Examples of Design for Cathodic Protection Systems

CURRENT REQUIREMENTS

From Estimated Exposed Surface Area

Estimating current requirements from expected exposed surface is always subject to error. There are many factors, which affect the results.

Consider:

- Total surface area in contact with soil or other electrolyte.
- Dielectric properties of any protective coating.
- Factors which may damage a protective coating during installation.
- Expected protective coating life under service conditions.
- Expected percentage coverage by protective coating.
- Past experience with coating applicators and construction contractors.
- Current density required for cathodic protection of the metal(s) in the environment.

In the end, the expected current requirement depends on calculating the area of exposed metal in contact with the electrolyte and multiplying it by the "best estimate" of current density for the conditions present.

There is an alternate approach for coated electrically isolated structures (pipes, underground storage tanks, etc.) where there is data available on existing cathodic protection systems.

The approach requires reliable local data on:

- Expected leakage conductance (Siemens/unit area) in 1000 ohm cm. soil for a class of coating (epoxy, polyethylene tape, etc.) and type of service (transmission pipeline, gas distribution, fuel tank).

- Soil resistivity in the service area.
- Structure to soil potential shift required to produce polarization needed to meet cathodic protection criteria. This is the immediate change in potential of an isolated structure measured to a point at "remote earth" when cathodic protection is applied. The value is not a criteria for protection. However, under a given set of operating and exposure conditions, a potential shift will provide a good estimate of current needed to meet accepted criteria.

The approach is best understood by using an example.

Example 5.1

A gas utility is planning to install 3049 meters (10,000 feet) of 5.1 cm (2 inch) coated steel distribution mains in a new development. The average soil resistivity in the area is 5,000 ohm cm. The corrosion engineer wishes to estimate the approximate current required to cathodically protect the pipes.

Experience in the utility has developed the following data on cathodic protection current requirements:

Average leakage conductance G for distribution type service is 2.14×10^{-3} S/m^2 in 1000 ohm cm soil.

Average potential shift measured to "remote earth" to achieve protection is -0.250 volt.

Calculations:

Total surface area of the proposed pipe.

$A_s = \pi d L = (5.1 \times 3.1416/100) \times 3049 = 488$ sq. meters

Estimated leakage conductance of new pipe in 1000 ohm cm soil.

$g = G \times A = 2.14 \times 10^{-3} \times 488 = 1.04$ Siemens

Since resistance = 1/conductance

Resistance to remote earth = 1/1.04 = 0.96 ohm

Estimated resistance to remote earth in 5000 ohm cm soil. (Resistance is directly proportional to resistivity).

$0.96 \times 5 = 4.8$ ohms

Estimated current to shift pipe potential to remote earth -0.250 volt. From Ohm's Law ($I = E/R$)

$0.250/4.8 = 0.052$ A.

Table 5.1 Typical Pipe to Earth Leakage Conductance for Dielectric Protective Coatings in 1000 ohm cm Soil

	AVERAGE COATING CONDUCTANCE	
Quality of Work	Siemans/ft^2	Siemans/m^2
Long Pipelines with Few Fittings		
Excellent	$<1 \times 10^{-5}$	$<1 \times 10^{-4}$
Good	1×10^{-5} to 5×10^{-5}	1×10^{-4} to 5×10^{-4}
Fair	5×10^{-5} to 1×10^{-4}	5×10^{-4} to 1×10^{-3}
Poor	$>1 \times 10^{-4}$	$>1 \times 10^{-3}$
Bare pipe (2″ to 12″) (5 cm to 30 cm)	4×10^{-3} to 2×10^{-2}	4×10^{-2} to 2×10^{-1}
Gas or Water Distribution with Many Fittings		
Excellent	$<5 \times 10^{-5}$	$<5 \times 10^{-4}$
Good	5×10^{-5} to 1×10^{-4}	1×10^{-3} to 5×10^{-4}
Fair	1×10^{-4} to 5×10^{-4}	1×10^{-3} to 5×10^{-3}
Poor	$>5 \times 10^{-4}$	$>5 \times 10^{-3}$
Bare pipe (2″ to 12″) (5 cm to 30 cm)	4×10^{-3} to 2×10^{-2}	4×10^{-2} to 2×10^{-1}

Table 5.1 lists ranges of coating conductance for piping in various classes of service in 1000 ohm cm soil.

From Field Tests

Field testing provides the most reliable way to estimate current requirements on an existing structure. If the structure is electrically isolated and provided with a dielectric protective coating (buried pipes and underground storage tanks), it should be possible to determine current requirements directly. A temporary anode (groundbed) is constructed and a portable power source (battery, generator or rectifier) is connected between the structure and the anode. If possible, the test anode should be located at or near a site suitable for the permanent installation. Tests similar to those described in Chapter 2 can then be made.

