ARID ZONE JOURNAL OF ENGINEERING, TECHNOLOGY & ENVIRONMENT
AZOJETE June 2022. Vol. 18(2):183-196
Published by the Faculty of Engineering, University of Maiduguri, Maiduguri, Nigeria.
Print ISSN: 1596-2490, Electronic ISSN: 2545-5818
www.azojete.com.ng

ORIGINAL RESEARCH ARTICLE

DESIGN, ANALYSIS AND CONSTRUCTION OF AN IMPRESSED CURRENT ELECTRIC DEVICE FOR CATHODIC PROTECTION

A. A. Hammajam*, M. A. Ibrahim and M. K. Adam
Department of Mechanical Engineering, University of Maiduguri, P.M.B 1069, Maiduguri, Nigeria
**Corresponding author's email address: hammajam92@gmail.com*

ARTICLE INFORMATION

Submitted 15 September, 2021
Revised 19 October, 2021
Accepted 25 October, 2021

Keywords:
Corrosion
cathodic protection
rectifier
design
electrical machine

ABSTRACT

This paper aimed at designing, analyzing and fabricating an impressed current electric device. Cathodic protection is a means to prevent corrosion by applying a flow of electrical current from an external source (anode) through the environment and to the metallic structure that is being protected. The protective current changes the environment around the metal thus halting the corrosion reaction. Cathodic protection is used to prevent corrosion in a wide range of applications where the structure being protected is surrounded by an environment that allows current flow. The impressed current cathodic protection systems have the benefit of using an external power supply to drive current. The study used sea water as electrolyte with locally constructed transformer rectifier and to select a proper material for the construction so as to illustrate the effect and how the impressed current system functions. The general performance evaluation was found that the device has a net driving potential of 10.5V and a life expectancy of 128 years of the anode. In conclusion, the construction was successful and easy to operate which can be used to protect metal structure against corrosion.

1.0 Introduction

The first application of Cathodic protection (CP) can be traced back to 1824, when Sir Humphry Davy, in a project financed by the British Navy, succeeded in protecting copper sheathing against corrosion from sea water by the used of iron anodes (Gerrard, 1962). Davy found out that he could preserve copper components in sea faring vessels by attaching them to thin layers of iron, zinc or tin. The copper became, as Davy puts it "cathodcally protected". This technique was later abandoned because, by protecting the copper, its antifouling properties became retarded, hence reducing the streamline of the ships, as they began to collect deposits of unwanted materials. In offshore structures, Khazreai (2006) reviewed the application of aluminum (Al) and aluminum-zinc (Al-Zn) alloys anode to be more desirable than the other sacrificial anode. It was also observed and found that titanium anode coated by layers of precious metals is a suitable anode for the impressed current method. Also steel that are used in construction of platform in particular in high stress area will be of a type that will not be susceptible to hydrogen embitterment if excess CP is applied. In view of the above, cathodic protection is a means of preventing corrosion by applying a flow of electrical current from an external source (anode) through the environment and to the metallic structure that is being protected (Brousseau, 1992). These protective current changes the environment around the metal thus halting the corrosion reaction. When properly designed and applied, cathodic protection systems stop the corrosion process. CP is used to prevent corrosion in a wide range of applications where the structure being protected is surrounded by an environment that allows current flow. Basically, the protective measure adopted in corrosion control are divided into three, namely, insulating coating (passive), CP (active), and most recently anodic protection (Callister, 2014).

1.1 Cathodic Protection

CP is an electrochemical process in which the entire steel pipe surface is made cathode by injecting a direct current (DC) into the ground bed at suitable location. "In theory a property designed, installed and operated CP system will eliminate all the anodic regions which exist on a metal by passing direct current to the material surface" (Peabody, 1978). Whatever the intrinsic quality of coating and however carefully applied, it will always have defects and it will never by itself completely prevent corrosion. In fact, corrosion becomes concentrated in the defects; crevice, cracks and pinholes that are present in coating. As a result coating requires supplementary (CP), which is an electrical technique for imposing potentials on the protected pipeline to counter the tendencies for electrochemical ion migration and stops corrosion almost completely (Jacques, 1984).

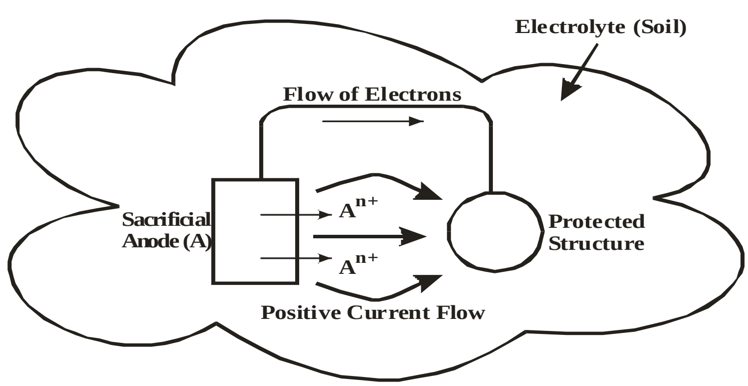
The Principles of Cathodic Protection: Metals extracted from their primary areas, has the tendency to revert back to its natural state under the action of water and oxygen. Therefore, the principle of CP is in connecting an external anode to the metal to be protected and passing electric (DC) so that the areas of the metal surface become cathodic and, therefore, do not corrode. The external anode may be a galvanic anode, where the current is the result of potential difference between the two metals, or it may be an impressed current anode, where the current is impressed from an external DC power source (Donald, 2010; Schweizer, 1998).

