Efficiency and Cost Analysis of Power Sources in Impressed Current Cathodic Protection System for Corrosion Prevention in Buried Pipelines of Balochistan, Pakistan

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Abstract. Corrosion is the physical deterioration of metals, including buried metal structures and gas pipelines, resulting from chemical reactions between metals and the surrounding environment. Cathodic protection of these underground metal structures & pipelines can be achieved either by the Impressed Current method or by the sacrificial anodes method. This research paper focuses on the corrosion prevention of buried metal structures in general and gas pipelines in particular, by the novel method of Impressed Current Cathodic Protection (ICCP) which uses electrical current from an external DC power source for its operation. Three major DC power sources i.e. Transformer Rectifier, Thermoelectric Generator and the Solar System are selected for this purpose and are projected over a period of time in a pre-designed ICCP for high transmission underground gas pipeline in Balochistan province of Pakistan. The efficiencies of these three power sources are then analysed and compared according to the climate effects, the versatility effects, the intensity of power output, their operational limitations and their initial, running and maintenance costs. The measured results will aid the selection of efficient and robust DC power source for ICCP design and will contribute to mitigating and controlling the corrosion rate in underground pipelines. Based on analysis of the measured results for the three available DC sources, the Solar System was found as the most efficient DC power source for Impressed Current Cathodic Protection of buried gas pipelines. The selection of efficient corrosion protection system will result in a smooth flow of oil and gas products through these buried pipelines which may otherwise lead to huge monetary and accidental losses when get corroded.

Keywords. Corrosion, solar system, impressed current cathodic protection

1. Introduction

The metals are extracted from their respective ores and are then structured in a reformed state after adding an enormous amount of heat into it. When these structured metals are exposed to the environment, the environmental contaminants such as oxygen, H₂O moisture, etc. react with these structured metals. Due to this reaction, the structured metals lose their energy and returns to their original state [1]. Uniform corrosion assaults uniformly at all areas of metals at the same rate, whereas localized corrosion assault some areas of metals at a different rate and in pitting corrosion pits are formed in the material [2].

1.1 Corrosion in Underground Pipelines

In case of underground iron pipelines, corrosion is a spontaneous or electrochemical process in which current leaves a structure at anode site and penetrates the structure at cathode site after passing through an electrolyte in which it is placed.

To analyze the mechanism of corrosion in iron it is observed that oxidation reaction take place at anode causing Fe²⁺ ions to release from the anode and OH⁻ ions are released from the cathode by a reduction reaction. The Fe²⁺ and OH⁻ ions combine to form a white precipitate of solid iron + hydroxide [1].
Equation (1), (2) and (3) shows oxidation reaction, reduction reaction and their net equation respectively.

\[
\begin{align*}
Fe(s) & \rightarrow Fe^{2+}(aq) + 2e^- \quad (1) \\
O_2(g) + 2H_2O(l) + 4e^- & \rightarrow 4OH^- \quad (2) \\
Fe^{2+} + 2OH^- & \rightarrow Fe(OH)_2(s) \quad (3)
\end{align*}
\]

This Fe(OH)_2 further undergoes oxidation in the presence of moisture and oxygen leading to the formation of brown solid called rust (see Equation (4)).

\[
4Fe(OH)_2(s) + O_2(g)2H_2O(l) \rightarrow Fe_2O_3.nH_2O(s) (rust) \quad (4)
\]

1.2 Effects of Corrosion on Underground Pipelines

Transportation of petroleum products and natural gas over long distances through underground and submerged pipelines is considered as most efficient, reliable and cost-efficient way of transporting these products. But these underground pipelines are vulnerable to mechanical damage, third party factors and corrosion.

The occurrence of corrosion in these pipelines can be understood by its adverse effects on industries and consumers alike.

- Corrosion may lead to the plant shutdowns and shutdown of process plants.
- Corrosion may cause loss of products and results in leakage of liquid from transportation pipelines, with a capacity to generate severe accidents and hazards. Replacement of corroded pipes causes huge monetary losses to companies and national economies [1].

