مجله نخبگان علوم و مهندسی

Journal of Science and Engineering Elites

جلد ۸- شماره ۳ - سال ۱۴۰۲

www.ElitesJournal.ir

Skin Effect in Overhead Conductors (A Brief Review)

Pooya Parvizi [1], Alireza Mohammadi Amidi [2*], Milad Jalilian[3], Hana Parvizi [4]

1- School of Engineering, University of Birmingham, Birmingham, United Kingdom. Pooya Power Knowledge Enterprise
2- Department of Electrical, Faculty of Science, Razi University, Kermanshah, Iran. Pooya Power Knowledge Enterprise
3- Department of Physics, Faculty of Science, Lorestan University, Lorestan, Iran. Pooya Power Knowledge Enterprise
4- Department of Science, Faculty of Science, University of British Columbia, Vancouver, Canada. Pooya Power Knowledge Enterprise

*alireza.moamidi@gmail.com

Received: June 2023 Accepted: August 2023

Abstract

The topic of reducing losses and using new generation conductors in electricity distribution networks is always discussed and among the research priorities. In order to plan optimally and properly in the electricity distribution industry, it is necessary to implement the plan to use the new generation of medium pressure conductors at the level of electricity distribution, taking into account the technical parameters and the necessary conditions for using this important issue in improving the utilization. In this research, we intend to first explain the skin effect of air conductors and express its equations, then we will investigate this effect and ways to eliminate it in various articles.

Keywords: Skin effect, Overhead conductors, Distribution network.

1- Introduction

Skin effect in overhead conductors refers to the concentration of current flow near the surface of the conductor as the frequency of the current increases. This phenomenon occurs in all types of conductors, including those used for power transmission lines or radio antennas. In aerial conductors, the skin effect can result in a decrease in the effective cross-sectional area of the conductor, reducing its ability to conduct electrical energy. This can cause power losses and other issues, especially at high frequencies. In some cases, the skin effect may be significant enough to require the use of specially designed conductors or other mitigation techniques to minimize the losses [1].

When a homogeneous cylindrical electrical conductor is used to transmit electrical energy or signals via direct current (DC), the current spreads evenly across the cross-sectional area of the conductor. However, if the conductor is not cylindrical, the direct current is not uniformly distributed and exists throughout the entire conductor. This is because the current supplied from the source of electrical energy is "time invariant" [2].

When an alternating current (AC), which is a type of "time-variant" current, flows through a cylindrical electrical conductor, it creates a magnetic field both inside and outside of the conductor. If there is any change in the current's magnitude as it passes through the conductor, the magnetic field's magnitude will also change in response. This creates an electric field and a secondary "time-variant" current (called an Eddy current), which counteracts the change in the current density. This counteracting force is known as the counter electromagnetic force [2-3].

The interplay of the time-varying magnetic field and the induced time-varying electric field generates what's called electromagnetic induction in the electrical conductor. This induction causes the electric current to flow on the surface of the conductor, instead of through the surface and within the conductor. Consequently, the current density flowing through the conductor is more concentrated on its surface (skin) and less concentrated at greater depths into the conductor. This phenomenon is referred to as the "skin effect," especially when it occurs at high frequencies [4]. The depth of the skin effect increases with higher frequencies, which ultimately results in increased effective resistance of the conductor [5].

The skin effect reduces the effective cross-sectional area of an electrical conductor that's available for conduction. At high frequencies, such as around 1,000 KHz, less than 0.1mm of the conductor's thickness (known as skin depth) is available for conduction [6]. This is problematic because it impairs the efficient transmission of electrical energy through large conductors at high frequencies. This review article aims to explain the principle of skin effect in electrical conductors, evaluate its consequences, and examine the attempts made over time to resolve the issue. Ultimately, the article concludes whether any commercially viable solution has been discovered.

