PERFORMANCE ANALYSIS AND MITIGATING THE EFFECTS OF STRAY CURRENTS ON UNDERGROUND METAL PIPELINES IN SOUTH AFRICA

By

Gerald Benjamin de Lange

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Supervisor: Professor I. E. Davidson
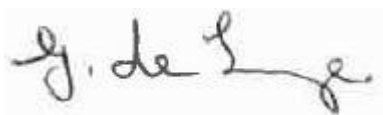
Co-Supervisor: Professor J. T. Agee

December 2016

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Abstract

The transport, distribution and utilization of electrical energy can often negatively influence other services in the vicinity due to leakage of stray currents or the influence of varying magnetic fields causing induction in nearby pipelines. When pipeline operators are informed of electrical abnormalities in the vicinity of their facilities, it raises considerable concern and triggers priority remedial reaction. It is well known that in the vicinity of DC stray current the risk of electrolytic corrosion on buried pipelines is very high. In the case of a good external pipe coating with a small defect in the coating, electrolytic corrosion current density at the coating defect will be high and penetration of the pipe wall can result in a short period of time. Invariably the license agreement to operate a pipeline is granted on condition that all necessary steps are taken to prevent spillages and that all actions taken to ensure the integrity of the pipeline are accurately recorded and be available at all times for inspection to the applicable investigating authorities.

The primary protection of pipelines against electrolytic corrosion is the external coating of the pipe. As no coating is deemed to be perfect and all coatings are subject to deterioration from aging and subject to damage during installation, a secondary or back-up means of corrosion protection is required. The most commonly used means of secondary corrosion protection for pipelines is cathodic protection. Cathodic protection works on the principle of polarizing all areas on the pipe surface to the same potential so that no corrosion cells can exist on the pipe surface. In addition the pipe surface is maintained at a potential more negative than its immediate surrounding so that it becomes the cathode with respect to the anode of the cathodic protection circuit. A cathodic protection system may consist of a combination of galvanic and impressed current technologies depending on varies factors such as, availability of power sources, soil resistivity, land availability for installation of anode beds and length of pipe to be protected.

In South Africa metal pipelines are frequently subjected to the influence of stray currents as a result of the DC rail traction network than spans across the country. Stray current is known to cause the most severe form of corrosion to underground metallic structures that could result in a pipeline leak in a very short period of time with devastating damage to the environment. Stray currents may also interfere with existing cathodic protection systems rendering them inadequate of providing the necessary protection to the pipeline. These currents also interfere

in such a manner that maintenance and operation of the existing cathodic protection becomes difficult and unpredictable. Knowledge of the presence of stray current is also critical when designing new pipelines and cathodic protection systems so that the necessary mitigating factors can be implemented in new designs. In South Africa cathodic protection has been proven to be an effective means of protecting both new and old pipelines.

This study analyses the challenges associated with the mitigation of stray current and the existing methodology used by a major South African pipeline operator to monitor the presence of stray current. Methodologies for detection and mitigation are briefly discussed in this dissertation. Based on the information studied proposals are suggested to enhance the current methodology and create greater awareness about the damaging effects of stray currents.

Acknowledgements

My thanks for the realisation of this dissertation is primarily due to my family for the patience they displayed while I had to withdraw myself from our social family activities in an effort to get this dissertation completed. This documented knowledge will be beneficial to all users of underground structures that exist within the areas of stray current influence.

A special word of thanks to my eldest daughter Charlene who so patiently accepted to proof read this dissertation often pointing out better ways of stating things.

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Abbreviations

AC	Alternating Current
AGMs	Above Ground Markers
CSE	Copper-Copper-Sulphate (Cu/CuSO$_4$) Reference Electrode
CDEGS	Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis Software
CP	Cathodic Protection
DC	Direct Current
DCVG	Direct Current Voltage Gradient
DJP	Durban to Johannesburg Pipeline
DSW	Downstream Weld
HSCB	High Speed Circuit Breaker
HV	High Voltage
HVDC	High Voltage Direct Current
ICCP	Impressed Current Cathodic Protection
kV	kilo Volt
LPG	Liquid Petroleum Gas
MW	Mega Watt
MCFC	Molten Carbonate-Fuel Cell
MFL	Magnetic Flux Leakage
NACE	National Association of Corrosion Engineers
n.d.	No date
OHTE	Over-Head Track Equipment
pH	Acidity Level
PPT	Pipeline Performance Technologies
PVC	Poly Vinyl Chloride
RPCD	Rail Potential Control Devices
SOFC	Solid Oxide Fuel cell
TRU	Transformer Rectifiers Units
USW	Upstream Weld
UT	Ultrasonic Tools
v	Volts

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Chapter 1

Background and Problem Identification

1.1 Introduction

Operating a pipeline whether it is above ground or below ground is an operation requiring strict compliance to safety and environmental discipline. Most pipelines in South Africa are buried pipelines installed in servitudes crossing many properties owned by both private landowners and the state. Although pipelines installations are normally designed to avoid passing through residential areas as it often happens, this is as a result of residential areas expanding to within close proximity of pipelines. Operating a pipeline in close proximity to residential areas demands intensified mitigation measures and even more so when the pipeline transports petroleum products.

Pipelines in South Africa are predominantly underground and this means that they operate in an environment conducive to electrolytic corrosion. In South Africa the extensive DC electrified rail network is a major contributor to electrolytic corrosion of underground pipelines.

Although the South African rail network is predominantly 3kV DC, 25kV and 50kV AC systems are also in use but at a much reduced scale and in specific areas only. In this dissertation, consideration of stray currents emanating from the rail network is focused on the 3kV DC system as damage from electrolytic corrosion is due to unidirectional current flow that is current flow between an anode and a cathode.

Substations feeding the 3kV DC traction network range from 3 to 6 MW in capacity with voltages that can rise to approximately 4kV under locomotive regeneration. These substations are spaced approximately 10 kilometres apart, with the distance depending of the local terrain and land geographical suitability. A 161mm^2 overhead contact wire in parallel with a catenary that ranges from between 80 and 250mm^2 and feeder that ranges between 480 and 800mm^2 feeds the locomotive power via a collecting pantograph mounted on the roof of the locomotive. Depending on the signalling requirements either one of both rails serve as the negative return circuit back to the traction substation.

The railroad consists of two rails mounted on a foundation of concrete beams, known as sleepers, traversing the two rails and keeping them a predetermined distance apart. The rails are mounted on insulated pads and not in direct contact with the concrete sleepers. In turn the concrete sleepers are laid on clean ballast stone to increase the insulation level to earth, serve to drain water away from the rails and provide a firm yet flexible bedding for the railroad.

In practice the negative return circuit insulation to general earth is lowered by many factors such as the accumulation of mud, dirt and moisture, blocked or poor drainage, faulty spark gaps and inadvertent shorting of the negative return to general earth mass all contributing to the accumulation of stray current from the rail to earth.

Stray current will tend to find the path of least resistance back to its source and if any metallic infrastructure immersed in the electrolyte forms part of this return circuit electrolysis of the infrastructure will result. The areas of primary concern from a metal loss perspective are those areas where current leaves the metallic object as positive metal ions these areas being referred to as anodic and the accompanying reaction an anodic reaction which is an oxidation reaction of the metal. The mass of metal loss as a result of the metal oxidation reaction is estimated using Faradays first law of electrolysis and in the simple case of constant current electrolysis can be written in equation form as shown in equation 1.1 [1].

$$m = QM \,/\, nF \; = \; ItM \,/\, nF \qquad\qquad (1.1)$$

Where

m   = the mass of substance liberated at an electrode in grams

Q   = the total charge passed through the substance in Coulombs

F   = the Faraday constant and has the value of 96485 $Cmol^{-1}$

M   = molar mass of the substance (grams per mol)

n   = the valency number of ions of the substance (electrons transferred per ion)

I   = current

t   = time

In compliance to Occupational Health and Safety Act [2] and incorporated regulations (Act 85 of 1993) it is reasonable to assume that pipelines are always wrapped with good quality insulation prior to being laid in the ground. Good high electrical resistance wrapping also has

the advantage of demanding lower cathodic protection energy so lower powered rectifiers may be used offering reduced capital, maintenance and running costs. The wrapping serves as the primary protection against corrosion and for this reason all due care is necessary not to damage the wrapping during pipe installation into the ground. To prevent sharp object penetration of the wrapping during soil back-fill, stone free bedding and cover soil is used surrounding the pipe. Despite all the care taken to prevent damage to the wrapping small punctures of the wrapping do occur.

Reference to equation 1.1 shows that metal loss is proportional to the charge transferred per unit time. Should the charge movement be concentrated to a small area as would be the case of a holiday (area of damage in the pipe wrapping) in a good wrapping then any metal loss would be from the holiday. This implies that even for low values of corrosion current the wall of the pipe could be punctured in a relatively short period of time.

1.2   Problem Identification

1.2.1   Influence of stray current on a pipeline cathodic protection system

Often it is found that pipeline servitudes run in close proximity to rail traction and other industries that can be a source of stray current sometimes also referred to as electrical interference. In South Africa, most of the traction network is 3kV DC and although this is not the only known source of stray current it is known to be a very dominant source of stray current influencing local pipelines. From the many papers published on the subject of DC traction stray current it is evident that electrolytic corrosion associated with DC traction is a world phenomena [3-12].

1.2.2   Deterioration of rail traction negative return circuit

The DC traction system used in South Africa is of the insulated floating rail design where the rails are lifted off natural ground and secured to concrete sleepers which in turn lies on well compacted ballast stone. The rails are insulated from the sleepers by mounting them on PVC pads and using similar insulation between the fasteners and the rail. Various factors can influence the integrity of the insulation leading to increasing magnitudes of stray current and area of influence. If left unattended the increased area of influence can encroach on other services such as buried pipelines that previous fell outside the area of influence or was designed to work within the area of influence at specific tolerance levels. The chemical composition of soil structure determines the resistivity of the soil and as a result directly

influences the magnitude of stray current, all other conditions assumed constant. As rate of corrosion is proportional to current or charge transfer, soil structures will have an influence on the rate of corrosion experienced on buried structures [4]. The chemical composition of soil often varies with depth and geographical location and this always need to be considered when analysing the effects of stray current.

1.2.3   Damage to other services

Other services, sometimes referred to as foreign services in the cathodic protection industry may be defined as any infrastructure either being influenced or influencing the services of another infrastructure owner or operator. Stray current is a major contributor to electrolytic corrosion and various mitigation methods have been investigated to mitigate the effects of stray currents [13]. The condition often exists when two pipelines intersect and stray current leaves the one pipeline to continue its path to its source through the foreign pipeline. At the location where the current leaves the first pipeline to enter the foreign pipeline, electrolytic corrosion will take place and again where the current leaves the foreign pipeline either to another structure or back to its source [5].

1.2.4   Damage to field survey equipment

Stray current often give rise to abnormal potentials in the ground and these potentials are known to destroy sensitive electronic field survey equipment. Limiting ground potentials and creating awareness of this potential risk in addition to recommending a means to test prior to using sensitive equipment in the field could prevent unnecessary damage to equipment and loss of production.

1.3   Main Objective of this Research

The main objective of this research is to investigate the current situation bearing influence on the distribution of stray current from the South African rail 3kV DC transit system. Analysing the effects of such stray currents on underground services and proposing mitigating actions that can be taken to reduce the leakage of stray current into the earth.

The research questions this mini-dissertation seeks to answer include:
- What type/s of traction system operate in South Africa?
- Is stray current mitigation included in the design of the rail transit system?
- Is the mitigation included in the design effective, if not, why?

- How is stray current managed?

1.4   Further Application

Identifying both poor and good practice that affect the magnitude of stray current is in the interest of all users of electrical energy. Sharing this knowledge and creating awareness of the damaging and costly effects of stray current interference on underground infrastructure cannot be under envisaged. Industry owners and operators of affected infrastructure need to be motivated to actively participate in corrosion committees so that the impact of corrosion is better understood and a sense of mutual responsibility is developed.

Pipeline leaks are invariably disastrous to the environment and can negatively impact on the safety of human and animal life. Rehabilitation is extremely costly, time consuming and unproductive. Managing stray current to acceptable limits have huge benefits and greater awareness of this need to be created.

1.5   Dissertation Outline

Chapter one explains the challenges faced by pipeline operators operating pipelines buried in ground.

Chapter two discusses the corrosion chemistry basics and diagrams commonly used when analysing or designing cathodic protection systems.

Chapter three presents a review of electrolytic corrosion literature. It discusses mitigation of electrolytic corrosion, minimum cathodic current requirements, cathodic protection monitoring and system modelling.

Chapter four discusses and analyses the floating traction design as used by the traction industry of South Africa. It focusses on the influence the traction stray current has on the pipeline industry in relation to electrolytic corrosion.

Chapter five presents conclusions and proposes recommendations to improve the current situation of stray current evolving from the rail transit system.

1.6   Conclusion

The protection of pipelines against stray currents plays a critical role in the maintenance of pipelines installed in aqueous solutions. Due to an extensive DC electrified rail network across South Africa, stray currents presents many challenges to rail transit operators and other industries operating in close proximity to sources of stray current. Although much research work has been done on the mitigation of stray current resulting from rail traction infrastructure such works are predominately based on conditions conducive to voltages of 750 volts DC a traction as used in European countries. Pipeline operators are one of the industries severely affected by stray currents and due to the nature of this transit system, a good understanding of stray current evolution, migration and associated risk is essential. Failure to identify the presence of stray current at an early stage can have disastrous results to both life and the environment. This is due to the fact that detrimental metal loss on a well-coated pipeline having a small holiday can occur within a short period of time causing a leak and substantial environmental damage. To enhance awareness on the impact that uncontrolled stray current can have on safety to life and the environment it is proposed that stray current be a regular topic at both the national and local cathodic protection meetings.

Chapter 2

Corrosion Chemistry

2.1   Introduction

The primary maintenance of an underground pipeline is the prevention of corrosion. This is a time consuming and costly exercise that contributes to a large portion of a pipelines operation maintenance budget each year. Understanding the basic chemistry of corrosion and using the knowledge to implement suitable fit for purpose mitigation measures at an early stage can save substantial costs associated with the rehabilitation of such corroded infrastructure. Various technologies are used to prevent corrosion of pipelines but often two technologies are used simultaneously to ensure adequate protection. The most common primary protection for petroleum pipelines is an insulated coating around the exterior surface of the pipeline of which a few technologies are available for use in different environments. As secondary protection impressed current cathodic protection is mostly employed; but this needs to be used with care and understanding of the degree of protection necessary and the environment in which the protection will be applied. Careless use of impressed current cathodic protection can damage pipe coatings and produce explosive atmospheres as a result of excessive hydrogen evolution during high levels of impressed current. In South Africa, the American standards of "NACE" which is the world authority in corrosion prevention and control [14], is adopted as the technical standards for the implementation of cathodic protection and compliance. The intention of this chapter is to serve as a refresher on the chemistry of corrosion so that the influences of cathodic protection and stray currents on buried structures are understood from both the electrical and chemical perspective and their interaction with each other.

2.2   Gibbs Free Energy

When metals are extracted from their ores, energy is transferred in the process. This difference in energy imparted in the refining process results in the various metals having different levels of available free energy when compared to each other. It is this energy, also known as the Gibbs free energy ($-\Delta G^0$), that causes spontaneous corrosion as the metals try to revert back to a lower energy level [15].

2.3   Basic Corrosion Cell

To form electrolytic corrosion cell the following four elements must be present [15]:

- Anode
- Cathode
- Electrolyte
- Metallic path

Figure-2.1 shows the concept when corrosion occurs on a buried pipeline with no influence from external driving forces such as cathodic protection or stray currents. This type of corrosion cell is referred to as a differential corrosion cell [15] [16]. The potential difference or driving force in this case could be as a result of various environmental factors. These factors could amongst others be differences in the oxygen content of the soil along the pipeline, variations in soil chemistry or differences in the molecular structure of the metal on the surface of the pipe.
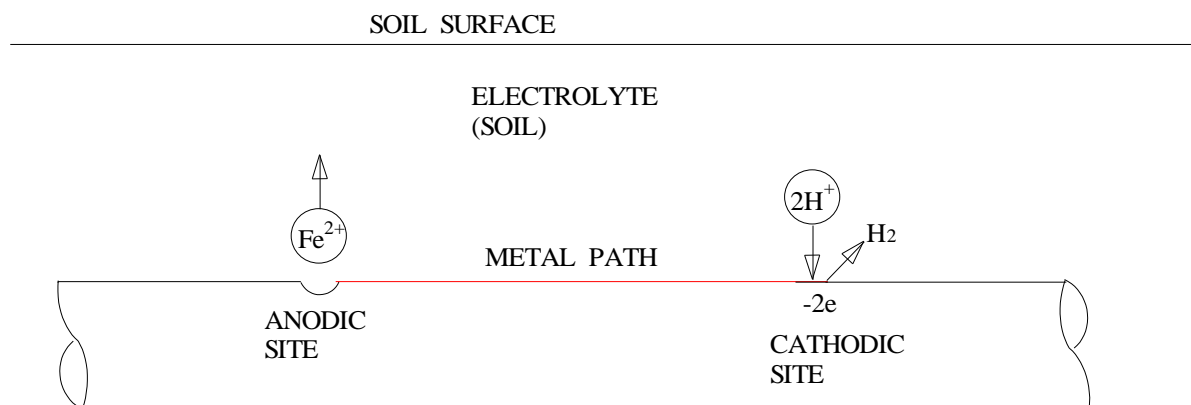
Figure-2.1   Typical corrosion cell of a pipeline buried in soil of acidic composition.

Corrosion in an electrolyte is an electrochemical process in which anodic and cathodic reactions occur simultaneously so as to combat a nett charge build-up on the corroding metal surface. As shown in figure-2.1 the corrosion process occurs with the removal of electrons from the anodic site (oxidation reaction) of the pipe and the consumption of electrons at the cathodic site (reduction reaction) by the positive ions available at the surface of the metal [16]. This removal of electrons at the anodic site causes ferrous ions to be released at the surface of the pipe creating a loss of metal at the anodic site.

