Conductivity and Selection of Copper Clad Steel Wires for Grounding Applications

George Eduful, Kingsford J. A. Atanga

Abstract**—**Copper clad steel wire (CCS) is primarily used for grounding applications to reduce the high incidence of copper ground conductor theft in electrical installations. The cross sectional area of the CCS is selected by relating the diameter equivalence to a copper conductor. The main difficulty is how to use a simple analytical relation to determine the right conductivity of CCS for a particular application. The use of Eddy-Current instrument for measuring conductivity is known but in most cases, the instrument is not readily available. The paper presents a simplified approach on how to size and determine CCS conductivity for a given application.

Keywords**—**Copper clad steel wire, conductivity, grounding, skin effect.

I. INTRODUCTION

THEFT of ground copper conductors is a phenomenon that is not new to the electric power industry. T&D World Magazine in 2010 reported the occurrence of about 5400 incidences of copper theft in ComEd's Distribution System in Chicago [1]. In South Africa, Eskom lost a total of US$35.8 million from copper ground conductor and transformer winding theft in 2013 [2]. The situation is no different in Ghana, where thieves are harvesting copper ground conductors used for distribution transformer grounding.

Generally, grounding is used to fulfill safety requirements imposed by national and international standards. Principally, it used to ensure personnel safety in electrical installations. Others include protection for manufacturing plants and equipment; thus, the theft of copper ground conductors in operational facilities can create a very dangerous environment. It is estimated that 35 to 50 deaths or injuries associated with copper theft occur every year [3].

To address the problem, some research articles have recommended the use of steel wire for grounding, using a cathodic protection scheme to minimize corrosion of the steel [4]. It should however be noted that deployment of cathodic protection scheme requires specialized skills. Aluminum conductors have also been used. Unfortunately, aluminum conductors are not suitable for buried ground applications. The authors have also seen cases where buried aluminum ground conductors have become powder after few years of installation.

Now, it appears utility companies have settled on CCS as the best alternative to copper. The CCS is composed of two metals, copper and steel, in a single composite conductor. It combines the high mechanical resistance of steel with the conductivity and resistance to corrosion of copper, and was found to be suitable for above and below ground applications.

Generally, the size and construction of the CCS is selected by matching the approximate diameter equivalence to a copper conductor. It should however be noted that the ampacity rating and the DC and AC resistance of the copper-clad steel wire conductor is not equivalent to that of the copper conductor. When deploying the CCS, its conductivity is of paramount importance, especially in relation to grounding for lightning protection system. CCS is designed for conductivity ranging from 15% to 40%.

The International Annealed Copper Standard (IACS) has established a standard for the conductivity of commercially pure annealed copper. Conductivity is usually expressed in terms of percent IACS. All other conductivity values are referenced to conductivity of annealed copper. The major challenge, however, is how to estimate or determine suitable CCS conductivity for a given application. In this paper, a simplified approach for sizing and determining CCS conductivity is presented. Conductivity formula for CCS is derived based on a parallel resistance concept in the DC circuit.

II. TECHNICAL CONSIDERATIONS IN THE SELECTION OF COPPER-CLAD STEEL CONDUCTORS

Basically, the resistance of a grounding system is made up of two components: the resistance of the ground conductor and the ground electrode resistance. The resistance of the ground conductor material is negligible compared to the resistance of the ground electrode. This is particularly true for conductive materials such as copper and steel, and this explains why steel wires with cathodic protection have still found a place in grounding applications.

A. Sizing of CCS

Usually, ground conductor sizing depends on a number of factors. These include material characteristics such as resistivity, thermal coefficient of resistivity, thermal capacity per-unit volume, ambient temperature, and maximum allowable operating temperature. A simplified formula used to calculate conductor cross-sectional area of any material is given as [4].

$$A_{mm^2} = \frac{I \times K_f \times \sqrt{t_c}}{1.974} \qquad (1)$$

George Eduful is with the Electricity Company of Ghana, Research and Development Division, P.O. Box AN 5278, Accra-North, Ghana (phone: +233246132736, e-mail: georgeeduful@yahoo.com).

Kingsford J.A. Atanga is with the Electricity Company of Ghana, Research and Development Division, P.O. Box AN 5278, Accra-North, Ghana (phone: +233249560723, e-mail: kantaga23@gmail.com).

I = R.M.S (symmetrical) fault current in kA; tc = fault duration current in seconds; Kf = constant for the material, 7 for annealed soft-drawn copper (Tm = 10830 °C), 15.95 for steel (Tm = 15100 °C); Tm = Fusing temperature in 0°C.