Example 5.2

An airport fuel distribution piping system is to be placed under cathodic protection. The piping is coated, and includes about 1524 meters (5000 feet) of 20.3 cm (8 inch) and smaller pipe. It extends from a tank farm in one corner of the airport to fuel hydrants at

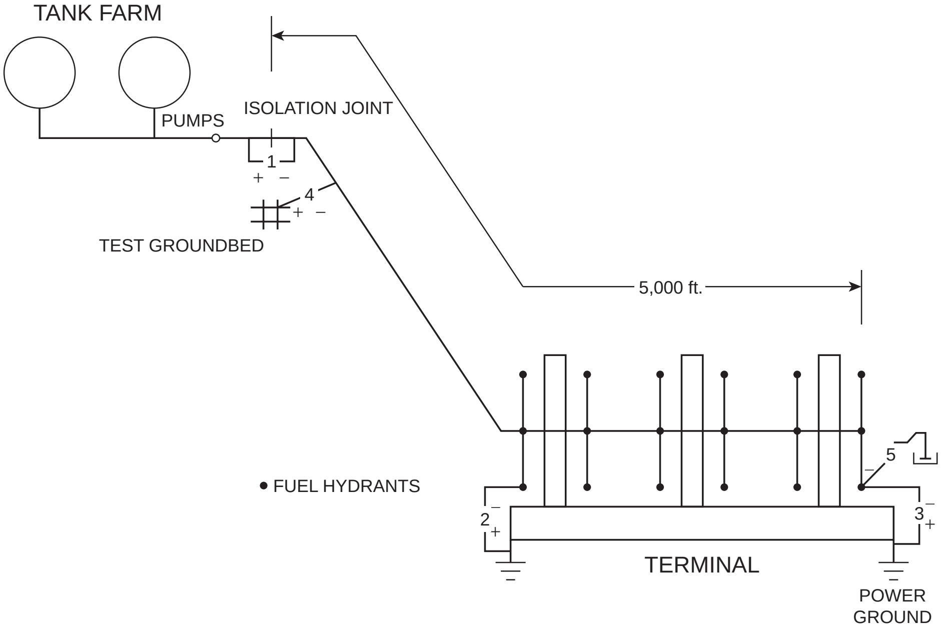


Figure 5.1 *Source*: NACE Cathodic Protection Level 3 Training Course Manual, © NACE International, 2000.

the terminal complex. All connections to other structures including fuel tanks, pumps and grounded structures have been electrically isolated. Fueling hydrants are not isolated from the pipe and have a driven ground rod attached to them. Because most of the pipe is under a concrete apron, the only practical location for the cathodic protection anode is at the supply end, near the tank farm. Soil resistivity averages 4000 ohm cm. How might the corrosion engineer determine the current required to protect this fueling system?

Step 1. Verify electrical isolation and electrical continuity of the piping

- Identify points where electrical contact can be made to the piping (fueling hydrants, line valves, above grade manifolds etc.). Prepare a sketch of the system. See Figure 5.1.
- Measure piping to earth resistance. In this case, the electrical resistance across the dielectric isolation joint at the tank farm would approximate the pipe to remote earth resistance. Using two attachments on each side of the isolation joint (Terminal 1 of Figure 5.1), the resistance $R_{1,1}$ was measured at 0.80 ohm. The total surface area of the piping is approximately 1000 m^2 (10,500 square feet). The resistance, 0.80 ohms, is equal to a conductance of 1.25 Siemens. The average conductance per unit area of coating (in 4000 ohm cm soil) is:

$$1.25/1000 = 1.25 \times 10^{-3}\ \mathrm{S/m^2}\ (1.2 \times 10^{-4}\ \mathrm{S/ft^2})$$

or

$$1.25 \times 10^{-3} \times 4 = 5 \times 10^{-3}\ \mathrm{S/m^2}\ \text{in 1000 ohm cm soil}$$

From Table 5.1, this equates to fair quality coating on distribution type piping with many fittings. Considering that the fuel hydrants have ground rods attached, there is nothing to suggest an electrical contact to a major grounded structure.

- Confirm isolation and continuity of the piping. Apply current at terminal 1 (Figure 5.1) and measure voltage change between piping and electrical power grounds in the terminal area. Electrical coupling values are 0.75 volt/A and 0.70 volt/A for $R_{2,1}$ and $R_{3,1}$ respectively. See Chapter 1—Network Analysis for an explanation of electrical couplings.