Therefore, steel oxidation of the metal to its ions occurs at the anode as shown in figure-2.1 and is written in equation as:

$$Fe \;>\; Fe^{2+} + 2e \tag{2.1}$$

The chemical reaction at the cathode is a reduction reaction and is dependent on the chemical composition of the electrolyte leading to the possibility of several reactions. In an acidic solution where hydrogen ions (H^+) are in abundance the expected reaction would be as described in equation 2.2 and shown in figure-2.1.

$$2H^+ + 2e \;>\; H_2 \tag{2.2}$$

In an alkaline solution hydrogen ions are not in abundance and water is often aerated with the result that a reduction of oxygen is most likely to occur to produce alkali at the surface of the metal and hydroxyl ions as described in equation 2.3 and shown in figure-2.2.

$$O_2 + 2H_2O + 4e \;>\; 4OH^- \tag{2.3}$$

SOIL SURFACE

ELECTROLYTE
(SOIL)

O + $2H_2O$

Fe^{2+} Fe^{2+} METAL PATH $4OH^-$

ANODIC $-2e \Rightarrow$ $-4e$
SITE $-2e \Rightarrow$ CATHODIC
                                       SITE
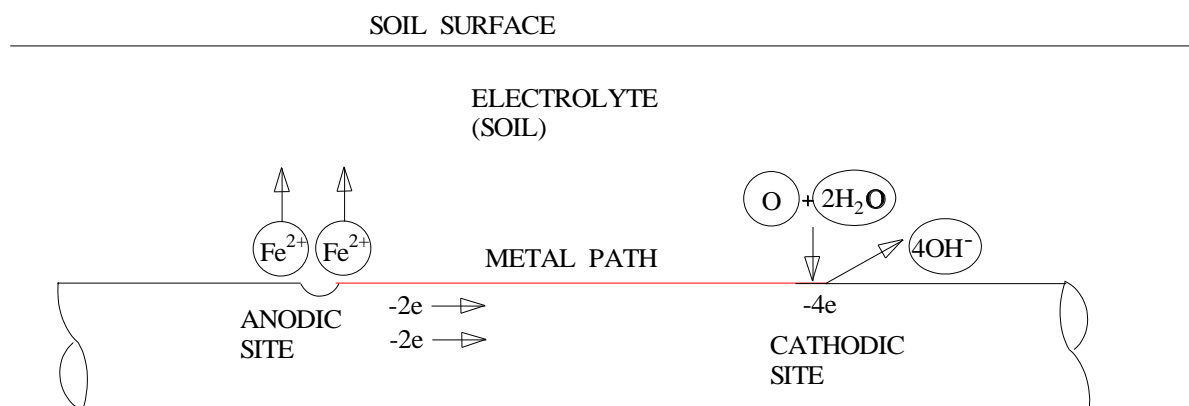
Figure-2.2   Typical corrosion cell on a pipeline buried in soil when oxygen serves as the reducing agent.

In the event of the alkaline solution being de-aerated the reduction of water will produce alkali and hydrogen as shown by equation 2.4.

$$2H_2O + 2e \;>\; H_2 + 2OH^- \tag{2.4}$$

From what has been described in equation 2.4 it can be seen from the reactions of oxidation and reduction that they are different and this means that the corrosion process is not reversible and not in equilibrium [16].

2.4   Corrosion Control

As previously stated the corrosion process requires an anodic site, a cathodic site, an electrolyte and a metallic path to exist. Interfering with any one of these four elements will cause an equivalent interference with the corrosion process. Advantage of this fact is taken by pipeline corrosion engineers firstly, by applying the best and most cost-effective coating insulation to pipelines prior to laying pipes in the ground. This step aims at isolating the pipeline from its surrounding environment, the electrolyte which is the soil and associated moisture. This is the primary action in the control against corrosion.

Figure-2.3   Verification dig to confirm DCVG result of good pipe coating.

It is well understood that no pipeline coating or wrapping as it is often referred to, is perfect. Also, the installation process is mechanical and damage to pipeline coatings do occur despite using best practice installation methods and for this reason a secondary form of corrosion protection is required. A method available to test and evaluate a buried pipeline coating is the direct current voltage gradient test (DCVG). Stray current and other ground signal

interference can distort DCVG results and for this reason verification digs as shown in figure-2.3 are done to physically confirm test results. Pipeline coating tests are necessary to predict the quality of a coating so that the capacity of secondary corrosion protection can be evaluated.

The most widely used secondary form of corrosion protection for pipelines is the use of impressed current cathodic protection. Protection is achieved by injecting electrons into the pipe from an external source to influence the rate of both the anodic and cathodic reactions and forcing the pipe to become the cathode in the electro-chemical cell. This action causes the pipe to become more negatively charged with respect to the electrolyte forcing it into the immunity zone as shown in figure-2.4. One of the NACE criteria for cathodic protection is applying a potential of -0,850 volts, CSE soil to pipe potential [16]. Based on figure-2.4 this places the protection level safely within the immunity zone for pH levels up to around pH15.
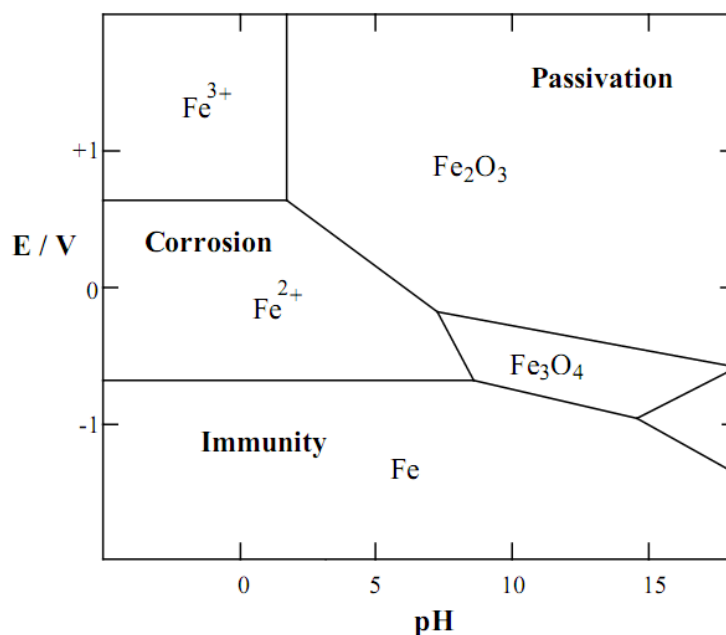
Figure-2.4   Iron Equilibrium Diagram [17].

Figure-2.4, known as a Pourbaix diagram shows different zones of activity into which iron in water at 25 degrees celsius will shift based on the pH versus electrolyte to pipe potential. From this diagram, it may seem safe to apply a larger negative voltage to the pipe to ensure it is forced into the immunity zone however field experience has shown this not to be the case [15]. Applying higher than necessary negative potentials leads to increased electro-chemical reactions and the evolution of specific ions depending on the electrolyte pH.

From equations 2.2, 2.3 and 2.4 it is seen that cathodic reactions generate either hydrogen or hydroxyl ions or both. Increasing hydroxyl ions will cause the electrolyte to increase in alkalinity while an increase in hydrogen ions will cause a shift towards acidity. Hydrogen ions are readily absorbed by certain grades of iron and this could lead to deterioration of pipes which is known as hydrogen embrittlement. Hydrogen gas, being an explosive gas, may also be a threat to safety and the environment. The alkalis caused by hydroxyl ions are known to cause disbonding of pipe coatings and in the event of this happening the primary protection of the pipe will be destroyed.
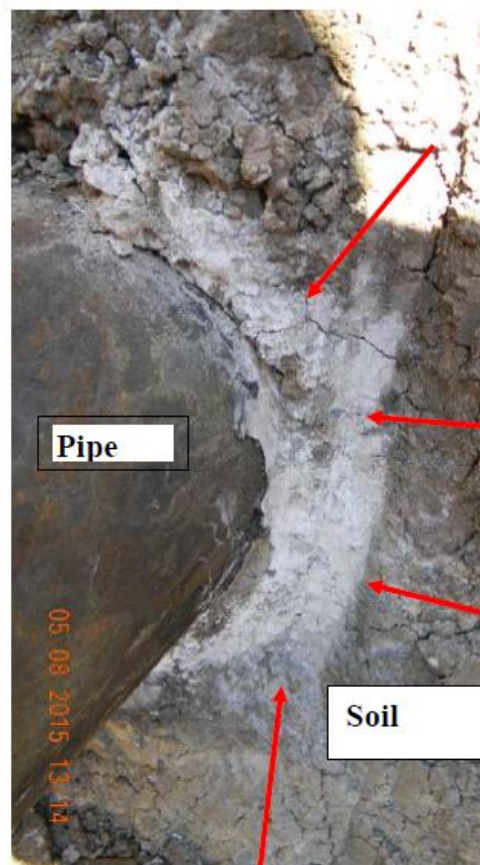
Figure-2.5 Calcareous deposit due to extensive evolution of hydroxyl ions [18].

Figure-2.5 shows the result of extensive hydroxyl ion concentration. The arrows show the areas of highest concentration surrounding the pipe as would be expected by the application of high negative pipe to soil potentials. This high alkalinity, typically 13 and higher [18] is observed by a white calcareous deposit in the electrolyte surrounding the cathodic protected pipe.

2.5 Corrosion Cell Kinetics

The pourbaix diagram is useful in predicting the state of protection in different electrolytes versus the applied soil to pipe potentials but it does not give any indication on the rate at which the corrosion occurs. Operation of the corrosion cell can be displayed on a diagram known as the polarisation or Evan's diagram. When the Evans diagram is plotted with the potential versus the logarithm of the current, the diagram is often a straight line and never zero, the corrosion current decreasing to a point then reversing direction as shown in figure-2.6. This turning point is where the Gibb's free energy for both the cathodic and anodic reactions is equal.
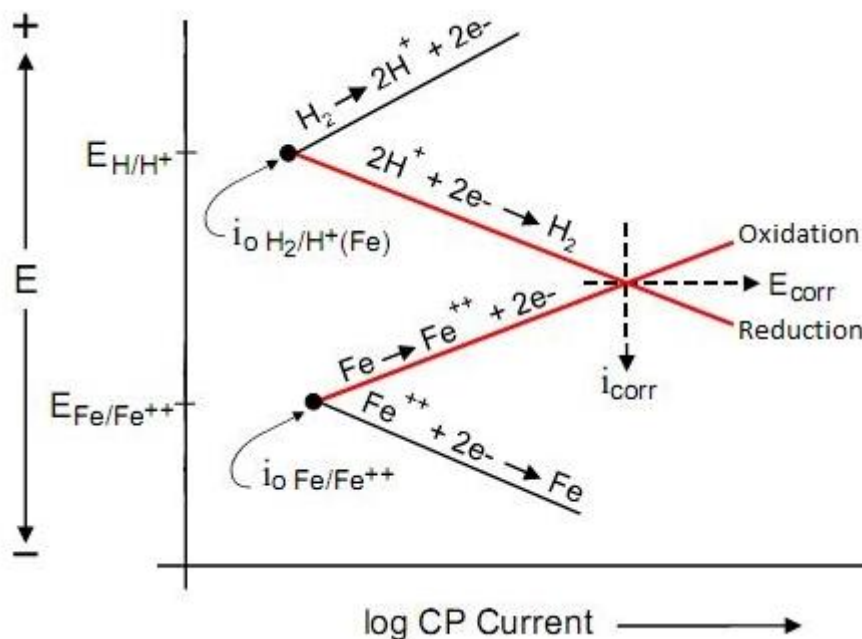
Figure-2.6 Polarisation Curves for Iron Corrosion in an Acidic Electrolyte [15].

At the turning point as an atom loses an electron due to the influence of any form of natural energy such as thermal energy; it is immediately captured by a metallic ion in solution at the metal-electrolyte interface to revert back to a metal atom. At this point, point of equilibrium has been reached with the result that there is no net reaction, no net charge flow and no nett current flow. At this point the polarisation potential is the equilibrium potential for the reaction as determined by the Nernst equation to be discussed later. The point of intersection of the oxidation and reduction curves yields the corrosion potential and current of the iron in the acidic solution [15]. Unlike the Evan's diagram in figure-2.6 most polarisation diagrams

only show the polarisation curves for the reactions of interest and always start from the equilibrium point, which is the intersection of the equilibrium potential and the exchange current.

Assuming the electronic path of a corrosion cell is an open circuit then the corrosion current would be zero and the open circuit anode and cathode voltages at the interface to the electrolyte could be measured with respect to a reference electrode. The potential difference between the anode and cathode is the corrosion cell driving voltage which equates to the Gibbs free energy of the metal as shown in equation 2.5:

$$E_{CELL} = \frac{-\Delta G^o}{nF} \qquad (2.5)$$

Where

Ecell   = corrosion cell potential (volts or joules/coulomb)

n   = number of charges transferred in the oxidation reaction

F   = Faradays constant (96500 coulombs)

ΔG^0 = change in Gibbs free energy (joules)

Closing the open circuit would cause the corrosion current to flow with the anode and cathode potential relationship being given by equations 2.6 and 2.7 respectively [15]:

For the anode: $E_{a,cc} = E_{a,oc} + \Delta E_{p,a}$ (2.6)

For the cathode: $E_{c,cc} = E_{c,oc} - \Delta E_{p,c}$ (2.7)

Where

$E_{a,cc}$ = anode closed circuit voltage

$E_{c,cc}$ = cathode closed circuit voltage

$E_{a,oc}$ = anode open circuit voltage

$E_{c,oc}$ = cathode open circuit voltage

$\Delta E_{p,a}$ = change in anode potential due to corrosion current across the metal-electrolyte
            interface

$\Delta E_{p,c}$ = change in cathode potential due to corrosion current across the metal- electrolyte
            interface

When plotting the operation of the corrosion cell on an Evans diagram, it is seen that both anode and cathode polarisation reduces the corrosion driving potential which means polarisation serves to reduce corrosion.
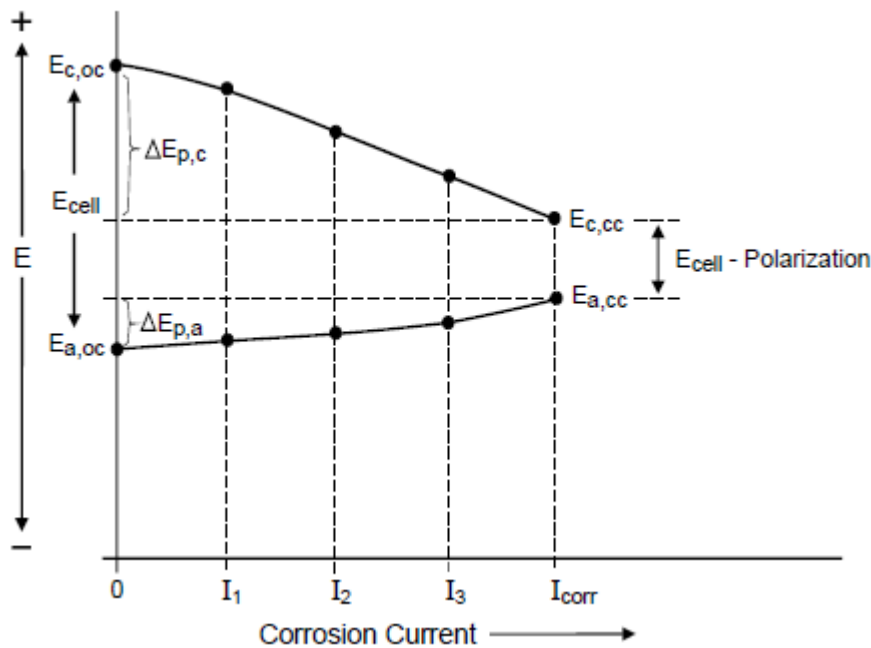
Figure-2.7 Evans diagram showing the effect of polarisation on a corrosion cell [15].

The change in potential, $\Delta E_{p,a}$ and $\Delta E_{p,c}$ at the anode and cathode interfaces is due to the energy used to transfer charge across the respective metal-electrolyte interfaces. This change in potential is referred to as polarisation. NACE standard SP0169 [19] specifies a 100mV polarisation shift as one of the three criteria that can be used for the prediction of adequate cathodic protection being applied to steel. The corrosion current I_{corr} gives an indication of the reaction rates while in this steady state.

In the case of figure-2.7; the greater potential difference occurs at the cathode which means that more energy is used at the cathode to transfer charge across the metal-electrolyte interface. In this case, it is seen that the polarisation at the cathode is greater than at the anode and so the corrosion cell is said to be under cathodic control.

As previously discussed the pourbaix diagram is useful in predicting the state of protection in different electrolytes at specific soil to pipe potentials but it does not give any indication on

the rate at which the corrosion occurs. The Evans diagram is a useful representation of a chemical cells potential versus the current through it. It graphically shows the state of corrosion activity and levels of polarisation.

Applying cathodic protection current to the corrosion cell causes the rate of cathodic reaction to increase beyond the initial steady state reaction rate as shown in figure-2.8.
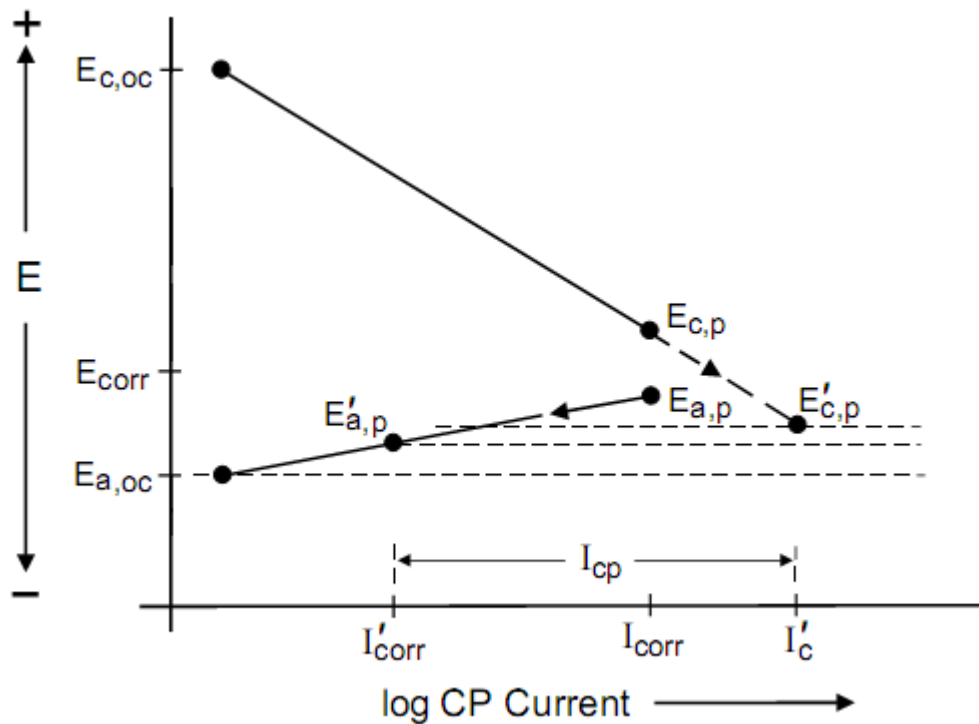
Figure-2.8 Evans diagram for a corrosion cell under cathodic protection [15].

With the increase in charge transfer at the cathode the level of polarisation increases, reducing the cathode polarisation potential from Ec,p to E'c,p resulting in a reduced driving potential and subsequent corrosion current, I_{corr}. Finally, a new steady state condition is reached with a lower anodic reaction or corrosion rate as shown by lower corrosion current I'$_{corr}$.

$$I'_{corr} = I'_c - I_{CP} \qquad\qquad (2.8)$$

Where

I'$_{corr}$ = anodic or corrosion current

I'$_c$ = total cathodic current

I_{CP} = the cathodic protection current supplied

It is evident from figure-2.8 that complete cathodic protection has not being achieved. To achieve complete cathodic protection additional cathodic protection current needs to be applied until the polarised potential of the cathode reaches the open circuit potential of the anode.

