Choosing Inductors and Capacitors for DC/DC Converters

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ABSTRACT

Wireless handsets, PDAs, and other portable electronic devices continue to shrink while increasing in complexity. As a result, engineers face design challenges with battery life, PC-board space, and power dissipation. These problems can be overcome by increasing the efficiency of the dc/dc converters used in these products.

Efficiency is often the primary design goal when using a dc/dc converter. Many design requirements involve converting the battery voltage to a low supply voltage. Although a linear regulator can be used, it cannot achieve the efficiency of a switching-regulator design. This article covers some of the common issues designers face when balancing circuit size, performance, and cost.

Large-Signal vs Small-Signal Response

Switching converters employ complex regulation schemes to keep efficiency high at both heavy and light loads. Modern CPUs require fast large-signal response from the regulator. For instance, when a processor is switching from idle to full-speed operation, the current drawn by the core can quickly rise from a few tens of microamps to hundreds of milliamps.

As load conditions change, the control loop rapidly responds to the new requirements in order to keep the voltage within the regulation limits. The amount and rate of load change determines whether the loop response is called a large-signal response or a small-signal response. We define the small-signal parameters based on a steady-state operating point. Consequently, we can typically consider variations below 10% of a steady-state operating point as being a small-signal variation.

In practice, when a load demands a sudden current increase, the error amplifier is in slew limit and does not control the loop. This is because the load transient occurs faster than the error amplifier can respond, so the output capacitors satisfy the transient current until the inductor current can catch up.

Large-signal response temporarily takes the loop out of operation. However, the loop must respond smoothly going into and out of large-signal response. The wider the loop bandwidth, the faster the load transient the loop can respond to.

Even though the regulation loop, from a small-signal prospective, may show enough gain and phase margin, the switching converter can still exhibit instability and ringing during line or load transients. When selecting external components, power supply designers need to be aware of these limitations, otherwise their designs could fail in practical use.

Inductor Selection

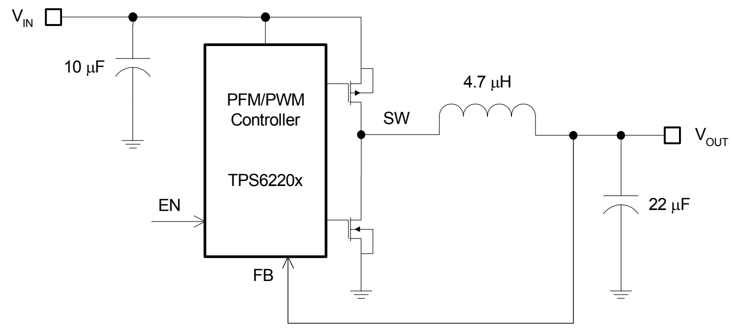

Figure 1. Basic Buck Regulator

The basic buck-regulator circuit shown in Figure 1 is used for the discussion of inductor selection.

For most TPS6220x applications, the inductor value ranges from 4.7 µH to 10 µH. Its value is chosen based on the desired ripple current. Usually, it is recommended to operate the circuit with a ripple current of less than 20% of the average inductor current. Higher V_{IN} or V_{OUT} also increases the ripple current as shown in Equation 1. The inductor must be able to handle the peak switching current without saturating the core, which would result in a loss of inductance.

$$\Delta I_L = \frac{1}{f*L} V_{OUT}\left(1-\frac{V_{OUT}}{V_{IN}}\right) \quad (1)$$

At the expense of higher output-voltage ripple, small-value inductors result in a higher output-current slew rate, improving the load transient response of the converter. Large-value inductors lower the ripple current and reduce the core magnetic hysteresis losses.

The total coil losses can be combined into the loss resistance (R_S), which is effectively connected in series with the ideal inductance (L_S). This results in the simplified equivalent circuit shown in Figure 2.

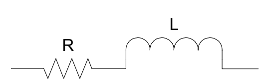

Figure 2. Inductor Simplified Equivalent Circuit

Even though the losses in R_S are frequency dependent, the dc resistance (R_{dc}) is also specified in inductor data sheets. This depends on the wire material and size, and the construction type of SMD inductors. It is characterized at room temperature by a simple resistance measurement.

The size of R_{dc} directly influences temperature rises in the coil. Prolonged operation above the current rating must be avoided.

The total coil losses consist of both the losses due to R_{dc}, and the following frequency-dependent components:

- Core-material losses (magnetic hysteresis loss, eddy-current loss)
- Skin-effect losses in the conductor (current displacement at high frequencies)
- Magnetic-field losses of adjacent windings (proximity effect)
- Radiation losses

All these loss components can be combined into a series R_S. This loss resistance is primarily responsible for defining the quality of the inductor. Unfortunately, mathematical determination of R_S is impractical. Therefore, inductors are usually measured over the entire frequency range with an impedance analyzer. This measurement provides the individual components $X_L(f)$, $R_S(f)$ and $Z(f)$.

