Application Note

Inductor Selection for the BQ2575X and BQ2585X-Q1 Family of ICs

Ethan Galloway

Abstract

Inductor selection is one of the most critical aspects of switching converters. Proper inductor selection can lead to increased efficiency, cooler temperatures, and a smaller converter size. This application note goes over how to calculate inductor losses and how to select the best inductor for your application.

Table of Contents

Trademarks

All trademarks are the property of their respective owners.

1 Introduction

The inductor is an intricate component that stores energy in the form of a magnetic field. This behavior can be used for switching converters. There are many factors that go into inductor selection. System specifications dictate the physical size of the inductor, the DCR of the inductor, and the inductance. Inductor selection is critical to increasing the efficiency, decreasing the size, or increasing the maximum available current.

Unlike a dedicated buck or boost converter, a 4-switch buck-boost converter must operate across a wider V_{IN} and V_{OUT} range. The inductor must be sized to handle the worst case scenarios for both buck and boost mode to maintain stability and to make sure the switching current can be handled.

For a buck, boost, or buck-boost converter, inductors are selected with the following requirements:

- Saturation current – The saturation current is where the magnetic field of the inductor cannot increase further. The saturation current must be greater than the peak current in the inductor.
- IDC – This is the maximum heat generating current that can go through the inductor. The inductor’s maximum DC current spec must be greater than the circuit’s DC current. This has units of Amps.
- DCR – DCR is the DC resistance of the inductor often listed in mΩ.
- Inductance (L) – L is the value of the inductor listed in µH.

Here are a few general terms for DC-DC converters:

- Continuous Conduction Mode (CCM) - This is when the inductor current is always above 0A.
- Discontinuous Conduction Mode (DCM) - This occurs when the inductor current goes to 0A. The BQ2575X family of parts can go into pulse frequency modulation (PFM) to increase the efficiency at this point.

An example circuit of the BQ2575X buck-boost circuit is shown in Figure 1-1.

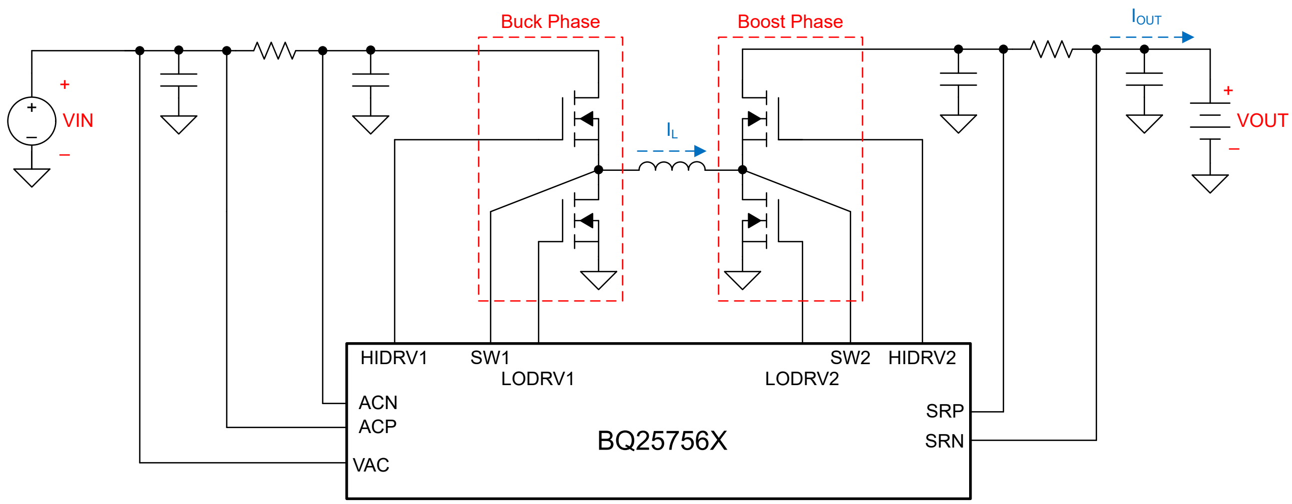

Figure 1-1. Simplified Buck-Boost Converter Circuit

In buck mode, HIDRV1 and LODRV1 work to step-down the input voltage to the output voltage. HIDRV2 stays ON and LODRV2 stays OFF. Figure 1-2 is an example of the switching waveforms with V_{IN}=35V, V_{OUT}=20V, I_{OUT}=4A, L=10µH, and the switching frequency is 350kHz:

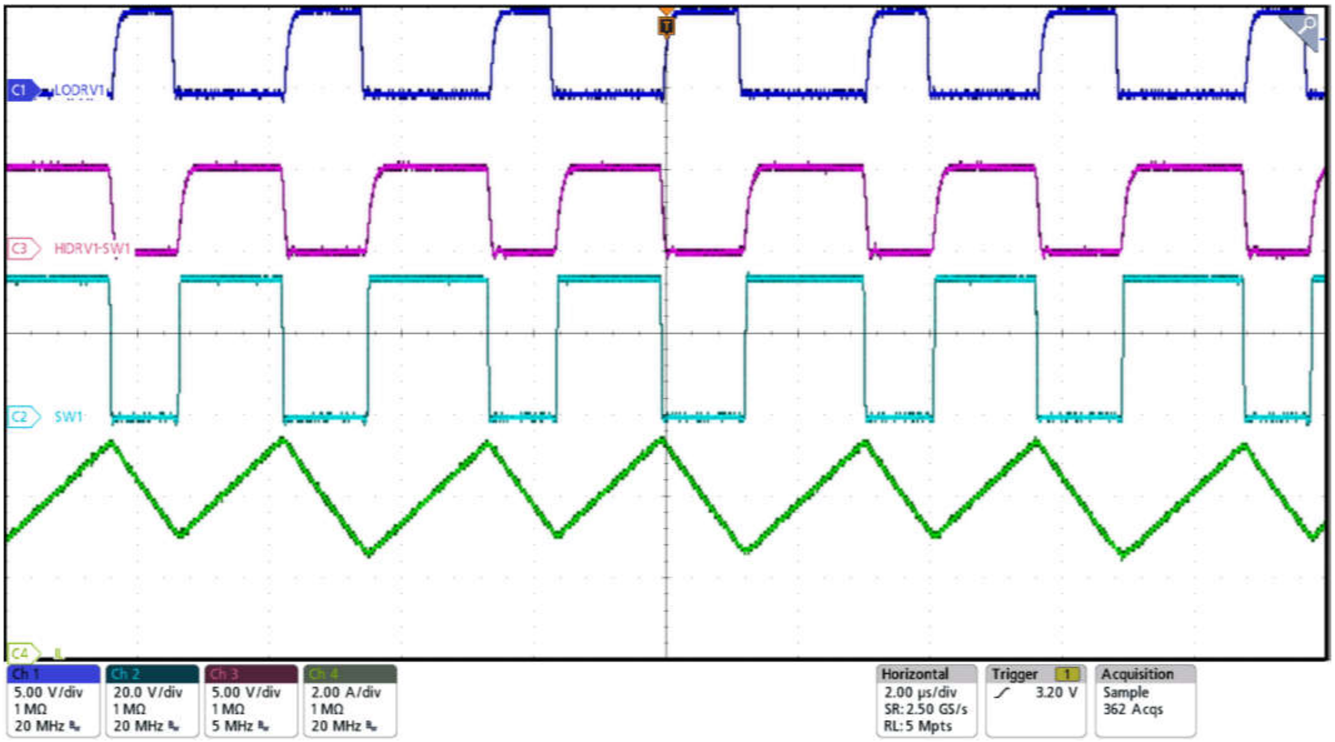

Figure 1-2. BQ25756 in Buck Mode

In boost mode, HIDRV1 stays ON and LODRV1 stays OFF. HIDRV2 and LODRV2 work to step-up the input voltage to the output voltage. Figure 1-3 is an example of the switching waveforms with V_{IN}=25V, V_{OUT}=40V, I_{OUT}=4A, and the switching frequency is 350kHz:

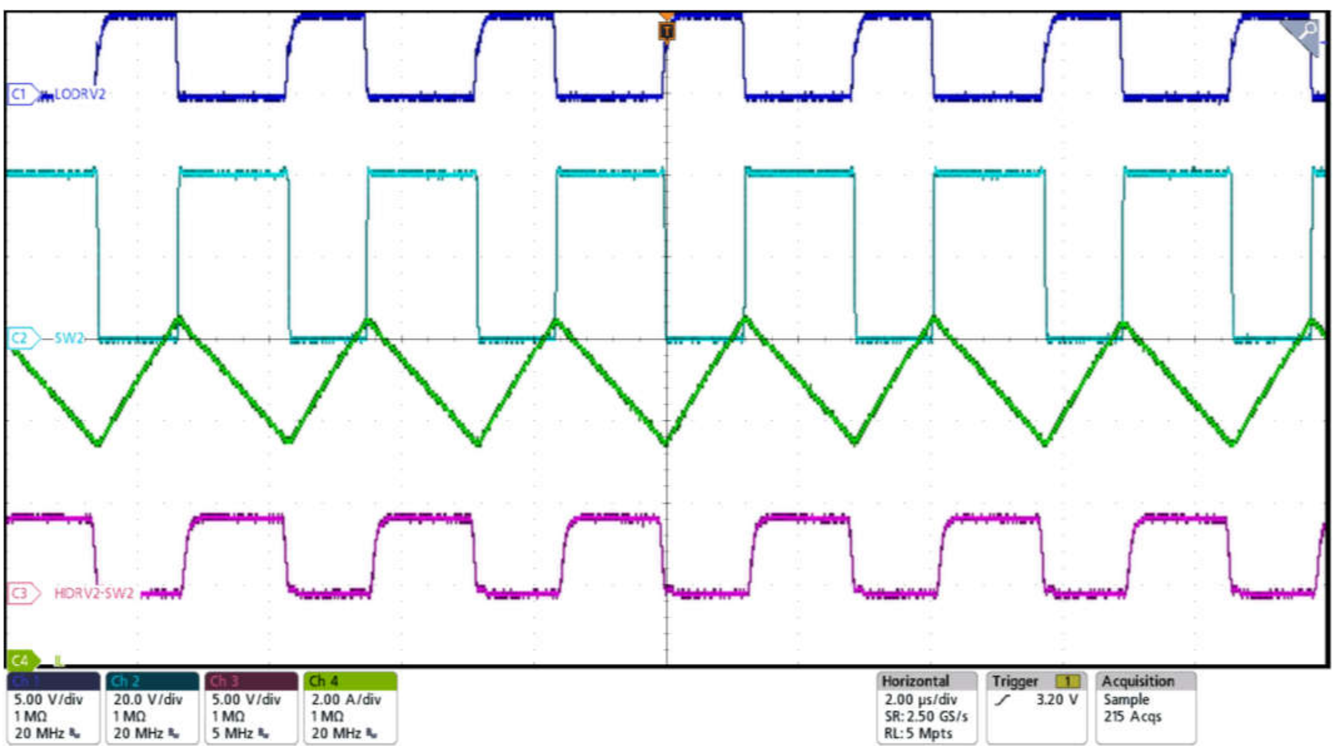

Figure 1-3. BQ25756 in Boost Mode

When VIN is approximately equal to V_{OUT}, the IC is in buck-boost mode. The buck and boost phases interleave. This means that the buck phase switches for 1 clock cycle. Then, the boost phase switches for 1 clock cycle.

Figure 1-4 shows buck-boost operation with V_{IN}=35V, V_{OUT}=35V, I_{OUT}=4A, and FSW=350kHz:

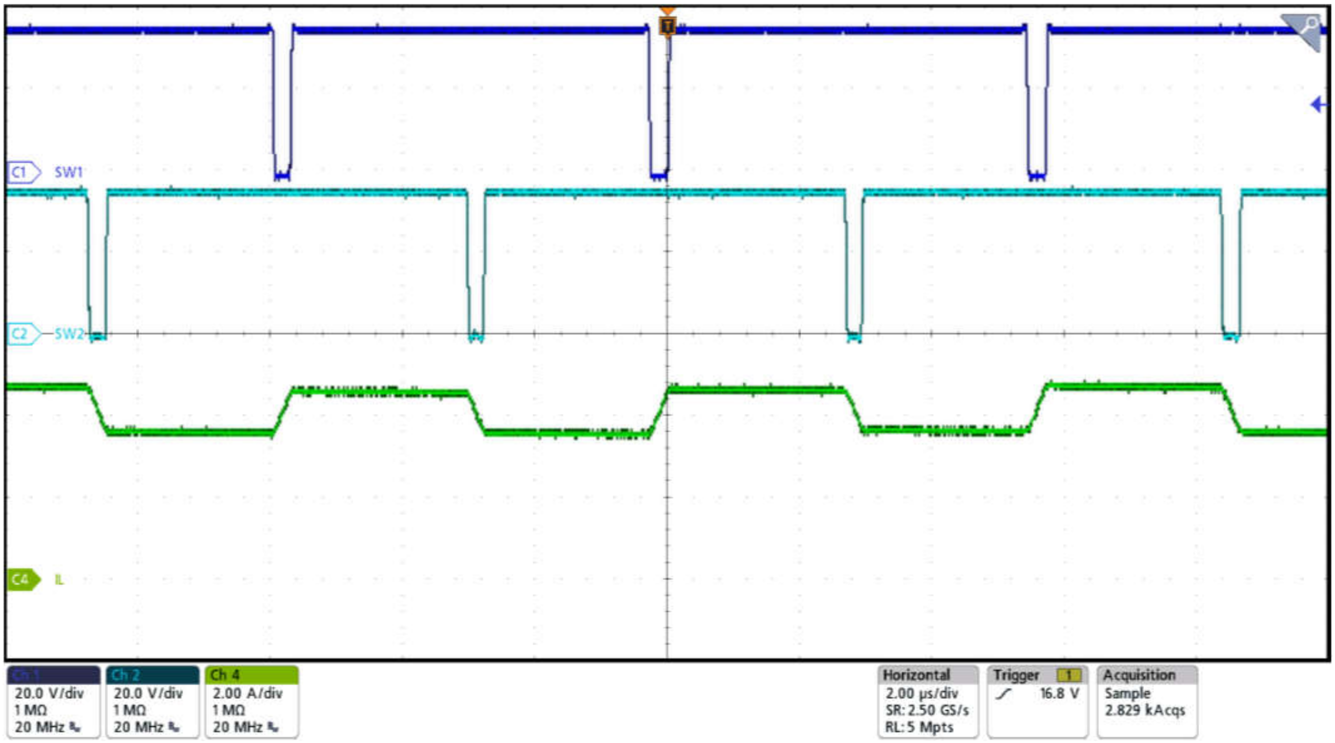

Figure 1-4. BQ25756 in Buck-Boost Mode

Interleaving the buck and boost pulses allows for a seamless transition from buck-mode to boost-mode.