This paper describes measurements, in a specially constructed nonmetallic hut In this paper, an efficient adaptive cross approximation (ACA) method is employed for the skin effect and proximity effect analysis. Multi-layer stranded cables with multiple strands and different materials are used for analysis to approximate the effect

To minimize skin effect in overhead conductors, it's common to use stranded conductors with multiple small wires instead of a single larger wire. This increases the surface area available for current flow, reducing the impact of skin effect. Additionally, using conductors made from high-conductivity materials, such as aluminum or copper, can help to minimize losses due to skin effect [7]. The simple and attractive solution to extract and approximate the skin and proximity effect matrix. Stranded cable with multi-strands and multi-layers are used in the model. Conductors used for analysis include all-aluminum alloy conductors (AAAC), aluminum alloy conductors (AAA), aluminum conductor steel reinforced conductors (ACSR) and solid conductors. [8]

The skin effect for the solid conductor and arbitrary shape conductor is studied [9], [10], [11]. In the next parts of the article, we will first give a comprehensive definition of skin effect, then we will state its equations, and finally we will provide solutions to reduce skin effect and present several articles in the field of skin effect.

2- Skin effect

Skin effect [12-18] is a phenomenon that occurs in alternating current power transmission lines and leads to a decrease in the current density in the center of the wire and an increase in the outer layers or wire shell. When alternating current passes through a wire, a magnetic field is created around the wire [19]. By changing the direction of the alternating current, the direction of the created field also changes. At this time, according to the Lenz law, a current is created in the wire in the opposite direction of the normal current to oppose the change of the field [20]. The generated current is more in the central layers of the wire and less in the outer layers, so that sometimes the net current in the center of the wire is zero and more concentrated in the outer layers or shell. He visits that is why it is called a skin effect. In fact, the skin effect causes the non-uniformity of the current density in the section of the wire. The higher the frequency of the current, the more the skin effect is found, and the opposite and repeated currents created in the center of the wire become more and more. For this reason, the skin effect at high frequencies leads to an increase in the resistance to flow [21].

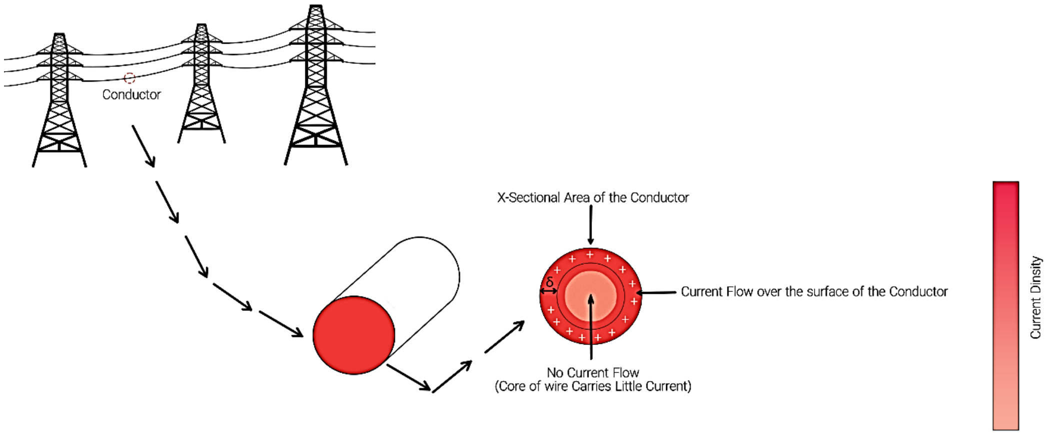

Fig1- Skin effect in conductor

3- Mathematical equation of skin effect losses

The skin effect is a phenomenon of an alternating electric current, so that the highest current density is near the surface of the conductor, and the closer we get to the depth of the conductor, the value of the current density decreases. The electric current mainly flows in the conductive skin, between the outer surface and a surface called penetration depth [22].

Conductors are usually used in the form of wires for alternating current electric energy transmission lines. The charge carriers made up of electrons are guided by an electric field to the source of electric energy, and an alternating current in the conductor and an alternating magnetic field in and around the conductors are created. When the current in the conductor changes, the magnetic field also changes. The change in the magnetic field, in turn, creates an electric field that is opposite to the change in the intensity of the current. This electric field opposite to the anti-electric force is called. This driving force of contact in the center of the conductor is very strong, as a result of which the electrons of the conductor are forced to move to the outer surface of the conductor. Alternating current is induced in a conductor due to an alternating magnetic field based on Faraday's law of induction.

