Choosing Inductors for DC/DC Regulators

When selecting an inductor for the output storage element of a switching DC/DC regulator, a designer can be faced with a bewildering array of options from different suppliers and even within the ranges of one supplier. Using a 'point of load' converter as an example, this article explains what the choices are and what advantage one choice might have over another. The principles generally read across to all inductor applications. **Paul Lee, Director of Engineering, Murata Power Solutions, Milton Keynes, UK**

A common requirement is to convert one DC level to another lower level at high efficiency without isolation. At high power, a modular, 'point of load' buck switching converter from one of the many suppliers is economic but for low power, many designers opt for a circuit utilising a control IC and the necessary discrete components. Excepting 'charge pump' circuits, an inductor is invariably required to store energy to maintain the output during the 'dead' periods of the usual pulse width modulation regulation methodology. Figure 1 shows the basic configuration.

Looking in the Specs

The IC application note will often guide selection of an appropriate inductor with a recommended part number from a magnetics manufacturer. However, this part may not be optimum for the actual application and may not be in the required mechanical format. If just an inductance is given, the designer must look even further into the specifications of available parts to select something appropriate. Also, inductance is a starting point that may need to be adjusted, perhaps to fall in line with preferred values or for the designer to understand how the circuit responds if the inductance is at the extreme of its tolerance.

Normally the inductance value is chosen to achieve a particular inductor ripple current according to:

$$\Delta I = U\, t / L$$

where ΔI is the peak to peak ripple current, U is the output voltage less free-wheeling diode or synchronous rectifier drop, t is the maximum 'off' time of the main switch and L is the inductance. Note this is load-independent.

Transients and EMI

A large inductance value will therefore give a low ripple current which is absorbed by the output capacitor giving a low output ripple voltage generated across the capacitor ESR and ESL. When electrolytic capacitors with relatively high ESR and limited ripple current ratings were the norm, it was important to keep the ripple current low and hence inductance high. However, monolithic ceramic or film capacitors are now common with extremely low ESR that allows much higher ripple currents for minimal heating and output ripple voltage. Smaller inductance values are therefore feasible giving correspondingly lower DC resistance and higher current ratings. A smaller inductance also allows faster load transient response time.

There are three problems associated with allowing a very high ripple current. Firstly, because the ripple is superimposed on the DC load current through the inductor, it can cause additional ohmic losses in the wire and AC losses in the core. Secondly, the peak of the ripple must not exceed the saturation limit for the inductor, and finally at a light load the 'valley' of the ripple current will cross over zero. For synchronous rectifiers that can conduct in both directions, this current can go negative and stay 'continuous'. For diode rectifiers, the current stops or goes 'discontinuous' for a part of each switching cycle for loads less than this minimum value. The transfer function of the converter changes as this minimum load value is crossed and the loop compensation has to be designed to give stability in both conditions. This normally results in a compromise if only in increased circuit complexity.

Having decided on an inductance, the inductor current rating must be chosen. Values in data sheets will be for a continuous current for either a given temperature rise or for a given inductance drop as the inductor starts to saturate. As mentioned, there may be significant ripple current so this must be allowed for. If temperature rise is the limit, it may be possible to run at high ripple currents or in excess of the rated load current if airflow is available. Note that different manufacturers rate their inductors for different

