

Impressed Current Cathodic Protection and Environmental Impacts

Aezeden Mohamed

Associate Professor, Papua New Guinea University of Technology,
Lae, Morobe Province, Papua New Guinea
aezeden.mohamed@pnguot.ac.pg

Noel Martin

Former Masters Student at Department of Civil Engineering,
Papua New Guinea University of Technology,
Lae Morobe Province Papua New Guinea

Abstract

The Impressed Current Cathodic Protection is one of the key methods of protecting steel structures including, jetties, gas pipelines, oil tanks, harbors wharfs, ships and bridges. Impressed current method is applied throughout the world as the advanced and modified method of protecting structures from rusting or evade possible corrosion. The method is also considered to be fit in an environment to ensure its free from releasing hazardous substances that may cause destructive to surrounding wildlife's and its natural beauties. In Papua New Guinea, the impressed current method of protecting structures from corrosion are practiced by both state and companies established to arrest and mitigate corrosion. The polarization and depolarization of currents or electrons vigorously mitigate the flow of electrons from anodes to cathodes. The electrons then tend to migrate (lose electrons) from the more active metals (anode) to less active (structure, cathode electrode). In the process, active metals decays and corrode thereby protecting the less active metals (steel pipelines and tanks). in the process, production of pollutants is imminent from anodes used and thus necessary steps are undertaken to ensure all is minimized and mitigated. Current from the transformer rectifier flows on a consistence manner which supplies negatively charged electrons from the cathode (structure) and proceeds it through connection cables towards anodes (polarization). At anode, the oxidation reaction takes place thereby gaining oxygen ions and loses hydrogen ions. Reduction reaction occurs at the cathode where the hydrogen ions are gained and releases oxygen ions and thus, the process continues until the design life of the anode elapse and the active element sacrificed and corrodes and worn-out for possible replacements.

Keywords

Anodes, Cathodes, Environmental Hazardous, Polarization, Pollutant

Introduction

The Impressed Current Cathodic Protection system is applied widely in major structures such as sea bed pipelines, tanks, jetties and harbors. It is first developed to arrest the corrosion rate by defusing electrons from an anode to cathode (Loto et al. 2019). The ICCP protection system is also important in protecting corrosion from reinforced steel structures. In impressed current cathodic protection system, the oxidation reaction occurs at the anode thereby gaining all oxygen ions and losing or transferring hydrogen ions towards cathode (B. Mainier FR, 2014). Associated reduction reaction is taking place at the cathode where all hydrogen ions are withheld and loses oxygen ions.

Transformer rectifiers stationed on site controls the current from anode to cathode. The rectifiers are the external power sources which are applied in impressed current cathodic protection system to convert alternating current (AC) to direct current (DC). It is useful in that the electrons or currents are discharged off the anode and onto the cathode or structure to prevent corrosion. The transformer converts the current from the power source to required output voltage and then to direct current DC (Johns 2005).

The installation of impressed current cathodic protection system requires prior approval based on effective data and related requirement from standard design procedure manuals. This encompasses thorough understanding of structural protection based on the evaluation from initial stage of feasibility studies to actual construction. Analyzing climatic conditions including temperature and humidity and the electrolyte (earth, river or concrete) resistivity are considered as vital aspects of impressed current cathodic protection and galvanic anode system (Classnotes 1996). The environmental safety is considered priority and paramount from initial stage to final stages.

Puma Energy in Papua New Guinea is one of the worldwide company which uses both types of cathodic protection. This particular paper will discuss on the Impressed current protection method on site used on site.

1.1 Cathodes

Cathode is the electrode or structure that is about to be protected, either unground pipeline or sea bed pipeline including jetties reinforced structure and tanks. The cathode acts as the electron receiving object from anode (releasing hydrogen ions). When depolarized from the current supply source, the cathode becomes positive ions and anode becomes negative ions. As the connection is established or charged, the anode becomes positive and cathode becomes negatively charged ions (Sataloff et al. 2001).

In an electrolytic composition, there is a chemical reaction taking place in which more active metals are given off electrons see figure 1. This tends to be active metals such as magnesium and other related elements found in electromotive force series as designated in table 3 or group one and two of the periodic table. The cathode electrode gradually gains electrons especially hydrogen ions and remains protected while oxygen ions continues to discharged into anode. The cathode electrode are then vigorously protected by gaining hydrogen and reducing oxygen and its known as reduction reaction at cathode electrode (M. Attarchi 2000).

1.2 Anodes

The anodes are electrodes that undergoes a consistent oxidation reaction where the hydrogen ions are given off to gain oxygen ions. during polarization, the ions flow from cathode to anode and the electrons are given off from anode into electrolyte (Basics et al. 1997). In this way, the active metals corrode as disintegrates into the soil thereby protecting cathode electrode or structure.

The anodes are more active elements which reacts quickly with the surrounding environment thereby protecting the cathode. The positively charged hydrogen ions are given off easily into the electrolyte (soil, water, concrete) which is then attracted to the negatively charged cathode electrode thus giving off oxygen ions. In this way, the structure is protected (Water & Treatment 2019).

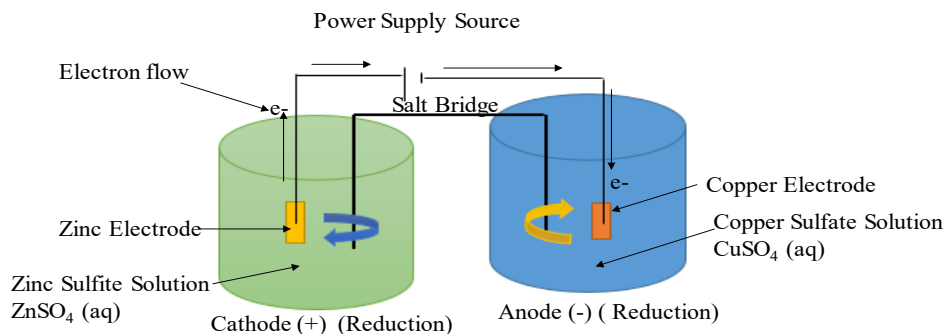


Figure 1. Simple electrochemical phenomenon of releasing electric charge particles from aqueous (aq) solution from anode to cathode (Brenna et al. 2005).



As designated on figure 1, the electrochemical process takes place in which the anode loses electrons during polarization and moved to cathode where reduction occurs. This is the same principal that is being applied at the

impressed current cathodic protection process. the more active zinc sulfate reacts quickly and loses to copper sulfate solution. Because the zinc electrons are exited and higher in activity series than copper the electrons flow from zinc electrode to the standard copper electrode. Salt bridge neutralizes both solutions to maintain unity while voltmeter is placed to measure the electrons potential of the zinc electrons.

1.3 Electrolyte

Electrolyte is the substance that is electrically conductive enough to allow current to flow through from negative terminal (anode) to positive terminal (cathode) as shown in figure 2. According to (Reactions 2001), the electrolyte can be liquid solution or soil that makes possible for current or electrical charges (electrons) to easily flow through or it can be concrete. The figure 1 depicts same principal that is practiced in impressed current cathodic protection.

