APPLICATION NOTE

Accurate Inductor Loss Determination Using Würth Elektronik's REDEXPERT

WÜRTH ELEKTRONIK

ANP029 RANJITH BRAMANPALLI

1. Introduction

In a Switch Mode Power Supply (SMPS) the majority of any power losses that occur are in the form of switching and magnetic losses. Magnetic loss occurs from the core and the windings in the storage/coupled Inductor. Determination of inductor power loss accurately has become more important to design reliable and efficient systems, especially in the era of green technology. Estimation of core losses in SMPS can require complex measurement set-ups, yet cannot be guaranteed whether the estimation is relevant to the particular application. Historically, core losses are calculated using Steinmetz equation and recently with the extension of Steinmetz equations. These equations can estimate losses reliably only for certain conditions or materials. Hence, Würth Elektronik eiSos have developed a state of the art new model to determine core losses effectively and accurately. This model has now implemented in our new design tool REDEXPERT.

2. Energy Storage in Magnetics

In a SMPS, the Inductor acts as storage component. It stores energy in the form of a magnetic field during the switching-cycle on time and delivers that energy to the load during the off time. Usually, an inductor consists of a coil pre-dominantly made of copper wire and a core which has magnetic properties. In terms of electromagnetic physics when a magneto-motive force with respect to the time is applied to the coil, it induces magnetic flux $\emptyset(t)$. An important point is that at any location, the magnetic flux density B is always proportional to field intensity H..

$$B(t) = \mu_r \, \mu_o \, H(t)$$

Where B is the magnetic flux density$(\emptyset/A)$, μ_r is the permeability of the material, μ_o is the permeability of air and H is the magnetic field Intensity.

The coil is wound around or placed inside the core with an air gap to tap the magnetic field effectively. The core contains air gap. The core is usually a ferrite material which has ferro-magnetic properties and much higher permeability than air. Hence, the air gap places a high reluctance element of air in series with low-reluctance ferrite material, thereby locating the bulk of the energy in the air gap.

Inductors operate according to the laws of Ampere and Faraday. Ampere's Law relates current in the coil or turns of wire to the magnetic field in the core of the inductor. As an approximation, one assumes the magnetic field in the inductor's core is uniform throughout the core length (l_e). That assumption lets us write Ampere's law as

$$H \times l_e = N \times I$$

Where N is the number of turns of the coil around the inductor core and I is the inductor current.

According to Faraday's Law, voltage applied across the Inductor is

$$V(t) = N \times \frac{d\emptyset}{dt} \quad \text{(or)} \quad V = L \times \frac{di}{dt}$$

From above theories Inductor value is calculated as

$$L = \mu \frac{Ac \, n^2}{le}$$

Where Ac is core cross-sectional area.

Because ferrite materials have high permeability, they offer an easy path for magnetic flux (low reluctance). This characteristic helps contain the flux within the inductor's core, which in turn enables the construction of inductors with high values and small size. This advantage is evident in the inductance equation above, in which a core material with high permeability value allows for a smaller cross-sectional area.

In SMPS the peak Magnetic flux density can be written as

$$B_{pk} = \frac{L}{N \times Ac} \times \frac{di}{dt}$$

Coupled Inductors (sometimes flyback transformers) are also inductors but having multiple windings. The windings do have some unique issues but core properties remain same.

3. Power Losses

Power dissipation in an Inductor occurs in the windings and the core and these are termed as windings loss and core loss.

3.1. Winding Loss

The power dissipation occurs in windings due to DC resistance (R_{DC}) of the windings, and phenomena such as skin effect and proximity effect. The loss due to DC resistance can be estimated using the equation

$$I^2 \times R_{DC}$$

The losses occurring due to the skin and proximity effects can be termed as AC resistance (R_{AC}) of the winding, which predominantly depends on operating frequency. There exist few techniques to determine these effects in the magnetic component, but one would have to follow complicated procedures like Dowell's method to estimate these losses.

