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Modeling & Simulation for West Qurna (Tuba-1) Cathodic Protection Design by using MATLAB Simulink

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Abstract

This study focused on the two systems of Cathodic Protection, CP, (temporary (Sacrificial Anodes, SACP) & permanent (Impressed Current, ICCP) that were used to protect West Qurna (Tuba-1) crude oil pipeline42 in / Basrah Oil Company, BOC, from corrosion challenges.

Design Calculations for CP systems were achieved according to the standards of National Association of Corrosion Engineers, NACE. These calculations were simulated using Matlab –Simulink Software 2018. Then, the simulated design was converted to Graphical User Interface, GUI. This GUI allows the user to enter the design data & perform the calculation faster & more efficiently. Furthermore, GUI was converted into a dependent program by installing Matlab Runtime Installer which enables the execution of Matlab files on computer without installed version of Matlab.

The results showed that there was matching between the calculations of CP design & the simulated design. SACP demonstrated that 4 Mg anodes are required to protect 1 km of sec.1 of pipeline for 4 years period while 6 Mg anodes are required to protect 1 km of sec.2 for 11 years period. ICCP system for sec.1 of pipeline requires 4 magnetite anodes to supply 2.86 v by rectifier in accordance with horizontal bed resistance $R_H \leq 1.5\ \Omega$ while sec.2 requires 25 magnetite anodes to supply 2.45 v by rectifier in accordance with vertical bed resistance $R_V \leq 1.5\ \Omega$. The designed program proved that it was easy to install & efficient in making Calculations.

According to the above, this program can be adopted in prediction studies to know the design outputs (No. of anodes, required current for protection & voltage supplied by rectifier).

Keywords: Cathodic Production, Sacrificial anode, Impressed Current, Matlab- Simulink, GUI, program.

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1. Introduction

Cathodic protection (CP) is an electrochemical technique used to reduce corrosion damage to active metal surfaces by reducing the potential difference between the anode and the cathode. It is used around the world to protect pipelines, water treatment plants, submarine and water storage tanks, ships and hulls, offshore production platforms, concrete structures and steel bars in docks, etc. [1] [2] . Pipes are used to transport fluids (liquids and gas), such as water, crude oil, and natural gas. In petroleum industry, they are used to transport oil from the production area to the export loading and unloading dock, or to processing units like oil refineries. Most of them made of carbon steel and built underground (subsoil of various types (dry and wet) and layers). Almost any water-containing environment can promote corrosion that occurs under many complex conditions in oil and gas production, processing, and piping systems [3] [4]. The heterogeneity of soil components leads to potential difference which are considered the main cause of corrosion cell development on the pipeline surface. Soil resistivity is considered a significant determinant for soil corrosivity [4]. CP with coating or paint are considered to be the best suggested solution to minimize corrosion challenges for buried pipelines. CP techniques are classified into two types, sacrificial anodes & Impressed currents. The 1st type is used for temporary protection (for short periods) for above water steel storage tanks & underground steel pipeline (during impressed current installation) while impressed current used for permanent protection (long period) for underground and subsea steel structures [5, 6]. Simulation modeling solves real world problems safely efficiently. It provides an important method of analysis which is easily verified, communicated and understood. Matlab software is considered the most common important program has a lot of applications in the lab and field. One of its applications is Simulink. It is utilized to simulate any process in different fields in an efficient and easy way [7, 8].

The aim of this study is to simulate the Cathodic protection design for West Qurna pipeline 42 in using Matlab Simulink 2018 and turn this simulation into dependent program achieves the design calculations of CP system efficiently.

2. Design Calculation

2.1 West Qurna Pipeline (1-Tuba)

The West Qurna pipeline 42 in (1.067 m) diameter with length of 70.5 Km is divided into two sections, the first section 46 km while the second 24.5 km. Table (1) illustrates the properties

Open Access
No. 34 part 1, March 2022, pp. 317-331

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E- ISSN: 2710-1096

of the West Qurna pipeline which were provided by BOC. Figure (1) shows the roots of the West Qurna pipeline.

Table (1) Properties of West Qurna pipeline.

Property		**Section (1),**	**Section (2),**
Pipeline length, L_p, m		46000	24500
Pipeline diameter, D_p, m		1.067	1.067
Soil resistivity, ρ (Ω .cm)		1000	4000
Coating Resistance, CR ($\Omega.m^2$)		4000	5000
Coating Efficiency, CE		95 %	
Type of coating		3 LPE	
Natural potential of pipeline,p_n,v		0.55	
Protection Potential of pipeline, v	Min potential, V_{pol}	-0.9	-0.9
	Max potential	-1.2	-1.2
Pipeline alloy type		Low Carbon Steel	
Pipeline alloy code		API 5LX-X60	