From what has been discussed it is clear that the aim of cathodic protection is to polarise all noble potential areas (cathodes) to the most active potential (anode) on the surface of the pipeline in turn reducing or eliminating any potential difference on the surface of the pipeline. In essence cathodic protection does not stop the corrosion process but it makes the pipeline the cathode of an intentional corrosion cell or circuit [15] [20].

To measure the potentials of metals a stable reference electrode is needed. The Nernst equation [15] shows the relationship of the measured metal potential with respect to important criteria to maintain stability of the reference electrode.

$$E_M = E_M{}^o + \frac{RT}{nF} \ln \frac{a(M^{n+})}{a(M^o)} \qquad (2.9)$$

Where

E_M	=	metal potential being measured
$E_M{}^o$	=	metal potential at standard conditions
R	=	gas constant (8,31 J/mol – °K)
T	=	absolute temperature
n	=	number of electrons transferred
F	=	Faraday's constant (96 500 coulomb)
$a(M^{n+})$	=	metal ion activity
$a(M^o)$	=	metal activity (assumed to be 1)
a	=	γm
γ	=	activity coefficient (always <1)
m	=	molar concentration of the metal ion

As seen the metal electrode potential is a function of the metal ion activity which is related to the metal ion concentration. An increased metal ion concentration increases the metal

electrode potential in the electropositive direction. For cathodic protection field work the copper-copper sulfate reference electrode is used [15]. As shown in figure-2.9 this electrode consists of a pure copper rod immersed in a saturated copper sulphate solution containing copper crystals to maintain the solution saturated ensuring a constant ion concentration level.
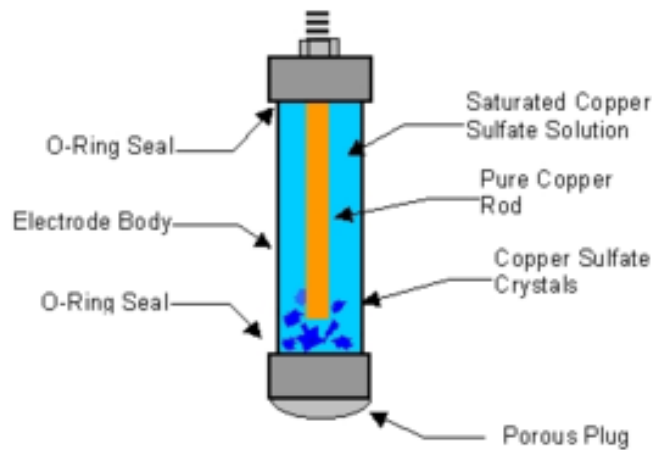
Figure-2.9 Copper-Copper-Sulfate reference Electrode (CSE) [21].

2.6   Practical Implementation

Potential measurements are extensively used in the cathodic protection industry to evaluate the corrosion activity along a pipeline. These measurements are made using the copper-copper-sulfate reference electrode (CSE) as this reference electrode is stable, robust, simple and safe to use and maintain. Investigations have shown that the most highly anodic area that can be expected on a steel pipeline in most soils and water have a potential of around -800mV CSE measured with the reference electrode contacting the environment immediately adjacent to the anodic area [16]. In practice, it is not possible to do this therefore it is suggested the reference electrode be placed on the ground surface directly above the pipeline and adjusting the voltage criteria to -850mV CSE to compensate for volt-drop [16]. This criterion is another one of the three criteria suggested in NACE standard SP0169 to indicate satisfactory pipeline cathodic protection.

2.7   Conclusion

Corrosion is an electro-chemical reaction that requires four basic elements for its existence. The prevention or the reduction of corrosion can only be materialised by eliminating or reducing the influence of any one of the four elements. Pipeline coatings are the primary means of protection used by pipeline operators to minimise corrosion by isolating the electrolyte from the pipe surface. Despite the best application and installation practice being employed, coatings are never perfect and installation activity always has some negative influence to the coating. For these reasons, some form of secondary corrosion protection is necessary. The secondary means of protection commonly used is cathodic protection by employing unidirectional impressed current or to a lesser extent the use of galvanic anodes. Cathodic protection reduces or stops corrosion of the structure to be protected by making the structure the cathode of an intentional electrolytic cell by polarising all cathodic areas to the potential of the highest potential anodic site on the structure. The high current available from impressed current cathodic protection rectifiers are known to cause excessive concentrations of hydroxyl ions that can be damaging to pipeline coatings. The evolution of hydrogen gas requires careful consideration to prevent hydrogen products forming that may be harmful and a risk of explosion.

Chapter 3

Literature Review

3.1   Introduction

Corrosion of metal generally occurs naturally as a result of inherent energy acquired during the refining process. For easy identification of metals based on their energy levels they are grouped in tabular form according to their natural potentials or free energy levels. This diagrammatic representation is known as the galvanic series and readily shows the corroding tendency in relation to each other. Figure-3.1 shows a typical galvanic series for some commonly used metals.
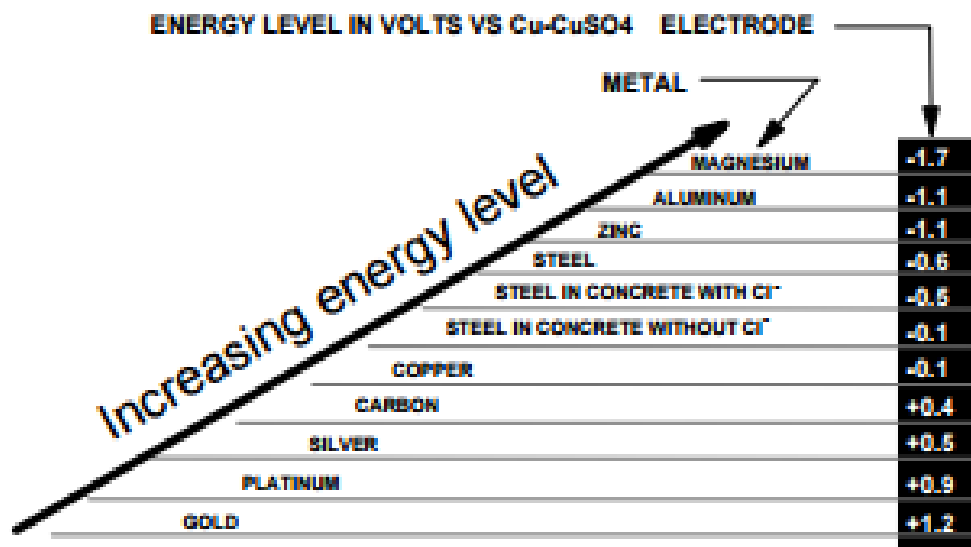
Figure-3.1   Galvanic Energy Series of some common metals [22].

The elements are arranged with the most noble metals at the bottom and the most active metals at the top. In the field of cathodic protection conventional current flow direction is assumed unless otherwise stated. This means that in a galvanic cell the current through an electrolyte will flow from the electrode at higher negative potential through the electrolyte to the electrode at lower negative or relative positive potential. Stated in another manner and referring to Figure-3.1, when two metals are inserted into an electrolyte current will flow through the electrolyte from the metal at higher energy level (more negative) to the metal of lower energy level. This is an important factor of metals which is put to good use in various industries such as cathodic protection, manufacturing of electro-chemical cells (batteries) and

electroplating to name a few. From a corrosion point of view, the most challenging corrosion is as a result of current using buried metal as a current carrier. The current forces cathodic and anodic sites at the locations where the current enters and exists the pipe respectively. This form of corrosion is termed electrolytic corrosion and normally occurs as a result of stray current. It is estimated that the American railway system loses 500 million dollars a year due to stray current corrosion [11]. Stray current defines all electrical currents running through the ground and can be from natural or manmade sources. A significant contributor to stray current interference is traction power systems [8] [23]. Buried pipelines transporting liquids or gas and various other buried structures are all at risk from metal loss due to stray current corrosion. The amount of metal loss due to stray current corrosion depends on the type of metal and in the case of iron one ampere is capable of oxidising 9,11 kilograms of iron in one year [11] [22]. Applying this to a pipeline with a good protective coating having a small defect it is easily understood that in a short space of time the pipeline can be penetrated as a result of the high current density.

3.2   Corrosion Characteristics

The standard practice of mitigating corrosion on a buried structure such as a pipeline is to polarise all cathodic areas on the surface of the pipe to the potential of the highest anodic site. The general recommended polarised potential is -0,850 volts CSE pipe to soil but may vary depending on the chemical structure of the electrolyte and external interference such as stray current [15] [24]. A limiting critical potential of negative 1200mV CSE is advised to prevent detrimental effects of hydrogen evolution and high pH at the metal surface [24]. Interference from stray current will disturb the cathodic protection and the protecting potential will intuitively be increased to a higher negative potential increasing the alkalinity of the soil at the defect zone where current enters the pipe. AC corrosion is characteristic of the formation of a very high pH at a coating defect combined with potential vibration caused by superimposed AC [25]. Changing the environment to a high alkaline environment as will be the case in the event of applying high negative potentials to protect the pipe against stray current will tend to worsen the corrosion activity should AC interference also be present. With reference to figure-3.2, it is seen that when the pH approaches above pH15 and with the potential still in the generally accepted criteria for cathodic protection a corrosion favouring zone is entered. It implies that the mitigation of AC corrosion tends to prefer lower levels of cathodic protection current so that the pH level is maintained at a lower level. In contradiction, the mitigation of DC corrosion is improved with higher levels of cathodic protection current but this will

increase the risk of AC corrosion [25]. Based on what has been discussed it is understandable that where pipelines experience both AC and DC interference it will be very difficult to get to an optimised level of cathodic protection. The recommended method to analyse and quantify what the likelihood of AC corrosion is through the use of coupons to simulate a pipe coating defect with known dimensions and then to assess the corrosion after a defined time [25]. NACE recommended practice (RP0104-2004) on the use of coupons is not focussed on the assessment of AC/DC interference and may not necessarily be applicable in such cases [25]. In some cases where AC/DC interference is high it may not be possible to successfully combat corrosion with cathodic protection in which case the source of interference needs to be located and the stray current minimised at the source [25].
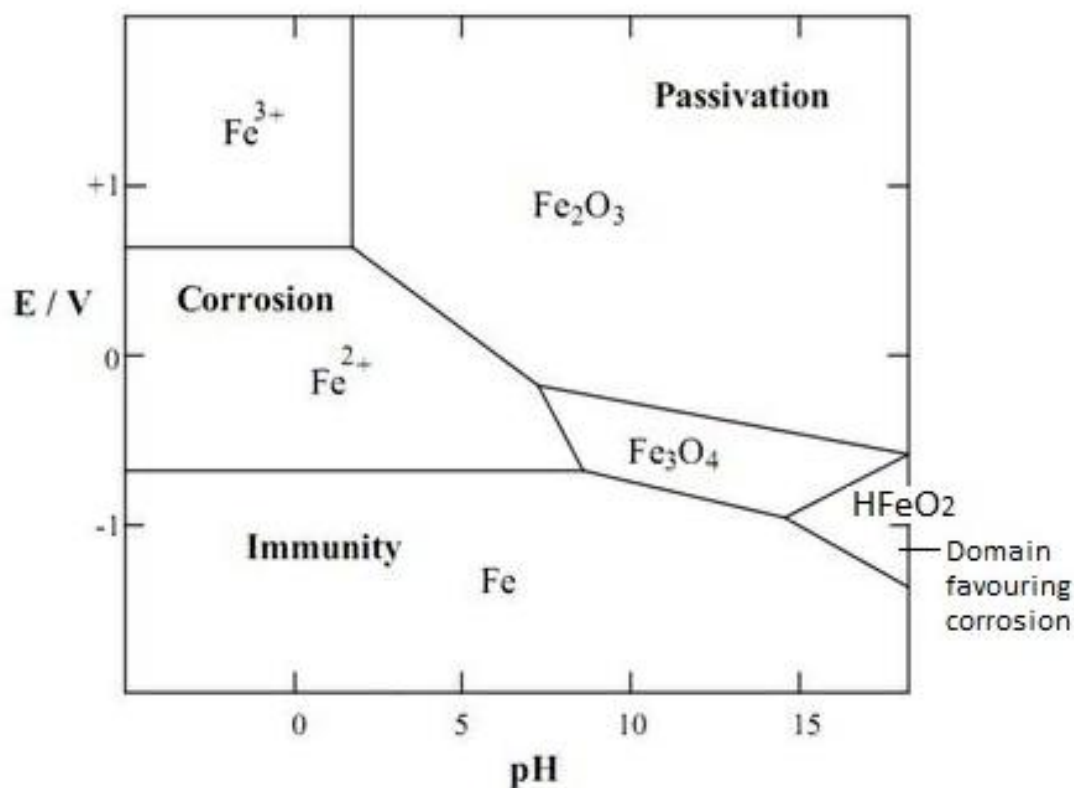
Figure-3.2   Potential – pH diagram for iron in water [17] [25].

Galsgaard [25] suggests an optimised cathodic protection system or "dynamic corrosion control" a system which measures the off-potential frequently and adjusts the rectifier to pre-programmed CP requirements. In anaerobic soils, such as clay where there exists an absence of free oxygen, sulphate--reducing bacteria may be active. This form of corrosion is generally very active and severe damage can occur in a short period of time. It is readily recognised by

the bright appearance of the metal surface where it is active and is associated with a rotten egg odour [26].

3.3   Cathodic Protection Methodologies and Technologies

Cathodic protection is an electrical method of preventing or controlling corrosion of metals placed in an electrolyte through the use of a unidirectional electrical current source. When the corrosion rate of a metal is less than 0,01mm per year it is deemed to be satisfactorily protected against corrosion [24]. The principle of cathodic protection was first discovered in 1824 by Sir Humphry Davy during his search for a method to mitigate corrosion on the copper clad hulls of British naval ships [22] [27]. His work included the attachment of zinc billets to the copper hull of ships; the zinc being sacrificed to protect the copper. This principle is still used in the application of cathodic protection and is one of the two basic methods of cathodic protection in use today; the second method being similar but making use of an external driving potential.

The first method known as sacrificial anode or galvanic anode cathodic protection uses the natural occurring potential differences between dissimilar metals to provide the driving potential for the cathodic protection process. The second method known as impressed current cathodic protection uses a driving potential that is derived by an external unidirectional current source [22].

Some of the primary advantages of using the impressed current method of cathodic protection is shown below [25]:

- Higher current is available for cathodic protection
- Potential output is user adjustable
- Control may be automated to accommodate varying current requirements to maintain a constant level of protection
- Current interrupters may be included in the rectifiers to facilitate various testing procedures such as direct current voltage gradient surveys (DCVG), off-potential measurements etc
- Long distance of pipeline may be protected by a single anode
- Optimised cathodic protection or "dynamic corrosion control" is possible [25].

Figure-3.3 shows the principle of galvanic cathodic protection. Connecting the pipeline with the magnesium anode forces the pipeline potential to be lowered to a value of at least the most anodic area on the pipeline surface. This action reduces all areas to the same potential so that no potential differences exist on the pipeline surface. This in essence means the driving voltage is removed from the original corrosion cell and the corrosion activity on the pipe is halted. Current from galvanic anodes is generally very low restricting their use to areas of localised protection.
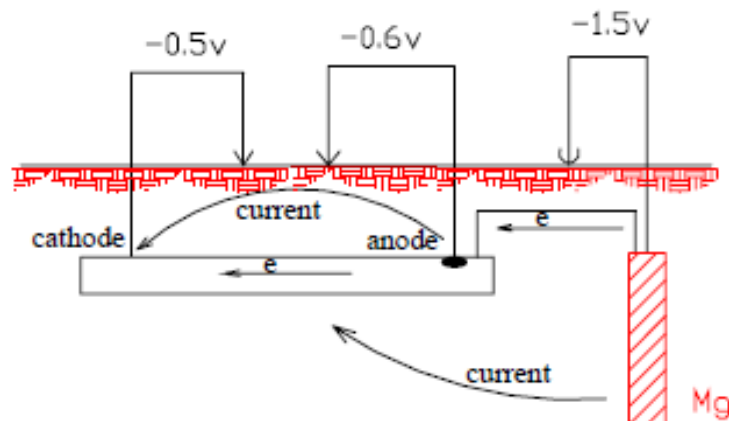
Figure-3.3   Sacrificial Anode Cathodic Protection [26].

Potential differences exist on the pipe due to various chemical differences either within the metal or the electrolyte surrounding the pipe at the different locations. Installing the galvanic anode in the ground and connecting it to the pipe will create a corrosion cell with the driving voltage occurring naturally due to the different inherent energy levels of the two metals (the pipe and the anode). Providing sufficient current is available from the anode installation, the pipe will be polarised so that no potential differences exist on its surface and the pipe surface corrosion cells will be eliminated.

Figure-3.4 shows the impressed current cathodic protection methodology. The basic setup for an impressed current cathodic protection system is to install a rectifier and an associated anode at a convenient location dictated by the cathodic protection design. During pipeline installation test points and coupons should be installed to provide a testing facility to the pipe and coupons. The coupons should be of the same material as the pipe being protected and serves to simulate the pipe for assessment of the cathodic protection being applied and the extent of corrosion activity experienced by the pipeline. The principle of operation of this

system is similar to what has been discussed except that the driving voltage in this instance is derived from an external source, the rectifier being represented in figure-3.4 by the battery.
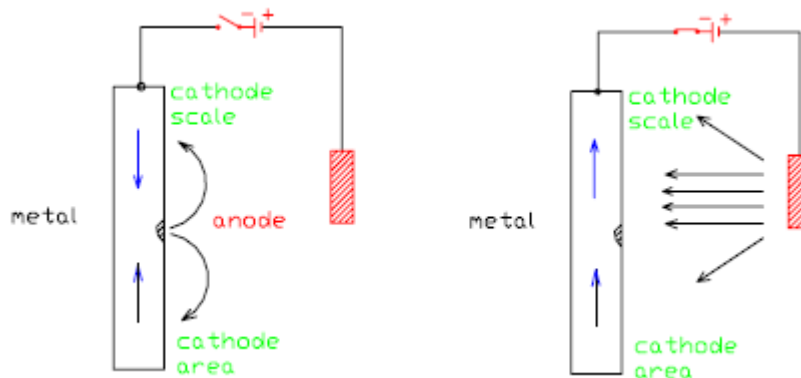
Figure-3.4   Impressed Current Cathodic Protection [26].