3.2. Core Loss

B is measured as H is increased. The response of B versus H is nonlinear and exhibits hysteresis, hence the name hysteresis loop. Hysteresis is one of the core-material characteristics that will cause power losses in the inductor core. A typical B-H curve is shown in figure 1 when a sinusoidal excitation is applied to the core.

Energy loss due to the changing magnetic energy in the core during a switching cycle equals the difference between magnetic energy put into the core during the on time, and the magnetic energy extracted from the core during the off time.

By using Ampere's & Faraday's Law, the Energy in the core can be expressed as:

$$E = \int H\,dB$$

Energy lost in the core is the area traced out by the B-H loop multiplied by the core's volume. The power loss is this energy (E) multiplied by the switching frequency.

This expression applies on the conditions that the core is not driven into saturation, and the switching frequency lies in the intended (linear) operating range. The hysteresis loop area (red region in fig 1) represents energy loss. Power loss depends on how many times per second the hysteresis loop is traversed. Thus, hysteresis loss varies directly with frequency.

APPLICATION NOTE

Accurate Inductor Loss Determination Using Würth Elektronik's REDEXPERT

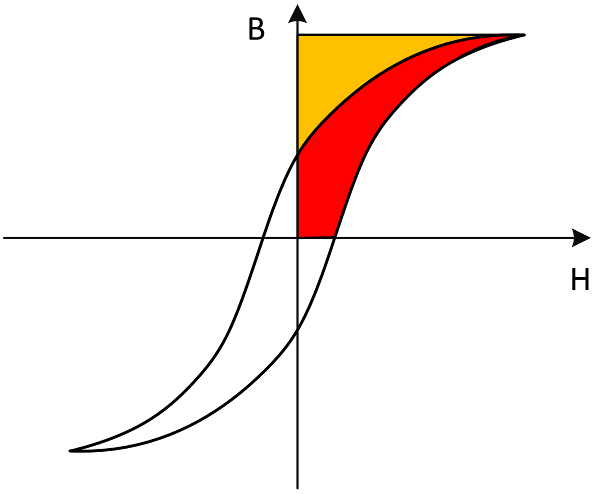

Fig 1: B-H Curve

The second type of core loss is due to eddy currents, which are induced in the core material by a time-varying flux$\frac{d\emptyset}{dt}$. According to Lenz's Law, a changing flux induces a current that induces a flux in opposition to the initial flux. This eddy current flows in the conductive core material and produces losses of I^2R.

4. Determination of Losses

Historically, core losses are estimated by using power equation (1), also called Steinmetz equation.

$$P_v = K \times f^{\alpha} \times B_{pk}^{\beta}$$

Where P_v is the core loss (Hysteresis & Eddy current loss) for unit volume, f is the frequency, B_{pk} is peak flux density of a sinusoidal excitation, K, α & β are the constants, derived from core loss graph shown in Figure 2.

The data given in figure 2 for core losses usually includes the effects of both hysteresis and core eddy currents.

Core-loss measurements are difficult because they require complicated setups for measuring flux density and because they involve the estimation of hysteresis-loop areas. For plotting these curves, a sine wave is applied to a toroidal (ring) core with 1 or 2 coil winding with 1 turn and extracts various data to plot the core loss chart. Then the constants are calculated using the graph in figure 2.

The major drawback of the Steinmetz equation is that it is mostly valid for sinusoidal excitation. This is a huge drawback because in most power electronic applications, the Inductor is usually exposed to non-sinusoidal flux waveforms. Even though there are other models which separates hysteresis & eddy current loss to overcome the problem of non-sinusoidal waveforms, the empirical Steinmetz equation has proven to be the most useful tool for sinusoidal flux-waveforms, because it provides better accuracy and is quite simple to use. Hence there are extensions to this power equation to make it accurately effective for non-sinusoidal flux waveforms.

