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Calculation of core loss and copper loss in amorphous/nanocrystalline core-based high-frequency transformer

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Amorphous and nanocrystalline alloys are now widely used for the cores of high-frequency transformers, and Litz-wire is commonly used as the windings, while it is difficult to calculate the resistance accurately. In order to design a high-frequency transformer, it is important to accurately calculate the core loss and copper loss. To calculate the core loss accurately, the additional core loss by the effect of end stripe should be considered. It is difficult to simulate the whole stripes in the core due to the limit of computation, so a scale down model with 5 stripes of amorphous alloy is simulated by the 2D finite element method (FEM). An analytical model is presented to calculate the copper loss in the Litz-wire, and the results are compared with the calculations by FEM. [http://dx.doi.org/10.1063/1.4944398]

I. INTRODUCTION

With the demand of high power electrical power conversion, the high-frequency transformers coupled with switching power converters have attracted significant attention in the recent years.[1,2] Thanks to the low loss property, amorphous and nanocrystalline alloys have been widely used for the core of high-frequency transformers. For the core of transformer design, the amorphous and nanocrystalline alloy strips are wound layer by layer. It is a smart choice to use Litz-wire as the high-frequency transformer winding. Litz-wires are weaved by several solid wires in a pattern, which can reduce the eddy current effect.

Eddy-current effects, including skin effect and proximity effect, cause the non-uniform distribution of current, increasing the copper losses. Skin effect is the phenomenon that the alternating current concentrates on the surface of conductor. Proximity effect is the phenomenon that the alternating current crowds to one side of conductor caused by the nearby conductors.

Several methods and models have been presented to calculate the core loss, including the empirical models, the loss separation methods, and the hysteresis models.[3] The empirical models allow a fast calculation, and they are mainly used in machine analysis models nowadays. The most famous model is the Steinmetz equation. Since Steinmetz equation assumes purely sinusoidal flux densities, there are nowadays several modifications used to take into account non-sinusoidal waveforms. A common method to analyze core loss in more detail is to separate it into different loss terms.

In the recent research, eddy current losses or AC resistance of Litz-wire have been investigated. Papers[4–6] analyzed the high frequency loss in transformer windings using Litz-wire by dividing the proximity effect into internal proximity effect (the effect of other currents within the bundle)

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and external proximity effect (the effect of current in other bundles). Paper[7] presented an approximate model for resistance calculation of multi-strand wire winding, including Litz-wire winding by taking into account the proximity effect and skin effect according to the Dowell's equation. Paper[8] presented a computational procedure to calculate the losses of Litz-wire according to the skin and proximity effect losses, based on a fast numerical simulation tool. Papers[9] and[10] tried to determine the number and diameter of strands to minimize loss in a Litz-wire transformer winding by evaluating the tradeoff between proximity effect losses and dc resistance, and develop a method to optimize the Litz-wire designs on the basis of cost and loss, and compare the results to optimized Litz-wire designs.

Finite element method (FEM) is widely used in simulation and calculation of core and wire windings. It usually simulates the core as a whole, while the core is wounded layer by layer actually, and there are gaps between any two layers.2D FEM can be used in resistance calculation of un-twisted parallel solid wires (Litz-wire without twisting) easily, and 3D FEM can be accurately, while it is still difficult to use FEM to simulate the Litz-wire due to the long computation time. Moreover, it is difficult to extend the FEM result of one case into another case.

Most of analytical models for calculating the resistances of Litz-wire under the 1D or 2D field analysis are 1D or 2D models. For the resistance calculation of Litz-wire is a 3D problem, it is difficult to calculate the resistance of Litz-wire accurately by these models.

In this paper, an analytical model for copper loss calculation of Litz-wire is developed. In order to calculate the core loss accurately, the additional core loss by the effect of end stripe is considered.

II. CORE LOSS CALCULATION

The core loss of soft magnetic material includes hysteresis loss, eddy current loss and anomalous loss and it can be calculated by

$$P_c = K_h f B_p^n + K_e (f B_p)^2 + K_a (f B_p)^{1.5} \tag{1}$$

where K_h, n, K_e and K_a are loss coefficients.

In traditional core loss calculation model, the core is considered as a whole. After the winding is excited, the magnetic flux density of the core and core loss can be calculated. While the core is wounded layer by layer actually, there are air gaps between any two layers.