1.3 Corrosion Prevention Techniques in Underground Pipelines

Methods widely used for the prevention of corrosion are:

- Use of material that is corrosion resistive such as stainless or plastic
- By changing the environment such as electrolyte soil
- By using a coating that isolates the structure electrically from the electrolyte e.g. epoxy paints, coal tar enamel and polythene coating.
- Use of cathodic protection techniques [2]

The first line of defence against corrosion protection in underground and submerged structures (pipelines) is insulation coating which can either be of coal tar enamel, polythene, tape or asphalt coating. Up to 50% – 99% of corrosion protection is achieved if the proper coating is ensured. But due to third party and mechanical damages during commissioning of these pipelines, this percentage reduces and achieving 100% corrosion protection through the primary line of defense is difficult. Therefore, the remaining corrosion protection is accomplished by a well-designed cathodic protection system also called secondary corrosion control techniques [3, 4]. In cathodic protection techniques, a direct current by means of an external source is utilized to make the structure (to be protected) at one potential and eliminating the anode and cathode site. The principal utilization of cathodic protection was traced in 1824 by Sir Humphrey Davy [5].

1.4 Cathodic Protection Techniques

Cathodic protection techniques are mainly classified into two types:

a. Sacrificial anode cathodic protection (SACP) method (Galvanic Anode Method).

b. Impressed Current Cathodic Protection (ICCP) method.

The choice of selecting these two methods for cathodic protection design depends upon the area of the structure to be protected (current requirement) and electrolyte (soil) resistivity. In both methods, the fundamental components are the anode, the cathode, DC power source (in ICCP an external power source), and electrolyte. The electrolyte is an electrically conductive solution from which electrons flow.
from anode to cathode. The type of electrolyte differs in context of moisture content, oxygen level, and soil resistivity level.

1.4.1. Sacrificial anode cathodic protection system

The Figure 1 illustrates the utilization of a metal (anode), which is normally more electro-negative (magnesium, zinc and aluminium etc.) than the metal (cathode) being protected (mild steel or carbon steel etc.). Current streams from the metal that is more electrically negative to the metal that is more electrically positive. 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 [6].

![Figure 1. Schematic of Sacrificial Anode Cathodic Protection Method](image)

1.4.2. The 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 [6].
The utilization of the external power source allows an impressed current cathodic protection system to generate comparatively higher current output and has a tendency to use larger voltage differences than any sacrificial anode system. The larger voltage available with impressed current permits remote anode location, delivering more efficient current distribution pattern along the protected structure. Specially in low conductive environments, these larger voltages are found useful [1]. The selection of right type of external DC power source is crucial in ICCP which has a tendency to be versatile, robust, and effective and cost-efficient [6].

2. State of the Art
The problem of corrosion takes more serious attention when underground metallic pipelines are considered. The problem of corrosion in buried gas pipelines and their remedial action through impressed current cathodic protection has been studied by various researchers. The research studied in [7] concluded that the Energy crisis and corrosion are two major problems for the 21st century and proposes Thermoelectric Device as a promising solution for addressing those two problems. The application of Rectifier DC power source is presented in a patent paper [8]. Another research study [1] is based on prevention of corrosion in iron pipelines by utilizing the novel method of Impressed Current Cathodic Protection. Instead of deploying a conventional AC power source, solar energy is utilized to drive the system. Adly G S [2] concluded that to minimize the risk of corrosion and overprotection is caused by an increase in DC current in underground structures. An automatic regulating cathodic protection system is hence proposed. This is to overcome problems associated with conventional cathodic protection system. The research [3] analyzes and calculated the parameters of PV solar system for ICCP system to protect tanks from corrosion.

None of the researchers have discussed, analyzed and compared more than one DC sources after implementing it over a time period by means of real-time in a pre-designed ICCP system for high transmission underground gas pipelines. The objective of this research work is to analyze and compare climate effects, versatility effects, intensity of power output, operation limitation, as well as initial running and maintenance cost of three different DC sources by implementing it in a pre-designed ICCP system over a period of time at high transmission gas pipelines.
3. Methodology
To achieve the research objective, a 12-inch diameter underground high transmission natural gas pipeline made up of mild steel material, at two different locations (Sibi and Bolan) differing in resistivity of soil and climate in the Balochistan province of Pakistan, was chosen. The pipeline has coal tar enamel coating having coating efficiency of 75% analyzed after closed interval potential survey at both locations. Three number of trials have been performed at each location in three different months of winter and summer seasons respectively. The ground bed efficiency at both locations was observed as 50% to 60% as per ground bed resistance and commissioning year.

Three DC sources i.e. thermoelectric generator (TEG), transformer rectifier (TR) and a solar PV system are implemented and analyzed in a pre-determined impressed current cathodic protection system at both locations, one at a time respectively. The results for Bolan and Sibi sites are given in table 1 and table 2 respectively.

