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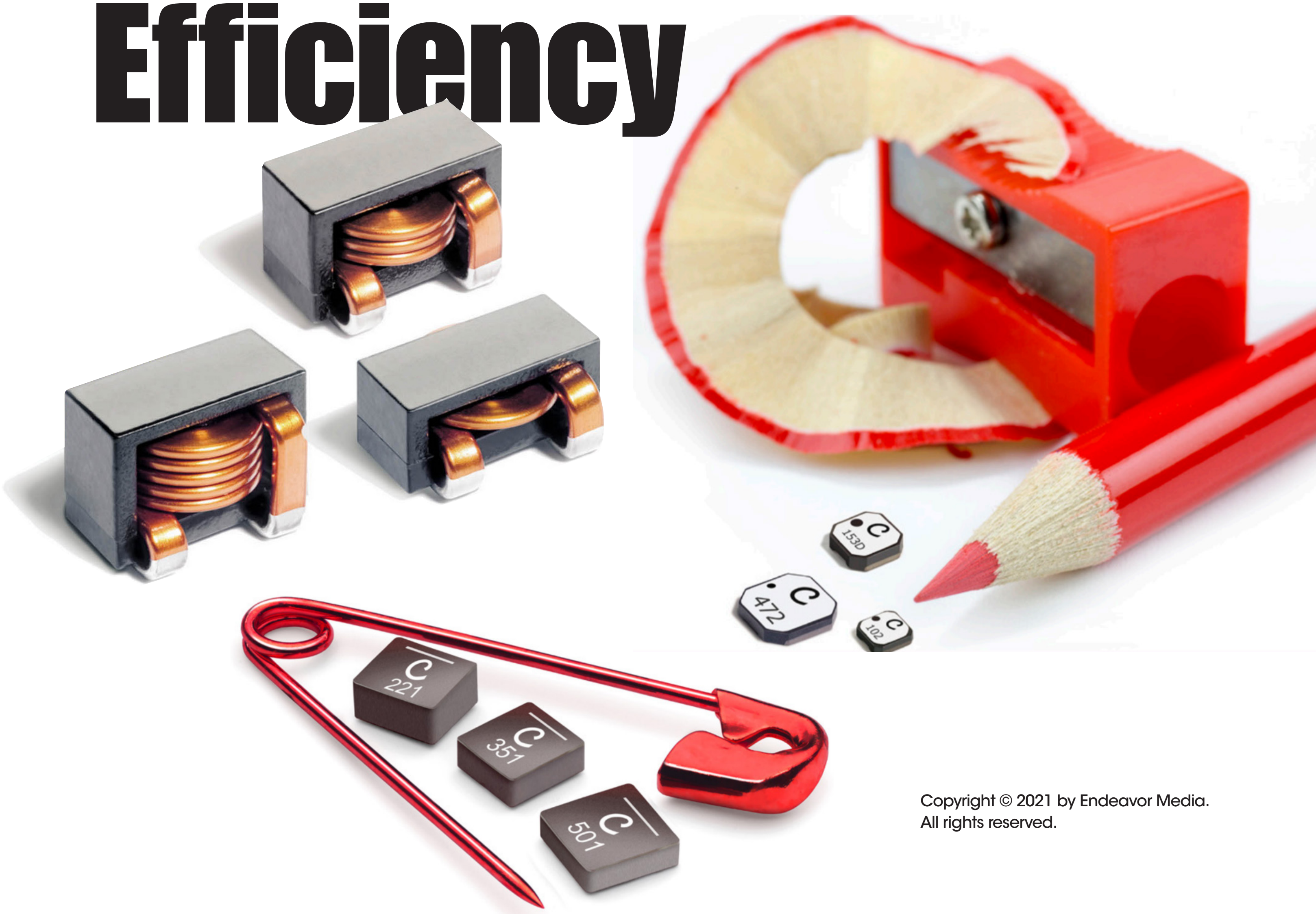
How Magnetics Improve Power Converter Efficiency



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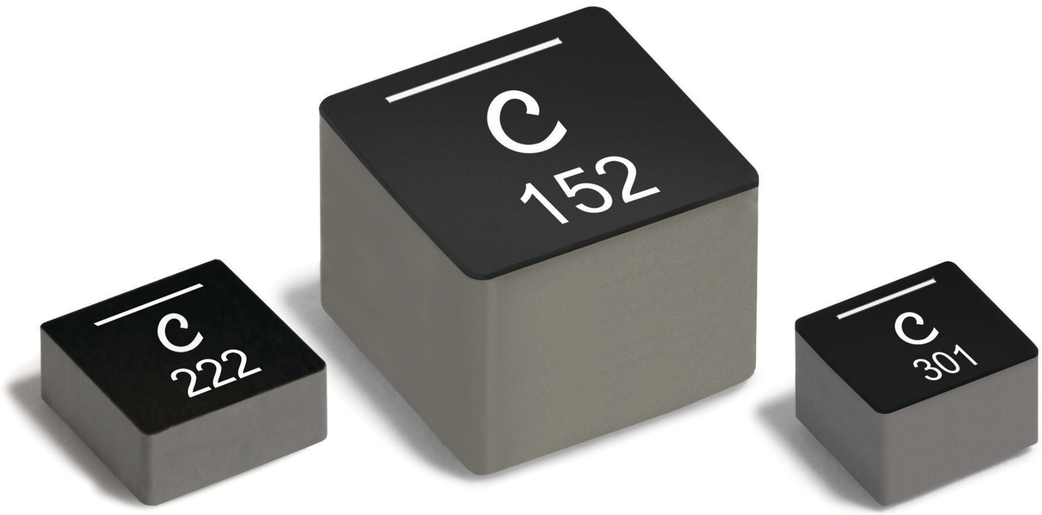
The (lowest) Loss Leaders



XGL Family power inductors feature the industry's lowest DC resistance and extremely low AC losses for a wide range of DC-DC converters

Coilcraft's XGL Family of molded power inductors is available in a wide range of inductance values (from 82 nH to 47.0 µH) and current ratings up to 43 Amps. With up to 60% lower DCR than previous-generation products, they are the most efficient power inductors available today!

Their ultra-low DCR and higher Irms also allow XGL Family inductors to operate much cooler than other components.

All XGL Family inductors are qualified to AEC-Q200 Grade 1 standards (with a maximum part temperature of 165°C) and have no thermal aging issues, making them ideal for automotive and other harsh environment applications.

Download the datasheets and request free samples at **www.coilcraft.com/XGL**.

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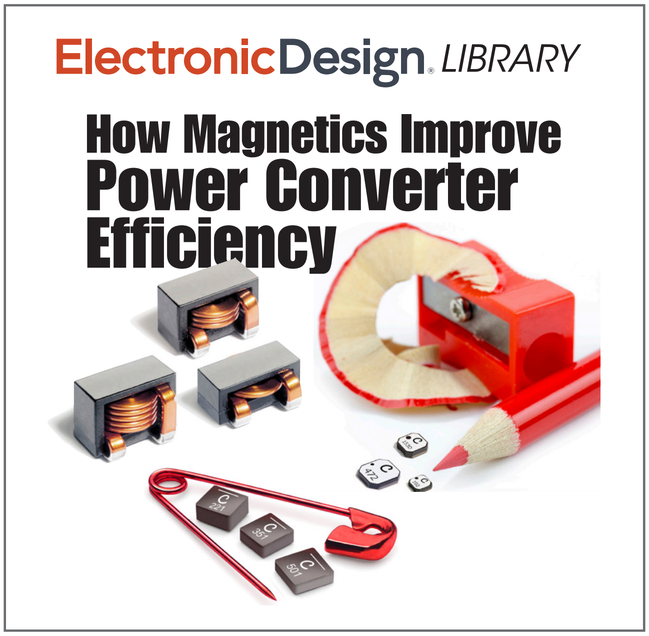

INTRODUCTION

Bill Wong
Editor,
Senior Content Director, Electronic Design & MWRF

INDUCTORS are part of the basics engineers learn in school along with components like resistors and capacitors. Simple, right?

The challenge is choosing the right device for a particular power supply that may include multiple inductors along with other components. Size, cost, efficiency and matching the specs to the design make this a non-trivial engineering task but one that is quite manageable especially given the variety of options available. This eBook delves into issues of design efficiency, test and inductor selection.

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CHAPTER 1:

Inductor Current Measurement in Switched Power Supplies

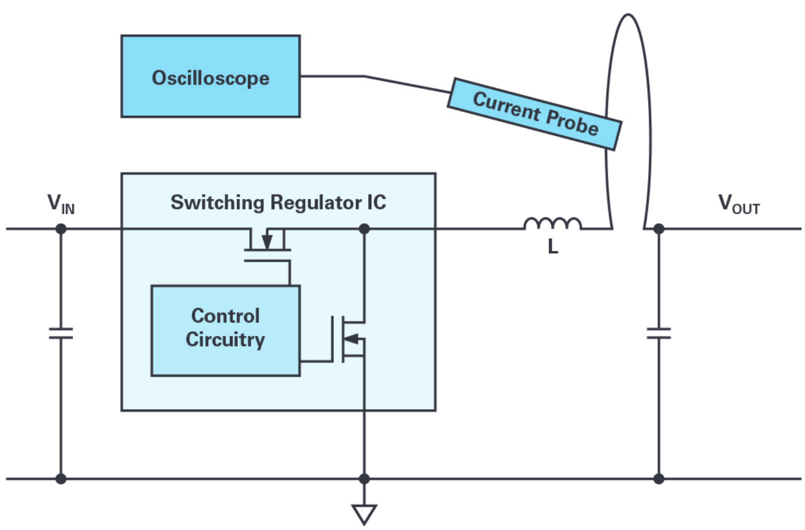
FREDERIK DOSTAL Field Applications Engineers at Analog Devices Inc.

> This "Rarely Asked Questions" blog post presents an optimal way to measure inductor current, opening a window into whether the right inductor was selected.

QUESTION: How do you measure inductor current?

ANSWER: Switched-mode power supplies commonly use inductors to temporarily store energy. In the evaluation of these power supplies, it's often useful to measure the inductor current to gain a complete picture of the voltage-conversion circuit. But what's the best way to measure the inductor currents?

Figure 1 shows a suggested setup for such a measurement using the example of a typical step-down converter (buck topology). A small auxiliary cable is inserted in series with the inductor. The cable is used to attach a current probe and display the inductor current with an oscilloscope. It's recommended that measurements be made on the side of the inductor where the voltage is stable. Most switching-regulator topologies use the inductor in such a way that the voltage on one side is switched be-



1. The schematic illustrates measurement of the inductor current in a switched-mode power supply.

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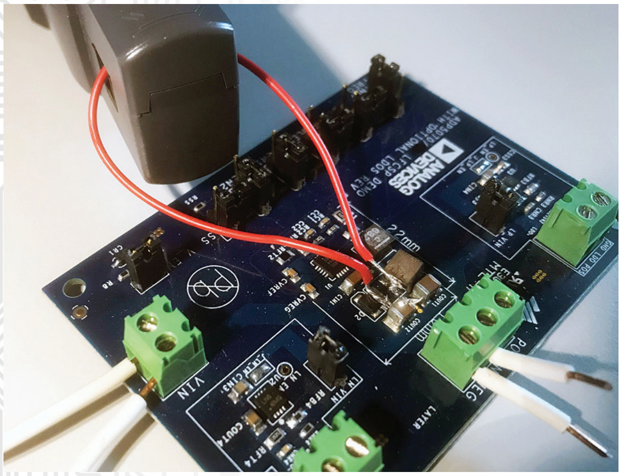
tween two extreme values, but it remains relatively stable on the other side.

With the buck converter in Figure 1, the voltage at the switching node—that is, the left side of inductor L—switches between the input voltage and the ground voltage at the speed of the switching edges. On the right side of the inductor is the output voltage, which is usually relatively steady. To reduce the interference due to capacitive coupling (electric field coupling), the current measurement loop should be placed on the quiet side of the inductor (Fig. 1, again).