1.2 Cathodic Protection System

There are basically two types of CP systems: galvanic (sacrificial) anode system and impressed current system.

i. Galvanic (Sacrificial) Anode System

The Figure 1 illustrates the utilization of a metal (anode), which is normally more electro-negative (magnesium, zinc and aluminium) than the metal (cathode) being protected (mild steel or carbon steel). Current streams from the metal that are more electrically negative to the metal that is more electrically positive (Denison, 1974). This current stream brings about a fast utilization of the anode. In SACP the voltage difference is limited to anode and cathode, usually 1 volt or less, contingent upon the anode material and the environment. Oxidation and reduction reaction takes place at anode and cathode respectively (Wulpi, 1999). Figure 1 shows the schematic diagram of sacrificial anode method.



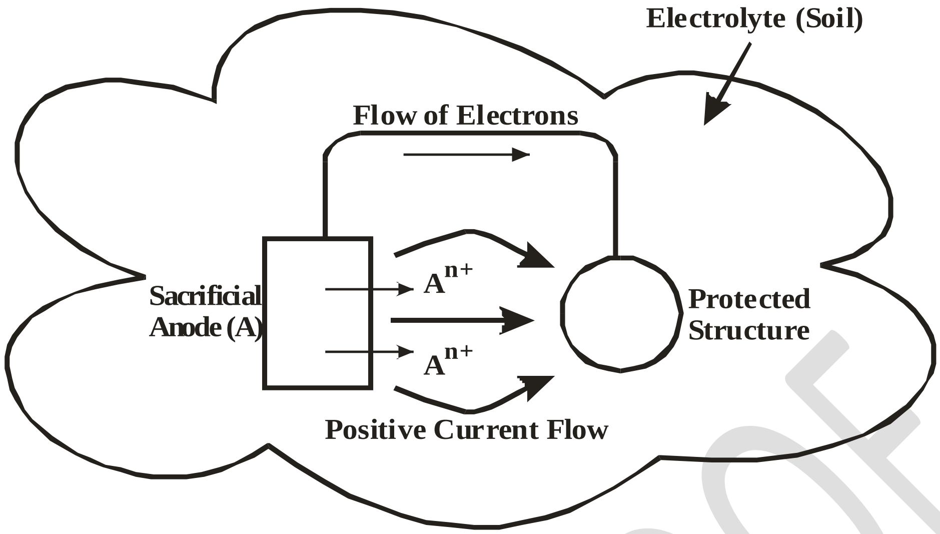


Figure 1. Schematic of Sacrificial Anode CP Method

As a result of potential difference, electric current will flow from the anode through a metallic connection between the anode and the structure.

ii. Impressed Current Cathodic Protection system

This system is comprised of an external DC power source, an auxiliary or impressed current electrode, the corrosive solution and the structure to be protected. The DC power source delivers positive current from the impressed current electrode on to the structure (being protected) through the corrosive solution. The structure is cathodically polarized (its potential is lowered) and the positive current returns through the circuit to the DC power supply, as shown in Figure 2.

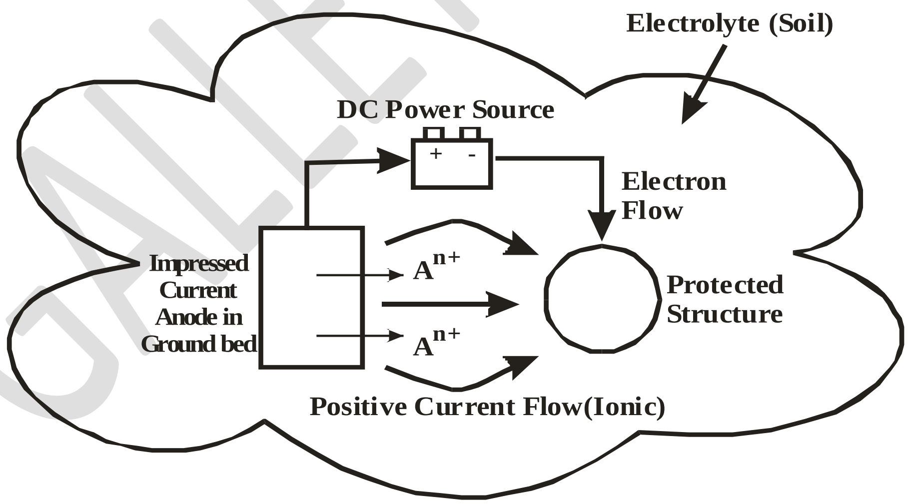


Figure 2. Schematic of Impressed Current Cathodic Protection Method (Michael *et al.*, 2012)