Figure-3.4 shows the corrosion process firstly prior to connection of the external source followed by the connection of the external source. Once again protection is achieved when the pipe is polarised to the most anodic area eliminating potential differences along the pipeline in so doing stopping the corrosion process. Generally, rectifier output voltages greater than 50 volts should be avoided for safety reasons failing which a risk assessment should be done to assess the impact on safety [24]. Furthermore, the depth of the anode bed should be such that the top of the conductive backfill is at least one metre below ground level [24]. Possibly the greatest disadvantage of an impressed current system is the availability of electric power to remote areas. This disadvantage is slowly being eliminated as alternative energy sources become more cost effective and acceptance within the cathodic protection industry gain momentum. Based on previous work of other researchers; Mohsen [27] proposes a system using solar panels and batteries for the protection of an oil and gas pipeline [27]. The capacity required by the cathodic protection system is given as 12.8 amperes at 37.74 volts equating to a power of 483 watts. The total system power proposed is estimated to be 755 watts. The proposed solution is a 48 volt system based on four 250AH batteries charged by a configuration of solar panels capable of delivering 40.04 amperes at 52.2 volts or 2090 watts [27]. Another alternative source of energy is power derived from fuel cells. Fuel cells to power impressed current systems is already a reality and slowly gaining momentum in the industry as pricing becomes competitive. Depending on the remoteness of the area fuel cells may already be the more economical solution [28]. For stationary applications the molten carbonate-fuel cell (MCFC) or the solid oxide fuel cell (SOFC) are the preferred options due to their higher efficiencies and the tolerance to start-up time and load following dynamics

being a secondary consideration [29]. A 500 watt LPG-powered system based on SOFC technology has a start-up time of approximately one hour and is already available for cathodic protection applications [28] [29]. The run time is dependent on the size of the LPG fuel tank and is claimed that a fuel supply of approximately 1200 litres will supply a load of 1300 watts for 8 weeks before refuelling is necessary [28]. Figure-3.5 shows a typical SOFC installation consisting of two 500 watt SOFC modules with remote monitoring.
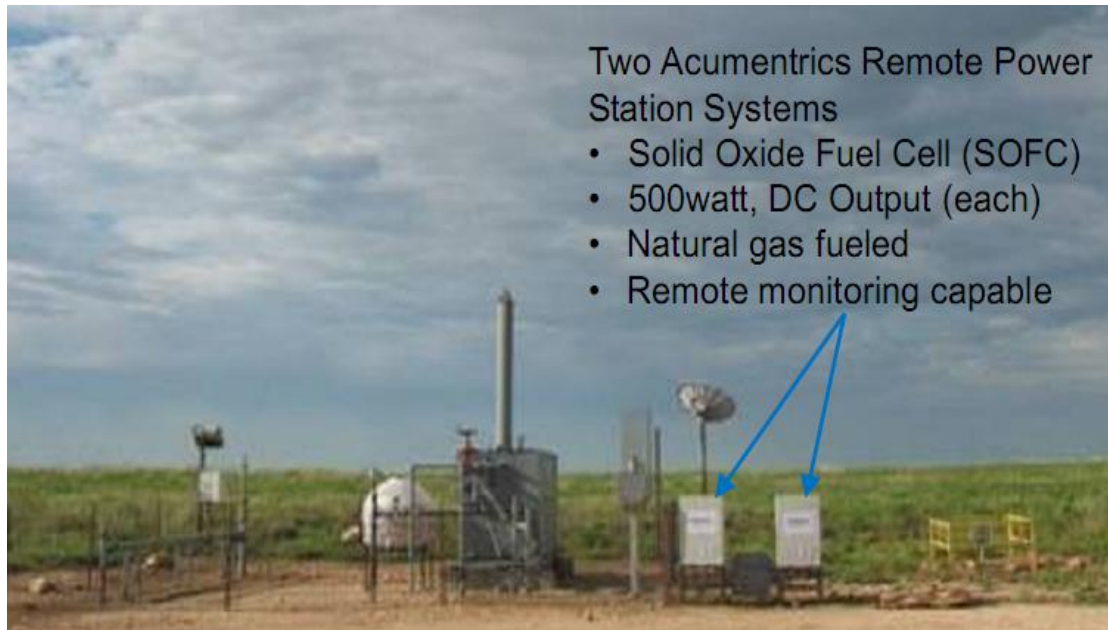
Figure-3.5   Solid-Oxide Fuel Cell Installation [28].

Further information on fuel cells and their application [29] is documented in the reference list given and will not be further discussed in this dissertation.

3.4   Assessing Minimum Cathodic Protection Current

In addition to the environment and the environmental dynamics the cathodic protection current required for protection of a pipeline is dependent on the area of metal to be protected which is related to the quality and condition of the pipeline coating [22]. Pipeline coatings deteriorate over time resulting in increased current demand to maintain an acceptable level of cathodic protection. A direct current voltage gradient (DCVG) survey may be performed to establish the condition of pipeline coatings if the condition of a pipeline coating is unknown or needs to be confirmed. As samples are most pipeline integrity testing and evaluation methods DCVG results are verified. Verification in the case of DCVG type surveys is by exposing samples lengths of the pipeline and physically checking the condition of the pipeline coating against the interpreted DCVG results. If a predetermined accuracy is met the results

are accepted as providing a true indication of the pipeline coating. In the event of coating damage, the exposed section will be removed and the pipe surface inspected for assessing the severity of corrosion. The soil surrounding the pipeline is also carefully examined for chemical deposits and bacterial activity.

For new pipelines the current demand can be calculated using equation 3.1 [24]:

$$I_{tot} = J \cdot F_C \cdot 2\pi r \cdot L \tag{3.1}$$

Where

I_{tot} = is the current required for cathodic protection in milliamperes

J = is the design current density for bare steel expressed in milliamperes per square metre

F_C = is the coating breakdown factor, dimensionless

r = is the outer radius of the pipeline in metres

L = is the length of pipeline in metres

Table 3.1 shows recommended design current densities for various types of pipeline coatings and pipeline design life based on an operating temperature of 30 degrees celsius or lower. For higher operating temperatures, the current density should be increased by 25% for each 10^OC increase in operating temperature. For existing pipelines SANS 15589 recommends that a current drainage test be conducted to determine the current demand. [24].

Table 3.1 Design current densities for coated pipe (J*FC): [24].

Pipeline coating	Design current density mA/m^2		
	10-year design life	20-year design life	30-year design life
Asphalt/coal-tar enamel Cold-applied tape	0, 4	0,6	0,8
Fusion-bonded epoxy Liquid epoxy	0, 4	0,6	0,9
3-layer epoxy-polyethylene 3-layer epoxy-polypropylene	0,08	0,1	0,4
For a design life of more than 30 years, correspondingly greater factors should be used.			
It is assumed that pipeline construction and operation is carried out in such a manner that coating damage is minimized.			
For pipelines operating at elevated temperatures, the current density values shall be increased by 25 % for each 10 °C rise in operating temperature above 30 °C.			
Alternative design current values may be used if reliable and properly documented.			
Current density requirements also depend upon the oxygen content and resistivity of the soil.			

Mohen [27], demonstrates an alternative method of calculating the current demand using the equation 3.2. This method assumes the current demand required per square metre of bare pipeline then applies two coefficients characterising the condition of the pipeline to calculate the current required for the specific pipeline. This method carries the risk of choosing the coefficients based on an accurate knowledge of the pipeline wrapping and its environment.

$$I = S \cdot i \cdot K \cdot C \qquad\qquad [27] \qquad\qquad (3.2)$$

Where

I   = maximum current demand (A)

S   = is the pipe exterior surface area (m^2)

i   = is the current density required for a bare structure (A/m^2)

K   = is the extension coefficient of embedded petroleum pipeline network

C   = damage coefficient

The equation is seen to be similar to that stated in the SANS 15589 [24] but has an additional coefficient, "the extension coefficient of embedded petroleum pipeline network". This additional coefficient (K) is not clearly defined in Mohsen's paper so it is not clear how one would choose an applicable value, in what range it could be or what the influencing factors are.

3.5 Monitoring Stray Current

Various sources of stray current exist with some of the most extensive causes of metal loss being due to DC rail traction stray current. Limited knowledge exists on the level of stray current that can be expected from a healthy floating traction power station [8]. In the Netherlands work performed in joint venture between the main gas pipeline operator, the Dutch railways and several other interested companies yielded a table of agreed DC traction stray current criteria [30]. The developed criteria are based on stray current as a percentage of protection current versus time. It is not clear from the published paper [29] how it is intended to be interpreted and further work will be required to establish the intended interpretation, for this reason no further discussion on the published criteria is entertained in this dissertation. Setting a baseline for leakage current could be done on a theoretical basis or practically by means of testing for leakage current from a known healthy floating traction system. As stray current from a well-functioning floating traction system could be low it would be necessary to

intercept the stray current over a practical distance before it notably distributes throughout the ground. This calls for minimum criteria to be established. Criteria should consist of at least the following [8]:

- type of collector, its dimensions, buried depth and method of installation.
- location in relation to the traction power station and the rail track
- location representing a worst-case scenario

The use of steel mesh mats and sheet steel piling has been used by various researchers as stray current collectors [8] [11] [13]. To reduce cost and time of installation a collector may consist of short lengths of wall or steel mat joined together with a thick wire conductor of low resistance. This construction closely simulates a continuous steel wall and may be used for monitoring and mitigation purposes [8]. Peelen [8] suggests the measuring of two electrical parameters, potential difference and current, to establish the stray current activity. For potential measurement, the standard reference electrode as used in cathodic protection applications was used. The current sensor was specifically developed for the purpose and consisted of a small steel plate of known dimensions and of the same steel as that for which the corrosion rate was to be determined, the concept is shown in figure-3.6
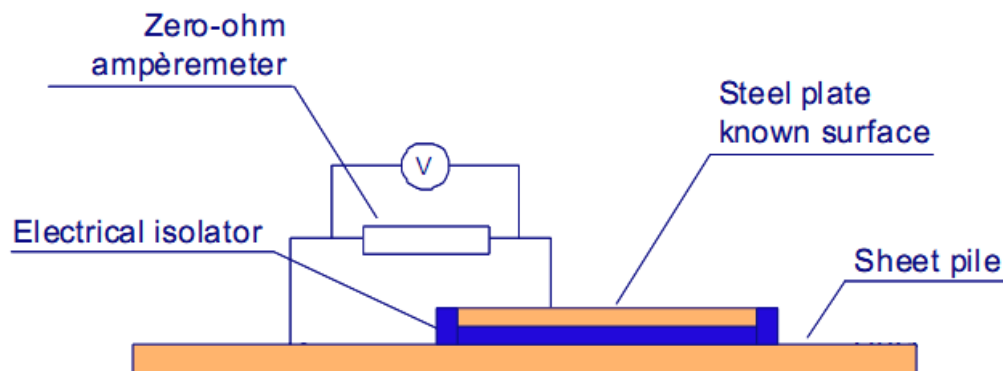
Figure-3.6   Current Sensor for measuring Stray Current [8].

The industry standard for monitoring pipeline corrosion activity and stray current interference is to measure the pipeline to soil potential. Soil to pipeline potential based assessments are however characterised by uncertainty due to system complexity and the many stray current paths that may exist [31].

3.6 Stray Current Interference and Mitigation Measures

At around 150 years of operation the oil and gas pipeline industry can be claimed to be mature yet it still faces many new challenges, the two major challenges been safety to life and the environment and security of supply especially with the older pipelines that require special attention and additional spending [32]. Corrosion has been identified as the main challenge affecting the efficiency of petroleum pipelines with electrolytic corrosion being considered the most severe [31] [33].

Some of the primary issues that impact on stray current are [5] [34].

- Conductivity of the traction return circuit

- Insulation quality between negative return system (traction earth) and general earth

- Substation and system earthing

- Spacing of traction substations

- Load current (Locomotive)

- Regenerative braking

To improve the conductivity of the negative return circuit rails are welded as opposed to being bolted together. Insulation quality is highly dependent on the effectiveness of the maintenance program and is further discussed in chapter four of this dissertation. As in Europe the South African 3kV DC substations negative pole (traction earth) is intended to be insulated from general earth mass to limit the magnitude of stray current into the ground [23]. No AC or electric light and power earth, as it is referred to in industry is permitted within a traction substation ensuring that the two systems are kept separate and insulated from each other. To maintain safe potentials between the two systems, rail potential control devices (RPCD) are installed as necessary. The RCPD is a device that monitors the potential difference between the two earth systems and when the threshold voltage is reached a contact closes and connects the two earth systems together through a resistor of low value. Once current has reduced below the threshold value and a minimum predetermined time has elapsed the RCPD will revert back to the open condition [23]. Closer spacing of traction substations means less resistance between the load current and its source so effectively the area of influence of stray current is reduced. Some of the primary factors influencing the distance between substations are financial benefit, geographical terrain, volt-drop due to load current and the influence of circuit impedance on circuit protection devices. Load current is dependent on the acceleration

of the locomotive, the gradient it is travelling over and the load it is pulling. Both acceleration and gradient are variables and as a result the load current will be variable over time and distance. Regenerative braking may be identified by current polarity reversal and smoothing of the traction load voltage. Regenerative braking can lift the traction voltage to just under 3,9kV this voltage rise being monitored and controlled by the traction system regenerative energy control system. As a last option and only if stray current cannot be limited to tolerable limits by improving the traction circuit should drainage bonds be considered as a mitigation measure [30]. A major disadvantage of drainage bonds is that they disturb the cathodic protection "on-potential". With pipelines of greater than 12 inch diameter the longitudinal resistance is sufficiently low to allow pipe to soil potential disturbances to propagate for up to 30 kilometres from the drainage bond connection [30].

As a pipeline ages, the coating which is the primary protection degrades and as the coating degrades cathodic protection is traditionally increased to maintain the level of polarisation to protect the pipeline. The more metal is exposed the greater the demand grows for cathodic protection current and the smaller the spread becomes from the impressed current anode further adding to the challenge the ability of trying to maintain an even spread of protection current. Increasing the cathodic protection current by increasing the rectifier output voltage increases the accumulation of hydroxyl ions at the pipe surface in the defect area. In turn the environment around the defect becomes increasingly alkaline and the coating fails to adhere to the pipe (substrate) a condition termed cathodic disbondment.

This condition is as a result of chemical dissolution and electrochemical reduction possibly aided by hydrogen pressure at the coating/metal interface [35]. Cathodic disbondment therefore generally does not occur unless a coating already has a defect [36]. Disbondment will generally worsen over time as cathodic protection current is continuously increased to protect the increased metal being exposed due to the cathodic disbondment. Under the influence of stray current the situation will be magnified as stray current is attracted to the defect and at the point of entry the stray current intensifies the cathodic protection resulting in an even greater influx of hydroxyl ions and quicker build-up of the alkalinity level around the pipe.

Figure-3.7 shows a typical situation of how stray current from an impressed current cathodic protection system can be distributed through an unprotected pipeline to enter the protected

pipeline at a remote location. The location at which current leaves the unprotected pipe will become an anodic site on the unprotected pipe increasing the rate of corrosion at this site. The location where current enters the protected pipe cathodic protection will increase increasing the alkalinity of the environment as previously discussed. The effectiveness of the anode will reduced due to current migrating to the foreign pipeline in search of a path of lower resistance back to its source. This practical example demonstrates the importance of knowing the environment in which anode beds are to be installed and ensuring they are installed remote of any buried metallic structures.
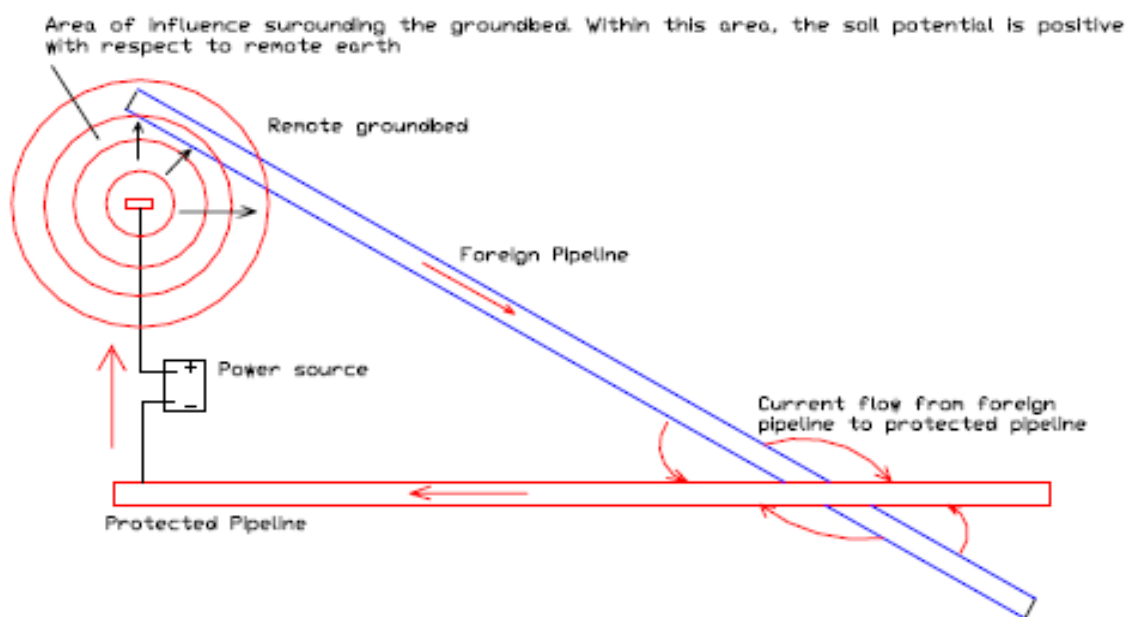
Figure-3.7   Stray Current from a Cathodic Protection System [26].

DC traction systems and HVDC systems are sources that inject high magnitude currents into the ground and as a result have a wide area of influence. Unlike HVDC which is more concentrated within narrower corridors DC traction is distributed throughout a wide geographical area of South Africa. Stray current collection mats and steel sheeting barriers have been used in some parts of the world in an attempt to reduce stray current interference from rail traction negative return rails [4] [13]. To determine the extent of stray current interference surface potentials are measured and a soil surface voltage profile is developed showing the interference zone. Surface voltage profiles are also developed on a theoretical basis to determine the interference levels that are expected to occur within an electrodes interference zone so that suitable mitigation measures can be implemented during installation to reduce interference on other services. An HVDC link like the one between Kenya and

Ethiopia when operating in mono-polar mode with ground return has the potential to generate a ground current of 2000 amperes [37]. It may appear feasible to install metallic bonds from an affected structure to the stray current source to limit the stray current through the soil but this practice is considered undesirable due to the interdependence that is then established between the two metallic paths. The use of any bonds between metallic structures and metallic structures and stray current sources needs careful consideration and should only be used as last option. This consideration applies equally to natural or forced drainage bonds [30].

