are plotted. It can be seen that at a certain point, where the red line is drawn, the relation number of anodes-total gross weight changes from linear to more than linear until it becomes almost asynthotic. This sharp change is due to the different constraint which changes from anode mass based to resistance based. On the left side of the red line the minimum number of anodes is determined by the relation given in equation 2.11. A structure with a CP system designed with the anode dimensions that can be found on the left side of the plot will have more anodic mass than necessary, resulting in a design life longer than strictly required.

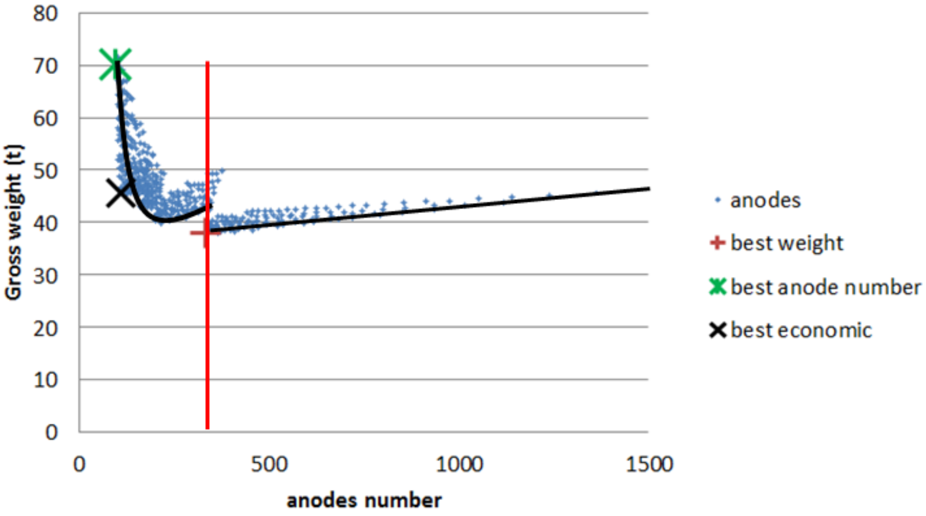

Figure 2.4.: Optimization process output of a typical structure, number of anodes vs gross weight.

2.8. CP system dimensioning of offshore pipelines

Offshore pipelines are steel coated pipes laid on the sea bottom, which are used to convey fluids which need to be transported from one point to another. They pose great challenges because of the harsh and scattered environment in which they are placed, and for the very high costs in the case of leakages or damages. In the North sea, where the oil and gas industry has been working for a few decades, the offshore pipeline transport system consists of more than 8000km of pipes and the problem of their corrosion protection is very much alive. A new section regarding offshore pipeline CP system dimensioning was added to the CP software for offshore structures developed in Tecnomare SPA.

2.8.1. Bracelet anode

Long pipelines are usually protected by means of coating and CP. CP is achieved by the use of bracelet anodes, which can be squared when the pipeline is coated with concrete[5] or tapered when the structure is coated by a different mean. The purpose of the software is to evaluate the anode spacing required to protect the pipeline, given environment, pipeline and anode characteristics. The software was conceived to respect the following requirement [18]:

> *"Pipelines may be divided into sections, e.g. where changes in depth, operating temperature or burial conditions can give rise to variations in design current density."*
>
> *ISO 15589-2 Annex A*

The pipeline under study can be subdivided in different sections with different characteristics and studied via a single software run. The algorithm behind CP dimensioning is similar to the one previously explained for jacket offshore structure. A brief explanation about the algorithm is given in figure B.3 in Appendix B and the software userforms are shown in figure B.4, which can also be found in appendix B.

The main peculiarities about the software are:

- Anodes made with Zinc or Aluminum alloys can be exerted;
- Electrochemical capacity of galvanic anodes is evaluated as function of anode temperature from table 4 of ISO standard number 15589-2 CP [18];
- Seawater resistivity is calculated as function of temperature and salinity;
- The algorithm takes into account the possibilities of "buried under mud" conditions, if there is any chance that the anode would get under the mud, mud resistivity is used to calculate anode resistance;
- Protection current density is defined as function of temperature. If the possibility of coating damage is very much alike, current requirement is calculated using the upper curve (more conservative) of

---

[5] concrete coating is used to ballast the pipeline

figure 2 ISO 15589-2 CP [18], otherwise the lower (less conservative) curve is used;

- Protection current is calculated as the weighted average of: current required to protect pipeline surface buried under mud and current to protect surface immersed in sea water;
- Anode spacing is calculated as multiple of the pipe joint length;
- Maximum spacing between anodes is 300m as specified in ENI 27589.VAR.COR.PRG [13]. Therefore, there was no valuable attenuation with galvanic anodes and there was no need to evaluate potential attenuation along the pipeline.

2.8.2. Pod anode

CP retrofitting on pipelines can be done via anode sistems arranged in “Pods”. Pods are made of Aluminum alloys anodes sustained by a steel frame, the structure is usually ballasted with concrete. The pod is lowered on the seafloor and electrically connected with a clamp to the structure[6]. In figure 2.5 it is shown a typical pod employed in a retrofitting work. The great advantage of this system is its installation easiness, the time required to set the pod in place is lower than other retrofitting systems. The installation can be done using divers or ROVs, making possible deep as well as shallow water retrofitting works [19]. The purpose of the implemented software is to design the required pod dimensions and number (in the case the structure requires a high protection current more than one pod can be installed). It was also implemented a specific tool to estimate potential attenuation along the pipeline by means of the Finite Difference Method. In figure B.6, found in appendix B, they are shown the software userforms created to guide the users in the input data process and results desplaying.

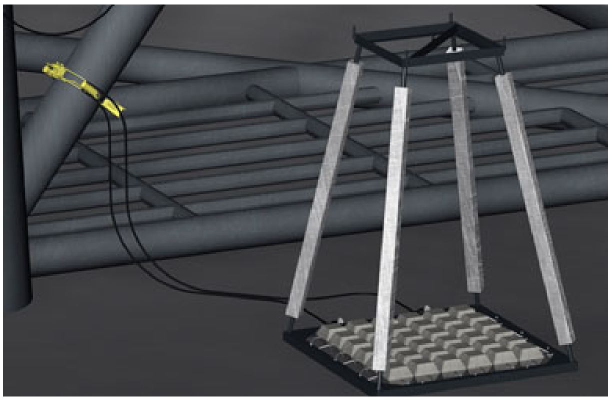

Figure 2.5.: RetroPod$^{\text{TM}}$[19].

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[6] Pods can be also used to protect the deepest sectors of jackets when retrofitting is required. They also can be effectively utilized for CP of subsea equipment.

The main characteristics of the software are summarized[7]:

- The current requirement are evaluated with the same approach used for the bracelet anodes CP design;
- The pipeline is not divided into sections but considered as one segment with homogeneous characteristics;
- The estimation of the potential attenuation along the pipeline is achieved discretizing the domain in 20 subdomains in which the potential is evaluated. The Finite Difference Method implemented is the one proposed by Hartt in the final report “RETROFIT CATHODIC PROTECTION OF MARINE PIPELINES ASSOCIATED WITH PETROLEUM PRODUCTION” [20]. The method implemented can be considered as a first step towards CP computer modelling, moving from the empirical approach to a more theoretical method. The potential attenuation tool was also implemented with VBA, and the convergence time of the model was approximatly five minutes.

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[7] In figure B.3 in Appendix B is shown a brief flowchart about the implemented algorithm.

3. Empirical design - onshore ICCP

> The pessimist complains about the wind;
> the optimist expects it to change;
> the realist adjusts the sails
>
> William Arthur Ward

The first succesfull application of CP was achieved on pipelines in the United States, the country where the oil and gas industry firstly developed. Pipelines are systems with one dimension, length, predominant than the cross sectional dimension, causing some unique challenges to the modeling, and the understanding of their CP system. Pipelines can be protected both by means of galvanic anodes and ICCP systems. Even though, galvanic anodes are used only in those situations where the pipeline seeking protection is relativly short or there is the need to protect only part of it [7], for this reason in the following chapter only ICCP systems will be taken into consideration.

3.1. Rules and Standards regarding onshore CP system design

Pipelines rupturing causing deaths, is an ordinary toll that could be easily avoided, if proper protection measures were put in place, following the standards and recommended practices present in the industry. After accidents due to excavation, corrosion is the next most common cause of pipeline breakdown [21]. Onshore structures, most often carrying or storing highly flamable fluids, have to be protected from corrosion attack, using the best available knowledge present in industry. The design criteria, standard practices and company specifications followed to develop this master thesis work were:

- UNI 10835 Cathodic protection of buried metallic structures Anodes and ground-beds for impressed current stations Design and installation criteria [22];
- NACE SP0572-2007 Design, Installation, Operation, and Maintenance of Impressed Current Deep Anode Beds, Standard Practice [23];
- ISO 15589-1 Cathodic protection of pipeline transportation systems. Part 1: On-land pipelines [24];

- ENI 20309.VAR.COR.PRG Cathodic Protection Of Buried Structures In Plant Facilities, Company specification for cathodic protection [25];
- ENI 05019.MAT.COR.SPC Dispersori Per Sistemi Di Protezione Catodica a Corrente Impressa, Company specification for cathodic protection (in italian) [26];

3.2. Coatings

Pipelines are practically never laid bare, but they are always coated. Different types of coating are usually applied to slow, and practically cease, cathodic surface reactions. The coating provides a barrier to oxygen and moisture. Depending on the environment where the pipeline is buried, its coating has to withstand different attacks such as from soil bacteria, acids or extreme temperatures. The mentioned attacks can break and damage the coating, leaving unprotected some sections of the pipeline. CP provides the additional shield to the spots, the holidays, where coating is damaged and the surface is left bare. The most frequently used pipeline coatings are[1]:

- Asphalt/coal-tar enamel (CTE): it was the first and most widely applied coating in the O&G industry, it still remains one of the most popular choices when it comes to corrosion protection.
- Fusion-bonded epoxy (FBE) are thermosetting coatings made of a mixture of epoxy resin, hardner and fillings. The first two elements composed are known as the binder, which keeps the filling particules together. It is applied as a powder on a heated surface, the heat melts the mixtures and the chemical components undertake an irreversible reaction. It is often used on girth weld joints and fittings but it can be also used on outer pipe surfaces.
- Three layer epoxy-polypropylene (3LPP) is a multilayer coating made of a first layer of FBE, a second layer of a polymeric adhesive and an outer layer made of polypropilene. It is the best solution for pipelines operating at high temperatures and in the need of excellent mechanical protection.
- Three layer epoxy-polyethylene (3LPE) is a coating similar to 3LPP a part from the outer layer which is made of polyethilene. Being polyethilene softer than polypropilene 3LPE is usually applied on pipelines working at low to moderate temperatures.

A pipeline with a perfect coating would not need any CP system to avoid corrosion damages, but during the construction stage and with the passing of time, coatings deteriorate and the current required to keep the pipeline protected increases. As the time passes by, aggressive soils and external factors, such as tree roots, damage the coating and increase the number of holidays. Temperature above ambient increases the protection current requirements. From the experience acquired on the field, protection current requirements were derived and they can be found in the international standards [24]. As good engineering practice dictates, protection current densities found in the standards should be regarded as

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[1] in appendix C, coating application and application processes figures are shown

guidelines and different protection current densities can be applied during the design phase, dependending on the environmental conditions on the field, such as soil resistivity and oxygen content.

3.3. Soil resistivity and properties

Pipelines are buried under the ground and the ICCP system required to protect the structure is dependent from soil characteristics. In a completly dry soil corrosion cannot take place. Corrosion processes on a structure are only possible when water is present in the soil. Ionic transfer can only take place inside an electrolyte. Unlike offshore structures immersed in seawater, buried pipelines are surrounded by soil, which can be a very heterogeneous media. The most influential soil characteristic is its resistivity, which is the electric resistivity measured between two opposite faces of a $1m^3$ cube, measured in Ωm. Resistivity is directly connected to the properties of the water retained in the porous structure of the ground. Resistivity directly impacts the length of the groundbed, the number of anodes required and the distance between earthing systems. From a corrosion point of view the other important soil characteristics are pH, microbiological activity, sulphates and chlorides content.

A high soil resistivity leads to slow corrosion processes but in the meantime a pipeline buried in a high resistivity soil is more difficult to protect via CP. The place to install the anode groundbed is dictated by electrical power availability and low soil resistivity. A groundbed placed in high resistivity soil is not as effective as a groundbed placed in a low resistivity area. Poor soil characteristics can be overcome by a more sophisticated grounding system. Soil resistivity usually changes with depth, the possibility to measure the resisitivity of the soil even in deep layers can be helpful to determine the best grounding system[2]. It needs to be taken into consideration that soil resistivity, depending on the soil moisture content, might be affected by seasonal variations. The two main methods to measure soil resistivity are:

- Wenner or four pin: it is the most widely used method. The resistivity measured is the average resistivity to a depth equal to the pin spacing. It is an easy method to measure soil resistivity but it can give approximate results when the soil stratigraphy is heterogeneous.
- Schlumberger: it is similar to the the Wenner's method but the pins are not kept stationary but the external ones are moved further away each time the resistivity measure is taken. The application of a numerical model, solved with a computer software, can give the resistivity of the different strata.

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[2] An important factor is the aquifer depth

3.4. Different groundbed

Depending on the soil characteristics and the type of pipeline requiring protection, differend groundbed can be chosen. A groundbed is the system in which anodes are placed, usually filled with a material more conductive than the surrounding soil, such as a carbonaceous or coke backfill. The previously mentioned backfills are active media and they can be considered just like anode materials because on their surface anodic reactions take place. Gypsum or bentonite backfill are instead considered inert, their function is to retain moisture, protect the anodes and increase ions diffusion. The main purpose of a groundbed is to decrease the anode resistence, and as a consequence the feeding voltage necessary to provide the protection current. The most widely used groundbed configurations are:

- Shallow vertical groundbed: the anodes are placed vertically. They are used when surface soil conditions are sufficiently favorable. Groundbed resistance can be calculated with Dwight's equation 3.1 for continuos groundbed with multiple anodes or with Sunde's equation 3.2 for multiple groundbeds with single anode[3].

$$R_{GBC} = \frac{\rho}{2\pi L}\left[ln\left(\frac{4L}{r}\right) - 1\right] \tag{3.1}$$

  - ρ soil resistance
  - L active length of the single groundbed
  - D Groundbed diameter

$$R_{GBS} = \frac{R_{GCB}}{N}\left[1 + \frac{\frac{2L}{g}\ ln0.656\ N}{ln\frac{8L}{D} - 1}\right] \tag{3.2}$$

  - R_{GCB} resistance calculated with Dwight's equation 3.1
  - L active length of the single groundbed
  - D Groundbed diameter
  - N number of groundbeds
  - g spacing between single groundbeds

- Shallow horizontal groundbed: the anodes are placed horizontally. It is used when soil conditions do not allow easy drilling and therefore surface digging is the most convenient solution. The main drawback is the surface encumbrance. Groundbed resistance can be calculated with a modified form of Dwight's equation 3.3 for continuos groundbed with multiple anodes or with equation 3.2 for multiple groundbed with single anode

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[3] Groundbed resistances are all provided by UNI 10835 standard [22]

$$R_{GBC} = \frac{\rho}{2\pi L}\left\{ln\left[\frac{2L}{HD}\left(L+\sqrt{4H^2+L^2}\right)\right]+\frac{2H-L-\sqrt{4H^2+L^2}}{L}\right\} \tag{3.3}$$

- ρ soil resistance
- H Groundbed burial depth
- L active length of the single groundbed
- D Groundbed diameter

$$R_{GBS} = \frac{R_{GBC}}{N}\left[1+\frac{\frac{2L}{g}\,ln0.656\ N}{ln\left[\frac{2L}{HD}\left(L+\sqrt{4H^2+L^2}\right)\right]+\frac{2H-L-\sqrt{4H^2+L^2}}{L}}\right] \tag{3.4}$$

- R_{GBC} resistance calculated with equation 3.3
- H Groundbed burial depth
- L active length of the single groundbed
- D Groundbed diameter
- N number of groundbeds
- g spacing between sigle groundbeds

- Deep verticall groundbed: several anodes are buried deep beneath the surface in a drilled well. It is a costly solution but it poses great advantages due to the limited surface requirement, more uniform current distribution, constant resistivity unaffected by seasonal changes and unimportant interference with adjacent structures [7]. A vent needs to be placed to remove the gas produced by the anodic reactions. Groundbed resistance can be calculated with Dwight's equation 3.1.

3.5. Anode material

There exist two main categories of anode material for ICCP use, inert and active. Inert anodic materials don't take place on the reaction and on their surface oxygen and chlorine evolution takes place to provide electrons, as explained in section 1.6. Active anode materials instead take place directly in the reaction and their ions dissolve as they provide electrons. The Anodic materials that can be found implemented inside the software are:

- Carbon steel: it was the first material used to produce ICCP anodes. The most common forms are rods, tubes or random shapes made of scraps (mainly used for temporaneous CP). They can be used in high resistivity soils but the density current output in this case is very low.
- Iron-silicon alloy: the anodes made with this material have similar characteristics as carbon steel but they can withstand more corrosive environments.

- Graphite: the anodes are made by extruding carbon rich materials (coke and coal tar) to produce rods. The rods are then graphitized and soaked in wax and oils to fill the porous matrix (waterproofing purposes). Graphite anodes are fragile and they do not provide high current densities. In chlorine rich environments the anodic reaction is chlorine evolution, in chlorine-free soils instead the anodic reaction is oxygen evolution that transforms graphite into CO and CO_2 gases.
- MMO Activated titanium: they consist of a titanium support and an activation Mixed Metal Oxide coating (MMO) made of noble metals oxides. The anodes made with this material were invented for the chloralkali process in the 60's and they have been used with succes for CP purposes since the 80's. They can be produced in different shapes from rods, the most common, to mesh which is used for CP systems in steel reinforced concrete structures. The main advantages are: low overpotential, high anodic current density and high resistance to acids. The only real drawback of this anodic material is in its cost. MMO anodes are usually employed in sea water and brackish water environments.

3.6. Transformer rectifier and Power Generation units

The electric energy required to keep the structure protected can be produced on site or taken from the grid, the AC is then transformed to the required voltage and converted to DC via a transformer rectifier.

Power Generation units

Pipelines are usually coated, leading to very low current density requirements, for this reason Cathodic protection systems for onshore application usually require small amount of power to operate. When available, the electric power is usually taken from the grid, otherwise small stand alone power producing units have to be set in place [5]. Pipelines stretching along remote areas are most likely to need such stand alone power devices. On the market there are many different types of stand alone electric generating units, some of them have been around for quite some time, others are totally new and therefore they have to be tested on the field. The use of renewable energy, such as wind or sun, to power stand alone CP systems is ideal, but the need of a large storage system can be prohibitive. Therefore two different approaches can be implemented to avoid vast energy storage devices: the use of a hybrid system[4] that decreases the need of energy storage or intermittent CP. Intermittent CP has been used and tested only for steel reinforced concrete structures exposed to brackish environment, such as bridges in Florida [27]. The application of intermittent CP for onshore pipeline it has not been studied yet. In table D.1 found in the appendix, the main characteristics of stand alone power generating units are briefly summarized.

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[4] A hybrid system consists in a renewable power unit and a fossile fuel generator. The fossile fuel generator is present only as a back-up power source. Often a small battery pack is also present functioning as energy buffer to mitigate power fluctuation.

Transformer rectifier

In an ICCP system a TR is needed to provide the required amount of energy to achieve pipeline polarization. A TR is an electronic device that rectifies the electric current from AC to DC and it transforms the voltage to the required one. TR current output tuning can be performed both automatically or manually, locally on site or from remote. A TR can be set to operate at constant current ouput conditions, constant voltage, or constant protected structure potential.

Feeding voltage

Feeding voltage is the voltage that has to be provided to operate the ICCP system. This voltage has to be kept below a maximum range, usually 50V, for safety reason. The voltage required is proportional to the resistances in the circuit, high voltages are needed to bear high system resitance. When the calculated voltage is above the safety limit, actions have to be taken, like the use of a more efficient groundbed. The evaluation of the required feeding voltage is explained in section 3.7, where the algorithm used to implement the software is described.

3.7. Onshore pipeline software

Tecnomare SPA has always been working in the offshore sector but in recent years there has been a growing interest in onshore projects too. A recent example is the engineering phase, which was awarded to Tecnomare, of a humongous brownfield[5] onshore project in the middle east. There was the need to create a software for onshore CP systems dimensioning, with similar characteristics to the one already created for offshore structures. The main purpose of the software was not only to design but also to quickly check projects performed by third parties. The software was designed on the basis of standards, recommended practices, previous works and scientific knowledge.

The software was implemented with similar concepts to the ones followed for its offshore counterpart. The main driver that sustained the design of this software was the ease of maintanability and the technicians' ease of use. Some differences were derived from the experience acquired during the testing phase of the offshore software, such as:

- As a first step before starting the software implementation phase, flow charts and software structure diagrams were firstly developed. The design phase of the software was not underestimated, for this

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[5] A brownfield is an oilfield which has reached its production plateau and the infrastructural development is well under its full potential, cost effective actions can be taken to improve hydrocarbons production [28]. Therefore great opportunities lie on it.

reason only minor problems arose when implementing the software code;

- The whole algorithm was implemented as VBA code, no equations were implemented inside excel sheets. Therefore excel sheets were only kept as database to store input and output data;
- Variable names inside the code were chosen to be self-explanatory. On top of each VBA code page the meaning of each variable used was explained;
- Comments inside the code were inserted for each step.

The input parameters to perform groundbed design and T/R dimensioning are:

- Environment data collection;
- Anode data collection;
- Groundbed data collection;
- Pipelines to protect characteristics;

The output parameters given by the software are:

- Number of anodes required to provide the protection current;
- Groundbed active length (in case of multiple anodes groundbed, in case of single anode groundbed this value is an input parameter);
- Protection current;
- T/R voltage requirement;

Pipelines are laid in corridors and different pipelines are usually placed in the same trench. Commonly a single ICCP system (T/R and groundbed) provides protection to all the pipelines placed on the same path. Accordingly, the software was created to satisfy the requirement of multiple pipeline protection.

Algorithm

Figure E.2 in appendix E shows the algorithm flow chart.

1. Environment data collection:
    - num: Number of pipelines requiring protection;
    - DL: Design life [$years$];
    - res: Soil resistivity [Ωm];
    - F_{safety}: Safety factor[6];
    - F_{spare}: spare factor[7].

---

[6] safety factor takes into account uknown structures that might be electrically connected

[7] spare factor takes into account future structures that might require protection in the future, which will be connected to

2. Anode data collection:
   - Material;
   - $diss$: Specific consumption $\left[\frac{kg}{A years}\right]$;
   - $i_{deliverable}$: Current density $\left[\frac{A}{m^2}\right]$;
   - $massa_{vol}$: anodic material density $\left[\frac{kg}{m^3}\right]$;
   - L_{anode}: Length $[m]$;
   - D_{anode}: Diameter $[m]$;
   - $Length_{cable}$: Distance groundbed-pipeline $[m]$.
3. Groundbed data collection:
   - Groundbes typology. As soon as the user clicks on the optionbutton, a new userform appears asking the required groundbed dimensions data;
   - Backfill typology;
   - sez_{cable}: Pipeline - T/R connecting cable section area $\left[mm^2\right]$.
4. Pipeline data collection. Once the previous data are inserted correctly the system requires that the user inserts the data about the pipelines connected:
   - D_{int}: Inner diameter $[m]$;
   - D: Outer diameter $[m]$;
   - L: Length $[m]$;
   - T: Pipeline - soil interface temperature $[°C]$;
   - Coating typology;
   - i_{corr}: Protection current density $\left[\frac{mA}{m^2}\right]$;
   - res_c: Coating insulation resistance $\left[\Omega m^2\right]$;
   - res: metal resistivity $[\Omega m]$.
5. Total protection current calculation. The value is increased by a $\frac{1}{0.7}$ factor[8]. Once the current, I, is calculated the user can decide wether use I calculated or another value. Usually T/R are sold with specific current ranges, for this reason the user is allowed to define a protection current different from the one calculated with equation 3.5.

$$I = \frac{1}{0.7} F_{safety}\, F_{spare} \sum_{i=1}^{n} \pi\, D_i\, L_i\, i_{corr,i} \tag{3.5}$$

---

the same CP system

[8] If $T_i > 30$ Then $i\_corr_i = i_{corr,i}\,(1 + 0.025(T - 30))$ $\left[\frac{mA}{m^2}\right]$

6. Required number of anodes. If anode type is inert (e.g. MMO activated titanium) the number of anodes needed to provide the protection current, N_{anodes}, is only dependent by anode current density. Else if anode type is active (e.g. carbon steel, iron silicon alloy or graphite), two different anode numbers are evaluated:
   - $N_{density}$ is dependent on final life deliverable current. To calculate anode current at the final life stage, final life anode dimensions are used. Final life anode dimensions are calculated via utilzization factor, UF.

   $$N_{density} = \frac{I}{\pi D_{anode,f} L_{anode} i_{deliverable}} \quad ; \quad D_{anode,f} = D_{anode} \left(\frac{UF}{0.9}\right)^2 \tag{3.6}$$

   - N_{mass} is dependent on anodic mass to keep the structure polarized for the whole design life;

   $$N_{mass} = \frac{I\, DL\, diss}{\frac{\pi\, D_{anode}^2}{4} L_{anode} UF} \tag{3.7}$$

   The final anode number is given by the highest value between the previously evaluated anode numbers.

   $$N_{anodes} = max\left(N_{density}\, ,\, N_{mass}\right) \tag{3.8}$$

7. Number of groundbeds required and groundbed length. In the case of single anode groundbeds the number of groundbed coincides with the number of anodes; groundbed length was previously specified by the user. In the case of multiple anodes groundbeds, the groundbed length can be calculated as:

   $$L_{GB} = \frac{N_{anodes}\, L_{anode} + (N_{anodes} + 1)\ spacing}{N_{GB}} \tag{3.9}$$

   - spacing is the distance between anodes, which was previously specified by the user with the other groundbed parameters.
   - N_{GB} is the required number of groundbeds. The algorithm performs an iteration, increasing the number of groundbeds until the condition $L_{GB} < L_{GB,max}$ is satisfied. $L_{GB,max}$ is a parameter previously specified by the user, which corresponds to the maximum allowable groundbed length. The number of anodes N_{anodes} is evenly distributed between the groundbeds, and it is evaluated by rounding up to the nearest integer the ratio total number of anodes required and number of groundbeds, as shown in equation 3.10.

   $$N_{anodes,GB} = RoundUp\left(\frac{N_{anodes}}{N_{GB}}\right) \tag{3.10}$$

8. Groundbed resistance. As function of the groundbed typology chosen by the user, the algorithm calculates the groundbed resistance with the equations precedently reported in section 3.4. The dimensions used to calculate the groundbed resistance are also dependent from the backfill material. When inert backfill materials are used, diameter and lengths used to evaluate the resistance are the anodes ones and not the actual groundbed dimensions. When active backfil materials are adopted instead, the input parameters for the groundbed reistance are the groundbed actual dimensions.

