Research on the AC Loss of Multi-strand Round Conductors

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Abstract. Conductors are very common in our life, such as high-voltage cables and all household appliances. The vast majority of conductors, especially home circuits, use alternating current. There will be so-called AC loss in AC circuits, which will limit our design and improvement of electrical appliances. In this paper, the AC loss in the charging conductor is influenced by skin effect and proximity effect. First of all, we will introduce these two effects. Both effects cause energy loss via induction current. Secondly, variables related to energy loss are pointed by using finite element analysis. After modelling and analysis, energy loss depends on frequency, loss increase with increasing frequency. Secondly, among the different arrangements of conductors, the arrangement of hexagons will be more energy-saving. Finally, the degree of energy loss is related to the conductor's diameter. As the conductor's diameter increases, the energy loss increases first and then decreases. In the end, energy loss relies on the size of frequency and the arrangement of conductors and the diameter of conductors

Keywords: Skin effect; proximity effect; AC loss; DC loss.

1. Introduction

Physically, the frequency of alternating current will have a great impact on the energy loss in the conductor, so called alternating current (AC) loss.

Many impacts have led to some engineering challenges. For example, Demko J. A. et al. [1] reports the loss of alternating current depends on the temperature of high-temperature superconductivity. If there is no guarantee that the temperature is below a certain value, the cable will generate vapor, resulting in higher AC loss. In addition, Oberly C E et al. [2] reported that the design of aircraft generators was limited by AC loss. At the same time, the conductor design is limited by substrate width thickness, filament width and barrier resistivity. In [3], Chudy M et al. explored the AC loss of HTS of wind turbine under different DC fields. In [4], M Vojenčiak et al. considered the shift of phase between the magnetic field and current, and studied the total energy loss in the special band.

Furthermore, in machinery such as motors, energy loss is very obvious. In the case of copper and aluminum conductors, the finite element analysis method can effectively estimate the loss through mush [5].

Bauer D et al. [6] and Roth, C. et al. [7] shows that the AC loss insulation management has a decisive impact on the efficiency and life of the machine.

This essay mainly talks about two phenomena. One is the skin effect and the other is the proximity effect. This influence brings many challenges to the design of batteries, voltmeter and inductors in engineering.

This paper starts from the electromagnetic theory, and then uses a finite element algorithm to show the energy loss in the conductor under different, frequencies, different permutations and different radius.

2. Skin and Proximity effect

2.1 Skin effect on copper conductor

Theoretically, when there are direct current (DC) in conductor, the current density is uniform which is shown in Fig. 1.

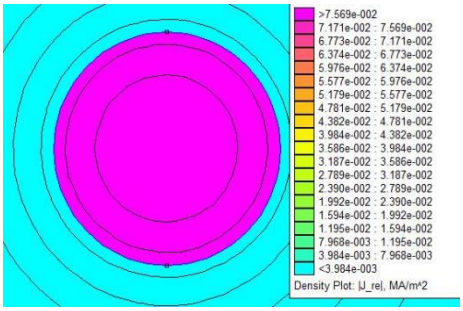


Fig. 1 Current density in DC

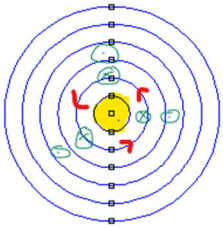


Fig. 2 Diretion of current (yellow), magenetic field (red) and eddy current (green)