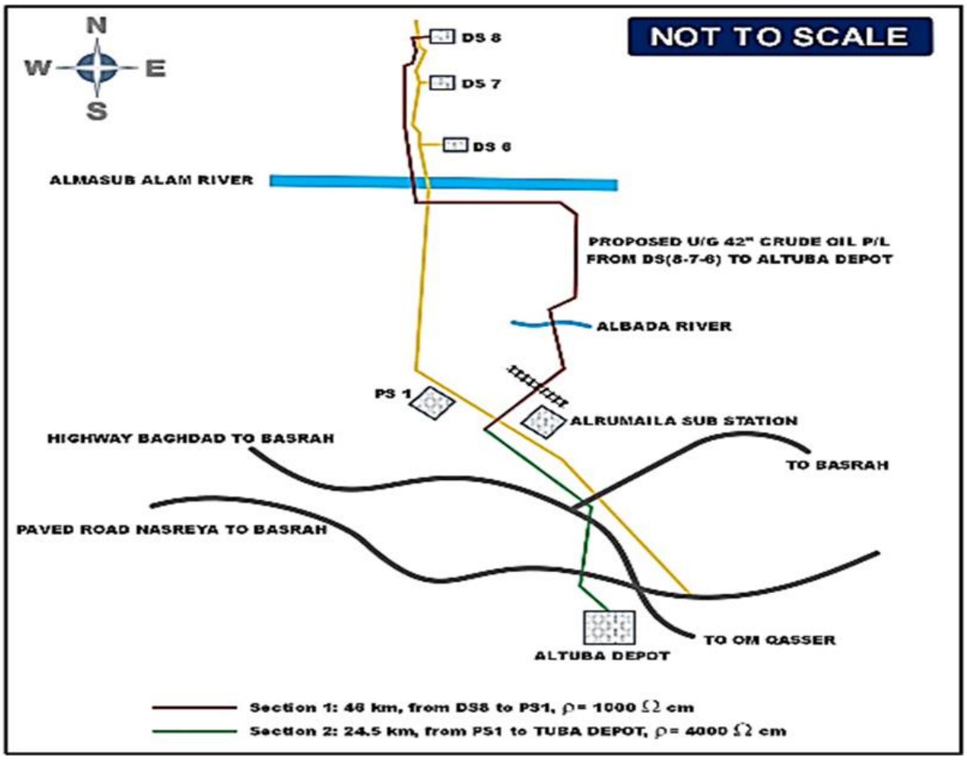

Fig. (1): Route of West Qurna pipeline (1-Tuba).

Open Access
No. 34 part 1, March 2022, pp. 317-331

P- ISSN: 2220-5381
E- ISSN: 2710-1096

2.2 Design Equations

2.2.1. Sacrificial CP design

SACP was designed to protect west Qurna pipeline for 5 years. Mg anodes were selected with cylindrical form of D-Shape. Mg Anodes Properties are demonstrated in Table (2). The design equations for sacrificial anodes CP system according to, National Association of Corrosion Engineers, NACE, standards are depicted in Table (3).

Table (2) Mg Anodes Properties [9].

Property, symbol, unit	Selected design Value
D-Shaped Magnesium Anode	
Open circuit potential voltage, V_{ocp}(v)	-1.75
Actual Capacity ,Ca (A-hr/kg)	1100
Consumption rate (kg/A.yr)	7.7
Current Efficiency, eff%	50%
Utilization factor	0.8
Anode length with backfill(m)	0.6
Anode diameter with backfill(m)	0.056
Anode spacing, S, (m)	1.55
Required anode design life, DL, year	5
Anode weight, W_a, kg	10

Table (3) Design equations for sacrificial anodes CP system according to NACE standards [10].

Parameters	Equation
Pipeline Area to be Protected, A (m^2)	$A = \pi * L_p * D_p$
Current Density, i(A/m^2)	$i = \frac{V_{pol} - P_n}{CR}$
Current Required (Bare), Ir (A)	$I_r = A * i$
Single Anode Resistance, Ra (Ω)	$R_a = \frac{0.005 * \rho}{\pi * L_a} [ln \frac{8 L_a}{D_a} - 1]$
Anode Current, I_a (A)	$I_a = \frac{V_{ocp} - V_{pol}}{R_a}$

Open Access
No. 34 part 1, March 2022, pp. 317-331

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Number of Anodes based on required Current, N_1	$N_1 = \frac{I_r}{I_a}$
Total Anodes Weight W_t (kg)	$W_t = \frac{Consumption\ Rate * DL * I_r}{Eff\% * Utilization\ Factor}$
Number of Anodes based on required design life, N_2	$N_2 = \frac{W_t}{W_a}$
Multiple vertical Anodes Resistance, R_N (Ω)	$R_N = \frac{0.005 * \rho}{\pi N L_a} [ln \frac{8\, L_a}{D_a} - 1 + \frac{2L_a}{S}\ ln\, 0.656N]$
Calculated Design Life for Anode, DL (year)	$DL = \frac{Utilization\ Factor * Capacity * W_a}{I_a}$

1.2.2 Impressed Current CP Design

ICCP was designed to protect West Qurna pipeline for 25 years. Magnetite anodes were selected with hollow cylindrical shape. Table (3) Shows Magnetite anodes properties. The design equations for impressed current CP system according to NACE standards are depicted in Table (5).

