Nigerian Research Journal of Engineering and Environmental Sciences 6(2) 2021 pp. 561-573
p ISSN: 2635-3342; e ISSN: 2635-3350

Nigerian Research Journal of Engineering and Environmental Sciences
Journal homepage: www.rjees.com

Original Research Article

Investigation of Alternating Current Density and its effect on Corrosion of Underground Hydrocarbon Pipelines in the Niger Delta Area of Nigeria

***Osabohien, H.O., Orumwense, F.F.O., Ebunilo, P.O. and Sadjere, E.G.**

Department of Mechanical Engineering, Faculty of Engineering, University of Benin, PMB 1154, Benin City, Edo State, Nigeria.
*osabohienhenry@yahoo.com

http://doi.org/10.5281/zenodo.5805161

ARTICLE INFORMATION

Article history:
Received 18 Oct, 2021
Revised 04 Nov, 2021
Accepted 26 Nov, 2021
Available online 30 Dec, 2021

Keywords:
AC density
AC corrosion
Pipeline coating defects
Soil resistivity
AC interference
Cathodic protection

ABSTRACT

The Niger Delta area of Nigeria is crisscrossed by several pipelines carrying hydrocarbon products from the oil and gas fields to the export terminals and refineries. However, due to the need to improve surveillance and avoid human population, most of the pipelines have been laid along the right of way of high voltage transmission lines (HVTL) resulting to Alternating Current (AC) interference on the pipelines which has led to a unique form of corrosion known as AC corrosion. This study sought to investigate AC density and its effect on corrosion of underground hydrocarbon pipelines within the Niger Delta area of Nigeria. Four hydrocarbon underground pipelines were chosen for the study. AC interference was measured daily for 92 consecutive days. Soil resistivity measurement and location / sizing of defects on the pipeline coating were carried out. AC density was determined and the rate of AC corrosion was measured using Electrical Resistance probes. The results indicated that AC density on the selected pipelines ranged from 1 to 70 A/m^2 and AC corrosion rate ranged from 0.001 to 0.1 mm/yr. Based on the results, this study, established that the higher the AC density, the higher the rate of AC corrosion.

© 2021 RJEES. All rights reserved.

1. INTRODUCTION

The oil and gas industry is the lifeline of the Nigerian economy. It provides over 90 percent of the country's export revenue (Soriola, 2018). The industry relies majorly on pipelines to transport and distribute its petroleum products making it a key element in its operations (Soriola, 2018).

H.O. Osabohien et al. / Nigerian Research Journal of Engineering and Environmental Sciences
6(2) 2021 pp. 561-573

Over 137 pipeline failures were reported in the Niger Delta area across the six states between 1999 and 2005 with corrosion accounting for 18 percent of these failures (Achebe et al., 2012). Amnesty International (2011) presented a report highlighting the devastating effect of two oil spills in Bodo town, Rivers State. The first spill occurred in August 2008 and the second spill occurred in December the same year. On investigation, several corrosion pits were found along this pipeline close to areas where it paralleled or intercepted high voltage transmission lines (HVTL). Adeyanju (2004) reported the case of Agoda / Brass oil pipeline failure which occurred in 1994 and was essentially due to corrosion. Several corrosion pits were located particularly around the areas on the pipeline close to HVTL. This incident resulted to the pollution of over 10 km^2 of farmland including the contamination of ponds, lakes and streams.

Alternating current (AC) corrosion is a type of corrosion initiated by the movement of AC current out of pipelines at small sized coating defects (Ames, 2015). AC current in pipelines originates from AC sources like HVTL and AC electrified railways then goes through the pipeline till the point where it discharges through small coating defects (Ames, 2015). It is predominant in pipelines laid in soil with low resistivity (Ames, 2015).

In Nigeria, the electric power network comprises of high voltage substations with a total transmission capacity of 7,500 MW and over 20,000 km of transmission lines (NERC, 2018). Notably, pipelines laid in a common right-of-way (ROW) with these HVTL present a high safety risk from electrical shock and create avenue for corrosion due to AC interference.

AC corrosion has been on the rise as a result of legislations which restrict public utilities to share common corridors due to the necessity of reducing cost of compensation, ensuring safety, easy surveillance, inspection, maintenance and other routine operations including environmental factors such as limiting impact on wildlife and land access (Gummow, 2014). Ames (2015) reported that the use of high dielectric coatings on pipelines in high voltage AC corridors causes these pipelines to suffer high current loads as a byproduct of capacitive, inductive and direct coupling consequences with the power lines. This can be related to a situation where the pipeline now assumes the position of the secondary winding of a transformer and the AC source as the primary winding. AC interference is a serious problem which places both the safety of the operator and the integrity of the pipeline at risk. It is caused by an uneven balance in the transmission system and high potentials at the grounding of transmission towers by reason of strikes from lightning and phase faults. The value of voltage induced depends on several factors such as: pipeline to power line geometry, distance between phase cables, HVTL operating current and the distance between the HVTL and the pipeline (Gummow, 2014). The most significant point of concern in this mode of corrosion is that it happens at defects that were considered small enough for cathodic protection (CP) system to protect adequately and unfortunately, only the CP system may not be sufficient to protect the pipelines from this form of corrosion (Corroconsult, 2017).

