PCB Design 007 *QuietPower* column

Do not measure PDN noise across capacitors!

Istvan Novak, Oracle, January 2013

Some application notes will tell you that to measure the output ripple of a DC-DC converter, the best way to make the connection is to attach the probe across the top of one of the output capacitors. While there is a legitimate argument for measuring the noise this way, be aware: if you measure the noise across a capacitor, it will most likely alter the noise signature…

Take for instance the evaluation board shown in Figure 1. It holds a small encapsulated step-down non-isolated DC-DC converter: it is the black rectangular package in the middle of the board. I use this board in my courses to show live measurements of converter loop stability and output impedance. It is very convenient for desk-top demos, because the input voltage range is a few volts, so the entire setup can be powered simply with three AA batteries. The converter can be loaded with up to 4A current. In addition to the converter module, which contains a fully working DC-DC converter [1], the evaluation module has banana receptacles for connecting the input supply and the load, a few ceramic capacitors across the input and output terminals, jumpers for setting the output voltage, and two BNC receptacles to connect oscilloscopes.

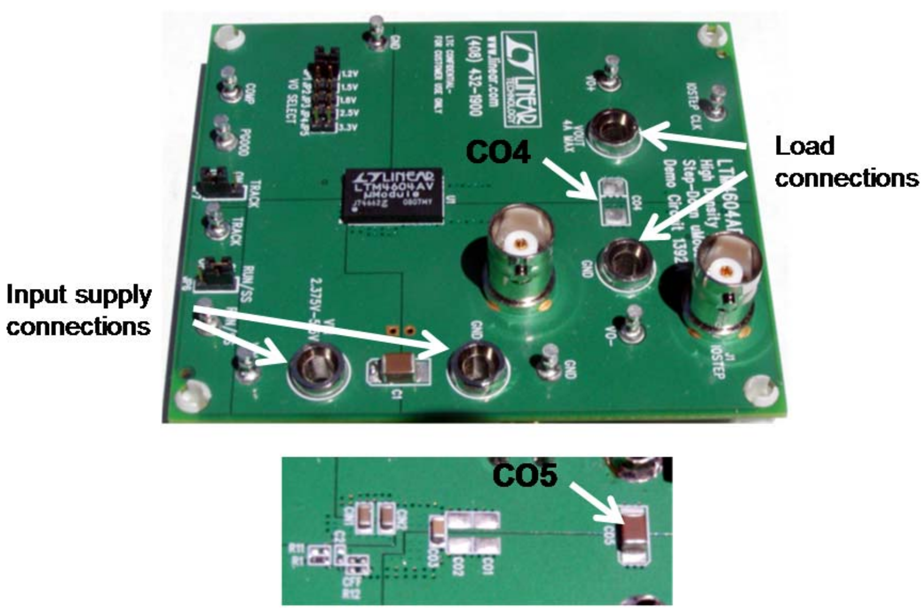

Figure 1: *Top view (on top) and partial bottom view (on the bottom) of the evaluation board for a Linear Technology LTM4604 DC-DC converter. Evaluation module: courtesy of Linear Tech.*

There are spare footprints for experimenting with additional components: CO4 is a capacitor footprint across the output terminals. It is marked by the white arrow and label on the top view of Figure 1. There is also a populated site with a 100uF ceramic capacitor at that same exact location (CO5), on the back side of the board. The DC load can be connected with banana plugs to the receptacles above and below of these capacitors.

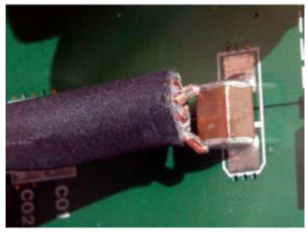

Figure 2: *Connecting a home-made semirigid probe across the top terminal points of an output capacitor, CO5.*

We can take an oscilloscope [2] and a home-made semirigid probe and measure the output ripple of the running converter at different locations. Figure 2 shows the connection of the probe across the top side of CO5, similar to how application notes may suggest.