4. Analysis and Results
4.1 Technical Analysis
4.1.1. Analysis of the climate effects
The climate effects comprise of two parameters, i.e. specific resistivity of electrolyte and the temperature.

While analysing the climate effect of all three DC sources selected and their performance in Quetta Bolan region, the constant variable is coating efficiency, ground bed efficiency, soil resistivity and capacity of the DC power source (220 Watts), whereas the dynamic variable is temperature.

During winter: it has been observed that during the winter season while considering the constant and dynamic variable conditions at a similar location, the three DC sources energizes the ground bed at different levels. It is noticeable that the power drawn from solar system energizes the anode bed greater than that of TEG and TR.

During Summer season: it has been observed that during summer season where the weather conditions become dry and the moisture content in soil reduces, the output current and voltage ratio drawn from DC source also changes. More voltage is required to carry out current and to maintain pipe to soil potential under specified protection level defined by National Association for Corrosion Engineers, NACE standard RP-01 i.e. at least 0.85 Volts, measured from CU CUSO4 reference electrode. It is noticeable that more power is delivered by solar system during the summer season. The result of a pipe to soil potential is also depicted in table 1.

While analysing the climate effect of all three DC sources selected and their performance in SIBI region, the constant variables are coating efficiency, ground bed efficiency, soil resistivity and capacity of the DC power source (220 Watts), whereas the dynamic variable is Temperature. Values are mentioned in table 2. In high resistive soil more, voltage is needed whereas in low resistive soil more current is needed to maintain the pipe to soil potential level.

During winter: The power delivered by individual DC source as well as the potential level of pipe to soil can be clearly analyzed from the values of the obtained results, mentioned in table 2. Solar PV systems can be seen as delivering more power subsequently energizing the available anode bed to ensure the Pipe to Soil Potential level greater than that of TEG and TR.

During summer: During the summer when the temperature rises the TEG loses its power by 0.8W / °C above 25 °C. But due to increase in solar irradiations during summer solar PV panels will deliver more power. The output power, voltage and current values to utilize the ground bed anodes and PSP readings are shown in table 2. One can easily compare the output power of all three DC sources and the PSP values of the pipeline.
| Specified DC Power Source | Soil Type | Location | Soil Resistivity (Ωcm) | Month | Ambient Temperature (Min-Max) (°C) | Output Voltage (V) | Output Current (A) | Power Output (Watt) | Groundbed Efficiency (%) | Coating Efficiency (%) | PSP using CU CUSO4 Reference Electrode (Volt) | Intensity of the Power output in terms of effectiveness over distance (kilo-meter) | Versatility Effect After connecting to a 300ft Microwave System (kilo-meter) | Moist Weather Conditions | Dry Weather Conditions |
|--------------------------|----------|----------|-----------------------|-------|----------------------------------|------------------|------------------|-------------------|----------------------|----------------------|--------------------------------|------------------------------------------------|------------------------------------------------|----------------------|---------------------|
| TEG                      | Rocky    | Spezand, Balochistan | 10,000 Ωcm | Dec    | 0 to 9                          | 13                  | 5                 | 65 W              | 50 to 60%            | 75%                  | 1.00 V                          | 1.52 V                      | 6 km                          | 6 km                        | 4.5 km                         | 4.5 km                         |
| TR                       | Rocky    | Spezand, Balochistan | 10,000 Ωcm | Jan    | 1 to 8                          | 18                  | 8                 | 144 W             | 50 to 60%            | 75%                  | 1.04 V                          | 1.55 V                      | 1.04 V                      | 7.5 km                     | 7.5 km                         | 6.5 km                         | 6.5 km                         |
| PV                       |          |           |                       | Feb    | 1 to 11                         | 20                  | 10.5              | 210 W             | 50 to 60%            | 75%                  | 1.10 V                          | 1.57 V                      | 1.10 V                      | 11 km                      | 11 km                         | 10.5 km                        | 10.5 km                        |
| TEG                      | Rocky    | Spezand, Balochistan | 10,000 Ωcm | June   | 13 to 35                         | 16                  | 3.8               | 608 W             | 50 to 60%            | 75%                  | 0.98 V                          | 1.49 V                      | 0.98 V                      | 5 km                       | 5 km                        | 3 km                           | 3 km                           |
| TR                       | Rocky    | Spezand, Balochistan | 10,000 Ωcm | July   | 18 to 39                         | 21                  | 6.3               | 132.3 W           | 50 to 60%            | 75%                  | 1.00 V                          | 1.52 V                      | 1.00 V                      | 7 km                       | 7 km                        | 5.5 km                         | 5.5 km                         |
| PV                       |          |           |                       | Aug    | 21 to 40                         | 23                  | 8.9               | 204.7 W           | 50 to 60%            | 75%                  | 1.05 V                          | 1.55 V                      | 1.05 V                      | 10 km                      | 10 km                        | 9 km                           | 9 km                           |