In one industrial area containing a high density of protected underground structures, protective current requirements rapidly rose to 20 mA/m^2 in several areas. The solution to this problem is cooperation between operators. For example, the stray-current problem could be prevented by electrically connecting the pipe by a bus connector and rearranging anodes. Cathodic protection involving impressed current anodes to reduce highway and other bridge maintenance costs is being done and substantial savings realized. Corrosion of the reinforcing

Corresponding author's e-mail address: hammajam92@gmail.com

steel is reduced. Cathodic protection is still more of an art than a science, and past experience is the best basis for judgment. This remark was made by a corrosion engineer who retired after 30 years of experience, mostly on cathodic protection of pipelines. There are many firms in the cathodic-protection business, and they should be consulted if you have a major project.

1.3 Design Theory and Methodology

The purpose of the design theory is to give an experience investigator enough information to replicate the study. A design theory is used to structure the design and to show how all of the major part of the design project, including the sample, measures and method of assignment, work together to address the central design question in the study. Based on documentation of the actual structures the total surface area of pipe to be protected shall be calculated. Figure 3 shows the circular object of pipe to be protected which requires only two views with dimension. Assuming that the total surface area of the pipe to be protected (A_{TP}) is given by;

$$A_{TP} = 2\pi\ (h+r) \quad (1)$$

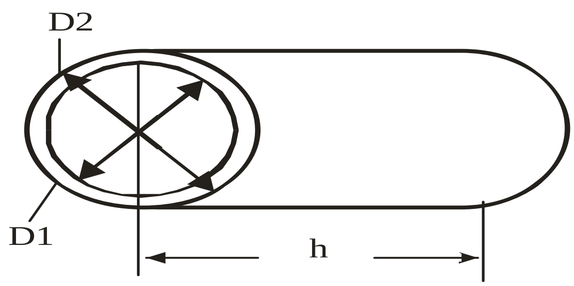


Figure: 3 Dimension of pipe to be protected

Total area of the aluminium anode, A_{TA} is giving by the equation

$$A_{TA} = 2A_{S1} + A_{S2} \quad (2)$$

where: A_{S1} = Surface area of the Circle; is given by πr^2

A_{S2} = Surface of area of the cylindrical part; is given by $2\pi r\ (h+r)$

Figure 4 show the circular views of aluminium anode with it dimensions requiring only two views.

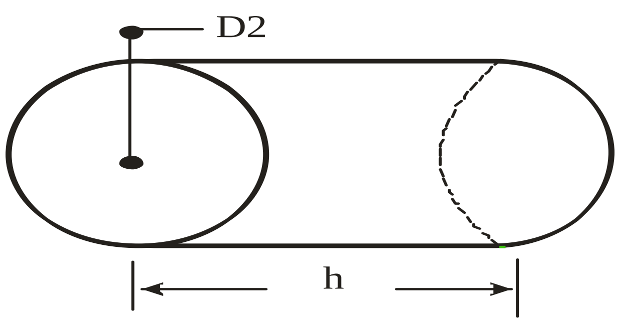


Figure 4: Circular view of the aluminium anode

Design methodology refers to the development of a system or method for a unique situation. - The key to design methodology is finding the best solution for each design situation whether it can be in industrial design, architecture or technology.

1.4.1 Cathodic Protection Design

The design sequence started after collection of all preliminary data and estimated protective current. 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. However, when this is not clear, the criterion used most widely is based on current density required and soil resistivity. If the soil resistivity is low (less than 5000 ohm-centimeters) and the current density requirement is low (less than 1 milliampere per square foot), a galvanic system can be used. However, if the soil resistivity and/or current density requirement exceed the above values, an impressed current system should be used. Thirteen steps are required when designing impressed current cathodic protection systems (ASTM D2000).

1. The review soil of resistivity. As with galvanic systems, this information will contribute to both design calculations and location of anode ground bed.
2. The required current requirement test to be used throughout the design calculations was reviewed
3. The Selection of anode. When impressed current-type cathodic protection systems are used to mitigate corrosion on an underground steel structure, the auxiliary anodes often are surrounded by a carbonaceous backfill. Backfill materials commonly used include aluminum, coal coke, and natural graphite particles.
4. The number of anodes needed to satisfy manufacture's current density limitations was calculated. Impressed current anodes were supplied with a recommended maximum current density. Higher current densities will reduce anode life. To determine the number of anodes needed to meet the current density limitations, (Talbot and Talbot, 1998) equation was used.

$$N = \frac{I}{(A_1)(I_1)}, \quad (3)$$

where: N = Number of anodes required,
I_1 = Total protection current in milliamperes,
A = Anode surface area in square feet per anode,
I = Maximum current density output in milliamperes.

