The Role of Modeling in Pipeline Integrity Management

Christophe Baeté
Elsyca N.V., Vaartdijk 3/603, 3018, Wijgmaal (Leuven), Belgium
Tel. +32 16 498178, Fax. +32 16 474961, e-mail : christophe.baete@elsyca.com

Jean-Marc Dewilde
Elsyca N.V., Vaartdijk 3/603, 3018, Wijgmaal (Leuven), Belgium
Tel. +32 16 498172, Fax. +32 16 474961, e-mail : jean-marc.dewilde@elsyca.com

ABSTRACT

The key point of pipeline integrity management with regard to external corrosion is the control of the corrosion activity at coating defects. In practice pipeline integrity management often results in the execution of intensive field surveys and monitoring programs leading to high operational cost.

The general approach is to apply ECDA techniques and to use ILI tools to gather as much information as possible on the corrosion status. CP and integrity engineers try to correlate different field data like wall thickness measurements, pipe-to-soil potentials, soil characteristics and coating conditions to predict the corrosion risk of the pipeline in a nonintrusive way. Since pipelines extend over long distance this might result in a large number of field data that need to be processed and analyzed. In some cases the corrosion assessment is not evident like in congested areas where access to the pipe is restricted and only few data is available or in collocations where interference affects the pipeline.

This article presents a new approach in pipeline integrity management. Applying modeling technology helps identifying the CP and corrosion condition of an entire pipeline network. The pipeline characteristics, operational CP settings and environmental conditions are considered and the simulation results can be compared with field data for a better understanding of the corrosion status of the pipeline. Different cases are discussed that illustrate how modeling invigorates pipeline integrity management strategies.

Introduction

Conventional pipeline integrity management systems (PIMS) are computer platforms that collect data on the pipeline infrastructure for ensuring the integrity of the pipeline and for making decisions on maintenance programs, inspection strategies, investments with respect to repairs or replacements. Nowadays PIMS is either a quantitative or a qualitative approach. The quantitative approach is based on probabilistic or statistical models (e.g. API RBI 581, API 1160) that require large amounts of data to feed the models. The qualitative approach is based on descriptive data using engineering judgment (e.g. BowTie methodology) that require an in-depth experience of the CP engineer.

Nowadays the CP engineer relies on ECDA data to understand and predict the corrosion behavior. In most cases pipeline surveys are limited to DCVG/ACVG surveys and ON/OFF potential measurements. The measurements provide only indirect information on the pipeline corrosion condition, and in fact, they cannot determine the true pipe-to-soil potential at the metal surface. The measurements are time consuming and increase the operational cost of the pipeline significantly. Moreover the survey results suffers from seasonal fluctuations and are prone to (human) errors which impede a good diagnostic of the pipeline corrosion status.

In order to increase the reliability of the risk assessment of a pipeline network, computer modeling technology is proposed. Modeling technology allows a better interpretation of the field data resulting in an increased knowledge of the CP efficiency and the corrosion risk. Knowledge gained by modeling is used to upgrade the asset database of a pipeline integrity management system with more quantitative data on the pipeline’s CP and corrosion condition. As a result, inspection, repair and investment programs are based on sound engineering data and are executed more efficiently.

Shortcomings of field measurements

In order to ensure an efficient corrosion protection of a pipeline, an understanding is required of the electrical behavior of the pipeline and cathodic protection system and the electrochemical processes taking place at the metal surface. The electrical behavior is described in terms of current and potential distributions in the soil and on the pipeline surface. The current received by the pipeline will polarize the bare metal surface at coating holidays modifying the electrochemical conditions. When a sufficient amount of current reaches the pipe surface, then the exposed bare metal will either passivate or enter in the immunity region depending on its polarization level. The polarization level is determined by the amount of current that is received at the coating defect of a given size. At moderate current densities the steel passivates due to increased alkalinity and the corrosion rate of the pipe is strongly reduced. At higher current densities the metal reaches immunity but excessive hydrogen gas is produced leading to increased risk of coating disbondment and alkaline stress corrosion cracking.

Unfortunately current densities at the pipeline surface can not be measured directly. Hence indirect (ECDA) methods like pipe-to-soil potential measurements are taken with the aim to verify the proper polarization potential and to evaluate the effectiviness of the CP system and its corrosion protection. The CP system must guarantee that the pipe-to-soil potential on the entire structure is more negative than a certain minimum protection level. According to common standards this level is −850 mV versus a copper-sulphate reference electrode (CSE), or 100 mV more negative than the native potential. The minimum protection level however is the potential measured with a reference electrode that is placed adjacent to the pipeline wall. In practice, it is generally impossible to put the reference electrode directly near the structure. Instead, the reference electrode is put at the ground level, directly above the structure which results in important IR-drop errors, especially when CP and stray currents flow in the soil.

An overview of the potentials that are commonly measured in the field is given below:

- The **pipeline potential w.r.t. remote earth** is obtained in normal operating conditions with all rectifiers on. One end of the voltmeter is connected to the test station and the other end to the reference cell. The operator walks away in the direction perpendicular to the pipeline. The pipeline potential w.r.t. remote earth is obtained if the meter reading no longer changes when the operator continues to distantiate himself from the pipeline. The remote earth potential is only indicative and cannot be used to determine corrosion activity. In congested and disturbed areas the real remote earth can not be found due to foreign sources that influence the soil potential.

- The **ON potential** is obtained in normal operating conditions with all rectifiers on. One end of the voltmeter is connected to the test station and the other end to a reference cell that is placed directly above the pipeline. The ON potential is influenced by the coating resistance, soil resistance and DC currents causing an IR –drop error in the measurement.

- The **IR-free potential** is the potential at the metal surface that must be measured to determine the protection criteria. As mentioned above it is difficult to obtain this value in practice. Coupons are sometimes used to measure IR-free potentials. Coupons are manufactured from the same metal as the structure being protected, they are located in the same electrolyte/soil as the structure being protected, and they are connected to the structure being protected. In this method, the current to the coupon is small and the IR drop is minimized. Placing the coupon so that a reference electrode can be placed very near to the coupon minimizes IR drops even further. In some cases, coupons are buried with long-life reference electrodes next to them. Installing coupons often occurs in cases where there is a strong indication of external corrosion threat.

- The **OFF potential** is measured by interrupting the rectifiers and measuring the instant potential before depolarization starts. The measurements are taken with a reference electrodes at grade level. The aim is to obtain pipe potentials that are close to the IR-free potential. However, stray currents from third party systems can interfere with the measurement. In addition, it can be difficult to switch off all CP systems that are delivering protection current to the pipeline. Sometimes depolarization phenomena between anodic and cathodic regions on the pipeline itselfs generate sufficient current to cause significant IR drop errors. For an isolated defect without (stray) current interference the OFF and IR-free potentials are equal.