The electrolyte (soil/water) plays an equal important role in ensuring electrons are transferred without much resistance which can affect the cathodic protection on the proposed structure. The corrosion rate of a structure is directly proportional to electrolyte resistivity (J. P. Guyer et al. 1989). When higher the resistance of an electrolyte to allow current/electrons through, the corrosion rate is minimized as there is less reduction and oxidation on both anode and cathode as designated on figure1 and equation 1.

The same process and the ideology is applied throughout the world. World renowned companies are soberer in delivering the project with effective management of environmental issues and chemicals if hazardous. PNG Limited Puma Energy is no different to the process, procedures and regulations



Figure 2. Flow of electrons from anode to cathode in pipeline installations with rectifier/transformer when polarized (Water & Treatment 2019).

As noted from figure 2, oxidation occurs at anode thus electrons move to cathode (pipeline). The reduction reaction associates at cathode side which gains hydrogen ions from anode to give off oxygen ions. The figures 1 and 2 shows the same phenomenon that is necessary to protect steel structures more effectively. Electrolyte (soil) of an impressed current cathodic protection plays an important role in ensuring the structure is protected from possible corrosion depending on its rate resistivity. If the resistivity of the soil is high, corrosion rate is high as the electrodes (cathode and anode) do not gives and gain electrons easily.

1.4 Transformer/Rectifier

The cathodic protection rectifiers are external power sources used to convert from alternating current (AC) to direct current (DC). Transformer is also housed in the junction box to reduce and increase voltages thus apply appropriate potential to ensure adequate protective electrons emitted during polarization (Summit 2019).

In bigger oil and gas industries, there are numerous transformers and rectifiers established in each interval of the pipelines to monitor the voltage and current for cathodic protection as designated in figure 2. Control transformer rectifiers are mounted and housed in two sections, with the main transformer which is the stepdown transformer being stationed together with rectifier and mounted on top of the rectifier to ensure that voltages is reduced to supply adequate direct current to the cathodic protection structure (Types & Conditions 2002).

1.5 Instant-Off Potential

Instant-off potential is the measure of cathodic protection immediately after current is switched off from the CP rectifier. Driving forces within the cathodic protection system can be difficult to analyze the data to exactly understand the negative electrons present in the structure (Zafiris & Midstream 2011).

In an instant-off potential estimation in a pipe-to-soil, the pipeline potential appears more negative than its genuine potential due to electrolyte IR-drop mistakes caused by cathodic protection (Brenna et al. 2005). The instant-off potential estimation remedies these mistakes. The CP current is quickly halted to create a "genuine" pipe-to-soil potential, which is free from undesirable IR drop impacts and taken some time prior to obvious depolarization. When the CP current is turned off, the current descends to zero ($I=0$ amps) and causes the IR drop (Mehdi Attarchi, 2008). This estimation produces a rectify degree of the level of assurance afforded to the pipeline. When it isn't conceivable to quickly halt the CP current, an elective strategy such as a corrosion coupon is utilized.

Literature Review

Impressed current cathodic protection (ICCP) system is one of the most reliable method of arresting corrosion reaction in structure such as, oil pipelines (both underground and sea), jetties, harbors, wharfs, oil/gas tanks, water pipelines etc. The reactions of both oxidation and reduction resulted in structure protected from possible corrosion and thus is guided throughout the lifespan of the established structure through consistent monitoring and check. With respect to exposed structure or pipes, this notion is possible and is more affordable for visual inspection.

However, in submerged structures, it is difficult to understand and monitor or propose for necessary rectification works as the objected is covered and buried some meters below earth's surface. In such cases, the impressed current protective system is more reliable method to protect the underground structure without much destructive testings. the most reactive elements compared to structure is placed as anode approximately five meters away from the structure and less reactive becomes cathode electrode (structure). The rectifier/transformers are also stationed to monitor current and potential of electrons.

Corrosion is an electrochemical process in which the current leaves a portion of a structure (anode) and passes through an electrolyte and re-enters the structure at cathode side. As described in figure 1, oxidation occurs at the anode and reduction takes place at cathode (Ee 2015). The process is quite useful because the section where the electrons depart is protected while the corrosion takes place at the cathode. In other words, the corrosion is simply giving off energy to become stable and return into earth or soil.

The cathodic protection is necessary to protect the structure and arrest corrosion to maintain effective rust resistance mechanism. In the absence of the transfer of electrons, iron structures easily give off energy and returns to soil thus become stable. The substances that taken out from the soil easily returns to the soil and become stable when not protected.

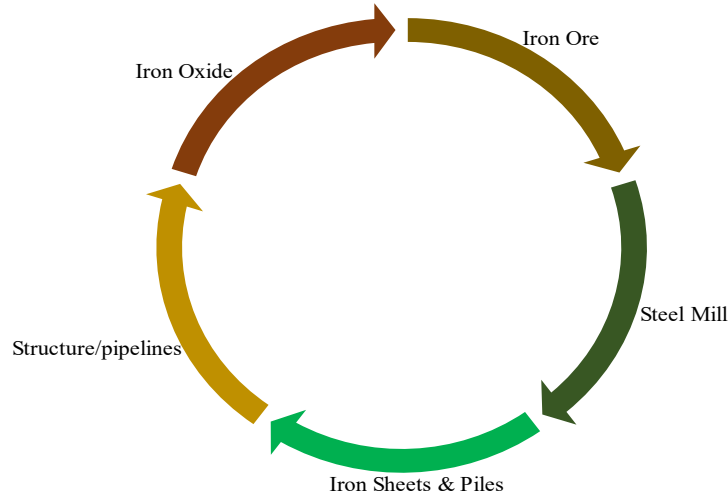
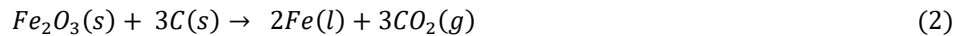


Figure 3. The electrochemical process in which the iron ore changes from steel and returns to iron oxide (Basics et al.1997).



From figure 3, it can be seen that the iron ore is reprocessed with ejecting much energy through a controlled temperature with adequate energy to produce iron sheets in the form of melted liquid. The carbon dioxide or carbon monoxide is given off as the main gas during ferrous production in mills. The process is then reversed and energy is given off when rust or corrode and results in iron oxide as designated.

2.1 Electrolyte Resistivity

Electrolyte resistivity is the ability of any electrolyte (soil, water) that do not allow electrons and current to flow through. In a solution or soil that accepts current is a good conductor of electricity. However, in an impressed current cathodic protection system, the resistivity of an electrolyte is important for the benefit of the structure because electrons may not be easily accepted which will allow more electrons loos resulting in corrosion. The good resistivity of an electrolyte would mean that the effective cathodic protection is imminent and the cathode electrode is anticipative to be protected for its design life.

According to (E. Design & Protection, 1985), the resistivity of an electrolyte is directly proportional to structure's corrosion rate. In an impressed current cathodic protection system, when electrolyte resistivity decreases, more current or electrons are allowed to flow into the electrolyte from the structure thus structure corrodes rapidly (Ee 2015). Increase in electrolyte resistivity would mean less corrosion occurs at the cathode structure. Resistivity electrolyte can be soil, water, sea and other mediums that allows or restricts flow of current as depicted on table 1.

It is very useful for impressed current CP system to determine the electrolyte resistivity first using appropriate instruments or through laboratory testing to ensure the type of electrolyte is known for possible impressed current CP system construction. This gives associate estimates of the approximate actual design life of a structure prior to corrosion.

