PCB Design 007 *QuietPower* column

How to read the ESR curve

Istvan Novak, Oracle, October 2012

The most widely used power distribution component is undoubtedly the bypass capacitor. After the nominal capacitance, its next most important parameter is its Effective Series Resistance, or ESR. To use bypass capacitors properly, we need to understand what exactly ESR means and how to read the ESR curve in measured or simulated plots.

A real-world capacitor, whether it is a discrete capacitor or the capacitance of a power-ground plane pair, is never ideal. It always has parasitic resistance and inductance. The inductance is associated with the shape and size of the capacitor electrodes as well as the shape and size of external connections: pads, vias and planes closing the current loop around the capacitor. The size of the current loop, which determines the inductance, depends only partly on the capacitor itself. It is a widely recognized and accepted fact that the loop inductance of a capacitor also depends on how we connect it to our board.

In contrast, we tend to assume that the ESR of the capacitor depends only on the capacitor and it does not depend on its external connections. While this may be true for many applications, there are cases (as we will show in a future column) where even the ESR of a capacitor depends on the external connection geometry. To get to that interesting case, we first need to understand the contributors to ESR, and that is what we look at in this column.

The resistance of a capacitor comes from two sources: conductor losses and dielectric losses. For instance, in a multi-layer ceramic capacitor, the capacitor plates and the connecting terminals have finite resistance and they make up the series losses. The dielectric layers, especially if we have high dielectric constant materials, have finite loss tangent and will create a parallel loss conductance. When we use a series C-R-L equivalent circuit for the capacitor, the series and parallel losses get combined into a single series resistance, called Effective Series Resistance, or ESR. This is shown in the equivalent circuits of *Figure 1*.

The conductive loss follows the frequency dependence of skin loss: starting from a DC resistance value, the resistance rises with the square root of frequency. In some cases it may be important that different contributors of conductive losses, such as terminal and capacitor-plate losses, may have different DC resistances and knee frequencies. *Figure 2* shows a simple example: the Rs(f) conductive resistance with 10 mOhm DC resistance and 1MHz knee frequency.

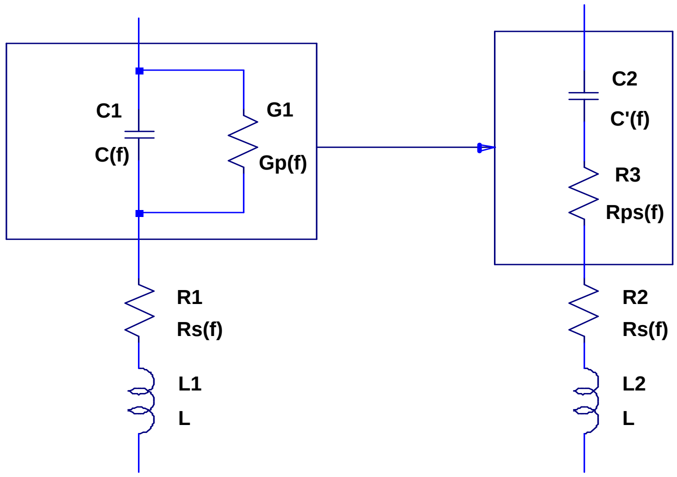

Figure 1.: *Equivalent circuit of a capacitor with separate conductive and dielectric losses on the left and combined effective series losses on the right. ESR is the sum of the Rs(f) conductive and Rps(f) dielectric losses.*

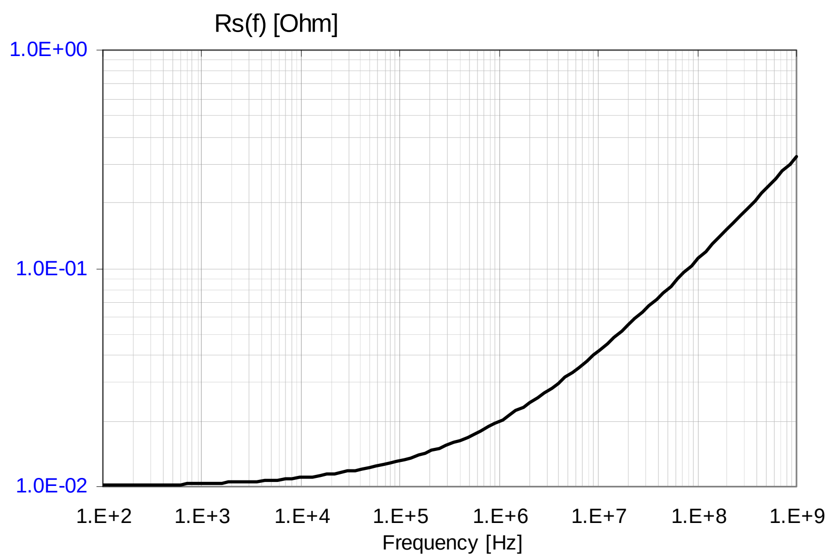

Figure 2.: *Typical frequency dependence of conductive losses in a ceramic capacitor.*

The parallel losses are described by a DC leakage current and a dielectric loss tangent, D(f). For AC modeling we can usually ignore the DC leakage. In a simplified model we can also assume that the dielectric loss tangent is frequency independent and therefore the parallel conductance is G = ω C Df. If we want a causal model, the slight frequency dependence of C and Df has to be taken into account. *Figure 3* shows the conductance (G) and the capacitive susceptance (B) for a 1uF capacitor with 1% Df using the causal wideband Debye model. *Figure 4* shows the series equivalent of the same lossy capacitance.