Figure 1 – conventional ECDA approach for corrosion assessment

To conclude, a reliable pipeline assessment requires the knowledge of:

- the current density at a coating defect
- and the true polarization level (IR-free potential) for that given current density

As mentioned above both current density and true IR-free potential are very difficult to obtain in the field. Nowadays the CP engineer relies on ON and OFF potentials (and DCVG signals) to estimate the corrosion risks. Modeling technology bridges the gap between “what could be measured” and “what should be measured”. It enables to retrieve more accurate data on the coating condition and true protection potential of the pipeline by comparing available field measurements such as ON and OFF potentials and DCVG signals with simulation results of those parameters and then calculate the true IR-free potential at coating defects. This innovative approach will be explained in the following chapters.

Fundamentals of pipeline corrosion modeling

The current that is delivered by the rectifiers of a CP system flows from the anode bed through the soil towards the pipeline and other grounded structures that are connected to it. The current flows through the pipe wall and returns back to the rectifier via the cathode cable. The current distribution is determined by variations in soil resistivity adjacent to the pipeline and the pipeline coating. This resistive path influences the ON potential measured over the pipeline.

Dedicated pipeline cathodic protection simulation software was developed by Elsyca that links the potential and current density distribution in the soil with the current and axial voltage drop along the pipeline. The same holds for other metallic objects in contact with the soil such as anodes and other grounded structures. The link between current flow in the pipe and in the soil is made by combining a Boundary Element Method (BEM) for the soil with a Finite Element Model (FEM) for the internal pipeline voltage drop.

Through modeling it is possible to determine all the relevant potentials and current flows used in cathodic protection. As mentioned above, the pipe wall at coating defects must receive sufficient current for proper polarization.

The pipe potential and soil potential are linked with each other through current balances that couple:

- axial current I-axial along the pipeline,
- radial current density J-radial through the wall of the pipeline.

The amplitude of the above currents strongly depends on:

- the axial resistance of the pipeline,
- the coating resistance of the pipeline.

As mentioned above the current distribution depends on the local resistance of the pipe that is mainly determined by the coating resistance and local soil resistivity. The software uses a two-layer model based on global (average) soil resistivity values but takes into account the local soil resistivity in the area around the pipe in the calculation of the equivalent coating resistance. The axial resistance of the pipe is automatically calculated based on the specific resistivity of steel material, pipe length, diameter and wall thickness.

A pipeline is sectionized in different pipeline elements of user defined length. For each pipe element a specific coating property, material property, soil resistivity and polarization behaviour can be defined.

The coating resistance is defined as a porous coating or as a coating with distributed holidays having a given size and specific soil resistivity (both size and resistivity determines the spread resistance and current density of a defect). The porous coating model is rather used for older degraded pipelines with an overall coating breakdown factor while the model for a coating with distributed holidays is used for newer high-performance coatings with small defects. The coating properties in the model can be refined based on DCVG/ACVG and ON potential field measurements. The voltage drop at the rectifier can also be used for verification of the coating resistance.

The solver calculates the pipeline potential V and the soil potential U in the entire soil. Taking into account the notations as used in Figure 2, the procedure to calculate the ON and IR-free potentials can be summarized as follows:

- V = pipeline potential,
- U1 = soil potential directly near the pipeline,
- U2 = soil potential at earth surface level directly above the pipeline.

These potentials are calculated relative to the remote earth (where all potential gradients are zero). The ON-potential is then obtained by post-processing the calculated values as follows:

- ON = V - U2

In addition to the above ON potential, the OFF potential is calculated as follows:

- OFF = V - U1

In its simplest form the relationship between the current density and potential is linear. However in reality the polarization behaviour is not lineair near the native metal potential and an overpotential exists at the pipe surface because of the electrochemical reactions taking place. This polarization potential η is included in the IR-free potential. The polarization data is derived from theoretical Butler-Volmer equations or is measured directly in the field on coupons installed near the pipeline.

- IR-free = η(J-radial)

Finally the calculated IR-free potential is compared with the cathodic protection criteria that define the CP efficiency.

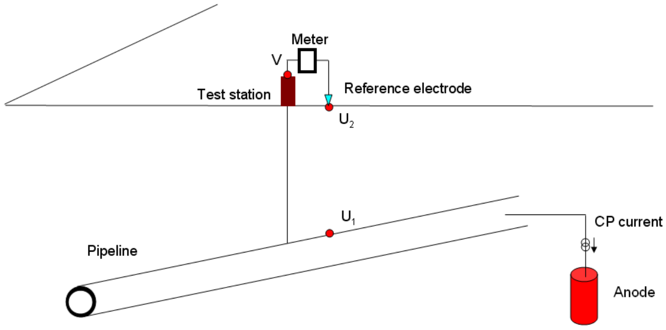


Figure 2 – schematic presentation of a CP pipeline system

The above calculations are performed for each computational node in the model. The model can be very complex such as extended pipeline networks with various branches, multiple pipeline corridors, or even pipelines under DC interference networks of industrial plants. Both SACP and ICCP systems can be included.

Integrating modeling in PIMS

The above described pipeline CP software technology is integrated in a computer-based graphical simulation platform for the integrity management of pipeline networks w.r.t. external corrosion. A computational graphical model of the pipeline network is built based on data that is extracted from the asset database. There are three major steps in the modeling process of the CP pipeline network as shown in figure 3:

- step 1: creating a baseline model
- step 2: calibrating the model based on avaialble field data
- step 3: including AC and DC interference effect from third party systems

