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Supplying Constant Impressed Current by Using Photovoltaic Panels to Slow-down the Rate of Corrosion of Underground Gas Pipeline to the Remote Area

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Abstract: *The motto of this study is to use best reliable, durable, and cost-effective energy sources that will allow to slow down the rate of corrosion of underground gas pipelines to the distant areas. Cathodic protection is the most common electromechanical method used to protect buried metal pipelines from corrosion where the wrapped coating has failed or been damaged exposing uncovered gas pipelines metal to the soil. In many countries, there are some strict rules and regulation to apply cathodic protection for the natural gas pipelines, vessel, well casing, tanks, and marine structure and it is done by applying current through galvanic cell and external energy sources as direct current to the sources of the metal. In this investigation, the constant trace current known as impressed current cathodic system (ICCS) is being used.*

Keywords—Cathodic Protection, Coating, Corrosion, Impressed Current, Anode, Cathode, DC to DC converter, MATLAB

INTRODUCTION

Cathodic protection system (CP) is a technical application of electrical energy to prevent corrosion to enhance and ensure the safety, integrity, and longevity of offshore and onshore gas pipelines system. Corrosion is a natural phenomenon as metals don't like being metals, they tend remaining as ores**.** Impressed current cathodic protection (ICCP) is one of the techniques to control corrosion of metallic structures, and it is widely used in the marine, oil and gas, and ports industries, where it protects assets from natural degradation. Thus, it protects process continuity and safety as well as environmental damage, as it decreases the risk of leakages from oil and gas pipelines and other metallic infrastructure. Photovoltaic micro grid and PV panel provide confidence and efficiency for operators to provide constant voltage supply and, it is particularly important for operators of remote and off-grid sites, where it can be challenging and tough to maintain a schedule maintenance and visit by a qualified engineer, technician, and inspector for taking care of valuable assets [1].

However, there are two influential methods of providing cathodic protection: sacrifice anode and impressed current. In the sacrificial anode system, the naturally occurring electromechanical potential differences between different metallic elements, such as Magnesium (Mg), Aluminum (Al) and Zinc (Zn) are being used, in which the impressed current cathodic protection system uses distributed and renewable external energy sources with inert anode to create potential difference. A properly designed cathodic protection will be effective and economical.

OBJECTIVES

In this project, the focus is to study reliable and durable current sources for the cathodic protection system using solar photovoltaic panel and energy backup storage system. Besides that, is to learn the integration system of using power electronics to the renewable power generations.

METHODOLOGY

A. Corrosion: Corrosion is a naturally occurring phenomena, and it can be defined as the degradation and destruction of a material (usually a metal) by its chemical reaction or electromechanical reaction with the environment. It is the most common and serious problem that is faced by the oil and gas industries. General corrosion occurs when most or all the atoms on the same metal surface are oxidized, damaging the entire surface. Most metals are easily oxidized: they tend to lose electrons to oxygen (and other substances) in the air or in water. As oxygen is required (gains electrons), it forms an oxide with the metal.

TYPES OF CORROSION AND MODES OF CONTROLLING CORROSION

Corrosion can be broadly classified in two forms [8]:

a) Chemical dissolution of the metal.
b) Galvanic, or electrically driven.

Within these two basic classifications there are five types of corrosion:

1) General or uniform corrosion.
2) Intergranular corrosion.
3) Galvanic corrosion, including pitting and crevice corrosion.
4) Stress corrosion cracking
5) Microbiologically induced corrosion.

There are five different types of corrosion prevention methods [11]:

1) Barrier coatings
2) Hot-dip galvanization
3) Alloyed Stell (Stainless)
4) Cathodic protection
5) EnCoat

B. Cathodic Protection: Cathodic protection (CP) is an electrical technique used to prevent the formation of rust on metal surface due to oxidation reaction in the presence of oxygen and moisture. It is done by supplying external anodes and the protective metal as a cathode of an electrochemical cell. A simple method of protection connects the metal to

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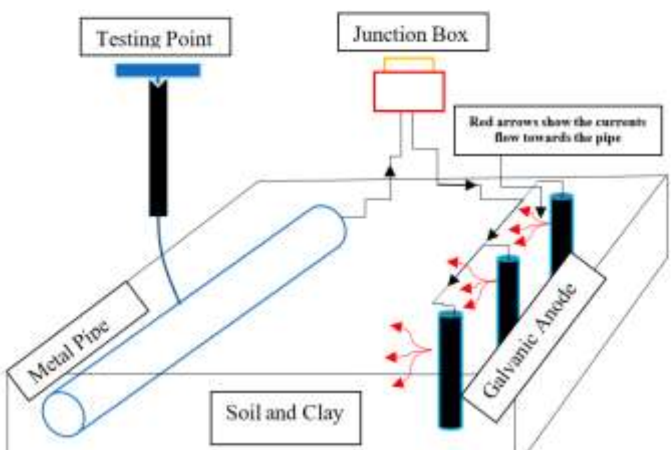
be protected to a more easily corroded "sacrificial metal" to act as the anode. The sacrificial metal then corrodes instead of the protected metal. For the long pipelines, where passive galvanic cathodic protection is not enough to protect the structure, an external DC power supply is used to provide sufficient current.

Cathodic protection systems protect a wide range of metallic structures in various environments. Most common applications are: fuel or steel water pipelines and liquid storage tanks such as home water heaters; ship; steel pier piles; and boat hulls; onshore oil well casings; and offshore oil platforms offshore wind farm foundations and metal reinforcement bars in concrete structures and buildings. Another common application is in galvanized steel, where a sacrificial coating of zinc on metal parts protects them from corrosion. Cathodic protection can, in some cases, prevent stress corrosion cracking [2].

C. Galvanic (Sacrifice) Anode Technique: It is the independent current source technique to prevent corrosion of metals. This system is also widely known as sacrifice anode cathodic protection (SACP). Galvanic corrosion accelerates the normal corrosion of a metal in an electrolyte. In the sacrifice galvanic method, one metal corrodes preferentially when in electrical contact with a different type of metal, both metals are immersed in an electrolyte such as and soil, and there is no need of external power supply to make return current path. Due to limited current capacity based on the mass of the anode, effectiveness is less in high resistivity environment. Sacrificial method needs periodic voltage inspection. Besides that, periodical replacement of anode due to the rapid corrosion, because of losing ions, in remote area during the harsh weather season is seriously difficult.