   When more than one groundbed is necessary the groundbed resistance is calculated as follows:

$$R_{GB} = \frac{R_{GB,single}}{N_{GB}} \tag{3.11}$$

9. Calculation of the total electric resistance given by the contribution of metal and coating resistance. The equivalent electric circuit is shown in figure 3.1, its semplification after calculating R_{m+c} is shown in figure 3.2.

$$R_{metal,i} = \frac{res\,L}{\frac{\pi\left(D_i^2 - D_{int,i}^2\right)}{4}} \quad ; \quad R_{coating,i} = \frac{res_c}{\pi\,D_i\,L_i} \tag{3.12}$$

$$R_{m+c} = \left[\sum_{i=1}^{n} \frac{1}{R_{metal,i} + R_{coating,i}}\right]^{-1} \tag{3.13}$$

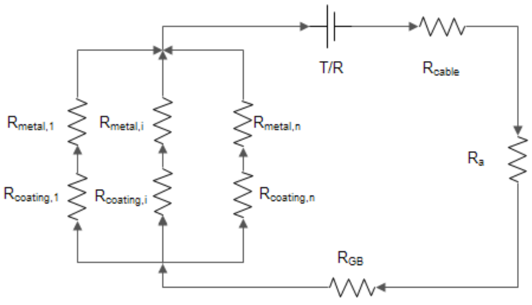

Figure 3.1.: Equivalent electric circuit

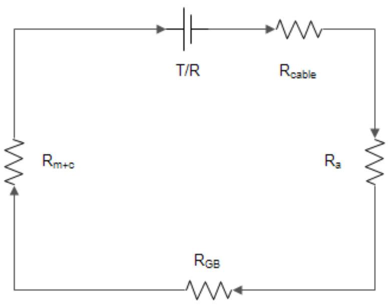

Figure 3.2.: Electric circuit, simplified

10. Connecting cable resistance. res_{cable} is the metallic cable resistance [Ωm].

$$R_{cable} = \frac{Length_{cable}\,res_{cable}}{sez_{cable}} \tag{3.14}$$

11. T/R voltage. It is the T/R rated voltage that the T/R is required to provide to deliver the required current. It can be calculated with three different approaches:

    - as suggested by UNI10835 [22]. The total voltage is calculated as:

$$\Delta V_{tot} = \frac{R_{GB}}{0.85}\,I \tag{3.15}$$

- as evaluated in previous project carried out in Tecnomare SPA. The resistance R_{m+c} is estimated as 5% of the R_{GB}. ΔV_a is the voltage drop due to kinetic and thermodynamic effects on the anode, it is an input parameter inserted by the user.

$$\Delta V_{tot} = (1.05 R_{GB} + R_{cable})\ I + \Delta V_a \tag{3.16}$$

- analytical. This approach evaluates the total resistance taking into account the R_{m+c} calculated at point 9, equation 3.13, of this algorithm.

$$\Delta V_{tot} = (R_{m+c} + R_{GB} + R_{cable})\ I + \Delta V_a \tag{3.17}$$

If the evaluated ΔV_{tot} is greater than $50V$, the user necessitates to change some parameters such as:

- groundbed typology;
- D_{GB};
- groundbed placement[9].

---

[9] seeking a site with lower soil resistivity, res.

4. Computer modeling

If you're not failing 90% of the time, then you're probably not working on sufficiently challenging problems

Alan Kay

4.1. History

The last few decades showed a disruptive increase in the application of computers in a countless number of fields. In the Forties, engineering applied to military purposes was the main driver that brought to the invention of electronic digital computer. Nowadays, Computer Aided Engineering is used with different intensity in numerous engineering fields. The use of computer is becoming every day more and more important in all engineering disciplines. Computer simulations help modern engineers to have a thorough understanding of their design. International standards about CP design are starting to introduce the concept of computer modeling applications in CP studies [29].

> *"Computer models can be used in the detailed design to verify the protection of parts with complicated geometry e.g. in the pile area for jackets, conductor guide frames and J-tube bellmouths and to evaluate any interference effects between anodes and/or between structures."*
>
> *Norsok M-503*

CP effectivness can be greatly increased by the upgrading of computer modeling. Computer modeling can be easily and quickly applied to estimate and improve the performances of a CP system, by reproducing a structure with a realistic virtual model. The virtual model can be tested and the impact of different design conditions can be analyzed. Different corrosion prevention techniques can be implemented and investigated to understand the possible damaging scenarios. Computer modeling is a cost effective way to provide that confidence needed to avoid expensive repairs and unnecessary site surveys that heuristic based design necessitates [30].

4.2. Different modeling approaches FDM - FEM - BEM

Finite Difference Method (FDM), Finite Element Method (FEM) and Boundary Element Method (BEM) are three different modeling approaches that can be implemented to design cathodic protection systems. FDM and FEM are methods in which the whole domain under study is discretized, BEM is a method in which only the boundary is discretized. CP problems with different characteristics can be studied effectively with one of the three methods.

FDM

FDM is a method in which derivatives are approximated with incremental ratios. FDM is the less complicated numerical method and the model convergency is easily predicted. It is still a competitive approach to solve simple problems with the following characteristics:

- homogeneous media;
- isotropic material;
- smooth boundaries;
- the describing equations do not require approximation of a higher order than the ones introduced by the central difference method.

FDM is an interesting tool for those problems that can be simplified into elementary geometries. Its implementation in a software is easy, practical and it can be performed even in programs such as VBA. From the experience acquired by the author, FDM has interesting solving capabilities for problems such as potential attenuation along pipelines. Because pipelines show a dimension, length, much greater than the other two, the cross section dimensions, a 3D problem involving a pipeline can be correctly modelled as a 1D problem. The 3D pipeline geometry “collapses” into a one dimension line. Like all numerical techniques, the geometry needs to be discretized, divided in subdomains, to form a grid. The solutions for the equations involved are found in the points where the geometry was discretized. A practical example for this method was implemented in the off shore pipeline pod anode software, presented in section 2.8.2.

FEM

FEM is the most promising numerical method to solve CP related problems. It can be used for large and complicated geometries. It does not have the limitations dictated in FDM and it can be applied to solve complex geometries like a jacket structure. On the market there are different engineer simulation softwares, which are developed to solve problems via FEM. The two most developed and adopted in a wide range of engineering fields are Ansys and Comsol. The tools provided by these softwares allow engineers to test their products virtually before the physical construction begins. These softwares can be used to build multiphysics simulations, where different physics interact with each other.

Multiphysics simulations are replacing many experiments in laboratories. Computer simulations have the advantage of being cheaper and faster to reach results than physical laboratory experiments. The simulation work is usually integrated with laboratory experiments. Recently, there has been a trend to make simulation software more user-friendly than it was in the past. Specific interfaces for specific problems are set to help users to quickly build a model and put it under test. Companies are looking at the simulation world with increasing interest. In a company, the R&D department is usually the branch where computer simulations are most widely used.

BEM

BEM has the great advantage that only the boundaries need to be discretized. BEM has been used widely in CP systems simulations in the past due to the lower computer requirements needed to solve problems. With the increased software and hardware capabilities which can be found nowadays, the benefit of lower computer requirements is not such a paramount property. Beasy^{TM} is the most famous software dedicated to CP modeling. BEM can solve problems with irregular boundaries, as FEM does.

4.3. Laplace's equation

The main purpose of a CP computer model simulation is to determine the electrical field in the electrolyte. The potential distribution is evaluated by simulating the conditions and the electrochemical reactions on the structure surfaces. To achieve so, in a pure ohmic system[1], Laplace's equation has to be solved in the electrolyte domain. Laplace's equation is derived from two different specific equation [31]:

- Ohm's law:

$$i = \frac{\nabla E}{\rho} \tag{4.1}$$

  - ρ: resistivity
  - ∇E: potential gradient

- Charge conservation, which is a continuity equation:

$$div(i) + \frac{\partial q}{\partial t} = 0 \tag{4.2}$$

  - $div(i)$: divergence of the current density i

---

[1] A system can be accepted as pure ohmic when overpotential contributions can be considered negligible or are absent.

- $\frac{\partial q}{\partial t}$: rate change of the density of charge q

In a stationary case, supposed $\frac{\partial \rho}{\partial t} = 0$, equation 4.2 can be summarized as:

$$div(i) = 0 \tag{4.3}$$

Laplace's equation is derived combining Equations 4.1 and 4.3:

$$\nabla^2 E = 0 \tag{4.4}$$

Laplace's equation can be applied in many fields of study to describe different phenomena, such as temperature, pressure and gravity force potential distribution. The solutions of problems solvable with Laplace's equation, which were carried out in disparate scientific disciplines, can be also utilized to describe the electric field distribution. Laplace's equation can be solved analitically only for very basic analysis and geometries, leaving the remaining problems to be solved numerically. Computer modeling does not have any major restrictions regarding geometry and nonlinear boundary conditions. Additionally, computer modeling allows engineers to perform time-dependent studies.

The current distribution in a real system is more complicated than the one forecasted by ohm's law for the following reasons:

- On the electrolyte-electrode boudary interface there is a potential drop, which is due to the surface electrochemical reactions and the electrolyte properties;
- Concentration polarization phenomena. On the boundary interface where electrochemical reactions take place, chemical components are produced or consumed, creating a concentration gradient in the electrolyte. Convection and diffusion tend to re-establish equilibrium conditions. In sea water CP modeling, the concentration polarization phenomena is negligible. In CP modeling of steel reinforced structures instead, concentration polarization is a significant parameter because of the oxygen diffusion barrier in the concrete cover.
- Overpotential conditions on the electrolyte-electrode boudary due to current exchange.

A model, that makes use of the above mentioned Laplace's equation to solve the electric potential field, follows the so called primary current distribution. A more detailed and precise model can be set using secondary current distribution, which takes into account activation overpotential on the electrolyte-electrode boudary interface. The most complete model is obtained taking into account the concentration polarization due to the transfer of ions in the electrolyte, which is referred as tertiary current distribution or Nernst-Planck distribution.

4.4. Boundary conditions

Boundary conditions are the most important factors concerning cathodic protection computer simulation. They are usually derived from laboratory and open sea measurements in the field. In the past a lot of scientific researches were conducted to collect data regarding cathode and anode behaviors in different envronmental conditions. Boundary conditions, needed to simulate numerically cathodic protection, are mainly the relations on the surfaces of the electrodes between currents and potentials. Main parameters influencing E-i relation are the same ones influencing cathodic protection empirical design (see section 2.2).

4.4.1. Anode boundary conditions

Constant potential boundary condition is usually set on the surface of galvanic anodes. Galvanic anodes materials, such as alloys used in the offshore industry made of Aluminum-Zinc-Indium[2], have very low polarization properties. Surface potential can be considered constant and equal to the free corrosion potential. For a more precise model when current densities on the anode are high, polarization can be taken into account, and boundary conditions such as a Tafel slope can be used.

Constant current or constant current density output can be set to model the surface of impressed current anodes. A current density parametric sweep, inside a plausible range, can help to understand the current required to keep the surface potential above the corrosion limit. A model which employs constant current output is described in section 5.6, regarding an offshore jacket ICCP revamping.

4.4.2. Cathode boundary conditions in sea water

From a mathematical point of view, each chemical reaction is associated with a local current density related to the surface potential. Therefore an equation describing current density in function of electrical potential is defined for each electrochemical process taking place on the surface. The total local current density is the result of the superposition effect of the single current densities associated with each reaction. The many different reactions, which take place on the cathode surface, can be also modeled using one single equation. In Comsol the electrolyte-electrode boundary interface can be used to model the electrode kynetics due to the charge transfer on a non porous electrode [32]. The charge balance at the interface can be expressed as:

$$\vec{i_l}\vec{n} = i_{loc} \quad ; \quad \vec{i_s}\vec{n} = -i_{loc} \tag{4.5}$$

- $\vec{i_l}$ current density vector in the electrolyte

---

[2] Indium is added in the alloy to avoid passivation on the anode surface.

- $\vec{n}$ norml vector
- $\vec{i_s}$ current density vector in the electrode
- i_{loc} local charge transfer current density

i_{loc} can be written in three different ways, with increasing complexity, depending on the current distribution:

- Primary current distribution (overpotential is negligible). The transport of ions in a uniform electrolyte is predicted using Ohm's law in combination with a charge balance (resulting in Laplace's equation). It is used to predict ohmic losses in semplified models. The predictions given by these distributions are valid when potential losses due to activation and mass transfer are negligible compared to Ohmic losses.
- Secondary current distribution. This modeling assumption gives good estimations when activation potentials have a strong influence in the potential distribution and mass transport potential losses are negligible. Current density is function of overpotential conditions. Current density changes along the surface as a function of electrolyte-electrode boundary interface potential.

  There are many different versions of the governing equation, which give as output the same relation E-i. The following equation is quoted from Tommaso Pastore's PhD thesys [33], the meaning of the parameters is listed below. The constants included in the equation, relativly a material immersed in a particular environment, can be easily obtained from the experimental polarization curve.

  $$i_{loc} = i_{Fe} e^{\frac{\eta}{B_{Fe}}} - i_L - i_H e^{\frac{-\eta}{B_H}} \tag{4.6}$$

  - i_{Fe} Iron exchange current density
  - i_H Hydrogen exchange current density
  - i_L Oxygen limiting diffusion current density
  - B_H Cathodic Tafel's slope for Hydrogen
  - B_{Fe} Anodic Tafel's slope for Iron

- Tertiary current distribution - Nernst Plank. Current densities are not only function of electric potential, but also the concentrantration of the reacting species on the surface is considered. Mass transport is taken into account due to diffusion, migration and convections.

4.4.3. Insulation boundary conditions

An insulation boundary describes the condition on the boundaries where no current is exchanged between surface and electrolyte. In sea water CP simulation this boundary condition is used to define the six faces composing the parallelepiped enclosing the geometry. In Comsol multiphysics, all the boundaries not defined are automatically set as insulation boundaries by default. Equation 4.7 describes the insulation boundary condition.

$$\vec{i_k}\vec{n} = 0 \tag{4.7}$$

- $\vec{i_k}$ is the current density vector
- $\vec{n}$ is the normal vector

4.5. Mesh

Meshing is the modeling step during which the geometry under study is divided in subdomains. The process of discretization is necessary to transform a continuos object, rapresenting the real geometry, into a numerical entity of which a numerical simulation can be performed. From the experience acquired running a countless number of simulations during this study, the process of meshing is probably the most complex and influencing operation in CP computer modeling. Mesh dimensions have to be chosen according to the specific dimensions of the geometry under study. A low number of elements created during the mesh process can lead to improper modeling results, and a higher than needed number of elements instead causes longer computing time. For this reason a trade off exists between modeling accuracy and computational time. The optimum number of elements depends on the physical problem under study and structure dimensions. A default mesh is created by Comsol but it is often not suitable for the simulation, therefore a custom mesh is created based on the experience of the engineer. To create a mesh constraints are set on edges, boundaries and domains. The main parameters which were changed from the default ones set by comsol during the mesh process were:

- maximum element size;
- minimum element size;
- maximum element growth rate.

A moving mesh is used to simulate time dependent cathodic protection problems, a typical example is the simulation of galvanic anodes behaviours. The mesh created to discretize the domain has to change for each time step, to take into account the galvanic anodes geometry change. The shape and volume of the anodes change as time passes by, in function of current density on the surface and property of the anodic material. Models employing a moving mesh are presented in section 5.7.

4.6. Solver

The solver is the algorithm used to solve the equations defined in the domain. In this section are explained the most important solver settings defined in the models. The solver used was the so called MUltifrontal Massively Parallel sparse direct Solver, MUMPS, which is particularly valuable for large linear systems. MUMPS, like all linear solvers, use LU decomposition to solve a problem. Most of the parameters were left as the ones automatically given by Comsol. Only very few settings were changed manually during the simulations:

- The relative tolerance was set at 10^{-6}, adimensional;
- The nonlinear method set was Automatic highly nonlinear(Newton), in which the solver automatically determines a damping factor in each iteration of the Newton's method;
- The automatic damping factor, with initial damping factor of 10^{-4} and a minumum damping factor of 10^{-8} was set;
- The termination technique used was tolerance based, with a maximum number of iterations equal to 250 and a tolerance factor of one. The maximum number of iterations was a very important paramater to change from the default one which was set at 25. On average 70 iterations were required to achieve convergency.

4.7. Batch mode Comsol

To make the most of the time and tools available, the simulations were run in batch mode. Batch mode gives the possibility to run Comsol without Graphical User Interface and without manual intervention. The models were created using Comsol with its GUI and later when a number of models were ready to be computed, the simulations were solved using Comsol in batch mode. To run Comsol in batch mode the following procedure had to be implemented:

- create a text file with a stringline for each simulation file .mph, the string had to contain the following command:

  ```
  comsolbatch−inputfile fpath\fname.mph−outputfile fpath\fnameout.mph−batchlog path\fnameout.log
  ```

- save the file as .bat;
- copy the file inside Comsol\bin\win64;
- run the batch file

When a simulation did not reach convergency or a problem arose (e.g. a problem in meshing the domain) Comsol was exited, the simulation saved and a new simulation was opened and run, all automatically with no manual intervention. Batch mode was the most proficient tool to optimize the time available.

4.8. Computer requirements

Computers are tools that, like nothing else ever invented by mankind, have gone through an exponentially rapid development in recent years. Until two decades ago it would have been impossible to think about the use of a personal computer to perform complex computer simulations. To perform the work necessary to develop this master thesis two computers were used. At the beginning the first simulations were performed using a consumer laptop, a HP Pavilion dv6 Notebook PC, with the following characteristics:

- quad core
- 8Gb Ram
- Intel(R) Core(TM) i7-2630QM CPU @ 2.00GHz

Soon after the first simulations, it was realized that the laptop characteristics were not sufficient to perform the most complex simulations. The main issue, regarding the use of a laptop to perform long run simulations, lasting a few hours, was overheating. A laptop is a machine designed to optimize space and weight characteristics, leading to challenging cooling problems. From the experience aquired running simulations on a laptop, with the previously specified characteristics, it can be stated that this type of computer should not be used to run secondary current distribution simulations with more than five million elements, and no moving mesh. When time dependent, moving mesh simulations are involved, the maximum number of elements in a simulation should not exceed a million element. The best option was to move from a laptop to a desktop or a working station type computer. More complex simulations were run on a desktop computer, assembled to be able to work continuosly 24/7 without major issues. A desktop computer was intrinsically more efficient than a laptop, from a cooling-issues point of view. The computer was assembled to be able to run safely the heaviest simulations, the apparatus had the following characteristics:

- eight core
- 32Gb Ram
- AMD FX-8150 Bulldozer CPU @ 3.6GHz (it supports turbo core technology with overclock speeds up to 4.2GHz)
- liquid cooled

A dedicated workstation would have been a better option, but because of budget constraints a desktop computer with the afore mentioned characteristics was the best trade off for the type of work required for this master thesis. It was also installed the software HWMonitor to monitor temperature and fans frequency of rotations. The maximum CPU temperature reached during summer time simulations never exceeded $70°C$ and none of the eight cores ever passed the $50°C$ temperature mark.

4.9. Model validation

Because of the huge amount of money involved, and the dangerous operations undertaken, the Oil and Gas industry is very conservative and reluctant to introduce new techniques, unless clearly proved and validated. When something already worked in the past there is no reason to believe that it will not in the future. Numerical modeling has been around for decades and it has often been regarded as a toy for scientists in many discipline, CP design included. Only in recent years it has been understood the great capabilities and opportunities offered by computer simulations, even in marginal engineering fields most often dominated by empirical design. Optimization processes and design validation can be successfully achieved with the use of computer modeling. Though, the numerical model approach itself needs to be validated. As stated on Beasy brochure about their Oil & Gas Cathodic Protection System Design software [30]:

> *"Proven track record in the offshore industry "*

As a matter of fact Beasy was made purposely for CP design and testing, and it has been around for a long time, allowing the industry to put it under test. Beasy also includes in the software package a ready to use potential-current density database from which boundary conditions can be set. The software used during this work, Comsol, has not such a proven track of records regarding CP design. Comsol though, understanding the potential of CP and computer modeling of corrosion problems, has just released in May 2012 a new software upgrade, including a corrosion module. Comsol corrosion module is a more versatile and general purpose software tool than Beasy. It is possible to perform both micro scale (e.g. pitting) and macro scale corrosion modeling, coupling the simulations at both scales when necessary [34]. This new tool will need validation via its use in practical design of CP systems by the offshore industry.

The major concerns about the validation of a CP computer model are the boundary conditions that need to be set on the cathodic surface. Boundary conditions are site and material specific and a large database from where CP designers can cater the needed data is a necessity. A great number of studies were done on the field to collect the data needed as input in CP numerical simulation, so it would not be hard to create such a database. To become really competitive on the market, Comsol should implement a database with the previously mentioned, ready to use, boundary conditions.

Boundary conditions and model input

To implement a correct model that represents the real behaviours which the model under study will show, precise and correct boundary conditions are needed. For cathodic protection purposes, collecting data from the field, in which the structure under study is or will be placed, is the minimum requirement that needs to be fullfilled to achieve correct output results from a simulation. The process of collecting data can be done in different ways, with increasing effort:

- Searching in literature or in a database if E-i data were already collected in a previous study, for analogous working conditions;
- Performing studies on structures similar to the one under study, which were already placed in a similar environment;
- Performing a data collecting campaign on the field if no data are available for a particular set of conditions (as it has been done recently for deep water conditions).

Anodic current and cathodic current

Because the model under study is considered a closed system the current provided by the anodes has to be equal to the current absorbed by the cathode. If not so, a mesh refining in the normal to the surface direction can be the solution. A mesh refining process is shown in figure 4.1. To calculate the current output from a surface, a surface integral of the current density has to be computed. During the post processing of a simulation in Comsol this can be evaluated easily.

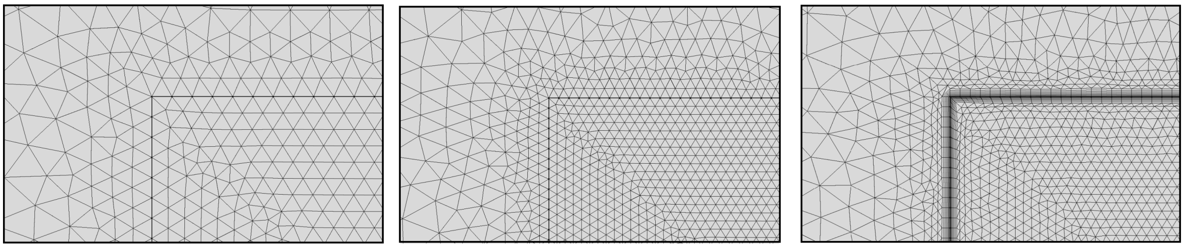

Figure 4.1.: mesh refining process ouput, from left to right

E-i of the model must fullfill input Buttler-Volmer

If the model arrived to convergency properly, in whichever point on the cathode in which a Buttler-Volmer type boundary condition was set the characteristic E-i from the output must coincide with the one from the input.

Electrochemical efficiency in a time dependent model

In a time dependent model, the electrochemical efficiency calculated from the ouput parameters must coincide with the one calculated through Faraday's relation. A time dependent problem, which takes into consideration the shrinkage of anode dimensions, can be set up by defining the chemical reactions taking place on the anodic surfaces. The anode contraction is related to the current provided to keep the structure polarized. The energy density, $\left[\frac{A\,h}{kg}\right]$, calculated as $\dfrac{I\,\Delta time}{\Delta Volume_{an}\,density_{an}}$, has to assume a value equal to the one calculated via Faraday's relation for all the time steps under study.

5. Modeling a Jacket CP system

> Everything should be made as simple as possible, but no simpler.
>
> Albert Einstein

Jacket structures are used worldwide to support exploration and production operations for oil and gas. The wind energy industry also benefits from jacket structures designed for O&G production. It is forecasted by the author that in the near future such lattice structures will be employed more to support wind turbines than hydrocarbon processing units[1]. A geometrical model of a jacket was built for the purpose of this master thesis. Different simulations were performed on this structure to test different design conditions and situations.

The main steps followed during the modeling process were:

- Variable parametrization in the parameter table, numerical values were assigned for each variable (e.g. $rho_{mud} = 1.5\,[\Omega\,m]$, $L_{anode} = 2\,[m]$);
- Geometry creation;
- Boundaries, edges and points geometry selection (or defined as probe), which can be recalled in later steps;
- Boundary conditions setting;
- Meshing process;
- Solver settings;
- Problem solution;
- Results and output data processing.

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[1] O&G exploration and production is moving towards deeper water and more flexible solutions like FPSOs and FPUs coupled with subsea developments.

5.1. Geometry

With the CAD import module, Comsol Multiphysics gives to the user the opportunity to import a geometry previously built with a different software inside the Comsol simulation environment. For example a file created with Solid works can be imported and it is ready to be used in Comsol. During the jacket design phase, usually, 3D drawings are not made with the anodes attached. Technical drawings showing the CP system are only made on 2D, resulting useless from a FEM modeling point of view. As it was previously stated the academic Comsol licence that was used during this thesis didn't allow any commercial work. Because of the afore mentioned reasons it was chosen to draw the whole geometry directly from the CAD interface present in Comsol. All the geometries used in this work were created by the author with the sole purpose of this scientific study.

The geometry was parametrized in such a way that parametric and optimization studies could have been carried out easily. All the parameters employed in each model were set as variables in the global definition node. The geometry was created as assembly of simpler geometries (e.g. cylinders, blocks), placed in the domain via cartesian coordinates. An important step after the geometry was created consisted in the selection of Domains, Boundaries or Edges which will be later used to set the boundary conditions. The items selection step can be extremely time consuming if not properly considered and set from the beginning (e.g. for a large jacket structure the anode boundaries can consist of up to one thousand elements).

5.2. Boundary conditions

Common boundary conditions were set in all the models under study. Boundary conditions[2] in Comsol have to be given as input in a particular manner, the typical $E - \log i$ curve has to be mirorred around the x-axys.

- Cathode: Buttler-Volmer relation. A modified version of equation 4.6 was set as boundary condition, and the input cathode boundary condition is equation 5.1. All the parameters involved in the equation were written inside the parameter table. The parameters were kept constants for all the simulations apart for i_L for which a parametric model was studied, as explained in section 5.4.

$$i_{loc} = i_{Fe} \exp\left(-\frac{E - E_{Fe}}{B_H}\right) - i_L - \exp\left(\frac{E - E_H}{B_{Fe}}\right) \tag{5.1}$$

  - i_{loc} local current density

---

[2] In section 4.4 the theoretical background about boundary conditions was explained in detail.

  - $i_{Fe} = 0.05\frac{A}{m^2}$
  - $i_H = 2e^{-5}\frac{A}{m^2}$
  - $i_L = 0.05\frac{A}{m^2}$
  - $B_H = 0.0521V$
  - $B_{Fe} = 0.026$
  - $E_{Fe} = 0.6V$
  - $E_H = 0.7V$
  - E electric potential

- Anode Potential. A fixed electric potential was set as anode boundary condition for all simulations apart for the time dependent models.

$$E = -1.1V \tag{5.2}$$

- Anode in moving mesh models. Only for time dependent, moving mesh model, a Buttler-Volmer with an almost horizontal line in the E-*logi* plot (constant potential conditions) was set as anode boundary condition. The parameters involved in the equation were kept constant during all the simluations.

$$i_{loc} = i_0 \left[\exp\left(\frac{\alpha_a F \eta}{RT}\right) - \exp\left(\frac{-\alpha_c F \eta}{RT}\right) \right] \tag{5.3}$$

  - i_{loc} local current density
  - $i_0 = 100\frac{A}{m^2}$
  - $\alpha_a = \alpha_c = 0.5$
  - F Faraday constant
  - η overpotential
  - R universal constant
  - $T = 298K$

- Electrolyte resistivities:
    - $r_{sw} = 0.25\,\Omega m$, sea water resistivity;
    - $r_m = 1.5\,\Omega m$, mud resistivity.

5.3. Geometry parametric studies of a jacket node

The jacket node is the most vulnerable spot of a jacket structure, therefore several different studies were performed on it. The reason of its weakness is the high ratio $\frac{surface\,to\,protect}{electrolyte\,volume}$ which can create possible underprotection conditions. The jacket node is a particular weak point also because frail heat affected zones can be present on the surface, which were caused by the many existing welds concentrated close to the node.

5.3.1. Anode positioning

After the dimensioning phase the engineers involved in cathodic protection design have to decide where to place the anodes. Standards and best practices only give very little help regarding anode positioning and this step is usually done following previous experiences. Computer modeling can highlight the flaws made during this stage and help to reposition the anodes to provide a better potential distribution on the surface. Modern softwares, like Comsol, include also tools to optimize some defined parameters, such as potential distribution. Two different models were built to study the potential distribution along a chord of a platform node protected with stand off anodes. A parametric study was made by changing a single geometrical parameter for each model.