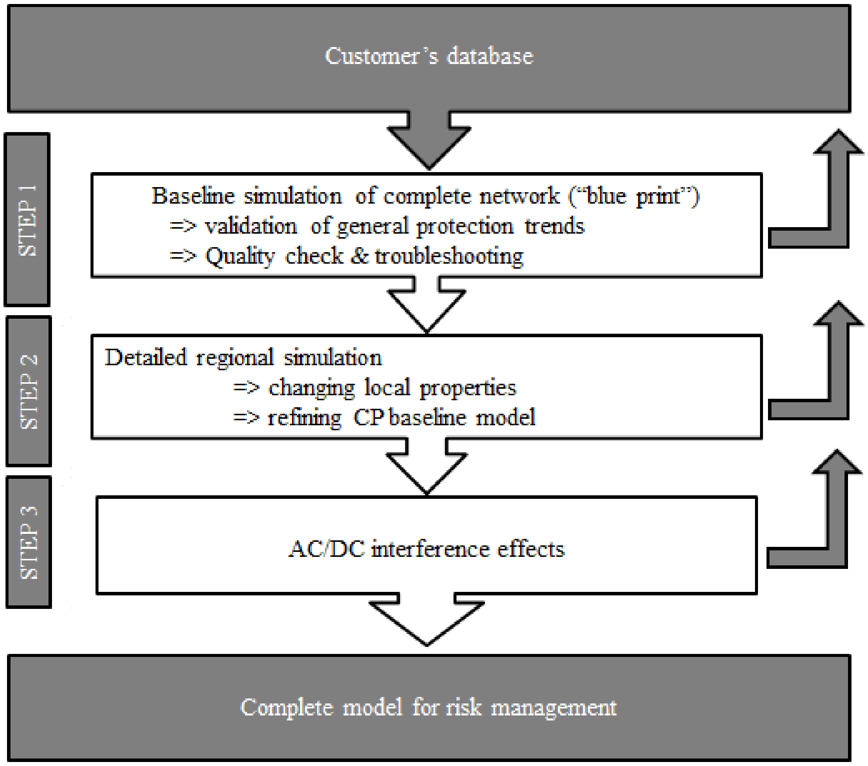
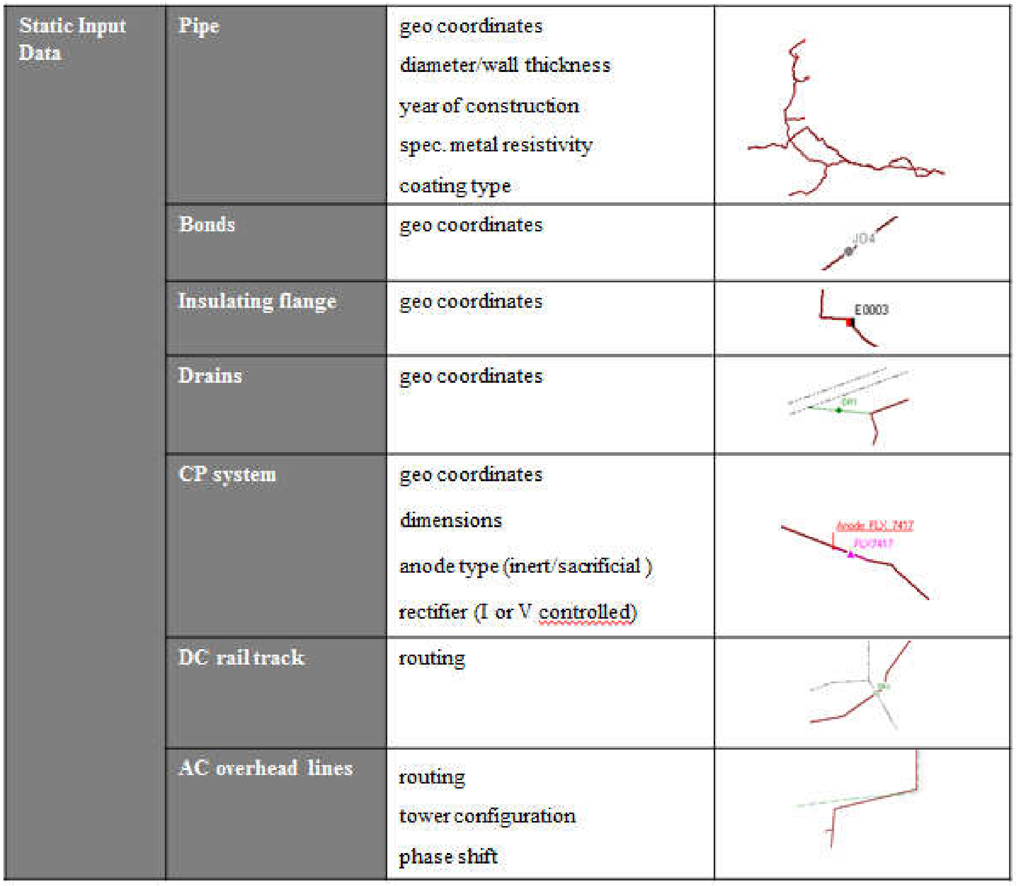


Figure 3 - flow chart of modeling approach for pipeline integrity assessment

Step 1: base model

First the pipeline layout and its CP infrastructure is entered through geographic coordinates. The model consists of elementary pipeline elements, anodebeds, rectifiers, bonds, drainage systems, etc. This data is labeled ‘static’ since it does not change in time unless the network configuration is modified. Figure 4 shows the static data that is used in the computational model with the corresponding symbols. The properties of the different assets are also entered in the model. This data, labeled as ‘dynamic’ is more related to the operational conditions of the CP system and the interference sources and thus changes over time. The dynamic data is shown in Figure 5. The static and dynamic data is extracted from the asset database and can be readily imported if available in digital format.



Static Input Data	**Pipe**	geo coordinates diameter/wall thickness year of construction spec. metal resistivity coating type
	Bonds	geo coordinates
	Insulating flange	geo coordinates
	Drains	geo coordinates
	CP system	geo coordinates dimensions anode type (inert/sacrificial) rectifier (I or V controlled)
	DC rail track	routing
	AC overhead lines	routing tower configuration phase shift

Figure 4 – static input data of the CP pipeline model

Dynamic Input Data	**Bonds**	status (open/close) internal resistance
	Insulating flange	status (open/close) internal resistance
	Diodes	status (open/close) internal resistance activation voltage
	Anodebeds	resistance to earth
	Rectifiers	control setting (I or V) Internal resitance
	DC rail tracks	rail potential ballast resistance
	AC overhead lines	steady-state current load

Figure 5 – dynamic input data of the CP pipeline model

The software generates all CP relevant data that can be used to compare the simulation results with the measured field data for example. At this stage the trends in the field should be confirmed by the modeling results. Discrepancies between calculated and measured data require in-depth analysis and further refinement of the model. They can originate from errors in the customer's asset database, erroneous field data, external influences that are not taken into account, wrong estimates of the coating condition, etc.

Hence simulation results trigger the CP engineer for further refinement of the model and for in-depth analysis. A first troubleshooting is performed by the CP engineer and as a result a more effective field survey is planned for those areas where there is a requirement for more qualitative data.