In Faraday's law of induction, the magnetic flux passing through a conductive loop, if it is of variable magnitude or direction, induces an electric potential difference in the loop, which is called the magnetic field, and this potential difference causes A current flows in the ring Every current passing through a conductor creates a magnetic field in the space around the conductor, which is called the induced field. According to Lenz's law, the direction of the induced current is opposite to the direction of the induced current. This law examines the action and reaction of inducing and induced forces, which is an example of Newton's third law. Regardless of the driving force, the current density on the surface of the conductor is more than its value in the center of the conductor, so that even its value in the center of the conductor reaches zero. This decrease in current in the center of the conductor is called skin effect [23].

Reference number [24] explains by solving the cylindrical mathematical equations of the conductors that in ACSR conductors, the presence of a steel core leads to an increase in the magnetic leakage current, eddy currents (Foco) and, the current density between the layers of non-ferrous wires and the core magnetic losses cause a part of the voltage to drop in the direction of the longitudinal induction element in each layer to be in phase with the current in the same layer. Therefore, the resistance of that layer increases. The Bessel's equations for these losses in overhead transmission lines have been obtained by RADULET and are fully described in reference [10]. Equation 1 is generally used for the depth of penetration and it means:

$$\delta = \sqrt{\frac{2\rho}{\mu\omega}}\sqrt{\sqrt{1+(\rho\omega\varepsilon)}+\rho\omega\varepsilon} \tag{1}$$

Where:
δ is Depth of penetration
ρ is Electrical resistivity and conductivity
ω is Angular frequency
μ is Magnetic permeability coefficient

At very low frequencies, the value inside the large radical is close to unity, and equation 1 will often be equation 2:

$$\delta = \sqrt{\frac{2\rho}{\mu\omega}} \tag{2}$$

Also, when the penetration depth is not small according to the radius of the wire, the current density can be described in terms of Bessel functions. The current density inside the round conductor away from the influence of other fields is given as a function of the distance from the axis according to equation 3.

$$J_r = \frac{KI}{2\pi R}\frac{J_0(Kr)}{J_1(KR)} \tag{3}$$

Where:
r is Distance from the axis of the wire
R is wiring radius
I is current through
J_0 is Bessel function of order zero
J_1 is First order Bessel function

Now that the definition of skin effect and its mathematical relationships have been stated, we will examine some methods to reduce the skin effect.

4- Using different winding structures, and conductor types for reduce skin effect in transformer windings [25]:

This paper examines a high frequency transformer in the presence of eddy currents and skin effect by exploring various conductors and winding arrangements. The study investigates the impact of skin effect on the windings by using different types of conductors, such as circular, square shaped, and foil wires, and analyzing the current density within the conductors at frequencies of 20 MHz and 20 kHz using finite element method (FEM) simulation. Additionally, the magnetizing inductance, leakage inductance, and AC winding resistance of all transformer types are determined and compared. Based on the results, the skin effect leads to an increase in AC winding resistance and a decrease in leakage inductance as the frequency increases [23].

As a result, at higher frequencies, the skin effect causes a decrease in leakage inductance and an increase in AC resistance in conductors like circular and square wires, as studied in this paper. To address this issue, foil conductors are a better option due to their shape. Additionally, the winding arrangements in transformers play a crucial role in mitigating parasitic and loss behavior, as demonstrated in the previous section. Despite having the same magnetizing inductance, variations in the conductor shape and structure can significantly impact leakage inductance and winding AC resistance. Additionally, in wire conductors, the shape of the wires can impact parasitic and loss behavior, even with the same cross-sectional area, due to the slight variations in skin effect behavior [23].

