Finite Element Analysis in The Investigation of Methods to Model AC Resistance in A Coated Conductor

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Abstract. In our electricity dependent and rapidly automated society, the manipulation and usage of electricity to transmit energy is of significant prevalence. In particular, the application of current in high frequency transformers, inductors and motor generators presents a unique efficiency problem: The loss of energy through the spiking of effective resistance intrinsically related to the skin and proximity effects of an AC current. By the usage of Finite Element Analysis (FEA) in the simulative investigation of various variables on AC resistance, this paper seeks to provide insights into how coated conductors might offer advantages over the standard conductor in certain conditions, thus guiding future design and application in high-efficiency electronics. The papers findings reveal that adding a layer of coating with a lower conductivity than the core material could offer reduced energy losses up to the point when the skin depth matches the coating's thickness. Moreover, the study explored the influence of the coating's conductivity, suggesting that an increased conductivity of the coating material could further minimize copper losses, albeit with the trade-off of potentially higher costs. The study concludes with a Taylor Series approximation of the relationship between AC resistance and frequency using simulative data.

Keywords: Copper Losses; Skin Effect; Proximity Effect; Coated Conductor; AC Resistance.

1. Introduction

In our electricity-dependent and rapidly automated society, the manipulation and usage of electricity to transmit energy are significantly prevalent. Particularly, the application of current in high-frequency transformers [1], inductors [2], and motor generators [3] presents a unique efficiency problem: the loss of energy through the spiking of effective resistance intrinsically related to the skin and proximity effects of an AC current. Furthermore, the rapid downsizing of electronics in small machine systems accentuates this predicament, especially in machines with high-density energy requirements – such as EVs and smartphones where AC losses are substantial. Thus, the copper losses resulting from these effects need to be alleviated to achieve true high-efficiency electronics.

The skin effect occurs in high-frequency AC current where the current diverges from the center of the conductor and instead flows through the skin depth of the conductor due to the eddy currents formed by its varying magnetic field. As a result, the cross-sectional area the current flows through is substantially decreased, resulting in spiking effective resistance. The proximity effect occurs in alternating current circuits where two or more conductors are close to each other, and the magnetic fields created by the movement of electric current affect the distribution of current in adjacent conductors. This is particularly emphasized in small-scale, high-power electronics where the proximity effect is far more pronounced [4]. Proximity effect refers to the effect in an AC circuit where the magnetic field formed by the movement of current affects the distribution of current in adjacent conductors when two or more conductors are close together. This effect is particularly prominent in high-frequency circuits, causing current to tend to flow through conductors with less effective area, thereby increasing effective resistance and leading to energy loss.

Using 2-D Finite Element Modelling (FEM), we can model the AC resistance of a conductor by considering its cross-section. To achieve accurate simulative data, we need to consider the quality of the mesh as the Finite Element method essentially solves Maxwell's equations for each of the defined and finite elements, with the result as the sum of the obtained solutions in each element. Thus, the accuracy of this simulation depends on the accuracy of the modeling. However, finer elements may

also lead to numerical instability [5], thus a compromise must be made between accuracy and processing time. In the case of this paper, smart meshing on FEMM 4.2 was used to create an accurate simulation for our purposes.

Different techniques have been developed to mitigate these losses, including Litz wire, stranded conductors, as well as optimized geometry of wire configurations. Although there are simplified formulas to model resistance in a standard conductor, the modeling of AC resistance in a coated conductor remains unclear. In fact, the quantitative formulation of a model to derive AC resistance as a function of the variables within the situation is quite difficult due to the intricate nature of a coated conductor. This paper will endeavor to investigate circumstances in which a coated conductor would show benefits over the standard conductor by simulating the effects of certain variables on the effective resistance of wires analyzed and validated by Finite Element Analysis (FEA), as well as approximating the modeling of AC resistance as a proportion of its variables. Through Finite Element Analysis, this paper seeks to validate this design while showing the effects of different parameters, which can guide further design. By first simulating the isolated coated conductor in Section 2, the paper investigates how the skin effect changes in a coated conductor according to different variables such as the radius of the coated layer, electrical conductivity, frequency, and amperage. Proceeding to Section 2, the paper will investigate the confluence of the proximity effects and skin effects in different configurations of multiple conductors, investigating the factors that affect how they amalgamate into the copper losses of the conductor. Section 4 will discuss the approximation of the trends established, and Section 5 will be the conclusion of the paper.

