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RAQ Issue 220: Analysis of Switch-Mode Power Supply and Rectification: Inductor Violations

Abe Ibraheim, Central Applications Intern,
Kenneth Armijo, Central Applications Engineer, and
Piyu Dhaker, Staff Engineer

Question

Why is my power supply making a ringing sound and overheating?

Answer

Improper inductor sizing and violation of the inductor saturation current rating can cause a wide variety of issues within DC-to-DC converters, two of which are audible ringing and overheating.

Abstract

This article is the first in a series where common switch-mode power supply (SMPS) design errors will be discussed as well as their appropriate rectification. It aims to address complications that arise with the power stage design of DC-to-DC switching regulators, focusing on the inductor. Designers opt for inductor values outside the recommended range for various advantages, such as smaller output ripples and minimizing the solution's footprint. However, selecting components with values that are too big or too small will result in unintended consequences that can lead to serious damage to the chip as well as decreased efficiency. This article will also examine what happens when proper care is not taken to ensure the load current does not exceed the maximum saturation rating of the inductor.

What Is A Switch-Mode Power Supply

An SMPS is a highly efficient regulator that either steps down an input voltage (buck converter), steps up an input voltage (boost converter), or can do both (buck-boost converter). Basic switching converter topologies can be seen in Figure 1.

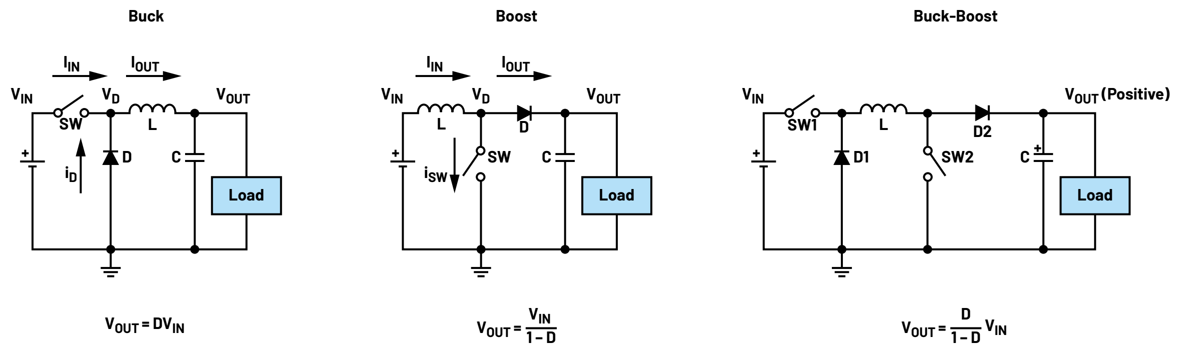

Figure 1. Common SMPS topologies and their output formulas.

Every SMPS works by storing energy in an inductor and utilizing pulse width modulation (PWM) techniques to obtain the desired output. The guiding principle of these converters is the volt second balance law, which dictates that when operating in a steady state, over one period the average current of an inductor must be zero. This means that the inductor must discharge all the current it stored in the charging stage before another period begins.

Operation of Buck Converters

This article uses only buck converters to demonstrate common design errors. Four components make up the power stage of a buck converter: the inductor, the output capacitor, the top FET as represented by a switch, and the bottom FET, which is represented by a diode (see Figure 2).

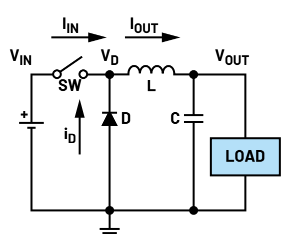

Figure 2. Simplified buck converter power stage.

The voltage across the inductor is given by: $V_L = L\ di_L/dt$. This voltage is the difference of the switch node from the output voltage. When the top FET is on, V_L is the difference between the input voltage and the output voltage. When the top FET is off, the difference is 0 V minus the output because the switch node is grounded. di_L/dt (or Δi_L) is the change in inductor current over time, commonly referred to as the inductor current ripple. When the top FET is closed (and the bottom FET is open), the inductor stores energy in the form of magnetic flux as the current through the inductor increases. When the top FET is open and the magnetic field collapses, a path to ground is formed by the bottom FET, allowing current to still flow to the load as it decreases. This can be seen in the inductor current waveform shown in Figure 3. The output capacitor is used to smooth out the output ripple and help maintain the desired output voltage. The output voltage of a buck converter is given by $V_{OUT} = DV_{IN}$, where D is the duty cycle and is defined as the percentage of the time out of the total period where the top FET is on and charging the inductor.