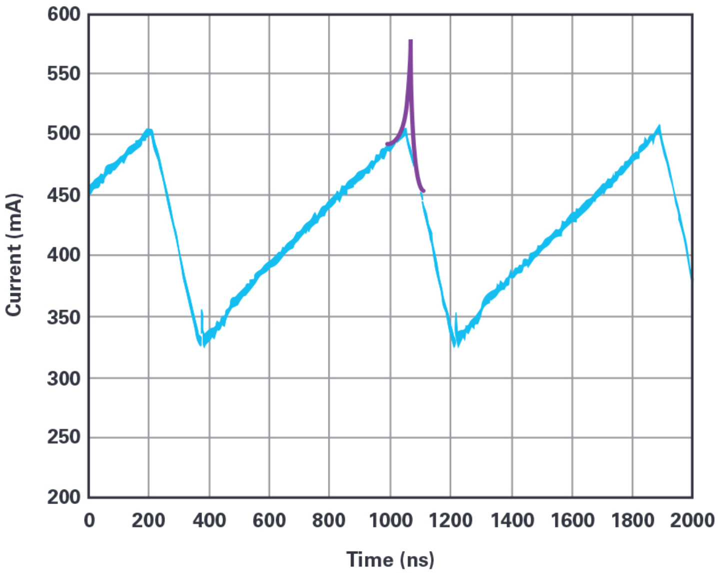
Figure 2 shows the practical setup for this measurement. The inductor is lifted and obliquely soldered back with one of the two terminals on the board. The alternate terminal is connected to the board with the auxiliary wire. This conversion can be accomplished quite easily. Desoldering with hot air is a proven method for detaching the inductor. Many surface-mount-device (SMD) rework stations offer hot air with an adjustable temperature.



2. Here's a practical setup for inductor current measurement.

Current probes are offered by manufacturers of oscilloscopes. Unfortunately, they're usually quite expensive. Thus, the question continually arises as to whether the inductor current could also be measured by means of a shunt resistor. This is possible in principle, but there's a drawback: The switching noise generated in a switched-mode power supply can easily couple into a voltage measurement via a shunt resistor. Consequently, especially at the points of interest, when the inductor current changes direction, the measurement results would not be a true representation of the inductor current's behavior.

Figure 3 shows the measurement of the inductor current (in blue) for a switched-mode power supply sensed with a current probe compatible with the oscilloscope used. In addition to the measurement shown in blue, a purple marking was added, indicating how the current flow through the inductor would look when the inductor starts to saturate excessively toward the peak currents. This happens when an inductor is selected that doesn't have enough current rating for a given application. One of the main reasons for measuring inductor current in a switched-mode power supply is the ability to recognize whether the inductor was properly selected or inductor saturation will occur in operation or during a fault condition.



3. The inductor current measurement is shown in blue; the behavior of a saturated inductor has been added, as indicated by the purple color.

Measurement with a shunt resistor instead of a current clamp would show strongly coupled noise, especially at the peak currents, making it difficult for inductor saturation to be detected.

Sensing of the coil current is very useful in the evaluation of a power supply and can easily be accomplished with suitable equipment.

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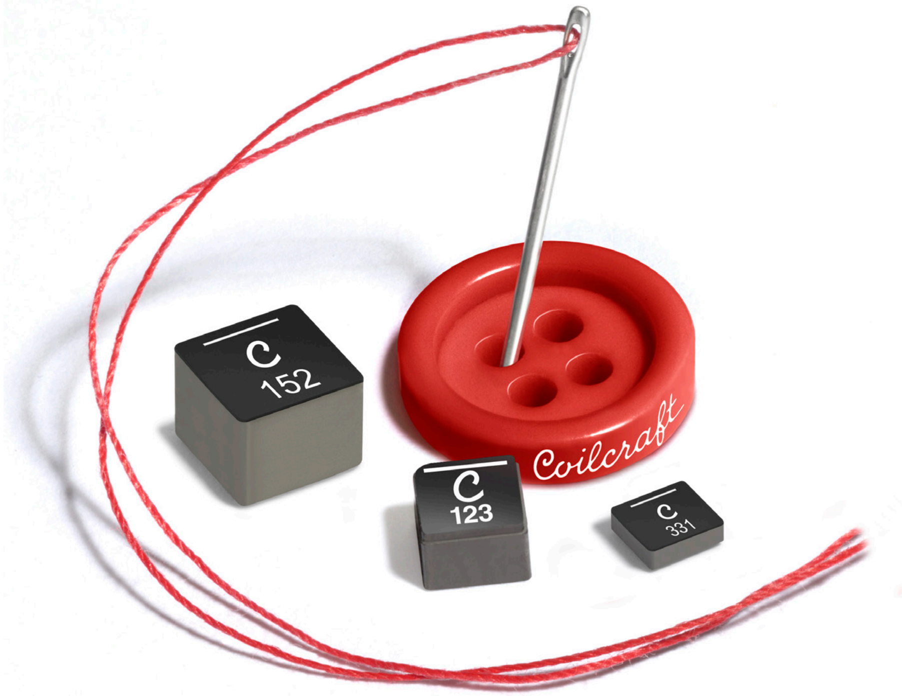

CHAPTER 2:

Choosing Inductors for Energy Efficient Power Applications

LEONARD CRANE 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:

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

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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.

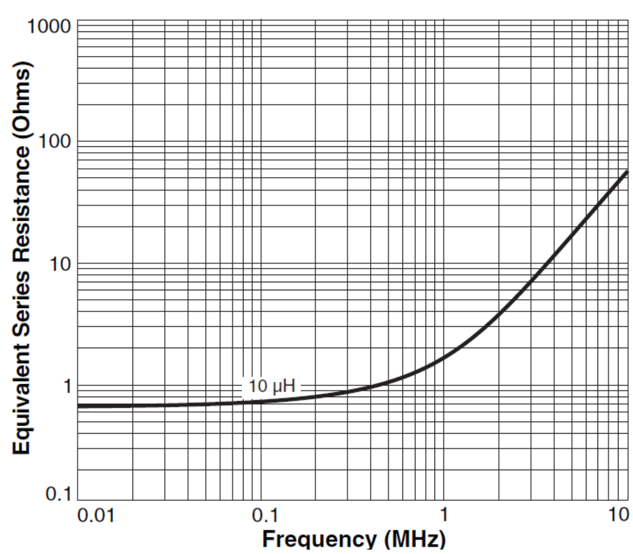

Figure 1. ESR vs Frequency

For example, consider the ESR vs frequency curve shown in **Figure 1**. 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 approximate-

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ly 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.

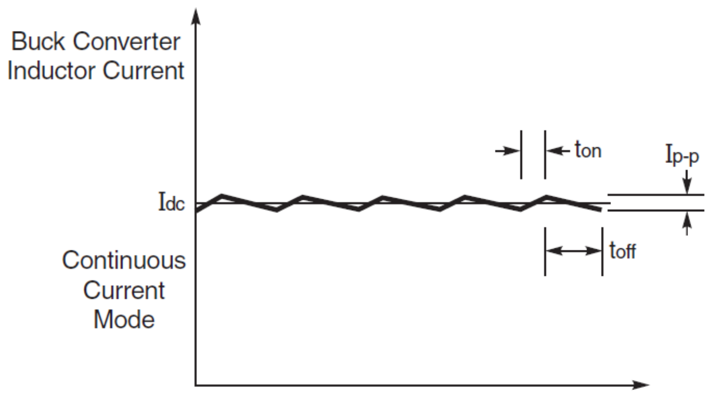

Figure 2. Ideal Converter Waveform with Small Ripple Current

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.

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

To get the total loss, we must add that to the high frequency loss, which is I^2R. In this

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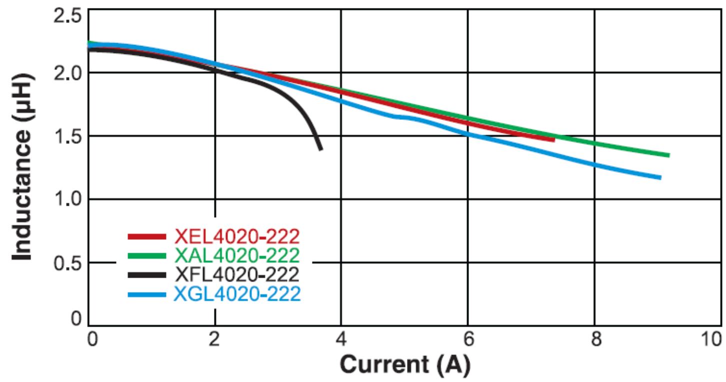

Figure 3. Comparing L vs I of XAL, XEL XFL and XGL 2.2 µH inductors

case the R is the ESR and the I is the rms value of the ripple current only.

Approximate rms ripple current:

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

At 250 kHz the ac loss would be:

$(0.0087\ \text{A})^2 \times (0.8\ \Omega) = 0.00006\ \text{W}$.

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:

$(0.0087\ \text{A})^2 \times (10\ \Omega) = 0.00076\ \text{W}$.

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.

Table 1. Comparing XGL, 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

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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. **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.

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,

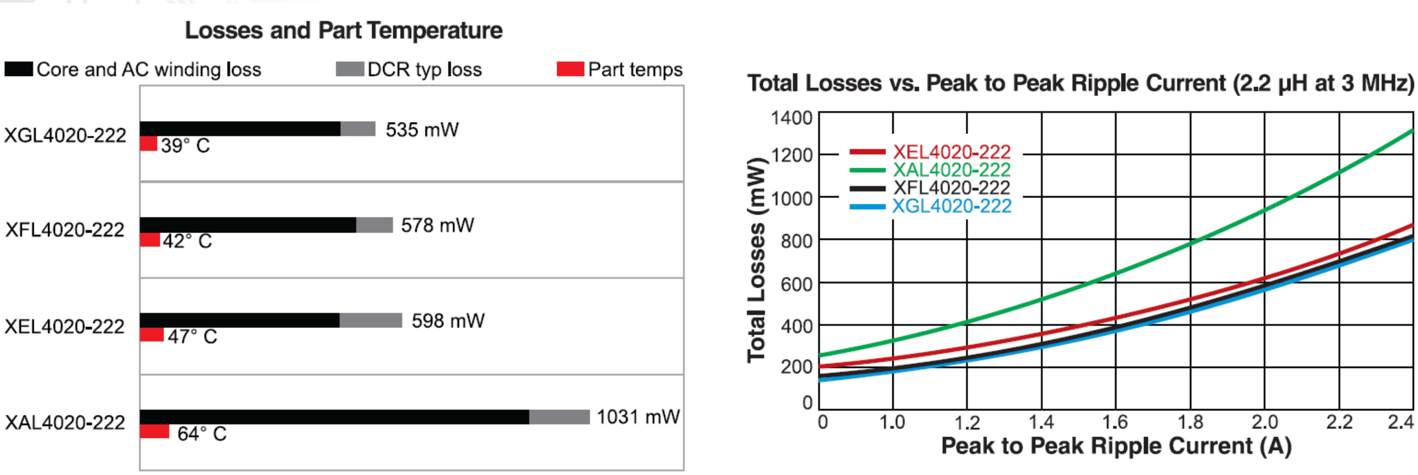

Figure 4. Comparing AC Losses and Total Losses of XAL, XEL, XFL, and XGL at 2 MHz

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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

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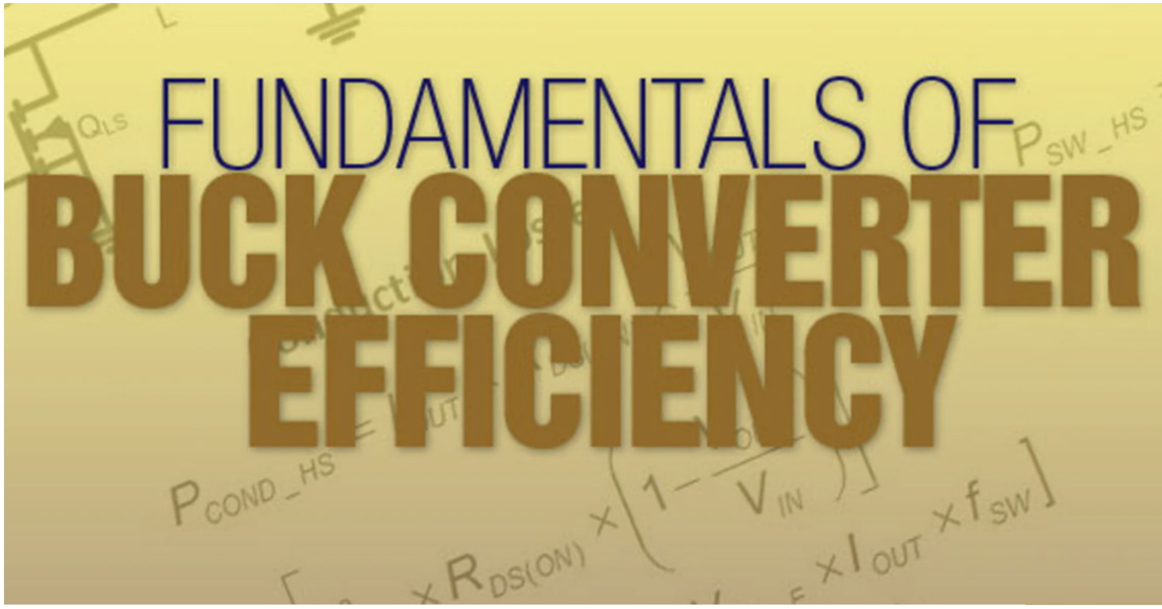

CHAPTER 3:

Fundamentals of Buck Converter Efficiency

CHRIS COOPER Avnet Electronics Marketing Americas

This engineering essentials on buck converter efficiency presents the relevant equations needed to estimate power losses in the converter. Following the equations, which are presented in a unique tabular format, are explanations of all the relevant parameters used in the equations.

