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A New Approach to Pipeline Integrity – Combining In-Line Inspection and Cathodic Protection Simulation Technology

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ABSTRACT

The integrity of pipelines can be assessed by using in-line inspection (ILI) tools and direct assessment (DA) methods. Conventional ILI techniques like magnetic flux leakage (MFL) and ultrasonic thickness (UT) quantify the severity of corrosion that has already occurred, but they do not give any information on the performance of the cathodic protection (CP) system. Traditional DA data often require a great deal of interpretation, leaving unanswered questions about what is really happening on the pipeline and more importantly, what to do about it. Traditional DA surveys are slow, labor intensive, operator- dependent, and costly to execute.

This paper presents an advanced inspection method that combines a CP current measurement ILI tool with a CP simulation technology. The ILI CP tool measures the true electrical current patterns on the pipe that originate from a CP system or interference source. The current density data from the CP ILI tool are then used by the simulation model to predict pipe-to-soil potentials.

A case study is discussed where a simulation model is constructed for an 8 in. (219 mm) pipeline 16.15 miles (26 km) in length. The axial current measured by the CP tool is used by the model to predict the local coating resistance, local ON/OFF potentials, and enables prediction of the corrosion risk.

This combined approach offers the benefit that a simulation model can be developed that fits well to the actual conditions of the pipeline with a minimum of assumptions. Through modeling, the CP system can be further improved by running different "what-if" scenarios such as changing the rectifier outputs, connecting/disconnecting bonds, changing coating condition (e.g., long-term degradation), varying soil resistivity, etc., with a minimum amount of survey cost and greatly reduced field time.

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Key words:
Cathodic protection, current, in-line inspection, current measurement, potential modeling, simulation

INTRODUCTION

In order to ensure highly efficient and low cost protection of structures, it is necessary to have an optimized CP system design. This requires a complete understanding of the behavior of the electrical and electrochemical process performance in terms of current and potential distributions on the pipeline system and in the soil. In the field, the CP currents that reduce corrosion to acceptable levels are not usually measured and the pipeline condition is indirectly assessed by potential measurements.

The major parameters determining the effectiveness of a given CP system (with fixed geometry and anode configuration) are:

- coating quality
- soil resistivity
- structure polarization

These parameters vary significantly along the structure which complicates the design of the CP system and its monitoring.

The most commonly accepted goal of a cathodic protection system is to obtain a structure-to-soil or IR-free (IR = ohmic drop) potential on the entire structure that is more negative than a certain minimum protection level. Care must be taken in order to avoid excessive hydrogen formation that leads to coating disbondment and increased risk of stress corrosion cracking. This IR-free potential can only be measured with a reference electrode that is placed directly adjacent to the structure in order to reduce the IR-drop in the electrolyte. In practice this is nearly impossible due to the hidden nature of the structure. Conventional pipeline surveys are therefore limited to ON and OFF potentials taken at the earth grade in an effort to reduce the error caused by IR drop in the soil.

The OFF potential is measured by interrupting the rectifiers and all other current sources and measuring the instant pipe-to-soil potential before depolarization starts. This measuring technique eliminates the IR-drop caused by current flowing in the soil, but only on the condition that no stray current interference or any other currents are present on the structure. In addition, it can be difficult to switch off all CP systems that are delivering protective current to the structure. In the case of sacrificial anodes, no OFF potentials can be obtained unless the anodes are disconnected from the structure. A small amount of current will still be flowing to the structure leading to a potential drop in the electrolyte, and thus causing an error in the potential reading.

Potentials are measured at test points or at locations where there is a direct access to the pipe. In a more intensive form, close interval potential surveys (CIPS) can be performed. Potential readings are combined with coating surveys like direct current voltage gradient (DCVG) or alternating current voltage gradient (ACVG) in order to assess the severity of corrosion attack as performed in external corrosion direct assessment (ECDA) programs. Executing ECDA programs is very labor intensive, slow, costly, and does not always give reliable results, as is evident in congested areas, submerged areas, paved areas, complex installations, or pipelines subject to AC or DC interference.

