Application Note 1197 Selecting Inductors for Buck Converters
Selecting Inductors for Buck Converters

Introduction
This Application Note provides design information to help select an off-the-shelf inductor for any continuous-mode buck converter application. The first part shows how the designer should estimate his requirements, specifically the required inductance. The next part takes an off-the-shelf inductor and shows how to interpret the specs provided by the vendor in greater detail. A step-by-step procedure is provided.

Finally, all the previous steps are consolidated in a single design table, which answers the question: “How will the selected inductor actually perform in a specific application?” The important point to note here is that though every inductor is designed assuming certain specific ‘design conditions’, that does not imply that these conditions cannot be varied. In fact every inductor can be satisfactorily used for many applications. But to be able to do this, the designer must know how to be able to accurately predict, or extrapolate, the performance of the inductor to a new set of conditions, which are his specific ‘application conditions’. It will be shown that ‘intuition’ can be rather misleading. A detailed procedure is required and is presented in the form of the Design Table (Table 2) and the Selection Flow Chart (Figure 2).

Background: The Inductor Current Waveform
Refer to Figure 1, which shows the current through an inductor in continuous mode operation (bold line). Consider its main elements:

1. \( I_{DC} \) — is the geometrical center of the AC/ramp component — is the average value of the total inductor current waveform — is the current into the load, since the average current through the output capacitor, as for any capacitor in steady state, is zero

2. \( I_{PEAK} \) is \( I_{DC} + \Delta I/2 \), and it determines the peak energy in the core (\( e = \frac{1}{2} L I^2 \)), which in turn is directly related to the peak field the core must withstand without saturating.

3. \( I_{TROUGH} \) is \( I_{DC} - \Delta I/2 \) and determines the constant residual level of current/energy in the inductor. Note that it depends on the load, even though it is not itself transferred to the load.

4. The AC component of the current is \( I_{AC} = \Delta I = I_{PEAK} - I_{TROUGH} \)

5. The DC component is the load current for the case shown in the figure. \( I_{BC} = I_O \)

where \( I_O \) is the maximum rated load.

6. and ‘\( r \)’ is defined as the ratio of the AC to DC components (current ripple ratio) evaluated at maximum load, \( I_O \). Note that by definition ‘\( r \)’ is a constant for a given converter/application (as it is calculated only at maximum load), and it is also defined only for continuous conduction mode.

\[ r = \frac{\Delta I}{I_O} \]

A high inductance reduces \( \Delta I \) and results in lower ‘\( r \)’ (and lower RMS current in the output capacitor), but may result in a very large and impractical inductor. So typically, for most buck regulators, ‘\( r \)’ is chosen to be in the range of 0.25—0.5 (at the maximum rated load). See Appendix to this Application Note. Once the inductance is selected, as we decrease the load on the converter (keeping input voltage constant), \( \Delta I \) remains fixed but the DC level decreases and so the current ripple ratio increases. Ultimately, at the point of transition to discontinuous mode of operation, the DC level is \( \Delta I/2 \) as shown in Figure 1. So

• The current ripple ratio at the point of transition to discontinuous mode is 2. Therefore, the upper limit for ‘\( r \)’ is also 2.

• The load at which this happens can be shown by simple geometry to be \( r/2 \) times \( I_O \). So for example, if the inductance is chosen to be such that ‘\( r \)’ is 0.3 at a load of 2A, the transition to discontinuous mode of operation will occur at 0.15 times 2A, which is 300 mA.

Note: If the inductor is a ‘swinging’ inductor, its inductance normally increases as load current decreases and the point of transition to discontinuous mode may be significantly lower. We do not consider such inductors in this Application Note.

Estimating Requirements for the Application
There are two equivalent ways to go about calculating the required inductance and the designer should be aware of both.

**BASIC METHOD TO CALCULATE L**
From the general rule \( V = L \frac{\Delta I}{dt} \) we get during the ON time of the converter:

\[ V_{IN} = V_{SW} - V_O = L X \frac{\Delta I}{D/f} \]

where \( V_{IN} \) is the applied DC input voltage, \( V_{SW} \) is the voltage across the switch when it is ON, \( D \) is the duty cycle and \( f \) is the switching frequency in Hz. Solving for \( \Delta I \) we can write ‘\( r \)’ as:

\[ r = \frac{(V_{IN} - V_{SW} - V_O) \times D}{L \times f \times I_O} \]

Now, for a buck regulator, we can show that the duty cycle is
Estimating Requirements for the Application  (Continued)

where \( V_D \) is the forward drop across the catch diode (\( \approx 0.5V \) for a Schottky diode).

\( r \) can be finally written as:

\[
\begin{align*}
    r &= \frac{(V_{IN} - V_{SW} - V_O) \times (V_O + V_D)}{(V_{IN} - V_{SW} + V_D) \times L \times f \times I_0} \\
\end{align*}
\]

and \( L \) is therefore

\[
L = \frac{(V_{IN} - V_{SW} - V_O) \times (V_O + V_D)}{(V_{IN} - V_{SW} + V_D) \times r \times f \times I_0} \times 10^6 \mu H
\]

where \( f \) is in Hz.

EXAMPLE 1

The input DC voltage is 24V into an LM2593HV buck converter. The output is 12V at a maximum load of 1A. We require an output voltage ripple of 30 mV peak-to-peak (\( \pm 15 \) mV). We assume \( V_{SW} = 1.5V, V_D = 0.5V \) and \( f = 150,000 \) Hz.

