DESIGN OF STEEL GROUNDING SYSTEM IN A HEAVY INDUSTRIAL PLANT

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Pankaj K. Sen
Senior Member IEEE
Department of Electrical Engineering and Computer Science
University of Colorado at Denver
Denver, Colorado 80204

Consultant: Fichtner / Lee Wan, Golden, CO. 80401

ABSTRACT

Based on the National Institute of Standards and Technology statistical data on the corrosion of steel [7], an equation is developed to estimate the corrosion rate of underground steel that varies with resistivity, pH value, moisture content and aeration of the soil. This formula, together with the IEEE Standard No. 80-1986 [1], is used in the design of steel grounding for a large heavy industrial plant. Formulas are also discussed on how to design proper cathodic protection methods to minimize corrosion of steel grounding. A numerical example is discussed to enhance the understanding.

INTRODUCTION

IEEE Standard No. 80-1986 entitled "IEEE Guide for Safety in AC Substation Grounding" discusses in detail the design of ground grid for AC sub-station with primarily copper as the ground grid material. Reference [10] shows that steel grounding has been used in the USA and in other countries where copper is expensive.

The selection of material used in the electrical ground grid depends primarily on the following factors:

* Fusing or current carrying capabilities
* Conductor resistance
* Corrosion
* Availability & cost of conductor material

Copper, in addition to high conductivity, has the advantage of freedom from underground corrosion and is the most commonly used metal in the grounding grid design. However, bare copper conductors buried in the ground form a galvanic cell with the buried steel in the vicinity and corrodes steel. Unless some corrosion reduction technique is adopted, damage may extend to all steel or galvanized members, such as conduit, structure footings, metallic sheathed cables and pipes.

Steel has been used as a substitute for copper as ground grid material for the following reasons [4][5]:

* Reduction of galvanic action between dissimilar metals (particularly copper)
* Ability to provide cathodic protection to steel pipes and other steel structures
* Low cost and availability
* Mechanical strength

The key technical characteristics of steel are [2][6]:

* Steel absorbs 1.36 times as much heat as an equal volume of copper before fusing
* Steel can withstand higher temperature before melting (1810 K compared to 1365 K for copper)
* It requires about 5.6 times as much steel to achieve the same resistance as copper
* Steel is twice as mechanically strong as copper for the same cross-sectional area

This paper discusses the corrosion and corrosion control of steel as applied to the steel grounding design.

CORROSION ESTIMATION

Most of the corrosion of metals in underground service is the result of an electro-chemical reaction. Corrosion occurs through the loss of metal ions at anodic points or areas to the electrolyte. Cathodic areas are protected from corrosion because of the deposition of hydrogen or other ions that carry current.

Factors that affect underground corrosion are:

1. **"Soil Resistivity"** dependents on natural ingredients, the amount of salts dissolved in soil, and the moisture content. The following table gives the relationships between soil resistivity and the corrosivity.

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Table I: Soil Resistivity and Corrosion[2]

Soil Resistivity (ohm-meter)	Class Typ. Corrosion Rate (mils/yr)
< 25	Severely corrosive (>13)
26-50	Moderately corrosive (9-12)
51-100	Mildly corrosive (4-9)
> 100	Very mildly corrosive (<4)

2. **"pH Value"** of soil affects the corrosion process greatly. The more acidic soil is, the higher the corrosion rate. pH value ranges generally from 5 to 10 in soil, a value of 7 indicates neutrality; lower values, acidity; and higher values, alkalinity. At very high pH values, corrosion is greatly reduced. The relationship is shown in Table II.

3. **"Moisture"** contents depend on season, location, particle size and ground water level. Corrosion increases with higher moisture contents due to higher salt solubility.

4. **"Aeration"** is a measure of the availability of oxygen to the metal and are dependent primarily on particle size and distribution. Corrosion increases with the increase in aeration.

5. **"Miscellaneous"** factors are those that are difficult to classify because they are a combination of many factors and include the effect of temperature, bacterial or interference current effects. These factors contribute no more than 10% to the total corrosion rate and are neglected.

A relationship is obtained from the National Institute of Standards and Technology data [7] to represent the corrosion rate of steel (Bessemer Steel). These data were produced from actual experimental data taken in 44 different soils over a period of 12 years. These tests used 1½ inch and 3 inch diameter samples. It was noted that the 3 inch samples corroded 13% more than the 1½ inch samples, with an error of ± 10%.

A general equation including the effects of the above factors is provided in the following form.

$$Y = f(X_1, X_2, X_3, X_4) \quad \ldots \quad (1)$$

where, Y = Corrosion rate (mils/yr)
X_1 = Resistivity (ohm-cm)
X_2 = pH value
X_3 = Moisture (%)
X_4 = Aeration (%)

Using multiple regression, the following equation is obtained to estimate the corrosion of steel in any environment:

$$Y = 3.36 - 9.63\text{E-}05 * X_1 + 0.29 * X_2 + 0.034 * X_3 + 0.012 * X_4 \quad \ldots \quad (2)$$

Equation (2) is limited by extreme corrosion conditions such as extremely high resistivity (> 10,000 ohm-cm) or extremely low aeration quantities (< 3%). This equation is applicable for all steel rods up to 3 inch diameter and is applicable for first 12 years. It has been found that the average rate of corrosion in the following 12 years is half of that in the first 12 years and negligible thereafter.

