

Cathodic Protection System Design Framework

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Abstract— The aim of this article is to establish a cathodic protection (CP) system design framework for the petrochemical industry in South Africa. The CP system design framework is destined to be used as a guideline when designing CP systems for structures such as tanks, underground pipelines, and plant areas within the petrochemical industry. Certain aspects of corrosion and corrosion mitigation are addressed in this paper. The research approach and analytical design methods used during the formulation of the proposed design framework are discussed. The verification and validation of the proposed design framework are addressed in terms of simulated and measured results for an underground pipeline network. The simulated results used for verification purposes were obtained from computer software utilizing the boundary element method in determining potential distributions on the surfaces of protected structures.

Keywords— *Cathodic protection, design framework, petrochemical industry, pipeline network, boundary element.*

I. INTRODUCTION

Corrosion is one of the major challenges faced by the petrochemical industry in modern society. The cost of corrosion is well known in the petrochemical industry as tens of millions of dollars in lost income and treatment costs are reported annually. Projections to June 2013 indicated that the total corrosion related costs, direct and indirect, will have exceeded \$1 trillion or roughly 6% of the gross domestic product (GDP) in the USA [1].

Apart from the economic impact that corrosion has on the industry, there is also a social impact. It is reported that corrosion causes great ecological damage to the environment along with the loss of human life [2]. According to a study conducted on available careers in corrosion mitigation it became apparent that highly skilled personnel in corrosion mitigation are pursued by employers. While job titles and specific duties vary from one position to another, cathodic protection (CP) skills are high in demand [3].

Based on the preceding paragraph, it is clear why corrosion mitigation is so important in the petrochemical industry. In terms of CP skills it is the proper design and implementation of CP systems that are focused on in this paper. This article presents a CP system design framework that can be implemented in general in the design of CP systems for the petrochemical industry.

Due to the electrical nature of the electrochemical cell, the mitigation of corrosion can be approached from either an electrochemical or an electrical point of view [4]. The use of CP in mitigating corrosion in the petrochemical industry has become common practice in most countries, due to its effectiveness when properly designed and implemented.

The design of CP systems developed as an art where corrosion engineers used their skills and experience to produce satisfactory designs [5]. These skills were later combined with using the finite element method to evaluate CP system designs. More recently, boundary element formulations and genetic algorithms have been developed to aid in the design and analysis of CP systems [6].

This paper proposes a design framework to be used when designing CP systems for the petrochemical industry. The proposed framework is based on the data of two different case studies. The first being the CP system design for a small tank farm and the second, for an underground pipeline network.

The paper is organised as follows. Corrosion and corrosion mitigation are addressed in section II while section III provides the experimental design for the proposed framework. The analytical design approach is addressed in section IV. Results and the discussion of results follow in section V and VI respectively. The proposed design framework is presented and discussed in section VII, followed by the conclusions in section VIII.

II. CORROSION AND CORROSION MITIGATION

Corrosion is a natural phenomenon that occurs across the globe and plays a major part in the failure of metal structures, especially in the petrochemical industry. All natural processes tend toward their lowest possible energy states and thus corrosion tends to return refined steel products to their lowest natural state, i.e. hydrated iron oxides. The hydrated iron oxides, commonly known as rust, are similar in chemical composition to the original iron oxide [7].

Corrosion can be explained as the deterioration of a material due to the reactions the material has with the environment in which it is installed. The material most susceptible to corrosion is most often metal. Electrochemical reactions between the metal and the electrolyte in which it is immersed, i.e. chemicals present either in the soil and/or water, form corrosion cells. The corrosion cells formed are responsible for the degradation of the metallic surface [8].

A corrosion cell can be compared to a battery in an operational sense, and therefore contains the same basic elements found in a battery: an anode, a cathode, a conductive electrolyte and a metallic return path for the current. Corrosion can be prevented when one or more of the elements of the corrosion cell are removed [8].