Table (4) Magnetite anodes properties [9]

Property, unit	**Value**
Cast cylindrical and hollow shaped	
Required design life, DL, year	25
Anode Weight with backfill, W_a (kg)	22
Anode length without backfill, l_a, (m)	0.7
Anode diameter without backfill, D_a(m)	0.055
Anode length with backfill, l_a (m)	1
Anode diameter with backfill, d_a (m)	0.16

Open Access
No. 34 part 1, March 2022, pp. 317-331

P- ISSN: 2220-5381
E- ISSN: 2710-1096

Table (5) Design equations for impressed current ICCP system according to NACE [10].

Parameters	Equation
Pipeline Area to be Protected, A (m^2)	$A = \pi * L_p * D_p$
Current Density, i(A/m^2)	$i = \frac{V_{pol} - P_n}{C.R}$
Current Required (Coated), I_r (A)	$I_r = A * i * (1 - CE)$
Current Required (with Safety Margin, SM), I_r (A) where BP, By Pass wasted current	$I_r = A * i * (1 + SM + BP)$
Current Required (Bare), I_r (A)	$I_r = A * i$
Anode Current density, i_a,(A/m^2)	$log_{10} i_a = 3.3 - \ log_{10} DL$
Anode Current, I_a (A)	$A_a = \ \pi D_a L_a, I_a = A_a * i_a$
Number of Anodes required current, N	$N = \frac{I_r}{I_a}$
Anodes Horizontal Ground Bed Resistance, R_H(Ω) L_{gh} ,ground bed length	$R_H = \frac{0.005 * \rho}{\pi * L_{gh}} \left[ln \frac{4\, L_a}{D_a} + ln \frac{L_a}{h} - 2 + \frac{2h}{L_a} \right]$ $Lgh = ((NL_a) + \left(0.75(N-1)\right))$
Anodes vertical Ground bed Resistance , (Ω)	$R_v = \frac{0.005 * \rho}{\pi N L_a} [ln \frac{8\, L_a}{D_a} - 1 + \frac{2L_a}{S}\ ln\, 0.656N]$
Pipeline Resistance, Rp (Ω)	$R_p = \frac{CR}{A}$
Cable Resistance, Rc (Ω) where, L_{cp} cable positive header length, R_{cp} cable positive header resistance & R_{cn}, cable negative header resistanc	$R_c = \left(L_{cp} * R_{cp}\right) + (L_{cn} * R_{cn})$
Total Resistance, R_T (Ω)	$R_T = (R_H or\ R_v) + R_c + R_p$
Protection Voltage ,V_{pr} (volt)	$V = (I_r R_T) + 2_{Backvoltage}$

1.2.3 Ground beds

A shallow horizontal Ground bed was selected for sec.1 while deep well vertical ground bed was selected for sec.2. Table (6) shows the ground bed properties for each section.

Open Access
No. 34 part 1, March 2022, pp. 317-331

P- ISSN: 2220-5381
E- ISSN: 2710-1096

Table (6) Ground bed properties for sections (1) & (2).

Section 1, Shallow horizontal ground bed		Section 2, Deep well vertical ground bed	
Property	Value	Property	Value
Ground Bed resistance [11], Ω	≤ 1.5	Ground Bed resistance [11], Ω	≤ 1.5
Depth, h ,m	2	Spacing (distance between anode centers), m	1.9

1.3 Simulation

The CP design for West Qurna pipeline was simulated using Matlab – Simulink 2018. Figure (2) depicts the steps of the simulation in Matlab software.

