External Corrosion Control of the Underground Steel Pipelines Using Cathodic Protection Systems

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Abstract

The paper discusses the cathodic protection (CP) technique used for corrosion mitigation of underground steel piping. Since corrosion and CP are electrochemical processes involving electrical current and an exchange of charged ions, electrical models can be developed. The main objective of this paper is studying the CP systems of underground steel piping to develop equivalent electrical models, which can be used in simulation of such systems. In this paper, the equivalent models for CP systems are prepared through the electrical modeling for the electrode-electrolyte interface by Randle's circuit model. The study herein is based on that the charge-transfer overpotential (activation polarization) appears only at the electrode; i.e. in the absence of mass-transfer effects, thereby Randle's circuit model is composed of a double-layer capacitance (C_{dl}) in parallel with the polarization resistance (R_p). The equivalent models of CP systems can enable us to validate the design procedures of CP systems. Also through these models, the impact of pipeline polarization resistance on applying the CP can be simulated. Simulation and results examining are performed using MATLAB/SIMULINK program. The study assumes that the soil along the pipeline is homogenous.

Keywords— Corrosion, Cathodic protection, sacrificial anode, impressed current, polarization resistance

I. INTRODUCTION

Corrosion is defined as the deterioration of a material by chemical or electrochemical reaction with its environment. Most of the underground metals corrosion is as a result of an electrochemical reaction involving the transfer of electrical charge across the metal/electrolyte interface. Corrosion may cause significant economic and human damage. Cathodic protection (CP) is an electrical method for preventing or mitigation of the corrosion on metallic structures which are in electrolytes such as soil or water. CP is the most widely applied electrochemical corrosion control technique and its use has increased greatly in the last three decades. Before the mechanism of CP could be established, it is necessary to review the electrochemical nature of the corrosion.

II. ELECTROCHEMICAL NATURE OF CORROSION

When a metal electrode is inserted in an electrolyte, an equilibrium interfacial potential (E) known as the half-cell potential (alternatively referred to as the open-circuit potential (E_{oc})) is established between the metal and electrolyte, in a very narrow interphase region. This potential determines the place of metal in the electromotive (galvanic) series. Galvanic series is a list of the metals and alloys arranged in order of the magnitude and polarity of their equilibrium potentials in an electrolyte, with respect to a standard reference electrode. The metal which has most negative potential is the anode and that has most positive potential is the cathode [1]. The metal electrode can be exposed to different equilibrium potentials in Non-Homogeneous electrolyte. When a continuous metal electrode (e.g. pipeline) has different equilibrium potentials in an electrolyte, anodic and cathodic sites will be established on the metal it follows that, a current would leave the metal at the anode site, pass through the electrolyte, and reenters the metal at the cathode site causing electrochemical corrosion at the anode (Fig. 1) [2]. At the anode the metal atoms give up one or more electrons through oxidation reactions and become metal ions, with a net positive charge. At the cathode the metal is protected from becoming an ion through reduction reactions.
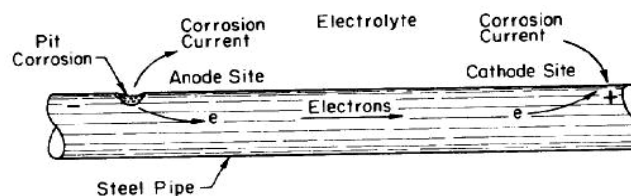

Figure 1. Pipeline corrosion due to localized anode and cathode [2]

A corrosion cell consists of the anode, cathode, electrolyte, and metallic path between anode and cathode [2], and can be represented by a simple equivalent circuit as in Fig. 2 [1]. I is the corrosion current and can be calculated as shown in equation (1) [3].
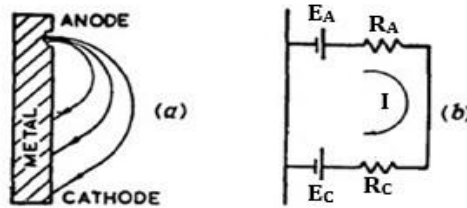
Figure 2. Equivalent circuit of simple corrosion cell [1] (*a*) Corrosion cell. (***b***) **Equivalent circuit**

$$I = \frac{E_A - E_C}{R_A + R_C} \qquad (1)$$

where: E_A is the open-circuit potential of anode, R_A is the effective anode resistance, E_C is the open-circuit potential of cathode and R_C is the effective cathode resistance.

III.   CORROSION CELL KINETICS (POLARIZATION)

An electrochemical reaction will either produce or consume electrons. The exchange (corrosion) current; I, generated by the electron flow between the anodic and cathodic reactions is an effective measurement of the corrosion rate, since it is directly proportional to mass loss during anodic dissolution (Faraday's law) [4, 5]. A current density (*i*), with the usual units of A/cm^2, is a measure of the kinetic rate of the electrode reaction. The exchange current density (i_o) is merely a convenient way of representing the rates of oxidation and reduction of a given single electrode at equilibrium and must be determined experimentally [4, 5, 6]. As a result of the electrochemical reactions that occur at the electrode surface the half-cell potential of electrode can change causing a polarization or overpotential (η) at the electrode surface. Polarization is the deviation from equilibrium potential due to the electrical energy used up in the transfer of charge across the respective electrode/electrolyte interfaces. This polarization occurs in opposing the electromotive force across the reacting interfaces. When electrons are supplied in excess to the electrode surface (reduction reaction), a negative or cathodic polarization (η_c) occurs and the electrode potential becomes more negative, whereas the removal of electrons from the electrode surface (oxidation reaction) provokes a positive or anodic polarization (η_a). There are two types of mechanisms that govern polarization phenomena. According to which one is the limiting factor, polarization is said to have either activation (kinetic or charge-transfer) control or concentration (mass-transport or diffusion) control [4, 5, 6, 7].