  If the piping were short circuited to a grounded structure, the pipe to earth resistance would normally be considerably less than 0.1 ohm. If the pipe contained an unknown isolation joint between the tank farm and the terminal, $R_{2,1}$ and $R_{3,1}$ would be greatly less than $R_{1,1}$.

Step 2. Determine current required to protect piping

- Drive steel rods into the ground at the tank farm to form a test groundbed (Terminal 4, Figure 5.1).
- If a potential shift of −0.300 volt between the pipe and earth is commonly required to polarize coated steel pipes in the region, and the electrical coupling value is 0.70 volt/A, then the estimated current needed to protect the piping at terminal 3 would be (from Ohm's Law):

$$I = 0.300/0.7 = 0.429\ \mathrm{A}$$

- Measure the pipe to soil potential at the fuel hydrant using a copper/copper sulfate reference electrode placed next to the hydrant. If possible locate the reference cell in the hydrant pit in contact with native soil.
- Apply 0.450 ampere at the test groundbed and monitor the potential to the reference at terminal 5. After about 15 minutes interrupt the current flow and check for polarization. If no polarization is present, increase the current and repeat the test.

ANODE RESISTANCE-TO-EARTH

General

The calculation of the electrical resistance of anode systems to remote earth is generally performed using mathematical formulas developed by Dwight (H.B. Dwight,

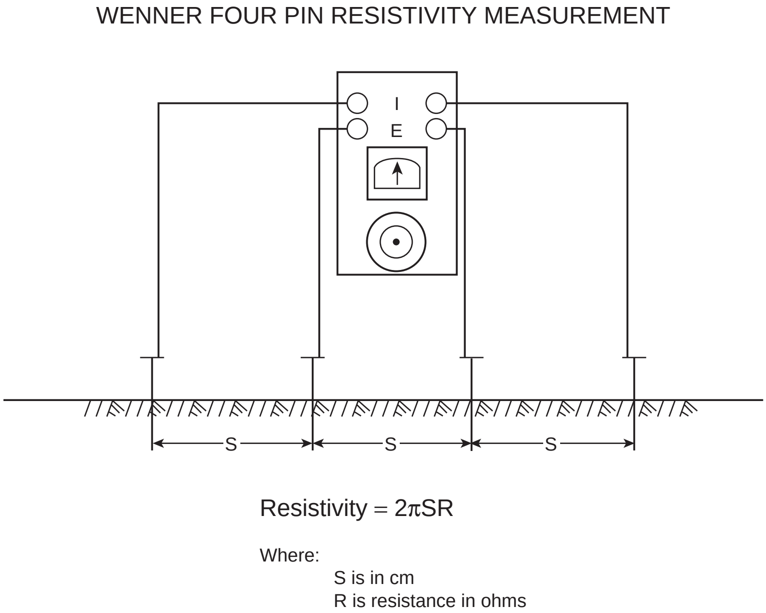


Figure 5.2 *Source*: NACE Cathodic Protection Level 3 Training Course Manual, © NACE International, 2000.

"Calculation of Resistance to Ground", *Elec. Eng.*, **55**, 1319–1328, December 1936). Manufacturers of anodes often provide tables or graphs specific to the size and shape of their anodes. In any case, the average resistivity of the soil (or other electrolyte) will be needed to make the calculation. The resistivity value used must be representative of the volume resistivity affecting the anode. The best way obtain the resistivity is to use the Wenner four pin method (ASTM G57-78).

Four equally spaced metal pins are driven into the soil in a straight line. The current source of the instrument is attached to the outer pins and the voltage measurement terminals are connected to the two inner pins. The arrangement is shown in Figure 5.2.

The resistance (ohms) is read directly from the instrument. The resistivity of the soil is calculated by the expression:

$$\rho = 6.28\ SR$$

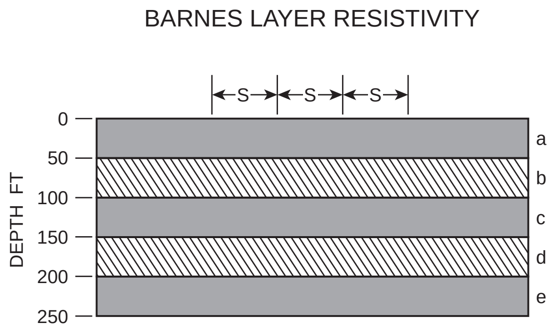
where ρ = resistivity (ohm-cm)

S = spacing between pins (cm)

R = resistance measured (ohms)