In order to simulate the effect of end stripe, a scale down model with 5 stripes of amorphous alloy is simulated by the 2D FEM, as shown in Fig. 1(a).

The distribution of flux line can be shown in Fig. 1(b). It can be found that the flux line change its direction and into the magnetic stripe.

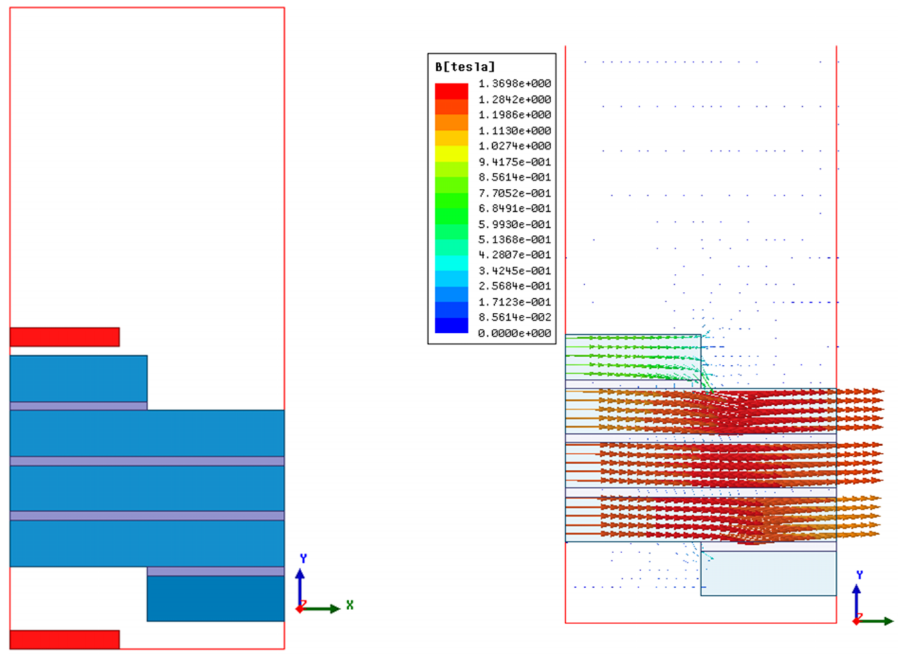
The flux density of core by considering the effect of end stripe can be shown in Fig. 2(a), while the flux density of core without considering the effect of end stripe can be seen in Fig. 2(b), as a comparison.

It can be found that the maximum magnetic flux density and core loss by considering the effect of end stripe are 1.3 T and 501.7 W/kg, respectively, while the maximum magnetic flux density and core loss without considering the effect of end stripe are 1.1 T and 383.7 W/kg, respectively, at the frequency of 20 kHz.

For the actual high-frequency transformer, it is obvious that the number of stripes is much more than 5. Assuming that the thickness of the core is 25 mm, the average thickness of the amorphous stripe is 20 μm, the stacking factor is 0.8, and then the number of stripes in the core is 1000. Thus the additional eddy current loss caused by the effect of end stripe is insignificant, and can be ignored.

III. COPPER LOSS CALCULATION

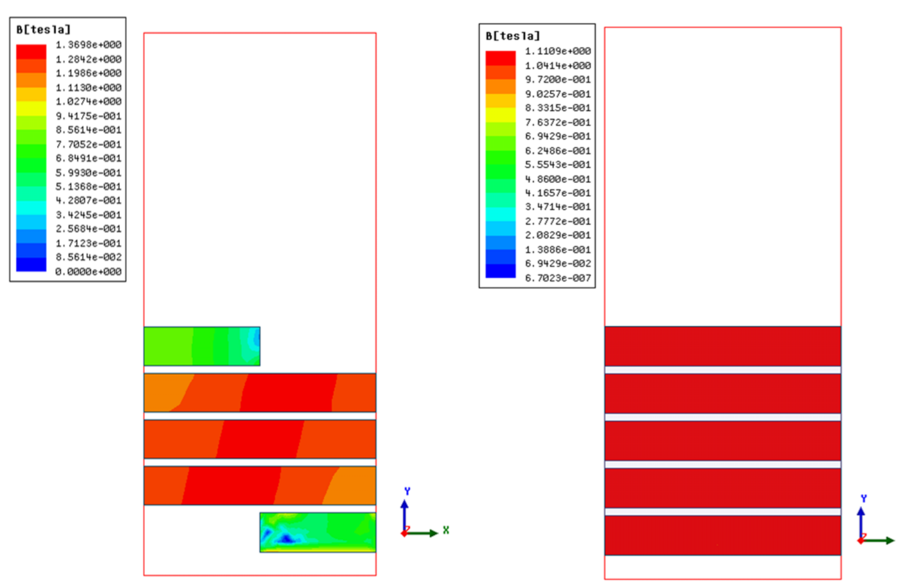
There are a lot of different kinds of Litz-wires, and the number of strands or wires is quite uncertain. In this paper, a Litz-wire with 7 single wires is presented as a classical example.