Activation polarization (η_{act}) is a function describing the charge transfer kinetics of the electrochemical processes. The charge-transfer reaction involves moving an electron from the electrode surface to the reactant on the electrolyte side of the interface. The relationship between the current density and potential of anodic and cathodic electrode reactions under charge-transfer control is given by the following relationship (Butler-Volmer equation) [6]:

$$i_{reaction} = i_0 \left\{ \exp\left(\beta_{reaction} \frac{nF}{RT} \eta_{reaction} \right) - \right.$$
$$\left. \exp\left(-(1 - \beta_{reaction}) \frac{nF}{RT} \eta_{reaction} \right) \right\} \quad (2)$$

where: $i_{reaction}$ is anodic or cathodic current density (mA/cm^2), i_o is exchange current density (mA/cm^2), $\beta_{reaction}$ is charge transfer barrier or symmetry coefficient for the anodic or cathodic reaction, usually close to 0.5, $\eta_{reaction}$ is the overpotential relative to the equilibrium potential, n is number of participating electrons, R is universal gas constant, that is, (8.3145 J/mol °K), T is absolute temperature (298.16 °K) and F is Faraday's constant (96,485 coulombs/mol of electrons)

By applying the logarithmic function and rearranging the terms of equation (2), the activation polarization can be described by the following equation [4, 6].

$$\eta_{act} = \pm b \, log_{10} \left(\frac{i_{reaction}}{i_0} \right) \quad (3)$$

where: b is the Tafel slope and must be determined experimentally.

Equation (3) is known as the Tafel equation because in case of the activation polarization of an electrode the variation of the logarithm of current density with potential; Evans diagram, will be given by a straight line in which the slope is precisely the Tafel slope b and this linear region is known as the Tafel region. The Tafel slope is a function of the specific reaction, the electrolyte chemistry, and the reacting surface [4, 5, 6, 8]. When η_{act} is anodic, the Tafel slope is positive and vice versa. The Tafel slope can be described by as follows [6].

$$b = 2.303 \frac{RT}{\beta nF} \quad (4)$$

Concentration polarization is caused by concentration change in the environment adjacent to the electrode surface. Anything that causes a depletion of available reactants or a buildup of reaction products results in a decrease in the reaction rate and an increase in concentration polarization. Concentration polarization (η_{conc}) is a function describing the mass-transport limitations associated with electrochemical processes. The limiting current density i_L (A/cm^2) appears when the concentration of species is completely depleted at the surface. For intermediate cases, that is, when the reaction current ($i_{reaction}$) is smaller than the limiting current density (i_L), concentration polarization can be given by as follows [4, 6, 8]:

$$\eta_{conc} = \frac{2.303 \times RT}{nF} \, log_{10} \left(1 - \frac{i_{reaction}}{i_L} \right) \quad (5)$$

The limiting current density can be described by the following equation [4].

$$i_L = \frac{D \, n \, F \, C_B}{x} \quad (6)$$

where: D is the diffusion coefficient (cm^2 s^{-1}), n is number of electrons transferred, F is Faraday's constant, C_B is reactant concentration in bulk solution (mol/cm^3) and x is thickness of diffusion layer; must be determined experimentally, (cm)

In sum, anodic dissolution can be said to occur normally under pure activation control, disregarding concentration effects; however, in the case of cathodic reduction the concentration of reactant species must be taken into account; the cathodic reactions can either be activation or concentration controlled. In this case, it is more correct to refer to a combined or total polarization control ($\eta_{T,c}$) that is the direct algebraic sum of activation (charge-transfer) polarization; η_{act}, and concentration (mass-transport) polarization; η_{conc} [5].
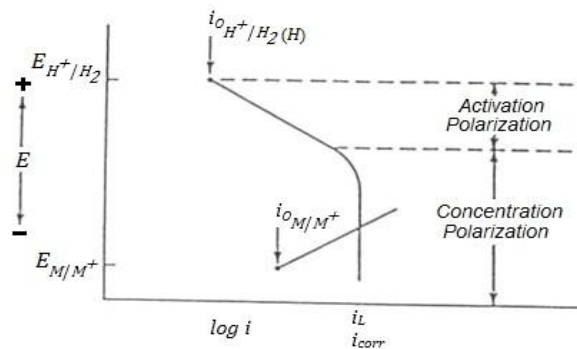

Figure 3. Schematic diagram for corrosion of metal M under concentration (diffusion) control

Figure 3 shows a system where the reduction process is under concentration control. Initially, the reduction rate of hydrogen ions is under activation control and at higher reduction current it is controlled by concentration polarization. The anodic dissolution reaction of metal is under activation control. The corrosion rate is determined by the intersection between the total reduction rate and the total oxidation rate.

IV. THE ELECTRICAL MODEL OF THE ELECTRODE-ELECTROLYTE INTERFACE

As mentioned above, when a metal electrode is inserted in an electrolyte, a charge separation, and therefore a potential difference occurs at the metal interface, in a very narrow interphase region. As a result of the electrochemical reactions that occur in the interphase region the electrical potential of electrode can change away from the equilibrium condition; i.e. the electrode is polarized. In a general sense, an oxidation reaction refers to a reaction that involves an increase in the oxidation state (i.e. loss of electrons from the reactant) and a reduction reaction refers to a reaction that involves a decrease in oxidation state (i.e. gain of electrons of the reactant). However, in a strict sense, not all changes in the oxidation state leads to electron transfer, while all electron transfer leads to a change in oxidation state. Therefore, it is preferred to use

the term Faradaic redox reaction to distinguish between these two cases, where Faradaic refers to the case where electron transfer between reacting species takes place and non-Faradaic refers to the case where there is no electron transfer. Accordingly there are two primary mechanisms of charge transfer at the electrode/electrolyte interface: a non-Faradaic reaction (Capacitive charge transfer), and a Faradaic reaction. Non-Faradaic reaction occurs initially and involves the repulsion and attraction of ions in the electrolyte in response to the electric charge variation on the metal electrode; the positively charged ions move towards the negative electrode while the negatively charged ions move towards the positive electrode. It follows that an electric double-layer arises between the electrode and electrolyte. The electric double-layer refers to a formation of two layers of opposite charge at the interface between the electrode and electrolyte; there is one layer of charged particles on one side of the interface (i.e. electrode) while another layer of oppositely charged particle on the other side (i.e. electrolyte). Through non-Faradaic reaction, no electrons are transferred between the electrode and electrolyte. This is essentially like charging or discharging an electrical capacitor. Consequently, non-Faradaic reaction is represented electrically by an electrical capacitor called the double-layer capacitance (C_{dl}). Non-Faradaic reaction is reversible. The second mechanism; Faradaic reaction, occurs when the electrons begin to move between the electrode and electrolyte, resulting in reduction or oxidation of chemical species in the electrolyte, thus changing the chemical composition in the electrolyte. At the electrode-electrolyte interface, a flow of electrons in the metal electrode is converted into a flow of ions in the electrolyte. Unlike the capacitive charge transfer mechanism, Faradaic charge reaction forms products in electrolyte therefore it may or may not be reversible. Thereby the net rate of a Faradaic reaction is either under activation (kinetic or charge-transfer) control or under concentration (mass-transport or diffusion) control. For a given metal electrode and electrolyte, at electrical potentials sufficiently close to equilibrium, the reaction rate is under kinetic control. When the electrode potential is sufficiently far away from equilibrium, the reaction rate is under mass-transport control [6, 7, 9, 10, 11].

