BETTER GROUND GRIDS, PART I: IMPROVING CONTACT SURFACE AREA

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***Abstract*— This technical publication explores how a conductor's surface area in contact with the soil can dramatically improve the transmission of electrical fault energy into the ground for high power substation grounding applications. It is common for substation designers to overlook this performance characteristic because common round stranded copper cables, ranging from #2 AWG to 500 kcmil, do not vary much in their resistance to ground. Furthermore, copper strip conductors have almost completely been removed from recent versions of IEEE Standard 80, *Guide for Safety in AC Substation Grounding*. However, a new family of composite strip conductors, having widths several times greater than traditional copper cables, can be used to significantly reduce the resistance to ground in any soil condition. The newly engineered conductors are thin for flexibility and training in the field but strong for long service life when buried in the soil, exhibiting a copper layer twice the thickness of a common grounding electrode (ground rod).**

The benefits of composite strip ground grid conductors, when compared to standard 4/0 copper grounding cables, include 1.) better electro-thermal performance (I^2t), 2.) better mechanical break load strength, 3.) better theft resistance, 4.) better flexibility for field installation, and most importantly, 5.) a 6%-20% lower resistance to ground.

Keywords— Grounding contact surface area, resistance to ground, grounding conductors, ground grid, and power grid

I. ORIGINS OF GROUNDING

Since the Age of Enlightenment, the Earth itself has been used as an economic common return path for experimentation with electricity.

A grounding circuit requires both metal conductors and conductive soil to function. There are two competing understandings of electrical grounding discussed by electrical grounding experts today. The origins of both trace to the development of electrically transmitted communications, i.e. telegraph and telephone. For short transmission lines less than a few miles long, the Earth may be considered as *"one-half of the conducting chain forming the circuit with the line wire."* This hypothesis was first proposed by C. A. Steinheil, in Munich, Germany in 1837 for telegraph installations. [1] But for long transmission lines, the Earth may be considered *"an extremely large conductor of almost infinitely large mass, capable of absorbing the electricity as fast as it is developed."* The latter hypothesis was first explained in 1884 by Thomas D. Lockwood, a lawyer and electrical engineer at American Bell Telephone Company in the era of Alexander G. Bell and Watson. [2]

Prior to 1950, installation of a 4/0 copper ground grid under a substation was very unusual. Common practice was to drive electrodes (ground rods) deeply into the soil and connect them directly to electrical transmission equipment.

To add substance to the point, in 1952, a proficient engineer from General Electric designing a ground grid for a hydroelectric power plant built on impenetrable bedrock near the Colorado River in Texas considered the resistance to ground for several grid designs including metal strips in a grid, metal wires in a grid, and isolated plates. His analysis ultimately suggested the most economic and effective grid was made of 0.025-inch copper thread (No. 22 AWG gauge copper wire) in a two-foot grid net dropped in a reservoir to form a mesh that approximates the performance of a series of two-foot square plates in the water above the dam. [3]

Electrical infrastructure expanded in the United States between 1935 and 1955. The establishment of the REA (Rural Electrification Administration) initiated the utilization of electric power as part of the New Deal under President F. D. Roosevelt. By 1955, it is estimated that 90% of farms and ranches had electrical service and the American Institute of Electrical Engineers (AIEE, the predecessor to IEEE) provided a technical forum for discussion. [4]

II. DEVELOPMENT OF GROUND GRIDS

The modern copper ground grid is first found mentioned in the available literature in 1953 by Dr. Eric T. B. Gross, a pioneer in electric power engineering education, who explained that *"grounding grids are used in high-voltage stations when rocky ground makes the use of driven ground rods impractical".*

Gross created a new mathematical model of effective ground grids using the resistance and capacitance of the Earth. His analysis suggested ground grids made of 0.03-foot radius copper, which is a 500 kcmil cable, as shown in Fig. 1. He also recommended that the buried depth of the ground grid for most high voltage electrical applications should be 2 feet deep. [5]

	1950s GROUNDING CONDUCTORS		
	Diameter (Inch)	Radius (Inch)	Radius (Feet)
1/0 AWG	0.37	0.18	0.01
4/0 AWG	0.53	0.26	0.02
500 kcmil	0.81	0.41	0.03

Fig. 1. Modern conductors described in decimal feet.