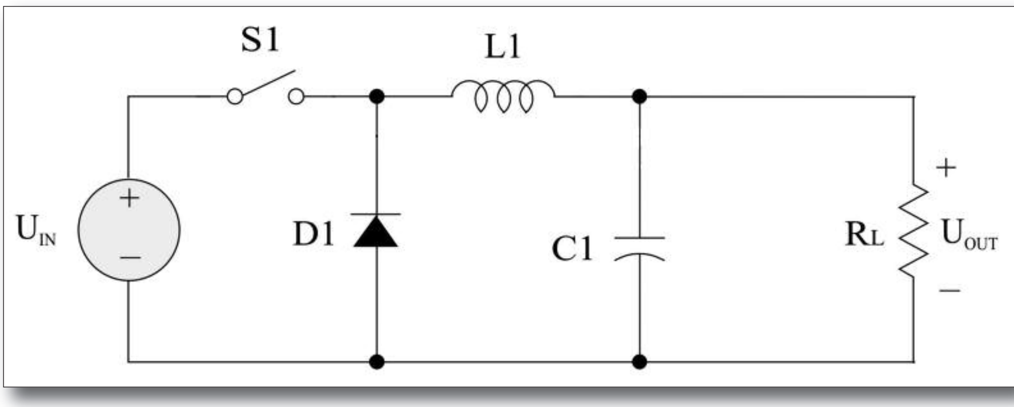


Figure 1: Buck converter schematic

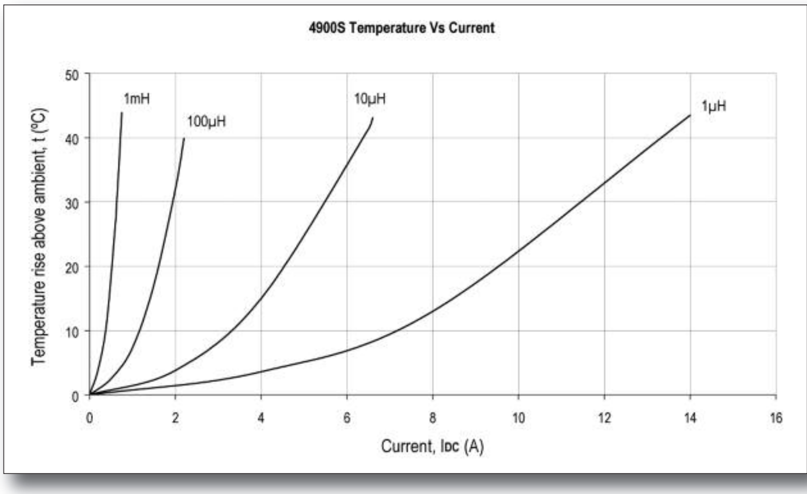


Figure 2: Current vs temperature graph for an example inductor

temperature rises and percentage drop in inductance. For example, Murata Power Solutions use 40°C rise and 25 % drop respectively. From their data sheets you can see that the 4900S series is saturation-limited as their 11.8 A rated part has a rise of only 33°C at this current (see Figure 2).

It is worth examining also how inductance falls off with current. Different core materials and shapes saturate more or less sharply. Transient and overload conditions should be considered which might, with some materials, cause a sudden, considerable drop in inductance with resultant damagingly high peak currents in semiconductors. Powder cores generally saturate more gradually though they will have higher core losses with AC applied. It should be appreciated that saturation levels vary strongly with temperature typically dropping 20 % between 25°C and 100°C. A correctly specified inductor will factor this into the rated current value.

Some powder materials have a designed-in 'swing' of permeability so that at very light load, the inductance is much higher and therefore can give lower ripple current which helps with the mode change stability problem mentioned previously.

Inductor DC resistance will be quoted in data sheets which will cause volt drop and dissipation. The value will normally be quoted at 25°C and will rise with the temperature coefficient of copper at about 0.4 % / K. Again, a correctly specified inductor will include this effect in current rating.

A little-considered specification is the impulse voltage rating of an inductor. In low voltage applications, this is not an issue. However, some buck converters drop rectified mains voltage to logic levels and the inductor can see up to around 400 V end-to-end at high frequency. The construction of the inductor should be such that the wire breakdown voltage is appropriate, particularly between winding start and finish where the wires may cross. MnZn ferrite is essentially conductive having a resistivity of typically 1-10 Ωm and may provide a 'sneak' path for breakdown. NiZn ferrite has high resistivity, typically 105 Ωm and is used for the bobbin-less drum core styles of inductor but for a high voltage application a style with an insulating bobbin would still be recommended. If not stated in the data sheet, the inductor manufacturer should be able provide an impulse rating from product qualification testing.