Based on the charge transfer mechanisms and the diffusion effect of the interface, it is possible to deduce an equivalent electrical circuit model and match the circuit components with the physical characteristic of the interface. In a simple case, the electrode/electrolyte interface can be modeled electrically by a Randle's circuit, composed of a double-layer capacitance C_{dl} in parallel with the series combination of a charge-transfer Faradaic resistance R_f (alternatively referred to as a charge transfer resistance R_{ct} or a polarization resistance R_p) and Warburg impedance Z_W, as shown in Fig. 4a. Charge-transfer Faradaic resistance represents the electrode's resistance to corrosion. The Warburg impedance represents mass-transfer limitations by diffusion and becomes gradually less important if the concentrations of reactants are high near the interface. When the Warburg impedance is negligible (*i.e.* mass-transfer effects are absence), the equivalent model can be reduced to the parallel combination of the double-layer capacitance and the Faradaic resistance as shown in Fig. 4b [10].
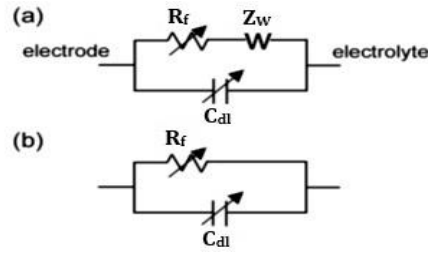
Figure 4. Randle's equivalent circuit model of electrode-electrolyte interface [10]

Randle's circuit in Fig. 4 illustrates single Faradaic impedance representing the electron transfer reaction. Generally there may be more than one Faradaic reaction possible, which is modeled by several branches of Faradaic impedance (one for each reaction), all in parallel with the double-layer capacitance. The net current (i_{total}) passed by an electrode, modeled as shown in Fig. 4, is the sum of currents through the two parallel branches, equation (7) [7, 11]:

$$i_{total} = i_c + i_f \qquad (7)$$

where: i_c and i_f are the currents through capacitance and Faradaic element respectively.

The current through the Faradaic element is given by the Butler-Volmer equation (equation (2)). This equation relates the overpotential or polarization (η) to net current density ($i_{reaction}$) through an electrode going into a Faradaic reaction, and defines the full characteristics of the Faradaic impedance in the absence of mass-transport effects. The exponential dependence of Faradaic current on polarization indicates that for a sufficiently small polarization; near equilibrium, there is little Faradaic current; i.e. all charge initially flows through the capacitive branch for charging the double-layer capacitance. When more charge is exchanged through electrode interface, the electrode capacitance continues to charge, the polarization increases and the Faradaic current begins to be a significant fraction of the total current. The current through the capacitance is given by the following equation [7, 10, 11].

$$i_c = C_{dl} \frac{dv}{dt} = C_{dl} \frac{d\eta}{dt} \qquad (8)$$

When the polarization becomes great enough, the Faradaic current increases and equals the total current and the electrode potential doesn't change, corresponding to the capacitor not charging any further. As more charge is exchanged and reaction products are built, the reactants concentration may decrease at the surface and the Faradaic current will then begin to level off, corresponding to the current becoming limited by mass-transport of reactant. In this case the Faradaic reaction is under mass-transport control and the Warburg impedance must be taken into account in Randle's circuit model. As mentioned previously, the current in this stage is known as the

cathodic limiting current $i_{L,c}$ (for negative overpotentials) or anodic limiting current $i_{L,a}$ (for positive overpotentials) [11].

The electrode interface model of Fig. 4 neglected the equilibrium interfacial potential (E_{oc}) that exists across the interface at equilibrium. This is modeled as shown in Fig. 5 which illustrates an electrical circuit model of a three-electrode system, including the working electrode (WE), counter electrode (CE) and reference electrode (RE) immersed into an electrolyte. Also, the electrolytic solution resistance R_S (alternatively referred to as the Ohmic resistance R_Ω) that exists between two electrodes in an electrolyte is modeled in Fig. 5. The electrolyte resistance between the working electrode interface and the reference electrode interface is called the uncorrected (uncompensated) electrolyte resistance R_U and must be minimized as much as possible to decrease the error in measurement circuit. R_{COR} is the corrected electrolyte resistance. The Faradaic impedance $Z_{faradaic}$ in Fig. 5 is equivalent to the series combination of charge-transfer Faradaic resistance R_f and Warburg impedance Z_W shown in Fig. 4 [11].
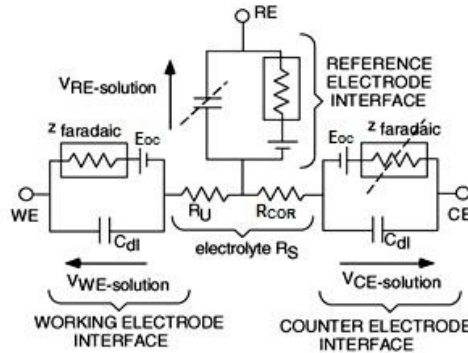

Figure 5. Electrical circuit model of a three-electrode/electrolyte interface system [11]

An ideal reference electrode has a Faradaic reaction with very fast kinetics, which appears in the electrical model as a very low resistance for the Faradaic impedance $Z_{faradaic}$. In this case, no significant overpotential occurs at the reference electrode during current flow, and the interfacial potential $V_{RE-solution}$ is considered constant even upon current flow [11].

