بسم الله الرحمن الرحيم

Sudan University of Sciences & Technology

College of Petroleum Engineering & Mining

Department of petroleum transportation and refining engineering

Project Title:

Modeling of impressed current cathodic protection system using matlab simulink

Case study (12"pipeline connecting ALrawyan (Elgaily) area with Madani strategic storage Tanks)

نمذجة منظومة حماية كاثودية بالتيار القسري بإستخدام برنامج الماتلاب سيميولنك

Graduation project submitted to college of petroleum engineering & mining in Sudan University of Science &technology for partial fulfillment of the requirements for the degree of Bachelor

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قال تعالى:

سُورَةُ النَّمْلِ

فَتَبَسَّمَ ضَاحِكًا مِّن قَوْلِهَا وَقَالَ رَبِّ أَوْزِعْنِي أَنْ أَشْكُرَ نِعْمَتَكَ الَّتِي أَنْعَمْتَ عَلَيَّ وَعَلَى وَالِدَيَّ وَأَنْ أَعْمَلَ صَٰلِحًا تَرْضَىٰهُ وَأَدْخِلْنِي بِرَحْمَتِكَ فِي عِبَادِكَ الصَّٰلِحِينَ ﴿١٩﴾

صدق الله العظيم

Dedication

With much love and respect, this study dedicated to our loving parents and kind brothers and sisters who have supported us in our life to this day, our teachers and friends and all those who helped us by one way or another in our long educational journey, and to everyone who could not complete his educational journey against his will. We wish you happiness and may God bless you and give you what you want

Acknowledgements

Abstract

In the modern age of Industrial world, the oil refineries, petroleum products, and petrochemicals form the major part of the industrial set-up all over the world. It is often economical and practical to carry the liquid and gaseous products through pipelines rather than by tankers over long distance. Passing through land, rivers, sea, mountains, crossing other services like roads, railways, transmission lines, underground Pipes/Cables etc. The structures of the pipelines are designed to withstand several environmental loading conditions to ensure safe and reliable distribution from point of production to the shore or distribution depot. This pipelines passing through soils which can be considered as corrosive environment; therefore it suffers from underground corrosion.

In this research, an impressed current cathodic protection system was modeled using Matlab Simulink for two stations with the same design data but different soil resistivity to calculate the required protection current, the number of anodes and the rectifier voltage.

The results show that the station that has lower soil resistivity needs a larger amount of current required for protection than the station that has high soil resistivity.

التجريد

في العصر الحديث للعالم الصناعي ، تشكل مصافي النفط والمنتجات البترولية والبتروكيماويات الجزء الأكبر من البنية الصناعي في جميع أنحاء العالم. غالبًا ما يكون نقل المنتجات السائلة والغازية لمسافات الطويلة عبر خطوط الأنابيب أفضل من الناحية العملية والإقتصادية من الناقلات . تمر هذه الأنابيب عبر البر والأنهار والبحار والجبال وتتقاطع مع الخدمات الأخرى مثل الطرق والسكك الحديدية وخطوط النقل ,و الأنابيب / الكابلات تحت الأرض وما إلى ذلك. لذلك تم تصميم هياكل خطوط الأنابيب لتتحمل مجموعة متنوعة من ظروف التحميل البيئية لضمان التوزيع الآمن والموثوق من نقطة الإنتاج إلى ميناء التصدير أو مستودع التوزيع. ولكن هذه الأنابيب التي تمر عبر التربة والتي يمكن إعتبارها بيئة مسببة للتآكل تعاني من تآكل تحت الأرض.

في هذا البحث تم نمذجة نظام حماية كاثودية بالتيار القسري باستخدام الماتلاب سيميولنك لمحطتين بنفس بيانات التصميم ولكن بمقاومة تربة مختلفة لحساب تيار الحماية المطلوب وعدد الأنودات والجهد .

أظهرت النتائج أن المحطة ذات مقاومة التربة المنخفضة تحتاج إلى تيار حماية أكثر من المحطة ذات مقاومة التربة العالية .

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CP	Cathodic Protection
DC	Direct Current
AC	Alternative current
pH	Potential of Hydrogen
3LPE	Three Layer Poly Ethylene
3LPP	Three Layer Poly Propylene
ICCP	Impressed Current Cathodic Protection
HSCI	High Silicon Cast Iron
MMO	Mixed Metal Oxide
NACE	National Association of Corrosion Engineers
SPPC	Sudanese Petroleum Pipelines Company
SPE	Sudanese Petroleum Corporation
MOP	Ministry Of Petroleum
CPS	Cathodic Protection Station
CSE	Copper Sulfate Electrode

Chapter 1

Introduction

1.1 Introduction:

Cathodic protection (CP) is one of the few methods that successfully mitigate corrosion. It can be applied in any situation where the environment surrounding the metal acts as a conductor for electric current. It has been successfully applied to offshore structures, ships, pipelines, storage tanks, piers, bridges, instrumentation etc.

The primary method of preventing or mitigating external corrosion on buried pipelines involves a combination of CP and coatings.

CP is a method to reduce corrosion by minimizing the difference in potential between anode and cathode (Mil-HDBK, April 1985). This is achieved by applying a current to the structure to be protected from some outside source. When enough current is applied, the whole structure will be at one potential and thus anode and cathode sites will not exist.

CP has two forms of mechanisms, the first mechanism is the sacrificial anode CP, and the second mechanism is the impressed current CP, The two forms differ in the source of current and type or operation of the anode. In both techniques of CP, the current flows from the auxiliary anode through the soil to structure to be protected, where this current flow onto a structure from the surrounding electrolyte (soil or seawater), the potential of the structure is made more negative (Samoudi, 2015).

Coating function is to separate the structure from the electrolyte, and thus prevent corrosion. The application of CP alone to protect against corrosion would not be practical because the amount of current required is proportional to the area to be protected, and it would be too expensive to cathodically protect a long, bare pipeline. Therefore coatings are needed to reduce the amount of exposed area as much as possible.

Coating alone would not be totally effective because it is impossible to produce a perfect coating over an entire pipeline. As well some damage during construction and degradation over time are inevitable. Therefore CP is needed to prevent corrosion at the breaks (holidays) in the coating.

If a portion of the structure does not receive current, the normal corrosion activity will continue at that point. If any of CP current picked up by the structure leaves that structure to flow back into the electrolyte, corrosion will be accelerated at the location where the current is discharged (Samoudi, 2015).

The need of CP can be summarized in the following points (Samoudi, 2015):

- 3% to 5% of Gross National Products (GNP) is attributed to corrosion damage
- USA spend about $300 Billion per year due to corrosion
- CP saved about one third of the money that spent on corrosion

1.2 Problem statement:

Corrosion in buried pipelines is a major challenge and causes several economical, technical and environmental problems such as product loss due to leakage, the cost of replacing corroded pipes, frequent shut down, products contamination, polluting water sources and killing plants etc... In addition to social effects such as injuries to workers which can lead to death in some cases.

Good line protection ensures safe line operation, reduces the possibility of corrosion, and reduces its severity if it occurs.

1.3 Research objectives:

The primary objective is to model a CP system using impressed current for buried pipeline to predict the number of anodes used and its operating voltages and currents under the pipe operation conditions to mitigate the phenomenon of external corrosion. And other objectives are:

1. Showing the effect of the soil resistivity change in the calculations of the requirements of the CP system.

1.4 Scope of work:

The study was carried out on a 12" buried pipeline with total length of 216.16 km connecting Alrawyan station at Khartoum to Madani storage terminal station at Madani city.

15 km of the pipeline was taken from Madani terminal station as a scope for the modeling calculations.

Chapter 2

Theoretical Background and Literature Review

2.1Historical background:

In 1824, Sir Humphry Davy presented a series of papers to the Royal Society in London, in which he described how zinc and iron anodes could be used to prevent the corrosion of copper sheathing on the wooden hulls of British naval vessels. His paper shows a considerable intuitive awareness of what are now accepted as the principles of CP. Several practical tests were made on vessels in harbor and on sea- going ships, including the effect of various current densities on the level of protection of the copper. Davy also considered the use of an impressed current device based on a battery, but did not consider the method to be practicable(Ashworth and Elsevier: New York, 2010).

The first 'full-hull' installation on a vessel in service was applied to the frigate HMS Semarang in 1824. Four groups of cast iron anodes were fitted, and virtually perfect protection of the copper was achieved. So effective was the system that the prevention of corrosion of the copper resulted in the loss of the copper ions required to act as a toxic for marine growth, leading to increased marine fouling of the hull. Since this led to some loss of performance from the vessel, interest in CP waned. The beneficial action of the copper ions in preventing fouling was judged to be more important than preventing deterioration of the sheathing. CP was therefore neglected for 100 years, after which it began to be used successfully by oil companies in the United States to protect underground pipelines(Ashworth and Elsevier: New York, 2010).

It is interesting that the first large-scale application of cathodic protection by Davy was directed at protecting copper rather than steel. It is also a measure of Davy's grasp of the topic that he was able to consider the use of two techniques of cathodic protection, namely sacrificial anodes and impressed current, and two types of sacrificial anode, namely zinc and cast iron(Ashworth and Elsevier: New York, 2010).

2.2 Corrosion:

Corrosion is the deterioration of metals from interaction with the environment and the corrosion of most engineering materials occurs in moist environments (containing water) and is electrochemical in nature. The aquatic environment is also referred to as electrolyte, in the case of underground corrosion it is moist soil .The corrosion process involves removing electrons (oxidation) from the metal and consuming these electrons through other reactions, such as oxygen or water reduction [Equations (2) and (3),respectively] (Peabody, 1971):

$$Fe \rightarrow Fe^{++} + 2e^{-} \tag{1}$$

$$O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-} \tag{2}$$

$$2H_2O + 2e^{-} \rightarrow H_2 + 2OH^{-} \tag{3}$$

The oxidation reaction is usually called the anode reaction and the reduction reaction is often called the cathode reaction, and these two reactions are necessary for the corrosion process .The oxidation reaction is the real reason for losing the metal, but the reduction reaction must be present to consume the electrons generated from the oxidation reaction to keep the charge even(Peabody, 1971).

Why do metals corrode?

Most metals are found in nature as ores. The manufacturing process of converting these ores into metals involves the input of energy. During the corrosion reaction the energy added in manufacturing is released, and the metal is returned to its oxide state.

$$Metal\ ore \xrightarrow{reduction\ (add\ electrones)} Metal \xrightarrow{oxidition\ (strip\ electrones)} Corrosion\ product$$
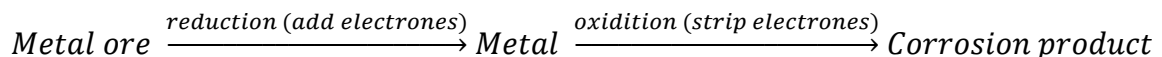
In the marine environment, the corrosion process generally takes place in aqueous solutions and is therefore electrochemical in nature (Roberge, 2006).

2.2.1 Corrosion cell:

For the corrosion reaction to occur there must be four things necessary, which are: -

1. **The anode :**

Is the metal that loses electrons (oxidizes) and has a negative voltage difference greater than the cathode and less noble than it.

2. **The cathode :**

This is the location where protection occurs. The cathode is the point in a corrosion cell where electricity is passed by chemical means from the electrolyte to the surface of the metal. This chemical reaction is a reduction reaction.

Anode/cathode relationship: An electrode becomes either an anode or a cathode in an electrochemical corrosion cell depending upon its electrical potential compared to the other electrode. This electrical potential difference is the electromotive force of the cell and is the voltage difference between the anode and the cathode. The electrode which is more electrically active, or more negative in voltage, undergoes the corrosion, so by definition is the anode. The electrode that is more noble (less negative in potential) is the cathode and does not undergo corrosion (oxidation reactions) (Guyer, 2014)

3. Electrolyte :

The electrolyte is the location where ions flow. The electrolyte is any material in contact with both the anode and the cathode that will allow ions to migrate. The electrolyte is the part of a corrosion cell which allows oxidation and reduction reactions to occur.

4. An electrical connection:

It is the metallic path that completes the circuit and allows the electrons to flow. The metallic path is any metal that contacts both the anode and the cathode and allows electrons to flow. This electron flow must be present for electrochemical corrosion to occur. In the case of pipeline this can be the pipe itself, or it can be a metallic bond to a different metallic structure.

2.2.1.1 Anode reaction:

At the anode the metal atoms give up one or more electrons and become metal ions. The general formula for this reaction is written:

$$M_o -> M^{n+} + ne^-$$
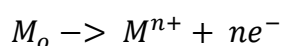
M_o represents a metal atom such as iron or copper in a metallic structure. The arrow represents the direction in which the reaction is occurring. The symbol M^{n+} represents a metal ion. Metal ions formed in the corrosion reaction leave the metal structure and enter the environment (electrolyte). The symbol e- represents the negatively charged electron released by the formation of the metal ion. The free electron that is formed in the corrosion reaction remains within the metal structure.

2.2.1.2 Cathode reaction:

At the cathode there are many possible reactions. The simplest common cathodic reaction is the reaction of hydrogen ions, which are present in water solutions with

electrons to form hydrogen gas. This reaction is written:

$$2H+ \; +2e^- \; -> H_2$$
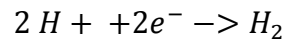
This represents the reaction of two hydrogen ions (2H+) with two electrons (e-) to form two hydrogen atoms, which then combine to form one molecule of hydrogen (H2) gas. As in the case of anodic reactions, there is no change in net charge in this reaction (+2 + -2 = 0).
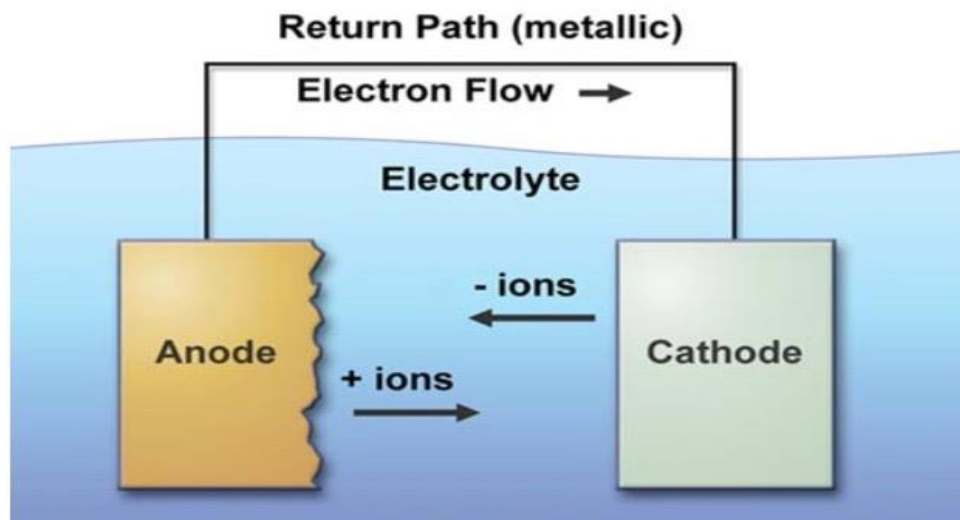
Figure2.1 Basic corrosion cell (Fessler and Hazardous Materials Safety Administration, 2008)

2.3 Types of corrosion:

There are many different types and form of corrosion varies from internal to external surface of metallic structures.

Commonly identified forms associated with corrosion of a metal in an electrolyte include (Bureau of Reclamation, 2013)

- General corrosion – in which metal loss is more or less even.
- Galvanic corrosion – in which electrically connecting dissimilar metals causes accelerated corrosion of one while reducing corrosion of the other.
- Crevice corrosion – such as corrosion at mating surfaces or under deposits.
- Pitting corrosion – which leaves pinholes in a surface.
- Inter-granular corrosion – in which the borders of metal crystal grain boundaries are attacked, causing grains of metal to drop out, and leaving a sugary appearance.

- Selective leaching – wherein a component of an alloy selectively corrodes, leaving a mechanically weak structure with essentially original dimensions.

- Erosion corrosion – wherein velocity combines with corrosion to produce synergistic damage.

- Stress corrosion – in which corrosion and stress combine to crack a metal.

In our study we concerned with external corrosion where cathodic protection can be applied to overcome or to mitigate it. Basically, there are four ways corrosion can occur. Corrosion can occur through a chemical reaction or three general types of electrochemical reactions. The three general types of electrochemical reactions that occur depend on the cause of the potential difference between the anode and the cathode. This potential difference can be caused by differences in the environment, differences in the metal, or by external electrical sources of DC current. Understanding this principle leads to an understanding of the principles of operation of cathodic protection systems. These four types are general corrosion, concentration cell corrosion (electrochemical cell caused by differences in the electrolyte), galvanic corrosion (electrochemical cell caused by differences in the metal), and stray current corrosion (electrochemical cell caused by external electrical sources).