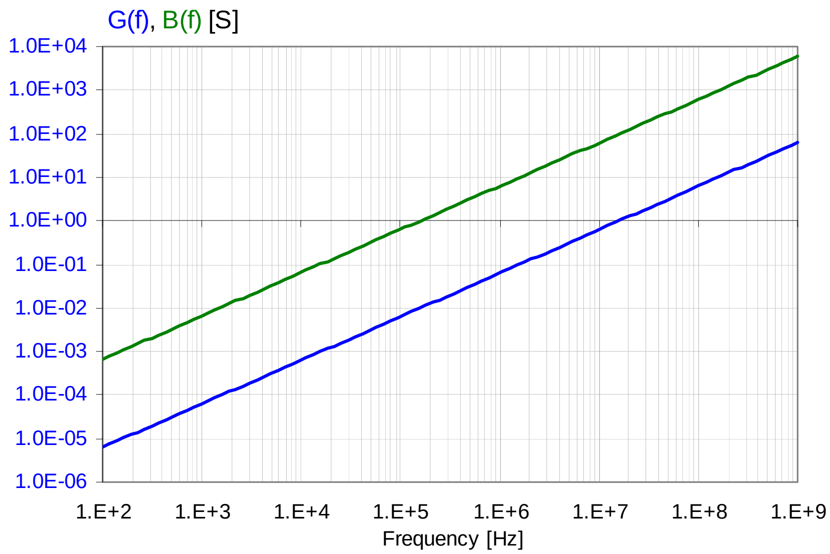

Figure 3.: *Parallel conductance and capacitive susceptance as a function of frequency.*

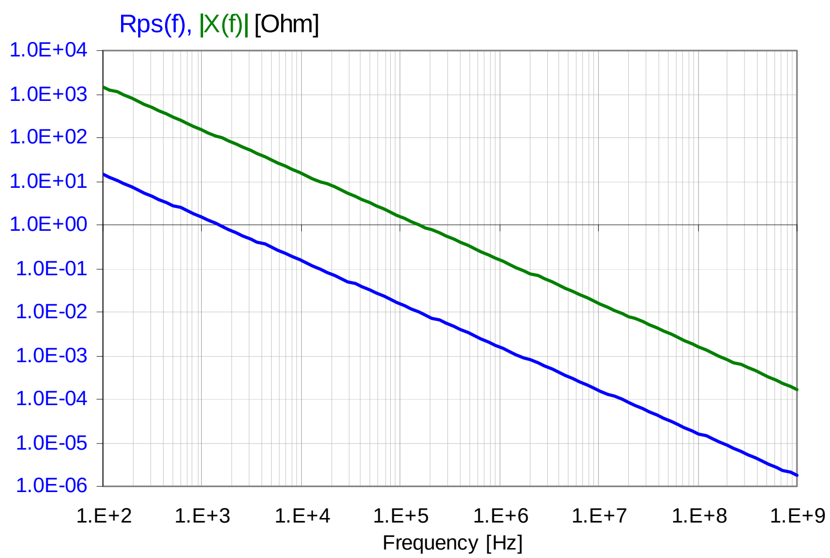

Figure 4: *Series equivalent of the parallel conductance and series capacitive reactance for the capacitor from Figure 3.*

We can notice that the two contributors of the equivalent series resistance vary with frequency the opposite way: the resistance of conductor losses increases, the resistance of the dielectric losses decreases with increasing frequency. The sum of the two creates a typical basin-like plot as shown in *Figure 5*. With reasonably low Df values and at low frequencies, the ratio of the magnitude of capacitive reactance |X(f)| and ESR(f) is constant and equals the (approximately frequency independent) loss tangent. We can see that in *Figure 5* in the 100 Hz to 10 kHz frequency range the red ESR curve is approximately 100 times smaller than the green |X(f)| curve, which corresponds to a 1% Df loss.

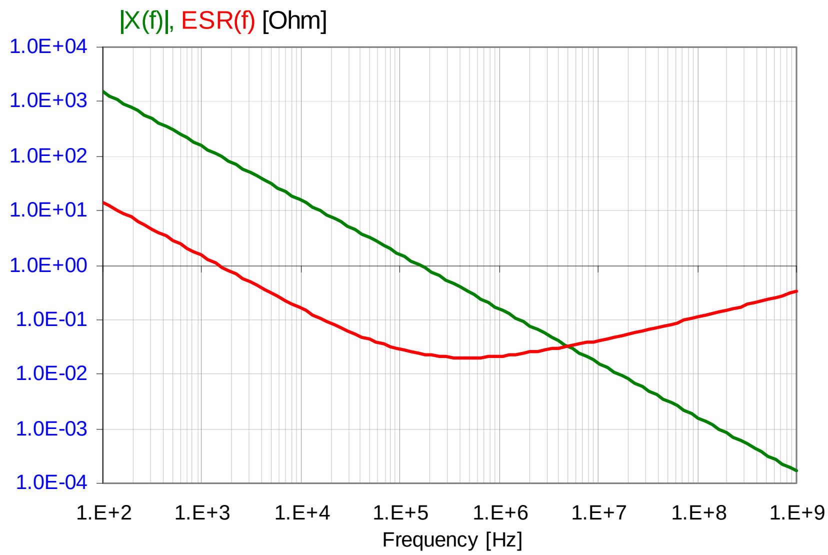

Figure 5: *Capacitive reactance and Effective Series Resistance (ESR) of a 1uF capacitor with 1% Df and 10 mOhm DC series resistance.*

You can try different input numbers, plot the result and see all the expressions behind these calculations in the Bypass_capacitor_model_v-w01.xls, available at http://www.electrical-integrity.com/