PCB Design 007 *QuietPower* columns, June 2010

Inductance of Bypass Capacitors, Part I

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In the coming few columns we will look at the most important component of the power distribution network: the bypass capacitor. In this first part we start with the basics.

An ideal capacitor 'smoothes out' the voltage: finite current fluctuations do not create sudden voltage jumps across the part. Described in equation:

$$v(t) = \frac{q(t)}{C} = \frac{1}{C}\int_{t_0}^{t} i(\tau)d\tau + v(t_0) \qquad (1)$$

In this equation *v(t)* is the voltage across the capacitor as a function of time, *q(t)* is the charge held in the capacitor as a function of time and *i(t)* is the current through the capacitor as a function of time. This equation tells us that the voltage across the capacitor is proportional to the integral of the current flowing through the part and inversely proportional to a parameter, which is called capacitance (C). The first half of the equation also tells us that the capacitor acts like a charge reservoir: pumping charge into the capacitor raises its voltage, pulling charge from the capacitor lowers its voltage. Higher capacitance will result in a smaller change in voltage for the same amount of charge transfer. This makes the capacitor very convenient for PDN applications: medium term it behaves like a battery, holding up its voltage across its terminals against the current draw. Though as we will see in later columns, inductors can also be used to store charge (think about DC-DC converters!), it is just a little more complicated to use them for this purpose.

As shown in *Figure 1*, any physical implementation of a capacitor will inevitably yield at least two more elements in its equivalent circuit: an Equivalent Series Resistance (ESR) and an Equivalent Series Inductance (ESL).

Figure 2 illustrates the magnitude of the impedance of a bypass capacitor. Below the Series Resonance Frequency (SRF) the impedance drops according to the 1/ωC expression. Above SRF, however, the part follows the ωL impedance slope of an inductance. While higher capacitance helps us to keep voltage fluctuations small, higher inductance does just the opposite: above SRF, higher inductance results in more voltage fluctuations for the same change in current. However, we should not think that above SRF the bypass capacitors are totally useless; though they nevertheless loose some of their effectiveness to suppress voltage fluctuations above SRF.

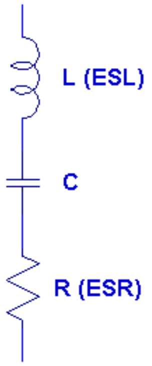

Figure 1: *Equivalent circuit of bypass capacitors.*

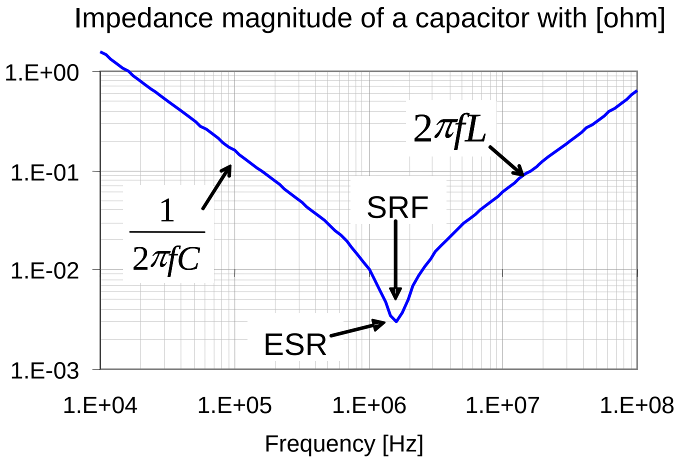

Figure 2: *Impedance magnitude versus frequency of a bypass capacitor.*

When we specify capacitors for our designs, we can select the capacitance from standard lists of values. ESR is also specified on the data sheet. But ESL is different.

Regarding ESL, it is fair to say that in general a bypass capacitor with lower inductance (everything else being equal) is more effective in bypassing. But here comes the problem: when we try to get ESL data from vendors, we may get confusing or outright contradictory numbers: different vendors may quote very different numbers even for the same nominal part. *Figure 3* shows an example. Lets look up for instance the ESL of a 4.7uF X5R 0805-size multi-layer ceramic capacitor (MLCC) with 6.3V voltage ratings. Major component manufacturers have this data available in different forms: usually the data is in a stand-alone application with embedded data base that we can download and run locally. *Figure 3* compares data from two vendors.

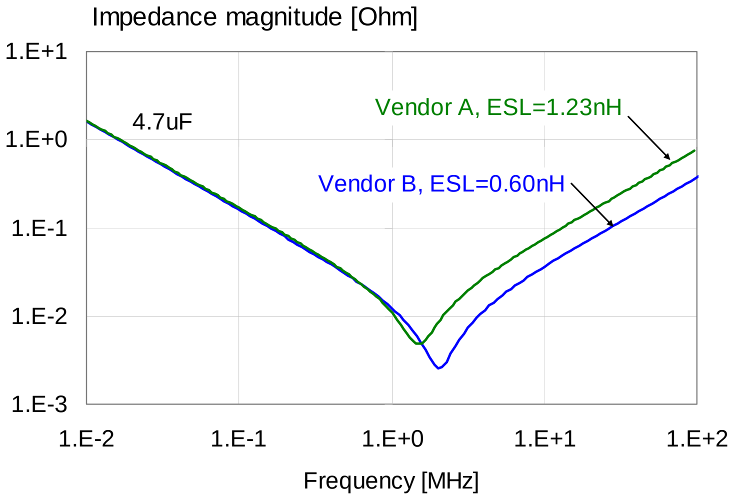

***Figure 3**: Plot of impedance magnitude for a 0.805-size X5R 6.3V 4.7uF capacitor from two different vendors.*

We can notice that below SRF the two curves run on top of each other, indicating that in fact the capacitance values are the same. Above SRF, however, there is a striking difference: the reported ESL is more than two times different between the two vendors and also ESL appears to be proportional to ESR: the part with lower ESR shows lower ESL as well. What is the reason for this difference? ESR is related to the amount and type of conductive material in the capacitor plates and terminals, so differences in ESR can be easily explained by these factors. ESL, on the other hand, is primarily determined by the geometry of the capacitor body. Could it be that one of the two inductance values is incorrect or is the difference an indication of very different qualities (very different internal geometries) of these two capacitors? Or, could both numbers be correct and yet could they still refer to the same quality of product? Stay tuned, this is what we will look at in the coming columns.