To illustrate the factors that play a role in a buck converter's efficiency, the Table below lists the equations used to *estimate* the most significant power losses. The parameters to minimize for high efficiency can be quickly determined utilizing these equations. The dominant losses in a buck converter design depend on the specific operating conditions of the circuit, and hence, it is important to perform the calculations below for your application. (*See table on next page*)

Efficiency Parameters

From these equations, the following parameters can be used to improve the efficiency of a buck converter. Keep in mind that typically the output voltage and current are fixed by the load requirement.

Parameters to Minimize for High Efficiency

Switching Frequency, fsw

MOSFET
- On-resistance, $R_{DS(ON)}$
- Gate Charge, Q_G

Inductor
- DC resistance, DCR
- Core Losses

For Synchronous:
Low Side MOSFET
- Body Diode Forward Voltage, V_{BD_F}

For Non-synchronous:
Power Diode
- Forward Voltage, V_F

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	Conduction Losses	Switching Losses
High-Side MOSFET	$P_{COND\_HS} = I_{OUT}^2 \times R_{DS(ON)} \times \frac{V_{OUT}}{V_{IN}}$	$P_{SW\_HS} = \left(\frac{V_{IN} \times I_{OUT}}{2}\right) \times (t_{RISE} + t_{FALL}) \times f_{SW}$
Low-Side MOSFET (Synchronous)	$P_{COND\_LS} = \left[I_{OUT}^2 \times R_{DS(ON)} \times \left(1 - \frac{V_{OUT}}{V_{IN}}\right)\right] + \left[(t_{DT(R)} + t_{DT(F)}) \times V_{BD\_F} \times I_{OUT} \times f_{SW}\right]$	P_{SW_LS} : negligible
Power Diode (Non-synchronous)	$P_{COND\_D} = V_F \times I_{OUT} \times \left(1 - \frac{V_{OUT}}{V_{IN}}\right)$	P_{SW_D} : negligible Assuming a Schottky Diode

	DC Losses	Core Losses
Inductor	$P_{DC\_L} = I_{OUT}^2 \times DCR$	See Supplier Information or Reference 1

Other Supporting Equations

$$D = \frac{V_{OUT}}{V_{IN}} \qquad t_{RISE} = \frac{Q_{G(SW)}}{I_{DRIVER(RISE)}} \qquad t_{FALL} = \frac{Q_{G(SW)}}{I_{DRIVER(FALL)}} \qquad Q_{G(SW)} \approx Q_{GD} + \frac{Q_{GS}}{2} \qquad t_{DT(R)} + t_{DT(F)} \approx 2 \times t_{DELAY}$$

I_{OUT}	DC Output Current	$t_{DT(R)}$	Time period between when Q_{LS} turns off and Q_{HS} turns on. Also known as the dead time	$I_{DRIVER(RISE)}$	Controller gate drive current during turn on
$R_{DS(ON)}$	MOSFET drain-to-source resistance in the on-state	$t_{DT(F)}$	Time period between when Q_{HS} turns off and Q_{LS} turns on	$I_{DRIVER(FALL)}$	Controller gate drive current during turn off
V_{OUT}	DC Output Voltage	V_{BD_F}	Q_{LS} body diode forward voltage	Q_{GD}	MOSFET gate-to-drain charge
V_{IN}	DC Input Voltage	V_F	Power diode forward voltage	Q_{GS}	MOSFET gate-to-source charge
t_{RISE}	Duration of the turn-on transition	DCR	Inductor DC resistance	t_{DELAY}	Controller dead time delay
t_{FALL}	Duration of the turn-off transition	D	Duty Cycle		
f_{SW}	PWM Switching Frequency	$Q_{G(SW)}$	MOSFET gate charge during the switching period		

Switching Frequency (f_{SW})

Decreasing the switching frequency will decrease the losses in the MOSFETs, rectifier and the inductor core. Practical considerations usually limit the switching frequency. As the switching frequency decreases, the inductance and capacitance must increase in order to maintain an acceptable amount of inductor current ripple and output voltage ripple. As a result, the physical size of the inductors and capacitors will increase, and may not be acceptable in some applications.

At low switching frequencies, the conduction losses will dominate and little is gained by decreasing the switching frequency any further. In the majority of point-of-load applications, an acceptable lower frequency range is approximately 150 to 350 kHz.

Switching frequencies much greater than 350 kHz are possible while maintaining good efficiency as long as care is taken in selecting MOSFETs. Today's MOSFETs allow for reasonable efficiencies at switching frequencies reaching 1.5 MHz without a substantial cost penalty.

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High-Side MOSFET

Both conduction and switching losses can be significant in the high-side MOSFET. Conduction losses are proportional to the $R_{DS(ON)}$, whereas switching losses are proportional to the gate charge, Q_G, of the MOSFET. Unfortunately, for a given MOSFET fabrication process, low $R_{DS(ON)}$ devices will tend to have a higher gate charge and vice versa. Deciding which MOSFET parameter is best to optimize depends on the duty cycle and switching frequency. For low duty cycles (< 0.5), switching losses tend to dominate, especially at high frequencies. In this case, it is important to minimize the gate charge. For high duty cycles, conduction losses play a larger role, and it is important to minimize the $R_{DS(ON)}$.

Low-Side MOSFET

Unlike the high-side MOSFET, the voltage across the drain-to-source of the low-side MOSFET is much lower during turn-on and turn-off transitions due to the conduction of its body diode during the dead time. As a result, switching losses in the low side are often negligible. This is fortunate since the calculations for the low-side switching losses are much more complex (see Reference 2). It is most beneficial to select a low-side MOSFET that has the lowest achievable $R_{DS(ON)}$. Low $R_{DS(ON)}$ MOSFETs require larger die area, and as result, can be expected to be in a larger IC package and be relatively more expensive.

To ensure the contribution of the body diode is minimal, a low forward voltage Schottky diode should be placed externally across Q_{LS} or select an integrated MOSFET + Schottky device.

Power Diode

The power lost in the diode is largely determined by the forward voltage, V_F. A Schottky diode should be used whenever possible since it has a very low forward voltage (~ 0.3V) and minimal reverse recovery time.

Synchronous versus Non-Synchronous

In most applications, especially those that operate at low duty cycles and near the full load current, a synchronous buck will be more efficient than a non-synchronous buck. Non-synchronous bucks can sometimes deliver a higher efficiency when operating at lighter loads or at very high duty cycles. For more details see Reference 3.

Inductor

Inductor power losses are mainly a result of the DC resistance of the winding, DCR, and hysteresis within the core magnetic material. To decrease the DC conduction losses for a given inductance, a larger diameter wire for the coil should be used. To minimize the core losses a lower switching frequency should be selected. Both of these will result in a physically larger inductor that may be more costly but will achieve better efficiency. For more details on inductor power losses see Reference 1.

To identify an inductor with a low DCR rating, look for one with a current specification that is higher than is required for the buck design.

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Other Losses

The methods described thus far can provide large efficiency gains if appropriate design practices are utilized. There are many additional losses throughout a real switching buck converter circuit that can also be reduced with some detailed analysis. Reducing these may only provide little return; however, they should be considered if the operating conditions are atypical or to achieve maximum efficiency.

Additional Power Losses in a Buck Converter

- PCB trace copper losses
- Charging HS MOSFET's output capacitor
- Controller quiescent current
- Charging external Schottky diode's capacitance
- Gate drive losses
- Reverse recovery losses of body diode
- Input and output capacitor ESR losses

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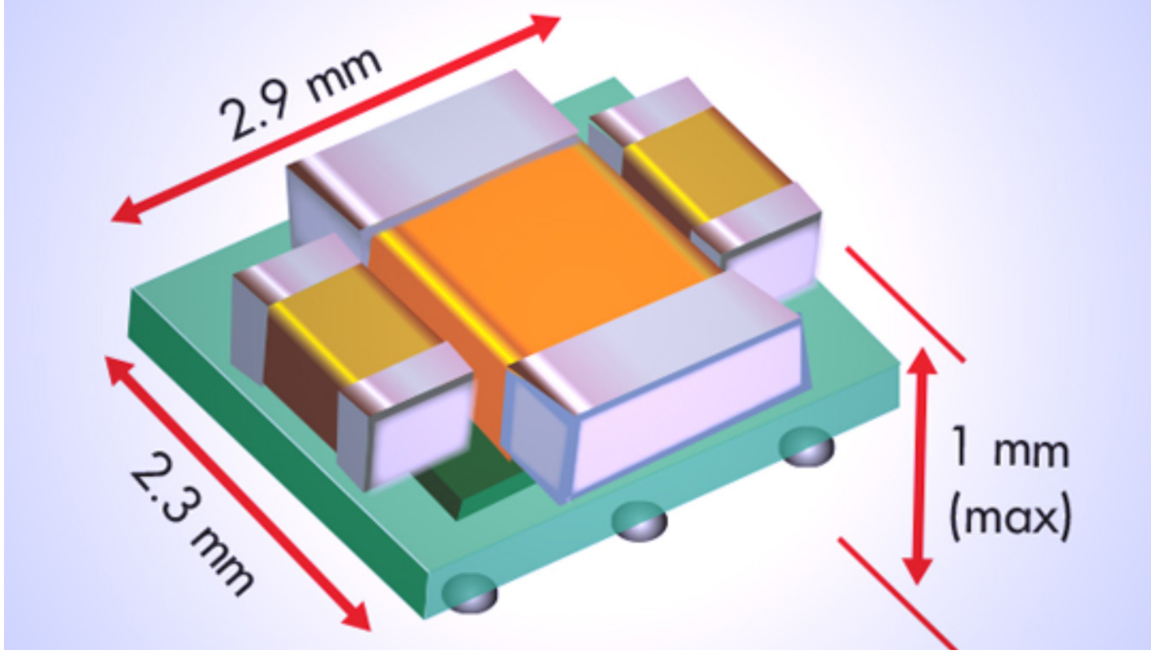

CHAPTER 4:

Deciding Between DC-DC Modules or Discretes When Facing a Space Jam

PAUL PICKERING Contributing editor

For space-constrained power-system design, one must weigh shorter design cycle and a smaller footprint versus potential performance differences and higher costs.

Two trends in electronics show no signs of abating: The shift to portable and mobile products across multiple applications; and packing more and more features into each successive generation of equipment.

For the end user, it all sounds great. For the power-system designer, though, it translates into making the most efficient use of the available power, since portable devices are typically space-constrained with no room to add extra batteries.

The drive to get the most out of ever-smaller designs has led to the dominance of power systems based on switching, rather than linear, technology. Switched-mode power supplies (SMPSs) can attain efficiencies greater than 90%. That extends battery life in portable systems and frees up space otherwise needed for heat-dissipation components. Even in line-powered equipment, switching technology rules, because greater efficiency translates into lower operating costs. Consequently, switching designs are increasingly dominating all but the lowest-cost applications.

This increased efficiency has a downside, though, in the form of more complex design. Although not taught at Hogwarts, many engineers consider SMPS design in the same category as other Dark Arts such as Poisonous Potions and Unforgivable Curses.

Switching power supplies generate noise that interferes with sensitive analog and RF circuits. Their design also requires a diverse skill set, including knowledge of analog and digital circuits, magnetics, and control systems. The complexity can be overwhelming, especially for small development teams lacking an SMPS design specialist.