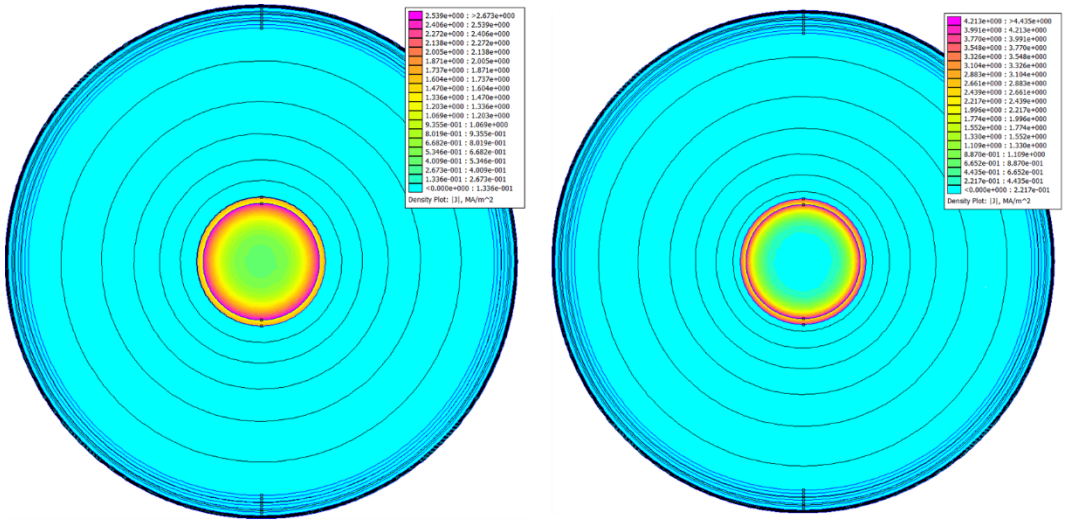
2. Single Coated Conductor

By considering the single, isolated case of a coated conductor, we can investigate how different variables effect its resistive losses. In this isolated case, the skin effect takes precedent as the only phenonmenom which effects the resistance of the wire. In this Section, the paper will investigate certain situations where a coated conductor could show advantage against a non-coated conductor by considering the wire as an isolated body.

Generally, industry standards rarely dictate a standard, specified level of coating thickness, and instead control the thickness thorugh various other requirements like electrical resistance and weight. These requirements are detailed in the ASTM Standards [6]. This paper will take the thickness of the coating to be in a ratio of 1:9 with the core thickness, taking 10% of the wire’s total thickness.

2.1. Coating without Replacement

In the analysis of the rectilinear coated conductor in an isolated setting, the influence of the skin effect on current distribution at high frequencies can be investigated. Coated conductors are frequently substituted for pure element conductors to achieve weight reduction, cost reduction, or improved efficiency. This section will examine data obtained from FEA, comparing the efficiencies of a coated conductor with those of a conductor containing only the core element. Fig. 1 depicts the analysis of current density within a coated conductor featuring a copper core with a radius of 0.5mm and a coating possessing 50% of copper's conductivity, with a thickness of 0.05mm and a depth of 1000mm with frequencies at 200kHz and 900kHz.



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Fig. 1 Current density in a single coated conductor. (a) at 200kHZ; (b) at 900kHz.

As illustrated in Fig. 1, the skin effect becomes significantly more prominent at higher frequencies and starts to influence the coating layer beyond a certain threshold determined by the skin depth. To compare the performance of the coated conductor with that of the non-coated conductor, where the core material is not replaced by the coating layer, data on the effect of high frequency on resistive losses has been collected, plotted, and compared in Fig. 2.

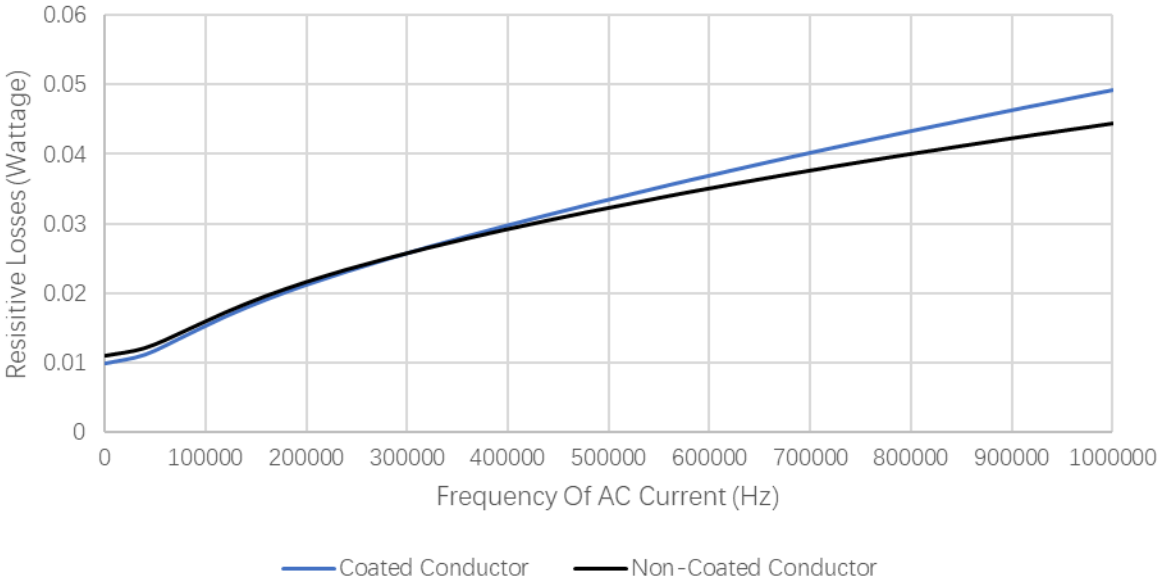


Fig. 2 The resistive losses of a coated conductor compared to a non-coated conductor.

In this specific case, the coating layer – which has a defined effectiveness of 50% – seems to provide an advantage over an un-coated copper wire for frequencies under approximately an AC current with a frequency of 350kHz as shown in Fig. 2. However, as frequencies begin to get higher, the coated conductor seems to become much less efficient than its non-coated counterpart. This critical point in which this occurs could potentially be when the skin effect starts to affect the coated component of the conductor, causing most of the current to flow in the less conductive coating – increasing the effective resistance of the conductor.