2 Inductor Selection

To select the inductor, the following parameters need to be specified:

- Input voltage range
- Maximum output voltage
- Charging current
- Maximum possible FSW

Based on these specifications, the following parameters can be calculated:

1. Duty cycle of worst case operating conditions in buck and boost modes
2. Minimum inductance in buck mode
3. Minimum inductance in boost mode
4. The inductor ripple current

2.1 Duty Cycle

The first step of any switching converter design is to calculate the duty cycle. The duty cycle controls the switch current which controls the inductance and efficiency. The points of the maximum inductor current need to be found for both boost mode and buck mode.

For a buck converter, the maximum inductor current occurs at the maximum input voltage to the lowest output voltage.

$$D_{BUCK} = \frac{V_{OUT}}{V_{IN(MAX)} \times \eta} \tag{1}$$

For a boost converter, the maximum inductor current occurs at the minimum input voltage to the maximum output voltage.

$$D_{BOOST} = 1 - \frac{V_{IN(MIN)} \times \eta}{V_{OUT}} \tag{2}$$

In the above equations:

- $V_{IN(MAX)}$ = Maximum input voltage
- $V_{IN(MIN)}$ = Minimum input voltage
- V_{OUT} = Desired Output voltage
- D_{BUCK} = Minimum duty cycle for buck mode
- D_{BOOST} = Maximum duty cycle for boost mode
- η = Estimated efficiency

2.2 Inductance Selection

A good rule for the inductor selection is to have the ripple current to be 20% to 40% of the output ripple current, or $0.2 < r_{ind} < 0.4$.

For buck-mode, Equation 3 can be used to estimate the inductance needed:

$$L > \frac{V_{OUT} \times (V_{IN(MAX)} - V_{OUT})}{r_{ind} \times F_{SW} \times V_{IN(MAX)} \times I_{OUT}} \tag{3}$$

In the above equation:

- $V_{IN(MAX)}$ = Maximum input voltage
- V_{OUT} = Desired output voltage
- F_{SW} = Switching frequency
- $r_{ind} = \frac{\Delta I}{I_{OUT}}$ This is the inductor ripple current relative to the maximum output current. r_{ind} is a constant for the specific application. r_{ind} is only defined for continuous conduction mode.

For boost-mode, Equation 4 can be used to estimate the inductance needed:

$$L > \frac{V_{IN(MIN)}^{2} \times \left(V_{OUT} - V_{IN(MIN)}\right)}{F_{SW} \times r_{ind} \times I_{OUT} \times V_{OUT}^{2}} \tag{4}$$

In the above equation:

- $V_{IN(MIN)}$ = Minimum input voltage
- V_{OUT} = Desired output voltage
- F_{SW} = Switching frequency
- $r_{ind} = \frac{\Delta I}{I_{OUT}}$ This is the inductor ripple current relative to the maximum output current. r_{ind} is a constant for the specific application. r_{ind} is only defined for continuous conduction mode.

2.3 Inductor Ripple and Peak Current

There are two cases for finding the maximum inductor current, buck-mode and boost-mode. For the rest of the application note, use the greatest maximum inductor current.

In buck-mode, the maximum current occurs at $V_{IN(MAX)}$. Equation 5 is used to calculate the maximum switch current and Equation 6 is used to calculate the ripple current.

$$I_{SW(MAX)} = \Delta I + I_{OUT} \tag{5}$$

$$\Delta I = \frac{\left(V_{IN(MAX)} - V_{OUT}\right) \times D_{BUCK}}{F_{SW} \times L} \tag{6}$$

In the above equation:

- $V_{IN(MAX)}$ = Maximum input voltage
- V_{OUT} = Desired output voltage
- F_{SW} = Switching frequency
- D_{BUCK} = Minimum duty cycle for buck mode
- L = selected inductor value
- ΔI = Maximum AC ripple current
- $I_{SW(MAX)}$ = Maximum current through inductor

In boost-mode, the maximum switch current occurs at $V_{IN(MIN)}$. Equation 7 is used to calculate the maximum switch current and Equation 8 is used to calculate the ripple current.

$$I_{SW(MAX)} = \frac{\Delta I}{2} + \frac{I_{OUT}}{1 - D_{BOOST}} \tag{7}$$

$$\Delta I = \frac{V_{IN(MIN)} \times D_{BOOST}}{F_{SW} \times L} \tag{8}$$

- $V_{IN(MIN)}$ = Minimum input voltage
- V_{OUT} = Desired output voltage
- F_{SW} = Switching Frequency
- D_{BOOST} = Maximum duty cycle for boost mode
- L = selected inductor value
- ΔI = Maximum AC ripple current

2.4 Using the BQ2575X Design Calculator

The BQ25756 Design Calculator can be used for all of the BQ2575X and BQ2585X-Q1 families of devices. This calculator can help with resistor programming, IC set-up, and the BOM selection process. The calculator can also take user inputs about the operating conditions, BOM, and system requirements to estimate the power loss and efficiency. Note that the calculator does not take into account power losses from other sources, like magnetic core losses, or copper trace losses.