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Rise of the DC-DC Power Module

Here's an ugly truth: Much as we power engineers might like to think otherwise, many system designers regard power more as a "necessary evil" than a point of product differentiation. Given the complexity of SMPS design and shrinking development cycles—another trend—it's not surprising that engineers are looking for ready-made solutions that provide efficient power without the attendant headaches.

With dc-dc modules, multiple SMPS components are integrated into a single package to simplify the design process. Thanks to improvements in semiconductor and packaging technology, such modules have become increasingly popular. Their higher levels of integration simplify the overall design and consume smaller printed-circuit-board (PCB) area than a custom design.

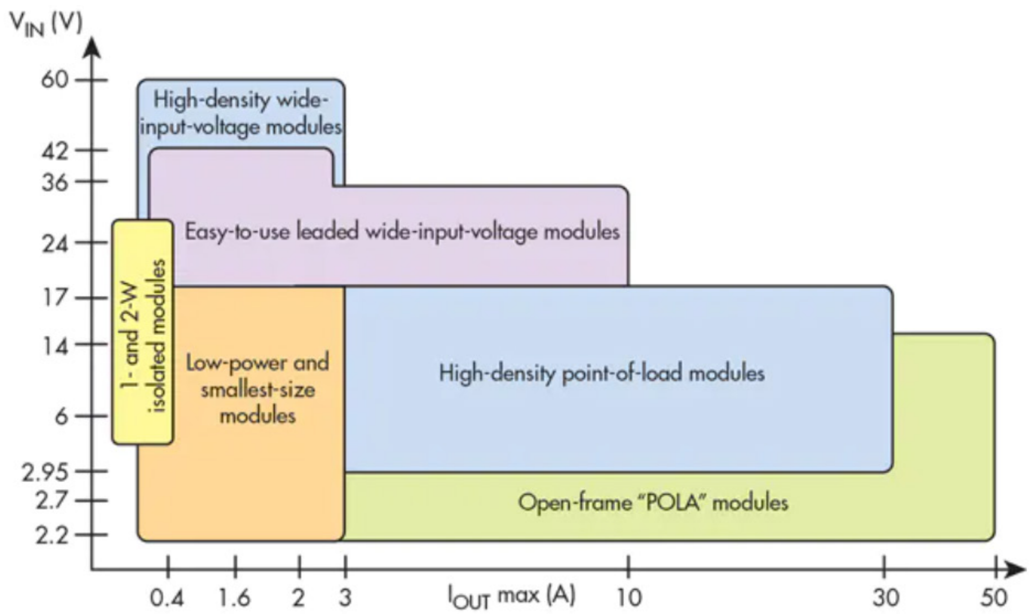
Using a module reduces the time needed for design and verification. A market report by research firm Darnell Group found that a module-based design requires 45% fewer man-hours to complete than a discrete dc-dc regulator design. The reasons include robust designs, careful component selection, and EMI testing to ensure compliance with industry standards such as the EN55022 Class B Emissions test.

In fast-moving markets like consumer electronics, such a savings in development time can easily make the difference between being early to market with a new product and missing the market window altogether. In other applications, the development team can spend that time adding or refining new features.

DC-DC Module Overview

TI offers dc-dc power modules for input voltages up to 60 V and power levels up to 50 W. Modules are primarily step-down (buck) converters, although boost, buck/boost, and negative output modules are available.

In general, these dc-dc modules don't provide galvanic isolation between input and output. However, for low-power isolated dc-dc conversion, there are standard brick modules



1. A wide range of applications can take advantage of dc-dc power modules, with a variety of technologies servicing different power levels. (Courtesy of Texas Instruments)

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up to 30 W, and the DCP and DCR families of miniature unregulated and regulated dc-dc converters come in 1- and 2-W versions.

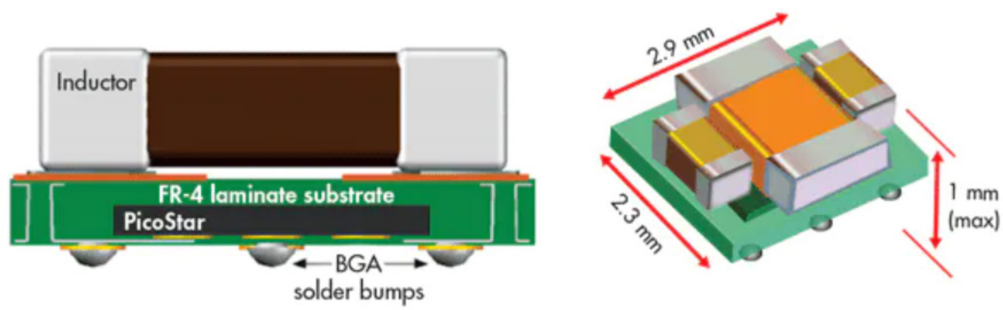
Adding a dc-dc power module isn't an "all-or-nothing" approach. Depending on the application and power level, a range of integration options is available. In fact, many of the options overlap (**Fig. 1**). Several package types are used for dc-dc modules in this power range.

MicroSiL and MicroSiP Power Modules

For low-power applications where smallest size is a priority, the MicroSiL and MicroSiP power modules integrate the required passives and the integrated circuit (IC) into a single device. In both technologies, the IC is embedded into an FR4 laminate substrate and the inductor is mounted on top of the substrate material.

A MicroSiL device integrates the power inductor and the regulator IC; the required capacitors are external. The module outline and pinout are similar to a QFN-type package. For example, the TPS82085 power module can deliver 3 A from an 8-pin package that measures 3 mm × 2.8 mm. External input and output capacitors, feedback resistors, and an optional power-good resistor complete the design. MicroSiL devices are available with inputs up to 17 V.

The fully integrated MicroSiP power modules integrate both IC and passive components into a single device with a ball-grid-array (BGA) format. The regulator is embedded inside the PCB, and the passive components are mounted on top. This is the simplest solution with the highest integration level. The smallest modules can achieve a footprint of less than 7mm2(**Fig. 2**).



2. The MicroSiP package integrates the switching regulator, inductor, input/output capacitors, and other passives; the solution is less than 1 mm high. (Courtesy of Texas Instruments)

The TPS8268x power module, for example, is a 1.6-A synchronous step-down dc-dc power supply in a single package. The five devices in this family offer output voltages from 0.9 V (TPS8268090) to 1.8 V (TPS8268180)

Another option for space-constrained applications is a Simple Switcher buck regulator integrated into a Micro-SiL module. The LMZ21700 Nano Module, for example, can drive up to 650 mA load at up to 95% efficiency with an input voltage range of 3 to 17 V and output voltage range from 0.9 to 6 V. Input and output capacitors and two feedback resistors complete the basic design.

Wide-Input-Voltage Modules

POL applications with wide input voltages up to 60 V can take advantage of Simple Switcher-based modules, which come in a variety of leaded and leadless packages. The

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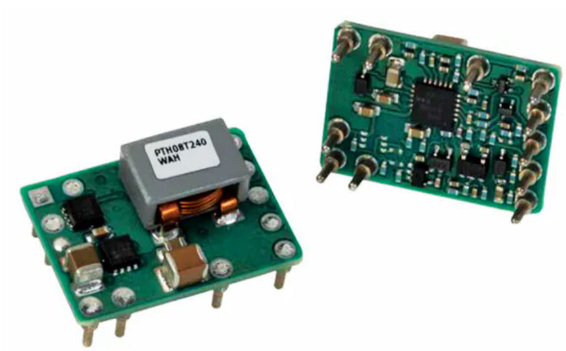
3-A LMZ23603, for example, can accept an input voltage between 6 and 36 V and deliver an adjustable output voltage as low as 0.8 V. The package for the LMZ23603 measures 10.16 mm × 9.85 mm; a complete solution requires three external capacitors and two external resistors.

High-Current DC-DC Open-Frame Modules

For higher-current applications where small size is important, designers can stay with a ready-made design by using a traditional open-frame module, such as one of TI's PTH family. The PTH08T240 (**Fig. 3**) is a non-isolated buck regulator that operates at up to 93% efficiency. It can supply up to 10 A; other PTH family members are able to supply up to 30 A.

The PTH pinouts conform to the specifications of the Point Of Load Alliance (POLA) consortium. POLA members, including Texas Instruments, offer pin-compatible, non-isolated, point-of-load plug-in power modules.

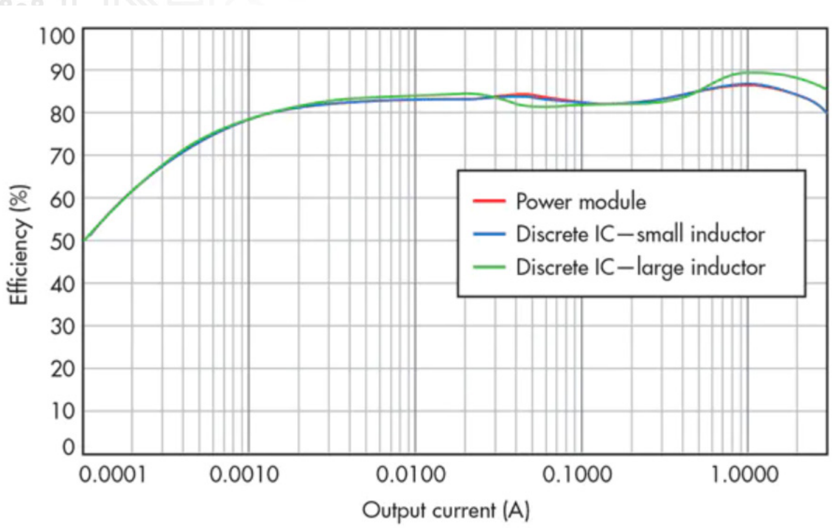


3. For higher currents, an open-frame module might be the best option for space-constrained applications. The PTH08T240 can deliver up to 10-A output current; its output is adjustable from 0.69 to 5.5 V. (Courtesy of Texas Instruments)

DC-DC Module Design Tradeoffs

There's no doubt that designers have a lot of choices when it comes to power modules—TI's SiP family includes over 200 devices. But is a dc-dc module always the best solution for every design?

Integration doesn't come for free—there are always tradeoffs to be considered. For example, a power module integrates various discrete components, so it must include a method of interconnecting them. A PCB is the preferred choice in the TPS82xxx MicroSiP family; the packages stack the inductor on top of the controller. Clearly, both of these design



4. The size of the inductor is the main cause of the performance difference between different versions of the same design. Power modules with stacked packages use smaller inductor sizes to reduce their footprint versus the equivalent discrete solution at the cost of increased height. (Image source: Electronic Design/TI)

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choices increase the height of a MicroSiP module compared to a discrete design.

Designing for minimum footprint requires reducing the inductor's size. The inductance of a coil is proportional to coil area, all other factors being equal. Reducing the coil area while keeping the same inductance increases the amount of wire used. This in turn increases the dc resistance, which lowers efficiency slightly, especially at higher loads.

Figure 4 compares the efficiencies of three different solutions based on the TPS62085 3-A synchronous step-down converter: the TPS82085 MicroSiP version; a discrete design using a small-size inductor; and a discrete design using an inductor of the same value, but in a larger size.

COMPARING MODULE AND DISCRETE DESIGN COSTS

	Efficiency at 1-A load	Efficiency at 3-A load	Solution size (mm^2)	Maximum solution height (mm)	Component count	Device cost (1 ku)	Solution cost (1 ku)
Power module	87%	81%	35	1.33	5	$2.75	$2.86
Discrete IC, small inductor	87%	81%	45	1	6	$0.95	$1.36
Discrete IC, large inductor	90%	86%	62	1.6	6	$0.95	$1.36

Comparing the costs of module and discrete designs involves more than just the components; it must also include manufacturing and design NRE costs. (Image Source: Electronic Design/TI)

Comparing the relative sizes of these three solutions shows that the MicroSiP saves 22% in board area, but increases height by 33% compared to the equivalent discrete design. Compared to the discrete design with the larger inductor, though, the board-area savings are 43%.

Efficiency is another story. The results show that with identically sized inductors, the MicroSiP and the discrete design have identical efficiencies across their range. However, the discrete design with the large inductor has an advantage at higher currents, as much as 5% at full load.

Cost is a paramount issue for many designs. The cost of an integrated dc-dc module will be higher than that of the discrete regulator because it includes the inductor and perhaps other components. To get an accurate comparison, though, other costs must be included, such as increased assembly costs, the costs associated with a larger BOM, and non-recurring items like component selection and qualification, increased design time, potential layout issues, and PCB respins.