Note: TEG Stands for 'Thermoelectric Generator', TR stands for 'Transformer Rectifier', PV stands for 'Photovoltaic System', PSP stands for 'Pipe to Soil Potential'.
Table 2: Test Results of Location 2 (Sibi)

| Specified DC Power Source | Soil Type | Location | Soil Resistivity (Ω cm) | Month | Ambient Temp (Min-Max) (°C) | Output Voltage | Output Current | Power Output (Watt) | Coating Efficiency (%) | Groundbed Efficiency (%) | Coating Efficiency (%) | PSP using CUSCO4 Reference Electrode (Volt) | Intensity of the Power output in terms of effectiveness over distance (kilo-meter) | Versatility Effect After connecting to a 300ft Microwave System (kilo-meter) |
|--------------------------|-----------|----------|-------------------------|-------|-----------------------------|----------------|---------------|-------------------|-----------------------|------------------------|------------------------|-----------------------------------------|-------------------------------------------------|---------------------------------------------------------------------------------|
| SIBI SECTION (WINTER SEASON) |           |          |                         |       |                             |                |               |                   |                       |                        |                        |                          |                                         |                                                    |                                                                                |
| TEG                      | Hard Clay | Shohri Balochistan | 2500 Qm              | Dec   | 8 to 25                        | 5.5 V          | 14A           | 77 W              | 50 to 60%             | 75%                   | 0.89 V                | 1.38 V                | 0.89 V                  | 7 km                     | 7 km                          | 6 km                           | 6 km                          |
| TR                       |           |          |                        | Jan   | 4 to 17                         | 7.5 V          | 19.9 A        | 149.25 W          | 50 to 60%             | 75%                   | 0.94 V                | 1.45 V                | 0.94 V                  | 8.5 km                   | 8.5 km                         | 7.5 km                         | 7.5 km                         |
| PV                       |           |          |                        | Feb   | 9 to 23                         | 8.5 V          | 25 A          | 212.5 W           | 50 to 60%             | 75%                   | 1.03 V                | 1.53 V                | 1.03 V                  | 12 km                    | 12 km                          | 11.5 km                        | 11.5 km                        |

| SIBI SECTION (SUMMER SEASON) |           |          |                         |       |                             |                |               |                   |                       |                        |                        |                          |                                         |                                                    |                                                                                |
| TEG                      | Hard Clay | Shohri Balochistan | 2500 Qm             | June  | 28 to 41                        | 4V             | 17A           | 68 W              | 50 to 60%             | 75%                   | 0.88 V                | 1.31 V                | 0.88 V                  | 5.5 km                   | 5.5 km                          | 4 km                           | 4 km                           |
| TR                       |           |          |                        | July  | 30 to 47                         | 5.9 V          | 23 A          | 135.7 W           | 50 to 60%             | 75%                   | 0.90 V                | 1.42 V                | 0.90 V                  | 8 km                     | 8 km                           | 7 km                           | 7 km                           |
| PV                       |           |          |                        | Aug   | 31 to 48                         | 7.4 V          | 27 A          | 199.8 W           | 50 to 60%             | 75%                   | 1.00 V                | 1.56 V                | 1.00 V                  | 11.5 km                  | 11.5 km                          | 4 km                           | 4 km                           |

Note: TEG stands for 'Thermoelectric Generator', TR stands for 'Transformer Rectifier', PV stands for 'Photovoltaic System', PSP stands for 'Pipe to Soil Potential'.
4.1.2. Analysis of Versatility effects
The Versatility effects mean that how much larger structure of the ICCP system can handle when relating to three different DC sources having similar power capacity i.e. 220 W. The 12-inch diameter underground pipeline is coupled with 300 feet high iron made a tower for microwave system at both selected locations. The PSP of the pipeline is recorded at feeding point, upstream end and at downstream ends of the pipeline. In the light of results recorded the PV Solar system takes clear-cut advantage over TEG and TR in context of versatility effects at both locations.

