Guide to Selecting Inductors for Switching Regulators

By Chris Likely, Field Applications Engineer, Cooper Electronic Technologies

Selecting an off-the-shelf inductor with correct inductance value for a switching regulator is no simple process. As a designer, you're faced with different current ratings, core constructions, and materials—making the job even more complicated. Here's a guide that simplifies this process.

In all switching regulators, the inductor is used as an energy storage device. When the semiconductor switch is on, the current in the inductor ramps up and energy is stored. When the switch turns off, this energy releases into the load. The amount of energy stored is given by Energy = ½L.I² (Joules)

Where L is the inductance in Henrys and I is the peak value of inductor current.

The amount by which the current in the inductor changes during a switching cycle is known as the ripple current and is defined by the following equation:

$V_l = L.di/dt$

Where V_l is the voltage across the inductor, di is the ripple current, and dt is the duration for which the voltage is applied. From this, we can see that the value of ripple current is dependent on the value of the inductance.

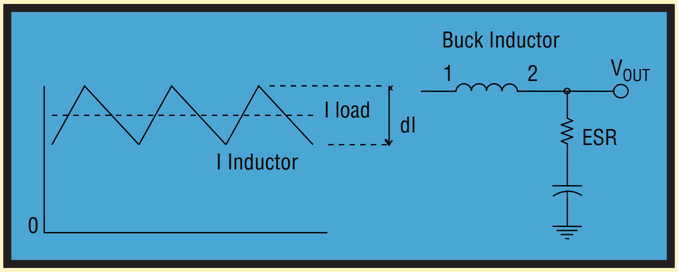

Fig. 1. *Inductor ripple current and Buck output circuit.*

Buck Converter Considerations

For a buck converter, choosing the correct value of inductance is important to obtain acceptable inductor and output capacitor sizes and sufficiently low output voltage ripple.

As you can see from **Fig. 1**, the inductor current is made up of ac and dc components. Because the ac component is high frequency, it will flow through the output capacitor, which offers a low HF impedance. This will produce a ripple voltage due to the capacitor equivalent series resistance (ESR), which appears at the output of the buck converter. This ripple voltage needs to be sufficiently low—so not to affect the operation of the circuit the regulator is supplying. It is normally in the order of 10-500mVpk-pk.

Selecting the correct ripple current also affects the size of the inductor and the output capacitor. This capacitor must have a sufficiently high ripple current rating, or it overheats and dries out. To get a good compromise between inductor and capacitor size, you should choose a ripple current value of 10% to 30% of maximum load current. This also implies that the current in the inductor will be continuous for output currents greater that 5% to 15% of full load.

You can operate buck converter inductors in continuous or discontinuous mode. This means that the inductor current can flow continuously or can fall to zero during the switching cycle (discontinuous). However, operating in discontinuous mode is not recommended as it makes for a more complex converter design. Selecting an inductor ripple current less than two times the minimum load ensures continuous mode operation.

Inductor Selection

When selecting an inductor for a buck converter, as with all switching regulators, you'll need to define or calculate the following parameters:

- Maximum input voltage
- Output voltage
- Switching frequency
- Maximum ripple current
- Duty cycle

For the buck converter shown in **Fig. 2**, for example, let's assume a switching frequency of 200 kHz, input voltage range of 3.3V±0.3V and output of 1.8V at 1.5A with a minimum load of 300mA.

For an input voltage of 3.6V, the duty cycle will be:

$D = V_o/V_i = 3.6/1.8 = 0.5$

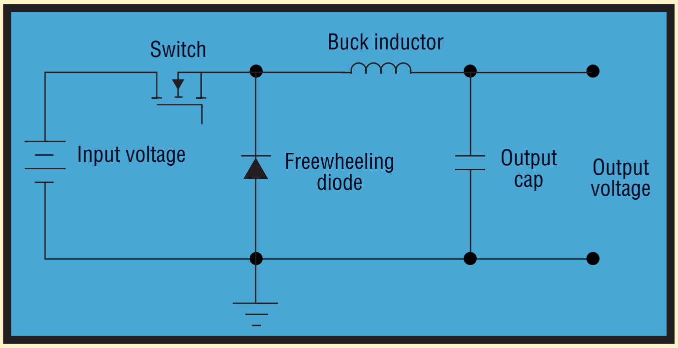

Fig. 2. *Buck Converter.*

Where V_o is the output voltage and V_i is the input voltage.

