GROUNDING AND BONDING CONDUCTORS: SOLID, STRANDED, BARE OR INSULATED?

Paper No. PCIC-2018-03

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Abstract – Recent discussions between governmental agencies, engineers, and standards / code making panels have raised the question of the appropriate type of grounding system conductor. What type of conductor should be used in grounding connections? What factors affect the life of grounding conductors? How should grounding conductors be sized? How do the current NEC requirements affect the quality of the ground system? In many cases, the selection of the appropriate conductor to be used is considered a matter of preference. However, the proper selection of the conductor can enhance or degrade system reliability and performance. This is especially true in critical or high energy applications. The technical factors that go into selection of a grounding conductor are discussed. Reliable criteria for selection of the appropriate grounding conductor are developed and presented.

Index Terms – Grounding, bonding, conductor, ground grid, ground ring, corrosion, stranded, solid, basket weave

I. INTRODUCTION

Grounding and bonding are common and necessary factors in all electrical installations. They are also one of the most misunderstood areas of electrical system design.

Nearly all electrical engineers are aware of the need for power system grounding per standards requirements and can perform the basic table lookup functions for minimum grounding electrode conductor (GEC) and equipment grounding conductor (EGC) selection. However, standards tables merely specify minimum conductor sizing and do not address all the factors necessary in selection, installation and maintenance of effective grounding and bonding conductors for commercial and industrial locations.

The broad reasons for installation of effective grounding and bonding generally fall under three categories: personnel safety, equipment protection and fire prevention. Of these, the most critical, of course, is personnel safety. In general, a system designed to minimize exposure to personnel from electrical hazards is one that, de facto, provides reasonable equipment protection and reduces the risk of fire ignition. [1,2] Factors in addition to personnel protection must also be addressed in an effective grounding system.

An effective bonding and grounding system consists of three areas:

1. An effective, low impedance connection to earth, comprised of the system ground.
2. An effective, low impedance path from equipment to be protected (and from protection equipment) to the system ground.
3. An effective, low impedance bonding path between metallic equipment to equalize potential.

For each of these three areas, the proper selection of conductor material, size and construction is crucial.

The goal of an effective bonding and grounding system is easy to state and nearly as easy to understand: '*an effective bonding and grounding system provides a path to equalize the potential of all metallic surfaces and to dissipate any errant electrical energy to earth*.' The design, selection and maintenance of an effective system to accomplish this goal, however, is not nearly as straightforward. The complexity is particularly true in critical system applications, or in systems where elevated levels of energy are present.

II. TYPES OF CONDUCTORS

Many varied materials and construction types may be used for grounding conductors. Each has distinctive characteristics which make it more or less appropriate for different areas of grounding and bonding. The use of building materials as part of the grounding system is out of scope for this treatise.

A. Conductor Materials

The materials most commonly used in grounding and bonding conductors (including buried conductors) are depicted in Table 1. Key electrical and mechanical characteristics are also correlated. A qualitative discussion of each material follows:

1) Copper (Cu): Copper is by far the most commonly used material for grounding and bonding conductors. The choice is due to copper's relatively high conductivity and very low permeability. In addition, Cu has reasonable tensile strength and resistance to corrosion in most conditions. Cu should be tin or lead plated in high sulfur environments, including the presence of H_2S. Cost (per kg) may be a significant factor, as copper can be 3-5 times the cost of aluminum and 7-10 times the price of galvanized steel. Copper is approximately equivalent in price (per kg) to most grades of stainless steel.

Table 1 – Properties of Conductor Materials

Material	Conductivity (% IACS)	μ_r	Melting Point (°C)	Density (kg/m^3)	Tensile strength (N/mm^2)	Temp coeff of R (°C^{-1})	Relative Cost
Copper	100%	1.0	1084	8940	345	4.29x10^{-3}	$$$$
Aluminum	65%	1.0	660	2712	221	3.8x10^{-3}	$$
Copper Clad Steel	20-40%	165-720	1084*	8100-8200	350 - 400	3.8x10^{-3}	$$$
Stainless Steel 300	1.7-2.5%	1.4 - 3	1375 - 1450	7480-8000	~520	~0.94x10^{-3}	$$$$$
Stainless Steel 400	2.4-3.1%	180 – 380	1425 - 1530	7480-8000	415 - 655	~1.0x10^{-3}	$$$$$$$
Galvanized Steel	~10%	~100	420*	~7850	~400	~5x10^{-3}	$
***** lowest melting point of combined metals							

2) Aluminum (Al): Aluminum is often used for bonding conductors due to its relatively low cost. Al has somewhat high conductivity and is much lighter weight than copper (approximately 30% Cu density). Aluminum conductors are flexible and easy to handle. Aluminum conductors are highly susceptible to corrosion. As a result, they are not appropriate for ground grids or areas exposed to ground contact. In fact, codes and standards prohibit the use of aluminum for these areas [3,4,5,8,10]. Aluminum also has a very low melting point compared to other conductor materials. Consequently, conductors using aluminum must be much larger than those using other materials to avoid melting under fault conditions.