Components: Anode, Cathode, and Electrolyte.



A typical sacrifice anode (Galvanic anode) cathodic protection (SACP) system with current testing point.

Figure 1: ASCP and ICCP

D. Impressed Current System: Impressed current is a type of cathodic protection utilizing electromechanical means to obtain protection against corrosive reaction. Impressed current cathodic protection (ICCP) systems consist of anodes connected to a DC power source, often a transformer-rectifier connected to AC power. In the absence of an AC supply, alternative power sources may be used, such as solar panels, wind power or gas-powered thermoelectric generators.

Anodes for ICCP systems are available in a variety of shapes and sizes. Common anodes are tubular and solid rod shapes or continuous ribbons of various materials. These include high silicon cast iron, graphite, mixed metal oxide

(MMO), platinum and niobium coated wire and other materials.For pipelines, anodes are arranged in ground beds either distributed or in a deep vertical hole depending on several design and field condition factors including current distribution requirements [2].

Components: External DC voltage supply, Anode, DC to DC converter, Battery Backup system

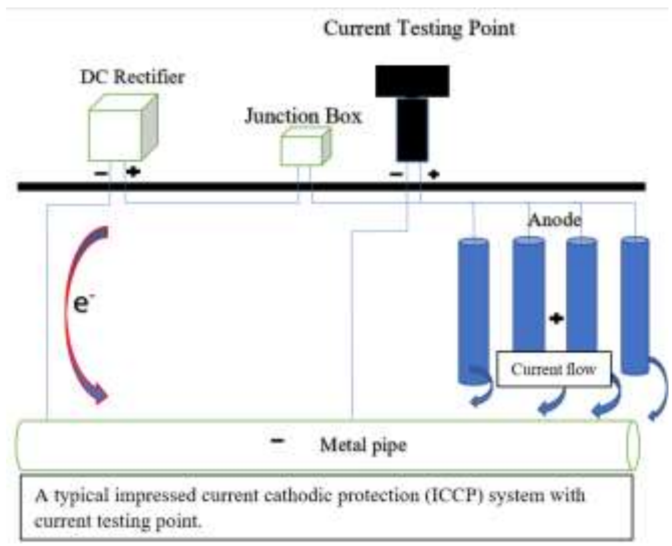


Figure 2: ASCP and ICCP

CHARACTERISTICS OF SACP AND ICCP

In this section, galvanic sacrificial anode corrosion protection and impressed current protection methods are introduced as a construction method to prevent corrosion in onshore buried pipelines.

E. SACP: SACP is a method to prevent steel pipes from generating corrosion currents by producing a protective current generated due to a potential difference, which is a result of forming a metal secondary battery through electrical connection of steel pipes with metals whose ionization tendency is high, such as magnesium (Mg) and zinc (Zn). It lets targets that need protection come into electrical contact with metals such as Al, Zn, or Mn, which have low electric potentials, thereby supplying electrons generated during dissolution of the sacrificial anode to targets requiring protection. Zn or Al is mainly used in underwater steel structures cooling water, or ships, while Mg is mainly used in buried pipes or tanks onshore whose resistivity is high

After the metal atoms at the anode site release electrons, there are four common cathode reactions:

1) In aerated wet soil: $O_2 + 2H_2O + 4e^- = 4OH^-$
2) In aerated wet acidic soil: $O_2 + 4H^+ + 4e^- = 2H_2O$
3) In neutral seawater: $O_2 + 2H_2O + 4e^- = 4OH^-$
4) In de-aerated soil or water: $2H_2O + 2e^- = 2OH^- + H_2$

The anodic reaction as per anode type can be represented as follows:
$Fe = Fe^{2+} + 2e^-$, $Mg = Mg^{2+} + 2e^-$, $Zn = Zn^{2+} + 2e^-$, $Al = Al^{3+} + 3e^-$

In soft soil, the reference electrode is used $4Cu/CuSO_4$. The corresponding reaction is $CuSO_4 + 2e^- = Cu + SO_4^{2-}$, whereas in sea water, AgCl is used with the corresponding reaction:
$AgCl + e^- = Ag\ Cl^-$

F. ICCP: It is a method to protect corrosion by allowing a suitable direct current (DC) to flow continuously throughout the metal bodies in contact with clay and soil or a corrosive aqueous solution. It employs an alternative current from the distributed power system using rectifier or a direct current/alternative current from the renewable energy sources using rectifier and DC to DC converter. This is also called constant current method. Typical anodes are high silicon cast iron (HSCI), polymer (AnodeFlex) graphite, titanium, and iron.

The reduction reactions at the cathode are:

1) In aerated wet soil: $O_2 + 2H_2O + 4e^- = 4OH^-$
2) In aerated wet acidic soil: $O_2 + 4H^+ + 4e^- = 2H_2O$
3) In neutral seawater: $O_2 + 2H_2O + 4e^- = 4OH^-$
4) In de-aerated soil or water: $2H_2O + 2e^- = 2OH^- + H_2$

The oxidation reactions at the anode are:

1) In water or in wet soil: $2H_2O = O_2 + 4OH^- + 4e^-$
2) In salt or brackish water: $2Cl^- = Cl_2 + 2e^-$
3) In graphite anodes: $C + 2H_2O = C_2O + 4H^+ + 4e^-$

DESIGN CRITERIA OF CATHODIC PROTECTION SYSTEM

Before making decision, which type of cathodic protection galvanic or impressed current system should be used for the system design, appropriate initial information and data must be collected [3].

a) Protected physical dimension of the structure that means the total area must be calculated [5].

b) Structural drawing to be protected. The installation drawings should include material type, shapes, sizes, and locations of parts of the body to be protected [6].

c) If a metallic body is to be protected from corrosion by the cathodic system, it should be electrically connected to the anode, as figure 1-2 shows. Sometimes body parts of a structure or a system are electrically isolated from each other by insulators. For instance, in a gas distribution pipeline system, the inlet pipe section to each system must contain an electrical insulator to separate in-house piping from the pipeline [3].

d) In the cathodic protection system, there should not be any short circuit between the old and new cathodic system. Physical contact between pipping systems may create short circuits, causing interference with CP system. In design and upgrading of cathodic protection system, the 1st and important step should be elimination short circuit [5].

e) Historical data of the of the locations, where the protective structure should be placed, must be studied because of helping to design the CP system. The corrosivity of the soil can be easily examined by the previous study and it will be good and informative source to make decision [6].

f) Corrosion of a metallic body or structure is proportional the electrolyte resistance. If it not catholically then electrolyte resistivity will be decreased, and more current will flow from the structure into the electrolyte; as a result, the structure will corrode more rapidly. The tabular data sheet for soil resistivity will be used to design converter or rectifier needed and the physical dimension of anodes in designing the CP system [3].