Since, for loop stability reasons, we should not use any output capacitor of less than 100 m\( \Omega \), and since we do not wish to use an LC post filter, our \( \Delta I \) must be

\[
\Delta I = \frac{30 \text{ mV}}{100 \text{ m}\Omega} = 0.3A
\]

So '\( r \) is

\[
r = \frac{0.3}{1.0} = 0.3
\]

The required inductance is

\[
L = \frac{(24 - 1.5 - 12) \times (12 + 0.5)}{(24 - 1.5 + 0.5) \times 0.3 \times 150000 \times 1.0} \times 10^6 \mu H
\]

\[ L = 127 \mu H \]

The required energy handling capability is next calculated. Every cycle, the peak current is

\[
I_{PEAK} = I_0 + \frac{\Delta I}{2} = 1.0 + \frac{0.3}{2} = 1.15A
\]

The required energy handling capability '\( e \)' is

\[
e = \frac{1}{2} \times L \times I_{PEAK}^2 \mu J
\]

where \( L \) is in \( \mu H \). So

\[
e = \frac{1}{2} \times 127 \times 1.15^2 = 84 \mu J
\]

Note: During a hard power-up (no soft start) or abnormal conditions like a short circuit on the output, the feedback loop is not effective in limiting the current to the value used above for calculating the energy handling capability. The current is actually going to hit the internal current limit of the device, \( I_{CLIM} \) in Figure 1, and this could be much higher than the steady state value calculated above. If the inductor has saturated, and if the input DC voltage is higher than 40V the current could slew up at a rate so high that the controller may not be able to limit the current at all, leading to destruction of the switch. Luckily, most off-the-shelf inductors are designed with large inherent air gaps and do not saturate very sharply even under overload conditions. However we strongly recommend that at least when the input voltage is above 40V, the inductor should be sized to handle the worst case energy \( E_{CLIM} \):

\[
e_{CLIM} = \frac{1}{2} \times L \times I_{CLIM}^2 \mu J
\]

where \( L \) is in \( \mu H \) and \( I_{CLIM} \) is the internal limit of the regulator in amps.

VOLTS/SECONDS METHOD TO CALCULATE \( L \)

Talking in terms of voltseconds allows very general equations and curves to be generated. Here we talk of volts/secs or 'Et' which is simply the voltage across the winding of the inductor times the duration in seconds for which it is applied.

Note:

- Current ramps up to the same peak value whether \( V \) (the applied voltage across inductor) is large but \( t \) (the time for which \( V \) is applied) is small, or whether \( V \) is small but \( t \) is large. So an infinite number of regulators with different combinations of input and output voltages but having the same voltseconds are actually the same regulator from the viewpoint of basic magnetics design. \( Et \) is what really counts. (The only exception to this is the Core Loss term since this depends directly on the absolute value of the frequency too, not just the \( Et \)).
- Also, \( Et \) can be calculated during the ON-time, (Vs/secs gained), or during the OFF-time (Vs/secs lost). Both will give the same result since there is no net change in Vs/secs per cycle in steady state.
- Also, remember that though \( Vs/secs \) is related to the energy in the core, it does not tell us the total energy. The Vs/secs gives information only about the AC component of '\( r \)', i.e., \( \Delta I \). Combined with the DC component \( I_{DC} \), it determines the peak current and energy of the inductor. So both \( I_o \) and \( Et \) are the variables on which our design procedure and tables are based upon. But a given application is completely defined by certain \( I_o \) and \( Et \) (and frequency for the core loss term), and so these cannot be changed. Our only degree of freedom is \( L \) (or '\( r \)') and we fix it according to the guidelines in the Appendix.

From the general equation \( V = L \Delta I/dt \) we can write that \( V = L \Delta I \\
where \( L \) is in \( \mu H \), '\( r \)' can therefore be written as

\[
r = \frac{E_t}{L \times I_0}
\]

Solving for \( L \)

\[
L = \frac{E_t}{r \times I_0} \mu H
\]

which gives us an alternate and more general way of calculating \( L \).
Estimating Requirements for the Application  (Continued)

EXAMPLE 2
We repeat Example 1 from the viewpoint of Et.
The ON-time is
\[ t_{ON} = \frac{D}{f} = \frac{(12 + 0.5) \times 10^6}{(24 - 1.5 + 0.5) \times 150000} \mu s \]
\[ t_{ON} = 3.62 \mu secs \]
So Et is
\[ Et = (V_{IN} - V_{SW} - V_{CL}) \times t_{ON} = (24 - 1.5 - 12) \times 3.62 \ \text{V} \mu \text{secs} \]
\[ Et = 38.0 \ \text{V} \mu \text{secs} \]
L is therefore
\[ L = \frac{Et}{r} \mu \text{H} \]
\[ L = \frac{38.0}{0.3 \times 1.0} \mu \text{H} \]
\[ L = 127 \ \mu \text{H} \]
which gives us the same result as in Example 1 as expected.

SUMMARY OF REQUIREMENTS
- An inductance of 127 \mu H (or greater, based on maximum ‘r’ of 0.3)
- DC load of 1A (to ensure acceptable temperature rise, specify \( \Delta T \)) OR steady state Energy handling capability of 84 \mu J
- Peak load of 4.0A (to rule out core saturation if DC input voltage \geq 40V) OR peak energy handling capability of 1016 \mu J. (Max Current Limit of LM2593HV is 4.0A)
- Et of 38 V\mu secs
- Frequency 150 kHz
These can be communicated directly to a vendor for a custom-built design.