3) Copper Clad Steel (CCS): CCS is a bimetallic material which is essentially a steel core with an outer layer of copper. The steel offers higher tensile strength, while the copper layer increases the conductivity to between 20% and 40% of Cu. The copper layer also acts as a corrosion protection layer for ground contact applications. CCS is less flexible and somewhat lighter weight than Cu conductors. CCS is most commonly used in ground grid and ground rod applications as opposed to bonding or grounding connectors. For application in high frequency applications, CCS is a reasonable selection as the skin depth is less than the Cu layer.

Care must be taken when using construction where the Cu is merely attached to the outside of the steel rather than being electrically or chemically deposited. Coated type conductors are easily damaged when bent. CCS is generally less expensive than Cu, but more expensive than Al conductors.

4) Stainless Steel (SS): Stainless steel encompasses a very wide range of material compositions. For grounding conductors, typically 300 series materials are used. This series is valued in corrosive environments, including ground contact, because of their high resistance to corrosion (excluding chloride environments). The major downside to stainless steel conductors is the very low conductivity of the material. Care must be taken to consider the increased permeability of cold worked (drawn) stainless steel conductors in high frequency applications, such as lightning. The cost of SS has made the material prohibitive for use as a conductor, except in the most extreme applications. Generally, the size of SS conductor must be 5-7 times the size of a CU conductor for the same ampacity.

Two important cautions must be taken when using SS. The first is to avoid low-grade stainless steels due to the high resistance and high permeability, without the benefits of good corrosion protection. The other is to avoid high grade (400 series) stainless steels due to the very high permeability, which greatly increases impedance of the path.

5) Galvanized Steel (GS): In some applications, galvanized steel is used for grounding / bonding conductors in areas where cost is the ultimate driving factor. Some IEC standards allow the use of galvanized steel, even for lightning protection conductors [5]. Despite being allowed by industry standards, extreme caution must be undertaken when using GS for grounding and bonding conductors. The relatively low conductivity and very low melting point of the galvanized layer make sizing of the conductors difficult. Additionally, the high permeability must be considered when used in high frequency environments. Care also must be taken to avoid mechanical stresses, which can cause the galvanized layer to mechanically separate from the underlying steel. GS is a very low-cost solution, with prices (by weight) approximately 10% of Cu or SS.

In addition to the varied materials available, diverse conductor construction is used for grounding conductors. Construction affects such things as (1) ease of installation, (2) mechanical strength, (3) high frequency impedance and (4) soil contact area. A brief discussion of the qualitative characteristics of each of the conductor constructions follows.

B. Solid Conductors (Sol)

Solid conductors, in general, have the highest overall resistance to mechanical damage. In addition, they have the highest resistance to corrosive damage, due to the reduced surface area exposed to the corrosive environment. Two types of solid conductors are normally used for grounding applications: round and flat (strap).

The most common solid conductors are round. Vertical ground rods tend to be round solid conductors. Round rods can handle being driven and are generally self-supporting in the soil. Round solid conductors have the lowest flexibility of all conductor types, making them the most difficult to bend and install. Due to skin effect issues, solid conductors also have greater high-frequency impedance, which makes them less suitable for applications such as lightning protection.

In contrast, flat solid conductors (strap) have very good flexibility for the size of conductors, at least in one direction. Because of the thin, wide shape of strap, it has very low inductance and exhibits lower impact from skin effect, resulting in very low impedance in high-frequency applications.

When strap is used in soil, the ribbon has a very high contact area with the soil, leading to overall lower ground contact impedance. As an example, a 1-inch copper strap (1” X 0.022”) has the same soil contact area as a 5/8” driven ground rod. The downside of copper strap, is that the shape is more prone to mechanical damage than round conductors. The contour is also somewhat more prone to corrosion damage in soil applications.

C. Stranded Conductors (Str)

The overall category of stranded conductors encompasses many different configurations. Certain types of stranded conductors - such as sector, compact and segmented - are not discussed as they are very rarely applied in grounding applications. The following paragraphs describe common types of stranded conductors being used in grounding applications.

1) Bunch Lay (BL): conductors have no geometric consistency. As such, the impedance characteristics of this type conductor are inconsistent. Similarly, the mechanical strength and flexibility are incongruous. Consequently, for critical or high-energy applications, this construction should generally be avoided. Bunch lay conductors are a less expensive construction type.

2) *Concentric Lay (CL):* conductors are the most common type of stranded conductor. In this construction, a center strand is surrounded by one (or more) layers of helically laid wires. This provides a more consistent impedance and mechanical characteristic than BL.