2.3.1 General corrosion:

This type of corrosion is chemical or electrochemical in nature. However, there are no discrete anode or cathode areas. This form of corrosion is uniform over the surface of the metal exposed to the environment. The metal gradually becomes thinner and eventually fails. The energy state of the metal is basically what causes this reaction. High levels of energy are added to the raw material to produce the metal. This high energy level causes an unnaturally high electrical potential. One law of chemistry is that all materials will tend to revert to its lowest energy level, or its natural state. After high levels of energy are added to the metal, when it is exposed to the environment (an electrolyte), it will tend to revert to its natural state. This process is normally extremely slow, and is dependent on the ion concentration of the electrolyte that it is exposed to. Only under very extreme conditions (acidic electrolyte) can this form of corrosion be significant. General corrosion tends to slow down over time because the potential gradually becomes lower. Failures of pipelines or tanks would not quickly occur from this type of corrosion since no pitting or penetration of the structure occurs. However, in nature, the metal is not completely uniform and the electrolyte is

not completely homogeneous, resulting in electrochemical corrosion cells that greatly overshadow this mild form of corrosion (Guyer, 2014).

2.3.2 Concentration cell corrosion:

This type of corrosion is caused by an electrochemical corrosion cell. The potential difference (electromotive force) is caused by a difference in concentration of some component in the electrolyte. Any difference in the electrolyte contacting the metal forms discrete anode and cathode regions in the metal. Any metal exposed to an electrolyte exhibits a measurable potential or voltage. The same metal has a different electrical potential in different electrolytes, or electrolytes with different concentrations of any component. This potential difference forces the metal to develop anodic and cathodic regions. When there is also an electrolyte and a metallic path, the circuit is complete, current flows, and electrochemical corrosion will occur. Soil is a combination of many different materials. There are also many different types of soil, and even the same type of soil varies greatly in the concentration of its constituents. Therefore, there is no such thing as a truly homogeneous soil (Guyer, 2014).

Following are examples of common forms of concentration cell corrosion:

2.3.2.1 Dissimilar environment:

Pipelines tend to pass through many different types of soils. The metal exhibits different electrical potentials in different soils. The electrical potential in those soils determines which areas become anodic and which areas become cathodic. Since both the anode and cathode are electrically continuous and the electrolyte is in contact with both, current flows, resulting in oxidation and reduction reactions (corrosion and protection). Since the ground tends to consist of horizontal layers of dissimilar soils, pipelines that traverse several layers of soil such as rock, gravel, sand, loam, clay, or different combinations of these materials tend to be affected by this type of corrosion frequently. There are over 50 general types of soil that have been characterized for corrosion properties. Each of the different types of soils has different soil resistivity values. In areas where the soil resistivity values vary greatly in relatively short distances, dissimilar environment corrosion cells are formed. These types of electrochemical corrosion cells are most serious when the anode is relatively small, soil resistivity is the lowest, and the electrical potential difference is the greatest.

Examples of corrosive soils are Merced (alkali) silt loam, Montezuma (alkali) clay adobe, muck, and Fargo clay loam (Guyer, 2014).
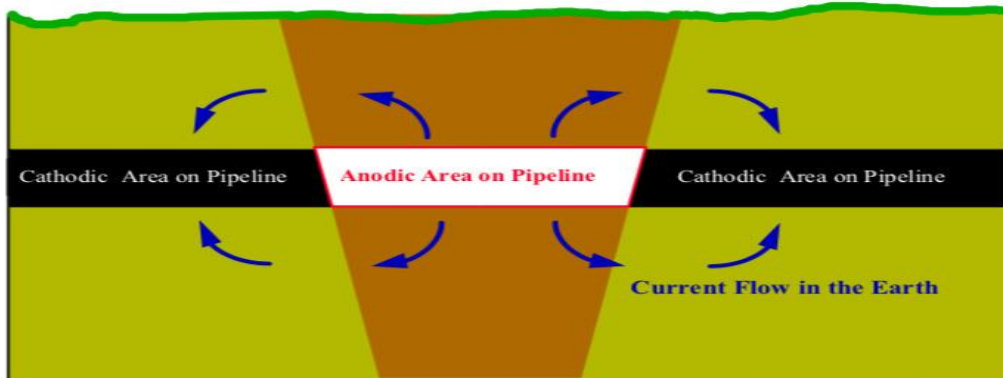
Figure2.2 Concentration cell caused by different environments

2.3.2.2Oxygen concentration:

Pipelines that are exposed to an electrolyte with a low oxygen concentration are generally anodic to the same material exposed to an electrolyte with high oxygen content. This is most severe when a pipeline or tank is placed on the bottom of the excavation, then backfill is placed around the remaining part of the structure. The backfill contains a relatively high amount of oxygen during the excavation and backfill operation. This can also occur when the metal is exposed to areas that have different levels of oxygen content (Guyer, 2014).
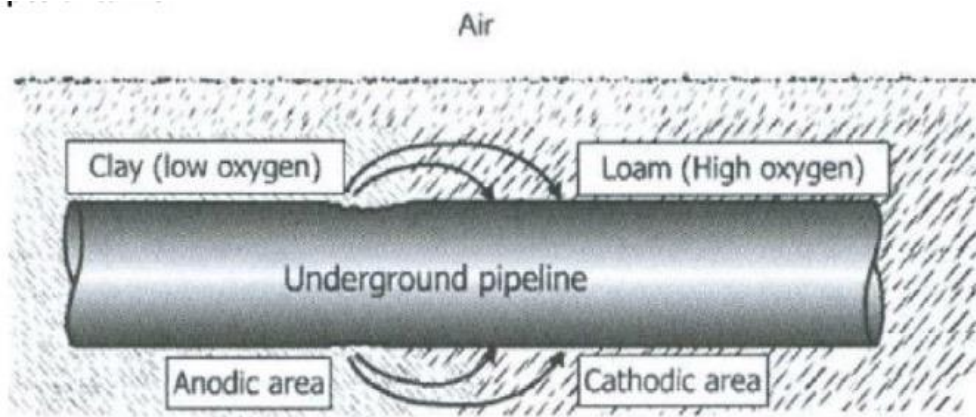
Figure2.3 Concentration cell caused by different concentrations of oxygen (Ahmad, 2006)
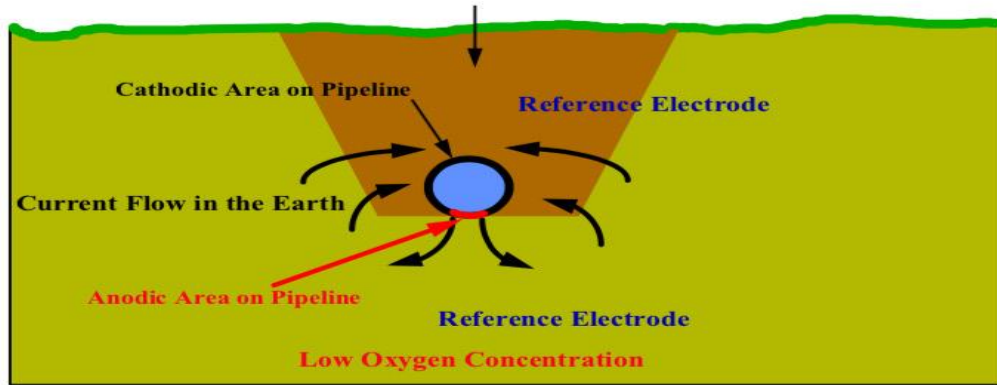
Figure2.4 Concentration cell caused by different concentrations of oxygen

2.3.2.3 Moist and dry electrolyte:

Pipelines that are exposed to areas of low and high water content in the electrolyte also exhibit different potentials in these different areas. Generally, the area with more water content becomes the anode in this electrochemical corrosion cell. This is most severe when a pipeline passes through a swampy area adjacent to dry areas (Guyer, 2014).

2.3.2.4 Concrete and soil interface:

Pipelines that are in contact with cement and exposed to other electrolyte exhibit different potentials in each area, the area not in contact with cement becomes the anode in this electrochemical corrosion cell (Guyer, 2014).
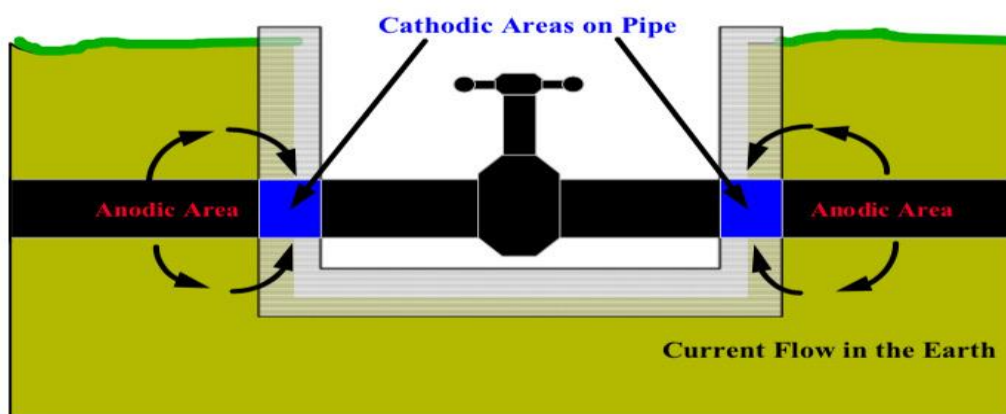
Figure2.5 Concentration cell caused by concrete and Soil Electrolytes

2.3.2.5 Backfill impurities:

This is similar to the non-homogeneous soil concentration cells, except that the "backfill impurities" are materials that do not normally occur in the soil, but are foreign materials mixed into the electrolyte during or between the excavation and the backfill process. This can be any material that forms anodic or cathodic areas on the structure. It can also be an isolating material that forms different conditions in the electrolyte, or a metallic material which actually becomes an anode or cathode when in contact with the structure (galvanic corrosion) (Guyer, 2014).

2.3.3 Galvanic corrosion:

This type of corrosion is localized corrosion and arises due to the presence of two minerals of different nature in contact with each other and in a corrosive medium. Following are examples of common forms of galvanic corrosion.

2.3.3.1 Dissimilar metals:

This type of corrosion arises when two different metals are in the electrolyte and metallically bonded in some manner. Each metal has its distinctive potential or voltage. When two different metals are connected, the metal with the most negative potential is the anode; the less negative metal is the cathode. Dissimilar metal corrosion is most severe when the potential difference between the two metals is the greatest. The potential difference is a driving force in this type of corrosion.

Examples of active metals are new steel, aluminum, stainless steel (in the active state), zinc, and magnesium. Examples of less active metals are corroded steel, copper, bronze, carbon, gold, and platinum.
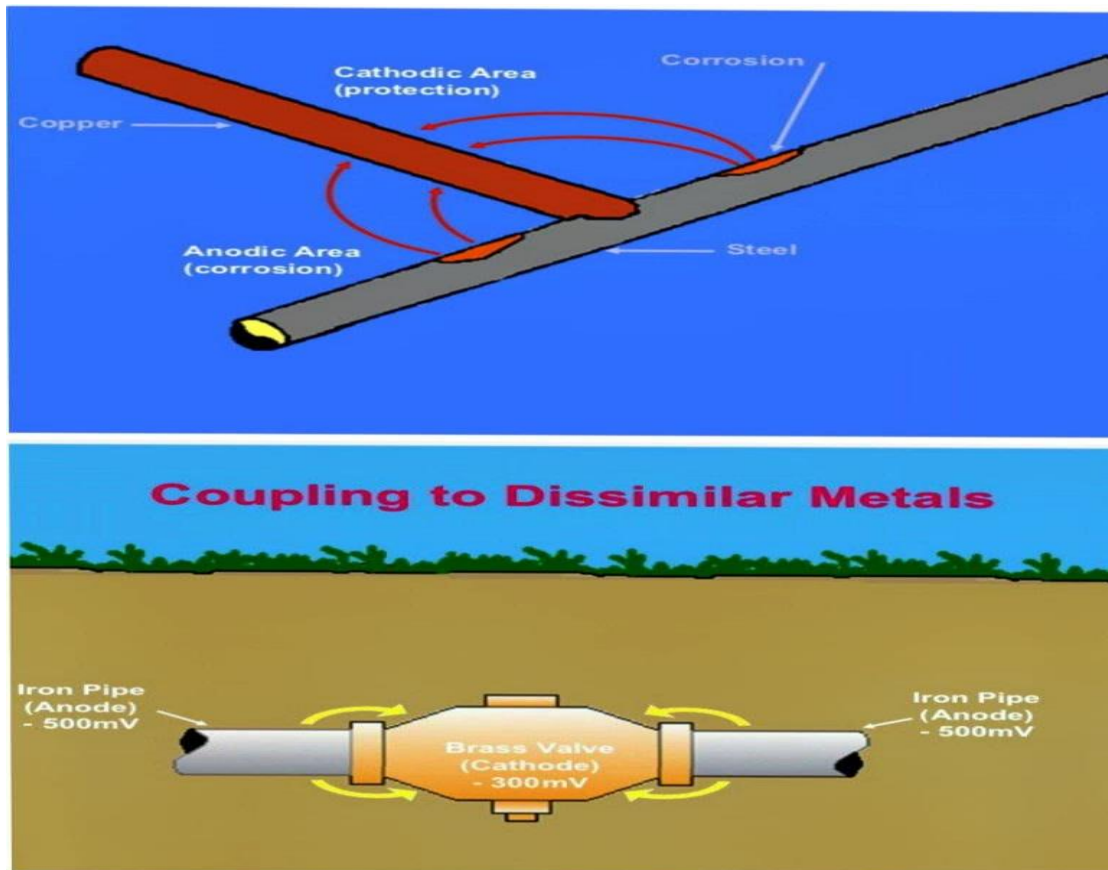
Figure2.6 Galvanic corrosion cell caused by different metals

2.3.3.2 Old and new:

This type of corrosion can also be rather severe. Steel is unique among metals because of the high energy put into the process of producing the steel. New steel is more active than old steel. The potential difference between the high negative potential of the new steel and the low negative potential of the old steel is the driving force of this electrochemical corrosion cell.

A severe and common example of this type of corrosion is when an old steel pipeline fails, and a small section of the pipeline is replaced with a new section of steel. The new section is the anode and corrodes.
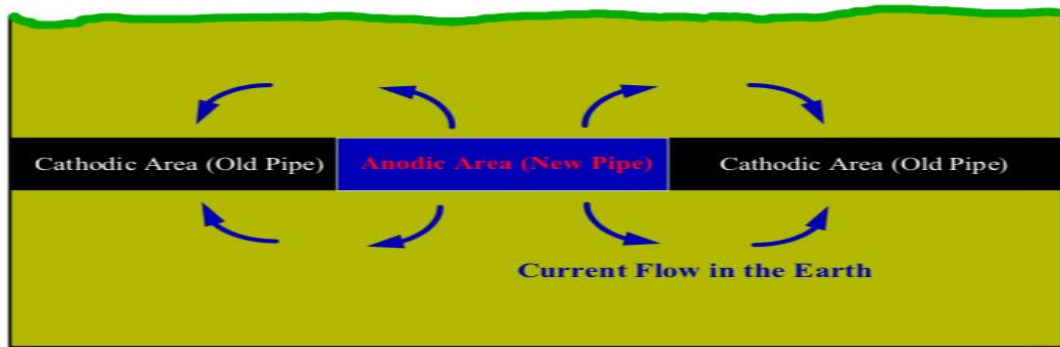
Figure2.7 Galvanic corrosion cell caused by old and new steel (Guyer, 2014)

2.3.3.3 Dissimilar alloys:

The most obvious example of this type of corrosion is different metal alloys. For example, there are over 200 different alloys of stainless steel. Also, metals are not 100 percent pure. They normally contain small percentages of other types of metals. Different batches of a metal vary in content of these other metals. Different manufacturers may use different raw materials and even the same manufacturer may use raw materials from different sources. Each batch of metal may be slightly different in electrical potential. Even in the same batch of metal, the concentration of these other materials may vary slightly throughout the finished product. All these differences will produce the electromotive force for this type of corrosion to occur (Guyer, 2014).

