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Design of Deep Anode Ground Bed for Cathodic Protection of Oil Pipelines Using Pv Modules At Port Harcourt, Nigeria

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Abstract *- The design and installation of an impressed current cathodic protection (CP) deep anode ground bed system was carried out at Port Harcourt. Deep anode ground bed CP systems using photovoltaic (PV) modules have become an industry standard. A deep anode system is an impressed current CP arrangement in which the anodes are located in wholly, or partially, electrically remote earth extending down vertically from the surface in a hole drilled for the purpose. During the life time of an oil pipeline, conditions may develop which will require routine and special operational measures in order to maintain the integrity of the pipeline system, or warrant its efficient, reliable and economic operation. The results of the pipe-soil potentials along the 8" oil pipeline were the same as those obtained by locating anodes electrically remote laterally from the structure and near the surface. The remote earth system provided optimum current distribution along the protected structure and minimized voltage gradient variation, thus adequately safeguarding the pipeline system from the corrosive coastal environment.*

Keywords - anode, cathodic protection, photovoltaic, current, pipelines, corrosion

1. INTRODUCTION

Oil pipelines play a very significant role in and around oil producing communities and the country at large conveying crude, gas and refined petroleum products across the length and breadth of the Niger Delta for export and local consumption respectively. These pipes are buried in the corrosively aggressive coastal soils and deterioration after burial of pipes underground is a common problem. It is generally considered that the most economical way of prolonging the lives of pipes today is by combining a suitable coating with the application of a cathodic protection current provided from an external anode (Trethewey and Chamberlian, 1995; Wansah *et al.*, 2004). Cathodic protection (CP) is a technique used to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell (Peabody, 2001). Cathodic protection and corrosion control can be effectively monitored using standard copper/coppersulphate electrode and also by using pipeline telemetry system (a system that transmits data captured by instrumentation and measuring devices to a remote station where it is recorded and analyzed). In the Niger Delta, millions of Naira (₦) is used annually in the maintenance and replacement of corroded oil pipes due to the reaction of these pipes with their environments (Melchers, 2005). If this situation were to be allowed to continue, a chunk of the country's budget will always go into the corrosion control sector every year for pipeline maintenance, replacement and environmental/community related issues. There is therefore, an urgent and compelling need to arrest this menace through proper design, adequate CP and the use of modern remote corrosion monitoring techniques. Deep anode ground bed system is an array of electrodes installed in carbonaceous (coke breeze) backfill well at about 100m deep to prevent corrosion of underground metallic structures (Holtsbaum, 2001) by impressing electrical potentials thereon to make such structures cathodic with respect to the surrounding soil which functions as an electrolyte. This is typically used for impressed current CP system with a massive array of pipeline network system. Corrosion monitoring is important for measuring the rate of degradation and ensuring that the rate of corrosion remains within acceptable limits (through suitable corrosion control methods).

Cathodic protection is a method of preventing oxidation (rusting) of metal structures by imposing between the structure and the ground a small electrical voltage that opposes the flow of electrons and is greater than the voltage that is present during oxidation. Cathodic protection is divided into galvanic or sacrificial anode cathodic protection and electrolytic or impressed current cathodic protection (Wansah *et al.*, 2004). In galvanic cathodic protection, the corroding object is made the cathode of a galvanic cell, the anode of which is a more reactive metal such as magnesium, aluminium or zinc, and which by being sacrificed, protects a valuable structure. The corroding object is made the cathode of the galvanic cell, the anode of which is a baser metal (Mg, Zn) (Peabody, 2001), and which by being sacrificed protects valuable steel pipes. Fig. 1

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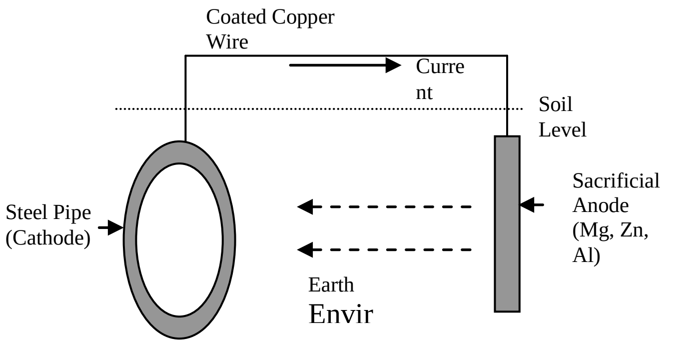

Fig. 1: Galvanic Cathodic Protection of Underground Pipeline

shows the cathodic protection of buried pipeline using a sacrificial anode.