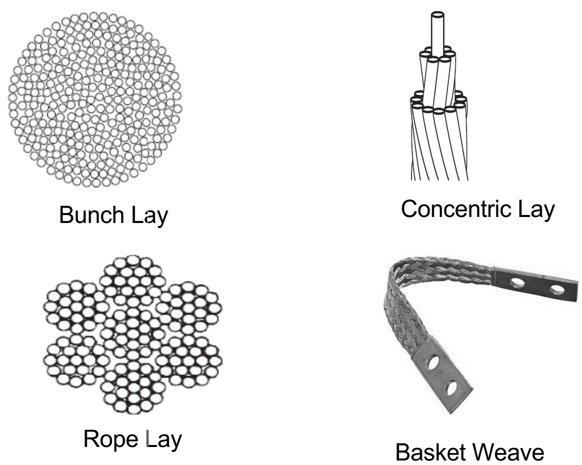

Fig. 1 - Cable Types

3) Rope Lay (RL): conductors are used when flexibility and conductor size (diameter) are critical. RL conductors are similar to CL, with the addition that each individual helically laid “wire” is actually a stranded conductor. Multiple filaments allow much smaller stranding to be used, increasing the flexibility and reducing the interstices in the conductor. RL construction has a lower overall impedance than CL for the same amount of conductor material, particularly at higher frequencies. The tradeoff is that the small strands of RL conductors tend to be more prone to mechanical damage, particularly in uninsulated configurations. RS conductors are generally used in moveable or mobile type equipment where flexibility and ease of handling are paramount.

4) Basket Weave (BW): or braided wire is a method of creating a conductor where individual strands are woven together. The intent is the conductors cross each other at higher angles. This reduces the concentration of magnetic fields caused by parallel conductors, which decreases high frequency impedance. BW also reduces the parasitic capacitance losses in the conductor. [21]

Braided conductors are very flexible, and maintain the flexibility in all directions. Additionally, mechanical movement of the braided conductor does not cause crimps and damage as easily as would occur in solid conductors. Braided conductors are used for bonding of moving equipment, such as gates or thief hatches on production tanks. *Overall, braided conductors provide the best balance of low impedance, flexibility and ease of use for high-frequency and high-energy applications, such as lightning or transient grounding protection.*

D. Conductor Insulation

For most installations, the question of bare vs. insulated for grounding conductors is less one of technical aspect but rather convenience. Conventionally, conductors pulled in raceways are insulated (particularly stranded conductors). Similarly, solid conductors connecting to ground rods are bare. Most grounding electrode conductors (GECs) used to connect equipment to local grounding locations are constructed of bare stranded conductors. In some situations, however, insulation on a grounding conductor can affect its functionality.

1) Isolated Ground: The most common and critical location for insulated ground conductors is in isolated ground (IG) systems. IGs are used to eliminate noise for sensitive electronic systems, and are required in certain hospital locations. In IG systems, the entire grounding conductor from the point of use to the isolated grounding electrode system should be insulated and isolated from all metallic components, which could provide an unintended path to the system ground. [6]

2) Buried Conductors: Any buried grounding conductor (with the exclusion of IG conductors) should be bare. Uninsulated allows for increased soil contact and lower ground contact impedance. In areas of highly corrosive soil, practice often allows insulated conductors for static dissipation or lighting protection system (LPS) bonding. The intent is to increase the life of the bonding conductors. However, the use of insulated buried conductors defeats the purpose of the grounding system by isolating the bonding from earth. Concerns about conductor life are better addressed by proper inspection and maintenance.

3) Personnel Safety: In some locations, personnel may be exposed to hazardous voltages during a fault condition. Proper sizing of grounding conductors, as discussed below, can prevent the voltage from rising to dangerous levels. Locations with metal raceways experience as much as half of fault current flowing in the raceway, rather than in the grounding conductor. [14] The raceway is at least as exposed to personnel as is the grounding conductor. Nevertheless, in locations where grounding conductors are exposed to personnel, the use of insulated conductors can provide some modicum of increased safety without compromising the functionality of the grounding system.

III. CONDUCTOR SIZING

The selection of grounding conductor size is not a simple table lookup process! Note that conductor sizes specified in IEEE 80, the NEC, IEC 62305, NFPA 780 and other standards [4,8,10,15] are *minimum* conductor sizes for a specific installation and not *specified* conductor sizes. Several factors go into the sizing of a grounding conductor. The final selection should take all the following into account. The *largest* conductor size from any of the applicable methods below should be chosen.

A. Sizing based on Standards

Although standards contain tables for minimum size lookup, there is always language which states that care must be taken. Choose the conductor appropriate for the actual installation, rather than just the minimum. An example is taken from NFPA 70, the National Electrical Code (NEC).

NEC Table 250.122 lists the "Minimum Size Equipment Grounding Conductors" based on the size of the overcurrent device ahead of the equipment. However, the note below the table states "Where necessary to comply…the equipment grounding conductor shall be sized larger than given in this table". Additionally, Article 250.4(A)(5) addresses functionality.

IEC 62305-4 Table 1 lists the minimum cross-sections for bonding components in a lightning protection system governed by this standard. However, Article 5.6 states that "Material, dimensions and conditions of use shall comply with IEC 62305-3". IEC 62305-3 lists many more factors which must go into bonding conductor size. Factors include mechanical strength, location, corrosion damage, etc. [5] The selection of minimum size from standards is merely a starting point.