NACE SP21424 (2018), Bresford (2015), Finneran (2015), Jiang and Lu (2013), Di Biase et al (2010), Kajiyama (2011), Shwehdi and Johar (2003), Ellis (2001) and Dawalibi et al. (2000) among others have conducted researches on the mode of AC corrosion. However, none of the researches has been narrowed down to the details of AC density and its effect on corrosion of underground pipelines. Thus, this work sought to understudy the interaction between HVTL, underground pipelines and the soil around the pipelines as to determine the effects of AC density on corrosion of underground pipelines with concentration on the Niger Delta area of Nigeria.

2. MATERIALS AND METHODS

2.1. Pipelines and Coating

Four pipelines were chosen for this study due to their proximity to HVTL. The pipelines were:

i. 457 mm (18 inches) diameter and 1.2 km long underground gas pipeline operated by Nigerian Gas Company (NGC). The pipeline links Shell Petroleum Development Company (SPDC) Imo River Flow Station to NGC Owaza Compressor Owaza, Abia State.
ii. 457 mm (18 inches) diameter and 4 km long underground gas pipeline operated by NGC. The pipeline links Umudi intermediate pigging station (IPS) to Alaoji pressure reduction and metering station (PRMS) Alaoji, Abia State.
iii. 508 mm (20 inches) diameter and 36 km long Kolo creek trunkline (KCTL). It is a crude oil pipeline and part of Trans Niger Pipeline (TNP) connecting Kolo creek manifold at Kolo creek field in Bayelsa State to Rumuekpe manifold at Rumuekpe field in Rivers State. It is owned and operated by SPDC.
iv. 609.6 mm (24 inches) diameter and 30 km gas pipeline from Ikpe Annang/Ukanafun in Etim Ekpo/Ukanafun Local Government Area (LGA) in Akwa Ibom State to Oma power plant at Orgwu-Ogwe Town in Ukwa West LGA in Abia State. The pipeline is owned and operated by Oma Power Generation Company a joint venture company owned by General Electric International Benelux, B.V. and Geometric Power Limited (an indigenous Nigerian power developer).

The pipelines were all coated with 3-layer polyethylene coating with similar properties. The 3-layer polyethylene coating is able to withstand a service operating temperature of (+) 65 °C and conforms to 'S' Type of coating as per DIN 30670 (2012). The relevant information relating to the coating used are shown in Table 1.

Table 1: Coating data (Nestoil, 2010)

Property description	Test method	Value
Tensile strength	ASTM D638	18 N/mm²
External coating thickness	-	3.2 mm
Water absorption	ASTM D570	0.04 %
Dielectric strength,	ASTM D149	30,000 Volts/mm
Cathodic disbondment	ASTM G42/ASTM G8	15 mm and 7 mm respectively radius of disbondment

2.2. High Voltage Transmission Lines

Owaza gas pipeline: the section surveyed lies parallel to a 33 kV overhead power line for about 28 m i.e., between kilometer point (KP) 1+000 and KP 1+028. This pipeline lies about 5.2 m away from the HVTL tower.

Alaoji gas pipeline: the section surveyed lies parallel to a 132 kV overhead power line for about 38 m i.e. between KP 3+500 and KP 3+538; this pipeline lies about 7 m away from the HVTL tower.

KCTL: the section surveyed lies parallel to a 132 kV HVTL for about 22 m i.e. between KP 10+600 and KP 10+622; this pipeline lies about 6 m away from the HVTL tower

Oma gas pipeline: the section surveyed lies parallel to a 132 kV HVTL for about 18 m i.e. between KP 9+200 and KP 9+218; this pipeline lies about 7 m away from the HVTL tower.

The height of the towers is about 18 m above ground level. The conductors used were made of aluminum with steel core giving the cable its needed strength. These conductors are bare, with the air around them providing the required insulation. Each conductor consists of several wires twisted together making it more flexible and more exposed to air, a feature that helps cool the conductor and therefore increase its conductivity. Bundled conductors were used on the power lines in order to reduce energy losses (as a result of corona effect), audible noise and radio interference. Due to this, they improve the power transmission process.

2.2. Methods

2.2.1. AC interference measurement

The induced AC voltage from the HVTL for the different pipelines were measured once daily at 7 pm for 3 months (92 days consecutively) in the wet season (May, 2018 to July, 2018) and at the same time for one month (31 days consecutively) in the dry season (January, 2019). The time of measurement allowed for monitoring AC interference during the day's peak period of power consumption. The AC interference and resistivity measurements in both wet and dry season allowed for AC density comparison for both seasons. The extensive period of measurement allowed for AC interference monitoring which may fluctuate over time due to load variation. A control survey for sections without AC interference needed to compare results with areas under AC interference was carried out for the pipelines for three months in the wet season expected to be the period of the year with least soil resistivity (May, 2018 to July, 2018). For Owaza gas pipeline, the control station was at KP 0+220, while for the Alaoji gas pipeline, KCTL and Oma gas pipeline, it was at KP 2+033, KP 20+025 and KP 20+032 respectively.

Electrical resistance (ER) probes were installed in the areas suspected to be at risk of AC interference and control areas to monitor and compare the possible rates of AC corrosion. The rates of corrosion of the buried pipelines were measured once daily for the same period as the AC density. This survey was carried out in accordance with the test specification delivered in the framework of the CEN/TS 15280 (2013). This technical specification was adopted in 2006 to cope with AC corrosion. It applies to buried or immersed cathodically protected metallic structures and influenced by AC traction systems and/or AC power lines. AC interference levels on the underground pipelines were measured from test stations (TS) closest to the pipeline sections selected for investigation. The amount of induced AC voltage was measured by connecting one of the measuring probes of the AC/DC digital clamp multimeter tester DT3266L to the pipeline test terminals and inserting the second measuring probe slightly into the soil above the buried pipeline. The instrument in turn displayed the amount of induced AC voltage in the pipeline which was equivalent to the level of AC interference from the HVTL.

