

# Steel Grounding Design Guide and Application Notes

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**Abstract:** Based on the National Bureau of Standards [presently called The National Institute of Standards and Technology or "NIST"] statistical data on corrosion of steel<sup>[4]</sup>, an equation is introduced to estimate the corrosion rate of underground steel. The variables include the major soil characteristics (parameters), namely: resistivity, pH value, moisture content and aeration. This formula, together with the IEEE Standard No. 80-2000<sup>[1]</sup>, is used in the design of steel grounding. Also discussed, in detail, the design procedures for cathodic protection scheme to minimize corrosion of steel grounding. Numerical examples are included in the paper to enhance the understanding of steel grounding design for high voltage AC substations.

## INTRODUCTION

IEEE Standard No. 80 - 2000: "IEEE Guide for Safety in AC Substation Grounding" discusses, in detail, the ground grid design procedure for AC substation with copper as the primary grid material. Section 11.2.4 in the same IEEE Guide states: "Steel may be used for ground grid conductors and rods. Of course, such a design requires that attention be paid to the corrosion of the steel. Use of galvanized or corrosion-resistant steel, in combination with cathodic protection, is typical for steel grounding systems."

Literature review reveals that steel-grounding system is widely used and readily accepted in many other countries worldwide, where copper is very expensive. It is also used in many occasions by the utilities (nuclear and fossil fuel power plants), industrial plants (petroleum refinery, chemical plants, cement plants, steel plants, etc.) and REA's (or Rural Electric Coops) substations as the ground grid material in USA. Such installations usually require great amounts of sub-surface steel piping, tanks and pilings so that there are major advantages in minimizing the extent of underground copper for grounding or other purposes.

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Overall corrosion protection then becomes easier to achieve either for coated or bare steel pipes, tanks and steel structures underground.

Unfortunately, there is no simple, concise and practical design guide available for the use of steel as ground grid material and how to design the cathodic protection system. The main focus of this paper is to develop a practical design guide for steel grounding including the cathodic protection system.

## FUNDAMENTALS OF GROUNDING

In the event of short circuits (faults) and transient phenomena (lightning and switching operations), a safe grounding practice has two major objectives:

- Personnel Safety, and
- Equipment Protection.

There are three major considerations in the design of such grounding systems:

- The grid must be able to withstand the maximum ground fault current without the danger of burn-off or melting. This is also referred as the "Fusing ( $I^2Rt$ ) Characteristics."
- The grid must produce sufficiently low voltage between any two points on the ground to prevent all personnel hazard. This takes into account the acceptable limits of "Step, Touch and Mesh Potentials," and
- The grid must minimize the "Ground Potential Rise (GPR)" with respect to remote ground (or zero potential point) by having a low contact resistance to ground (commonly referred as "Ground Resistance") fault current.

There are five major parameters considered in the ground grid design:

- Soil Resistivity (most predominant factor),
- Tolerable Body Current (determines allowable "Step" and "Touch" potentials),

- Power System Network Configuration (determines the “Current Division Factor” and the actual amount of current flowing into the ground),
- Single-Line-to-Ground Fault Current magnitude at the station and the X/R ratio, and,
- Grid Geometry (determines the “Mesh, Step and Touch” voltage).

The IEEE Standard No. 80-2000 discusses, in detail, the design of ground grid for AC substation and should be consulted for additional information.

## MATERIAL SELECTION

Copper is by far the most common metal used as ground grid conductors. Copper-clad steel is usually used for ground rods, and sometimes as ground conductors. There are four reasons why copper has been used primarily as ground grid conductor:

- Familiarity of electrical characteristics of copper when used as ground grid conductors.
- Higher conductivity (compared with steel) making it suitable for installations with high fault currents.
- Good mechanical strength, and most importantly,
- Freedom from underground corrosion. Grid integrity will not be compromised, if conductors are adequately sized and not subjected to any mechanical injury.

It is the unfamiliarity of using steel, lack of experience data, unavailability of any design standard and guide, and the fear of ground grid integrity due to corrosion, that steel is not commonly used. Also the IEEE standard provides limited information about the design procedure of the grounding system with materials other than copper.