5. Calculate number of anodes needed to meet design life requirement. Equation 4 is used to find the number of anodes:

$$N = \frac{LI}{(1000)(W)} \quad (4)$$

where: N = Number of anodes, L = Life in years, and W = Weight of one anode in pounds.

6. Calculate number of anodes needed to meet maximum anode ground bed resistance requirements. Equation 5 is used to calculate the number of anodes required:

$$R_a = \frac{\rho k}{(NL)} = \frac{\rho p}{S} \quad (5)$$

7. The numbers of anodes to be used were selected. The highest number calculated by equation 3, 4 or 5 will be the number of anodes used.
   The area for placement of anode bed was selected. The area with the lowest soil resistivity was chosen to minimize anode-to-electrolyte resistance.
8. The determination of total circuit resistance. The total circuit resistance used to calculate the rectifier size needed were also outlined.
9. The calculated rectifier voltage. Equation 6 is used to determine voltage output (V_{rec}) of the rectifier:

$$V_{rec} = (I)(R_T)(150\%) \quad (6)$$

Where I = Total Protection current in amperes,
R_T = Total circuit resistance,
150% = Factor to allow for aging of the rectifier stacks.

Corresponding author's e-mail address: hammajam92@gmail.com

10. The selection of a rectifier. A rectifier has been chosen based on the results of eqn. 6 The calculation of system cost. As with the galvanic CP system, the choice of anode for design calculation is almost arbitrary. Several anodes have been used in the design calculations, an economic analysis.

1.4.2 Design Parameters and Analysis

The data below were used for component sizing and analysis.

$h = 520mm = 0.52m$; $r_2 = D_2/2 = 25/2 = 12.5mm = 0.0125m$

$r_1 = D_1/2 = 21/2 = 10.5mm = 0.0105m$

Using equation 1

$A_{TP} = 2\pi r_2 (h+r_2)$; $A_{TP} = 2 \times 3.142 \times 0.0125 (0.5+0.0125)$; $A_{TP} = 0.04m^2$

Therefore, the total surface area of a steel pipe $A_{TP} = 0.04m^2$

Total area of aluminium anode is obtained using Equation 2

$A_{TA} = 2As_1 + A_{S2} = 2(\pi r^2) + 2\pi r (h+r)$

$A_{TA} = 2(\pi \times 0.021/2)^2 + 2\pi(0.021/2) \times (0.2 + 0.021/2)$; $A_{TA} = 0.14m^2$

The current density can be obtained, for sea water from typical current density requirement of cathodic protection of uncoated steel. Assume current density **I'** = 20mA per square meter.

The total protective current (I) can be calculated using the equation below

$I = (A_{TP}) (I')$; Where $A_{TP} = 0.04m^2$; $I = (0.4304) (20) = 8.61mA$

The total resistance $(R_T) = \Delta E/I$

Where ΔE is the Net driving potential of Aluminium anode = 0.25 to 0.50V as obtained from the standard. Thus, assuming the Net driving potential $\Delta E = 0.50V$

$R_T = 0.50/8.61 \times 0.001 = 58.07\Omega$

The rectified voltage (V_{rec}) is obtained from equation 6 and given by $V_{rec} = (I) (R_T) (150\%)$

$V_{rec} = (8.61 \times 0.001) (58.07) (150/100) = 0.75V$

For the power supply using equation

$$V_{rms} = V_s \times \sqrt{2} \quad (7)$$

Where V_s is the selected D.C voltage for the device = 12V

$V_{rms} = 12 \times \sqrt{2} = 16.9V$

The D.C voltage is obtained from equation

$$V_{dc} = 2V_{rms}/\pi = 2 \times 16.9/3.142; \; V_{dc} = 10.75V \quad (8)$$

Using equation 9 to calculate the form factor (F_f)

$$F_f = V_{rms}/V_{dc} = 16.9/10.75; \; F_f = 1.572V \quad (9)$$

Therefore, the ripple factor (R_f) can be calculated using equation

$$R_f = \sqrt{F_f{}^2 - 1} = \sqrt{1.572^2 - 1} = 1.21V \quad (10)$$

For the peak to peak ripple, regulated voltage (V_r) is calculated using equation

$$V_r = I/FC \quad (11)$$

Where I is the load current = 8.61mA; F is the frequency = 100Hz; C is the capacitance = 470µf

$V_r = 8.61 \times 0.001/100 \times 470 \times 10^{-6} = 0.183$; Therefore, $V_r = 0.183 \times 100Vpp = 18.32Vpp$

For the peak reversed voltage (V_{pr}), it can be calculated using equation

$$V_{pr} = 2V_{rms} = 2 \times 16.9 = 33.8V \quad (12)$$

Finally, the life expectancy of aluminium anode for the design can be calculated using equation 4.

$$L = \frac{N \times W \times 1000}{I}$$

Where N is the number of anode = 1; W is the anode weight in pounds = 0.5kg = 1.105lb

I is the design current = 8.61mA; L is the life expectancy of an anode in years

$$L = \frac{1 \times 1.105 \times 1000}{8.61} = 128 \text{ years}$$

2. Manufacturing Procedures

Step 1: The rectangular box was developed and produced with dotted lines indicating the position of the shape to be bent.

