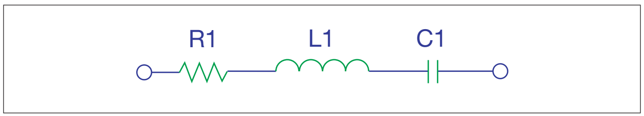
Output Filter Design

Abstract

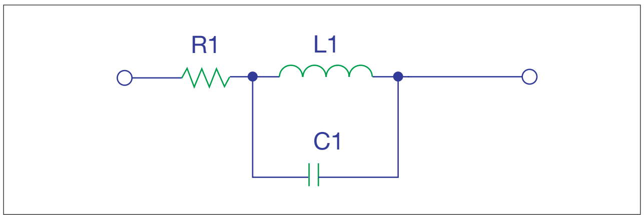
All DC/DC converters from Ericsson Power modules have a built-in output filter, which mainly consists of L and C elements. However, in some applications there is a requirement for better ripple performance than what the product is specified for. This design note is intended to be a design guideline and describes the steps to design a simple LC filter aimed to reduce the fundamental output ripple of our DC/DC modules. Other parameters such as cost, component availability and size should also be taken in consideration when designing the filter.

Capacitors



There is no perfect capacitor. The equivalent circuit below of a capacitors is above. R1 (ESR) value will decide performance of attenuation and not only the capacitance value. L value will affect max operating frequency for the capacitor. The impedance of a capacitors is: $X_C = 1/(2 * \pi * f * C$.

Inductors



There is no perfect inductor. You will have the parasitic elements R1 and C1. R1 will lower the efficiency due to resistive losses. C1 will conduct high frequencies due to capacitive coupling between windings and lower the usable frequency range. The impedance for the inductor is: $X_L = 2 * \pi * frequency * L$.

LC filter design

The LC filter consists of an inductor and a capacitor connected as follows:

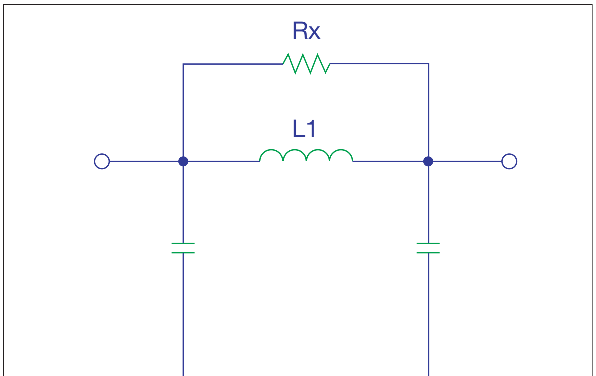


Figure 1. LC filter

The first step is to choose an inductor. The current rating of the inductor has to be equal to or larger than the maximum output current of the converter. The inductor must not be saturated. If the inductor saturates the inductance will decrease and the output ripple will increase. Remember that the inductance has a negative influence on the dynamic load response. If the inductance is high the dynamic response will be slower. It often requires a small value to achieve the desired damping of the output ripple. Selecting a large inductor will require a large capacitor in order to counteract the large voltage drops caused by load transients.

The next step is to choose a capacitor. The aim here is to select a capacitor with as high a value as possible with considerations taken to voltage ratings, size, cost and dynamic response. The added cost, for choosing a higher value of the capacitance than the minimum required, is usually compensated for by the enhanced performance, in terms of ripple and dynamic load response, of the filter and should be considered when selecting components. The following equation is used to calculate the required values of the filter components in order to achieve the desired damping ratio:

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Minimum required damping of the filter =

$$\frac{V_{max\ ripple}}{V_{Oac}} = \frac{X_C}{X_C + X_L}$$

$V_{max\ ripple}$ = Maximum allowed output ripple of the filter

V_{Oac} = Listed output ripple of the filter of the DC/DC converter

where

$$X_C = \frac{1}{2\pi \times f \times C} \quad [\Omega]$$

$$X_L = 2\pi \times f \times L \quad [\Omega]$$

f = the switching frequency of the DC/DC converter

C = Capitance

L = Inductance

Determining the value of the filter components is a process of trial and error and may require a few calculations to optimise the LC filter. Another thing to consider is the LC filter resonant top that is created at the cut off frequency. The resonant top must be damped to not affect the stability of the converter.

