Effectiveness and potentialities of the use of Cathodic Protection simulation software for managing underground natural gas pipelines

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Abstract: Cathodic protection is an electrochemical technique used to prevent the corrosion phenomena for metallic underground materials and pipelines. It is essential because the external coating could be insufficient for corrosion protection. The real corrosion protection level of a structure, a pipeline for example, is usually evaluated through measures made in few points of the pipe, generally once a day. In this way, the protection level of the whole structure is unknown. Advanced cathodic protection simulation software are spreading in order to fill this gap, especially for application in the oil and gas industry. The aim of this study is to evaluate what kind of advantages can derive from the application of simulation software to model the cathodic protection level for natural gas distribution pipeline. A real case study has been conducted in order to examine the real potentiality of this instrument. The main evaluated aspects are about the improvement of the process control effectiveness, its implementation costs and the break-even point of the investment.

Keywords: Cathodic protection, underground natural gas pipeline, simulation software.

1. Introduction

Corrosion is a well-known phenomenon caused by chemical or electrochemical reactions derived from the interaction between the material of which a system is made, and its environment ("Wiley," n.d.). It must be avoided and controlled because it causes changes in the material properties that impact on the performance of the system itself. For this reason, different actions are usually carried out in order to remove, or at least minimize, corrosion phenomena.

Cathodic Protection (CP) is one of the most used techniques for protecting metallic structures from corrosion. Many applications require both CP and insulating coating, since this last method is often insufficient alone because of the degradation of the applied coating over time.

A general CP system involves a cathode (that is the metallic structure), an anode (that protects the metal) and an electrolyte. The main aim of a CP system is to reduce the potential of the metallic structure: when this potential is lower than the equilibrium one, the oxidation process (causing corrosion) cannot take place. For steel in an aerobic electrolyte, the reference protection potential is commonly considered to be -850 mV (this threshold value derives especially from experimental results).

CP techniques are usually defined according to how electricity circulates in the system: "Sacrificial Anode Cathodic Protection" (passive) and "Impresses Current Cathodic Protection" (active) are the most widespread kind of CP systems (Garverick, 1994). The first method is simpler because it requires only an anode that is the negative electrode of the system and that sacrifices itself. Sacrificial anodes are usually made by pure active metals (such as zinc or magnesium) that are low noble metal and less electronegative than the structure to be protected.

In an Impressed Current CP system there are anodes connected to a DC power source. In particular, anodes are connected to the positive DC output terminal, while the negative one is connected to the structure to protect.

The implementation of a CP system requires an accurate design phase with the study of the main features of the structure to be protected, in order to better define the kind of CP to adopt (active or passive). In this phase, simulation models can be very useful to design optimization and to evaluate alternatives. In fact, they are able to test different alternatives solutions without building the real system. Furthermore, the main performance parameters, like the distribution of the potential on the structure and the energy consumption, can be estimated.

After the CP system design and implementation, it is essential to control its performance over the time that is if its protection capacity against corrosion is the same. Simulation models could be very useful in this phase too: they allow verifying if the structure is totally protected, if anodes are completely consumed or not, if the impressed current is enough to protect the whole structure, and so on.

Even if the physical structure of a CP system seems quite simple, its total configuration is not thus: the geometry of most structures is complex and there are many different aspects to be considered. Therefore, a numerical simulation approach is necessary (DeGiorgi et al., 2007). It allows determining the protection level along all the structure and to point out if there are some insufficiently protected or overprotected parts. Consequently, the simplification and optimization of installation, maintenance and repair of CP system can be achieved.

The CP system behaviour is defined by a mathematical model based on the conservation of charge in the electrolyte. Applying this idea with some realistic hypothesises (homogeneous electrolyte, steady-state situation, etc.) (Chuang et al., 1987), the reference mathematical model is the Laplace equation

$$\nabla^2 \emptyset = 0 \ in \ \Omega \qquad (1)$$

where $\emptyset$ is the electrical potential, Ω is the domain of the electrolyte and ∇ is the Laplacian operator. It is usually written in three dimensions as

$$\frac{\partial^2 \emptyset}{\partial x^2} + \frac{\partial^2 \emptyset}{\partial y^2} + \frac{\partial^2 \emptyset}{\partial z^2} = 0 \qquad (2)$$

Boundary Element Method (BEM) is one of the most used methods to solve Laplace equation. It was developed by Brebbia in 1970s (Brebbia and Walker, 2013): in order to find the solutions of a partial differential equation, we firstly look at its solution on the boundary, and then we use this information to find the solution inside the domain. BEM is usually preferred to Finite Element Method (FEM) because it displays better accuracy, efficiency and easiness of data preparation (Karami and Hakimhashemi, n.d.).