If the spacing (S) is measured in feet, the expression becomes

$$\rho = 191.5\ SR$$



Pin Spacing (S) Feet	Resistance (H) Ohms	Conductance (1/R) Siemens
50	0.50	2.00
100	0.40	2.50
150	0.35	2.56
200	0.20	5.00
250	0.10	10.00

Measured

Layer	Layer Conductance Siemens	Layer Resistance Ohms	Layer * Resistivity Ohm-cm
a	2.0 – 0 = 2.0	0.5	4,788
b	2.5 – 2.0 = 0.5	2.0	18,151
c	2.88 – 2.5 = 0.36	2.8	26,510
d	5.0 – 2.86 = 2.14	0.47	4,500
e	10 – 5 = 5.0	0.2	1,913

Calculated

*Resistivity = 101.5 × Layer thickness × Layer resistance

Figure 5.3 *Source*: NACE Cathodic Protection Level 3 Training Course Manual, © NACE International, 2000.

Instruments for measuring soil resistivity by this technique are widely available. Pin spacing should be selected such that the measurement reflects the mean volume resistivity for the extent of the anode bed. The pin spacing must be about the same as the linear dimension of the groundbed. This is particularly important where the resistivity varies greatly with depth.

For deep anodes (discussed below), resistivity must be estimated either from samples obtained by well drillers in the area or by the Barnes layer analysis technique. Consider the example, given in English units, shown in Figure 5.3. Represented is a profile of soil layers each 50 feet (15.2 meters) deep and having different average resistivities. Surface measurements of total resistance (R_T) using the Wenner four pin method at pin spacings of 50, 100, 150, 200 and 250 feet (15.2, 30.4, 45.6, 60.8 and 76 meters) yield the resistance values shown. The first reading is the resistance "seen" by the instrument as the average for a soil layer 50 feet deep. The second reading is the resistance measured in the first layer paralleled by the resistance "seen" in the next layer from 50 feet to 100 feet. Increasing the pin spacing another 50 feet adds a third layer in parallel with the first two. The procedure can be continued as long as the instrument has the sensitivity to resolve the small differences in measured total resistance. The equation which allows us to calculate resistances in parallel is:

$$1/R_T = 1/R_1 + 1/R_2 + 1/R_3 + \cdots + 1/R_n$$

or in the form of conductance

$$G_T = G_1 + G_2 + G_3 + \cdots + G_n \text{ Siemens}$$

To calculate the average resistance of any layer (n), subtract the conductance ($1/R_T$) measured at the pin spacing representing all the soil on top of the layer of interest from the conductance that contains the layer of interest. In the example shown in Figure 5.3, the resistance of the layer between 200 ft and 250 ft can be calculated as follows:

$$1/R_e = 1/R_{T250} - 1/R_{T200}$$

$$1/R_e = 1/0.1 - 1/0.2 = 5 \text{ Siemens}$$

$$R_e = 0.2 \text{ ohm}$$

Since the layer between 200 and 250 feet is 50 ft thick, the resistivity of the layer can be calculated from the formula:

$$\rho = 191.5\, SR$$

$$\rho = 191.5 \times 50 \times 0.2 = 1{,}915 \text{ ohm-cm}$$

Care needs to be exercised with respect to test methods, instrumentation and subsurface geology when measuring resistivities to depths greater than approximately 15 meters (50 feet).

Conventional Groundbed

Most conventional groundbeds consist of either a straight horizontal bed similar to a length of pipe or a row of short vertical anodes in a straight line. The resistance of a horizontal bed can be approximated using Dwight's formula for a horizontal rod (or pipe) in earth.

$$R = (0.005\rho/\pi L)[\ln(4L/d) + \ln(L/h) - 2 + (2h/L)]$$

where ρ = average soil resistivity (ohm-cm)

L = length of groundbed (meters)

d = diameter of groundbed (m)

h = depth to center of groundbed (m)

Example 5.3

Estimate the resistance of a horizontal groundbed 30.5 cm (12 inches) in diameter by 15.2 meters (50 feet) long in soil averaging 4,000 ohm-cm in resistivity. Assume the depth of the groundbed to be 1.2 meters (4 feet).