3.7 System Modelling

Simulation models of various complexity for investigation of stray current distribution have been reported in literature [5] [7] [13] [23] [30] [31] [34]. Modelling tools are useful for analysing the effects of various installation and mitigation parameters prior to implementation so that funds may be invested on decisions based on most informed technical information available. Two modelling approaches that may be followed is the field approach or the electric circuit approach. The field approach is often used to model the electro-chemical polarisation that occurs on the pipeline while the electric circuit approach is based on the earth return circuit theory [31]. Dedicated software such as CPMaster® is available for modelling cathodic protection systems although other software such as CatPro®, Matlab/Simulink, SPICE, CDEGS and Finite element software are also used [4] [13] [30] [36]. CDEGS software has built-in soil modules and simulations have been demonstrated using this to simulate resistivity interaction with a traction system having a stray current collector mat and a buried pipeline.

Some of the models demonstrated in literature are based on multi-layer soil structures in different horizontal and vertical formations. Soil resistivity measurement is not a simple exercise and requires knowledge of the environment in which measurements are to be taken including weather conditions (seasonal changes). Buried metallic structures will also severely distort resistivity measurements with errors as high as 50% being possible [4]. Although a stray current collector mat below the rail significantly reduces the magnitude of stray current, stray current is not eliminated. The stray collector mat reduces the magnitude of stray current by acting as a parallel path to the traction negative return rail. This may not be a preferred solution as dependence on the stray current collector path is created. Improving the quality of the rail to earth insulation remains an important parameter especially where simulations demonstrate a lower lifetime of the metallic structures [4].

3.8   Related Work

Understanding the soil structure and how various layers of soil conduct electrical current is of interest to a variety of scientific disciplines. Electrical engineers seek methods to test for the lowest ground return paths for fault currents, geologists employ electrical sounding methods to explore for possible ground water and cathodic protection engineers study the different soil layers to find suitable areas for anode ground bed installations. Further related work includes the natural phenomena of solar storms and the effects of associated geo-magnetically induced currents on electrical equipment [39].

3.9   Conclusion

Stray current can originate from various sources and can be either AC or DC. The most common sources of stray current interference include electrical power transmission systems, impressed current cathodic protection systems and rail traction systems. Stray current is estimated to cost the American railways in the region of 500 million dollars a year. In South Africa DC rail traction is known to be a major contributor to stray current but the financial impact is yet to be established. Pipeline owners in particular are very sensitive to the influence of stray current as coatings are generally of good quality and a small defect will result in a high current density area with a high corrosion rate that can rapidly puncture the pipe wall. In this dissertation the contradictory action necessary for the mitigation of AC and DC corrosion has been briefly discussed. In instances where the risk of both AC and DC interference exists the installation of coupons is highly recommended to enable improved accuracy monitoring of the corrosion rate. Monitoring is recommended at close intervals until such time that one is confident an optimised level of cathodic protection has been achieved, after which the inspection period may be increased based on the corrosion data acquired. In severe cases of combined AC and DC interference cathodic protection may not be the secondary corrosion mitigation solution it is desired to be. In such cases, it is recommended that the source of stray current be identified and minimised at the source [25]. Experience has shown that coupon current density and spread resistance combined with monitoring the pipeline AC voltage are of the best indicators of a potential corrosion risk [25]. Modelling software is a valuable tool when faced with finding the most suitable design and mitigation measure and invariably leads to a more cost effective installation and asset lifespan. Legal compliance is becoming more demanding and involves the process of risk assessment, good record keeping and in Line Inspections that are core to integrity management programmes [40].

Chapter 4

Pipeline Integrity Management – Systems Design and Analysis

4.1   Introduction

Stray current can be both alternating and unidirectional current and could originate from a variety of sources such as welding machines, HVDC electrification schemes, HV transmission lines, cathodic protection systems and rail transport networks. Corrosion caused by stray current is considered to be the most severe form of corrosion [31]. In the South African environment stray current from cathodic protection systems and DC traction is considered to be significant [8] [24]. In this dissertation the focus is on stray current emanating from the DC traction rail transport network of South Africa.

When designing and maintaining a rail traction railway three electrically associated engineering disciplines need to be considered and satisfactorily engineered in the design and maintenance procedure. Traction power engineering, signal engineering and corrosion engineering have a degree of conflicting engineering requirements that need to be satisfied so that all three disciplines can operate at an acceptable engineering standard without compromising safety. Traction engineers aim to use the rail as a negative return conductor while keeping rail to earth potentials at safe levels, signal engineers aim to isolate and insulate section of rail for signalling purposes and corrosion engineers aim to keep the rail insulated from earth to avoid stray current distribution [7].

The 3kV DC traction system in use in South Africa is of the floating earth design. This means that the negative return circuit comprising of either one or both of the rails and the negative return conductor is insulated from the soil or ground upon which it is installed. Due to various factors such as poor maintenance practice, insulation break down, high rail resistance and poor drainage, some return current will leave the rail to find alternative paths back to the traction substation/s. These alternative paths may include any metallic structure or pipeline buried in the ground offering a path of lower resistance back to the source of the current. For design purposes IEC 61228 part 2 (equivalent to EN 50122 part 2) recommends values for rail-to-earth insulation (in terms of conductance per kilometre) to limit the intensity of stray current [31]. The 2010 edition of the same standard specifies a permissible level for stray

current as 2,5mA/m suggesting that if it is expected to be exceeded a detailed risk assessment needs to be performed [31].

4.2   Electrolytic Corrosion

Unlike galvanic corrosion where the driving voltage is created naturally through dissimilarities at different locations at the surface of a metal or the presence of dissimilar metals within an electrolyte, electrolytic corrosion is a form of corrosion in which the driving potential is derived from an external source. In the event of a structure, such as a pipeline buried beneath the ground the point at which the current enters the structure becomes the cathode and the point at which the current leaves the structure becomes the anode. This implies that with electrolytic corrosion the corrosion current forces the development of anodic and cathodic sites. Electrolytic corrosion normally occurs unintentionally and if buried metallic assets are not constantly monitored for the presence of this corrosion premature failure can result in a short period of time in the absence of effective mitigation measures.

When stray current flows through an electrolyte and encounters a metallic structure such as a pipeline along its path it will flow onto the metal structure due to this path of lower resistance and eventually exist at another location closer to the source. This action leads to the creation of an electrolytic corrosion cell with the point of current entering the object becoming the cathode and the point of current exit becoming the anode, the stray current being the driving potential for the corrosion cell. In the previous chapter a typical case of stray current corrosion was demonstrated where an unprotected pipeline passes through the interference zone of a cathodic protection systems anode bed.

According to Faradays law the rate of corrosion will be proportional to the magnitude of the corrosion current and the time it flows in the corrosion cell this being shown by equation 4.1 [11]:

$$M = C \int_{t1}^{t2} i(t) \, d(t) \qquad\qquad (4.1)$$

Where

M   = is the mass reduction as a result of anodic interaction

C   = is the electrochemical coefficient of the metallic structure

i   = is the current flowing in the corrosion cell

t   = is the time duration of current flow

The equation also shows that the rate of corrosion is also dependant on the type of metal being corroded.

4.3   Electrified Rail Traction in South Africa

Electrified traction infrastructure consists of the superstructure (i.e. rail, fastening system and sleeper), the substructure (i.e. ballast, sub-ballast and sub-grade materials), and the electrification (masts and overhead traction equipment). With the introduction of concrete sleepers the traditional track structure became significant stiffer and an elastic pad or rail pad was introduced between the rail and the concrete sleeper. The rail pad reduces the high-frequency force components that result from dynamic wheel-rail interaction and insulate the rail from the sleeper [41]. A typical rail insulating arrangement for use with concrete sleepers is shown in figure-4.1.
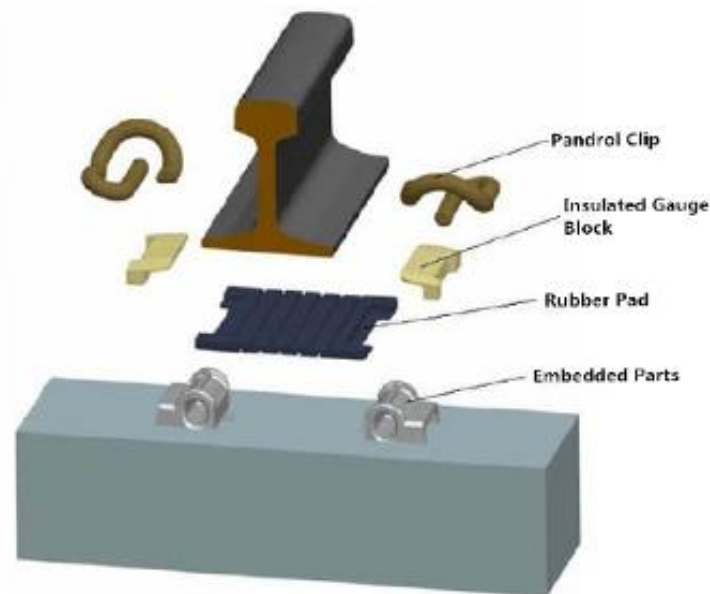
Figure-4.1 Exploded view of an Insulated Rail Fastener Arrangement [42].

In South Africa electrified rail traction consists of three different voltages these being 3kV DC, 25kV AC and 50kV AC. The three traction systems all have the positive or live conductor suspended above the rail with either one or both rails forming the return path back to the substation. Two of the networks are A.C systems using nominal voltages of 25kV and 50kV respectively and is not included in the focus of this dissertation.

The third and largest network is the 3kV DC network which is also the oldest of the traction networks. Figure-4.2 shows the single line diagram of a typical South African 3kV DC traction substation. The system is of the floating earth design with the AC and DC earth systems being kept completely insulated from each other during normal operating conditions. The industry standard is to refer to the traction negative return as DC earth or rail. AC earth is identified in the single line diagram by the standard electrical earth symbol. Rectifiers are primarily six phase full wave rectification giving 12 pulse output to the traction network from a single unit substation or 24 pulse from a dual unit substation.
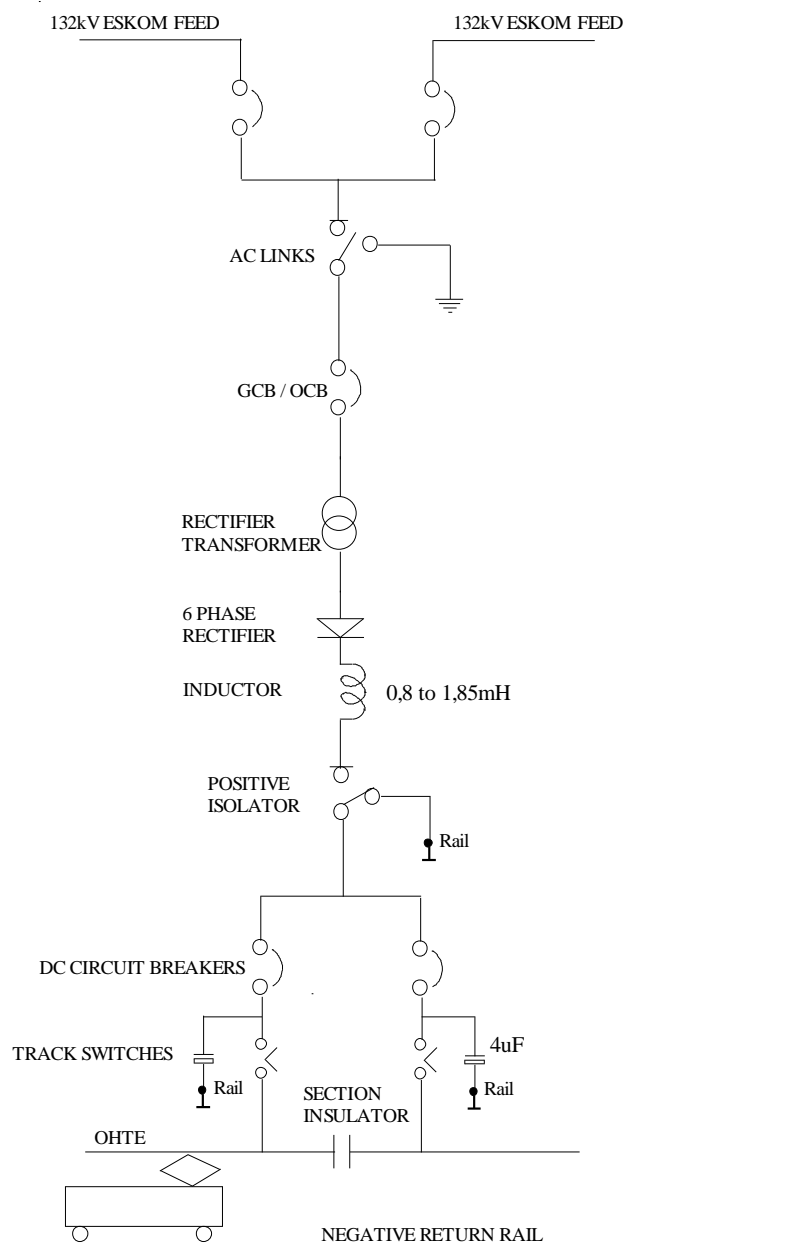
Figure-4.2   Typical 3kV DC Traction Substation.

Figure-4.2 is briefly summarised as follows. Electrical energy is received from the supply authority at either medium or high voltage. This alternating supply which is often a dual supply to ensure redundancy is fed via the supply authority protection devices to a set of AC links (AC isolator) owned and operated by the traction network operator. All equipment from and including the AC links to the load is owned and maintained by the rail traction owner. From the AC links power is fed via a protective device, either an oil or gas circuit breaker to the traction transformer and then stepped down to yield six phases for feeding to the traction rectifier. The inductor provides some smoothing and limits the rate of rise of fault current during fault conditions allowing the high speed DC circuit breaker to clear the fault at a lower level of fault current. From the rectifier through an inductor and positive isolator the DC is fed through a high speed DC circuit breaker to the overhead traction supply infrastructure track switches. The track switches finally feed the traction positive network in sections as shown in the single line diagram of figure-4.2. Track switches permit maintenance on selected sections of the overhead conductors without having to isolate the entire system so preventing disruption to the entire train service.

Voltage is known to rise to approximately 3,9kV during locomotive regeneration and under control of the substation regenerative energy control system. The control system is able to distinguish voltage rise as a result of regenerative energy from source voltage fluctuations by comparing the supply authority source voltage to the load side AC voltage (ie Input AC voltage to Output AC voltage). Should AC and DC voltage rise in harmony to each other, then regenerative energy absorption is disabled by the controller. Ripple and time duration of rise are a further two conditions monitored by the regenerative energy controller and only once all three conditions are favourable for regenerative energy absorption will the controller enable the absorption of excess energy. The voltage between the two earth systems may rise due to various parameters so to maintain a safe potential between the two-earth systems spark; gaps are strategically installed to limit potential rise between the two systems to approximately 90 volts. In European countries, the potential difference between the two earths is limited to approximately 65 volts using RPCDs [23]. In substation yards where the two earth systems come into close proximity of each other gate switches are provided to bridge the two earth systems while maintenance technicians perform routine maintenance. Arcing horns are installed on the overhead traction equipment to discharge energy induced into the overhead conductors during lightning storms.

The overhead infrastructure comprises either of prefabricated concrete masts embedded in concrete foundations or steel masts mounted on top of concrete foundations and secured with bolt groups embedded in the foundations. Insulating kits are used to insulate steel masts from the bolt groups and the concrete foundation to maintain the floating negative return path.

Figures-4.3 and 4.4 shows two variations of traction installations typically found in South Africa. Steel masts traditionally consist of redundant worn rail track salvaged for reuse as overhead traction mast poles but this is being replaced with universal column or concrete masts as upgrading becomes due.

Figure-4.3   Concrete Masts used to improve the South African Rail Infrastructure [43].
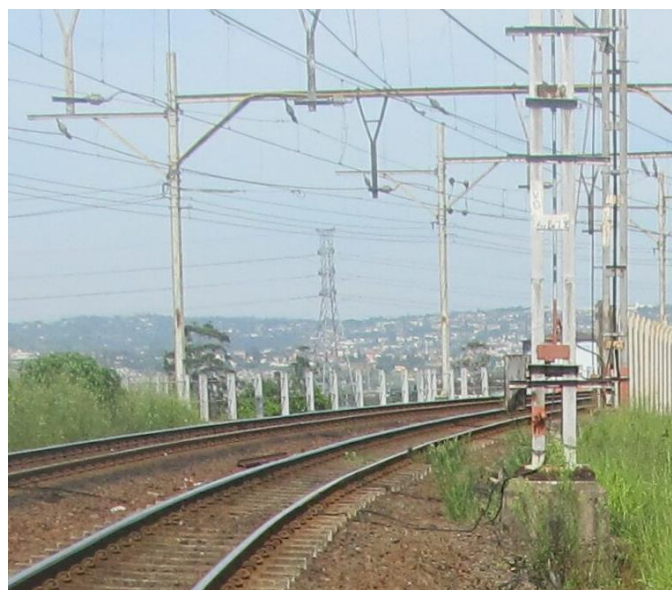
Figure-4.4   Rail Mast on Concrete Foundation.

A primary reason for replacing rail masts with universal column mast was that traction rail is brittle and readily snap when subjected to mechanical shock as in the event of a train accident. Both universal column and concrete masts are extensively used in South Africa at the moment with prefabricated concrete masts being the preferred option within the coastal regions due to improved weathering properties and consequent reduced maintenance. From the mast overhead assembly, the positive pole from the source (the rectifier) is distributed between a group of conductors suspended off insulators as is seen in figures-4.3 and 4.4. This positive group consist of the following conductors a positive feeder cable, a catenary wire from which the contact wire is suspended and the solid copper contact wire. Power is collected by the load, the locomotive, through a pantograph that slides on the contact wire. The negative return is through either one or both traction rails back to the traction sub-station. Although it is preferred to use both rails for the traction negative return often one rail is reserved for signalling purposes. The copper contact wire used on 3kV DC rail traction throughout South Africa has a cross-sectional area of 161-millimetre square. On most routes this conductor size is inadequate to safely transfer the necessary power to the locomotives so a parallel conductor known as the feeder cable is run above the catenary and connected at regular intervals to the contact wire using flexible jumpers. Feeder cables are normally 800-millimetre square stranded aluminium conductor. The voltage of 3kV is nominal and may vary from just below 3kV during high load to approximately 3,9kV during conditions of locomotive regenerative braking.

4.4   Traction Negative Return Circuit

The negative return circuit as previously noted consists of either one or both rails. It has been found that in some instances the single rail is insufficient to adequately support the load resulting in excessive volt-drop and subsequent low voltage across the load. In such instances an additional negative return conductor is installed in parallel with the negative return rail to increase the overall cross sectional area and increase the current carrying capacity. It is not known if previous analysis of this occurrence has been done but it will be shown later in this that other factors such as undesirable maintenance practice could be contributing to this low voltage problem. When an additional negative return conductor is used it is normally suspended on the side of the traction overhead structures mainly for convenience but also as protection against theft. Increasing the negative return cross sectional lowers the return circuit resistance in turn reducing the stray current distribution through the soil and associated step and touch potentials. Figure-4.5 shows part of a typical South African traction railroad.