The skin depth is defined as:

$$\delta = \sqrt{\frac{\rho}{\pi f \mu_r \mu_o}} \tag{1}$$

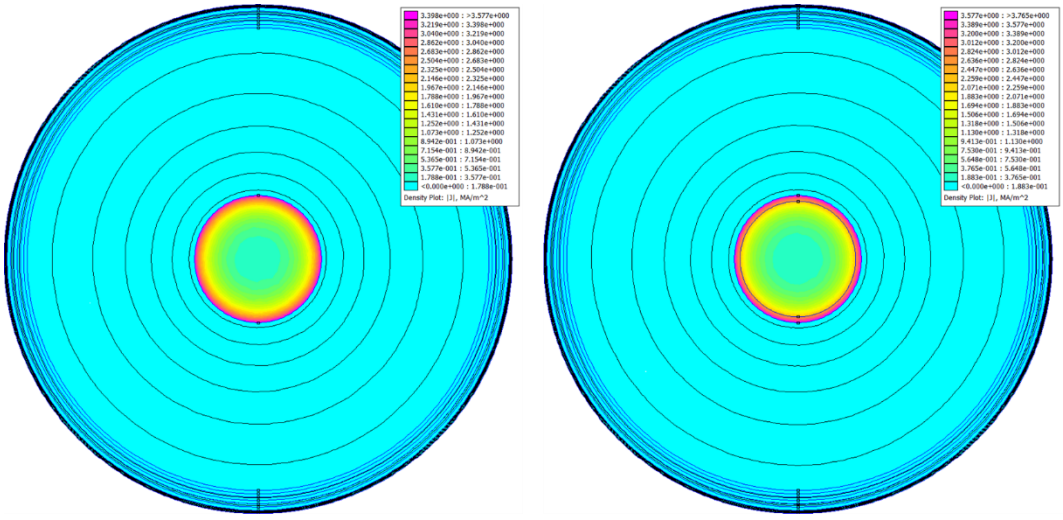
Substituting the values of the simulation and solving for frequency f gets the value of 349kHz, which is congruent with the understanding of why the coated conductor loses its advantage over the non-coated conductor.

Before the skin depth is reached, the coated conductor provides an advantage over the un-coated conductor. It should be noted that in this case, the coating is not replaced by the core material in the non-coated conductor, and as a result the cross-sectional area of the coated conductor is higher than non-coated conductor. These results suggests that potentially, a coated copper conductor may show advantage over a purely copper conductor (without the coating replaced) monetary wise. The usage of a cheaper material in place of copper – in this case – suggests a 9.5% increase in efficiency, decreasing akin to a root-function with respect to frequency until the critical point is reached - where the skin effect starts to take place on the coating of this less conductive conductor.

2.2. Varying Conductivity of Coating Material

In the quest to enhance the efficiency of transformers and high-frequency electronics, replacing the original wiring with a wider coated wiring seems impractical, as device configurations rely on the wire diameter. Therefore, alternative methods must be explored to reduce copper losses in machines without altering the wire diameter. Considering that the skin effect concentrates AC current on the wire surface, the rationale for coating the conductor with a higher conductivity material becomes evident.

This paper will examine the impact of conductivity within the wire coating on the copper losses of the conductor, ranging from 29 MS/m to 63 MS/m, while maintaining the same diameter. These effects will be analyzed and validated using Finite Element Analysis (FEA). Current density maps of a purely copper conductor and a copper conductor with a silver coating at 300 kHz, with dimensions as outlined in Section 2.1, are depicted in Fig. 3.



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Fig. 3 Current density maps of a single conductor at 300kHz. (a) purely copper; (b) with a silver coating.

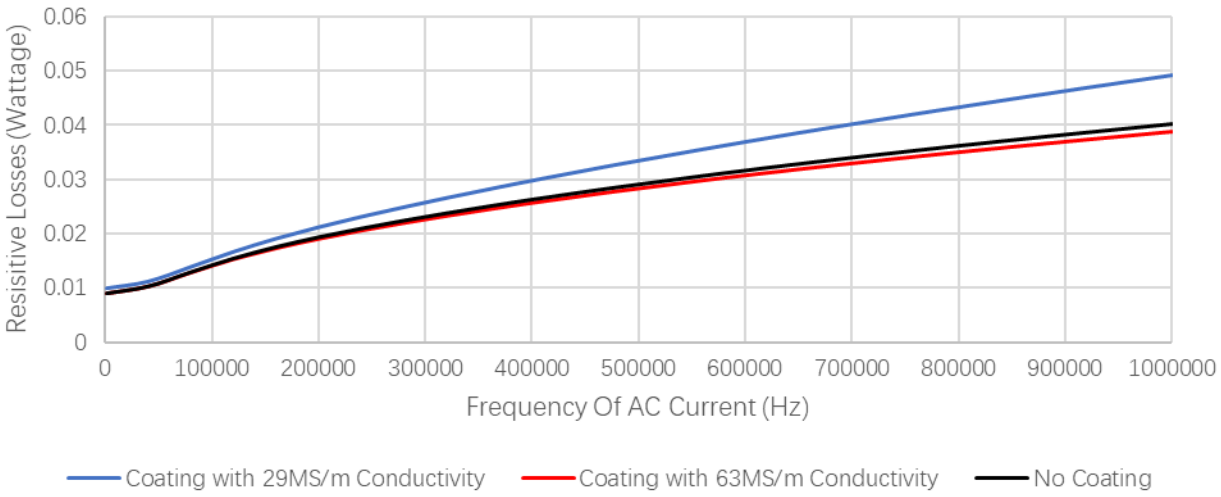


Fig. 4 The resistive losses of a conductor with no coating compared to with a coating that has a lower conductivity and a higher conductivity.