Therefore, Laplace equation is solved by BEM thanks to some proper boundary conditions that refer to specific elements of the system, for example to the cathodic and anodic surfaces.

In literature there are many works about the implementation of BEM for CP modelling: BEM is applied to different kinds of systems like pipelines (Orazem et al., 1997), ships (DeGiorgi et al., 1998) and so on. BEM, in fact, allow to define the potential distribution on the boundary of the structure, that is the only necessary information to design a CP system (Chuang et al., 1987). BEM is used to define the mathematical model in CP simulation software too.

Cathodic protection regards all the metallic underground objects, like tanks and pipelines above all. Pipelines are generally used to transport different kinds of materials such water or gas. Natural gas distribution pipelines are the elements considered in this work.

The distribution system is the last step of a more general natural gas supply chain, as showed in Figure 1.

The first step regards natural gas procurement: it could be extracted from ground and ocean floor, or imported. From here, it is stored and transported to distribution centres, to finally arrive to the final users (residential, commercial and industrial users).

Even if it could seem a simple and linear chain, the system that allows natural gas to arrive from well to end users is very complex: there are valves, metering and compression stations and pipelines.

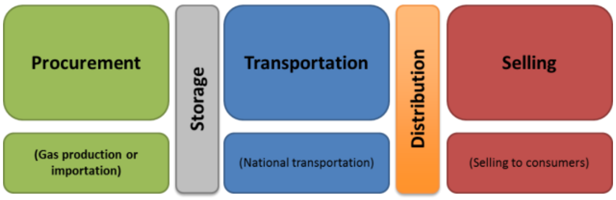

Figure 1: Natural gas supply chain: the first step regards natural gas procurement (production or importation); from here, it is stored and transported to distribution centres; the last step regards sale to final users (residential, commercial and industrial users).

There are three major types of pipelines that bring gas from the point of production to utilization ones (Hamedi et al., 2009):

- gathering lines that are low-pressure and low-diameter pipelines transporting raw natural gas from the wellhead to the processing plant;
- transmission lines that are used to transport natural gas from a gathering, processing or storage facility to another processing or storage facility, large volume customer or distribution systems;
- distribution pipelines that represent the final step in delivering natural gas to users.

Pipelines are a very critical element, since their failures can have severe consequences both for economic and environmental aspects (Bortels, 2003). Furthermore, since they are underground systems and, for this reason, barely accessible, numerical modelling has been applied to this topic.

In this paper, a cathodic protection simulation software was applied to a real case study in order to evaluate the real potentiality of this instrument. The second section presents the main properties of cathodic protection simulation software while, in section 3, the real case study is introduced. In sections 4 and 5 experimental results and discussions are presented, while the last section shows some conclusions.

2. Cathodic protection simulation software

Simulation approach is fully widespread in many fields because of its many advantages, first of all the possibility of studying the behaviour of a system without building it and, therefore, of performing "what-if" analyses. It is based on the definition of a model, representative of the real system, that is usually developed on a computer software. Simulation software are generally applied in engineering fields to model electronic circuits, chemical reactions, production process, and many other situations.

Lately, cathodic protection simulation software have been applied in order to optimize the process itself. Some contributions on this topic have been identified in literature. Adey and J. Baynham (Robert A Adey and Baynham, n.d.), for example, present two applications of a software designed to simulate the CP performance (for a ship's ICCP and for storage tanks); Parsa et al. (Parsa et al., 2010) show a case study for oil well casings.

Cathodic protection simulation software are based on the same process. The first step regards modelling of facilities (pipeline, tank, vessel, etc.) considering all the necessary simplification of the real system; then the kind of protection method used is chosen (sacrificial anodes or impressed current anodes) and the electrochemical data of the problem have is set (resistivity, polarization curve, and so on). Finally, simulation results are useful to determine a lot of information about the system, like the potential in the electrolyte, the current density or the rate consumption of the anode.