As a general guide, IEEE standard 80 provides that the ground conductor should be sized to meet fault requirement of 18 kA at 1 s [5]. This requirement is generally used to size ground conductor for both power system (50Hz) and lightning protection system grounding.

It is important to note that lightning has high frequency components that range from 100 kHz to 120 MHz [6]. At these frequencies, lightning current will not flow through the entire cross sectional area of the ground conductor, but flows and concentrates on the surface of the conductor, a phenomenon known as the skin effect. The skin on the surface of conductor or the surface thickness of the conductor where the lightning current resides and flows is referred to as the skin depth. The relation for calculating the skin depth is giving as:

$$\delta_s = \left(\frac{1}{\pi \times f \times \mu \times \sigma}\right)^{\frac{1}{2}} \qquad (2)$$

μ = permeability (4π* 10^{-7} H/m); π = pi; δs = skin depth (m); ρ = resistivity (Ω*m); ω = radian frequency = 2π*f (Hz); σ = conductivity (mho/m).

Since the conductivity of CCS depends on the thickness of the copper cladding, CCS could be designed and sized such that the thickness of the copper clad is equal to the depth of skin caused by the lightning current.

III. CONDUCTIVITY OF CCS

In selecting CCS for grounding application, it is equally important to consider the skin effect of a lightning current and select the CCS of copper thickness that is approximately equal to the skin depth. The thickness of the copper clad determines the IACS conductivity of the CCS. However, in practice, one hardly finds a relation that determines CCS conductivity based on the thickness of the copper coating. Generally, Eddy-Current instruments are used for CCS conductivity measurement but this is mostly conducted at the electrical laboratories. This section presents a simplified approach to determining CCS conductivity based on the thickness of the copper clad. Fig. 1 shows a cross-section of CCS with a copper clad thickness of *t*

For one meter length of CCS, resistance of the copper clad is given as:

$$R_{\_copper} = \frac{\rho_{\_copper}}{\pi\left(a^2 - b^2\right)} \qquad (3)$$

where a is the overall radius of the CCS and b is the radius of the steel core.

For the steel wire, the resistance will be:

$$R_{\_steel} = \frac{\rho_{\_steel}}{\pi b^2} \qquad (4)$$

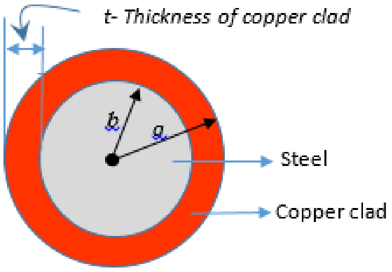

Fig. 1 Cross Sectional Area of Copper Clad Steel Wire (CCS)

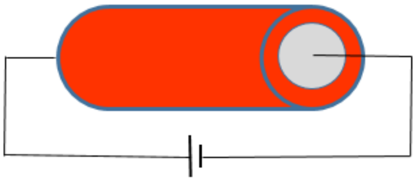

Fig. 2 Representation of CCS as load with a source

The CCS could be represented as load, as shown in Fig. 2. Due to the low resistance of copper compared to steel, it is expected that more current will flow through the copper cladding section than the steel section. With this current division concept, the CCS can be modeled as a two resistor connected in parallel, see Fig. 3.

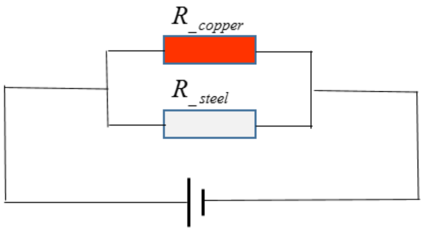

Fig. 3 Parallel Model of CCS

From Fig. 3, the equivalent resistance of the CCS can be expressed as:

$$R_{\_equivalent} = \frac{R_{\_copper} \times R_{\_steel}}{R_{\_copper} + R_{steel}} \qquad (5)$$

Substituting (3) and (4) into (5) yields:

$$R_{\_equivalent} = \frac{\rho_{\_copper} \times \rho_{\_steel}}{\pi\left[b^2 \rho_{\_copper} + \rho_{\_steel}\left(a^2 - b^2\right)\right]} \qquad (6)$$

Recall that resistance of one meter length of a conductor is given as:

$$R = \frac{\rho}{A} \qquad (7)$$

where ρ is the resistivity of the conductor material and A is the cross-sectional area of the conductor. So that,

$$\rho = R \times A$$

Assuming ρ is the equivalent resistivity of the CCS, R the equivalent resistance of the CCS and A is the cross sectional area of the CCS then,

$$\rho_{\_equivalent} = \frac{\rho_{\_copper} \times \rho_{\_steel} \times A}{\pi\left[b^2\rho_{\_copper} + \rho_{steel}\left(a^2 - b^2\right)\right]} \qquad (8)$$