2.3.3.4 Deformed or scratched surface:

A deformed or scratched surface becomes anodic to the surrounding metallic surface. This is similar to the old-to-new syndrome. This electrochemical corrosion cell is caused by the difference in the electrical potential of the scratched surface compared to the remaining surface of the structure. Examples of this type of corrosion are Threaded pipe, marks from pipe wrenches and other tools, and marks from backhoes. This situation is further aggravated because the metal thickness is also reduced in these areas.
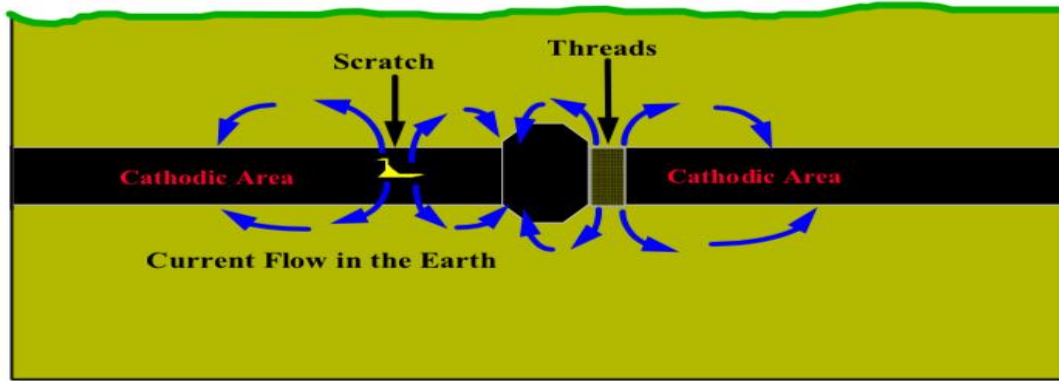
Figure2.8 Galvanic corrosion cell caused threads and by scratched surfaces (Guyer, 2014)

2.3.4 Stray current corrosion:

This type of electrochemical corrosion cell is caused by an electromotive force from an external source affecting the structure by inducing a current in the metal, which forces part of the structure to become an anode and another part a cathode. This pickup and discharge of current occurs when a metallic structure offers a path of lower resistance for current flowing in the electrolyte. This type of corrosion can be extremely severe because of very high voltages that can be forced into the earth by various sources. The potential gradient in the electrolyte forces one part of the structure to pick up current (become a cathode) and another part of the structure to discharge current (become an anode). The amount of current (corrosion) depends on the external power source, and the resistance of the path through the metallic structure compared to the resistance of the path between the external source's anode and cathode.
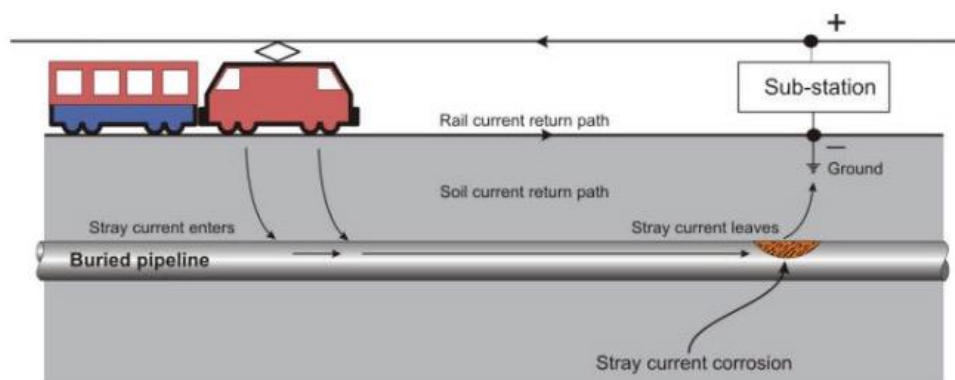
Figure2.9 Stray current corrosion (Roberge et al., 2005)

An example of stray current corrosion is caused by impressed current cathodic protection systems, where a "foreign" electrically continuous structure passes near the protected structures anodes and then crosses the protected structure (cathode). This corrosion is usually found after failures in the foreign structure. Stray current corrosion is the most severe form of corrosion because the metallic structure is forced to become an anode and the amount of current translates directly into metal loss. If the amount of current leaving a structure to enter the electrolyte can be measured, this can be directly translated into metallic weight loss. Different metals have specific amounts of weight loss when exposed to current discharge. This weight loss is normally measured in pounds (or kilograms) of metal lost due to a current of one amp for a period of one year (one amp- year) (Guyer, 2014).

Table2.1 Weight loss of specific metals at a current of one ampere for one year (1 Amp-Year)(Guyer, 2014)

Metal (Ion)	Weight Loss(Kilograms)
Magnesium	4.00
Aluminum	2.95
Zinc (Zn++)	10.66
Chromium	5.65
Cadmium	18.39
Iron (Fe++)	9.13
Cobalt	9.63
Nickel	9.58
Copper (Cu++)	20.77
Copper (Cu++)	10.39
Tin	19.39
Lead (Pb++)	33.87
Carbon (C+)	1.91
Carbon (C++++)	1.00

Following are examples of common forms of stray current corrosion:

2.3.4.1 Direct current transit Systems:

Electrified railroads, subway systems, street railway systems and mining systems that operate on DC are major sources of stray current corrosion. These systems may operate load currents of thousands of amperes at a common operating potential of 600 volts. Tracks are laid at ground level and are not completely insulated from the earth. Some part of the load current may travel through the earth. These currents could be extremely high (Guyer, 2014).

2.3.4.2 Cathodic protection systems:

CP systems are a major source of stray current on other metallic structures. An example of this electrochemical corrosion cell is when a foreign pipeline passes near an anode, and then crosses the protected structure (cathode) (Guyer, 2014).

2.3.4.3 Welding operations:

DC welders are a source of DC current.

2.4 Indicators of corrosive environments

The most reliable method is to perform site corrosion testing to determine the corrosion susceptibility of a metal in the environment; this may include field corrosion coupon testing, chemical analysis of the environment, and resistivity testing. However, project requirements may not allow sufficient time for an exhaustive study (Bureau of Reclamation, 2013).

2.4.1 Soil corrosivity:

High soil corrosivity, low soil resistivity and electrical property of materials are generally coincide. This is because low soil resistivity typically results from high levels of dissolved salts in the electrolyte. When an electrolyte contains much dissolved salt, its low resistivity and resistance allow corrosion cells to readily express themselves, even at long distances. However, environments that have a low resistivity because of other chemical constituents may not be as corrosive (Bureau of Reclamation, 2013).

2.4.2 Water corrosivity:

Because of rapid diffusion and convection, water is often more uniform in composition than soils. However, some variations may still exist. For instance, deep waters may be less aerated than those near the surface; variations may also be present if a location in the water is being aerated or if there is an outfall nearby.

Analysis of pH, chloride content, and resistivity (conductivity) provide an idea as to the corrosivity of waters. Corrosion significantly accelerates at low pH. While pH 4 and below may be considered quite corrosive. Chloride levels in the 10s of parts per million (ppm) raise alarm, and 100 ppm chlorides and higher can be expected to be significantly damaging. Conductivity readings are usually more readily obtained than resistivity readings in the case of water (Bureau of Reclamation, 2013).

2.5 Corrosion consequences:

Corrosion in general leads to many problems and risks that have serious consequences and are generally divided into:

2.5.1 Economic:

Corrosion results in the loss of $8 - $126 billion annually in the U.S. alone. This impact is primarily the result of (Roberge, 2006):

1. Downtime
2. Product Loss
3. Efficiency Loss
4. Contamination
5. Overdesign

2.5.2 Safety and loss of life:

Corrosion can lead to catastrophic system failures which endanger human life and health. Example includes a 1967 bridge collapse in West Virginia which killed 46. The collapse was attributed to stress corrosion cracking (SCC) (Roberge, 2006)

The most common methods of protecting against corrosion in pipelines are coating and cathodic protection

2.6 Coating:

it represents the first line of defense to protect against corrosion by isolating the pipe

from the surrounding environment and to be effective it must be a good electrical insulator and can be installed without problems and has the ability to withstand soil changes and earth movements and constitutes on initially perfect film that will remain so with time And it has high resistance to reduce the induced protection current, improve current distribution, increase the protected area, and reduce intersections with other external structures. To ensure complete protection of the line, cathodic protection must be used with coating because experiments have shown that failure to use cathodic protection leads to accelerated failure.

- ❖ There are currently four popular methods for coating pipelines:
- Three-Layer PE (3LPE)/PP (3LPP) PROS: Relatively low material cost. ...
- Fusion Bonded Epoxy (FBE) PROS: Excellent chemical resistance. ...
- Coal Tar Enamel (CTE) PROS: Extremely inexpensive. ...
- Asphalt Enamel and Polyurethane (PUR)

2.7 Cathodic protection:

CP is a technique to reduce the corrosion rate of a metal surface by making it the cathode of an electrochemical cell. This definition is explained in greater detail here.

Anodic areas and cathodic areas are present on the pipe surface. At the anodic areas, current flows from the pipeline steel into the surrounding electrolyte (soil or water) and the pipeline corrodes. At the cathodic areas, current flows from the electrolyte onto the pipe surface and the rate of corrosion is reduced. In light of the above, it becomes obvious that the rate of corrosion could be reduced if every bit of exposed metal on the surface of a pipeline could be made to collect current (Peabody, 1971)
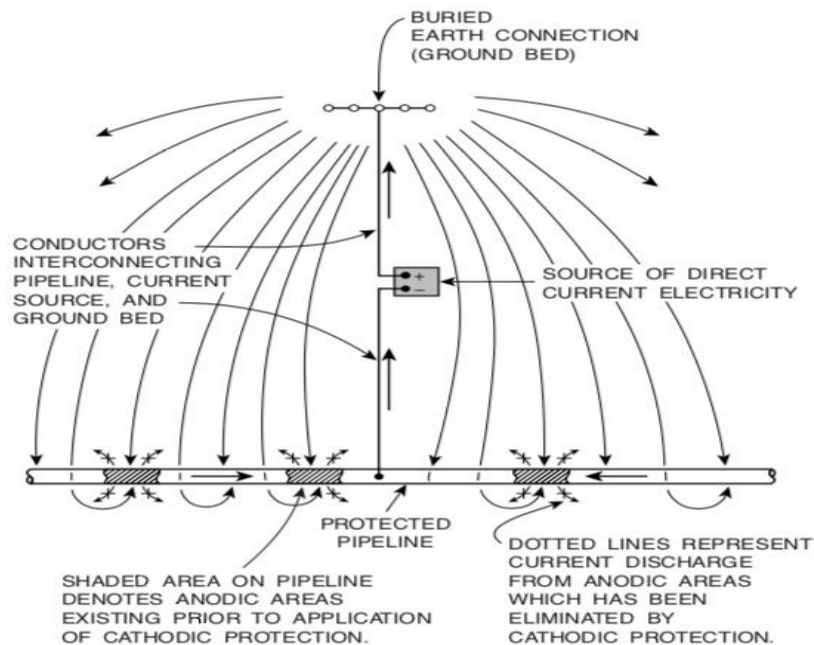
Figure2.10 Basic CP installation (Peabody, 1971)

This is exactly what CP does. Direct current is forced onto all surfaces of the pipeline. This direct current shifts the potential of the pipeline in the active (negative) direction, resulting in a reduction in the corrosion rate of the metal. When the amount of current flowing is adjusted properly, it will overpower the corrosion current discharging from the anodic areas on the pipeline, and there will be a net current flow onto the pipe surface at these points. The entire surface then will be a cathode and the corrosion rate will be reduced. This concept is illustrated in Figure (2.10). A major activity of a CP engineer is to determine the actual level of CP required reducing the corrosion rate to an acceptable level. Monitoring, in conjunction with the application of CP criteria, are used for this determination (Peabody, 1971).

.In cathodic protection this is achieved in one of two basic ways. The first way is by using the galvanic series to select a more active metal, install that metal in the electrolyte and provide a metallic path. This method is called sacrificial cathodic protection, or galvanic cathodic protection. The second basic method of cathodic protection is applying a source of DC current that forces the current to flow from an installed anode(s) to the structure, causing the entire structure to be a cathode. This method is called impressed current cathodic protection.

Cathodic protection is primarily feasible when the surfaces to be protected are buried or submerged. External surfaces of buried metallic structures, surfaces of metal

waterfront structures and the internal surfaces of tanks containing electrolytes such as water are applications where cathodic protection is usually technically feasible and is commonly utilized in protecting such structures (Ahmad, 2006).

2.7.1 Sacrificial anode:

Sacrificial anode techniques cathodic protection systems provide cathodic current by galvanic corrosion. The current is generated by metallically connecting the structure to be protected to a metal that is electrochemically more active than the material to be protected. Both the structure and the anode must be in contact with the electrolyte. Current discharges from the expendable anode, to the electrolyte, and onto the structure to be protected (Abed, 2013).

The amount of corrosion is dependent on the metal being used as an anode and is directly proportional to the amount of current supplied.

To provide a uniform electrolyte around an anode in soil, maintain moisture, and lower the resistance of anode-to-earth, a special backfill is used.

A galvanic cathodic protection system makes use of the corrosive potentials for different metals. Without cathodic protection, one area of the structure exists at a more negative potential than another, and corrosion results. If however, a much active object (that is, with much more negative potential, such as magnesium anode) is placed adjacent to the structure to be protected, such as pipeline, and a metallic connection (insulated wire) is installed between the object and the structure, the object will become the anode and the entire structure will become the cathode. That is, the new object corrodes sacrificially to protect the structure as shown in Figure (2.11). Thus the galvanic CP system is called a sacrificial anode CP system (Abed, 2013)

2.7.1.1 Galvanic series:

The two major factors affecting the rate of corrosion in an electrochemical corrosion cell are the electrical characteristics of the electrolyte (resistivity), and the voltage difference between the anode and the cathode. The resistivity of the electrolyte is normally not a controllable characteristic, but it is measurable. The voltage or potential of the metal anode and cathode is also a measurable characteristic. The voltage measured is the voltage difference between the two electrodes (Guyer, 2014).

The galvanic series determines the electrochemical potential and nobility of metals and metal alloys. Each alloy or metal has a distinctive corrosion potential. The more negative a metal or alloy is, the more likely it is to suffer galvanic corrosion. Since this voltage is dependent only on a voltage difference, there must be a reference that all other electrodes can be measured against, to give a relational table, or series, of the potential of any given electrode.

Many types of reference electrodes have been used. In the laboratory the hydrogen/hydrogen (hydrogen electrode, hydrogen electrolyte) is common. For field use, the copper/copper sulfate (copper electrode, fully saturated copper sulfate electrolyte) is in common use, except in salt water where silver/silver chloride (silver electrode, silver chloride electrolyte) is used. Using these references, the potential value of any metal in any electrolyte can be recorded. A table of such measurement is called a galvanic series of measurements (Guyer, 2014).

Table2.2 Potentials with respect to saturated Cu-CuSO4 electrode (Roberge, 2008)

Material	Potential
Pure Magnesium	-1.75
Magnesium Alloy	-1.60
Zinc	-1.10
Aluminum Alloy	-1.00
Cadmium	-0.80
Mild Steel (New)	-0.70
Mild Steel (Old)	-0.50
Cast Iron	-0.50
Stainless Steel	-0.50 to +0.10
Copper, Brass, Bronze	-0.20
Titanium	-0.20
Gold	+0.20
Carbon, Graphite, Coke	+0.30

2.7.1.2 Types of sacrificial anodes:

There are three materials that are commonly used as galvanic anodes: magnesium, aluminum alloy, and zinc. Each material has different grades or types available. Each type is available in a multitude of sizes and shapes.

Table2.3 Sacrificial anodes specification (Samoudi, 2015)

Metal	Potential (Volts)	Density (g/cm³)
Magnesium (Mg)	-1.55	1.70
Aluminum (Al)	-1.15	2.70
Zinc (Zn)	-1.10	7.10

Anodes are connecting to the pipe at recorded intervals along it. The anodes are regularly lifted for inspection and replaced when necessary. To minimize anode consumption, the pipe work is given primary protection by a coating such as a tarred wrap.

CP in the sacrificial anode system is essentially a controlled electrochemical cell. Anode life is dependent upon the amount of current emitted by the anodes and their size (Abed, 2013).

The application of galvanic anodes is limited by the small potential difference (normally less than 1 volt DC) that can be obtained. Galvanic systems generally can only be economically used on small or well-coated structures in low resistivity electrolytes (Guyer, 2014).

2.7.2 Impressed current:

Impressed current type cathodic protection systems provide cathodic current from an external power source. As in galvanic anode systems, impressed current systems supply current for cathodic protection of a metal surface. However, in the case of an impressed current system, the protective current is supplied by a rectifier (or other DC power source) instead of by the natural potential difference of the anode to the structure The external power source is usually a rectifier that changes input AC power to the proper DC power level, the rectifier can be adjusted, so that proper output can

be maintained during the systems life. Other power source such as a battery, solar cell, direct current generator, or thermoelectric generator may be used.

The potential difference between the anode and cathode is forced from a non-reactive anode bed by the action of additional energy from a rectifier to force the electron flow that would be normally produced in the corrosion reaction. The effect of these electrons at the structure being protected is the same as that derived from the sacrificial anode type of cathodic protection system. However, the anode material serves only as a source of electrons and anodic (oxidation) electrochemical reactions.

In practice, materials such as graphite, high silicon cast iron (HSCI), platinum or mixed metal oxide, are used for impressed current cathodic protection system anodes because they are slowly consumed (they have a very low kilogram (pound) per amp year weight loss). To provide a uniform electrolyte, a lower resistance to earth, and venting of gases and acids, a special backfill is used. This earth contact backfill is normally coke breeze or calcined fluid petroleum coke (Guyer, 2014).