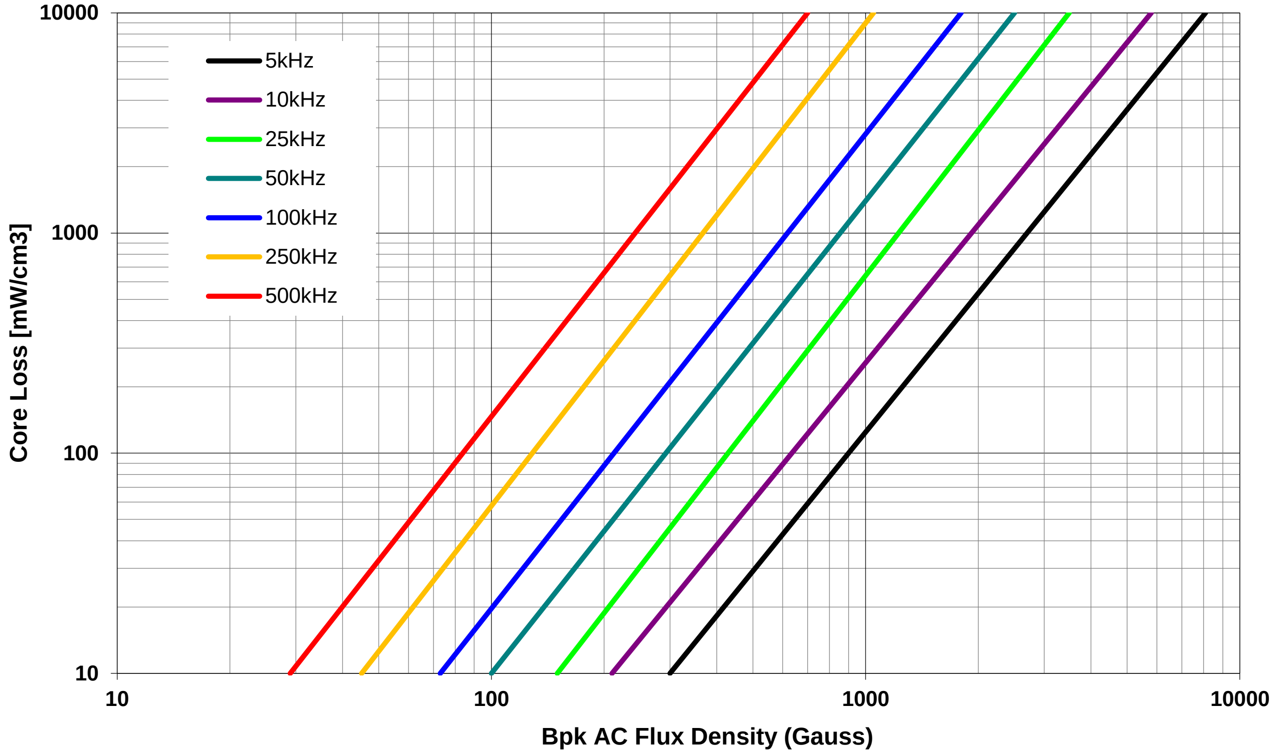

Figure 2: Core Loss graph plotted against peak flux density at different frequencies

In order to utilize the Steinmetz equation for non-sinusoidal waveforms to estimate core losses, a later extension, "the Modified Steinmetz Equation" (MSE) (2) has been utilized widely.

$$P_v = \left(K \times f_{eq}^{\alpha-1} \times B_{pk}^{\beta}\right) \times f \quad \text{where} \quad f_{eq} = \frac{f}{2\pi \times (DC - DC^2)}$$

f_{eq} being the equivalent frequency with respect to change in the duty cycle (DC) of non-sinusoidal waveforms.

Due to some disadvantages posed by MSE, later brought forth the Generalized Steinmetz Equation (GSE) to be developed - as shown in the equation.

$$P_v = \left(K \times f_{eq}^{\alpha} \times B_{eq}^{\beta}\right) \quad \text{where} \quad B_{eq} \text{ is } \frac{1}{4}\int_0^T \left|\frac{dB}{dt}\right| dt$$

Hence, as the GSE & MSE core loss charts are also based on sinusoidal excitation, there exists some limitations which will be discussed later. There also exist some other models developed by core manufacturers which works best with the cores only manufactured by them.