The node consisted of a $22m$ long $1m$ diameter leg with attached 7 $0.5m$ diameter crossbeams. The stand off anodes had the following dimensions:

- $L_{anode} = 2m$
- $W_{min} = 0.2m$
- $W_{max} = 0.3m$
- $H = 0.2m$

The constraints regarding the element size parameters of the mesh are shown in table 5.1. To increase the precision of the models, regarding exchanged current evaluation, boundary layer conditions were also set as a mesh constraint. The boundary layer properties consisted in: 4 boundary layers with a 1.2 stretching factor. The definition of a boundary layer constraint increases greatly the number of elements, because the element growth close to the prescribed boundaries is restricted. The time required to mesh the domain also increases greatly.

Table 5.1.: mesh element size parameters of the node mesh.

Selection	**mesh type**	**min (m)**	**max (m)**	**max growth rate**
anode	free triangular	0.005	0.025	1.5
cathode	free triangular	0.04	0.4	1.5
electrolyte	free tetrahedral	0.005	1	1.5
total number of mesh elements	2,209,163			

It was learnt from this work that the best meshing properties were found when the number of elements discretizing the anode and the cathode surfaces were almost equal. In this model for example the anode surface was discretized in 82680 elements, the cathode surface in 99440 elements.

Changing anode distance from the node

It is current practice in CP design to place the anode as close as possible to the node. To verify this common practice a model was created, performing a parametric study of the geometrical distance of the anodes from the node. $2m$, $4.5m$, $7m$ node-anode distances were studied. The potential distribution of the three cases is presented in figure F.1. The three cases under study lead to the following conclusions:

- $L = 2m$ shows a very good potential distribution close to the node, but the potential value drops quickly close to $0.8V$ at the end of the steel support.
- $L = 4.5m$ is the best of the three solutions because the lowest potential on the surface, $0.83V$, is the highest of the three considered solution. It shows the smoothest and most uniform potential distribution.
- $L = 7m$ is the worst solution because the potential on the node has a value below the safe potential $0.8V$.

It can be stated with confidence that the best distance from the node, where the anode has to be placed, is found in between $(2 < L < 4.5)m$. An optimization can be performed to achieve the same potential in the two most critical points: on the node and on the end point of the steel structure. A CP designer should aim to the condition of equal potential reached at the two extremes.

Changing anode distance from the steel surface

It is a standard requirement to place the stand off anodes at a distance greater than $30cm$ from the steel structure [10]. A parametric study was performed changing the distance from $20cm$ to $60cm$ to evaluate the influence on potential distribution along the steel structure. As it is shown in figure F.2 the most influenced area on the steel structure is the one directly facing the anode. When the anode is positioned at $d = 20cm$ the potential reaches the highest value and the potential distribution is not smooth. The electric field on the steel surface is smoothed by anodes placed further away from the steel structure. The potential on the node and at the end of the steel structure is practically not influenced by this parameter.

5.3.2. Changing anode length

A model was created to show the effect on potential distribution, on a steel crossbeam part of a jacket node, as the anode length changes. In figure F.3 is shown the potential distribution along a chord in function of anode length. Anode length is usually specified before performing any computer simulation, but in a near future it might be the case that anode dimensions will be evaluated via an optimization procedure executed automatically. Coupling the optimization module with the secondary current distribution module leads to the possibility of evaluating a specific anode length that brings the point with the lowest electric potential to a specific value (protection potential), as it is stated in equation 5.4.

$$L_{an} \mid (\min(E)_{surface} = E_{protection}) \tag{5.4}$$

- $L_{anode} = 1m$ the surface results under protected, $\phi_{l,node} < 0.8V$;
- $L_{anode} = 2m$ the structure is sufficiently protected;
- $L_{anode} = 3m$ close to the node the potential is very much similar to the $L_{anode} = 2m$ solution, at the opposite side instead the potential maintains a much higher value.

5.4. Changing oxygen limiting diffusion current density

A parametric study was undertaken to show the influence of the oxygen limiting diffusion current density, i_L, on the potential distribution. In a real situation i_L can increase due to stronger sea currents, loss of calcareous deposits as storms hit the structure or particular water depth. An i_L decrease instead can be seen as calcareous deposits build up on the surface. In figure 5.1 is shown the $E - log(i)$ plot as i_L changes value. If the input equations to create figure 5.1 were the ones required by Comsol, that would lead to a $E - log(i)$ graph mirrored around the x-axys. In figure F.4 is shown the potential distribution in function of i_L. It can be seen that with a current density above $50\frac{mA}{m^2}$ the structure results under protected. The electric field is much smoother as current density decreases.

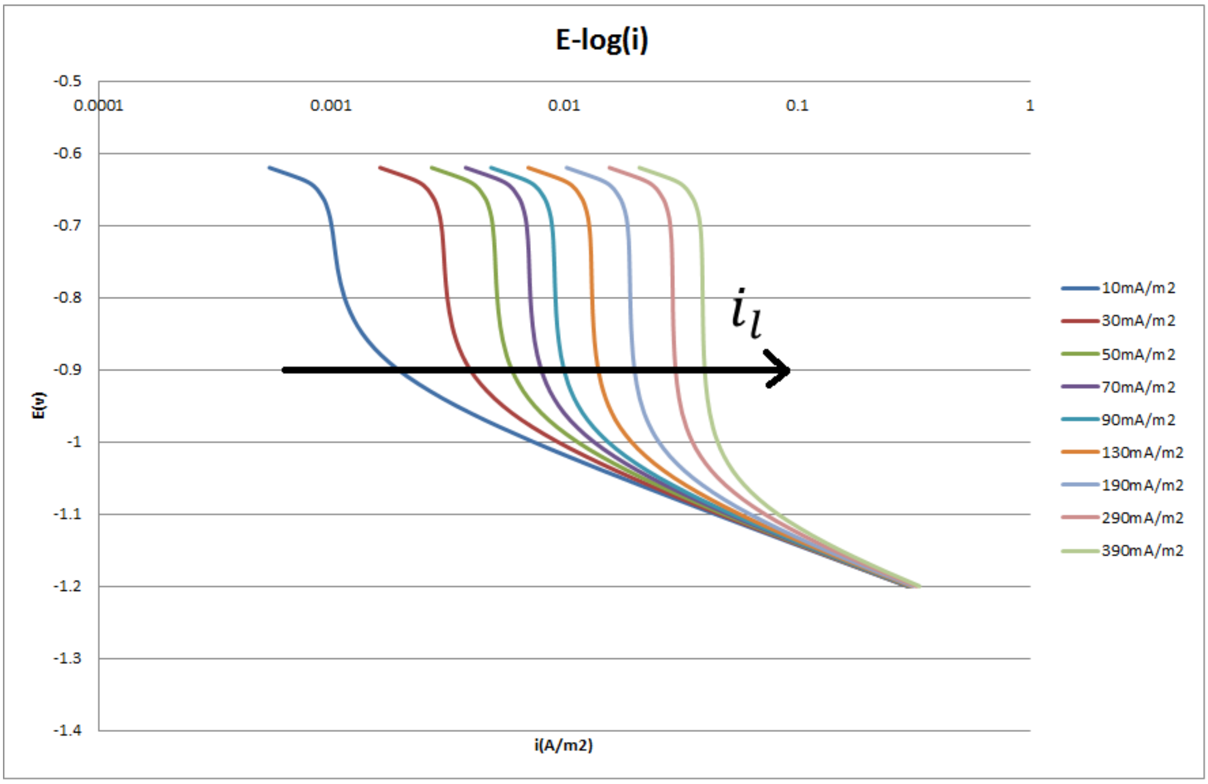

Figure 5.1.: E-log(i) relation as i_L changes.

5.5. What if scenarios

During the life of a structure many unforecasted situations can arise. Some of the most common cases were modeled and studied. Computer modeling is a very powerful tool to study those situations where specific conditions apply and the experience doesn't suffice to give an answer to the recurring question:

> *"Will the structure stay under protection conditions anyway?"*

The structure geometry consisted of:

- 4 foundation poles 50m long, 2m diameter, connected to the jacket structure with sleeves placed in the bottom section of the jacket. During the first simulations the mud-mats were modeled too, but it was soon realized that mud mats complicated too much the model mesh. Therefore in the simulations presented in this report mud mats were not taken into consideration;
- the bottom section of the jacket composed of 24, 0.5m diameter steel cross beams, and 4 foundations pole sleeves. The whole section was protected by 96 stand off anodes. The anodes placed on this section were supposed to protect the foundation poles too;
- 12 nodes identical to the ones studied in section 5.3;

- 24, $0.5m$ diameter conductors[3]. The conductors were 116m long, of which 44m buried in the mud.

The constraints set to generate the mesh are described in table 5.2.

Table 5.2.: mesh element size parameters of the entire jacket mesh

Selection	**mesh type**	**min (m)**	**max (m)**	**max growth rate**
anode	free triangular	0.05	0.05	1.5
cathode, sw	free triangular	0.05	0.4	1.5
cathode, mud	free triangular	0.2	1	1.8
electrolyte	free tetrahedral	0.05	5	1.3
total number of mesh elements	16,400,713			

Mud level rising

It can happen that because of sea currents or other natural effects the mud level rises, covering the bottom section of the jacket structure and the galvanic anodes attached to it. The main concern regarding this situation is due to the lower effectivenes of anodes immersed in mud. One of the main concern is the lower protection level on the foundations. A model with mud rising from normal level up to three meters was studied. This model took the longest time to compute out of all the studies evaluated. Approximatly 24h were required to reach convergency for five mud rising steps. The reason of such a long computing time is the need to re-mesh the whole domain for each modeling step[4]. The potential distribution along the foundation pole is shown in figure F.6.

Losing an anode

Standards and procedures have to be respected during the production phase of anodes, though, it can happen that anodes lose their active material and only the support is left. It can also happen that the welds attaching the support to the structure break down, resulting in the anode loss. A study was made for this case. The two top anodes of the jacket leg were considered as detached and the potential distribution is shown in figure F.7. The potential in the upper part of the leg decreases but the structure remains under protection conditions.

---

[3] A jacket supporting such a large number of conductors is typical for gas storage projects.

[4] The mesh needs to be recomputed for each step in a parametric study in which the geometry changes

Attaching a riser

When attaching a new riser during a revamping work of a jacket, it is often the case that anodes present on the legs have to be removed. The question is if there is the need to replace those anodes. The change in protection conditions were studied for this case. Figures F.7 and F.8 show the potential distribution along a chord of the jacket foundation pole and leg. The removal of such a number of anodes affects greatly the electric potential distribution but the protection conditions are still respected. It can be seen in all the scenarios that the the potential along the surfaces of the foundation pole reaches under-protection value (below $0.9V$), already $5 - 10m$ below the mud line.

5.6. Revamping with ICCP

The increased price of hydrocarbons induces oil companies to increase recovery factors from reservoirs well above the planned, resulting in a longer than expected life time of the related offshore structures. Consequently, the galvanic anodes installed are brought to their end-life and a cathodic protection revamping is necessary. Renovation of galvanic anodes is a costly activity, requiring divers working in saturated conditions for a long time. Due to the fact that fewer anodes are required to be installed underwater for an impressed current cathodic protection system, this arrangement or a hybrid one can be very competitive in the case of a CP revamping. Two models were implemented to study a possible retrofitting on the previously studied jacket geometry. The two modeled systems are similar to the retrolink^{TM} and retrobuoy^{TM} solutions provided by deepwater [19]. The galvanic anodes were not removed but left in place and their potential was considered lowered from the usual $-1.1V$ to $-0.9V$, to take into account the anodes aging.

The study of an entire jacket structure can also help to position the potential probes. The monitoring of cathodic protection performances is achieved via potential measurement with potential probes. The positioning of the probes is also demanded to the designer's experience. A FEM simulation can help engineers to find the most significant spots where most likely the potential will reach the lowest value on the structure.

string anodes

Close to each leg of the platform they were placed 2 strings carrying 15 ICCP anodes equally spaced 5m apart. Anode strings are a common mean of revamping, the strings are steel cables clamped to the structures on which anodes are attached. The main drawback that was noted after performing the simulation was the lack of protection in the lower sections of the structure. The lower section, where the pile sleeves are placed, is a region with a vast surface to protect. The anodes were modeled as equally spaced, leading to an uneven potential distribution. A better solution would have been the one with an increased number of anodes close to the seabottom. Potential distribution along a chord on a foundation pole, in function of total protection current, is shown in figure F.9, potential distribution along the leg is shown in figure F.10.

sled anodes

A sled carrying four ICCP anodes was placed 20m away from each leg of the jacket. The potential distribution along the structure is more uniform than the potential distribution given by string anodes retrofitting. Potential distribution in the electrolyte is shown in figure F.11. Potential distribution along the chord of a foundation pole, as a function of total protection current, is shown in figure F.12, potential distribution along the leg is shown in figure F.13.

5.7. Anode consumption-moving mesh

Time dependent simulations were made to understand anode consumption behaviours. A time dependent simulation like the one performed can condense the whole thirty plus year anode life in a few seconds movie frame. The first simulations to understand the process of simulating a corrosion process utilizing a moving mesh were done with a very simple 2D geometry, to move to more realistic 3D simulations later on. The anode and cathode boundary conditions used in all the models were the ones explained in section 5.2. The time dependent simulations shown in this report were performed using steady boundary conditions, unchanging with time. In a real model the current density required to protect the structure would diminish with time due to the formation of a thicker scale layer[5]. The anodes were considered as made of pure aluminum, with a molar mass of $27\frac{g}{mol}$ and a density of $2700\frac{kg}{m^3}$.

5.7.1. 2D simple geometry

It was created a very simple simulation consisting in two concentric squares. The inner square, $side\,length = 0.1m$, represented the anode and the edges of the outer square, $side\,length = 1m$, reproduced the cathode boundary. The meshing process consisted in defining constraints about mesh size dimensions, as it is described in table 5.3. In figure 5.2 is shown the meshed domain, the anode mesh, being particularly small, is magnified.

---

[5] As calcareous deposits form on the structure, oxygen diffusion through the scale is inhibited.

Table 5.3.: mesh, element size parameters of the 2D simple geometry, moving mesh study

Selection	**mesh type**	**min (m)**	**max (m)**	**max growth rate**
anode	free triangular	0.0003	0.01	1.3
cathode	edge	0.0003	0.01	1.3
electrolyte	free triangular	0.0003	0.1	1.3
total number of mesh elements	36,096			

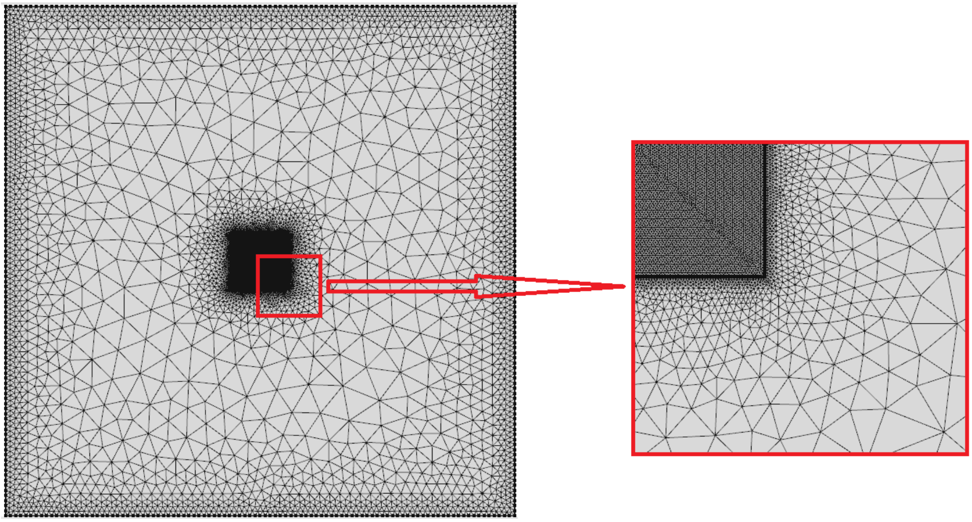

Figure 5.2.: 2D mesh, the anode domain is magnified

On the meshed domain it was performed a time dependent study, using 100 days long time steps, ranging from $time = 0\,days$ to $time = 7200\,days$. The results of the study are briefly summarized in figure G.1 in appendix G. It can be noted the anode shape shrinks from a square to a circle. The reason of this change of geometry is due to the lower ratio $\frac{perimeter}{area}$ possesed by the circle. This model follows exactly what it would happen in nature, where a corroding geometry has the tendency to expose the lowest surface possible.

5.7.2. 3D stand off anode

For offshore applications two different type of anodes geometry are mainly used: stand off and flush mounted. These type of anodes have the same prismatic geometry with a trapezoidal base[6]. The difference is given by the support, which keeps the flush mounted type attached to the structure and the stand off type more than 30cm away from the surface [10]. A typical stand off anode is shown in figure 5.3. The first models were studied including the anode support but it was soon realized that the influence of the support on the model results was minimal (the steel supports represented just a small fraction of the cathode surface). A model with the steel support included required a much finer mesh and an increased number of mesh elements which resulted in longer computing time. Therefore, for modeling ease, the anode support was not taken into consideration.

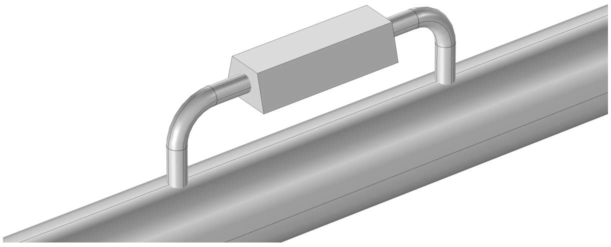

Figure 5.3.: Stand off anode with support

After the succesful first attempt with the 2D geometry a 3D geometry was studied. The model represented a stand off anode immersed in an electrolyte, to protect a cylindrical shaped structure. The electrolyte was modeled as a block containing the structure to protect and the anode. The mesh constraints are presented in table 5.4, and the meshed domain is shown in figure 5.4.

Table 5.4.: mesh element size parameters of the 3D stand off anode, moving mesh study

Selection	mesh type	min (m)	max (m)	max growth rate
anode	free tethraedral	0.01	0.03	1.5
cathode	free triangular	0.04	0.2	1.5
electrolyte	free tethraedral	0.01	1	1.2
total number of mesh elements	218,004			

---

[6] The base is trapezoidal because of the ease given by this shape during the extraction from the mould after casting.

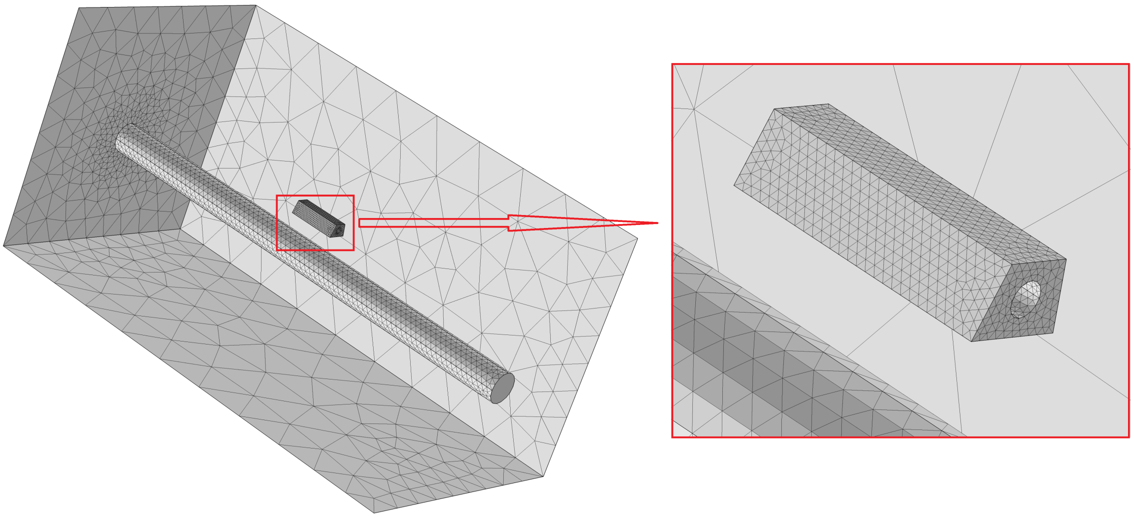

Figure 5.4.: Stand off anode mesh

The boundary conditions were set as:

- cathode: cylinder outer surface;
- anode: six outer faces of the stand off anode geometry;
- insulation: the six faces of the block and the inner faces of the anode, where the support is supposed to be placed.

On the meshed domain it was performed a time dependent study, using 100 days long time steps, ranging from $time = 0\,days$ to $time = 14000\,days$. The electrolyte potential distribution in four particular moment of the structure life is shown in figure G.2 in appendix G. The change in anode dimensions and shape is easily detectable. The potential distribution along the upper chord of the cylinder, which is closer to the anode, it is shown in figure . It can be seen that:

- The absolute value of the potential decreases as time passes with a more than linear relation;
- The highest potential is found closer to the anode;
- The potential reaches an horizontal asymptote.

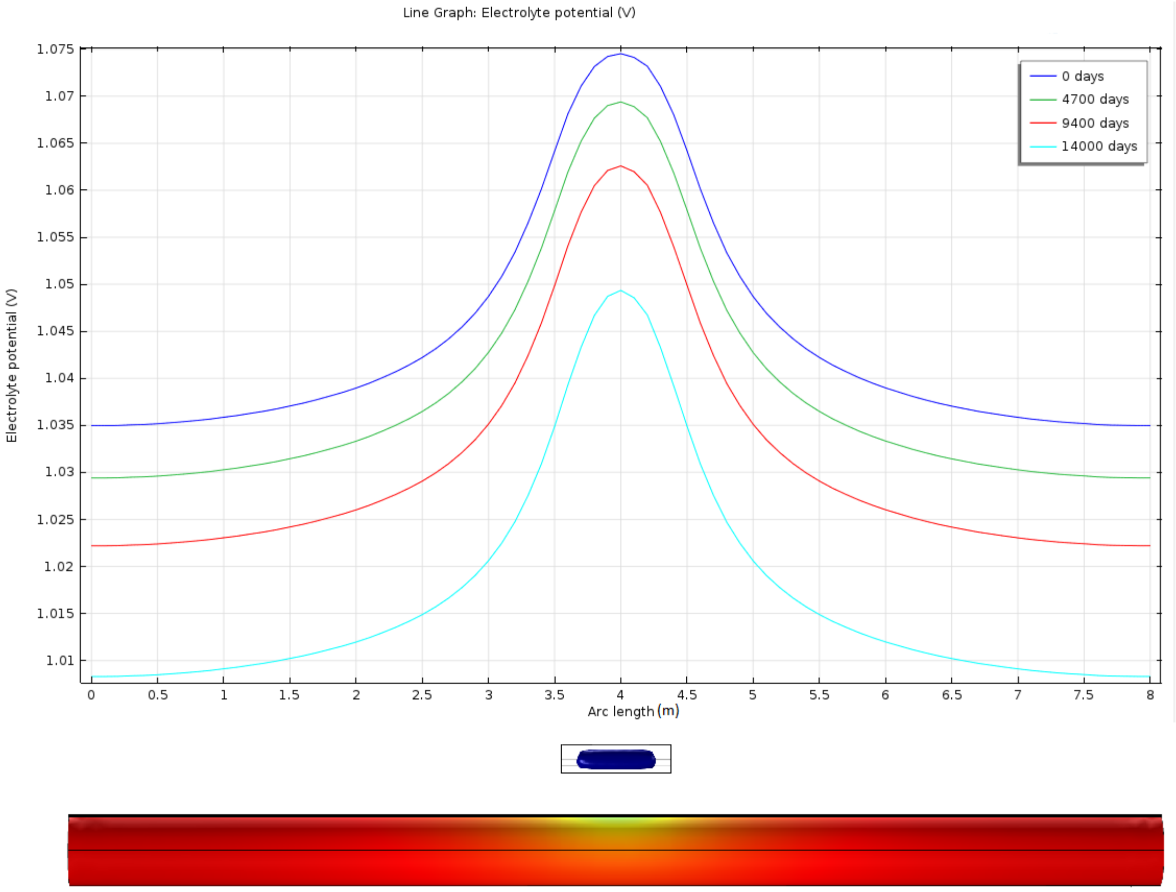

Figure 5.5.: Stand off anode potential distribution along a chord

Jacket node

A model of a structural node of a jacket was built. Eleven stand off anodes were placed around the structure. Like in the previous case the support of the anodes was not modeled. The influence on the output results of the support is minimal and the problems connected to modeling the support greatly overcome the benefits. The constraints regarding the mesh are displayed in table 5.5, and the meshed domain is shown in figure 5.6.

Table 5.5.: mesh element size parameters of the jacket node, moving mesh study

Selection	**mesh type**	**min (m)**	**max (m)**	**max growth rate**
anode	free tethraedral	0.01	0.05	1.5
cathode	free triangular	0.1	1	1.5
electrolyte	free tethraedral	0.01	5	1.5
total number of mesh elements	675'388			

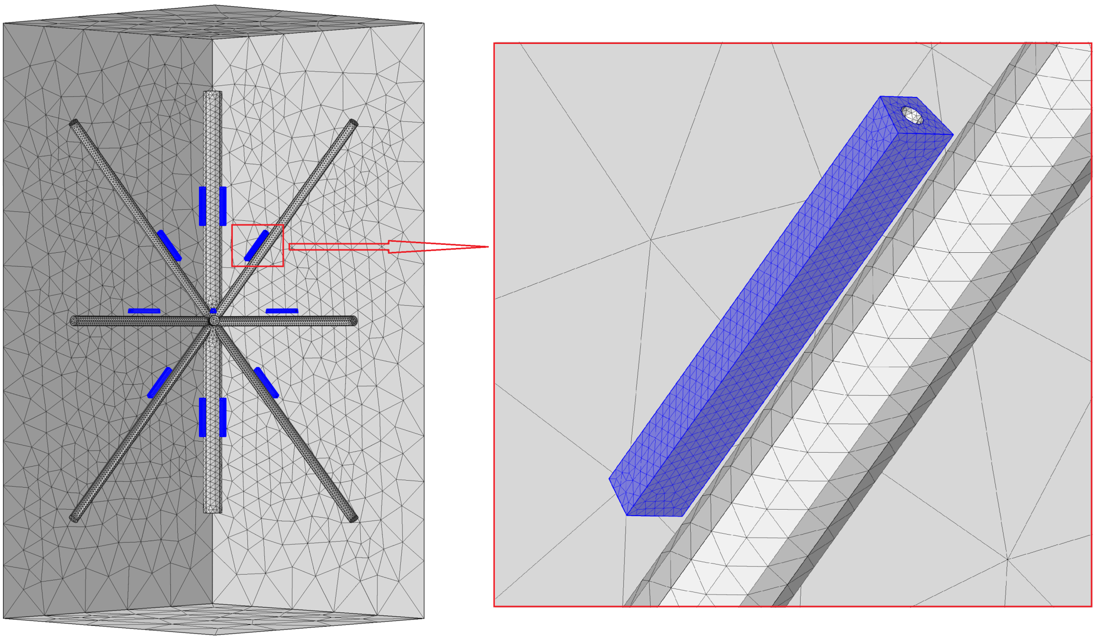

Figure 5.6.: Jacket node anode and structure mesh

The boundary conditions were set as:

- cathode: steel structure consisting in the outer surfaces of the eight cylinders;
- anode: six outer faces of all the eleven stand off anodes;
- insulation: the six faces of the block and the inner faces of the anodes, where the support is supposed to be placed.

On the meshed domain it was performed a time dependent study, using 1 year long time steps, ranging from $time = 0\,years$ to $time = 36\,years$. The electrolyte potential distribution in four particular moment of the structure life is shown in figure G.6 in appendix G. Under protection conditions are never reached but it can be seen that the least protected surface (blue color) increases in size as anodes shrink. In figure G.7 it is shown a magnified figure of one of the anode as time passes by, both length and section decrease in size. Figure 5.7 shows the graph of the potential distribution along a chord of the structure. The same circumstances noted for the previous case can be noted in this model too, other information visible in this grapgh are:

- The potential distribution at the edges (close to 0 and 22 meters arc length) it is probably not correct. As it was noted in the previous case for the single anode the potential should reach an asympthote. This is probably due to the electrolyte insulation boundary posistioning.
- The potential distribution is not simmetrical, which is correct because the structure geometry is not symetrical and the anodes are not placed symetrically(on the three horizontal supports the anodes are placed on the upper side);
- The potential minimum is found close to the node where the ratio $\frac{surface\,to\,protect}{electrolyte\,volume}$ reaches the highest value.

