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ABSTRACT

The demand for high efficiency, higher density power supplies, creates new challenges for designers of high frequency (HF) planar transformers. In order for the power system to achieve the desired efficiency, the transformer losses have to be calculated precisely.

This paper will describe a step by step procedure for designing HF planar transformers and give an overview of the two predominant causes of conductor loss (Skin and Proximity effects) in multi-layer PCB transformer designs.

INTRODUCTION

In the majority of conventional transformer designs, calculating the total power loss was limited to core and copper losses ($I^2 \cdot R_{dc}$). In today's HF, multilayer planar design, two effects, Skin and Proximity, increase the resistance of a winding above the DC resistance value.

In an effort to understand these loss effects, and provide a meaningful and comprehensive way to calculate them, Pulse has devoted significant engineering resources to understanding and documenting these phenomena. As a result, Pulse is in a strong position to support Electrical Engineers who incorporate planar transformers into their designs. The following article is intended to help design engineers understand the dominant loss factors and how planar products are the best choice to achieve efficiency gains in future generation power supply circuits.

Calculating DC copper losses without Skin and Proximity analysis can cause a significant error in winding loss calculation. This forces the designer to calculate the AC resistance of a winding to arrive at an estimate of power loss. This AC resistance is measured by multiplying the DC resistance of the winding by a correction factor called "Fr(m,x)" .

EQUATION 1

$$Fr(m, x) := (SKIN) + (PROXIMITY)$$

$$Fr(m, x) := \frac{x}{2} \cdot \frac{\sinh(x) + \sin(x)}{\cosh(x) - \cos(x)} + (2 \cdot m - 1)^2 \cdot \frac{x}{2} \cdot \frac{\sinh(x) - \sin(x)}{\cosh(x) + \cos(x)}$$

x = (conductor height / skin depth)

m = number of layers in a winding section from MMF = 0 to MMF= Max point

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Figures 1- 7 illustrate the necessary steps in the design process.

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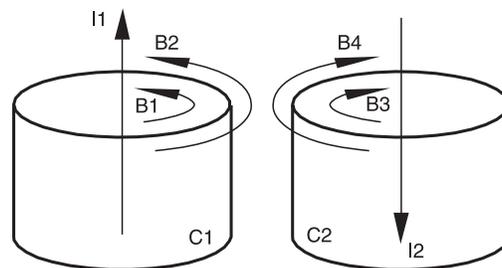


FIGURE 1

Figure 1 illustrates two conductors (C1 and C2) carrying currents in opposite directions (I_1 and I_2) with their internal (B1 and B3) and external (B2 and B4) generated fields.

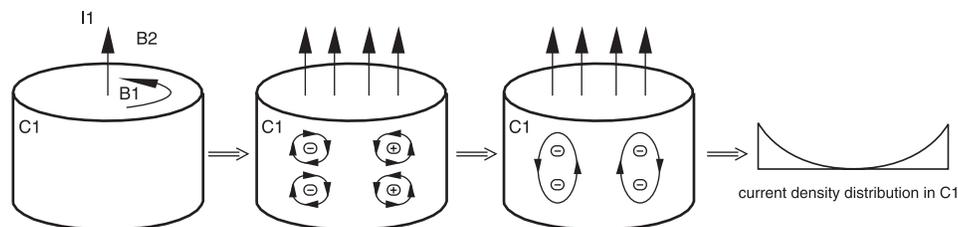


FIGURE 2

Figure 2 concentrates on the effect of the internal generated field (B1) and ignores the external field (B2). A positive sign means the internal field (B1) is entering the conductor

and a negative sign means the field is exiting the conductor surface. The circles around the positive and negative signs show the generated eddy currents and their corresponding directions.

Notice the addition of eddy currents and I_1 on the surfaces of conductor C1 and their reduction in the center. This phenomenon causes a change in the distribution of the current density throughout the diameter of conductor C1, resulting in a higher current distribution on the surfaces.

Next, analyze the effect of the external field (B_2) in C1 on conductor C2. For simplicity assume conductor C2 is not carrying any of its own current.

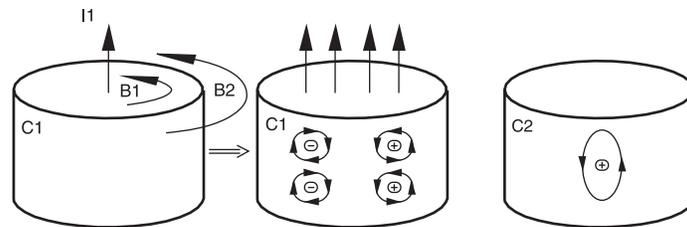


FIGURE 3

Figure 3 shows that even if conductor C2 is not carrying any of its own current, it will have an induced eddy current caused by the external field of another conductor (C1). An example of this type of conductor is a shield around a transformer.