There are, however, two disadvantages in using copper that may override the benefits in some situations:

- Relatively high initial cost, and
- It forms “**Galvanic Cell**” with buried steel pipes, conduits, rebars, etc. in the vicinity and corrodes the steel. Unless some corrosion reduction technique is adopted, damage may extend to all steel or galvanized members, such as conduit, structure footings, rebars, metallic sheath and steel pipes.

A survey reported in Ref. [6] shows that, in many applications, steel grounding has been used in USA

and in other countries where copper is expensive. Hot galvanized steel and other corrosion-resistant steel are very durable in almost all kinds of soil. It is also suitable for embedding in concrete.

The technical limitations of steel when considering the fusing characteristics, mechanical strength, ground grid resistance and minimizing the step and touch potentials, are similar to those of copper.

The material selection used in the grounding system design depends primarily on the following factors:

- Fusing characteristics & current carrying capabilities,
- Conductor resistance,
- Corrosion,
- Mechanical Strength,
- Availability and
- Cost of conductor material.

Steel has been used <sup>[3][8]</sup> as a substitute for copper as grounding grid material for the following reasons:

- Lower cost,
- Reduction of galvanic action between dissimilar metals (particularly with copper) in the earth,
- Ability to provide (cathodic) protection to steel pipes and other steel structures connected to it, and
- Higher mechanical strength.

A detail discussions on all the properties of steel as ground grid material is beyond the scope of this paper. The relevant key technical characteristics <sup>[1]</sup> are:

- Steel absorbs approximately 1.36 times as much heat as an equal volume of copper before fusing (when considering the specific weight, specific heat and the melting temperature).
- Steel can withstand higher temperature before melting (1510°C compared to 1083°C for copper).
- It requires about 5.6 (ratio of resistivity =  $\rho_{Cu} / \rho_{Fe}$ ) times as much steel to achieve the same resistance as copper.
- Steel is approximately twice as mechanically strong as compared to copper for the same cross-sectional area.

A generalized and simple cost comparison between steel and copper as grounding material is difficult. Each installation needs to be evaluated separately. Based on the prices of steel and copper in USA, substantial (estimated at approximately 40%) savings can be achieved in some steel grounding design after

incorporating the effect of corrosion and cathodic protection. The savings would be much higher in other countries, where copper is very expensive.

## CONDUCTOR SIZING

Conductor sizing depends on a number of factors including material characteristics like resistivity, thermal coefficient of resistivity, thermal capacity per-unit volume, ambient temperature, and maximum allowable operating temp. It also depends on the actual current magnitude, X/R ratio at fault location, and the duration of fault ( $t_c$ ). This is discussed, in detail, in Ref. [1].

The simplified formula to calculate the conductor cross-sectional area for any material is given by<sup>[1]</sup>:

$$A_{\text{kcmil}} = I \cdot K_f \cdot \sqrt{t_c} \quad (1)$$

$$A_{\text{mm}^2} = \frac{I \cdot K_f \cdot \sqrt{t_c}}{1.974} \quad (2)$$

Where,

$A_{\text{kcmil}}$  = Area of conductor in kcmil

$A_{\text{mm}^2}$  = Area of conductor in  $\text{mm}^2$

$I$  = RMS (symmetrical) fault current in kA

$t_c$  = Fault duration in sec, and

$K_f$  = Constant for the material

$T_m$  = Fusing temperature in  $^{\circ}\text{C}$

The value of the constant " $K_f$ " calculated<sup>[1]</sup> at  $40^{\circ}\text{C}$  ambient temperature ( $T_a$ ):

= 7.00 for "annealed soft-drawn copper" ( $T_m = 1083^{\circ}\text{C}$ )

= 15.95 for "1020 steel" ( $T_m = 1510^{\circ}\text{C}$ ).