The table summarizes the tradeoffs in cost and performance between a discrete power supply IC and a dc-dc module, without considering non-recurring costs. For this comparison, the inductor cost is estimated at $0.30, the capacitors at $0.05 each, and the resistors at $0.005 each.

Conclusion

For harried designers working within short design cycles, dc-dc modules offer several advantages in space-constrained designs, including a shorter design cycle and a smaller footprint. These advantages need to be weighed against potential performance differences and higher costs before deciding on the optimum approach for any given application.

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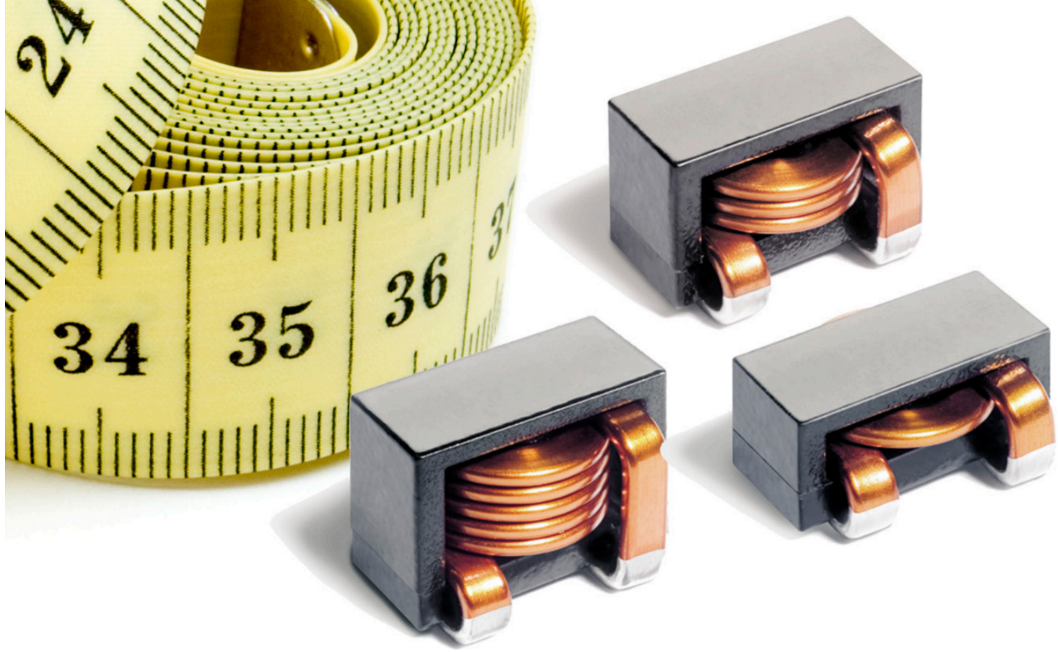

CHAPTER 5:

Selecting the Best Inductor for Your DC-DC Converter

LEONARD CRANE Coilcraft

Understanding the Data Sheet

Abstract

Proper inductor selection requires a good understanding of inductor performance and of how desired in-circuit performance relates to the information available in sup- plier data sheets. This article walks both the experienced power conversion specialist and nonspecialist through the inductor catalog and the important specifications.

Introduction

The use of dc-dc converters is increasing. As electronic systems become more miniaturized, mobile, complicated, and popular, the power requirements become more varied. Available battery voltages, required operating voltages, size, and shape requirements are ever chang- ing, leaving equipment designers constantly in need of new power conversion solutions. As product require- ments constantly drive performance improvement and size reduction, optimization is crucial. A "one size fits all" approach to power conversion does not fit all applica- tions. For example, low profile components as shown in **Figure 1** are much in demand.

Not only is the market for purchased converters growing, but also many circuit designers now design their own

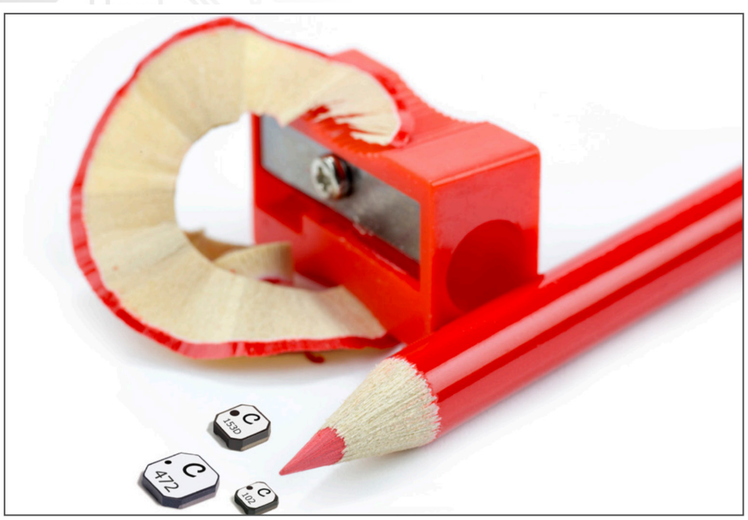

Figure 1. Thin Inductor Shapes Allow Low Profile Converter Design

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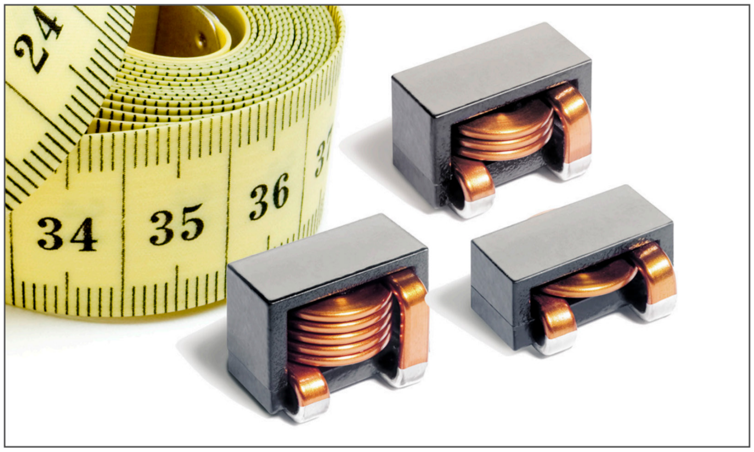

Figure 2. E-Core Inductor with Flat Wire

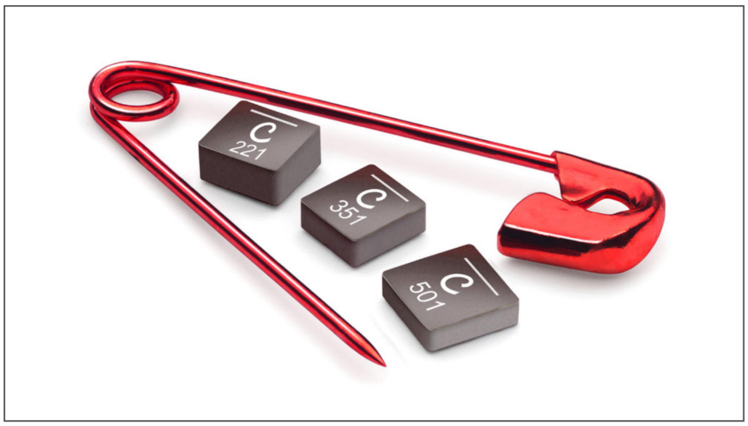

Figure 3. Molded inductors are mechanically rugged and magnetically shielded for use in high density circuits

dc-dc conversion circuits instead of relying on power supply specialist companies. This increases the number of circuit designers involved in selecting components. Basic dc-dc conversion circuitry is fairly mature technology and continues to evolve rather slowly. Because of this it has become quite practical and useful for authors to create "cookbook" design aids by which equipment designers can create their own converter design. Software is also readily available to facilitate these designs[1].

After deciding on a circuit topology, one of the key design tasks is component selection. Many circuit design pro- grams produce a list of the required component values. The task for the designer then is to get from knowing the desired inductance value to selecting an available component to do the job. Inductors that can be used in dc-dc converters come in a wide variety of shapes and sizes. **Figures 2 and 3** show just two of the possible inductor shapes. In order to compare types and choose the optimal part for the application, a designer must rely on correctly understanding published specifications.

DC-DC Converter Requirements

Simply stated, the function of a dc-dc converter is to provide a stable dc output voltage from a given input voltage. The converter is typically required to regulate the dc output voltage given a range of load currents drawn and/or range of input voltage applied. Ideally the dc output is to be "clean", that is with ripple current or voltage held below a specified level. Furthermore, the load power is to be delivered from the source with some specified level of efficiency. Power inductor selection is an important step to achieving these goals.

Table 1. Typical Inductor Catalog Excerpt[2]

Part number	L ±20%[a] (µH)	DCR max (mOhms)	SRF typ (MHz)	Isat[b] (A)	Irms[c] (A)
XAL4020-102	1.0	14.6	79	8.7	9.6
a. Inductance tested at 1 MHz, 0.1 Vrms					
b. Inductance drop = 30% typ. at Isat					
c. For 40° C temperature rise typ. at Irms					
d. All parameters tested at 25° C.					

Power Inductor Parameters

Inductor performance can be described by a relatively few numbers. **Table 1** shows a typical data sheet excerpt for a surface mount power inductor intended for dc-dc converters.

To use the ratings properly, one must understand how they were derived. Since it is not practical for a data sheet to show performance for all possible sets of operating conditions, it is important to have some understanding of how the ratings would change with different operating conditions.

Inductance (L)

Inductance is the main parameter that provides the desired circuit function and is the first parameter to be calculated in most design procedures. Inductance is calculated to provide

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DEFINITIONS

L – Inductance The primary functional parameter of an inductor. This is the value that is calculated by converter design equations to determine the inductors ability to handle the desired output power and control ripple current.·

DCR – DC Resistance The resistance in a compo- nent due to the length and diameter of the winding wire used.

SRF – Self Resonant Frequency The frequency at which the inductance of an inductor winding resonates naturally with the distributed capacitance characteristic of that winding.

Isat – Saturation Current The amount of current flowing through an inductor that causes the induc- tance to drop due to core saturation.·

Irms – RMS Current The amount of continuous current flowing through an inductor that causes the maximum allowable temperature rise.

a certain minimum amount of energy storage (or volt-microsecond capacity) and to reduce output current ripple. Using less than the cal- cu- lated inductance causes increased ac rip- ple on the dc output. Using much greater or much less inductance may force the converter to change between continuous and discontin- uous modes of operation.

Tolerance

Fortunately most dc-dc converter applica- tions do not require extremely tight tolerance inductors to achieve these goals. It is, as with most components, cost effective to choose standard tolerance parts and most converter requirements allow this. The inductor in Table 1 is shown specified at ±20% which is suitable for most converter applications.

Test Conditions

■ **Voltage**. The inductance value rating should note the applied frequency and test volt- age. Most catalog inductance ratings are based on "small" sinusoidal voltages. This is the easiest and most repeatable method for the inductor supplier, and suitably indi- cates the inductance for most applications.

■ **Wave shape**. The use of sinusoidal voltage is a stan- dard instrumentation test con- dition, which usually serves quite well to ensure that the inductance value calculated from the design equations is delivered.

■ **Test Frequency.** Most power inductors do not vary dramatically between 20 kHz and 500 kHz so a rating based on 100 kHz is quite often used and suitable. It must be remem- bered that inductance eventually decreases as frequency increases. This can be due to the frequency roll off characteristic of the core material used or it may be due to the self- res- onance of the winding inductance resonating with its self capacitance. As most converters operate in the 50 kHz to 500 kHz range, 100 kHz has been a suitable standard test fre- quency. As switching fre- quencies increase to 500 kHz, 1 MHz, and above, it will be more important to consider ratings based on the actual application frequency.

Resistance

DC Resistance (DCR)

DCR is simply a measure of the wire used in the induc- tor. It is based strictly on the wire diameter and length. Normally this is specified as a "max" in the catalog but can also be specified as a nominal with a tolerance. This second method can be a little more instructive by giving a better indication of the nominal or expected resistance, but also may unneces- sarily tighten the specification as almost always no harm is done by a part having too little resistance.