B. Sizing based on Fusing Temperature

Sizing of grounding conductors for fault conditions has long been based on the fusing temperature of the conductor and the anticipated fault current. The general form of the equation used to calculate the ampacity of a given conductor is shown in (1). [8,13]

$$A = 4.889 \cdot I \sqrt{\frac{\rho \cdot t \cdot 10^{-4}}{\frac{1}{\alpha_0} \cdot s_w \cdot s_h \cdot \ln\left(\frac{T_{max} - T_{ambient}}{\frac{1}{\alpha_0} + T_{ambient}} + 1\right)}} \quad (1)$$

where

I	Current	Amperes RMS
A	Conductor cross section	mm^2
t	time current is applied	seconds
T_{max}	Max allowable temp	°C
$T_{ambient}$	Ambient temp (40)	°C
α_0	Thermal coeff of resistivity	$°C^{-1}$
ρ	resistivity of material	μΩ·cm
s_h	specific heat of material	cal/gram/°C
s_w	density of material	$gram/cm^3$

Equation (1) calculates the absolute minimum size conductor required to keep the conductor at or below the fusing temperature. Reasonable safety factors should be applied depending on the quality of the information known, specifically regarding fault size and duration. Based on (1), the minimum size conductor per amp is shown in Table 2. Included are various conductors assuming a 1 second fault. Additional tables are contained in Appendix A.

According to IEEE 837, the maximum temperatures for conductors with connections are dramatically lower than the fusing temperature of just the material itself. An exception is exothermically welded, which takes on the properties of the conductor. Regardless of material, the maximum temperature for a brazed connection is 450°C and the maximum temperature for a bolted or crimped connection is 250°C. [7] If the grounding conductor is insulated, then the maximum temperature rating of the insulation must also be considered.

Table 2 – mm^2 per Amp for 1 second fault

Material	**Conductor Only**	**Brazed Conns**	**Bolted Conns**	**Insulated (90°C)**
100% Cu	3.41×10^{-3}	4.47×10^{-3}	5.66×10^{-3}	10.4×10^{-3}
97% Cu	3.46×10^{-3}	4.53×10^{-3}	5.75×10^{-3}	10.6×10^{-3}
Aluminum	5.61×10^{-3}	6.57×10^{-3}	8.16×10^{-3}	15.2×10^{-3}
40% CCS	5.02×10^{-3}	6.63×10^{-3}	8.45×10^{-3}	15.7×10^{-3}
20% CCS	6.86×10^{-3}	9.06×10^{-3}	11.6×10^{-3}	21.5×10^{-3}
300 SS	17.7×10^{-3}	28.0×10^{-3}	67.7×10^{-3}	74.7×10^{-3}
400 SS	15.5×10^{-3}	24.7×10^{-3}	33.2×10^{-3}	65.7×10^{-3}
GS	13.8×10^{-3}	13.8×10^{-3}	17.0×10^{-3}	31.0×10^{-3}

Application of these tables is simple. Consider a location with a 20kA fault current and having bonding conductors comprised of hard drawn Cu (97% conductivity). The minimum cross-sectional area of the bare conductor, with only exothermic connectors would be $69mm^2$(trade size 3/0 AWG or $95mm^2$). In contrast, the minimum size for a bare conductor with bolted or crimped connections would be $115mm^2$, which is trade size 250kcmil or $120mm^2$.

C. Sizing based on Damage Curves

Another method for selecting conductors is similar to, but more detailed than, the just discussed fusing temperature. The fusing temperature method described above only considers the maximum fault current and assumes a clearing time. The alternative damage curve method considers all types of faults and the actual settings of the protective devices. [12,14]

As an example, Hughes et al discuss the case of a 400A molded case circuit breaker protecting a circuit fed by one 500 kcmil conductor per phase. The maximum fault current at the location is 20kA, which is not atypical for a large commercial or small industrial location.

According to NEC Table 250-122, the minimum size conductor for the EGC is #3 AWG Cu. The conductor is protected against bolted ground type faults (e.g. 20kA). However, a wide range of fault currents, between ~500A and 2000A, would allow the EGC to be damaged with no protection pickup. The damage curves are exhibited in Fig. 2. According to these curves, a 3/0 AWG Cu conductor would be required to avoid damage. The wire size is multiple times larger when selected using the damage curve. The use of damage curves, then, is a valuable tool in evaluating the size of grounding conductors. This method of sizing also meets the thermal sizing requirements of IEC 60364[15].

D. Sizing based on Electric Shock Calculation

IEC 60364, IEEE 80, and other standards address the sizing of ground conductors for personnel protection. [8,15] The standards approach the protective-sizing in different ways, depending on the application and ground connection of the system. The methods include (1) calculating maximum body current, (2) calculating impedance necessary to clear protective devices in a given time, or (3) a simply stated maximum touch potential. In general, the touch potential at any location in the system, and under maximum fault conditions, cannot exceed 50 VAC at 50-60 Hz conditions. The application of the other methods is beyond the scope of this treatise. Nevertheless, under certain conditions, the required size of the system grounding and bonding conductors can be impacted by the necessity to keep the system safe for personnel. Additional reading on these topics can be found in the standards [3,4,8,10,15] and in [12,17,18,19].