It is to be noted here, that much lower values of operating temperature ( $620^{\circ}\text{C}$  and  $500^{\circ}\text{C}$ ) has been recommended (based on deterioration of mechanical properties and limitations on joints) and used in some design calculations for steel grounding<sup>[3]</sup>. Lower temperature values usually result in approximately 30% increase in cross-sectional area. Also effects of corrosion have not been considered in this equation.

The **time duration of fault ( $t_c$ )** depends primarily on the protection scheme, protective relays, and circuit breakers operating time. The backup clearing time is usually adequate for sizing the conductor. For smaller substations, this may approach 3 sec (or even longer). However, because large substations usually have complex and redundant protection schemes, high speed breakers and digital relays, the fault will generally be cleared in 1 s or less. For grounding calculations,

the most common practice in the industry is to use 1 sec.

Based on the above equation, the current carrying capability of copper and steel conductors can be calculated and is shown in the following Table I.

**Table I**  
**Ultimate Current Carrying Capabilities of Grounding Conductors**

Cable Size (AWG)	Nominal Cross Section ( $\text{mm}^2$ )	Current Carrying Capacity (kA)	
		Annealed Cu	1020 Steel
1/0 (105.5 kcmil)	53.48 (0.368 in diameter)	15.1	6.6
4/0 (211.6 kcmil)	107.20 (0.528 in diameter)	30.2	13.3
250 kcmil	126.65 (0.574 in diameter)	35.7	15.7
350 kcmil	177.36 (0.678 in diameter)	50.0	21.9
500 kcmil	253.27 (0.814 in diameter)	71.4	31.3

Mechanical strength requirements often dictate the minimum size. Based on common design practices, #1/0 copper is recommended as the minimum copper conductor size. Many utilities use a minimum size of #4/0 copper. For steel grounding, the most commonly used recommended minimum size is 250 kcmil.

## CORROSION ESTIMATION

Corrosion, in general, can be defined as the deterioration of a substance or its properties due to the reaction with its environment. The corrosion process can be chemical, electrochemical, or physical. Corrosion should be considered when designing a grounding system. The ground conductors and connectors could be affected by corrosion when they are buried or submerged in a corrosive environment.

References [2][5] are recommended for in-depth studies on corrosion. Most of the corrosion of metals in underground applications at normal or moderate temperatures is the result of an electro-chemical reaction. Corrosion occurs through the loss of metal ions at anodic areas to the electrolyte. Cathodic areas are protected from corrosion because of the deposition of hydrogen or other ions that carry current.

A basic and simple corrosion cell, as shown in Figure 1, has four components:

- Anode
- Electrolyte (Soil)
- Cathode, and
- Metal Return Path (External).

In simple term, electrochemical reaction due to potential difference causes loss of metal ions at the Anode (where the current is flowing out)

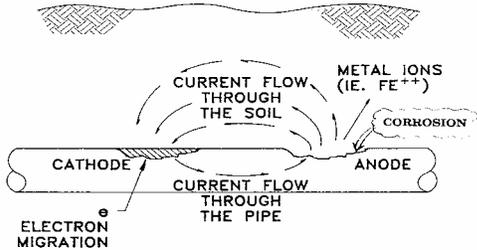


Fig. 1 Simple Corrosion Cell

There are a number of corrosion mechanisms. However, for this application, four major corrosion mechanisms (discussed below) are of importance:

- **Uniform Corrosion:** The most common form of corrosion, where current flows between different sites on a single metal, causing a wide area of metal to be progressively corroded (shown in Fig. 2).

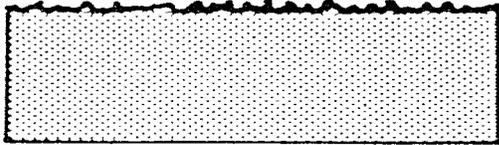


Fig. 2 Uniform Corrosion

- **Pitting:** A localized corrosion, which originates at susceptible sites on the surface of some alloys that resist uniform corrosion. The holes are deeper (Fig. 3) and the action is more severe as corrosion proceeds.