The principle advantage of impressed current CP is its much greater output capacity as compared to galvanic anode system. Therefore, whenever corrosion protection is desired for very large, poorly coated, or bare structures, impressed current is often the system choice (Abed, 2013).
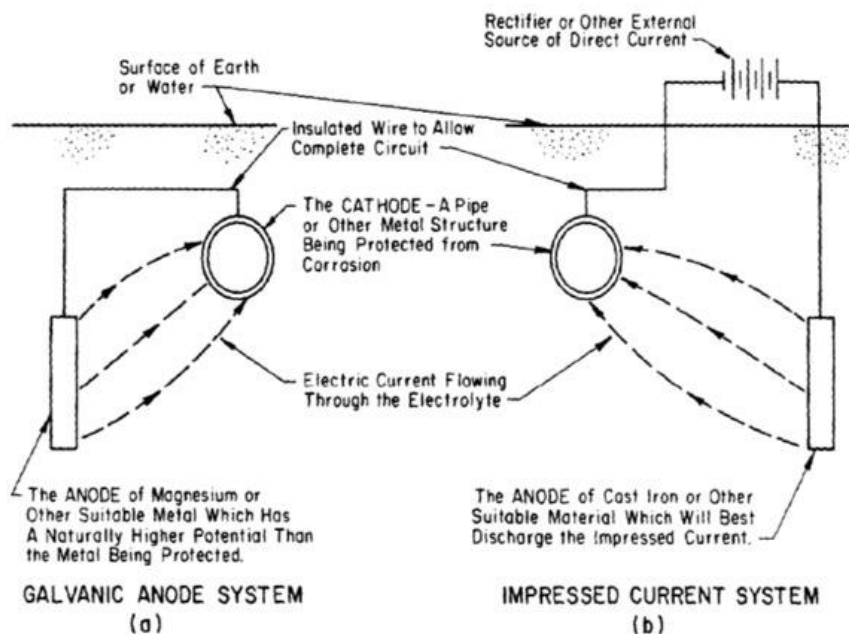
Figure2.11 Type of cathodic protection (Abed, 2013)

2.7.2.1 Impressed current rectifier:

Rectifiers used for cathodic protection commonly use an adjustable step down transformer, rectifier stacks, a shunt to measure output current, meters to indicate output current and voltage, circuit breakers, lightning arresters, and transformer tap connections, all in one case. The function of the rectifier is to convert alternating current into controlled (pulsating) direct current (Guyer, 2014).
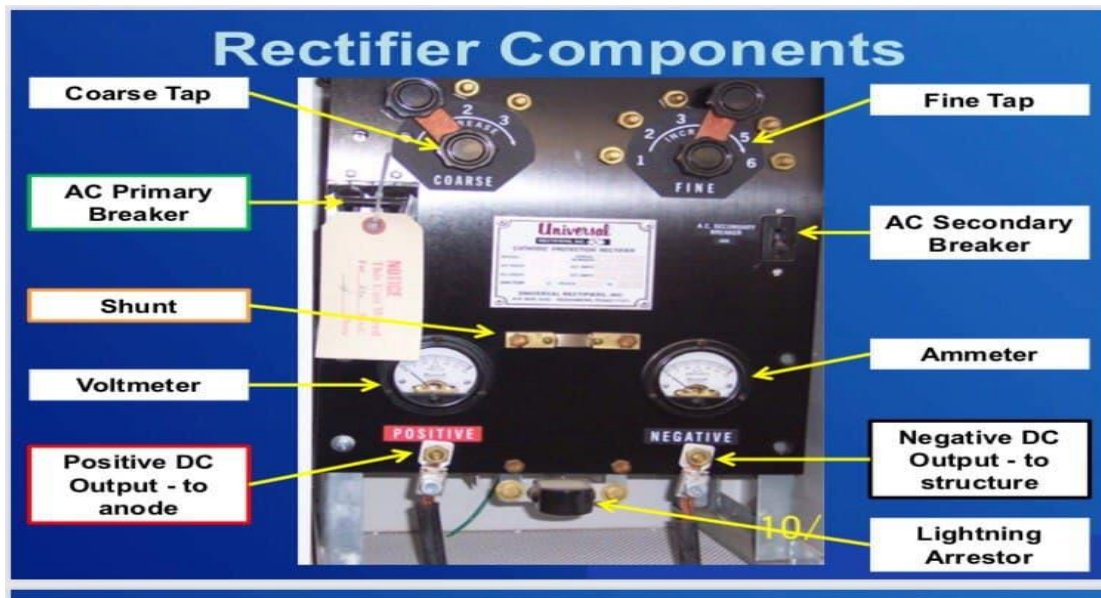
Figure2.12 ICCP rectifier components

2.7.2.2 Impressed current anodes:

The anodes of an impressed current system provide the means for the protective current to enter the electrolyte. Since the anodes form the corroding part of the system, the best material is one that has a low rate of weight loss per ampere-year. The most commonly used materials for impressed current anodes are graphite and high-silicon cast iron, Platinum coated titanium or niobium anodes and mixed metal oxide anodes are becoming more prevalent as impressed current anode material.

Anodes for impressed current are selected according to their size and chemical composition. This determines the current output and design life.

Some examples of ICCP anodes:

    1. Graphite anodes:

The basic configurations consist of round or square rods, manufactured from slurry of powdered petroleum coke and coal tar resin. There are many types of graphite compositions and the type used for cathodic protection groundbed is one of the most porous. Graphite should not be operated at current densities exceeding 10.76 amperes

per square meter (1 ampere per square foot) in soil or 2.70 amperes per square meter (0.25 amperes per square foot) in water (Guyer, 2014).

2. Scrap steel and iron

Scrap steel and iron represent consumable anode material and have been used in the form of abandoned pipes, railroad or well casings, as well as any other scrap steel beams or tubes. It has the advantage of being cheap and abundantly available, the rate of consumption of mild steel scrap is 6.6-9.0 kg/A year (Abed, 2013)

3. Mixed-metal oxide anodes (MMO)

Mixed metal oxide coated titanium anodes are based on electrode technology developed in the early 1960s for production of chlorine and caustic soda. Usually the mixed metal oxide films are thermally applied to precious metal such as titanium or niobium cores. These oxide coatings have excellent conductivity, are resistant to acidic environments, are chemically stable, and have relatively low consumption rates (Abed, 2013)

4. High silicon cast iron (HSCI)

Cast iron anodes are produced in two alloy types with the principal addition of chromium, developed in 1959, to improve the life in chloride soils and water. The principal reason for superior cast iron performance is the formation of a silicon oxide (Si02) film that forms on the anode surface, reducing the rate of oxidation, and retarding the consumption rate.

Manufacturers of cast iron anodes developed cable-to-anode connection procedures which distributors are required to follow. Therefore, there has been a lower incidence of connection failures, compared to graphite anodes (Guyer, 2014).

Specifications for impressed current anodes are provided in table (2.4).

Table2.4 Impressed current anodes

Anode Material	Recommended current density A/m^2	Consumption Rate g/A-yr
Scrap steel	Varies	200-9,000
Graphite	10	30-450
Silicon-Chromium-cast iron	10-100	90-250

2.7.2.3 Anode groundbed:

The term groundbed usually refers to a group of anodes interconnected and operated as a unit. They are two types of groundbed remote groundbed, close groundbed (represented by distributed anode system). The terms, close and remote, are related to the area of influence in the electrolyte around the anode (Abed, 2013) .

The types of impressed current anode beds are dependent on the placement, orientation, and depth of the anodes. Impressed current anode beds are normally placed in remote earth, and distribute current over long distances of the protected structure

Impressed current anodes are usually surrounded by a carbonaceous backfill. Types of materials are used include metallurgical coke and petroleum coke. The dual purpose of the carbonaceous backfill is to reduce the ground-bed resistance by increasing the effective size of the anode and to provide a surface on which oxidation reactions could occur. The latter function prolongs anode life. To ensure good electrical contact, the backfill must be tamped around the anode. Resistivity of carbonaceous backfill is in the range of 10 - 50 Ohm.cm. Particle size and shape is also important when specifying a backfill. Both parameters determine the contact area between anode and surrounding soil whilst influencing the porosity of the column which is important for gas ventilation (Samoudi, 2015).
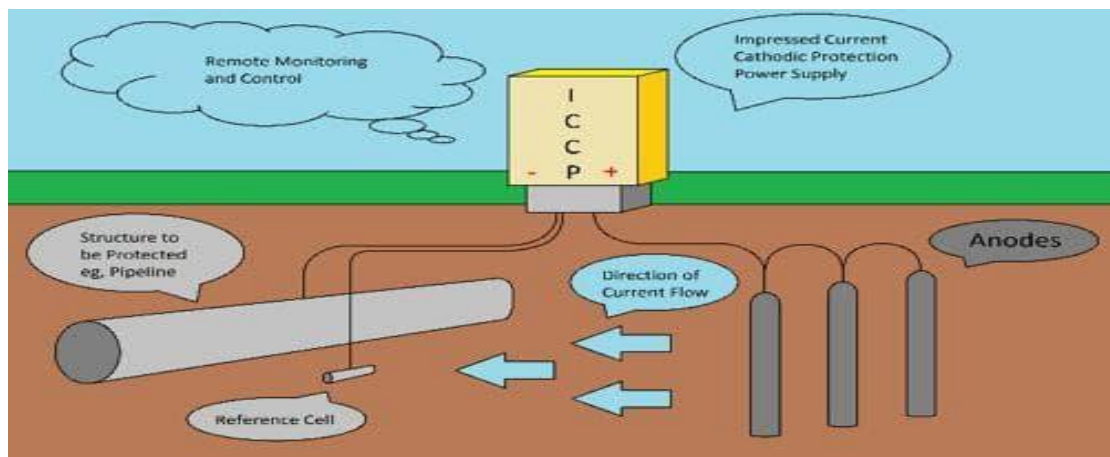
Figure2.13 ICCP system

2.7.3 Select of the cathodic protection system:

The choice between impressed and sacrificial cathodic protection depends many factors and may be just personal preference. There are, however, situations where one

or the other provides the correct choice. The advantages and disadvantages of each type of CP system are described in table (2.5) and table (2.6).

Table2.5 Advantages of impressed and sacrificial anodes system

Advantages	
Impressed current	**Sacrificial Anodes**
Variable control of current and potential	Economically feasible when installed with the structure.
Large current available, even in very high resistivity electrolytes	Extremely small possibility of overprotection
Light weight and fewer anodes	Very little operation or maintenance requirements (very small chance of premature failure or breakdown)
Economically feasible when installed on existing structures.	Needs no supervision
Can provide sufficient current to protect very large, poorly coated, or uncoated structures.	Simple to install

Table2.6 Disadvantages of impressed and sacrificial anodes system

Disadvantages	
Impressed current	**Sacrificial anodes**
Complex installation and maintenance	Small driving voltage available (limited potential difference)
Requires external power source	Extremely small current available in higher resistivity electrolytes
Anodes requires dielectric shields	Anodes may be damaged
Anodes may be damaged	Anodes have finite life

	Not economically feasible to install
Probability of stray current corrosion	or replace anodes on large or extensive existing structure

2.8 Cathodic protection test:

Cathodic protection systems require periodic attention to ensure that they function properly. Some checks only require visual observations. Others require a portable high-impedance voltmeter, leads in good condition, and a calibrated reference cell (usually a copper/copper sulfate reference cell).

2.8.1 Test the pipe-to-soil voltage potential:

By comparing to a copper sulfate half cell. The copper sulfate half-cell is a specialized half of a battery cell which, when placed in contact with the ground and connected through a volt meter to a metal in contact with the ground, will produce a comparative voltage for the metal to soil. The comparative voltage for a corrugated metal (iron) pipe that is protected should be 0.85 volt or higher. Less than 0.80 means the pipe probably is corroding (USDA, 2012).

2.8.2 The voltage output of the anode:

This test is a comparative test using the copper sulfate half-cell as in Test 1. The normal anode potential voltage will be in the range of 1.4 to 1.6 volts. A 0 to 0.3 voltage reading means the wire or a connection is broken between the test box and the anode (USDA, 2012).

2.8.3 Measure anode current:

Measure the current flowing through each anode and record on the data sheets. This also requires a portable high-impedance voltmeter, normally set to take DC millivolt readings. These readings are taken with current flowing by measuring the voltage across the anode shunt resistor connection tabs and employing Ohm's Law to calculate the current (Bureau of Reclamation, 2013).

This could vary from 5 mA (0.005 amp) to 300+ mA (0.3 amp), depending on pipe area, soils resistivity, and soil moisture. A current flow larger than the design current usually means the pipe is protected to a higher level than needed and a waste of the anode, which will result in a reduced anode life. If the current is more than 1.3 times

the design needs, a resistance should be added to the circuit to extend the life of the anodes. This is done with a length of special high- resistance wire between the connections in the test box (USDA, 2012).

2.9 Cathodic protection design:

Cathodic protection uses direct current to mitigate metal corrosion in an electrolyte. Cathodic protection makes the protected metal surface the cathode of a galvanic or electrolytic cell. This protective current may come from:

• A more active metal such as zinc or magnesium.

• An external source of power such as a rectifier.

The use of cathodic protection is an economic consideration. Cathodic protection usually in conjunction with protective coatings, can allow a long service life equivalent to that from using more expensive alloys. Cathodic protection however may not be practical for some structures, such as the interior surfaces of small diameter pipelines. There may be instances when other corrosion mitigation measures are preferable.

2.9.1 Required information:

Before deciding which type of cathodic protection system will be used and before the system is designed, certain preliminary data must be gathered.

This data include:

2.9.1.1 Physical dimensions of structure to be protected:

One important element in designing a cathodic protection system is the structure's physical dimensions (length, width, height, and diameter). These data are used to calculate the surface area to be protected. Also the design life of the structure must be determined.

2.9.1.2 Electrical isolation:

If a structure is to be protected by the cathodic system, it must be electrically connected to the anode. Sometimes parts of a structure or system are electrically isolated from each other by insulators. For example, in a gas pipeline distribution system, the inlet pipe to each building might contain an electric insulator to isolate in-house piping from the pipeline. Also, an electrical insulator might be used at a valve along the pipeline to electrically isolate one section of the system from another. Since

each electrically isolated part of a structure would need its own cathodic protection, the locations of these insulators must be determined (Ezekiel Enterprises and Science, 2015)

2.9.1.3 Corrosion history of structures in the area:

Studying the corrosion history in the area can prove very helpful when designing a cathodic protection system. The study should reinforce predictions for corrosivity of a given structure and its environment; in addition, it may reveal abnormal conditions not otherwise suspected. Facilities personnel can be a good source of information for corrosion history (Ezekiel Enterprises and Science, 2015)

2.9.1.4 Electrolyte resistivity survey:

A structure's corrosion rate is proportional to the electrolyte resistivity. Without cathodic protection, as electrolyte resistivity decreases, more current is allowed to flow from the structure into the electrolyte; thus, the structure corrodes more rapidly. As electrolyte resistivity increases, the corrosion rate decreases. Resistivity can be measured either in a laboratory or at the site with the proper instruments. The resistivity data will be used to calculate the sizes of anodes and rectifier required in designing the cathodic protection system (Ezekiel Enterprises and Science, 2015)

Table2.7 Corrosivity of soils based on soil resistivity

Soil resistivity range (ohm-cm)	Corrosivity
0 to 2000	Severe
2000 to 10,000	Moderate to severe
10,000 to 30,000	Mild
Above 30,000	Not likely

2.9.1.5 Electrolyte pH survey:

Corrosion is also proportional to electrolyte pH. In general, steel's corrosion rate increases as pH decreases when soil resistivity remains constant (Ezekiel Enterprises and Science, 2015)

2.9.1.6 Structure versus electrolyte potential survey:

For existing structures, the potential between the structure and the electrolyte will give a direct indication of the corrosivity. According to NACE Standard No RP-01, the potential requirement for cathodic protection is a negative (cathodic) potential of at least 0.85 volt as measured between the structure and a saturated copper-copper sulfate reference electrode in contact with the electrolyte. A potential which is less negative than -0.85 volt would probably be corrosive, with corrosivity increasing as the negative value decreases (Ezekiel Enterprises and Science, 2015)

2.9.1.7 Current requirement:

A critical part of design calculations for cathodic protection systems on existing structures is the amount of current required per square foot (called current density) to change the structure's potential to -0.85 volt. The current density required to shift the potential indicates the structure's surface condition. A well coated structure (for example, a pipeline well coated with coal-tar epoxy) will require a very low current density (about 0.05 milliampere per square foot); uncoated structure would require high current density (about 10 milliamperes per square foot). The average current density required for cathodic protection is 2 milliamperes per square foot of bare area. The amount of current required for complete cathodic protection can be determined three ways:

   • An actual test on existing structures using a temporary cathodic protection setup.
   • A theoretical calculation based on coating efficiency.
   • An estimate of current requirements using tables based on field experience.

The second and third methods above can be used on both existing and new structures.