The major disadvantages of the Steinmetz and its extended models are:

- Dependent on Core Manufacturer's empirical data, (for core loss charts). One must depend on the core manufacturer's data and the passive component manufacturer does not have any control over the test setup.
- Low accuracy with pulsating and triangular waveforms. Because the core loss graphs are created using the data from sinusoidal excitation.
- Due to errors occurred in parameter conversion, the extension of Steinmetz models works best only for 50% duty cycle and limited frequency range.
- Only confine to components made with particular materials or by manufacturer.
- Due to the complexity of estimating Magnetic path length, the estimation of core loss using existing models for Iron Powder materials & Metal Alloys is not only challenging, but the accuracy varies widely.

- Due to change in flux density with respect to time, there also exist losses in the component winding due to skin effect, proximity effect etc. and the above methodologies fail to include AC losses of the winding.
- Unable to estimate losses in the component which has more than one material.
- Complexity of the set up to produce accurate empirical data.

5. The Würth Elektronik AC Loss Model

Würth Elektronik eiSos has developed state of the art model, allowing customers to effectively select the inductor and optimize the system. The model is based on the empirical data, derived from real time application set up.

In the Würth Elektronik eiSos model the total loss of the Inductor is divided into two separate losses as AC loss and DC loss. The power dissipation occurs due to DC current in the inductor windings and will be listed as the DC loss. The additional power loss occurred due to AC flux swing in the coil and the core is termed as AC loss.

The DC-DC converter as shown in figure 3 is utilized to produce an empirical data. A pulsating voltage is applied over the Inductor and the power Input, P_{in} and Power output P_{out} are measured, then $P_{Loss} = P_{in} - P_{out}$ is estimated and then AC loss of the Inductor P_{AC} is separated. This process is repeated over wide range of parameters including variation of peak flux density swing, frequency, ripple current, etc., to produce the empirical data. This empirical data is then used to create an equation to calculate AC loss in the form of $P_{AC} = f(\Delta I, freq,\ DC,\ k1,\ k2)$.

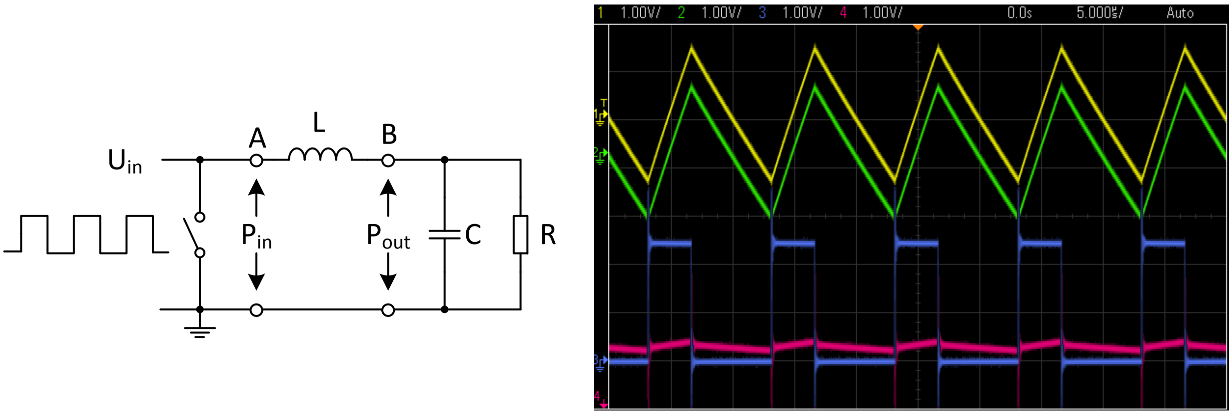

Fig 3: Setup of DC-DC Converter for Loss Determination and resulting scope shots

The hysteresis loops shown in the typical core material data sheets represent the core overdriven by a sinusoidal waveform from + to - saturation and the hysteresis loop area represents energy loss shown in figure 4a. This is the same approach used to produce empirical data for the core loss charts as shown in figure 2.