In this set up no external source of electromotive force (emf) is required. The magnesium alloy (or other material) is sacrificed in generating the current and so the anodes need periodical replacement, which is a source of inconvenience and expense to the oil company.

With electrolytic cathodic protection (CP), the corroding object is made the cathode of an electrolytic cell, which is supplied with direct current from an outer current source (rectifier). The auxiliary anode of this cell is usually insoluble (Pt, Pb, C, Ni) (Peabody, 2001). Protection by impressed polarization using alternating current (ac) mains or diesel generator is shown in Fig. 2.

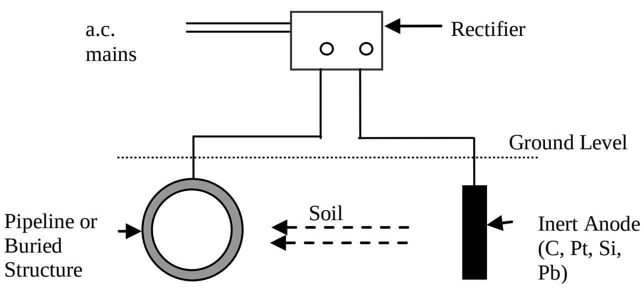

Fig. 2: Impressed Cathodic Protection of Pipeline Using a Rectifier

Generally, electrolytic method of cathodic protection is more economical than the galvanic method especially if long lines or large bare surfaces or poorly coated metal structures are involved. Electrolytic method of cathodic protection requires a source of direct current and an auxiliary electrode (anode) usually of graphite located some distance away from the protected structure (Lilly *et al.*, 2007). Diesel generators have been used as a source of current, although maintenance is troublesome. Even so, where the structure is extensive, it may be necessary to have more than one anode, each associated with its own generator. Also the current supply from the a.c. mains is erratic and does not favour CP thus a more reliable system – a stand-alone PV system is required for effective pipeline protection (Seong-Jong *et al.*, 2008).

A stand-alone PV system is a self-sufficient system that is not hooked to electricity grid and can have a back-up system (Nwokoye, 2010) of batteries. This system is connected directly to the application device and power is supplied during the sunshine hours, with storage batteries in the system to make power available during the night (Wansah *et al.*, 2005, Koutroulis *et al.*, 2006, and Lalwani *et al.*, 2011), as shown in Fig. 3.

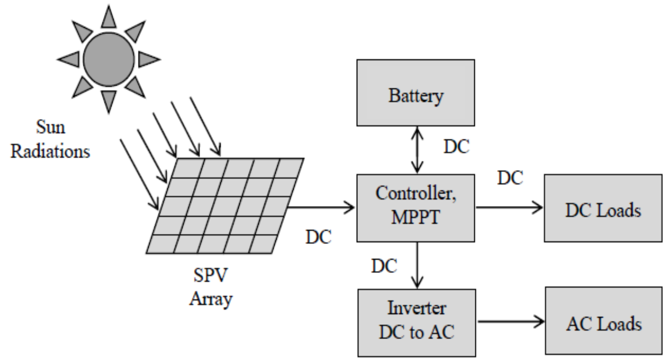

Fig. 3: Stand-alone PV Power Supply System

In this study, the deep anode ground bed has been designed to utilize the stand-alone PV system as a reliable, independent, cost effective and environmental friendly source of power supply.

2. MATERIALS AND METHOD

The application of rational design principles were taken into consideration while using 80.08W solar PV modules, copper/coppersulphate electrode, 12V-100Ah solar batteries, LIDA anodes, charge controller, Wenner meter, digital multimeter, bore hole equipment and other accessories. Schlumberger also measures soil resistivity for cases where the depth of investigation is greater than 50m (Parker and Peattie, 1999). The following field tests and measurements were carried out for effective design of the CP system.