Table 1. Corrosivity of soil for steel based on soil stricture as noted from (Ee, 2015).

Soil Resistivity range (ohm-cm)	Corrosivity
0 - 2,000	Severe
2,000 - 10,000	Moderate to server
10,000 - 30,000	Mild
> 30,000	Unlikely

Though there are different methods used to arrest and contain corrosion, soil resistivity has great effect on controlling and minimizing corrosion. As noted earlier, more resistive the electrolyte (soil), less corrosive the structure and ultimately, structure is protected from possible corrosive reactions. The same principle may be applied on liquid electrolyte in cases of seabed oil pipelines that run through under sea.

Electrolyte resistivity determines the effective design life of a structure and thus important to take into consideration when designing a cathodic protection system.

2.2 Cathodic Protection Current

Cathodic protection current demand is the amount of electricity required to polarized electrons in a structural cell membrane (Classnotes 1996). Current changes the environment around the metal thus delays the corrosion reaction. In an impressed current CP system, current drives the corrosion electrons from the cathode through conductor cables into rectifier or junction box and deposited into the anode. When the current from the external power source is switched off, the electrons depolarized and oxidation occurs at cathode instead of anode.

In impressed current CP system, current plays a vital role in driving polarized corrosive electrons from the cathode and deposited into the anode. Anode corrodes and decays instead of cathode which is why the process is known as impressed current cathodic protection. As such, it is best to allow current flow within the cables connected from cathode to anode according to standards and specifications (Summit 2019).

The structure - to - electrolyte voltage is measured between the stable reference electrode pinned into the nearest cathodic structure and structure surface as designated in figure 4. This is performed to monitor the exact flow of current to drive electrons from cathode to anode.

2.3. Environmental Impacts

The environmental impacts are considered minor but may also cause long term effect when anodes are dissolved into the soil. When anodes decay and decomposed chemically during electrochemical reaction, there is a possibility of imparting chemical waste into the streams and soil (Interior et al. 2013). When rainwater infiltrates into the soil, it dissolved the decomposed buried anodes and deposits into the rivers and streams. Thus, there's a possibility of potential impacts on the environment including all cathodic system and not only impressed current. The changes of environmental impacts via impressed current is minimal compared to sacrificial anode cathodic protection system. This is because unlike sacrificial anodes where it entirely depends on its anode potential difference, ICCP entirely relay on external power source to force the protective current through from anode to cathode and in this way, the chemicals are not possible to release to the surrounding environment (Dhany 2021). Additionally, the impressed current anodes corrosion-resistant which are basically selected Irons and graphite's which are not too hazardous to the surrounding environment and thus minimal or no environmental impacts are imminent.

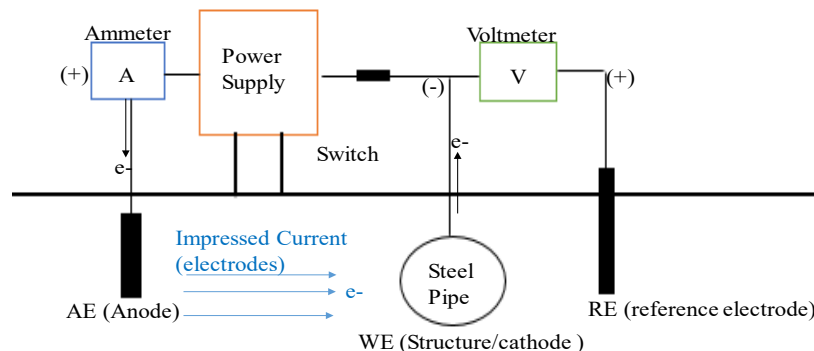


Figure 4. The flow of current that drives electrons from cathode to anode when polarized (J. P. Guyer et al., 1989).

As illustrated in figure 4, when the switch is turned on, polarized electric charges are driven by current through conductor connected to cathode from power supply and further down to anode stationed as sacrificial reactor. When the corrosive electrodes are deposited on the anode side, oxidation reaction takes places in which the hydrogen ions

are released to cathode through electrolyte (soil) as impressed current. At the cathode or structure, reduction reaction occurs in which the hydrogen ions are gained and releases oxygen ions (corrosive electrons).

Thus, pipe is protected from possible corrosion through this process and is known as impressed current cathodic protection. It is seen that the impressed current electrode discharges positive current and thus, it acts as an anode within the cell (Ashworth 2010). Voltmeter (V) is placed to measure the electron potential of the negatively charged electron particles while ammeter (A) is also installed to measure the flow of electric current from cathode to anode. Reference electrodes are placed to monitor the flow of exact current throughout the flow cycle.

2.3 Environmental Influence on Cathodic Protection

Designing cathodic protection on offshore pipelines installation will not be similar from the fuel tank installation on land. On the same manner, the installation of water tank from inland will not be same as that of pipeline connections at the coastal. This is because variations in climatic conditions and environment will drastically affect efficiency of the system both electrochemically and mechanically (Reserved 2009). In the humid environment, there is enough dissolved chloride in the air that rapidly gets trapped in the metals or ferrous materials and reacts quickly which results in producing brownish colors formed (rust) on the surface of steels unlike in cold environment.

As per the studies, it has been found that much of the corrosion differences in various locations have been subject to humidity, temperate, wet climates, differences in inlands and coastlands (Academy 2011). Of those mentioned and others, to effectively mitigate corrosion control and arrest corrosion deterioration of the ferrous metal structures, it is advisable to study and or analyze the type of environment especially climatic condition as warm climate contains more dissolved chloride ions than in cold climate. Most of the corrosion reaction is assisted by temperature and especially climatic conditions of proposed locality of the structure both mechanically and electrochemically (Davis et al. 1972).

2.3.1 Temperature

The influence on temperature on cathodic protection has been analyzed and studied to be important in that the polarized potential is decreased and hydrogen permeate into the steel can be susceptible for hydrogen embrittlement risk. Thus, increase temperature increases the risk of hydrogen embrittlement. It is therefore important to have cathodic protection structures maintained at a relatively low temperature (Liu et al. 2019).

2.3.2 Humidity

Humidity is a measure of how much water vapor in the atmosphere. In humid climate, there is more warm air than cold air thus results to more dissolved chlorine which usually occurs in the coastlands. In sea water it was discovered that, more than 1.9% mass of the ocean is chloride ions. Chloride ions are most often present in the humid temperature (warm) than in cold climate. Thus it is known that corrosion on ferrous metals in humid climate is more rapid than in cold and underground structure and pipes (Murray 1998).

Hence it is important that the various construction of cathodic protection structure also depends on the type of humid climate as there's variations in chemical element composition. In coastal areas, there are more dissolved chloride ions in humid atmosphere and deposits into the metals as water vapor. As such, the corrosion in humid is most rapid and hardly mitigate through other means except for impressed current cathodic protection system (Ambat 2001).