V.   CATHODIC PROTECTION PRINCIPLE

Since corrosion is the loss of positive metal ions from the metal surface, thereby if a positive current is applied to flow to all parts of the surface from an external source, the corrosion can't occur. This is the principle of CP. Figure 6 illustrates the CP principle for a buried pipeline, with the electrons supplied to the pipeline by using a DC source and an ancillary anode. When enough current is applied, the whole metal will be at one potential and anode and cathode sites won't exist, thus corrosion cell

disappears and corrosion can't occur [3, 6]. As in Fig. 6, the applied protection current (I_2) enters the pipe at the cathode first, assuming equal resistance paths. From the equivalent circuit of a corroding cell shown in Fig. 6 [1]:

$$I_1 = \frac{E_A - (E_C + R_C I_2)}{R_A + R_C} \qquad (9)$$

where: I_1 is the current from anodic area and I_2 is the applied protection current from external anode.
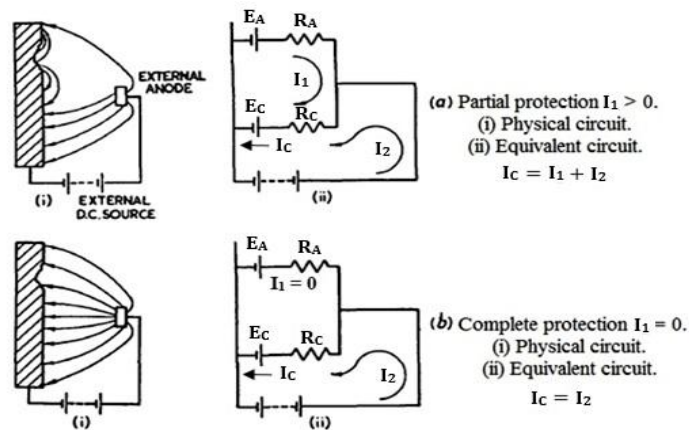

Figure 6. Equivalent circuits of cathodically protected metal [1]

For corrosion to cease I_1 must be zero, therefore $(E_C + R_C I_2) = E_A$. This means that sufficient current must flow through R_c for the total voltage drop at the cathode to equal the open-circuit potential of the anode [1].

A. ***Cathodic Protection Systems***
1. ***Sacrificial anode (Galvanic) system***
In sacrificial anode systems, CP is applied by connecting sacrificial anodes to a structure (Fig. 7). Basically, the principle is to create a galvanic cell, with the anode representing the less noble material that is consumed in the galvanic interaction. The structure will be protected as a result of the galvanic current flow from the anode to structure through the soil [6].
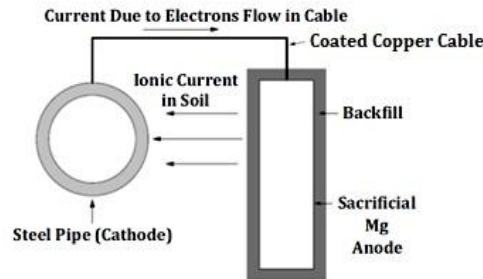
Figure 7. Schematic diagram of CP with sacrificial anode system [6]

The most commonly used materials for sacrificial anodes are zinc, magnesium and aluminium. They are either relatively pure active metals or alloys. The anode material must provide a certain driving voltage to generate sufficient current to adequately protect a structure [12]. To provide a uniform environment around the anode in soil, maintain moisture, and lower the resistance of anode-to-earth, a special chemical backfill is used [13]. Sacrificial anode systems are generally used in cases where relatively small amounts of current are required (typically less than 1A) and areas where soil resistivity is low enough (typically less than 10,000 ohm-cm) to permit obtaining the desired current with a reasonable number of anodes [14].

2.   *Impressed current (rectifier-type) system*
In impressed current systems, CP is applied by means of an external DC power source as shown in Fig. 8. The external source causes a positive current flow in the electrolyte (soil) from the anode to the protected structure, which is thereby rendered cathodic. In contrast to the sacrificial anode systems, the anode consumption rate is usually much lower and the impressed current anode potential is more electropositive than structure potential. In practice, materials such as graphite, high silicon cast iron, magnetite, platinum or and newly developed mixed metal oxide, are used as impressed current anodes. For buried anodes, a special backfill consisting of carbonaceous material is normally used to decrease the electrical resistance of the anode, to provide a uniform and low resistivity environment surrounding the anode and to allow for the venting of gasses and acids produced at the anode surface. Impressed current systems typically are favored under high-current requirements and/or high-resistance electrolytes [4, 6, 12].
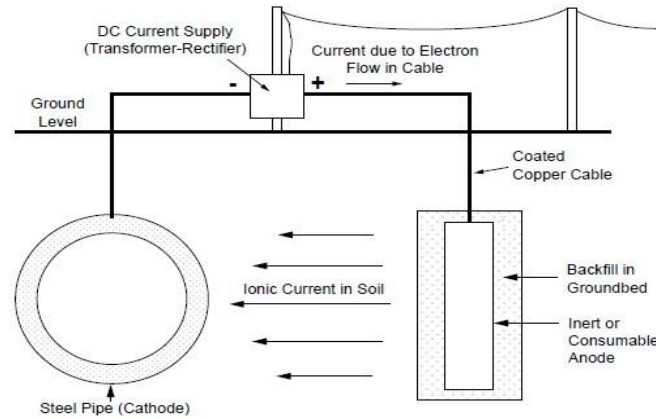
Figure 8. Schematic diagram of CP with impressed current system [6]

The external voltage source required depends upon the CP current required (I_{cp}) and the total CP circuit resistance (R_{cp}). Since the impressed current anodes have corrosion potentials more positive than steel structures, so it is necessary to use an additional e.m.f. of 2 volts to overcome the contact potential difference which exists between the impressed current anodes and steel [1]. According to [4], the required supply voltage (E_o) for impressed current system is given by the following equation:

$$E_o = I_{cp}R_{cp} + E_b \qquad (10)$$

where: E_b is the back voltage (additional e.m.f. of 2 volts).

B.   Electrical Circuits of Cathodic Protection Systems

The CP circuit for a sacrificial anode system (Fig. 7) and an impressed current system (Fig. 8) can be illustrated by the electrical schematic in Fig. 9 and Fig. 10 respectively [4].