The ground bed was drilled and anodes installed, Fig. 4. The coke breeze was thoroughly tamped (loose backfill can give high resistance and shorten anode lives (Parker and Peattie, 1999)). Buried connections were protected with extreme precautions against the entrances of any moisture (because any discharge of current to earth from the cable will destroy it in a matter of hours or days (Parker and Peattie, 1999)). The cable connection to the anode was protected because the tiniest crack will permit the entrance of moisture with inevitable failure. The anodes were buried at a sufficient depth to protect them against accidental damage.

After the installation, the ground bed was hooked to the cathodic protection (Kharzi, 2009) and corrosion remote monitoring system, Fig. 4. The pipeline system was cathodically protected against corrosion using solar PV modules (Mishra *et al.*, 2000, Mohsen *et al.*, 2013).

Electrical measurements and inspection were carried out to ensure that the required protection potential (Tanasesco *et al.*, 1988) had been established according to the applicable criteria, and that each part of the CP system was operating properly.

2.1 Design Calculations for Anode Ground bed Installation

The following field tests and measurements were carried out for effective design of the CP system. From Dwight's equation for single vertical anode resistance to earth (NACE, 2000), the deep anode ground bed resistance is given by

$$R_a = \frac{0.1588\rho}{L}\left(\ln\frac{8L}{D} - 1\right) \quad (1)$$

where R_a is anode resistance (Ω), ρ is medium resistivity ($5x10^{-2}$Ω-m), L is anode length (1.0m) and D is anode diameter (1.6 x 10^{-2}m). The combined resistance of anodes and hence the anode ground bed resistance, taking into consideration the mutual interference was obtained from Dwight's equation (NACE, 2000),

$$R_{gb} = \frac{R}{N} + \left(\frac{\rho}{\pi NS}\right)\ln 0.66xN \quad (2)$$

where R_{gb} is ground bed resistance (Ω), N is number of anodes (4), S is anode spacing (2.50m) (it is got by dividing the length of the active region by the number of anodes after subtracting the total length of the anodes from it) and R is single anode resistance (0.041Ω), which is less than 1Ω as desired (Peabody, 2001).
Minimum CP current requirements was given by considering: pipeline surface area

$$A = \pi(D + 2t_w)L \quad (3)$$

Minimum current density is 0.01mA/m^2 (i.e., ratio of minimum CP current required to pipeline surface area), corrected current density (C_i) is 0.125mA/m^2 and minimum CP current required is C_i x A. The spread protection current was determined using the attenuation constant, *a* given by

$$a = \left[\frac{R_o}{t_w \times R_c}\right]^{\frac{1}{2}} \quad (4)$$

Characteristic resistance is

$$R_k = \left[\frac{R_o R_c}{\pi^2 D^2 t_w}\right]^{\frac{1}{2}} \quad (5)$$

where R_o is resistance of pipeline material, R_c is coating leakage resistance and R_k = 3.76 x 10^{-5}Ω

This is very low and good for cathodic protection current flow (Peabody, 2001). The anode parameters provided by the LIDA anodes manufacturer are given in Table 1.

Table 1: Anode Parameters

S/N	Anode Parameters	Value/Unit
1	Anode type	LIDA anode
2	Anode dimensions	100cm x 1.6cm
3	Net weight	0.230kg
4	Nominal consumption rate	0.0027kg/yr
5	Maximum output per anode (at 100A/m^2 current density)	2.5A
6	Utilization factor	90%
7	Required lifetime	25yrs

Anode weight, *W* is given by:

$$W = I_p \, x \, Q \, x \, Y \, x \, F \quad (6)$$

where I_p is total current required (4.6A) (i.e., from attenuation current of 0.129A and bonding interference mitigation of 3.0A, giving a total current of 3.129A. For CP design, the power source current was assumed to be 150**%** of the protection current. Then for effective cathodic protection, the effective protection current, I_p was 1.5 x 3.129A), Q is nominal consumption rate of anode (0.0027kg/yr), Y is required lifetime (25yrs), F is utilization factor (0.9). Thus, number of anodes, N required is

$$N = \frac{W}{W_a} \quad (7)$$

where N is number of anodes required, W is anode weight (0.2802kg) and W_a is individual anode weight (0.115kg). Approximating to the next higher even number, N is 4. The number of anodes required for a given impressed current (Peabody, 2001) were also calculated from