But in an SMPS application, the core is usually driven by a much smaller rectangular waveform with peak flux density limited by core losses to a minor hysteresis loop as shown in figure 4b. Power loss depends on how many times per second the hysteresis loop is traversed. Thus, hysteresis loss varies directly with frequency. The hysteresis loop changes shape somewhat with wave shape, current or voltage drive, and temperature. This variability, makes it very hard to predict core loss accurately. The minor loop area depends on the voltage above the Inductor. This minor loop is followed by the point of operation approach of Würth Elektronik to produce empirical data for Würth Elektronik's AC loss model. Hence, this approach has proven robust, accurate over wide range of parameters like frequency, ripple current and duty cycle.

APPLICATION NOTE

Accurate Inductor Loss Determination Using Würth Elektronik's REDEXPERT

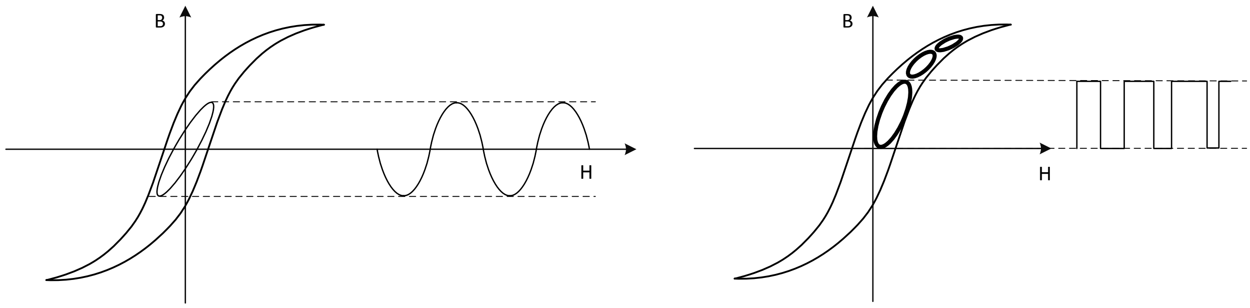

Fig 4a & 4b: Typical modelling used for Steinmetz equation and it's extensions on the left and Würth Elektronik's point of operation approach on the right

Advantages of Würth Elektronik's AC loss model:

- Hence the empirical data is purely based on real time parameters with accurate estimation of losses for any given Duty Cycle being achieved.
- The model is also accurate over wide range of frequency (10 kHz to 10 MHz) as the constants of the power equation are derived over a wide range with respect to the flux swing.
- Considers even small change in core material and winding structure.
- Valid for the components, which have more than one material.
- Accurately estimates losses of Iron powder and Metal alloy materials.
- Valid for any core shape and winding structure.
- Includes AC winding losses.

6. Performance of the Würth Elektronik AC Loss Model

Würth Elektronik model has been validated extensively and compared with existing models and measured data. The AC loss for various materials like WE-Super flux , Iron powder, NiZn, MnZn, etc., are measured at a wide range of duty cycles, frequencies and other parameters compared with theoretical models as shown in figures 5 to 9. In below charts Pst, Pmse, Pgse are core losses determined using Steinmetz power equation, the Modified Steinmetz equation and the Generalized Steinmetz equation respectively. REDEXPERT is the AC loss calculated using Würth Elektronik AC loss model. Real is the measured AC loss.