Off the shelf there are various simulation software that are able to model different kinds of cathodic protection problems. The most common fields of use are the marine sector (offshore oil platform, vessels) and the terrestrial sector (underground pipelines, storage tanks). PROCOR, for example, is a high-performance simulation software tool used in marine environments. A case study solved through MATLAB has been found too (Naseer A. Al Habobi and Shahad F. Abed, 2013).

The software used in this work allows to model different kind of systems, like tanks, systems operating on the sea and underground pipelines (from here on we will refer to this last type of problem). It is based on the graphical representation of all the elements that characterize the CP system (pipeline, sacrificial anodes, etc.). First, they are arranged in a space called Bounding Box that represents the land where pipelines are. The second step is the definition of the main features of all the elements of the system: the geometrical and constitutive properties of the pipe (material, material coating, external and internal diameter, and length), the main properties of the sacrificial anodes and the average soil resistivity. The last step refers to the problem resolution: the software solves the CP systems thanks to the implementation of Laplace equation solved through BEM approach. Finally, the main results are summarized in the post-process section. Figure 2 shows a typical output of the software related to a simple pipe: each colour corresponds to a specific potential value, according to the associated value scale.

Figure 2: typical output of the CP simulation software related to a simple pipe.

In the 5th section, all the possible utilizations of the output for evaluating and improve the CP systems will be presented.

3. Case study

In order to examine the real potentiality of the cathodic protection simulation software, a real case study has been conducted. It derives from the collaboration with a natural gas distribution company managing the distribution pipelines in a quite wide zone of Italy.

The pipeline network is complex (about 260 different networks), with many ramifications all over the covered zone.

The geological properties of the soil where are the pipelines, have an important effect on its conductive or isolating capacity. For this reason, in order to have more information about the corrosion level of its underground pipelines, the company commissioned a study of the soil features to a geologist: 26 lithological classes for the covered zone were identified. The morphological properties of the interested area, in fact, are very complex and various (mountains, rocks, clays, and so on are present in the area) because of the complex morphological structure.

All the underground pipelines are protected from corrosion both with sidings and cathodic protection systems. The effectiveness of these protection systems is usually verified through daily potential measures made on points of each network. These data are controlled by some operators, verifying if any undesired situation has occurred (potential value higher than threshold value). All the anomalies are practically verified through some inspection on the site, in order to identify the area where the problem has occurred and the reason why. This action usually requires some days (both for the organization of the inspection and for the identification of the problem) and is considerable as a waste (both of time and of money). When a potential value greater than the threshold one is identified, in fact, it is necessary to dig in different points of the network in order to identify where the problem is indeed localized. This research could require either an hour or some days: insufficient information, in fact, is available from the only daily remote measures.

The company would like to improve the effectiveness and profitability of its cathodic protection control systems. For this reason, it is considering the possibility to use cathodic protection software as a tool to control the real effectiveness of protection systems used against corrosion phenomena.

4. Theoretical and experimental validation of the CP software

Before of using the software, it is useful to discuss on its results reliability. For this reason, some theoretical and experimental testes have been done.

First of all, a simple model presented in literature and solved by Laplace's equation application, has been identified. It refers to a simple underground steel pipeline, of which all the main properties are known (internal and external diameter, length, electrical conductivity, etc.).

The system was solved by the application of Laplace's equation, explained by the Boundary Element Methods and the results is a distribution of the potential value along the pipeline.

This same system has been implemented in the software, then it was solved and the potential distribution along the pipeline was estimated. Finally, this result was compared with the one gained through the Laplace's equation resolution, as shown in Figure 3. It shows that trend of the two results are similar; the differences for the central part of the pipe (a more linear trend for the simulative results and lower linear trend for the theoretical model results) depend on some simplifying hypotheses for the design of the pipeline on the software. Furthermore, for the experts working in the company, the variations between the two data are certainly acceptable.