Characterizing an Off-the-Shelf Inductor
With reference to our design flow chart in Figure 2, the first pass selection is based upon inductance and DC current rating. We tentatively select a part from Pulse Engineering because its L and IDC are close to our requirements, even though the rest does not seem to fit our application (see Table 1 and bullets below). In particular the frequency for which the inductor was designed is 250 kHz, but our application is 150 kHz. We are intuitively lead to believe that since we are decreasing the frequency our core losses will go up, and so will the peak flux density. In fact the reverse happens in our case, and that is why it is important to follow the full procedure presented below. ‘Intuition’ can be very misleading.

The vendor also states that:
- The inductor is such that 380 mW dissipation corresponds to 50°C rise in temperature.
- The core loss equation for the core is \( 6.11 \times 10^{-18} \times B^{2.7} \times f^{2.04} \) mW where f is in Hz and B is in Gauss.
- The inductor was designed for a frequency of 250 kHz.
- \( E_{t_{100}} \) is the V\mu secs at which ‘B’ is 100 Gauss.

Note: For core loss equations it is conventional to use half the peak-to-peak flux swing. So, like most vendors, the ‘B’ above actually refers to \( \Delta B/2 \). This must be kept in mind in the calculations that follow.

The step-by-step calculations are:

a) AC Component of Current:
This can be easily calculated from
\[ E_t = L \Delta I \ \text{V} \mu \text{secs} \]
where L is in \mu H.
So
\[ \Delta I = \frac{E_t}{L} = \frac{59.4}{137} = 0.434 \text{A} \]
\[ r = \frac{\Delta I}{I_0} = \frac{0.434}{0.99} \]
\[ r = 0.438 \]
at a load current of 0.99A.

c) Peak Current:
\[ I_{PEAK} = I_0 + \frac{\Delta I}{2} = 0.99 + \frac{0.434}{2} \text{A} \]
\[ I_{PEAK} = 1.21 \text{A} \]

d) RMS Current:
\[ I_{RMS} = \sqrt{I_0^2 + \frac{\Delta I^2}{12}} \text{A} \]
\[ I_{RMS} = 0.998 \text{A} \]

e) Copper Loss:
This is
\[ P_{CU} = I_{RMS}^2 \times DCR \text{ mW} \]
where DCR is in m\Omega.
In most cases, to a close approximation, we can simply use \( I_{DC} \) instead of \( I_{RMS} \) in the above equation. Also sometimes, the vendor may have directly given the RMS current rating of the inductor.
\[ P_{CU} = 0.998^2 \times 387 \text{ mW} \]
\[ P_{CU} = 385 \text{ mW} \]
f) The AC Component of the B-Field:
This is proportional to the AC component of the inductor current.
Characterizing an Off-the-Shelf Inductor (Continued)

The vendor has provided the information that an Et of Et₁₀₀ = 10.12 Vµsecs produces 100 Gauss (B). So since the inductor is designed for an Et = 59.4 Vµsecs, we get

\[ B = \frac{Et}{Et_{100}} \times 100 = \frac{59.4}{10.12} \times 100 \text{ Gauss} \]

\[ B = 587 \text{ Gauss} \]

But this is half the peak-to-peak swing by convention. So

\[ \Delta B = 2B = 1174 \text{ Gauss} \]

CHECK: We can use the alternative form for \( \Delta B \) as given in Table 2. We asked the vendor for more details than he had provided on the datasheet and we learned that the effective area of the core, \( A_e \), is 0.0602 cm² and the number of turns is \( N = 84 \). So

\[ \Delta B = \frac{100 \cdot Et}{N \cdot A_e} \text{ Gauss} \]

\[ \Delta B = \frac{100 \cdot 59.4}{84 \cdot 0.0602} = 1175 \text{ Gauss} \]

which is what we expected.

g) The DC Component of the B-Field:

This is proportional to the DC component of the inductor current. In fact the instantaneous value of B can always be considered proportional to the instantaneous value of the current (for a given inductor).

The proportionality constant is known from f) above, i.e., a ∆I of 0.434A produces a ∆B of 1174 Gauss. So the DC component of the B-field must be

\[ B_{DC} = \frac{\Delta B}{\Delta I} \times I_{DC} \text{ Gauss} \]

where

\[ I_{DC} = I_O = 0.99A \]

\[ B_{DC} = \frac{1174}{0.434} \times 0.99 \text{ Gauss} \]

\[ B_{DC} = 2678 \text{ Gauss} \]

h) Peak B-Field:

Since B is proportional to I, we can write for the peak B-field

\[ B_{PEAK} = B_{DC} + \frac{\Delta B}{2} \text{ Gauss} \]

\[ B_{PEAK} = 2678 + \frac{1174}{2} \text{ Gauss} \]

\[ B_{PEAK} = 3265 \text{ Gauss} \]

i) Core Loss:

The vendor has stated that core loss (in mW) is \( 6.11 \times 10^{-18} \times B^{2.7} \times f^{2.04} \) watts where \( f \) is in Hz and \( B \) is in Gauss.

\[ P_{\text{CORE}} = 6.11 \times 10^{-18} \times B^{2.7} \times f^{2.04} \text{ mW} \]

\[ P_{\text{CORE}} = 6.11 \times 10^{-18} \times 587^{2.7} \times 25000^{2.04} \text{ mW} \]

\[ P_{\text{CORE}} = 18.7 \text{ mW} \]

j) Total Inductor Loss:

\[ P = P_{\text{Cu}} + P_{\text{Core}} \text{ mW} \]

\[ P = 385 + 18.7 \text{ mW} \]

\[ P = 404 \text{ mW} \]

k) Thermal Resistance of Inductor:

The vendor has stated that 380 mW dissipation corresponds to a 50°C rise in temperature. So thermal resistance of the inductor is

\[ R_{\text{TH}} = \frac{50}{380} \text{ °C/W} \]

\[ R_{\text{TH}} = 131.6 \text{ °C/W} \]

l) Estimated Temperature Rise of Inductor:

\[ T = R_{\text{TH}} \times \frac{P}{1000} \text{ °C} \]

\[ \Delta T = 131.6 \times \frac{404}{1000} \text{ °C} \]

\[ \Delta T = 53°C \]

Here the temperature rise ‘\( \Delta T \)’ is the temperature of the core, ‘\( T_{\text{CORE}} \)’ minus the worst case ambient temperature ‘\( T_{\text{AMBIENT}} \)’. The ‘ambient’ is the local ambient around the inductor.

m) Energy Handling Capability of Core:

\[ e = \frac{1}{2} \times L \times I_{\text{PEAK}}^2 \text{ µJ} \]

where \( L \) is in µH

\[ e = \frac{1}{2} \times 137 \times 1.21^2 \text{ µJ} \]

\[ e = 100 \text{ µJ} \]

As before, we warn that the energy in the core during hard power-up or a short circuit on the outputs, may be significantly higher.

In case of soft-start it should also be remembered that there are several ways to implement this feature, and not all lead to a reduction in switch or inductor current at start-up. The worst condition is start-up with a short already present on the output. The inductor waveforms should therefore be monitored on the bench during all conditions to check this out. Also it will be seen that all inductors of a ‘family’, i.e., using the same core will typically have the same rated energy capability. So if this core is found to be inadequate, normally the only way out is to move to a physically larger core/inductor. Other options include the use of improved and more expensive core materials.
SUMMARY OF INDUCTOR PARAMETERS

- The inductor is designed for about 50˚C rise in temperature over ambient at a load of 1A.
- The copper losses (385 mW) predominate (as is usual for such inductors/core materials) and the core losses are relatively small.
- The peak flux density is about 3200 Gauss, which occurs at a peak instantaneous current of 1.2A.
- The rated energy handling capability of the core is 100 µJ.

Note: Most vendors do not explicitly provide the material used, though an astute designer can figure this out by looking at the exponents of B and f in the core loss equation provided, or of course simply by asking the vendor. In this case we know that the material is ferrite and can typically handle a peak flux density of over 3000–4000 Gauss before it starts to saturate. (Caution: not all ferrite grades are similar in this regard and also that the saturation flux density BSAT falls as the core heats up.)

Evaluating the Inductor for the Actual Application

Above we have the limits of the inductor operating under its design conditions. We will now extrapolate its performance to our specific application conditions. Unprimed parameters are the original ‘design values’, and the corresponding primed parameters are the extrapolated ‘application values’.

The following are the design conditions (these may be allowed to change):
- IDC
- Et
- f
- TAMBIENT

The ‘Application Conditions’ are:
- IDC
- Et
- f
- TAMBIENT

In going from the ‘Design Conditions’ to the ‘Application Conditions’ the following are considered constant:
- L
- DCR
- Rth

The core loss equation

\[ \text{Thermal resistance of inductor in free air (˚C/W)} \]

If any of these are unknown, the vendor should be contacted. Table 2 condenses the step-by-step procedure given earlier and also shows how to ‘extrapolate’ the performance of the inductor.

EXAMPLE 3

This shows the complete selection procedure. Refer to Table 2 and Figure 2. We have seen that the ‘Design Conditions’ of the inductor are:
- Et = 59.4 Vµsecs
- f = 250,000 Hz
- IDC = 0.99A

Our ‘Application Conditions’ are
- Et’ = 38 Vµsecs
- f’ = 150,000 Hz
- IDC’ = 1A

(We assume that TAMBIENT is unchanged so we can ignore it above).

We need to verify that using the inductor in the given application:

a) current ripple ratio ‘r’ is close to desired
b) peak flux density/current are within bounds
c) temperature rise is acceptable

Using Table 2:

a) r:

Design Value:

\[ r = \frac{Et}{L \cdot IDC} \]

r = \frac{59.4}{137 \cdot 0.99} = 0.438

r’ = r \cdot \left( \frac{Et' \cdot IDC'}{Et \cdot IDC} \right)

r’ = 0.438 \cdot \left( \frac{38 \cdot 0.99}{59.4 \cdot 1} \right)

r’ = 0.277

We expected r’ to be slightly lower than 0.3 since the chosen inductor has a higher inductance than we required (137 µH instead of 127 µH). This is acceptable however as the output voltage ripple will be less than demanded.

b) Peak Flux Density

Design Value:
Evaluating the Inductor for the Actual Application (Continued)

\[ B_{\text{PEAK}} = \frac{200}{E_{\text{100}}} \left( I_{\text{DC}} \cdot L + \frac{E_t}{2} \right) \text{ Gauss} \]

\[ B_{\text{PEAK}} = \frac{200}{10.12} \left( (0.99 \cdot 137) + \frac{59.4}{2} \right) \text{ Gauss} \]

\[ B_{\text{PEAK}} = 3267 \text{ Gauss} \]

Extrapolated to our Application:

\[ B'_{\text{PEAK}} = B_{\text{PEAK}} \left( 2 \cdot L \cdot I'_{\text{DC}} + \frac{E_t}{2} \right) \text{ Gauss} \]

\[ B'_{\text{PEAK}} = 3267 \left( 2 \cdot 137 \cdot 1 + 38 \right) \left( 2 \cdot 137 \cdot 0.99 + 59.4 \right) \text{ Gauss} \]

\[ B'_{\text{PEAK}} = 3084 \text{ Gauss} \]

which is less than \( B_{\text{PEAK}} \) and therefore acceptable.

c) Peak Current

To ensure that the regulator will deliver rated load, we need to ensure that the peak current is less than the internal current limit of the Switcher IC.