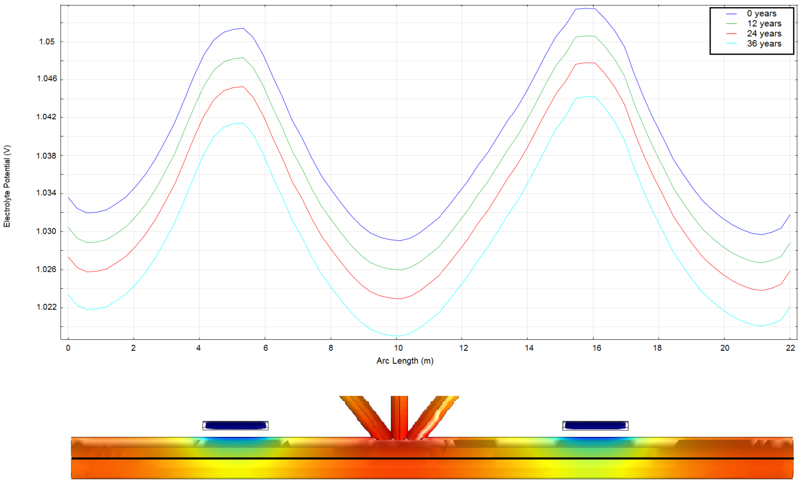

Figure 5.7.: Knot of a jacket potential distribution along a chord

In figure 5.8 is represented the current exchanged between anodes and cathode, I, in function of time as anodes dimensions shrink. I is calculated as $\iint\limits_{S_c} i\,dA_c = \iint\limits_{S_a} i\,dA_a$. It is also shown in the same graph the specific consumption of anodic material, Δm, in function of time. As time goes by anode extensions shrink and the electric resistance associate with the anodes dimensions builds up. Consequently I diminishes. The product $I\,\Delta time$ evaluates the energy released in the electrochemical processes and the ratio $\dfrac{I\,\Delta time}{\Delta m}$ estimates the electrochemical efficiency, ϵ, of the anodic material. The electrochemical efficiency, along all the time steps considered, was evaluated at an almost constant value of $\epsilon = 2980\frac{A\,h}{kg}$. A constant value of ϵ is an assurance of good model behaviour.

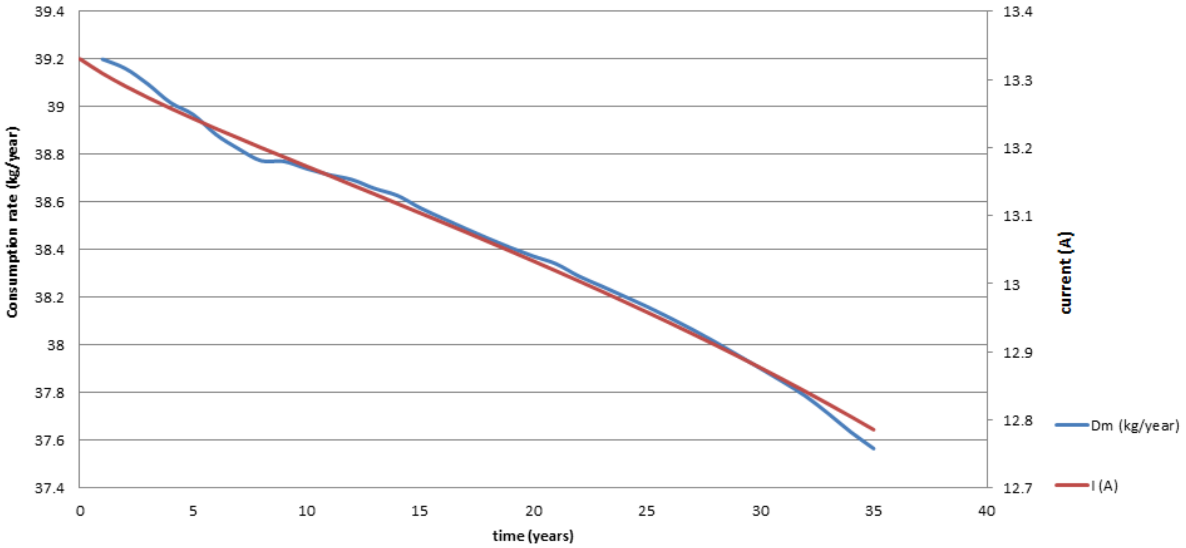

Figure 5.8.: Current provided by the 11 galvanic anodes and their specific consumption, in fuction of time

5.7.3. 3D Flush mounted anodes

Flush mounted anodes are usually employed for those structures such as FPSOs and ships, for which hydrodinamic is an important parameter. This type of anode offers less drag resistance than a flush mounted type. Another field of application of this anode type is inside caissons and places with little space available. Flush mounted anodes are coated with an insulating paint on the surface facing the structure to protect, as required by DNV-RP-B401 [10]. A time dependent computer model was created to study the potential variation as time passes by and the anode dimensions shrink. The insulating shield was modeled as 1cm thick block, covering the anode surface that faces the cathode as it can be seen in figure 5.9 coloured in blue. The mesh constraints are shown in table 5.6.

Table 5.6.: mesh element size parameters of a flush mounted anode, moving mesh study

Selection	**mesh type**	**min (m)**	**max (m)**	**max growth rate**
anode	free tethraedral	0.004	0.02	1.5
cathode	free triangular	0.04	0.2	1.5
insulation	free triangular	0.001	0.03	1.5
electrolyte	free tethraedral	0.001	1	1.2
total number of mesh elements	280'432			

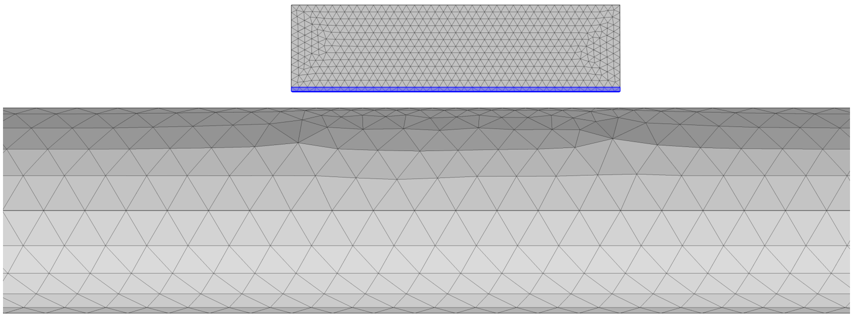

Figure 5.9.: flush mounted anode with insulation (blue colour) meshed domain

The boundary conditions were set as:

- cathode: cylinder outer surface;
- anode: five outer faces of the stand off anode geometry;
- insulation: the six faces of the block and the six faces of the insulating material

The study was conducted from $time = 0days$ to $time = 8000days$. It was tried to perform a study with longer final time but the model did not converge. The surface potential of the structure close to the node is shown in figure G.3 and the potential distribution along the chord of the structure can be seen in figure G.4. The potential distribution shows that the surface of the structure facing directly the anodes has a lower potential than the surroundings, because of the insulating material modeled underneath the anode.

A comparison of the potential distribution given by a flush mounted anode and the one given by a stand off type is shown in figure G.5. The two anodes used had the same geometric dimensions. It can be seen that the flush mounted anode type gives a potential distribution less smooth compared to the stand off anode distribution, this is mainly due because of the shorter distance anode-structure for the flush mounted case. A good solution for flush mounted type anodes is coating the surface nearby the anode with an insulating paint[7] or insulating material.

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[7] The paint has to be cathodic disbondment proof

6. Conclusion and future work

> Some day I'm going to climb Everest.
>
> Sir Edmund Hillary

6.1. Conclusion

This chapter reports summarily the results achieved during this master thesis work. The achievements of the work accomplished in Tecnomare with the empirical design softwares, and the attainments reached modeling CP systems with Comsol are presented.

6.1.1. Offshore structure software

The offshore structures software created in Tecnomare enables CP designer to quickly reach optimized and consitent results. The software can be employed to design CP systems of different offshore structures, both coated and uncoated. The software was designed for O&G jacket but it can be used safely for offshore wind turbine platforms. Time is saved for the whole CP design process, the temporal length needed from the beginning of the design activity to the issue for comments phase is greatly reduced compared to previous design procedures. The software was created as user friendly as possible to guide the user through the data input process and explain the output via help buttons and Graphical User Interfaces. The optimization tool help to select the anode geometries that minimize weight or cost, keeping the design always inside safety limits dictated by rules and Standards. The automatic creation of the Word report, ready for issue, is a useful tool that homogenizes the output results of the CP design and saves the time needed to compile the documents. The software can be used as a tutorial to help newcomers to understand rapidly CP deisgn. The validation process, which has has been the first of its kind done by Tecnomare, sets a benchmark for new validation processes and software implementation.

6.1.2. Onshore pipelines software

The CP design software for onshore pipelines was created after its offshore counterpart, beacuse of the experience aquired during the offshore software implementation, most of the mistakes made previously were avoided (e.g. the software maintenance was kept as a paramount factor during all the implementation phase). The software guides the user through the design of the CP system dimensioning. The program is also helpful to quickly check the results of projects developed by third parties using different approaches to calculate the feeding voltage requirements. The software was created with ease of maintance and user-friendliness in mind.

6.1.3. CP computer modeling

The work accomplished with Comsol in this thesis pushes forward the boundaries of CP FEM computer modeling for practical applications in the O&G industry. It was shown that even an entire jacket structure can be studied and placed under test with commonly used computer tools. Coupling CP systems heuristic design with computer modeling can help designer to avoid project flaws and increase safety. The results obtained show the advantages of parametric studies and optimization analysis employing modern computer tool (e.g. in the positioning of the anodes phase of CP system design). What if scenarios can be easily implemented, and effective solutions evaluated. CP time dependent moving mesh studies can forecast galvanic anode behaviours as time goes by for the whole structure design life. These models could not be implemented for entire jacket structures because of hardware constraints, but instead they proved very useful, and of feasible implementation, to study specific parts. In a near future with more powerful computers, time dependent models (coupled with a moving mesh) of entire jacket CP systems, will be probably attainable.

The use of computer modeling during the design stage of CP system design can assist to:

- reduce the conservative approach, increasing efficiency and effectivness;
- improve CP systems performances;
- increase design confidence;
- simulate real cases and what if scenarios.

The main drawbacks about CP computer modeling:

- need of reliable boundary conditions, mainly in function of calcareous deposits, which is the main disadvantage of CP computer models and a change in CP system design approach is required;
- longer design time and effort to produce noteworthy results.
- need of validation and long track of records;

- dedicated software licences and predisposed computers have to be bought (the estimated costs to set up a commercial CP computer modeling activity are $\approx 20 - 30kEuro$);
- need to train qualified personnel[1], which is an additional cost.

Corrosion protection, showing its long run effectiveness mainly in the future, remains an underestimated topic and the scarce and late applications of CP computer modeling is a clear symptom of it. To secure an intense use of computer modeling, applied to CP systems, it is firstly required to the O&G industry to give more consideration to CP design and its implications.

6.2. Future work

More work needs to be carried out for the empirical design software and more possibilities were open by the use of FEM computer modeling with Comsol.

6.2.1. Empirical design Software

The offshore external structure software can be considered completed and only maintanance work is required, instead the offshore and onshore pipeline softwares require to be validated. Optimization modules and automatic Word reports implementation should be created for all the softwares. A software procedure, to follow during all the future projects implemented with VBA undertaken in Tecnomare SPA, should be written and followed with the aim to simplify maintenance and homogenize the softwares produced.

6.2.2. Need of validation

Model validation is probably the most important step during the process of computer modeling. The Boundary conditions set in the models came from empirical experiments, therefore the model basis were already validated. A validation of the presented complete models could not be done during this work for the following reasons:

- The time and economical effort required to undertake a potential monitoring campaign on a real structure was prohibitive;
- The Comsol licence possessed didn't allow any commercial work, therefore no real structure was modeled but only realistic structures.

In the case a company is interested in CP computer modeling with Comsol only the geometry and the boundary conditions will need to be changed to obtain real models. The algorithm and the main concepts to model CP are already set and stated in this work and in the models produced.

---

[1] From the experience acquired, it was understood that personnel can be self motivated and even excited to learn CP computer modeling approach, therefore augmenting its productivity with real benefits for the company.

6.2.3. Interference induced by a nearby structure

Interference from nearby structures due to stray currents, such as oil tankers or barges mooring on a wharf, can nullify corrosion protection from the CP system. A computer model can help to estimate and predict interference with the aim to reduce their negative effects. Interference mitigation required in the past a considerable and expensive work on the field to track electric potential changes on adjacent structures[30].

To model interference related problems the usual boundary conditions apply on the structure, additionally another constraint needs to be set on the surface. The additional constraint is shown in equation 6.1, which dictates that all the interference current entering the electrode surface, S, has to leave from the same surface S. To set such a constraint in Comsol the usual current distribution module has to be coupled with the Partial Differential Equation or the Optimization module. The domain in such a problem is constituted by both the electrolyte and the electrode. Interference related models were implemented in Comsol during this work but no satisfactory results were achieved so far.

$$\oint_{S} i \, \mathrm{d}S \tag{6.1}$$

6.2.4. Coated structures

Coating offshore jackets provides the opportunity to reduce the current necessary to polarize the structure. Lower current requirements means less anodic material, which is needed to protect the platform. Less anodes means less drag, lighter structures and consequently lower costs. A new possibility to apply protective coatings to structures comes from FPSO CP requirements, though cathodic disbondment and coating protection uncertainty are very much present points of focus. Wind turbine platform could also benefit from computer modeling of coated structure to design their CP systems.

Computer modeling can be a very helpful tool to study coated structure CP systems and mitigate the problems related to it. Anodes positioning has to be done much more carefully when dealing with a coated structure than in the case of bare surfaces. The most critical point of this technique is the possibility of coating damage. A damaged coating could lead to above corrosion potential conditions, resulting in an unprotected structure. Also, cathodic protection applied to a surface, coated with a not suitable paint, might lead to the cathodic disbondment phenomena, where the barrier coating detaches from the surface because of the formation of hydrogen at the coating-metal surface interface. In the past, coating the surfaces of jacket was tried in the North Sea area, to mitigate the large currents needed to keep structures protected. Because of the above mentioned problems, this technique was abandoned. Coating cathodic surfaces is kept as a possibility in corrosionists' mind in cases where factors such as long design life, severe environmental conditions, and structures with high surface to volume ratio, are found.

6.2.5. Multiphysics modeling of cathodic protection

As it was stated in section 2.2.2 calcareous deposits is the most influencing parameter in CP design. The ability to model calcareous deposition, in function of time, can give the opportunity to understand thoroughly CP systems design. The improvements in computers software and hardware have given the possibility to model not only single physics phenomena but to couple different physics simoultaneosly to have more sophisticated and reliable models. Scale deposition can be studied with a time dependent multiphysics model in Comsol, coupling different physics to attain a realistic forecast of calcareous formation and consequent current requirements to protect the structure. As it is stated by Comsol in the tertiary current distribution module [34], about the equations involved:

> *"These are solved while considering the transport of ions and neutral species in the solution, the current conduction in the metal structure, and other phenomena such as fluid flow and heat transfer."*

The Comsol modules[2] necessary to set a multiphysics model of calcareous deposits formation in sea water are:

- Fluid dynamics, which specifies the velocity field;
- Mass transfer of chemical components, in which the diffusion and convection of diluted species is calculated via the coupling with the fluid dynamics and chemical reactions modules both in the electrolyte and in the scale deposit;
- Chemical reactions, which determinines the chemical reactions involved in calcareous deposition as function of species concentration and current distribution;
- current distribution, which is function of the chemical reactions taking place on the surface.

Firstly, simple models and laboratory tests should be set up to gather all the required parameters and to validate the multiphysics models. The hardware and software tools available nowadays are already able to solve these problems.

---

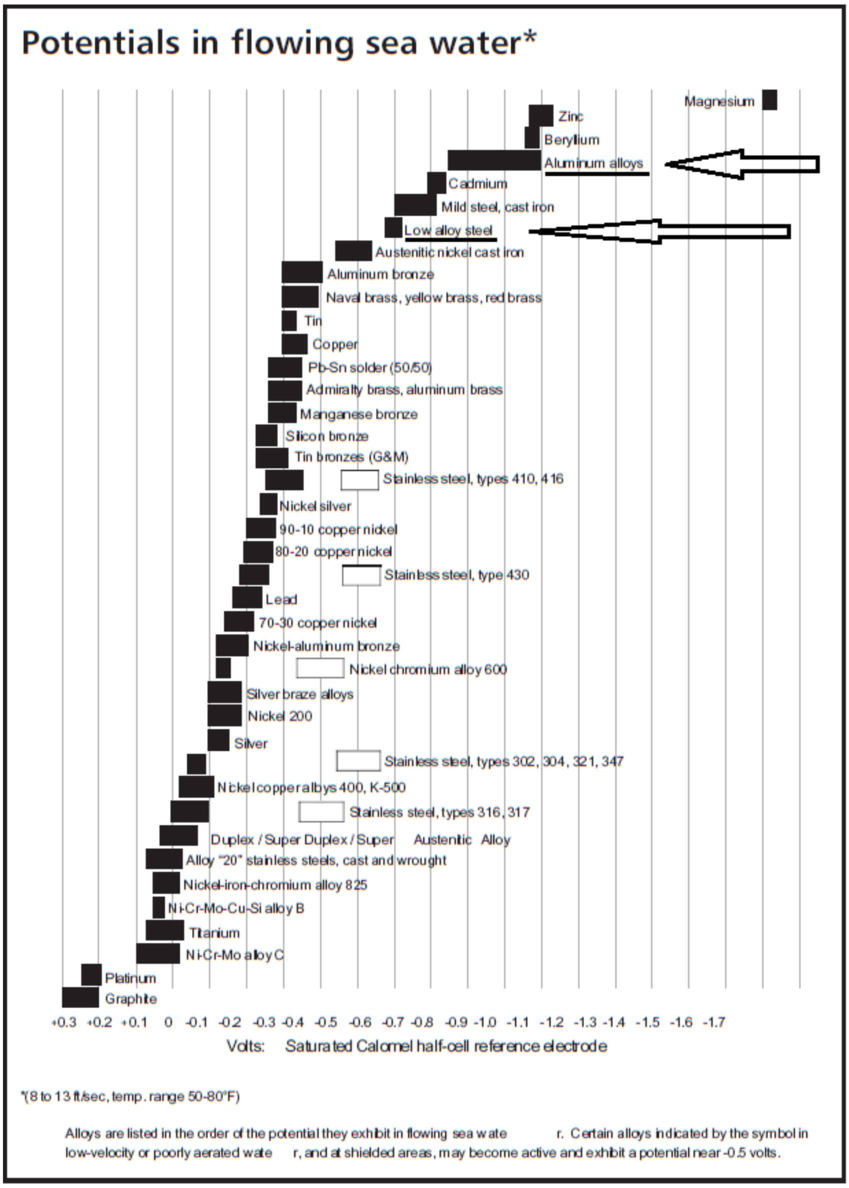
[2] The heat transfer module is not necessary for seawater scale deposition modeling on CP protected surfaces.

Nomenclature

$\Delta_r G$	Molar Gibbs reaction Energy
γ	stoichiometric coefficient
a_i	activity of the i^{th} species
AC	Alternate Current
BEM	Boundary Element Method
$CCVT$	Closed cycle vapor turbogenerators
CEN	European Committee for standardization
CP	Cathodic Protection
DC	Direct Current
DNV	Det Norsk Veritas
E	Electric potential
$E-i$	Electric potential-current relation
E_{eq}	reaction equilibium potential
ENI	Ente Nazionale Idrocarburi
F	Faraday's constant
FDM	Finite Difference Method
FEM	Finite Element Method
$FPSO$	Floating Production Storage and Offloading
FPU	Floating Production Unit
G	Gibbs energy

GUI	Graphical User Interface
i_a	anodic reaction current density
i_{corr}	corrosion current density
i_c	cathodic reaction current density
$ICCP$	Impressed Current Cathodic Protection
ISO	International Organization for Standardization
$NACE$	National Association of Corrosion Engineers
$O\&G$	Oil and Gas
R	Univeral constant
T	Temperature
TR	Transformer Rectifier
VBA	Visual Basic for Application
z	number of electrones involved in the reaction
ΔE	electric overpotential
$\Delta E_{anodic\ process}$	anodic process activation overpotential

A. Galvanic series



*(8 to 13 ft/sec, temp. range 50-80°F)

Alloys are listed in the order of the potential they exhibit in flowing sea water. Certain alloys indicated by the symbol in low-velocity or poorly aerated water, and at shielded areas, may become active and exhibit a potential near -0.5 volts.

Figure A.1.: Galvanic series of metal in flowing sea water [35]

B. Offshore structures

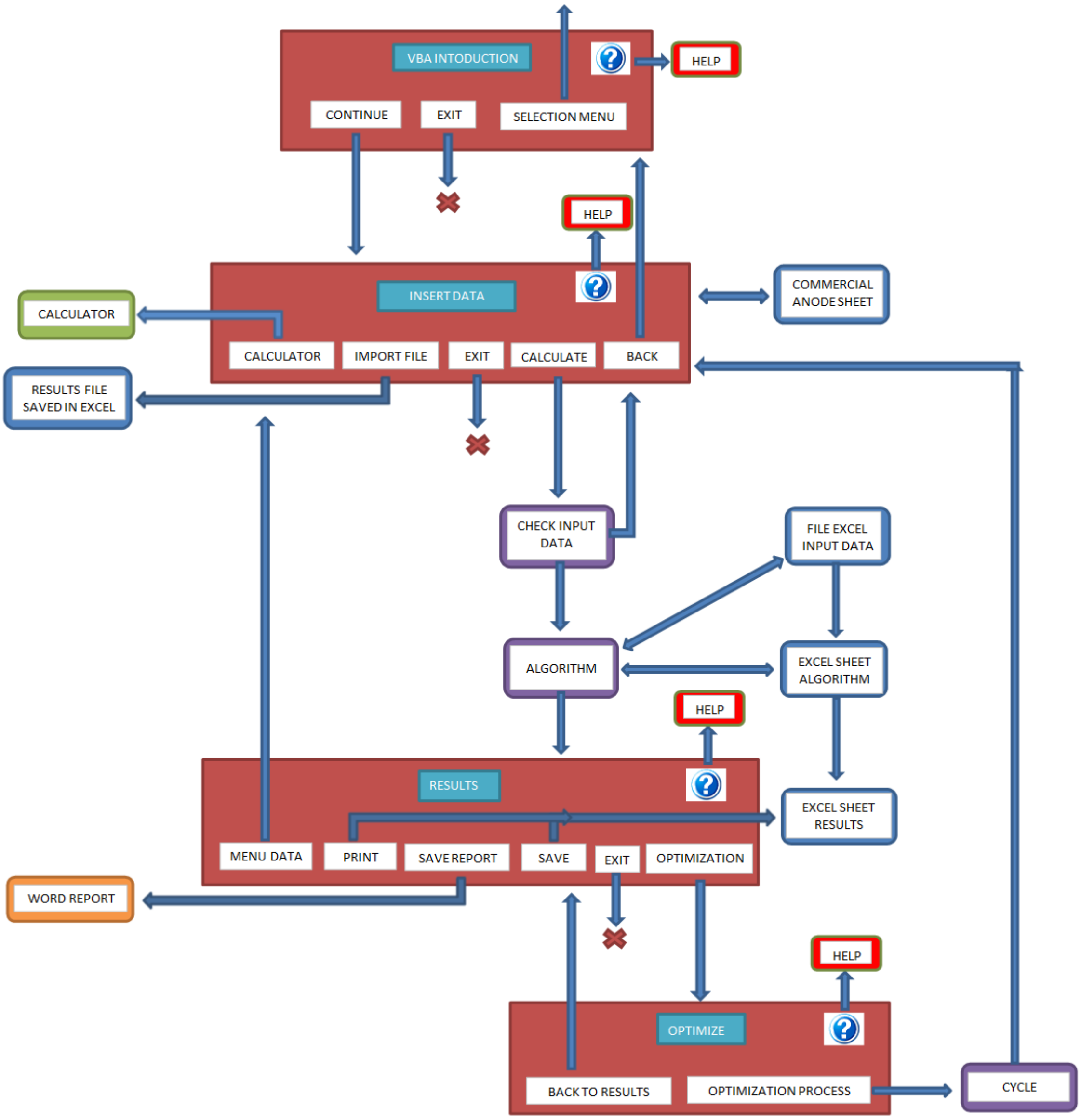
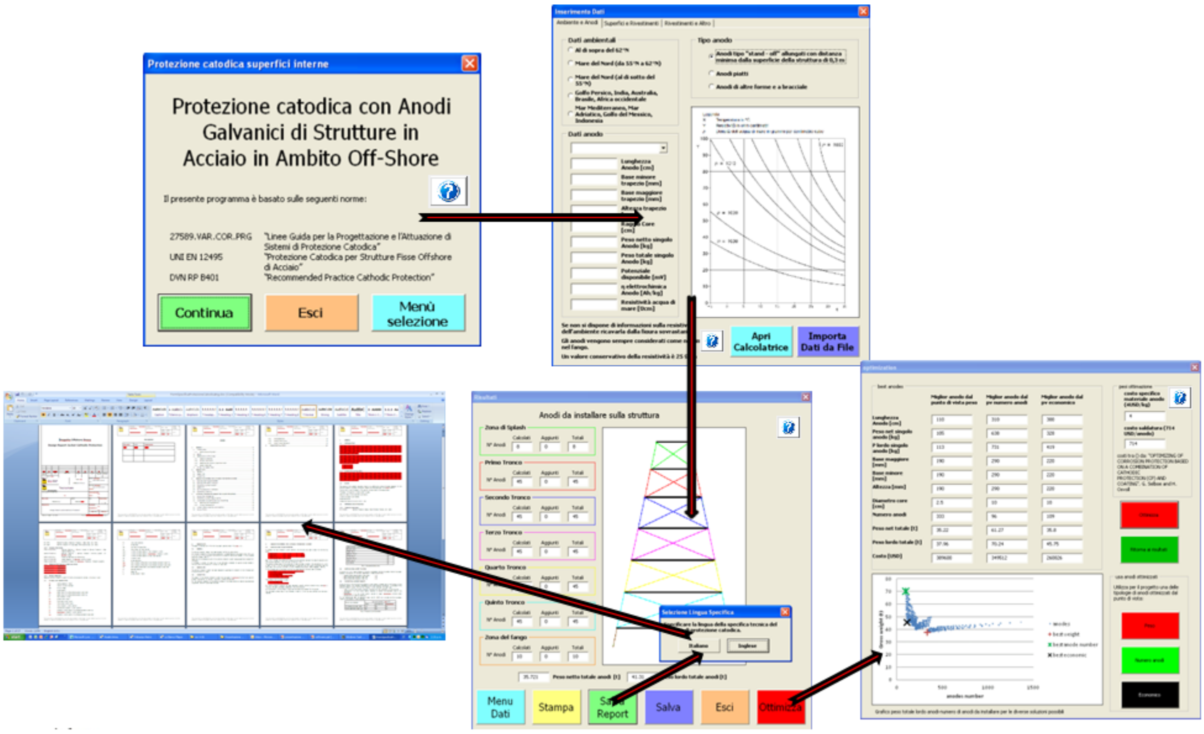


Figure B.1.: Software flow chart.