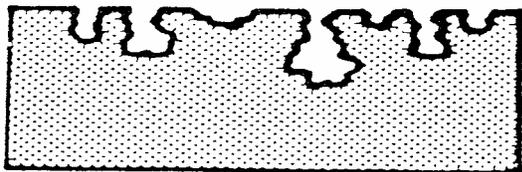


Fig. 3 Pitting

- **Electrolytic Corrosion:** This happens in a metal pipe when DC current flows through a pipe (as shown in Fig.4). This is caused by external source.

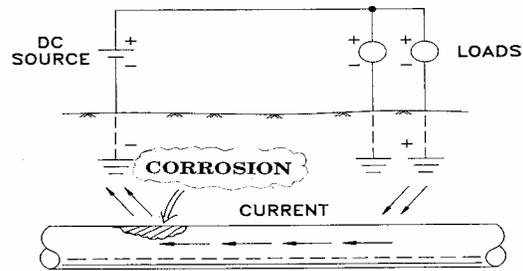


Fig. 4 Electrolytic Corrosion

- **Galvanic Corrosion:** When a difference in electric potential exists between two dissimilar metals, as an example, say copper and iron, connected externally and buried in soil (Fig. 5), the electrolyte (soil) allows some current to flow and causes corrosion in steel.

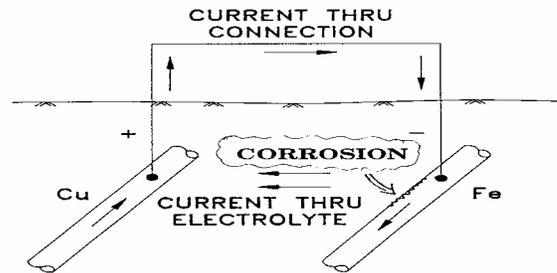


Fig. 5 Galvanic Corrosion

There are four basic factors that determine the magnitude of electrochemical corrosion activity (i.e. the corrosion current):

- Electrical continuity between sections of the underground structures.
- Magnitude of voltage developed between dissimilar materials (e.g. steel structure and copper ground grid). (see Appendices A and B for additional info).
- Ratio of exposed anodic area to that of the cathodic area (steel structure to that of the copper ground grid), and most importantly,
- Electrical resistance of the electrolyte (soil) between the steel structure and copper ground grid.

There is no single index of corrosivity. In general, *corrosive soil* is acidic, contains substantial moisture, contains clay and is dark in color, has organic material, is warm, and holds little oxygen. *Non-corrosive soil* usually has a higher pH value, lower moisture content, a sandy structure and is light in color, has little organic material, a high oxygen content, and lower temperature.

Major interrelated factors that affect underground corrosion are as follows:

- **Soil Resistivity** depends on natural ingredients, the amount of salts dissolved in soil, and the moisture content. The corrosivity increases with the reduction of soil resistivity. Table II provides the relationship between soil resistivity and corrosivity.

**Table II**  
**Soil Resistivity and Corrosion**

Soil Resistivity Class (ohm-meter)	Typical Corrosion Rate (mils/year)
Less than 25	Severely Corrosive (> 13)
26 – 50	Moderately Corrosive (9 -12)
51 – 100	Mildly Corrosive (4 – 9)
Greater than 100	Very Mildly Corrosive (< 4)

- **pH Value** of soil affects the corrosion process greatly. The more acidic the 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). The general relationship between the pH values and the corresponding corrosion is shown in Table III.

**Table III**  
**pH Values and Corrosion**<sup>[5]</sup>

Soil Characteristics	PH Values	Corrosion Rate
Extremely Acid	Below 4.5	Highest Corrosion
Very Strongly Acid	4.5 - 5.0	
Strongly Acid	5.1 - 5.5	
Medium Acid	5.6 – 6.0	
Slightly Acid	6.1 – 6.5	Least Corrosion
Neutral	6.6 – 7.3	
Mildly Alkaline	7.4 – 7.8	
Moderately Alkaline	7.9 – 8.4	
Strongly Alkaline	8.5 – 9.0	Higher Corrosion
Very Strongly Alkaline	9.1 - Higher	

- **Moisture** contents depend on season, location, soil type, particle size and ground water level. The degree of wetness contributes to the corrosion by dissolving soluble salts thereby changing the soil composition. Generally, corrosion increases with higher moisture contents (for normal ranges).