DCR varies with temperature in the same manner as the resistivity of the winding ma- terial, typically copper. It is important that the DCR rating makes note of the ambient test

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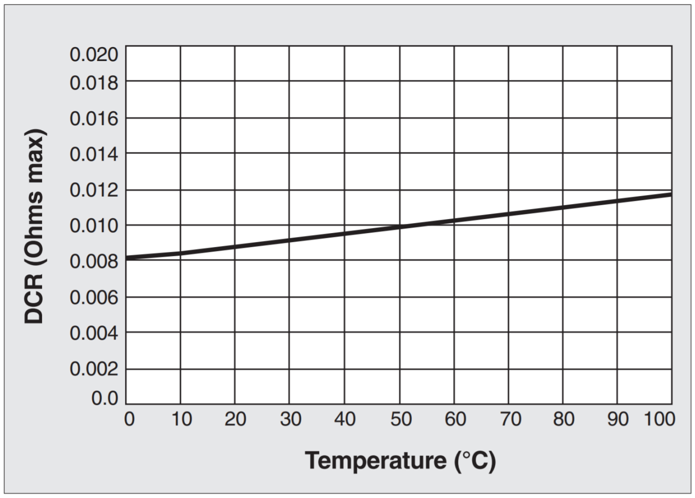

Figure 4. Expected DCR Based on 0.009q Max at 25°C.

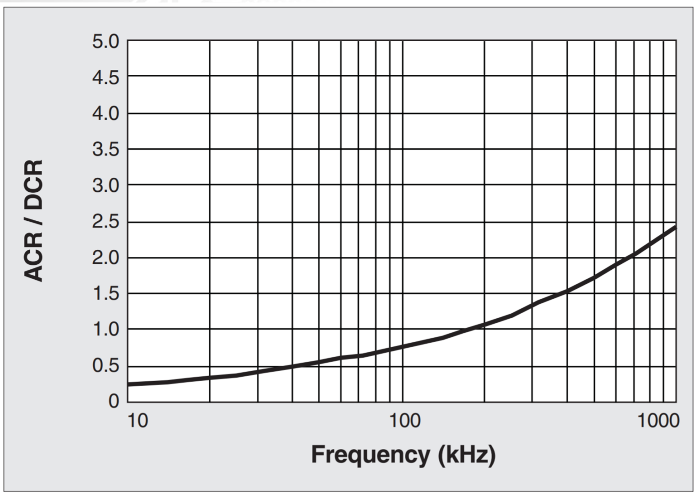

Figure 5. ACR/DCR for #22 AWG Round Copper Wire

temperature. The temperature coefficient of resistance for copper is approximately +0.4% per degree C[3]. So the part shown rated at 0.009 Ohms max would have to have a corresponding rating of 0.011 Ohms max at 85°C, only a 2 milliOhm difference in this case, but a total change of about 25%. The expected DCR versus temperature is shown in **Figure 4**.

AC Resistance

This is a parameter that is not commonly shown on inductor data sheets and is not typically a concern unless either the operating frequency or the ac component of the current is large with respect to the dc component.

The resistance of most inductor windings increases with operating frequency due to skin effect. If the ac or ripple current is relatively small compared to the average or dc current then the DCR gives a good measure of the resistive loss to be expected. The skin effect varies with wire diameter and frequency[3], so to include this data would require a full frequency curve for each inductor listed in a catalog.

This has not been necessary for most applications working below 500 kHz. As can be seen from **Figure 5** the ac resistance does not become comparable to the dc resistance at frequencies below about 200 kHz. And even above that frequency the ac resistance will not be an issue if the ac current is not large compared to the dc component. Nevertheless at frequencies above 200-300 kHz it is recommended to ask the supplier for loss versus frequency information to supplement the published information.

The designer should try to choose the component that has the largest possible resistance if the size of the com- ponent is to be minimized. Typically to reduce the DCR means having to use larger wire and probably a larger overall size. So optimizing the DCR selection means a tradeoff of power efficiency, allowable voltage drop across the component, and component size.

Self Resonant Frequency (SRF)

Every inductor winding has some associated distributed capacitance which, along with the inductance forms a parallel resonant tank circuit with a natural self-resonant frequency. For most converters it is best to operate the inductors at frequencies well below the SRF. This is usually shown in the inductor data as a “typical” value.

Current Rating

Current Rating is perhaps the rating that causes the most difficulty when specifying a power inductor. Current through a dc-dc converter inductor is always changing throughout the switching cycle and may change from cycle to cycle depending on converter operation, includ- ing temporary transients or spikes due to abrupt load or line changes. This gives a

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constantly changing current value with sometime a very high peak-to-average ratio. It is the peak-to-average ratio that makes specification difficult. If one takes the highest possible instantaneous peak current and looks for an inductor with this "current rating" the inductor is likely to be overkill for the applica- tion, yet if one looks for a current rating for the average current, the inductor may not perform well when passing the peak current. The way to address this problem is to look for an inductor that has two current ratings, one to deal with possible core saturation from the peak current and one to address the heating that can occur due to the average current.

Saturation Current

One effect of current through an inductor is core saturation. Frequently dc-dc converters have current wave shapes with a dc component. The dc current through an inductor biases the core and can cause it to become saturated with magnetic flux. The designer needs to understand that when this occurs the inductance drops and the component no longer functions as an inductor. **Figure 6** shows a typical L vs current curve for a gapped ferrite core. It can be seen that this curve has a "knee" as the inductor moves into the saturation region. Defini- tion of where saturation begins is therefore somewhat arbitrary and must be defined. In the example of Table 1, saturation is defined at the point at which the inductance drops by 10%. Definitions in the range of 10-20% are common, but it should be noted some inductor catalogs may use figures of 50% inductance drop. This increases the current rating but may be misleading as far as the usable range of current is concerned.

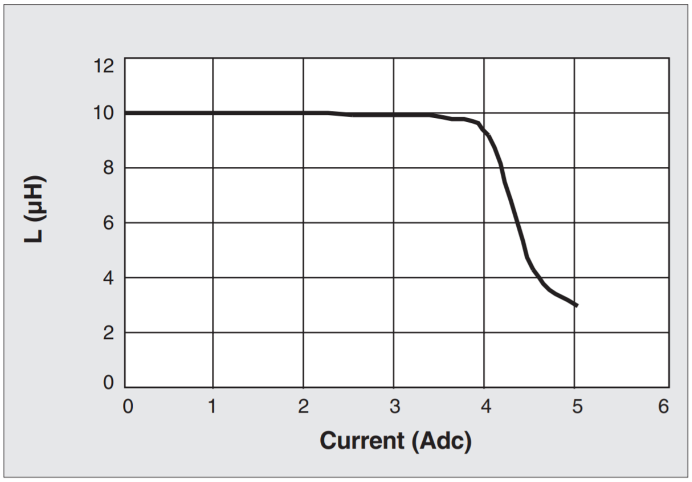

Figure 6. L vs DC Bias Current for Coilcraft DO3316P-103

Inductor core saturation can often be observed directly in the converter current waveform where di/dt is inversely proportional to inductance. As inductance drops due to core saturation, the current slope increase rapidly. This can cause noise and damage to other components.

If the inductor is operated at currents only slightly exceeding the saturation current rating, however, the problem may not be so dramatic. In many cases a slight rise in the slope of the current waveform is acceptable. Despite the potential pitfalls, it is typically desirable to operate with current peaks near the saturation rating because this allows the smallest possible inductor to be chosen. Increasing the saturation current rating typically means using a larger size component or selecting a smaller inductance value in the same size.

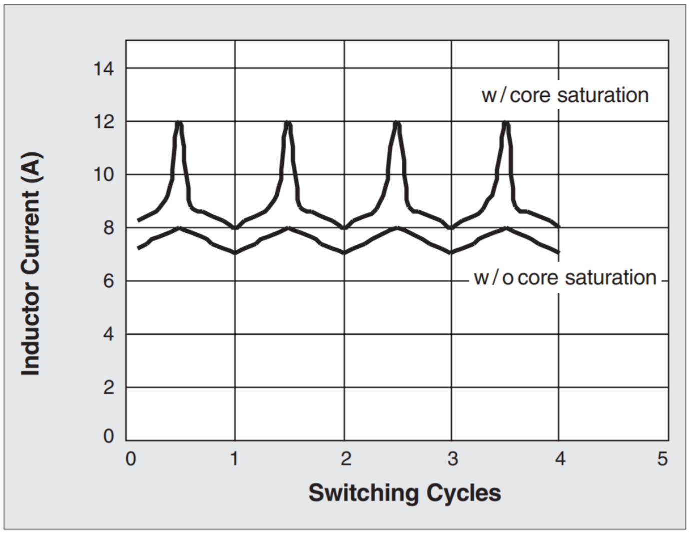

Figure 7. Inductor Current Waveform With and Without Core Saturation.

RMS Current

The second major effect of current is component self- heating. The RMS current is used to give a measure of how much average current can continuously flow through the part while producing less than some speci- fied temperature rise. In this case the data sheets almost always provide a rating based on

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Table 2. Summary of Important Inductor Ratings

Parameter	Rating Should Include
Inductance	• Nominal value • Tolerance • Test frequency • Test voltage • Ambient test temperature
DCR: The wire resistance.	• Nominal with tolerance or max value • Ambient test temperature
SRF: The frequency at which the winding self capacitance resonates with the inductance.	• Typical or nominal value
Isat: The current at which inductance drops due to core saturation.	• Minimum or typical value. • Definition of saturation.
Irms: The current which causes a specified amount of temperature rise.	• Minimum value. • Ambient test temperature.

application of dc or low frequency ac current, so this does not include heating that may occur due to skin effect as mentioned earlier or other high frequency effects. The current rating may be shown for a single temperature rise point as in the example, or some suppliers provide helpful graphs of temperature rise versus current or factors that can be used to calculate temperature rise for any current.

The Irms rating should include the ambient temperature at which it was measured. Normally an inductor speci- fication includes an operating temperature range. This is the range of ambient temperature environment within which the inductor is expected to be used. Temperature rise due to self heating may cause the inductor to be at a temperature higher than the rated range. This is nor- mally acceptable provided the insulation ratings are not exceeded. Most inductors presently use at least 130°C or 150°C insulation types.

As with other parameters it is important to know the inductor temperature rise so this can be traded off with other parameters when making design choices. If lower temperature rise is desired, a larger size component is most likely the answer.

Conclusion

It can be seen that inductors for dc-dc converters can be described by a small number of parameters. However each rating may be thought of as a “snapshot” based on one set of operating conditions which may need to be augmented to completely describe expected perfor- mance in application conditions. Table 2 summarizes the ratings that should appear in a power inductor data sheet.

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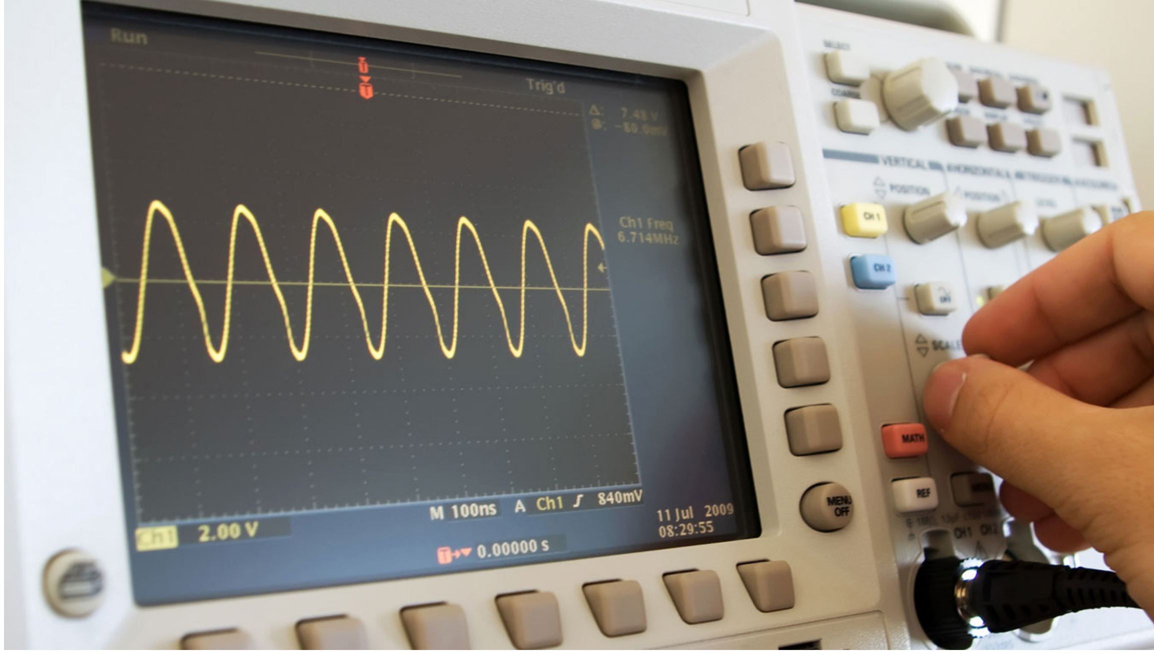

CHAPTER 6:

Performing In-Circuit Inductor and Transformer Measurements in SMPS

WILSON LEE Technical Marketing Manager at Tektronix

Inductors and transformers serve key roles in switch-mode power supplies. Ensuring they perform as expected requires thorough in-circuit measurements performed under operating conditions. Here's what you need to know.