Step 2: The development was cut out from a brass sheet metal and all corners notches.

Step 3: The edges of the dotted lines was bent using hatchet stake and iron. The sides were bent up using bending machine as shown in Figure 5.

Figure 5. The casing

Step 4: A length of angle brass was produced and cut to a dimension (Table 1) using grinding machine. A hole of dimension was drilled at the end of the cut iron as shown in Figure 6.

Step 5: The angular brass was fastened to the developed casing as shown in Figure 6 and a rectangular brass sheet metal was also cut to a dimension and fastened on the cut angle brass.

Figure 6. Part Assembled and Angle brass

Step 6: The method of connecting the circuit of the transformer rectifier is shown in Fig. 7.

Figure 7. The circuit and the metering device

Step 7: Finally, transformer rectifier was then, placed on the top metal sheet and terminals was removed so as to provide connections for both the anode and the structure to be protected (cathode) as shown in Figure 8 while the 2D Orthographic projection of ICCP device is shown in Figures 9a and 9b.

Figure 8. General part assembled

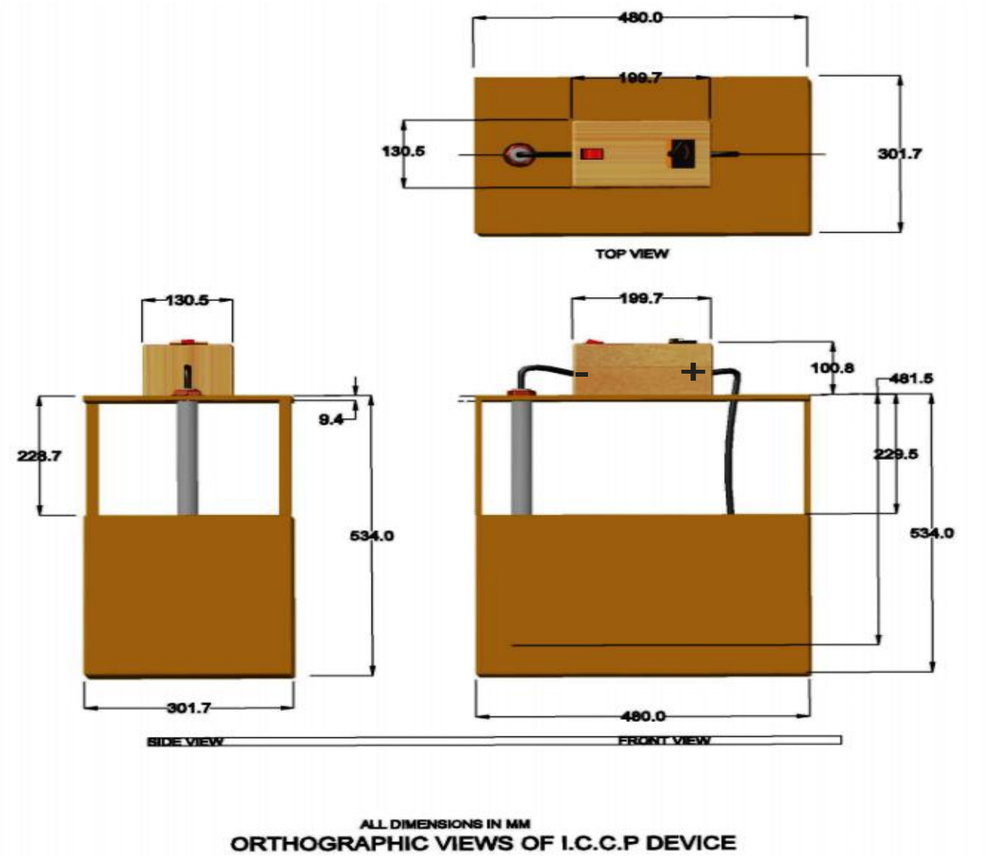


Figure 9a. 2D Orthographic projection of ICCP device

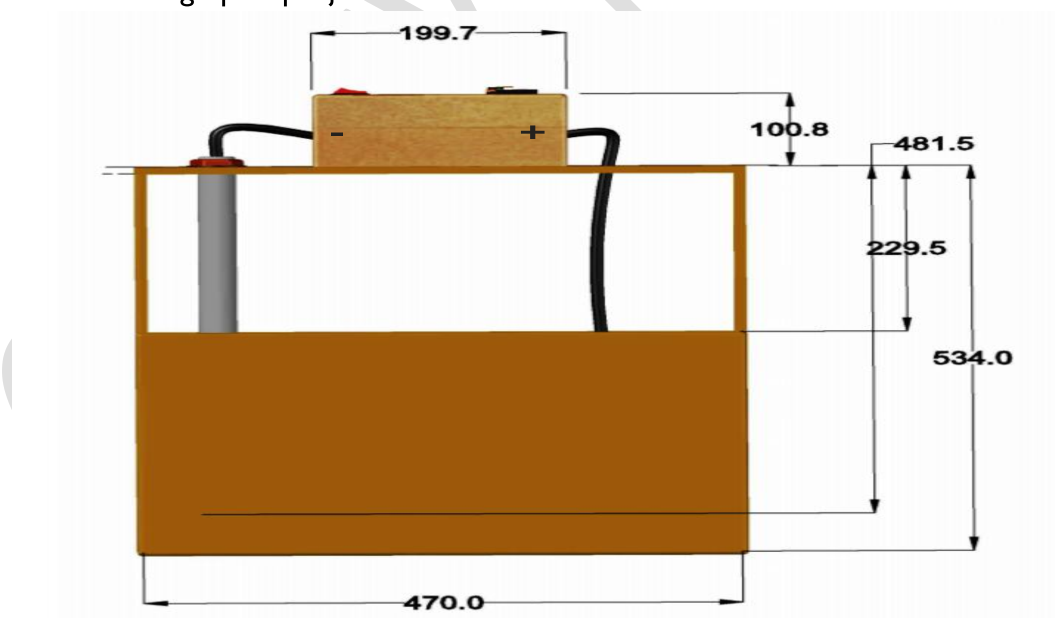


Figure 9b. 2D Orthographic projection of ICCP device front view. (*All dimensions in mm)*

2.1 Performance Evaluation of Designed Device

In the last few decades, after thorough investigation on cathodic protection, the criteria for cathodic protection have been compiled by National Association of Corrosion Engineers (NACE). NACE RP-0169-96 specifies; "A negative (cathodic) potential of at least 850mV versus Cu/CuSO4 should be applied to protect any corroding structure" (Onyechi, et al 2014). Thus, in the presence of sulfides, bacteria, elevated temperatures, acid environment and dissimilar metals, the criteria of -850mV may not be sufficient. Accordingly, researcher should also take into account the IR drop at the metal/soil