2.4 Chloride Ions in Ocean

The chloride ions are more dangerous to ferrous metals as its negative chloride electrons attracts more quickly to the anode (positive electrons) electrodes of the structure. The chloride electrons move towards cathode during depolarization and as a result, it competes with dissolved oxygen and hydrogen ions to form corrosion by reacting with oxygen and pushing out hydrogen in the form of gas (These 2001). Thus, in humid climate, the corrosion rate is more rapid than in cold climate. As such, the impressed current cathodic protection in offshore pipelines and onshore tanks requires effective corrosion protective methods to ensure chloride ions are arrested so that the structure do not reacts with dissolved oxygen and attracts chloride by positive electrodes (anode).

This is why, there are more and rapid corrosion in coastal areas than in inland cold climates because the amount of chloride composition in the atmosphere is less and in active thus corrodes very slowly. However, in less chloride sea waters, chloride ions are developed at the anode and releases chloride gas as shows in figure 5.



This chemical formula designates how chlorine ions are reduced to chlorine gas at anode in good sea waters.

2.5 Sacrificial Anode Electrodes

The anode electrodes play a vital role in protecting main structure from corrosion in cathodic protection system. Most active elements in the periodic table are considered and selected to sacrifice which in turn protects cathode from corrosion or re-categorized based on electromotive force series, see table 3. Elements such as, magnesium, zinc, aluminum or titanium and their alloys are considered useful in protecting abundant and commonly used element like iron and steel which forms cathode in cathodic protection for oil or gas pipelines and tanks including ship hulls and propellers (Parthiban et al. 2008).

Because sacrificial anodes are active and gives off electrons by nature and reacts more quickly, these elements have a profound electrochemical potential to attract corrosive electrons such as oxygen ions from iron and steel during polarization. This makes them more useful and sacrificial anodes for cathodic protection in pipelines, tanks and ships construction industries across the globe. During depolarization, anodes becomes negative and the electron charges changes from positive to negative and same is true for cathode side (Notes & Academy 1998).

When current is switched on and polarized in an impressed current cathodic protection, the anodes drives the current from the cathode through electrolyte (soil, water, concrete) and deposit the hydrogen ions into the cathode. This is where the reduction reaction occurs in which oxygen is released and gained hydrogen ions whereas in anode, oxidation occurs where oxygen is gained or arrested (corrosive ions) and releases hydrogen ions to cathode (Methods 2020). More deposition of hydrogen ions may cause hydrogen embrittlement on protected structure and care is taken to ensure right amount of current is supplied for adequate potential to drive the electric charges or current through.

2.5.1 Magnesium and its Alloys

Magnesium is electrochemically the most active elements widely used in common structural alloys of iron and aluminum. Magnesium is largely used in sacrificial anodes in any cathodic protection system of underground and offshore metallic structures such as, ships, submarines, pipelines, tanks, bridges and many other cathodic protection structures. Magnesium is not only used in CP system but also used in other products such as jet factories, vehicles because its alloys are considerably accepted to all criteria used in the industries such as, density, strength, stiffness and corrosion resistance (C. P. Design 1996).

The pure magnesium metals and its alloys are likely selected in cathodic protection as anode because its positive ions are easily oxidized to realize hydrogen ions to cathode. Dissolved oxygen ions react with magnesium ions to form magnesium oxide hence withholding corrosive ions flowing to the cathode electrode. Magnesium potteries some of the important aspects of an optimum elements compared to other element as noted earlier (Parthiban et al. 2008). Magnesium has specific high strength to weight ratio of 35% lighter than aluminum, 75% lighter than iron. Typical magnesium alloys weigh ~25% less than their aluminum counterparts at equal stiffness (P.E 2001).

2.5.2 Zinc and its Alloys

Countries such as India, USA and Canada including others around the world incur mush of the costs in corrosion up to billions and if not trillions of dollars annually to rectify or reconstruct corroded structures. There are various means of protecting steel structures thus, zinc and its alloys are preferable elements or compounds used to arrest corrosions. Zinc is equally used like magnesium with its alloys due to their tendency to loose electrons and corrode hence sacrificed to protect cathode electrode (Dqg et al. 1991).

In cathodic protection, zinc and its alloys are widely used like magnesium to protect important structure such as jetties, tanks, pipelines, and harbors for the benefit of cathode electrodes. This is considered useful due to its nature of rapid electrons loss and is profoundly used in cathodic protection in major structures. Zinc alloys are also used in other produce as its compounds do not react with oxygen or chloride easily thus corrosion resistance in alloy forms.

Methodology

The sustainable impressed current cathodic protection system is used in various structures to arrest and mitigate corrosive electrons as its one of the most common enemies of ferrous materials. As ferrous materials are abundant in nature and is commonly used throughout any type of structures due to its stiffness and hardness, it also associates with the corrosion risks (Staerzl, 1994). This is because ferrous electrons easily oxidized to form iron oxides (rust) and can be easily eaten away by reacting with other active elements such as oxygen and chloride. The energy is then released in the process with time to return back to the soil or become stable.

As such, various protective means of protecting steel or ferrous materials or from corrosion and hence the more reactive elements than irons are used to protect the steel known as sacrificial protection or impressed current protection. To effectively protect the ferrous materials from foreign materials, it involves sophisticated process and procedures and associated expenses are incurred (Shaw 2000).

The anode and cathode electrode of the impressed current cathodic protection is widely practiced across countries. Massive amount of funds are involved to ensure the service delivered effectively and efficiently to sustain goods demanded with the safest method that will not interrupt continuous supply of resources (J. P. Guyer 2017). As discussed earlier, cathode, electrolyte, anodes and current or potential are precisely required in their right portion to protect structures from corrosion. The serviceability of any size of structure depends on the design of cathodic protection system and the materials used as durability of time is the only limited factor that solely determines the quality of duration it last (Tezdogan & Demirel 2013).

There is a huge demand in this area of cathodic protection throughout the globe that requires best design practice for the rightful purpose to attain effective service life of designed structure. As corrosion is not resistant and it's a natural action that occurs where iron/steel gives off energy or recycle to its stable stage. Every material produced through ejecting energy must be protected and preserved at all cost as the natural actions are so profound that it tries to reverse it back to its stable stage (J. Guyer 2009).

3.1 Electrolyte Resistivity Data analysis

As analyzed from (Mailah & Bashi 2005), the following results are genuine based on research and experiments conducted for resistivity of an electrolyte. As previously discussed, the more resistant of an electrolyte, the better the cathode is preserved as electrons do not pass easily to cathode electrodes to be oxidized. This is why the cathode electrode depends partly on the electrolytic resistivity to offer a perfect corrosion resistant agent, retrieved from (Olthuis et al.1995) as shown in table 2. As noted earlier, electrolyte can be any medium that allows electrons to pass through with potential. There are various researches and experiments conducted to analyze the electrolyte of impressed current cathodic protection system.

Table 2. Effective protection of an impressed current CP based on their resistivity and conductivity as retrieved from (For et al. 2004).