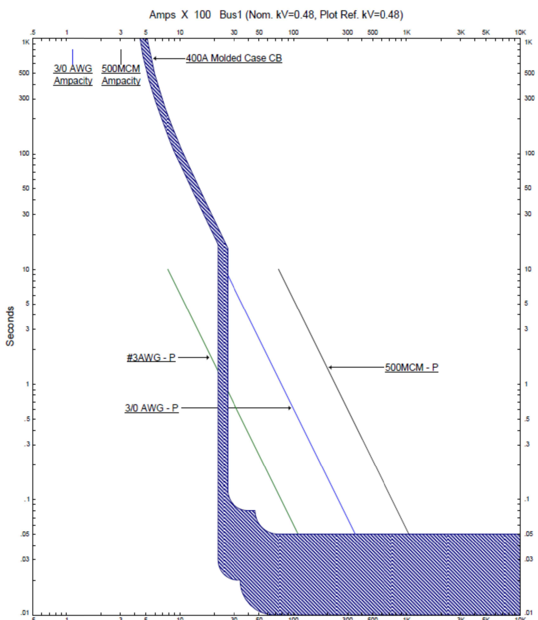

Fig. 2 – Sizing based on Damage Curve

E. Sizing based on Mechanical Damage

The previous sections largely deal with sizing of grounding conductors for fault current from the electrical power system. Sizing grounding conductors for lightning protection systems (LPS) involves more than the I^2R based sizing discussed above. Inductive reactance must be seriously considered. Reactance is driven by permeability of the conductor material and conductor construction. In addition, mechanical damage often comes from the lightning event itself.

‘In many cases, the minimum conductor size specified in the standards is not sufficient to withstand a 98th percentile lightning event of 200 kA. Table 3 summarizes the minimum size LPS conductors for both IEC and NFPA standards.

Each individual lightning stroke is comprised of three primary components from the transient curve [11]:

- Component A is a relatively fast (200 μS duration) high current peak with peak currents up to ~200kA.
- Component B is an ~500 - 2,000 μS component of reducing current from ~10 kA to ~400 A.
- Component C is follow-on current of ~400 A lasting out to 0.75 S.

Table 3- Minimum Sizes of LPS Conductors

Standard	**Type Conductor**	**Material**	**Min Size** mm^2 (AWG)
IEC 62305-4	Bonding Bars	Cu, Fe	50 (1/0)
	Downcomers	Cu Al Fe	16 (#4) 25 (#2) 50 (1/0)
	Jumpers	Cu Al Fe	6 (#8) 10 (#6) 16 (#4)
NFPA 780 (Class I)	Downcomers	Cu Al	29 (#2) 50 (1/0)
	Jumpers	Cu Al	13.3 (#6) 20.8 (#4)

A lightning flash generally contains between 4 and 20 of these individual strokes. Rakov et al have demonstrated that these strokes will typically have the same attachment point. [22] Consequently, an LPS conductor must be able to withstand several intense strokes.

When sizing lightning conductors, components B and C are responsible for the I^2R heating of the conductor. An examination of the tables in the appendix shows that for a very small 10,000 A current lasting 0.25 S, the minimum conductor size Cu conductor is 17.3 mm^2 (#4). For the 400 A component which lasts 0.5 S, the minimum conductor size is 1 mm^2 (#16). Thus, the specified down-comers in the standards are appropriately sized for these current components.

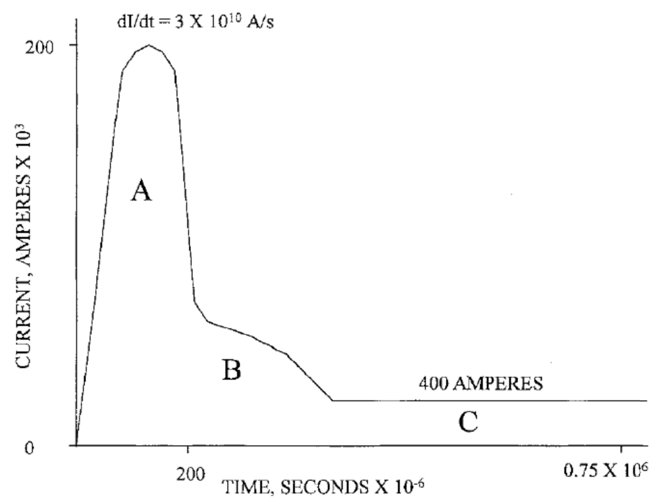

Fig. 3 - Lightning Waveform Components (not to scale) [11]

Component A contributes very little energy to ohmic heating due to the very short duration of the event. This component, however, is the primary contributor to mechanical damage. The Biot-Savart law states that any current flowing through a conductor generates a magnetic field which, generally, exerts an electromagnetic force on the conductor. Skin effect dictates that the current density is very high on the outside edges of the conductor and much lower towards the interior. An unequal distribution of the magnetic field results.

For the very high currents associated with a lightning stroke, the magnetic force can be substantial enough to cause compression of the conductor as well as mechanical damage to the metal. A mechanical failure of an LPS conductor during a lightning event not only removes protection but also creates localized arcs and sparks. These can serve as a source of ignition and create increased risk for personnel. The risk is particularly high in Classified (Hazardous) locations.

