Choosing Inductors for Energy Efficient Power Applications

Coilcraft

Energy efficiency can be as much about the inductors as the circuit topology

In high frequency DC-DC converters, inductors filter out the AC ripple current superimposed on the DC output. Whether the converter steps the voltage down – buck – or steps the voltage up – boost – or both up and down – SEPIC, the inductor smooths the ripple to provide a pseudo-DC output.

For battery powered applications, battery life is extended by improving the efficiency of the entire power supply circuit, and inductor efficiency is often a major consideration in the design. Careful consideration of inductor efficiency can mean the difference between having your battery work when you need it and having to stop in the middle of an important task to plug it into a charger.

Inductor efficiency is highest when the combination of core and winding losses are the lowest. Therefore, the goal of highest efficiency is met by selecting an inductor that provides sufficient inductance to smooth out the ripple current while simultaneously minimizing losses. The inductor must pass the current without saturating the core or over-heating the winding.

Accurately predicting core and winding loss of an inductor can be fairly complicated. Core loss depends on several factors, such as peak-peak ripple current, ripple current frequency, core material, core size, and turn count. The required ripple current and ripple current frequency are application-dependent, while the core material, core size, and turn count are inductor-dependent.

The most commonly-used equation to characterize core loss is the Steinmetz equation:

$$P_{core} = K(f)^x(B)^y$$

Where:
P_{core} = power loss in the core
K, x, y = core material constants
F = frequency
B = flux density

This equation shows that core loss depends on frequency (f) and flux density (B). Flux density depends on ripple current, so both are application-dependent variables. It also shows that the core loss is inductor-dependent, where the core material determines the K, x, and y constants. Note that flux density is also a function of the core area (Ae) and the number of turns (N), therefore core loss is both application-dependent and inductor-dependent.

By comparison, DC winding loss is simple to calculate:

$$P_{dc} = I_{dc}^2 \times DCR$$

Where
P_{dc} = DC power in Watts dissipated
I_{dc} = Effective DC (rms) value of the inductor current.
DCR = DC resistance of the inductor winding

AC winding loss is more complicated and may include the effects of increased resistance at higher frequency due to both skin effect and proximity effect. ESR (effective series resistance) or ACR (AC resistance) curves may show some of the increased resistance at higher frequency, however, these curves are typically made at very low current levels, so they do not capture current-dependent (core) loss. They are also subject to possible misinterpretation.

For example, consider the ESR vs frequency curve shown in Figure 1

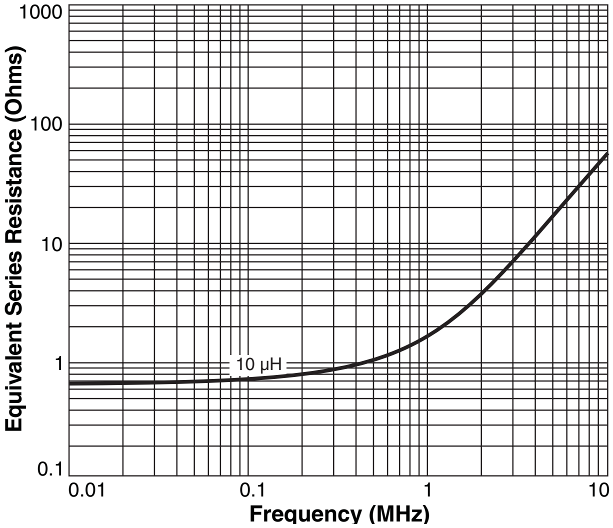


Figure 1. ESR vs Frequency

An initial observation indicates that the resistance looks very high above 1 MHz. This would strongly suggest that this part cannot or should not be used at that frequency due to the expected very high loss due to the ESR. However, it has been observed that parts with curves like this have performed very well in actual converters – much better than would be suggested by these curves.

Consider the following example:

Assume a converter is needed to provide an output of 5 V at 0.3 A (1.5 Watts). We will use a 10 µH Coilcraft inductor with a typical ESR vs frequency as shown in Figure 1. If the converter operates at 250 kHz, we see from the graph that the ESR, which includes both ac and dc resistance is approximately 0.8 Ohms.

For a buck converter, the average inductor current equals the load current, 0.3 A.

We can calculate the loss in the inductor:

$$I^2R = (0.3\ A)^2 \times (0.8\Omega) = 0.072\ W.$$

0.072 W ÷ 1.5 W = approx 5% of output power is lost in the inductor.

However, if we were to run the same converter at 5 MHz, we can see from the ESR curve that R is between 10 Ohms and 20 Ohms. If we even assume R = 10 Ohms, then the power loss in the inductor should be:

$$I^2R = (0.3\ A)^2 \times (10\Omega) = 0.9\ W$$

0.9 W ÷ 1.5 W = 60% of the output power is lost in the inductor!

Based on this very simple example it would seem obvious that a designer should not choose to use a component like this.

It has been observed that converters, in fact, often achieve better performance than the ESR curves predict. The following explanation illustrates why.