No.	Resistivity (Ohm.cm)	Conductivity (mS/m)	Total Current (mA)
01	50,000	002	00474
02	25,000	004	952.60
03	12,500	008	1,9120
04	06,250	016	03,803
05	04,167	024	05,688
06	03,125	032	20,564
07	02,000	050	29,131
08	01,250	080	37,462
09	01,000	100	79,000
10	00833	120	92,488

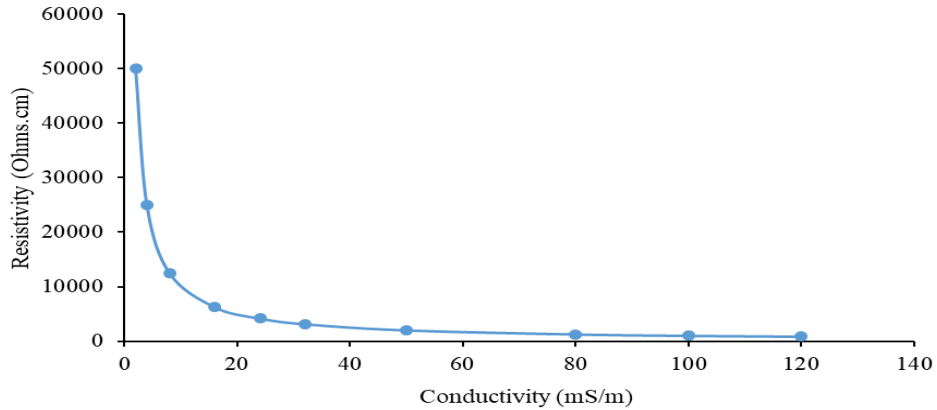


Figure 5. Conductivity versus resistivity of an electron potential in an electrolyte (soil) with various resistance.

As per figure 5, it can be concluded that flow of electrons depends on the type of electrolyte which eventually determines the effective protection offered to the structure. As resistance of an electrolyte increases, the current or electron flow is minimized and thus there's limited chances of cathode corrosion thus is good for the structure to be constructed. The more resistance the electrolyte, the more corrosion resistance is imminent and thus is a good electrolyte in cathodic protection system (Sasiadek 2008).

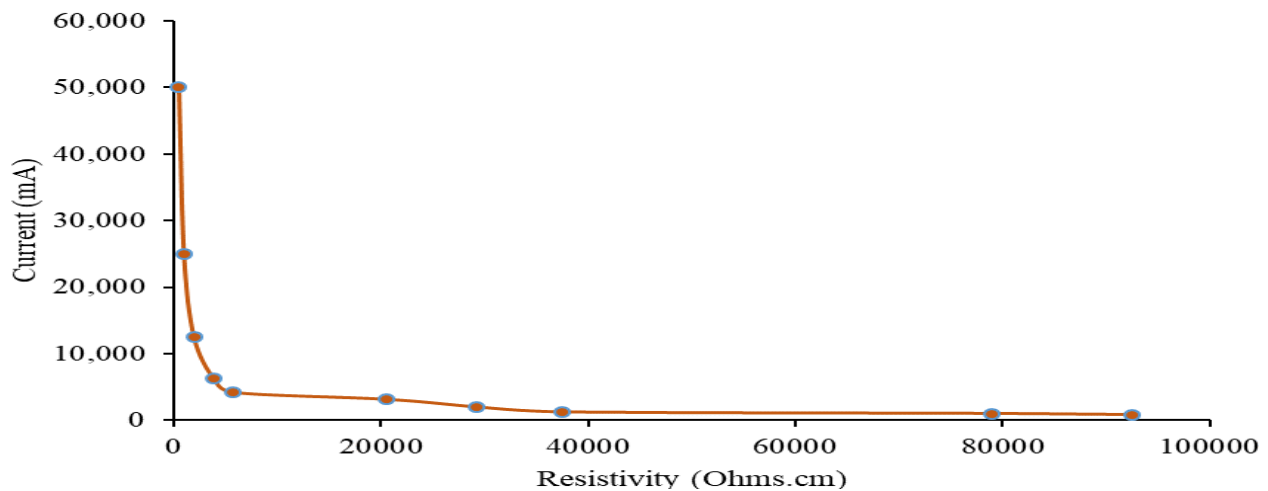


Figure 6. Shows current flow is highest at low resistivity of any electrolyte (soil).

As can be concluded from figure 6, at highest electrolytic resistivity the current flow is lowest as designated. This implies that the flow of corrosive electrons can be minimized when electrolyte resistance is highest and thus cathode is effectively protected from harmful and degrading electrons such as oxygen and chloride passing through electrolyte (soil) to react with the cathode. The cathode is safest at the highest electrolyte resistivity (Maiti & Bidinger 1981).

3.2 Electromotive Force Series

The electromotive force is difference in potential that gives rise to an electric current. EMF series are noted to be important in that thorough analysis may lead to effective selection of anode materials that will protect cathode electrode from possible corrosion (J. Guyer 2008). While corrosion is inevitable in nature, certain techniques such as sacrificial anodes, impressed current protection and galvanic protection assists in determining the structure's design life and productive service for years (Ashworth 2010).

Electromotive forces are selected based on their availability, costs effective and more active in nature depending on the type of work required. In anodic nature, iron tends to be less anodic while potassium is more active and is most

anodic. This means that iron steel can be protected from corrosion by sacrificing potassium. In order of ascending, iron can be protected by elements more anodic after iron. Which further signifies that more active elements in anodic cluster shall be used as anode while iron becomes cathodic electrode (Rose-Innes 1985).

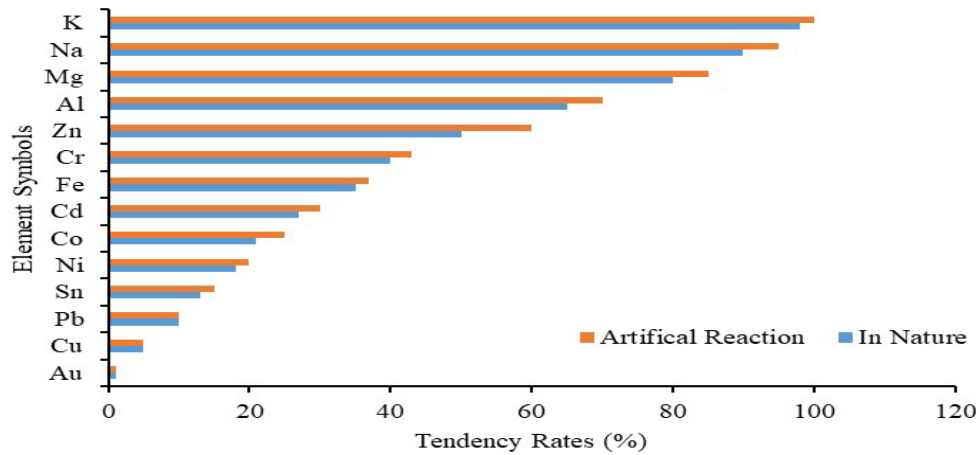


Figure 7. The tendency of elements to corrode from most reactive to least reactive.

From figure 7, both in nature and human actions, elements corrode and decays away except gold tends to very corrosion resistant because of its stable electrons in nature. Most reactive and corrosive elements tend to be Potassium (K) while least tends to be gold (Au) (U.S. Naval Academy 2003). Least corrosive elements can become cathode while more corrosive becomes sacrificial elements to protect cathode electrodes from further corrosion as per figure 7 and table 3 respectively. Thus, in impressed current cathodic protection system, least anodic becomes cathode electrode while more anodic becomes sacrificial elements to protect cathode electrodes. Examples of such are as designated (Kara 2001).