- **Aeration** is a measure of the availability of oxygen to the metal. Aeration characteristics of a soil are dependent primarily on particle size and distribution. Corrosion decreases with the increase in aeration.

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

A mathematical relationship is obtained from the National Bureau of Standards data<sup>[4]</sup> to calculate the corrosion rate of steel (Bessemer Steel). These data were produced from actual experiments in 44 different soils conducted over a period of 12 years. These tests used 1.5-inch and 3-inch diameter samples. The 3-inch samples corroded 13% more than the 1.5-inch samples, with an error of ± 10%.

Since, none of the above factors is present by itself in any soil, a general equation including the effects of all of the above factors in the following form is provided.

$$Y = f ( X_1, X_2, X_3, X_4 ) \tag{3}$$

where,

Y = Corrosion rate (mils/yr)

X<sub>1</sub> = Resistivity (ohm-cm)

X<sub>2</sub> = pH value

X<sub>3</sub> = Moisture (%)

X<sub>4</sub> = Aeration (%)

Using simple multiple regression analysis, the following equation is obtained for estimation of corrosion of steel in any environment (for normal operating ranges):

$$Y = 3.36 - 9.63 ( 10^{-5} ) ( X_1 ) + 0.29 ( X_2 ) + 0.034 ( X_3 ) + 0.012 ( X_4 ) \tag{4}$$

Equation (4) is obtained from experimental data and is limited by extreme corrosion conditions, such as, extremely high resistivity ( > 10,000 ohm-cm) or extremely low aeration quantities ( < 3%). Corrosion reduces by these conditions to almost zero. This equation is applicable for all steel rods up to 3-inch diameter and is applicable for the first 12 years. It has also been obtained experimentally<sup>[3]</sup> that the average

corrosion rate in the following 12 years reduces to half of that value in the first 12 years and is negligible thereafter.

### CORROSION PREVENTION AND CATHODIC PROTECTION <sup>[2][3][8]</sup>

Some of the most common corrosion prevention measures that are used to minimize corrosion of grounding material and/or steel piping are:

- Use of tin coated bare copper cable or hot galvanized or corrosion-resistant steel as a grounding conductor to minimize the potential difference between the steel structures and the ground cable,
- Use of cathodic protection,
- Use of insulated copper ground cable in areas near pipes, and
- Electrical isolation of piping from other plant structures and the grounding system.

The first two items are most commonly adopted in practical design:

Coating has been used to control corrosion rate. It initially protects the underlying metal. When the continuity of the coating is destroyed, it is 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, any coating as a sole means of protection is not very effective.

Cathodic protection is most commonly utilized to protect 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.

Cathodic protection can be designed for 30 years of life expectancy. There are two basic methods of cathodic protection, although there are many variations of these methods. Both provide satisfactory results, but each has advantages and disadvantages.

□ **Sacrificial or Galvanic Anodes** are applicable and effective where current requirements are low (less than 100 mA), and the structures to be protected are well-coated in a low resistivity soil. The anode consists of a metal, which is electro-negative to the protected structure. These anodes are self-energized and are connected directly to the protected structure (as shown in Fig. 6).

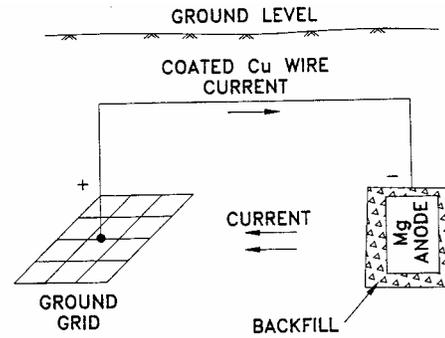


Fig. 6 Cathodic Protection: Sacrificial or Galvanic Anode Material

Sacrificial anodes, usually distributed along or around the protected metal parts, consume themselves in protecting the other metal. The consumption rate depends on the magnitude of current generated as well as the material of which the anode is made of and is given by Farady's Second Law of Electrolysis.