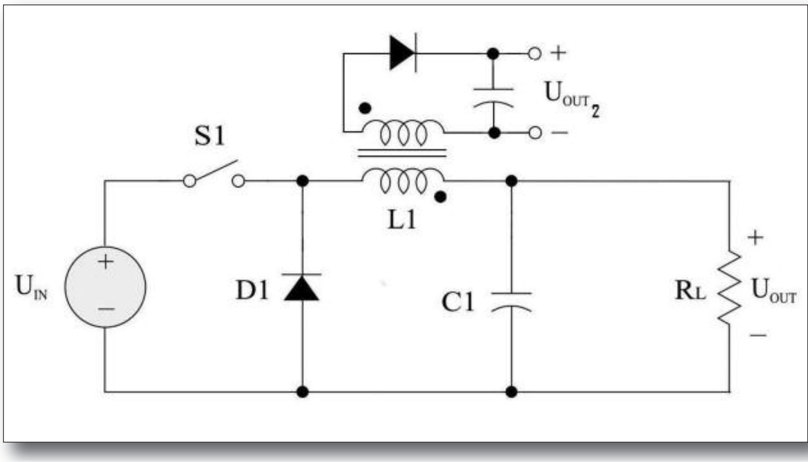
Another characteristic to consider is the self-resonant frequency (SRF) of the inductor that can be in the 100s of kHz for high inductance values. Any simulation of the circuit should include parallel winding capacitance and DC resistance for best accuracy. Data sheets will give inductance and SRF so the capacitance can be derived from

$$C = \frac{1}{4\pi^2 (SRF)^2 L}.$$

Any inductor is a potential source of radiation. Where this may be an issue, a toroidal core would be preferable with a distributed gap such as Murata Power Solutions' 3200 series. A ferrite drum core such as utilised in their 2800 series is usually lowest cost but its open construction can lead to EMC problems. The necessary core gap is effectively the distance between the bobbin flanges outside of the winding. Some suppliers provide inductors with optional ferrite sleeves that provide screening such as the Murata Power Solutions 2300 series shown in Figure 3. If the electrically 'hot' end of the inductor is arranged to be the 'start' of the winding, that is, the innermost layer, the outer layers provide a degree of natural electrostatic screening. Look for the dot or marking on the body of the inductor to signify which terminal is the start. A degree of magnetic screening can be achieved with a copper 'belly band' around the component but it would normally be more cost effective to select a part designed to contain magnetic fields.

Stubborn EMC problems could also be addressed by the placement and orientation of the inductor. Unscreened tracks under the component should be avoided. Remember that copper ground planes only provide electrostatic screening,

Figure 3: Use of ferrite sleeves example, Murata Power Solutions 2300 series



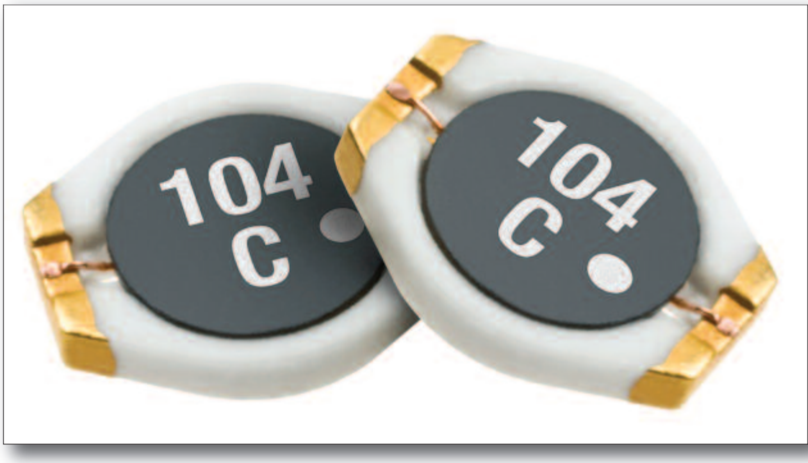


Figure 4: Generating an auxiliary low power voltage

that is, they provide a diversion route for capacitatively coupled currents. Attenuation of electromagnetic coupling requires a ferrite screen or a copper band that effectively provides a 'shorted turn' to the external field.

Observe peak voltage

An interesting fact is that the peak voltage across the inductor when the main switch S1 is off is essentially constant with load and line variations in a buck converter so if you add an extra winding to the inductor and peak rectify the waveform as in Figure 4, you get a low power, isolated and semi-regulated voltage for free!

Finally there is a choice of mounting style. Through hole and SMT parts are available with a variety of terminations allowing for high vibration environments and low profile versions such as the Murata Power Solutions 2700T series (Figure 5) are available at just 1 mm high for the most space sensitive applications.

Figure 5. Space constrained applications benefit from low profile surface mount inductors