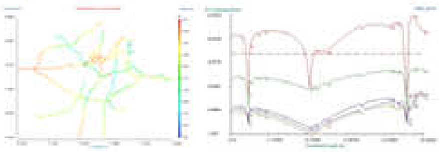
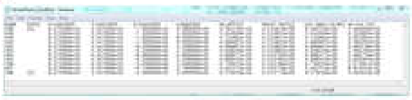
Output Data	**Pipe**	ON potential OFF potential current density axial current	**Colour plots**  **ASCII**  **SVG** 
	Bonds	delta V and I	
	Insulating flange	delta V and I	
	Drains	delta V and I	
	Anodebed/rectifier	applied V or I resulting I or V	

Figure 6 – output data of the CP pipeline module

Step 2: detailed regional simulation
A second iteration consists of further refining the model on a regional scale. Better values for the soil resistivity and coating resistance are chosen. This is done by selecting a specific network region in the model for which better values for the local soil resistivity and coating resistance are found. This step of refinement is repeated until a good correlation with measured field data (e.g. ON potentials) is achieved. The exercise is done for the various regions in the model. After calibration of the various regions the model contains the as-is status of the entire pipeline network.

At this stage the model contains consistent data with correct values for the coating resistance and local soil resistivity and more important, generates correct IR-free potentials and current densities along the pipe routing. As a result a more quantitative corrosion risk assessment is now in place. Furthermore the current flowing through rectifiers, bonds, drains etc. is calculated and can be verified with field data as well.

Step 3: AC and DC interference
In some cases AC and DC interference may influence the pipeline integrity.

The modeling platform allows the simulation and mitigation of inductive steady-state and fault AC interference effects. The user models the HVAC transmission line configuration in the model and determines the proper operational conditions of the energized line. For inductive steady-state interference, the user defines the operational current load and can then simulate the induced pipeline AC voltages and compare these to the measured voltages. With respect to fault scenarios, the user selects a specific tower and defines the fault current, and can then simulate the resistive and inductive effects.

Modeling of DC interference is done by defining external voltage sources in the areas of the network where interference is observed and has been measured.

- In the case of static DC interference originating from third party CP systems, the third party structure is added to the model and connected with an external voltage source. The imposed voltage is equal to the actual pipeline potential resulting from its own CP infrastructure.

- In the case of dynamic DC interference caused by traction systems, multiple voltage sources are defined that are connected to the rails. The imposed voltages are equal to the measured rail-to-soil potentials. Multiple voltage sources can be defined within a single interference zone for a good distribution of the stray current since interference is typically spread out over a large region.

The static or dynamic interference levels are then verified by comparing the simulated results with the measured pipeline potentials, the current flow through bonds and drainage systems.

Benefits of modeling

An important feature of the modeling software is the graphical visualization of the CP and corrosion condition in a geographic map. The model and the simulation results are exported to a cartography system such as a commercial GIS software or Google Earth, as shown in Figure 5. This allows easy troubleshooting of CP performance and enables fast identification of areas with increased corrosion risk that require more intensive surveys and/or excavation of the pipeline in question.

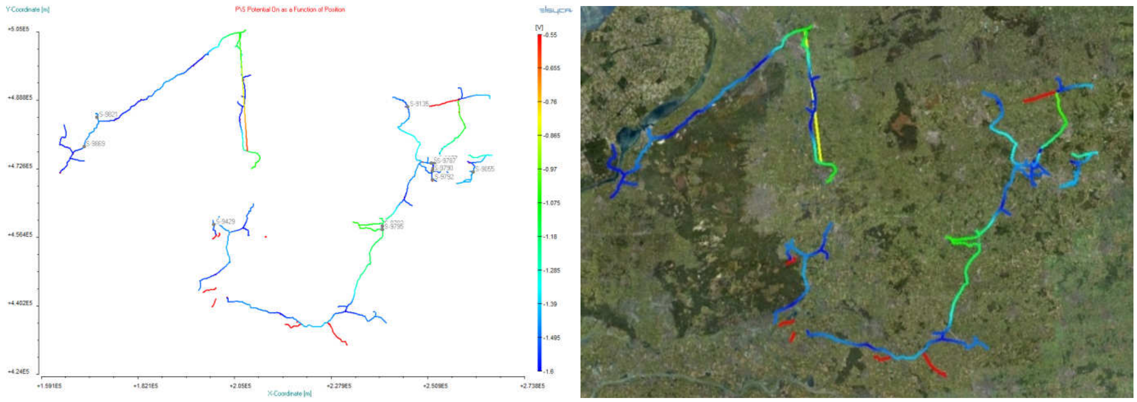


Figure 7 – visualization of the CP and corrosion health status

Once a model of the actual status is in place, the CP engineer can further exploit the model to study different scenarios that might impact the pipeline network or that could improve its integrity. Possible scenarios could be:

- steering rectifier current outputs in order to bring protection levels in a safe range of IR-free potentials
- investigating the influence of different soil resistivity, coating upgrade and/or degradation, accidental short-cuts, failing CP systems, etc. on the CP performance
- engineering upfront CP design for new pipeline sections
- evaluating interferences of newly built and existing structures in the neighborhood of the operator’s pipelines

Case studies

Two industry cases are discussed that illustrate the role of modeling in a pipeline integrity management environment.

1. IR-free determination

This case illustrates how computer modeling is used for troubleshooting erroneous OFF-potential measurements in the field. The case shows a 24 inch 3 LPE pipeline that crosses an old third party pipeline near an anode bed. There is no electrical connection between the two pipes. The soil resistivity in the area is 403Ωm.

The well coated pipeline has an ON-potential of -1.9 VCSE. The foreign pipeline has a measured ON-potential of -4.5V. The far negative value is due to the presence of the anode bed near the crossing and the high soil resistivity in that area. Figure 8 shows the ON and OFF potential measurement along the pipeline. Some concerns arise in the area near the crossing where the ON potential is around -1.2V and the OFF potential is -0.23V. The OFF potential is far more positive than the -0.85V protection criterion and therefore corrosion was suspected.

