Renco Electronics, Inc.

The Effects of Increasing Frequency on Magnetic Components

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Abstract

The operating frequency of most electronic circuits has been increasing since the late 1950's. While the increase in frequency has reduced the overall weight and size of most consumer electronics now available, some engineers may not realize that the bulk of the reduction in weight and size has occurred in the magnetic components designed in to the circuits. The increase in frequency still continues today and as a result there is some occasional confusion as to the effects of increasing the frequency on the magnetic components. This paper discusses the consequences, good or bad, of increasing the frequency on magnetic components primarily used in power supply applications.

Introduction

Electronics consumers have been requesting smaller and lighter electronics products for decades. Design Engineers have been able to reduce the size and weight of electronic products by increasing the frequency the magnetic components need to operate at. However, the consequences of increasing the frequency on the magnetic components can be confusing depending on the literature that is reviewed. In order to be able to continue increasing frequency the effects of increasing frequency on magnetic components must be understood.

Increasing Transformer Operating Frequency

When considering increasing the operating frequency to reduce transformer size and, therefore overall product size, the WaAe (Window Area X Core Area product) formula should be evaluated. A quick review of this formula will immediately show the impact of an increase in operating frequency on the size of the transformer. The WaAe formula has been derived in detail in Abraham Pressman's book, "Switching Power Supply Design, 2nd Edition," and is defined below:[1]

$$WaAe = \frac{Pout \times D_{cma}}{K_t \times B_{\max} \times f} \qquad \text{Eq. 1}$$

Where:

$WaAe$ = Product of the window area and core area in cm^4
$Pout$ = Output power in Watts
D_{cma} = Current Density in circular mils/amp
B_{max} = Flux Density in Gauss
f = Frequency in Hertz
K_t = Topology constant

Kt = 0.00100 Push Pull Kt = 0.00140 Half Bridge
Kt = 0.00140 Full Bridge Kt = 0.00050 Forward Converter
Kt = 0.00033 Flyback (Single Winding)
Kt = 0.00025 Flyback (Multiple Winding)

If everything except frequency and WaAe is kept constant in equation 1, then it is clear that as frequency is increased the window area and core area product is decreased. In other words, as the frequency is increased the size of the transformer can be decreased. Some magnetic core vendors list the WaAe for their cores and this is very handy when trying to determine which transformer package can be used when considering increasing or decreasing the frequency.

Once the frequency analysis is completed using equation 1, a common form of the basic Faraday's Law formula should be used to determine the necessary primary turns and complete the transformer design. See equation 5

Skin Effect and Proximity Effect

Skin effect and proximity effect are probably the two biggest topics in the world of magnetics design that cause headaches for some engineers. While an in depth analysis of these topics is beyond the scope of this paper, basic concepts will be covered. In addition, there are many well written and thorough papers and chapters of books written on skin effect and proximity effect.

Skin effect is simply when the current going through a copper wire travels on the outside skin of the copper rather than throughout the entire diameter of the copper wire. See Figure 1. As the frequency is increased more of the current travels on the outside "skin" of the copper and; consequently, this leads to an increase in Ac resistance losses and the related temperature rise.[2]

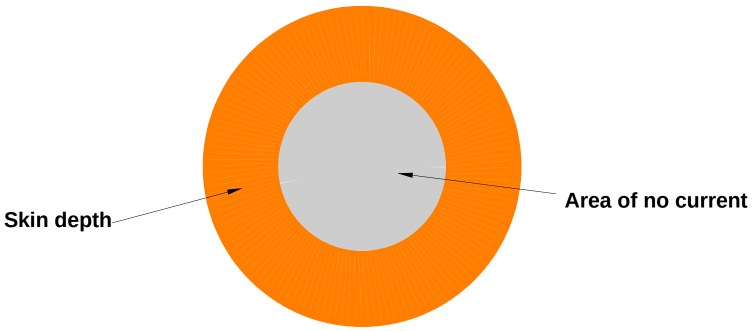

Figure 1. Skin depth and magnet wire

The most common way to reduce the losses due to skin effect is to use a smaller diameter wire where the skin depth is half the diameter of the wire, but care must be taken to ensure the chosen wire diameter can still handle the required continuous current. Otherwise multiple strands of the appropriate wire diameter must be used to ensure the required current can be handled while also decreasing the skin effect losses. In some cases a multiple stranded wire known as litz is used. New England Wire has a detailed litz wire reference guide on their website. For more information click on: http://www.newenglandwire.com/litz.asp