In switched-mode power supplies (SMPS), magnetic components, namely inductors and transformers, play critical roles. Much of the SMPS design process relies on component specifications and simulation models. However, due to actual signal conditions, parasitics, temperature, and other environmental factors affecting magnetic components' performance, a power supply may not perform exactly as predicted by specs and simulations. As a result, in-circuit measurements of inductors and transformers under operating conditions are critical to ensuring reliable real-world performance.

With the right tools on hand, making these measurements doesn't have to be difficult or time-consuming. We'll first review the basic theory of inductors and transformers, especially as it relates to in-circuit measurements. We'll then walk through the use of oscilloscope and probes during power-supply operation, and explore the use of induction measurements and B-H curves to gain performance insight.

Inductor Theory

Faraday's and Lentz's laws tell us that the current through an inductor and the voltage across the inductor are related as:

$$v = -L\frac{di}{dt}$$

This shows that inductance can be thought of as the extent to which a changing current results in an opposing voltage. By integrating, rearranging, and ignoring the sign, we can get:

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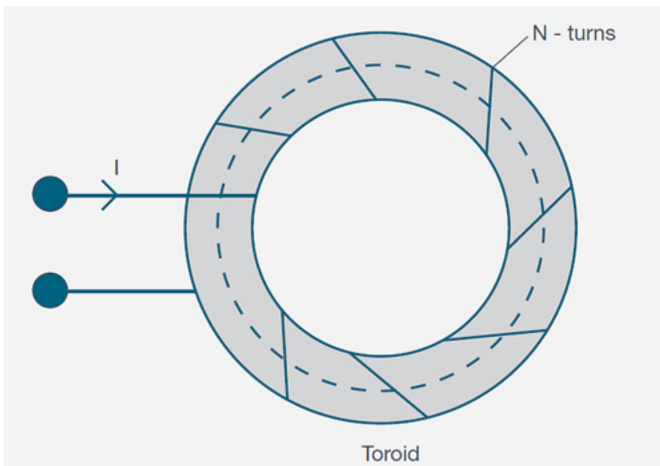
$$L = \frac{\int vdt}{i}$$

This reveals that inductance may be determined as a function of voltage and current over time. Such a time-domain measurement is best accomplished using an oscilloscope equipped with a voltage probe, current probe, and the ability to perform integration and plot X versus Y.

In contrast to a theoretical inductor, the inductance value of a real inductor depends on current levels, temperature, and frequency of operation. In a power supply, these characteristics vary in real time with operating conditions.



1. A basic inductor is a coil wound on a closed ferromagnetic core. Current of I amperes flows through the coil, which has N turns. The inductance of the coil describes the relationship between the current flowing in the coil and the magnetic flux.

As an example, the inductance of the toroid in Figure 1 may be approximated by:

$$L \approx \frac{\mu N^2 A}{2\pi r}$$

where μ is magnetic permeability of the core; N is the number of turns of wire on the toroid; r is the radius of the core from the dashed center-line in cm; and A is the cross-sectional area of the core in cm^2 (assumed to be small relative to the radius of the toroid).

Since this number of turns is squared, it's the biggest contributor to inductance. Furthermore, the permeability of the core material plays a significant role. However, the value of the inductance is also related to the physical size of the component. To minimize the size of the inductor, most inductors in electronics use core materials that have a much higher permeability than air.

In short, the characteristics of the core material and geometry are critical in determining inductance over various operating conditions, as well as power loss in the device.

Inductance Measurements

Power-supply designers typically use simulation techniques to determine the appropriate inductor value for a design. After manufacturing the inductor, a common practice is to verify the inductance using an LCR meter. However, most LCR meters stimulate the component with sinusoids over a narrow frequency range, so while this is a good technique for con-

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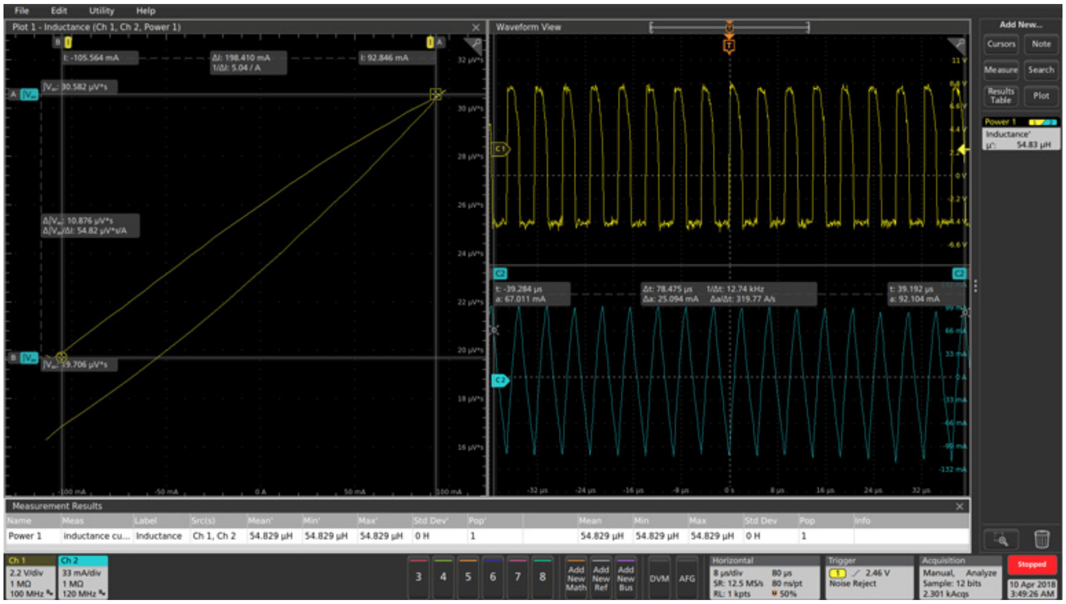
firming that the component is roughly the correct value, it's a poor predicter of in-circuit performance.

The inductance characteristics of an inductor depend on the current and voltage source excitation signal, wave shape, and frequency of operation, which may vary in real-time operating conditions. Therefore, it's important to measure and observe the behavior of an inductor in the dynamically changing environment of the power supply.

These measurements are made by probing the voltage across the device, usually with a differential voltage probe. A current probe is typically used to measure the current through the magnetic component. To determine inductance, scope-based power-analysis software integrates the voltage over time and divides by the change in current. It also removes any dc offset and uses averaging to calculate the inductance value.

When measuring a transformer's inductance, it's important to avoid loading the secondary winding. Measuring inductance at the primary winding under a no-load condition is equivalent to measuring the inductance for a single-winding inductor. When you're measuring the inductance of the coupled inductor with multiple windings on the same core, the measured value of the inductance will deviate from the actual value, due to the influence of the current on the other winding(s).



2. Average inductance value in henries.

In **Figure 2**, the inductance measurement gives the average inductance value in henries. The yellow waveform (CH1) is the voltage across the inductor and the blue waveform (CH2) is the current through the inductor. The plot on the left shows current, i versus ∫vdt, the slope of which is inductance.

Figure 3 shows the I vs. ∫V measurement, which provides additional insight on inductor performance. Here you can see any dc bias as it builds up over multiple cycles. The yellow waveform (CH1) is the voltage across the inductor and the blue waveform (CH2) is the current through the inductor.

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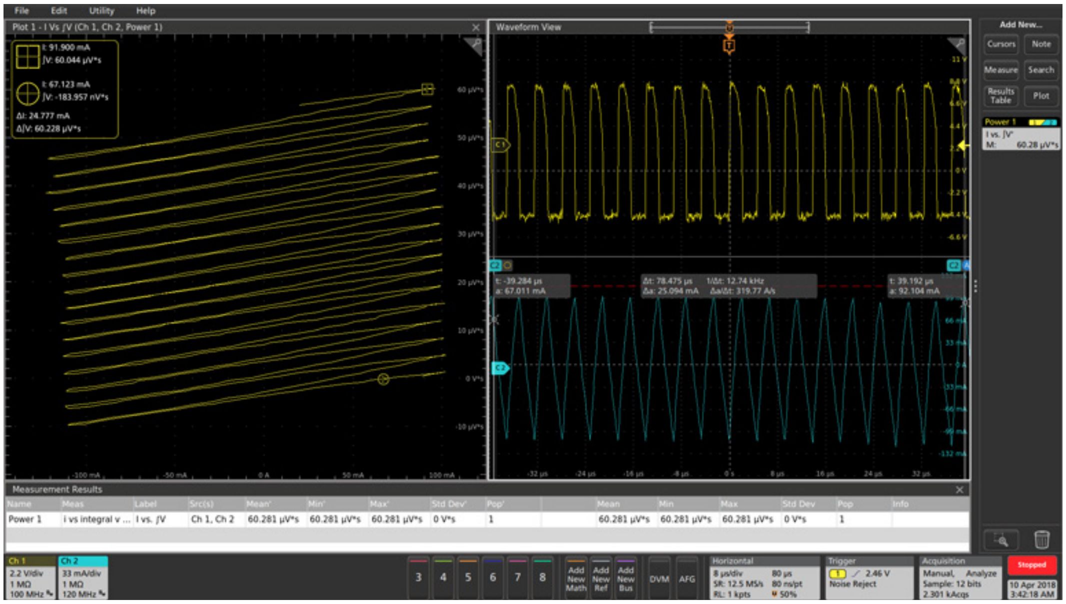
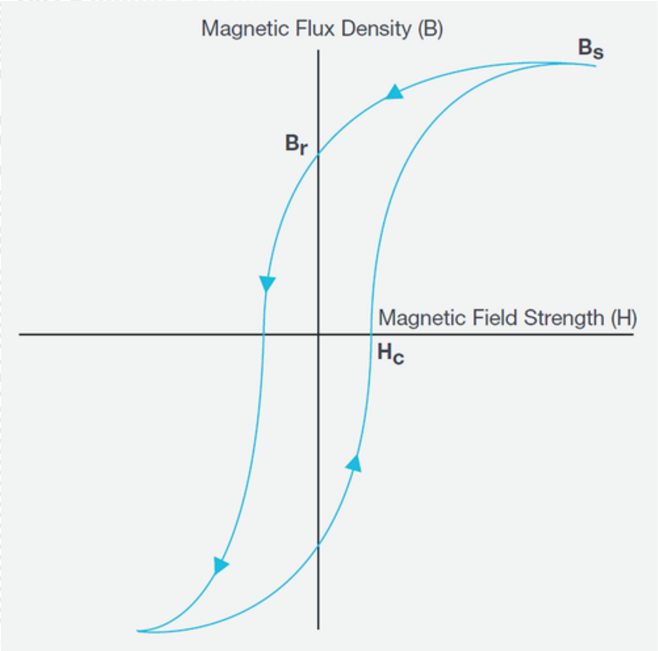


B-H Curve Measurements

Magnetic power-supply components are designed for expected operating voltage, current, topology, and the particular type of power converter. The operating regions of inductors and transformers help determine the stability of a SMPS. However, power-supply operating characteristics can vary during power-on, steady-state operation, load changes, and environmental changes, making it extremely difficult to consider all possible scenarios during the design process.



4. Manufacturers of core material may provide such a hysteresis curve as part of their specifications.

To ensure the stability of the power supply, it's important to characterize the operating region of a magnetic component in the SMPS. Generally, the goal is to avoid saturation and operate in the linear region of the hysteresis curve. However, it's extremely difficult to design a magnetic component and ensure that it will operate in a linear region under all conditions.