Table 1: Corrosivity of soils on steel based on soil resistivity

Soil Resistivity Range (ohm-cm)	Corrosivity
0-2000	Severe
2000-10,000	Moderate to Severe
10,000-30,000	Mild
Above 30,000	Not Likely

U.S Air Force [3][5][6].

g) Electrolyte works as catalyst for the corrosion. The value of pH is more important to consider for designing cathodic system, as rate of corrosion increases with the decrease of pH when the resistivity of soil remains constant [6].

h) From the potential difference between the metallic structure and electrolyte, we can find the corrosivity of the soil.

According to National association of Corrosion Engineers (NACE) Standard No. RP-01, the workable potential of cathodic protection should be at least-0.85 volt between the protective structure and a $CuSo_4$ reference electrode in contact with the soil. A potential is defined as less than negative 0.85 is known as corrosive potential [3].

i) The most critical section for the designing of cathodic protection system is current calculation per square foot is known as current density. Surface conditions should be easily detectable by the current density. A good, coated pipeline with coal-tar epoxy will need a very low density of current, and it is approximately 0.05 mA/ft^2. If the structure is bare, then high density of current would require that is 10 mA/ft^2. For the unwrapped surface area, the average current density needed for the corrosion protection is 2 mA/ft^2[5].

There are three ways to determine the current needed for complete cathodic protection [6]:

1) By setting the temporary cathodic protection system physically on the existing system.

2) Based on coating efficiency, a theoretical calculation will help to determine the current.

3) By using a data table, which is prepared by field experience, we can estimate cathodic current.

SELECTING THE METHODS OF DESIGNING CATHODIC PROTECTION

When all primary design data and information have been accumulated and the required current has been calculated, the design sequence may begin. The first step to ask is: which method (galvanic or impressed current) cathodic protection is needed? Sometimes the site conditions dictate the choice.However, when the data is not enough, the standards used most widely in based on soil resistivity and current density required. If the current density requirement is low which is less than 1 mA/ft^2, the soil resistivity is low that is less than 5000 ohm-centimeters and, a sacrifice galvanic system can be used. However, if the current density and/or soil resistivity requirement exceed the mentioned values, then an impressed current cathodic system should be used according to design sequence of figure 3.

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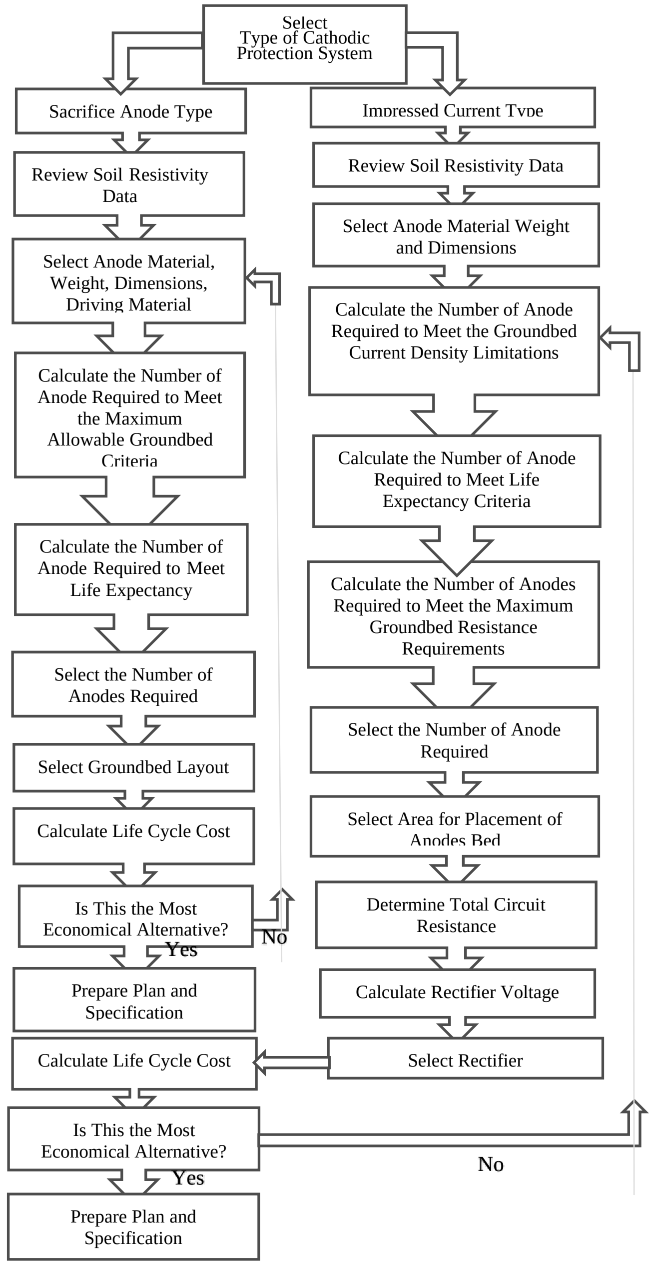

Figure 3: Design sequence of cathodic protection system. [3][5][6]