Current requirements can be calculated based on coating efficiency and current density (current per square foot) desired. The efficiency of the coating as supplied will have a direct effect on the total current requirement, as Equation 1 shows:

$$\mathbf{I = (A)\big(\acute{I}\big)(1.0 - CE)} \hspace{3cm} \text{Equation (1)}$$

Where I is total protective current, A is total structure surface area in square feet, $\acute{I}$ is required current density, and CE is coating efficiency. Equation 1 may be used when a current requirement test is not possible, as on new structures, or as a check of the current requirement test on existing structures. Coating efficiency is directly affected by the type of coating used and by quality control during coating application. The importance of coating efficiency is evident in the fact that a bare structure may

require 100,000 times as much current as would the same structure if it were well coated.

Current requirements also can be estimated from Table (3.2). The table gives an estimate of current, in milliamperes per square foot, required for complete cathodic protection. That value, multiplied by the surface area of the structure to be protected (in square feet) gives the total estimated current required (Ezekiel Enterprises and Science, 2015)

2.9.1.8 Coating resistance:

A coating's resistance decreases greatly with age and directly affects structure-to-electrolyte resistance for design calculations. The coating manufacturers supply coating resistance values (Ezekiel Enterprises and Science, 2015)

2.10 Sudanese petroleum pipelines company Ltd. (SPPC):

The Sudanese Petroleum Pipelines Company Ltd. is a pioneer of pipelines for transporting petroleum materials, a company affiliated with the Ministry of Oil and Gas, one of the main pillars of the oil industry in Sudan, as it was established in 1976 and established the first pipeline for petroleum products with a diameter of 8 inches and a length of 815 km between Port Sudan and Khartoum. Then, in the year 2005, it added a second line with a diameter of 12 inches and a length of 741 km between ALrawyan "Elgaily Refinery" and Port Sudan to export surplus gasoline, and it developed the lines to operate in both the export and import directions. Since its inception, the company has pumped more than 20 million tons of petroleum products through pipelines.

Now Sudanese Petroleum Corporation (SPC) intends to install a new 12" multiproduct pipeline connecting ALrawyan (Elgaily) area with Madani strategic storage depots.

Whereas SPPC, one of SPC subsidiaries, is the sale custodian of MOP/SPC's petroleum products pipelines, therefore it has been awarded the contract of this project.

The Pipeline shall consist of 12", 220 km long multiproduct transport Pipeline from Alrawyan Station at Khartoum to Madani Storage Terminal Station at Madani City. The facilities will have provisions for the future connection of branch connection with

10" block valves with blind flanges at Suba and Aljinid areas in addition to 12" Midpoint intermediate station (valve + Booster station future Tie-in point).

The new petroleum products pipeline shall be initially designed to operate at maximum allowable capacity using the existing main pumps, currently feeding Alshagara and Port Sudan pipelines, and with future provision for expansion to a maximum design capacity that could be achieved by an intermediate pumping station.

2.11 Review of the previous work:

Glass (1951) designed a cathodic protection including a 2300 V overhead distribution line which was constructed parallel and adjacent to the pipeline (142.3 km). Soil resistivity was 1638 ohm.cm, anodes used carbon anodes, and performance data on rectifiers which are placed three per mile of pipeline protected, experience with groundbeds (6-10) anodes for each station, current requirements to maintain protection, bonding procedures with parallel and/or crossing foreign structures. An economic study is made of the system based upon investment charges, operating and maintenance costs, and actual power costs (Glass, 1951).

Gurrappa (2004) studied the types of cathodic protection and anodes available apart from a brief review on sacrificial and impressed current cathodic protection. The necessatiy of desiging of an effective cathodic protection system for cooling waters pipelines had been emphasized. In addition, the economics of cathodic protection has been highlighted with an example. After installation of CP system, operation and maintenance part had also been mentioned (Gurrappa, 2005).

Salih (2005) studied the effect NaCl concentration, distance between cathode and anode and the temperature on the cathodic protection current density in order to protect submerged pipelines from corrosion. The structure used is carbon steel metal pipe. The carbon steel results showed that the cathodic protection current density increases with increasing the above studied variables. Also icp showed sharp increasing when the fluid was stirred. The corrosion potential became more negative as temperature increases so that cathodic protection criterion was investigated to be more negative to some extent in order to make adequate protection (Salih, 2005).

Ajeel and Ghalib (2007) found that cathodic protection current density increases with increasing temperature and concentration. The current density also slightly

increases with increase distance between cathode and anode. The effective sequence of these parameters on cathodic current density was as follows (Ajeel et al., 2008):

Temperature > concentration > pH of solution > cathode − anode distance

Laoun B., K. Niboucha and L. Serir (2009) designed a cathodic protection system by impressed current supplied with solar energy panels applied to a 36 pipeline, The output current was high enough to protect the pipeline with low costs (Laoun et al., 2009).

Chapter 3

Methodology

3.1 Introduction:

The most important requirements of the cathodic protection system is to calculate the required current, the number of anodes and the voltage, and this is done by either calculations using design equations or by using Matlab simulink by constructing a diagram that expresses the equations in the form of a block diagram.

3.2 Simulation model:

The simulation of the ICCP system is done in the MATLAB program which is a short for (Matrix Laboratory) is a programming package specifically designed for quick and easy scientific calculations. It has literally hundreds of built-in functions for a wide variety of computations and many toolboxes designed for specific research disciplines, including statistics, optimization, solution of partial differential equations, data analysis (Samoudi, 2015).

3.2.1 Simulink application:

Simulink is a software package for modeling, simulating, and analyzing dynamic systems. It supports linear and nonlinear systems, modeled in continuous time, sampled time, or a hybrid of the two. Systems can also be multi rate, i.e., have different parts that are sampled or updated at different rates (Samoudi, 2015).

And one of its features is to reduce the error rate and simplify the calculations and display them in a neat and simplified form that is easy to understand and easy to make adjustments to any of the variables of the calculation process without the need to repeat all the calculations, and that is done by changing the value and running the program, then it will automatically recalculate all the calculations related to this new value.

3.3 Determining type and design of cathodic protection system:

When all preliminary data have been gathered and the protective current has been estimated, the design sequence can begin. The first question to ask is: which type (galvanic or impressed current) cathodic protection system is needed? Conditions at the site sometimes dictate the choice (soil resistivity, required current, structure dimension, design life of structure to be protected, coating efficiency…etc (Ezekiel Enterprises and Science, 2015)

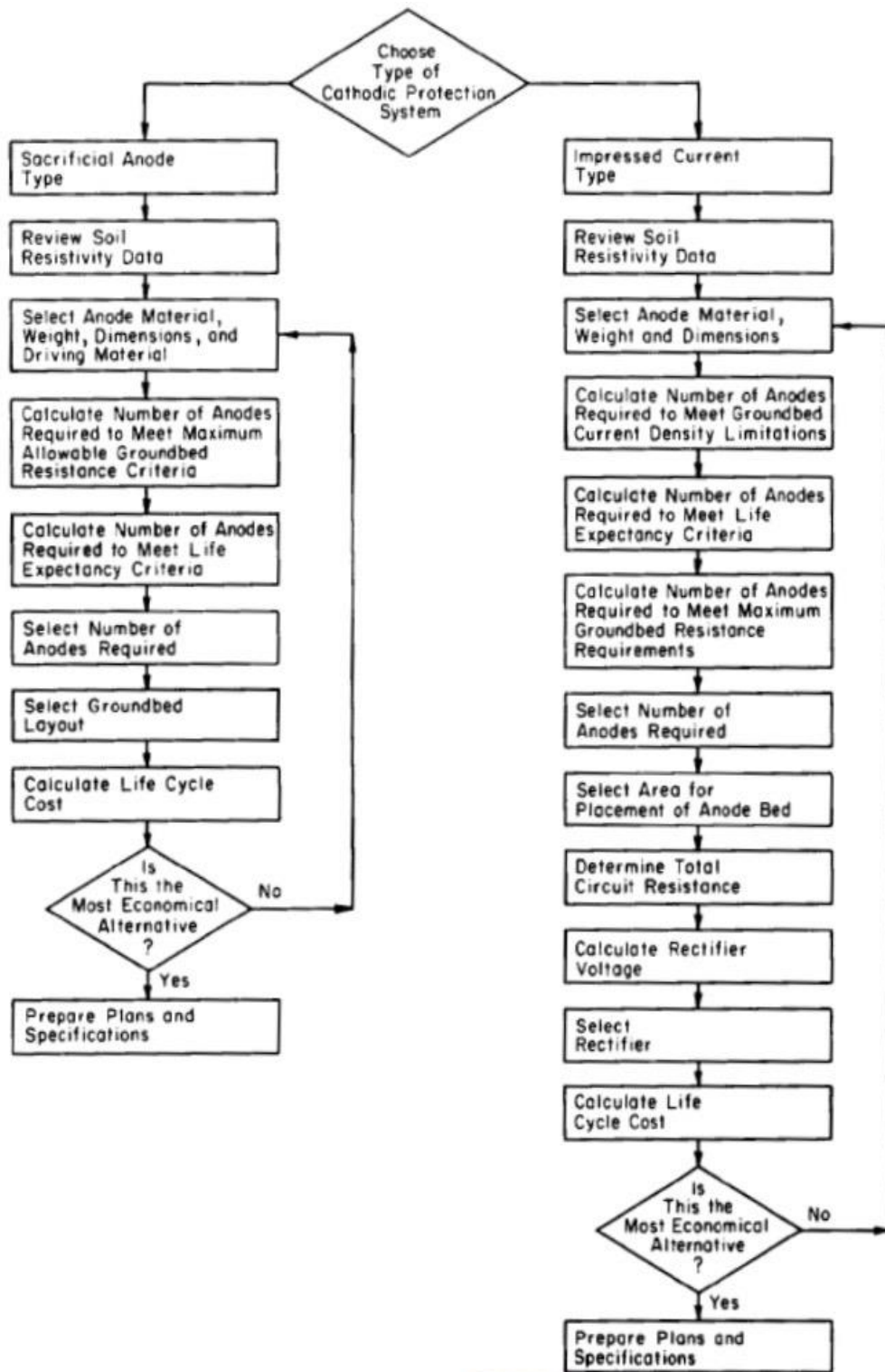Design sequences for each type of cathodic protection system are given below

Figure3.1 Design sequence of cathodic protection system (Ezekiel Enterprises and Science, 2015)

3.4 Simulation variables:

Mathematical models were developed to predict cathodic coated pipelines protected

by parallel anodes. This work was motivated by the need to estimate current and voltage of the rectifier as well as the numbers of anodes used for each situation when anodes are placed nearby (Abed, 2013)

Simulink accomplished by using the size and geometry of the structure to be protected, coating efficiency, design life for anode, soil resistivity, anode dimensions current density required, etc.

Mathematical equations used for the simulation are:

1. Pipe surface area

$$= \pi \times D \times L \hspace{6cm} \textbf{Equation 1}$$

2. Current requirement

$$= A \times I \times (1 - CE) \hspace{5cm} \textbf{Equation 2}$$

Where

  I   required current density

  A   total structure surface area

  CE   coating efficiency

3. Number of anodes to meet anode supplier current density

$$= \frac{I}{(A1 \times I1)} \hspace{6cm} \textbf{Equation 3}$$

Where

  A1   anode surface area

  I1   recommended maximum current density out put

4. Number of anodes to meet the design life requirements

$$= \frac{L \times I}{1000 \times W} \hspace{5.5cm} \textbf{Equation 4}$$

Where

  N   number of anodes

  L   life

  W weight of anode

5. Maximum number of anodes required to meet the groundbed requirements

$$= \frac{\rho \times K}{La \times \left(Ra - \frac{\rho \times P}{S}\right)}$$

<div align="right">**Equation 5**</div>

Where

   ρ Average soil resistivity

   K anode shape factor from table (3.2)

   S center to center spacing between anode backfill column.

   P paralleling factor from table (3.3)

   La length of anode backfill column

6. **Ra** (anode ground bed resistance)

$$= \frac{\rho \times K}{La \times N} + \frac{\rho \times P}{S}$$

<div align="right">**Equation 6**</div>

7. **Rw** (the groundbed header cable)

$$= (Ohm/ft)(L)$$

<div align="right">**Equation 7**</div>

8. **Rc** (structure to Electrolyte resistance)

$$= \frac{R}{A}$$

<div align="right">**Equation 8**</div>

Where

   R coating resistance

9. Total resistance

$$(Rt) = Rc + Rw + Ra$$

<div align="right">**Equation 9**</div>

10. Rectifier voltage

$$= I \times Rt \times 150\,\%$$

<div align="right">**Equation 10**</div>

Required information's for the simulation inputs are (Design Data):

  1. Average soil resistivity for CPS1 and CPS2 (2000-1000 ohm-cm) respectively.

  2. Effective coating resistance at 25 years is 2800 Ohm/ft^2.

  3. Pipe outside diameter 12-inch nominal (12.750 in).

  4. Pipe length for the specified station 15000m.

  5. Design life 25 years.

6. Design current density per square foot of bare pipe was chosen for each station according to soil resistivity as shown in table (3.4) is 0.5-1.4 mA/ft² respectively.

7. Design for 90% coating efficiency.

8. The pipeline must be isolated from the pump house with an insulating joint on the main line inside the pump house.

9. High silicon cast iron anodes is used with anode size (2-inch×60-inch) and backfill (10-inch×84-inch) spaced 10-feet apart and the anode weight and surface are 44-lb and 2.6-inch as shown in table (3.1).

10. Groundbed cable (length 500 ft, resistance 0.0159 ohm/100, type HMWPE, size no. 2 AWG)

11. Anode bed resistance must not exceed 2 Ohms.

The modeling of the ICCP system is depending on the equations that used in the mathematical design and these equations is modeled in the Simulink application in matlab.

Table3.1 Weight dimensions of selected circular high-silicon chromium-bearing cast iron anodes (Ezekiel Enterprises and Science, 2015)

Anode Weight (lb)	Anode Dimensions (in)	Anode Surface Size (ft²)	Package Area (ft^2)
12	1×60	1.4	10×84
44	2×60	2.6	10×84
60	2×60	2.8	10×84
110	3×60	4.0	10×84

Table3.2 Shape factor for ICCP anodes (Ezekiel Enterprises and Science, 2015)

L/d	K	L/d	K
5	0.0140	20	0.0213
6	0.0150	25	0.0224
7	0.0158	30	0.0234
8	0.0165	35	0.0242

9	0.0171	40	0.0249
10	0.0177	45	0.0255
12	0.0186	50	0.0261
14	0.0194	55	0.0266
16	0.0201	60	0.0270
28	0.0207		

Where L is effective anode length and d is anode/backfill diameter.

The highest number calculated by Equation 3, 4, or 5 will be the number of anodes used.