(a) (b)

FIG. 1. Simulated model (a) 5 stripes of amorphous alloy simulated model, and (b) distribution of flux line.

The analytical model is setup according to the cross section of the Litz-wire, assuming that the average current density in each wire is J_0, the radium of each wire is r_0, and the distance between any round wires to central wire in Litz-wire is m, and there is a point A in any wire, that the distance of the point to the center of the selected wire O_1 is r, the angle of AO_1O is φ, as shown in Fig. 3, and $0 \leq r \leq r_0, 0 \leq \varphi \leq 2\pi$.



(a) (b)

FIG. 2. Flux density of core (a) Flux density of core by considering the effect of end stripe, (b) Flux density of core without considering the effect of end stripe.

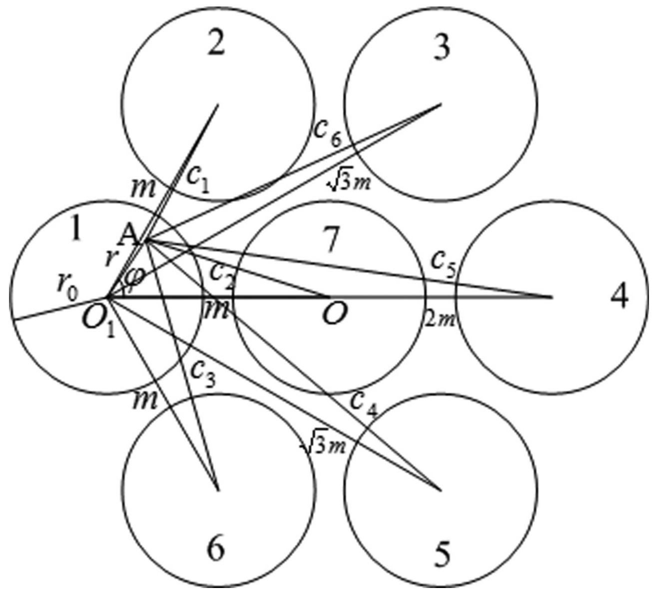


FIG. 3. Analytical model.

The current density in any wire due to the skin effect can be calculated by[11]

$$J_s(r) = \frac{\partial I}{2\pi r_0}\frac{I_0(\partial r)}{I_1(\partial r_0)} = I\frac{j^{\frac{3}{2}}k}{2\pi r_0}\frac{I_0(j^{\frac{3}{2}}kr)}{I_1(j^{\frac{3}{2}}kr_0)} \tag{2}$$

where $\partial = \frac{1+j}{\delta}$, $k^2 = \sqrt{\omega\gamma\mu}$, $I = \pi r_0^2 * J_0$, δ is the skin depth, ω is the angular frequency, γ is the electric conductivity of wire, μ is the magnetic permeability.

The current density in the selected wire (wire 1 in Fig. 3) affected by the other wires together in the Litz-wire can be calculated by[12]

$$\begin{aligned} J_{p1}(r,\phi) &= \frac{k^2 J_0}{4}((r^2 - \frac{{r_0}^2}{2}) \\ &+ r_0^2(\sum_{i=1}^{3}\ln(1 - 2\frac{r}{m}\cos(\varphi + \frac{\pi}{3} * (i-2)) + \frac{r^2}{m^2}) \\ &+ \ln(1 - 2\frac{r}{\sqrt{3}m}\cos(\varphi - \frac{\pi}{6}) + \frac{r^2}{3m^2}) \\ &+ \ln(1 - 2\frac{r}{\sqrt{3}m}\cos(\varphi + \frac{\pi}{6}) + \frac{r^2}{3m^2}) \\ &+ \ln(1 - \frac{r}{m}\cos\varphi + \frac{r^2}{4m^2})) \end{aligned} \tag{3}$$