It is very important to have an adequate model that describes the performances of the cathodic protection system and the real pipeline behavior. In this article, powerful modeling software is discussed that simulates the electrical/electrochemical processes going on at the pipe metal surface based on the current flowing from the soil into the pipe wall. This current flow is measured and recorded by an in-line inspection tool.

MODELLING CATHODIC PROTECTION

The protection level of a structure can be obtained through modeling since measuring errors or interference problems only occur in the field. A cathodic protection system and pipeline can be represented as a complex electrical network. The current and voltage output of the rectifier is determined by the characteristics of this complex electrical network. The voltage at the rectifier is determined by the total resistance of the network and the current flowing through it. The main resistive components are the soil and the coating resistance which can vary locally resulting in different current densities and protection potentials at the pipe metal surface.

Elsyca's CatPro™ software† is a BEM/FEM based computational tool that allows simulating the behavior of a pipeline with cathodic protection applied. A model of the pipeline network and the cathodic protection system is built including insulating flanges, grounding, joints, anode beds, connection cables and rectifiers. In case of DC and AC interference, the rail track and HVAC line route can also be included. At the pipe metal surface current density reaching the pipe will polarize the pipe to a certain extent and this is dictated by the polarization curve of steel for a specific soil.

† Trade name.

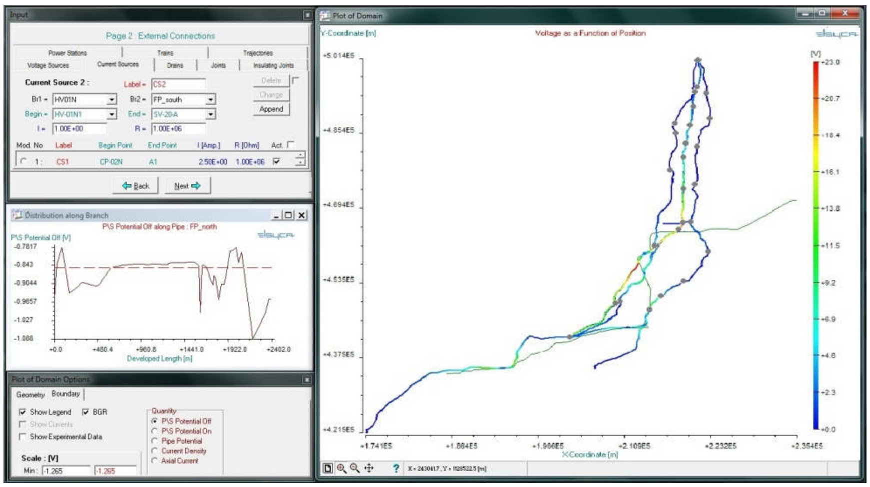

Figure 1: Example of simulated ON potentials of a pipeline network

The entire pipe is divided into discreet sections to which different properties like coating condition and soil resistivity can be addressed. Under normal usage the rectifier current output, coating resistance, soil resistivity and pipe-to-soil polarization behavior is given. Operational data and pipeline characteristics are gathered from surveys or extracted from pipeline integrity management systems.
The modeling software calculates:

- IR free potentials at pipe-to-soil interface over the full pipe route
- ON and OFF potentials at different soil grade levels
- axial current flow to the pipe wall
- local current density
- rectifier voltage

In the software simulation results can be compared to experimental field data which is useful for troubleshooting CP anomalies.

Once the model is in place different “what-if” scenarios can be investigated, for example:

- influence of rectifier settings or failures
- long-term coating degradation
- changes in soil resistivity
- effect of bonds
- shorted insulating flanges
- impact of DC and AC interference

As an example the ON potential at grade level of a poorly protected chemical plant piping system with centralized anode bed is shown in Figure 2.