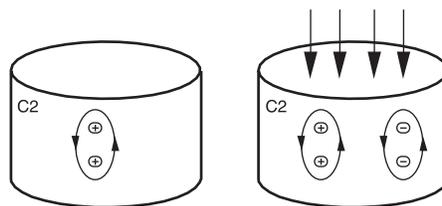


FIGURE 4

Figure 4 reveals the distribution of the current in C2 caused by its own current (I_2) and the current generated by the external field of another conductor (C1).

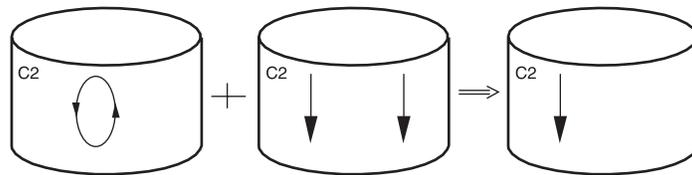


FIGURE 5

Figure 5 illustrates a significant effect: the current in C2 redistributes itself on only one side, which increases the AC resistance of the winding.

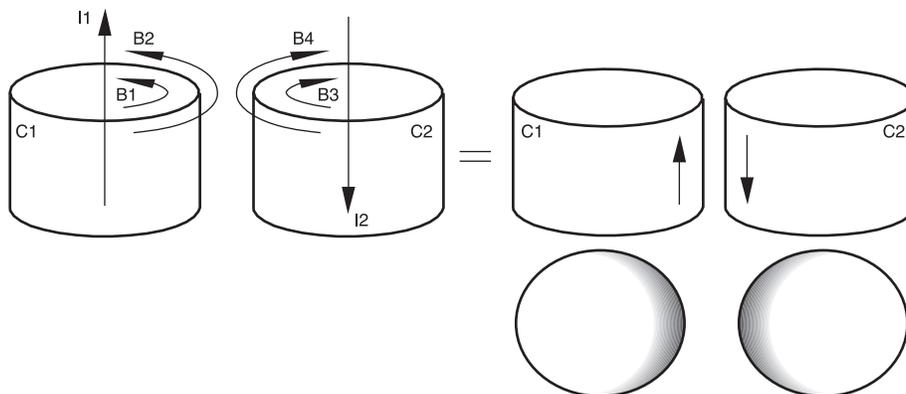


FIGURE 6

Figure 6 shows the effect of two conductors in close Proximity. This causes the current to concentrate only on the two adjacent sides. The Proximity effect is often the primary cause of winding loss in high frequency multi-layer transformer design.

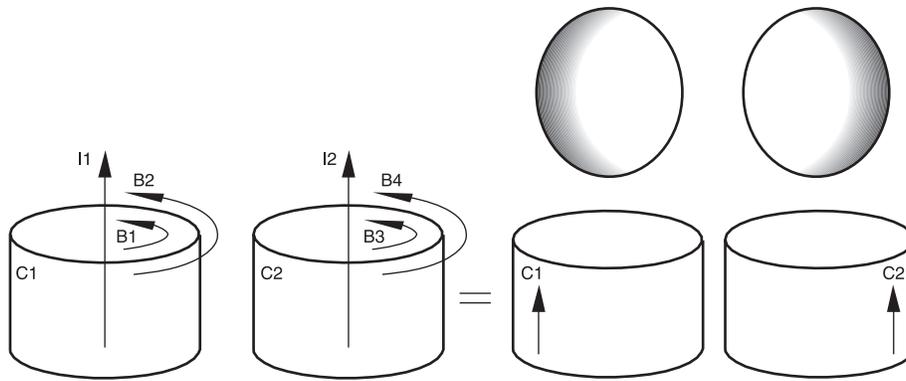


FIGURE 7

Figure 7 represents two conductors with current flowing in the same direction.

Now that we are familiar with Skin and Proximity effects, we can return to **Equation 1** and define the variables "x" & "m".