interface, which is included in most practical measurements; it is of uncertain value, depending on the electrolyte (soil) resistance. For other metals such as aluminum and copper piping, NCAE RP-0169-96 suggests a minimum of 100mV cathodic polarization between the structure surface and a stable reference electrolyte contacting the electrolyte. Similar findings were reported by Onyechi et al. (2014). The 3-D diagram of the system is presented in Figure 10.

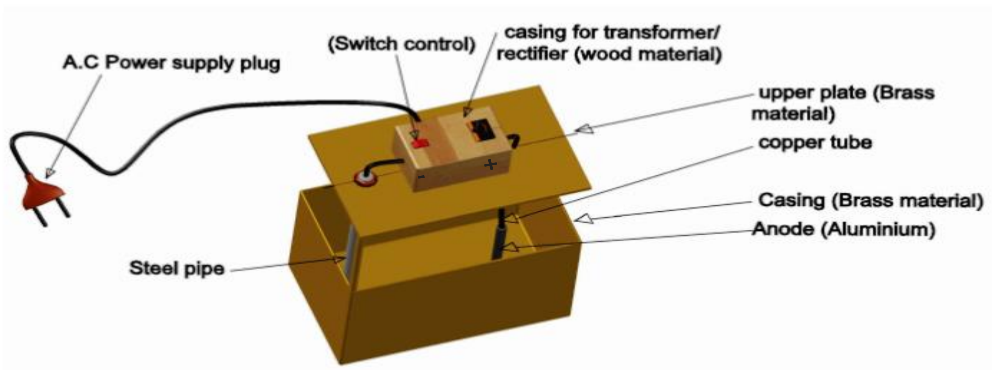


Figure 10. 3D model of Impressed Current electric device

The investigations were carried out at Chevron Pipeline System, of Nigeria, Western Division. The studies were centered on the evaluation of the cathodic protection of pipelines with emphasis on the Trans-Niger Pipelines (TNP). Due to the fact that other oil companies operate in the area, there are presences of Shell, Agip (NAOC), and Elf pipelines which interface across one another manifold. Thus there are also presences of Nigeria National Petroleum Corporation (NNPC). The study involved, onsite to and monitoring of CP operations at Rumuekpe manifold, where the SPDC, Elf and Agip pipelines cross each other. This manifold receives crude oil from Assa-Egbema, as well as Adibawa oil wells. The TNP lines from this manifold are 14inch, 20inch, 28inch, and 36inch pipelines respectively. Another location visited was the Ibaa manifold, which uses solar power as its source of electricity for the CP. Also visited was the Agbada manifold. There are the Agbada I and Agbada II locations which have flow stations. The monitoring and subsequent evaluation of the CP performance on these pipelines was undertaken through these processes: (a) the Pipe-to-soil potential measurement (CIPS) (b) the on/off pipe-to-soil potential measurement (c) Electrical Interference evaluation (d) Sacrificial Anode installation. Table 1 below show the data from the performance evaluation which when compare to the standard values in table 3 has significant indicator of good attributes.