Design Value:

\[ I_{\text{PEAK}} = \frac{I_{\text{DC}} + \frac{E_t}{2}}{A} \]

\[ I_{\text{PEAK}} = 0.99 + \frac{59.4}{2 \cdot 137} \]

\[ I_{\text{PEAK}} = 1.21 \text{A} \]

This corresponds to a B-field of 3267 Gauss as calculated above.

Extrapolated to our Application:

\[ I'_{\text{PEAK}} = I_{\text{PEAK}} \left( 2 \cdot L \cdot I'_{\text{DC}} + \frac{E_t}{2} \right) \text{ A} \]

\[ I'_{\text{PEAK}} = 1.21 \left( 2 \cdot 137 \cdot 1.0 + 38 \right) \left( 2 \cdot 137 \cdot 0.99 + 59.4 \right) \text{ A} \]

\[ I'_{\text{PEAK}} = 1.14 \text{A} \]

This corresponds to a B-field of 3084 Gauss as calculated above and is less than \( I_{\text{CLIM}} \) (Min Current Limit of LM2593HV is 2.3A).

d) Temperature Rise:

Design Values:

\[ P_{\text{CU}} = DCR \left( I_{\text{DC}}^2 + \frac{E_t^2}{12 \cdot L^2} \right) \text{ mW} \]

\[ P_{\text{CU}} = 387 \left( 0.99^2 + \frac{59.4^2}{12 \cdot 137^2} \right) \text{ mW} \]

\[ P_{\text{CU}} = 385 \text{ mW} \]

\[ P_{\text{CORE}} = a \left( \frac{b}{E_{\text{100}}} \cdot 100 \right)^b \cdot f^c \text{ mW} \]

\[ P_{\text{CORE}} = 6.11 \cdot 10^{-18} \cdot \left( \frac{59.4}{10.12} \cdot 100 \right)^{2.7} \cdot 2.04 \text{ mW} \]

\[ P_{\text{CORE}} = 18.7 \text{ mW} \]

So,

\[ \Delta T = \frac{P_{\text{CU}} + P_{\text{CORE}}}{1000} \text{ °C} \]

\[ \Delta T = \frac{50}{0.380} \cdot \frac{385 + 18.7}{1000} \text{ °C} \]

\[ \Delta T = 53^\circ \text{C} \]

because the vendor has stated that 380 mW dissipation in the inductor causes 50°C rise in temperature.

Extrapolated to our Application:

\[ P'_{\text{CU}} = P_{\text{CU}} \cdot \frac{(12 \cdot I'_{\text{DC}}^2 \cdot L^2) + \frac{E_t^2}{2}}{(12 \cdot I_{\text{DC}}^2 \cdot L^2) + \frac{E_t^2}{2}} \text{ mW} \]

\[ P'_{\text{CU}} = 385 \cdot \frac{(12 \cdot 1.1^2 \cdot 137^2) + 38^2}{(12 \cdot 0.99^2 \cdot 137^2) + 59.4^2} \text{ mW} \]

\[ P'_{\text{CU}} = 389 \text{ mW} \]

\[ P'_{\text{CORE}} = P_{\text{CORE}} \cdot \left[ \left( \frac{E_t'}{E_t} \right)^b \cdot \left( \frac{I'_{\text{DC}}}{I_{\text{DC}}} \right)^c \right] \text{ mW} \]

\[ P'_{\text{CORE}} = 18.7 \cdot \left( \frac{38}{59.4} \right)^{2.7} \cdot \left( \frac{150000}{250000} \right)^{2.04} \text{ mW} \]

\[ P'_{\text{CORE}} = 2 \text{ mW} \]

So,

\[ \Delta T' = \Delta T \cdot \left[ \frac{P'_{\text{CU}} + P'_{\text{CORE}}}{P_{\text{CU}} + P_{\text{CORE}}} \right] \text{ °C} \]

\[ \Delta T' = 53 \cdot \left[ \frac{389 + 2}{385 + 18.7} \right] \text{ °C} \]

\[ \Delta T' = 51^\circ \text{C} \]

which is considered to be acceptable in this application.
Conclusions
By the detailed selection procedure above, we can expect
the selected inductor to work well for the given lower fre-
cuency application example. As mentioned earlier, we would
have ‘intuitively’ thought that since the inductance and cur-
cent rating is about what we need, if we lowered the fre-
cuency from 250 kHz to 150 kHz, the peak current and field
would increase. But they actually decrease as we can now
see. The reason being, that the inductor was designed for a
higher Et in mind (59.4 Vµsecs vs. our 38 Vµsecs). As stated
early, Et in effect, defines the regulator configuration itself,
so we did not just lower the frequency, we actually went to an
entirely different input-output voltage combination to what
the inductor had been originally designed for. As we can now
guess, the original inductor had been probably designed for
a much higher applied voltage to what we subjected it to. But
this was not obvious at first sight. The full procedure as given
in Figure 2 and Table 2 is therefore necessary to avoid such
‘errors of intuition’.
The data sheets of National’s Simple Switchers also gener-
ally include simple nomograms and these are useful in most
cases, but limit the selection to certain previously specified
or custom built inductors and are also based on certain
assumptions. In particular, there are many factors to con-
SIDER when fixing a certain current ripple ratio ‘r’, which
happens to be the key input in the process of selection an
inductor. Nomograms are easy to use but assume a certain
‘r’ which may not be ideal for all purposes. In fact in the
example discussed above, we did in fact select an induct-
ance higher than what the nomograms may have recom-
mented, because of output voltage ripple considerations.
In general, this Application Note should help in selecting a
more optimum and readily available off-the-shelf inductor.