Contemporary discussion in engineering journals of Gross' suggestion indicated that the design basis for sizing of copper grounding cable had very little scientific rigor but great sensitivity to mechanical strength, physical handling, and corrosion throughout the life of the ground grid. Some were even concerned that 500 kcmil copper was too small for their ground grids. Their critics referred to this sensitivity as the *"margin of ignorance"*. [5]

In 1954, the predecessor to IEEE Standard 80 (Std-80), released as *AIEE Grounding Guide*, parts of which were captured by the 1961 version of Std-80, provided some relief to electric substation designers by establishing the now-familiar standard ground grid on twenty-foot centers buried twelve to eighteen inches deep with a ground rod electrode set at each of the four corners of the overall system. It also recommended the use of 1/0 copper for brazed joints but also recognized that *"a large segment of the industry has set the 4/0 copper as a minimum for mechanical reasons."* Interestingly, it mentioned that even a network of a few connected ground rods is often sufficient for a suitable "grid". [6]

The 1954 AIEE Grounding Guide also documented the common use of buried copper strip as an alternative to buried copper cable for the creation of efficient ground grids and electrode networks.

Perhaps surprisingly, a counterargument to those who assume the predominance of 4/0 copper grounding is found in the 1976 version of Std-80, itself. Here it stated the following:

> *"Mechanical ruggedness will set a practical minimum conductor size. The earlier AIEE Grounding Guide, in effect, recommended minimum sizes of 1/0 and 2/0 copper for brazed and bolted joints respectively. It further stated that 'a large segment of the industry has set the 4/0 copper as a minimum for mechanical reasons.' On the other hand, many utilities have successfully used smaller sizes (down to No. 3 AWG in at least one case) with no appreciable mechanical trouble."* [7]

III. Overlooked Advantages of Strip

H. B. Dwight of both Massachusetts Institute of Technology (yes, *that* MIT) and New England Power Company (now part of National Grid) introduced mathematical expressions for the calculation of resistance to ground in 1936. His work included cables, plates, rods, and flat strips. [8]

Expanding upon Dwight's work, Reinhold Rudenberg of Harvard University wrote in 1945, *"we see that a flat strip follows a relation quite like that of a circular rod, and a strip thus is equivalent to a rod or a wire of a diameter equal to half the width of the strip."* His diagram is shown in Fig. 2. [9]

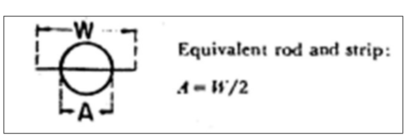


Fig. 2. Rudenberg equivalencies for rod and strip.

In other words, to make an equivalent ground grid from metal strip, Rudenberg suggested that the strip selected must be twice as wide as the substituted copper cable. Following this logic, one could reason that to make a more efficient one, the strip needed to be more than twice as wide. Such a conductor would have more contact surface area with the soil than any cable could reasonably provide.

Subsequent publications of Std-80 ended the discussion of buried grounding strips by introducing a simplified formula for substation ground resistance using a theoretical circle having the same area as occupied by the ground grid. The intent was to establish a preliminary design based on this approximation and then refine it, but in practice, the refinement of the preliminary design value was often neglected in favor of another simplified formula introduced by Laurent and Niemann. The 1961 version of Std-80 even indicated that *"resistance of a long electrode depends only to a slight extent on its diameter... it is therefore useless to depart from the circular type of conductor which is the sturdiest mechanically",* which this technical publication aims to dispute. The 1986 version of Std-80 added *"for typical conductors ranging from AWG 1/0 to 500 kcmils, the conductor diameter has negligible effect on the mesh voltage"*. And thus, the 1986 version of Std-80 introduced today's modified version of Schwartz's equations, as modified by chairman Sverak, for round grid conductors only. [6, 9, & 10]