The current density of central wire affected by the other round wires in the Litz-wire can be calculated by

$$J_{p7}(r,\varphi) = \frac{k^2 J_0}{4}((r^2 - \frac{{r_0}^2}{2}) + {r_0}^2(\sum_{i=1}^{7}\ln(1 - 2\frac{r}{m}\cos(\varphi + \frac{\pi}{3} * (i-2)) + \frac{r^2}{m^2})) \tag{4}$$

The AC resistance of Litz-wire can be calculated by

$$R_{ac} = \frac{\sum_{k=1}^{n}\frac{1}{\gamma}\int_s {J_k}^2 ds}{7 * I^2} \tag{5}$$

where $J_k = J_s + J_{pk}$, k is the No. of wire, and $k = 1 \ldots n$, n is the number of single wire in Litz-wire, $n = 7$ in this model, s is the area of cross section of single wire.

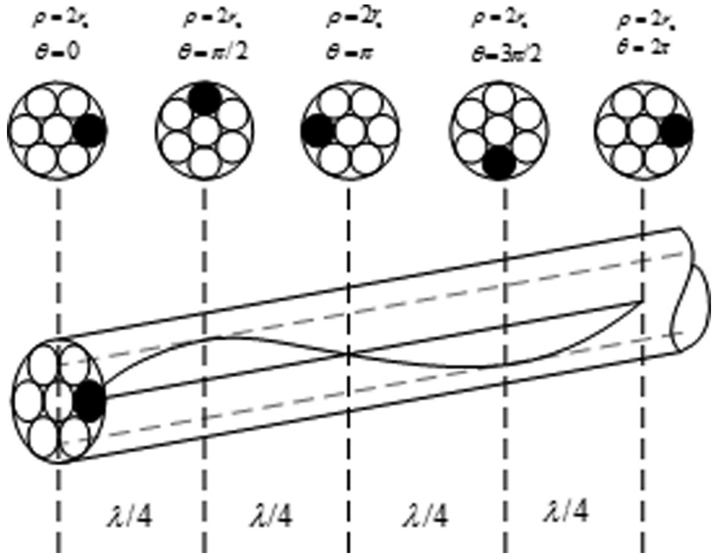


FIG. 4. Litz-wire twisted by azimuthal transposition.

By considering the wires twisted, the 2D analytical model can be extended to full model.

The Litz-wire can be twisted by providing azimuthal transposition of all strands as shown in Fig. 4, r_c is the radius of each solid wire, λ the pitch of Litz-wire, ρ and θ are phase position and angle of transposition.

It is obviously that the actual length of Litz-wire l_d is longer than it goes straight. The actual length of Litz-wire can be calculated by

$$l_d = \frac{\lambda}{\cos\phi} = \sqrt{\lambda^2 + (2\pi r_c)^2} \tag{6}$$

where ϕ is the twist angle, as shown in Fig. 5.

The current density of selected wire affected by the other wires in the Litz-wire can be calculated by

$$\begin{aligned} J_{p1}(r,\varphi+\theta) &= \frac{k^2 J_0}{4}((r^2 - \frac{r_0{}^2}{2}) \\ &-r_0^2(\sum_{i=1}^{3}\ln(1-2\frac{r}{m}\cos(\varphi+\theta+\frac{\pi}{3}*(i-2))+\frac{r^2}{m^2}) \\ &+\ln(1-2\frac{r}{\sqrt{3}m}\cos(\varphi+\theta-\frac{\pi}{6})+\frac{r^2}{3m^2}) \\ &+\ln(1-2\frac{r}{\sqrt{3}m}\cos(\varphi+\theta+\frac{\pi}{6})+\frac{r^2}{3m^2}) \\ &+\ln(1-\frac{r}{m}\cos(\varphi+\theta)+\frac{r^2}{4m^2})) \end{aligned} \tag{7}$$

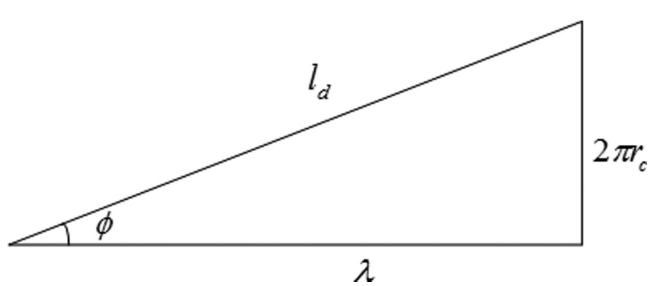


FIG. 5. Diagram of actual length of Litz-wire.