Table II: pH Values and Corrosion [7]

Extremely acid	Below 4.5	Highest Corrosion
Very strongly acid	4.5 to 5.0	
Strongly acid	5.1 to 5.5	
Medium acid	5.6 to 6.0	
Slightly acid	6.1 to 6.5	
Neutral	6.6 to 7.3	
Mildly alkaline	7.4 to 7.8	
Moderately alkaline	7.9 to 8.4	
Strongly alkaline	8.5 to 9.0	
Very strongly alkaline	9.1 & higher	Least Corrosion

CORROSION CONTROL & CATHODIC PROTECTION

Coating has been used to control corrosion rate. When the continuity of the coating is destroyed, it was observed that the corrosion rate of the base metal is normal or above normal depending on the type of coating and the underlying metal. Zinc-coated (galvanized) steel is the most used type of coating. However, coating may not be used as a sole means of protection.

Cathodic protection is the most effective way of protecting underground structures. It operates by stopping the current flow from the metal to the electrolyte by neutralizing it with a stronger current of opposite polarity from an external source.

There are two basic methods of applying cathodic protection.

1. **"Sacrificial or Galvanic Anodes"** [2][8], are applicable and effective where current requirements are low and the structures to be protected are well-coated in a low resistivity soil. The general arrangement is shown in Fig. 1. The anode consists of a metal which is electro-negative to the structure. These anodes are self-energized and are connected directly to the structure to be protected. Sacrificial anodes consume themselves in protecting the other metal. The rate of consumption is dependent upon the magnitude of current generated as well as the material of which the anode is made. Zinc and Magnesium are the two main metals used as galvanic anodes.

   Magnesium has received much wider application than zinc, primarily because of its higher driving voltage. The solution potential of magnesium is -1.55 volts to a copper sulphate reference electrode and that of zinc is -1.1 volts. Considering steel grounding grid to soil potential of -0.85 volts as the protective measure, the driving potential of zinc is 0.25 volts, while magnesium is 0.75 volts. The actual ampere-hours per lb. of zinc is 335 as compared to 500 for magnesium. The following formulas may be used to determine the life expectancy of a given anode weight or to determine the current output when the anode weight is given [3].

$$L_m = \frac{57.08 * w}{i} \qquad \ldots \qquad (3.a)$$

$$L_z = \frac{38.24 * w}{i} \qquad \ldots \qquad (3.b)$$

where, L_m = life of magnesium anode, yr
L_z = life of zinc anode, yr
w = weight of anode, lb
i = current output of anode, mA

The efficiency of zinc is assumed to be 90%, and for magnesium 50%, of their theoretical output. Soil resistivity is a major factor affecting the current output of an anode. It is not practical to install sacrificial anodes for soils with a resistivity of 5000 ohm-cm or higher. The following equation and Table III may be used to determine the approximate current outputs

$$i = \frac{150,000 * K}{X_1} \quad \text{for Mg anode} \quad .. \quad (4.a)$$

$$i = \frac{40,500 * K}{X_1} \quad \text{for Zn anode} \quad .. \quad (4.b)$$

where, i = current output, mA
X_1 = soil resistivity, ohm-cm
K = factor from Table III

Table III: Values of K for Different Anode Size

Anode size, lb	K
3	0.59
5	0.66
9	0.81
17	1.00
32	1.16
50	1.22

The main advantages of sacrificial anodes are: no external power supply is necessary; minimum maintenance costs after installation; seldom causes interference problems to other structures; installation costs are low; and little or no right-of-way easement costs. The main disadvantages are: limited driving potentials and current outputs; soil resistivity limitation; and mutual interference in multiple or parallel installations.

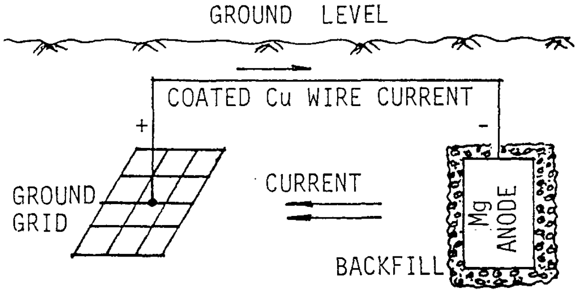

Fig. 1 Sacrificial Anode

2. **"Impressed Current"** method, as shown in Fig. 2, uses current injection from an external direct current power supply or an existing AC power supply with the use of a rectifier. This will develop an electrolytic cell, with the protected structure and the ground rod of the rectifier. The ground bed (anode) consists of a number of parallel graphite, carbon, duriron, or junk iron anodes. The structure, connected to the negative of the rectifier, receives the current from the soil and is protected. The protective current from the rectifier is usually sufficient to overcome the galvanic currents, leaving the anodic areas of the structure. This method of protection is generally used where large amounts of currents are required at relatively few locations.