$$N = \frac{CR \times DL \times I}{UF \times Wt} \quad (8)$$

where N is number of anodes , CR is consumption rate (0.0027kg/yr), DL is desired life (25yrs), I_p is current required (4.6A), UF is utilization factor (0.9) and Wt is weight per anode (0.115kg) as specified by the anode manufacturer. Also approximating to the next higher even number, N is 4. Therefore, 4 LIDA anodes at maximum current output were sufficient to supply the ground bed current of 4.6A. Anodes group weight is W_a x N. Anode consumption, A_c at maximum ground bed current output for 25 years is

$$A_c = Y \times I_p \times Q \tag{9}$$

where Y is required lifetime, I_p is total current required, Q is nominal consumption rate of anode and A_c anode consumption is 0.3168kg/yr. This is less than the anode group weight and hence met the anode quantity requirements for the specified life of the pipeline.

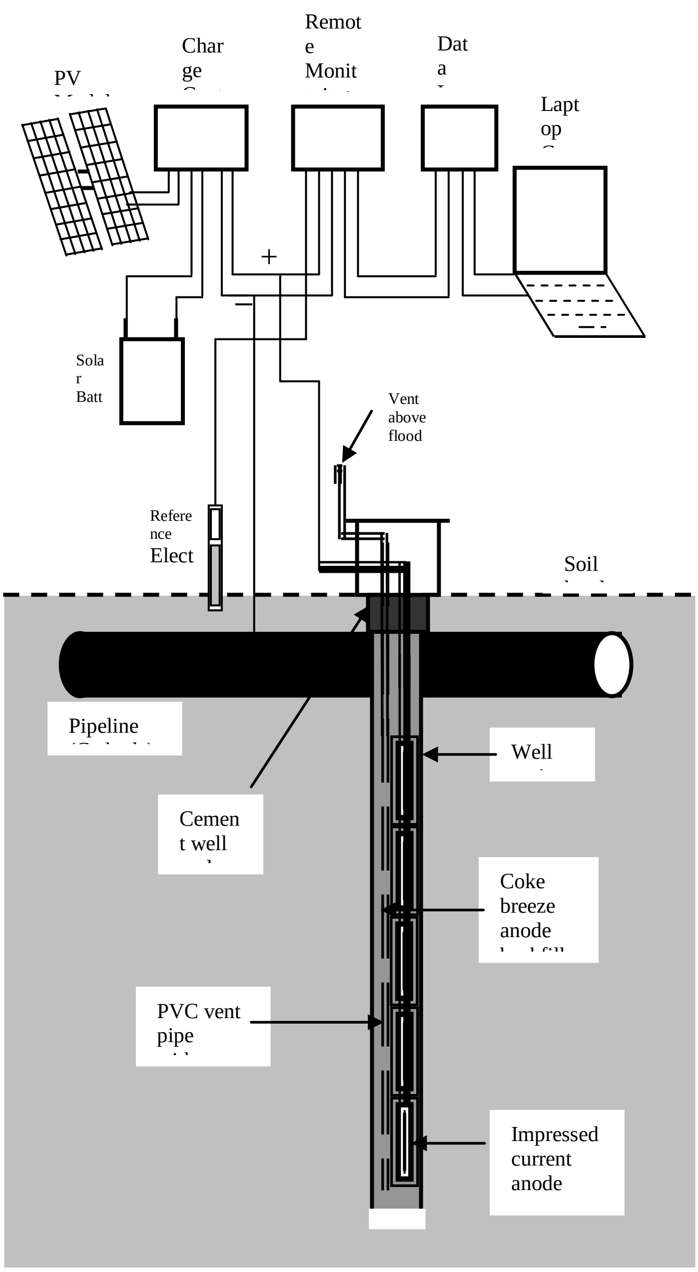

Fig. 4: Deep Anode Ground Bed Cathodic Protection System and Monitoring Unit

3. RESULTS AND DISCUSSION

The borehole for the deep well anode ground bed consists of an inactive section of non-conduction sleeve of 8" (203.2mm) PVC with a minimum wall thickness of 9.9mm. The casing for the active section of the deep anode ground bed is 6° (152.4mm) steel pipe (RP0572-95). The perforated sections of the casing had a minimum of 25% of the external area removed by drilling 25mm diameter holes. The specifications of the PV modules used are shown in Table 2.