Voltage across the inductance:

$V_l = V_i - V_o = 1.8V$ when the switch is on;

$V_l = - V_o = -1.8V$ when the switch is off.

Selecting a 600mA ripple current, the required inductance is: $L = V_l.dt/di = (1.8 \times 0.5/200 \times 10^3)/0.6$

$L = 7.5\mu H$

To allow some margin, you should select a value of 10µH. This gives a nominal peak-to-peak ripple current of 450mA. In the finished design, this can be seen as an output ripple voltage of 0.45 × output capacitor ESR.

Inductor Current Ratings

Inductors are normally specified with two current ratings: continuous (Irms) and peak (Isat). Irms is normally specified as the dc current that produces an inductor temperature rise of 40°C. Isat is the peak current that produces a specific roll off in inductance—specified as a percentage reduction from the open circuit value and can vary from 5% to 50%. These current ratings are a guide to the inductor performance. The actual maximum operating current will depend on the application. With this in mind a number of factors need to be checked to ensure correct inductor selection.

First, it's important to look at how the inductance "rolls off" with increasing current. For materials such as Iron powder, molybdenum permalloy powder (MPP), sendust and amorphous powder that employ a distributed air gap the inductance roll off starts at very low current levels and continues in an almost linear manner as the current is increased. Where a ferrite material is employed, any incremental change in inductance is swamped by the large gap that must be introduced to store the energy. As a result, the inductance falls sharply at the point where the whole core becomes saturated. Before this point is reached, the inductance remains almost constant. You can find examples of

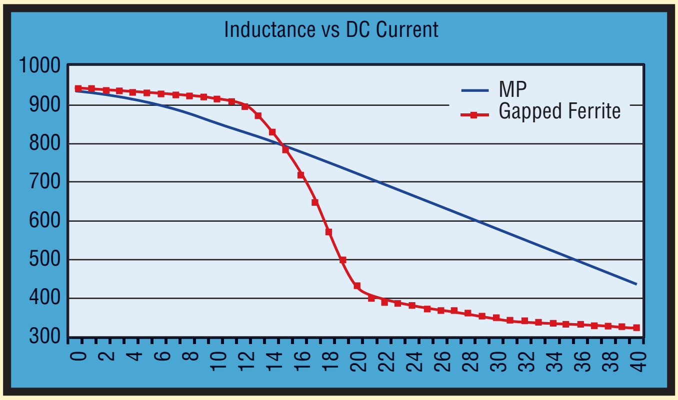

Fig. 3. *Inductance roll off curve for two 920 mH inductors using MPP and gapped ferrite.*

these two roll off characteristics in **Fig. 3**. This figure shows the roll off curves for two 920µH inductors—one made using ferrite and the other MPP.

For ferrite core materials, the peak current would normally be specified for a 10% to 30% reduction in inductance from the open circuit value. Operation at higher current levels are not recommended, as the inductance would quickly fall to a low level. However, for powdered materials the peak current could be specified at anything up to a 50% roll off with operation beyond this been possible provided the inductor is not overheated. From the examples in **Fig. 3**, peak currents would be specified at 16A to 17A for the ferrite part and as high as 36A for the MMP.

Core Loss and Temperature

Allowable losses for an inductor are limited by the maximum permissible temperature. Thus, for most off-the-shelf parts, this limit is a surface temperature of 125°C—although it can be higher. The rms current rating is typically the dc current that leads to a 40°C temperature rise, theoretically allowing operation in an 85°C ambient temperature. However, in most applications, some ripple current resulting from core loss exists. Under such conditions, Irms would need to be de-rated to keep the temperature rise down to 40°C. Also, the specified 40°C rise is normally achieved with no restrictions in airflow due to natural convection, which in most applications is not the case.