Protezione catodica superfici interne

Protezione catodica con Anodi Galvanici di Strutture in Acciaio in Ambito Off-Shore

Il presente programma è basato sulle seguenti norme:

27589.VAR.COR.PRG "Linee Guida per la Progettazione e l'Attuazione di Sistemi di Protezione Catodica"

UNI EN 12495 "Protezione Catodica per Strutture Fisse Offshore di Acciaio"

DVN RP B401 "Recommended Practice Cathodic Protection"

Figure B.2.: Jacket, software userforms

Figure B.2 explanation:

- upper left: introduction
- upper right: input data, multipage userform
- lower left: Microsoft Word report italian/english
- lower center: results
- lower left: optimization

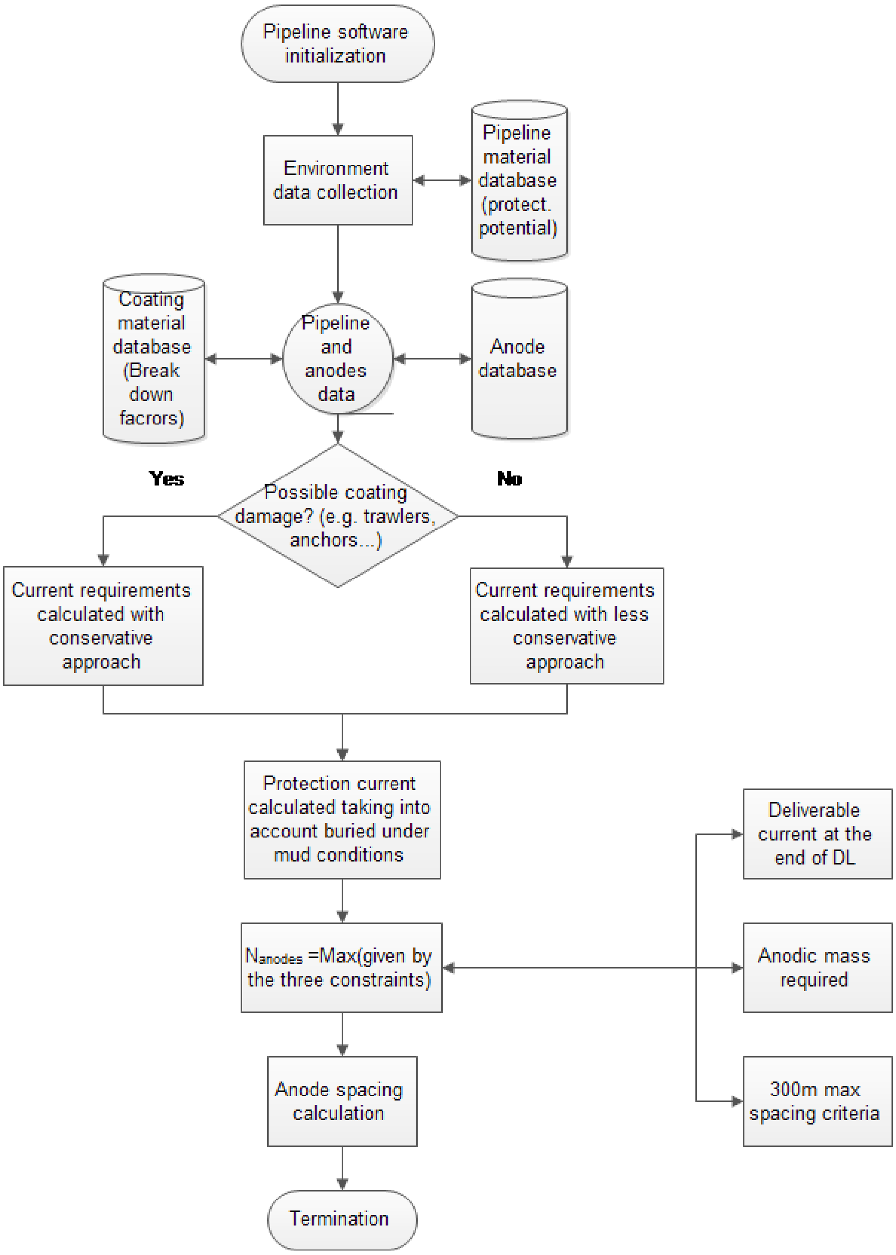
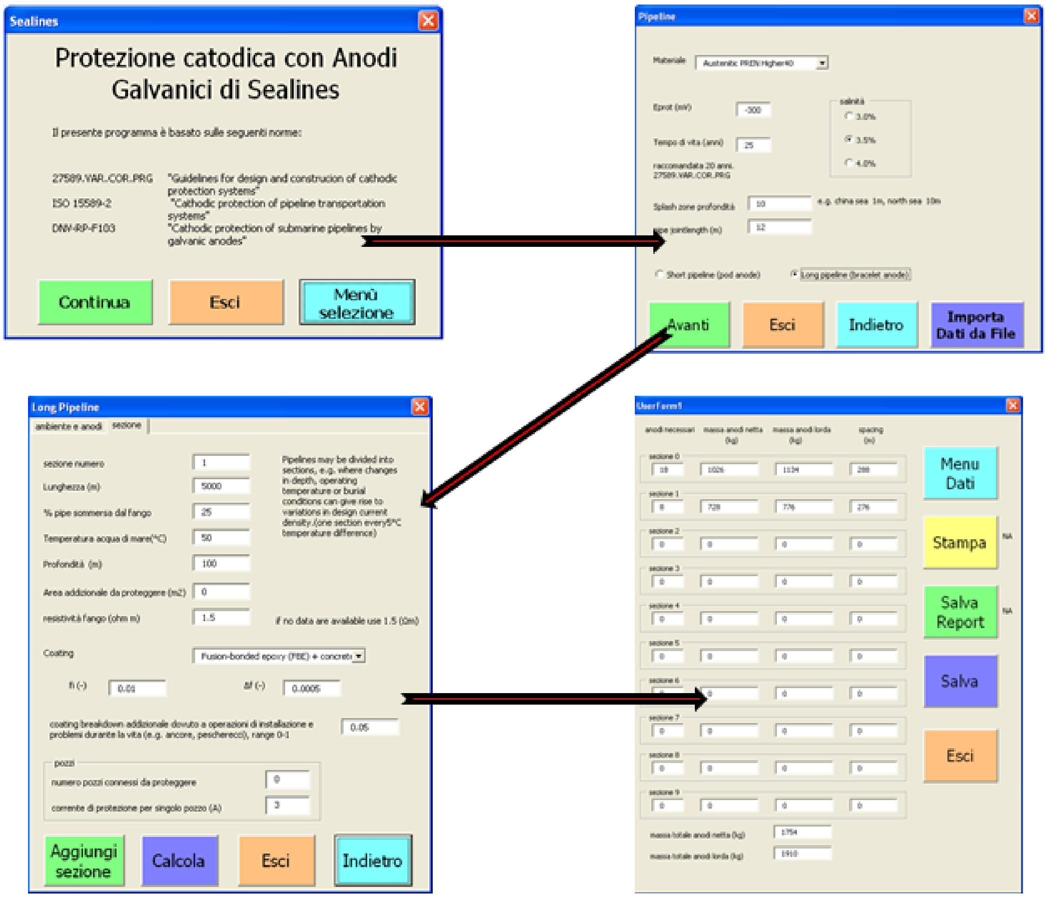


Figure B.3.: Bracelet anodes offshore pipeline CP system dimensioning, brief algorithm flow chart.



Protezione catodica con Anodi Galvanici di Sealines

Il presente programma è basato sulle seguenti norme:

27589.VAR.COR.PRG	"Guidelines for design and construcion of cathodic protection systems"
ISO 15589-2	"Cathodic protection of pipeline transportation systems"
DNV-RP-F103	"Cathodic protection of submarine pipelines by galvanic anodes"

Materiale: Austenitic PREN Higher40

Eprot (mV): -300

Tempo di vita (anni): 25

raccomandata 20 anni. 27589.VAR.COR.PRG

salinità: ○ 3.0% ● 3.5% ○ 4.0%

Splash zone profondità: 10 e.g. china sea 1m, north sea 10m

pipe jointlength (m): 12

○ Short pipeline (pod anode) ● Long pipeline (bracelet anode)

sezione numero: 1

Lunghezza (m): 5000

% pipe sommersa dal fango: 25

Temperatura acqua di mare(°C): 50

Profondità (m): 100

Area addizionale da proteggere (m2): 0

resistività fango (ohm m): 1.5 if no data are available use 1.5 (Ωm)

Pipelines may be divided into sections, e.g. where changes in depth, operating temperature or burial conditions can give rise to variations in design current density.(one section every5°C temperature difference)

Coating: Fusion-bonded epoxy (FBE) + concrete

fi (-): 0.01 Δf (-): 0.0005

coating breakdown addizionale dovuto a operazioni di installazione e problemi durante la vita (e.g. ancore, pescherecci), range 0-1: 0.05

pozzi

numero pozzi connessi da proteggere: 0

corrente di protezione per singolo pozzo (A): 3

	anodi necessari	massa anodi netta (kg)	massa anodi lorda (kg)	spacing (m)
sezione 0	18	1026	1134	288
sezione 1	8	728	776	276
sezione 2	0	0	0	0
sezione 3	0	0	0	0
sezione 4	0	0	0	0
sezione 5	0	0	0	0
sezione 6	0	0	0	0
sezione 7	0	0	0	0
sezione 8	0	0	0	0
sezione 9	0	0	0	0

massa totale anodi netta (kg): 1754

massa totale anodi lorda (kg): 1910

Figure B.4.: Offshore pipeline, Bracelet anodes, software userforms

Figure B.4 explanation:

- upper left: introduction
- upper right: environment input data
- lower left: pipelines and anodes input data, multipage
- lower center: results

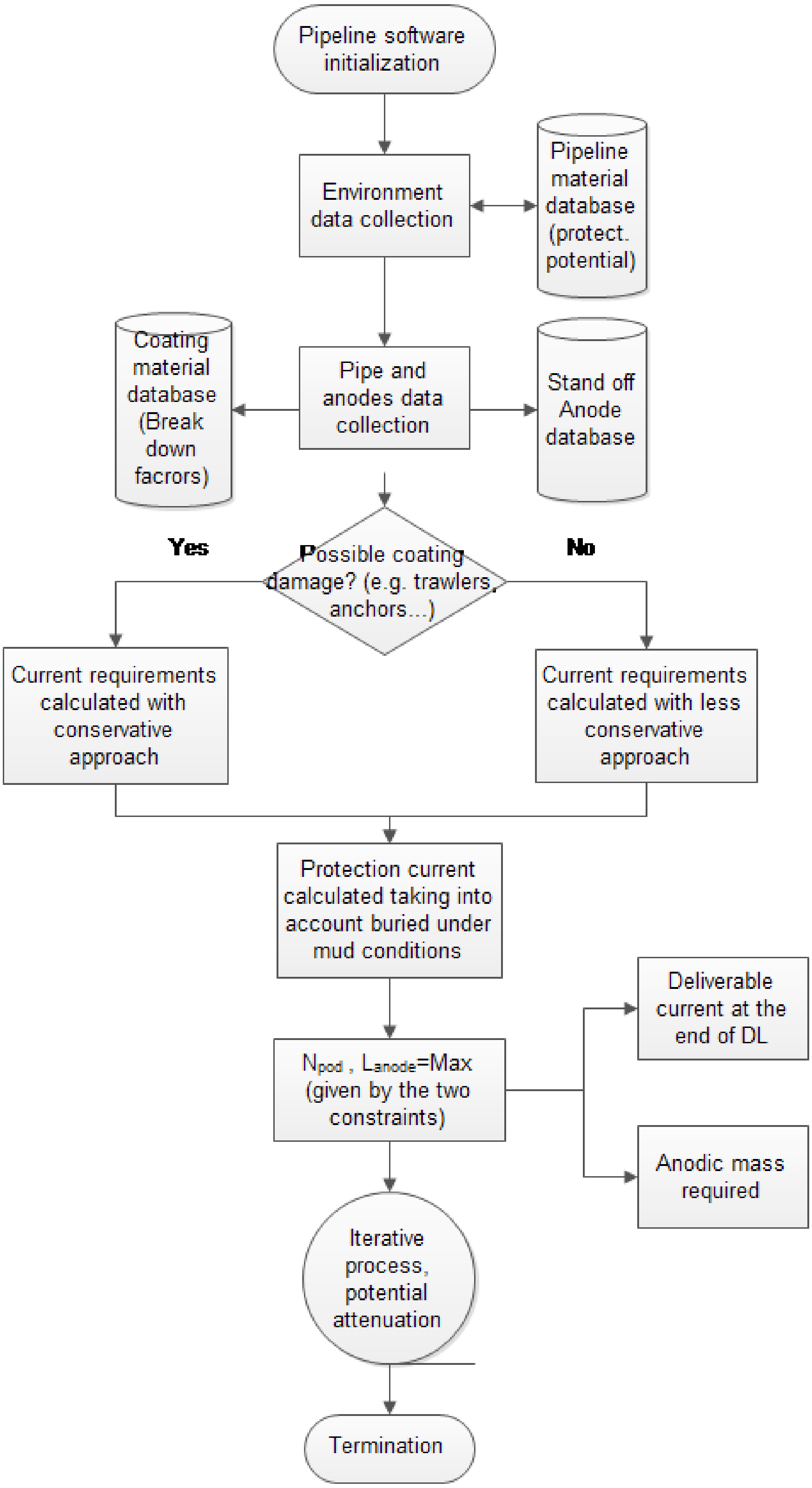
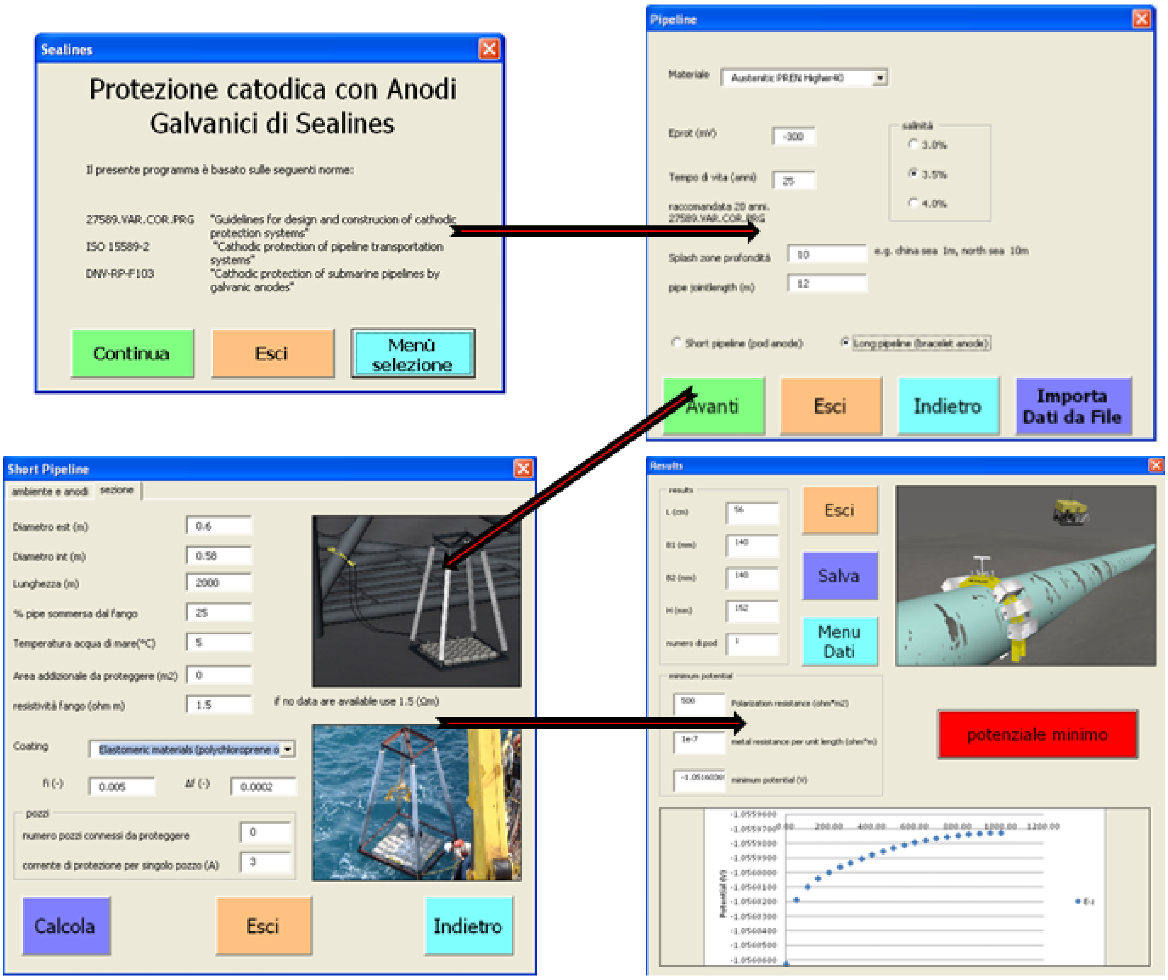


Figure B.5.: Pod anode offshore pipeline CP system dimensioning, brief algorithm flow chart.



Protezione catodica con Anodi Galvanici di Sealines

Il presente programma è basato sulle seguenti norme:

27589.VAR.COR.PRG "Guidelines for design and construcion of cathodic protection systems"
ISO 15589-2 "Cathodic protection of pipeline transportation systems"
DNV-RP-F103 "Cathodic protection of submarine pipelines by galvanic anodes"

Materiale: Austenitic PREN Higher40
Eprot (mV): -300
Tempo di vita (anni): 25
raccomandata 20 anni. 27589.VAR.COR.PRG
salinità: ○ 3.0% ● 3.5% ○ 4.0%
Splash zone profondità: 10 e.g. china sea 1m, north sea 10m
pipe jointlength (m): 12
○ Short pipeline (pod anode) ● Long pipeline (bracelet anode)

Diametro est (m): 0.6
Diametro int (m): 0.58
Lunghezza (m): 2000
% pipe sommersa dal fango: 25
Temperatura acqua di mare(°C): 5
Area addizionale da proteggere (m2): 0
resistività fango (ohm m): 1.5 if no data are available use 1.5 (Ωm)
Coating: Elastomeric materials (polychloroprene o
fi (-): 0.005 Δf (-): 0.0002
pozzi
numero pozzi connessi da proteggere: 0
corrente di protezione per singolo pozzo (A): 3

results
L (cm): 56
B1 (mm): 140
B2 (mm): 140
H (mm): 152
numero di pod: 1
minimum potential
500 Polarization resistance (ohm*m2)
1e-7 metal resistance per unit length (ohm*m)
-1.0516036 minimum potential (V)

Figure B.6.: Offshore pipeline, pod anodes, software userforms

Figure B.6 explanation:

- upper left: introduction
- upper right: environment input data
- lower left: pipeline and anodes input data, multipage
- lower center: results

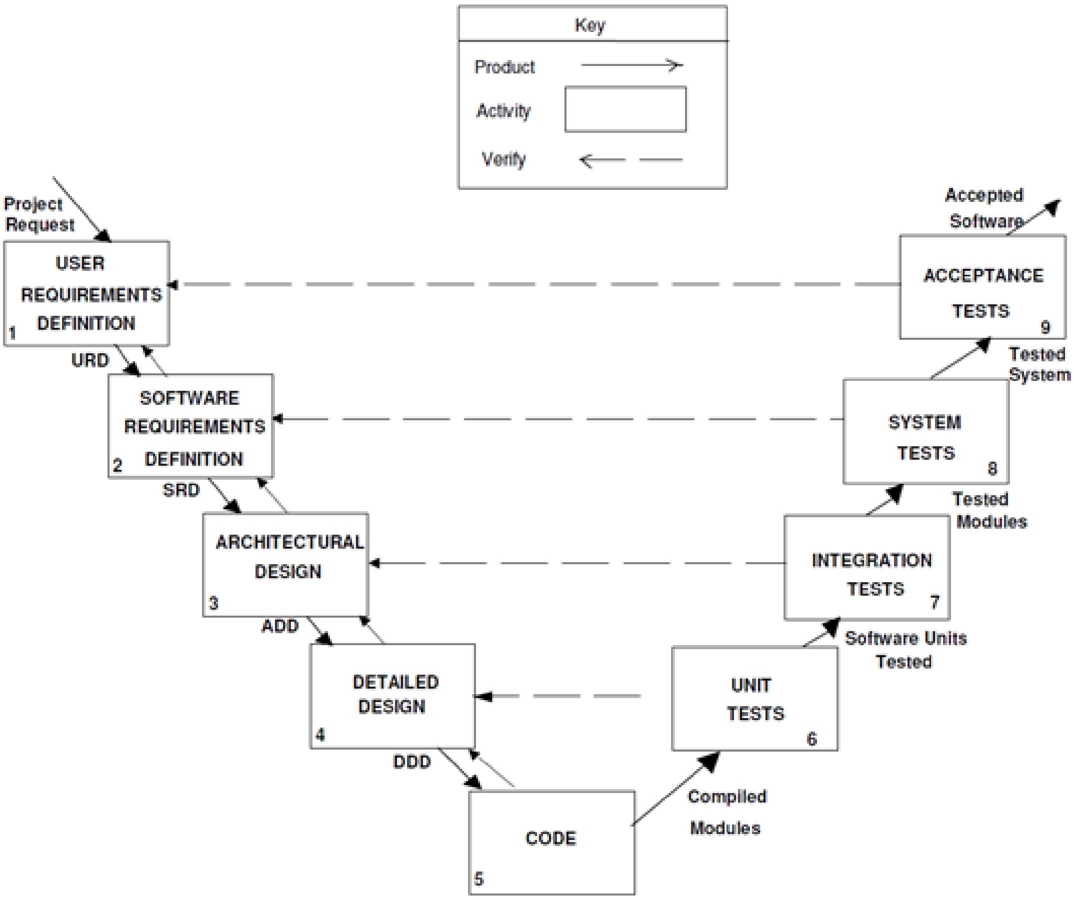


Figure B.7.: software validation procedure, internal procedure PROC-039 [36]

C. Coating applications and application processes

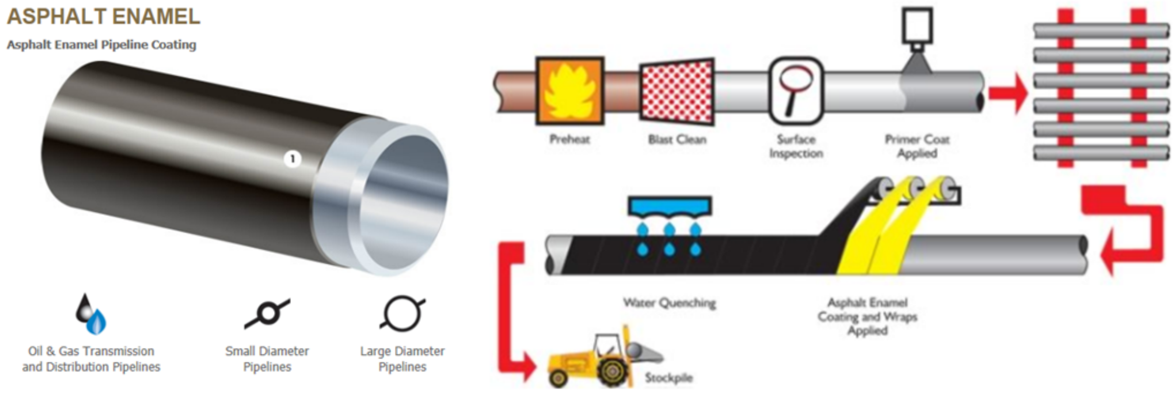


Figure C.1.: Asphalt Enamel Coating applications and application process; revisited from [37]

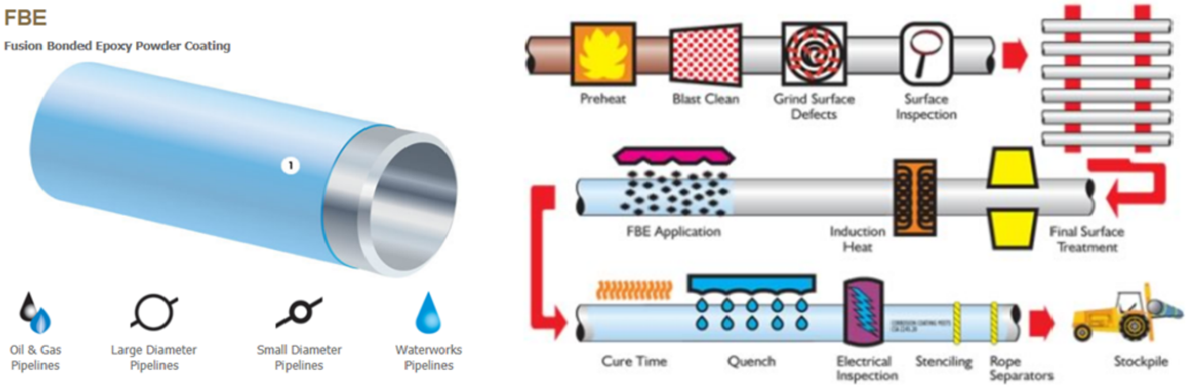


Figure C.2.: Fusion-bonded epoxy applications and application process; revisited from [37]

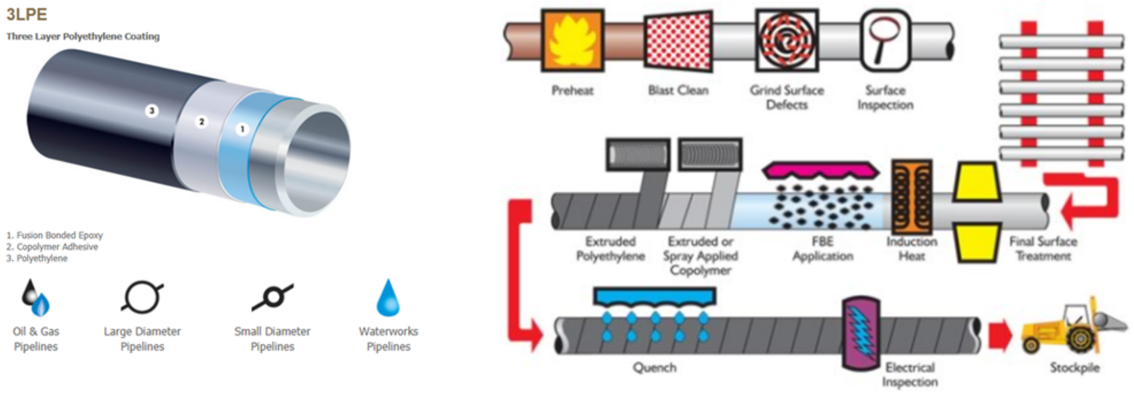


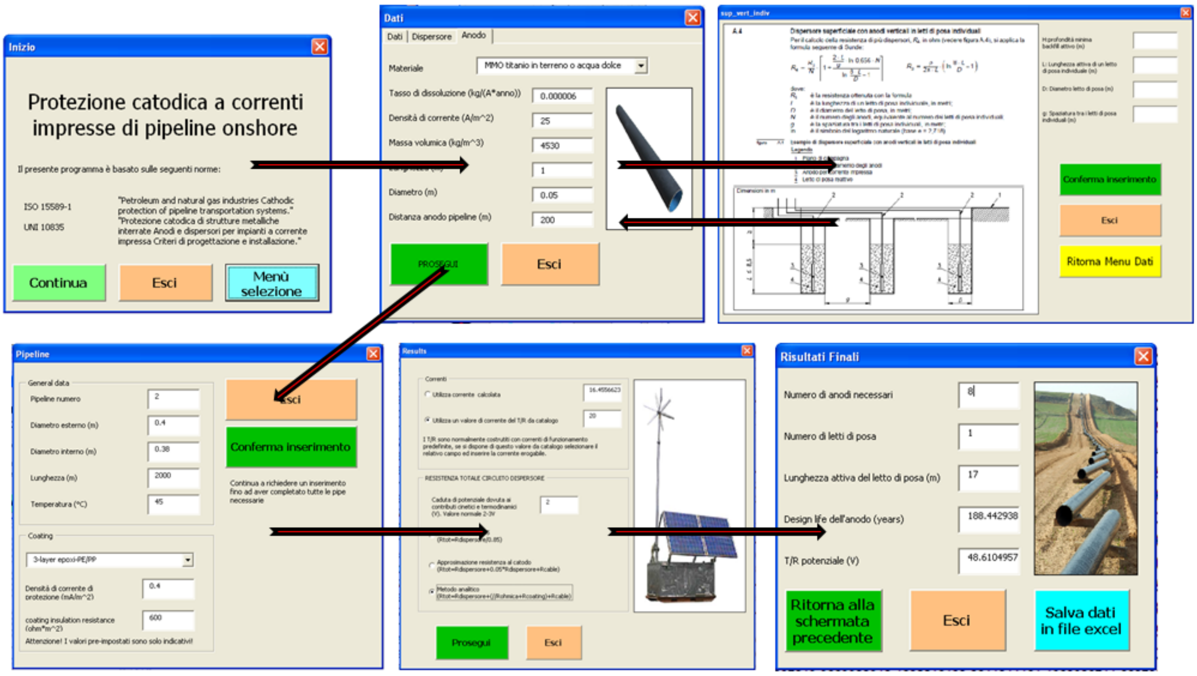
Figure C.3.: Three layer epoxy-polypropylen applications and application process; revisited from [37]

D. Stand alone electric producing units characteristics

Table D.1.: Stand alone electric producing units

Power Source	**Pros**	**Cons**
Engine Generator	robust contruction	need of fuel maintainance
CCVTs	limited moving parts multifuel	expensive
Thermoelectric generators	no moving parts	need of fuel low efficiency
PV systems	no moving parts no fuel required	large battery storage need of a sunny location
Batteries	low set up costs	for very small applications
Wind turbines	no fuel required	large battery storage maintanance required
Pressure drop turbines	no fue required	pressure drop in the stream
Fuel cells	no moving parts high efficiency	still in a developing phase need of fuel
Hybrid (wind+pv+generators)	small or no battery storage very little fuel needed	complicated expensive

E. Onshore pipeline



Protezione catodica a correnti impresse di pipeline onshore

Il presente programma è basato sulle seguenti norme:

ISO 15589-1 "Petroleum and natural gas industries Cathodic protection of pipeline transportation systems."