Appendix: Optimizing the Size of the Inductor
The size of the inductor is related to the energy handling
capability required. The energy handling capability is
\( \frac{1}{2} L \times I_{\text{PEAK}}^2 \). For a given application, if we reduce induct-
ance, it seems that this would increase \( \Delta I \) and thereby
\( I_{\text{PEAK}} \), which would cause the energy requirement to in-
crease since it depends on square of current. However, a
detailed calculation shows again that reality is counterintui-
tive. The energy handling requirement is actually substan-
tially reduced if the inductance is decreased. In terms of ‘r’,
we can in fact write the energy handling capability as

\[
e = \frac{I_C \times E_t}{8} \left( r + \frac{2}{r} \right)^{1/2} \mu J
\]

where ‘r’ is \( \Delta I/I_C \) and Et is in Vµsecs.

For a given application, Et is fixed as is \( I_C \), so the term in
square brackets gives ‘e’ the shape shown in Figure 3. We can
see that the energy handling requirement (size of induct-
or) decreases as ‘r’ increases (L decreasing). The best
value is the ‘knee’ and so it is a good idea to target an ‘r’ of
30%–40%. No great improvement in the size of the inductor
will take place by increasing ‘r’ much more than this, but the
RMS current in the output cap, and also the RMS current in
the input capacitor (especially for large duty cycles), will
increase substantially. The absolute value of the RMS ripple
current in the input capacitor is much higher than in the
output capacitor, and the designer should watch out for the
cost penalty on the input capacitor too! Refer to Table 3 for
the complete set of optimization equations expressed as a
function of ‘r’.

While optimizing, the following points need to be considered:

- For a given application, having defined input and output
  voltages and load current, Et is fixed as are D and \( I_O \).
  So the only degree of freedom is in selecting the ‘r’. The
  equations in Table 3 are therefore written in terms of ‘r’.
- Table 3 provides the general equations required for opti-
mization but also provides the values at an ‘r’ of 0.3 in the
  adjacent column as a benchmark. This is also equivalent
to the ‘flat top approximation’ often used for quick esti-
mates.
- Figure 3 plots the variation of each parameter, normal-
ized to the benchmark values (i.e., set to unity at an ‘r’ of
0.3).
- Note that when calculating dissipation in the switch, one
  must consider whether the switch is a bipolar transistor or
  a FET. If it is a FET, we need to apply \( I^2 R \) where I is the
  RMS switch current and R is the \( R_{DS} \) of the FET. If it is
  bipolar, we need to use \( V \times I \) where V is the saturation
  voltage across the switch, and I is the average switch
current. That is why both have been provided in Table 3.
  Also note that for a bipolar switch, the dissipation is
  seems almost independent of ‘r’. In practice, the satu-
ration voltage drop depends on the instantaneous value of
current, so dissipation does increase slightly with ‘r’.
- Referring to Figure 3 we can see that the RMS inductor
current hardly changes over a very wide range of ‘r’.
That is why, earlier in this Application Note, it was mentioned
that for the purpose of evaluating copper losses we may
use \( I_C^2 \) instead of \( I_{\text{RMS}}^2 \).
- The core losses also increase substantially with increas-
ing ‘r’. It can be shown that even if we keep the same
core size, the flux density \( B_{AC} \) will go up as \( n^2 \). Going to
a smaller core could increase this further.
- The RMS capacitor currents in the input and output are
the main components to consider because they can in-
crease rapidly with ‘r’. So for example, if we increase ‘r’ to
0.6 (from 0.3), the energy handling requirement of the
inductor falls by about 35% but the dissipation in the
output capacitors (if ESR is unchanged) will increase by
400%! Alternatively stated, we now need to select an
output capacitor with twice the ripple current rating.
- It must also be kept in mind that there is an output voltage
ripple \( \Delta V = ESR \times \Delta I \) associated with the current ripple.
Now, the ESR of the output capacitor cannot usually be
decreased below 100 mΩ–200 mΩ (with voltage mode
control) for loop stability reasons. So for high loads (and
high ‘r’), the dissipation in the output capacitor will nec-
essarily be high since we cannot reduce ESR further.
This may call for physically large sized output capacitors
to handle the dissipation. In addition, the output voltage
ripple will be high too, and since we cannot reduce this by
reducing the ESR, we will need to add on a post LC filter.
So, for high load currents, it may become necessary to
decrease ‘r’ substantially. This in turn will lead to a large
inductor with slow transient response ability.
Appendix: Optimizing the Size of the Inductor  (Continued)

- We have implied that the physical size of the inductor is related to its energy handling capability only. This in turn suggests that we are talking of inductor designs that are core-saturation limited. While this is usually true if the core material is a ferrite, it may not be true of some powdered iron inductors for example. The size of these may be limited not by core saturation but by core losses, which depend on flux swing, or $\Delta I$, not $I$ (or 'e'). So, while Figure 3 is still valid, the criterion of ‘best choice’ may change. It may be necessary to choose or restrict $r$ to much smaller values than the ‘knee’.

This completes the information required to optimize not only the inductor but the buck regulator itself. The key factor affecting cost/size of almost all the components is the current ripple ratio $r$ and this needs to be carefully optimized as discussed above.

