

Electronics in Motion and Conversion

May 2023

ZKZ 64717

Partnering for the Safe Supply of Industrial Power Modules

Advanced Inductor Circuit Models

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Advanced Inductor Circuit Models

In this article, Dr. Ridley describes new advanced circuit models that can be used to accurately predict the performance of off-the-shelf inductors. This allows the designer to rapidly assess power supply inductor losses by using standard circuit simulation packages.

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Off-The-Shelf Inductors

Over the past 10 years, magnetics manufacturers have made great progress in providing power designers with standard magnetics at reasonable prices. After the product development, the main focus of the technical teams has been to develop comprehensive application test results. These results are provided in custom programs which show the losses with different operating conditions of voltage and frequency.

Figure 1 shows the example inductor that we will be discussing in this article. It is a helical foil inductor from Coilcraft, rated for use up to about 20 A. A lot of time and effort has been spent to provide detailed loss characteristics for the component which can be found interactively by using their DC-DC optimizer program [1].

This data is tremendously useful to a power designer. It's an important step in providing detailed circuit models that are verifiable with test data.



Figure 1: Coilcraft Inductor with Helical Foil Windings

Buck Converter Circuit with Basic Inductor Model

Figure 2 shows a buck converter application with the inductor in place. Notice that the basic circuit model for the inductor includes just the dc resistance and



Figure 2: Buck Converter Circuit with Coilcraft Inductor DC Parameters

the fixed inductor value. As we will see, the dc resistance value will provide a very low estimate of the inductor dissipation. There are two ways to assess the performance of the inductor. From the designer's point of view, the most convenient way would be to run an LTspice simulation and just click on the inductor component to see the loss during the simulation. This is what we can do with every other component in the schematic, and it has become a standard for every component EXCEPT the magnetics.

The other way to assess the inductor performance is to use the customized tools developed by the manufacturer of a component for the operating point of the converter. For the inductor being used here, extensive data has been collected and this can be seen by running the Coilcraft DC-DC Optimizer program [1]. Figure 3 shows the graph of this data for different operating points of the buck converter. The graph on the left is for 200 kHz operation with the input voltage varied from 80 V to 130 V. (Output is 24 V at 10 A).

SER 2918H-153 Losses - 200 kHz

On the right hand graph, the input voltage is fixed at 130 V (highest dissipation voltage) and the frequency varies from 100 kHz to 300 kHz. At low frequencies, the losses increase substantially. Ripple currents are higher and flux excursions in the core are higher. This is not intuitively obvious since you will often read papers claiming that magnetics losses will increase with frequency, not decrease.

While the data is available for the inductor losses through the software from Coilcraft, this is not exactly convenient for the designer. Imagine what a chore it would be if every component of the circuit required a custom program from the vendor to assess its losses. In the semiconductor world, you cannot sell a part unless it has a reasonably accurate simulation model. This expectation has not been applied to the magnetics. There are many reasons for this, but it does not need to be that way.

Advanced Inductor Model in Buck Converter Circuit

Figure 4 shows a much more advanced simulation model for the inductor. In addi-Loss (W) SER 2918H-153 Losses -130 V



Figure 3: LTspice Simulation Results for DC Inductor Loss Plotted versus Coilcraft DC-DC Optimizer

You can see from the left hand graph how the losses increase with input voltage on the data provided by the Coilcraft DC-DC optimizer. The red curve shows the losses predicted straight from the simulation of the circuit in LTspice. With the dc model, the predicted losses are very low, and there is minimal variation with input voltage. tion to the series DC resistance, you can see a block labelled Rac. The resistance of the windings increases with frequency due to proximity losses. There is also a block representing the core loss of the inductor. This is very specific to the core material, number of turns used, and the core dimensions.

All of the parameters of the ac resistance and the core loss model were derived with the help of RidleyWorks design software [2]. These are described later in this article.