DESIGN THEORY OF SACP IN BURIED PIPES

In this section, the theory of SACP is discussed. The initial current required for onshore buried pipes shall be calculated accordingly using Eq. (2)[9]

$$I_{initial} = A\,(1-\alpha)C_c + A\alpha C_B \;\; (mA) - - - - - (2)$$

where A is the surface area of the buried pipes, $(\pi \times OD \times L)\; m^2$,
α is the rate of damage of the anticorrosion coating after the pipes are buried (1%), Cc is the current density of buried pipeline at design temperature (below 30°C is 0.025 mA/m^2 and above 30°C, the current density will be increased 2.5% for every 1°C increases in temperature), C_B is the current density of buried pipeline 10 mA/m^2 . The maximum electrode potential that can be generated by an anode is calculated using Eq. (3)

$$E_D = E_{anode} + E_p + E_{polar} \qquad (Vol\ t) - - - -(3)$$

where E_{anode} is the standard electrode potential (Cu/$CuSo_4$) in volts, E_p is the protective potential of buried piping (NACE standard RP0169-83) in volts, and E_{polar} is the potential change of anode during current flow in volts. The equations below explain the anode and anode ground resistances with relation to anode installation. Ground resistance of anode using the Dwight formula (Dwight, 1936) for single anode is expressed as in Eq. (4)

$$R_{al} = \frac{\rho_s}{2\pi L_A}\left[\ln\left(\frac{8L_A}{OD_A}\right) - 1\right] (\Omega) - - - - - - - - (4)$$

where ρ_s is the resistivity of soil (Ω-m), L_A is the anode length (m), and OD_A is the anode diameter (m). If a vertically connected array of anodes is used, the ground resistance of the anode is expressed by Sunde (1949) equation as shown in Eq. (5)

$$R_{al} = \frac{\rho_s}{2\pi L_A N}\left[\ln\left(\frac{8L_A}{OD_A}\right) - 1 + \frac{2L_A}{S}\ln(0.656N)\right] (\Omega) - - - (5)$$

where N is the number of anodes and S is the vertical spacing of the anode (m). If anodes are installed horizontally, the ground resistance of the anode is expressed by Sunde (1949) equation as shown in Eq. (6)

$$R_{al} = \frac{\rho_s}{2\pi L_A N}\left[\ln\left(\frac{4\,L_A^2 + 4\,L_A\sqrt{S^2 + L_A^2}}{OD_A S}\right) + \frac{S}{L_A S} - \frac{\sqrt{S^2 + L_A^2}}{L_A} - 1\right] (\Omega) - - - - - - - - - - - -(6)$$

where S is two times the depth at which the anode is buried (m) Nevertheless, equations 3, 4 and 5 can be used to obtain only ground resistance of filling materials, ρ_s, OD_A, and L_A, for grounding electrode. However, to obtain an electrical resistance of buried pipeline, ρ_b, OD_B, and L_B will be represented as filling materials in eq. (7) instead of above parameters

$$R_{metal} = \rho_{metal}\frac{L_p}{A_p}\ (\Omega) ----------(7)$$

Where ρ_{metal} is the resistivity of steel pipe ($\rho_{metal} = 2.2 \times 10^{-7}\ \Omega - m$), L_p is the distance between the buried pipe and the anode (m), and A_p is the cross-sectional area of the buried pipe

$$[A_p = \pi\frac{OD^2 \ - (OD - 2t_{\omega)}^{\ 2}}{4}\ \ (m^2)]$$

The electrical resistances of anode, junction box, and cathode wires of buried pipes can be expressed using Eq. (8)

$$R_{cable} = \rho_{cable}\left(\frac{L_{c1}}{A_{c1}} + \frac{L_{c2}}{A_{c2}}\right)\ (\Omega) ----- (8)$$

where R_{cable} is the resistivity of cable (R_{cable}= 1.68×10^{-8} Ω-m) L_{c1}, L_{c2} are the wire length between the anode and junction box and between the buried pipe and junction box (m), and A_{c1}, A_{c2} are the cross- sectional area of the wire between the anode and junction box, and between the buried pipe and junction box ($A_{c1} = A_{c2} = \pi\,\frac{d^2}{4}\ \ m^2$)

Thus, the total electrical resistance of anode and ground can be expressed using Eq. (9)

$$R_{total} = R_{a1} + R_b + R + R_{metal} + R_{cable}\ \ (\Omega) ----- (9)$$

Thus, the maximum generating current of anode, I, can be expressed as in Eq. (10)

$$I = \frac{E_D}{R_{total}}\ \ (mA) -------------- (10)$$

Based on the above maximum generating current, the quantity and the spacing of the anode can be calculated from the required current and relationships of buried pipe using Eq. (11) and (12)

$$N_{req'd} = \frac{I_{initial}}{I}\ \ (Nos) --------- (11)$$

$$S_{\ span\ req'd} = \frac{L}{N_{req'd}}\ \ (m) --------(12)$$

where L refers to the entire length (m) of onshore buried pipes. Note that when an arrangement of anodes is connected vertically, some adjustment may be needed regarding anode distance $S_{\ span\ req'd}$, if in some cases, anodes are installed horizontally. However, the life of an anode shall be examined separately depending on the type of anode or value of electrical resistance in the ground. The calculation/value can be obtained from Eq. (13)

$$Y_{req'd} = \frac{P_{ac}}{I_{initial}} U_f \quad (hour) --------(13)$$

where P_{ac} is the capacity of the anode (A. hr/kg), U_f is the utilization factor of the anode (U_f=85%). For the calculation of driving voltage and lifetime of the anode, equations (14) and (15) are used. Eq. (14) is employed when a single vertical anode is used, and Eq. (15) is employed when multiple vertical or horizontal anodes are used.

$$V_d = \frac{0.106922398589065 W_a N_{req'd} R_b}{L_f} \quad (Volt) --(14)$$

$$V_d = \frac{0.016979026455\ W_a \rho_a}{L_f L_A}\left[\ \ln\left(\frac{8L_A}{OD_A}\right) - 1 + \left(\frac{2L_A}{S_{\text{span req'd}}}\right)\ln(0.656 N_{req'd})\right](Volt) ------- (15)$$

Where W_a is the net anode mass per piece, M_A / $N_{req'd}$ (kg), $M_A = N_{req'd} V_A \rho_A$ is the net anode total mass (kg) , V_A, ρ_A is the net anode volume per piece and unit mass, and (m^3 , kg/m^3), $L_f = Y_{req'd}$ is the lifetime of the anode (years).