Table 2: Photovoltaic Module Specifications

Parameter	**Value/Unit**
Peak Power, P_{max}	80.08W
Voltage, V_{mp}	17.96V
Current, I_{mp}	4.46A
Open Circuit Voltage, V_{oc}	22.915V
Short Circuit Current, I_{sc}	5.01A
Maximum Series Fuse	8A
Tolerance	±5%

For this experimental day, the average instantaneous power output per module of about 41W is a fair approximation for the month of July but not an accurate representation of the month. In this study, two solar PV modules (SPVM) of 80W each were tested outdoor in series and parallel connections under tropical evergreen rain forest environment in July; the result is shown in Table 3. The readings were taken on hourly basis from 8:00am (1hr) to 6:00pm (11hrs) local time.

From Table 3, the solar radiation for the day varied from about 98.08Wm^{-2} at 8:00am in the morning to about 564.09Wm^{-2} at 2:00pm in the afternoon and then dropped to about 68.09Wm^{-2} at 6:00pm in the evening. The ambient temperature increased from 26.0°C at 8:00am to a maximum of 30.5°C at 2:00pm and then decreased to about 26.0°C at 6:00pm. Table 3 also shows the results of two PV modules power output connected in series and parallel for the experimental day in the month of July. The month of July was chosen because in the coastal area, the months of July, August and September more often experience the heaviest cloud cover in the year due to heavy and continuous rainfall. The total hourly PV power output for the parallel connection (i.e. 1,115.18W) was higher than for the series connection (i.e. 879.12W) for the experimental day in July because there is more voltage gain in parallel connection and more current gain in series connection (Woyte *et al.*, 2003). So generally, PV modules connected in parallel give greater power output than those connected in series, although a good combination of parallel and series connection is required for the best and desired output.

Table 3: Power Output from two 80W SPVM Connected in Series and Parallel

Time (hrs)	Power output in series connection (w)	Power output in parallel connection (W)	Solar radiation (Wm^{-2})	Ambient Temperature (^0C)	Weather conditions
1	39.94	56.55	98.08	26	Clear
2	49.88	75.17	228.24	27	sunny
3	87.31	100.48	344.96	28	Sunny
4	92.12	108.03	397.48	28.5	Sunny
5	93.96	121.3	465.74	29	Sunny
6	115.6	129.3	476.89	30	Sunny
7	122.52	150.00	564.09	30.5	Sunny
8	96.74	123.03	429.98	29	Sunny
9	69.94	108.45	385.76	28	Sunny
10	69.72	82.86	187.85	27	Sunny
11	48.39	60.01	68.09	26	Dull
total	879.12	1,115.18			

The power output from the 80W PV modules was good for cathodic protection corrosion control system although storage system was provided for use at nights and cloudy days. In some locations in Port Harcourt, PV systems provide the only acceptable method of providing the necessary electrical power at such remote sites (Wansah *et al.*, 2004, Al-Faiz and Mezher, 2012), especially in water-logged coastal areas and the creeks. The soil resistivities and the pipe-soil potentials along the oil pipelines were measured using Wenner meter and digital multimeter respectively. The values of pipe-soil potentials show that the steel oil pipeline is adequately protected thus preventing sudden failure, (for protected steel pipeline, the pipe-soil potential lies below -0.850V) (Protopopoff and Marcus, 2003) and the resistivity values are very low showing that the soil is very corrosive. Soil type and soil resistivity values are shown in Table 4.

Table 4: Corrosion of Steel in Soil

S/N	Soil Type	Soil Resistivity (Ω-cm)
1	Very corrosive	< 500
2	Corrosive	500 – 1,000
3	Moderately corrosive	1000 – 2000
4	Mildly corrosive	2,000 – 10,000
5	Non-corrosive	> 10, 000

The soil in the coastal area has resistivity values below $500\,\Omega cm$ and therefore very corrosive, this is as reported by the US Bureau of Standards (Alonso-García *et al.*, 2006), thus all the steel oil pipes laid in this coastal area should be adequately coated and protected cathodically to control corrosion using a very cheap and renewable source of energy like solar energy (Kawamura *et al.*, 2003). Generally, the lower the soil resistivity, the higher the corrosivity as indicated in Table 4. The soil resistivity values are an indication that moisture and dissolved salts are present and corrosivity of the soil is almost proportional to the decrease in resistivity (Kumra *et al.*, 2012). The summary of the major CP findings in the study are listed in Table 5.