With respect to cathodic protection system, iron is the widely used material that is known today. However, it is also a material that is more attractive to oxidation forming iron oxides. To evade corrosion, there are certain elements that are mixed or compounded to make iron alloys or galvanized using zinc and titanium to resist corrosion. As iron releases its energy through natural actions (oxidization) to attain stable stage, certain technologies are developed to protect from further deterioration. These are galvanic protection, impressed current cathodic protection and sacrificial protection (Ee 2015).

To minimize and arrest corrosion on active ferrous steel, impressed current cathodic protection system is the only reliable technique utilized worldwide to effectively contain deterioration. Current and voltages of each material used such as anode, cathode and electrolyte are precisely measured and used for the benefit of efficient cathode electrode (structure) protection (Storage et al. 2018). In protecting iron steel from rusting, most anodic materials such as zinc or magnesium are used to attract more corrosive electrons which in turn corrodes in place of iron and is mentioned as sacrificial corrosion (Academy 2000). The electric current is also important in that it drives the oxidizing electrons away from the cathode electrode and deposited into the anode resulting in oxidization reaction at the anode electrode. The reaction at anode tends to be more rapid due to nature or tendency to attract electrons quickly compared to steel pipelines and or steel tanks.

3.3 Effects of Corrosion in an environment/Steel structure

All materials found in the surface of the earth, whether it exists in the form of compound or pure elements, they always find its way back to their origin. This process may be time consuming and very unpleasant but ultimately they reach their equilibrium or stable stage thus energy is released in the process (Ahmed et al. 2017).

Regardless of how cathodic protection intends to apply for betterment of proposed structure for its service, there is always corrosion happenings as long as the oxygen molecules are present in a living environment. The presence of corrosive ions is due to oxidation in the anode electrode. To measure the corrosion rates in any micro environment

may be very tedious such as pH of soil, moisture content in a humid environment, and presence of chloride level in warm climates. Corrosion charts are also difficult to develop due to many variables present in any given micro environment (Brown et al. 1931).

The other theoretical phenomenon to determine whether the material will corrode depends on the electromotive theory. As discussed, most cathodic in EMF series do not corrode as their molecules and atom are in stable condition and thus do not take part in the sharing and gaining electrons to decompose or make compounds. This means that their changes to corrode is very less or never happened and that is why they exist as stable elements, however can be forced or use more energy to form expensive alloys and other compounds. Most anodic elements are susceptible to corrosion compared to most cathodic electrodes (U.S. Naval Academy 2003).

In Papua New Guinea, the corrosion rate is also considered same as that of other parts of the world. However, compared to sacrificial anodes, impressed current provides an effective protection to the structures of Puma Energy facilities in the country.

Table 3. Recent measurement of oil pipelines which are protected from impressed current method in Madang province Papua New Guinea.

Location	Test Point	UP (mV)	P (mV)	P/F	MPV (mV)	Comment
TM	8" Pipeline		-850	Pass	-850	Re/CuSO ₄
BTD	8" Pipeline	N/A	-850	Pass	-850	Re/CuSO ₄
OVF	8" Pipeline	N/A	-850	Pass	-850	Re/CuSO ₄
OPNGPF	8" Pipeline	N/A	-850	Pass	-850	Re/CuSO ₄
OPSY	8" Pipeline	N/A	-850	Pass	-850	Re/CuSO ₄
PNGPG	8" Pipeline	N/A	-850	Pass	-850	Re/CuSO ₄
PNGPW	8" Pipeline	N/A	-850	Pass	-850	Re/CuSO ₄
WM	8" Pipeline		-850	Pass	-800	Re/CuSO ₄
NFWS	3" Pipeline		-850	Pass	-850	Re/CuSO ₄
TPT	3" Pipeline	N/A	-850	Pass	-850	Re/CuSO ₄
INFWM	3" Pipeline		-850	Pass	-850	Re/CuSO ₄

Keys; UP = unprotected, P = Protected, P/F = Pass/Fail, MPV = Maximum Protected Voltage, TM = Terminal Manifold, BTD = Back of Terminal in Ditch, OVF = Outside VSO Fence, OPNGPF = Outside PNG Power Fence, OPSY = Outside Ports Service Yard, PNGPG = PNG Ports Gate, PNGPW = PNG Ports Warehouse, WM = Wharf-end Manifold, NFWS = Near Filter Water Separator, TPT = Test Point on Terminal, INFWM = Insulating Flange near wharf-line manifold.

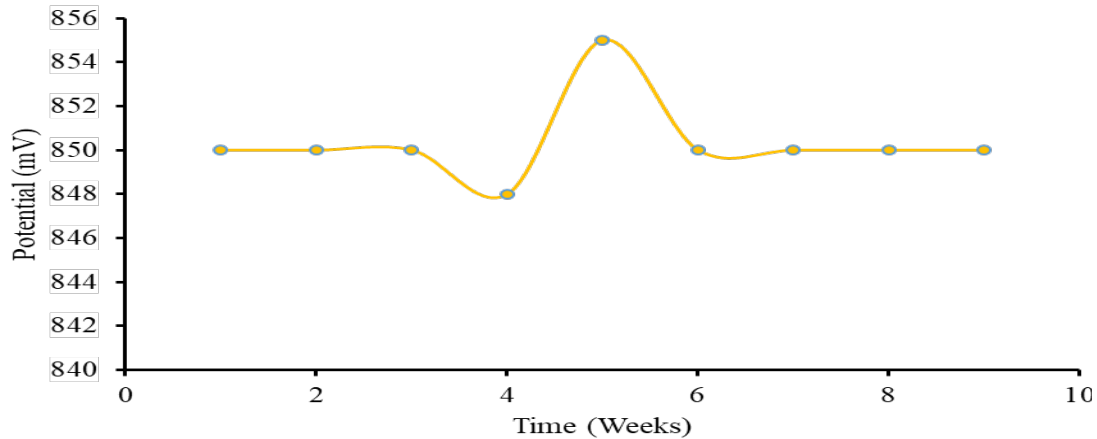


Figure 8. The graph of ICCP values (mV) in Madang (PNG)

As noted from figure 8, because the impressed current system was used and is the only CP used to protect facilities in one of the provinces in PNG, it provides adequate protection to the structure as indicated. According to international corrosion manual, the best protection is -850 to -880 mV and such is revealed in the table and graph as noted. The structures were adequately and efficiently protected from corrosion and thus it will possibly last for its design life.

The environmental conservation is within the international environmental protection laws sustaining healthy flora and fauna. There is no release of toxic or any chemical which is the byproduct of chemical reaction from impressed current as it never produces except corrosion only. The environment conservation and regulations in the country is also inside limits and is safe for all living creatures within the vicinity of Puma Energy locality and ICCP site.

Recommendation

For benefit of effective impressed current cathodic protection, it is necessary that right amount of current is driven through by optimum potential. This will also abstain hydrogen embrittlement on the protected structure. The right information is needed to exactly determine or analyze corrosion in a microscopic environment such as soil pH, moisture content in a humid place and level of chloride in a warm environment (Herring 2010).

To understand and use the right cathodic protective materials, the electromotive force series is the fitting and best table that shows the order of more cathodic in an ascending order and less anodic to most anodic in a descending order. This arrangement is useful and thus important in what type of materials to be used in an anodic system in a preferable electrolytic environment based on effective experiment and analysis. Because anode electrodes have the tendency to loose electron, it is also proper and fitting to ensure there is precise portion of elements used as anode to avoid wastage or too much will result in more reduction reaction at cathode electrode which will lead to hydrogen embrittlement (Academy 2005).