Tobias [11] has demonstrated the effects of the magnetic force on conductors used for lightning protection. For this study, various size conductors were exposed to 150 kA – 200 kA artificially generated lightning strokes. The conductors tested were 13 - 27 mm^2 (#6 - #3) Cu solid, stranded and braided wire, 38.5 mm^2 (#2) Al braid, and 30 mm^2 (#2) steel braid.

A summary of the test results is described below.

- In virtually all conductors tested notable reduction in diameter of the conductor occurred. Even the solid Cu conductor exhibited some reduction. In at least one case reduction was enough to cause failure.
- The high resistance and inductance of the steel braid made testing at full current impossible. Test currents reached only 75% of desired value.
- Only the 27 mm^2 (#3) Cu and 30 mm^2 (#2) steel braid conductors survived well during the 200 kA series of tests. However, recall the steel was not able to be tested at full 200 kA.
- The Al braid conductor, despite having the largest cross-section, did not survive even a single 150 kA event.
- Sharp bends in the conductors caused an increase in inductance and a local concentration of forces. In all cases except the steel braid, the effect was a catastrophic failure of the conductor.

The following conclusions can be drawn.

- IEC requirements for both downcomers and jumpers (Cu and Al) are insufficient for sizing of lightning conductors. The conductor sizes specified would not survive a high percentile lightning event.
- NFPA 780 specifications for Cu downcomers were sufficiently sized to prevent mechanical damage. Specifications for Cu jumpers are sufficient to survive a 100 kA event. If these jumpers are judiciously placed so that each will never carry more than 50% of the lightning current, they are sufficient. In other words, at least two down-comer paths are necessary.
- Extreme caution must be exercised when using Al conductors for an LPS conductor. The extremely low tensile strength of aluminum makes failure during a lightning event very likely.
- While the tensile strength of steel conductors allows them to survive the mechanical forces generated, the leads are not ideal for LPS. The electrical characteristics makes steel a poor conductor, especially at higher frequencies.
- Evidence validates that sharp radius turns thwart proper operation of the lightning protection system.

IV. LIFE OF GROUNDING SYSTEM

The performance of a grounding system and the related bonding connections is crucial during an electrical fault or lighting strike. Transient events occur whether a facility is new or 30 or 40 years after construction. A properly designed and maintained system will provide required protection throughout the entire life of the facility, even if multiple faults occur over the years. In addition to the electrical criteria of a system, a thorough design must address the following operational issues.

- Install to protect and preserve integrity of the system.
- Avoid situations which may cause accelerated corrosion or component degradation.
- Conduct periodic inspection and maintenance.
- Upgrade the grounding and bonding to coincide with facility changes and additions.

A. Grounding Installation Considerations

A grounding system must be installed in a manner such that all components of the system are protected from physical damage, including vandals, thieves, traffic, landscaping equipment or industrial equipment such as forklift traffic. Conductors which are exposed on the exterior wall of a structure require means of protection from physical damage, up to a height of 6' above grade. [4]

In areas where burglary is a concern, theft-deterrent conductors are an appropriate choice. CCS conductors are much more difficult to cut than pure copper conductors and tend to discourage theft and vandalism. In addition, CCS has less market value to miscreants. Composite cables are also available which include steel strands woven with copper or aluminum to discourage larceny. For example, some electric utilities use composite steel and tin-plated copper conductors for exposed grounding conductors on poles.

In some environments, ground enhancement materials are employed to improve the electrical performance of a grounding system. Common materials are bentonite clay, petroleum coke fines and salts. Many of these require periodic maintenance and replacement. IEC 62561-7 conforming materials meet conservation requirements, electrical performance standards and physical strength specifications. Since IEC 62561-7 materials contain cement and cure to a hardened state, the products provide long-term electrical performance, physical protection for conductors and theft-deterrence. [23]

B. Corrosion Mitigation

The most likely cause of time-induced degradation in grounding systems is corrosion. Several long-term grounding studies have been completed. [23,25,26] The studies considered various applications, diverse materials, soil conditions and environmental factors. Some of the most important observations from these studies are noted.

1. Corrosion occurs on metal components whenever moisture and oxygen are available.
2. Corrosion can be accelerated by stray DC current (or the DC component of an asymmetrical AC current) in the surrounding earth from outside sources.

3. Chlorides and sulfides in the soil increase the corrosion rates of metals.
4. Microbial activity in the soil can cause corrosion.
5. Contact between dissimilar metals causes electrochemical corrosion. The effect is most serious in mechanical connections of metals with large differentials in electrochemical potential [26, 26]. Mechanical connections are most susceptible because contamination and moisture can penetrate between the mating surfaces, allowing an electrolyte to isolate the conductors.
6. Low resistivity soils promote good electrical performance of grounding systems but tend to enhance corrosion rates of the conductors.

Key conclusions of the long-term grounding system studies are as follows.