2.2.2. Direct current voltage gradient (DCVG) survey

A DCVG survey was carried out to identify the smallest sized coating defects on the pipeline within the sections under investigation. The survey was done in accordance with the test procedure outlined in McMiller (2017).

2.2.3. Dig site verification

After potential defects were identified during the DCVG survey, the defects were verified by exposing the pipeline manually and visually inspecting the coating of the pipeline to confirm the presence of the defect. On confirmation of the defect, the size was measured using a vernier caliper. The pipeline was exposed by carefully removing the top soil followed by other layers while preserving each layer of the soil to enable reuse after the defects were confirmed and measured.

2.2.4. Soil resistivity measurement

The soil resistivity was measured using earth ground resistance tester DY4300 at 1 to 3 m depth at three different locations along the pipelines close to the sections identified to be at risk of AC interference and control areas with no risk of AC interference. As adopted in ASTM G57-06 (2012), the resistivity measurements were done applying the Werner's four-pin method with each electrode arranged in a straight line at equal intervals. The length of the spacing of the electrodes equals the depth to be tested. The depth of the electrodes into the ground was always between 10 to 15 cm. A steady current, (I), was passed through the two outer metal electrodes, thereafter the potential difference, ($\Delta\varphi$) between the two inner reference electrodes (e.g. Cu-$CuSO_4$) was measured and the soil resistivity computed by the instrument.

2.2.5. Corrosion rate monitoring

This test was carried out by adopting the procedure recommended by Cosasco (2019). The rate of AC corrosion on the underground pipelines was determined using the Cosasco Model 620HD underground ER probe. The probes were installed in test station (TS) closest to the pipeline suspected to be at risk of AC interference from HVTL and the control areas. The ER probes work by monitoring the rate of corrosion on a known surface area of metal exposed to the soil and connected to the pipe.

2.3. Theory

2.3.1. AC density

According to Allen (2017), the AC density was determined applying Equation 1.

$$i_{ac} = \frac{8V_{ac}}{\rho\pi d} \tag{1}$$

Where i_{ac} = AC density, V_{ac} = AC voltage, d = Defect size and ρ = Resistivity

2.3.2. Soil resistivity

As adopted in ASTM G57-06 (2012), soil resistivity was determined applying Equation 2.

$$\rho = \frac{2\pi a \Delta\varphi}{I} \tag{2}$$

Where a = Distance between electrodes, I = Steady current from a battery and Δφ = Potential difference

2.3.3. Coating defects

The method for measuring the size of coating defect is as shown in Figure 1. As adopted in McMiller (2017), Equation 3 was applied to determine the IR drop at the defect locations.

$$IR\ drop\ at\ defect\ location = IR\ drop\ at\ TS1 + [a \times (IR\ drop\ at\ TS2 - IR\ drop\ at\ TS1)] \tag{3}$$

Where IR drop = Difference between the “ON” and the “OFF” potentials and TS = Test station

Therefore, magnitude of total mV from the current in the pipe around the area of defect expressed in relationship with IR drop in the soil also referred to as %IR is determined applying Equation 4.

$$\%IR = \left(\frac{Total\ mV}{IR\ drop}\right)/100 \tag{4}$$

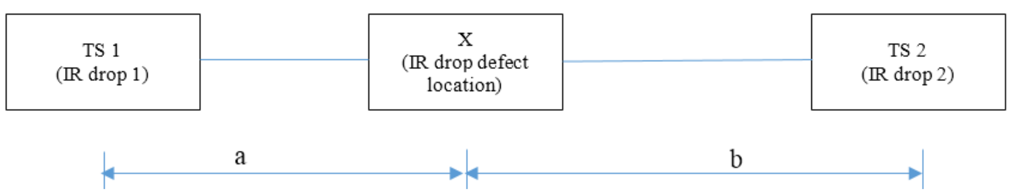

Figure 1: Schematics for measuring the size of coating defect

2.3.4 Rate of AC corrosion

As adopted by Olesen (2018), rate of AC corrosion was obtained by applying Equations 5 to 9. Resistance of the conducting metal was determined by applying Equation 5.

$$R = \rho(T)\frac{L}{w.\sigma} \tag{5}$$

Where ρ(T) is the resistivity of the conducting metal dependent on temperature

$$\rho(T) = \rho_0(1+\alpha)T - T_0) \tag{6}$$

α is the specific temperature coefficient of the conducting metal and ρ_0 is the resistivity at reference temperature (T_o).

$$\sigma_c(T) = \sigma(t_0) \cdot \frac{R_c(t_0)}{R_r \cdot \sigma} \cdot \frac{R_r(t)}{R_c(t)} \tag{7}$$

Where t_0 is the initial thickness.