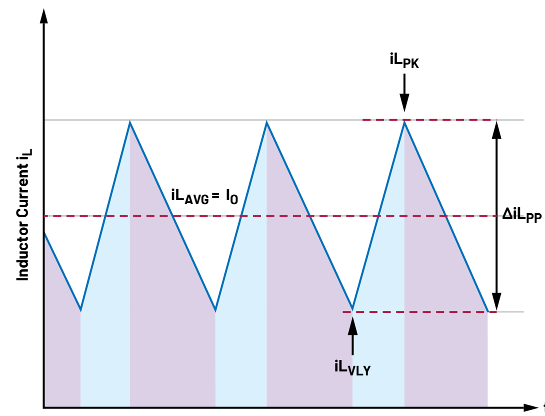

Figure 3. Inductor current waveform. The current through the inductor charges when the top FET is on and discharges when the top FET is off.

Recommended Inductor Sizing

When designing an SMPS, the right inductor value must be chosen to ensure an acceptable inductor current ripple (Δi_L). It is recommended that the inductor ripple should be between 30% and 40% of the applied load current for buck converters. This range is considered to be optimal as it is big enough to capture and deliver an accurate signal to the current-mode control feedback system, but not too big that the power supply goes into discontinuous conduction mode (DCM). DCM is a state where the current ripple is too large, forcing the current to go below 0 A to maintain the load current at the desired value. However, once hitting 0 A, the diode inside the FETS no longer conducts, keeping the current from decreasing below 0 A. A general way to select the correct inductor can be obtained by the formula:

$$L = \frac{V_{OUT} \times (V_{OUT} - V_{\text{IN}})}{\Delta i_L \times f_{Switching} \times V_{\text{IN}}} \quad (1)$$

This formula shows that switching frequency and inductance are inversely proportional, meaning with higher frequencies, the charge time is reduced, allowing proper operation with a smaller inductor (saving footprint size and cost).

Saturating the Inductor

One of the most common and catastrophic errors in SMPS design is neglecting the current saturation rating when selecting the power inductor. When the current through the inductor exceeds the saturation current rating, the core of the inductor saturates, meaning that the magnetic field generated will no longer increase proportionately to the current drawn. This disrupts the volt second balance law, leading to a loss of linear characteristics in both the inductor current ripple and the output voltage ripple. When the iron core saturates, it loses inductance rapidly, behaving more as a resistor than an inductor. Since the effective series resistance (ESR) of the inductor increases, and the practical inductance decreases, the change in current is forced to increase to satisfy volts second balance. The peaking observed in the saturated current waveform is due to the exponential increase in the current slope and can be seen in Figure 4. This current peaking carries over to the output voltage, leading to more noise and voltage spikes, as seen in Figure 5. The noise and voltage spikes can potentially damage downstream components if the voltage spikes too much and exceeds a downstream component's maximum voltage rating, as well as degrade EMI performance.

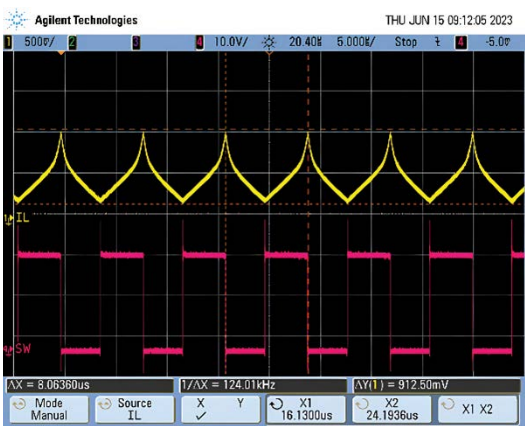

Figure 4. Saturated inductor current waveform. The waveform behaves normally until the current surpasses the saturation rating.