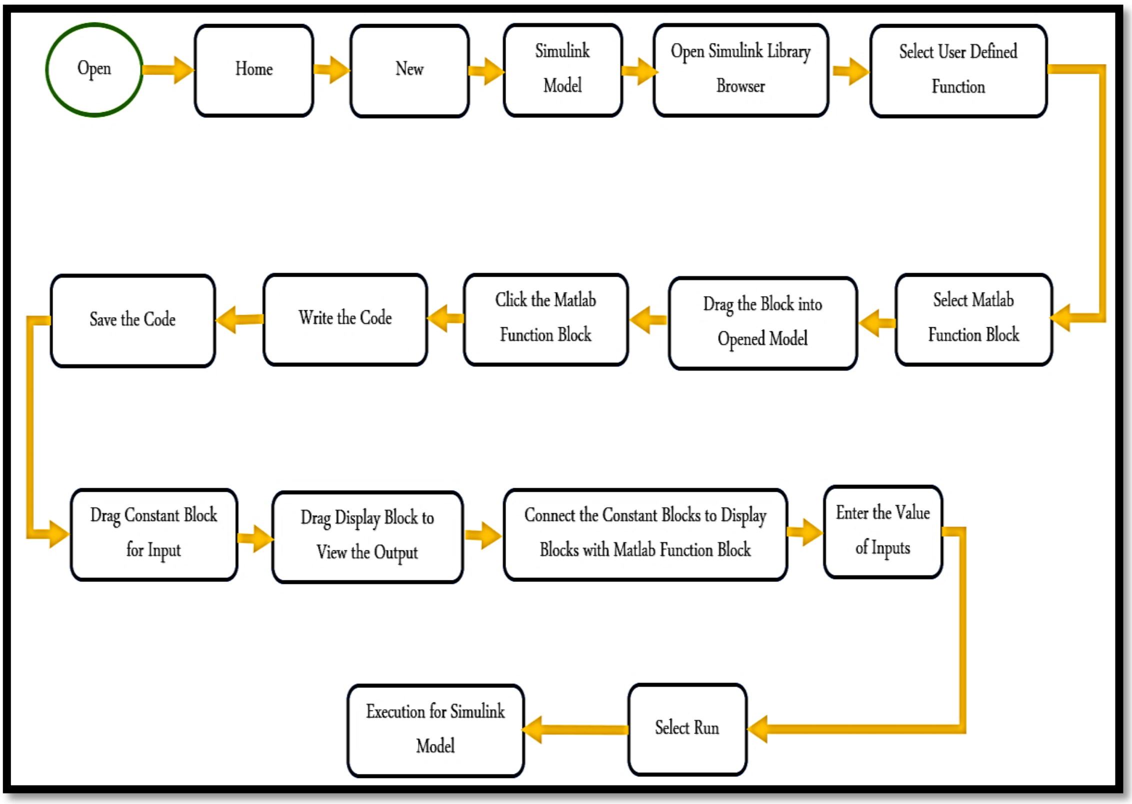

Fig. (2): Steps of the simulation in Matlab software.

Open Access
No. 34 part 1, March 2022, pp. 317-331

P- ISSN: 2220-5381
E- ISSN: 2710-1096

3. Results & Discussion

3.1 CP Design Outcomes

For sections of West Qurna pipeline, Table (7) represents the values obtained from the sacrificial anodes –design equations.

Table (7) sacrificial anode design results for sec.1 and sec.2 of West Qurna pipeline.

Item, unit	Values-sec.1	Values- sec.2
Area to be Protected A (m^2)	154117.48	82084.31
Current Required (bare), Ir (A)	13.49	5.7459
Anode Current, Ia (A)	0.09285	0.0232
Number of Anodes based on Current required	**4**	**11**
Number of Anodes based on required anode design life	3	3
Total Anodes Weight, W_t (kg)/1 Km	28.239	22.583
Single Anode Resistance, Ra (Ω)	9.154	36.62
Calculated Design Life for Anodes, DL (year)	11	44
Multiple Anodes Resistance, R_N (Ω)	2.784	4.805
Anode Current, Ia (A)	0.3053	0.1769
Final Design Life per Anode, DL (year)	**4**	**6**

The results obtained from the impressed current design equations for sec. (1) and sec. (2) of the West Qurna pipeline are shown in Table (8).

Table (8) Impressed Current design results for sec. (1) & sec.(2) of West Qurna pipeline.

Item, unit	Values-sec.1	Values-sec.2
Area to be Protected A (m^2)	154117.48	82084.31
Current Required (Coated), Ir (A)	0.6746	0.2874
Anode Current, Ia (A)	9.653	9.653
Number of Anodes based on Current required	0.069~1	1
Length of anodes ground bed, m	6.25	/
Protection Spread Calculation (number of Cps)	2 Cps	2 Cps
Horizontal Ground bed Resistance, (Ω)	1.23	1.49
Final Number of Anodes	4	25
Pipeline Resistance, Rp (Ω)	0.02594	0.06088
Cable Resistance, Rc (Ω)	0.01818	0.01818
Total Resistance, R_T (Ω)	1.274	1.57
Protection voltage, V, volt	**2.86**	**2.451**

Open Access
No. 34 part 1, March 2022, pp. 317-331

P- ISSN: 2220-5381
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3.2 Simulation Outcomes

The simulation results for sacrificial anodes CP system for West Qurna pipeline sections are illustrated in Figures (3-A), (3-B) respectively.