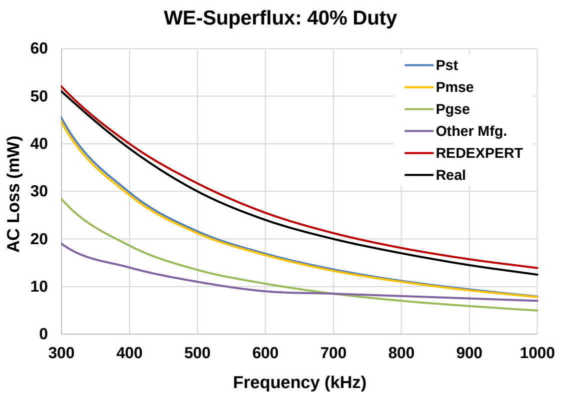

Fig 5: Inductor made of WE Superflux at 40% DC

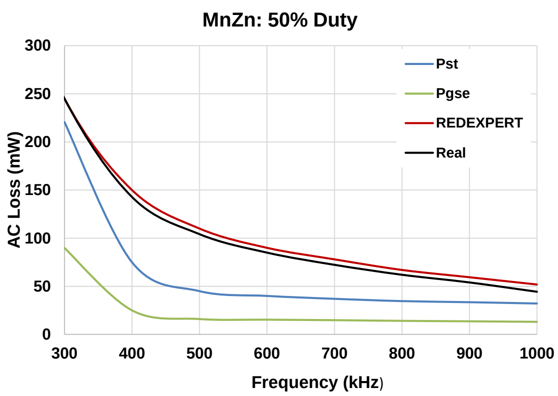

Fig 6: Inductor made of MnZn material at 50% DC

APPLICATION NOTE

Accurate Inductor Loss Determination Using Würth Elektronik's REDEXPERT

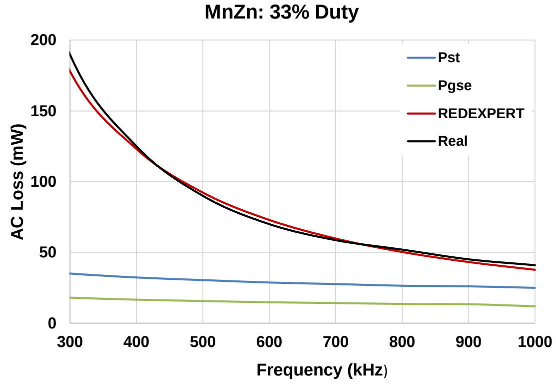

Fig 7: Inductor made of MnZn Material at 33% DC

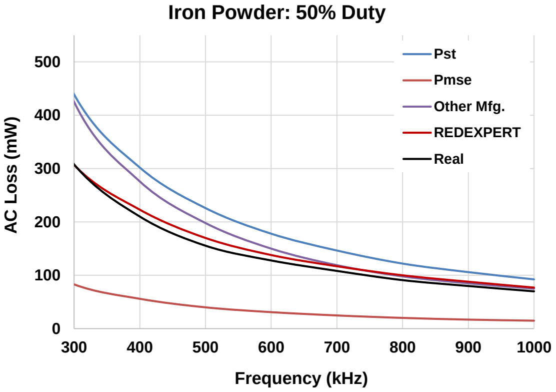

Fig 8: Inductor made of Iron powder at 50% DC

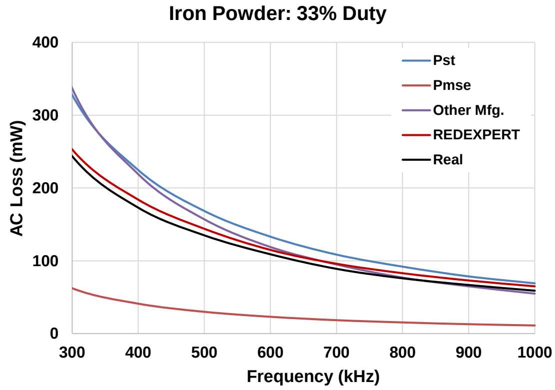

Fig 9: Inductor made of Iron Powder Material at 33% DC

APPLICATION NOTE

Accurate Inductor Loss Determination Using Würth Elektronik's REDEXPERT

7. Determination of Power Inductor Losses with REDEXPERT

REDEXPERT is Würth Elektronik's new online component selection and simulation tool which gives an option to the customer to select an appropriate power inductor based on the application. REDEXPERT is simple and effective tool, which allows an engineer to compare and select the inductors in no time. Once, the user enters their input and output parameters in the desired topology, the tool will calculate the inductance value and display the inductor choices. A screenshot of REDEXPERT web tool is shown in figure 10.