Figure 2 shows a very simplified version of a possible buck converter waveform, with continuous conduction and the ripple current is relatively small compared to the average current.

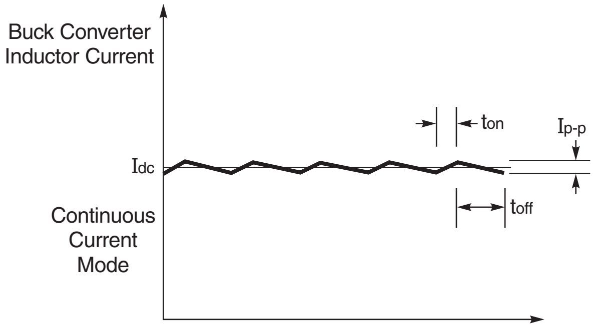


Figure 2. Ideal Converter Waveform with Small Ripple Current

Let's assume that the ripple current peak-peak is about 10% of the average current. From the previous example this means:

I_{dc} = 0.3 A
I_{p-p} = 0.03 A

In order to predict the inductor losses correctly, this must be separated into two components. For the low frequency or dc loss, we use the low frequency resistance (effectively DCR), which we can see from the graph is 0.7 Ohms. The current is the rms value of the load current plus the ripple current. In this case the ripple current is small, so the value is approximately equal to the dc load current.

Low frequency loss = $Idc^2R = (0.3\ A)^2 \times (0.7\Omega) = 0.063\ W$

To get the total loss, we must add that to the high frequency loss, which is I^2R. In this case the R is the ESR and the I is the rms value of the ripple current only.

Approximate rms ripple current:

$$I_{p-p} \div 2\sqrt{3}\ ) = 0.03\ A \div 3.464 = 0.0087\ A$$

At 250 kHz the ac loss would be:
$(0.0087\ A)^2 \times (0.8\ \Omega) = 0.00006\ W.$

Therefore, at 250 kHz, we predict the total inductor loss is 0.063 W + 0.00006 W = 0.06306 W.

We see that operating at 250 kHz predicts only slightly more loss (less than 1%) than predicted simply by the DCR.

Now, let's look at the same example at 5 MHz. The low frequency loss is still the same 0.063 W.

The ac loss calculation must use the ESR, which was previously estimated at 10 Ohms:
$(0.0087\ A)^2 \times (10\ \Omega) = 0.00076\ W.$

So, the total inductor loss at 5 MHz: 0.063 W + 0.00076 W = 0.06376 W.

This loss is more significant, with a predicted loss of about 1.2% greater than DCR loss, but is not nearly the 0.9 W originally predicted by multiplying the ESR by the entire load current. Also, this example is not exactly fair, because we wouldn't use the same inductor value at 5 MHz as we would at 250 kHz. We would use a much smaller L and therefore we would get a much smaller DCR.

In summary, the inductor loss must be calculated by a combination of the DCR and ESR, and for a continuous current mode converter in which the ripple current is small compared to the load current, the losses will be reasonable.

In typical applications, ripple current is kept to approximately 40% of the load current or less. Regardless of ripple content, ESR curves do not capture current-dependent core loss at higher current, and ***total*** inductor loss determines the overall inductor efficiency.

Therefore, inductor manufacturers optimize inductor efficiency by selecting low loss materials and designing inductors for minimal total loss. The use of rectangular "flat" wire may provide the lowest DCR in a given size to minimize DC loss. Improvements in core materials have led to inductors with very low AC core loss at high frequency resulting in higher inductor efficiency.

For example, Coilcraft's industry-leading XGL Family of molded power inductors are optimized for high frequency, high peak current applications. These offer soft-saturation, while also providing the lowest AC loss at frequencies of 2 MHz and higher. They also have extremely low DCR for their size.

Figure 3 shows the inductance vs current characteristics of the 2.2 µH value in the XGL, XEL, XAL, and XFL Series. The XGL, XEL, and XAL series are clearly the best choice for holding inductance at around 3 A or higher current. Table 1 compares the DCR and Isat of these inductors.

Table 1. Comparing XAL, XEL and XFL

	L nom	DCR typ	Isat (30%)
XGL4020-222	2.2 µH	19.5 mOhms	5.9 A
XEL4020-222	2.2 µH	35.2 mOhms	5.9 A
XAL4020-222	2.2 µH	35.2 mOhms	5.6 A
XFL4020-222	2.2 µH	21.4 mOhms	3.7 A