Calculating thickness with respect to resistance and differentiating with respect to time will yield the rate of AC corrosion, (v_{corr}).

$$\sigma = \rho(T)\frac{L}{w \cdot R} \tag{8}$$

$$v_{corr} = \frac{d\sigma}{dt} = -\frac{dR}{dt} \cdot \frac{w\sigma^2}{l\rho(T)} \tag{9}$$

Where $Probe\ life\ (P) = \frac{w\sigma^2}{lp(T)}$

4. RESULTS AND DISCUSSION

4.1. Soil Resistivity

Table 2 shows the soil resistivity values of three different locations along the Owaza gas pipeline ROW under the risk of AC corrosion due to AC interference from HVTL. In addition, the results for the soil resistivity survey for three other locations along the pipeline ROW without AC interference were also presented and these locations were referred to as control locations in this text. The soil resistivity values for Owaza gas pipeline as measured from ground level down to a depth of 3 m ranged from 50 Ωm to 56 Ωm for wet season and 59 Ωm to 66 Ωm for dry season. These indicate lower resistivity for the wet season due to conductivity of pore fluid and tortuosity (ASTM G57-06, 2012). The results taken from the control areas showed similar values with the areas identified to be at risk of AC interference indicating no consequent effect of AC interference on the resistivity of the soil (ASTM G57-06, 2012). These results corroborate earlier results presented by Okiongbo and Ogobiri (2013).

Table 3 shows the soil resistivity values for Alaoji gas pipeline as measured from ground level down to a depth of 3 m ranged from 58 Ωm to 65 Ωm for wet season and 67 Ωm to 79 Ωm for dry season. These indicate lower resistivity for the wet season (ASTM G57-06 (2012). It also shows the resistivity of the soil taken along the control areas of the pipeline ROW. The results for the control areas showed similar values with the areas identified to be at risk of AC interference indicating no consequent effect of AC interference on the resistivity of the soil. These results also corroborate earlier results presented by Okiongbo and Ogobiri (2013).

Table 4 shows the soil resistivity values for KCTL as measured from ground level down to a depth of 3 m ranged from 22 Ωm to 35 Ωm for wet season and 47 Ωm to 59 Ωm for dry season. These indicate lower resistivity during the wet season. (ASTM G57-06, 2012). It also shows the resistivity of the soil taken along the control areas of the pipeline ROW. The results for the control areas showed similar values with the areas identified to be at risk of AC interference indicating no consequent effect of AC interference on the resistivity of the soil. These results corroborate earlier results presented by Okiongbo and Ogobiri, (2013).

Table 5 shows the soil resistivity values for Oma gas pipeline as measured from ground level down to a depth of 3 m ranged from 68 Ωm to 81 Ωm for wet season and 81 Ωm to 94 Ωm for dry season. These indicate lower resistivity during the wet season (ASTM G57-06 (2012). It also shows the resistivity of the soil taken along the control areas of the pipeline ROW. The results for the control areas showed similar values with the areas identified to be at risk of AC interference indicating no consequent effect of AC interference on the resistivity of the soil. These results corroborate earlier results presented by Okiongbo and Ogobiri (2013).

Table 2: Soil resistivity for Owaza gas pipeline

Location	Depth (m)	Soil resistivity (Ωm)		Soil resistivity in control location (Ωm)	
		Wet season	Dry season	Wet season	Dry season
1	1	56	65	57	64
	2	54	62	54	63
	3	51	61	51	61
2	1	55	64	54	64
	2	53	63	53	62
	3	50	59	51	60
3	1	55	66	53	65
	2	53	64	53	65
	3	50	63	50	62

Table 3: Soil resistivity for Alaoji gas pipeline

Location	Depth (m)	Soil resistivity (Ωm)		Soil resistivity in control location (Ωm)	
		Wet season	Dry season	Wet season	Dry season
1	1	65	71	64	70
	2	63	68	63	68
	3	58	67	57	65
2	1	64	78	63	77
	2	62	74	63	74
	3	59	73	59	71
3	1	65	79	64	78
	2	64	78	62	76
	3	58	78	57	75

Table 4: Soil resistivity for KCTL

Location	Depth (m)	Soil resistivity (Ωm)		Soil resistivity in control location (Ωm)	
		Wet season	Dry season	Wet season	Dry season
1	1	35	50	32	51
	2	29	49	30	49
	3	28	49	27	48
2	1	32	55	33	53
	2	28	48	27	47
	3	25	47	26	46
3	1	33	59	28	59
	2	27	55	28	57
	3	22	53	24	54

Table 5: Soil resistivity for OMA gas pipeline

Location	Depth (m)	Soil resistivity (Ωm)		Soil resistivity in control location (Ωm)	
		Wet season	Dry season	Wet season	Dry season
1	1	72	94	74	95
	2	68	89	71	90
	3	68	88	70	87
2	1	81	88	73	87
	2	75	85	71	86
	3	69	81	69	81
3	1	81	92	78	94
	2	73	90	72	90
	3	71	87	72	86

H.O. Osabohien et al. / Nigerian Research Journal of Engineering and Environmental Sciences
6(2) 2021 pp. 561-573

4.2. Coating Defects

The IR drops from Table 6 and Table 7 indicate the "ON" and "OFF" potential differences at TS 1, TS 2 and the defect locations for the four pipelines under survey. Applying equation 4, %IRs were computed in Table 8 and 9. According to PML Cathodic Protection (2018), the %IRs as shown in Table 8 and 9 fall within the severe range in terms of size of coating defects and therefore defect verification would be required. Contrary to the conventional belief that the larger the size of the coating defect the higher the risk of corrosion, AC corrosion increases with reducing "%IR drop" or coating defect size due to spread resistance effect (Allen, 2017). Coating defects were present both for areas under AC interference and the control areas.