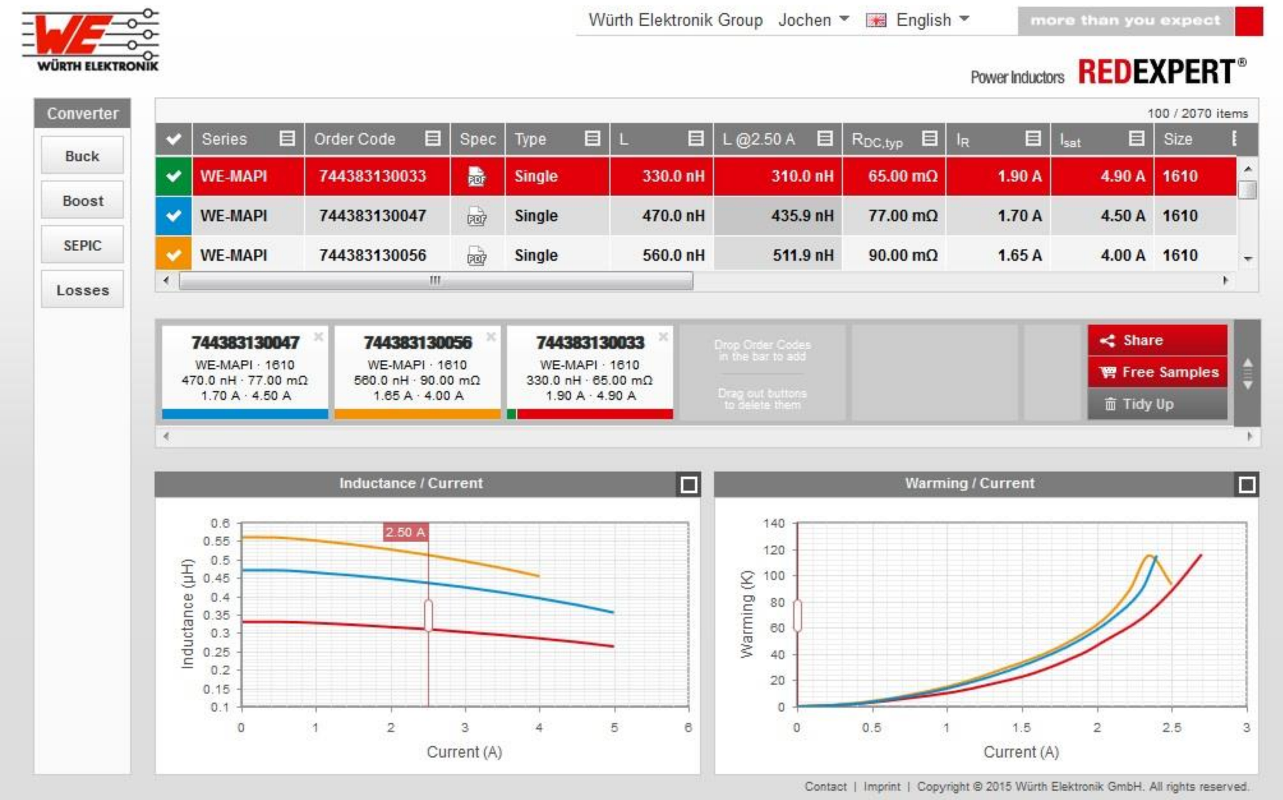

Fig 10: Screenshot of REDEXPERT online tool

Since, Würth Elektronik eiSos has a wide range and variety of inductors, there is a good possibility that the user is filled with options. Then the user can chose the inductor according to the size & performance which suits the application. Calculating AC loss in a magnetic component is critical and complex, but not with REDEXPERT as the new Würth Elektronik AC model is implemented in this tool. With AC loss being calculated accurately, the estimation of temperature of a component is also apt with the application.

An example is shown in figure 11. A buck converter has been chosen. The operational parameters are 8 – 12 V is given as the input voltage, 5 V is given as output, switching frequency as 800 KHz, with inductor ripple as 40% and output current as 1 A. The REDEXPERT tool has estimated the optimal inductance (Lopt) as 9.6 µH, Ton as 550 ns and duty cycle as 0.44 and it has displayed more than 200 inductors to choose from. Let's assume that the application requires miniature and low loss Inductor, the WE-MAPI series is the one we have chosen.