In Fig. 4, as observed through FEA, it becomes evident that with the AC current operating at progressively higher frequencies, the coated conductor with a higher conductivity coating demonstrates a greater advantage over the standard coat-less conductor in terms of minimizing copper losses. However, incorporating a silver coating onto the copper wires can pose as an expensive alternative, and thus, the manufacturing cost should be duly considered in the design process.

2.3. Alternative Geometry

Another important factor to take into consideration is the geometry of such a coated conductor. The geometry of conductors within electrical engineering applications profoundly influences their characteristics of thermal, electrical, and mechanical variables. A departure from the traditional rectilinear conductor may show a possible advantage considering both from the resistive losses and the practical considerations. Among alternatives to the traditional rectilinear conductor is the square-shaped conductor. In a bid to optimize the spatial efficiency of transformers, the square-shaped conductor offers a compelling alternative. The rationale behind the utilization of the square-shaped conductors is derived from their packing-density advantages in winding assemblies.

An analysis of the current density in a coated square conductor with the same cross-sectional area in previous sections running in an 1A RMS AC Current with a 300kHz frequency is shown in Fig. 5.

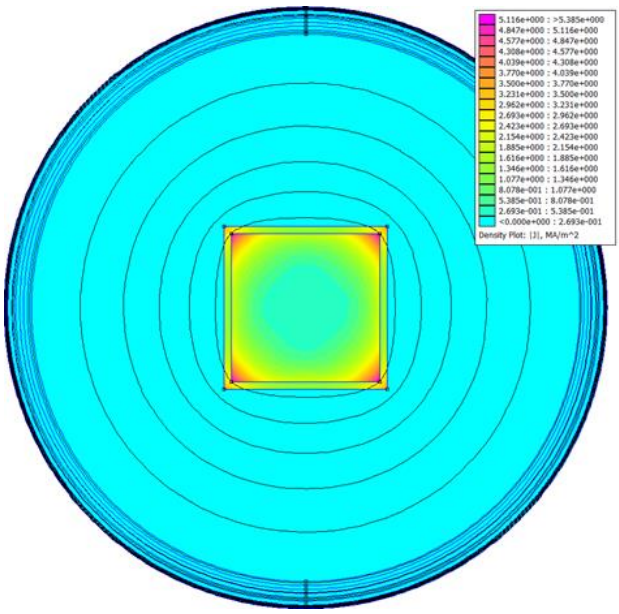


Fig. 5 Current density in a coated square conductor.

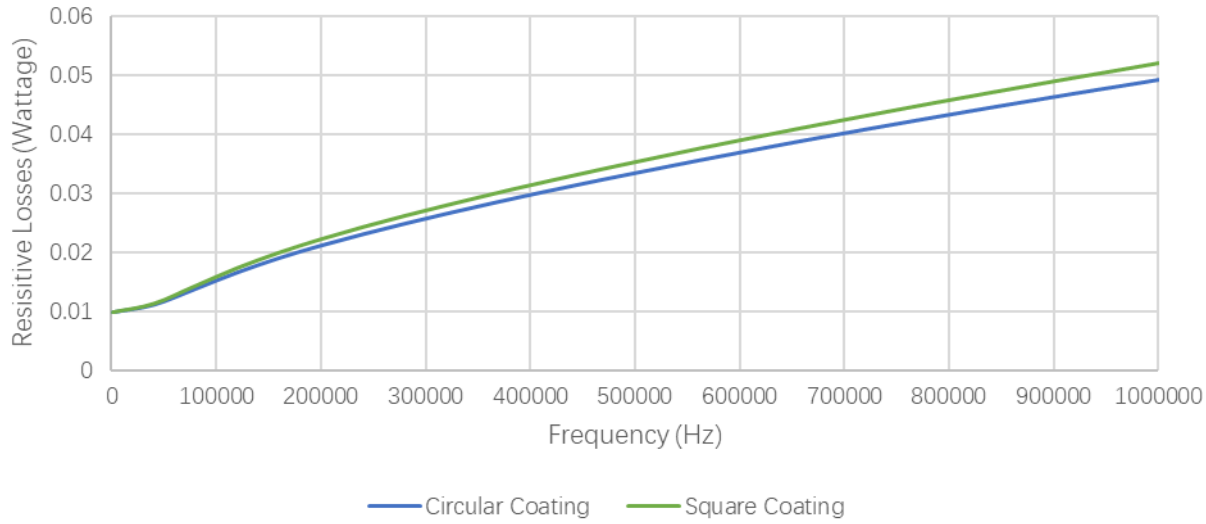


Fig. 6 The resistive losses of a coated circular conductor compared to a coated square conductor with the same coating conductivity.