The two main issues with this area of inductor selection are calculating the core loss and the required de-rating of Irms to keep the temperature rise down to an acceptable level. Different inductor manufactures have different ways of expressing core loss—some give no details at all, while others provide the information required to calculate dissipation. However, one of the more practical approaches comes from the Coiltronics® catalog, which shows the maximum allowable percentage loss from Irms against applied volt-seconds at various frequencies. Since the volt-seconds product is proportional to core loss, it can be easily determined by using these curves.

Final Selection

Final inductor selection depends on four main design requirements: efficiency, electromagnetic interference (EMI), available space, and cost. In handheld battery powered equipment high efficiency from the smallest possible part is required. Also as the electronics are tightly packed, low EMI is essential. In an industrial application where the bulk dc supply, is generated via the ac utility supply the efficiency becomes less of a concern. As a result, the lowest cost solution is often employed.

Using the previous buck converter example you can now look at three possible solutions offering different trade offs against the four design considerations (**Table 1**).

Before looking at the performance of each of these parts against the design criteria you must first look at their roll off characteristic. In our example, the nominal peak current was 1.725A (1.5A output current plus half the ripple current) and the maximum peak current was 1.8A (as maximum allowable ripple current was 600mA).

Looking at the roll off curves for each inductor, you can obtain the following operating inductances:

CTX10-1-52—7.5µH
CTX10-1A—8.0µH
DR74-100—9.5µH

The CTX10-1-52 is already a marginal design, as 7.5µH

Coiltronics Part No.	Irms (A)	Isat (A)	DCR (mΩ)	Volt-µseconds rating (100 kHz)	Size/Volume (mm/mm^3)	Core Material	Core Shape
CTX10-1-52	2.4	2.1	48.1	5.4	8.6 dia. x 4.7 / 273	Iron Powder	Toroid
CTX10-1A	2.84	2.5	46	10.25	8.89^2 x 4.19 / 331	Amorphous	Toroid
DR73-100	2.11	2.47	63.4	11.5	7.6^2 x 3.55 / 205	Ferrite	Shielded Drum

Table 1. *Inductor Options for Buck Converter Example.*

Coiltronics Part No.	Rated Inductance at 1.8Apk (µH)	Dissipation (mW) (for 40˚C rise)	De-rated Irms (A)	Core Loss (mW)	I2R Loss (mW)	Total Loss (mW)
CTX10-1-52	7.5	277	1.98	88.4	108.3	196.7
CTX10-1A	8	371	2.7	35.7	103.5	129.2
DR73-100	9.5	282	2.03	11	142.7	153.7

Table 2. *Comparative Inductor Losses.*

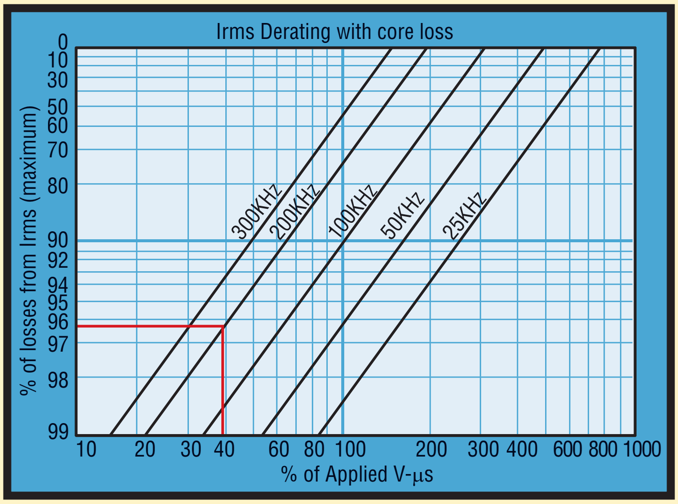

Fig. 4. *DR73 Irms De-rating Curve*

is the minimum inductance required to achieve a maximum ripple current of 600mA. We'll continue to look at this part to show the performance of an Iron powder device.