From Dwight's equation for a horizontal rod:

$$R = [0.005 \times 4000/(15.2\pi)] \times [\ln(400 \times 15.2/30.5) + \ln(15.2/1.2) - 2 + (2 \times 1.2/15.2)]$$

$$R = (0.419)[5.3 + 2.54 - 2 + 0.16]$$

$$R = 2.51 \text{ ohms}$$

If the groundbed consists of a group of short vertical anodes in a row, the Sunde equation provides a good approximation of the resistance to remote earth.

$$R_N = (0.005\rho/\pi \; NL)[\ln(8L/d) - 1 + (2L/S)\ln(0.656N)]$$

where R_N = groundbed resistance (ohm)
ρ = average soil resistivity (ohm-cm)
N = number of anodes in parallel
L = length of an anode (m)
d = anode diameter (m)
S = spacing of anodes in groundbed (m)

Example 5.4

Estimate the resistance of a groundbed 15.2 meters (50 feet) long in 4,000 ohm-cm soil when it consists of 6 each, 0.305 m (12 inch) diameter vertical anodes on 3.05 meter (10 ft) centers. The anodes are 1.52 meters (5 feet) long and have a nominal 0.46 meter (18 inches) of cover. (Note that the Sunde formula does not consider the depth of the anode below grade.)

$$R_N = [(0.005/(6 \times \pi \times 1.52)](4000)[\ln(12.2/.305) - 1 + (2 \times 1.52)/3.05 \times \ln(3.9)]$$

$$R = (0.698)[\ln 40 - 1 + 1.36]$$

$$R = 2.83 \text{ ohms}$$

Deep Anode

Dwight's equation for a single vertical rod or pipe to remote earth is:

$$R = (0.005\rho/\pi L)[\ln(8L/d) - 1]$$

where ρ = resistivity (ohm-cm)
L = length of anode (meters)
d = diameter of anode (m)

In this equation, the length of the rod extends down from grade a length L meters. In practice, L represents the length of active anode in a deep anode system. The top of the active anode section may be some distance below the surface. For practical estimation of anode to remote earth resistance, ignoring the effect of the layer between the top of the active anode and grade does not appear to produce significant error.

Example 5.5

Assume the Barnes layer resistivities shown in Figure 5.3. Estimate the resistance of a deep anode 20.3 cm (8 inches) in diameter to remote earth if the active section will be located between 45.7 and 76.2 meters (150 and 250 feet) below grade.

Solution

Calculate the average soil resistivity in the zone where the active anode element will be located (layers d and e)

Conductance of d + e = 5.0 + 2.14 = 7.14 S

Resistance of layers = (1/7.14) = 0.14 ohm

$\rho = 0.14 \times 6.28 \times 3048 = 2{,}680$ ohm-cm

Note that 3048 cm (100 ft) in the above equation is the total thickness of layers d and e. Using Dwight's equation for a vertical rod

$$R = (0.005\rho/\pi L)[\ln(8L/d) - 1]$$

where ρ = average soil resistivity (2,680 ohm-cm)

L = active length of anode (30.48 meters)

d = anode diameter (0.20 meters)

$$R = (0.140)(7.09 - 1) = 0.853 \text{ ohm}$$

Distributed Anodes

Distributed anodes are frequently located close to the structure they are designed to protect. This proximity tends to reduce the effective resistance between the anode and the structure. An estimate of anode-to-remote earth resistance using the Sunde equation is, therefore, conservative. In distributed anode systems, the linear resistance of the feeder cable may be a significant factor. Voltage and current attenuation along the anode

Table 5.2 Paralleling Effect

S (meters)	R_N (ohms)	Avg. R/anode (ohms)
0.5	4.800	96.0
1.0	2.751	55.0
1.5	2.069	41.4
2.0	1.727	34.5
2.5	1.522	30.4
3.0	1.386	27.7
3.5	1.288	25.8
4.0	1.215	24.3
4.5	1.158	23.2
5.0	1.113	22.3
5.5	1.075	21.5
6.0	1.044	20.9

feeders must be considered. Attenuation calculations require an estimate of the average conductance to earth of a unit length of the distributed anode system. The calculations also require the value of linear resistance for the anode feeder (bus) wire. Unless individual anodes in the distributed anode system are widely spaced, there will be a paralleling effect. The electric field produced by current flow from an anode affects the field and therefore the current output of all other anodes in the vicinity. This mutual effect increases the effective resistance of each anode above that of the resistance for a single anode in a given soil resistivity. See Table 5.2 for an example for 5,000 ohm-cm soil.

Sunde Equation

$$R_N = (0.005\rho/\pi NL)[\ln(8L/d) - 1 + (2L/S)\ln(0.656N)]$$

where R_N = groundbed resistance (ohm) [See table]

ρ = average soil resistivity (5,000 ohm-cm)

N = number of anodes in parallel (20)

L = length of an anode (1.52 m)

d = anode diameter (0.305 m)

S = spacing of anodes in groundbed (m) [See table]

For spacing greater than 6 meters (20 feet) the paralleling effect is negligible.