Electrochemical analysis of cathode electrode and anode electrodes of an elements with its right mixture of aqueous solution is also better phenomenon that gives a vivid idea of how cathodic and anodic element behave during polarization and depolarization (Faraday 1899). In depolarization stage, the anode becomes negative ions and cathode becomes positive ions. however, in polarization stage the charges of ions in a cell membrane becomes opposite charges. This occurs when the current is switch on for potential to force the electrons through. Thus, it is recommended that to understand the impressed current cathodic protection system theory, it is proper to visit electrolysis reaction in two separate test tubes with salt bridge and flow voltage or current as shown in figure 1. This explicitly explains the all theory and hence real hand on experiment will be much better and certainly recommended (Rathod et al. 2019). The Puma Energy in PNG is effectively protected by ICCP method and is considered safe and better thus, expected to last for its design life without release of any toxic or hazardous elements which may be harmful to the environment. As such, the structures are adequately protected, however requires efficient and regular maintenance on certain intervals.

Conclusion

The Impressed Current Cathodic Protection (ICCP) is one of the key methods of protecting steel structures including, jetties, gas pipelines, oil tanks, harbors wharfs, ships and bridges. Impressed current cathodic protection is applied throughout the world as the advanced and modified method of protecting structures from rusting or evade possible corrosion. The electrolyte resistivity, humidity or climatic conditions determines it severity of corrosion due to rapid attach on structures by dissolved oxygen and chloride as they are main elements involved in oxidation reaction. In order to fully understand the cathodic protection phenomena, it is quite proper to understand the effective use of electromotive force series which may profoundly signal the right material to use as anode from cathode.

The polarization and depolarization of currents or electrons vigorously mitigate the flow of electrons from anodes to cathodes. The electrons then tend to migrate (lose electrons) from the more active metals to less active (structure) (J. Guyer 2021). In the process, active metals decays and corrode thereby protecting the less active metals (steel pipelines and tanks). To vividly understand the rate at which the structure corrodes, it is only necessary to perform effective experiments and make calculations based on results obtained from laboratory (J. Guyer 2018). The results obtained can then be plotted into the equations designated to determine the corrosion rates.

Current from the transformer rectifier flows on a consistence manner which supplies negatively charged electrons from the cathode (structure) and proceeds it through connection cables towards anodes. At anode, the oxidation reaction takes place thereby gaining oxygen ions and loses hydrogen ions (Rms, 2008). Reduction reaction occurs at the cathode where the hydrogen ions are gained and releases oxygen ions and thus, the process continues until the design life of the anode elapse and the active element then corrodes and worn-out for possible replacements (Standards & Commission 2009). Impressed current cathodic protection system is the most reliable method of protecting all structure both underground and offshore from rusting. This is because both cathode and anode are subject to the flow of current/electrons from alternating current (AC) to direct current (DC) that drives the electrons throughout cables connected to each (Utilities, 2020). As the current drives both positive and negative charged ions from anode and cathode respectively, it ultimately reduces the chances of oxidations in the cathodes.

Puma Energy facilities are protected by both impressed current and sacrificial anodes in Papua New Guinea. However, majority of the facilities are protected by sacrificial anodes system due to its cost effectiveness and simple method of installation and maintenance. Due to its potential limits to drive to corrosive elements out, the facilities are rotting and corroding. Impressed current protection effectively protects only facilities in one of the sites in PNG and is the only site being protected by ICCP method. The environment impacts perpetuated by impressed current cathodic protection is considered minor and not possible. It's safe but care must be taken during construction or installation to avoid possible mismanagement of any chemicals that may be used. This if spelled or leaked will cause catastrophic impacts on the environment and thus will cost the company more and it's a waste of money.

Notes:

Acknowledgments

We would like to express our sincere thanks to Gabriel Kais the Technical Engineer for Puma Energy PNG Limited for the survey.

Author contributions

NM analyzed and interpreted all the data related to this study and writing the manuscript and AM performed a major contribution in recommending for editing and guiding NM for better manuscript. All the authors read and approved the final manuscript.

Funding

There was no funding for carrying-out this research.

Compliance with ethical standards

Conflict of interest

The authors declare of having no conflict of interest.

Ethical approval

This study requires no ethical approvals.

Informed consent

Informed consent after explaining the nature of investigation was obtained from each participant in this study.

References

- Academy, U. N., Continue Impressed current cathodic protection principle pdf. *CONFERENCE*, 12(May), 29, 2000.
- Academy, U. N. , Electromotive Force Resistor Circuits. *Conference on International Cathodic Experts*, 1(October), 12–45,2005.
- Academy, U. N. (2011). Introduction to Cathodic Protection. *Conference*, 10(May), 20.
- Ahmed, M. I., Ali, N., & Islam, A., *Determination of Corrosion Rate on Mild Steel in Different Medium Measuring Current Density*,2017.
- Ambat, R., . A review of Corrosion and environmental effects on electronics. *Concrete Solutions - Proceedings of Concrete Solutions, 6th International Conference on Concrete Repair*, 2016, 12(May), 30–42,2001.
- Ashworth, V. (2010). 18 Principles of Cathodic Protection. *International Conference on CP Design*, 2(May), 3–10.
- Attarchi, M., Instant-Off Potential Analysis in Cathodic Protection of Coated Tank Bottom. *International Conference on Underground Cathodic Protection on Steel*, 12(September), 12–20,2000.
- Attarchi, Mehdi., Instant-Off Potential Analysis in Cathodic Protection of Coated Tank. *Journal of Chemical Engineering and Information*, 32(December), 1–8, 2008
- B. Mainier FR, L. F., Application of Anticorrosive Techniques Compatible with the Environment to Engineering Education. *International Journal of Chemical Engineers*, 6(April), 176–181,2014.
- Basics, N. C., Loss, P., & Loss, E., Corrosion basics. *International Journal of Chemical Engineering and Applications*, 27(March), 20–31,1997.
- Brenna, A., Lazzari, L., Ormellese, M., Pedferri, M., & Milano, P. (2005). Interpretation and use of the off-potential technique for the assessment of cathodic protection condition. *Internal Conference*, 10(May), 12–15.
- Brown, R. H., Roetheli, B. E., & Forrest, H. O. (1931). The Initial Corrosion Rates of Metals. *Industrial & Engineering Chemistry*, 23(4), 350–352.
- Classnotes, S., Environmental Conditions , Other Structures Potential for Cathodic Protection Impressed Current , Sacrificial Anode Table of Contents. *Concrete Solutions - Proceedings of Concrete Solutions, 6th International Conference on Concrete Repair*, 2016, 10(May), 10–21,1996.
- Davis, J. G., Doremus, G. L., & Graham, W. F., The Influence of Environment on Corrosion And Cathodic Protection. *Journal of Petroleum Technology*, 24(March), 323–328,1976.
- Design, C. P. (1996). APPENDIX Potential for Cathodic Protection. *International Conference on CP*, 10(September), 1–30.
- Design, E., & Protection, C., Technical Manual of Electrical Design ELECTRICAL on Cathodic Protection. *Conference on Cathodic Protection Design*, 10(April), 19–21,1985.
- Dhany, E. K. A. & B. S., Corrosion control of reinforced concrete structures in construction industry. *Journal of US Academy*, 12(06), 3,2021.
- Dqg, X., Ri, H., Ri, H., & Ri, H., Cathodic Protection System in Steel Pipelines and buried and submerged Tanks. *Conference*, March(5), 20, 1991.
- Ee, C., Introduction to Electrical Design for Cathodic Protection Systems. *Conference on South-Indo Pacific in Electrical Design*, 19(3923), 19–29,2015.
- Faraday, M., Electromotive Forces of an Electrons, Protons and Neutrons. *Conference*, 3(August), 1–14.1899.
- For, A., Release, P., & Unlimited, D. (2004). Unifed Facilities Criteria (UFC) Design: Electrical Engineering Cathodic Protection. *International Conference Electrical Engineering*, 12(January), 42.
- Guyer, J., Electromotive force series. *Conference*, 12(May), 20, 2008.
- Guyer, J. , *Effective Cathodic Protection Methodics* (pp. 1–31),2009.
- Guyer, J., Cathodic protection system 2018.07. *Conference*, 10(December), 12,2018.
- Guyer, J., Impressed Current Cathodic Protection. *Conference on International Cathodic Experts*, 10(November 2008), 1–38,2001.
- Guyer, J. P., An Introduction to Cathodic Protection to Underground Structures. *International Conference on Underground Corrosion Prevention Measures*, 23(August), 21–34, 2017.
- Guyer, J. P., Asce, F., & Aei, F., An Introduction to Cathodic Protection. *Journal of Cathodic Protection on Steels*, 10(877),