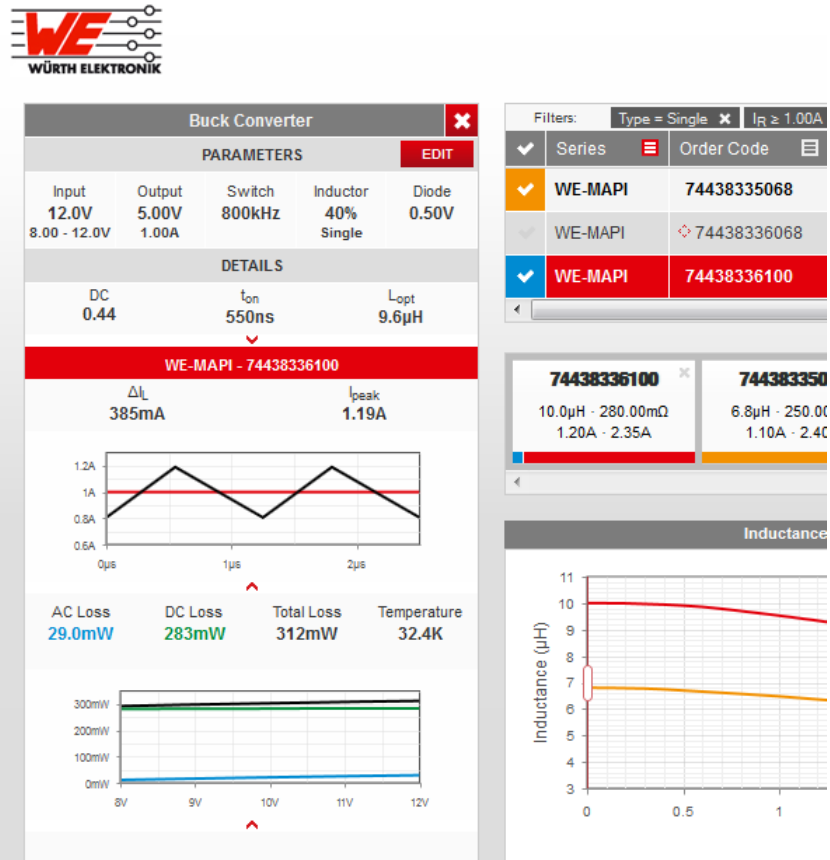

Fig 11: Buck-Converter Example

Currently REDEXPERT has three topologies Buck, Boost and SEPIC where the user can select the component for those applications. Furthermore, there is a Loss calculator for single inductor irrespective of the topology. REDEXPERT is a web based tool and the user does not have to bother about downloading and updates.

8. Summary

The Würth Elektronik's AC loss model is accurate and practical model for determining AC losses. The model has been experimentally verified over wide range of frequency, ripple currents and duty cycles and proved to be robust. Due to the fact that this AC loss model is implemented in REDEXPERT, the user does not have to request core loss charts. Overall, REDEXPERT is power online calculation tool saves the engineer's time in determining the losses and selecting the right component.

References

- Magnetics Design for Switching Power Supplies by Lloyd H. Dixon
- On the law of hysteresis by C.P. Steinmetz
- "Calculation of losses in ferro- and ferrimagnetic materials based on the modifiedSteinmetz equation" by Reinert, J.; Brockmeyer, A.; De Doncker, R.W.
- "Improved calculation of core loss with nonsinusoidal waveforms by Jieli Li; Abdallah, T.; Sullivan, C.R.

APPLICATION NOTE

Accurate Inductor Loss Determination Using Würth Elektronik's REDEXPERT

IMPORTANT NOTICE

USEFUL LINKS

Application Notes:
http://www.we-online.com/app-notes

Component Selector:
http://www.we-online.com/component-selector

Toolbox:
http://www.we-online.com/toolbox

Product Catalog:
http://katalog.we-online.de/en/

CONTACT INFORMATION

Würth Elektronik eiSos GmbH & Co. KG
Max-Eyth-Str. 1, 74638 Waldenburg, Germany
Tel.: +49 (0) 7942 / 945 – 0
Email: appnotes@we-online.de
Web: http://www.we-online.com