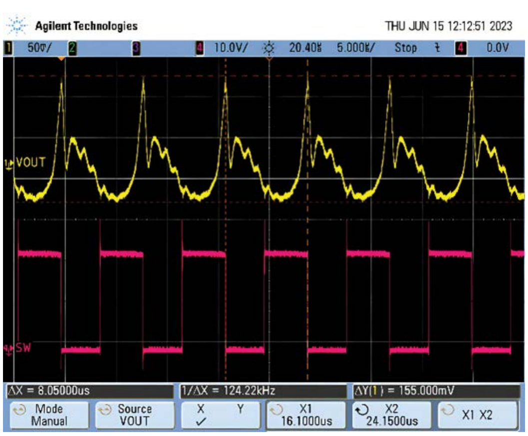

Figure 5. Saturated inductor output ripple. Peaking is carried over to the output, which contains noise and voltage spikes.

Furthermore, with high current fluctuations, the inductor experiences rapid hysteresis loss leading to excess heat dissipation of the inductor, as seen in Figure 6, as well as audible noise. This excess heat can damage other nearby components, especially the regulator chip itself.

Figure 6. Saturated inductor heat dissipation is 226°F (107.78°C).

To avoid running into this issue, designers should choose inductors with a current rating at least two times greater than the expected maximum current. When calculating the maximum current, it is important to account for the inductor current ripple as well as the load current drawn from the output. Furthermore, designers can refer to their chosen inductor data sheet to find out at what current the inductance drops by 10% to 30% of its original value, which is where saturation is defined. Choosing an inductor with the proper saturation current rating will result in normal operation of the system, as seen by a linear current through the inductor in Figure 7. The output voltage spikes will disappear, as seen in Figure 8. Finally, the system will operate at a much lower temperature, as seen in Figure 9, stressing the device less and improving the lifetime of the device.

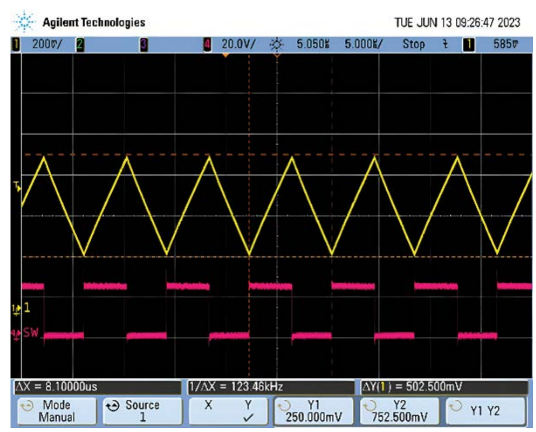

Figure 7. Nominal inductor current waveform.

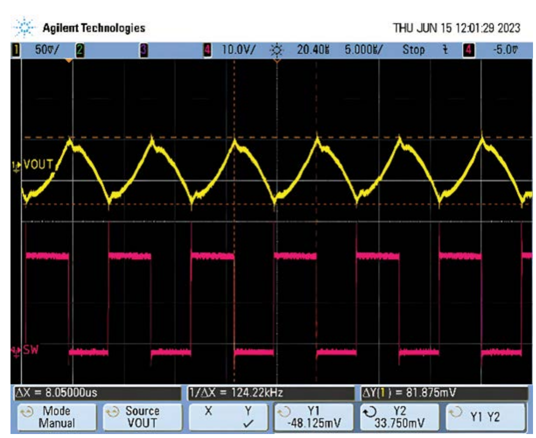

Figure 8. Nominal inductor output ripple.

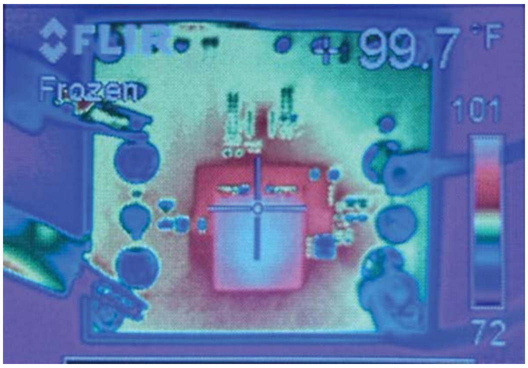

Figure 9. Nominal inductor heat dissipation is 99.7°F (37.61°C).

Complications of an Undersized Inductor

Designers often prefer smaller inductors to save footprint space, since smaller value inductors typically have smaller physical dimensions due to a smaller coil count. However, if the inductor is too small, the ripple current will be large and will force the converter to go into DCM, which is undesirable for SMPS because the device will be less efficient and display worse electromagnetic interference (EMI) performance. This degraded EMI performance can be seen in the presence of ringing in the switch node, caused by parasitics as well as the LC tank (creating a resonant circuit), which can be seen in Figure 10. This ringing will carry over into the output voltage, leading to a larger ripple and more voltage spikes, as seen in Figure 11. Furthermore, the power supply is no longer in continuous conduction mode (CCM), and the derived SMPS output formulas no longer apply.