From Fig. 9 and Fig.10, the total CP circuit resistance (R_{cp}) for a sacrificial anode system and an impressed current system can be calculated as in equations (11) and (12) respectively [4].

$$R_{cp} = R_{gb,re} + R_{s,re} + R_c \qquad (11)$$

$$R_{cp} = R_{gb,re} + R_{s,re} + R_{c,a} + R_{c,s} \qquad (12)$$

The anode resistance to remote earth ($R_{a,re}$ or $R_{gb,re}$) can be obtained through direct equations by knowing the soil resistivity, and the orientation; horizontally or vertically, depth, diameter, length, number and spacing of the anodes [4, 12, 14]. In these equations, it is assumed that the soil resistivity is uniform and the outside dimensions of the packaged anode are be used in the calculation rather than the actual casting dimensions without introducing appreciable error. The structure resistance to remote earth ($R_{s,re}$) is dependent primarily on the condition of the coating. For

instance, For sizable bare pipelines, the pipe resistance to remote earth is usually small compared to $R_{gb,re}$ and could be neglected, but it must be taken into account if the pipeline is short and well coated [3]. The pipe resistance to remote earth can be obtained either by measurement or by direct relationship as in the case of the coated pipeline by knowing the specific coating resistance and the total surface area of pipe [4]. Cable resistance (R_c) is usually small value compared to the other components; $R_{s,re}$ and $R_{gb,re}$, as to be negligible from a practical standpoint. Cable resistance can be calculated by knowing the cable resistance per unit length and the cable length [12, 15].
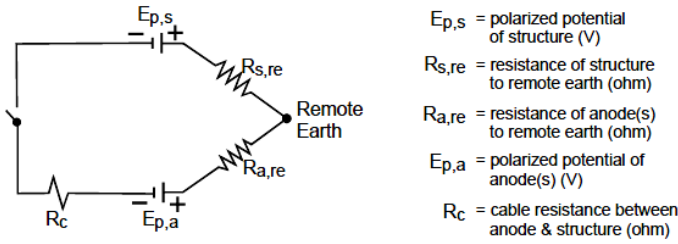

$E_{p,s}$ = polarized potential of structure (V)

$R_{s,re}$ = resistance of structure to remote earth (ohm)

$R_{a,re}$ = resistance of anode(s) to remote earth (ohm)

$E_{p,a}$ = polarized potential of anode(s) (V)

R_c = cable resistance between anode & structure (ohm)

Figure 9. Electrical schematic for an operating sacrificial anode CP system [4]

$R_{c,s}$ = resistance of negative cable from the structure

$E_{p,s}$ = polarized potential of structure (V)

$R_{s,re}$ = resistance of structure to remote earth (ohm)

$R_{gb,re}$ = resistance of groundbed to remote earth (ohm)

$E_{p,a}$ = polarized potential of the groundbed (V)

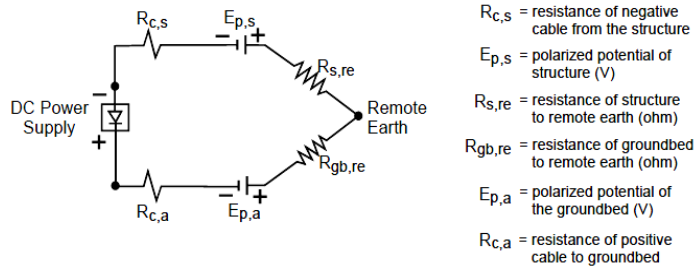$R_{c,a}$ = resistance of positive cable to groundbed

Figure 10. Electrical schematic for an operating impressed current CP system [4]

The main objective of this paper is preparation equivalent electrical models for CP systems, which can be used in simulation of such systems. The electrical modeling for the electrode-electrolyte interface by Randle's circuit model can enable us to develop the simulation models for CP circuits shown in Fig. 9 and Fig. 10. The study herein is based on that the activation (charge-transfer) polarization appears only at the electrode in the absence of concentration (mass-transfer) effects, i.e. Faradaic reaction is under kinetic control, therefore Randle's circuit model for electrode/electrolyte interface is composed of the resistance of electrode surface to electrolyte (R_e) in series with the parallel combination of the double-layer capacitance (C_{dl}) and the polarization resistance (R_p) as in Fig. 11.
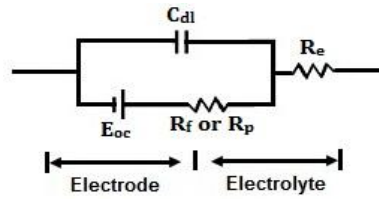
Figure 11. Schematic diagram for the electrical circuit model of electrode/electrolyte interface in the absence of mass-transfer effects

The resistance of electrode surface to electrolyte (R_e) depends on the conductivity of the electrolyte and the geometry of the electrode. R_e represents the structure resistance to remote earth ($R_{s,re}$) or the anode resistance to remote earth ($R_{gb,re}$) in CP circuits [4]. Double-layer capacitance (C_{dl}) represents the ability of an electrode to cause charge flow in the electrolyte without electron transfer. Its value depends on various factors such as electrode polarization, ionic concentrations, oxide layers, temperature, electrode roughness, etc. C_{dl} must be normalized because it is electrode area dependent. On a bare metal immersed in an electrolyte, 20-60µF of capacitance can be measured for every 1cm^2 of the electrode. For carbon based materials, the capacitance ranges anywhere from 30 to 200µF/cm^2 [16]. The value of C_{dl} is usually in the range of 10–100µF/cm^2 [17]. C_{dl} is inversely proportional to the charge-transfer resistance [5].

Polarization resistance (R_p) represents the electrode's resistance to corrosion. It is electrode area dependent and has the dimensions of specific resistance (Ω-cm^2) [10, 18]. The value of R_p is variable and depends on many variables including the electrode characteristics, temperature, reactants concentrations in the electrolyte solution, etc. The polarization resistance (R_p) of an electrode can be calculated by taking the inverse of the slope of the current potential curve near open-circuit potential in the linear region and this technique is called as the linear polarization resistance (LPR) method. The polarization resistance of an electrode can be defined by the LPR method as follows [6, 19]:

$$R_p = \left(\frac{\Delta E}{\Delta i}\right)_{\Delta E \to 0} \qquad (13)$$

where: ΔE is the variation of the electrode potential around the corrosion (open-circuit) potential (V) and Δi is the resulting (corresponding) polarization current (A/cm^2)

For small polarization η, the Butler-Volmer equation can be reduced to [6, 18, 20, 21]:

$$i_{corr} = B \cdot \left(\frac{\Delta i}{\Delta E}\right)_{\Delta E \to 0} \qquad (14)$$

where: i_{corr} is the corrosion current density (µA/cm^2), B is the empirical polarization resistance (Stern-Geary) constant (V), and $(\Delta i/\Delta E)_{\Delta E \to 0}$ represents the inverse of polarization resistance; equation (13).