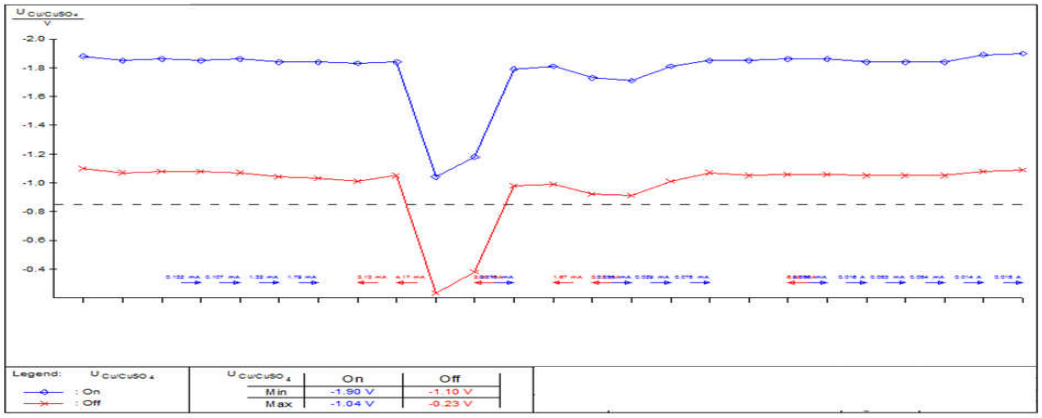


Figure 8 – measured ON and OFF potential on owner's pipeline

Figure 8 shows the computational model of the area of concern. A voltage source of -1.9 and -4.5V versus remote earth is applied at the end of the owner's and foreign pipeline respectively.

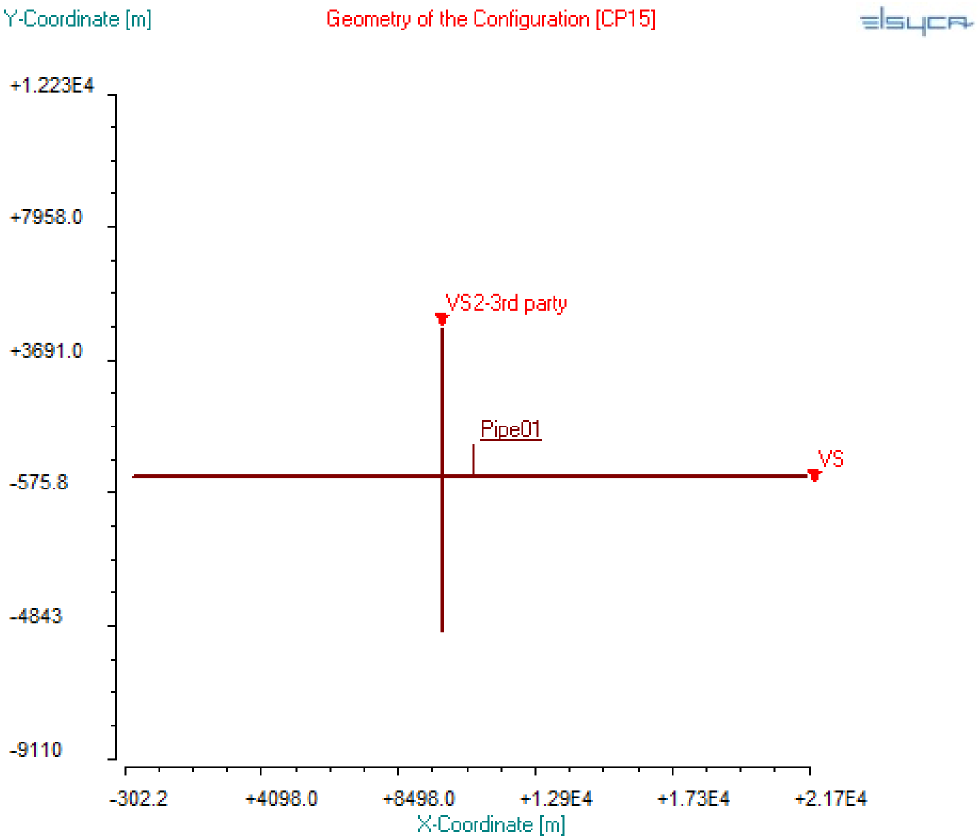
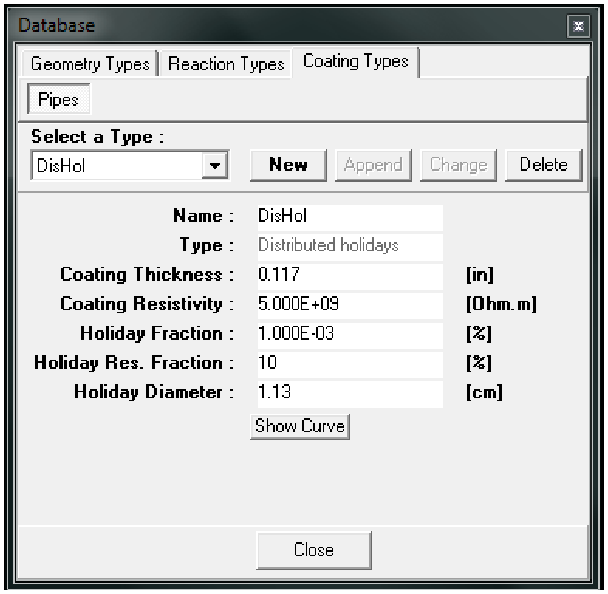


Figure 9 – computational model case 1

It is assumed that the owner's pipe has an overall small coating resistance of 7.7e6 Ωm2 except for a small area at the crossing where a coating defect is assumed. A coating with distributed holidays is defined for a section length of 800 m at the crossing. The properties of the coating and the coating defects are shown in Figure 10. In the model, the diameter and surface fraction of the holidays can be entered. The resulting coating resistance for that section is 4.47e4 Ωm2.



Select a Type : DisHol

Name : DisHol
Type : Distributed holidays
Coating Thickness : 0.117 **[in]**
Coating Resistivity : 5.000E+09 **[Ohm.m]**
Holiday Fraction : 1.000E-03 **[%]**
Holiday Res. Fraction : 10 **[%]**
Holiday Diameter : 1.13 **[cm]**

Figure 10 – model characteristics for damaged 3LPE coating at crossing

Figure 11 shows the ON potential on the pipelines when the rectifiers are activated. The overall potential is -1.9V as applied while at the crossing the ON potential is reaching a value of -1.22V. This corresponds well with the measured field data (dip in the upper curve in Figure 8). The simulated IR-free potential is -0.965V as shown in Figure 11. The remaining pipeline has a simulated IR-free potential of -1.192V which corresponds well with the measured OFF potential in the field (red line with crosses in Figure 8). Now the dip in the measured OFF potential towards measured values of -0.23V can be explained by the model. The simulated IR-free potential -0.965V is applied as boundary condition at the owner's pipe and the simulated potential at earth grade is extracted from the model as shown in Figure 12. The simulated OFF potential value is -0.298 V and is in close agreement with the field data. Through modeling it can be concluded that the pipeline is properly protected (IR-free potential of -0.965V) whilst the field measurements shows far positive OFF potentials due to the potential gradient in the soil between the two pipelines.