UNI 10835 "Protezione catodica di strutture metalliche interrate Anodi e dispersori per impianti a corrente impressa Criteri di progettazione e installazione."

Materiale: MMO titanio in terreno o acqua dolce

Tasso di dissoluzione (kg/(A*anno)): 0.000006

Densità di corrente (A/m^2): 25

Massa volumica (kg/m^3): 4530

1

Diametro (m): 0.05

Distanza anodo pipeline (m): 200

H:profondità minima backfill attivo (m)

L: Lunghezza attiva di un letto di posa individuale (m)

D: Diametro letto di posa (m)

g: Spaziatura tra i letti di posa individuali (m)

General data

Pipeline numero: 2

Diametro esterno (m): 0.4

Diametro interno (m): 0.38

Lunghezza (m): 2000

Temperatura (°C): 45

Coating: 3-layer epoxi-PE/PP

Densità di corrente di protezione (mA/m^2): 0.4

coating insulation resistance (ohm*m^2): 600

Attenzione! I valori pre-impostati sono solo indicativi!

Continua a richiedere un inserimento fino ad aver completato tutte le pipe necessarie

Correnti

○ Utilizza corrente calcolata: 16.4556623

● Utilizza un valore di corrente del T/R da catalogo: 20

I T/R sono normalmente costruiti con correnti di funzionamento predefinite, se si dispone di questo valore da catalogo selezionare il relativo campo ed inserire la corrente erogabile.

RESISTENZA TOTALE CIRCUITO DISPERSORE

Caduta di potenziale dovuta ai contributi cinetici e termodinamici (V). Valore normale 2-3V: 2

(Rtot=Rdispersore/0.85)

○ Approssimazione resistenza al catodo (Rtot=Rdispersore+0.05*Rdispersore+Rcable)

● Metodo analitico (Rtot=Rdispersore+(1/(Rohmica+Rcoating))+Rcable)

Numero di anodi necessari: 8

Numero di letti di posa: 1

Lunghezza attiva del letto di posa (m): 17

Design life dell'anodo (years): 188.442938

T/R potenziale (V): 48.6104957

Figure E.1.: Pipeline onshore, software userforms

Figure E.1 explanation:

- upper left: introduction
- upper center: environment, type of groundbed and anode data, multipage
- upper right: groundbed data
- lower left: pipelines data (dimensions and coating)
- lower center: current requirements
- lower center: results

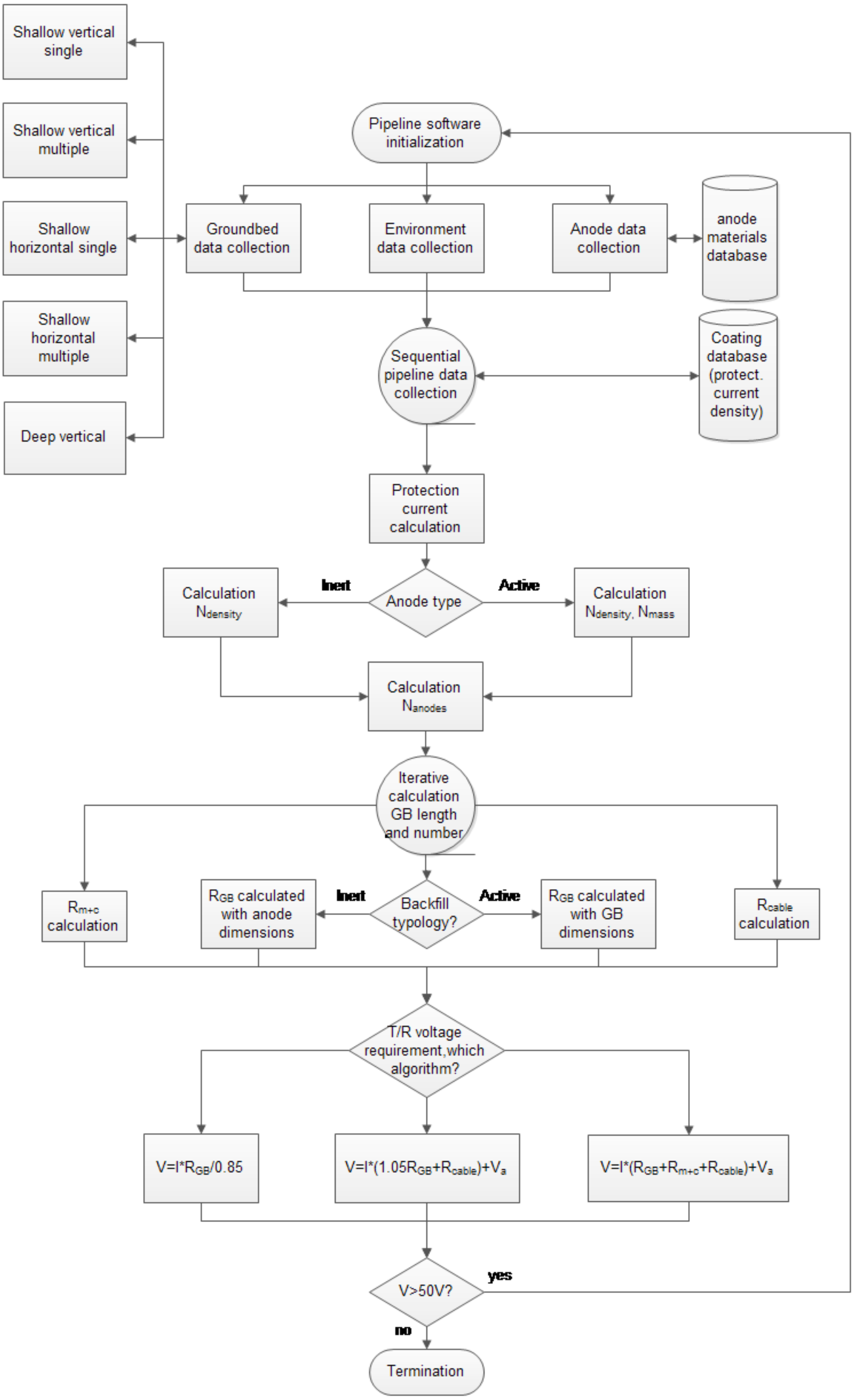


Figure E.2.: Pipeline onshore, algorithm flowchart

F. Computer modeling

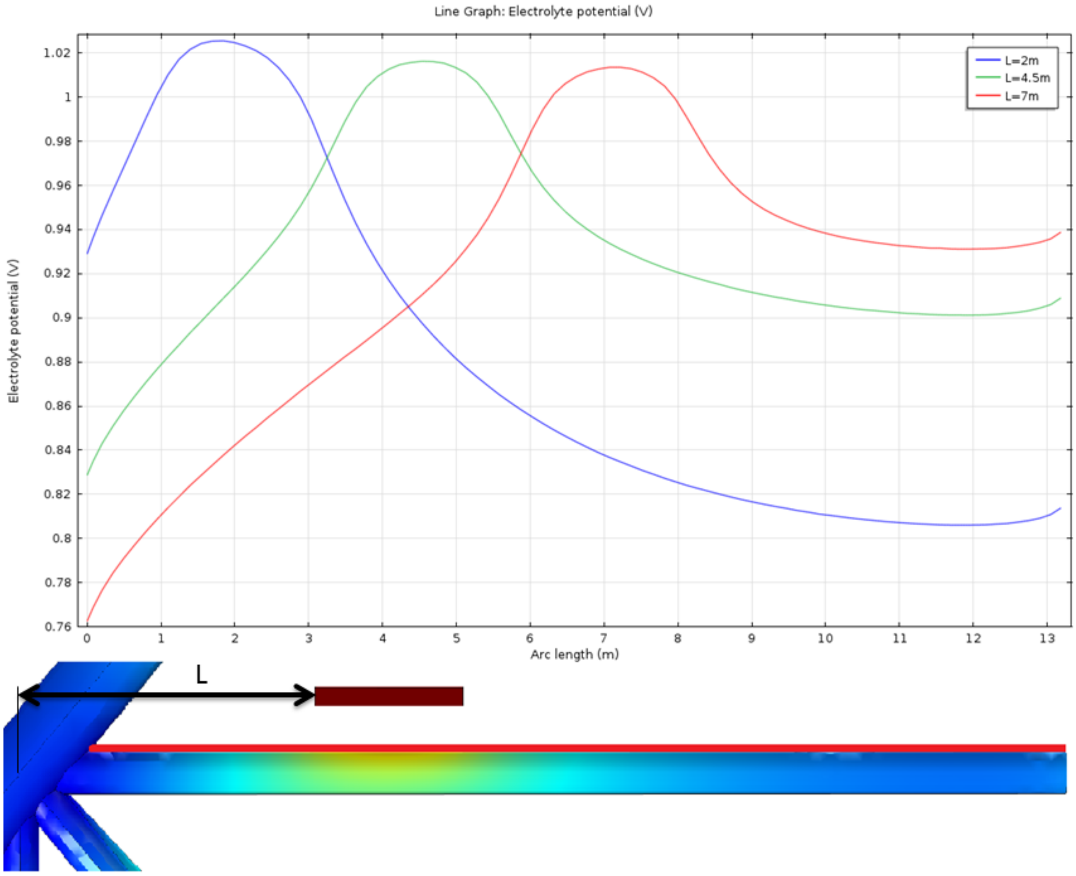


Figure F.1.: potential distribution along a chord of a jacket node as anode distance from the node changes

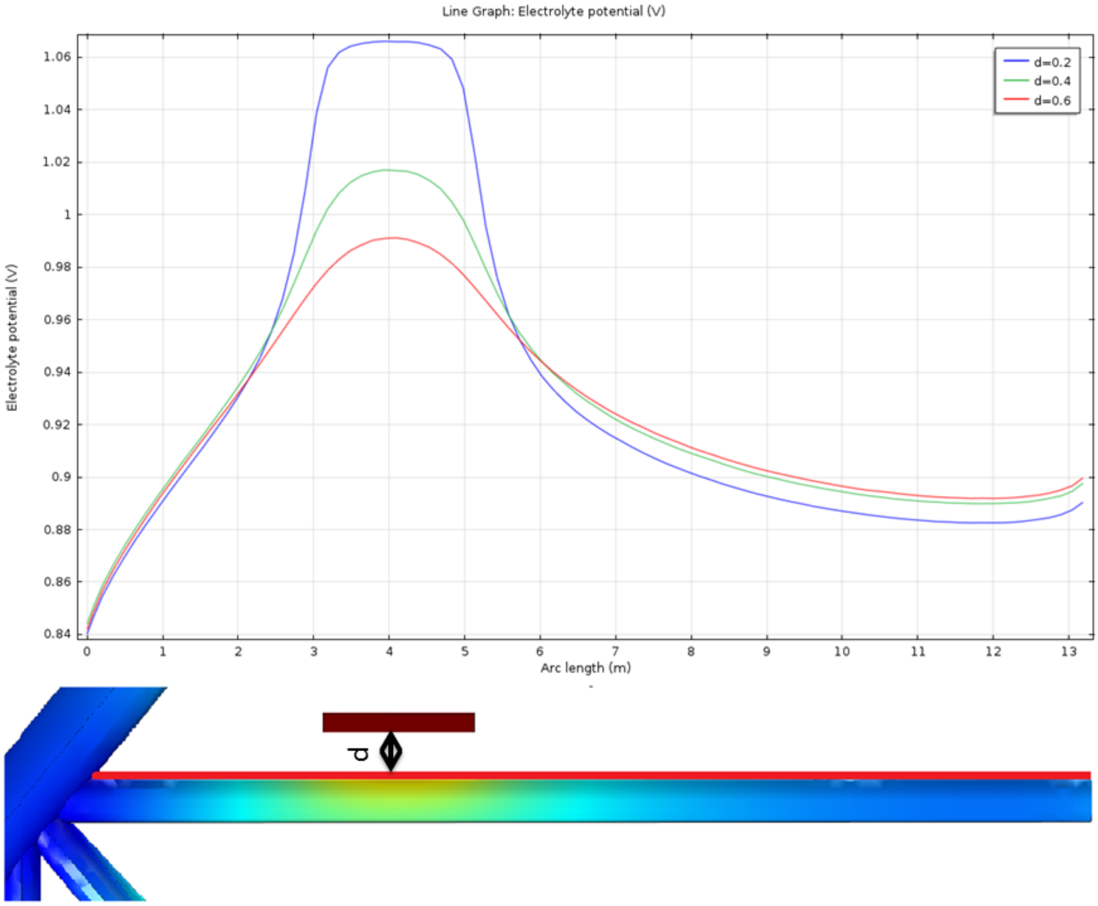


Figure F.2.: potential distribution along a chord of a jacket node as anode distance from the steel surface changes

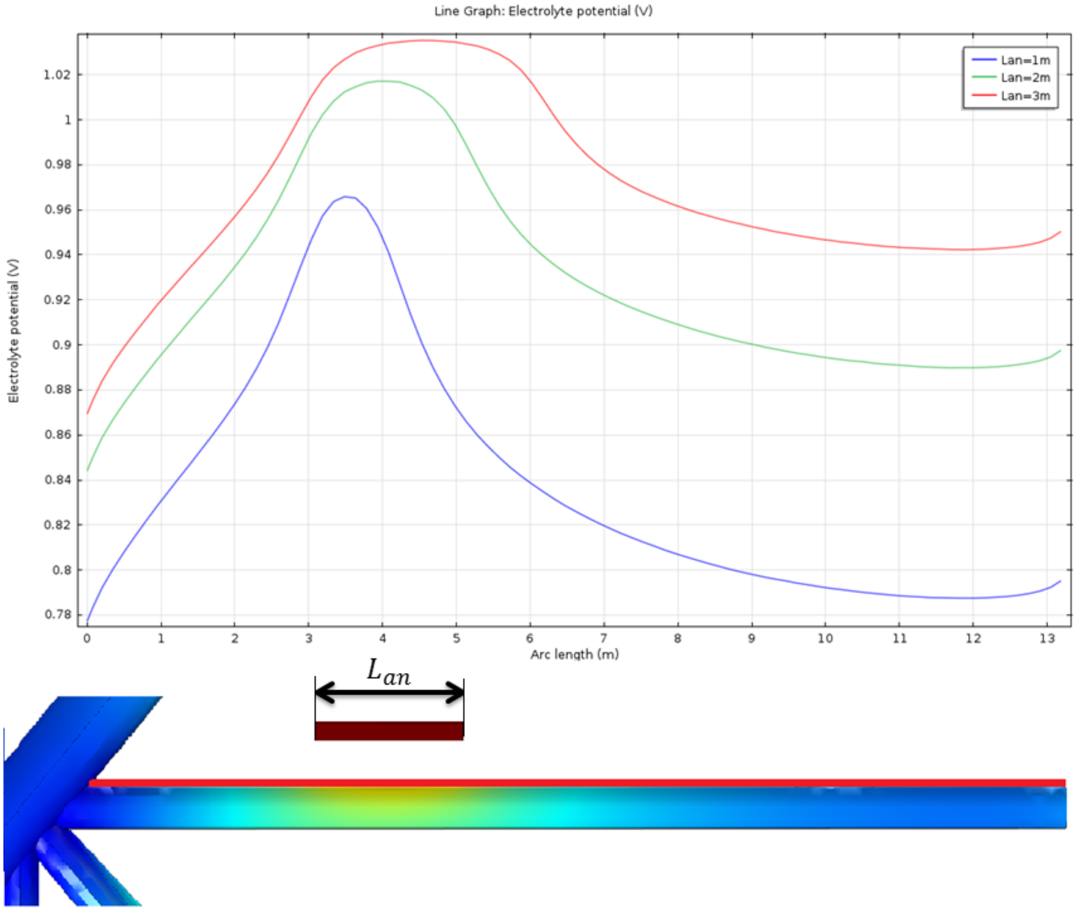


Figure F.3.: potential distribution along a chord of a jacket node as anode length changes

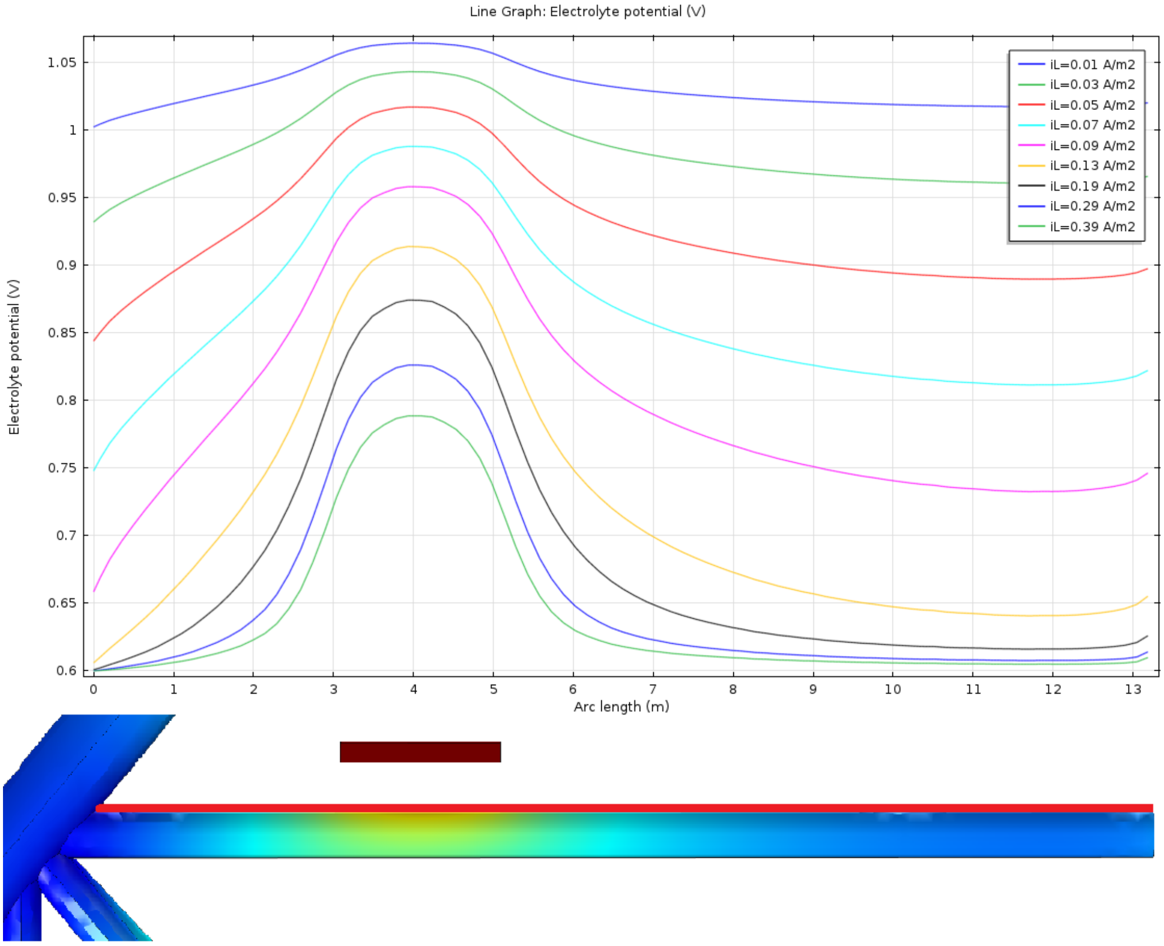


Figure F.4.: potential distribution along a chord of a jacket node as oxygen limiting current density changes

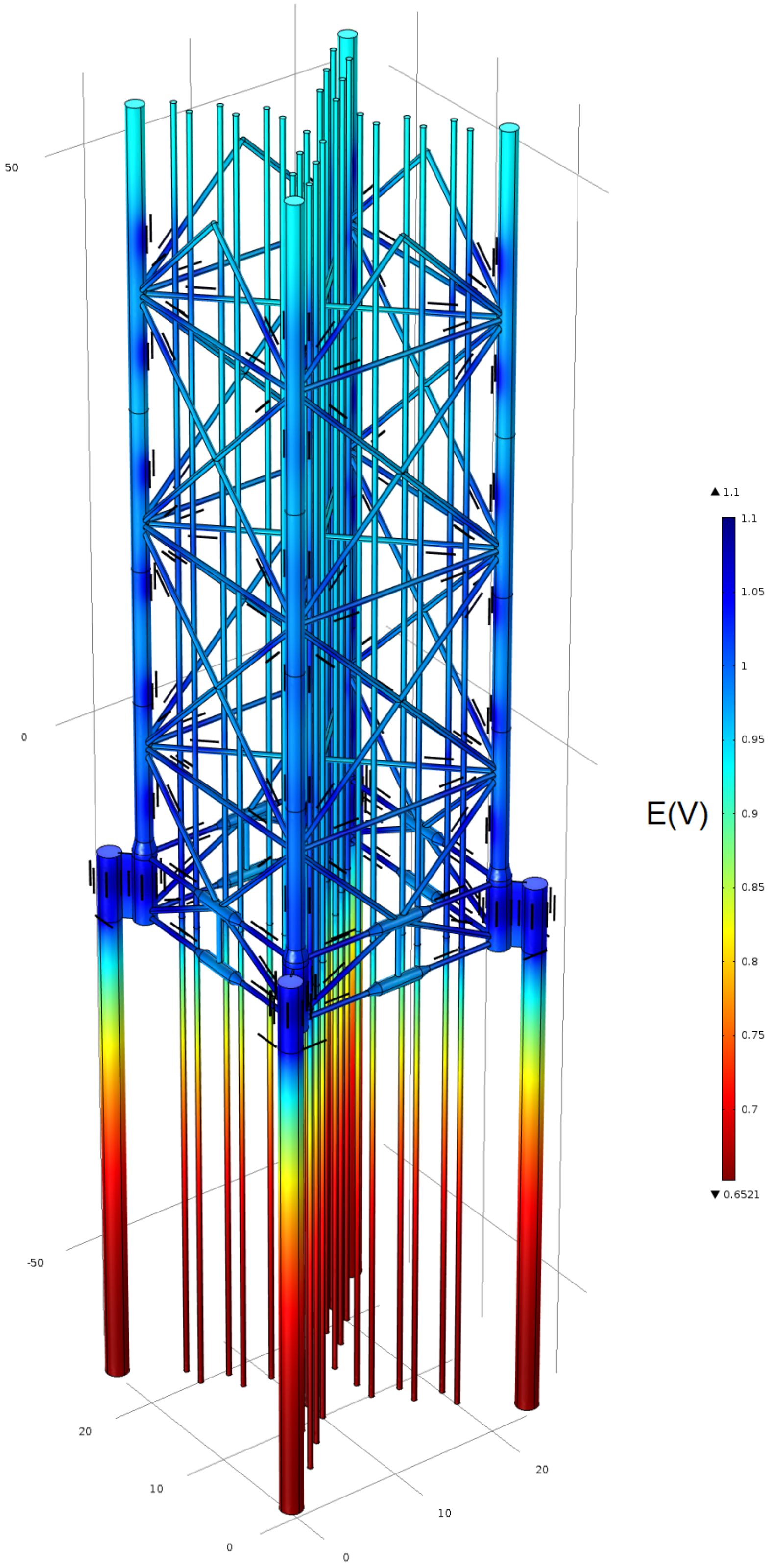


Figure F.5.: Complete jacket with conductors

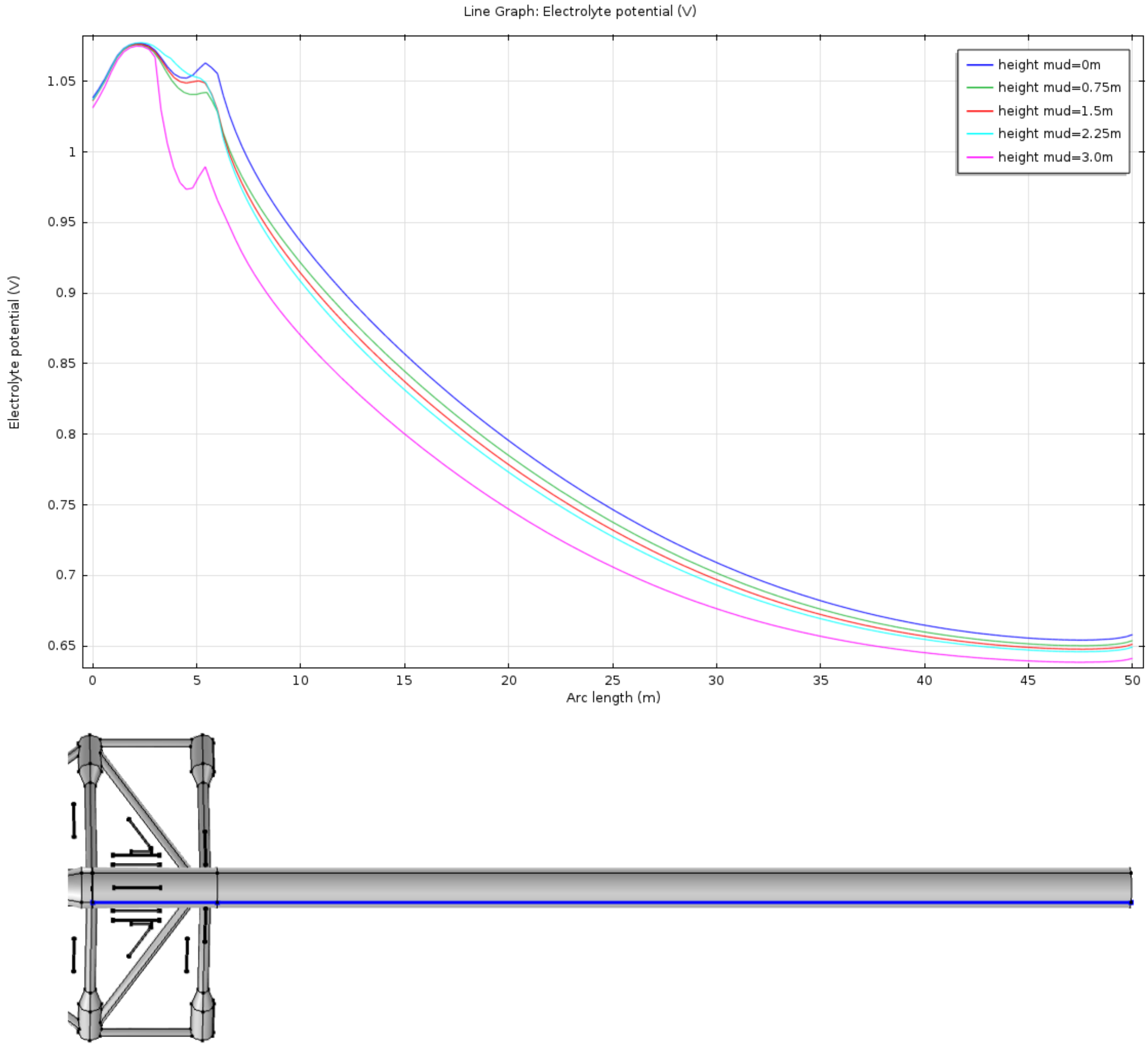


Figure F.6.: potential distribution along a chord on the jacket foundation pole as sea bottom level rises