Besides the mechanical requirements for using clean well drained ballast stone and insulating pads beneath the rail footing the rail system needs to be kept electrically floating with respect to general earth mass to limit stray current to acceptable limits.

Figure-4.5 Well maintained railroad assists to reduce leakage of stray current [44].

Considering a rail track mounted on pre-cast concrete sleepers, the rail insulating components comprise the following components. A bedding of well drained ballast stone, insulating rail footing pad for insertion between the rail foot and the sleeper and applicable insulating kit for the type of rail fastener used.
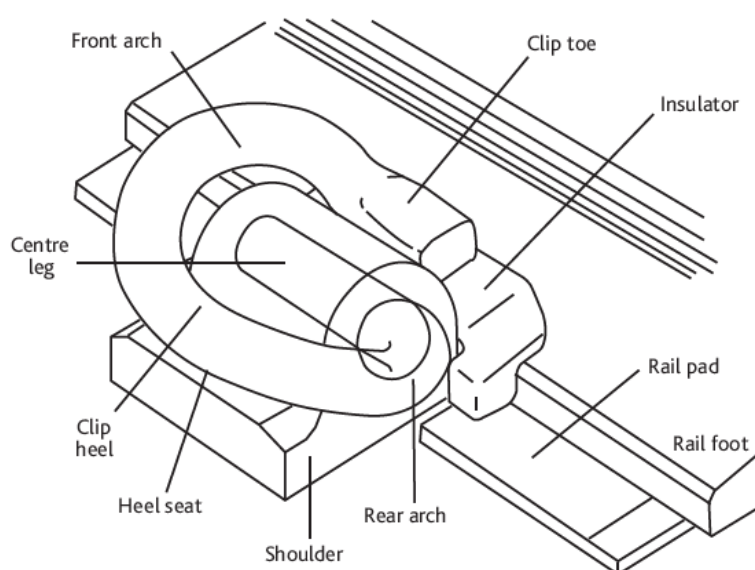
Figure-4.6 Electrically Insulated Rail Fastener Arrangement [45].

Figure-4.6 demonstrates the rail fastener assembly necessary for insulating the rail from the sleeper both at the fastening clip and at the foot of the rail. Failure of any one of these components to perform to specification will lead to an increase in stray current. It is obvious that the conductor connecting the rail to the substation also needs to be insulated to maintain the integrity of the floating system but this has been found to be overlooked in some instances. In areas where cable theft occurs on a regular basis it has been seen that sections of railway line laid directly on the ground is used as a replacement for the negative return cable. This practice effectively short circuits the floating system to general earth mass with the possibility of substantially increasing the magnitude of stray current. Complying with the criteria of minus 1200mV CSE as the most negative limit of polarised potential for pipelines is often not possible in environments of aggressive stray current and higher negative voltages may be experienced [24]. Higher negative voltages mean increased cathodic protection which is commonly referred to as over protection. Over protection introduces problems that will be discussed later in this text.

4.5   Traction Stray Current

The floating traction negative return system has been discussed and the critical dependence on good maintenance and installation on the magnitude of stray current cannot be over emphasised. It is also well documented that malfunctioning traction power systems are a major contributor to the cause of electrolytic corrosion as a result of traction stray current [8]. Increasing track to earth resistance is an effective measure in the mitigation of stray current magnitude [6] [7] [11]. Despite attempts to keep the rails insulated from the general earth mass the practical implementation of a perfectly insulated or floating negative return circuit is difficult to achieve and maintain. This breakdown or imperfect insulation is what contributes to the distribution of stray current along unintended paths back to its source. Traction stray current occurs when the current along the length of the rail returning to the traction substation finds alternative paths to assist the return of current. The load creating this current is the locomotive as it travels along the rails. As a result of this moving load the magnitude of stray current will vary depending on the magnitude of the load current, the position of the load, the resistance to earth, the resistivity of the soil along the path of the load and the distance to the respective source/s. As these parameters are fluctuating all the time as the load changes its position relative to its source of energy the resulting stray current will be of a fluctuating nature. Figure-4.7 shows the potential shift and the areas of anodic and cathodic influence on a pipeline relative to the position of a locomotive.
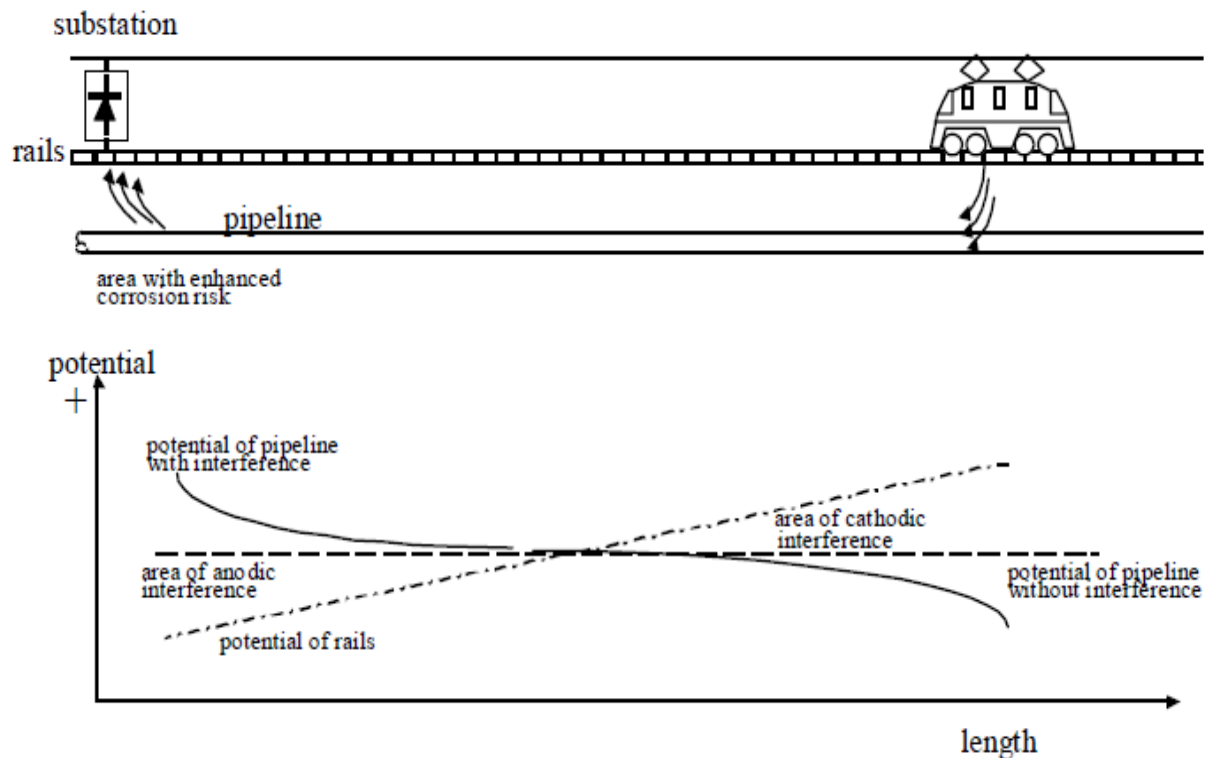
Figure-4.7   Typical Distribution of Traction Stray Current Interference [24].

It is seen that closer to its source the stray current leaves the pipe to return to its source gradually increasing the pipe potential as it crosses from the cathodic area of influence and enters into the area of anodic influence. This implies that some areas of the pipeline will receive additional cathodic protection while other areas may be deprived of cathodic protection. Cathodic protection above the recommended level is termed over protection and is characterised by high negative pipe potentials. This is not desirable as it may have a number of undesired results such as coating disbondment, accelerated influx of hydroxyl ions around the pipe, stress corrosion or the evolution of excessive hydrogen gas. Figure-4.8 shows how the rails are welded together as opposed to using the dated technology of fish-plates and fasteners to bolt the rails together. Welded rail construction improves track noise, eliminates wheel knocking damage and reduces rail longitudinal resistance greatly contributing to a reduction of stray current.

4.6   Traction System Maintenance

Recent inspection of the 3kV traction system revealed that poor electrical practice during maintenance and repair work unnecessarily poses a high risk of severe stray current corrosion. It is widely accepted that the elimination of stray current from a traction system is not practical or economical but needs to be maintained to within acceptable limits [6]. An inspection in the Durban area showed that generally the civil engineering maintenance was of

an acceptable standard in respect of limiting stray current leakage into the ground. Work performed by the electrical department however raised serious concern. Figure-4.8 shows work performed by the respective electrical team. Here the floating traction return system is solidly grounded by substituting the main negative return cable with a pair of traction rails. This conductor is the primary negative connection to the traction rails and in this case serves at least two sets of busy traction routes. The white building in the background is the traction substation which is the source to which the traction return conductor is routed. Reference to figure-4.8 may suggest that this arrangement is not a serious defect as it is located close to the substation with a remote possibility of stray current distributing via buried structures. This may at first glance appear to be so but no evidence of testing to this effect is known to exist. Stray current distribution during the time a train is a long distance away from the traction substation will depend on the geographical location of all the substations feeding the load. This being an urban area means substations are scattered and not placed along a relatively straight route and this could further increase the complexity of the stray current distribution. All this considered the real issue is that the floating system design has being jeopardised by what definitely amounts to a serious defect. This practice cannot be ignored as the original design intent of having a floating traction system will not be possible.

Figure-4.8   Bare Rail used as a Negative Return Conductor.

It is understandable that frequent cable theft needs to be addressed but this should be engineered and not simply substituted with alternatives lacking engineering. The concern with this solution is that it shows ignorance to the principle of having a floating negative return system and a lack of knowledge of the distribution of stray current and the detrimental effect it may have on buried steel structures. Figure-4.9 shows an enlarged view of the termination between the actual negative return rail and the negative return conductor which in this case is the bare rail previously discussed. Notice the multiple joints in the very short copper tails. Welds, crimp and bolted electrical lugged joints are used all evidence of a "quick fix" repair that has become a permanent repair. The short insulated copper tails from a traction return rail connect to bare copper tails on the substation main return conductor (rails). Termination between the tails are by means of lugs clamped together using diameter 10mm machine screws. The conductors are estimated at best to have a cross sectional area of 95mm^2 per tail yielding a total cross sectional area of 285mm^2 and a current rating of 714 amperes [46].

Figure-4.9   Traction Substation Negative Return Terminations.

This method of terminating leaves much to be desired in terms of good practice and safety and is further evidence of poor maintenance and deliberate short circuiting of the floating traction system. Figure-4.10 shows a different traction negative return rail connected to the substation main negative return conductor (rails). In this case only two 95mm^2 tails are used yielding a total cross sectional area of 190mm^2 and a current rating of 476 amperes [46]. In this instance the two tails connecting to the traction rail are both attached to a single fastener with the one lug sitting on the shoulder of the other preventing a secure and solid connection. This connection was visibly a serious concern and slight pressure proved that it was indeed a

loose connection and therefore a high resistance connection. The three empty lugs attached to the traction rail further raised suspicion on the quality of maintenance and repair conducted on this section of the negative return circuit. The inconsistent number of tails used for the different negative return rails shows a possible lack of knowledge of current carrying capacity of conductors and the negative impact it has on the distribution of stray current.

Figure-4.10   Termination of Traction Negative to Substation Negative Return Conductor.

4.7   Pipeline Maintenance and Monitoring

Operating a pipeline is a business demanding responsible and proactive action to ensure the sound integrity of the pipeline being operated. It requires close cooperation and regular intervention with industry partners to ensure systems capable of influencing each other are maintained to an agreed standard. Transnet Pipelines one of the major pipeline operators in South Africa own, operate and maintain 3800km of high pressure underground steel pipelines. Due to the critical nature of the business all sites are declared national key points; access is highly restricted and only accessible by prior arrangement. The oldest pipeline is the Durban to Johannesburg (DJP) 12 inch pipeline which was commissioned in 1965 and now being

scheduled for replacement by the new 24 inch multi-product pipeline [47]. The DJP pipeline has become a maintenance intensive pipeline due to the aging coal tar enamel wrapping. As the coating continues to deteriorate increased demand is placed on the cathodic protection system to mitigate electrolytic corrosion. This means higher cathodic protection current and increased negative potentials on the pipe. As discussed earlier high negative potentials, despite providing satisfactory cathodic protection, in areas of DC interference it can worsen the corrosion effects when AC stray currents are present. In addition to this high negative pipe to soil potentials will increase the rate of accumulation of hydroxyl ions and the evolution of hydrogen in turn increasing the rate of wrapping disbondment. The result is an escalation of the deterioration process with the wrapping eventually disbonding over the entire section of pipe receiving the continuously increasing cathodic protection current.

The Transnet Pipeline network which includes the recently installed 24 inch multi-products pipeline is shown in figure-4.11:
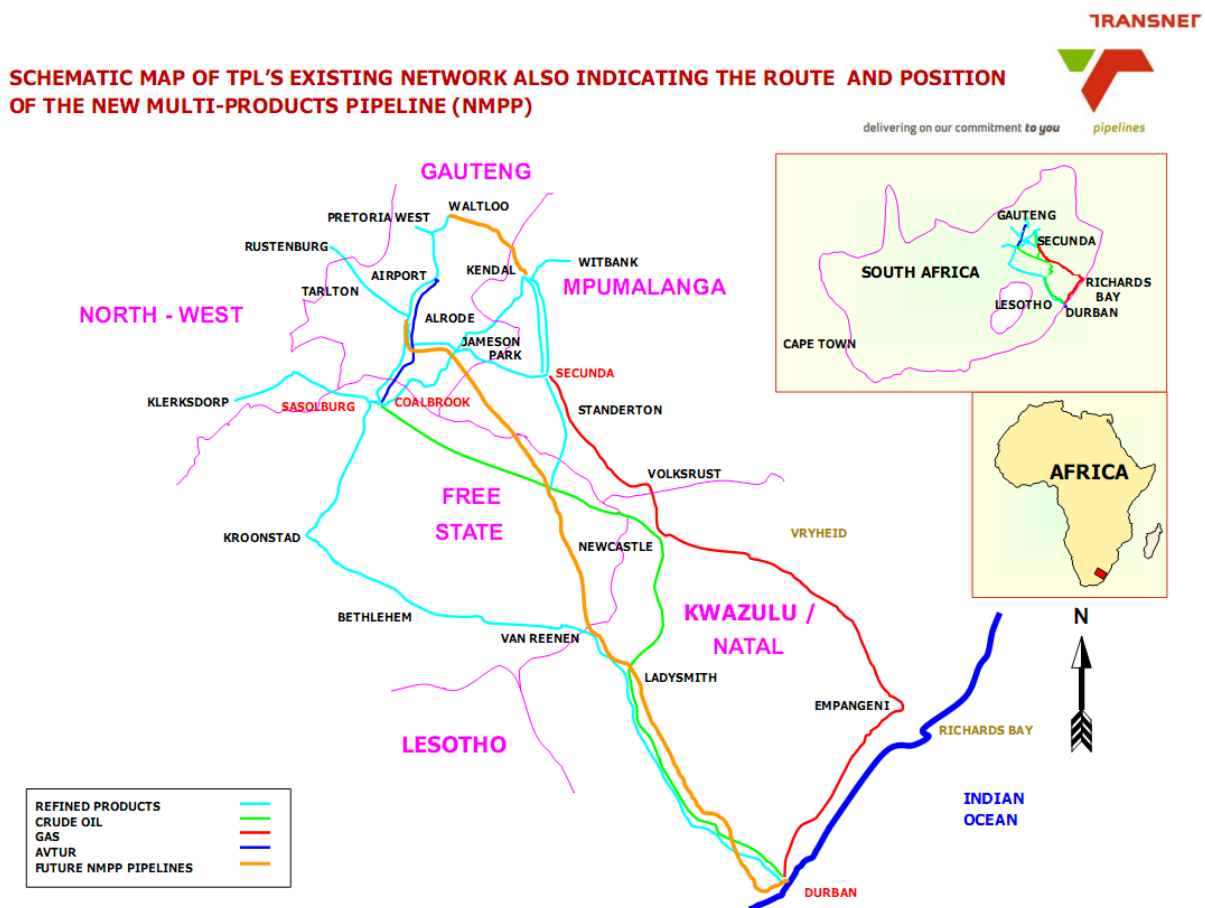
Figure-4.11   Major Pipeline Routes of South Africa Operated by Transnet Pipelines [47].

The pipeline layout shows that Transnet Pipelines operations spread over five of the eleven provinces of South Africa. All five provinces have 3kV DC traction networks and stray current problems are experienced in each province. To assist in managing the level of the cathodic protection applied to the various pipeline sections Transnet Pipelines use purpose developed pipeline monitoring recorders. The recorders are specifically designed and manufactured for Transnet Pipelines based on a specification compiled by Transnet cathodic protection specialists.

The recorders have five analogue input channels and two digital output channels for alarming purposes. The five analogue channels are assigned as follows:

- Channel 1: Pipe to reference cell (soil) potential
- Channel 2: Coupon to reference cell (soil) potential
- Channel 3: Rectifier output voltage
- Channel 4: Rectifier output amperes
- Channel 5: AC voltage

At rectifier sites recorders are built into the rectifiers and provide remote monitoring of these sites. At other sites portable recorders of the same specification are used when data is required either for routine maintenance or for an investigation triggered by a specific event such as suspected high stray current interference. Data from remote monitored sites are collected and stored on site for a period of 24 hours after which it is automatically transmitted each morning (06h30) to a server for review and relevant action by the respective cathodic protection field technicians. In addition to the daily reports, which are date and time stamped and have the respective site identification, a monthly report is generated showing any rectifier power outages together with date and time power was lost and restored, total hours out of service, the total kWh consumed for the month, the total number of times the tamper alarm was triggered together with the date and time of trigger and reset of the tamper alarm. User interface is through a keypad and liquid crystal display. Pre-allocated levels of authority ensure data security while providing restricted access for setup and adjustment as applicable.