This calculator also includes a thermistor qualification tab to estimate the minimum/typical/maximum temperature falling and rising thresholds for the various temperature charging windows. This tab can be used to select a thermistor for the application of interest, but this section focuses on the inductor calculation steps in the design calculator.

To use this calculator, skip over the warning about circular references and fill in the yellow cells. The cells with red tabs contain additional information about the adjacent cell. Red cells highlight the cells that can have an issue.

First, enter the input voltage range, output voltage, and maximum output current into the calculator

5	**Step 1: Operating Specifications**		
6	**Input Voltage - Min, $V_{AC(min)}$**	**20**	**V**
7	**Input Voltage - Nom, $V_{AC(nom)}$**	**25**	**V**
8	**Input Voltage - Max, $V_{AC(max)}$**	**35**	**V**
9	**Battery Voltage, V_{BAT}**	**16.8**	**V**
10	**Full Load Output Current, $I_{OUT(max)}$**	**5**	**A**

Figure 2-1. Design Calculator Step 1

Second, enter the desired switching frequency. The calculator can be quickly used to find the resistor value for a given frequency. The *Buck Voltage Limitation* row lists the maximum possible output voltage for a buck-only part.

12	**Step 2: Switching Frequency**		
13	**Desired Switching Frequency, F_{DFW}**	**250**	**kHz**
14	Recommended Switching Frequency Resistor, R_{FSW}	133.33	kΩ
15	**Selected Switching Frequency Resistor, R_{FSW}**	**133**	**kΩ**
16	Recognized Switching Frequency, F_{SW}	250.38	kHz
17	Boost Duty Cycle Limitation	94.37	%
18	Buck Duty Cylce Limitation	96.24	%
19	Boost Output Voltage Limitation at $V_{AC(min)}$	N/A	V
20	Boost Output Voltage Limitation at $V_{AC(nom)}$	N/A	V
21	Boost Output Voltage Limitation at $V_{AC(max)}$	N/A	V
22	Buck Voltage Limitation at $V_{AC(min)}$	19.25	V

Figure 2-2. Design Calculator Step 2

Third, enter in the proposed inductor. This section can be used to calculate the ripple current and ripple current percentage.

The BQ2575X and BQ2585X-Q1 ICs can support an inductor of 2.2µH to 15µH and a DCR of 1.75mΩ to 60mΩ. The max possible time constant for the ICs is 1.26µH/mΩ.

24	**Step 3: Filter Inductor**		
25	Maximum Average Inductor Current, $I_{L(MAX)}$	4.67	A
26	Selected Inductor Saturation Current, I_{SAT}	26	A
27	Minimum Inductance, L	0.79	µH
28	**Selected Inductance, L**	**10**	**µH**
29	Minimum Recommended Inductance	2.20	µH
30	Maximum Recommended Inductance	15.00	µH
31	Minimum Recommended Inductor DCR	1.75	mΩ
32	Maximum Recommended Inductor DCR	60.00	mΩ
33	**Selected Inductor DCR**	**12**	**mΩ**
34	Selected Inductor Time Constant	0.83	µH/mΩ
35	Maximum Inductor Time Constant	1.26	µH/mΩ
36	Pk-to-Pk Ripple Current at $V_{AC(min)}$, ΔI_{L1}	1.07	A_{pk-pk}
37	Pk-to-Pk Ripple Current at $V_{AC(nom)}$, ΔI_{L2}	2.20	A_{pk-pk}
38	Pk-to-Pk Ripple Current at $V_{AC(max)}$, ΔI_{L3}	3.49	A_{pk-pk}
39	ΔI_L as a % at $V_{AC(min)}$	21.47	%
40	ΔI_L as a % at $V_{AC(nom)}$	44.02	%
41	ΔI_L as a % at $V_{AC(max)}$	69.78	%
42	Peak Inductor Current, $I_{L(PEAK)}$	5.20	A

Figure 2-3. Design Calculator Step 3

3 Inductor Losses

Assistance from inductor manufacturers is needed to calculate the magnetic core losses. There are three sources of loss for an inductor. Total power lost can be expressed with Equation 9:

$$P_{IND} = P_{CORE} + P_{DCR} + P_{ACR} \tag{9}$$

Where:

- P_{CORE} = Losses from the magnetic core losses in the inductor. Core losses are generally the dominant source of loss in the inductor
- P_{DCR} = Losses from DC current flow through the windings
- P_{ACR} = Losses from the skin effect and proximity effect from high frequency current

Calculating all forms of inductor losses is unpractical for the DC-DC converter designer. This section aims to explain where losses in an inductor come from and what relates to the power losses.