After manually and carefully removing the soil above and around the defect location on the pipeline as identified during the DCVG survey, the pipeline condition and sizes of the defects on the pipeline were measured with vernier caliper and they are shown in Table 10. The results of the physical verification confirms that these coating defects on the pipelines exist and are sufficient to initiate AC corrosion (Allen, 2017). The results show coating defect both for areas with AC interference and the control areas. Advance Polymer Coatings (2021) articulated the various reasons for coating defects on pipelines viz. errors resulting from manufacturing or coating application, cathodic disbondment and environmental factors like temperature, pH, relative humidity and dew point among others. AC current does not prevent nor cause damage to pipeline coating apart from the case of phase ground fault or lightning strikes on transmission structures (Gummow, 2014). When this happens, a huge voltage sphere is created around the pylon grounding system, creating an arc between the pipeline and grounding of the powerline (Gummow, 2014). This interaction could amount to damage on the coating or walls of the pipe (Gummow, 2014).

Table 6: IR drop at defect location for pipeline areas under the influence of AC interference

Pipeline description	IR Drop TS 1 (mV)	IR Drop TS 2 (mV)	Distance from TS 1 to defect (miles)	Distance from defect to TS 2 (miles)	IR Drop at the defect location (mV)
Owazza pipeline	250	480	0.13	0.18	279.9
Alaoji pipeline	602	602	0.28	0.34	602
KCTL	500	750	0.44	0.32	610
OMA gas pipeline	635	690	0.5	0.7	662.5

Table 7: IR drop at defect locations for pipeline control sections

Pipeline description	IR Drop TS 1 (mV)	IR Drop TS 2 (mV)	Distance from TS 1 to defect (miles)	Distance from defect to TS 2 (miles)	IR Drop at the defect location (mV)
Owazza pipeline	320	350	0.15	0.12	324.5
Alaoji pipeline	400	425	0.21	0.35	405.25
KCTL	501	501	0.43	0.25	501
OMA gas pipeline	623	400	0.28	0.52	560.56

Table 8: %IR drop for pipeline areas under the influence of AC interference

Pipeline description	Total mV (mV)	IR drop at the defect location (mV)	%IR drop	Defect category (Size)
Owazza gas pipeline	95	279.9	33.94	Severe
Alaoji gas pipeline	204	602.0	33.89	Severe
KCTL	301	610.0	49.34	Very severe
Oma gas pipeline	280	662.5	42.26	Very severe

Table 9: %IR drop for pipeline control sections

Pipeline description	Total mV (mV)	IR drop at the defect location (mV)	%IR drop	Defect category (Size)
Owazza gas pipeline	83	324.5	25.58	Severe
Alaoji gas pipeline	250	405.3	61.69	Very severe
KCTL	310	501.0	61.88	Very severe
Oma gas pipeline	263	560.6	46.92	Very severe

Table 10: Pipe defect sizes

Pipeline description	Pipe defect diameter (m) with AC interference	Pipe defect diameter (m) control area
Owazza gas pipeline	0.0150	0.013
Alaoji gas pipeline	0.0143	0.015
KCTL	0.0181	0.016
Oma gas pipeline	0.0133	0.017

4.3. AC density / AC corrosion rate for the pipelines

Figures 1 to 8 show AC interference levels, AC densities and AC corrosion rates for dry season (January) and wet season (May). According to Allen (2017), the AC density was higher in the wet season due to lower soil resistivity even when both wet and dry seasons shared similar level of AC interference. The amount of AC voltage on the pipeline at the areas in close proximity to HVTL compared to the control areas confirms the impact of HVTL on pipelines laid close to it (Gummow, 2014). According to Ames (2015) and Gummow (2014) the corrosion rates for Figures 2 and 4 were shown to increase as AC density increased. The AC density level is very important in determining the rate of AC corrosion (Ames, 2015). The amount of AC density leading to corrosion is considered not necessarily in the pipeline itself but at the point of discharge from the pipeline into the soil (Ames, 2015). The AC interference levels on Alaoji gas pipeline were higher compared to the AC interference levels on Owaza gas pipeline indicating that the level of AC interference increased with increasing power transmission (Gummow, 2014). Alaoji gas pipeline section under survey was laid parallel to 132 kV HVTL while Owaza gas pipeline was laid parallel to 33 kV HVTL.

The Alaoji and KCTL gas pipeline (Figures not shown) showed similar levels of AC interference but the AC density for KCTL was higher than Alaoji gas pipeline because of the lower resistivity of the soil around KCTL implying that AC density is indirectly proportional to soil resistivity Allen (2017). The AC voltage, AC density and AC corrosion rate from Oma gas pipeline (Figures not shown) further corroborate all the points discussed on the results from KCTL, Owaza and Alaoji gas pipelines regarding the direct proportionality between AC density and AC interference and the indirect proportionality between AC density and the resistivity of the soil (Allen, 2017). The average rates of AC corrosion both for areas exposed to AC interference and control sections are shown in Table 11. Table 11 shows the lower values of AC corrosion rate for the control areas relative to the areas under the influence of HVTL due to higher AC density as a result of the AC interference. This summarily indicates that AC corrosion rate increases with increasing AC density Ames (2015).