1. SS, Cu, CCS and GS conductors are generally suitable grounding materials. Aluminum is unstable in soil and must not be used in ground contact.
2. Although SS grounding components provide the best resistance to corrosion, the cost and electrical properties (high X and R) of stainless steel dictate the material would only be used in facilities where corrosion resistance is paramount.
3. Cu has excellent electrical characteristics and corrosion resistance in most soils. However, high purity Cu does not have the tensile strength generally needed to be used as a driven ground rod.
4. Corrosion is generally most severe near grade level, where moisture and oxygen are available. Deeply buried grounding systems have both better electrical performance and lower rates of corrosion. Deeper grounding systems also tend to be more stable in varying environmental and seasonal effects on the soil.
5. CCS, produced by cladding or electroplating, makes a good ground rod. The strength of the steel allows deep driving and the copper outer layer provides improved electrical performance and good corrosion resistance.
6. If joining conductors of dissimilar metals is required, the connection must be of the following types:
   - A molecular bond between the two metals (exothermic welding, friction welding, etc.),
   - A connection in which the conductors made of dissimilar metals are separated by stainless steel,
   - A connection enclosed or sealed in a manner that eliminates moisture entering the contact region.
7. GS conductors are cost effective but provide inferior service life. The zinc coating provides electrochemical protection for the core, even in areas where the steel is exposed. Corrosion will eventually consume the zinc while the steel is protected until the zinc deteriorates. At this stage, the steel core becomes unprotected and will corrode very quickly.

C. Periodic Inspection and Maintenance

The performance of a grounding system can vary significantly as a result of environmental changes. [26] For example, soil that exhibits low resistivity during a rainy season may have significantly higher resistivity during the dry season. Multiple soil surveys performed at a site before the design of grounding system begins should reveal worst case conditions. These surveys should be conducted after any soil import has concluded. Once the grounding system is designed and installed, the system performance must be evaluated to confirm that design criteria are met. The system must also be evaluated periodically over the life of the facility to ensure that it has not been subject to excessive corrosion, physical damage or changes in soil conditions. [26]

Soil electrical properties should be evaluated prior to system design.[9] The Wenner Four Pole (Probe) Method may be employed to collect soil data, which is then used to develop a multilevel soil model. Once the design is implemented, the Three Pole (Probe) Fall of Potential method may be applied to evaluate the performance of the grounding system. System evaluation must be done without a utility connection to the facility to avoid interference from the utility connection. Other interference must be considered.[9]

Ground access test wells should be installed at ground rod connection locations to allow inspection and evaluation. Electronic hand-held, earth resistance measurement instruments are available to analyze the performance of a facility’s grounding system as an on-going basis. These instruments are convenient, safe and can be used any time, even when the utility connection to a facility is in place.

When inspecting and maintaining grounding systems, heed components that are susceptible to physical damage. For example, temporary ground connections to vehicles during loading or unloading of hazardous materials are easily damaged from handling. Bonds for gates and fences are also easily damaged or fatigued from cyclic motion.

When new catwalks, metal stairs, storage tanks, etc. are installed, the proper bonding and grounding is often overlooked, creating hazards during lightning strikes or electrical fault conditions. Each and all of the structural metal equipment must be properly grounded and bonded.

D. System Upgrades

A facility typically has significant functional adaptations over its life. In some cases, facilities will be totally revamped or repurposed. After any structural, mechanical, or electrical modifications to the facility, an upgrade to facility grounding will likely be required.

When upgrading a grounding system, the common approach is to add ground rods or a ground loop. The additions must be properly bonded to the existing grounding system network. Specifically, address the connections between aged conductors and new conductors. Aged conductors, especially those buried in the earth, will have some surface corrosion. When corrosion has materially reduced the effective cross-sectional area of a conductor, the conductor must be replaced or augmented.

Aged conductors must be thoroughly cleaned prior to connection with a new conductor. Exothermic welding is highly recommended with aged connections. The flow of molten metal in the welding process tends to penetrate the base metal and displaces the corrosion byproducts. Ensure that aged cables are carefully dried before welding, since the heat generated turns water into rapidly expanding water vapor.

Before upgrades, the present system must be thoroughly evaluated. As noted above, gather data on existing soil conditions during different seasonal conditions. Evaluation of the existing grounding system should include electrical tests and thorough inspections for corrosion, damage and missing elements of the system. Finally, after implementation, ground resistance should be tested before commissioning and at regular intervals afterwards.

V. CONCLUSIONS

The selection of grounding conductors is a more involved process than simply looking up the minimum conductor size from tables in Standards and codes. The selection of (1) materials, (2) construction, (3) insulation and (4) size all impact the performance of the grounding conductor both in the short term and over the life of the facility. Mechanical strength, corrosion resistance, I^2R heating, conductivity, inductive reactance and exposure to hazards must all be considered.

In almost all situations, the minimum size conductor listed in codes and standards is insufficiently sized for quality or lightning performance. Aluminum conductors should be used rarely and only where they are not at risk of ground contact or other corrosive atmospheres. Stainless steel can be used in highly corrosive environments, but consider the very high R and X inherent in the material. Galvanized steel, though allowed by codes and standards in some situations, is a very poor choice for conductor and generally should not be used.

Copper provides the best balance between flexibility, corrosion resistance, conductivity and low reactance. Basket weave construction reduces inherent reactance and is generally preferred for all grounding applications. The use of insulation reduces the ampacity of the conductors, resulting in larger wire size and reduces the effective ground contact resistance. The grounding system must be routinely inspected throughout the life of the facility to ensure continued performance.