Table 5: Summary of CP Calculations

S/N	Item	Value/Unit
1	Length of pipeline per segment, *L*	1000.0m
2	Pipeline protection current, I_p	4.6A
3	Anode resistance, R_a	0.041Ω
4	Ground bed resistance, R_{gb}	0.0076Ω
5	Pipeline surface area, *A*	$5.20 \times 10^3 m^2$
6	Minimum CP current required	0.650A
7	Attenuation constant, *a*	$2.00 \times 10^{-6} m^{-1}$
8	Characteristic resistance, R_k	$3.76 \times 10^{-5}\Omega$
9	Anode weight, *W*	0.2802kg
10	Number of anodes, *N*	4
11	Anode consumption, A_c	0.3113kg

The effectiveness of cathodic protection, S_{cp} was about 99.5% showing that the steel oil pipeline was adequately protected from the very corrosive coastal environment. The corrosion rate, c_r was about 9.6×10^{-7}mpy, which is very minimal in a very corrosive coastal soil. The deep anode ground bed resistance of 0.0076Ω is less than 1Ω as desired (Peabody, 2001). Also the characteristic resistance of 3.76 x 10^{-5}Ω is very low and good for cathodic protection current flow (Peabody, 2001). Anode consumption at maximum ground bed current output for 25 years of 0.3113kg is less than the anode group weight and hence met the anode quantity requirements for the specified life of the pipeline. Abem Terrameter, SAS 300 was used for the well logging and the results obtained are presented in Table 6. The LIDA anodes were planted from the depth of about 100m where the soil resistance was very low and very good for voltage flow along the pipeline network system.

Table 6: Soil Resistivity of the Deep Anode Ground Bed Well

Depth (m)	SP (mV)	16" Soil Resistivity (Ωm)	32" Soil Resistivity (Ωm)
5	93	1066.01	2376.79
10	77	1179.60	2539.44
15	67	1336.04	2927.67
20	57	1150.61	2348.06
25	27	1014.23	2308.85
30	16	1242.31	2867.80
35	54	2287.88	6531.01
40	91	2406.67	8105.05
45	142	1815.09	5762.05
50	156	1059.01	3428.64
55	165	1215.01	3115.18
60	177	2021.81	5218.61
65	180	2397.13	7453.85
70	189	2475.90	7777.23
75	174	2330.07	7724.58
80	177	2357.92	7348.35
85	187	2234.88	6854.67
90	202	1975.21	6388.56
95	209	1621.41	4452.21
100	266	1674.01	4655.22
105	279	928.85	2711.99
110	263	773.91	2215.31

The power output from two 80W SPVM in series and parallel connections is shown in Fig. 5.

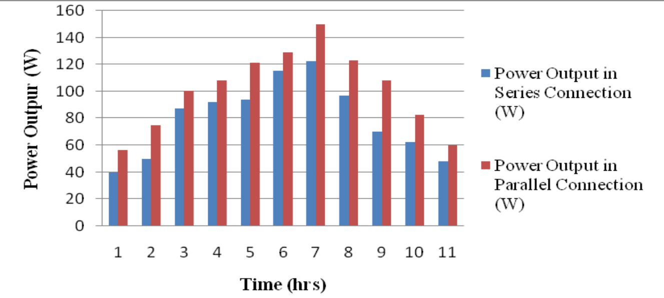

Fig. 5: Power Output from two 80W SPVM in Series and Parallel Connection

From Fig. 5, the maximum power output for series and parallel connections for two SPVMs occurred at 2:00pm which were about 122W and 150W respectively. The maximum power output of the total PV array is always less than the sum of the maximum power output of the individual modules. This difference is as a result of slight inconsistencies in performance from one module to the next and is called module mismatch and amounts to at least 2% loss in system power (Protopopoff and Marcus, 2003). The voltage (V) and current (I) output from the two 80W SPVMs for a typical day are presented in Fig. 6. The voltage output is good for cathodic protection of steel oil pipelines in the very corrosive coastal environment. The voltage drop in the later part of the day is due to low insolation. Impressive results from impressed current CP systems using solar energy have also been reported by Mohsen *et al.*, (2013).