DESIGN THEORY OF ICCP IN BURIED PI PES

There are thirteen steps to design impressed current cathodic protection systems [3].

1) Reviewing the soil resistivity is the 1st step of impressed current cathodic protection system and the informative data will help to both design calculations and select the area of anode groundbed.

2) Current requirement test is the critical part throughout the design calculations.

Calculated and protective current required to protect $1ft^2$ of uncoated pipe will allow the values in Table 3.

3) Anode selection depends on economic conditions, and it is arbitrary for the galvanic system. Tables 2-4 provides the data for the common specifications and anode sizes.

Table 3: Weights and dimensions of selected circular high silicon chromium-bearing cast iron anodes

Anode weight(lb.)	Anode dimension (in)	Anode surface size (in)	Package area (sq ft)
12	1x60	1.4	10x84
44	2x60	2.6	10x84
60	2x60	2.8	10x84
110	3x60	4.0	10x84

Reproduced from Harco Corporation, Catalog of Cathodic Protection materials, 1971 [3][5][6].

Most of the ICCP system anodes are made of high-silicon chromium-bearing cast-iron (HSCBCI). During the mitigation of oxidation reaction using impressed current system of underground structure, carbonaceous backfill materials are used to surround the auxiliary anodes. Backfill materials generally used include gypsum, sodium sulphate, calcined petroleum coke breeze, coal coke, natural graphite particles and bentonite clay. There are three basic functions of backfill materials:

(a) effective size of anodes is inversely proportional to earth resistance.

(b) by providing extra anode material, it enhances the CP system's operational life and

(c) lessening harmful and localized attack, it gives a steady environment around the anode. Due to well compact of backfill materials, the life expectancy of ground bed anodes can be expected [5].

4) To satisfy the manufacturer's current density limitations, we must calculate the number of anodes needed. To meet the current density limitation, we have to calculate the anodes needed for impressing the current system by the following equation (16)

$$N = \frac{I}{A_1 I_1} \text{ (Nos)} ----------- (16)$$

where N = number of anodes needed
I = total protection current in mA
A_1 = anode surface area in ft^2/anode and
I_1 = recommended maximum current density output in mA

5) To meet design life length, we have to calculate number of anodes needed by the following equation (17)

$$N = \frac{L\,I}{1000\,W} \text{ (Nos)} ---------- (17)$$

Where N = number of anodes
L = life in years and
W = weight of one anode in pounds

6) To meet maximum anode ground bed resistance requirements, we have to calculate the number of anodes needed by the following equation (18).

$$R_a = \frac{PK}{NL} + \frac{\rho P}{S} \ (\Omega) ------------ (18)$$

where R_a = the groundbed anodes' resistance in Ω
ρ = soil resistivity in Ω-cm
K = the anode shape factor from Table 4
N = the number of anodes
L = length of the anode backfill column in ft
P = the paralleling factor from Table 5 and
S = center-to center spacing between anode backfill columns in ft.

Table 4: Shape functions (K) for impressed current cathodic protection anodes where L is effective anode length and d is anode/backfill diameter.

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		

Reproduced from W.T. Bryan, Designing Impressed Current Cathodic Protection Systems with Durco Anodes, The Duriron Company, 1970[3][5][6].

Table 5: Anode paralleling factors (P) for various numbers of anodes (N) installed in parallel

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		

Reproduced from W.T. Bryan, Designing Impressed Current Cathodic Protection Systems with Durco Anodes, The Duriron Company, 1970[3][5][6].

7) From the calculation of anodes requirements, we must use the highest numbers of anodes to satisfy the current requirements for the cathodic protection.

8) Area selection for placing the anodes is important because of electrolyte and resistivity of soil.

9) To calculate the circuit voltage, we have to calculate the total resistance of the system.

a) Using equation (18), we have to calculate the ground bed resistance.

b) Ground bed header cable resistance should be calculated by the following equation (19), and it is typically provided with a specific resistance in ohms per 100 ft.

$$R_w = \frac{\text{Ohms} \,(L)}{100 \text{ ft}} \quad (\Omega) -------------(19)$$

where L = the structure's length in ft
Choosing a cable, economics are important to determine. The total annual cable cost can be calculated by the following equation (20).

$$T = \frac{0.0876\, I^2\, R\, L\, P}{E} = \; 0.15\, S\, L \quad (\$) \; ------(20)$$

Where T = total annual cost in dollars per year
I = total protection current in amperes
R = cable resistance in Ω per 1000 ft
L = cable length in ft
P = cost of electrical energy in KWh
E = the rectifier efficiency expressed as percent and
S = the cable's initial cost in $/ft.

c) Using equation (21), we can calculate the resistance of electrolyte in the CP system

$$R_c = \frac{R}{a} \; (\Omega) -----------------(21)$$

where R_c = the structure-to-electrolyte resistance in Ω
R = the coating resistance in Ω/ft^2 and
a = the coated pipeline surface area in ft^2

d) Total circuit resistance, R_T is calculated by the following equation (22)

$$R_T = \; R_a + \; R_w + R_c \quad (\Omega) ---------- (22)$$

10) The cathodic protection system voltage is calculated by the following equation (23)

$$V = \; I\, R_T\, (150\%) \quad (\text{Volt}) ------(23)$$

where I = total protection current in amperes
R_T = total circuit resistance in Ω and
150 % is a factor to allow for aging of the rectifier/converter stacks.
11) A rectifier/DC to DC converter should be selected based on the calculated result of equation (23)[5]. A solar power cathodic protection system may be considered for off grid site.

12) System design cost should be calculated because is the on the major consideration of cathodic protection design.

13) According to the above calculation we have to prepare plans and specifications.

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CURRECT REQUIREMENT TESTING

A. Current test: A critical element in designing impressed current cathodic protection systems and sacrifice galvanic is the current required for complete CP system. A fulfill complete CP is achieved when the potential is -0.85 volt with respect to a $Cu/CuSo_4$[5].