Table3.3 Paralleling factors for various numbers of anodes installed in parallel (Ezekiel Enterprises and Science, 2015)

N	P	N	P
2	0.00261	14	0.00168
3	0.00289	16	0.00155
4	0.00283	18	0.00145
5	0.00268	20	0.00135
6	0.00252	22	0.00128
7	0.00237	24	0.00121
8	0.00224	26	0.00114
9	0.00212	28	0.00109
10	0.00201	30	0.00104
12	0.00182		

Table3.4 Current density with respect to soil resistivity (FRESHWATER, 2010)

Soil resistivity (ohm.cm)	Current density (mA/m^2)
50 to 500	20 to 40

500 to 1500	10 to 20
1500 to 5000	5 to 10
Over 5000	5
Fresh water	10 to 30
Moving fresh water	30 to 65
Brackish water	50 to 100
Sea mud zone	20 to 30

3.5 Collected data:

Pipeline main data:

- Diameter (m)   :0.3048
- Wall thickness(mm)   :6.4
- Length(m)   :216,616
- Pipeline material   :Carbon steel API 5L X60
- Product   :kerosene/Gasoil/Mogas
- Coating   :3LPP
- Protection potential   : -.85 V

3.6 Modeling procedures:

Enter Matlab and open the simulink from the toolbox as shown in the figure (3.2):
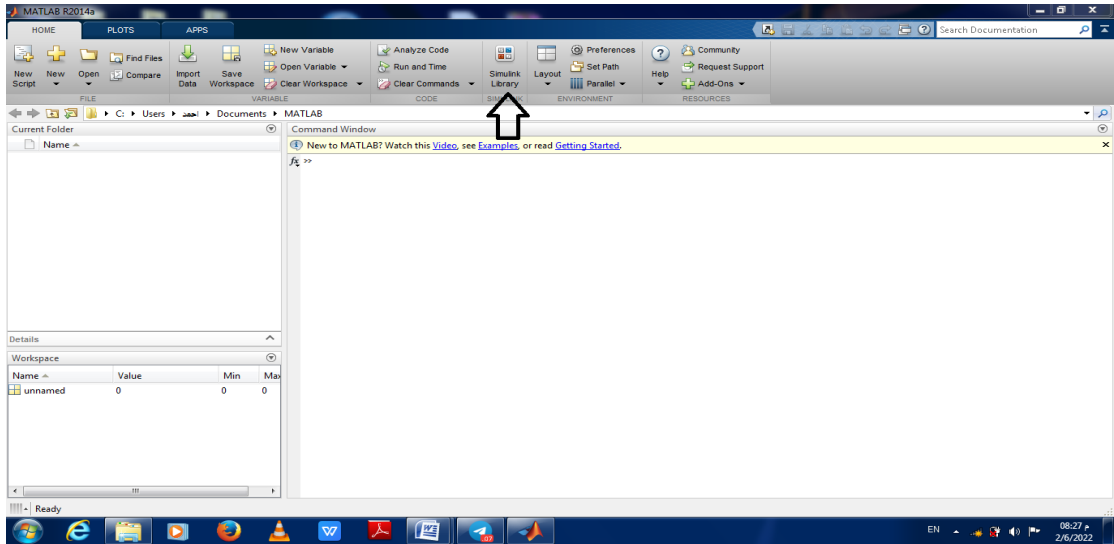
Figure3.2 Matlab interface

Open the library browser as shown in figure (3.3):
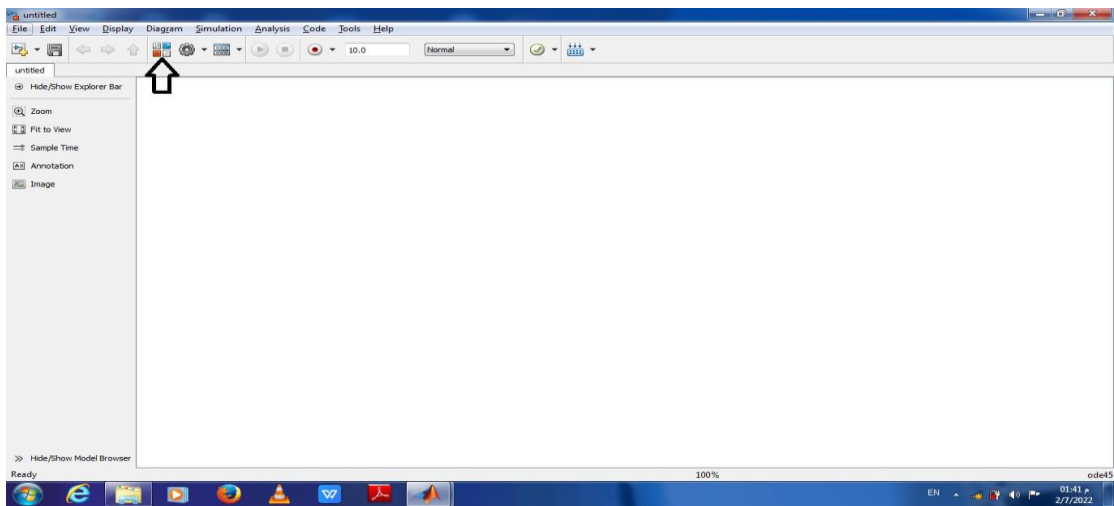
Figure3.3 Simulink interface

Search and choose the appropriate block parameters to use from the simulink library browser:
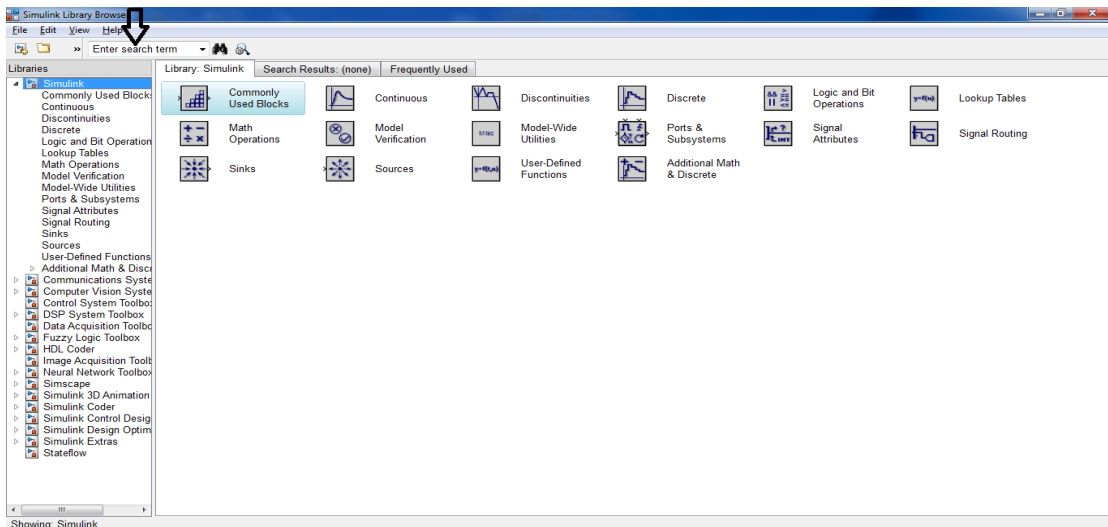
Figure3.4 Simulink library browser

We choose the block parameter constant to represent the variables to be inserted and we choose the appropriate function block parameter to do the mathematical operation and then insert the sink block parameter display to show the result as show in figure(3.5) and figure (3.6)
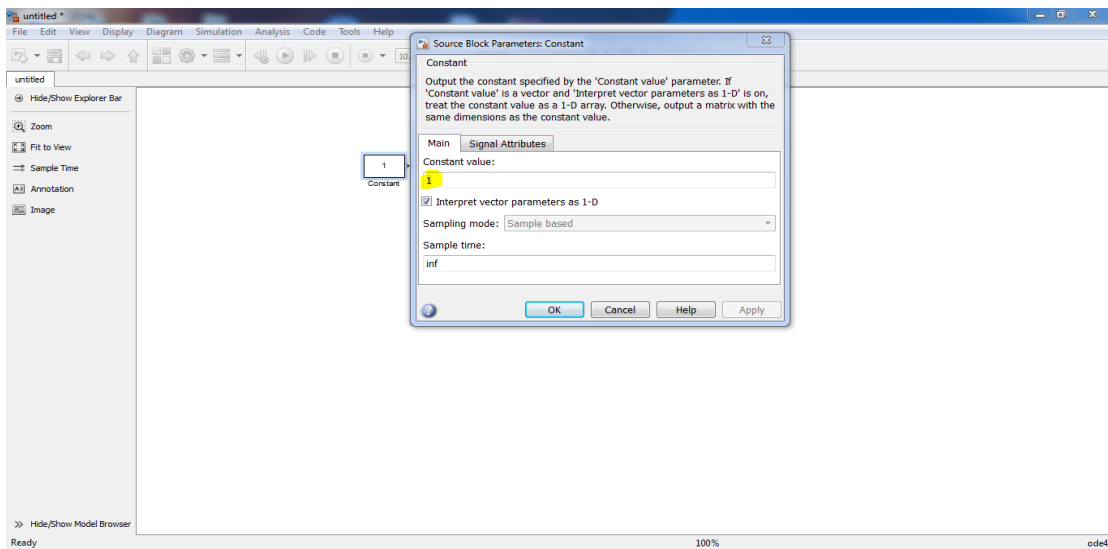
Figure3.5 Variables insert in constant block
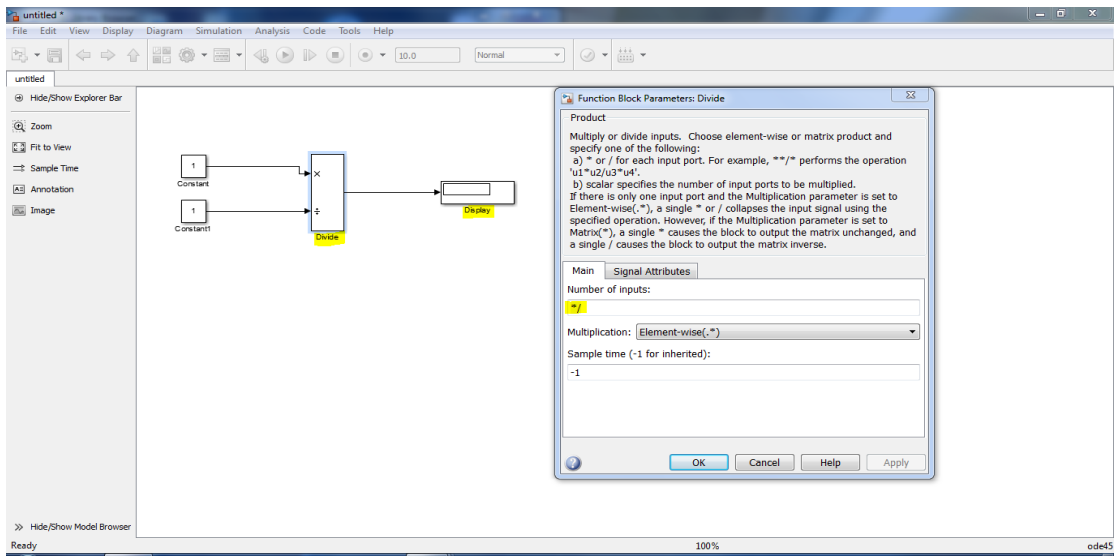
Figure3.6 Example of mathematical operation

Now we calculate the current required to protect the structure by representing Equation 2 in the simulink
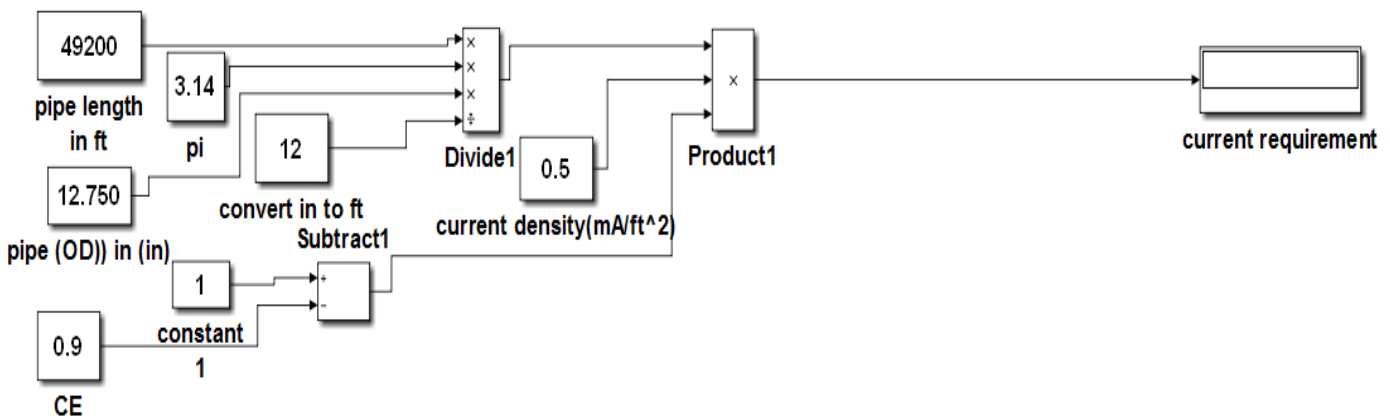
Figure3.7 Current requirements

And then we calculate the number of anodes using current density method, design life method and groundbed requirement method using Equation 3 Equation 4 Equation 5
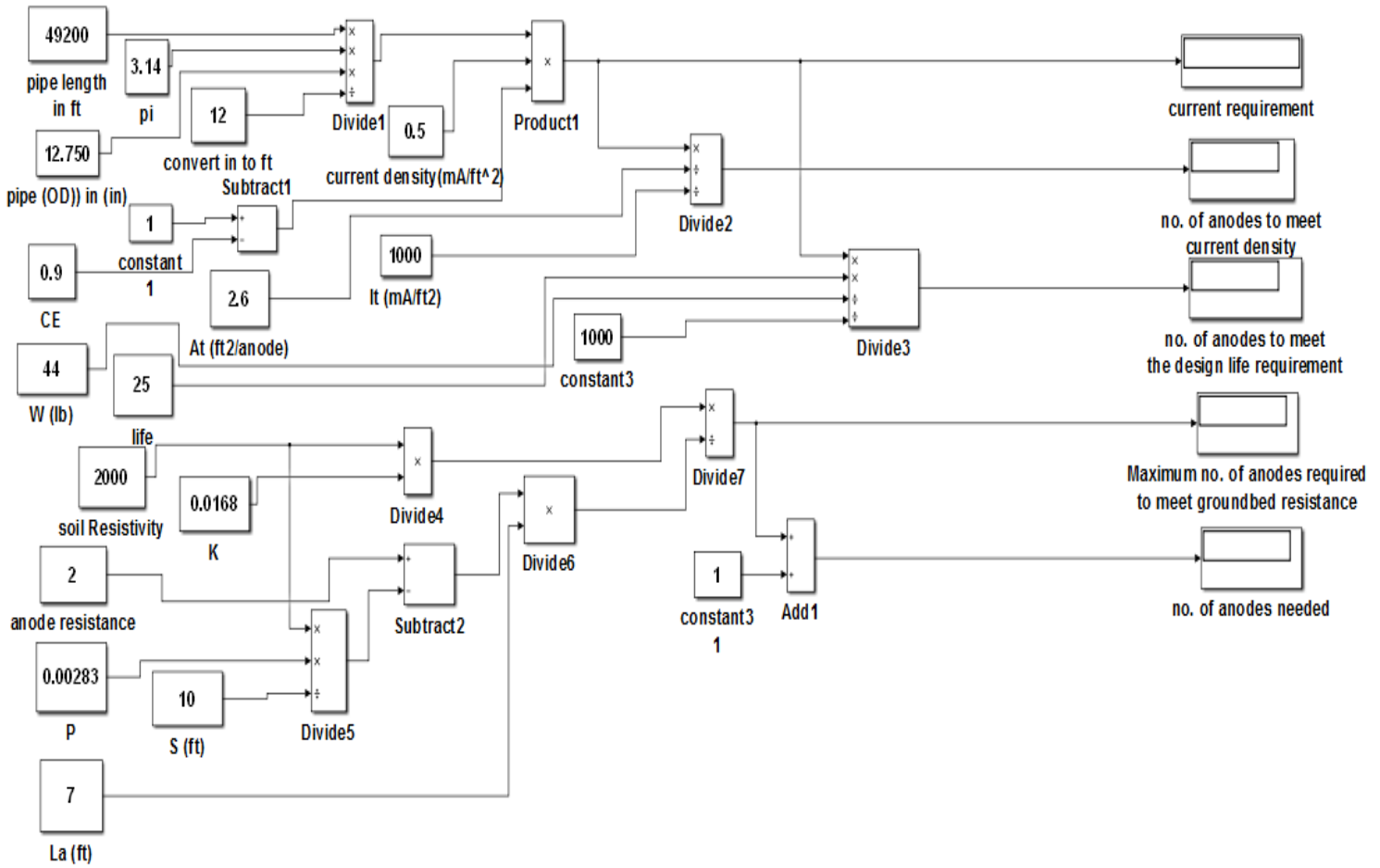
Figure3.8 Calculate number of anodes

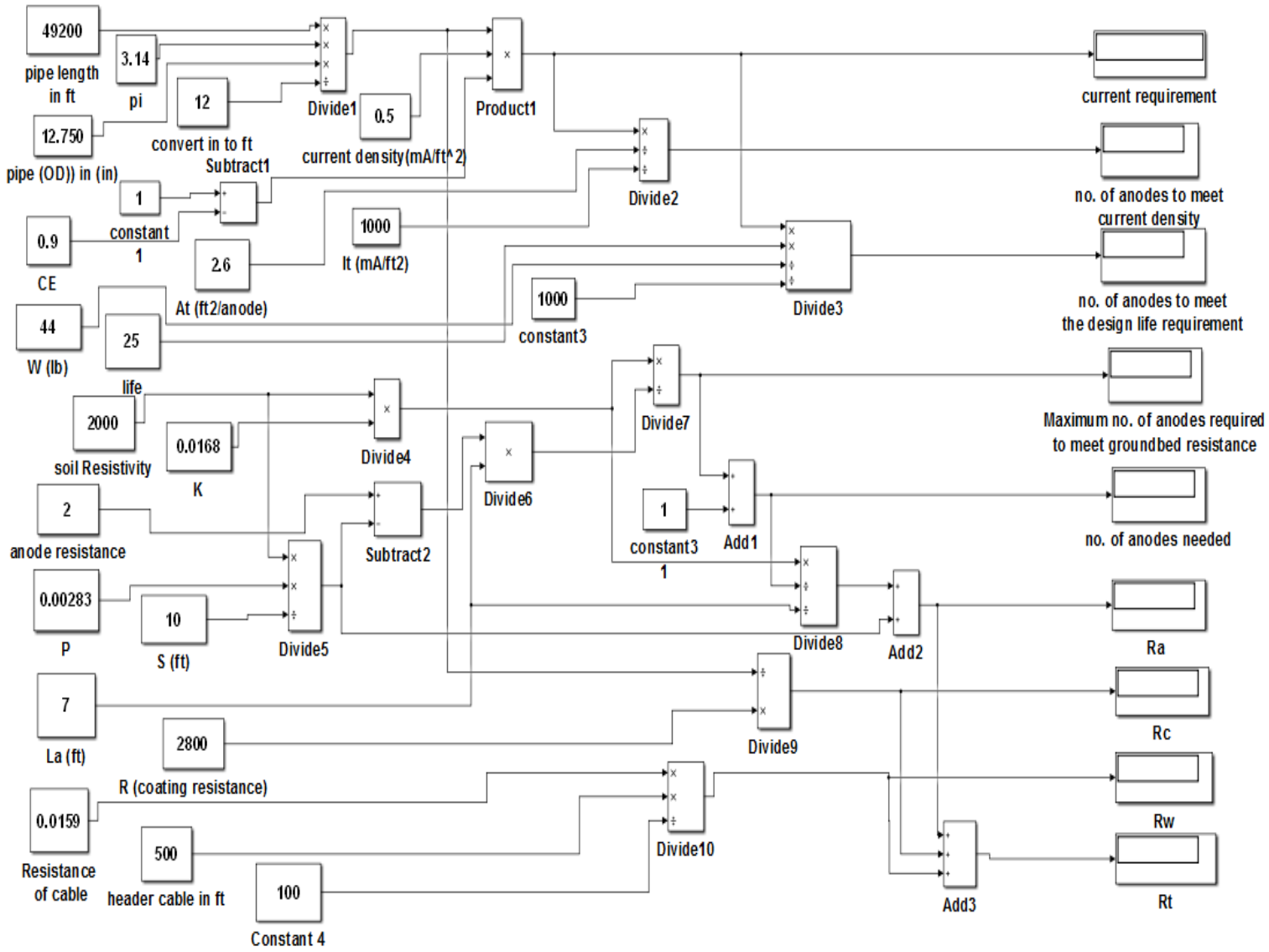After that we calculate the total resistance which is the summation of Equation 6 Equation 7 Equation 8