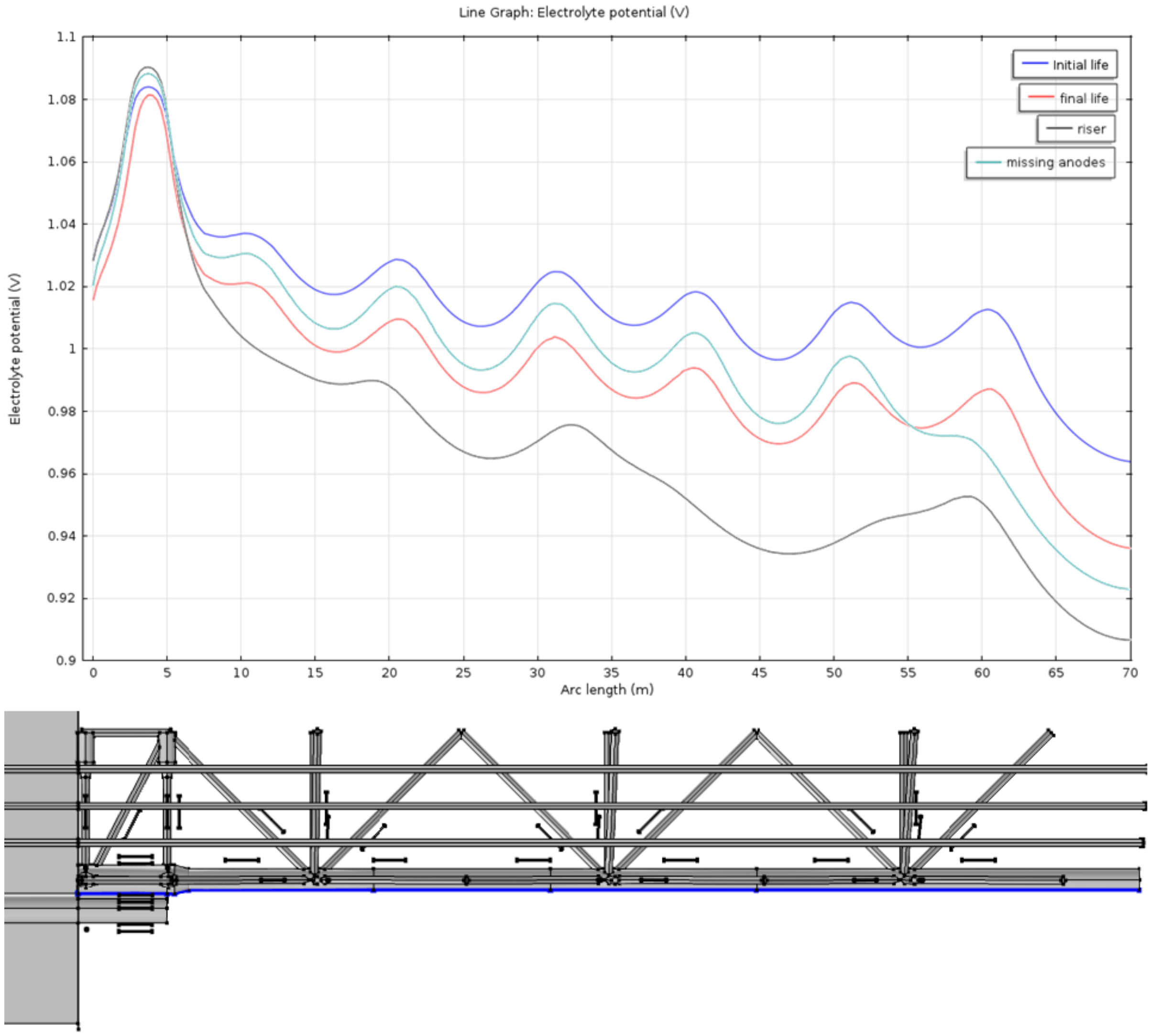


Figure F.7.: potential distribution along a chord on the jacket leg

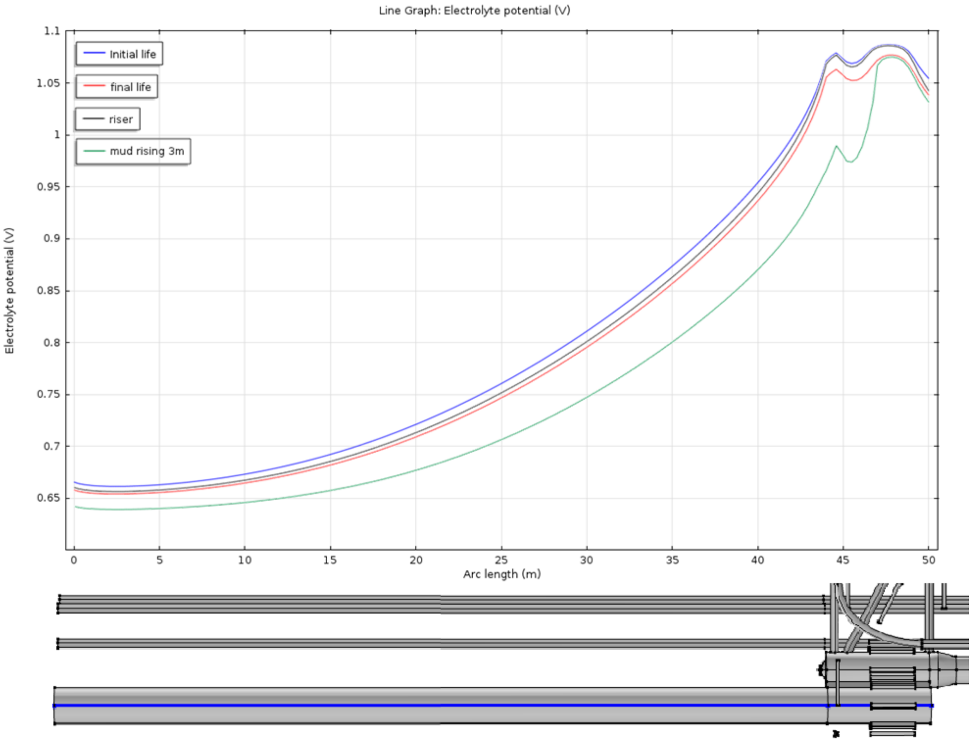


Figure F.8.: potential distribution along a chord on the jacket pole

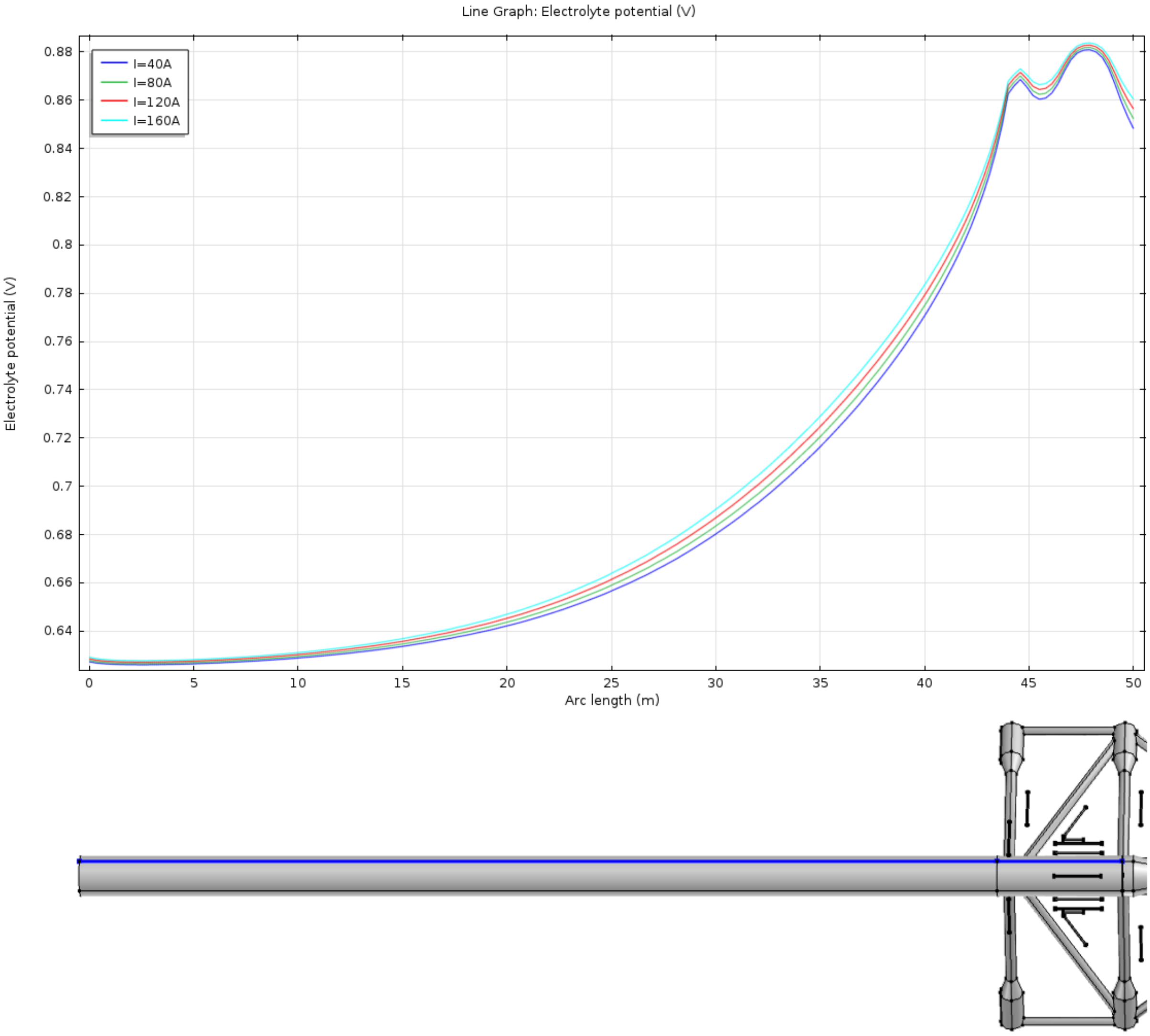


Figure F.9.: potential distribution along a chord of a retrofitted jacket foundation pole as total current provided by ICCP anodes changes

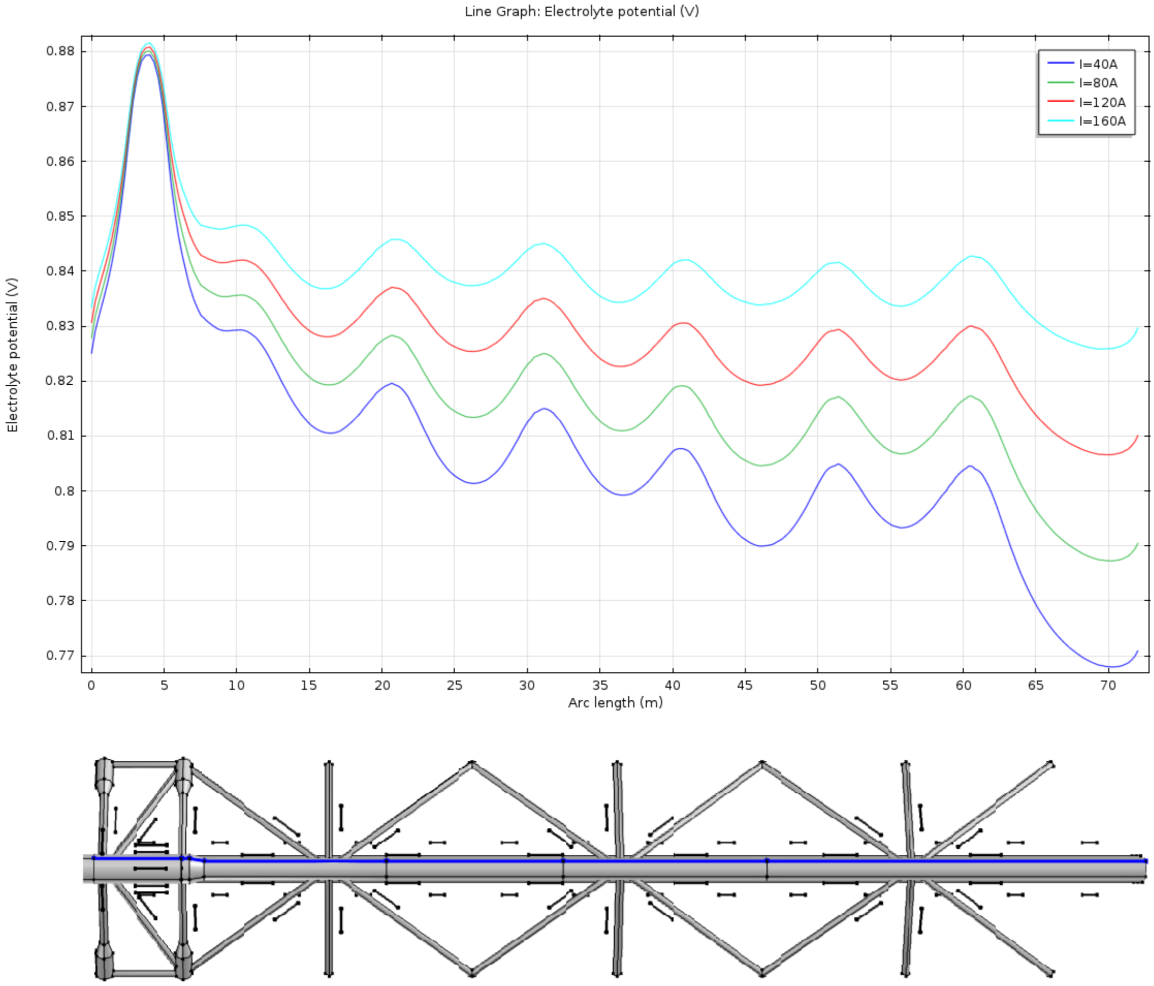


Figure F.10.: potential distribution along a chord of a retrofitted jacket leg as total current provided by ICCP anodes changes

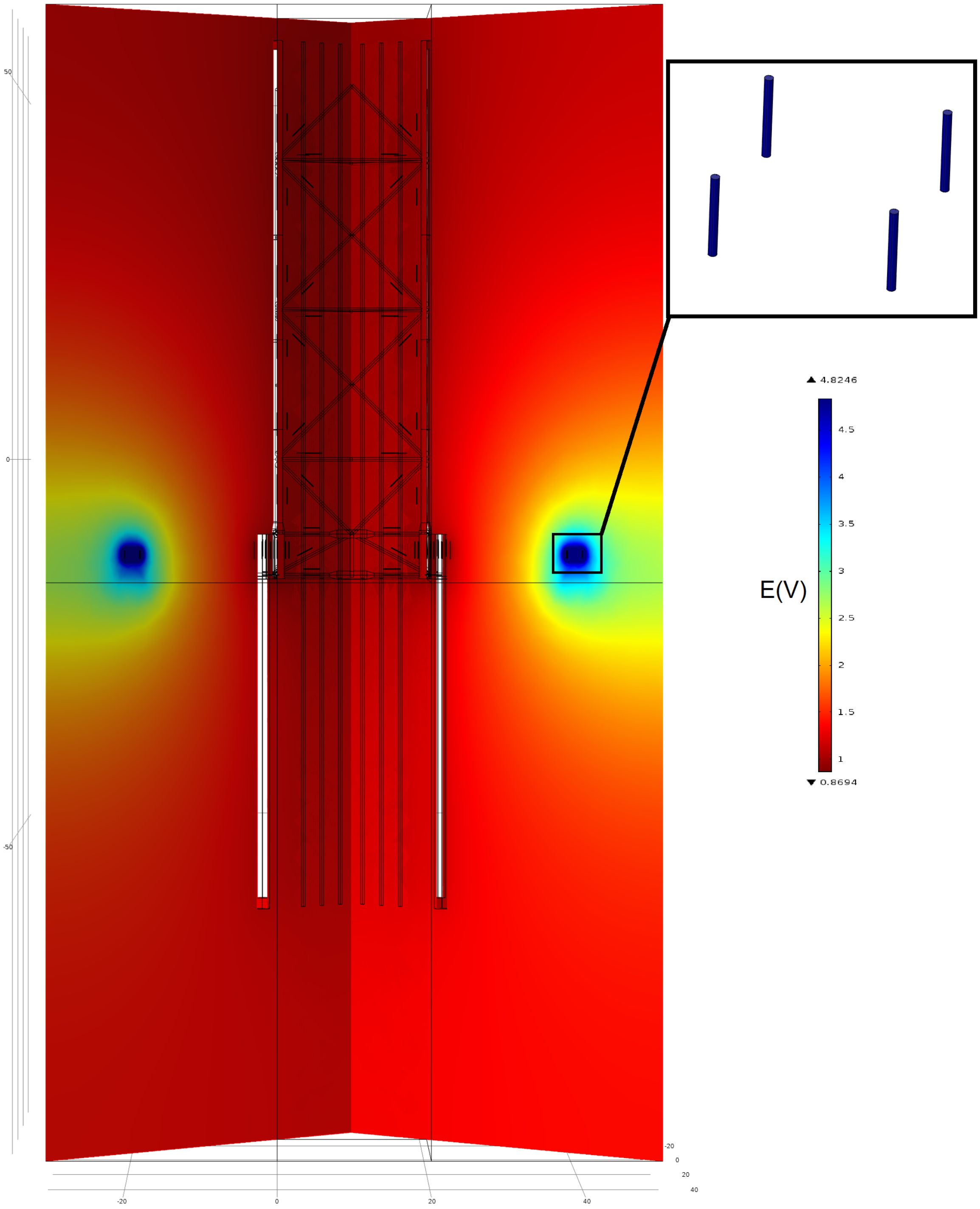


Figure F.11.: potential distribution in the electrolyte provided by 16 ICCP anodes placed 20 m away from the jacket

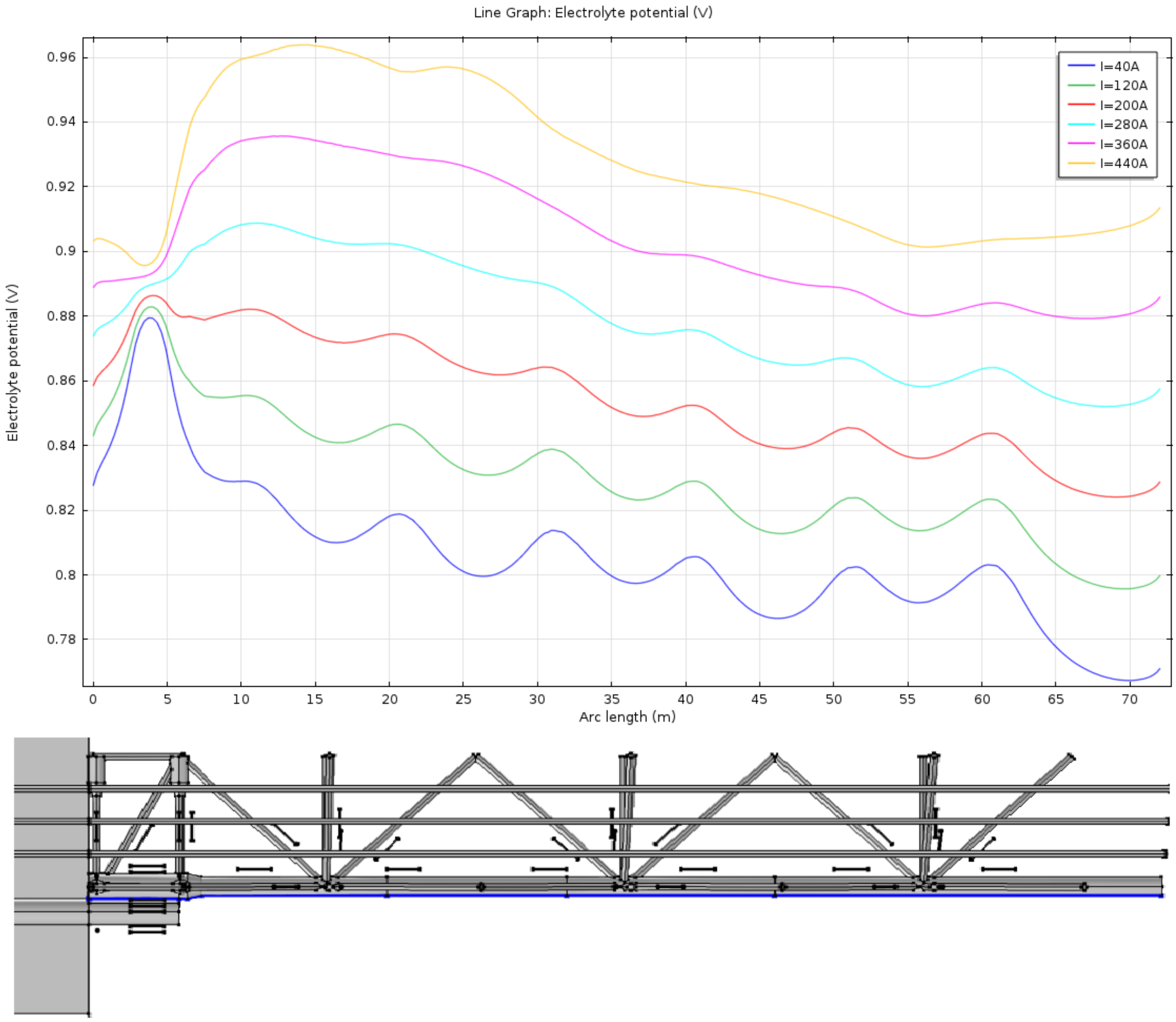


Figure F.12.: potential distribution along a chord of a retrofitted jacket leg as total current provided by ICCP anodes changes, retrobuoy

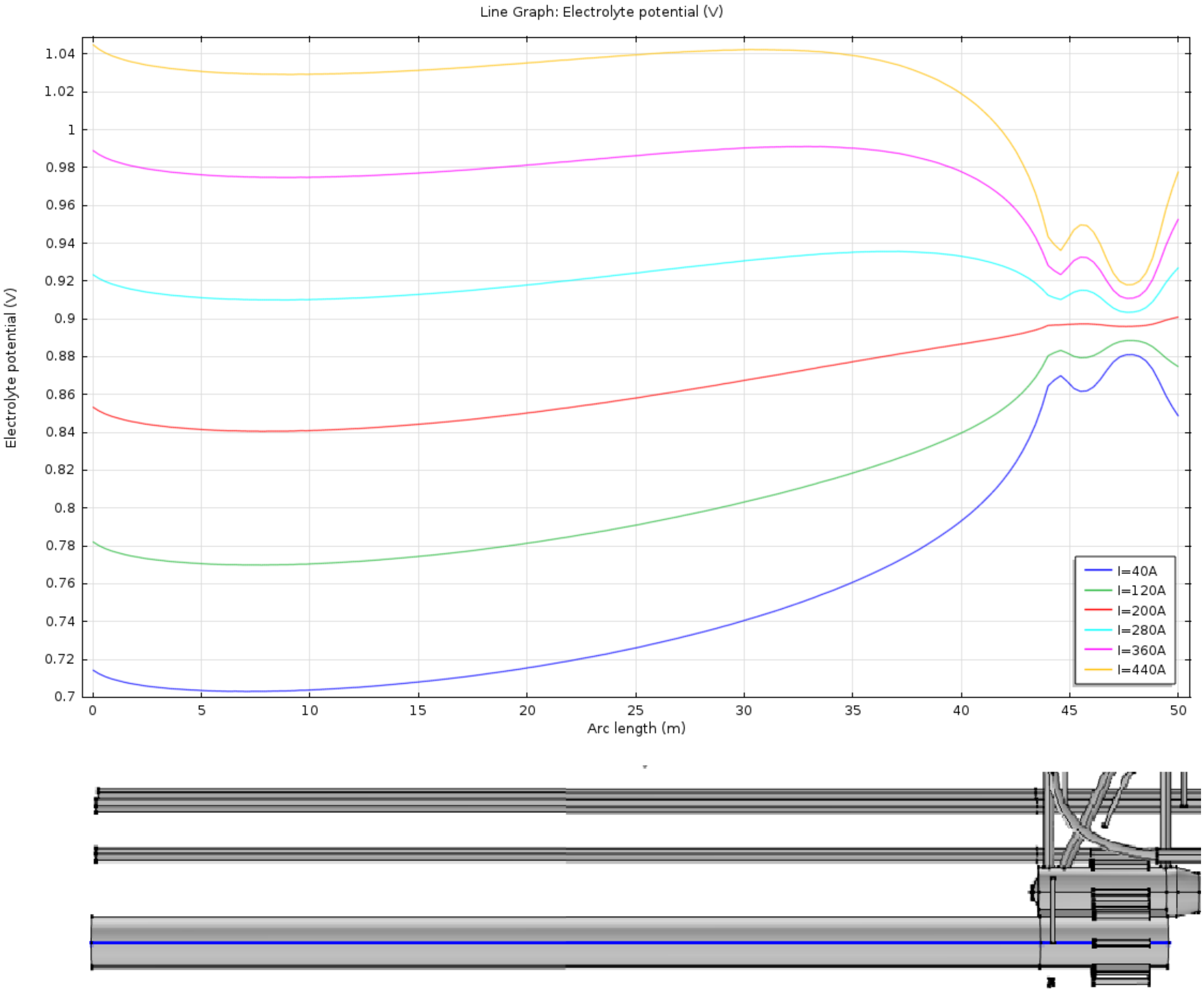


Figure F.13.: potential distribution along a chord of a retrofitted jacket foundation pole as total current provided by ICCP anodes changes, retrobuoy

