Application Bulletin AB-12

Insight into Inductor Current

Introduction

The design of the main power inductor in a switching power supply provides many challenges to the engineer. Not only must an inductance value be chosen, but also how much current the inductor can handle, the winding resistance, mechanical factors, etc. This Application Bulletin looks at one of these considerations: understanding the effects of DC current on an inductor. This will provide some of the background necessary to making an informed selection of an inductor.

Understanding the Function of the Inductor

An inductor is often described as being part of an LC filter at the output of a switching power supply (with the "C" being the output capacitors). Although this is correct, for the purposes of understanding the design of an inductor it is necessary to have deeper insight into the inductor's operation.

In a buck converter (the type used by all Fairchild switching controllers), one end of the inductor is attached to the output voltage, which is DC. The other end is alternately attached to the input voltage or ground, the alternation occurring at the switching frequency (see Figure 1):

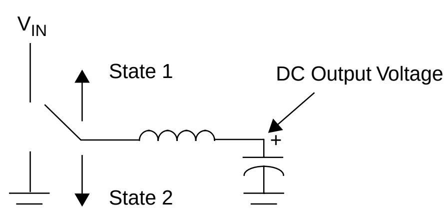


Figure 1. Basic Switching Action of a Converter

In State 1, the connection is made to the input voltage: this is done by turning on a ("high-side") MOSFET. In State 2, the connection is made to ground. Depending on the type of controller being used, this may be done in one of two ways: the connection to ground can be made with a diode, or with another ("low-side") MOSFET. In the latter case, the converter is called "synchronous".

Now consider what happens to the inductor's current during these two states. In State 1, the input voltage is being applied to one side of the inductor, and the output voltage to the other side. For a buck converter, the input voltage is <u>necessarily</u> larger than the output voltage, and so there is a net positive voltage across the inductor. Conversely, in State 2, ground is applied to the side of the inductor that was previously attached to the input voltage. For a buck converter, the output voltage is <u>necessarily</u> positive, and so there is a net negative voltage across the inductor.

We recall that the current through an inductor changes according to

$$V = L\frac{dI}{dt}$$

Thus when the voltage across the inductor is positive (State 1), the inductor current increases; when the voltage across the inductor is negative (State 2), the inductor current decreases. The net current through the inductor is shown in Figure 2:

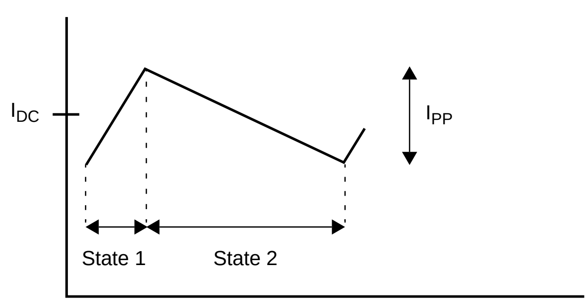


Figure 2. Inductor Current

Inspection of this figure shows that the maximum current that the inductor ever sees consists of the DC current, plus half of the peak-to-peak current due to the switching. This latter is called the ripple current. Using the equation above, we can calculate this peak current as:

$$I_{PK} = I_{DC} + \frac{I_{PP}}{2} = I_{DC} + \frac{1}{2}\frac{(V_{in} - V_{out}) \times t_{on}}{L} =$$

$$I_{DC} + \frac{1}{2}\frac{(V_{in} - V_{out}) \times T \times DC}{L}$$

where t_{on} is the time that the converter is in State 1, T is the switching period (one over the switching frequency) and DC is the Duty Cycle, that is, the percentage of time that the converter is in State 1.

Caveat: This calculation has assumed that the voltage drops due to the various components (such as the resistive drop of the MOSFETs and inductor or current sense resistor, or the forward voltage of a schottky in a non-synchronous converter) are negligible compared to the input and output voltages. If they are not, use these more accurate equations instead:

Synchronous Converter:

$$I_{PK} = I_{DC} + \frac{1}{2}\frac{(V_{in} - V_{out} - I \times R)}{L}\frac{(V_{out} + I \times R)}{V_{in}}T$$

Nonsynchronous Converter:

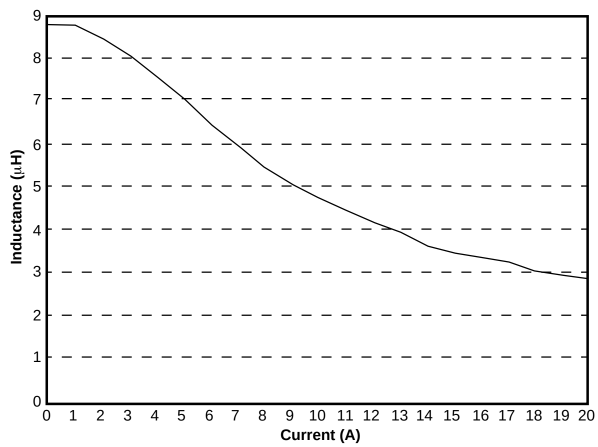
$$I_{PK} = I_{DC} + \frac{1}{2}\frac{(V_{in} - V_{out} - I \times R)}{L}\frac{(V_{out} + I \times R_S + V_f)}{(V_{in} - I \times R_M + V_f)}T$$

where R_S is the sum of the sense resistor's resistance and the winding resistance of the inductor, V_f is the forward drop of the schottky, and R is the sum of the resistance of R_S and the on-resistance of the MOSFET, $R = R_S + R_M$.

Inductor Core Saturation

Having now calculated the peak inductor current, we can look at what this does to the inductor. The fundamental fact to know is that as the current through an inductor increases, its inductance decreases. This is due to the underlying physics of the core material. How much the inductance decreases is the important question: if it decreases too much, the converter may not work properly any more. The current at which the inductor does not function properly in the circuit any more is called the "saturation current", and is a fundamental parameter of the inductor.

In practice, the switching power inductors used for converters always have a "soft" saturation. What this means can be understood by viewing a plot of actually measured inductance vs. DC current:



This inductor has a "soft" saturation characteristic because its inductance doesn't radically decrease at some particular current: as the current increases, the inductance very gradually tails off.

NOTE: The relatively large drop in inductance shown in this curve is typical of most inductors such as toroids, gapped E-cores, etc. However, rod core inductors show almost no change in inductance at almost any current.

Given this soft saturation characteristic, it is apparent that in most converters, it is adequate to specify the inductor's minimum inductance at the DC output current; adding a little bit of extra current due to the ripple doesn't greatly affect the inductance. In most applications, ripple current will be relatively small anyway, since it directly impacts output ripple voltage. Thus it is common practice in the industry to specify inductance at the DC output current, and to ignore the ripple current in the spec.

Notes:

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