B. Sample current test: It is done by arranging and applying using an instant test setup and regulating the current from the power source until appropriate protective voltage are obtained. Figure 4 shows a temporary test setup and in this setup, batteries can be used as the power source, in series with heavy-duty adjustable resistors. The resistors can be adjusted to increase the current until the potential at the location of interest, such as in Figure 4 is at -0.85 volt with respect to $Cu/CuSo_4$. The current provided is the current required for CP system. Shown in Figure 4, the effectiveness of the insulating joints can also be tested. The voltage at point B and point C are measured, first with the current interrupter switch is off, then with it on. If there is any potential difference in between the two points, then the joint is not insulating completely [6].

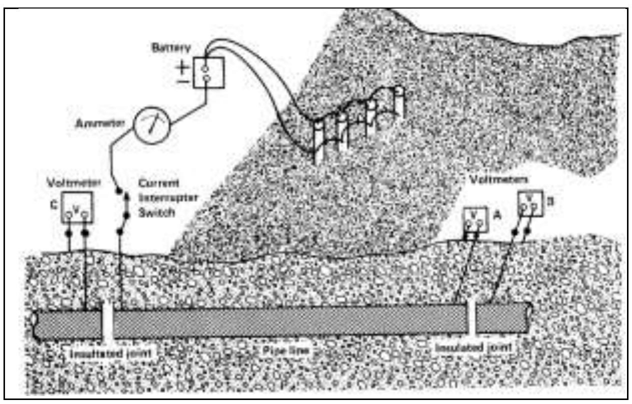

Figure 4: Current requirement test on pipeline [5]

IMPRESSED CURRENT CATHODIC PROTECTION DESIGN

A. Design Data and Assumptions [3][5][6]

1. Average soil resistivity is 2000 Ω-cm
2. Effective coating resistance for 20 years is estimates at 2500 ohms/ $feet^2$.
3. Pipe has a 10-inch outside diameter.
4. Pipe length is 10 km= 32808.4 feet
5. Design for L=20-year life.
6. Design for current density, $I' = 2$ mA/sq ft of uncoated pipe.
7. Assume for 90% coating efficiency (CE) based on practice data.
8. Gas pipeline must be isolated from each end the system.
9. HSCBCI anodes should be used with carbonaceous backfill.
10. The pipeline should be wrapped with hot-applied coal-tar epoxy and will be before installation.
11. Anodebed resistance must not exceed 2 Ω.
12. Power is available at 120/240 volts a.c or d.c. single phase from a solar photovoltaic (PV) grid that must be designed.
13. 2.36 amperes are needed for appropriate CP system according to current requirement test.

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B. Computations

4) Calculation of gas pipeline areas:

$Pipe\ size = 10\ in = \frac{10}{12}\ ft$, Pipe length= 10 Km= 32808.4 ft

$Pipe\ Area = \ \pi DL = 3.1416 \times \frac{10}{12}\ ft \times 32808.4$ ft

= 85892.39 ft^2

5) Calculation of current:

$$I = A\,I'\,(1.0 - CE\,) = \ 85892.39\ \ ft^2 \times 2\ \frac{mA}{ft^2} \times (1.0 - 0.9)$$
$$= 17178.478\ mA = 17.178\ A$$

which pertaining to the current requirement test indicated in (13)

6) Choose an anode from table 3, choose the HSCBCI, 60-pound anode with a 2.8 ft^2surface area (arbitrary selection).

7) Calculation of the number of anodes for the supplier's current density limitations by the following equation

$$N = \frac{I}{A_1\,I_1} = \frac{17178.478\ mA}{\left(2.8\ \frac{ft^2}{anode}\right) \times 1000\,\frac{mA}{ft^2}} = \ 6.13 \approx 6\ \ (Nos)$$

8) Calculation of the number of anodes required to meet the design life requirements for the system

$$\mathrm{N} = \frac{\mathrm{L\ I}}{1000\ \mathrm{W}} = \frac{20 \times 17178.478\ \mathrm{mA}}{1000\ \ \times 60/\mathrm{anode}} = 5.72 \approx 6\ (\mathrm{Nos})$$

9) To meet maximum anode groundbed resistance requirements we calculate the number of anodes required

Shape functions (K) for impressed current cathodic protection anodes where L is effective anode length and d is anode/backfill diameter. L/d=8, K=0.0165, L= 7 ft, d= 0.875

$$\mathrm{R_a} = \frac{\rho \mathrm{K}}{\mathrm{NL}} + \frac{\rho \mathrm{P}}{\mathrm{S}}\quad (\Omega)$$

$$\mathrm{N} = \frac{\rho\mathrm{K}}{\mathrm{L}\left(\mathrm{R_a} - \frac{\rho\mathrm{P}}{\mathrm{S}}\right)} = \frac{2000\ \times 0.0165}{7\left(2 - \frac{2000\ \times 0.00283}{20}\right)} = 2.74 \approx 3\ (\mathrm{Nos})$$

7) According to the calculation of anodes required for the cathodic system, we will use the maximum number of anodes. By the following equation we calculate the anodes groundbed resistance:

$$\mathrm{R_a} = \frac{\rho \mathrm{K}}{\mathrm{NL}} + \frac{\rho \mathrm{P}}{\mathrm{S}}\quad (\Omega)$$

$$R_a = \frac{2000 \times 0.0165}{6 \times 7} + \frac{2000 \times 0.00283}{20} = 1.0687 < 2 \ (\Omega)$$

(8) Select an area for anode bed placement. The area of lowest resistivity will be used, which is 100 feet from the pipeline.

(9) Determine the total circuit resistance.

a) Calculation of the groundbed resistance for a 500-foot header cable by using equation (19). The resistance specified by the manufacturer is 0.0159 ohm per 100 ft of No.2 AWG cable [13]:

$$R_w = \frac{\text{Ohms}\ (L)}{100\ \text{ft}} = \frac{0.0159\ \text{Ohms} \times \ (500\ \text{ft})}{100\ \text{ft}} = 0.0795\ (\Omega)$$

b) Using equation (21), we calculate structure-to-electrolyte resistance

$$R_c = \frac{R}{a} = \frac{2500\ \text{ohms/ft}^2}{94481.63\ \text{ft}^2} = 0.0265\ (\Omega)$$

10**)** Total resistance, RT is calculated by equation (22)

$$R_T = R_a + R_w + R_c$$
$$= 1.0687 + 0.0795 + 0.0265 = 1.175 \ (\Omega)$$

11) Calculate voltage. Equation (23) is used to determine voltage output (V) of the coveter.

$$V = I\, R_T\ (150\%) = 17.178 \times 1.175 \times 1.5 = 30.276\ \text{Volts}$$

12). According to calculated data of 30.276 volts and 17.178 amperes, a buck converter can be chosen.