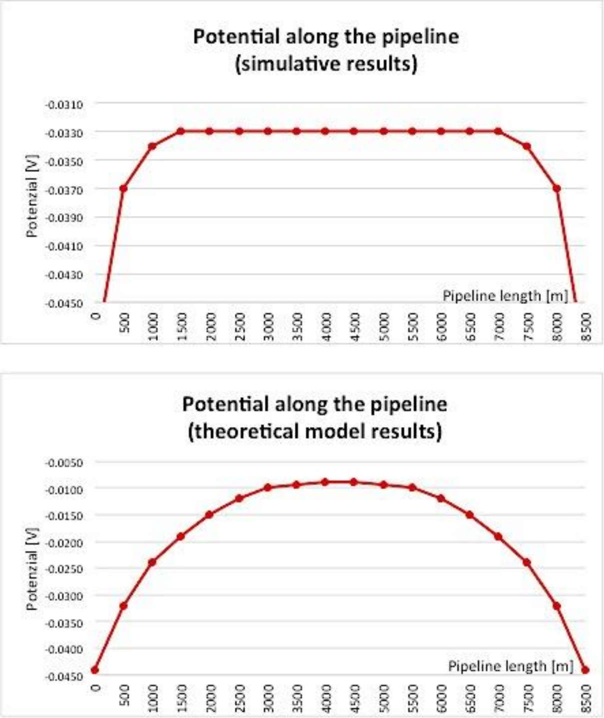

Figure 3: Potential along a pipeline: comparison between the results gained by simulation software and by the Laplace's equation resolution.

Another evaluation of the CP software reliability was made through the comparison between empirical data and simulation results. Six real pipeline networks of natural gas distribution managed by the company were implemented in the software.

Figure 4: Potential distribution on a real pipeline network gained by the CP simulation software.

In Figure 4, there is the graphical output of the software for the implementation of a real pipeline network managed by the company.

At the same time, empirical measurements of real potential for the same networks was conducted. In Figure 4 are highlighted the different points in which real measurement were conducted.

The two kinds of result have been compared both for trend and value (mean potential for real measurements and for simulative results, standard deviation, etc.). The difference between the mean potential measure value (in the seven points) and simulative one (in absolute value) is around 55 mV which is an acceptable value.

This delta potential, in fact, does not influence the final characterization of the network in terms of effectiveness of protection against corrosion: if we consider the potential threshold value for underground steel pipeline (-850 mV) and we add or subtract the absolute mean potential measure error (55 mV), we can see that the final potential value (the simulative one +/-55mV) is lower than -850 mV. In Table 1, such results are summarized.

Table 1: Potential values for seven points of a real pipeline network.

Point	Simulated potential [mV]	Measured potential [mV]	Δ	Simulated potential +/- absolute mean error (55mV)
1	-1025	-980	45	-1080/-1070
2	-1000	-990	10	-1055/-945
3	-1000	-1150	-150	-1055/-945
4	-1000	-930	70	-1055/-945
5	-1000	-990	10	-1055/-945
6	-1000	-1050	-50	-1055/-945
7	-1000	-1050	-50	-1055/-945

The same analysis was done for other 10 real pipeline networks with comparable results.

5. Cost-benefit evaluation of the software implementation

This section presents the main advantages related to the CP simulation software use.

One of the main benefits is the opportunity to define the Electrical Reference State (ERS): this represents the electrical situation of each structure in reference to its specific cathodic protection features. Furthermore, it is used as a reference state for all the controls of the system itself. The potential values measured on a pipeline network, in fact, are usually compared to the ERS of the same network and to the reference value defined of the international technical standard, in order to verify if the pipeline is protected or not. The ERS is furthermore mandatory because it is one of the documents controlled by the national authority for electrical energy, gas and hydro system.

The ERS is usually defined through the evaluation of the potential values on different points for each pipeline network. This activity could be done by the company itself, or by outsourcing such measuring to companies qualified for this work. Obviously, the best solution is chosen considering both costs and competencies.

Here we show a brief evaluation of the costs to support the decision of doing such measuring. It refers to three different areas (Area 1, Area 2 and Area 3) managed by the company.

There are three main activities to do: the first one regards the enrolment, for 24 hours, of the OFF potential of the pipeline in the measurement points; then the ON/OFF potential (for 24 hours) is evaluated and finally, for the same period (24 hours) and in the same measurement points, the ON potential is measured.

Two kinds of equipment are necessary to do these activities: cyclic switch and digital recorder. Both cyclic switch and digital recorder cost 500 €.

Some of them are already available for one of the three areas and this availability will be considered in the costs evaluation. Therefore, the final need for each area is summarized in Table 2.