By putting a resistor in parallel with the inductor, the damping of the resonant to can be made. The value of the resistor can be equal as the impedance of the inductor. If the resistor is not put there, it can create resonant problems due to high Q.

Example:

Requirement: maximum allowed output ripple
$V_{max\ ripple}$ = 20 mV

In data:

Vout = 3.3V

V_{Oac} = 50 mV

f = 500kHz frequency.

I_{Omax} = 2A

Inductor:

Max rated current of Inductor ≥ I_{Omax} of application.
Selected inductor value is: 1 µH

Capacitance:

Minimum required damping = $\frac{V_{max\ ripple}}{V_{Oac}} = \frac{10\ mV}{50\ mV} = 0.2$

$$X_C \leq \frac{0.2}{(1 - 0.2)} \times X_L$$

i.e.

$$C \geq \frac{(1 - 0.2)}{0.2} \times \frac{1}{(2\Omega \times f)^2 \times L} \approx 0.4\ \mu$$

Select a C typically 1uF, where L = 1mH

A good rule of thumb is that the voltage rating of the capacitor should be more than twice the nominal voltage. Figure 1 shows the result of a LC filter for the PKF module with an inductance of 1mH (rated to 2,6A) and a capacitance of 1mF (rated to 10V).

In order to achieve good ripple damping it is necessary to keep the ESR value of the capacitor as low as possible. This is due to the fact that the ESR dependent ripple current sets the limit for how well the ripple can be dampened.

If the ESR value is high enough it will be the most significant parameter affecting the output ripple. The formula below shows how to calculate the contribution of the ESR to the ripple. The result is an approximation and it should be applicable for most DC/DC modules. The example used has an ESR value of 30mW, which is a typical value for ceramic capacitors. It is important to select a proper ESR value of the output capacitor, so the ESR does not Affect the stability of the converter. If the ESR value is low it can affect the converter and made it unstable.

If RL (load resistance) >>ESR then

$$U_{ESR\ ripple} = i_{ripple} \times ESR$$

$$i\ ripple = \frac{U_{ripple}}{2 \times L \times f_{switching}}$$

$$U_{ESR\ ripple} = \frac{100\ mV}{2 \times 1\ \mu \times 500\ K} \times 0.03 = 3\ mV$$

If RL(resistance load) =< ESR then

$$U_{ESR\ ripple} = i_{ripple} \times ESR//RL$$

$$i\ ripple = \frac{U_{ripple}}{2 \times L \times f_{switching}}$$

$$U_{ESR\ ripple} = \frac{100\ mV}{2 \times 1\ \mu \times 500\ K} \times 0.03 = 3\ mV$$

Examples of suitable types of capacitor for this filter application are ceramic and tantalum capcitors.

The damping resistor value can be selected as the same impedance as the inductor, R= XL = 2 * pi * f * L.

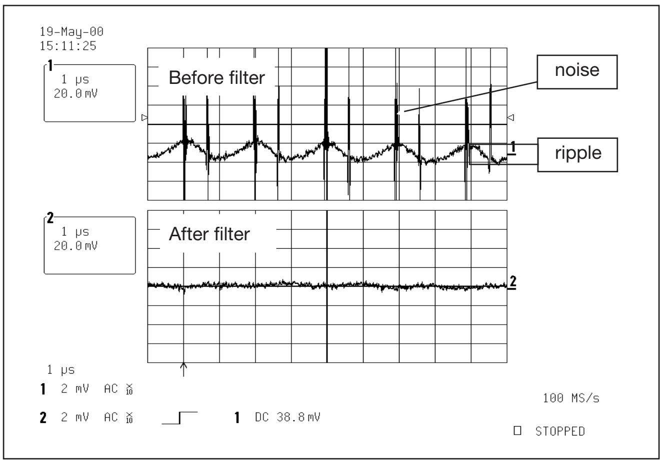

Figure 1. Measurement of a PKF module with a LC filter using one 1 μH inductor and two ceramic capacitors of 1 μH and 100 nF.

Noise

All switched power supplies generate high frequency noise which is derived from the actual switching, see figure 2. Using small ceramic capacitors in the 100 nF range connected as close to the load as possible easily dampens this. The reason is that the copper trace inductance together with this capacitor will create a LC filter that is effective for these high frequencies. The figure below shows the result of using a 100 nF ceramic capacitor (type X7R) together with the LC filter designed in the previous steps.

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