$$\text{Total Weight Loss (gm)} \equiv \frac{A \cdot i \cdot t}{V (96,500)} \quad (5)$$

Where,

A = Atomic Weight of the Metal

i = Current in A

t = Time duration of Current Flow in Sec

V = Valence Electron of the Metal

Zinc (Zn), A = 65.38, V = 2, and Magnesium (Mg), A = 24.32, V = 2

Zinc and Magnesium are the two most commonly used metals as galvanic anodes. Magnesium has received much wider applications than zinc, primarily because of its higher driving voltage. The solution potential of magnesium is -1.55 volts to a copper sulphate reference electrode compared to that of zinc value of -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. It can be derived from equation (5), that the actual ampere-hour per lb. of zinc is 335 as compared to 500 for magnesium. The efficiency of zinc is assumed to be 90%, and for magnesium 50%, respectively, of their theoretical output.

The following formulas (also derived from equation (5)) 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.

$$L_m = \frac{57.08 (w)}{i} \quad (6)$$

$$L_z = \frac{38.24 (w)}{i} \quad (7)$$

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

In other words, for every ampere-year of current flow, about 17.5 lbs of magnesium or 26.2 lbs of zinc is lost.

Resistivity of soil is the major factor affecting the current output of an anode. It is not practical to install sacrificial anodes for soils with a resistivity of 5,000 ohm-cm or higher. Zinc is very effective for the soil resistivity of 1,000 ohm-cm and below, whereas, magnesium can be effectively used in soil with resistivity up to 5,000 ohm-cm. When the soil resistivity is known, the following equation and Table IV may be used to determine the approximate current output of a magnesium anode.

$$i = \frac{150,000(K)}{X_1} \quad (8)$$

The current output for a zinc anode is given by

$$i = \frac{40,500(K)}{X_1} \quad (9)$$

where,

i = current output, mA

$X_1$  = soil resistivity, ohm-cm

K = observed factor from the following table

**Table IV**  
Values of K for Different Anode Size

Anode Size (lb)	Value of "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 (limited to 100 mA); soil resistivity limitation; and mutual interference in

multiple or parallel installations. Also sacrificial ground rods must be periodically replaced.

Design and installation of cathodic protection with sacrificial anodes requires judgment on the part of the application engineer as well as specialized experience in corrosion control. The criterion for selection is an analysis of performance and cost. Performance is measured by: anode life, and current output. Costs involved with installation and operation of galvanic anodes can be categorized as: material costs, installation costs and maintenance costs.

The following questions must also be answered before designing such cathodic protection scheme:

- How much current output can be expected from each anode?
- How much total current is needed to shift the neutral to the designated potential?
- What type of anode should be used?
- How many are needed?
- Where should anodes be placed?

□ **Impressed Current** uses current injection from an external DC power supply or an existing AC power supply with the use of a rectifier. Typical ratings of the rectifier or the DC power supply (adjustable) is 20-100 V, and 10-100 A. An electrolytic cell, is developed 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, usually distributed along the protected structure and placed deep in the soil. 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. The general arrangement is shown in Figure 8 below.

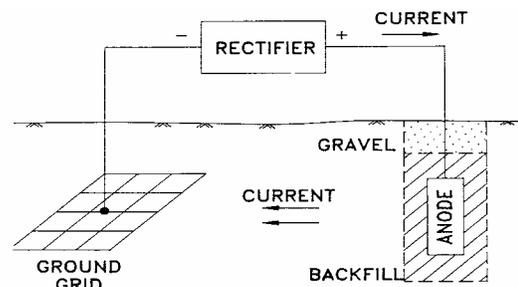


Fig. 8 Cathodic Protection: Impressed Current or Rectifier Type

Studies have shown that it requires anywhere from 1 to 40 mA of current to protect 1 ft<sup>2</sup> of bare metal surface area, the higher the soil resistivity the lower the current requirement. On the average, it takes only 1 to 3 mA to protect 1 ft<sup>2</sup> of conductor surface area. When coating is used, current requirement is greatly reduced to typically less than 0.1 mA/ft<sup>2</sup> of surface area.