10–20, 1989.

- Herring, D. H. , Hydrogen Embrittlement. *Conference*, 10(November), 2–5, 2010.
- Interior, U. S. D. of the, Reclamation, B. of, & Denver, C., Corrosion and Cathodic Protection. *Journal of Commonwealth on Environmental Impacts*, 4(September), 2013.
- Johns, R. T. , Rectifier Operation and maintenance. *International Conference on Chemical Engineers*, 10(May), 32–35, 2005.
- Kara, S. (2001). *Cathodic Protection and Measurement on Corrosion Rates*.
- Liu, Y., Gao, Z., Lu, X., & Wang, L., Effect of Temperature on Corrosion and Cathodic Protection of X65 Pipeline Steel in 3 . 5 % NaCl Solution. *20, 14*(August), 150–160, 2019.
- Loto, C. A., Loto, R. T., & Popoola, A. P. (2019). Performance evaluation of zinc anodes for cathodic protection of mild steel corrosion in HCL. *Chemical Data Collections*, 24(May), 10–11.
- Mailah, N. F., & Bashi, S. M., A study of Cathodic Protection System. *Internation Conference on Cathodic Protection*, 14(2), 47–59, 2005.
- Maiti, & Bidinger. (1981). Sacrificial Anodes and Impressed Current Cathodic Protection. *Journal of Chemical Information and Modeling*, 53(9), 1689–1699.
- Methods, E., Comparing the Effects of Types of Electrode. *Internal Conference on CP*, 12(December), 30, 2020.
- Murray, J., Impressed Current Cathodic Protection on Steel Pipelines. *Journal of Cathodic Protection System*, 12(July), 1–13, 1998.
- Notes, E. C., & Academy, U. S. N., EN380 Naval Materials Science and Engineering Course Notes, U.S. Naval Academy. *International Conference on Naval Engineering*, 10(June), 1–11, 1998.
- Olthuis, W., Streekstra, W., & Bergveld, P. (1995). Theoretical and experimental determination of cell constants of planar-interdigitated electrolyte conductivity sensors. *Conference*, 25(July), 252–256.
- P.E, D. L. R. , Cathodic Protection & Corrosion Prevention | Farwest Corrosion Control. *Organizations of Cathodic Protection Committee*, 10(October), 1–30, 2001.
- Parthiban, G. T., Parthiban, T., Ravi, R., Velu, S., Palaniswamy, N., & Sivan, V., Cathodic protection of steel in concrete using magnesium alloy anode. *Corrosion Science*, 50(May), 33–35, 2008.
- Rathod, N., Slater, P., Sergi, G., Seveviratne, G., & Simpson, D., A fresh look at depolarisation criteria for cathodic protection. *Conference*, 03011(May), 20–27, 2019.
- Reactions, B. R. , Chapter 18 : Electrochemistry & Electrolysis. *Journal of Petroleum Technology*, 2(June), 29–35, 2001.
- Reserved, C. , Corrosion protection & the environment : *Organization of Corrosion Technology*, 2(Ref 2), 10–29, 2009.
- Rms, M. A., Portable Transformer Rectifier Unit Model for Cathodic Protection. *Internation Cobference on Cathodic Protection*, 1(May), 4–50, 2008
- Rose-Innes, A. C., Electromotive force. *Physics Education*, 20(6), 272–274, 1985.
- Sasiadek, M. J. (2008). Cathodic Protection Advanced Course. *The Neuroradiology Journal*, 21(December), 3–6.
- Sataloff, R. T., Johns, M. M., & Kost, K. M., *Application of Anticorrosive Techniques Compatible with the Environment to Engineering Education*, 2001.
- Shaw, W. J. D., Impressed Current Cathodic Protection on Steel Pipelines and Submerged Structures. *Journal of Cathodic Protection*, 19(May), 29–39, 2000
- Staerzl, R. E. (1994). Cathodic protection controller. *International Conference of Chemical Engineers*, 10(December), 1–16.
- Standards, G., & Commission, I. E., Transformer Rectifier Perfection in transformer rectifier production. *Internation Conference in Tarnsformer Rectifier*, 10(May), 11–29, 2009
- Storage, U., Branch, T., Protection, C., Evaluation, T., & Evaluation, C. E., UST Impressed Current Cathodic Protection Evaluation 1. *Conference*, 4227(August), 40, 2018.
- Summit, C., Cathodic Protection Rectifier. *Conference on Cathodic Protection Design*, 12(June), 10–11, 2019.
- Tezdogan, T., & Demirel, Y. K., An overview of marine corrosion protection with regards to cathodic protection and coatings. *RINA, Royal Institution of Naval Architects - International Conference on Marine Coatings*, 65(February), 5–12, 2013.
- These, E. (2001). Electrochemistry and Cathodic Protection System. *Journal of CP Technology*, 2(January), 15–17.
- Types, A., & Conditions, C., Transformer Rectifiers and Controls Option. *Internation Conference on Transformer Rectifier*, 44(October), 1–4, 2002.
- U.S. Naval Academy., Corrosion and electromotive potential. *South Pacific Conference on Corrosion Prevention*, 3(1996), 1–18., 2003
- Utilities, S. P., CSI Specifications for Cathodic Protection. *Internation Conference on Rectifier Perfection*, 4(November), 10–15, 2020.
- Water, E., & Treatment, W. (2019). Basic Concepts In Electrochemistry. *Conference of Chemical Engineers*, 6(May), 1–

19.

Zafris, N., & Midstream, E. (2011). Criteria for Cathodic Protection. *International Conference of Cathodic Protection Technology*, 3(October), 12–15, 2011.