5- New application of skin effect suppression technology for long wiring

This manuscript proposes a modern application of skin impact concealment innovation for long wiring on high-speed & low-delay I/O board. This proposition will overcome the trouble of assist lessening the transmission misfortunes on the I/O board with vert >vert 50 Gb/s information rate. In past investigate of this domain, it was illustrated that concealment of the skin impact by electroplated conductor/magnetic multi-layer, and evaluated that the degree of transmission misfortune diminish at 16 GHz would be 5 %. The reason of this ponder is to propose a lower misfortune plan strategy as compared with past inquire about by employing a calculation strategy for transmission line. The strategy takes into consideration attractive fabric misfortune and copper misfortune counting skin impact. A major challenge in this paper is to propose an electromagnetic field calculation hypothesis for rectangular multi-layer transmission line, and confirm it beneath the same conditions, clarify a lower misfortune structure by calculating models in which thickness of each layer is changed. Moreover, it is extended to moo misfortune plan innovation.

The calculation hypothesis of electromagnetic field dispersion in thought of the skin effect within the rectangular multi-layer transmission line stacked with numerous materials was determined by amplifying the hypothesis of a single rectangular structure. Within the taking after, the hypothetical equations are portrayed alongside the determination prepare of the hypothesis. By applying Maxwell's equations for the conductor and simplifying its relationships according to reference 12, we get the following relationship for transmission line losses:

$$\mathrm{loss_n} = \int_{y_{n-1}}^{y_n} \frac{|J_{zn}(y)|^2}{\sigma_n} dy + \int_{y_{n-1}}^{y_n} \frac{1}{2}\omega\mu_{rn}|H_n(y)|^2 dy \qquad (4)$$

In above equation J_{zn} , σ_n ,ω and $\mu_{rn}$are the AC current, electrical conductivity, angular frequency and permeability, respectively. The misfortune of each layer of the rectangular multi-layer transmission line can be gotten by the condition (4). The primary term is the copper misfortune gotten from the current thickness and conductivity of each layer. The moment term is the attractive misfortune due to the fanciful portion of the complex penetrability of the negative porousness fabric. The attractive misfortune can be gotten from the nearby attractive field H(r) and the fanciful portion μ” of the complex attractive penetrability. The overall misfortune can be assessed by including the copper misfortune and the attractive misfortune. Hence, the misfortune of the whole transmission line such as skin effect misfortune can be obtained. As a result, an objective function will obtain to optimize losses.

In this paper it is obvious that electromagnetic field calculation hypothesis for the transmission line with the rectangular conductor structure, and based on the hypothesis, it was examined skin effect loss concealment by stacking negative penetrability fabric. Compared to customary thickness by a steady proportion, in that proposition, they evaluated that the loss would drop to 92% in ideal thickness. By offsetting the stage alter of current thickness, a lower loss structure and structure with a decreased number of layers may well be decided [26].

6- Impact of skin effect on ACSR conductors [27]

This study utilizes numerical models, including a single cylinder model, two coaxial cylinder models, and cylinder layer models. The authors compare these models to one another, as well as to an established analytical solution and a direct current mode. The accuracy of the numerical models is verified through a comparison with the analytical solution. The findings reveal that the single cylinder model produces inaccurate results for ACSR conductors. The objective of study is to elucidate the impact of skin effect on ACSR conductors when operating at mains frequency. In the first step a fundamental equation of skin effect is stated as follow:

$$\mathrm{I} = \frac{2\pi R}{\sqrt{-j\omega\mu\gamma}} J_1(x) J_{m0} \qquad (5)$$

Where I is the complex amplitude of the total current; J_1 is the first-order Bessel function of the first kind; R is the conductor radius. By utilizing equation 5 a model of conductor is obtained. In the initial phase, a cylindrical conductor model and validated its accuracy by comparing analytical and numerical solutions are developed. This model, referred to as the "cylinder model," demonstrated an absolute error of less than 6×10^{-6}, which is within the realm of computer accuracy for real numbers. Hence, we can confirm the correctness of the numerical model.

In the subsequent stage, we focused on the most commonly used conductor type, namely the aluminum conductor steel reinforced (ACSR), which consists of a steel core enveloped by aluminum layers. To analyze this configuration, we constructed a two coaxial cylinders model. The smaller cylinder represented the steel core, while the larger cylinder depicted the aluminum layers. This model, known as the "coaxial model," shared similarities with the cylinder model, except for variations in the absolute magnetic permeability (μ) and the electrical conductivity (γ) among different materials.