Figure3.9 Total resistance calculations

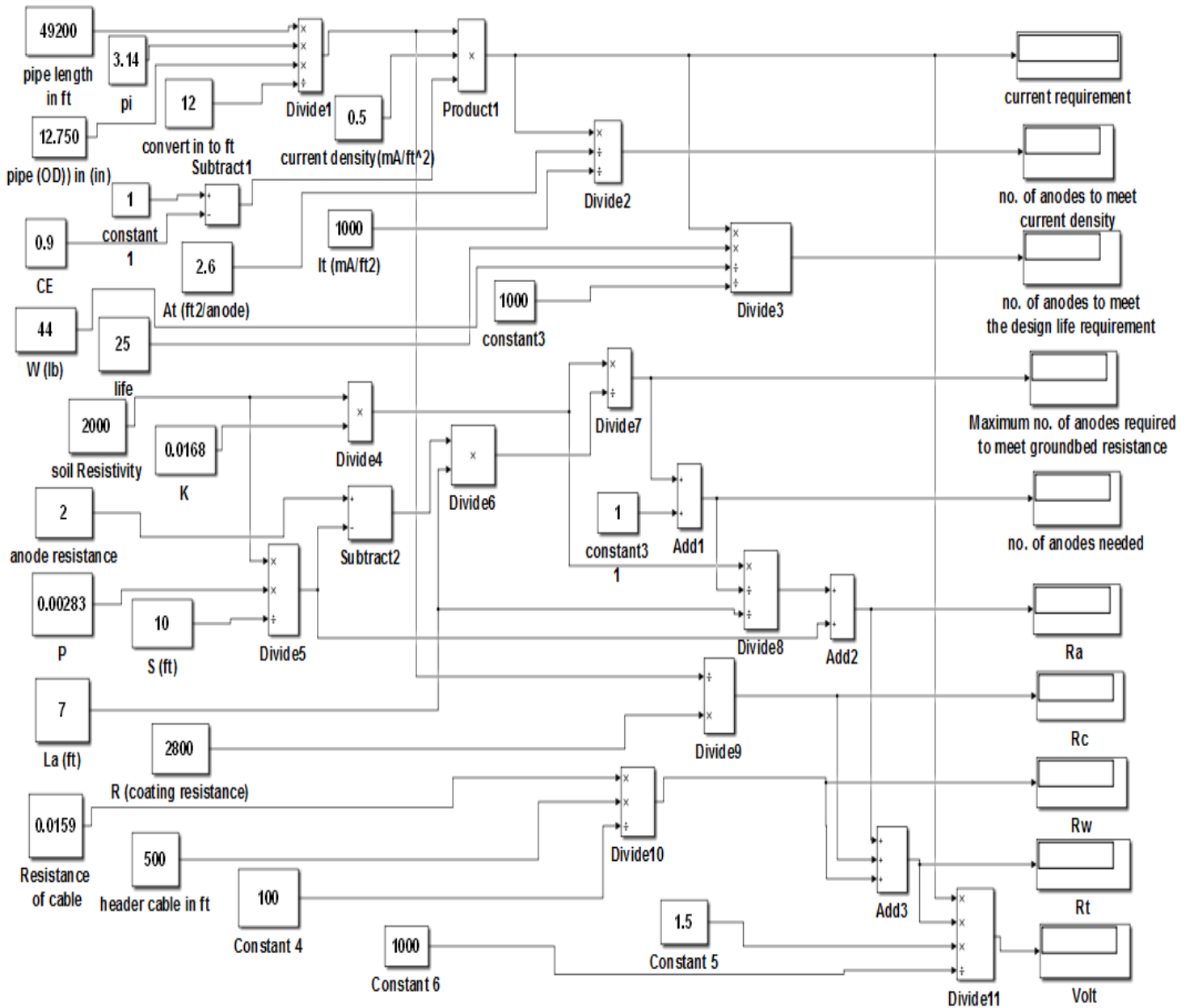Finally we calculate the rectifier voltage using Equation 10

Figure3.10 Rectifier voltage calculations

Chapter 4

Result and Discussion

4.1 Introduction:

This chapter describes the result of the simulation work done for the two CPS's and show the comparison between the results using the same design data with different soil resistivity.
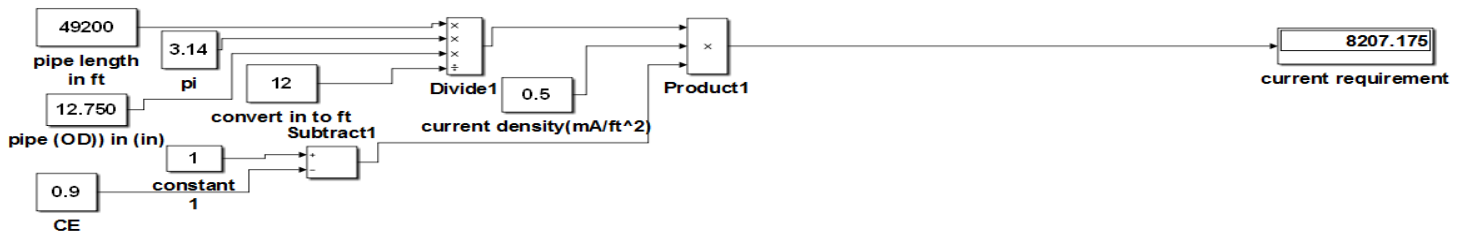
4.2 Results:
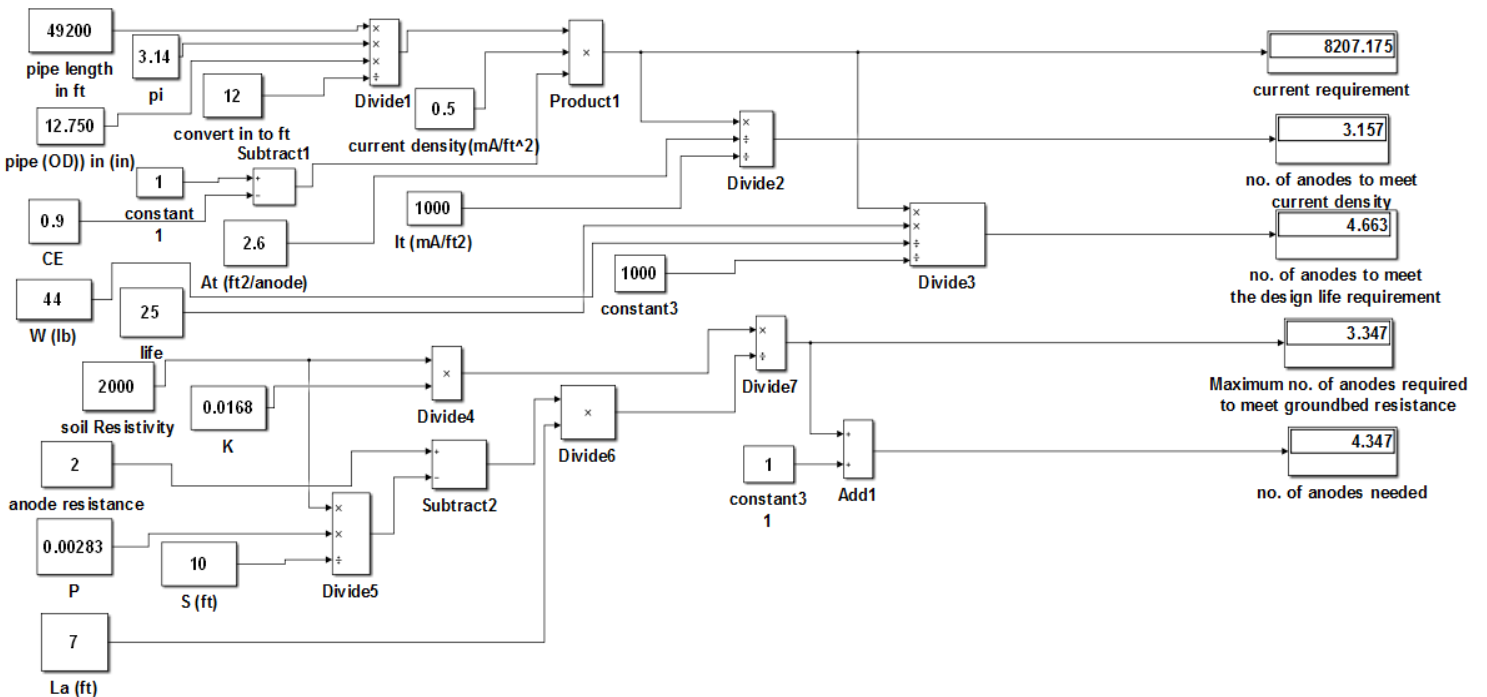
4.2.1 First CPS Result

Figure4.1 current requirement
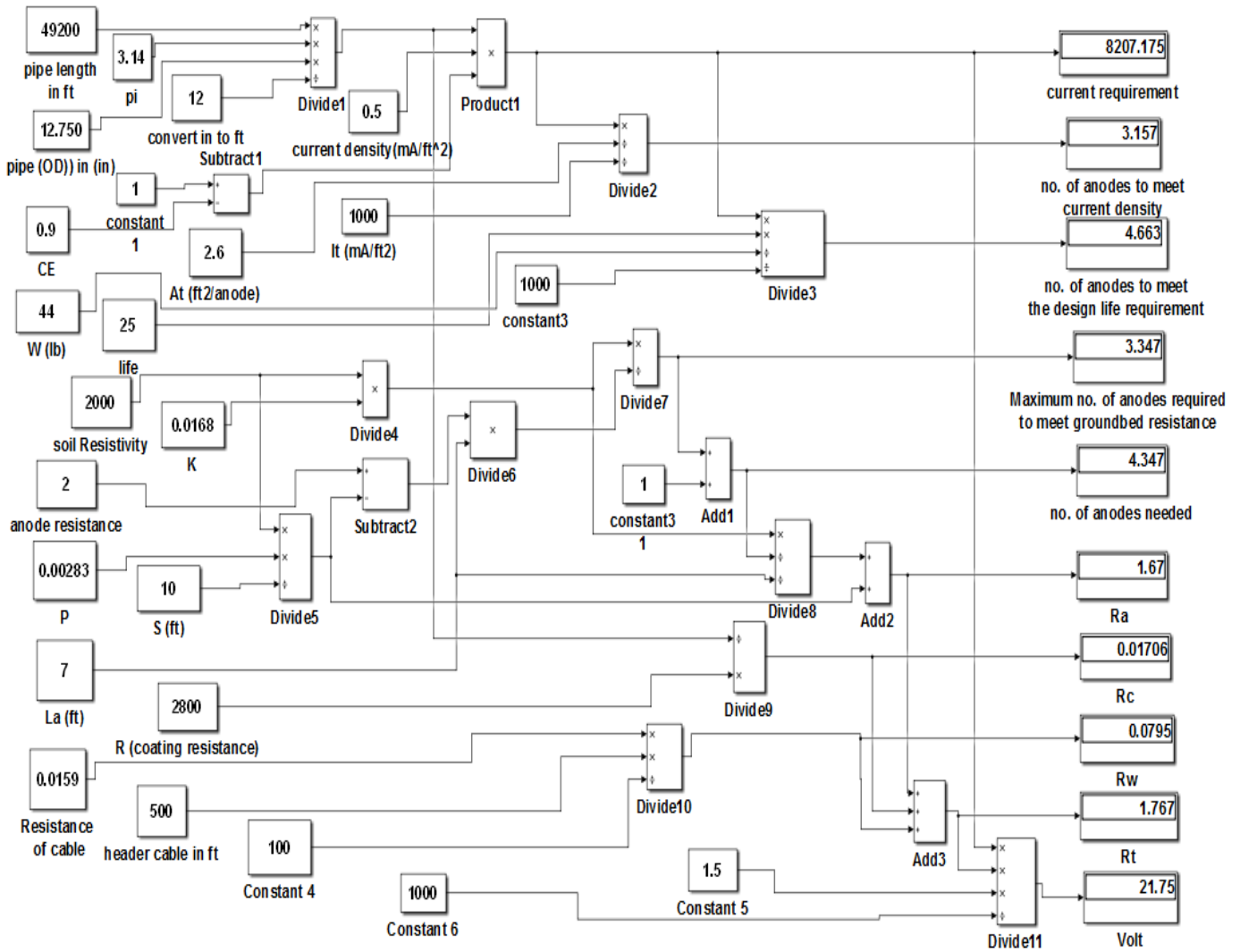

Figure4.2 Number of anodes

Figure4.3 First CPS result
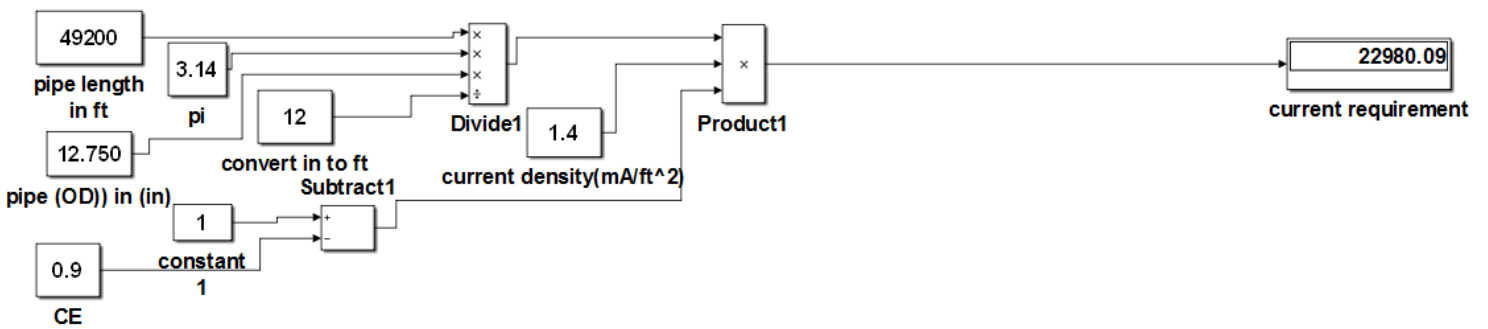
4.2.2 Second CPS result:
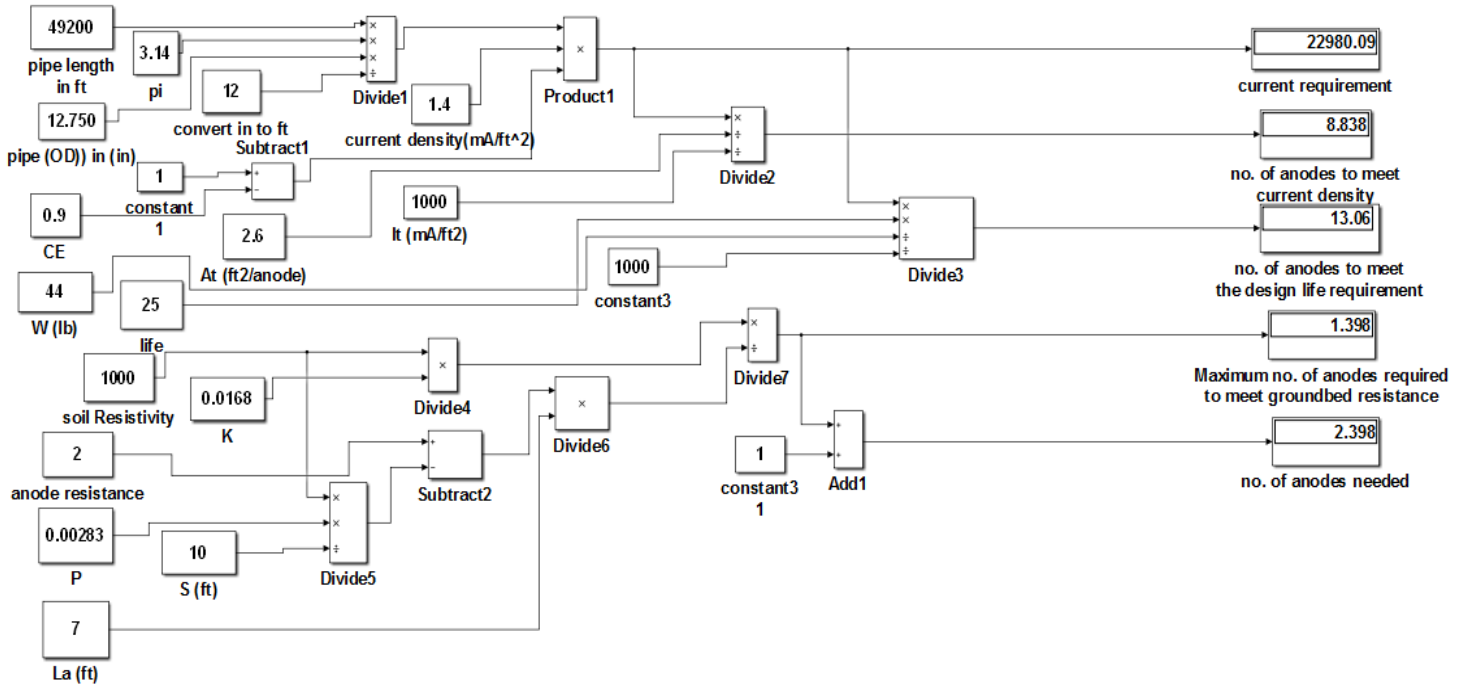