In the equivalent circuit of a corrosion cell as illustrated in Figure 1. E_A represents the open circuit potential of the anode electrode, E_C the open circuit potential of the cathode

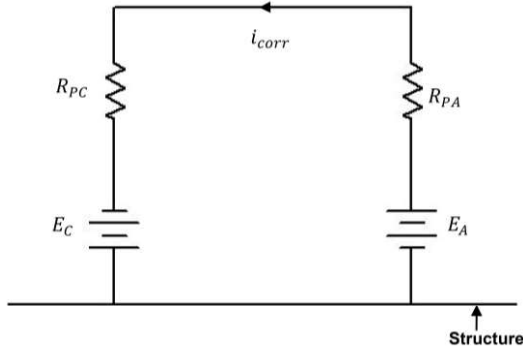


Figure 1: Equivalent circuit of corrosion cell [9]

electrode, R_{PA} the effective anode electrode resistance, R_{PC} the effective cathode electrode resistance, and i_{corr} indicates the corrosion current in the circuit.

Corrosion occurs at the anodic areas on the surface of the metal structure where oxidation reactions take place. Oxidation is normally explained as the loss of electrons by an atom, molecule or ion. The reactions that occur at the cathodic areas on the surface of the metal structure are known as reduction reactions. Reduction is generally explained as the gain of electrons by an atom, molecule or ion [10].

To further support the statement that the corrosion process can be viewed from an electrical perspective, a better understanding of corrosion from first principles is necessary. The most important aspects when analyzing corrosion will present itself in the form of the basic thermodynamics behind the corrosion process and the corrosion kinetics. The basic thermodynamics of corrosion are used to better understand and analyze the energy associated with the corrosion process.

A. Electrochemical kinetics of corrosion

The basis of electrochemical reactions is Faraday's Law. Electrochemical reactions either produce or consume electrons [11]. The proportionality between electron flow and the mass of metal reacted in an electrochemical reaction is given by Faraday's Law [11]:

$$m = \frac{Ita}{nF}, \quad (1)$$

with m the mass reacted, I the current in amperes, t the time, a the atomic weight, n the number of equivalents exchanged, and F Faraday's constant. The rate of corrosion can be obtained by dividing (1) by t and the surface area [11]:

$$r = \frac{m}{tA} = \frac{ia}{nF}, \quad (2)$$

with r the corrosion rate, A the surface area, and i defined as the current density, i.e. I/A . Equation (2) shows the proportionality between the loss of mass per unit area and current density [11].

B. Corrosion potential and current density

Whenever a metallic structure is corroding in an electrolyte, both the anodic and cathodic half-cell reactions occur simultaneously on the surface of the metallic structure. Each of the reactions has its own half-cell electrode potential and exchange current density. This is an important statement, as these half-cell electrode potentials cannot coexist separately on an electrically conductive surface [11]. Each of the reactions must polarise to a common intermediate value. This intermediate value is referred to as the corrosion potential or mixed potential.

As the oxidising and reduction reactions occur on the surface of a metallic structure, the half-cell electrode potentials change accordingly. The polarisation on the same surface will continue until the electrode potentials become equal at the corrosion potential. At the corrosion potential, the rates of the anodic and cathodic reactions are equal and the rate of anodic dissolution is identical to the corrosion rate in terms of current density [11]:

$$i_c = i_a = i_{corr}. \quad (3)$$

i_c and i_a are the cathodic and anodic dissolutions respectively, and i_{corr} the corrosion rate in terms of current density. With the rate of corrosion well documented at this stage, the mitigation of corrosion follows. Cathodic polarisation is generally referred to as the underlying principle of CP and is discussed in the following section.

C. Cathodic polarisation

Whenever an excess of electron flow is applied to a corroding electrode, it causes the electrode potential to shift negatively [11]. This negative potential shift from the corrosion potential, E_{corr} , to a potential, E , where corrosion will cease, is defined as cathodic polarisation. The cathodic polarisation, ε_c , is given by

$$\varepsilon_c = E - E_{corr}. \quad (4)$$

The excess of electrons associated with cathodic polarisation suppresses the rate of the anodic reaction from i_{corr} to i_a and similarly increases the cathodic reduction reaction from i_{corr} to i_c [11]. The difference between the two reactions must be equal to the applied current, $i_{app,c}$ in order to fulfil the principle of charge conservation:

$$i_{app,c} = i_c - i_a. \quad (5)$$

An excess of electron flow, $i_{app,c}$, is applied to a corroding electrode. The corrosion potential, E_{corr} , and the rate of corrosion, i_{corr} , as a current density, are defined by mixed potential theory. The application of an excess electron flow causes a negative potential shift, ε_c , which causes the anodic ionization rate, i_a , to decrease and the cathodic discharge rate, i_c , to increase. This is the fundamental operation of cathodic protection.