C. Power & Energy Calculation and PV Panel Design

The required power for the ICCP system can be calculated by the equation (24) and the required energy for one day is calculated as in equation (25)

$$P_R = V \times I \ \ (\text{Watt}) - - - - - - - - - - (23)$$

Total power required, $P_R = 30.276 \times 17.178 = 520$ Watt

$$E_R = P_R \times 24 \ (\text{Wh}) - - - - - - - - - - -(24)$$

Required energy for one day, $E_R = 520 \times 24$

$$= 12480\ \text{Wh} = 12.48\ \text{KWh}$$

Energy lost by the PV system is almost 23.89%, so the energy required per day by the cathodic protection system [13][14]

So, total energy required per day from PV panels is

$$E_R = 12.48 + 12.48 \times 0.2389 = 15.46\ \text{KWh}$$

Total Panel efficiency is measured under **standard test conditions** (STC), based on a cell temperature of 25°C, solar irradiance of 1000W/m2 and Air Mass of 1.5. The efficiency (%) of a panel is calculated by the maximum power rating (W) at STC, divided by the total panel area in meters [15].

Efficiency of PV panels is

$$\%\ \text{Efficinecy} = \frac{P_{max}}{(A \times 1000 \frac{W}{m^2})} \times 100$$

Where P_{max} is the max panel power (W) power and A is the panel area in m^2

Table-6: PV module specification of under standard test condition (irradiation = 1 KW/m^2, T=25°C and A.M = 1.5) [20]

Monocrystalline, Neon R,	LG380Q1C-V5
Manufacturer	LG
Maximum power (P_{max}))	380 W
Open circuit voltage (V_{oc})	42.90 V
Maximum power point voltage (V_{mpp})	37.4 V
Short circuit current (I_{sc})	10.84 A
Maximum power point current (I_{mpp})	10.17A
NOCT	44 ±3
Temperature coefficient of I_{sc}	0.037 %/°C
Temperature coefficient of V_{oc}	-0.24 %/°C
Temperature coefficient of power	-0.3 %/°C
Module efficiency under STC	22%

[19] Solar panel output energy, $E_{out} = \emptyset\, W_p\, H$ (KWh)
$E_{out} = 0.75 \times 0.380 \times 4$ =1.140 KWh

Where Ø is the operating correction factor [17] and H is the irradiance KWh/m^2 per day [16] (1 peak sun hour = 1000 W/m² of sunlight per hour.)

Number of PV panels required to satisfy the given estimated daily load is

$$N_{panel} = \frac{\text{Total energy required per day}}{\text{Solar panel output energy per day}} \text{ (Nos)}$$

$$= \frac{15.46 \text{ KWh}}{1.140 \text{ KWh}} = 13.56 \approx 14$$

D. Battery bank sizing:

Battery bank size (KWh) =

$$\frac{(\text{Daily energy usage in KWh} \times \text{Numberof days of automony})}{1 - \text{SoC}}$$

$$= \frac{15.46 \times 3}{1 - 0.50} = 92.76 \text{ KWh}$$

The standard sizing calls for 3 days and an SoC of 50% [18], where SOC stands for state of charge and alternative of the same measure is the depth of discharge (DoD).

$$\text{Battery Ampere} - \text{hours} = \frac{\text{Energy Storage(kWh)}}{\text{Battery Voltage (Volt)}}$$

$$= \frac{92760\text{(Wh)}}{48 \text{ (Volt)}} = 1932.5 \text{ Ah}$$

$$\text{Number of battery} = \frac{1932.5 \text{ Ah}}{500 \text{ Ah}} = 3.865 \approx 4$$

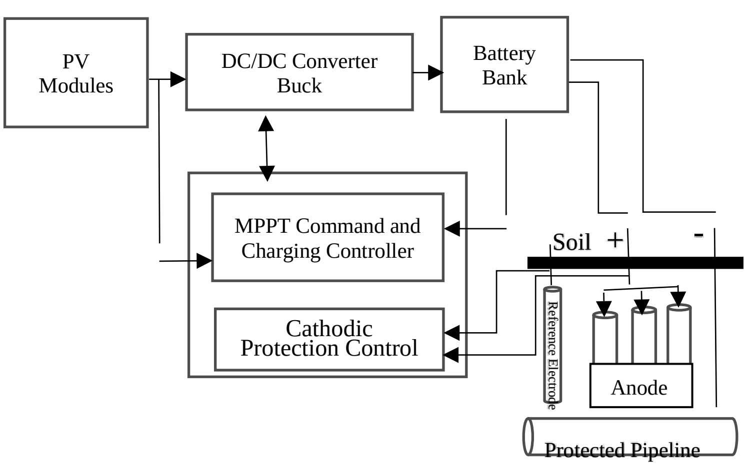

Figure-5: Block Diagram of Regulated Cathodic protection system [21]

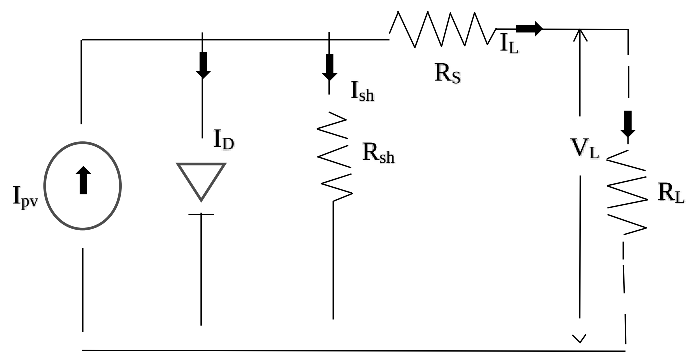

Figure-6: PV Module Equivalent Circuit Diagram

RESULT AND DISCUSSION

The design of PV system for the impressed current cathodic protection consisted of 7 parallel strings and 2 serious modules out of 14 modules. DC to DC buck converter has been used, and 4 lead acid batteries of each 48 volts 500 Ah have been connect with the MPPT for the maximum output and charging. Depth of discharge (DoD) is considered 50 % for ICCP system. The characteristic curves of used PV panel shown in figure 7.