The ratio of reactance (X_L) to total resistance (R_S) of an induction coil is known as the quality factor Q, see Equation 2. Q is defined as a quality characteristic of the inductor. The larger the losses are, the poorer the inductor acts as an energy storage element.

$$Q = \frac{X_L}{R_S} = \frac{\omega L}{R_S} = \frac{\text{Reactance}}{\text{Total Resistance}} \qquad (2)$$

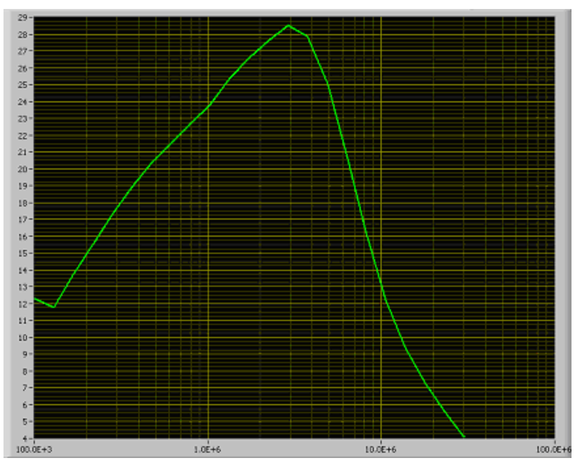

Figure 3. Q vs Frequency (Hz)

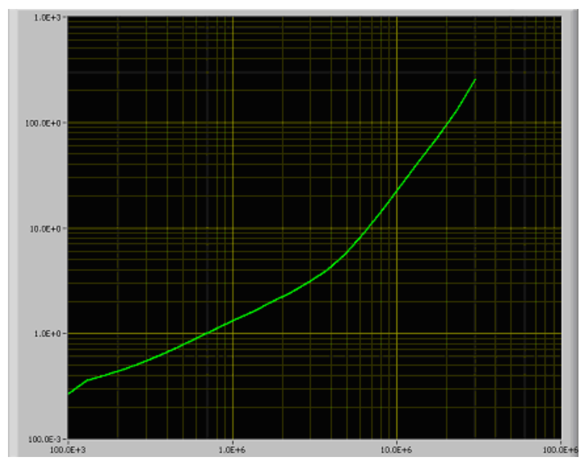

Figure 4. R_S (Ω) vs Frequency (Hz)

4.7-µH wire wound inductor, R_{dc} = 240 mΩ, I_{SAT} = 700 mA

The quality-frequency graph is helpful in selecting the best inductor construction for the particular application. As it appears on the measurement results in Figure 3, the operating range with the smallest losses (highest Q) can be defined up to the quality turning point. If the inductor is used at higher frequencies, the losses increase rapidly, and Q decreases.

A properly designed inductor degrades efficiency by only a small percentage. Different core materials and shapes change the size/current and price/current relationship of an inductor. Shielded inductors in ferrite material are small and don't radiate much energy. Choosing an inductor often depends on the price/size tradeoffs, and on requirements for radiated-field/electromagnetic-interference suppression.

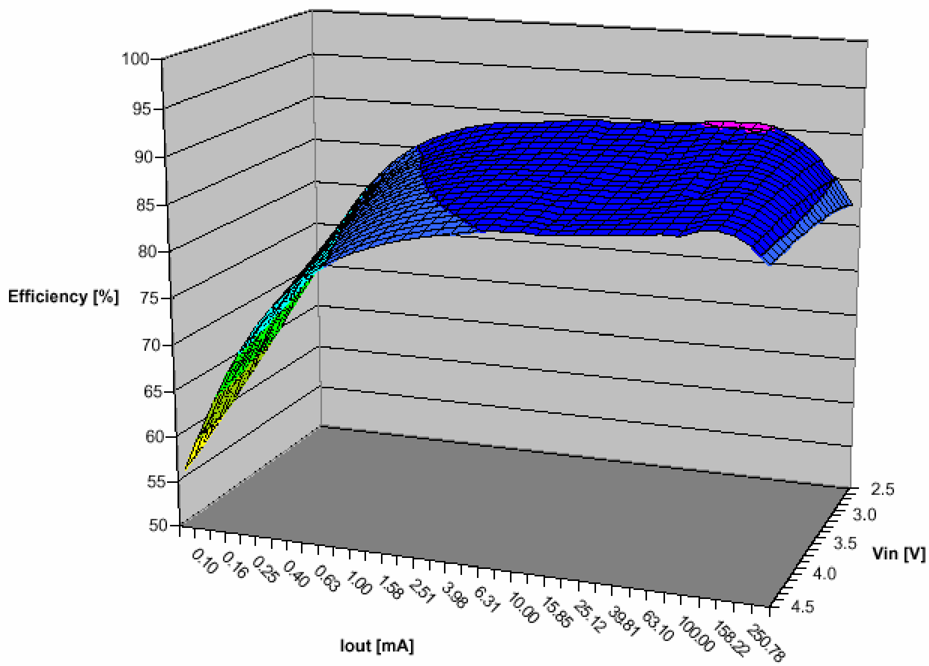

Figure 5. TPS62204 (1.6V) Efficiency vs Load Current vs Input Voltage With 4.7-µH Wire-Wound Inductor, R_{dc} = 240 mΩ / I_{SAT} = 700 mA

Output Capacitor

The designer can downsize the output capacitor to save money and board space. The basic selection of the output capacitor is based on the ripple current and ripple voltage, as well as on loop stability considerations.