D. Cathodic Protection

The history of CP is well documented within academic literature. The first use of CP is generally attributed to Sir Humphrey Davy in the early 1800's [8]. It is generally accepted in literature that the first use of CP in the petrochemical industry was documented in the USA around 1950.

The introduction of CP in industry coincided with the introduction of thin-walled steel pipes for the underground transmission of oil and gas. The UK followed suit in the use of CP systems in the early 1950s. CP is a well-established technology today and is used to protect a wide variety of underground or immersed structures in the petrochemical industry.

Cathodic protection is an active form of corrosion control in which electrons are supplied to the metal structure to be protected [12]. The principle of CP can best be described in terms of polarization. Once the anodic areas in the electrochemical cell can be polarized to, or beyond, the potential of the corresponding cathodic areas, corrosion will cease to exist. Two systems are readily used to achieve the polarization of the anodic areas:

1) Impressed current cathodic protection (ICCP)

Impressed current CP systems require an external direct current source, which is connected between the external anode and the structure to be protected. The external source is used to provide the required driving power to the external anode. Generally, a number of external anodes are installed along with an impressed current CP system, referred to as a ground bed of anodes. The anode ground bed is forced to discharge as much CP current as is desirable by connecting the positive terminal of the external source to the anode ground bed. The negative terminal of the external source is connected to the structure to be protected. This external power source is generally referred to as the transformer rectifier unit (TRU).

2) Sacrificial anode cathodic protection (SACP)

Sacrificial anode cathodic protection sacrifices one metal, referred to as the anode, in order to protect a given structure against corrosion. Galvanic coupling is used to connect the anode to the metal structure. For the anode to provide effective protection against the effects of corrosion, the metal from which the anode is manufactured must be more anodic than the metal to be protected. No external power source is present in a SACP system and anodes of a high negative potential and current density act as the power sources to the system.

A general equivalent circuit of a corroding cell connected to a CP system is illustrated in Figure 2. CP systems are synonymous with the implementation of an external anode as illustrated in Figure 2. The external anode is used to allow current, $i_{app,c}$, to flow from the anode, through the electrolyte, to the entire exposed surface area of the metal structure to be protected. The resistance-to-earth of the external anode is denoted by R_A' , while E_A' represents the external power source connected between the external anode and the structure to be protected.

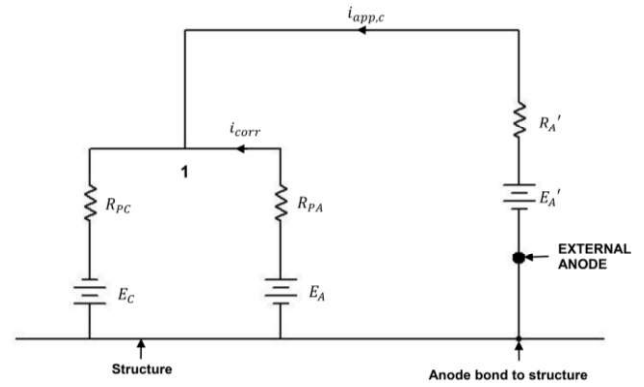


Figure 2: Equivalent circuit of corroding cell with "protection" current flowing from external source [9]

The flow of current, $i_{app,c}$, forces the original anodic areas on the metal surface to become cathodic with respect to the external anode. The moment at which the original anodic areas become cathodic, corrosion is prevented since the metal surface no longer gives up electrons [12].

III. EXPERIMENTAL DESIGN

The purpose of this section is to explain the experimental approach followed to arrive at a validated CP design framework. Analytical design steps are iteratively formulated based on the analytical designs of CP systems for a small tank farm and an underground pipeline. The process is continued with iterative verification through simulation of both of these cases and completed with iterative validation through measurements on the underground pipeline network. The aim with this iterative process was to arrive at a generalised CP design framework for the petrochemical industry.