Figure4.4 Current requirements

Figure4.5 Number of anodes

The assumed paralleling factor (P) value does not match the calculated number of anodes, so we impose a new value for the paralleling factor and recalculate until the calculated number of anodes matches the number of anodes in the table where the value of the paralleling factor was imposed.
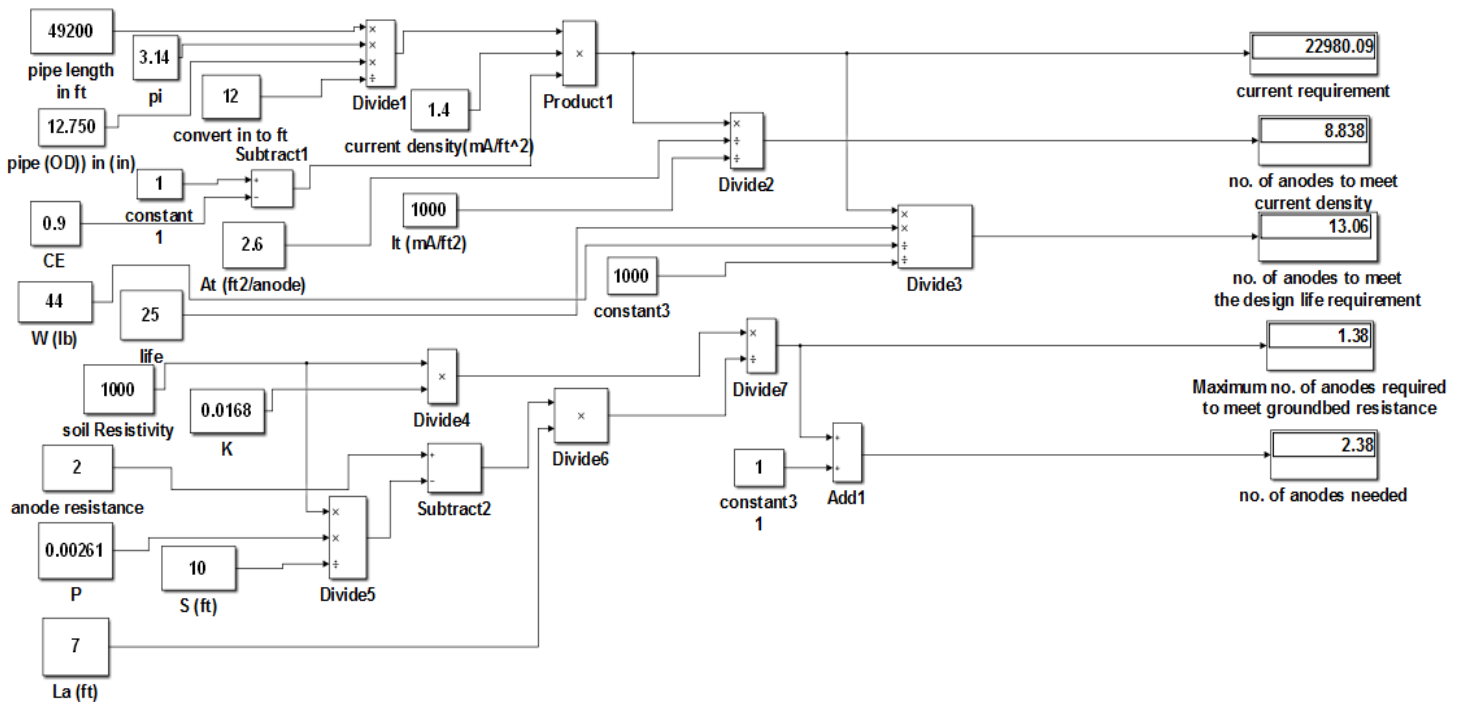

Figure4.6 Number of anodes

The calculated number of anodes by using the new imposed value of paralleling factor matches the number of anodes from the table.
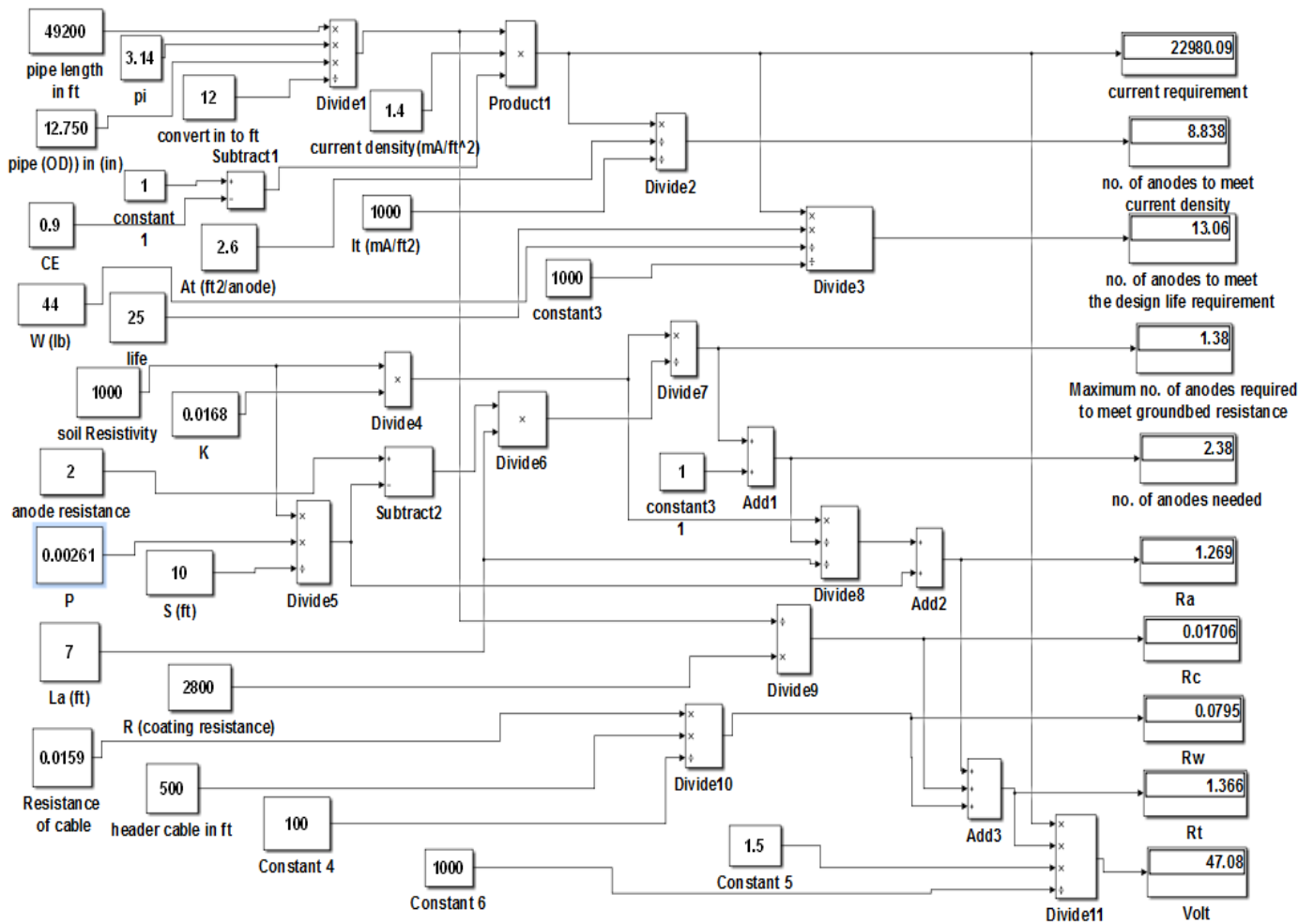
Figure4.7 Second CPS result

4.3 Result comparison:

Table4.1 Results comparison

Simulation Result	First CPS	Second CPS
Required current	8.207 (amp)	22.98 (amp)
Number of anodes	5	14
Groundbed resistance	1.67 (ohm)	1.269 (ohm)

Rectifier voltage	21.75 (volt)	47.08 (volt)

It's clearly that we choose the highest number of anodes calculated from the three equations for the two CPS's to provide the required current through the design life of the structure to be protected and to meet the groundbed requirement.

4.2.3 DC power specifications:

In consideration of factors, such as greater CP current will be required at initial polarization stage for pipeline, on the other hand, grounding resistance of anode bed will be increased in dry season and along with the time extension, the capacity of SPU shall be designed with sufficient surplus and may accommodate any unforeseen increases in anode grounding resistance. The table below includes the size of the SPU chosen accordance to the available manufacture catalogue.

Table4.2 DC power specifications

CP Station	Current required (A)	Output Voltage (V)	DC power rating
CPS 1	8.207	21.76	24V/10A
CPS 2	22.98	47.13	50V/30A

Chapter 5

Conclusions and Recommendation

5.1 Conclusions:

Based in work presented through this study the following conclusions can be pointed:

- The model has been successfully developed and proved to be effective in calculation of the current required, total number of anodes needed and the rectifier output voltage.

- The results show that the applied current increases as the soil resistivity decreases

- Also As the number of anodes increases the total resistance of anode groundbed decrease, just like if the amount of moisture around the anode increase the resistance of anode ground bed decrease this lead to an increase of current discharge by an anode.

- This study confirms that modeling of the ICCP system increases the accuracy of the results, reduces the time required to perform the calculations, and allows the variables to be modified without the need to repeat all the calculations.

5.2 Recommendation:

From the outcomes of the research, the following recommendation can be pointed:

- Installing a sufficient number of cathodic protection stations along the line.

- Periodic inspection and maintenance of CP system components.

- Paying attention to the areas of interference with other lines, railways, or any other external current sources (stray current) if found.

- This model was developed with a new pipeline data, in the future we recommend to use this model to evaluate the performance of an existing CPS.

- We recommend studying the effect of other parameters in future researches, such as pipeline length and diameter, anode weight and dimensions and efficiency.

- This study focus only on the modeling of ICCP system without considering the economic side in details, so its recommended that Incase a new study made, economic aspects can be take into consideration with more details.

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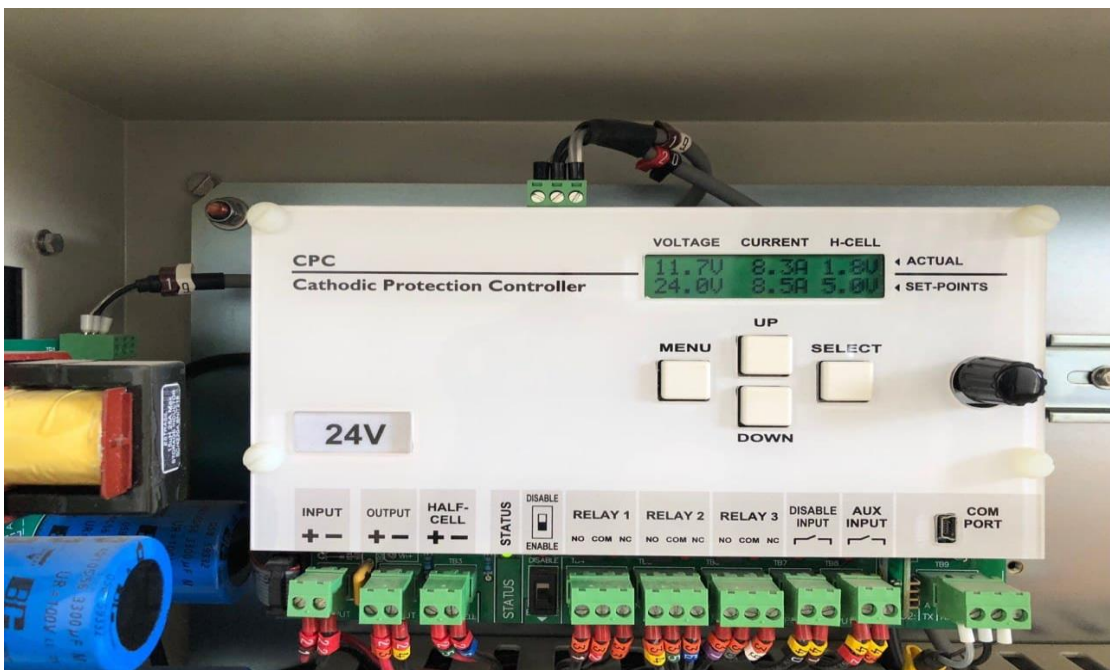
Appendix

Image shows CP station

Image shows the CP controller for solar power (rectifier)

Image shows rectifier for AC power

Image shows scrap steel anodes

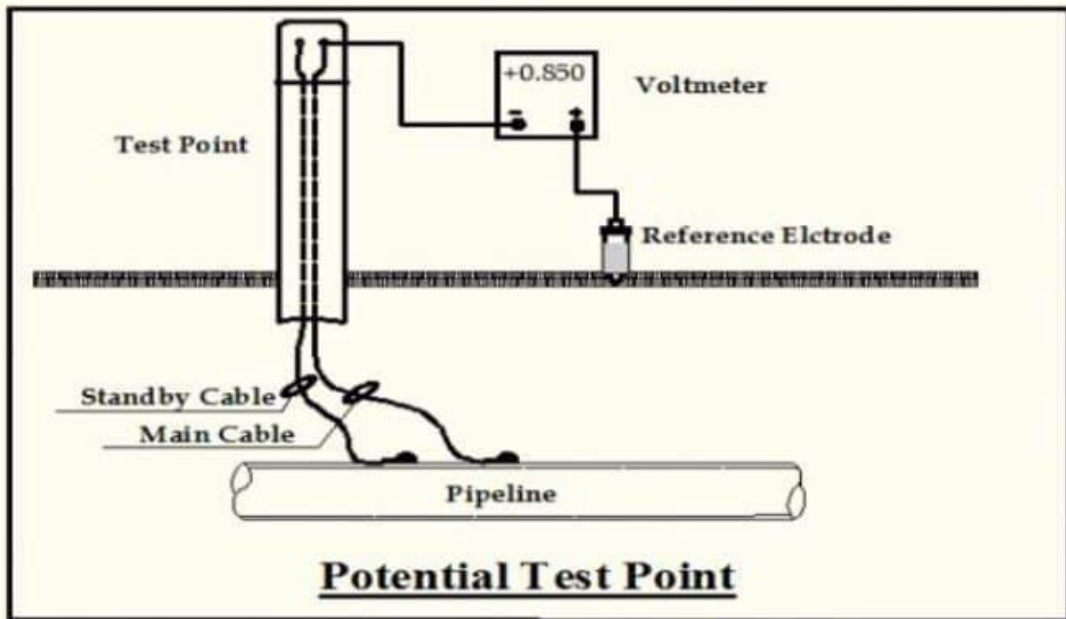**Image shows MMO anodes**

Image shows CSE

Image shows multimeter

Figure shows pipe to soil potential test