Table 1: Typical current density requirements for cathodic protection of uncoated steel from onsite field data

S/N	Environment	Current density AFM 88-9a	(mA/m^2) Gerrard (1962), b
1.	Neutral soil	0.3 to 1.3	0.3 to 1.3
2.	Well aerated neutral soil	2 to 3	2 to 3
3.	Wet soil	1 to 4	2.2 to 5
4.	Highly acidic soil	2.2 to 12	3.2 to 12
5.	Soil supporting active sulphate-reducing bacteria	6 to 39	Up to 39
6.	Heated soil	2 to 20	3 to 21
7.	Stationary fresh water	0.7 to 5.5	4.8
8.	Moving fresh water containing dissolved oxygen	4.5 to 13.5	4.5 to 13.5
9.	Sea water	2.7 to 9.5	5 to 23

3. Results and Discussion

This study shows some great difference when compared to initial system of preventing corrosion using the impressed current system with aluminium anode and salt water instead of the sacrificial system with magnesium anode. The installation of impressed current system with aluminium anode was very easy with little effort applied while providing suitable working to the device without any regulation.

For the constructed impressed current electric device, it is observed that the aluminium anode employed also facilitates the flow of electrons to the cathode (structure to be protected), thereby increasing the life expectancy of the structure. The device was tested and was observed to overcome the structure length of 600mm and 30mm diameter respectively. Table 2 below shows the dimension of the pipe to be protected and the aluminium anode.

Table 2: Dimension of the pipe to be protected and aluminium anode

Material	Length (mm)	Diameter D_1 (mm)	Diameter D_2 (mm)
Steel pipe	520	30	25
Aluminium anode	200	21	17

The current requirements also can be estimated from Table 3. The Table gives an estimate of current, in milliamperes per square meter, required for complete CP That value, multiplied by the surface area of the structure to be protected (in square meter) gives the total estimated current required. Caution should be used when estimating, however, as under- or overprotection may result.

Table 3: Typical current density requirements for cathodic protection of uncoated steel (Adopted from Army T.M Air Force AFM 88-9)

S/N	Environment	Current density AFM 88-9a	(mA/m^2) Gerrard (1962), b
10.	Neutral soil	0.4 to 1.5	0.4 to 1.5
11.	Well aerated neutral soil	2 to 3	2 to 3
12.	Wet soil	1 to 6	2.5 to 6
13.	Highly acidic soil	3 to 15	5 to 15
14.	Soil supporting active sulphate-reducing bacteria	6 to 42	Up to 42
15.	Heated soil	3 to 25	5 to 25
16.	Stationary fresh water	1 to 6	5
17.	Moving fresh water containing dissolved oxygen	5 to 15	5 to 15
18.	Sea water	3 to 10	5 to 25

The total protective current (I) was obtained as 8.61mA from the calculation when the current density was assumed to be 20mA per square feet. The total resistance (R_T) was calculated as 58.07Ω as the maximum resistance of the system when the net driving potential (ΔE) was assumed to be 0.50V. The calculated value of the D.C voltage (V_{dc}) was 10.75V and regulated to 10V but the measured value indicated 10.5V on the multimeter. This little deviation from the calculated value may be accounted due to physical changes in temperature or tolerance, limit of discrete component like variable resistors and capacitors. The form factor (F_f) of 1.572 and ripple factor (R_f) of 1.21 are set to be within the specification limit. The peak to peak ripple factor (V_r) of 0.183 (i.e. 18.3%) is said to conform to the standard because it is below 50%.
Eventually, with peak reverse voltage (V_{pr}) of 33.8V implies that the device will fail when V_{pr} is greater than the stated value of 33.8V.

3.1 Corrosion Rate

Figure 11 illustrates the effect of corrosion rate of low carbon steel in 1 M HCl solution. From the result, the rate of corrosion increase with an increase in all concentrations except for 500 ppm which decreases indicating that at this ratio the extract was able to be absorbed by the surface of the low carbon steel at 192 hrs of the experiment. Generally, it can be observed that the corrosion rate is significantly decreased after 192 hrs except for 500 ppm which later decreased at 312 ppm. Moreover, it could be observed that the corrosion rate was gradual for all level of the concentration used. Equally, the un-inhibited low carbon steel specimen demonstrated to be the least protected expectedly. On the other hand, the corrosion rate decreased with an increase in inhibitor concentration as observed.