The predominance of the 4/0 copper cable ground grid ever since caused the removal of the strip conductor resistance calculations from later versions of the standard, as well as stifling industry discussion. [10, 11, & 12]

However, just before the removal of strip conductors from technical discussion, an interesting riddle about contact surface area with the soil was presented in the 1976 version of Std-80, the same version that offered alternatives to 4/0 copper. An opportunity for future research was introduced.

> *"The effect of diameter on the resistance of the ground electrode (ground rod) formed by the buried conductor, and on the local gradients, has not been mentioned as a factor determining conductor size. Increase in diameter has a favorable effect in reducing both, other things being equal. However, the effect is small, the touch voltage varying approximately in proportion to the logarithm of the reciprocal of the diameter."* [7]

IV. Timeline of Grid Design Innovations

To clarify the most important developments in grounding conductor sizing and selection, this section summarizes the previous three sections, with emphasis on changes to IEEE Standard 80.

1837 Use of soil as an experimental return path for a telegraph communication circuit

1884 Use of soil as an electro-thermal sink for U.S. telephone fault current via vertical grounding electrodes (ground rods)

1936 Intellectual discussions about the transmission of grounding energy into the soil via various shaped conductors, including cables, plates, rods, and flat strips

1953 Introduction of a mathematical model for substation grounding design and attempts to standardize on 500 kcmil copper cable

1954 First publication of Std-80 recommending ground grids where ground rods proved impossible to install; minimum 1/0 copper

1961 Revised Std-80 for U.S. ground grids suggesting 4/0 copper cable, misstating that resistance to ground varies only slightly with diameter of the grid conductor

1976 Acknowledgement in Std-80 of the correlation between resistance and contact surface area of ground rods, but confusingly, not that of grid conductors

1986 Removal of Rudenberg's work from Std-80-in favor of chairman Sverak's modified Schwartz equations for round ground grid cables only

2000 Improvements to Std-80 language

2013 Improvements to Std-80 language

2024 Launch of composite strip conductors for buried substation ground grids and their equipment connections (risers)

V. Introducing the Modern Strip Grid

In the Spring of 2023, a small team of hands-on product development engineers decided to explore the empirical development of European-style flat strip grounding conductors made of composite metals that would deter copper theft, one common design for the U.S. and non-U.S. utilities. The team was led by the authors of this technical publication.

Top of mind was the need for a theft-resistant conductor with sufficient flexibility for making 90-degree bends by hand in the field during installation. The 90-degree bend, although not electrically ideal for conducting fault currents in substations, would permit tight fitting from equipment along a concrete foundation pad and into the ground to avoid a trip hazard for 99 % of time when the grounding conductor lies dormant. Equally important is the other 1% of the time when the conductor is being used for emergency grounding service, i.e. the attenuation of stray currents and the transmission of occasional catastrophic electrical fault current into the ground.

In the Summer of 2024, a new extrusion technology was created to produce the desired strip conductor.

One version of the new conductor, called ARMOR-965™, is a thin and wide strip over four times wider than 4/0 copper but with the same cross-sectional area. The resulting patent-pending design also includes a relatively thick continuous copper sheath—more than twice as thick as a common copper clad steel ground rod—around an encapsulated metal core that provides theft-deterrence, added strength, and a fault current heat sink. Test results demonstrate that the copper sheath provides 10% higher electro-thermal capacity (I^2t) and the core provides 78% higher mechanical break load capacity than 4/0 copper cable. Resistance to ground is 12% lower than that of 4/0 copper cable, assuming a ground grid made of 1,000 meters of conductor in contact with 100 ohm-meter soil and buried 0.5 meters deep, per Rudenberg's 1945 equations.