Equation 2 is used to determine what the skin depth is at the application frequency and is the first step in reducing losses due to skin effect.

$$\delta = \frac{K_M}{\sqrt{f}} \qquad \text{Eq. 2}$$

Where:

δ = Skin depth in cm
f = Frequency in Hertz
K_M = Copper Constant (7.5 at 100 ºC and 6.6 at 20 ºC)

Thinking back to Electromagnetics 101, it is known that when there is an Ac current flowing through a conductor there is also an Ac magnetic field flowing through the same conductor. This Ac magnetic field induces eddy currents in adjacent turns of wire and winding layers and alters the distribution of current flowing through the turns of wire and winding layers and this is simply known as proximity effect.[3] This leads to an increase in Ac resistance losses and the related temperature rise. Therefore, the way to reduce proximity effect is to use multiple strands of wire (litz) and keep the layers of windings to two layers or less.

Both skin effect and proximity effect losses increase as the application frequency increases; consequently, these losses need to be evaluated when increasing the application frequency. As mentioned earlier, there are many well written and more detailed articles on the topics of skin and proximity effect and a more in depth study of these topics should be done before attempting a high frequency transformer design.

Increasing Inductor Operating Frequency

When considering increasing the operating frequency to reduce inductor size; and therefore, overall product size, equation 3 should be evaluated. It is industry practice to set the peak-peak ripple current to 10%-30% of the output current. With this in mind, as the frequency is increased the inductance should be reduced proportionately to keep the peak-peak ripple current within the 10%-30% range. This is what allows for a reduction in inductor size. For example, if an existing design uses a 100 uH inductor at 200 kHz and if the frequency is increased to 400 kHz the inductance should be reduced to 47 uH, which is an industry standard inductance value. This reduction in inductance keeps the ripple current within the acceptable range and allows for a reduction in size and total inductor losses. This may be a surprise to some that have known core losses to rise with an increase in frequency. A thorough discussion on the effect of increased frequency on core losses will take place beginning on page 4 of this paper.
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$$\Delta i = \frac{V}{L \times f} \qquad \text{Eq. 3}$$

Where:

V = Voltage in Volts
L = Inductance in Henries
F = Frequency in Hertz
$\Delta \boldsymbol{i}$ = Peak-peak ripple current in amps

Core Losses and Increased Operating Frequency

The graph in figure two is commonly used to determine the core losses when designing transformers and inductors. A similar graph can be found in almost every magnetic core vendor's catalog. At first glance, at Figure 2, it would seem that as the frequency increases the core losses also increase, but this is not always the case. A careful analysis of the Steinmetz equation (Eq. 4), which is the foundation of the graph in Figure 2, needs to be completed to see why core loss can actually decrease when the frequency is increased.