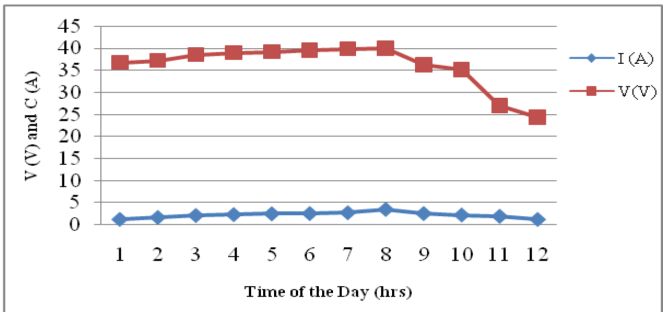

Fig. 6: Voltage and Current Output from Two 80W SPVMs in Parallel Connection

The power output for two 80W SPVMs in parallel connection and the ambient temperature for the experimental day are shown in Fig. 7.

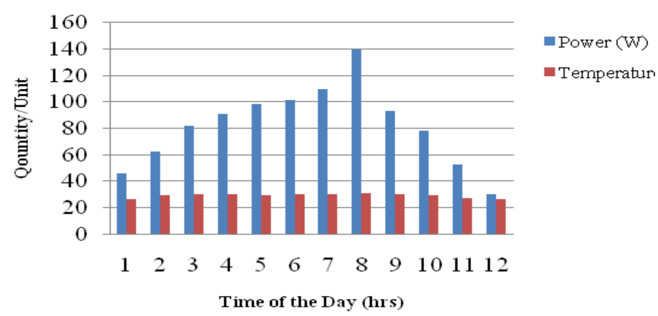

Fig. 7: Power Output from Two 80W SPVMs in Parallel Connection

The power output increased from about 45W at 8:00am in the morning to about 140W at 3:00pm in the afternoon and then decreased to about 30W at 6:00 pm in the evening. The power output is good to mitigate pipeline corrosion according to Popoola *et al.*, (2013), despite the low insolation for that day. The ambient temperature increased from 26°C in the morning to 31°C in the afternoon and then decreased to about 26°C in the evening. The pipe-soil potentials from the anode ground bed (i.e., taking the deep anode position as the starting point - zero position) along the pipeline are shown in Fig. 8.

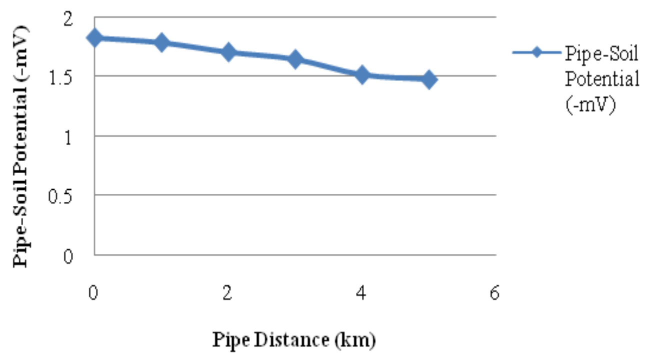

Fig. 8: Pipe-Soil Potentials along Oil Pipeline

The values of the pipe-soil potentials decreased gradually with distance due to drop in potential along the pipeline from anode position as result of soil resistivities and where it is above -850mV, another anode is required to augment the protection current. The steel pipeline requires continuous monitoring to ensure adequate and sustained cathodic protection as reported by Wansah *et al*., (2012) and Onyechi *et al*., (2014). SPVM systems provide a more convenient and cost-effective solution for the provision of relatively small amounts of power needed for CP systems. Thus the application of appropriate and adequate design of deep anode ground bed CP system is extremely very economical for the cathodic protection of oil pipeline systems, minimizes the cost of installing anodes along oil pipelines at various locations and communities.

4. CONCLUSION

Deep anode ground bed cathodic protection (CP) system for associated pipeline network using photovoltaic (PV) modules has been carried out following the best industrial standards. The results of the pipe-soil potentials along the 8" oil pipeline were the same as those obtained by locating anodes electrically remote laterally from the structure and near the surface. The remote earth system provided optimum current distribution along the protected structure to maintain the integrity of the oil pipeline system thereby warranting its efficient, reliable and economic operation being remotely monitored for a minimum period of 25years.

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