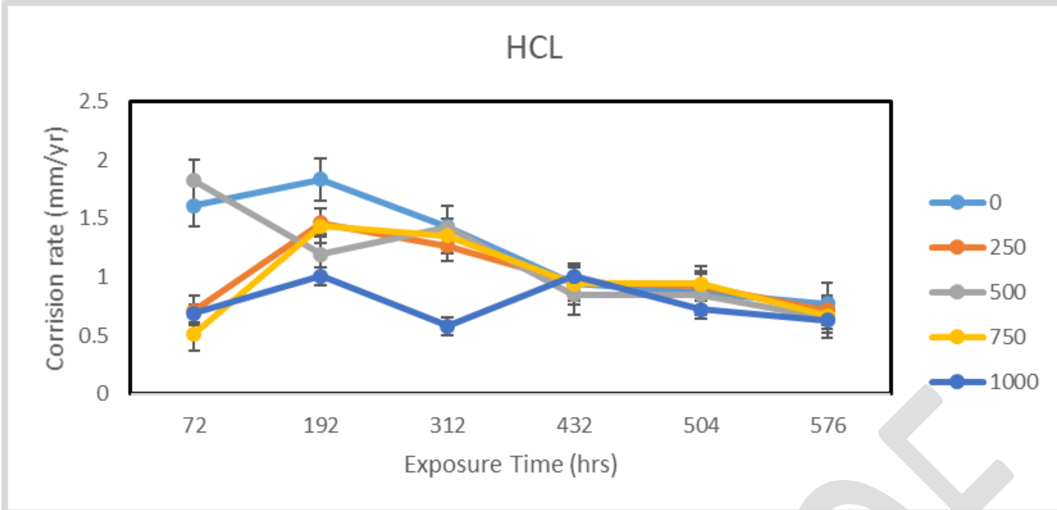


Figure 11: Variation of Corrosion Rate (mm/yr) against Exposure Time (hr) of low carbon steel in 1 M HCl at different concentration of leaves extracts on cathodic impress device

4. Conclusion

An impressed current electric device designed in its simple and portable form. In conclusion, the construction was successful and easy to operate which can be used to protect metal structure against corrosion. The performance evaluation was carried out, it has been found that the device has a net driving potential of 10.5V and a life expectancy of 128 years of the anode. Its construction can be improved upon by subsequent researchers. Its financial consideration for production is moderate.

Reference

Ashby, MF. 2005, Materials Selection in Mechanical Design 3rd ed. Amsterdam: Elsevier Publishers, pp.309-317.

ASM Handbook, 2000, Vol.8. Mechanical Testing and Evaluation, ASM International, USA, pp.443-449.

Brousseau, R. 1992. Cathodic protection for steel reinforcement. IRC (NRC Canada) Publication, 1992. 2nd Edition, pp.209-213.

Callister, DC. Jr. 2014. Materials Science and Engineering, 5th ed. New York: Wiley and Sons, pp. 221-225.

Denison, IA. 1974. Contribution of Sir Humphry Davy to cathodic protection, Corrosion, 3(6): 295 – 298.

Donald, RA. 2010. The Science and Engineering of Materials. 6th Edition.New York, USA;. pp. 27.

Gerrard, JS. 1962. Practical applications of cathodic protection. Corrosion, Vol 2 (LL. Shreir, Ed), Nownes-butterworths, London, pp.11.

Jacques, Louis Vincent-Genod 1984. Fundamentals of Pipeline Engineering. 2nd Edition.Inc. UK, pp.612-620.

Khazreai, MA. 2006. Short History of Cathodic protection for fixed offshore structure. The Journal of Corrosion Science and Engineering, 9: 47.

Michael, J. Schofield, Alan, D. McNaught and Andrew Wilkinson; 2012. Engineering Corrosion of Chemical Terminology: IUPAC recommendations. https://www.goldbook.iupac.org.

Saleh, RA. Badrkhani, O., Shahrabi T.; 2000. Different parameters for designing cathodic protection system for offshore structures; Journal of Zang, 7(5), pp. 87-94.

Schweizer, PA. 1998. Encyclopedia of Corrosion Technology, Marcel Dekker, New York City, USA, pp. 1021-1031.

Onyechi, PC., Obuka, Nnaemeka SP., Agbo, Cornelius, O., and Igwegbe, CA., 2014. Monitoring and evaluation of cathodic protection performance for oil and gas pipeline: A Nigerian Situation. International journal of advanced scientific and technical research. Issue 4 volume 1, ISSN 2249-9954. Pp47-65.

Peabody, AW., 2000. Control of pipeline corrosion; NACE, TEXAS; 1978. Official methods of analysis, 4th Editions, Texas, USA, pp.24.

Talbot, D., and Talbot, J. 1997, Corrosion Science and Technology CRC Press,Boca Raton, Florida USA, pp. 490-499.

Theraja, BL., Theraja, AK.; 2000. A to L book of Electrical Technology; Schand & Company Ltd; 2000; NewYork, USA, chapter 4, pp. 68.

Wulpi, DJ., 2017. Understanding How Components Fail, 2nd edition. ASM International, Fort Wayne, Indiana, USA; pp. 99-107

Corresponding author's e-mail address: hammajam92@gmail.com