Equation (14) is known as Stern-Geary equation or polarization resistance method which relates the polarization resistance of an electrode to the corrosion current density. Stern-Geary constant (B) is calculated from known Tafel slopes where both cathodic and anodic reactions are activation controlled as follows [6, 20, 21]:

$$B = \frac{b_a b_c}{2.303\,(b_a + b_c)} \qquad (15)$$

where: *ba* is the slope of the anodic Tafel reaction in V/decade and *bc* is the slope of the cathodic Tafel reaction in V/decade.

The Tafel slopes are measured from the experimental data where both cathodic and anodic reactions are activation controlled, that is, there are distinct linear regions near the corrosion (open-circuit) potential on an $E \log i$ plot. It is possible to estimate *ba* and *bc* from the deviation from linearity of polarization curves in the 20–50 mV region around the corrosion potential [20].

By rearranging equation (14), one obtains the following equation [20].

$$i_{corr} = \frac{b_a b_c}{2.303\,(b_a + b_c)} \left[\frac{1}{R_p}\right] = \frac{B}{R_p} \qquad (16)$$

This equation shows that the polarization resistance is inversely proportional to the corrosion current; *i.e.* a high polarization resistance value implies high corrosion resistance. The knowledge of R_p and Tafel constants enables direct determination of corrosion current at any instant in time using equation (16) and hence determination of corrosion rate [21]. Stern showed that the majority of reported Tafel constants values are between 0.06 and 0.12 V [22]. By substituting this range of values in equation (15), then Stern-Geary constant (B) will range from 13.03 to 26.05 mV, and therefore if the corrosion current for the underground steel pipeline is known, it is possible to know the range where the pipeline polarization resistance value be found, using equation (16).

Faraday's Law can be used to calculate the corrosion rate, either in terms of penetration rate (CR) or mass loss rate (MR) as follows [20]:

$$CR = K_1 \frac{i_{corr}}{d}\, EW \qquad (17)$$

$$MR = K_2 i_{corr}\, EW \qquad (18)$$

where: *CR* is given in mm/yr, *MR* is given in g/m^2 d, K_1 is constant = 3.27 x 10^{-3} mm g/µA cm yr, K_2 is constant = 8.954 x 10^{-3} g cm^2/µA m^2 d, i_{corr} is the corrosion current in µA/cm^2, *d* is the metal density in g/cm^3, and *EW* is the equivalent weight of metal, it is considered dimensionless in these calculations.

The calculation of penetration or mass loss from electrochemical measurements herein assumes that uniform corrosion is occurring. In cases where non-uniform corrosion processes are occurring, the use of these methods may result in a substantial underestimation of the true values [20]. By the knowledge of corrosion

rate for the underground steel piping, the corrosion current density ($\mu A/cm^2$) can be calculated using equations (17) or (18), and therefore it is possible to know the range where the pipeline polarization resistance value be found using equation (16). Accordingly, the impact of the polarization resistance values on applying the CP can be simulated. It is assumed that the soil along the pipeline is homogenous therefore uniform corrosion processes occur. This paper focuses on the corrosion of metals, with emphasis on corrosion of carbon and low-alloy steels used in underground pipelines.

VI. ESTIMATION OF CORROSION RATE FROM SOIL PROPERTIES

The accurate prediction of metal loss rates in soil isn't always easily determined because the external corrosion rate of metal is influenced by a significant number of soil and environmental parameters which makes it difficult to determine a realistic estimate. The estimation of corrosion rates from soil properties in this paper is based on: 1) historical data of corrosion-rate predictions based on soil parameters, (2) corrosion estimates based on the American Water Works Association (AWWA) guidelines, (3) utility measurements of corrosion-rates in various soils and (4) the National Institute of Standards and Technology (NIST) database of field corrosion-rate measurements in various soil types and conditions [23]. These studies can provide us the tables and maps through which the corrosion rates of undergrounded steel piping can be estimated from soil properties using a general description of the aggressiveness of the soil environment. For example, corrosion nomograph or King Method (Fig. 12) shows a relationship between corrosion rate of steel pipe and soil environment, described by pH and resistivity. Depending on whether the soil is acidic or alkaline, the corrosion rate corresponding to that combination of resistivity and pH is shown in either the axis above or below the chart. This method predicts negligible rates of corrosion for alkaline soils with moderate to high resistivity and very high rates of corrosion in acidic soils with low resistivity [24, 25]. Although the corrosion rate values are approximate, they can enable us to study the impact of soil properties on the pipe polarization resistance and therefore the impact on applying the CP.
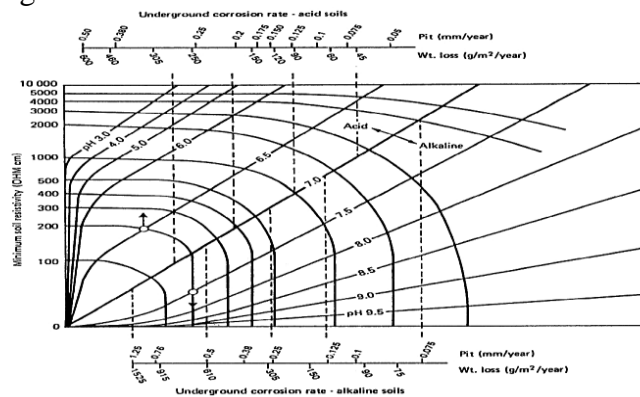

Figure 12. Nomogram for estimating the corrosion rate of steel pipe [26]

VII.   METHODOLOGY

The CP circuits of a galvanic system (Fig. 9) and an impressed current system (Fig. 10) can be represented in MATLAB/SIMULINK through the electrical modeling for the electrode-electrolyte interface by Randle's circuit model in the absence of mass-transfer effects as shown in Fig. 13 and Fig. 14 respectively. Randle's circuit herein illustrates single Faradaic resistance representing the electron transfer reaction. The simulation models shown in Fig. 13 and Fig. 14 can be used to validate the design procedures of CP systems by the knowledge of the polarization amount which can occur for the pipeline potential as a result of applying the CP. Also, through these models the impact of polarization resistance of underground steel piping on the application of CP can be simulated. These simulation models are applied to the bare metals; in case of coated metals Randle's circuit model varies and the values of polarization resistance and double-layer capacitance for metal depends mainly on the coating quality. These models don't match the practical reality fully, but significantly give approximated and useful end. The study herein assumes that the soil along the pipeline is homogenous.