The average conductance for a typical 1.52 meter (5 ft) × 0.305 meter (1 ft) anode with 6 or more meters of separation in 5,000 ohm-cm soil is:

$$g = (1/R_a) = 1/20.9 = 0.048 \text{ Siemens}$$

If a No. 4 AWG copper wire (0.82 ohm/1000 m) is used, and the anodes have 15 meter (49.2 ft) separation, the unit resistance of the wire is:

$$r = (0.82 \times 15/1000) = 0.0123 \text{ ohm/unit}$$

The resistance between the input end of a long distributed anode bus to remote earth is given by the equation:

$$R = R_G \coth(\alpha x)$$

where $R_G = (r/g)^{0.5}$ (characteristic resistance)

$\alpha = (rg)^{0.5}$ (attenuation constant)

$x =$ unit distance (number of units) from the open end

coth = is the hyperbolic cotangent

Example 5.6

Calculate the resistance of the feed end of a 1,000 meter (3,280 ft) long distributed anode bus to remote earth. The bus is AWG No. 4 copper wire (0.82 ohm/1000 m), the anodes have 15 meter (50 ft) separation, the individual anodes are 1.52 meters (5 ft) long and 0.3 meters (1 ft) in diameter. The average soil resistivity is 5,000 ohm-cm.

Solution

Consider each anode and the 15 m (50 ft) of bus wire as a unit. The total number of units in the system are

$$x = (1{,}000/15) = 66$$

From Table 5.2 and the calculations shown:

$$g = 0.048 \text{ Siemens/unit}$$

$$r = 0.0123 \text{ ohm/unit}$$

Therefore

$$R_G = (r/g)^{0.5} = (0.0123/0.048)^{0.5} = 0.506 \text{ ohm}$$

$$\alpha = (rg)^{0.5} = (0.0123 \times 0.048)^{0.5} = 0.024$$

$$R = R_G \coth(\alpha x) = 0.506 \coth(0.024 \times 66)$$

$$R = (0.506)(1.088) = 0.551 \text{ ohm}$$

If attenuation were not considered, what would the resistance of the 66 anodes be when measured to remote earth?

$R_s = 1/66g = 1/(66 \times 0.048) = 0.316$ ohm

CATHODE RESISTANCE-TO-EARTH

From Estimated Coating Characteristics

The subject of leakage conductance was covered in detail under Current Requirements in this chapter. Calculation of cathode-to-earth resistance is essentially what was done when calculating the current needed to lower the potential to earth a specified amount. To review:

- Calculate the total surface area of the structure.
- From experience with construction practice and average coating characteristics calculate the total leakage conductance for the structure.
- Take the reciprocal of the total conductance ($1/G$) to obtain the structure to remote earth resistance.

From Field Tests

As with long distributed anode systems, attenuation may be involved in determining the structure to earth resistance. Measuring the resistance between an electrically isolated structure and any well grounded structure will give the approximate resistance of the cathode to remote earth. Example 5.2 used this technique. Another approach is to apply a test current between the structure and either a test groundbed or the permanent groundbed and measure the structure to earth coupling (v/A) at several locations on the structure. The reference electrode used to obtain the earth potential shift must be far enough from the structure such that any further separation will not result in any further change in value of the coupling. Unless there is significant attenuation involved, the average of the several coupling values will be the resistance of the structure (cathode) to remote earth.

TOTAL DC CIRCUIT RESISTANCE

Anode to Structure Resistance

The anode to structure resistance is the sum of the resistances of the anode and the structure to remote earth. In the case of a non coated or poorly coated structure and closely arranged anodes the anode to structure resistance may be lower than the sum of the resistances to remote earth. This is frequently the case when anodes are used to protect components in process equipment or for "hot spot" protection on buried piping systems.

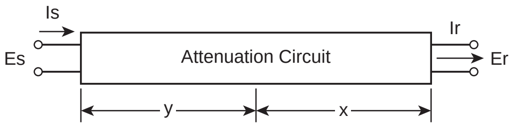
Other Sources of Resistance

Electrical connections, wire and internal resistance in power systems all may include some resistance. Such resistances are in series with the anode to earth and structure to earth resistances.

CURRENT ATTENUATION

Figure 5.4 presents a number of useful attenuation formulas. The formulas can be applied to either long structures (pipelines, cables, etc.) or extended anode systems. The formulas apply only where the environment has a relatively uniform resistivity.