Table 2: Equipment necessary for the measuring in each zone.

Area	cyclic switch	digital recorder
Area 1	5	5
Area 2	5	20
Area 3	5	20

Considering the number of systems for each area and the time to complete each system measurement (around 5 days for each network), the following necessary periods were appreciated:

- Area 1: 1,5 years
- Area 2: 1,5 years
- Area 3: 1 year.

This assessment considers one person employed to do this kind of work (including vacation periods). Considering the hourly labour cost and the time required for each activity, we have the total costs of labour cost for each zone.

All these information are summarized in Table 3.

Here it is possible to see that the total cost related to the decision of doing such measuring in-house (buying the indispensable equipment as explained here) is around 440.000 €. The outsourcing decision, on the other hand, is more expensive.

The use of a CP simulation software could be a proper alternative solution. In order to verify if this solution is cheaper than the in-house measuring, it is possible to compare the costs related to each choice for the same timeline (24 years in this case).

The first scenario is about the ERS definition by in-house measuring. The costs are explained in Table 3. Obviously, the "equipment" and "business vehicles" costs must be supported only once (at the beginning of the period).

Table 3: Evaluation of the costs to support the decision of doing such measuring; it refers to three different areas (Area 1, Area 2 and Area 3) managed by the company.

Descr.	Costs Area 1 [€]	Costs Area 2 [€]	Costs Area 3 [€]	Total cost [€]
Labour	110.000€	80.000€	120.000€	310.000€
Equipment	2.500€	12.500€	12.500€	27.500€
Business vehicles	11.000€	8.000€	12.000€	31.000€
Total indirect cost	**123.500€**	**100.500€**	**144.500€**	**368.500€**
Planning activities	21.500€	14.500€	25.500€	71.500€
TOTAL COST	**155.00€**	**115.000€**	**170.000€**	**440.000€**

The second scenario is about the ERS definition by using the software: in this case, the costs refer to licensing and training courses. Also a smaller activity of measuring should anyway be done on some sampling pipeline networks (for example the 5% of the total networks in order to continuously validate the software outcomes). Considering the current availability, the necessary equipment are five cyclic switches and five digital recorders.

Since the APCE (italian association for the protection of electrolytic corrosion) guidelines don't define a precise revision period, suggesting 3 or 6 years, we conservatively suppose that the ERS must be revised each 6 years.

Table 4 shows the costs for the two different scenarios.

Table 4: Cost evaluation for the 2 different scenarios

Year	Cost scenario 1	Cost scenario 2
1	€ 293.333,33	€ 96.775,00
2	€ 146.666,67	-
3	-	-
4	-	-
5	-	-
6	-	-
7	€ 254.333,33	€ 21.775,00
8	€ 127.166,67	-
9	-	-
10	-	-
11	-	-
12	-	-
13	€ 254.333,33	€ 21.775,00
14	€ 127.166,67	-
15	-	-
16	-	-
17	-	-
18	-	-
19	€ 254.333,33	€ 21.775,00
20	€ 127.166,67	-
21	-	-
22	-	-
23	-	-
24	-	-

In order to evaluate which is the most affordable alternative, the cash flows must be actualized: the actualized cash flow for the Scenario 1 is € 1.206.899,75 while € 127.806,61 for Scenario 2. In addition to the economic advantages, using the CP simulation software, it is possible to redefine the ERS by necessity.
Many other advantages could be achieved by the software implementation. Some of them are explained here:

- It is possible to model the whole structure and to know the potential value in all its points (not only in the measuring points);
- It is possible to reduce energy consumption: the impressed current must not be too high both because of energy reason, and to avoid hydrogen gas bubble formation (that could cause the damage of the metal).
- The CP simulation software allow identifying contingent leaks easily.

6. Conclusions

The goal of this paper is to evaluate the benefits and the costs related to CP simulation software use.
After verifying the reliability of the main output results, a brief evaluation of the main advantages achievable using the software was done.
One of them is about the possibility to define the Electrical Reference State of each pipeline network: this is essential since it is the reference state for all the controls of the system. At the same time, the economic evaluation of the costs to support the decision to define ERS in a classic way, showed the economic convenience of the software. Using the CP simulation model, moreover, the ERS could be redefined by necessity.
Other deepen evaluation could be done in order to explain the advantages achievable using CP simulation software.

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