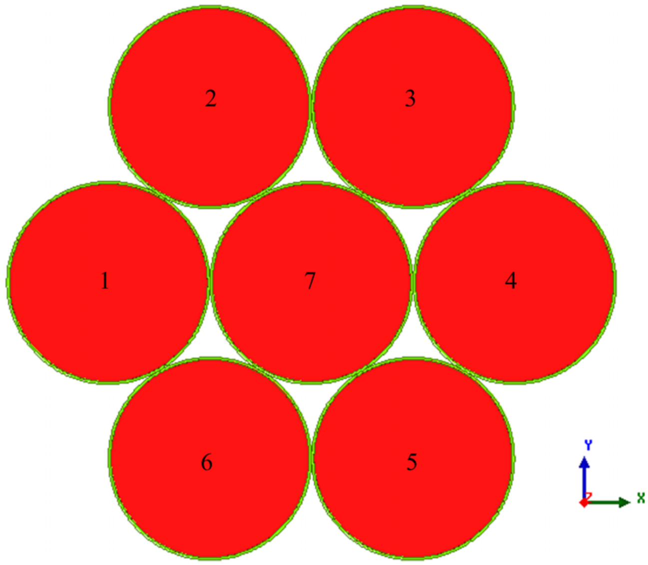


FIG. 6. Simulated model.

The current density of central wire affected by the other round wires in the Litz-wire can be calculated by

$$J_{p7}(r,\varphi+\theta)=\frac{k^2J_0}{4}[(r^2-\frac{{r_0}^2}{2})-r_0^2(\sum_{i=1}^{7}\ln(1-2\frac{r}{m}\cos(\varphi+\theta+\frac{\pi}{3}*(i-2))+\frac{r^2}{m^2})] \tag{8}$$

The AC resistance of Litz-wire for the length l_d can be calculated by

$$R_{ac}=\frac{\sum_{k=1}^{n}\frac{l_d}{\gamma}\int_s {J_k}^2 ds}{7*I^2} \tag{9}$$

where $J_k = J_s + J_{pk}$, J_s is expressed by equation (2), k is the No. of wire, and $k = 1\ldots n$, n is the number of single wire in Litz-wire, s the area of cross section of single wire.

A Litz-wire simulated model is set up under ANSYS Maxwell environment, as shown in Fig. 6. The red sections are copper of the wires, the green sections are insulations of the wires, and there are 7 single wires in the simulated model, as named by No.1 to No. 7. In the simulated model,

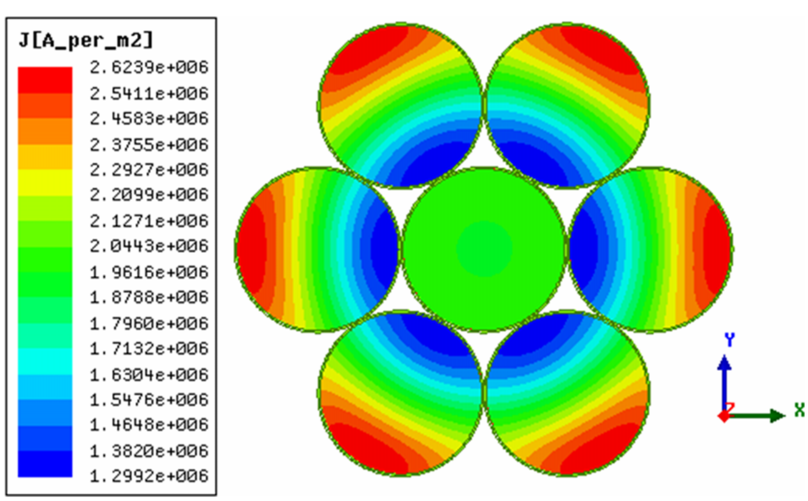


FIG. 7. Current density distribution of Litz wire.