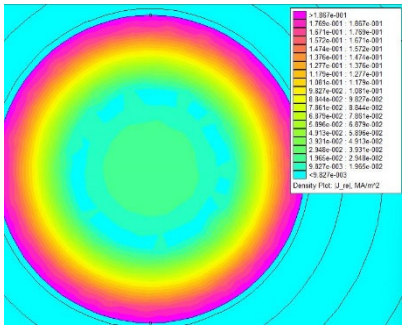


Fig. 3 Current density in AC

However, if there is alternating current (AC) in same conductor. As shown in Fig. 2, firstly, assuming current is out of page. While the direction of AC (yellow part) changes, the direction of magnetic field (red part) produced from current in conductor also changes. Then, the changing magnetic field conduces the eddy current (green part) due to Len's Law (current induces in opposite direction of existing magnetic field in this case) at the conductor around the current. Eddy current inside the page cancels with current and less current at the core of conductor, meanwhile, a part of eddy current is out of pages which has same direction with current added with current. Therefore, the current density increases at outside of conductor and decreases in core of conductor. Furthermore, less cross-sectional area can be used for transferring delocalized electrons and thus current resistance increases and energy loss rise, shown in Fig. 3.

It is interesting that the skin effect loss model is difficult to estimate. Wigington R L, Nahman N S [8] assumes that this loss has ideal square root frequency dependence, and uses the Laplace transform method to analyze conductors with skin effect loss.

Skin effect loss has been studied many times in recent years, and many circuit models have been built, but these circuit models are rarely used for transient analysis of transmission lines. Yen C S et al. [9] proposed two circuit models, in which the combined modeling of the series energy storage circuit composed of resistors and inductors was used to simulate the skin effect loss of each part of the transmission line

2.2 Proximity effect

Proximity effect bases on similar principle of skin effect. When two conductors are closed, the electromagnetic field interact with each other. The eddy current forms due to Len's Law and affects the current density. Therefore, there are energy loss.

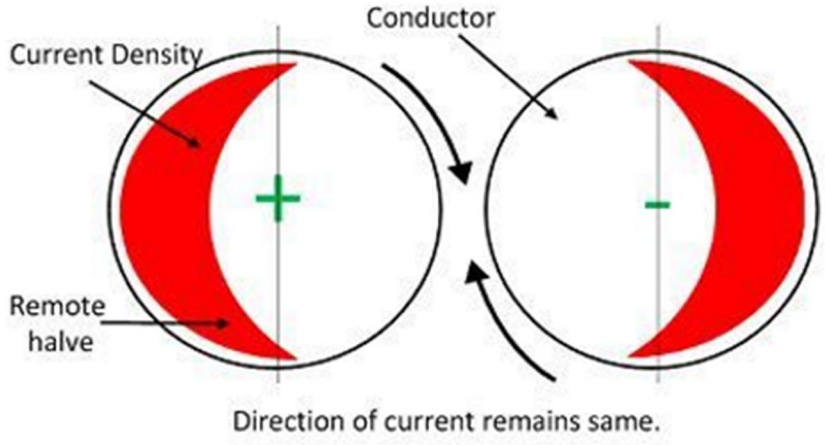


Fig.4 Current in two adjcent conductor [10]

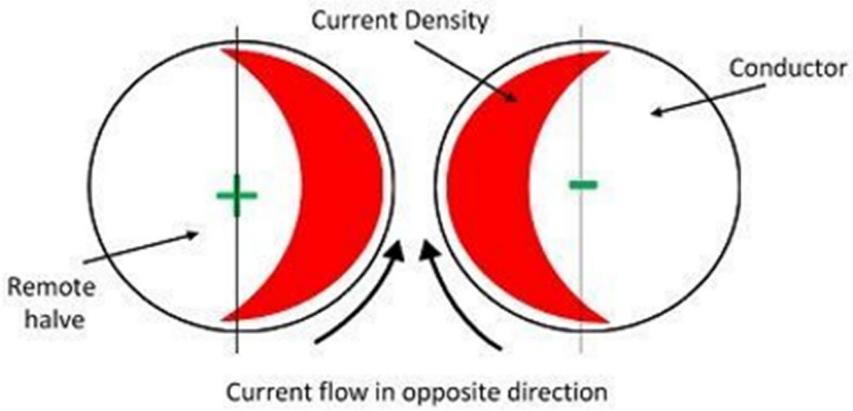


Fig.5 Opposite current in two adjacent conductors [11]

Regarding to the current density, when the current has same direction, current concentrates in the remote hub portion of the conductor. If current is opposite, the closed part of the conductor carries more current, shown in Fig. 4 and Fig. 5. Definitely, this effect also causes energy loss.