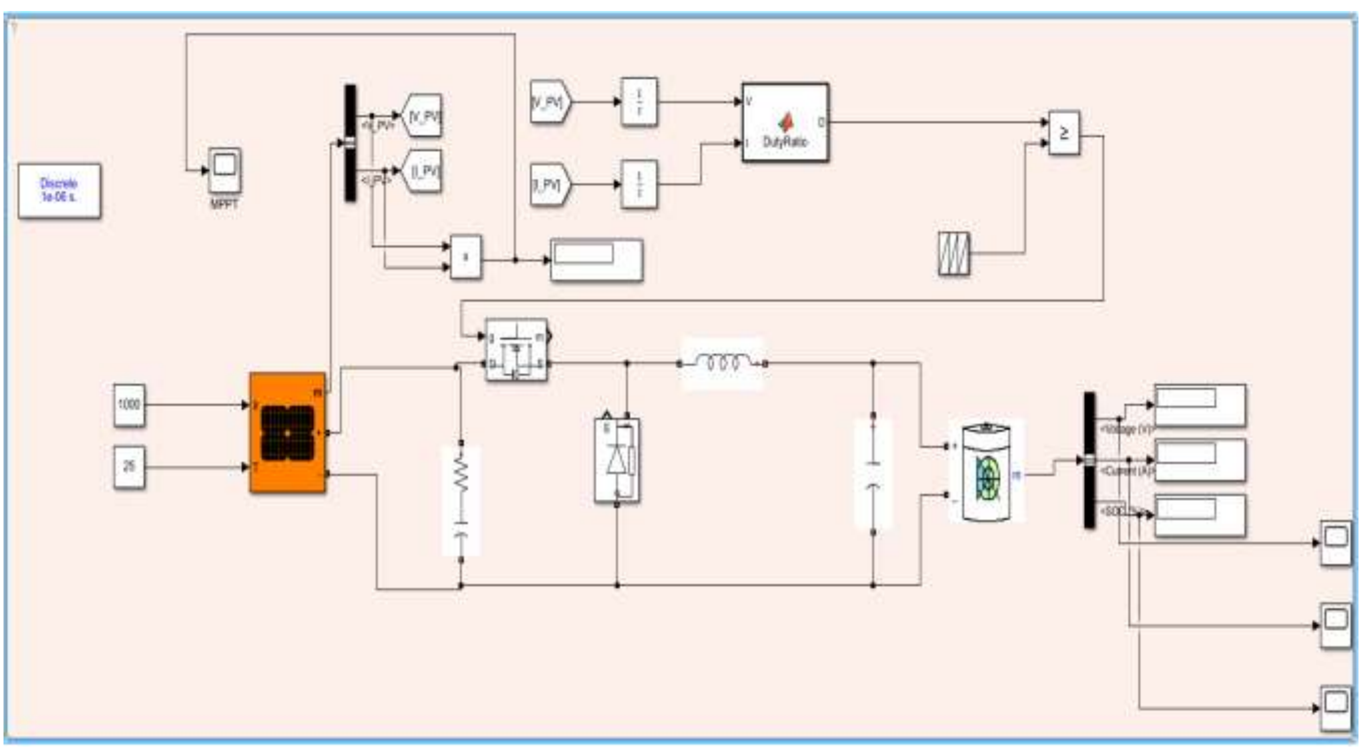

Figure-8: Simulink drawing of ICCP system pertaining to the characteristics of standards test conditions PV modules. In the simulation, the duty ratio of buck converter is generated by the microcontroller's output signal according to program to reach the criteria of the impressed current cathodic protection system that is consisted of 0.85 volt and 1.5 volt (reference electrode).

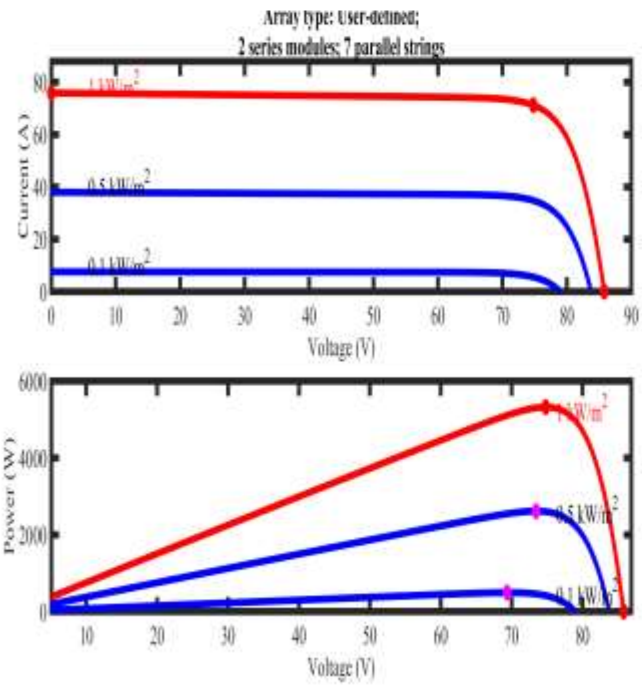

Figure-7: PV and VI characteristic curves of 380 W solar panel

CONCLUSION

Impressed Current Cathodic Protection (ICCP) system is mainly used for controlling corrosion of larger metallic structures where the current requirement is high and external DC source is needed. External DC supply can be utilized from the distributed power or renewable energy sources using power electronic converters. The focus of this study is to mitigate the

The efficiency of solar PV panel was found a fair solution to reduce the corrosion rate of underground pipelines according to the measured results. This system saves energy as it automatically adjusts and controls the voltage to supply constant current during the temperatures. The ICCP system is the most effective which is available throughout the year. In this study, the mathematical design has been done for the 10 in 10 km underground as pipelines, and the results shows the impressed current cathodic protection is very economical because of using non consumable anodes and renewable energy sources.

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