Figure 5 compares the data produced by an LTspice simulation of the advanced model with the measured manufacturer's data. The deviation between measured and simulated is very small. This is exactly what the circuit designer wants – a straightforward model that predicts the losses from the

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simulation, just like every other component in the circuit. Once the designer has a trusted circuit model, it's no longer necessary to use customized software to get the needed results. You can also put the circuit model in ANY topology you like, with arbitrary circuit waveforms, and expect to get reliable results. network. This type of circuit was first proposed for magnetics winding modeling in [4] and has been used for many years by a few select researchers. It is the basis of the circuit models generated by RidleyWorks. We don't see any usage of this by magnetics manufacturers yet.



Figure 4: Advanced Inductor Model in Buck Converter Schematic



Figure 5: LTspice Simulation Results for Advanced Inductor Model Loss Plotted versus Coilcraft DC-DC Optimizer

Winding Proximity Loss Model

There are two elements needed to match the total losses in the inductor. The first is the winding loss which should be frequency dependent. This is achieved with the circuit diagram shown in Figure 6 which is comprised of 5 inductors and 5 resistors. The circuit values are chosen automatically by RidleyWorks to match the desired ac resistance characteristics. (In the next installment of this article, we will explain how the ac resistance values were derived to give accurate simulation models.)

At dc, all the inductors of the network are short circuits, and the only resistance left is Rdc. The inductors become higher impedances with increased frequency, sequentially increasing the resistance of the

	Inducto	or Proximity Mod	e
	Rac1	3.98 mΩ	
	Rac2	12.30 mΩ	
${}^{2} \left\{ \right\} \left\{ \right\} {}^{\kappa_{ac2}}$	Rac3	0.16 Ω	
	Rac4	1.72 Ω	
$_{3} \zeta \leq R_{ac3}$	Rac5	21.32 Ω	
\subseteq	Lac1	0.37 µH	
$\{ \xi \}_{R_{eff}}$	Lac2	0.29 µH	
	Lac3	0.37 µH	
5	Lac4	0.40 µH	
° {	Lac5	0.41 µH	
			
$\leq R_{dc}$			
1			

Advanced Core Loss Model

The second element needed to provide accurate simulation data is a good core loss model. You will find many attempts in the literature to solve the problem of core loss simulation, but none of them have become mainstream.

Figure 7 shows the circuit model derived by RidleyWorks for the sample Coilcraft inductor. This is a set of six parallel R-L branches driven by the voltage across the inductor. A dependent voltage source is used to model the nonlinear exponent of core loss with amplitude, while the R-L branches model the proper frequency dependence. This circuit will provide the needed characteristics - the resistor value decreases with frequency showing highest core loss at the lowest frequency. Further explanation of this model will be included in the next installment of this article.

Summary

It is quite reasonable to expect that you can have an accurate simulation model for inductors which will give the power designer exactly what is needed – losses found directly from the simulation that correspond closely with actual measured results. We have shown that for a specific inductor this can be done reliably and with relatively little effort. We hope that the inductor manufacturers will start providing users with these kinds of accurate and advanced models to speed up the design process for working engineers.

References

You can read more information on this topic in each of these references.

- Coilcraft DC-DC Optimizer software https://www.coilcraft.com/en-us/tools/ dc-dc-optimizer
- 2. RidleyWorks design software https:// www.ridleyengineering.com/softwareridley/ridleyworks/ridleyworks-software. html
- 3. Measurement of Rac using the Ridley-Box https://www.ridleyengineering.com/ hardware/ridleybox
- 4. Francisco de Leon, Adam Semlyen, "TIME DOMAIN MODELING OF EDDY CURRENT EFFECTS FOR TRANSFORM-ER TRANSIENTS" IEEE Transactions on Power Delivery, Vol. 8, No. 1, January 1993. https://tspace.library.utoronto. ca/bitstream/1807/9972/1/Semlyen_9842_2827.pdf
- 5. Join 6000+ engineers in our Power Supply Design Center Group on Facebook. https://www.facebook.com/groups/ ridleyengineering/





Figure 7: Core Loss Circuit Model for the Coilcraft Inductor

Figure 6: Winding Loss Circuit Model for the Coilcraft Inductor

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