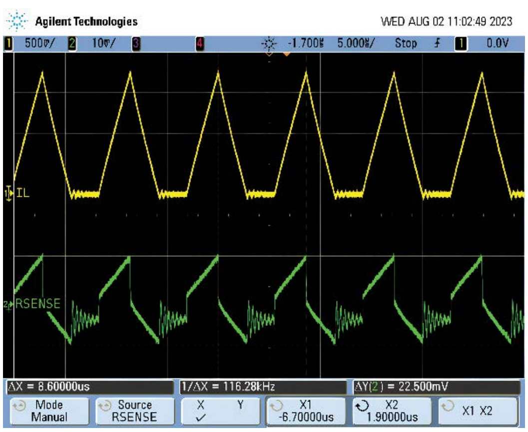

Figure 10. Undersized inductor output waveform. Ringing can also be observed in the switch node if the inductor current is inaccessible.

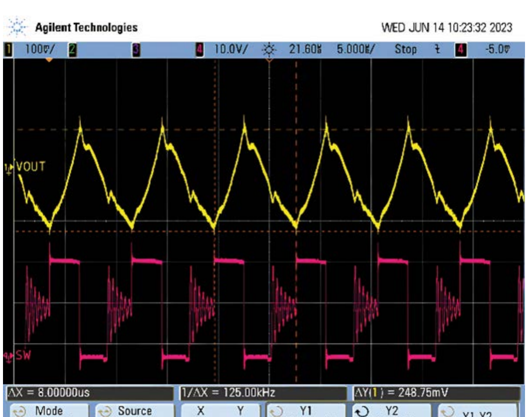

Figure 11. Undersized inductor current waveform. The ringing present in the current and R_{SENSE} indicate the power supply is in DCM.

To fix this issue, designers should take care to choose an inductor that will provide a current ripple of about 30% to 40%. Doing so will reduce the magnitude of the inductor current ripple and bring the device back into CCM from DCM, as seen in Figure 12. This will improve the output voltage ripple as well and remove the voltage spikes, as seen in Figure 8. If a designer is having trouble calculating the desired inductor value and choosing a viable component, they can use LTPowerCAD to assist with the design and selection of power stage components.

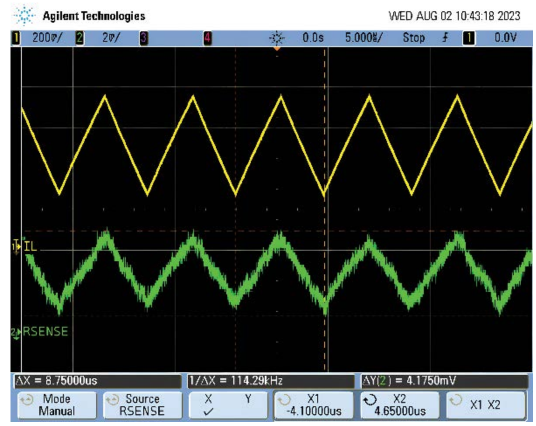

Figure 12. Nominal inductor current waveform.

Complications of an Oversized Inductor

The downstream electronics connected to an SMPS typically have specified supply voltages with an associated tolerance. If the ripple on the voltage rail is too large, it will drastically affect the operation of the system. For example, if a microcontroller has a supply specification of 3.3 V ±50 mV, having a ripple larger than ±50 mV may cause the microcontroller to shut off. One way that designers often try to mitigate this ripple is by increasing the size of their inductor. However, if the inductor is sized too big, the current ripple along with the output voltage ripple decreases significantly. Although this sounds desirable, it will lead to issues with the feedback system, and can also result in a much slower transient response. A small ripple will make it extremely hard for the series sense resistor to detect changes, distorting the usual triangular waveform that is passed into the feedback loop. When the inductor current ripple is small, the signal-to-noise ratio (SNR) deteriorates. This results in the feedback loop registering noise as the signal from the inductor, resulting in unwanted instability at the output, which manifests itself as jitter as seen in Figure 13.