We can also connect the same probe across the vacant capacitor site, CO4. Remember, these sites are at the same location on the board; CO4 on the top, CO5 on the bottom. Since we measure the output ripple at the same location on the board, we would expect to see the same voltage. This is not the case, however, as it is shown in Figure 3.

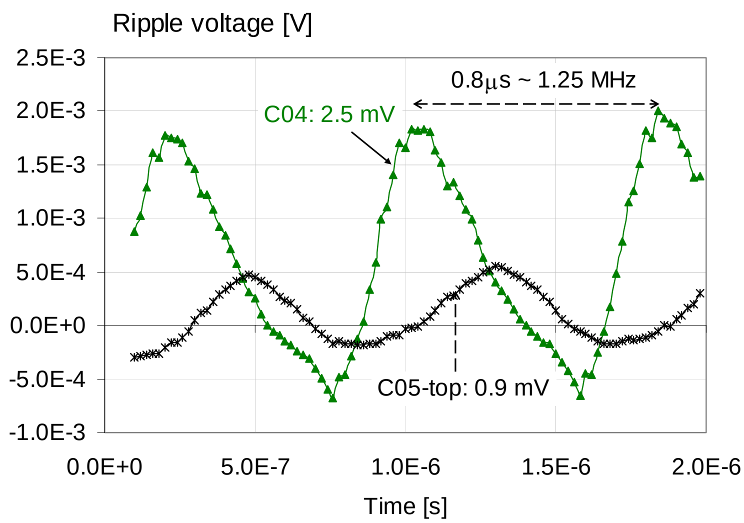

Figure 3: *Output ripple waveform of the running DC-DC converter module, measured at the same location on the top (CO4) and on the bottom (CO5, across the capacitor terminals). The magnitude ratio at the two locations is approximately 3x.*

We can see that the voltage waveform across the top terminal points of CO5 is almost sinusoidal and the magnitude is 0.9 mVpp. When we measure across the vacant capacitor site on the other side of the board, we get a more distorted, harmonic-rich waveform, and almost three times bigger magnitude: 2.5 mVpp. Why do we have such a big difference, when we measure practically at the same location? We can get the answer by looking at the equivalent circuit of our connections. Figure 4 shows the equivalent circuit when we measure across the top terminals of a capacitor, CO5 in our case.

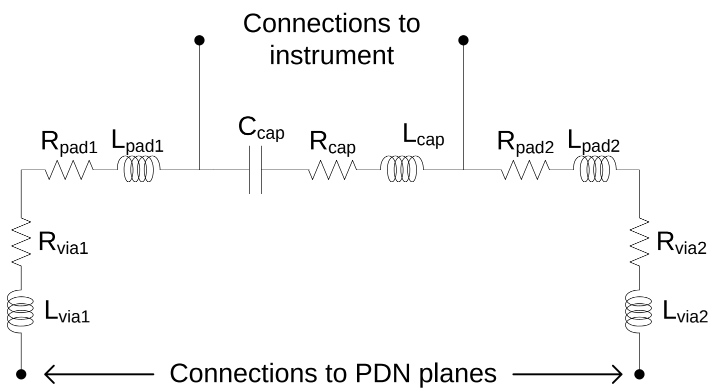

Figure 4: *Equivalent circuit of the connection when measuring across a capacitor.*

The bottom of the equivalent circuit connects to the power and ground planes. This is where we really want to know the output ripple. Why on the planes (which are usually inside the PCB stackup) and not on the surface, across a capacitor? Because the loads this converter has to feed, are connected to the converter through the planes. The planes will carry any output ripple from the converter output to the load. We don't have any load connected across the top terminals of capacitors, and therefore the voltage there is irrelevant for our purposes. Instead, we need to know the noise across the planes.