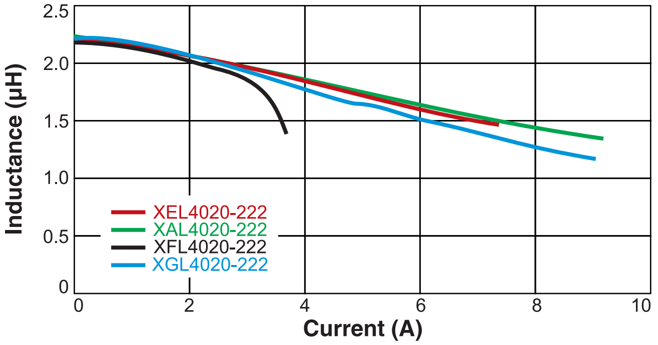
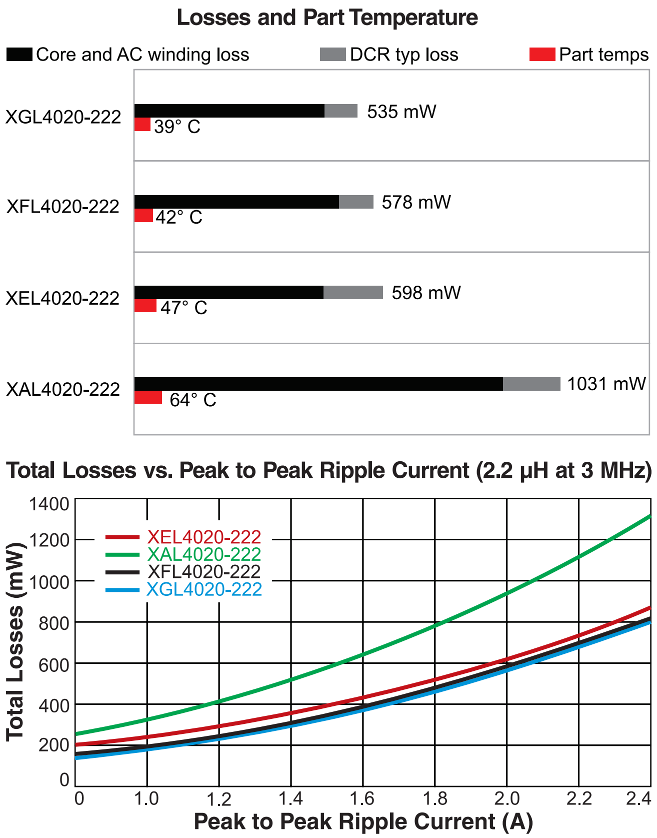


Figure 3. Comparing L vs I of XAL, XEL XFL and XGL 2.2 µH inductors

Figure 4 compares the AC loss and total loss of the same inductors at 2 MHz. The XGL utilizes an innovative construction that exceeds all previous designs, resulting in a combination of the lowest DC and AC losses. This makes the XGL Family the best choice for high frequency power converter applications that must withstand high peak current with lowest DC and AC losses.


Losses and Part Temperature

Total Losses vs. Peak to Peak Ripple Current (2.2 µH at 3 MHz)

Figure 4. Comparing AC Losses and Total Losses of XAL, XEL, XFL, and XGL at 2 MHz

To speed up the design process for engineers selecting inductors, Coilcraft has developed tools that calculate measurement-based core and winding loss for each possible application condition. The results from these tools include current-dependent and frequency-dependent core and winding loss, eliminating the need to request proprietary inductor design information, such as core material, Ae, and number of turns, and the need to perform hand calculations.

If your application is a DC-DC converter, the Coilcraft DC-DC Optimizer Tool calculates the inductance value, peak current, and peak-peak current requirements based on your operating conditions and amount of AC ripple current you choose. It then feeds this information into our Power Inductor Finder tool to display a list of inductors that may meet these requirements. The list includes the inductance at peak current, current rating, total losses, and resulting part temperature for each inductor listed.

If you already know the inductance value and current ratings required for your application, you can enter this information directly into the Power Inductor Finder. The results include core and winding (total) loss and saturation current ratings for each inductor, to verify that the inductance will remain close to the design requirement at the peak current condition for your application.

The tool may also be used to graph the inductance vs current behavior to compare traditional hard-saturating inductors to soft saturation types. To select the highest efficiency inductor, the results can be first sorted by total loss. Multiple sorts allow selection by multiple parameters.

Inductor loss is closely related to core size and wire size. In many cases, lowest loss corresponds to larger part size, or it corresponds to using a hard-saturation core material. As with any design, there may be compromises that require analyzing trade-offs in size or inductance at peak current vs efficiency. Having all of the inductor information in a complete list that allows multiple sorting facilitates such an analysis.

Conclusion

Designing for highest efficiency performance requires selection of inductors with the lowest total loss at application conditions. Calculating total loss can be complicated, but these calculations are built into the Coilcraft power magnetics tools, making selection, comparison, and analysis as simple as possible.

References:

XGL, XEL, XAL, or XFL? – Which Molded Power Inductor is Right for You?, Coilcraft web page: https://www.coilcraft.com/en-us/other/xal-or-xfl-or-xgl/

Coilcraft DC-DC Optimizer, Coilcraft website, https://www.coilcraft.com/en-us/tools/dc-dc-optimizer/#/search

Coilcraft Power Inductor Finder and Analyzer Tool, Coilcraft website, https://www.coilcraft.com/en-us/tools/power-inductor-finder/#/search