Therefore, equivalent conductivity of the CCS is:

$$\sigma_{\_ccs} = \frac{\pi\left[b^2\rho_{\_copper} + \rho_{\_steel}\left(a^2 - b^2\right)\right]}{\rho_{\_copper} \times \rho_{\_steel} \times A} \qquad (9)$$

Note (from Fig.1), if thickness of the copper cladding is t, then:

$$t = a - b$$

So that,

$$b = a - t \qquad (10)$$

Substituting $b = a - t$ into (9) will give:

$$\sigma_{\_ccs} = \frac{\pi\left[(a-t)^2\rho_{\_copper} + \rho_{\_steel}\left(2at - t^2\right)\right]}{\rho_{\_copper} \times \rho_{\_steel} \times A} \qquad (11)$$

For percentage conductivity of the CCs in terms of IACS,

$$\%IAC = \frac{\sigma_{\_material}}{\sigma_{\_copper}} \times 100$$

So that,

$$\%\text{IACS of CCS} = \frac{\sigma_{\_ccs}}{\sigma_{\_copper}} \times 100 \qquad (12)$$

Note that,

$$\sigma_{\_copper} = \frac{1}{\rho_{\_copper}} \qquad (13)$$

Substituting (11) and (13) into (12) finally gives conductivity of the CCS in terms %IACS as:

$$\%IACS = \frac{\pi\left[(a-t)^2\rho_{\_copper} + (2a-t)t\rho_{\_steel}\right]}{\rho_{\_steel} \times A} \times 100 \qquad (14)$$

It is important to note that (14) could also be used to determine %IACS conductivity of any conductor cladding especially, where two different materials are involved.

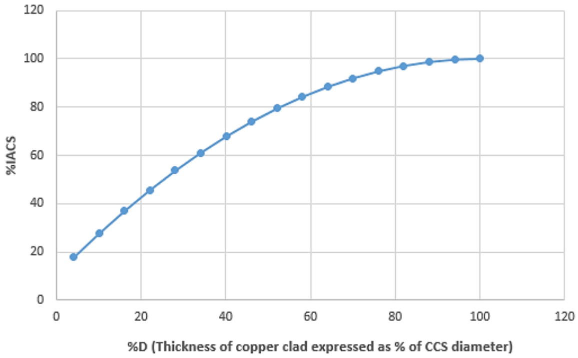

Fig. 4 % IACS of CCS against Copper Clad Thickness

A graphical relation of %IACS of CCS with respect to the thickness of copper cladding based on (14) is shown in Fig. 4. As can be seen, conductivity of CCS has a linear relation with thickness of copper cladding, increasing conductivity sharply with the increase in copper clad thickness. The curve however begins to saturate around 45% to 50% thickness of the copper clad. It should be noted that conductivity attained by the CCS at this thickness is about 80%.

A. Example of CCS Selection

Assuming a CCS is to be sized to meet a fault current requirement of 18 kA at 1 s. First, the CCS should be considered as steel wire with a constant material factor (K_f) of 15.95. Using (1), the conductor size for the fault requirement is 145 mm^2. It should be noted that this is “1020 steel’’ with IACS conductivity of 10%. Now, consider that this steel wire is to be clad with copper to enhance conductivity for the flow of a lightning current within the frequency range of 100 kHz to 120 MHz,

A lightning current of 100 kHz will cause a skin depth of 0.2 mm. When copper is used in the skin depth section of the conductor, %IACS conductivity of the steel increases to 15%. Similarly, a 120MHz of lightning current will result in skin depth of 0.00597 mm, resulting in 10.8% conductivity with copper coating in the region of the skin depth. It can therefore be seen that when CCS is designed based on the upper band of the lightning frequency, lightning current in the lower frequency range will not benefit from the conductivity of the copper coating. It is therefore advisable to design a CCS based on the lower band lightning frequency than the upper band frequency.

IV. CONCLUSION

The CCS is largely accepted by the utility companies as an alternative to the copper ground conductor, especially in areas where copper theft is of a major concern. The copper coating enhances the conductivity of the CCS and as well protects the conductor from corrosion. A general guide provided by the IEEE standard 80 can be used to size CCS for a given application. However, the literature is inadequate on how to determine conductivity of CCS from a mathematical relation. This paper has presented a simplified approach on how CCS conductivity can be determined from the perspective of skin effect. It is hoped that this paper will add to the stock of knowledge in relation to the selection of CCs for a given application.

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