Inductor Performance in High Frequency DC-DC Converters

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Understanding AC Losses

As switching frequencies increase above 1 MHz, the question of inductor performance often arises. While the relative merits of specific inductors can be compared based on parametric data, it is most important to consider the circuit application.

For example, consider ESR vs Frequency curves. In many cases an initial observation indicates that the resistance looks very high, for example, above 1 MHz. So high, in fact that 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 been observed to perform very well in actual converters – much better performance 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).

Assume we will use Coilcraft part LPO3010-103, which provides 10 µH in a 3 mm × 3 mm × 1 mm case size. The typical ESR vs frequency for this part is shown in Figure 1.

If the converter operates at 250 kHz, we can see from the graph that the ESR, which includes both ac and dc resistance is approx. 0.8 Ohms.

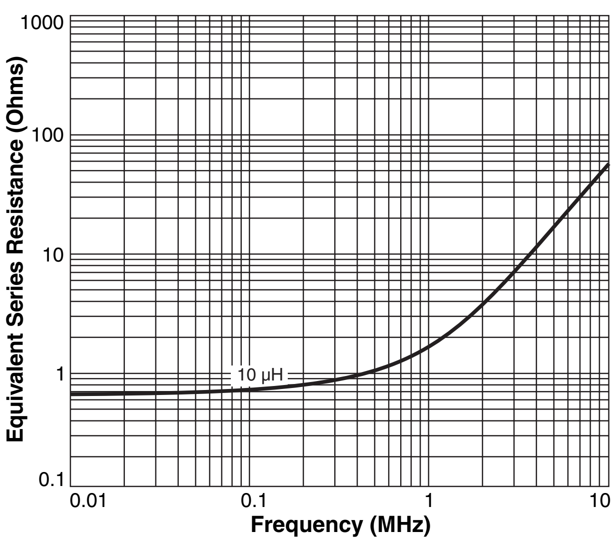

Figure 1. ESR vs F for Coilcraft LPO3010-103

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

We can calculate a loss in the inductor:
$I^2R = (0.3\ A)^2 \times (0.8\ \Omega) = 0.072\ W$.
$0.072\ W \div 1.5\ W$ = 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:

$I^2R = (0.3\ A)^2 \times (10\ \Omega) = 0.9\ W$.
$0.9\ W \div 1.5\ W$ = 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 our experience that converters, in fact, achieve better performance than the ESR curves predict.

The following explanation illustrates why the actual performance will (probably) be much better than the ESR curve might predict.

Figure 2 shows a very simplified version of a possible buck converter waveform. In this case it is assumed that the inductor current is continuous and that the ripple current is relatively small compared to the average current.

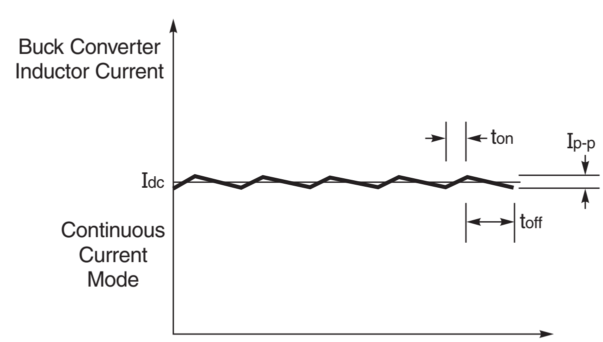

Figure 2. Ideal Converter Waveform with Small Ripple Current

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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
$I_{p\text{-}p} = 0.03$ 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 = $I^2R = (0.3\text{A})^2 \times (0.7\ \Omega) = 0.063$ W
($I = I_{dc}$)

To get the total loss, we must add that to the high frequency loss, which also 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:
$I_{p\text{-}p} \div \sqrt{3} = 0.03\text{ A} \div 1.732 = 0.0173$ A

At 250 kHz the ac loss would be:
$(0.0173\text{ A})^2 \times (0.8\text{ Ohms}) = 0.00024$ W.

Therefore, at 250 kHz, we predict the total inductor loss is 0.063 W + 0.00024 W = 0.06324 W.

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

Now, 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:

$(0.0173\text{ A})^2 \times (10\text{ Ohms}) = 0.003$ W.

So, the total inductor loss at 5 MHz:
0.063 W + 0.003 W = 0.066 W.

This loss is more significant, with a predicted loss of about 5% 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.

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

We should consider the case of the discontinuous current or the case in which ripple current is the maximum. Consider the waveform below. In this case ripple current is the same magnitude as the dc or load current. It is clear that the loss due to ESR will be very significant.

If we continued the previous example with a ripple current of 0.6 $A_{p\text{-}p}$, we would predict an ac loss at 5 MHz of $(0.6\text{ A} \div \sqrt{3})^2 \times (10\text{ Ohms}) = 1.2$ W, which is almost twenty times more than the predicted DCR loss alone.

We have observed examples like this with certain customer converters where the loss and therefore heating are much higher than predicted. Usually in these cases the ripple current is very high and the ac losses make the design unreasonable. We believe that for most of the time, typical converters operate with much less ripple than this.

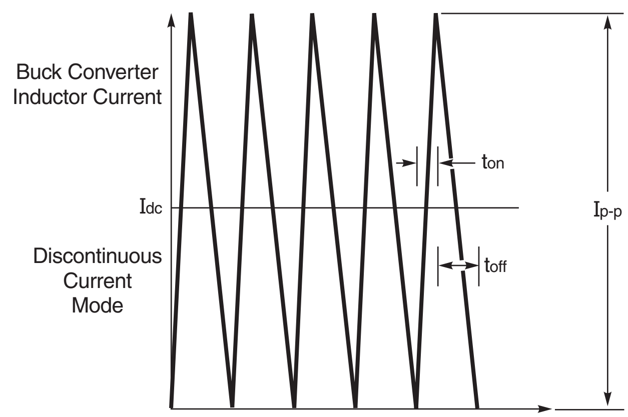

Figure 3. Ideal Converter Waveform with Large Ripple Current

Conclusions

ESR vs frequency curves can be used to predict inductor losses in higher frequency converters, but careful consideration must be given to the wave shape (ripple current) of each application.

We appreciate reader feedback. Please direct all questions regarding this article to:

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