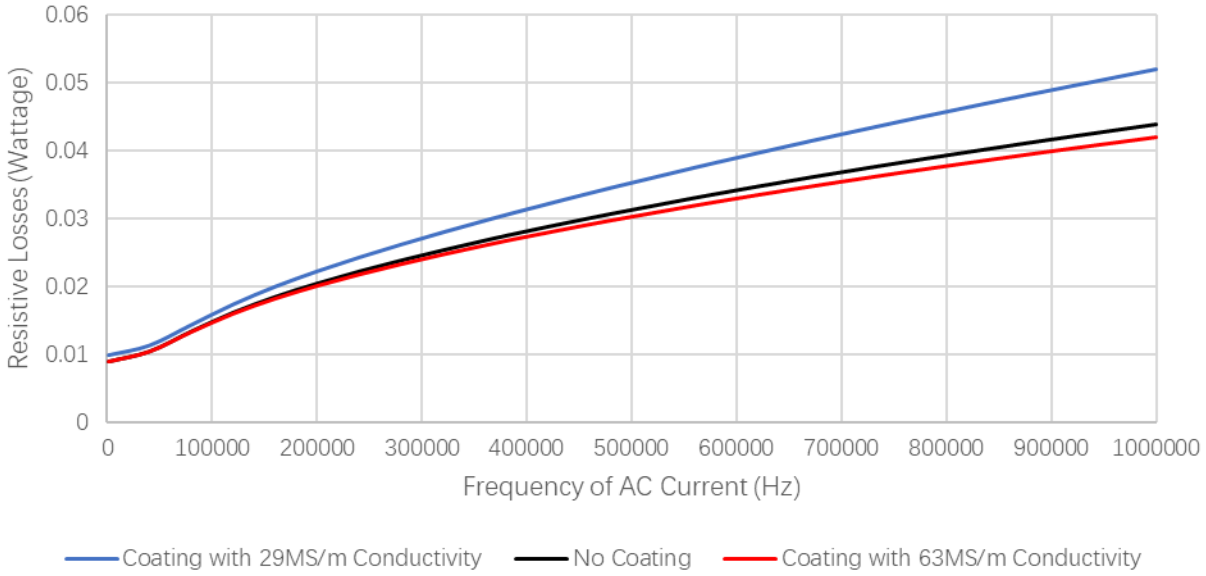


Fig. 7 Resisitve losses of a square conductor with varying coating conductivity

There is agreement between Fig. 7 and Fig. 4 regarding the relationship between the conductivity of the coating and resistive losses, suggesting that this trend may be independent of the conductor's geometry. As shown in Fig. 5, there is a clear hotspot of electrical conductivity at high frequencies near the edges of the square. However, as referenced in Fig. 6, isolated simulations may suggest that a square conductor exhibits a clear disadvantage compared to circular coating. Nevertheless, the isolated nature of this test diverges from the primary purpose of a square conductor – the advantage of spatial density in a wound assembly over a circular conductor. Consequently, this will serve as a key motivation for the paper in Section 3, where the modeling and comparison of both conductor types in a winding context will be conducted.

2.4. Summary

The FEA method has been utilized to analyze different variables that are proportional to the copper losses experienced by the coating layer in an isolated context. The relationship between these variables has been approximated, as well as the material feasibility of these situations.

However, it should be acknowledged that due to the limitations of this simulative method, the boundary resistance inherent in a cladded conductor has not been accounted for. To arrive at a clear conclusion, these complex variables need to be included. This omission underscores a notable

discrepancy: the resistances predicted by the paper's simulations are likely to be lower than the actual values encountered in practice. To refine the accuracy of our model and validate the highlighted relationships, a more extensive experimental investigation is necessitated.

Moreover, the scope of Section 2's simulations is confined to the analysis of an isolated conductor. Consequently, this presents a scenario divergent from practical applications in transformers, electrical machines, and inductors.

In light of these considerations, this paper will now extend to encompass the copper losses within an arrangement of multiple conductors. This progression aims to approximate a more realistic operational context, thereby enhancing the applicability of this investigation to real-world scenarios.

3. Multiple Coated-Conductor Systems

The intricate interplay of electromagnetic phenomena in electrical conductors is certainly affected by the addition of coatings, which can significantly alter the performance of the conductor. The previous section explored the case of a single, coated conductor, wherein the skin effect most predominantly affected the resistive losses of conductors. However, as established above, these tests were conducted in the context of an isolated system, which would be indispensable in practice. Thus, building upon the foundations and trends established in Section 2, the analysis will be expanded into multi-conductor systems that are prevalent in modern-day electronics. In order to simulate the modern-day applications of conductors in windings, this paper will investigate a 3 by 3 set of wiring, exploring both the circular conductors and the square-shaped conductors used in transformer windings.

3.1. Circular Conductors

This section will investigate the interplay between the proximity effect and the skin effect in a 3 by 3 configuration in empty space. Such an exploration is critical, given these effects are markedly pronounced in circular conductors deployed in high-frequency, high-density energy enviroments such as transformers, inductors and motor generators. An analysis of the current density in a 3 by 3 configuration of a coated circular conductors (with less conductive coating 29MS/m) at different frequencies is shown in Fig. 9.