First, let's look at the overall losses and efficiency. To work out the core loss you must first calculate the applied volt-seconds:

$V_l = 1.8V$

$dt = V_o/V_{IN} \times 1/fs = 2.5\mu s$

Applied volt-µsecond = $1.8V \times 2.5\mu s = 4.5V{-}\mu s$

Where

V_l = inductor voltage,

V_o = output voltage,

V_{IN} = input voltage,

dt = switch on time, and

fs = switch frequency.

Looking at the DR73-100, this part has a volt-second rating of 11.5V-µs at 100 kHz, which is the applied volt-seconds that contributes 10% of the losses required for a 40°C temperature rise.

In this example, the part is used at 1.5A rms, 1.8A peak and 4.5V-µs. So the DR73-100 is being used at 39% of its volt-second rating. Looking at **Fig. 4**, you can see that at 200 kHz and 39% applied volt-second the maximum allowable loss arising from Irms is approximately 96.25% of the total loss.

Total loss for a 40°C temperature rise equates to the dc resistance (DCR) multiplied by the Irms rating squared, so for the DR73-100;

Loss for 40°C rise = $0.0634\Omega \times 2.11^2 = 0.282W$

For our example, the loss due to Irms needs to be reduced to 96.25% of this 40°C rise figure, which gives us a required Irms loss of 0.271W. From this, you can work out the maximum allowable rms current, which is 2.03A. You also know that the core loss is approximately 11mW (difference between the loss for a 40°C rise and the required Irms loss of 0.271W).

Repeating this procedure for the CTX10-1-52 and CTX10-1A can give you the results shown in **Table 2**, on page 28.

Weighing the Pros and Cons

All three inductors have a power dissipation less than that required for a 40°C rise. Thus, thermal performance should not be a problem in most applications. In practice, the inductor losses will be higher than calculated. This is because you have not accounted for the ac winding losses due to skin and proximity effects. These losses become more significant with larger ripple currents and increasing frequency, but is generally less than the I^2R losses. Looking at each of the alternatives, you can weigh the pros and cons of each inductor and identify the applications that suit them best.

CTX10-1-52: Iron powder toroid construction means the best possible EMI performance from what is termed a closed field construction. In short, there's no stray magnetic field. It also means low cost, with Iron powder being the cheapest available core material. However, high core loss and a practical operating frequency limit of 300 kHz makes Iron powder unsuitable for most handheld application. Higher operating frequencies, in excess of 1 MHz, are commonly used to reduce the size of the required inductor in these products. Iron powder toroids make a good cost-effective solution in high power applications where high inductance values and current ratings are required.

CTX10-1A: This is the clear winner when it comes to efficiency. The use of a high permeability core means fewer turns are required, and, as such, the winding DCR is low. Combining this with reasonable core loss, even at frequencies in excess of 500 kHz, and the amorphous solution provides a total loss that equates to less than 5% of the output power. However, two problems follow this solution: amorphous materials are costly and they tend to have poor temperature stability. This makes them unsuitable for use in high ambient temperatures. For a lower cost solution that still offers better performance than Iron powder, you should consider MPP or Sendust. These materials offer both lower losses and higher frequency operation than Iron powder with only a moderate cost penalty.

DR73-100: Ferrite drum core inductors offer the lowest overall cost in a very energy-dense package, making them the most popular selection for low power converters in handheld, computer, and telecom applications. The use of ferrite means high frequency operation is possible, in excess of 1 MHz, allowing the use of lower inductance values and smaller parts. The only problem with the drum core design is EMI—as drum cores have a significant stray field. Except for the most sensitive applications, this problem can be overcome by using a magnetically shielded device, such as the DR73.

Toroid and drum core constructions provide the required solution in most switching regulator applications. However, in high current applications, E and U/I core solutions allow the use of cooper foil for reduced I^2R losses. For our example, the best solution is the shielded drum. This part offers the smallest, lowest cost solution that has acceptable EMI performance. The EMI performance could be traded for a small cost benefit, but to obtain a more efficient solution would require a disproportionate increase in cost for only a small improvement. **PETech**

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