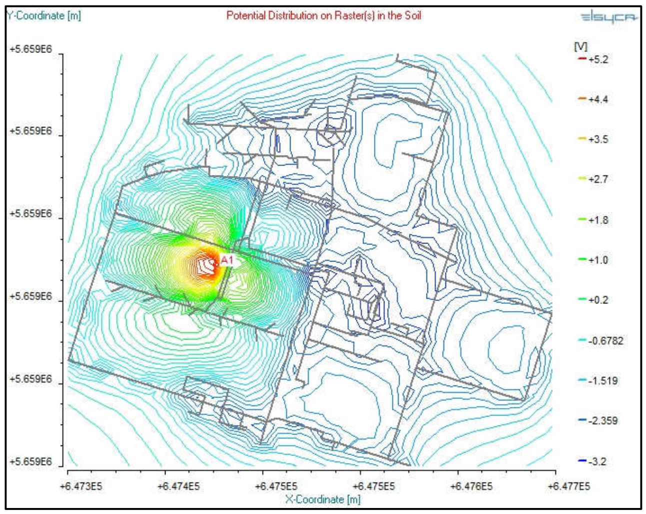

Figure 2: Example of calculated ON potentials at grade level

IN-LINE CATHODIC PROTECTION INSPECTION TOOL

A CP system is an electrically closed circuit. The cathodic protection current flows from the anodes into the soil to the pipeline, enters the pipe at coating faults, travels along the pipe wall (axial current flow) and leaves the pipe at the connection cable with the rectifier or sacrificial anode. Figure 3 shows a typical current flow in the CP electrical network. The applied current can deviate if the pipeline is electrically connected to foreign structures by (undesirable) shorts or bonds. The current is collected at the connection cable between the rectifier and pipe and has a polarity (+ or -) that depends on the return path.

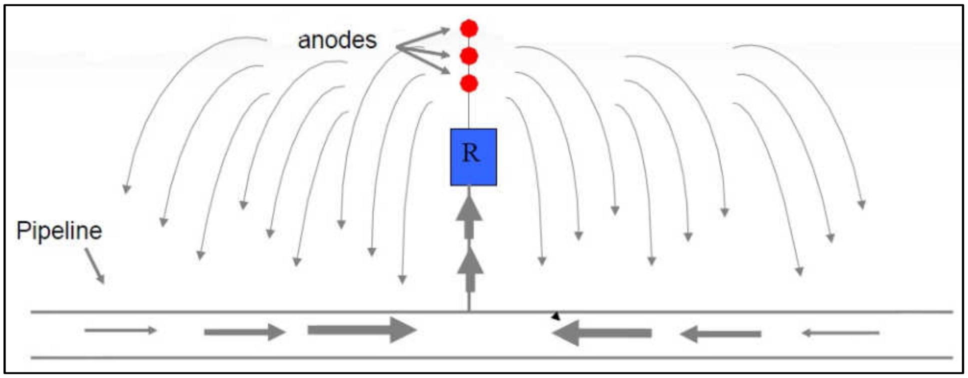

Figure 3: Current flows in typical CP system

Since there must be continuity of current flow in the CP circuit, measuring this current flow in the pipe wall will tell exactly how much current the pipe receives from the CP system or third party systems and where along the structure it receives the current in the inspected section. Current travelling on the pipe is very low at the furthest point from the rectifier and gradually builds until reaching a peak at the return connection to the rectifier.

The current flowing in the pipe wall (axial current flow) can be measured by the Baker Hughes† ILI tool. The cathodic protection current measurement tool (CPCM™)† inspects piggable pipeline sections while the cathodic protection system is in normal operation. The tool very accurately measures the potential drop along the pipe wall while traveling at a speed of a few miles per hour. The potential drop is converted to axial current flow through Ohm's law, I = E/R.

Figure 4 – set-up of the cathodic protection in-line inspection tool

† Trade name.

A typical axial current flow profile with multiple drain/source sections is given in Figure 5. The results from a cathodic protection ILI run have the same value as a combined CIPS and coating survey with the difference being that data is obtained much faster, more accurately and without the typical access/permissions problems associated with above ground surveys. The tool is able to:

- Measure current pick up along the protected structure
- determine local current density
- verify the current output of the rectifiers
- detect location of bonds/shorts in the pipeline that lead to current loss or current gain
- detect AC and DC interference