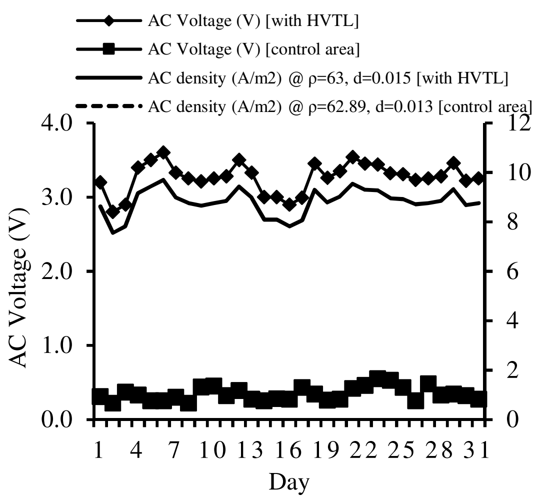

Figure 1: AC Density for Owaza gas pipeline (January – dry season)

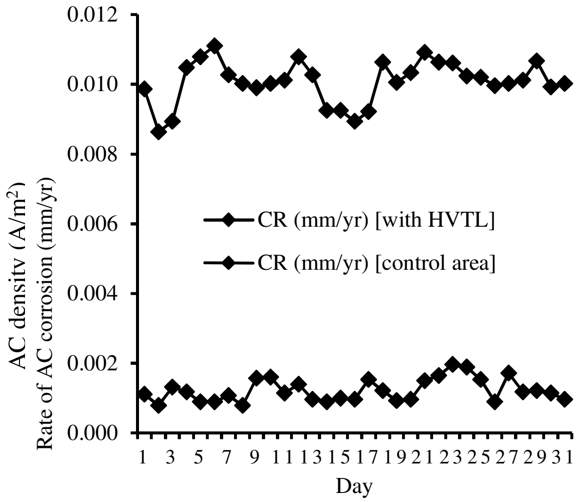

Figure 2: AC corrosion rate for Owaza gas pipeline (January – dry season)

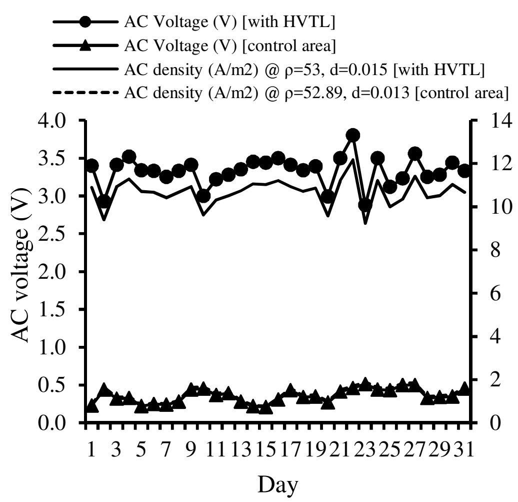

Figure 3: AC Density for Owaza gas pipeline (May – wet season)

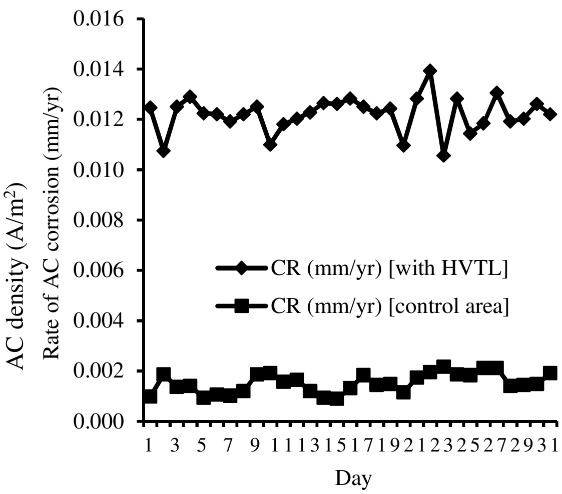

Figure 4: AC corrosion rate for Owaza gas pipeline (May – wet season)

H.O. Osabohien et al. / Nigerian Research Journal of Engineering and Environmental Sciences
6(2) 2021 pp. 561-573

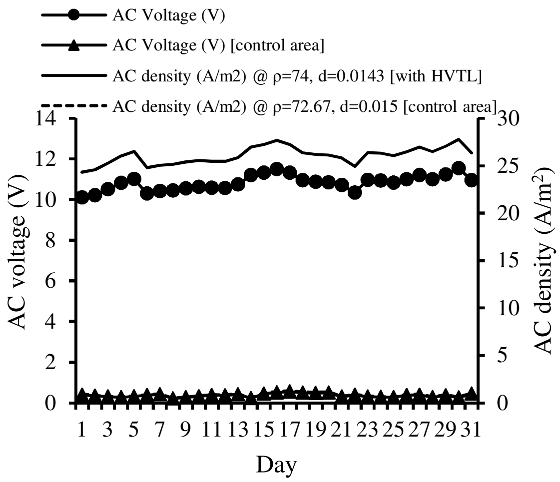

Figure 5: AC density for Alaoji gas pipeline (January – dry season)

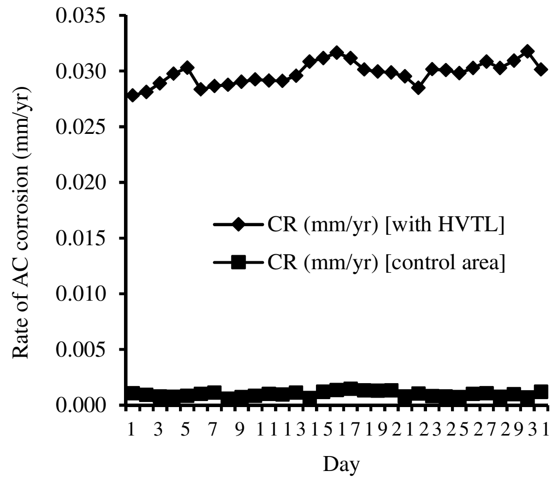

Figure 6: AC corrosion rate for Alaoji gas pipeline (January – dry season)