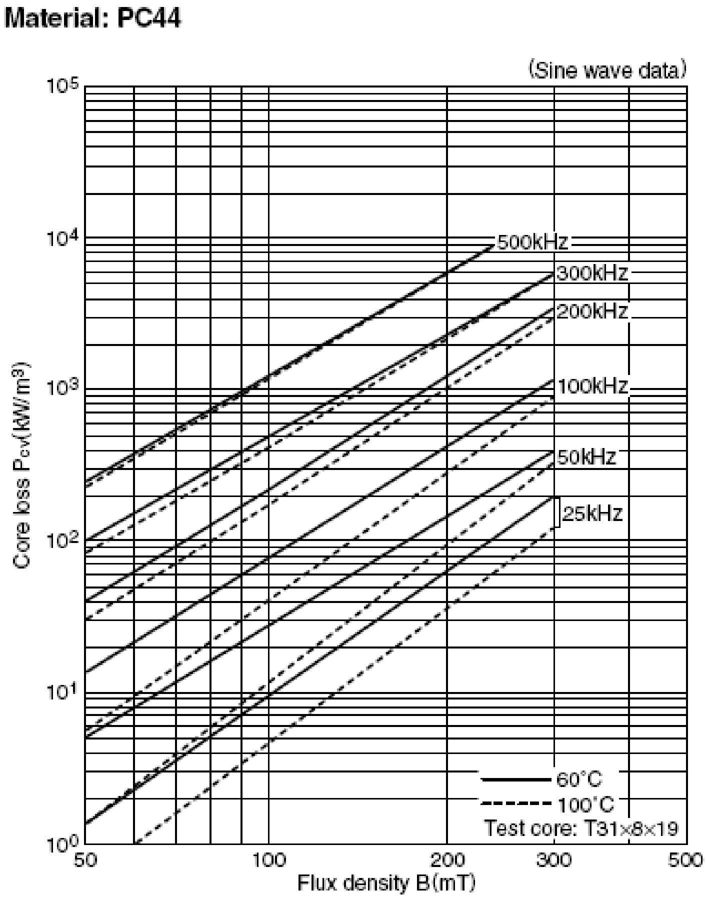

Figure 2. Typical core loss graph from TDK

The Steinmetz equation consists of a material constant (K_1) available for every magnetic material. The particular vendor catalog should be consulted for the K_1 value along with the Frequency exponent (X) and flux density exponent (y). Typical power ferrite materials have exponents of 1.5 and 2.5 respectively. [4]

$$P_{core}(mW) = K_1 \times f^{x} \times B^{y} \times V_e \qquad \text{Eq. 4}$$

Where:

$K1$ = Constant for core material
f = Frequency in kHz
x = Frequency exponent
B = Peak flux density in kGauss
y = Flux density exponent
Ve = Effective core volume (cm3)

In order to continue this analysis, equation 5 and equation 6 need to be reviewed below

$$Bpeak = \frac{Vt \times 10^{8}}{N \times Ae} \qquad \text{Eq. 5}$$

Where:

$Bpeak$ = Peak flux density in Gauss
V = Voltage in Volts
t = Time on in seconds
N = Number of Turns
Ae = Core area of selected core in cm^2

For this analysis the voltage, in equation 5, can be ignored for the time being and since frequency is inversely proportional to time on it can be inserted into the above formula. See below for the end result.

$$Bpeak\,\alpha\,\frac{1}{N \times Ae \times f} \qquad \text{Eq. 6}$$

Therefore, if the frequency, in equation 6, is increased with the turns and core area staying constant, then the peak flux density will decrease. Now looking at equation 4, a reduction in peak flux density will have a larger impact on core loss since the peak flux density will be reduced exponentially by 2.5 and the frequency is increased exponentially by 1.5. This is why the core loss does not increase with an increase in operating frequency, but instead decreases. However, if the core area, in equation 6, is reduced when the frequency is increased a reduction in core loss may not be evident.

As can be seen in equation 1, for transformer applications, if the frequency is increased, the core area; and therefore, overall package size can be reduced. However, the flux density must be kept constant in order to keep the core losses from increasing. If the core size is reduced when the frequency is increased, and flux density is kept constant by increasing the turns, then the core loss may even decrease. This is because the overall volume will have decreased and volume is an important part of the core loss equation. However, since the turns and, therefore, DC resistance were increased in this last scenario, the I^2R losses must also be evaluated.

For inductor applications, as was mentioned in the example earlier in this paper, if an existing design uses a 100 µH inductor at 200 kHz and the frequency is increased to 400 kHz, the inductance should be reduced to 47 µH, which is an industry standard inductance value. This reduction in inductance allows for a reduction in size and total inductor losses. The total inductor losses decrease in this example because of the reduction in inductance, core area, and volume.

Conclusion

This paper has discussed the effects of increasing operating frequency on transformers and inductors. Furthermore, the effect of increased operating frequency on core losses has been discussed in detail. Finally, it is evident that when increasing application frequency a careful review of the magnetics design must take place.

If you need assistance with your custom magnetics design contact Renco Electronics' Design Engineering team at Engineering@rencousa.com or call the Engineering hotline: 1-800-645-5828

References

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[1] Magnetics Inc, *2004 Ferrite Catalog*, p.4.6
[2] Lenk, Ron*, Practical Design of Power Supplies*. p. 108 and p. 109. New York, USA.1998
[3] "Proximity Effect (electromagnetism)" *Wikipedia, The Free Encyclopedia*. 16 Jun 2009, 02:04 UTC. <http://en.wikipedia.org/w/index.php?title=Proximity_effect_(electromagnetism)&oldid=296670888>.
[4] Maniktala, Sanjaya, *Switching Power Supply Design and Optimization*. p. 212 and p. 209. New York, USA, 2005.