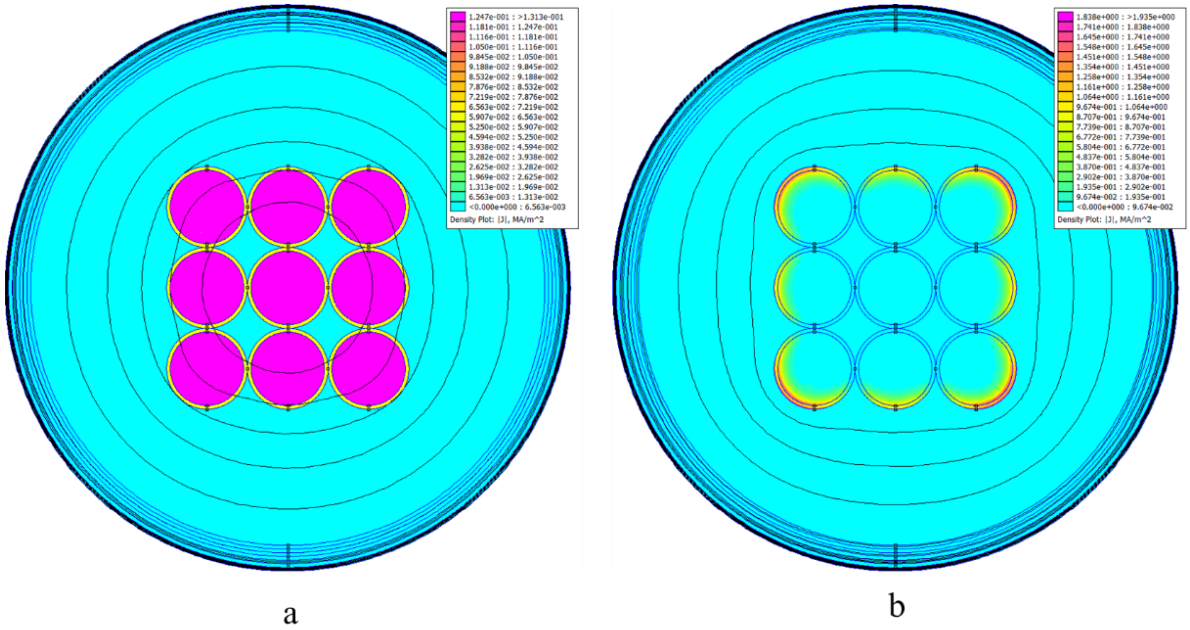


Fig. 8 Current density maps of a 3 by 3 configuration of circular conductors with less conductive coating layers. (a) at 1000 Hz; (b) at 300kHz.

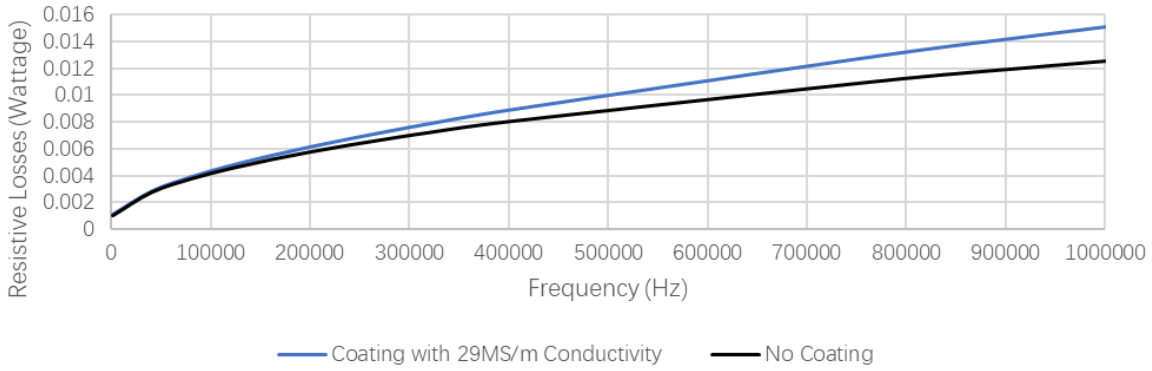


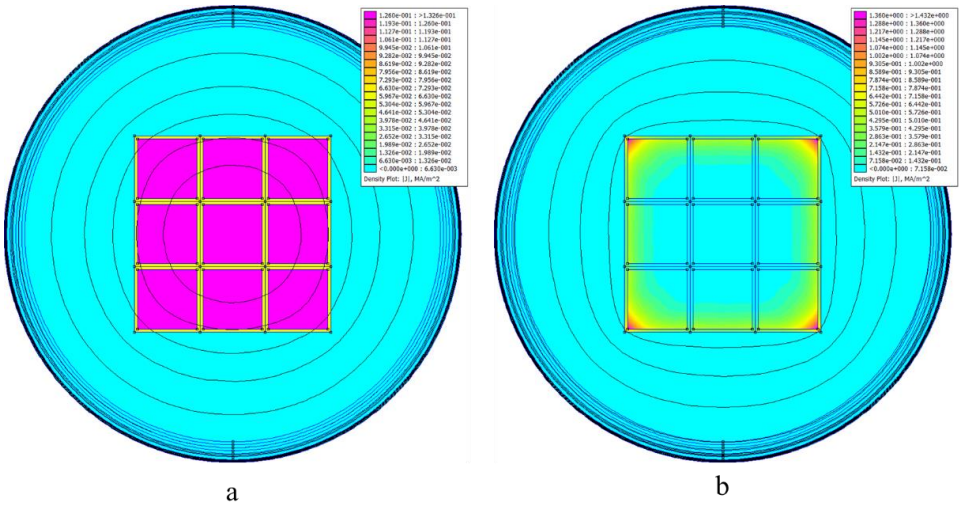
Fig. 9 Resisitve losses of a 3 by 3 configuration of circular conductors.