Or another way to describe ARMOR-965™ strip is by its comparable performance. While providing slightly better electro-thermal capacity (I^2t) than 4/0 copper, and for roughly the same market price as 4/0 copper, ARMOR-965™ has the break load strength of a 350 kcmil copper cable, and more significantly, it exhibits better resistance to ground than a traditional grid made of three-500-kcmil cables joined together in parallel, as shown in Fig. 3.

	Electro-Thermal (I^2t)	Break Load Force (lbs)	Contact Circumference (inch)	Resistance to Ground (Ω/1000ft)
ARMOR-965™	**1,061**	**8,762**	**5.2**	**0.081**
4/0 Copper	965	4,933	2.6	0.091
350 Copper	2,497	8,161	3.1	0.090
500 Copper	5,096	11,614	3.9	0.890
3x 500s	14,524	34,842	7.7	0.084

Fig 3. Summary of ARMOR-965™ strip grid performance.

VI. A Core for Theft Deterence and a Shape That is Identifiable to Theives

Electric utilities throughout the world are worried about copper theft and the likelihood of increased crime with the price copper at an all-time high.

The U.S. Department of Energy estimated in 2006 that copper theft conservatively totaled $900 million USD per year in the United States. Several large utilities, including Pacific Gas and Electric and Bonneville Power, documented their losses from copper theft at $1 million/year. The average price of copper has increased from $3.25/lb in 2006 to $4.50/lb in 2024, worsening the problem today. [13]

Theft-resistance can be achieved in many ways, but the easiest and most effective deterrent to grounding conductor theft is the incorporation of composite construction into its design. Like a tin can, which is actually a steel can plated with tin, a composite metal conductor like ARMOR-965™ can be recycled, but the cost of separating the metals consumes any value in the payout of the copper content. By removing the financial incentive to sell it, the conductor simply becomes economically unattractive to steal.

No place in the world is copper theft as big a problem as it is in South Africa, where a conductor called 70 mm^2 cable (I^2t = 343), roughly the size of a 2/0 copper cable (I^2t = 361), is the standard for ground grids. The country, which is twice the size of Texas, is primarily served by the public utility, ESKOM. City Power of Johannesburg alone, which is the other large utility in the country, estimates its losses to cable theft in recent years at $20 million to $30 million USD per year (R356 million to R533 million) due to organized crime. [14, 15]

To ESKOM and City Power, the benefit of a better grounding conductor that is identifiable and differentiable to thieves may total hundreds of millions of dollars in material and labor savings over the next decade, not to mention elimination of the overwhelming frustration and safety risks. Other major costs include destroyed equipment, such as a large power transformer due to absence of star point neutral connection to ground rendering protection systems "blind". Customer outages leading to lost production as a result theft and vandalism are also significant.

VII. Calcs for Strip Resistance to Ground

Rudenberg's formulas for the resistance to ground of various conductors are found in his 1945 AIEE technical publication, "Grounding Principles and Practices I – Fundamental Considerations on Grounding Currents", which was later incorporated into the original 1954 AIEE Grounding Guide. [6 & 8] These calculations assume soil resistivity of ρ = 100 ohm- meters, ground grid buried depth 0.46 m (eighteen inches) deep, and length of total conductor L = 1000 meters. Calculations also include an impedance factor for the image (or imaginary component) of a "deep wire" carrying alternating current. As such, it may be more correct to call it impedance of a transmission antenna to ground, rather than resistance.

Figs. 4 & 5 show the calculation for a resistance to ground of a round cable and flat strip respectively. Both sets of equations include a resistance multiplier for the imaginary portion of the alternating current impedance (see the term "deep wire" on the right).