B-H curves like the one shown in **Figure 4** help designers visualize the performance of an inductor and its core. In this example, H, measured in A/m, is the magnetizing force in the device. It's measured in amperes/meter and is proportional to the current:

The resulting flux density, B, is proportional to the integral of the voltage across the device. Magnetic flux density B, measured in units of Tesla, is the strength of the magnetic field. It determines the force that's exerted upon a moving charge by the magnetic field.

$$H = \frac{iN}{l}$$

- *Permeability, μ*. Measured in H/m. This is a characteristic of the core material, and it's the rate at which magnetizing force H (driven by current) produces flux density B (integrated

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voltage). It's the slope of the B-H curve. Designers use high-permeability material to enable physically smaller inductors and transformers.

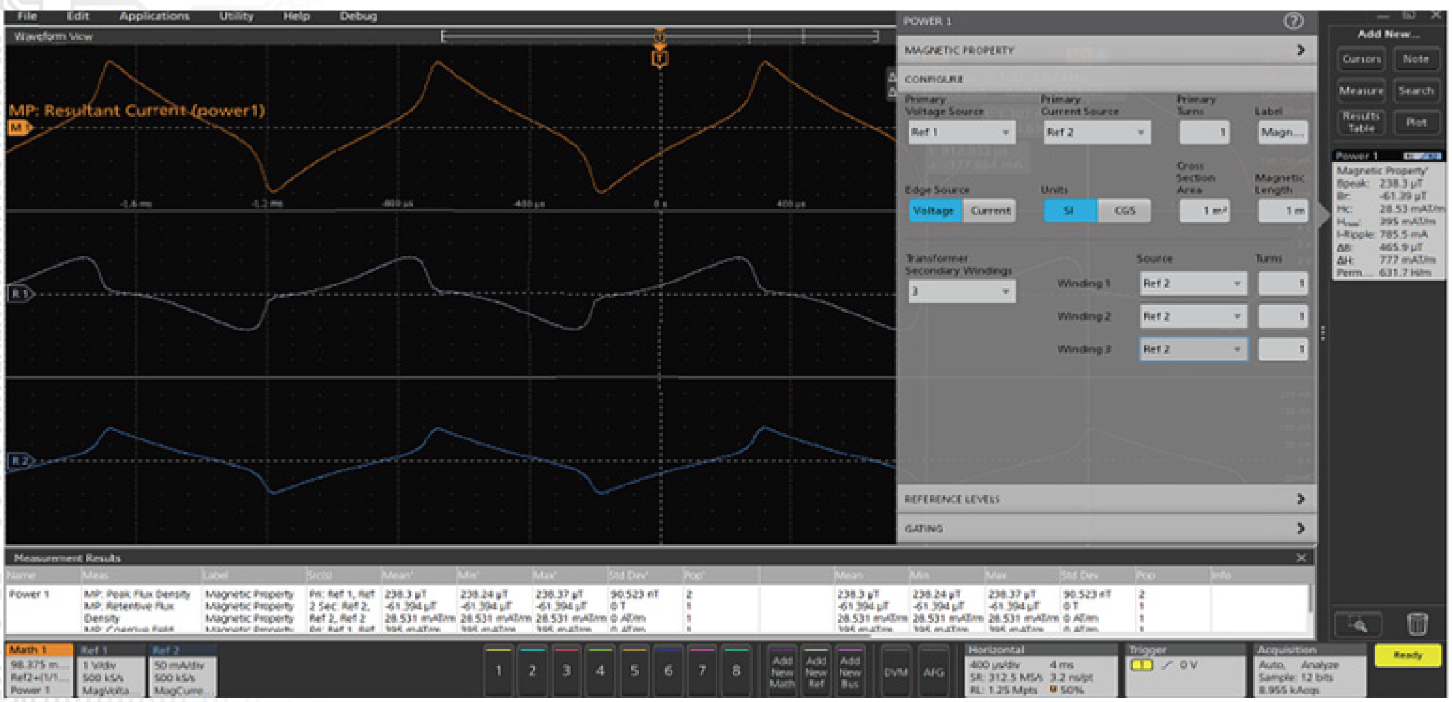
- *Saturation flux density.* The point at which additional magnetizing force, H, stops producing incremental flux density, B. Designers avoid saturation in most power-supply applications.
- *Hysteresis characteristics.* Hysteresis is the "width" of the curve and indicates loss in power supplies. Most designs seek to use magnetically "soft" core materials to minimize Remanence Br, the magnetic flux density that remains in the material after the magnetizing force, H, drops to zero and coercive force, or coercivity c, the value of H required to drive the flux density, B, to zero.

Indications of potential instability include:

- Measured peak flux density close to the saturation flux density specified by the core datasheet indicates that the component is getting close to the saturation.
- BH curves that change from cycle to cycle, indicating saturation. In a stable/efficient power supply, the BH curve will have a symmetrical return path and will trace this path consistently.

An oscilloscope can be used to perform an in-circuit measurement of voltage across, and current through, the winding of an inductor. Given the number of turns in the device, the magnetic length of the device, and the cross-sectional area of the core, it's possible to derive the actual B and H values based on real- time voltage and current measurements using an oscilloscope.

To generate a B-H plot, you need to measure the voltage across the magnetic element and the current flowing through it. In the case of a transformer, the currents through the



5. This shows magnetic measurements on multiple secondary winding transformers.

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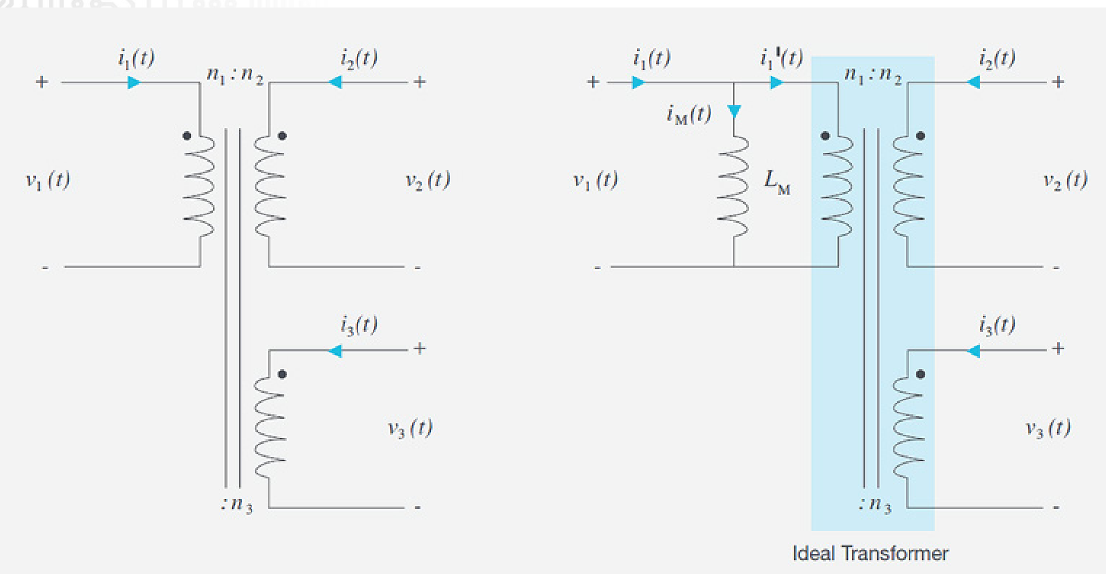
primary as well as secondary windings are of interest. A high-voltage differential probe is connected across the inductor or primary winding of the transformer. A current probe measures the current through the inductor or primary. Current probes are also used to measure the current through the secondary windings, if needed.

Figure 5 shows the magnetic measurements on a multi secondary winding transformer. The Ref1 (white) waveform is the voltage across the inductor and the Ref 2 (blue) waveform is the inductor current. In this case, the math wfm (orange), which is the resultant current wfm, shows up because the scope was set up to test multiple secondary windings.

B-H Curves for Transformers

To measure the magnetic characteristics of a transformer under operating conditions, care must be taken to account for current being transferred into the secondary. When measuring the B-H curve on a transformer, it's helpful to consider a theoretical element call the "magnetizing inductor."

The magnetizing current is the current that would flow through the primary of the transformer when the secondary is open (unloaded). In other words, the magnetizing current doesn't produce any current in the secondary. As shown in **Figure 6,** transformers are modeled with this magnetizing current flowing through a "magnetizing inductor" across the primary. Generally, this is used to model the magnetization characteristics of the core material.



6. In this transformer schematic (left) and equivalent circuit (right), the magnetizing current is flowing through an imaginary inductor, LM, in parallel with the primary. LM models the magnetic characteristics of the transformer.

Loss Analysis

Losses in magnetic components are significant contributors to overall loss in a power supply. Core loss depends on the magnetic properties of the material and includes hysteresis loss and eddy current loss. Copper loss results from the resistance of the windings; it also depends on the load connected to the secondary side of a transformer.

A number of techniques are used to estimate core loss. One more popular technique is the Steinmetz empirical formula, which relates core loss to frequency and flux density:

$$P_{Core} = kf^aB^b$$

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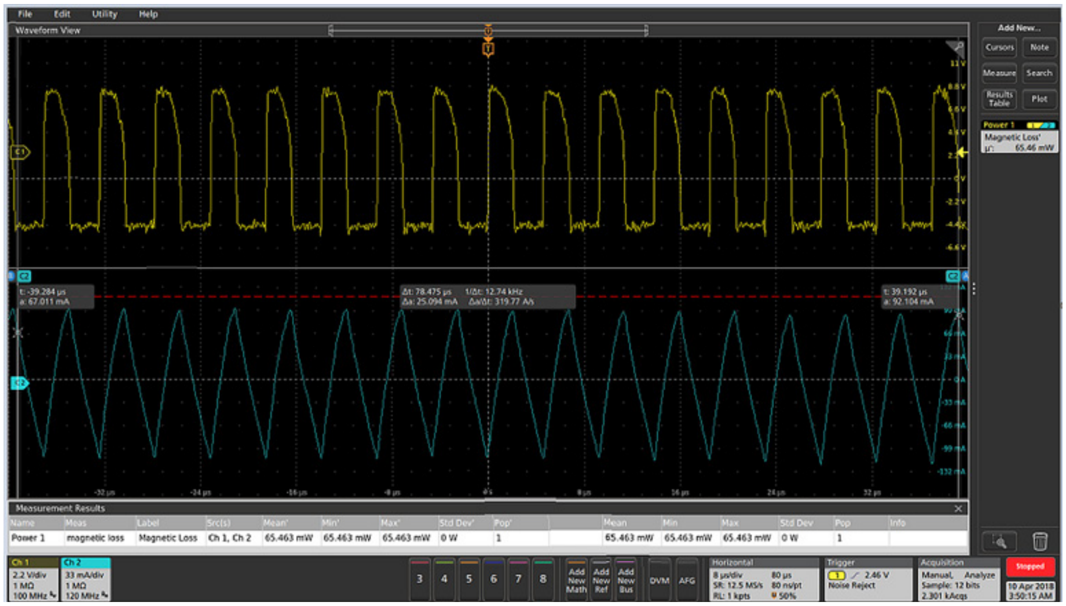
where k, a, and b are constants for the core material, generally taken from the core manufacturer's datasheet. Datasheets may also give loss estimates at various frequencies and flux densities that are typically given in response to sinusoidal excitation. However, in power applications, components are usually driven with non-sinusoidal stimuli, causing uncertainty in such approximations (**Fig. 7**).



7. Example of a total magnetic loss measurement.

Scope software can be used to compute total magnetic loss by averaging power of voltage and current waveforms, average (v(t) · i(t)). With this method, the total magnetic loss includes both copper loss and core loss. This is shown Fig. 7, where the magnetic loss measurement gives the total magnetic loss, including core and copper loss. You can find the core loss from the component manufacturer's datasheet and derive the copper loss by subtracting the core loss from the total magnetic loss.

Scopes are capable of calculating the magnetic loss in a single winding inductor, a multiple winding inductor, or even a transformer. In the case of a single-winding transformer, a differential probe is connected to measure the voltage across the primary winding. A current probe measures the current through the transformer. The power-measurement software can then automatically calculate the magnetic power loss.

Inductors and transformers serve key roles in switch-mode power supplies, including filters, step-up/step-down, isolation, energy storage, and oscillation. Ensuring they perform as expected requires thorough in-circuit measurements performed under operating conditions. As we've discussed, modern oscilloscopes equipped with power-analysis software offer fast setups and improved repeatability.

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