3.1 Resistance Losses

The following section gives information about the relation between these different losses. The relations between the variables is the most important rather than calculating the actual magnetic losses of the inductor.

Resistance losses are the easiest to start with and can be expressed with Equation 10:

$$P_{DCR} = {I_{DC}}^2 * R_{DCR} \tag{10}$$

Where:

- P_{DCR} = Losses from DC current flow through the windings
- I_{DC} = DC component of the inductor current
- R_{DCR} = DC resistance of inductor

At high frequencies, losses from the skin effect and the proximity effect start to take effect. At high frequencies, eddy currents in the conductor cause current to only flow along the outside of the wire. This is called the skin effect. The skin effect can be calculated with Equation 11:

$$\delta = \sqrt{\frac{\rho}{\pi f \mu}} \tag{11}$$

Where:

- ρ = conductor resistivity
- f = frequency of component
- μ = magnetic permeability of conductor

The conductivity of copper, ρ, is 1.724×10^{-6} Ω×cm at 25°C and 2.3×10^{-6} Ω×cm at 100°C. The relative magnetic permeability of copper is 1.

At 100°C, Equation 11 can be simplified to Equation 12:

$$\delta = \frac{7.5cm}{\sqrt{f}} \tag{12}$$

R_{ACR} is directly proportional to R_{DCR}. If the conductor is a wire and conductor thickness >> δ , Equation 13 can be used to estimate the equivalent AC resistance.

$$R_{ACR} = \frac{h}{\delta} R_{DCR} \tag{13}$$

For example, consider a 18awg wire (1.037mm) at 250kHz. The penetration depth is 150µm and R_{ACR} is $6.8R_{DCR}$.

The skin effect and corresponding losses need to be calculated for all frequency components of ΔI.

Finally, there is a third form of loss from the proximity effect. Magnetic fields in the inductor induce eddy currents in both the core material and the wires themselves. In the inductor's windings, these eddy currents can cause ohmic losses even if the wire is not carrying current. These eddy currents also cause current flow in the wire to shift. It's not possible for most engineers to calculate the proximity effect losses.

3.2 Magnetic Losses

The magnetic losses can be calculated with Steinmetz's equation shown in Equation 14:

$$P_{CORE} = K_{fe0}V_{CORE}\Delta B^{\beta}F_{SW}{}^{\alpha} = K_{fe0}V_{CORE}\left[\frac{|\vec{B}_{CORE(SAT)}|}{I_{SW(MAX)}}\right]^{\beta}\Delta I^{\beta}F_{SW}{}^{\alpha} \tag{14}$$

Where:

- $K_{fe0}V_{CORE}$ = constant depending on core material
- F_{SW} = Switching Frequency
- ΔI_{MAX} = Maximum AC ripple current
- $I_{SW(MAX)}$ = Maximum current through inductor
- α and β are curve fitting parameters. α is normally between 1 and 2. β is normally between 2 and 3. α and β must be fitted to the hystersis curves in the datasheet.

Once again, calculating the magnetic losses of the inductor is out of the scope for most engineers. The relations between the variables are the most important. P_{CORE} is directly proportional to ΔI and F_{SW}. However, ΔI is also indirectly proportional to F_{SW} and the constant β is usually bigger than α. These two facts taken together mean that the core losses decreases with increasing frequency.

3.3 General Rules for Inductor Selection

Here are few scenarios that can help with inductor selection:

To choose the smallest inductor, use the highest possible frequency the system allows for. A higher frequency reduces the ripple current and a reduced ripple current allows for an inductor with a lower value. Lower value inductors are smaller and have a lower DCR than larger value inductors. Keep in mind that higher frequencies reduce losses in the inductor, but increase the losses seen by the switching transistors.

To make a more efficient system, a larger value inductor can be used with a lower frequency. Lower frequencies cause less loss in the power transistors. The larger inductance is needed to reduce the increased ripple current seen at lower frequencies.

The ideal system needs to balance losses between the transistors, the inductor, and the size of the system. The average engineer must aim to keep the ripple current between 20% and 40%. This provides the best balance between inductor losses and switching FET losses without having to calculate the magnetic core losses of the inductor.

4 Bill of Materials (BOM) Evaluation

Several BOMs have been evaluated for their efficiencies and losses.