As an example. Morgan V T [12] reported that for a conductor core wire, its DC density increases as its resistivity decrease. However, in AC, Eddy current in the metal layer will produce magnetic flux in the iron core, resulting in power loss. Meanwhile, uneven distribution of current density and magnetic field density are changed. These effects increase resistance and decrease internal inductance

2.3 Summary

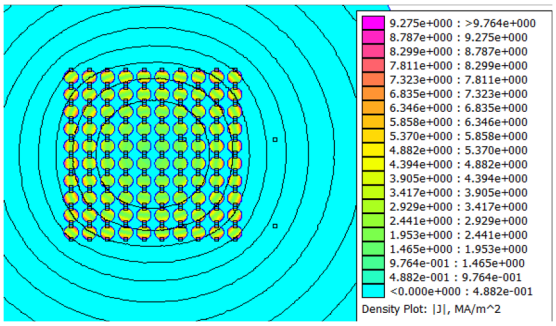


Fig. 6 Current in many conductors

In almost all engineering projects, these never only use one conductor. When many conductors are used at the same time, the skin effect and proximity effect will occur simultaneously and complicate the analysis of total loss. Next, the impact of different factors on the total energy loss by applying will be discussed.

3. Finite Element Method (FEM) Simulation Results

3.1 The relationship between frequency and energy loss

As discuss, the energy loss is mainly because of skin effect and proximity effect. In voltages and inductors, these use a lot of copper conductors and thus proximity effect is the main influence in those cases. Regarding to energy loss, theoretically, with increasing in frequency, the magnetic field's rate of change produced from current is higher and more inductive current are produced. Therefore, less cross-sectional area can be used. For a long cylindrical conductor, the resistance is

$$R = \rho * L/\pi(D - \delta)\delta \quad (1)$$

where ρ is the resistivity, L is length, D is diameter, δ is thickness.

In fact, D is much larger than δ,thus (1) can be approximate as

$$R = \rho * L/\pi D\delta \quad (2)$$

Based on attribution from F.E. Terman,

$$Dw = 0.2/\sqrt{f}$$

where f is frequency, Dw is useful diameter [13].

Therefore, with increasing frequency, resistance decreases.

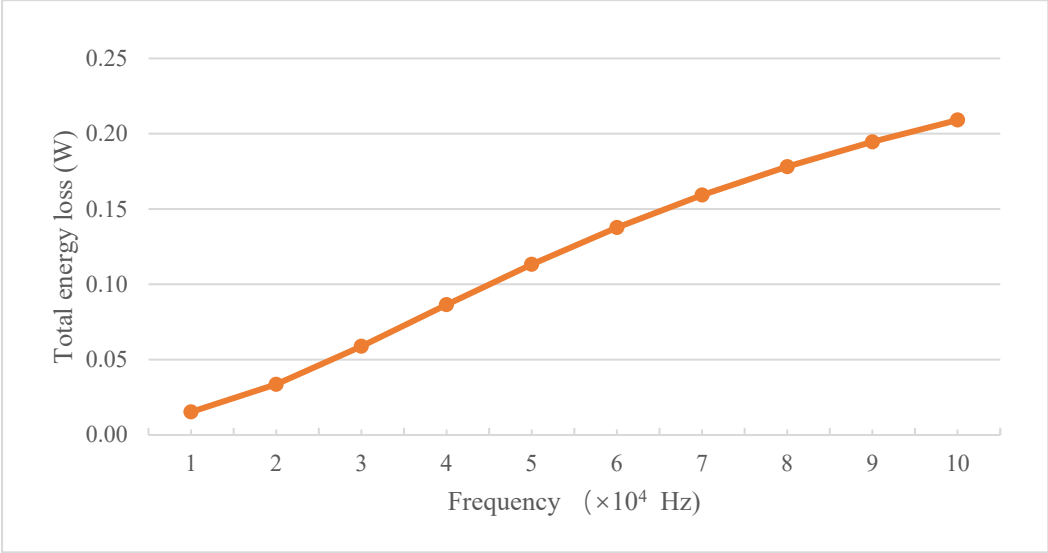


Fig. 7 Total loss of square arrangement

To clear the relationship between the frequency of alternating current and total energy loss of wires, FEM simulation is used. Total loss in all wires is simulated under different frequency. Fig. 4 shows the energy loss in 100 wires, arranged in square (shown in Fig. 7), each the circular conductor has 1