Figure-4.12 shows an actual pipe to soil potential recording of a section of pipeline residing in the influence zone of stray current. The 3kV DC traction system is a possible source of the stray current but this was not confirmed and will require further investigation and testing to

confirm the source of interference. The graph clearly shows how the pipe potential swings between being cathodic and anodic under influence of the dynamic stray current a situation typical under the influence of DC traction stray current. The four highest positive potentials occur at approximately 14h00, 17h30, 01h15 and 06h00 respectively. One would expect a train to have been in close proximity to this location at this time but enquiries to establish this was not successful and will need to be validated with more recent recordings.
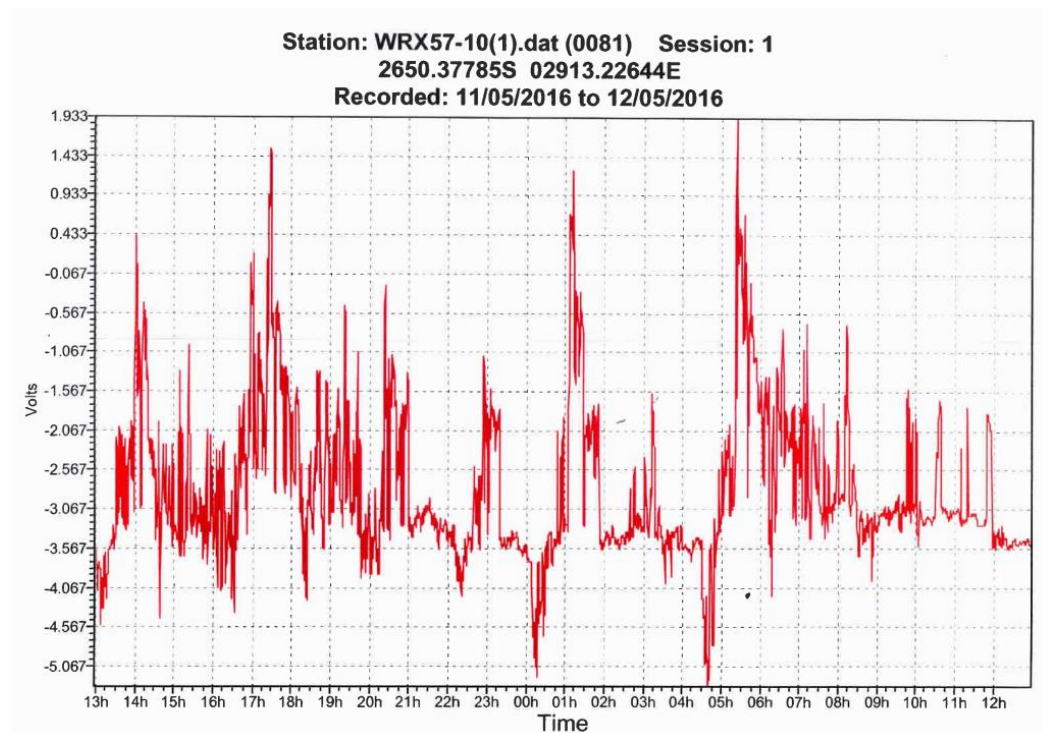
Figure-4.12   Pipe to Soil "ON" Potential on a section of Pipeline [48].

Although the anodic potentials do not exist for very long periods they are a concern as it is possible that this may be a regular occurrence. Assuming the stray current density on the pipe surface to be high as would be the case with a small coating defect the metal loss associated with this current will be concentrated to a small area. This implies that the pipeline wall is being corroded away at a specific location and the risk of a leak at this location is increasing with time. Although the actual "OFF" potential will be somewhat less than the "ON" potentials reflected in the graph, the possibility exists that high negative pipe to soil potentials exist. Increasing the negative potentials above the desired –0,85 volts CSE pipe to soil potential to combat the influence of stray current is standard practice within the cathodic protection industry. As previously discussed high negative potentials increases the risk of pipeline coating damage and AC corrosion. It is therefore recommended that the source of the

stray current be identified and alternative mitigation measures be implemented preferably by reducing the stray current at the source.

Figure-4.13 shows a section of pipeline that was recently surveyed using the DCVG method of surveying to identify pipeline wrapping defects. The results from the survey identified the location as a defect location, then to confirm the result the pipeline was exposed and the result confirmed as shown in figure-4.13. The wrapping disbondment is clearly visible and the pipe wall is seen to be in good condition proving that the cathodic protection was performing as desired at this location and most important that no significant cathodic protection current shielding is evident as a result of the disbondment. No noticeable calcareous deposit is present further indicating satisfactory cathodic protection at this location.

Figure-4.13   Coating Disbondment on a Petroleum Pipeline [48].

This pipeline was commissioned in 1965 so the wrapping has been in service for 51 years. The absence of calcareous deposit suggests that the most likely cause for the disbondment is aging of the coal tar enamel coating and not high negative cathodic protection potentials. The same survey did reveal locations where calcareous deposit was found around the pipe wall as previously shown in figure-2.5.

4.8   In-Line Inspection

To manage pipeline integrity and maintain legal compliance pipeline operators invariably have an on- going integrity programme. Included in this integrity programme it is common to

find an in-line inspection programme which makes use of technology where an inspection tool known as an intelligent pig is inserted in the pipeline and driven through the pipeline by the product. A number of different pigging technologies are available with the two primary tools being the Magnetic Flux Leakage (MFL) and the Ultrasonic Tools (UT) [49].

Figure-4.14 shows a typical magnetic flux leakage inspection tool or intelligent pig as it is commonly referred to in the pipeline industry. The pig is launched into the pipeline from a special section of pipe known as the launcher.

Figure-4.14   Magnetic Flux Leakage In Line Inspection Tool [50].

Figure-4.15 shows a pig being launched through the launcher door. Once launched product is routed behind the pig so as to push it into the pipeline to be inspected. Product drives the pig through the pipeline to the next pump station where it is retrieved, data down loaded and batteries changed before being launched again to continuing its journey to complete the next scheduled pipeline inspection.

Figure-4.15   Launching of a Magnetic Flux Leakage In Line Inspection Tool [48].

Any inspection tool has its limitations and data interpretation is not always accurate so periodic validation of the data and its interpretation is required. Once the data is collected it is downloaded from the inspection tool and interpreted by subject professionals to deliver results understandable to the field technician for validation and appropriate remedial action. Validation of data is done by selecting samples of data of the most severe defects and exposing the pipeline at the specific locations. The actual defects are then compared to the severity status indicated by the data collected. Once a predetermined number of samples over a predetermined length of pipeline prove valid the inspection tool data for the specific run is accepted as having delivered valid data. Once data is validated defects are scheduled for repair according to the severity of the defects. All defects and repairs are recorded and archived for reference and compliance purposes. Although in-line inspection tools are primarily used to determine the condition of a pipeline wall and the extent of metal loss any opportunity of having an open section of pipeline is also used to verify the condition of the pipeline coating and the effectiveness of the cathodic protection system.

Figure-4.16 shows a data plot referred to as a "C-scan" derived from the data of a MFL intelligent pig used on a local pipeline. As this type of data is of a sensitive nature the exact location may not be identified in this dissertation.
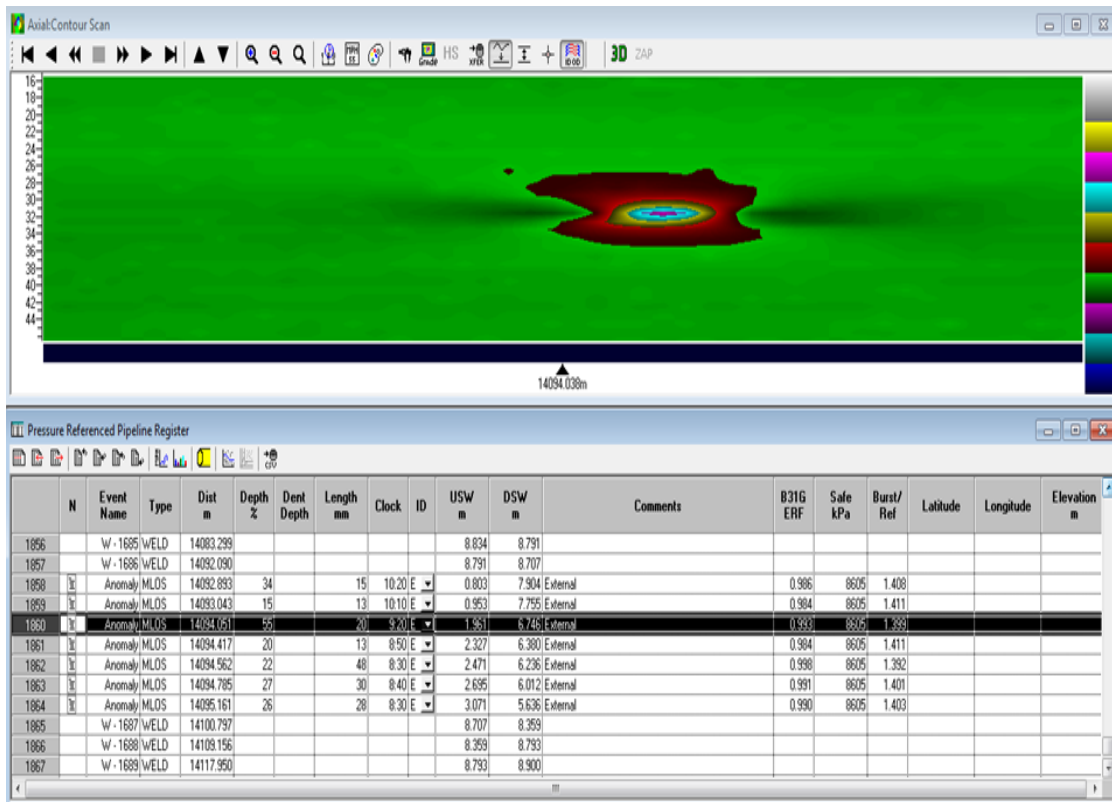

Figure-4.16   Magnetic Flux Leakage Plot [48].

The coloums are identified in table 4.1. The data when correctly interpreted is useful to locate and gauge the extent of metal loss defects within a pipeline wall. The green layer represents the pipeline nominal wall thickness in one a dimensional plot, meaning the pipe is cut longitudinally and pressed to form a flat plate. The location of the defect around the perimeter of the pipe is identified from the table in the column labelled clock. Looking in the direction of flow, 12 O' clock is the most upper edge of the pipe perimeter with the clock rotating in the normal or clockwise direction. Longitudinal distance to a defect is measured from reference points preselected by the pigging team and transmitted to the moving pig from a device placed above the pipe at ground level prior to the pig arriving at the specific location. In the "C-scan", figure-4.16, the defect is represented by the multi-colour patch on the pipe wall shown in green. The colours represent the percentage of metal loss and the colour bar on the right shows the severity represented by the different colours. To compliment this data a second plot as shown in figure-4.17 and referred to as the dig information sheet is derived. The dig information sheet shows the physical location of a defect. The digging team will use this sheet to expose the pipe at the respective defect so that it may be repaired or be further inspected for an appropriate decision on any necessary action to be taken.
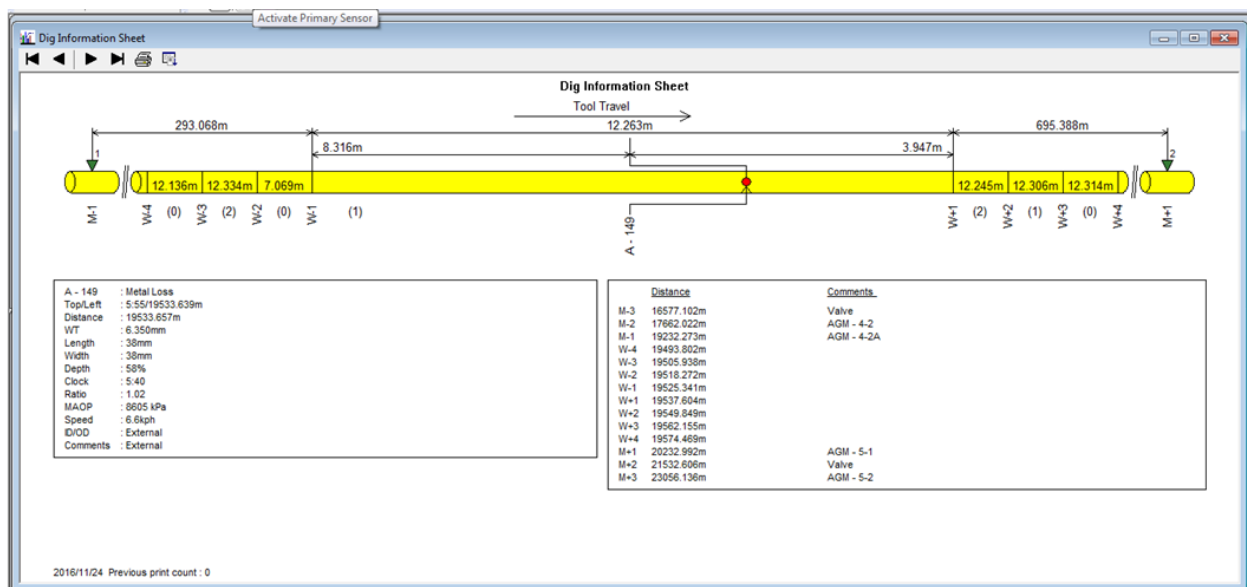
Figure-4.17   Dig Information Sheet for a Local Pipeline [48].

The pig dig information sheet is derived from the pigging data and Above Ground Markers (AGMs). AGMs are portable devices that are placed on the ground at pre-determined intervals directly above the pipe along the route to be pigged. The pig will pick up a signal from the AGM marking its location in the recorded pigging data sheet as indicated by the green arrows

at each end of the pipeline shown in figure-4.17. From the AGM reference points, distances are recorded to the welds joining the different pipe sections. The location of a recorded pipe defect is identified from either the closest Upstream Weld (USW) or the closest Downstream Weld (DSW) within a pipe length as shown by the red dot in figure-4.17.

Table 4.1 Magnetic Flux Leakage Plot Coloum Identification Table

	Coloum	Purpose
1	N	Dig sheet notes editor. Information inserted here will appear on the dig information sheet.
2	Event name	Description of the event, example Weld, Spool Number, Anomaly etc.
3	Type	States the type of event eg. Weld, Metal loss or Fitting
4	Dist	Distance from the Launcher at the Up- stream Pump Station.
5	Length	Length of the anomaly
6	Clock	The orientation of the Anomaly looking down the pipe spool in the flow direction.
7	ID	Identify the anomaly, Internal or External
8	USW	Distance to the anomaly from the up-stream weld on the effected pipe spool.
9	DSW	Distance to the anomaly from the down-stream weld on the effected pipe spool.
10	Comments	Any relevant information related to the feature listed in that row
11	B31G ERF	Estimated Repair Factor based on the B31 Specification (.> as 1 effected the operating pressure)
12	Safe kPa	Maximum operating pressure the anomaly will safely withstand
13	Burst ref	Burst pressure/reference pressure ratio entered on the pressure referenced anomaly assessment dialog

4.9   Cathodic Protection

The most widely used cathodic protection system for buried structures such as pipelines is Impressed Current Cathodic Protection (ICCP). This method of cathodic protection allows long lengths of pipeline to be protected with a single rectifier and associated anode bed the length being dependant on the pipeline coating condition, soil resistivity and maximum negative pipe to soil potential. The criteria for maximum negative potential is generally an "off" potential of -1,1 volts CSE pipe to soil [16] but SANS 15589-1:2009 [24] sets the limit

at -1,2 volt CSE pipe to soil. ICCP has the advantage that output voltage and current can be made variable allowing user adjustment to suit varying soil and pipeline coating conditions.

The cathodic protection system consists of various elements making up the cathodic protection system each carefully selected and engineered to provide a reliable and effective protection system to mitigate electrolytic corrosion. The primary components are the Transformer Rectifiers Unit (TRU), the associated anode bed and the associated test posts. The anode bed is a critical component of the ICCP system, being the component that will normally determine the life of the ICCP installation. The anode bed is installed at a depth of between 2 to 3 metres at some remote distance so that the areas of influence of both the pipe and the anode bed are well separated. A well located anode bed is necessary to assist in creating an even spread of the cathodic protection current. Figure-4.18 shows a typical anode bed installation. The installation shown is equipped with a perforated PVC pipe for watering to keep the soil moist around the anode during dry seasons. This is necessary to maintain a low anode to earth contact resistance. High soil resistivity will restrict the performance of the anode bed negatively influencing the cathodic protection on the pipeline to be protected.
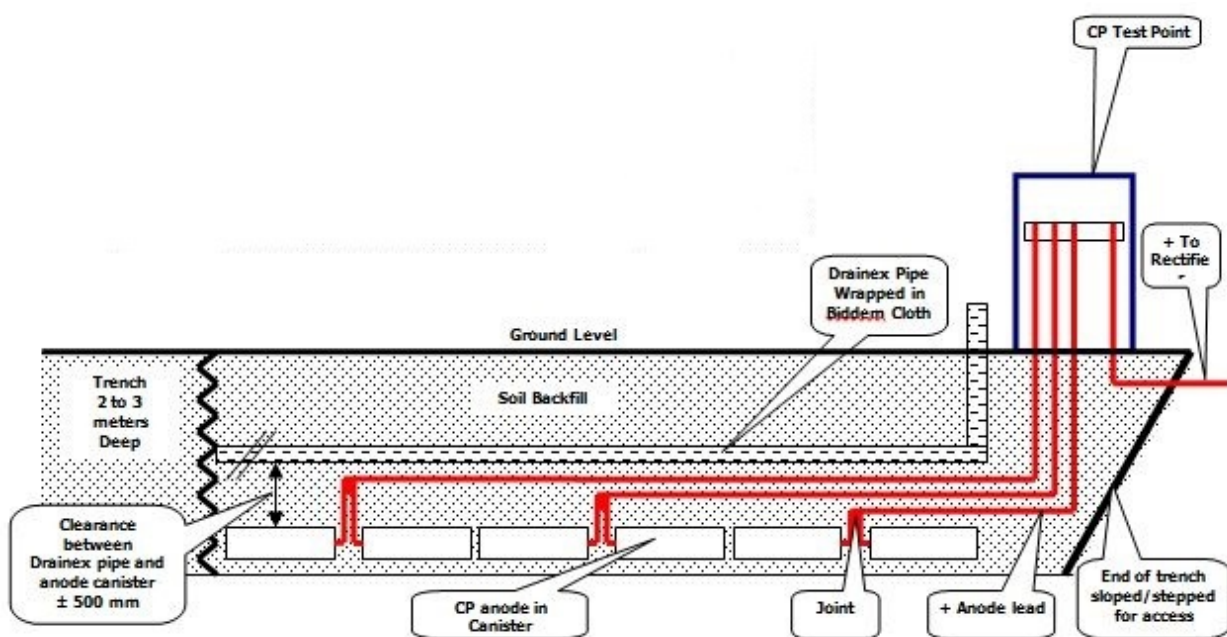

Figure-4.18   Anode Bed Installation [48].

As shown in figure-4.18 the anode bed consists of a number of anode canisters. The anode canisters are connected in pairs to an insulated lead which in turn is terminated in a test post. This methodology facilitates testing of any pair of anode canisters individually. Not shown in

figure-4.18 is the specially developed carbon backfill that is normally used around the anode to increase the outer surface area and improve soil to anode conductivity. The carbon backfill extends the electronic current path from the relatively small anode surface area into the carbon. Charge transportation changes from electronic to ionic at the surface of the carbon backfill which is much greater than the anode surface area increasing the life expectancy of the anode bed [15]. A second current path, the ionic current path exists due to water pores at the surface of the anode. In this case the electrochemical reaction, the change from electronic to ionic occurs at the relatively small anode surface and if not limited will reduce the life of the life expectancy of the anode bed. From the discussion it is clear that proper installation and tight carbon backfilling around the entire surface of the anode canisters is critical in ensuring good performance and life expectancy.