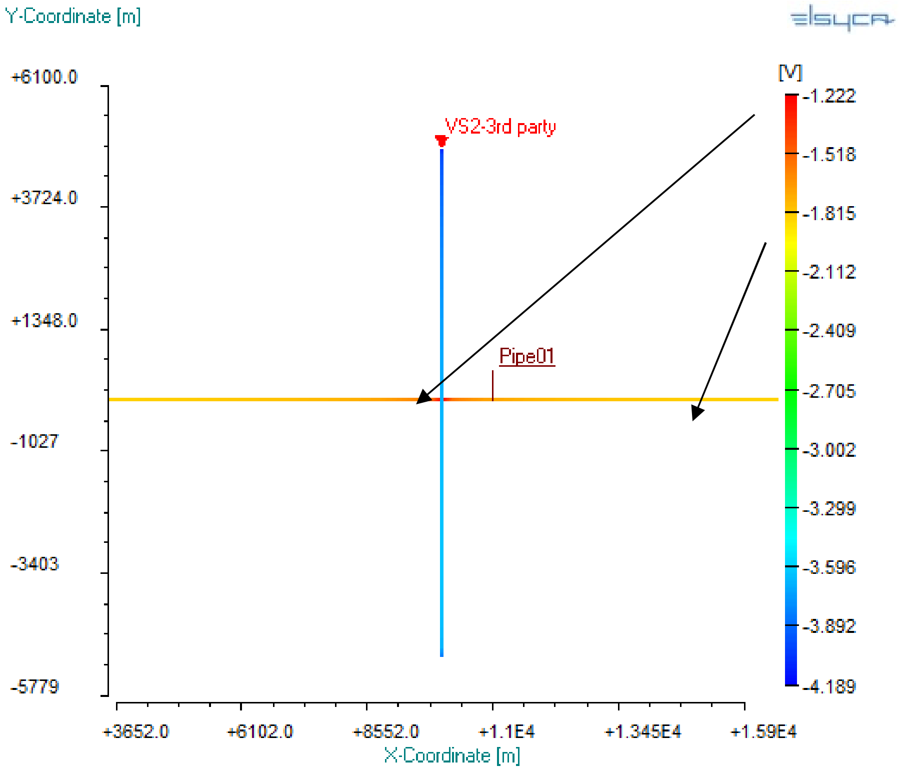


Figure 11 – simulated ON potentials for case 1

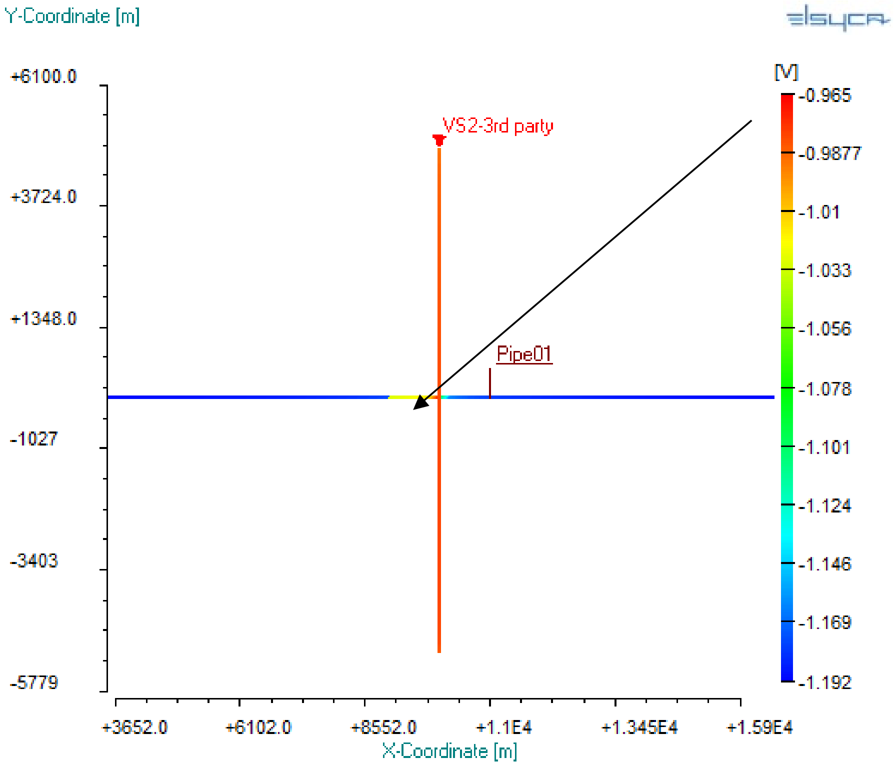


Figure 12 – simulated IR-free potentials of case 1

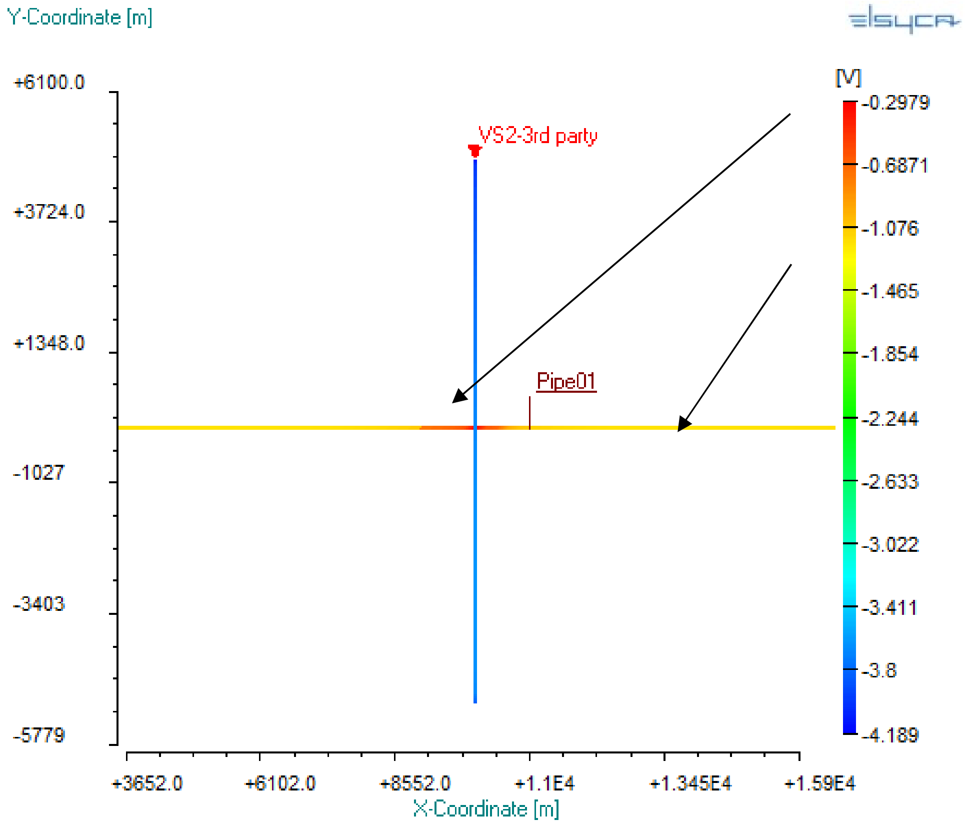


Figure 13 – simulated IR-free potentials of case 1

2. CP efficiency validation

An old 8 inch pipeline with an approximate length of 16 miles (26 km) was surveyed by close potential survey (CIPS). The majority of the line has a coal tar coating except for 3 re-route sections that are coated with Fusion Bonded Epoxy (FBE). In total, 12 rectifiers are protecting the pipeline with a total current output of 236 amps.

A computational model was built based on the XY coordinates of the pipelines and anode beds position. The pipeline has 3 bonds to foreign structures. Figure 14 shows the computational model of the pipe route with rectifier positions (pink triangles).

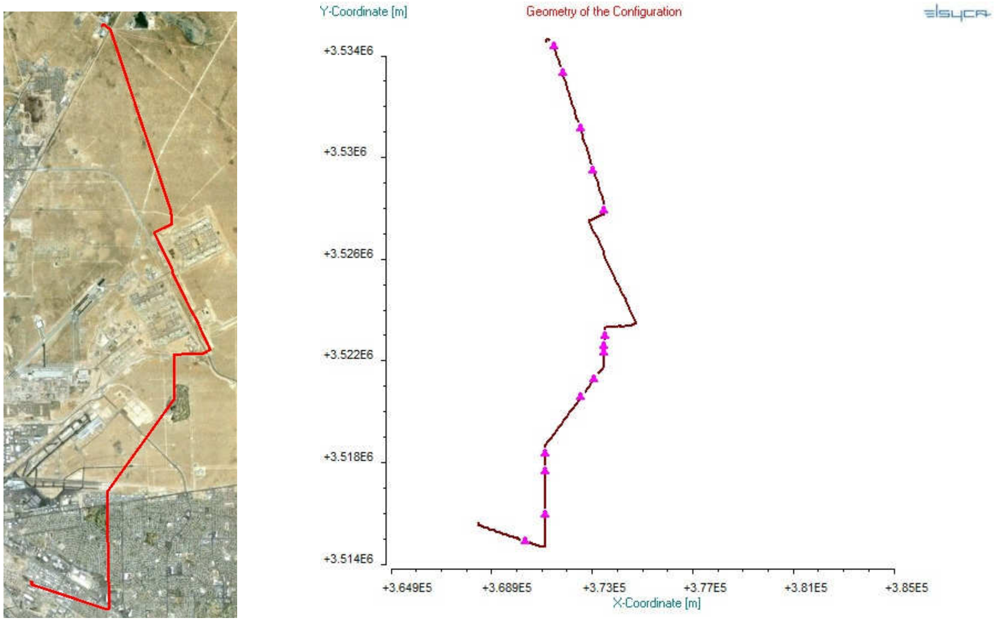


Figure 14 – Google earth representation of pipeline route and corresponding CatPro simulation model