As shown in Fig. 9 (b), the skin and proximity effects seem to push the current density outwards and, although the series consists of multiple conductors in parallel, it acts as one connected conductor in terms of current density. The inner conductor is approximately conducting zero current (confirmed by FEMM 4.2) and could be effectively removed without causing a substantial difference in resistive losses. This indicates that a transposition in the depth direction is needed to ensure each conductor faces the same flux linkage so that the parallel conductors can most effectively share the total current. Fig. 10 shows that the plain copper conductors outperform the coated ones in the frequency range of interest. This remains unchanged in the single conductor case, which implies that the proximity effects have not been significant enough in this 3 by 3 array.

It is important to observe that, within this configuration, the presence of air interspaces between circular conductors contributes to an underutilization of spatial resources, which may impinge upon the system's overall efficiency. As a result, many applications of winding wires in this fashion utilize square-shaped conductors to improve the system's spatial efficiency. This will be the main motivation for Section 3.2, where the paper will seek to validate these designs as well as investigate the presence of a coating on these phenomena.

3.2. Square Conductors

Having investigated the resistive losses in coated circular conductor frameworks, it is necessary to analyze square conductors in the same frameworks to develop a comparison. The usage of square conductors is most prevalent in intricate machinery like transformers, whose operation is inherently dependent on the optimization of their internal conductor geometry for enhanced performance. Square conductors, by virtue of their shape, offer an advantage in superior packing density within the core of a transformer.



a b

Fig. 10 Current density maps of a 3 by 3 configuration of square conductors with less conductive coating layers. (a) at 1000 Hz; (b) at 300kHz.

The observations made with the circular conductors could also be made with the square conductors, as shown in Fig. 11. As the frequency increases, the skin and proximity effects push the current away from each conductor and towards the skin of the conductors. Consquentially, the inner square also conducts less current, and the effective resistance spikes. However, the transposition of square conductors may be tricky in the depth domain if the conductor is relatively large. Serious connection could help to ensure that the same quantity of current is enforced to flow in the conductors.

Another interesting characteristic that is exhibited by both the square and circular conductor is the accumulation of current on the edges of the shapes. A possible experimental method to confirm this pattern could be running a high frequency current through a multi conductor system where the edges of the cross-sectional shape formed have metals of lower resistance (such as silver), testing whether the restive losses decrease as a result.

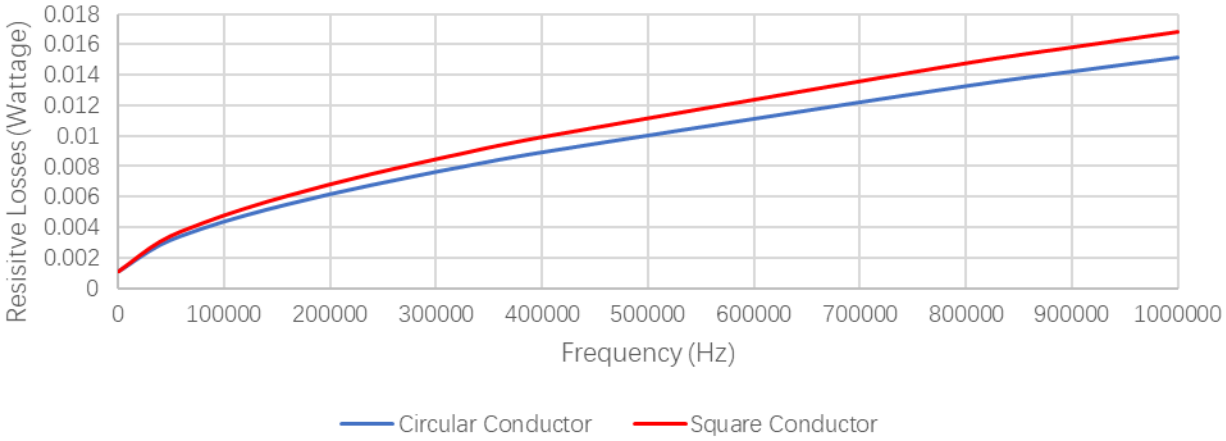


Fig. 11 Resistive losses of a 3 by 3 configuration of conductors, varying the shape of the conductor.

As shown in Fig. 12, although coated circular conductors show an advantage in resistive losses compared to coated square conductors, the spatial advantage provided by the square conductors could outweigh these disadvantages. The square conductors cover a volume 21.4% smaller than the circular conductor, suggesting that while coated circular conductors do exhibit an advantage in resistive losses, implementing square conductors could increase efficiency by leveraging spatial advantages. In other words, with the same space for windings, square conductors allow for more copper to be placed in that space, which can lower the DC-low frequency resistance. Additionally, copper is a far better thermal conductor than air or resin, which means square conductors can offer better thermal cooling conditions. This is why the so called “hairpin” windings are becoming popular in the electrical vehicle applications.

However, it is important to acknowledge that manufacturing feasibility needs to be taken into account when using such conductors, as well as their thermal performance.