It is expected that different types of anodes are to be used depending on the type of CP system to be implemented, i.e. SACP or ICCP. The different anode ground bed configurations that are generally installed may require more than one design to fully evaluate the efficacy and cost effectiveness of a design. This design approach will therefore require an iterative process to ensure the most effective CP system in terms of cost and performance.

Two case studies were used throughout the development of the proposed framework. The proposed design framework is based on the analytical CP system design for a small tank farm and an underground pipeline network. The analytical design of both the CP systems comprised iterative processes to ensure that the structures are effectively protected by the CP systems designed in each of the case studies.

For the purpose of this paper, design verification was achieved through the use of a computer simulation package. The simulation package used for verification purposes is known as BEASY™ CP and Corrosion. The results obtained from the simulation package were also used in an iterative process. The analytical design of the CP systems is altered based on the results obtained from the simulation package until the relevant CP criteria are met.

Validation of the CP system design framework is essential to ascertain whether the framework can generally

be used as a guideline regarding CP system design within the petrochemical industry. The validation of the proposed design framework was done using actual measurements taken from the underground pipeline network. This was the only available structure to be used for validation purposes. It was decided that the “ON” potentials will be measured at all available test points along the underground pipeline while also measuring the “OFF” potentials at a selected few test points along the underground pipeline.

IV. ANALYTICAL DESIGN

This section is dedicated to the analytical design of CP systems and the required information for the successful design of CP systems in general.

A. Site survey

Before commencing with the CP system design, it is necessary to gather important information from the site at which the CP system will be installed and the structure to be protected. A site survey is conducted to acquire specific detail regarding the structure to be protected and the surrounding environment. The information gathered from the site survey must be factored into the design and typically include the following [13]:

- From what material is the structure manufactured?
- What is the coating properties of the structure?
- What is the leak record on the existing line?
- Are there any changes in the diameter, wall thickness and weight per meter along the route of the structure?
- Are test locations and construction details of the test locations known for an existing structure?
- What is the construction method used on the couplers of the structure, all-welded or mechanical structures?
- What are the locations of branch taps and purposely isolating flanges or couplers?
- Are there route and detail maps of the structure available?
- Are there any other foreign cathodically protected structures in close proximity to the structure?
- Are there any other man-made sources of stray current in close proximity to the structure?
- At what temperature is the structure operated?
- Is AC power available to provide power to a transformer rectifier unit or is an alternative DC power source required?

B. CP system design calculations

The empirical design of CP systems is presented in this section. The calculations to be included are based on equations recommended in standard documents as well as literature. The design framework used to design CP systems is based on the following calculations:

- Surface area calculations
- Current requirement
- Required number of anodes
- System life calculations
- Grounding resistance calculations
- Total circuit resistance
- TRU output voltage and power (ICCP)

1) Surface area calculations

These calculations are used to determine the surface area of the structure to be protected. The equations used in the calculations are general surface area equations and depend on the shape of the structure to be protected.

2) Current requirement calculations

The current requirement calculations are dependent on various variables. These calculations can become very complicated in cases where the structure is exposed to varying electrolytes. The type of coating applied to the structure has the largest impact on the current requirement calculations. The current requirement calculations are based on the required potential shift of the material to be protected. Generally, the current requirement calculation is the product of the surface area to be protected and the required current density to cause the required potential shift to cease corrosion.

3) Required number of anodes

The required number of anodes is generally dependent on the type of anodes that are installed and the type of installation. Manufacturer datasheets for specific anodes are used to determine the current output of the anodes to be installed. The required number of anodes to be installed is generally calculated by dividing the required current by the maximum current output of the chosen anodes. It is considered good practice to take the expected lifetime of the anodes into account in these calculations.

4) System life calculations

System life calculations are calculated with the aid of manufacturer datasheets along with the required current output of anodes. The number of anodes installed in a specific CP system will largely determine the expected life of the anodes along with the current requirement of the structure to be protected. It is recommended that coating breakdown factors are considered in calculating the expected system lifetime. Including system breakdown factors will ensure that an adequate number of anodes are installed for the CP system to protect the structure for the expected lifetime.

