Cairo University

EXTERNAL CORROSION CONTROL OF THE UNDERGROUND STEEL PIPELINES USING CATHODIC PROTECTION SYSTEMS

By

Eng. MOHAMED SALAMA EL-SAYED HAMMAD

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
in
Electrical Power and Machines Engineering

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Title of Thesis:

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

Key Words:

Corrosion, Cathodic Protection, Sacrificial Anode, Impressed Current, Polarization Resistance.

Summary:

The thesis discusses the cathodic protection technique used for corrosion mitigation of underground steel piping. Since corrosion and cathodic protection are electrochemical processes involving electrical current and an exchange of charged ions, electrical models can be developed. The main objective of the thesis is study of the cathodic protection systems of underground steel piping to develop equivalent electrical models, which can be used in simulation of such systems. These equivalent models can be prepared through the electrical modeling for the electrode/electrolyte interface by Randle's circuit model. The study herein is based on that the activation (charge-transfer) polarization appears only at the electrode; i.e. in the absence of concentration (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 can enable us to validate the design procedures of cathodic protection systems by the knowledge of the polarization amount which can occur for the pipeline potential as a result of applying the cathodic protection. Also through these models, the impact of pipeline polarization resistance on applying the cathodic protection can be simulated. Simulation and results examining are performed by using MATLAB/SIMULINK program and the study assumes that the soil along the pipeline is homogenous.

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LIST OF SYMBOLS AND ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
A_s	Total structure surface area, (m^2)
A_x	Cross-sectional area of the pipe, (m^2)
AW	Atomic weight of the element
AWWA	American Water Works Association guidelines
A-y	Ampere per year
B	Empirical polarization resistance (Stern-Geary) constant, (V)
b	Tafel slope or Tafel coefficient, (V/decade)
C	Center-to-center spacing of anodes (anode spacing), (cm)
C_a	Theoretical capacity of the anode material, (A-y/Kg)
C_{cp}	Cathodic protection system electrochemical capacity, (A-y)
C_{dl}	Double-layer capacitor of an electrode in a corrosion cell, ($\mu F/cm^2$)
$C_{o,bulk}$	Concentration of species O in bulk solution, (mol/cm^3)
CR	Penetration corrosion rate, (mm/yr)
C_r	Theoretical consumption rate of the anode material, (Kg/A-y)
CSE	Copper-copper sulfate reference electrode ($Cu^{2+}/CuSO_4$ (Saturated))
D	Density of the element, g/cm^3
D_o	Diffusion coefficient of species O, ($cm^2\ s^{-1}$)
D	Pipe diameter or anode diameter, (cm)
E *or* E_{oc}	Equilibrium interfacial (Open-circuit) potential of an electrode, (V)
E_A *or* $E_{a,oc}$	Open-circuit potential of the anode, (V)
$E_{a,corr}$ ($E_{a,oc}$)	Corrosion (open-circuit) potential of the anode, (V)
$E_{a,p}$	Polarized (closed-circuit) potential of the anode, (V)
$E_{a,re}$	Anode potential to remote earth, (V)
E_b	Back voltage to overcome the potential difference between the structure & impressed current anode, (V)
E_C *or* $E_{c,oc}$	Open-circuit potential of the cathode, (V)
$E_{c,p}$	Polarized (closed-circuit) potential of the cathode, (V)
$E_{cp,gav}$	Operating driving (design) voltage for the sacrificial anode system, (V)
$E_{cp,imp}$ ($E_{T/R}$)	Required power supply voltage for the impressed current system, (V)
E_f	Electrochemical efficiency of the anode (%)
E_g	Galvanic voltage between the structure & impressed current anode, (V)
EIS	Electrochemical Impedance Spectroscopy method
E_{off}	Off-potential or polarized potential of the structure, (V)
E_{on}	On-potential of the structure, (V)
$E_{s,corr}$ ($E_{s,oc}$)	Corrosion (open-circuit or native) potential of the structure, (V)
$E_{s,crit}$	Chosen cathodic protection criterion for the structure, (V)
$E_{s,p}$	Polarized (closed-circuit) potential of the structure, (V)
$E_{s,re}$	Structure potential to remote earth, (V)

EW	Equivalent Weight (dimensionless)
F	Faraday's constant (96,485 coulombs/mol of electrons)
F_C	Crowding factor of the anode ground beds (multi-anodes) in soil
f_c	Coating breakdown factor
FHWA	Federal Highway Administration
$g/m^2.d$	Gram per square meter in day
g'	Specific leakage coating conductance, (Siemens/m^2)
I	Corrosion (exchange) current in corrosion cell, (A)
I_a	Output current per anode, (A)
$I_{a\text{-}Max}$	Maximum current supplied by the anode, (A) – From anode datasheet
$I_{a\text{-}Rated}$	Rated current supplied by the anode, (A) – From anode datasheet
i_c	Required current density to achieve a proper cathodic protection, (A/m^2)
I_{cp}	Total cathodic protection current required, (A)
i_{corr}	Corrosion current density, (A/cm^2)
i_L	Limiting current density, (A/cm^2)
i_o	Exchange current density, (A/cm^2)
$i_{reaction}$	Anodic or cathodic current density, (mA/cm^2)
ID	Pipe inside diameter = pipe outside diameter (OD) – 2 (wall thickness)
J_o	Flux of species *O* from bulk solution to electrode surface, (mol s^{-1} cm^{-2})
K_1	Constant (3.27×10^{-3}, mm g/μA cm yr)
K_2	Constant (8.954×10^{-3}, g cm^2/μA m^2 d)
L	Pipe length or anode length, (cm)
L_F	Anticipated service life of the cathodic protection system, (year)
LPR	Linear Polarization Resistance method
Mil/year (mpy)	Milli-inch per year
MMO	Mixed Metal Oxide canistered anode
mm/yr	Millimeters per year
MR	Mass loss corrosion rate, (g/m^2 d)
N	Number of anodes
N	Number of participating electrons in corrosion cell reaction
NACE	National Association of Corrosion Engineers
NBS	National Bureau of Standards
NIST	National Institute of Standards and Technology
pH	Acidity or Alkalinity of an electrolyte
Pmm	Parts per million
R	Universal gas constant, (8.3145 J/mol °K)
R_A	Effective anode resistance to electrolyte, (Ω)
$R_{a,re}$	Resistance of the single anode to remote earth, (Ω)
R_C	Effective cathode resistance to electrolyte, (Ω)
R_{ca}	Cable resistance, (Ω)
$R_{ca,a}$	Positive cable resistance from the transformer rectifier to the anode ground beds (multi-anodes) in the impressed current system, (Ω)
$R_{ca,g}$	Cable resistance from the anode ground beds (multi-anodes) to the structure in the sacrificial anode system, (Ω)