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

### EXAMPLES AND SAMPLE CALCULATIONS

Consider a substation with the following parameters to be used for the steel grounding design:

- Soil characteristics given by:
  - X<sub>1</sub> (resistivity) = 2,500 ohm-cm
  - X<sub>2</sub> (pH value) = 7,      X<sub>3</sub> (moisture) = 30%
  - X<sub>4</sub> (aeration) = 15%
- Present ground fault current = 10,000 A
- Current Division Factor = 1.0 (worst case)
- Fault duration = 1.0 sec.
- Decrement factor = 1.0, and
- System growth factor = 2.0

#### □ No Corrosion Considerations:

The design value of the ground fault current  
= 10,000 x 1.0 x 1.0 x 2.0 = 20,000 A

Following the design guidelines given in IEEE Standard No. 80-2000, the *steel conductor size* can be calculated (without taking into account any corrosion effect) from equations (1) and (2).

The conductor area = 161.6 mm<sup>2</sup> (or 320 kcmil)  
The radius of the conductor = 0.72 cm (0.283 in)  
Suggested conductor size = 5/8 in diameter  
Area of the Steel Conductor = 197.9 mm<sup>2</sup>

If copper conductor is used instead, the cross-sectional area of the conductor = 70.9 mm<sup>2</sup> (140 kcmil) or use # 3/0 copper (are 167.8 kcmil or 85 mm<sup>2</sup>).

Ratio of the actual steel over copper conductor area = 197.9 / 85 = 2.33

#### □ Corrosion Included:

Corrosion rate calculated from equ. (4) is given by,

$$Y = 3.36 - 9.63 (10^{-5}) (2,500) + 0.29 (7) + 0.034 (30) + 0.0121 (15) = 6.35 \text{ mils/yr}$$

Assuming, average grounding system life of 25 years (corrosion rate reduces to half for the second 12 years), with a safety factor of 1.5, the total corrosion loss is:

$$Y = (12) (1.5) (6.35) (1.5) = 171.47 \text{ mils} \\ = 0.436 \text{ cm}$$

To compensate for the corrosion loss, the radius of the conductor size must be increased by 0.436 cm.

Hence, suggested minimum radius of the conductor is:  
= 0.72 + 0.436 = 1.156 cm (0.456 in)

Steel conductor cross-sectional area = 419.8 mm<sup>2</sup>  
Suggested conductor size = 7/8 in diameter.  
Area of Steel = 387.9 mm<sup>2</sup>

The ratio of the actual steel conductor area over the corresponding copper is = 387.9 / 85 = 4.6

It can be seen that this ratio decreases with the increase value of the fault currents.

#### □ Life Expectancy Estimation of Sacrificial Anode

It has been discussed earlier that in order to determine the number, type, weight and locations of sacrificial anodes, a detailed study has to be performed. Amongst other considerations, this depends on the soil resistivity, exposed surface area, and physical layouts of underground equipment and structures.

Assuming, the use of 32 lbs magnesium sacrificial anode as a means of cathodic protection in the above design problem, the current produced by each anode is given by equation (8),

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

where, K = 1.16 for 32 lb. anode size

The expected life expectancy, for the given anode size and the current output, can be estimated by using equation (6),

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

## CONCLUSIONS

In summary, steel can be used very effectively as ground grid material. Typically the cross-sectional area of steel is about 3-5 times larger than that of copper. A minimum size of 250 kcmil is recommended for steel conductor. To supplement the steel grounding, the rebars on concrete footings of building columns and equipment foundations can also be included to form part of the grid. This is also recommended by the NEC (Appendix 3) and has been routinely used.