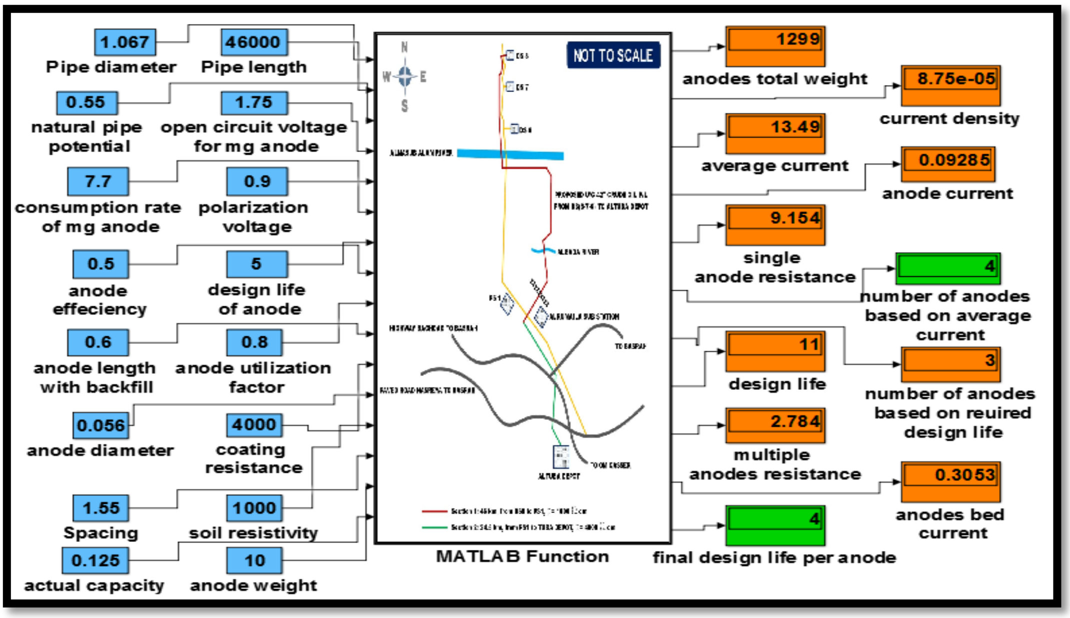

Fig. (3-A): Simulation results for sacrificial anodes CP system for west Qurna pipeline sec. 1.

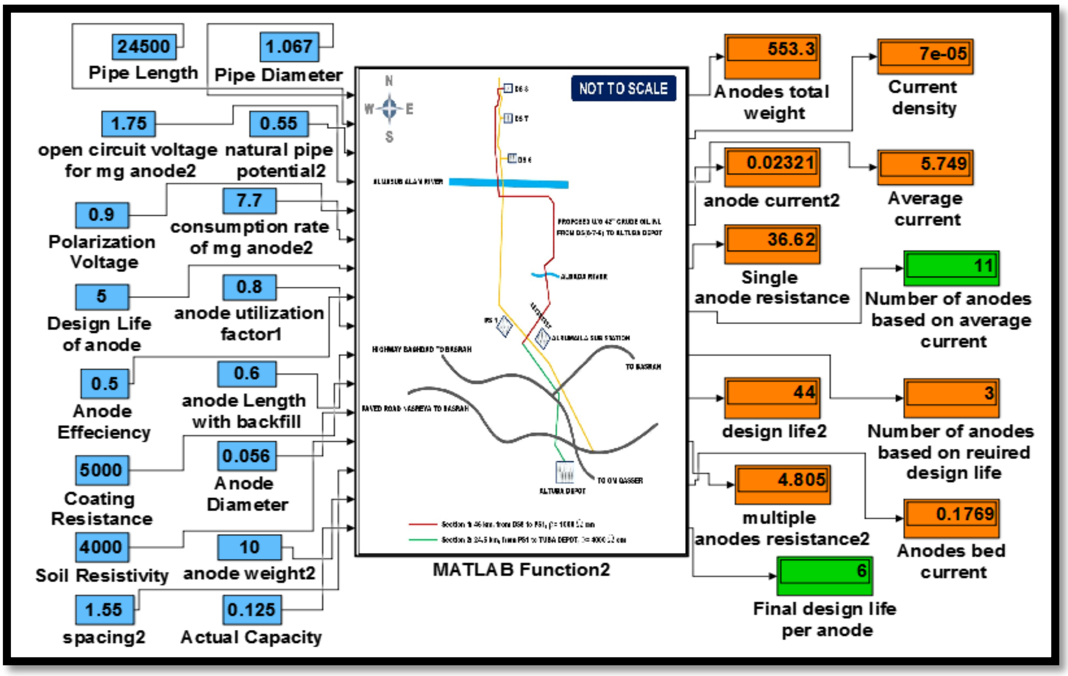

Fig. (3-B): Simulation results for sacrificial anodes CP system for West Qurna pipeline sec. 2.

Open Access
No. 34 part 1, March 2022, pp. 317-331

P- ISSN: 2220-5381
E- ISSN: 2710-1096

The simulation results for impressed current CP system for West Qurna pipeline sections are depicted in Figures (4-A) , (4-B) respectively.