While cost of conductors is a consideration, efforts to reduce up-front installation costs must not negatively impact system integrity over the life of the facility.

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VII. VITAE

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Appendix A
Minimum Cross Sectional Area for Different Conductor Materials and Fault Duration

Table A- 1 97% (Hard Drawn) Cu Minimum CSA per Amp

Time (sec)	Conductor (cir mils)	Brazed (cir mils)	Bolted (cir mils)	Insulated (Cir mils)	Conductor (mm^2x10^{-3})	Brazed (mm^2x10^{-3})	Bolted (mm^2x10^{-3})	Insulated (mm^2x10^{-3})
30	37.4	49.0	62.1	114.4	18.95	24.82	31.47	57.97
4	13.7	17.9	22.7	41.8	6.92	9.06	11.49	21.17
1	6.8	8.9	11.3	20.9	3.46	4.53	5.75	10.58
0.5	4.8	6.3	8.0	14.8	2.45	3.20	4.06	7.48
0.25	3.4	4.5	5.7	10.4	1.73	2.27	2.87	5.29

Table A- 2 Aluminum Minimum CSA per Amp

Time (sec)	Conductor (cir mils)	Brazed (cir mils)	Bolted (cir mils)	Insulated (Cir mils)	Conductor (mm^2x10^{-3})	Brazed (mm^2x10^{-3})	Bolted (mm^2x10^{-3})	Insulated (mm^2x10^{-3})
30	60.6	71.0	88.2	163.8	30.73	35.97	44.69	82.98
4	22.1	25.9	32.2	59.8	11.22	13.13	16.32	30.30
1	11.1	13.0	16.1	29.9	5.61	6.57	8.16	15.15
0.5	7.8	9.2	11.4	21.1	3.97	4.64	5.77	10.71
0.25	5.5	6.5	8.1	14.9	2.80	3.28	4.08	7.58

Table A- 3 30%CCS Minimum CSA per Amp

Time (sec)	Conductor (cir mils)	Brazed (cir mils)	Bolted (cir mils)	Insulated (Cir mils)	Conductor (mm^2x10^{-3})	Brazed (mm^2x10^{-3})	Bolted (mm^2x10^{-3})	Insulated (mm^2x10^{-3})
30	62.0	81.8	104.3	193.7	31.40	41.46	52.86	98.15
4	22.6	29.9	38.1	70.7	11.47	15.14	19.30	35.84
1	11.3	14.9	19.0	35.4	5.73	7.57	9.65	17.92
0.5	8.0	10.6	13.5	25.0	4.05	5.35	6.82	12.67
0.25	5.7	7.5	9.5	17.7	2.87	3.78	4.83	8.96

Table A- 4 40%CCS Minimum CSA per Amp

Time (sec)	Conductor (cir mils)	Brazed (cir mils)	Bolted (cir mils)	Insulated (Cir mils)	Conductor (mm^2x10^{-3})	Brazed (mm^2x10^{-3})	Bolted (mm^2x10^{-3})	Insulated (mm^2x10^{-3})
30	54.2	71.6	91.3	169.6	27.49	36.29	46.27	85.91
4	19.8	26.2	33.3	61.9	10.04	13.25	16.90	31.37
1	9.9	13.1	16.7	31.0	5.02	6.63	8.45	15.69
0.5	7.0	9.2	11.8	21.9	3.55	4.69	5.97	11.09
0.25	5.0	6.5	8.3	15.5	2.51	3.31	4.22	7.84

Table A- 5 300 Series SS Minimum CSA per Amp

Time (sec)	Conductor (cir mils)	Brazed (cir mils)	Bolted (cir mils)	Insulated (Cir mils)	Conductor (mm^2x10^{-3})	Brazed (mm^2x10^{-3})	Bolted (mm^2x10^{-3})	Insulated (mm^2x10^{-3})
30	190.9	302.4	407.2	807.4	96.71	153.21	206.33	409.10
4	69.7	110.4	148.7	294.8	35.31	55.95	75.34	149.38
1	34.8	55.2	74.3	147.4	17.66	27.97	37.67	74.69
0.5	24.6	39.0	52.6	104.2	12.49	19.78	26.64	52.81
0.25	17.4	27.6	37.2	73.7	8.83	13.99	18.84	37.35

Table A- 6 Galvanized Steel Minimum CSA per Amp

Time (sec)	Conductor (cir mils)	Brazed (cir mils)	Bolted (cir mils)	Insulated (Cir mils)	Conductor (mm^2x10^{-3})	Brazed (mm^2x10^{-3})	Bolted (mm^2x10^{-3})	Insulated (mm^2x10^{-3})
30	149.6	149.6	183.8	335.1	75.81	75.81	93.15	169.78
4	54.6	54.6	67.1	122.3	27.68	27.68	34.02	61.99
1	27.3	27.3	33.6	61.2	13.84	13.84	17.01	31.00
0.5	19.3	19.3	23.7	43.3	9.79	9.79	12.03	21.92
0.25	13.7	13.7	16.8	30.6	6.92	6.92	8.50	15.50