USEFUL ATTENUATION FORMULAS



α = attenuation constant
$\alpha = \sqrt{rg}$
R_G = characteristic resistance (ohms)
$R_G = \sqrt{(r/g)}$
r = unit resistance along circuit, ohm/unit length
g = unit conductance to earth Siemens/unit length
x = number of unit length from receiving end
y = number of unit length from sending end

General Equations

1. $E = E_r \cosh(\alpha x) + R_G I_r \sinh(\alpha x)$
2. $I = I_r \cosh(\alpha x) + (E_r/R_G) \sinh(\alpha x)$
3. $E = E_s \cosh(\alpha y) - R_G I_s \sinh(\alpha y)$
4. $I = I_s \cosh(\alpha y) - (E_s/R_G) \sinh(\alpha y)$
5. $R_{so} = R_G \coth(\alpha x)$
6. $R_G = \sqrt{R_{so} R_{ss}}$

where:
E_r = receiving end potential
I_r = receiving end current
E_s = sending end potential
I_s = sending end current
R_{so} = Resistance looking into open ended line
R_{ss} = Resistance looking into shorted ended line

Figure 5.4 *Source*: NACE Cathodic Protection Level 3 Training Course Manual, © NACE International, 2000.

Anode System

Example 5.6 showed the effect of attenuation on the input resistance of a long distributed anode. The mathematical equation for the voltage shift between an open ended anode buss and remote earth is:

$$E = E_s \cosh(\alpha y) - (I_s R_G) \sinh(\alpha y)$$

where E_s = the voltage shift at the input end of the anode bus

I_s = the current input to the anode bus

α = the attenuation constant

R_G = the characteristic resistance

y = the number of unit lengths from the input end of the anode bus

Example 5.7

In Example 5.6, what is the approximate current output of an anode 1,000 meters from the rectifier if the voltage between the structure and the anode buss at the rectifier is 15 volts when the rectifier is on and 3.0 volts when it is off? Assume that there is negligible resistance between the structure and remote earth and negligible attenuation on the structure.

Solution

The change in voltage at the source (E_s) is

$$E_{0\text{on}} - E_{0\text{off}} = 15 - 3 = 12 \text{ volts}$$

From Example 5.6

$R_G = 0.506$ ohms

$\alpha = 0.024$

$R_s = 0.551$ohms

There are

$$1{,}000/15 = 66 \text{ unit lengths (s)}$$

to the point of interest

$$E = E_s \cosh(\alpha y) - (I_s R_G)\sinh(\alpha y)$$

$$I_s = E_0/R_0 = 12/0.551 = 21.8 \text{ A}$$

$$E = 12 \cosh(1.584) - 11.03 \sinh(1.584)$$

$$E = 12 \times 2.54 - 11.03 \times 2.33 = 4.78 \text{ volts}$$

Since the average conductance of a single anode from Example 5.6 is 0.048 Siemens, the current from an anode near the 1,000 m location will be

$$I = 4.78 \times 0.048 = 0.229 \text{ ampere}$$

How does this compare with the average current output from anodes near the feed end of the bus?

$$I = 12.0 \times 0.048 = 0.576 \text{ ampere}$$

Structure

The attenuation of current on a long structure is similar to that for the long anode run described in Examples 5.6 and 5.7. If the structure is very long or has high average leakage conductance to remote earth, the resistance looking each direction from a cathodic protection power source will be approximately equal to the R_G (the characteristic resistance). For shorter structures and structures with low leakage conductance the resistance each direction from the power source will be given by the formula for an open ended line that was used in Example 5.6. The concept is illustrated in the following example.

Example 5.8

Consider a 20.3 cm (8 inch) welded steel pipeline (linear resistance = 0.0287 ohm/1000 m) which has a fair quality protective coating which averages 7.5×10^{-5} Siemens/m^2 leakage conductance. The pipeline is 32,200 meters long with isolation joints at each end. The soil averages 10,000 ohm-cm resistivity throughout the region. What is the cathode (structure) resistance to remote earth from the center of the line in each direction as "seen" by a power source located there? What will the relationship between the current density received by the pipe at each end (16,100 meters from the power source) to that received near the power source at the middle of the pipeline?

Solution

Consider a unit length to be 1,000 linear meters.
Given

$r = 0.0287$ ohms/1,000 m unit

pipe diameter $= 20.3$ cm (0.203 m)

leakage conductance $= 7.5 \times 10^{-5}\ \mathrm{S/m^2}$ in 10,000 ohm-cm soil.

$$g = 0.203\pi(7.5 \times 10^{-5})(1{,}000) = 0.0478\ \mathrm{S}/1{,}000\ \mathrm{m}$$

$$\alpha = (rg)^{0.5} = 0.037$$
$$R_{\mathrm{G}} = (r/g)^{0.5} = 0.775\ \mathrm{ohms}$$