ampere and has a radius of 0.5 mm and a length of 5 mm in the total area of 10×10 mm2. When the number remains unchanged and the center distance is 1.5 millimeter, the energy loss increases with increasing frequency. In this case, overall trend is upward. The figure of energy loss initially increases, followed by gradually approaching to a fixed value.

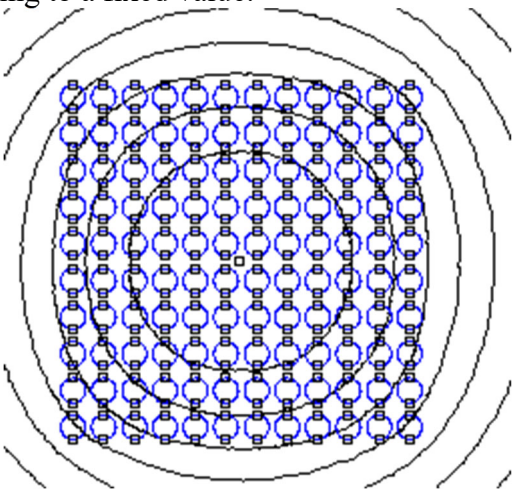


Fig. 8 Example of square arrangement

3.2 The energy loss in different arrangement

This section mainly compares the energy loss of conductors under square and hexagonal arrangement (shown in Fig. 10).

When the current of the conductor is 1 ampere, the circular conductor has a radius of 0.5 mm and a length of 5 mm in the total area of 10×10 mm2. When the number remains unchanged and the center distance is 1 millimeter, the conductors are arranged in squares and hexagons.

As shown in the Fig. 8, regardless of the frequency of alternating current, the energy loss of square conductors is always lower than that of conductors arranged in hexagons.