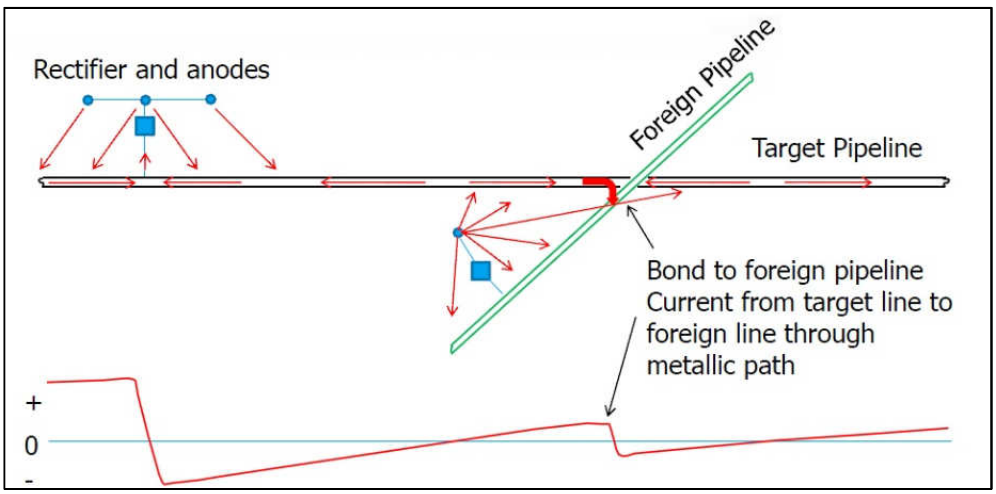

Figure 5: Typical axial current profile in presence of bond to foreign pipeline

The cathodic protection in-line inspection tool does not provide pipe-to-soil potentials, which have been defined by national and international standards for assessing the protection level of the pipeline. Modeling technology does provide this data and hence the idea to combine both technologies has resulted in a very powerful tool for the assessment of the CP efficiency. This new approach is very promising, since the NACE SP0169[1] standard allows latitude for the operator to use any assessment method as long as it provides at least the same level of assurance. This new approach was validated on a crude oil pipeline and the results are discussed in the following chapter.

CASE STUDY

An 8 inch (219 mm) pipeline with an approximate length of 16 miles (26 km) was investigated by the cathodic protection in-line inspection tool. The majority of the line has an old coal tar coating except for 3 re-route sections that are coated with fusion bonded epoxy (FBE). In total, 12 rectifiers protect the pipeline with a total current output of 236 amps.

The ILI tool took 11 hours to measure the complete pipe section with an inspection speed of 1.5 mph (2.4 km/h). In total 61 drain/source sections were identified based on the typical axial current profiles (see Figure 3 for an example). For each discrete section of pipe the current density was calculated and ranged widely from 0.014 to 13.03 mA/ft^2 with an average value of 1.33 mA/ft^2 or 14 mA/m^2. Summation of the currents per section revealed a total current of 245 A which was slightly higher than the current output from the rectifiers. The difference was due to current pickup from third party CP systems.

The axial current data from the ILI tool was used in the CP model to calculate all relevant cathodic protection parameters like IR-free potentials, coating resistivity, and ON/OFF potentials at earth grade.

The simulation model was built based on the XYZ coordinates of the pipelines. The exact position of the anode beds was not given but could be estimated based on the typical pattern of the current at the negative connection of the rectifier with the pipe (see figure 5 as example). From the inspection run it was concluded that the pipeline has three additional bonds to foreign structures at the beginning, middle and end of the pipe route under investigation. These bonds were also included in the computational model. Figure 6 shows the model of the pipe route with rectifier positions (pink triangles).