G. Computer modeling moving mesh

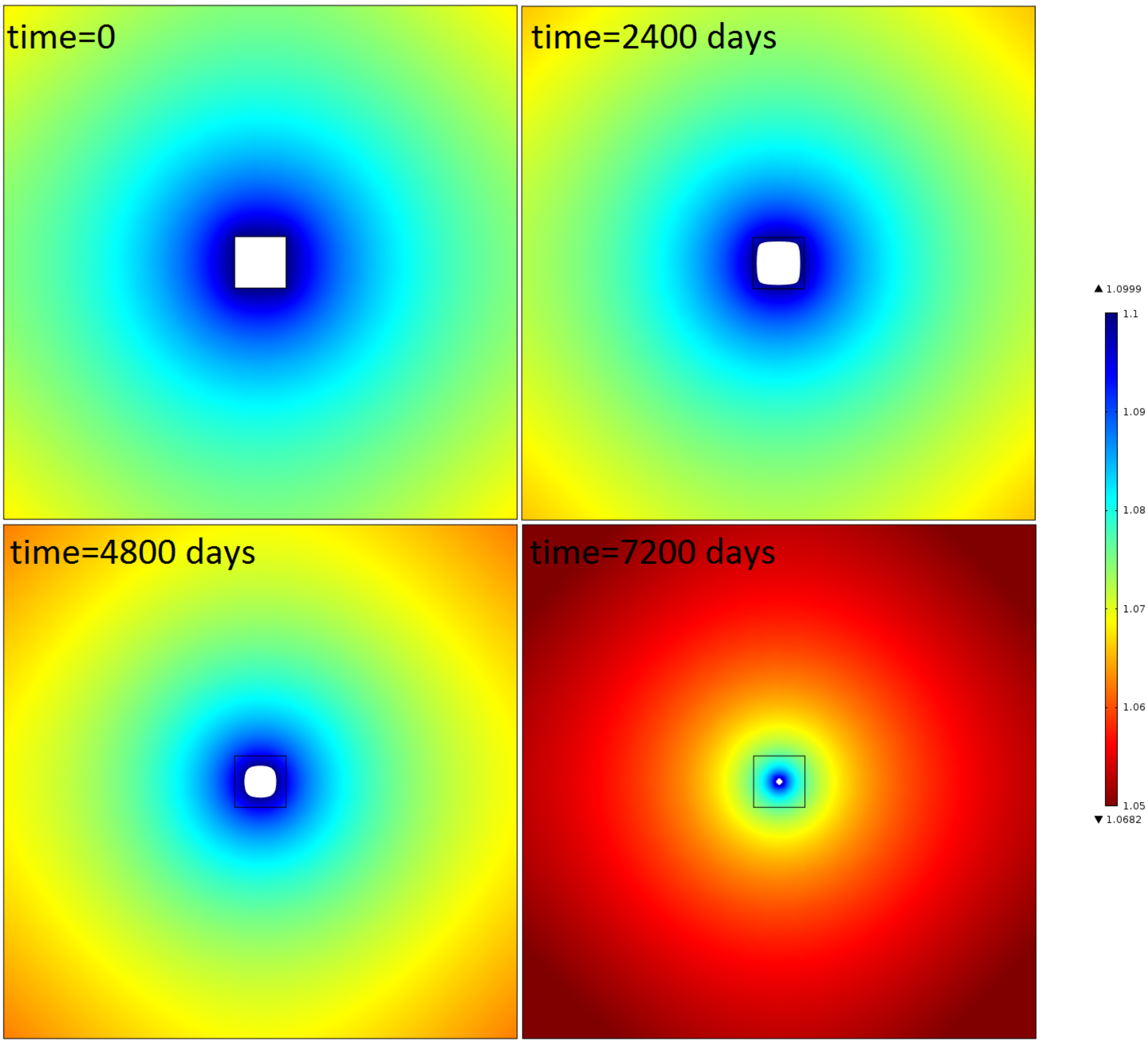


Figure G.1.: Moving mesh, 2D potential distribution as function of time

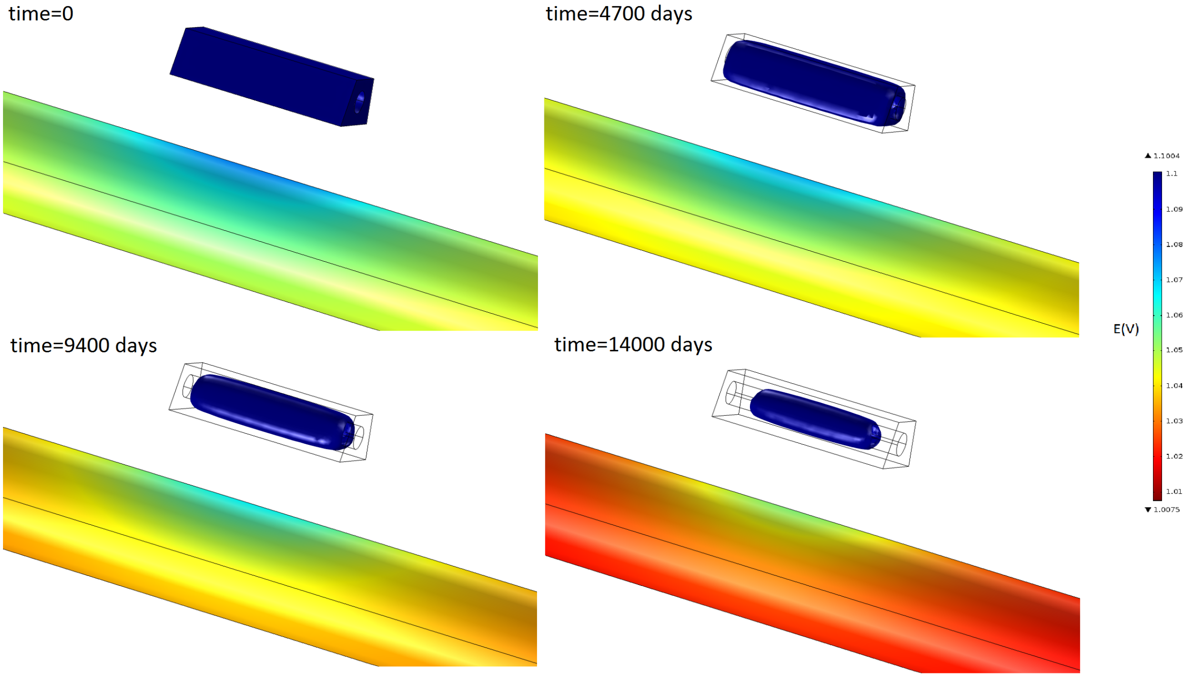


Figure G.2.: Moving mesh, anode consumption, Stand off anode potential distribution on the surface

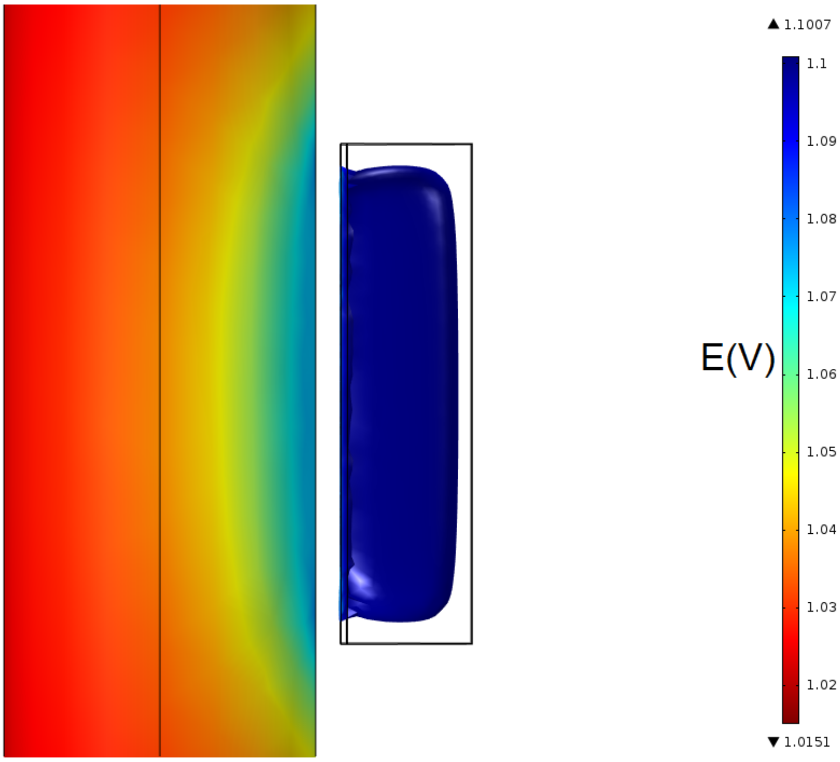


Figure G.3.: potential distribution on the surface of a structure protected via a flush mounted anode

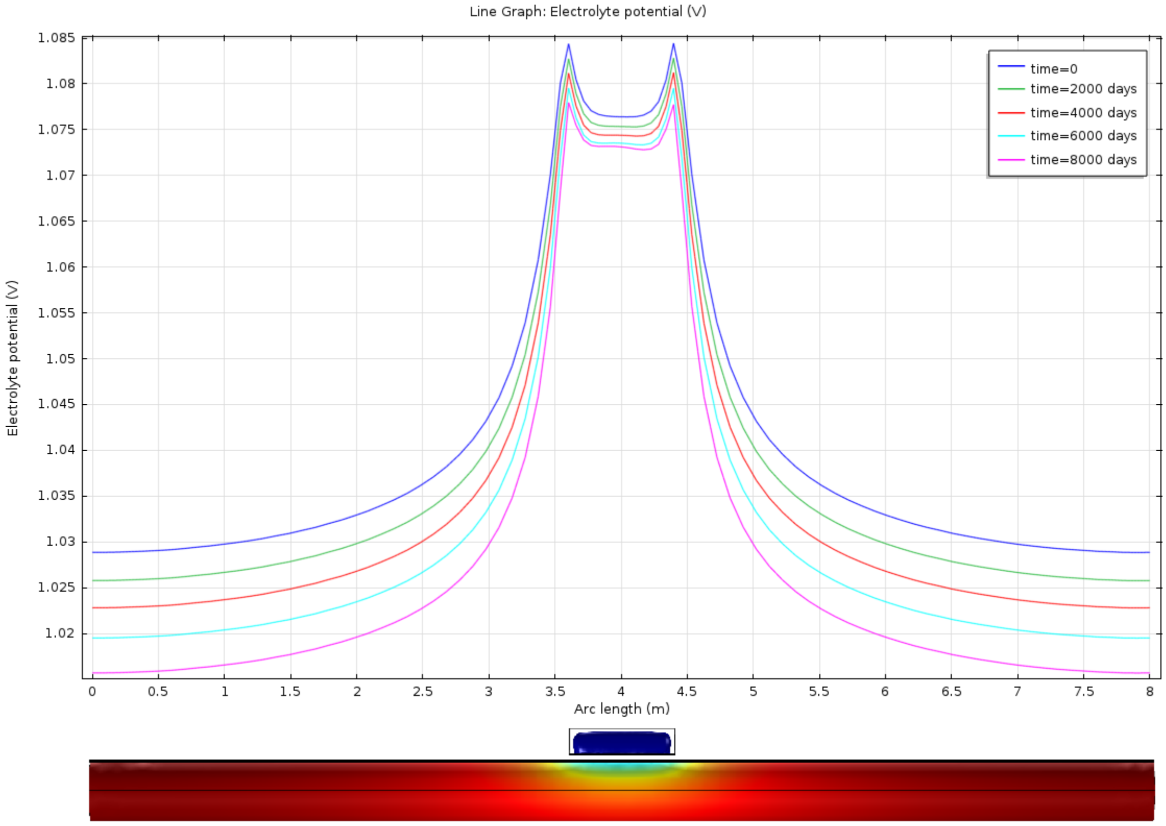


Figure G.4.: potential distribution on the surface of a structure protected via a flush mounted anode

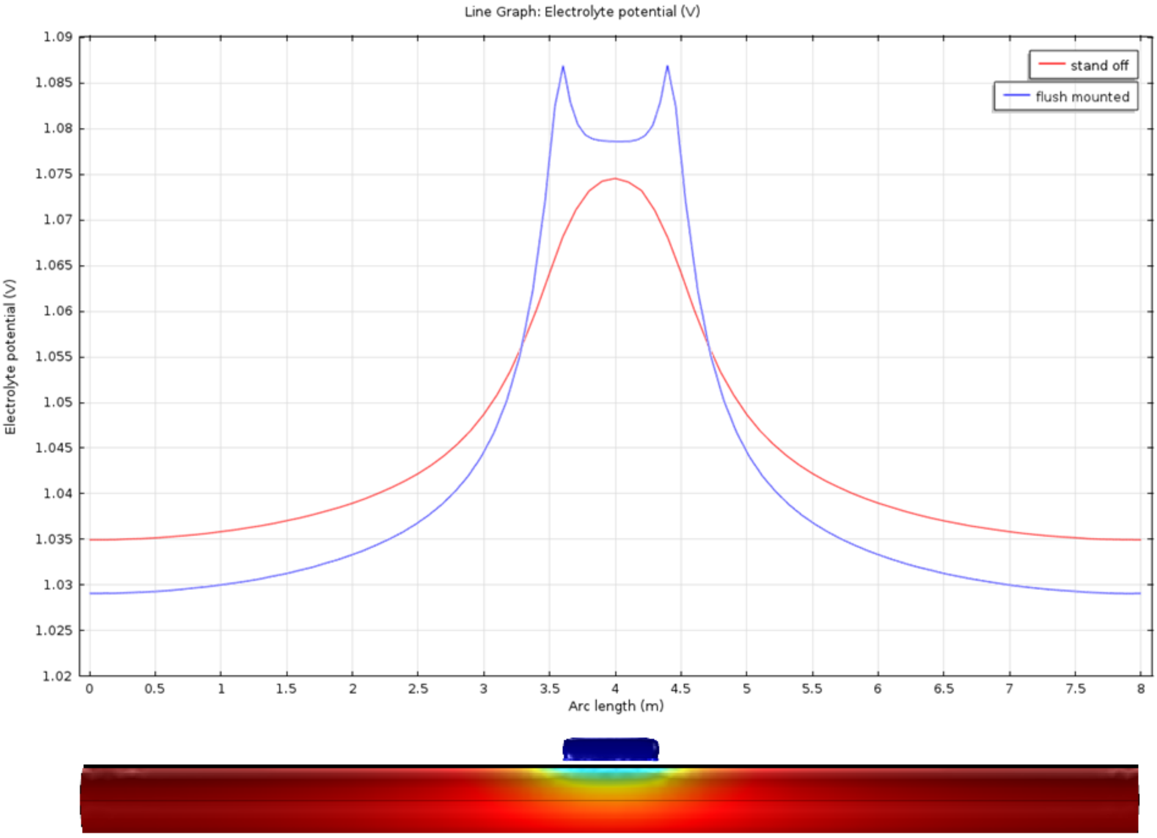


Figure G.5.: Comparison of potential distribution on the surface of a structure protected via a flush mounted anode and a stand off anode

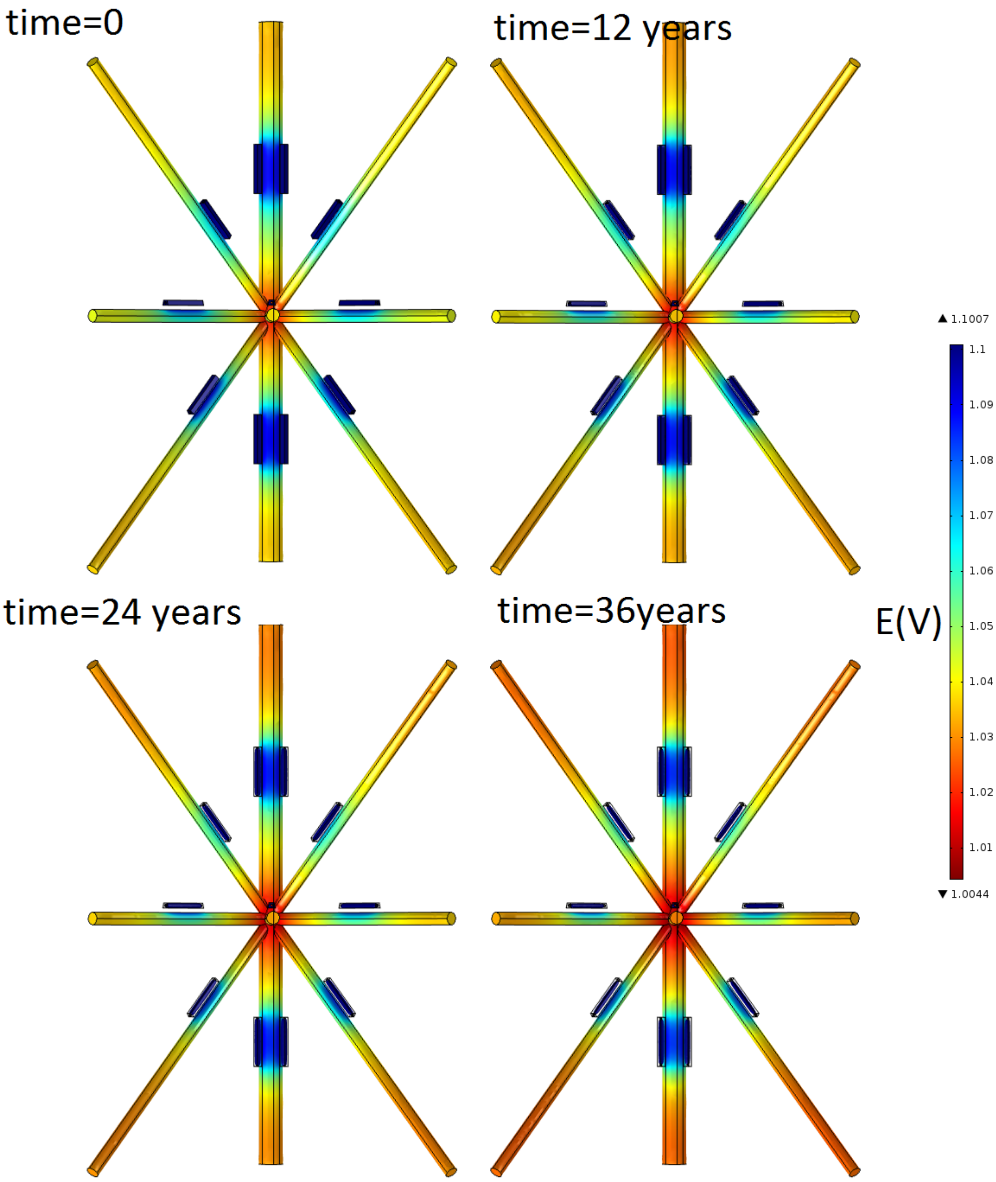


Figure G.6.: Jacket node anode and structure potential distribution on the surface

Figure G.7.: Time dependent model of anode consumption

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Riassunto in lingua italiana

> Un po' di corrosione non la si nega a nessuno
>
> Anonimo

Lo scopo di questo lavoro è di dare una panoramica sulle pratiche utilizzate e sullo stato dell'arte nell'ambito della progettazione di sistemi di protezione catodica, e di mostrare le potenzialità e i benefici dell'applicazione della modellazione numerica avanzata nell'industria petrolifera. L'idea di accoppiare due metalli, con l'intento di proteggere la superficie del più nobile, ha più di duecento anni. Molti meccanismi riguardanti la corrosione e la sua prevenzione sono stati compresi, ma molti altri sono ancora sconosciuti. Lavorando in un ambiente naturale e non in un contesto artificiale di laboratorio, implica che molte sono le variabili presenti che complicano la comprensione e la previsione dei fenomeni legati alla progettazione di sistemi di protezione catodica. La descrizione completa di un fenomeno elettrochimico in un ambiente naturale deve tenere conto di molte variabili e parametri incogniti che non possono essere tenuti sotto controllo ovvero agevolmente misurati. Un'enorme spinta allo studio dei meccanismi che regolano i sistemi di protezione catodica è stata data dall'industria petrolifera che ha lavorato in ambienti ostili e fortemente corrosivi per più di cento anni. Ai nostri giorni anche l'industria dell'energia rinnovabile, con la costruzione di enormi centrali eoliche in mare, sta muovendosi verso ambienti che richiedono l'applicazione di sistemi di protezione catodica.

La prevenzione attuata al fine di limitare i danni causati dalla corrosione è una questione di sicurezza ed efficienza. Molti incidenti accaduti in passato sono occorsi a causa di una sottostima degli effetti della corrosione. Disastri come l'affondamento di petroliere ed il rilascio di fluidi tossici da tubazioni corrose, sono avvenuti a causa di carente gestione dei problemi legati alla corrosività dell'ambiente di lavoro. Tutte le strutture posate in ambienti caratterizzati da elettroliti fortemente conduttivi (e.g. l'acqua di mare), sono particolarmente soggetti al degrado corrosivo. Quando una struttura è corrosa a tal punto che non può più svolgere in sicurezza le sue funzioni, deve essere messa fuori servizio ed in sostituzione una nuova opera deve essere costruita. La maggior parte dell'acciaio prodotto ai giorni nostri viene utilizzato per sostituire vecchie strutture che sono state smantellate per danni dovuti alla corrosione. La corretta applicazione di sistemi di protezione catodica può prolungare la vita prevista di un manufatto, risparmiando l'energia e i costi legati alla costruzione di una nuova struttura. Per le ragioni prima esposte, la protezione catodica può essere considerata uno strumento utile per promuovere l'efficienza energetica.

Il seguente testo è suddiviso in tre sezioni principali, una prima introduzione generale sui meccanismi di corrosione, un secondo studio circa le pratiche odierne usate dall'industria per la progettazione di sistemi di protezione catodica (sia offshore che onshore), ed una terza parte riguardante un approccio numerico per la modellazione di problemi relativi alla protezione catodica. Le prime due parti, i capitoli 1, 2 e 3 sono il frutto del lavoro svolto come apprendista durante un tirocinio di quattro mesi svolto presso Tecnomare SPA nel dipartimento di ingegneria. Tecnomare SPA è una società di ingegneria, controllata eni, che lavora principalmente nel settore offshore, e di recente si sta espandendo verso il settore onshore, fornendo servizi integrati di ingegneria che seguono tutta la design life di progetti upstream. Il bisogno di progettare sistemi di protezione catodica, e di vericare progetti svolti da terzi, ha spinto il dipartimento di ingegneria di Tecnomare ad implementare dei software per semplificare, standardizzare e velocizzare queste attività. Sono stati realizzati e parzialmente validati dei software, basati su standard internazionali e propri della compagnia, per dimensionare i sistemi di protezione catodica per strutture offshore ed onshore. L'ultima parte della tesi, descritta nei capitoli 4 e 5, è dedicata alla modellazione numerica dei sistemi di protezione catodica, un approccio utilizzato per comprendere a pieno i sistemi di protezione catodica e i parametri che ne influenzano il comportamento sotto le diverse condizioni di lavoro. Quest'ultima attività è stata svolta presso il Politecnico di Milano, i risultati ottenuti durante questo lavoro sono stati utilizzati per il solo fine di ricerca scentifica, soprattutto per mostrare le potenzialità e le opportunità di un approccio di modellazione numerica applicato a problemi di protezione catodica.

Protezione catodica e Corrosione

La protezione catodica è una tecnica di controllo della corrosione che può essere applicata con successo, per prevenire o mitigare i danni provocati dalla corrosione su una struttura immersa in un elettrolita. Questo metodo consiste nell'accoppiare la struttura metallica da proteggere, con un altro apparato, che può essere un sistema ad anodi galvanici o un dispositivo a corrente impressa. Il fine dell'utilizzo della protezione catodica è di portare la struttura ad un potenziale elettrico più basso del potenziale di libera corrosione. La corrosione è un processo elettrochimico che può essere spiegato con le reazioni ed il trasporto delle specie chimiche coinvolte nei processi corrosivi. Le due principali domande a cui si deve trovare risposta quando si trattano problemi di corrosione sono: il metallo in esame in quel determinato ambiente si corroderà? Quanto tempo sarà necessario perchè questo processo porti dei danni rilevanti alla struttura? La prima domanda ha una risposta che si rifà alla termodinamica mentre la risposta alla seconda domanda è relativa ad un problema di tipo cinetico.

Approccio empirico

L'applicazione di un approccio rigoroso durante la progettazione di sistemi di protezione catodica è stato concepito in seguito alle numerose defezioni occorse dopo i primi utilizzi di questi sistemi. Il primo e più famoso fallimento può farsi risalire alla prima applicazione di un sistema di protezione catodica attuato da Sir Humphry Davy. Altri insuccessi sono avvenuti quando non si è tenuto conto delle variate condizioni al contorno, dovute ai nuovi ambienti di lavoro dove le strutture sono state posate, e si sono applicati per il dimensionamento approcci ritenuti standard. Ad esempio i sistemi di protezione catodica delle prime piattaforme petrolifere costruite nel mare del nord diedero risultati deludenti, essendo basate sull'esperienza acquisita dall'industria petrolifera nel golfo del Messico, senza tenere in considerazione le più dure condizioni di lavoro e le maggiori correnti necessarie per mantenere la struttura in condizioni di protezione.

Gli ingegneri hanno bisogno di strumenti per effettuare la progettazione di sistemi di protezione catodica affidabili e sicuri. Per questa ragione dei software sono stati creati in questo lavoro per aiutare e guidare i tecici durante il processo di dimensionamento. I software sono stati creati seguendo le linee guida dettate dalle norme internazionali e dalla narmativa interna eni. I programmi sono inoltre stati implementati per essere intuitivi da utilizzare e facilmente manutenibili. Una prima versione del software, per il dimensionamento di sistemi di protezione catodica di piattaforme petrolifere, era stata creata in Tecnomare due anni fa, ed è stato il punto di partenza per il lavoro di questa tesi. Il software, creato con VBA ed implementato con interfacce grafiche utente, è stato aggiornato ed i problemi riscontrati sono stati risolti. Inoltre, un nuovo strumento di ottimizzazione delle dimensioni dell'anodo è stato aggiunto. Al programma per la progettazione dei sistemi di protezione catodica per strutture esterne è stato affiancato un nuovo modulo per la progettazione di sistemi di protezione catodica per sealine con anodi a bracciale o anodi tipo pod per retrofitting. Un metodo alle differenze finite è stato implementato per calcolare la distribuzione di potenziale lungo la superficie di una sealine protetta con anodi galvanici.

Tecnomare SPA ha sempre lavorato in ambiente offshore ma in anni recenti c'è stato un crescente interesse verso progetti sviluppati su terra ferma. Per questa ragione si è sentita la necessità da parte della società di sviluppare internamente un software che fosse in grado di dimensionare sistemi di protezione catodica a corrente impressa in ambito onshore e di controllare progetti sviluppati da terzi per conto di Tecnomare. Il software è stato sviluppato con caratteristiche simili alla sua controparte offshore, ma l'implementazione ha tenuto conto dell'esperienza maturata in precedenza e alcuni errori prima commessi sono stati evitati. Il programma è stato creato per dare massima flessibilità all'utente e guidarlo sia nel suo utilizzo che nella manutenzione. I software creati sono inoltre utilizzabili come strumenti didattici, utili per l'apprendimento delle pratiche di dimensionamento di sistemi di protezione catodica.

Modellazione numerica

Negli ultimi decenni l'applicazione dei computer in ambito ingegneristico è cresciuta esponenzialmente. Gli standard internazionali riguardanti i sistemi di protezione catodica stanno incominciando ad introdurre il concetto di modellazione numerica. La modellazione al computer può essere applicata per stimare e migliorare le prestazioni dei sistemi di protezione catodica. Il modello virtuale può essere testato e diversi scenari possibili possono essere simulati. Diversi sistemi di protezione catodica possono essere studiati e le caratteristiche e potenzialità di ogni singola soluzione possone essere valutate. La modellazione al computer è una tecnica economicamente vantaggiosa per evitare costose riparazioni e superflui sopralluoghi che una progettazione di tipo euristico richiederebbe.

Modelli geometrici, rappresentativi di strutture realistiche, sono stati creati e studiati nell'ambito di questa tesi con l'ausilio di un software agli elementi finiti. È stato mostrato che geometrie molto complesse e vaste, come un'intera piattaforma petrolifera, possono essere studiate e modellate dal punto di vista della protezione contro la corrosione. I risultati ottenuti mostrano i vantaggi derivanti dall'utilizzo di studi parametrici e di ottimizzazione, come per esempio durante la fase di posizionamento degli anodi (generalmente demandata all'esperienza del progettista). Diversi scenari possibili sono stati studiati e i risultati sono riportati nel capitolo 5. Studi tempo varianti, con l'ausilio di moving mesh, sono stati effettuati per prevedere il comportamento degli anodi galvanici, e delle conseguenti condizioni di protezione della struttura, con il passare del tempo. La maggior problematica riscontrata nell'applicazione concreta della modellazione numerica è la necessità di possedere delle condizioni al contorno rappresentative del fenomeno in esame. Bisogna inoltre tenere conto che le condizioni al contorno sono variabili legate a fenomeni tempo varianti e per questo di ancor più difficile acquisizione e comprensione. Un approccio multifisico alla modellazione dei depositi calcarei, parametro di maggior influenza nello studio dei sistemi di protezione catodica in acqua di mare, è stato teorizzato ma non ancora implementato. La validazione dei modelli qui presentati dovrebbe costituire lo step successivo a questo lavoro.