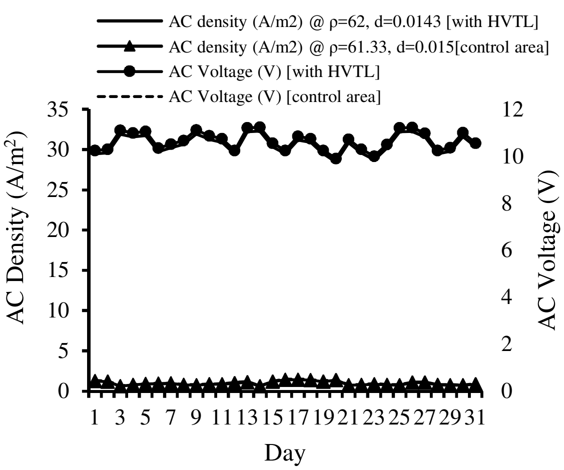

Figure 7: AC density for Alaoji gas pipeline (May – wet season)

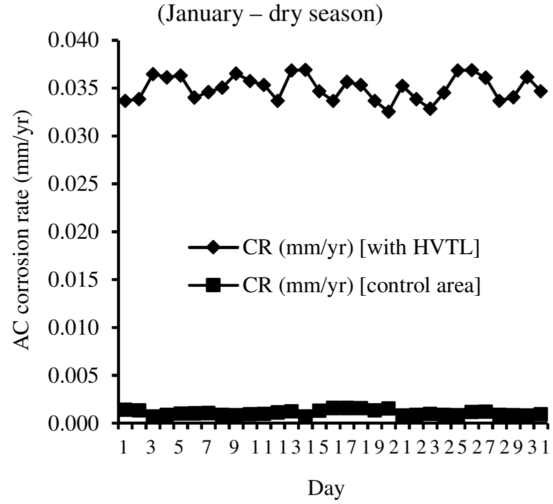

Figure 8: AC corrosion rate for Alaoji gas pipeline (May – wet season)

Table 11: Average rate of AC corrosion

Pipeline Description	Average AC density (A/m^2) [with HVTL]	Average AC density (A/m^2) [control areas]	Average rate of corrosion (mm/yr) [with HVTL]	Average rate of corrosion (mm/yr) [control areas]
Owaza gas pipeline	10.41	1.47	0.011629391	0.001642191
Alaoji gas pipeline	38.52	1.29	0.043032097	0.001441106
KCTL	66.98	12.06	0.074825801	0.013472666
Oma gas pipeline	35.02	5.98	0.039122119	0.006680476

4. CONCLUSION

This study outlined the basic steps and considerations required to determine the level of AC density on a pipeline. Measurements were carried out to determine the level of AC interference, soil resistivity, defects on the pipeline coating, AC density and rate of AC corrosion. The results of this study showed that:

i. AC density on pipelines under AC interference effect was higher in soil with low resistivity.
ii. AC density was directly proportional to the level of AC interference and indirectly proportional to the size of coating defect.
iii. The rate of AC corrosion increased with increasing AC density.
iv. Smaller coating defects compared to larger ones were more susceptible to AC corrosion due to direct proportionality between spread resistance and area of defect.

5. ACKNOWLEDGEMENT

The authors express their sincere gratitude to the managements of Nestoil PLC and the Nigerian Gas Company for the privilege to access their pipeline locations with minimal restrictions.

6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

REFERENCES

Achebe, C., Nneke, U. and Anisiji, O. (2012). Analysis of Oil Pipeline Failures in the Oil and Gas Industries in the Niger Delta Area of Nigeria. In: *Proceedings of the International Multi Conference of Engineers and Computer Scientists*, Vol II, IMECS 2012, Hong Kong.

Adeyanju, J. (2004). Government and the oil pollution crisis in Nigeria. *International Journal of Environmental Issues*, 2(1), pp. 217 – 227.

Advance Polymer Coatings (2021). Coatings Failure – Why a preventive strategy is the best way to avoid it. Ohio: *Advanced Polymer Coatings*. [online] Available at: https://www.adv-polymer.com/blog/industrial-coatings [Accessed 23 Oct. 2021].

Allen, F. (2017). AC Corrosion issues. [PDF]. *Engineering and Technical Services Incorporated*. Available at: https://www.aucsc.com/_aucsc%20speaker%20files/TT06%20-%20AC%20Corrosion%20Issues-2012-AUCSC.pdf [Accessed 2 Jan. 2017].

Ames, M. (2015). AC Corrosion and Mitigation. In: *KCC Pipeline Safety Seminar*. [PDF] Manhattan, KS. Available at: https://kcc.ks.gov/images/PDFs/pipeline/2015-seminar/ac_corrosion_andi-mitigation.pdf [Accessed 3 Feb. 2017].

Amnesty International (2011). The True 'Tragedy'. The delays and failures in tackling oil spills in the Niger Delta. [PDF] London: *Amnesty International Ltd.* Available at: https://www.amnesty.org/en/documents/AFR44/018/2011/en/ [Accessed 1 Jan. 2019].