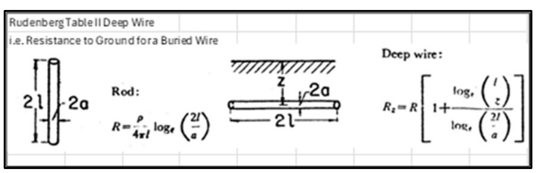


Fig. 4. Standard resistance to ground for round cables.

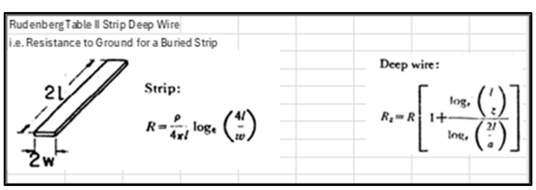


Fig. 5. Resistance to ground for flat strip conductors.

VIII. Improving Contact Surace Area

In the modern lexicon, the flow of electrical fault current away from a grounding conductor and into the soil is often called *"leakage current"*, as in the current that escapes from the metal conductor. This, of course, is not an accurate description. The grounding conductor should be designed to drive the fault current into the soil as efficiently as possible. This effect is proportional to the potential gradient as a function of the conductor and its surface contact area with the soil.

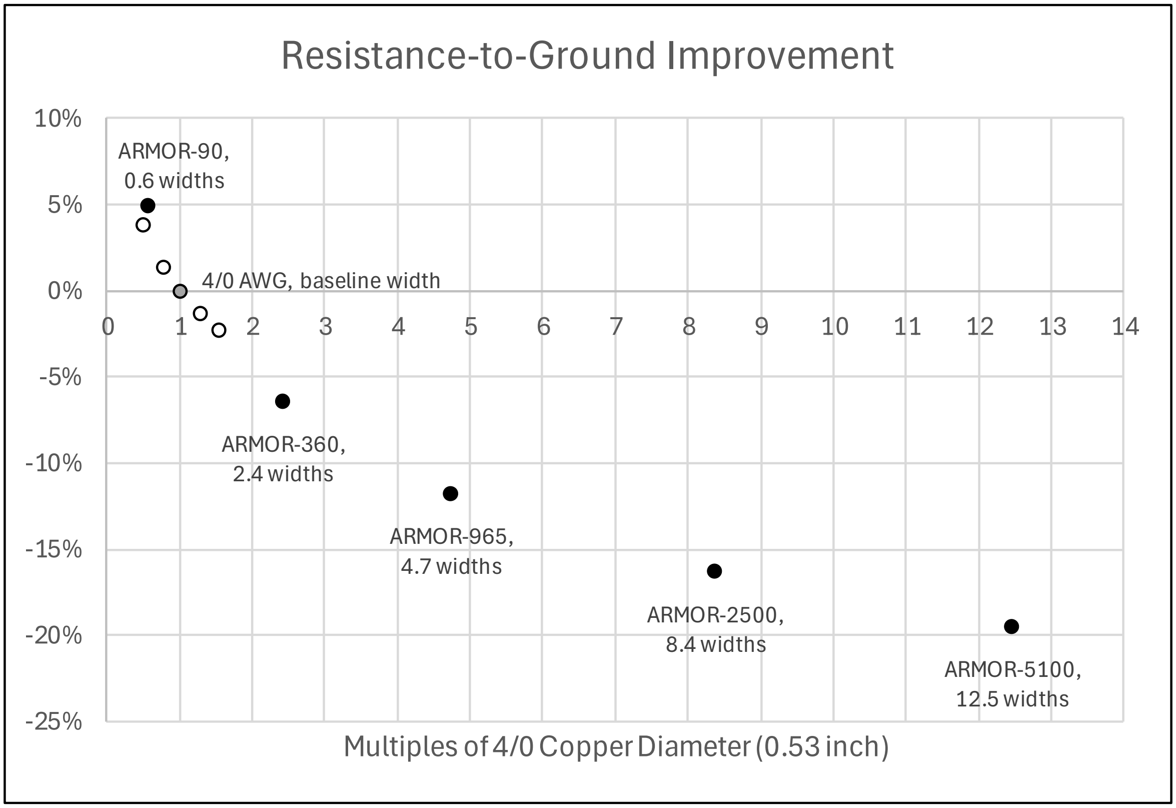
With this objective in mind, it is easy to see why successive chairmen of Std-80 minimized the value of increasing the diameter of the ground grid conductors. In fact, there really is little benefit to be gained when changing from one round conductor to another, as stated in Std-80-1986. However, other shapes are possible. And so, the lack of imagination on the part of these most respected chairmen is at issue here.