The current output of the different rectifiers was entered as input data. The soil resistivity was reported to be between 50 and 100 Ωm. The coating resistance for different sections was optimized in an iterative way until the simulated ON potentials were in line with the measured CIPS data. Sections with new FBE re-routes resulted in a coating resistance exceeding 5000 Ωm2 with a maximum of 22500 Ωm2. The coating resistance of the coal tar coating was as low as 250 Ωm2 in some areas.

Figure 15 shows the simulated IR-free potentials resulting from the model.

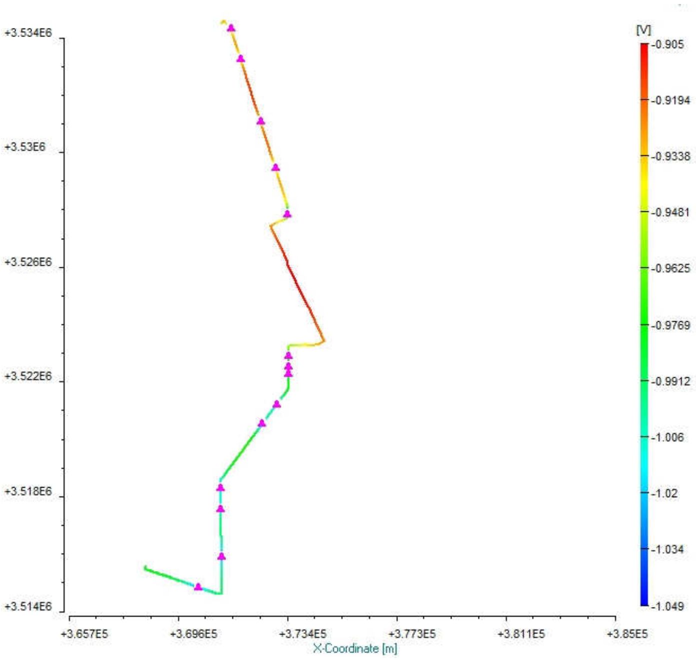


Figure 15 – Google earth representation of pipeline route and corresponding CatPro simulation model

The simulated OFF potentials are plotted against the measured native potential and the instant OFF potential as shown in Figure 16. The simulated OFF or IR-free potentials (red line with bullets) shows good correlation with the measured instant off potentials (green line). More scattering in the measured data during instant off measurements is noticed which is inherent to field measurements. The model confirms the trend in the OFF potentials indicating areas that do not meet the CP criteria. It also shows some discrepancy with the measured data in some areas that enables the CP engineer to execute more in-depth field survey.