Figure-4.19 shows how the performance of an anode bed is affected by seasonal changes.
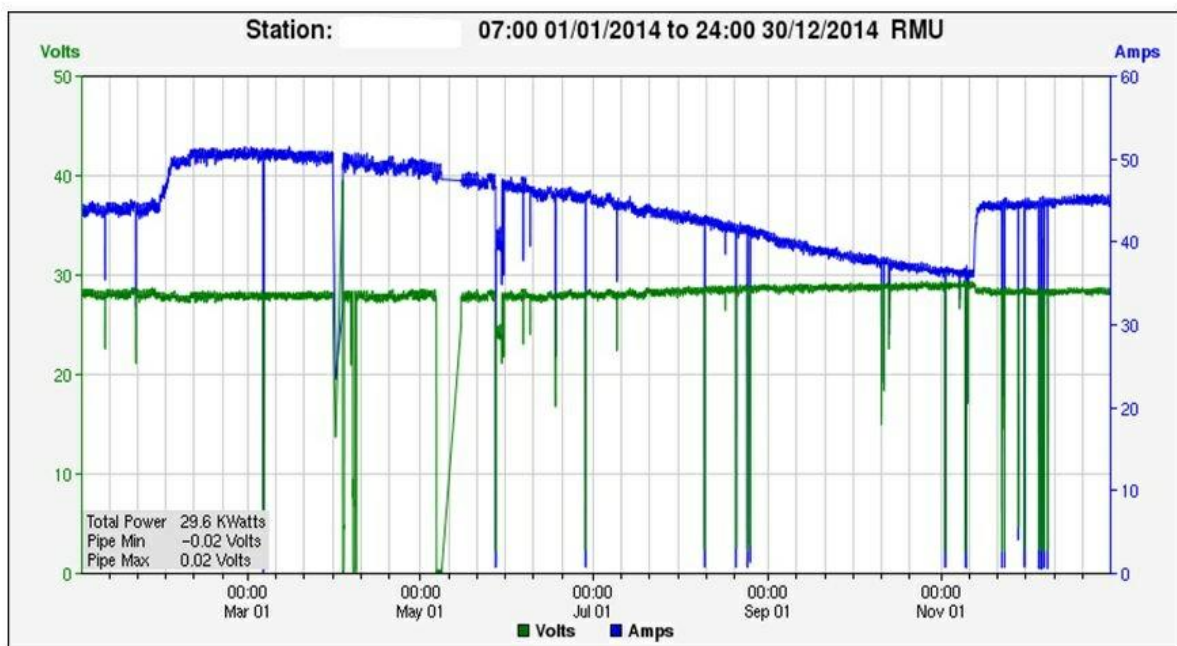
Figure-4.19   Anode Bed Performance Monitoring Plot [48].

The sharp dips in voltage and current are from interaction with the recorder by the field technician. With a constant voltage being maintained on the anode the blue line shows how the current output from the anode decays as the soil dries out during the dry season. Transition into the wet season or watering the anode bed will improve the performance as shown in the graph to the right of month November. Two options are possible to maintain an acceptable output current from the anode bed. The first and preferable option is to monitor the

output of the anode bed and to water it at intervals as necessary to maintain an acceptable level of protection on the pipeline being protected. The second option is to increase the driving voltage from the rectifier but this option is not preferred for public safety and reasons previously discussed. Another problem that can occur if an anode bed is left dry for a prolonged period is that the driving voltage will increase due to the lower current and resultant volt-drop through the ground causing chlorine gas to form on the surface of the anodes. When the anode bed becomes moist again there will be a gas block within the anode bed and the current output will not return to normal requiring extensive remedial work. Based on the graph data no serious stray current interference is noticeable at this location.

4.10 Conclusion

It has been identified that the floating traction system of South Africa is deliberately being grounded due to maintenance and repair malpractice. In some instances bare railway line buried directly into the ground is used as the main negative return conductor back to the traction substation. Poorly terminated and insufficient negative return conductors are all evidence of a poorly maintained traction system demonstrating a lack of consideration being given to the damaging effects of stray current.

Evidence shows that Transnet Pipelines applies state of the art technology to ensure a well maintained pipeline network. Pipeline integrity management is an in-house function staffed by professionals in the field of pipeline maintenance, repair and management. Internal inspection of the pipelines are cyclic program based and to ensure availability and access to the most advanced technologies available at the time this work is contracted out but performed under supervision of in-house professionals.

Future work recommended is research into using waveform analysis to determine the nature of stray current and assist in quickly locating the source of the stray current.

Chapter 5

Conclusions and Recommendations

5.1   Introduction

This chapter serves to summarise the stray current situation as experienced by Transnet Pipelines a major petroleum pipeline operator in South Africa. It has been identified that the South African electrified rail traction network consists of three different voltages. Two systems are alternating current operating at 25kV and 50 kV respectively. The third and most widely used system is the traditional 3kV DC system. The information presented in this dissertation primarily relates to the 3kV DC traction network. It is the traction network responsible for extensive stray current distribution and influence on buried pipelines. Stray current from other sources such as cathodic protection systems from other pipeline operators and industry in urban areas are occasionally encountered and although not part of the focus of this dissertation much of what is discussed may be applicable to such cases.

5.2   3kV DC Traction Civil Works

It has been shown that the traction system contains three primary disciplines, the civil, the signalling and the electrical component. The civil and the electrical disciplines are the primary disciplines responsible for determining acceptable criteria for stray current leakage and for maintaining the system within the agreed limits. Site visits to various locations both urban and mainline have shown that the civil component is generally well maintained with evidence of ballast stone bedding receiving regular maintenance. All rail fasteners inspected were found to be in good condition, rail foot pads has been used and found to be in good serviceable condition. Pandrol rail clamps with appropriate insulation is widely used and was found to be in good condition. During the inspection it was raining and drainage appeared to be functioning satisfactorily with no signs of water logging noticeable. Overall the conclusion is that civil works is performing as one would expect from a floating rail installation.

5.3   3kV DC Traction Electrification

Traction electrification can be split into two sections, the overhead traction equipment and the negative return circuit. Both sections are equally important as they both carry the same load current and together complete the traction electrical circuit from rectifier positive through the load returning through the track back to the rectifier negative pole. Generally the overhead or

positive side is well maintained as it is generally perceived to be the most important part. Often the consequence of a poorly maintained negative return circuit is overlooked as evidence from a recent inspection shows. The reason for this may be because damage is primarily related to stray current in the form of electrolytic corrosion which is not always properly understood by maintenance teams. Some rail mast construction sections are showing signs of neglect, mast bases are severely corroded and mast base insulation is soiled with debris. Evidence shows railway track buried directly in soil used as the negative return conductor back to the traction substation. It is understandable that the current practice is in desperation to maintain the train service threatened by cable theft but it defeats the entire reason for having a floating negative return system. This action short-circuits the floating traction system to the general earth mass and shows absolute disregard or a lack of knowledge for implementing a floating earth system. It is recommended that alternative methods of installing an insulated negative return conductor be investigated so that the floating system may be returned to its original design intent and specification. By restoring traction floating system rail to earth insulation quality to its original design specification it is reasonable to assume that stray current will be significantly reduced. Consequently high negative pipe potentials can be reduced together with the risk of damaging pipeline coatings and accelerating AC corrosion due to high alkalinity around the exterior surface of the pipeline.

Further evidence shows bonding between traction return rails and the main negative return conductor (rail) to be bare copper lying un-insulated on the track bedding ballast stone. In another instance negative return bonds were found to consist of short pieces of copper wire joined together using lugs clamped together with nuts and bolts. The number of bonds used was not consistent, in some cases two bonding conductors were being used while on a different track fed from the same traction substation three bonds were being used. Some spark gaps showed evidence of no maintenance for an extended period of time. On another track the negative return consisted of two negative return bonds fixed to the negative rail using lugs placed one on top of the other. It was noticed that the lugs in this case was not sitting on flat faces with one lug sitting on shoulder of the other a clear sign of poor workmanship. It is not known if the malpractice is restricted to specific sections and regions so further work will need to done to confirm this. From general observation the mainline rail network maintained by Transnet freight appears to be in a better condition with evidence that large sections had undergone recent upgrading. Information obtained from field technicians however claim that Transnet freight rail also have areas where bare railway track is being used as the negative

return conductor to its traction substation but this is still to be confirmed. It is recommended that the practice of using un-insulated conductor (railway track) as alternative to the main negative return conductor be investigated, analysed and quantified. This will allow the compilation of cost based data to be presented at corrosion committees.

Most areas of concern on the traction negative return circuit inspected was visually noticeable and required minimum skill and cost to restore to its original condition so that the floating system can be restored. Understandably the negative return rails used as an alternative to the main negative return conductor presents a challenge that needs to be engineered requiring some engineering skill. A suggestion could be to construct concrete trenches beneath the railway traction lines and lay the negative return rails on insulators back to the traction substation. Another alternative could be to revert back to insulated negative return cable fully encasing the cable in concrete to deter cable theft. Other commercially available solutions are available and have been used by various supply authorities to deter cable theft to varying degrees of success. It is recommended that a solution be chosen based on engineering fundamentals having all resistances and insulation levels calculated confirmed and documented. To confirm the integrity of visually compliant negative return circuits DCVG and CIP surveys may be performed to identify non-visual problem areas such as faulty spark gaps and poorly insulated rail sections [30]. Training focussed on the technical deficiencies identified is also recommended to improve the current situation.

5.4   3kV DC Traction Signalling

As expected it was confirmed that one rail is sometimes being used for signalling purposes. The signalling equipment seen appear to be in satisfactory condition. Cables are satisfactorily insulated and connections appear to be professional terminated. No further recommendation is made in this regard.

5.5   Collective Corrosion Management

Pipelines traverse over large distances and cross many property boundaries, rural and urban and for this reason good pipeline management is a collective co-operative management function. Maintenance of buried pipelines primarily consists of keeping pipeline corrosion to within industry acceptable limits. The primary protection against corrosion of buried pipelines, the coating is generally of a very high quality providing excellent corrosion protection. The secondary protection, cathodic protection has proved to be very successful

and economical in providing the necessary back-up corrosion protection method for small defects that may exist or occur in pipeline coatings. This is especially true for corrosion of pipelines in environments free of dynamic stray current. Challenges arise when the environment in which a pipeline is laid is plagued with dynamic stray current. The challenge is often intensified by industry members having limited knowledge of the damage possible by what may be perceived as insignificant levels of stray current. Good pipeline coatings generally imply that stray current has the potential of creating areas of high current density on a pipeline. The current density determines the rate of severity of corrosion and this is a fundamental criteria that needs to be well understood by all industry members both stray current producers and victims of stray current corrosion.

Pipeline corrosion protection in South Africa is managed on a three tier structure. The first tier is the pipeline operator who is ultimately responsible and accountable for the pipeline being operated. It is the duty of the pipeline operator to maintain the pipeline in a safe operational condition and to maintain evidence of employing world best practice in doing so. Transnet Pipelines meets these requirements by having a pipeline integrity department committed to ensuring compliance to legislation and remaining abreast of latest developments in the pipeline integrity environment. The second tier is the establishment of a local or regional corrosion committee made up of representatives from any sector of the community or industry affected by corrosion related influences within the regional boundaries of the respective committee. The regional committee generally meets on a quarterly term sharing areas of concern, recommending solutions and giving feedback on previously identified and agreed solutions for implementation. The third tier is the national corrosion committee made up of representatives from each of the local corrosion committees and relevant interested authorities. This tier generally looks at the larger "picture". Matters escalated from the regional committees are presented for discussion and recommendation. The first and third tier currently function well and with evidence that its objectives are being met. The second tier, the establishment and maintenance of a regional cathodic protection committee has suffered a setback possibly due to the retirement of a number of key members. Enquiry into its functioning delivered no confirmation that this committee still meets on a regular basis or even exists and most certainly will require reinstatement and motivation. Effective functioning of the second tier could lead to regional matters remaining unresolved for extended periods of time with the risk of corrosion being mitigated by desperate means such as high negative voltages in an attempt to suppress stray current interference. It is well

understood and documented that stray current is best mitigated at the source and for this reason stray current criteria need to be documented. Recommended practice would be to have an agreement between owners of affected industries clearly stating acceptable stray current criteria and response times for rectifying any deviations reported. This has been successfully done in the Netherlands and demonstrates a workable solution through mutual co-operation [30]. Agreements should be documented for future reference and discussion as applicable. Regular or preferably real time monitoring and prompt action to all deviations will assist in ensuring criteria is maintained and respected.
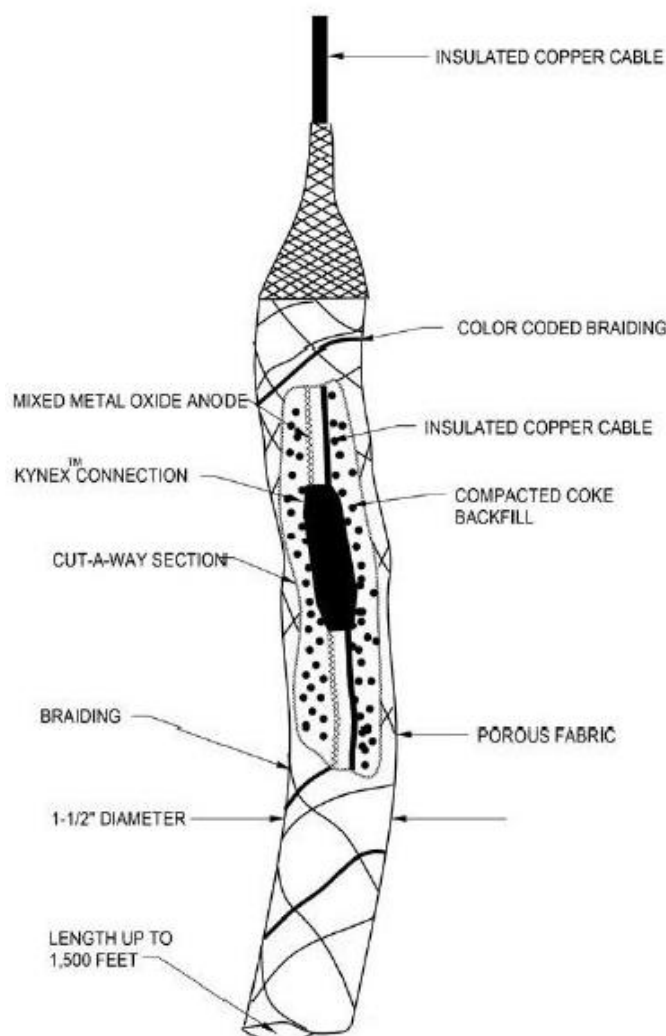
5.6   Cathodic Protection Rectifiers

The majority of Transnet Pipelines cathodic protection system consists of impressed current cathodic protection. Rectifiers are installed at regular intervals along the pipeline routes and are frequently upgraded. Recent upgrades include housing of rectifiers in heavily reinforced concrete enclosures as protection against vandalism and copper theft. Upgraded rectifiers have remote monitoring systems that allow rectifier outputs to be continuously monitored and recorded. Tamper monitoring is included in the monitoring system providing a record of all visits both official and unofficial. A recommendation would be to investigate automatically controlled rectifiers capable of being programmed to respond to changing environmental conditions as they occur. Response criteria should include monitoring for AC interference as high negative voltages to mitigate high levels of stray currents could create a situation of mitigating one problem at the expense of another.

5.7   Corrosion Protection of Older Pipelines

It has been discussed in this dissertation that pipelines exist in South Africa that has been operating in excess of 50 years. A recent DCVG survey provided evidence of severe coating disbondment of such a pipeline and further evidence showed high alkalinity deposits in the environment surrounding the pipe surface. The alkalinity is as result of higher influx than diffusion out of the area of hydroxyl ions caused by high negative cathodic protection potentials. If it was possible to eliminate high peaks of negative potentials and evenly spread the cathodic protection along the length of the pipeline a reduction in the concentration of hydroxyl ions can be expected. One reason for the high negative peaks is due to the large distances between rectifiers that were originally designed for a well coated pipeline requiring low levels of cathodic protection current. As the pipe coating ages and the coating progressively fail the demand for cathodic protection current grows to maintain protection

within the set criteria. The demand for more current is associated with increased rectifier output potentials and consequently higher negative peaks along the distribution area of a specific anode bed assuming homogenous soil resistivity.

Linear anodes are offering an alternative to traditional anode beds. Linear anodes are flexible anodes that can be installed in a narrow trench in close proximity to a pipeline. Figure-5.1 shows the construction of a typical linear anode. The anodes are constructed ready for installation in standard lengths of 500 metres but can be spliced on site to any specific lengths that may be required [51].

Figure-5.1   Construction of a Typical Linear Anode [51].

The linear anode forms part of an impressed current cathodic protection system with smaller rectifiers more frequently installed along the length of the pipeline to be protected.

Advantages of linear anodes includes:

- Evenly distributed cathodic protection current at lower current densities
- Can be installed within an existing pipeline servitude
- Requires a narrow trench for installation saving on land
- Machine installation is possible making installation relatively quick to install
- Land outside of servitudes for remote anode beds are no longer necessary
- Minimises the possibility of stray current interference on other services

Disadvantages of linear anodes includes:

- Rectifiers are more frequently required along the length of the pipeline
- Supply points to rectifiers may present various challenges

It is recommended that the application of linear anodes to extend the life of older pipelines with severe coating defects be investigated and modelled. Modelling will provide the opportunity to technically compare the traditional ICCP system to the linear anode ICCP allowing an informed decision to be made on its application.

5.8   Modelling

Transnet Pipelines pipeline integrity team do not use in-house modelling tools as research and development has never been included in the integrity management programme. Modelling is a useful tool offering financial benefit in terms of time, cost and choice of the most appropriate and cost effective technical solution to implement. In addition modelling provides reference values for measurement of installed systems [30]. Results of past and recent pipeline integrity surveys show evidence that the pipelines under the management of Transnet Pipelines are well managed and generally in good condition. The DJP pipeline has been in operation for over 50 years with an extremely low incident count. A recent survey has shown that the primary corrosion protection, the coating is showing signs of extensive coating disbondment. Should it be decided to maintain the service of the DJP it is recommended that consideration be given to the cathodic protection on this pipeline in view of it being the primary corrosion protection. Modelling could be a useful tool to explore various technical solutions in terms of technical soundness and cost effectiveness.

5.9   Real Time Monitoring

Localised real time recording of ICCP rectifiers and associated test points is been used by Transnet Pipelines with data made available to field technicians at 24 hour intervals. Recordings provide evidence of concerns for discussion at the electrolytic committees and strengthen the case for scheduled relevant action. It is recommended that this application of recorders be extended to include all test points so that data over the entire system can be captured on a continuous basis. This will allow a full date and time stamped picture to be developed of dynamic stray current movement across the entire system. Further recommendation would be to investigate the feasibility and advantages of real time monitoring.

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