The effective series resistance (ESR) of the output capacitor and the inductor value directly affect the output ripple voltage. The output ripple voltage can easily be estimated based on the inductor ripple current (ΔI_L) and output capacitor ESR. Therefore, a capacitor with the lowest possible ESR is recommended. For example, 4.7- to 10-µF capacitors in X5R/X7R technology have ESR values of approximately 10 mΩ. Smaller capacitors are acceptable for light loads, or in applications where ripple is not a concern.

The control-loop architecture developed by Texas Instruments allows the designer to choose the output capacitors and externally compensate the control loop for optimum transient response and loop stability. Of course, the internal compensation works best with one set of operating conditions and is sensitive to output capacitor characteristics.

The TPS6220x-series step-down converters have internal loop compensation. Therefore, the external L-C filter must be compatible with the internal compensation. For this device, the internal compensation is optimized for an LC corner frequency of 16 kHz, i.e., a 10-µH inductor and 10-µF output capacitor. As a general rule of thumb, the product of L*C should not vary over a wide range when selecting an output filter. This is especially important when selecting smaller inductor or capacitor values that move the corner frequency to higher frequencies.

During the time between the load transient and the turn-on of the P-MOSFET, the output capacitor must supply all of the current required by the load. This current supplied by the output capacitor results in a voltage drop across the ESR that is subtracted from the output voltage. A lower ESR minimizes the voltage loss when the output capacitor supplies the load current. In order to reduce the circuit size and to improve the load-transient behavior of the TPS62200 converter, a 4.7-µH inductor and a 22-µF output capacitor are recommended.

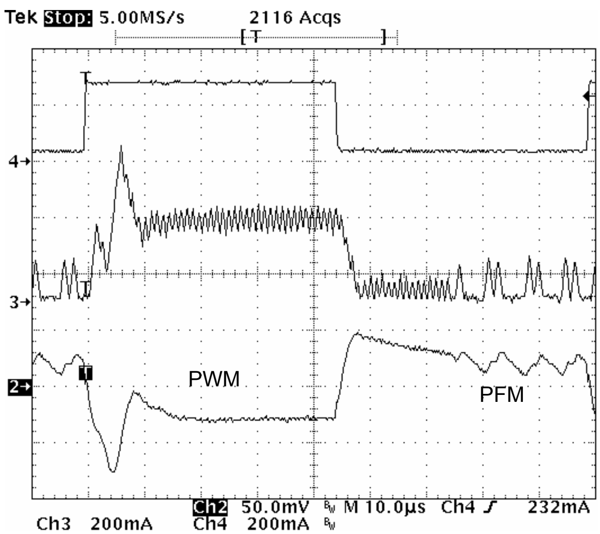

Figure 6. L = 10 µH / COUT = 10 µF

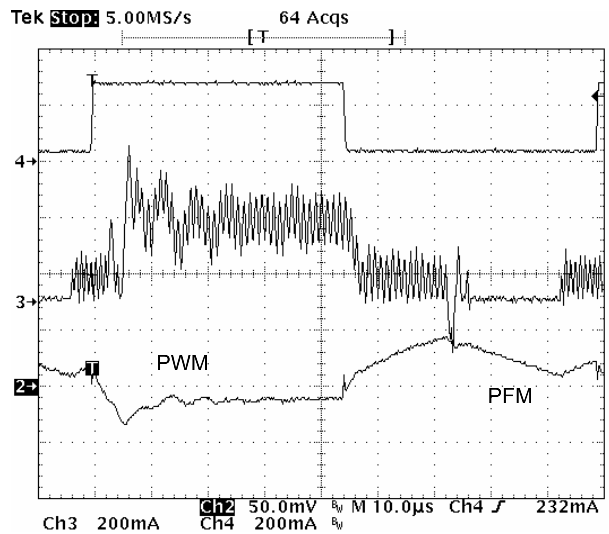

Figure 7. L = 4.7 µH / COUT = 22 µF

TPS62204 load transient performance vs L-C filter combination
3.6-V input voltage / 1.6-V fixed output voltage

References

1. Texas Instruments TPS62200 datasheet, *High-Efficiency, SOT-23 Step-Down, DC-DC Converter* (document number SLVS417), http://focus.ti.com/lit/ds/symlink/tps62200.pdf

2. *Trilogy of Inductors*, 2nd extended edition, ISBN 3-934350-73-9, Wurth Elektronik

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