The simulation model of a galvanic system (Fig. 13) consists of several elements which are the anode to be sacrificed, pipeline to be protected, reference electrode used in the measurement process and CP circuit resistance. The resistances $R_{U,a}$, $R_{U,p}$ and R_{COR} represent the ohmic resistance of the CP circuit (R_{cp}) shown in Fig. 9, composed of the cable resistance and the soil resistance (R_S) between the pipeline and the anode. The soil resistance (R_S) between pipeline and anode equals to sum of the pipeline resistance to remote earth ($R_{s,re}$) and the anode ground bed resistance to remote earth ($R_{gb,re}$). R_U is the uncompensated soil resistance located between the electrode (pipeline or anode) and reference electrode; $R_{U,p}$ for pipeline and $R_{U,a}$ for anode.

The simulation model of impressed current system (Fig. 14) is quite similar to the model of galvanic system (Fig. 13), but power source is employed in CP circuit and the open-circuit potential of impressed current anode is more electropositive than the open-circuit potential of pipe. In both simulation models, the polarization resistance of anode has insignificant value in chemical backfill, its value may vary mainly owing to the variation in the backfill characteristics and it can be measured by the LPR method (equation (13)). The reference electrode has a very low polarization resistance so that its potential remains constant. Double-layer capacitance values are selected in an average range of the values previously mentioned. The polarization resistance of pipeline can be accurately measured by the LPR method as with the anode polarization resistance or by any other advanced techniques, but in this paper it is determined approximately using equation (16), where the corrosion current will be determined approximately by knowledge of the corrosion rates estimated from soil properties using equation (18); as discussed previously, and Stern-Geary constant (B) ranges from 13.03 to 26.05 mV. Although the corrosion rate values are approximate, this method enables us to know the range where the polarization resistance value be found therefore know the range of polarization amount which can occur for the pipe potential as a result of applying the CP. Also this method can enables us to study the impact of soil properties on pipe polarization resistance and thereby the impact on

applying the CP.

After estimating the CP current required, selecting CP system type, knowing type and number of anodes used and selecting anode bed type, the total CP circuit resistance can be calculated. And thereafter the values of Randle's circuit elements for pipeline, anode and reference electrode will be determined as indicated above. Then all these values are simulated by the simulation models of CP systems, shown in Fig. 13 and Fig. 14. The simulation model of sacrificial anode system in this paper is used to simulate a sacrificial anode system to protect underground steel pipeline; soil resistivity 3,500 Ω-cm and pH = 6.5, by using high potential magnesium anode. While the simulation model of impressed current system is used to simulate an impressed current system to protect underground steel pipeline; soil resistivity 3,000 Ω-cm and pH near to neutral, by using Mixed Metal Oxide (MMO) anode type. It is assumed that the soil along the pipeline is a homogeneous and the chemical components in soil such as sulfate and chloride ions have small values.
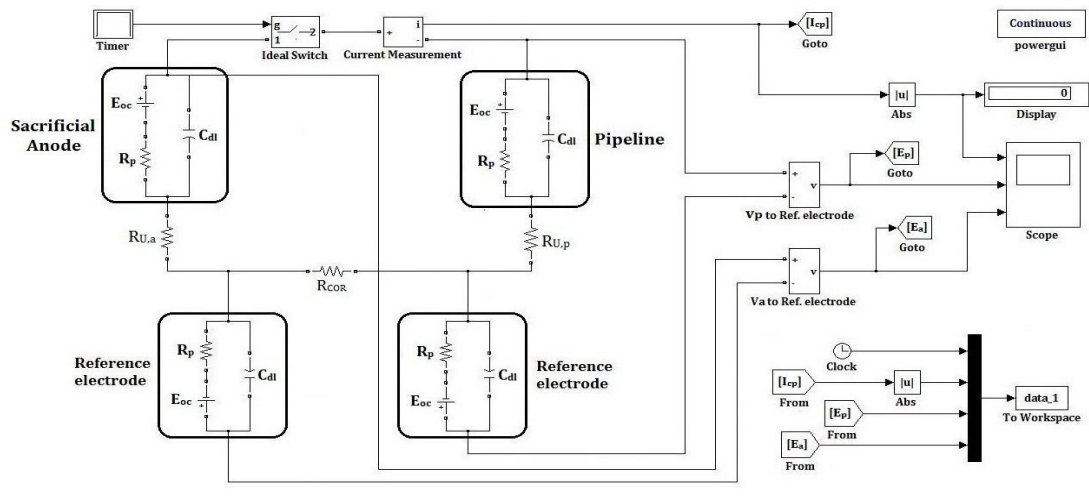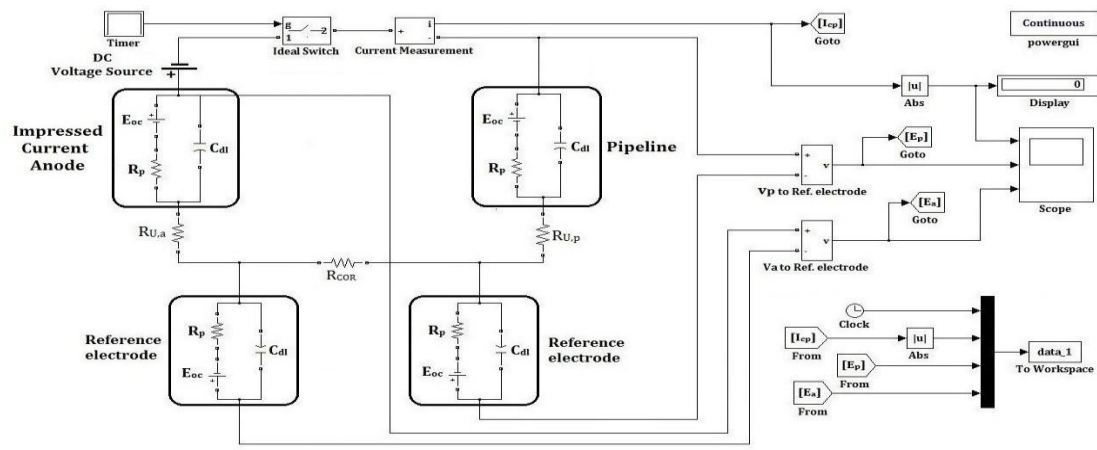