EQUATION 1

$$Fr(m, x) := (SKIN) + (PROXIMITY)$$

$$Fr(m, x) := \frac{x}{2} \cdot \frac{\sinh(x) + \sin(x)}{\cosh(x) - \cos(x)} + (2 \cdot m - 1)^2 \cdot \frac{x}{2} \cdot \frac{\sinh(x) - \sin(x)}{\cosh(x) + \cos(x)}$$

x = (conductor height / skin depth)

m = number of layers in a winding section from MMF = 0 to MMF = Max point

How to Find "X" in Equation

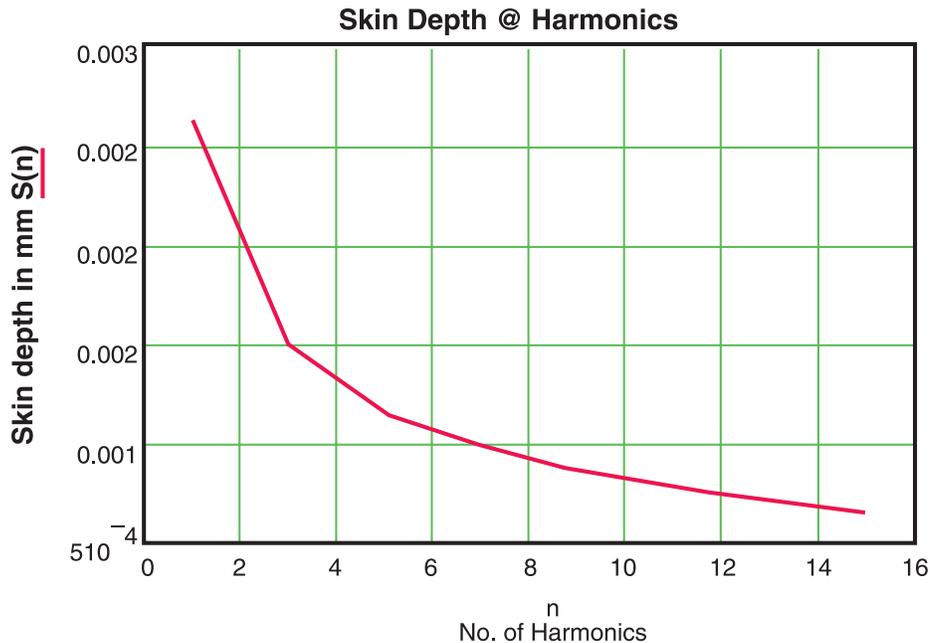
x = (ConductorHeight / SkinDepth)

Thk := .00007112mm Conductor's height for a 2 oz. copper conductor

s := $\frac{2.276}{\sqrt{Freq}}$ Skin depth for copper @70°C

This calculation shows that as frequency increases, it reduces the skin depth. So in order to find the skin depth at any harmonic (n), frequency can be replaced with: ($n \cdot \text{Frequency}$)

$$S(n) := \frac{2.276}{\sqrt{n \cdot \text{Frequency}}} \quad n := 1, 3 \dots 15 \text{ Harmonics}$$



Using this in **EQUATION 1**, we can find the AC resistance $\{Fr[m, X(n)]\}$ for any harmonics.

$$X(n) := Thk \cdot \frac{\sqrt{n \cdot \text{Frequency}}}{2.276}$$

Now we must be able to calculate the AC resistance for any number of layers. Before doing that, “m” in **EQUATION 1** must be defined.

How to Find “m” in Equation 1

M = Number of layers in a winding section from MMF = 0 to MMF = Maximum point

To calculate power loss and leakage inductance, it is essential to know the field intensity between layers in a winding section. We can use a spreadsheet application to find the optimum layer arrangement graphically. Keep in mind that the leakage energy is the energy stored between layers, which is a function of H^2 so interleaving reduces the field gradient (H) between each layer and causes a reduction in leakage inductance.