Table 4-1. Bill of Materials

BOM	MOSFET	Inductor	Switching Frequency
BOM1	AONS66408	SRP1050WA-100M (10μH, 20mΩ)	250KHz
BOM2	AONS66408	SRP1050WA-4R7M (4.7μH, 9mΩ)	250KHz

Here is the efficiency for the BOMs with different inductors. The test conditions are:

- FSW=250kHz
- VIN = 48V
- VOUT = 8V, 28V, 48V

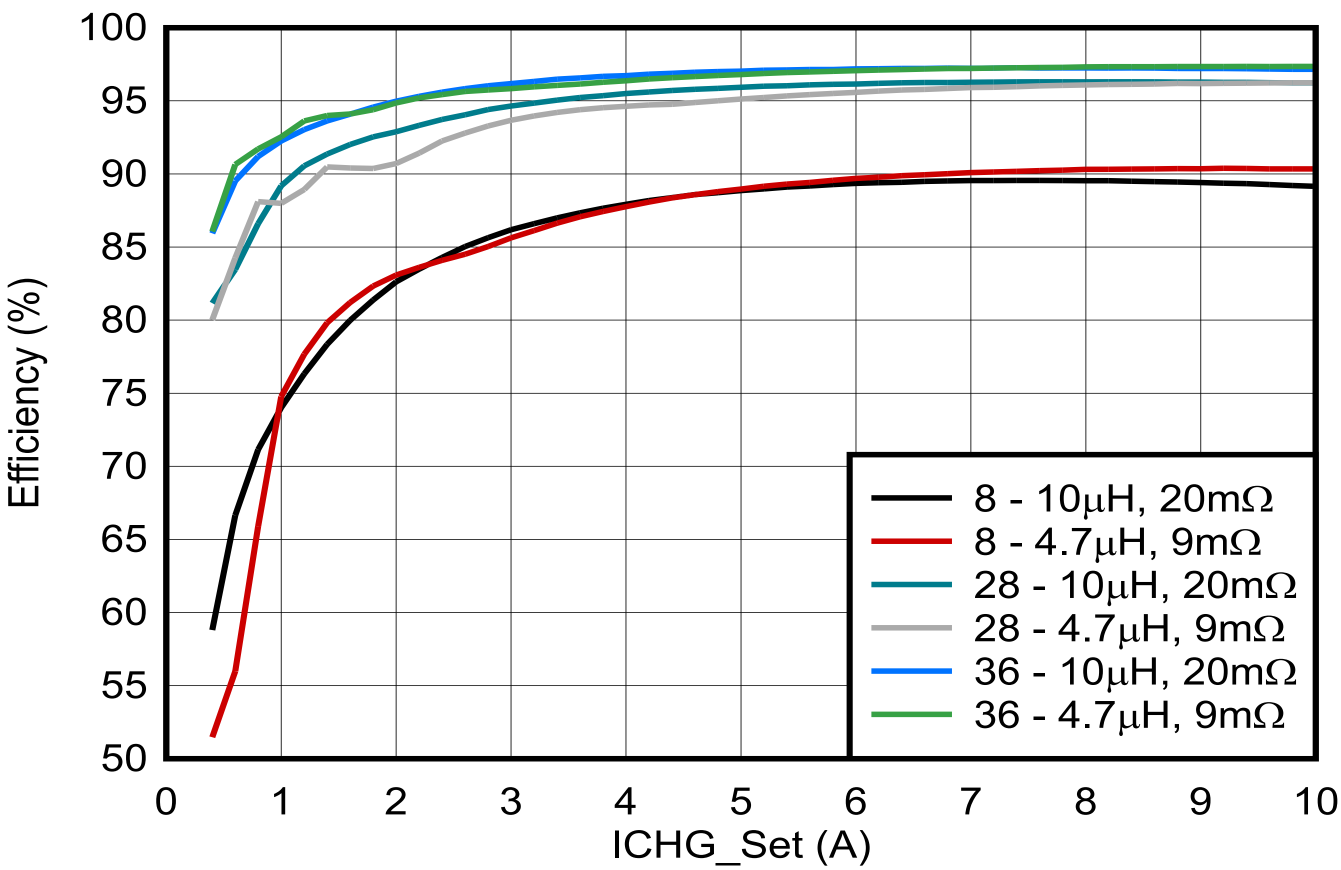

Figure 4-1. Efficiency of BOM1 Compared to BOM2 With VIN = 48V

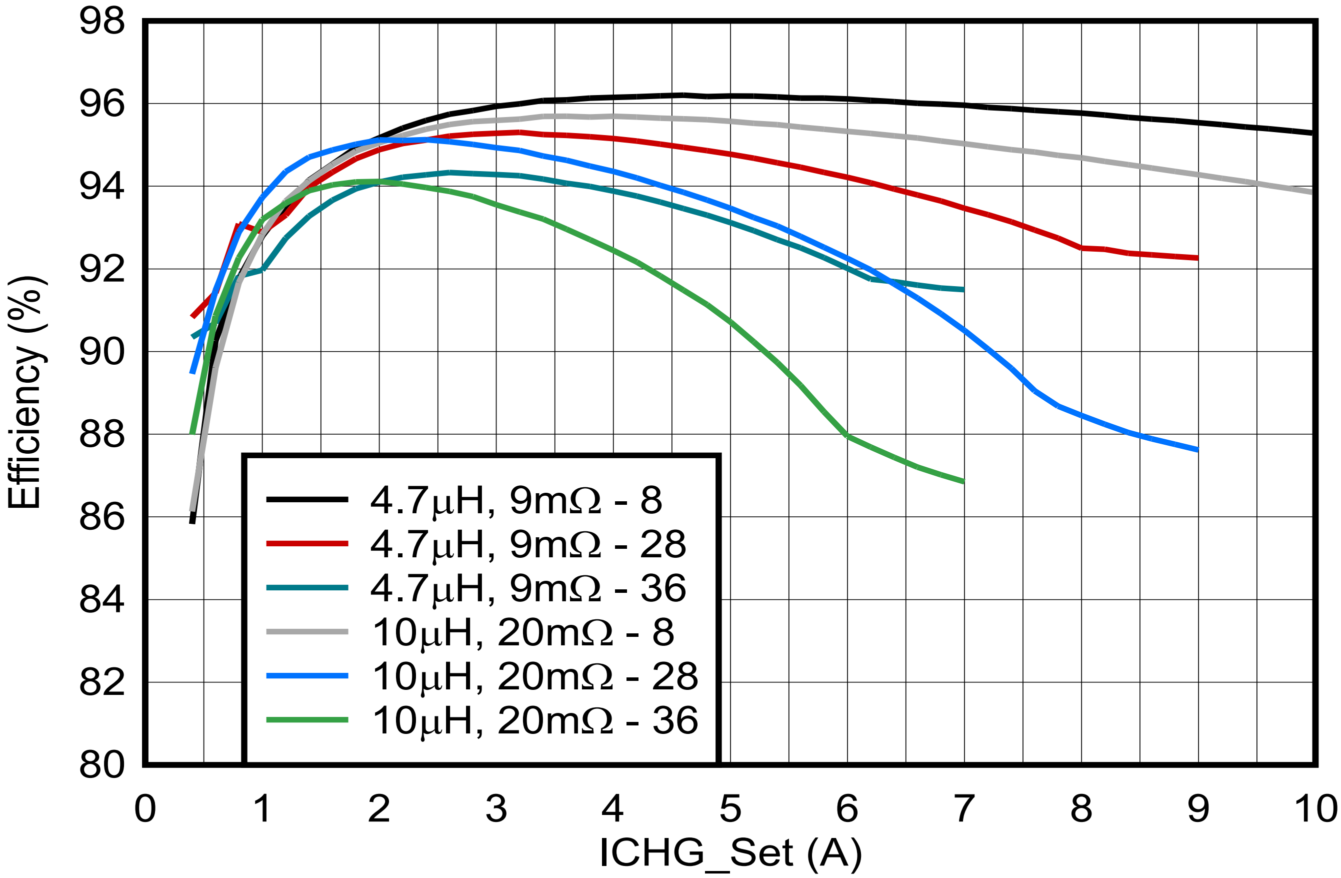

Figure 4-2. Efficiency of BOM1 Compared to BOM2 With VIN = 12V

Comparing the differences between inductors is often difficult. With most inductors, changing the inductance also changes the resistance. These two variables often make it hard to draw general conclusions.

From Figure 4-1, we can see that the losses between the inductors are roughly the same. The 4.7µH inductor has a much lower DCR, but higher ripple current. The higher ripple current causes more inductor core losses. From the chart, it looks like the high inductor core losses balances out the lower DC power losses from the lower DCR.

Figure 4-2 shows a more dramatic effect. Going from 12V to 36V requires significant input current. At 12V, the BQ25856-Q1 requires 21A of input to maintain a 36V output voltage at 7A. This is a lot of DC current so the DCR losses are more dominant here. This makes the 4.7µH inductor much more efficient.

5 Summary

There are many factors to consider when selecting an inductor. Inductors are complicated components and not all the parameters can be calculated by the normal power engineer. The inductance, DCR, and size must be carefully considered.

6 References

- Texas Instruments, *Selecting Inductors for Buck Converters* application report
- Texas Instruments, *Waveform Audit: Is Your Inductor Saturated?* technical article
- Texas Instruments, *MOSFET Selection Guide for BQ2575x Family* application note
- Texas Instruments, *BQ2575X / BQ2585X-Q1 Design Calculator* tool
- Texas Instruments, *Basic Calculation of a Buck Converter's Power Stage* application note
- Texas Instruments, *Basic Calculation of a Boost Converter's Power Stage* application note
- Texas Instruments, *Basic Calculations of a 4 Switch Buck-Boost Power Stage* application report
- European Passive Components Institute, *Winding Losses in Transformers and Inductors* article

IMPORTANT NOTICE AND DISCLAIMER