ASTM D149 (2020). Standard Test Method for Dielectric Breakdown Voltage And Dielectric Strength Of Solid Electrical Insulating Materials. Philadelphia: ASTM

ASTM D570 (2018). Standard Test Method for Water absorption of Plastics. Philadelphia: ASTM

ASTM D638 (2010). Standard Test Method for tensile Properties of Plastic. Philadelphia: ASTM

ASTM G42 / ASTM G8 (2019). Standard Test Method for Cathodic Disbonding of pipeline coatings subjected to elevated temperature. Philadelphia: ASTM

ASTM G57-06 (2012). Standard Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method. Philadelphia: ASTM

Bresford, C. (2015). Mitigating AC Corrosion of Cathodically Protected Pipelines. *Pipeline & Gas Journal*. October 2015 edition. American Innovations Inc., Oildom Publishing.

CEN/TS 15280 (2013). Evaluation of AC corrosion likelihood of buried pipelines – Application to cathodically protected pipelines. *European Committee for Standards works*. Brussels: CEN

Corroconsult (2017). AC Corrosion Demystified. Corroconsult Conferences. [online] Available at: www.corroconsult.com/blog-news/ac-corrosion-demystified/9/3/2018 [Accessed 10 Apr. 2019].

Cosasco (2020). Underground Electrical Resistance (ER) Probes. Carlifornia: Rohrback Cosasco Systems Inc.

Dawalibi, F., Southey, R., Ma, J. and Li, Y. (2000). The Mechanism of Electromagnetic Interference between Electrical Power Systems and neighboring Pipelines. [PDF] Canada: Semantic Scholar. Available at: https://www.semanticscholar.org/paper/On-the-Mechanisms-of-Electromagnetic-Interference-Southey-Dawalibi/93027a28b492ada0e521bae825889aaa92802517 [Accessed 2 Jan. 2019].

DIN 30670 (2012). Polyethylene Coating of Steel Pipes and Fittings Requirements and Testings. [PDF] Bonn: DIN. Available at: https://www.din.de/en/getting-involved/standards-committees/nmp/wdc-beuth:din21:149069094 [Accessed 30 Mar. 2019].

Di Biase, L., Cigna, R. and Fumei, O. (2010). AC Corrosion and Cathodic Protection of Buried Pipelines. In: *NACE International Corrosion 2010 Conference and Expo*. Texas: NACE International, Paper no. 10108.

Ellis, R. (2001). AC induced corrosion on onshore pipelines, a case history. [PDF] UK. Available at: http://www.ukopa.co.uk/pdfs/UKOPA-02-0034.pdf [Accessed 24 Aug. 2017].

Finneran, S. (2015). Criteria for Pipelines co-existing with Electric Power Lines. Dublin. *The INGAA Foundation*, Report No. 2015-04.

Gummow, R. (2014). AC Interference Guideline Final Report. [Online] Canada: *Canadian Energy Pipeline Association*. Available at: https://www.cepa.com/wp-content/uploads/2016/11/AC-Interference-Guidelines-Final-Report-FOR-PUB..pdf [Accessed 15 Aug. 2017].

Jiang, Z. and Lu, M. (2013). Case Study of AC Interference on 20 km Buried Pipeline: Field Test and Mitigation Design. *NACE International Conference Paper*. Texas: NACE International, ISBN: 02424 2013 CP.

Kajiyama, F. (2011). Strategy for eliminating risks of Corrosion and overprotection for buried modern Pipelines. [PDF] Tokyo: Semantic Scholar. Available at: https://www.semanticscholar.org/paper/STRATEGY-FOR-ELIMINATING-RISKS-OF-CORROSION-AND-FOR-Kajiyama/294733ed6fa5fc224f2c7dfc5d0f7b5299b3bab3 [Accessed 3 Feb. 2019].

McMiller (2017). DCVG Training Manual – DA Meter Version. [PDF] Florida, USA: M.C. Miller Co. Inc.. Available at: http://www.citethisforme.com/harvard-referencing [Accessed 21 Mar. 2017].

NACE SP21424 (2018). Alternating Current Corrosion on Cathodically Protected Pipelines: Risk Assessment, Mitigation, and Monitoring. Houston: NACE International.

Nigerian Electricity regulatory Commission (NERC) (2018). Electricity on Demand: Transmission. Nigerian Electricity regulatory Commission. [online] Available at: http://www.nercng.org/index.php/home/nesi/404-transmission [Accessed 8 Sept. 2018].

Nestoil, (2010). EGSP Engineering Design Dossier. Port-Harcourt: Nestoil, Emergency Gas Supply to PHCN Alaoji Power Plant.

Okiongbo, K. and Ogobiri, G. (2013). Predicting Soil Corrosivity along a Pipeline Route in the Niger Delta Basin Using Geoelectrical Method: Implications for Corrosion Control. *Engineering*, 5(3), pp. 237-244

Olesen, A. (2018). AC Corrosion of Cathodically Protected Pipelines. PhD. Technical University of Denmark, Department of Mechanical Engineering.

PML Cathodic Protection (2018). DCVG Coating Survey Data Sheet. [pdf] Suffolk: *Pipeline Maintenance Limited.*

Shwehdi, M. and Johar, U. (2003). Transmission Line EMF Interference with Buried Pipeline: Essential & Cautions. In: *International Conference on Non-Ionizing Radiation at UNITEN (ICNIR 2003) Electromagnetic Fields and Our Health*. [online]. Available at: http://www.who.int/peh-emf/meetings/archive/en/paper02shwehdi.pdf [Accessed 3 Apr. 2017].

Soriola, E. (2018). Importance of Crude Oil in Nigerian economy. Available at: https://www.legit.ng/1120356-importance-crude-oil-nigeria-economy.html [Accessed 10 Jul. 2019].