5) Grounding resistance calculations

The grounding resistance calculations are required to calculate the grounding resistance of the anodes with respect to the electrolyte. Various equations are used for the calculation of the anodes' grounding resistance with the most common being Dwight's formula. It has to be noted that the size and type of the anode ground bed to be installed will influence the grounding resistance calculations. Dwight's formula for a single vertical anode installation is given by:

$$R_v = \frac{0.1588\rho}{L} \left[2.3 \log \left(\frac{8L}{d} \right) - 1 \right], \quad (6)$$

with R_v the grounding resistance of a single vertical anode installation, ρ the specific soil resistivity of the electrolyte, L the length of the anode, and d the diameter of the anode. The resistance of several similar vertical anodes in parallel, can be calculated by [14]:

$$R_v = \frac{0.1588\rho}{nL} \left[2.3 \log \left(\frac{8L}{d} \right) - 1 + \frac{2L}{s} (2.3 \log 0.656n) \right], \quad (7)$$

with n the number of anodes and s the distance between the anodes. The applicable equation to use for the calculation of the grounding resistance of a horizontal anode installation (also derived from H.B. Dwight's equations) is given by:

$$R_h = \frac{0.1588\rho}{L} \left[2.3 \log \left(\frac{4L^2 + 4L\sqrt{t^2 + L^2}}{dt} \right) + \frac{t}{L} - \frac{\sqrt{t^2 + L^2}}{L} - 1 \right], \quad (8)$$

with R_h the grounding resistance of a single horizontal anode installation, ρ the specific resistivity of the electrolyte, L the length of the anode, t the depth to the centre of the anode measured from the surface of the electrolyte, and d the diameter of the anode.

The calculation of the grounding resistance for a number of horizontal anodes installed in parallel is based on calculating the vertical resistance of these anodes for a specific spacing. The grounding resistance for a single horizontal anode is calculated and then divided by the number of anodes installed in parallel. This result is then multiplied by the result of the vertical resistance for the same number of vertical anodes in parallel divided by the resistance of a single vertical anode divided by the number of anodes in parallel.

6) Total circuit resistance

The total circuit resistance of the CP system is the sum of all resistances within the CP circuit namely:

- Anode grounding resistance
- Grounding resistance of structure
- Resistance of interconnecting cables

7) TRU output voltage and power

The calculation of the required TRU output voltage is simply the product of the total circuit resistance and the required current calculated. On closer inspection one will see that this is just Ohm's Law that is used to calculate the required output voltage of the TRU.

V. RESULTS

The results are broken down into two sections and will be presented in terms of verification and validation of the proposed design framework.

A. Verification results

The proposed design framework is based on the CP system designs for the two case studies mentioned before. The CP systems were simulated with the aid of BEASY™ CP and Corrosion, utilizing the boundary element method for polarization calculations. The CP systems were defined in terms of soil resistivity, structure resistance-to-earth, anode polarization curves and cathode polarization curves. The simulated potential distribution on one tank bottom and the underground pipeline network is presented in Figure 3 and Figure 4 respectively.

The polarization results obtained from the simulations were evaluated in terms of the level of protection

experienced by the respective structures. The “polarized potential of -850 mV criterion” [14] was used in the evaluation of the simulation results obtained. This criterion was chosen for evaluations as the simulation software package calculates the polarized potential.

It has to be noted that two sets of simulation results were generated for the underground pipeline network. The two sets of results were defined for a newly installed system and a system that has been in service for 15 years. The system results for the system in service for 15 years were required for validation purposes as the underground pipeline was in service for 15 years at the time the measured results were obtained for validation purposes.

From the simulated potential distributions presented in Figure 3 and Figure 4 it is evident that the tank bottom will be sufficiently protected as the potential distribution is more negative or equal to -850 mV. The potential distribution of the aging underground pipeline network does not satisfy the “polarized potential of -850 mV criterion” for the entire surface area. The deviations are discussed in Section VI.