Fig. 6 demonstrates a clear advantage. Given the predominance of 4/0 copper cable as the historical ground grid conductor of choice, the benefit of thin and wide strip grounding conductor over round cable is presented in Fig. 6 in terms of multiples of the diameter of 4/0 copper. Here it is easy to see the cluster of various round cables in the upper left corner of the graph. Also, in that same area of the graph is a thin but not-so-wide strip, smaller than a 4/0 copper cable. Clearly, Rudenberg's rule of thumb—that a strip is equivalent to a rod or a wire of a diameter equal to half the width of the strip—is self-evident. That is, there is no advantage for small strips.

However, as the strip approaches 3 times the diameter of a comparable cable, efficiencies do improve significantly. So, using the diameter of 4/0 copper, which is just over 0.5 inch, as the basis of comparison, Fig. 6 shows that a strip with 4.7 times the diameter of 4/0 copper, such as ARMOR-965™, provides a 12% improvement in resistance to ground. Similarly, a strip with a width 12.5 times the diameter of 4/0 copper, such as ARMOR-5100™, provides a 20% improvement. Beyond that, the benefit diminishes asymptotically

IX. Conclusions

Increasing a grounding conductor's surface area in contact with the soil can dramatically improve the transmission of electrical fault energy into the ground for high power substation grounding applications. A new family of composite strip conductors, having widths several times greater than traditional copper cable, can be used to significantly reduce the resistance to ground in any soil condition. The benefits of composite strip ground grid conductors, when compared to standard 4/0 copper grounding cables, include better electro-thermal performance (I^2t), better mechanical break load strength, better theft resistance, better flexibility for field installation, and most importantly, a 6%-20% lower resistance to ground. These advantages are quantified herein for use by substation designers in their ground grid modeling efforts that aim to mitigate risk to personnel and equipment.



Size	Diameter (inch)	Width (inch)	Thickness (inch)	4/0 Widths (#)	Resistance (Ω/kft)	Improvement (%)
#2 AWG	0.26	-	-	0.5	0.095	3.8%
2/0 AWG	0.41	-	-	0.8	0.093	1.4%
4/0 AWG, baseline width	0.53	-	-	1.0	0.091	0.0%
350 kcmil	0.68	-	-	1.3	0.090	-1.3%
500 kcmil	0.81	-	-	1.5	0.089	-2.3%
ARMOR-90, 0.6 widths	-	0.31	0.083	0.6	0.096	4.9%
ARMOR-360, 2.4 widths	-	1.28	0.083	2.4	0.085	-6.5%
ARMOR-965, 4.7 widths	-	2.50	0.083	4.7	0.081	-11.8%
ARMOR-2500, 8.4 widths	-	4.42	0.083	8.4	0.076	-16.3%
ARMOR-5100, 12.5 widths	-	6.58	0.083	12.5	0.073	-19.5%

Fig. 6. Resistance to ground improvement from increased contact surface area with the soil.

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VITAE

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ADDENDUM

Corrections to the references, formating, and Fig. 6 are included in this updated version of XPUB-001a, with the "a" at the end of the name standing for *"addendum"*. Updates were made on January 22, 2025, to reflect the content presented on November 19th, 2024, at CEATI. Updates were then re-published the same day on ExeterGround.com so that this document may serve as refernce for an upcoming IEEE PES publication.