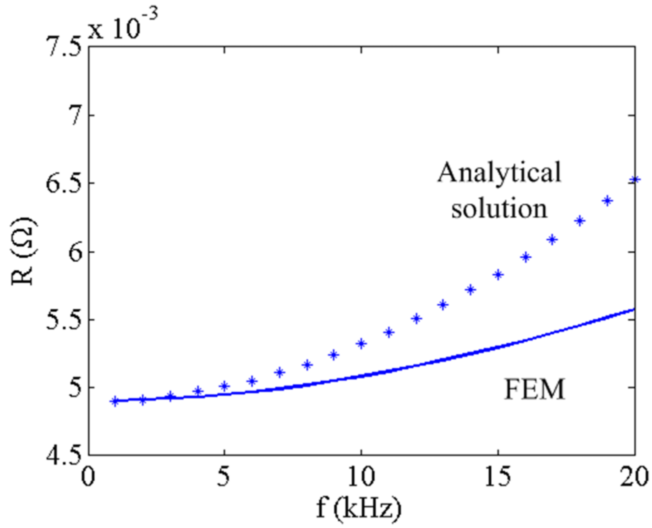


FIG. 8. Resistance calculation by FEM and analytical model.

the outer radium of each wire (include the copper and the insulation) is 0.41 mm, the inner radium of each wire is 0.4 mm (just include the copper), the current in each wire is 1A, the frequency is 20 kHz.

The current density of Litz-wire is calculated by FEM. Result of current density distribution of Litz-wire can be shown in Fig. 7.

Finally, the resistance of Litz-wire calculated by 2D analytical model and simulated model are 6.52 mΩ and 5.57 mΩ, respectively. The relative error is 17.0%.

The resistance calculated by FEM and analytical model is shown in Fig. 8. At low frequency (1 kHz), the resistance calculated by FEM and analytical model are 4.91 mΩ and 4.90 mΩ, respectively. The relative error is about 0.2%. It can be found that the relative error is increased when the frequency increased due to the eddy current effect.

In order to reduce the relative error, the current density affected by the proximity effect should be modified. A coefficient of proximity effect C_f, which is related to the frequency is added in the analytical model.

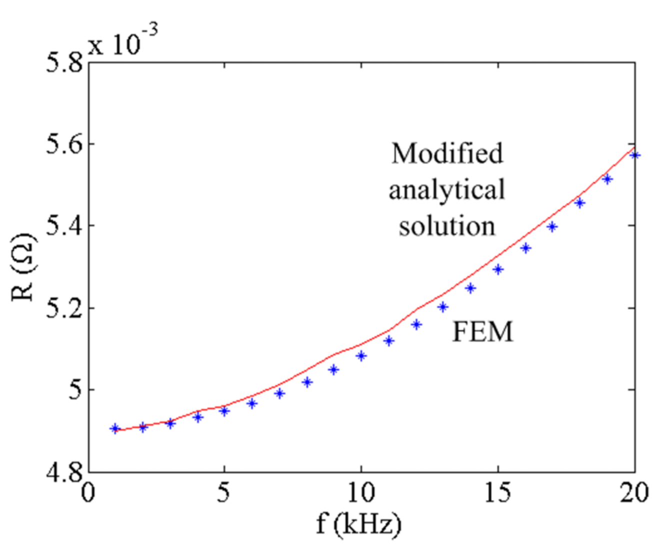


FIG. 9. Resistance calculation by FEM and modified analytical model.

The current density due to the proximity effect is modified by

$$J_{pm} = C_f * J_p \tag{10}$$

where $C_f = 1/(f/1000)^{0.2}$.

The resistance calculated by FEM and the modified analytical model is shown in Fig. 9. It can be found that the result of modified analytical method match well with the FEM. The relative error is no more than 1%.

IV. CONCLUSION

For accurately calculation of core loss, the additional core loss by the effect of end stripe is considered in the paper. It can be found that the core loss by considering the effect of end stripe is more than that without considering the effect of end stripe due to the scale down 5 stripes of amorphous alloy simulated model. While for the actually high-frequency transformer core, the number of stripes is much more than 5, usually hundreds or thousands, then the additional eddy current loss caused by the effect of end stripe is insignificant, and can be ignored. The analytical model for copper loss calculation of Litz-wire is quite effective and accurate, and it has huge potentiality for the design and optimization of electromagnetic devices, such as high frequency transformers and inductors.

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