No matter how carefully we attach our measuring probe, we will always have some parasitic impedance in the path. In Figure 4 the parasitic impedances are represented by four components in each leg: a resistance and inductance representing the series impedance of through holes or vias connecting between the planes inside the board stackup and the surface, and a resistance and inductance representing the series impedance of surface pads. These series impedances are usually small compared to the input impedance of our measuring instrument. We are talking about milliohms and nanohenries. These series impedances would create no significant distortion in the measurement results if we had no shunt element across our measuring instrument. But when we measure across a capacitor, we have the equivalent series C-R-L circuit of the capacitor across our measuring instrument. And because bypass capacitors are supposed to have low impedance, this shunt leg in the equivalent circuit will form a frequency-dependent voltage divider with the series impedances of vias and/or pads. We can easily calculate the transfer function of our measurement connection. We can do it either in a spreadsheet, coding the transfer function, or using circuit simulators to get the answer.

With typical values, such as a milliohm of via and pad resistance and a couple of nH via/pad inductance, we get a transfer function shown in Figure 5. At low frequencies we get no attenuation and no gain, because the shunt impedance of the capacitor is high. As the frequency increases, the impedance of the capacitor drops inversely with frequency and we go through series and parallel resonance frequencies. These resonances create a peak (gain) and a dip (high attenuation), followed by the high-frequency asymptote, which is set by the ratio of inductances of the capacitor and vias/pads.

The equivalent circuit of Figure 4 is generic, and it can be used also for cases when we have power planes only inside the stackup and not on the surface. The evaluation module we use here has multiple plane layers in the stackup and there are power and ground patches both on the top and bottom layers.

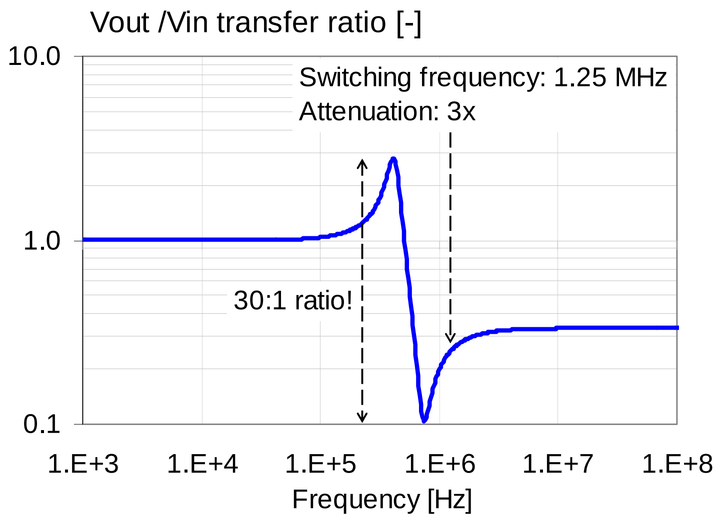

Figure 5: *Typical transfer function of the measurement connection when we measure across the top terminal points of a capacitor.*

Note that the vertical scale of Figure 5 is logarithmic; we can have a large ratio between the peak and dip of this transfer function. With our example numbers this ratio is approximately 30. We get a 3x amplification at the resonance peak and a 10x attenuation at the resonance dip. The high-frequency attenuation is approximately 3x. By comparing with data from Figure 3, we see that we get approximately 3x attenuation of the switching ripple when we measure across a capacitor.

So why would someone measure the converter output ripple across a capacitor? There is a ‘lazy’ answer and also a legitimate reason. The lazy answer is that there may be circuits where there are no dedicated test points or vacant component sites where we could conveniently probe the noise and ceramic capacitors having exposed side metallization extending all the way to the top of the part offer convenient connection points. The legitimate reason could be that DC-DC converters create not only the switching ripple as output noise, but also high-frequency burst noise. Measuring across a capacitor will attenuate the high-frequency burst noise. But whether we are just lazy or want to attenuate the high-frequency burst noise, we have to keep in mind that by measuring across a capacitor, the converter output ripple reading could be several times higher or many times smaller than the actual ripple across our loads.

You can read more about DC-DC converter characterization and measurements in [3].

References:

[1] LTM4604 data sheet. www.linear.com

[2] Handyscope HS3, http://www.tiepie.com/en/products/Oscilloscopes/Handyscope_HS3

[3] "Dynamic Characterization of DC-DC Converters ," DesignCon 2012, Santa Clara, CA, January 30 - February 2, 2012, available at http://www.electrical-integrity.com/