4. Approximating the Model of AC Resistance in a Coated Conductor

The Taylor Series fitting helps the understanding of the relationship between frequency and AC resistance; providing a tool for fast prediction of other frequency points that has not been simulated with FEA (as FEA simulations cost a lot of time and effort, normally considered as a slow simulation).

Fig. 12 and Fig. 13 shows the third order Taylor Series approximation of the resistive losses in the circular coated conductor and the square coated conductor as a function of the frequency respectively.

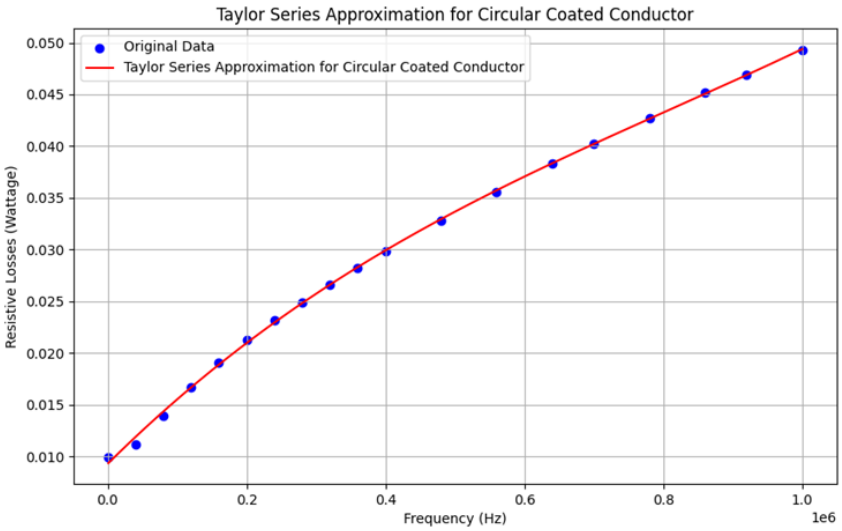


Fig. 12 A third order Taylor Series approximation of the resistive losses in a circular coated conductor as a function of the current's frequency

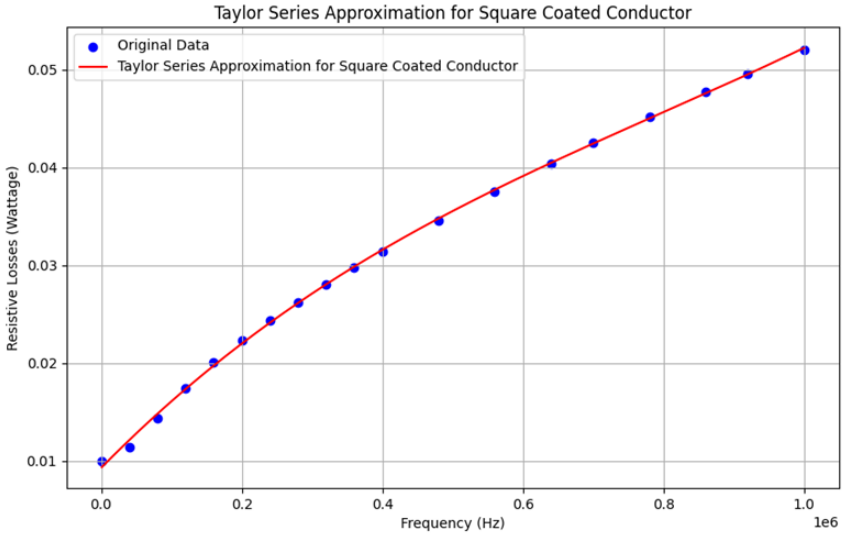


Fig. 13 A third order Taylor Series approximation of the resistive losses in a square coated conductor as a function of the current's frequency

By setting the current to be 1A RMS, the joule loss in the conductor is equal to the AC resistance. Hence the AC resistance of the coated circular conductor can be expressed as:

$$R = 1.846 \times 10^{-20} f^3 - 4.50 \times 10^{-14} f^2 + 6.66 \times 10^{-8} + 0.009278 \quad (2)$$

And the AC resistance of the coated square conductor is

$$R = 2.184 \times 10^{-20} f^3 - 5.186 \times 10^{-14} f^2 + 7.293 \times 10^{-8} f + 0.0093 \quad (3)$$

5. Conclusion

In this paper, FEA was utilized to investigate methods for modeling AC resistance in coated conductors, aiming to enhance the efficiency of high-frequency transformers, inductors, and motor generators. Through simulative investigations, insights were provided into how coated conductors could offer advantages over standard conductors under certain conditions, thereby guiding future design and application in high-efficiency electronics.

The findings revealed that adding a layer of coating with higher conductivity than the core material could reduce energy losses, particularly up to the point where the skin depth matches the coating

thickness. By extending the analysis to include square conductors, it was found that despite coated circular conductors showing advantages in resistive losses, the spatial efficiency provided by square conductors could outweigh these disadvantages. Square conductors offer superior packing density within transformer cores, potentially leading to enhanced efficiency and better thermal performance. However, it is important to consider manufacturing feasibility and thermal performance when implementing such conductors. Additionally, while the study provides valuable insights, further experimental investigations are necessary to refine the model and validate its applicability to real-world scenarios.

In conclusion, this research contributes to the understanding of AC resistance in coated conductors and provides a foundation for future advancements in high-efficiency electronics design and application.

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