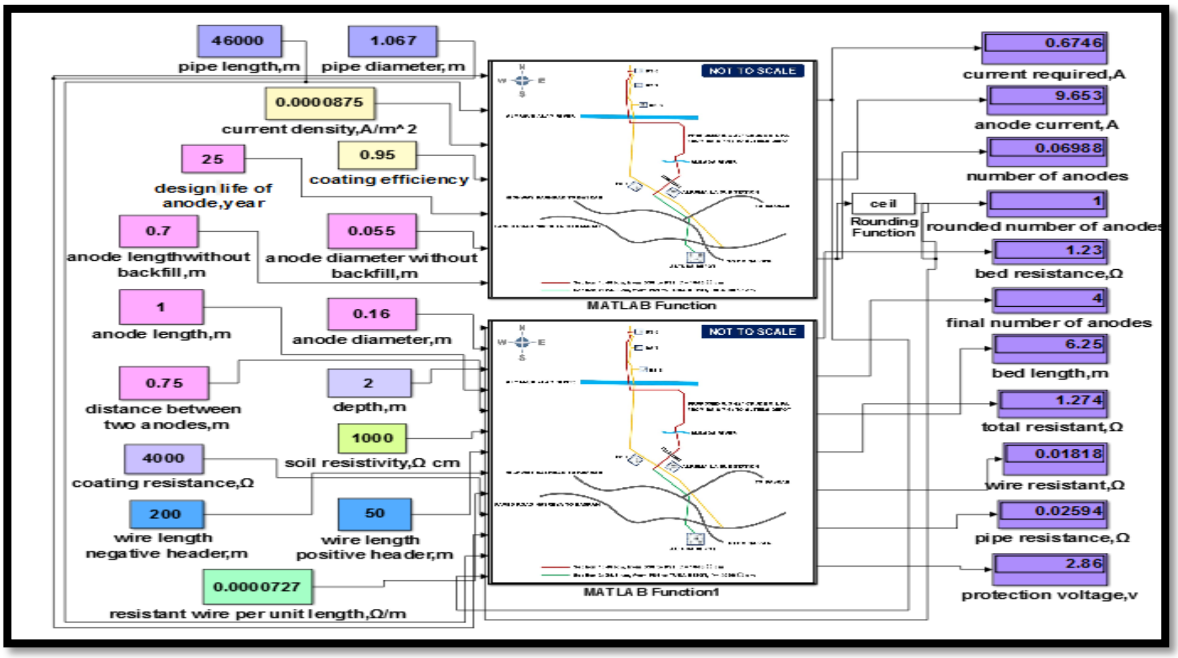

Fig. (4-A) Simulation results for Impress Current CP system for West Qurna pipeline sec. 1.

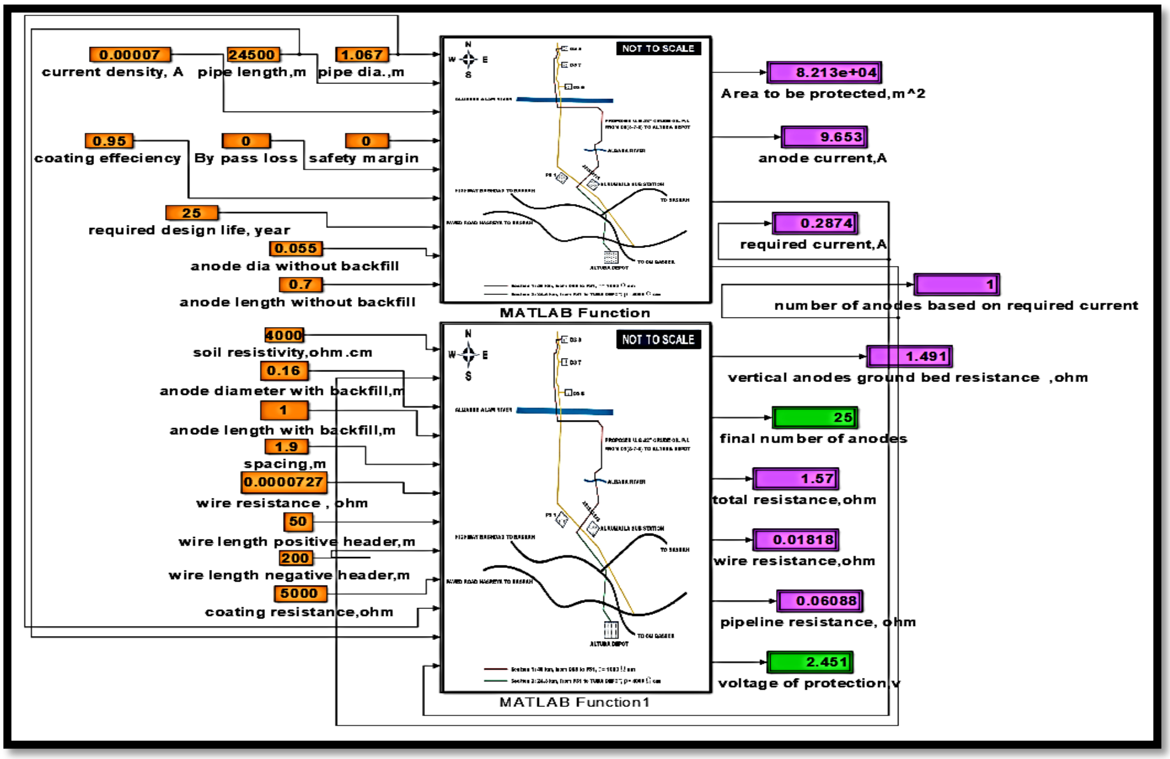

Fig. (4-B): Simulation results for Impress Current CP system for West Qurna pipeline sec. 2.