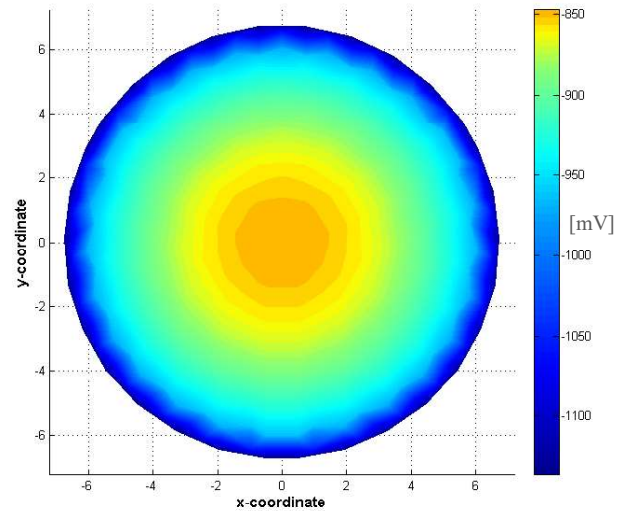


Figure 3: Simulated potential distribution on tank bottom in small tank farm

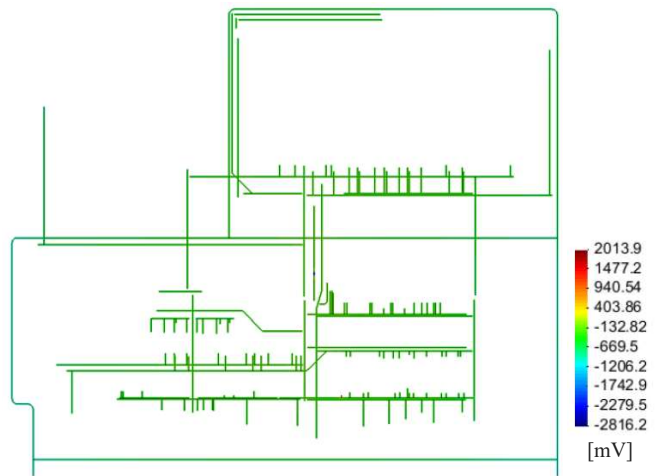


Figure 4: Simulated potential distribution on underground pipeline network with a service life of 15 years

B. Validation results

As mentioned before the actual measured results used for the validation of the proposed framework were obtained from the underground pipeline network that has been in service for 15 years. This section addresses the validation results of the proposed framework.

Figure 5 displays the comparison between two sets of results. The blue line represents a set of OFF-potential measurements taken at available test points installed along the underground pipeline network which has been in service for 15 years. The red line represents a set of simulated results obtained from the simulation software package utilizing the boundary element method in determining the potential distribution on the aged underground pipeline network. The instant OFF-potential of the underground pipeline network is used in the comparison of results as this potential is also referred to as the polarization potential which can be realistically compared to the simulated potential distribution.

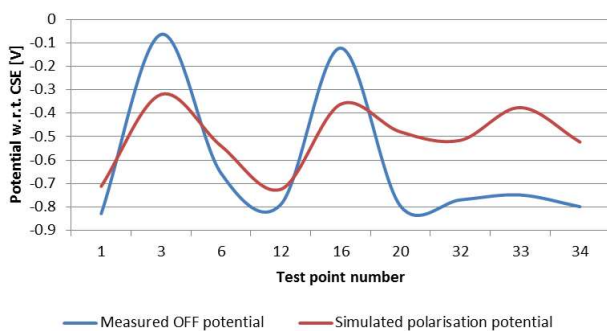


Figure 5: Measured OFF-potentials and simulated polarisation potentials along aged underground pipeline network

VI. DISCUSSION

It has to be noted that the results presented in Figure 5 are representative of an aging underground pipeline network and it was established that the level of cathodic protection is no longer adequate. Possible causes for the deviations in the results are provided and discussed in the following paragraphs.

In order to generate the simulated results of the underground pipeline network after a service life of 15 years, it was necessary to take into account the coating breakdown factor of the underground pipeline network. The CP system design framework initially didn't allow for the coating breakdown factor to be included in the calculations of current requirements as it only focused on new installations.