From equation #5 (Figure 5.4)

$$R_{\mathrm{so}} = R_{\mathrm{G}} \coth(\alpha x)$$
$$x = 16{,}100/1000 = 16.1\ \text{unit lengths}$$
$$R_{\mathrm{so}} = 0.775 \coth(0.037 \times 16.1) = 1.45\ \mathrm{ohms}$$

From equation #3 (Figure 5.4)

$$E = E_{\mathrm{s}} \cosh(\alpha y) - R_{\mathrm{G}} I_{\mathrm{s}} \sinh(\alpha y)$$

Assume a 1.0 volt shift in pipe to remote earth potential at the power source.

$$I_{\mathrm{s}} = E_{\mathrm{s}}/R_{\mathrm{so}} = 1.0/1.45 = 0.69\ \mathrm{A}$$
$$\alpha y = 0.037 \times 16.1 = 0.596$$

$$E = 1.0 \cosh(0.596) - (0.775 \times 0.69)\sinh(0.596)$$
$$E = 1.183 - 0.338 = 0.845\ \text{volt}$$

$$E/E_{\mathrm{s}} = 0.845$$

Since current density received on the pipe surface from earth is proportional to the voltage shift measured to earth

$$i_{\mathrm{r}} = 0.845\, i_{\mathrm{s}}$$

Note that all of the current attenuation calculations are valid at time zero, in the absence of any electrochemical polarization. The pipe-to-remote earth potential shifts calculated in the attenuation equations are the sum of IR drops between the pipe at the point of interest and remote earth, caused by the flow of the source current.

SYSTEM LIFE

Sacrificial Anodes

All components of a cathodic protection system have a finite service life. Rectifier components, wire insulation, and anodes all deteriorate with time. Sacrificial anodes are consumed in the process of production of current. Chapter 3 of this course discussed ampere hour capacity as it applies to various galvanic anode materials. Ampere hour capacity (with the efficiency factor for the specific anode material) allows us to determine what weight of anode metal is required to provide a given number of ampere hours of current. In estimating the system life for a galvanic anode cathodic anode system consider:

- Annual mean temperature of the environment and the effect of temperature on the anode potential, current requirements and circuit resistance.
- Anode circuit resistance.
- Cathode circuit resistance and its behavior with time.
- Total operating voltage including polarization of the cathode and the anode.

Example 5.9

A field test indicates 0.375 A is required to protect a coated section of pipe. At this current level, the pipe is polarized to −0.900 volt vs. a copper/copper sulfate reference electrode. The pipe has a resistance of 0.8 ohm measured to remote earth. Experience suggests that the resistance will slowly decrease during the next several years and level off at about half the present value (0.4 ohm). Assuming that the same pipe to remote earth potential shift will maintain protection, how many 7.7 kg (17 lb.) high potential magnesium anodes would be needed to protect the pipe section? How long would the expected useful service life be?

Solution

The potential shift at present is

$E = 0.375 \text{ A} \times 0.80 \text{ ohm} = 0.30 \text{ volt}$

The long term current required to maintain a potential shift of 0.30 volt is

$I = 0.30 \text{ volt}/0.40 \text{ ohm} = 0.75 \text{ A}$

The anode suppliers literature says that in 5,000 ohm-cm soil a high potential magnesium anode will output 0.040 A (40 ma) to a structure polarized to −0.85 volt CSE. The data infers that the structure has negligible resistance to earth and therefore no IR drop. The resistance to remote earth of a single high potential (−1.75 volt CSE) magnesium anode can be calculated

$R = (1.75 - 0.85)/0.040 = 22.5$ ohms

Assuming that the pipe section will continue to be polarized to −0.900 volt CSE, the available driving voltage for the galvanic anode system will be

$E_{\text{net}} = -1.75 - (-0.900) = -0.850$ volt

The total circuit resistance that will permit 0.75 A of current at a driving voltage of 0.85 volt is

$R_t = 0.85/0.75 = 1.133$ ohms

Since the pipe to earth resistance is estimated to become 0.40 ohm, the resistance of the sacrificial anodes must be

$\text{Ra} = 1.133 - 0.4 = 0.73$ ohm

Assume that the anodes can be spaced far enough apart to avoid the paralleling effect, the number of anodes required to give the needed groundbed resistance is

$N = 22.5/0.73 = 30.8(31)$ anodes

The total weight of magnesium in the anode system will be

$31 \times 7.7 = 239$ kg

The annual total ampere hours output will be

$365 \times 24 \times 0.75 = 6{,}570$ Ampere hrs/yr

The ampere hour capacity of the anode system (assuming 1100 amp. hrs./kg) is

$239 \times 1100 = 262{,}900$ amp. hrs.

The anode service is estimated at

$262{,}900/6{,}570 = 40$ yrs.