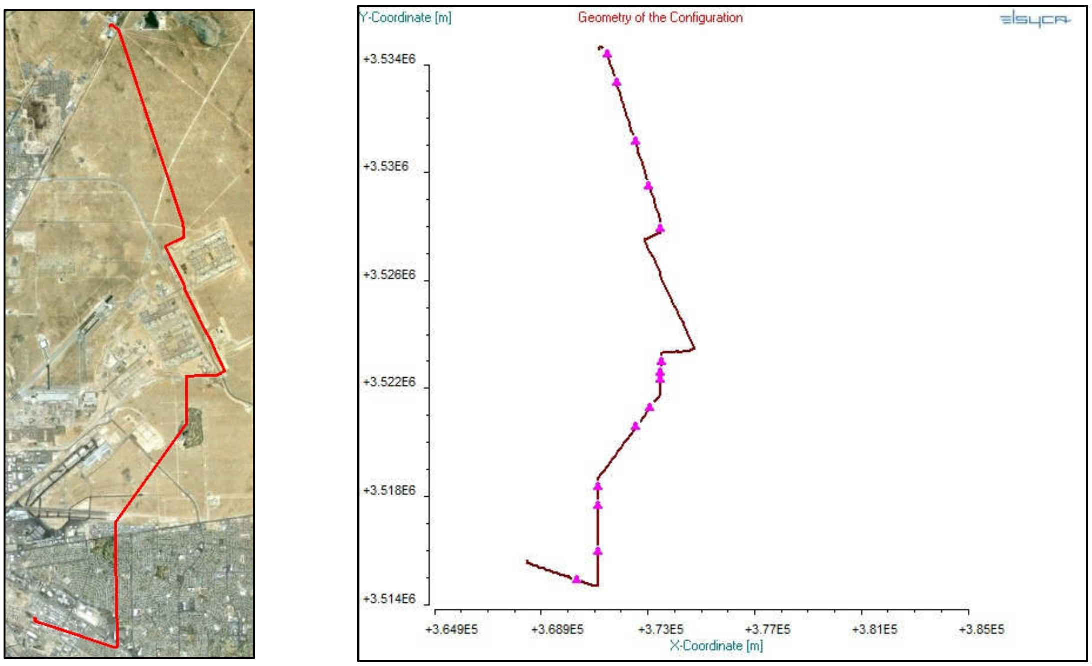

Figure 6: Representation of pipeline route and corresponding computational model

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 axial current data from the ILI tool was used to represent the coating condition in the model in an iterative way and a good fit was found between the simulated and measured axial currents. Figure 7 gives the comparison between the measured and simulated axial currents.

The resulting coating resistance from the model is given in Figure 8. Sections with new FBE re-routes are clearly seen showing values exceeding 5000 Ωm^2. The inset graph is a detail of the coal tar coating showing sections that have coating resistance below 250 Ωm^2. That region for example can be prioritized for detailed field coating survey or recoating.