Figure 13. Simulation model of a galvanic CP system

Figure 14. Simulation model of an impressed current CP system

VIII.   RESULTS AND DISCUSSION

For the sacrificial anode system, the surface area of pipeline to be protected is $3.28m^2$ and two anodes (distributed vertically) of a high potential magnesium anode type (#17D3) are used. By LPR method, the magnesium anode polarization resistance is approximately $0.3356\Omega\text{-}m^2$. By using Fig. 12 (at soil resistivity 3,500 Ω-cm and pH = 6.5), equations (18) and (16), the polarization resistance of steel pipeline will range from 1.981 to $3.962\Omega\text{-}m^2$; where Stern-Geary constant (B) ranges from 13.03 to 26.05 mV. Anode surface area used in the simulation process is the anode area without the galvanic backfill. The resistances values $R_{U,a}$ and $R_{U,p}$ are selected small values to reduce the IR drop. In the simulation process, the native (open-circuit) potential of the steel pipe and the high potential magnesium anode are selected $-0.6V_{CSE}$ and $-1.75V_{CSE}$ respectively. The all input simulation data are shown in Table (I). Figure 15 shows the simulation results at the polarization resistance of pipeline and magnesium anode are 1.981 Ω-cm^2 and 0.3356 Ω-cm^2 respectively.

TABLE I. INPUT SIMULATION DATA

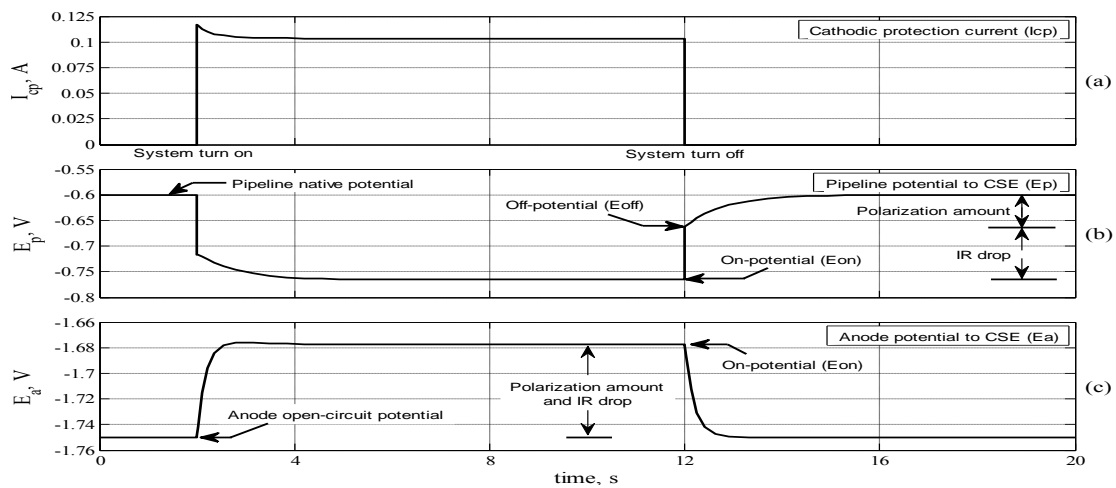|	**Steel pipeline to be protected**	**Two magnesium anodes**	**Copper sulfate reference electrode (CSE)**
Surface area (m^2)	3.28	0.484	1×10^{-4}
E$_{oc}$ w.r.to CSE (V)	-0.6	-1.75	$\square$
Rp (Ω)	0.604 to 1.208	0.6934	Very low
C$_{dl}$ (F)	1.312	0.2804	20×10^{-6}
R$_{cp}$ (Ω)	**R$_{U,a}$ (Ω)**	**R$_{U,p}$ (Ω)**	**R$_{COR}$ (Ω)**
	0.01	1	8.84

Figure 15. Simulation Results for R$_p$ (pipe) =1.981 Ω-m^2 and R$_p$ (anode) =0.3356 Ω-m^2

As shown in Fig. 15, once the CP system energized both the pipeline and anode potentials move away from their equilibrium values where the pipe potential is depressed in the negative direction and anode potential increases in positive direction. When the CP current is interrupted after the pipe takes sufficient time to polarize, the momentary interruption of current theoretically produces a reading free from undesirable IR drop effects and the pipe potential will then exhibit an exponential decay with time in the positive direction. This exponential decay in pipe potential represents the cathodic depolarization of the pipeline. The polarization amount that occurs due to applying the CP is the difference in potential between the native potential (E_{oc}) and the polarized potential (off-potential) of the pipe. As in Fig. 15, the polarization amount that has occurred for the pipe due to applying the CP in this case is approximately 62 mV in the negative direction.

If the pipe polarization resistance increased or the magnesium anode polarization resistance decreased, the polarization amount that can occur for the pipeline as a result of applying the CP will increase and vice versa. The pipe polarization resistance varies mainly with the soil properties (the pipe polarization resistance increases in Non-corrosive soil and vice versa) and the coating (the polarization resistance of coated pipeline will increase as compared to bare pipeline and its value may vary, mainly owing to coating quality). The anode polarization resistance varies for backfill properties. In corrosive soil, the corrosion current flowing from the metal to soil increases because of the low of metal polarization resistance, consequently to achieve the adequate CP, it must increase the CP current in order to stop or decrease the corrosion current. The CP current can be increased by reducing the CP circuit resistance through placing the anode in low soil resistance, adding additional anodes, using longer anodes, increasing the spacing of the anodes, and/or by increasing external voltage source as with the impressed current system. Most of these cases and other have been successfully simulated by simulation models of CP systems.

For the impressed current system, the same methodology is followed.

IX.   CONCLUSION

The main objective of the paper is studying the CP systems of underground steel pipelines to develop equivalent electrical models, which can be used in simulation of such systems. The simulation models for CP systems are developed in this paper through the electrical modeling for the electrode-electrolyte interface by Randle's circuit model in the absence of mass-transfer effects. Using these models the impact of soil properties on the application of CP systems can be simulated. Practically, because of the heterogeneity of soil and the complexity of the geometry of most buried structures which make the accurate analysis is impossible, the technique of applying CP is, and will probably remain, a field in which long experience is necessary to achieve the optimum results.

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