EXAMPLE 1

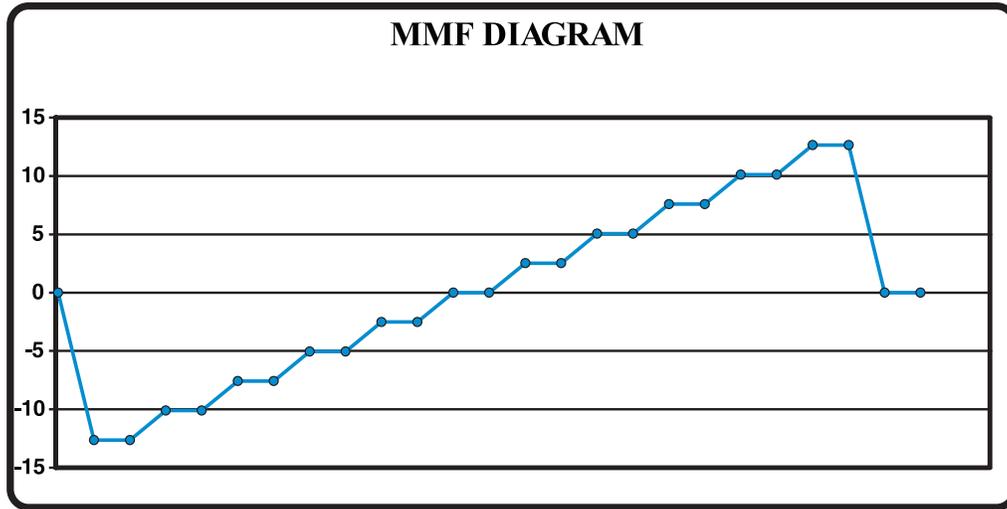
Pri = 10T

Sec = 1T

Layer arrangement: **Sec-Pri-Pri-Pri-Pri-Pri-Pri-Pri-Pri-Pri-Pri-Sec**

mp = No. of layers in the Pri winding section from zero to maximum MMF point mp = 5

ms = No. of layers in the Sec winding section from zero to maximum MMF point ms = 1