![FIGURE 1. Inductor Current Waveform](image)

<table>
<thead>
<tr>
<th>TABLE 1. Specifications of Available Inductor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part Number</td>
</tr>
<tr>
<td>--------------</td>
</tr>
<tr>
<td>$I_{DC}$ (Amps)</td>
</tr>
<tr>
<td>P0150</td>
</tr>
</tbody>
</table>
Appendix: Optimizing the Size of the Inductor

FIGURE 2. Design Flow Chart for Selection of Inductor
Appendix: Optimizing the Size of the Inductor

![Energy Handling Requirement diagram](image)

**FIGURE 3. Optimization Chart for Setting 'r'**

**TABLE 2. Complete Design Table for Evaluating the Inductor for a Given Application**

<table>
<thead>
<tr>
<th>Design Parameters</th>
<th>Design Conditions $I_{DC}, E_t, f, T_{AMBIENT}$</th>
<th>Application Conditions $I'<em>{DC} = I</em>{DC'}, E't, f', T'_{AMBIENT}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Component of Current Amps</td>
<td>$\Delta I = \frac{E_t}{L}$</td>
<td>$\Delta I' = \Delta I \cdot \left\lfloor \frac{E't}{E_t} \right\rfloor$</td>
</tr>
<tr>
<td>Current Ripple Ratio 'r' ($\Delta I/I_{DC}$)</td>
<td>$r = \frac{E_t}{L \cdot I_{DC}}$</td>
<td>$r' = r \cdot \frac{E't \cdot I'<em>{DC}}{E_t \cdot I</em>{DC}}$</td>
</tr>
<tr>
<td>Peak Current in Inductor Amps</td>
<td>$I_{PEAK} = I_{DC} + \frac{E_t}{2 \cdot L}$</td>
<td>$I'<em>{PEAK} = I</em>{PEAK} \cdot \left(\frac{2 \cdot L \cdot I_{DC} + E_t}{2 \cdot L \cdot I_{DC} + E_t} \right)^{1/2}$</td>
</tr>
<tr>
<td>RMS Current in Inductor Amps</td>
<td>$I'<em>{RMS} = \sqrt{I</em>{DC}^2 + \frac{E_t^2}{12 \cdot L^2}}$</td>
<td>$I'<em>{RMS} = I</em>{RMS} \cdot \sqrt{\left(\frac{12 \cdot I_{DC}^2 \cdot L^2 + E_t^2}{12 \cdot I_{DC}^2 \cdot L^2 + E_t^2} \right)^{1/2}}$</td>
</tr>
<tr>
<td>AC Flux Density Gauss</td>
<td>$\Delta B = \frac{E_t}{E_{100}} \cdot 200 = \frac{100 \cdot E_t}{N \cdot A_e}$</td>
<td>$\Delta B' = \Delta B \cdot \frac{E't}{E_t}$</td>
</tr>
<tr>
<td>Peak Flux Density Gauss</td>
<td>$B_{PEAK} = \frac{200}{E_{100}} \cdot \left[\left(I_{DC} \cdot L\right) + \frac{E_t}{2}\right]$</td>
<td>$B'<em>{PEAK} = B</em>{PEAK} \cdot \frac{2 \cdot L \cdot I'<em>{DC} + E_t'}{2 \cdot L \cdot I</em>{DC} + E_t}$</td>
</tr>
<tr>
<td>Copper Losses mW</td>
<td>$P_{CU} = DCR \cdot \left(I_{DC}^2 + \frac{E_t^2}{12 \cdot L^2}\right)$</td>
<td>$P'<em>{CU} = P</em>{CU} \cdot \left(\frac{12 \cdot I_{DC}^2 \cdot L^2 + E_t^2}{12 \cdot I_{DC}^2 \cdot L^2 + E_t^2}\right)^{1/2}$</td>
</tr>
<tr>
<td>Core Losses mW</td>
<td>$P_{CORE} = a \cdot \left[\frac{E_t}{E_{100}} \cdot 100\right] \cdot f^c$</td>
<td>$P'<em>{CORE} = P</em>{CORE} \cdot \left[\left(\frac{E't}{E_t}\right)^b \cdot \left(\frac{f'}{f}\right)^c\right]$</td>
</tr>
<tr>
<td>Energy in Core µJ</td>
<td>$\phi = \frac{1}{2} \cdot L \cdot \left[I_{DC}^2 + \frac{E_t}{2 \cdot L}\right]^2$</td>
<td>$\phi' = \phi \cdot \left(\frac{2 \cdot L \cdot I'<em>{DC} + E_t'}{2 \cdot L \cdot I</em>{DC} + E_t}\right)^2$</td>
</tr>
</tbody>
</table>
Appendix: Optimizing the Size of the Inductor

TABLE 2. Complete Design Table for Evaluating the Inductor for a Given Application

<table>
<thead>
<tr>
<th>Design Parameters</th>
<th>Design Conditions ( I_{\text{DC}}, E_t, f, T_{\text{AMBIENT}} )</th>
<th>Application Conditions ( I'_{\text{DC}} = I_0, E'<em>t, f', T'</em>{\text{AMBIENT}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature Rise ((\Delta T)) °C</td>
<td>( \Delta T = R_{\text{th}} \cdot \frac{P_{\text{Cu}} + P_{\text{Core}}}{1000} )</td>
<td>( \Delta T' = \Delta T \cdot \frac{P'<em>{\text{Cu}} + P'</em>{\text{Core}}}{P_{\text{Cu}} + P_{\text{Core}}} )</td>
</tr>
</tbody>
</table>

\( E_t \) in Vµsecs, DCR in mΩ, \( L \) in µH, \( f \) in Hz, Effective Area \( A_e \) in cm², \( N \) is number of turns