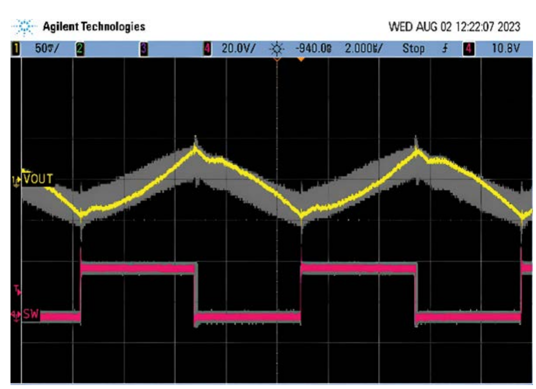

Figure 13. Jitter caused by the instability in the output. The waveform shown with the persist feature is the oversized inductor output waveform. The highlighted waveform is captured with the nominal inductor.

In addition, with higher valued inductors, the saturation current rating is usually smaller. This can lead to inductor saturation, which is dangerous for the device as discussed in the Saturating the Inductor section. The effect of saturating an extremely oversized inductor can be seen in Figure 14.

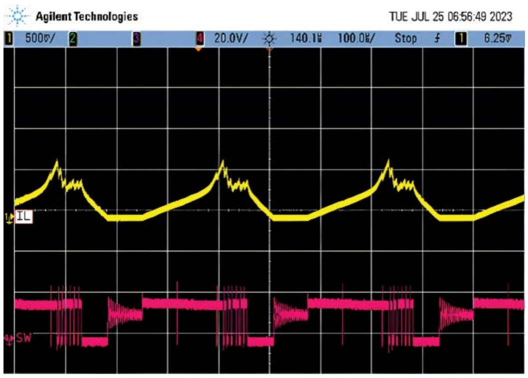

Figure 14. Saturated inductor output waveform with inductor that is 22 times the nominal value. The current rating does not increase proportionally with inductance.

To mitigate this issue, designers need to keep in mind that the output voltage ripple can be controlled by altering the output capacitors that were chosen. By either increasing the value of the output capacitor or decreasing its ESR, the output voltage ripple can be reduced without having to increase the inductor's value. This will allow the inductor current ripple to stay at a value between 30% and 40%, allowing the sensing architecture to properly acquire the signal. This can be seen in Figure 15.

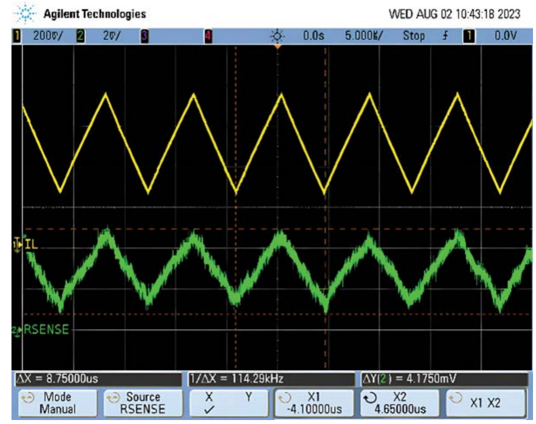

Figure 15. Nominal sense resistor waveforms.

Conclusion

This article serves as a guideline to analyze inductor design issues in the case of buck converters. Furthermore, it aims to provide practical solutions in case designers see any of the unwanted performances depicted here. Maintaining the inductor ripple in the 30% to 40% range of the output by properly sizing the inductor is critical to ensuring the device stays in CCM and does not cause unwanted jitter or saturation, which could be fatal for the load or the regulator's chip itself.

About the Author

Abe Ibraheim is a central applications intern, who joined Analog Devices in the summer of 2023. Abe is a rising third-year student at Worcester Polytechnic Institute, pursuing a bachelor's and a master's degree in electrical and computer engineering. His concentration is in microelectronics and power systems.

About the Author

Kenneth Armijo joined Analog Devices in 2022 as an associate engineer in central applications. He holds two bachelor's degrees from Worcester Polytechnic Institute in electrical engineering and robotics engineering, as well as a master's degree in electrical engineering. He specializes in the design and implementation of power management circuits, mainly switching regulators.

About the Author

Piyu Dhaker is an applications engineer in the North America Central Applications Group of Analog Devices. She graduated from San Jose State University in 2007 with a master's degree in electrical engineering. Piyu joined the North America Central Applications Group in June 2017. She also previously worked in the Automotive Power Train Group and Power Management Group within ADI.