4.1.3. Analysis of intensity of the power output
This effect means that up to how long the magnitude of the output reaches, that is delivered by the DC source in ICCP to energize the pipeline potential. The analyses were done by integrating three DC sources respectively, one at a time in ICCP system at both said locations and then recorded the PSP of pipeline up to several kilometres in the up and downstream ends. The solar system has proved its efficient magnitude in both soil types by maintaining the PSP up to several kilometres greater than that of TEG and TR. Analyzed results are depicted in table 1 and table 2.

4.2. Cost Analysis
The cost comparison of three DC power sources for ICCP was carried out using present worth or net present value (NPV) analysis. For economic analysis, constant discount rate, exchange rate, annual maintenance and operation costs throughout the useful life of the external DC power sources were assumed. The following parameters were considered as common for all the three DC power sources:
- Useful life = 20 Years
- Discount rate = 6%
- USD to PKR exchange rate as on 21/2/2018 = Rs110.76

4.2.1. Thermoelectric generator

- Initial cost = $3160
- Maintenance cost = $412 every five years
- Operational cost = $17526 per year
- Salvage value = $472 at the end of 20 years.

The economic formula for calculating present worth or present value (P) of a single payment and equal payment series are given in Equations (5) and (6) respectively [9].

\[ P = F \left( \frac{1}{1+i} \right)^N \]  
\[ P = A \left[ \frac{(1+i)^N-1}{i(1+i)^N} \right] \]

Where ‘P’ is the present worth (PW) or present value, ‘i’ is the discount rate or interest rate, ‘N’ is the number of discounting periods and ‘A’ is the annual payment. Figure 3 shows the cash flow for the thermoelectric generator as per calculation.

\[ PW = 31600 + \frac{412}{(1+0.06)^3} + \frac{412}{(1+0.06)^5} + \frac{412}{(1+0.06)^10} + 17526 \left[ \frac{(1+0.06)^{20}-1}{0.06(1+0.06)^{20}} \right] - \frac{472}{(1+0.06)^{20}} \]

\[ PW = \$233184.5 \]
4.2.2. Transformer Rectifier
Initial cost = $1120
Maintenance Cost = $73/year
Operational cost = $242/year
Annual O&M Cost = $242 + $73 = $315
Salvage value = $187 at the end of 10 Years
The cash flow diagram for Transformer rectifier as per computation is shown in Figure 4.

\[
P_W = 1120 + 315 \left[ \frac{(1+0.06)^{20}-1}{(1+0.06)^20} \right] - \frac{187}{(1+0.06)^20}
\]

\[PW = $4674.74\]  

4.2.3. Solar PV System
Initial cost = $8902
Maintenance cost = $7327 after 10 years
Operational cost = $0
Salvage value = $283 every 10 years.
The cash flow diagram for solar PV system after the calculation is shown in Figure 5.

\[
P_W = 8902 + \frac{7327}{(1+0.06)^{10}} - \frac{283}{(1+0.06)^{10}} - \frac{283}{(1+0.06)^{20}}
\]

\[PW = $12747.09\]

5. Conclusion
Cathodic protection systems are used to protect buried and submerged metallic structures from corrosion. Impressed Current Cathodic Protection (ICCP) system is used for protecting larger metallic structures where the current requirement is high and external DC source is required. The focus of this research
Work is to mitigate the rate of corrosion in underground metallic pipelines in general and natural gas pipelines, by integrating three different DC sources for a specified period of time at two different locations in the province of Balochistan with an ICCP system. The selected locations are distinct from each other according to climate & soil resistivity. The efficiency of each DC source has been thoroughly analyzed after comparing their technical and cost efficiencies. Based on measured results the technical efficiencies of the Solar PV system was found a promising solution in mitigating the rate of corrosion, since it has tendency to deliver more constant DC power to an ICCP system both in hot and cold temperatures as well as in high and low resistivity environments, as compared to other two DC Sources used i.e. Thermoelectric generator and transformer rectifier. Further, unlike TEG and TR the solar PV system is not dependent on commercial utility supply, for its operation, which make it more preferable, especially in areas where there is no availability of commercial utility supply but enriched solar irradiations. However, the computed results found that Transformer rectifier is an economical DC source for an ICCP system compared with that of the Thermoelectric generator and Solar PV systems. The calculation and measured results are quite straightforward based on real-time data. The proposed research will aid companies and industries in selecting the right type of external DC source while designing the ICCP system according to climate, versatility, output power intensity and cost efficiency for corrosion protection of underground pipelines.

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