Open Access
No. 34 part 1, March 2022, pp. 317-331

P- ISSN: 2220-5381
E- ISSN: 2710-1096

3.3 Debate of Simulation Results

3.3.1 Sacrificial anodes simulation

According to the findings, 4 Mg anodes per 1 Km of pipeline-sec.1 with a 4 year design life are required for CP system. While for sec.2. 11 Mg anodes per 1 Km of pipeline with 6 year' design life is required for CP system.

3.3.2 ICCP Simulation Discussion

For sec.1, the results revealed there are 4 Magnetite anodes that satisfy the horizontal ground bed resistance criteria (R_H <= 1.5 ohm) and the CP circuits power supply voltage is 2.86 V.

While for sec.2, the results revealed that there are 25 Magnetite anodes that satisfy the vertical ground bed resistance criteria (R_V<= 1.5 ohm) and the CP circuits power supply voltage is 2.45 V.

According to the above, it was noted that there was matching between design calculation results (that were explained in Tables 7 & 8) and simulation results as it was demonstrated in Figures (3-A), (3-B) , (4-A) & (4-B).

3.4. Debate of GUI Results

3.4.1. Sacrificial anodes GUI

Sacrificial anodes simulation model is turned into GUI using Matlab. The executed designed GUI for sacrificial anodes CP system is depicted in Figure (5).

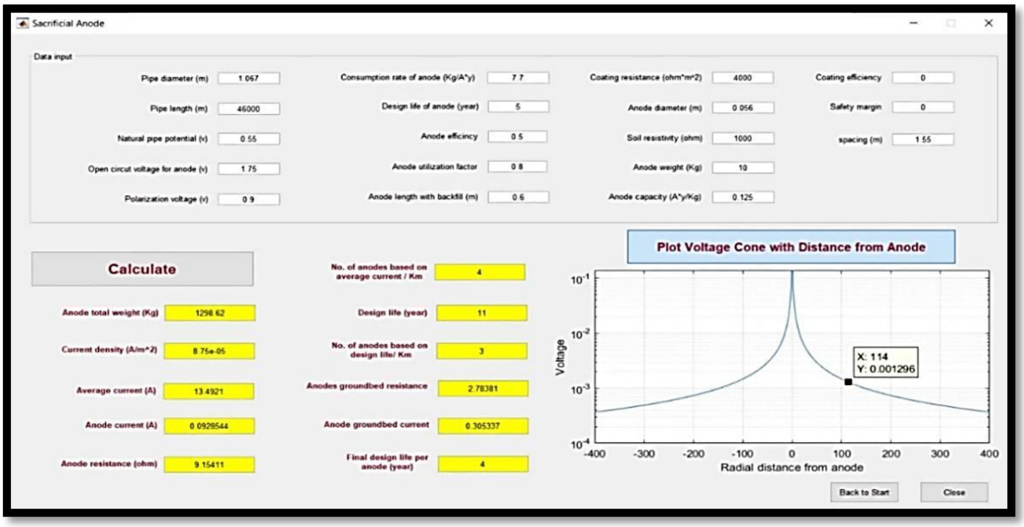

Fig. (5): GUI for the sacrificial anode CP system after entering the design inputs for sec.1.

Open Access
No. 34 part 1, March 2022, pp. 317-331

P- ISSN: 2220-5381
E- ISSN: 2710-1096

3.4.2. Voltage Cone Plot

Voltage cone [10]will happen due to pass a current from anode through soil (I.e. voltage drop from point to another in electrolyte) this gradient result in voltage rise in pipe to soil potential. Voltage rise can be calculated through (1).

$$U_r = \frac{0.005*\rho*I}{\pi*L} * \ln[\frac{L+\sqrt{L^2+r^2}}{r}] \qquad (1)$$

Where U_r, voltage rise, I, anode current, L, anode length, r, radial distance from anode as shown in Figure (6).

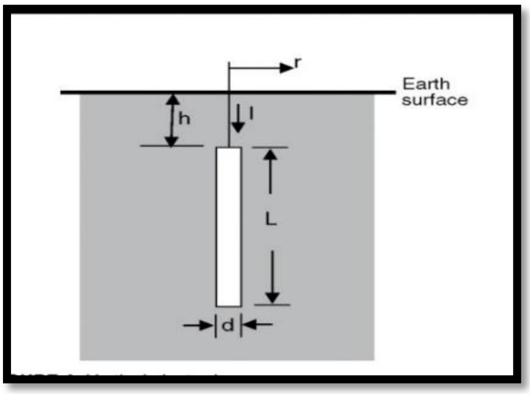

Fig. (6): Buried anode under earth surface.