Studies [8] have shown that it requires anywhere from 1 to 20 mA of current to protect 1 sq. ft. of bare surface, the higher the soil resistivity the lower the current requirement. On the average, it takes 1 to 3 mA to protect one sq. ft. of conductor area. When coating is used, that current requirement is greatly reduced, 1 to 3 µA.

The advantages of using this technique are: large current outputs applicable in high resistivity soil environments; applicable for bare and poorly coated structures; and flexibility of current output control protects large and more expensive structures. The disadvantages are: higher installation costs; higher maintenance costs; monthly power costs; and interference problem with neighboring structures.

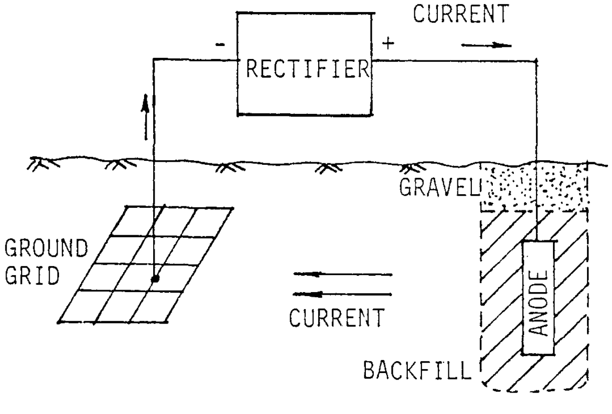

Fig. 2 Impressed Current or Rectifier Cathodic Protection

SAMPLE CALCULATIONS

Consider a substation in a heavy industrial plant with the following parameters to be used for the steel grounding design:

Soil characteristics are given by:

X_1 (resistivity) = 2,500 ohm-cm
X_2 (pH value) = 7
X_3 (moisture) = 30%
X_4 (aeration) = 15%

Fault current = 20,000 A
Fault duration = 1.0 s
Decrement factor = 1.0
System growth factor = 2.0

Following the design guidelines given in IEEE Standard No. 80-1986 [1], the steel conductor size can be calculated without taking into account the corrosion.

The conductor area = 565 mm^2
The radius of the conductor = 1.34 cm

The corrosion rate calculated from equation (2) is given by,

$$Y = 3.36 - 9.63E\text{-}5\ (2,500) + 0.29\ (7) + 0.034\ (30) + 0.0121(15) = 6.335 \text{ mils/yr}$$

Assuming average grounding system lifetime of 25 years, with a safety factor of 2.0, the total corrosion loss is

$$\begin{aligned} Y &= (12)(1.5)(6.335)(2.0) = 228 \text{ mils} \\ &= 228 \text{ mils (in/1000 mil)} * (2.54 \text{ cm/in}) \\ &= 0.58 \text{ cm} \end{aligned}$$

Therefore, radius of conductor size must be increased by 0.58 cm. (almost 43%) to compensate for the corrosion loss.

Suggested minimum radius of conductor = 1.34 + 0.58 = 1.74 cm.

With the use of cathodic protection, using magnesium sacrificial anode, original conductor size is maintained and the current required to protect the system from corrosion is given by equation (4.a),

$$i = \frac{150,000\ (1.16)}{2,500} = 69.6 \text{ mA},$$

where, K = 1.16 for 32 lb. anode size

The lifetime expected for the given anode size and required current output, using equation (3.a), is

$$L_m = \frac{(57.08)\ (32)}{69.6} = 26.24 \text{ years}$$

which agrees with the normal life expectancy of the plant.

CONCLUSIONS

Steel can be used effectively as grounding material. Corrosion can be compensated for by increasing the cross sectional area of the conductor and/or can also be controlled by using cathodic protection.

The use of steel grounding is practical when other steel structures are present in the vicinity. This will reduce the corrosion of other steel structures. To maintain the integrity of the ground grid itself, it is recommended that some modes of cathodic protection be designed and implemented together with the increased conductor size. It is also recommended that the continuity and the integrity of the ground grid be checked periodically by physical inspection at random locations to ensure the safety. The on-line corrosion monitoring techniques with real time corrosion information by using Electrical Resistance (ER) method or Linear Polarization methods (LPR) combined with microprocessor and computer technology are available. This enables the corrosion engineer to detect system problems. These fast responses may directly be used for controlling the process, thus resulting better design.

A generalized cost comparison between steel and copper grounding is very difficult. Each installation needs to be evaluated separately. Based on the prices of steel and copper in the USA, substantial (estimated at 40% or more) savings can be achieved in steel grounding after incorporating the effect of corrosion and cathodic protection. The savings will be much higher in other situations where copper is more expensive.

The typical corrosion rate of steel is between 5-7 mils/year as calculated from the derived equation (2). This agrees closely with the values of corrosion rates given in the following table [3][7]:

Table IV: Average Corrosion rates of several metals

Material Used	Corrosion Rate (mils/yr)
Open Hearth Steel	5.90
Wrought Iron	5.00
Bessemer Steel	5.30
Copper	1.25
Lead	3.00
Zinc	5.00

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