EXAMPLE 2

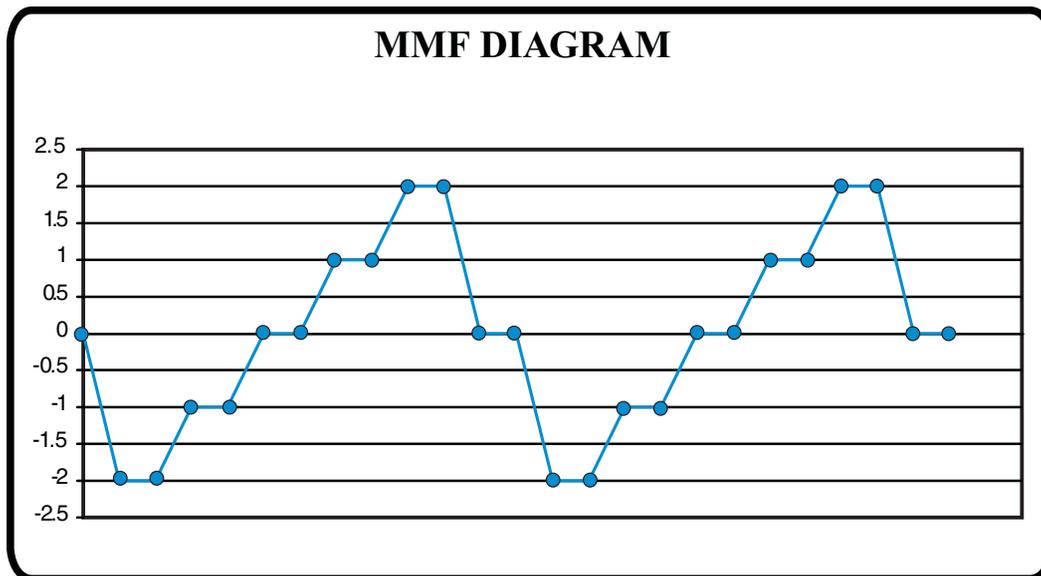
Pri = 8T

Sec = 4T

Layer arrangement: **Sec-Pri-Pri-Pri-Pri-Sec-Sec-Pri-Pri-Pri-Pri-Sec**

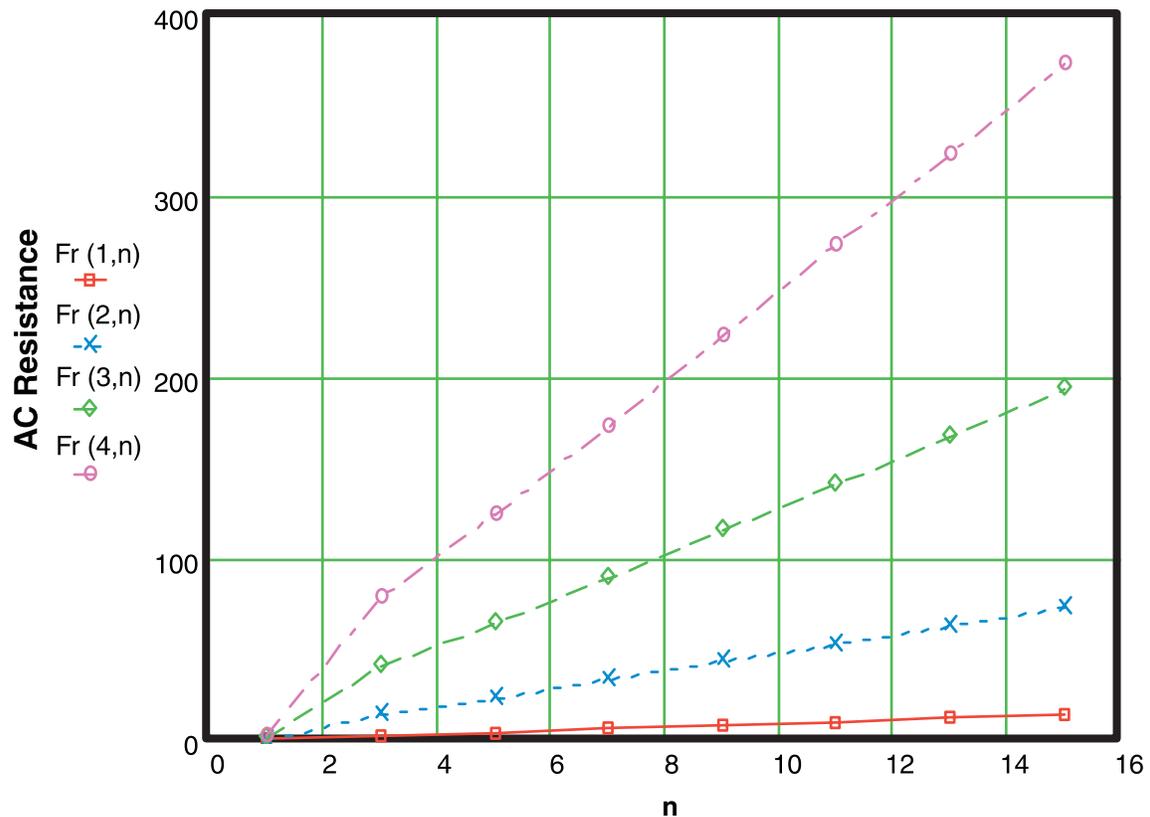
mp = No. of layers in the Pri winding section from zero to maximum MMF point mp = 2

ms = No. of layers in the Sec winding section from zero to maximum MMF point ms = 1



Now we can calculate the AC resistance for any number of harmonics and layers.

AC (Res) @ Harmonics for Different Layers



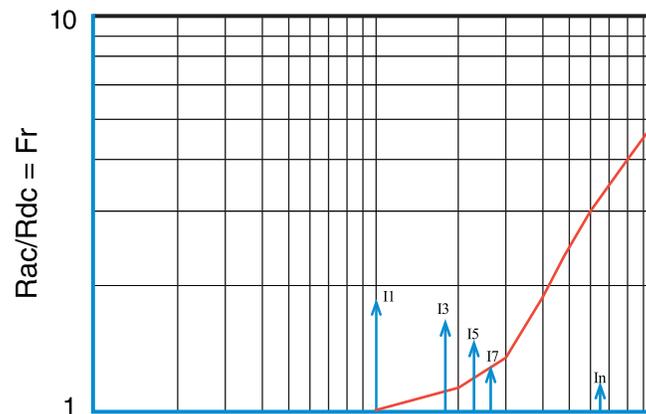
Knowing the AC resistance and the current at each harmonic, the power loss for each harmonic can be calculated.

Since we have a PWM square waveform with a given period (T) and Duty (D) the formula below can be applied to come up with a Fourier series equivalent of the current waveform:

EQUATION 2

$$I(D, I_{pk}, T) := \left[D + \left[\frac{2}{\pi} \cdot \sum_{n=1}^{12} \frac{(-1)^n}{n} \cdot (\sin(\pi \cdot n \cdot D) \cdot \cos(2 \cdot n \cdot \pi \cdot Freq \cdot 1000T)) \right] \right] \cdot I_{pk}$$

Fr AND HARMONICS



Since it is possible to calculate the correction factor (**EQUATION 1**) and the current for any harmonic (**EQUATION 2**), the total AC power loss for any given number of harmonics can be calculated by summation of power losses at each harmonic:

EQUATION 3

$$P_{LossAC} = \sum (EQUATION2)^2 * EQUATION1 \quad \text{EQUATION 3}$$

After calculating DC loss caused by the RMS current, DC resistance of the windings and the core loss, the transformer's total loss is represented by the summation of all three calculated losses.

Total transformer power loss is then:

EQUATION 4

$$P_{Total} = P_{LossAC} + P_{LossDC} + Core\ loss$$

Conclusions

1. Skin effect causes current to go to the surface of a conductor and Skin depth is inversely proportional to square root of frequency.
2. Proximity effect causes the current to flow ONLY on surfaces closest to each other.
3. In multilayer PCB transformers, losses in the inner layers can be an order of magnitude higher than on the outer layers. Therefore the innermost layers need to be the thinnest.
4. More interleaving causes a reduction in leakage inductance and better regulation with a penalty of higher intrawinding capacitance.