Then total rise voltage, E_T, is calculated through (2):

$$E_T = I_a * R_a \qquad (2)$$

$$\% = \frac{U_r}{E_T} * 100 \qquad (3)$$

In the above figure, voltage rise is calculated at r= 400 m from anode, and then divided the result on total rise voltage as shown in (3), the obtained ratio is 0.043 % < 5% [12] (for each sec. of pipeline) which is considered acceptable ratio.

3.4.3. Impressed current simulation

The executed designed GUI for Impressed current CP system is depicted in Figure (7).

Open Access
No. 34 part 1, March 2022, pp. 317-331

P- ISSN: 2220-5381
E- ISSN: 2710-1096

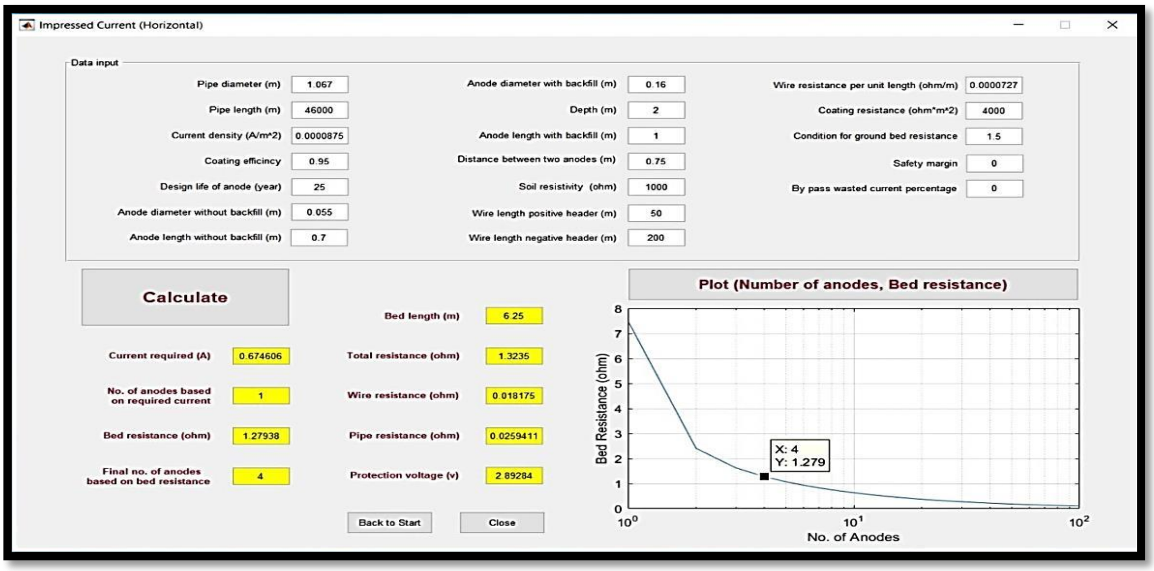

Fig. (7): GUI for Impressed current CP system after entering the design inputs for sec. 1.

From Figure (5) and (7), GUI results showed complete matching with the simulation results for each type of CP system.

Also, it was illustrated from the plot in Figure (7) that the relationship between resistant of vertical ground bed R_V and anodes number is inverse relationship,

GUI for each type of CP system is turned into an independent program by installing Matlab Runtime installer which enables the execution of Matlab files on computer without installed version of Matlab. Figure (8) illustrates the main interface of designed program.

Fig. (8) The main interface of designed program in Matlab.

Open Access
No. 34 part 1, March 2022, pp. 317-331

P- ISSN: 2220-5381
E- ISSN: 2710-1096

4. Conclusions

- Simulation results using Matlab – Simulink for each type of CP system clarified the following outcomes:

a- 4 Mg sacrificial anodes are required to protect 1 km of sec.1 of pipeline for 4 years period.

b- 6 Mg sacrificial anodes are required to protect 1 km of sec.2 of pipeline for 11 years period.

c- Utilizing impressed current CP system for sec.1 of pipeline requires 4 magnetite anodes to supply 2.86 v by rectifier in accordance with bed resistance $R_H \leq 1.5\ \Omega$.

d- Utilizing impressed current CP system for sec.2 of pipeline requires 25 magnetite anodes to supply 2.45 v by rectifier in accordance with bed resistance $R_v \leq 1.5\ \Omega$.

- The GUI model for each type of CP system proved its efficiency to calculate the required design outputs for protection.
- Installation and dealing with the designed program in a way that ensures accurate and quick calculations is simple.

Open Access
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