In many design, steel could yield substantial savings over copper, in addition to preventing corrosion of steel pipes, and other underground structures (additional savings). The main concern in using steel is the corrosion. This can be compensated partially by increasing the cross sectional area of the conductor. In addition, to maintain the integrity of the ground grid, it is recommended that some modes of cathodic protection be designed and implemented. Regardless, corrosion should be studied, in detail, before utilizing steel grounding. The use of steel grounding is very useful when other steel structures are present in the vicinity.

It is also recommended that the continuity and the integrity of the steel ground grid, when employed, be checked and tested periodically by physical inspection at random locations to ensure the safety. On-line corrosion monitoring techniques with real time corrosion information such as Electrical Resistance (ER) method or Linear Polarization methods (LPR), combined with microprocessor and computer technology are available. This enables the engineer to detect system problems. These fast responses may directly be used for controlling the process, thus resulting in a better design.

An equation for estimation of corrosion has been introduced. Based on equation (2), the typical average corrosion rate of steel is between 5-7 mils/year. This agrees with the values of corrosion rates given in Table V<sup>[2][5]</sup>. In the absence of all required data, the corrosion rate can be estimated. A typical value of 6 mils/year is a good estimate.

Designing the cathodic protection scheme requires additional data, most importantly the soil resistivity and soil characteristics. For low resistivity and highly corrosive soil, the current requirements can be estimated at 30 mA/ft<sup>2</sup> of exposed surface area, whereas, for high resistivity and low corrosive soil the number is closer to 3 mA/ft<sup>2</sup>.

**Table V**  
**(Average Corrosion Rates of Several Metals)**

Materials Used	Corrosion Rate (mils/year)
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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## APPENDIX - A

### Relative Corrosion Potential of Various Metals

Corrosivity	Metals
Least Corrosive (Cathodic)	1 - Gold (Noble) 2 - Graphite 3 - Silver 4 - Stainless Steel 5 - Copper, Bronze, Brass 6 - Tin 7 - Lead 8 - Lead / Tin Solders 9 - Cast Iron, Carbon Steel 10 - Aluminum 11 - Zinc*
Most Active (Anodic)	12 - Magnesium*

(\*) Used as sacrificial anode to protect steel from corrosion in Galvanic Cathodic Protection.

## APPENDIX - B

### Electrochemical Potential Series

Metal	Ion	Volts**
Magnesium	Mg <sup>+++</sup>	-2.400
Aluminum	Al <sup>+++</sup>	-1.660
Zinc	Zn <sup>++</sup>	-0.763
Iron	Fe <sup>++</sup>	-0.440
Stainless Steel	Fe <sup>++</sup>	-0.250
Tin	Sn <sup>++</sup>	-0.136
Lead	Pb <sup>++</sup>	-0.126
Hydrogen	H <sup>+</sup>	0.000
Copper	Cu <sup>++</sup>	+0.337
Silver	Ag	+0.780
Gold	Au	+1.360

(\*\*) Potential in salt solution of normal ion activity relative to normal hydrogen electrode.

## APPENDIX C

### NEC Requirements

The National Electric Code (NEC) Section 250-50 requires certain types of electrodes must be bonded together to create a grounding system. Metal underground water pipes and all underground piping systems are included in this as well as grounded building steel. Another type of electrode that requires this type of bonding is a concrete encased electrode. A concrete encased electrode is defined as either a steel

electrode longer than 20 ft., galvanized or non-galvanized, and larger in diameter than ½ in, or a copper electrode longer than 20 ft. and not smaller than #4 AWG, encased in at least 2 in. in concrete. Most building foundations, and many equipment foundations, if they use rebar larger than #4 AWG and are large enough to contain 20 ft. or more rebar, fall within the NEC's definition of a concrete encased electrode. Therefore, the rebar in these foundations must be bonded to the grounding system. Even if the rebar in a foundation doesn't fall within the NEC's definition of a concrete-encased electrode, it will still be beneficial to bond the rebars in concrete structures to the grounding system. This is especially true if the surrounding soil has high resistivity and the concrete foundation can become an effective part of the ground grid.

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