From the results obtained it became evident that the inclusion of the coating breakdown factor in the CP system design framework is very important for ensuring that a given CP system provides adequate protection through the entire expected service life of a structure. Therefore the coating breakdown factor was included in the CP system design framework for verifying whether a CP system will protect a given structure for the entire expected service life of the structure.

From the graphical comparison, in Figure 5, of the simulated polarized potentials and the actual OFF-potentials measured at the available test points on the underground pipeline network, it is evident that a certain difference between the results are present. This is a very important observation to be made as this comparison is based on a CP system in service for close to 15 years. The simulated polarized potentials are based on all the information gathered from the site survey presented in the CP system design framework and allowing for coating breakdown over a service life of 15 years.

The first important observation to be made is that the operating temperatures of the pipelines in the underground pipeline network have not been taken into account in the simulated results. The operating temperatures of the pipelines can have a major impact on the performance of the CP system as it influences the electrical conductivity of the pipeline material. This in turn will influence the current distribution on the surface of the pipeline and directly influence the potential distribution on the pipeline.

Stray currents are known to influence the potential of structures under CP. The absence of cross bonds on certain sections of pipeline will cause these sections to experience high levels of stray current corrosion due to the sections of pipeline being disconnected from the CP source. The current being induced by the anodes of the CP system can cause stray current corrosion on areas of the underground pipeline as sections of the pipeline are no longer connected to the source. As the condition of the cross bonds between the pipelines is unknown, the probability that stray currents are responsible for specific outliers is high.

The proposed design framework presented in this article can be successfully utilised for designing CP systems for the petrochemical industry. The design framework was verified with the aid of a simulation software package that simulated the performance of two respective CP systems. The first CP system was designed to protect five tanks situated in a small tank farm. This CP system was only verified with the use of BEASY™ CP and Corrosion and the results confirmed that the CP system design framework contains some shortcomings.

The shortcomings of the CP system design framework identified from the simulated results obtained for the tanks in the small tank farm confirmed that the electrical field strength surrounding structures protected by a CP system is paramount to the efficiency of the system. This conclusion is based on the fact that the initial depth of the anodes installed for the protection of the tanks had to be altered in order to provide a more uniform current distribution on the surface of the tanks. The electric field strength surrounding a given structure cannot be calculated with the use of the analytical design approach and can only be determined with the aid of the simulation software package hence its inclusion in the proposed design framework.

Validation of the CP system design framework revealed that a wide array of factors can have an influence on the performance of a CP system. Factors such as stray currents, non-uniform soil resistivity and electrical continuity of the

structure, coating holidays, and faulty reference electrodes can all compromise the integrity of the CP system.

The CP system design framework does not allow for all these factors to be taken into account during the initial design of a given CP system. It is almost impossible to incorporate all of the abovementioned factors into the CP system design framework as it will complicate the calculations in such a way that it will be impossible to use the CP system design framework in general. This statement is supported by the fact that each CP system is dependent on its surrounding environment and the characteristics of each underground structure are unique under operating conditions.

VII. DESIGN FRAMEWORK

The design framework that is suggested for CP system design for the petrochemical industry is presented in Figure 6. The design framework is based on procedures found in international standards as well as in literature. The flow diagram of the design framework is used for the visual representation of the framework that was used to perform the empirical CP system design for the small tank farm as well as that of the underground pipeline network.

Any CP system design starts with a comprehensive site survey. The data to be obtained during the site survey have been discussed in detail in section IV A. This information also forms part of the basic flow diagram of the design framework included in Figure 6. Depending on whether the CP system is to be designed for a new or existing structure, the required current demand to fully protect the structure is determined in different ways.

In the case of an existing structure it is possible to perform a current drain test in order to determine the required current for adequate protection of the tank. The same applies for measuring the resistance-to-earth of the structure and measuring the conductance of the structure. These are very important parameters to be used during the empirical design of the CP system.

In the case of a new installation the abovementioned measurements are not always possible to perform and the theoretical calculations of required current, structure-to-earth resistance, and coating conductance must be performed. These steps are also included in the basic flow diagram. The analytical CP system design comprises the use of analytical equations. The analytical calculations and the sequence of the calculations are clear from the information contained in the flow diagram presented in Figure 6.