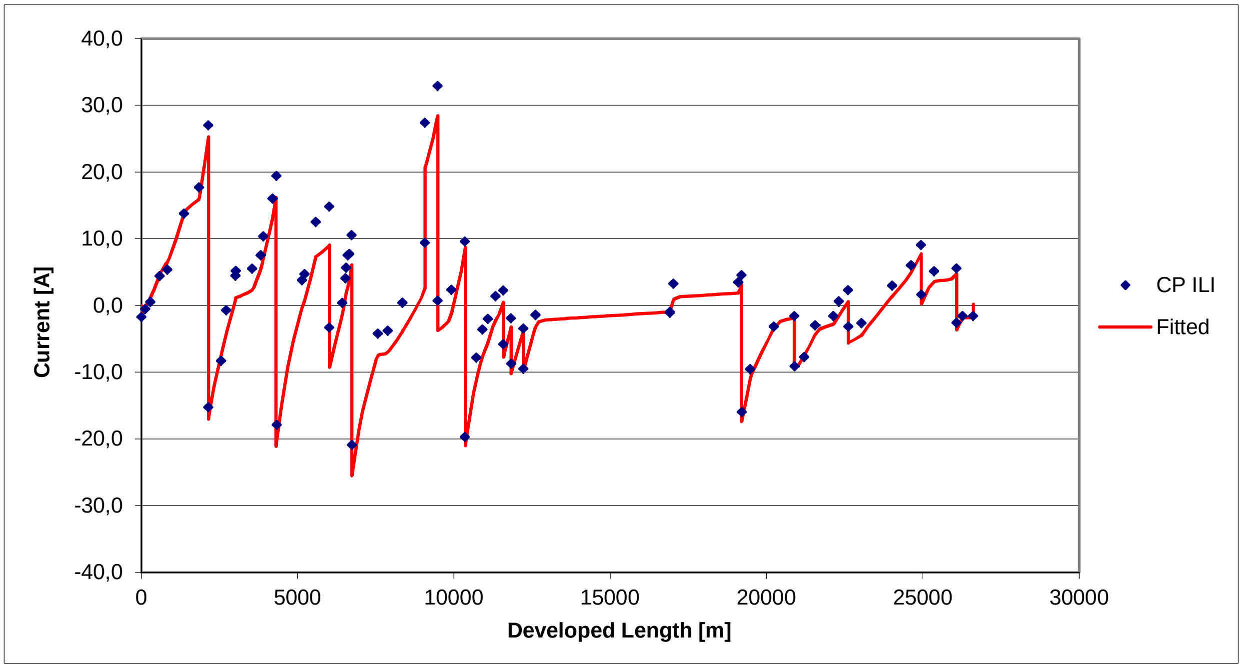

Figure 7: Axial current as a function of pipe chainage – simulated and CP ILI results

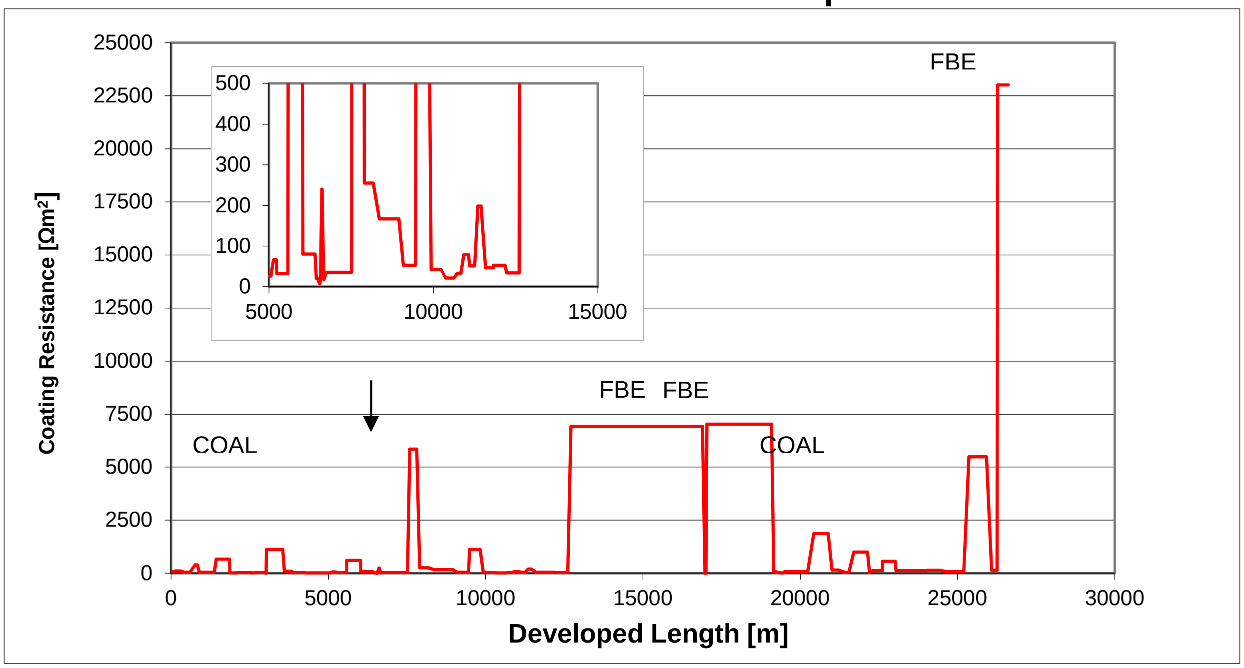

Figure 8: simulated coating resistance with zoom in of coal tar coating sections

The model simulates OFF potentials at grade level and results along the pipe route can be visualized in Figure 9. The simulation results indicate that the pipeline has IR-free potentials ranging between -0.905 and -1.049 V_{CSE} indicating proper protection. However, fixed polarization data was used for the entire pipe but the model can be further refined if different polarization curves are addressed to different pipeline sections. Therefore the native soil potentials were measured in the field by leaving the pipe depolarized (no cathodic protection) for several days. The native potentials were considerably less negative as can be seen in Figure 10. The data was used to refine the polarization curve for the individual pipeline sections in the model. The new simulations showed less negative IR-free potentials ranging from -638 to -963 mV. This was confirmed by close interval pipe-to-soil (CIPS) survey. The simulation results (red line) are plotted against the CIPS survey data (green line). The difference between the native and simulated IR-free potential indicates that the current of the rectifier can be reduced for some parts of the pipeline (e.g., FBE coated section between 12,000 and 18,000 m) if the 100 mV criteria is used.