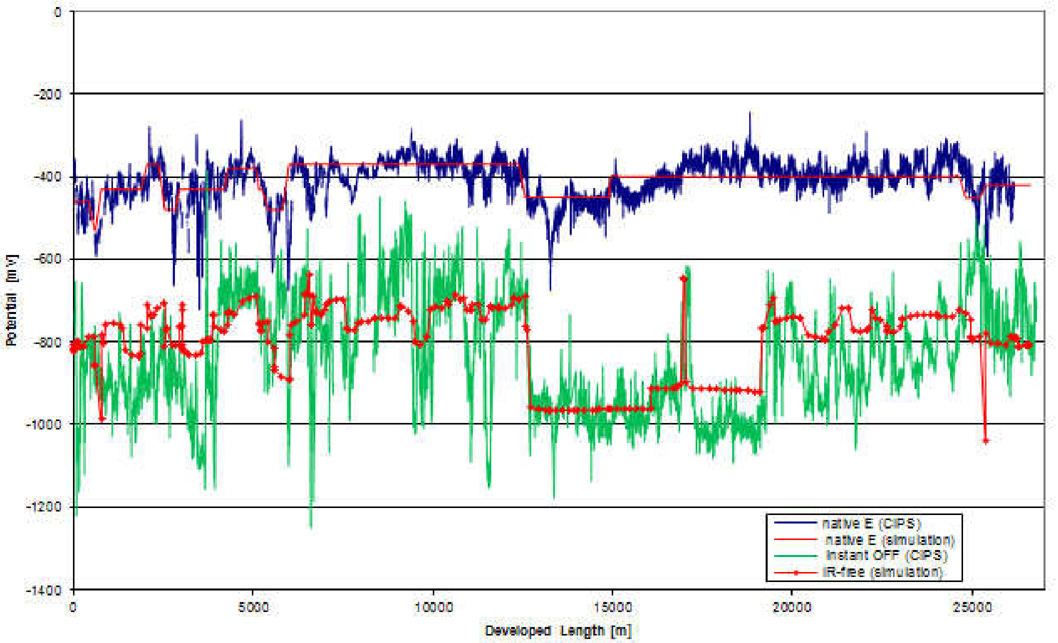


Figure 16 – comparison between simulated potentials and CIPS survey data (upper curve is native potential and lower curve is instant OFF potential)

Note that CIPS surveys have been performed in this case but this intensive effort is not absolutely necessary to validate the model. For example, the modelling results can be checked by measuring potentials at some test stations along the pipe route.

Once the model is in place and validated, different ‘what-if-scenarios’ can be studied. Whatever changes that are occuring, the effect on the protection level of the pipeline can be predicted up-front through simulations. For example Figure 17 shows the simulated axial current flow in the pipe wall for the situation with and without a bond to a foreign pipeline. Other influences like the effect of aging of the coating, rectifier failure, varying soil resistivities,… on the protection level of the pipeline can easily be predicted through simulation.

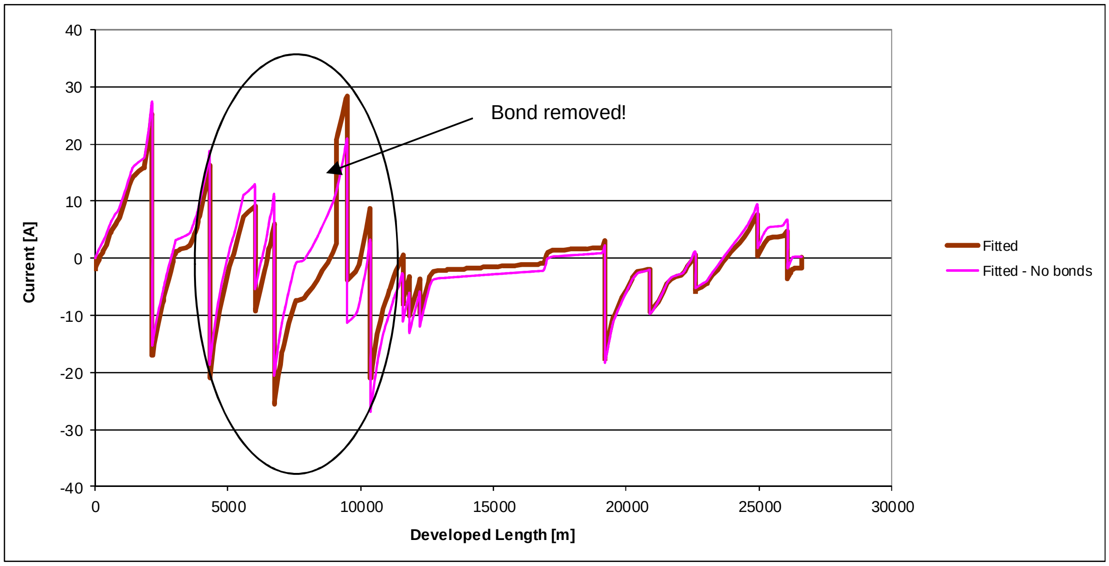


Figure 17 – effect of disconnecting a bond between pipes

Conclusions

The CP engineering software provides operators with a unique state-of-the-art management system for the assessment, design, optimization, monitoring, and troubleshooting of the pipeline network's corrosion protection, and ultimately leads to a better understanding of the integrity of the assets. Modeling offers more insight in the true protection level of the pipe and its coating property resulting in a more quantitative approach of pipeline integrity management without generating massive set of data.

- accurate prediction of true protection levels (IR-free potentials) along the pipeline networks
- better insight into the cathodic protection performance and influencing factors
- detection of anomalies in the CP system such as shorted casings and accidental grounding by correlation between simulated and measured values
- identification of pipeline areas with increased corrosion risk
- prioritization of preventive survey activities

Two examples are discussed that illustrate how modeling is used within a PIMS environment to analyze field measurements and to study in-depth the pipeline integrity.

References

[1] Towards a Fully Integrated Pipeline Integrity Management Software, L. Bortels, P. J. Stehouwer, K. Dijkstra,Nace conference paper, Houston, 2011

[2] L. Bortels, J. Deconinck, “Numerical Simulation of the Cathodic Protection of Pipeline Networks under Various Stray Current Interferences”, Chapter 8 in book “Modelling of Cathodic Protection Systems”, ISBN: 1-85312-889-9, WIT Press, Southampton, UK, 2006.

[3] L. Bortels “A User-Friendly Simulation Software for the Cathodic Protection of Large Networks of Buried Pipelines Influenced by DC-Traction Stray Currents”, Paper 02113, NACEExpo2002.

[4] A New Approach to Pipeline Integrity – Combining In-line Inspection and Cathodic Protection Simulation Technology, Dennis Janda, Chr. Baeté and L. Bortels, Nace conference paper #9277, Orlando, 2012/