TABLE 3. Optimization Table for Fixing Current Ripple Ratio \( r \)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>As a Function of ( r ) (to a first approximation)</th>
<th>For ( r = 0.3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Handling Capability µJ</td>
<td>( I_0 \cdot E_t \cdot \frac{r}{8} \cdot \left[ \frac{2}{r+1} \right]^2 )</td>
<td>( 2.2 \cdot I_0 \cdot E_t )</td>
</tr>
<tr>
<td>RMS Current in Output Cap Amps</td>
<td>( I_0 \cdot \frac{r}{\sqrt{12}} )</td>
<td>( 0.09 \cdot I_0 )</td>
</tr>
<tr>
<td>RMS Current in Input Cap Amps</td>
<td>( I_0 \cdot \sqrt{D \cdot \left[ 1 - D + \frac{r^2}{12} \right]} )</td>
<td>( I_0 \cdot \sqrt{D \cdot (1 - D)} )</td>
</tr>
<tr>
<td>RMS Current in Inductor Amps</td>
<td>( I_0 \cdot \sqrt{1 + \frac{r^2}{12}} )</td>
<td>( I_0 )</td>
</tr>
<tr>
<td>RMS Current in Switch Amps</td>
<td>( I_0 \cdot \sqrt{D \cdot \left[ 1 + \frac{r^2}{12} \right]} )</td>
<td>( I_0 \cdot \sqrt{D} )</td>
</tr>
<tr>
<td>Average Current in Switch Amps</td>
<td>( I_0 \cdot D )</td>
<td>( I_0 \cdot D )</td>
</tr>
<tr>
<td>Average Current in Diode Amps</td>
<td>( I_0 \cdot (1-D) )</td>
<td>( I_0 \cdot (1-D) )</td>
</tr>
</tbody>
</table>

\( r = \Delta I/I_0 \), \( E_t \) in Vµsecs

LIFE SUPPORT POLICY

NATIONAL’S PRODUCTS ARE NOT AUTHORIZED FOR USE AS CRITICAL COMPONENTS IN LIFE SUPPORT DEVICES OR SYSTEMS WITHOUT THE EXPRESS WRITTEN APPROVAL OF THE PRESIDENT AND GENERAL COUNSEL OF NATIONAL SEMICONDUCTOR CORPORATION. As used herein:

1. Life support devices or systems are devices or systems which, (a) are intended for surgical implant into the body, or (b) support or sustain life, and whose failure to perform when properly used in accordance with instructions for use provided in the labeling, can be reasonably expected to result in a significant injury to the user.

2. A critical component is any component of a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or system, or to affect its safety or effectiveness.

National does not assume any responsibility for use of any circuitry described, no circuit patent licenses are implied and National reserves the right at any time without notice to change said circuitry and specifications.
IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, modifications, enhancements, improvements, and other changes to its products and services at any time and to discontinue any product or service without notice. Customers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All products are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its hardware products to the specifications applicable at the time of sale in accordance with TI's standard warranty. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by government requirements, testing of all parameters of each product is not necessarily performed.

TI assumes no liability for applications assistance or customer product design. Customers are responsible for their products and applications using TI components. To minimize the risks associated with customer products and applications, customers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any TI patent right, copyright, mask work right, or other TI intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information published by TI regarding third-party products or services does not constitute a license from TI to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. Reproduction of this information with alteration is an unfair and deceptive business practice. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI products or services with statements different from or beyond the parameters stated by TI for that product or service voids all express and implied warranties for the associated TI product or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

TI products are not authorized for use in safety-critical applications (such as life support) where a failure of the TI product would reasonably be expected to cause severe personal injury or death, unless officers of the parties have executed an agreement specifically governing such use. Buyers represent that they have all necessary expertise in the safety and regulatory ramifications of their applications, and acknowledge and agree that they are solely responsible for all legal and regulatory requirements concerning their products and applications. Buyers must fully indemnify TI and its representatives against any damages arising out of the use of TI products in such safety-critical applications.

TI products are neither designed nor intended for use in military/aerospace applications or environments unless the TI products are specifically designated by TI as military-grade or "enhanced plastic." Only products designated by TI as military-grade meet military specifications. Buyers acknowledge and agree that any such use of TI products which TI has not designated as military-grade is solely at the Buyer's risk, and that they are solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI products are neither designed nor intended for use in automotive applications or environments unless the specific TI products are designated by TI as compliant with ISO/TS 16949 requirements. Buyers acknowledge and agree that, if they use any non-designated products in automotive applications, TI will not be responsible for any failure to meet such requirements.

Following are URLs where you can obtain information on Texas Instruments products and application solutions:

<table>
<thead>
<tr>
<th>Products</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Audio</td>
<td>Communications and Telecom</td>
</tr>
<tr>
<td>Amplifiers</td>
<td>Computers and Peripherals</td>
</tr>
<tr>
<td>Data Converters</td>
<td>Consumer Electronics</td>
</tr>
<tr>
<td>DLP® Products</td>
<td>Energy and Lighting</td>
</tr>
<tr>
<td>DSP</td>
<td>Industrial</td>
</tr>
<tr>
<td>Clocks and Timers</td>
<td>Medical</td>
</tr>
<tr>
<td>Interface</td>
<td>Security</td>
</tr>
<tr>
<td>Logic</td>
<td>Space, Avionics and Defense</td>
</tr>
<tr>
<td>Power Mgmt</td>
<td>Transportation and Automotive</td>
</tr>
<tr>
<td>Microcontrollers</td>
<td>Video and Imaging</td>
</tr>
<tr>
<td>RFID</td>
<td></td>
</tr>
<tr>
<td>OMAP Mobile Processors</td>
<td></td>
</tr>
<tr>
<td>Wireless Connectivity</td>
<td></td>
</tr>
</tbody>
</table>

TI E2E Community Home Page    e2e.ti.com

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2011, Texas Instruments Incorporated