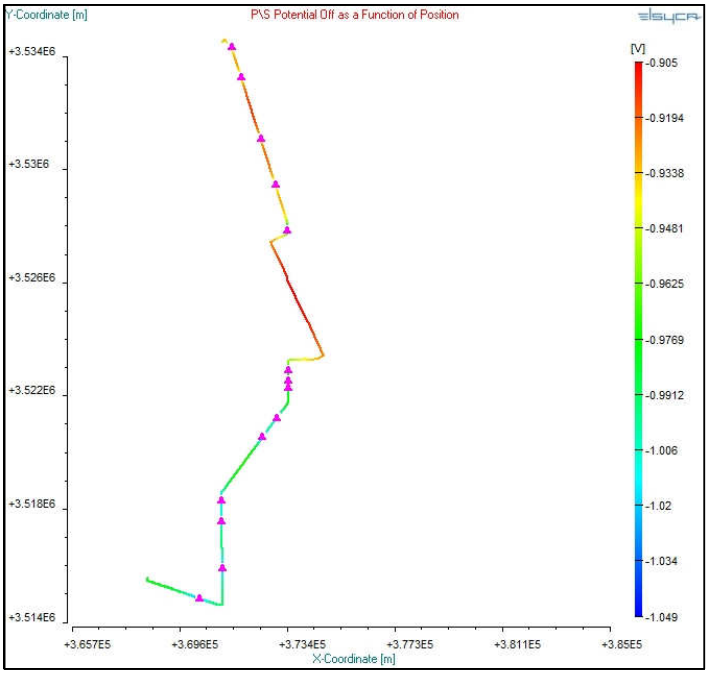

Figure 9: Plot of the simulated IR-free potential of the pipe

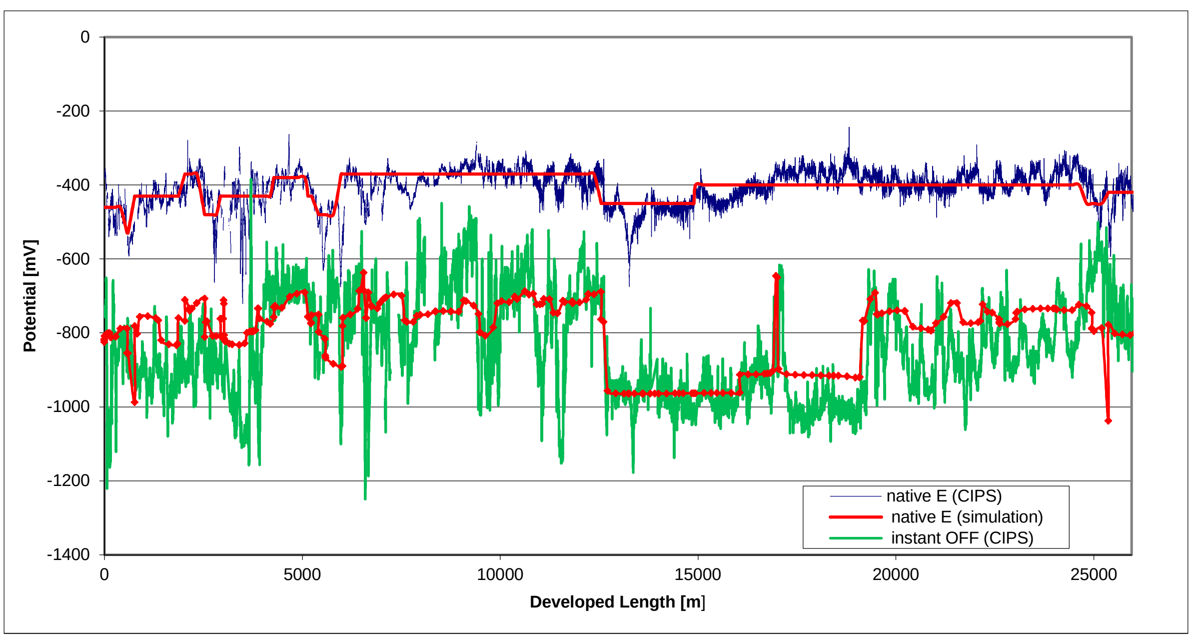

Figure 10: Comparison between simulated potentials and CIPS survey data

Note that CIPS surveys have been performed in this case but this intensive effort is not really necessary to validate the model. For example, the modelling results can be checked by measuring potentials at existing 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 11 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.