Consequently, the skin effect has a significant impact on all ACSR conductors. In certain cases, neglecting the consideration of the skin effect in calculations can lead to a calculation error of up to 40% of the total current. Furthermore, the traditional the skin effect also result in substantial errors when applied to ACSR conductors. Notably, the maximum error occurs for conductors with a medium radius of approximately 10 mm. Therefore, it is crucial to give careful attention to accounting for the skin effect in such cases.

Additionally, the advanced layers model and the coaxial model, both of which yielded better results compared to the traditional formulas are examined. However, these models still exhibited approximately 10% less accuracy than the layers model. It is anticipated that more precise numerical models would yield even greater differences. Furthermore, it is observed that the effect of increased penetration depth of the electromagnetic field in the conductor due to the electric field penetration between wires. This effect holds significance for thermoelectric models as it alters the distribution of Joule losses.

7- Conclusion

This article investigated the skin effect of air conductors and after providing a complete definition and expressing mathematical relationships, it presented two methods to reduce this effect. To minimize skin effect in aerial conductors, it's common to use stranded conductors with multiple small wires instead of a single larger wire. This increases the surface area available for current flow, reducing the impact of skin effect. Additionally, using conductors made from high-conductivity materials, such as aluminum or copper, can help to minimize losses due to skin effect. There are several ways to overcome skin effect in electrical conductors, including:

1. Using hollow conductors: By using hollow conductors with thin walls, the current can be made to flow on the surface of the conductor, where it is most effective. This helps to reduce the effective resistance of the conductor.
2. Using multiple strands: Using multiple smaller strands instead of a single large strand increases the surface area of the conductor, reducing the impact of skin effect. This is why most electrical power cables are made up of many small strands of wire rather than a single larger wire.
3. Using special alloys: Some special alloys, such as those containing silver, can help to reduce skin effect by increasing the conductivity of the conductor.
4. Using a skin effect correction coil: A skin effect correction coil is a coil of wire wound around the conductor that creates a magnetic field that counteracts the magnetic field created by the current flowing through the conductor. This helps to distribute the current more evenly throughout the cross-section of the conductor, reducing the impact of skin effect.
5. Reducing the frequency: Skin effect is more pronounced at higher frequencies. Therefore, reducing the frequency of the current can help to reduce the impact of skin effect. However, this is not always practical or possible in many applications

8- References

1. Stankiewicz, J. M. (2023). Analysis of the Influence of the Skin Effect on the Efficiency and Power of the Receiver in the Periodic WPT System. Energies, 16(4), 2009.
2. P. Zoya and P. Branko D., "Chapter 20 - The Skin Effect," in Modern Introductory Electromagnetics, New Jersey, Prentice Hall, 2000, p. 382.
3. W. Contributors, "Wikipedia, The Free Encyclopedia.," 26 August 2014.
4. T. R. Kuphaldt, "More on the “skin effect”," in Lessons In Electric Circuits, Volume II – AC, Design Science License, 2007, p. 77.