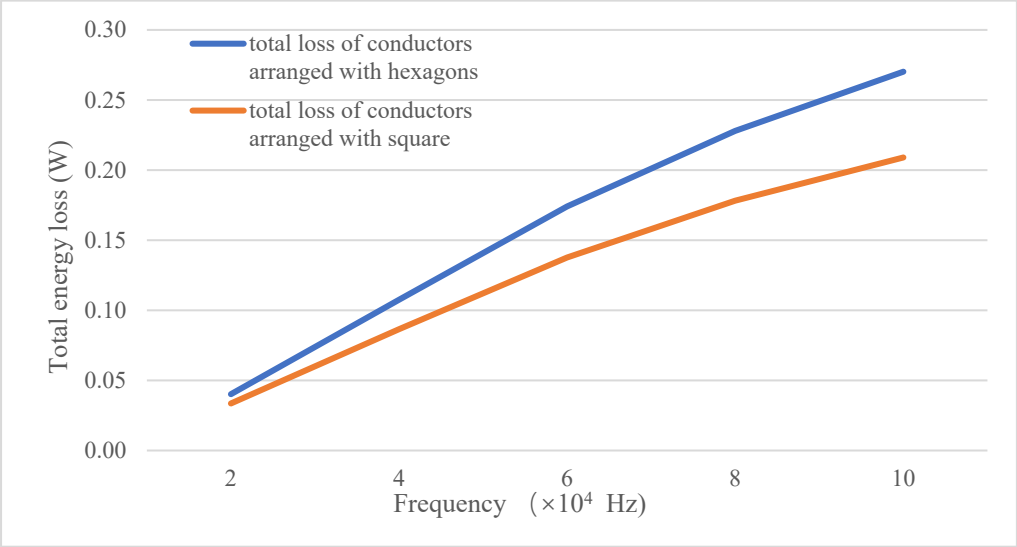


Fig. 9 Total loss of square and hexagonal arrangement

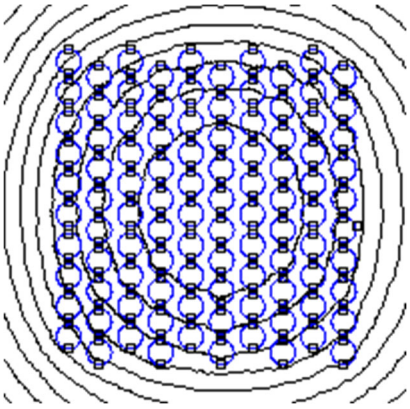


Fig. 10 Example of hexagonal arrangement

3.3The energy loss in increasing wires

The energy loss of conductors with different thicknesses are simulated. With the total area (10×10 mm2) and total current (100A) unchanged, all currents will be divided equally into each conductor.

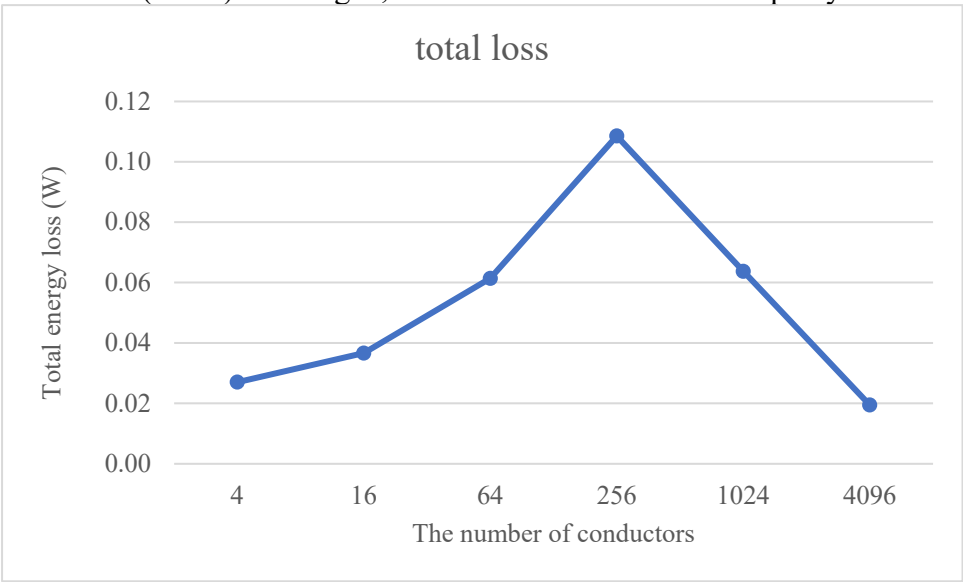


Fig. 9 Total loss of square arrangement in the various numbers of wires

The number of conductors arranged in squares gradually increased from 4 in the form of 42 to 4,096, while the radius of conductors gradually decreased from the beginning. Through the image, it is obvious that the total energy loss at the beginning increases with the decrease of the radius of the conductor and reaches a peak (0.108552 W) when the number of conductors is 256. Since then, as the number of conductors increases, the total energy loss shows a downward trend.

4. Conclusion

It is very obvious that whenever the frequency increases, the energy loss will inevitably increase. Secondly, in the case of different arrangement, the energy loss under the hexagonal arrangement is significantly higher than that of squares. Finally, as the radius of the wire decreases, the energy loss of the wire shows an upward trend, followed by a downward trend. To sum up, the frequency magnitude, conductor arrangement and diameter are the key factors that determine the total loss. Therefore, in order to reduce energy loss, the design should choose to use square arrangements and use as thin wires as possible to reduce energy loss. This conclusion is of reference significance for the engineering design.

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