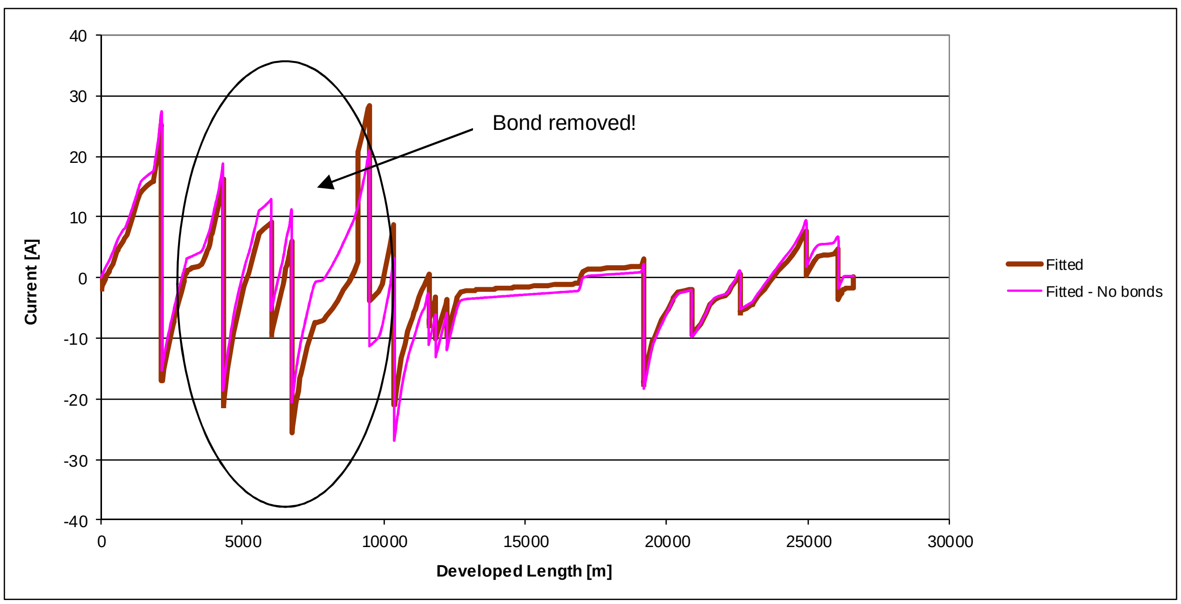

Figure 11: Effect of disconnecting a bond between pipes on axial current flow

CONCLUSION

A new approach is presented for assessing the cathodic protection efficiency of large pipeline networks and it consists of combining modeling technology with in-line cathodic protection inspection tool data collected for the entire pipe segment.

Long pipeline sections are accurately inspected in a single run and at considerable speed (few miles per hour). The local axial current flow in the pipeline is measured while the CP system is in normal operation and these measurements are than translated by modeling software into values for the most relevant cathodic protection parameters like current density, pipe-to-soil potentials and coating resistance.

This approach allows pipeline operators to assess the external condition of the pipeline in a cost-effective and accurate way with a minimum of amount of effort and with much less measurement error. After the first analysis the actual protection level of the full pipeline system is known at the actual level of output of the full CP system. The simulation model can then be used to predict the impact of possible changes in the system on the protection level of the pipeline. Monitoring of the CP system performance can easily be achieved by comparing simulation results with field data at test stations or from a new inspection run with the ILI cathodic protection tool.

REFERENCE

1. NACE SP0169 (latest revision), "Control of External Corrosion on Underground or Submerged Metallic Piping Systems" (Houston, TX: NACE).