It is very important to note that the flow diagram recommends that the analytically designed CP system is simulated with the aid of a computer software package. The results obtained from the simulation of the CP system are to be used to determine whether the system meets the relevant CP criteria required for the protection of the structure throughout its entire service life. Two important questions are raised after the simulation of the CP system: “Are the relevant CP criteria met?” and “Is the expected service life sufficient?”

If the answer to any of these two questions is no, the flow diagram enters an iterative process, i.e. the analytical design is altered until the desired criteria are met. Once the relevant CP criteria have been met and it has been established that the CP system will protect the structure for the expected service life, the design of the CP system is concluded.

The proposed design framework for CP systems has been verified by designing two different CP systems. CP systems for the protection of five tanks situated in a small tank farm and an underground pipeline network have been designed with the aid of the proposed design framework.

The verification process included the use of computer software that utilises the boundary element method to calculate the polarisation on the surface of metallic structures due to the application of CP. The calculated polarisation potential was evaluated in terms of the CP criteria presented in NACE Standard RP-01-69.

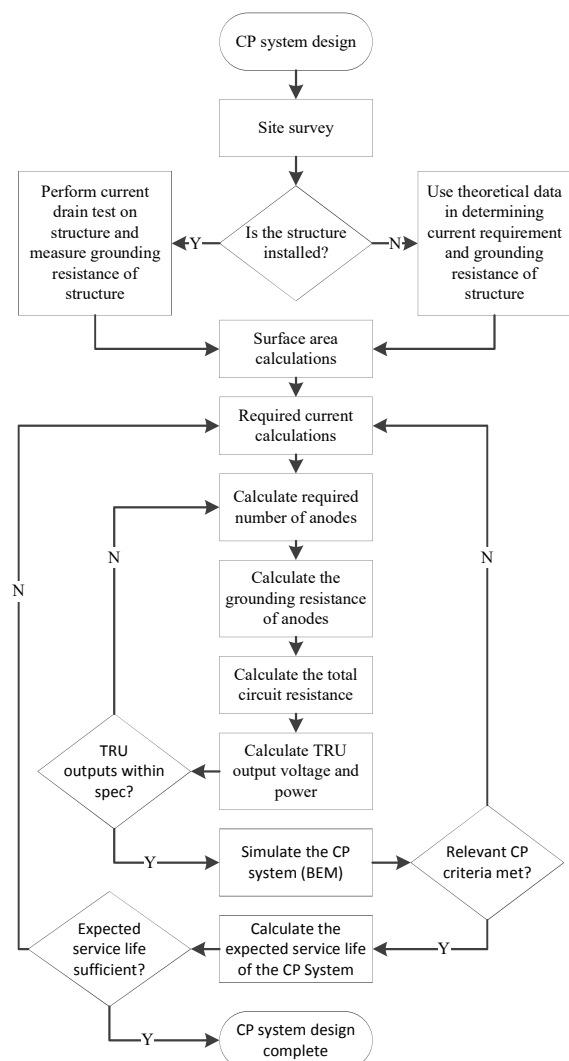


Figure 6: Flow diagram of design framework

VIII. CONCLUSIONS

Although the CP system design framework can be successfully utilized to design CP systems for various underground structures up to the end of its service life, the monitoring of the system and structure after the installation of the CP system is of utmost importance.

The design framework was successfully implemented for the empirical design of CP systems for the protection of tanks situated in a small tank farm as well as an underground pipeline network. The verification of the CP system design framework indicated that the design framework has certain limitations in terms of determining the electrical field strength over the entire surface of the structure to be protected. This limitation was identified using the simulation software package which indicated that the depth at which the anodes were initially installed at for the protection of the tanks in the small tank farm did not provide a uniform current distribution on the tank surfaces. By adjusting the depth of the anodes, the current distribution on the tank surfaces have improved and the tank surfaces were sufficiently polarised to satisfy the CP criteria.

It is recommended that future work is performed on determining the influence that the use of an average soil resistivity value during the analytical design of a CP system has on the overall performance of the system. This recommendation is based on the fact that every CP system requires that some adjustments are made to the voltage and current outputs of the TRU. Other factors contributing to the required adjustments must also be identified and the effects of these factors must be incorporated in the CP system design framework presented.

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