5. IET Labs Inc, Application Note - Skin Effect on Wirea, New York: IET Labs Inc, 2012.
6. T. R. Pearson, "Methods and Apparatus for Reduction of Skin Effect Losses in Electrical Conductors". Belvidere, IL (US) Patent US 2012/0125651 A1, 24 May 2012.
7. Raven, M. S. (2018). Skin effect in the time and frequency domain—comparison of power series and Bessel function solutions. Journal of Physics Communications, 2(3), 035028.
8. U.R. Patel et al.An equivalent surface current approach for the computation of the series impedance of power cables with inclusion of skin and proximity effectsIEEE Trans Power Deliv(2013)
9. Beryozkina S (2019) Evaluation study of potential use of advanced conductors in transmission line projects. Energies 12(5):822–848
10. R. A. Meyberg, F. M. A. Salas, L. A. M. C. Domingues, M. A. Sens, M. T. C. de Barros and A. C. S. Lima, "Magnetic properties of an ACSR conductor steel core at temperatures up to 230 °c and their impact on the transformer effect", IET Science Meas. Technol., vol. 15, no. 2, pp. 143-153, 2021.
11. S. A. Pignari and A. Orlandi, "Long-cable effects on conducted emissions levels", IEEE Trans. Electro Magnetic Compatibility, vol. 45, pp. 43-54, 2003.
12. Zhan Ying, Kai Feng, Zhijia Du, Yafang Liu and Junji Wu, "Thermal path model for calculating the relationship between high-voltage overhead conductor current and axial temperature[J]", Proceedings of the CSEE, vol. 35, no. 11, pp. 2887-2895, 2015.
13. M. Findlay and B. Zhang, "Distribution of current density in ACSR conductors", Proc. IEEE Can. Conf. Elect. Comput. Eng., pp. 165-168, 1994.
14. O.M.O. Gatous et al.T.R. Pearson, Methods and apparatus for reduction of skin effect losses in electrical conductors. Belvidere, IL (US).
15. Frequency-dependent skin-effect formulation for internal resistance and internal inductance of a solid cylindrical conductorIEE Proc Microw, Antennas Propag(2004)
16. Ruyguara A. Meyberg, Maria Teresa Correia de Barros, Farith M. Absi Salas, Luis Adriano M.C. Domingues, Antonio C.S. Lima, "Improved Electromagnetic Model for Steel-Cored Conductors", IEEE Transactions on Power Delivery, vol.37, no.1, pp.239-248, 2022
17. H. Banakar, N. Alguacil, F.D. Galiana, "Electrothermal coordination part I: theory and implementation schemes", IEEE Transactions on Power Systems, vol.20, no.2, pp.798-805, 2005.
18. D. W. Kim, Y. D. Chung, H. K. Kang, Y. S. Yoon and T. K. Ko, "Characteristics of contactless power transfer for HTS coil based on electromagnetic resonance coupling", IEEE Trans. Appl. Supercond., vol. 22, no. 3, Jun. 2012.
19. Martinez Alvarez, V. M., Barrios Vargas, J. E. & Foa Torres, L. E. F. Non-Hermitian robust edge states in one dimension: Anomalous localization and eigenspace condensation at exceptional points. Phys. Rev. B **97**, 121401(R) (2018).
20. "EN 50182", Conductors for overhead lines. Round wire concentric lay stranded conductors, May 2001.
21. Goryunov V N, Girshin S S, Kuznetsov E A, Petrova E V and Bigun A Y 2016 A mathe-matical model of steady-state thermal regime of insulated overhead line conductors IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC) pp 1-5.
22. Ruehli, A. E., Antonini, G., & Jiang, L. J. (2012). Skin-effect loss models for time-and frequency-domain PEEC solver. Proceedings of the IEEE, 101(2), 451-472.
23. Vincent T. Morgan, "The Current Distribution, Resistance and Internal Inductance of Linear Power System Conductors—A Review of Explicit Equations", IEEE Transactions on Power Delivery, vol.28, no.3, pp.1252-1262, 2013.
24. Menshov, A., & Okhmatovski, V. (2012). New single-source surface integral equations for scattering on penetrable cylinders and current flow modeling in 2-D conductors. IEEE transactions on microwave theory and techniques, 61(1), 341-350.
25. Radulet, R. (1978). the transient response of the electric lines based on the equations with transient line-parameters.
26. Nia, M. S. S., Saadatmand, S., Altimania, M., Shamsi, P., & Ferdowsi, M. (2019, October). Analysis of skin effect in high frequency isolation transformers. In 2019 North American Power Symposium (NAPS) (pp. 1-6). IEEE.
27. Aizawa, Y., Nakayama, H., Kubomura, K., Nakamura, R., & Tanaka, H. (2020). Theoretical study on lowering loss of skin effect suppressed multi-layer transmission line with positive/negative (Cu/NiFe) permeability materials for high data-rate and low delay-time I/O interface board. AIP Advances, 10(1), 015124.
28. Sukhichev, M., & Skochko, E. (2022, September). Influence degree of skin-effect for overhead line conductors. In Journal of Physics: Conference Series (Vol. 2339, No. 1, p. 012030). IOP Publishing.