# How PDN Filters Affect EMC Performance

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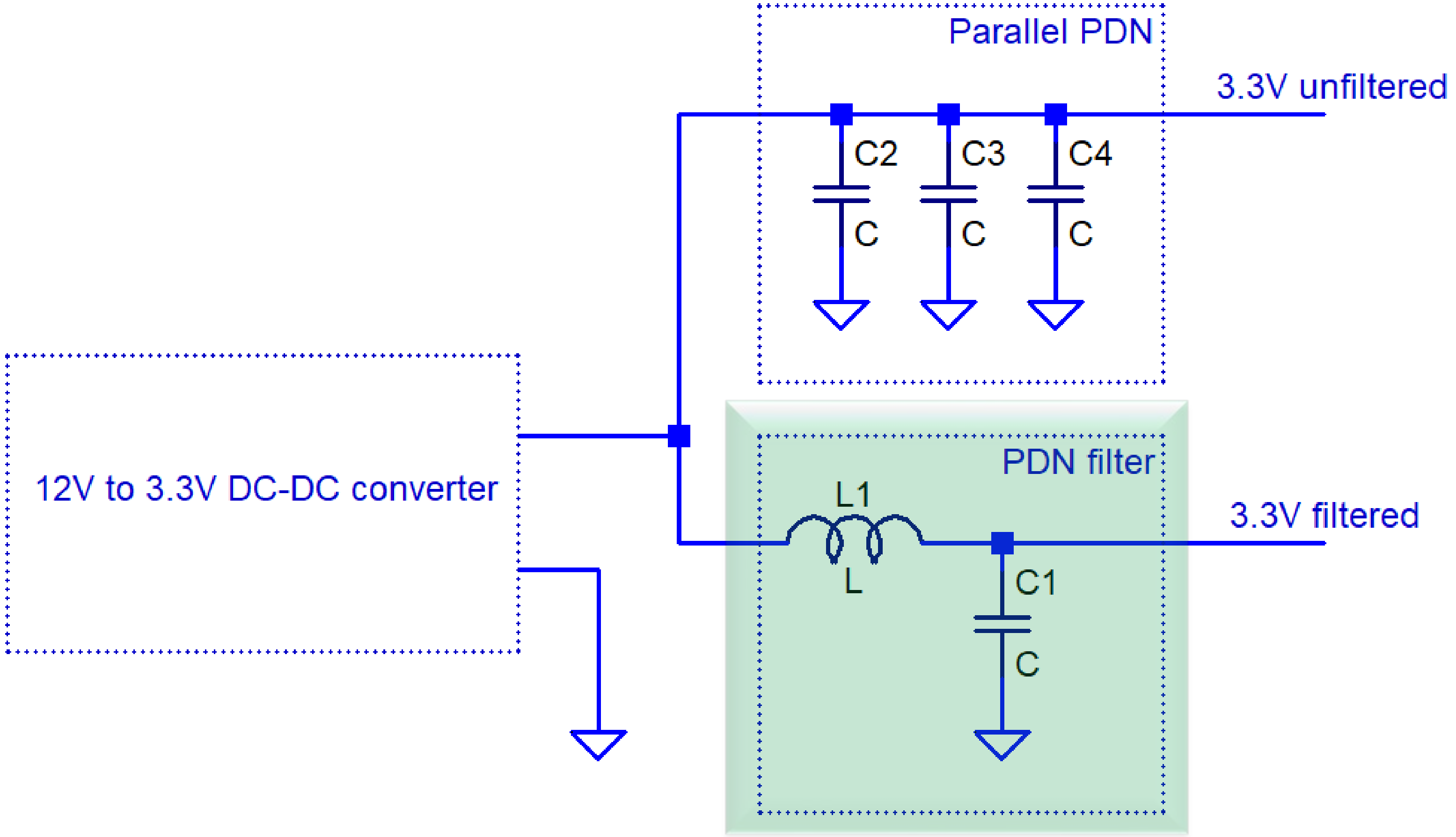
Samtec

# OUTLINE

- Background
- When we need a filter
- Typical noise sources
- Filter characteristics
- Filter illustrations
- Filter design process
- What can go wrong
- Summary
- Further reading

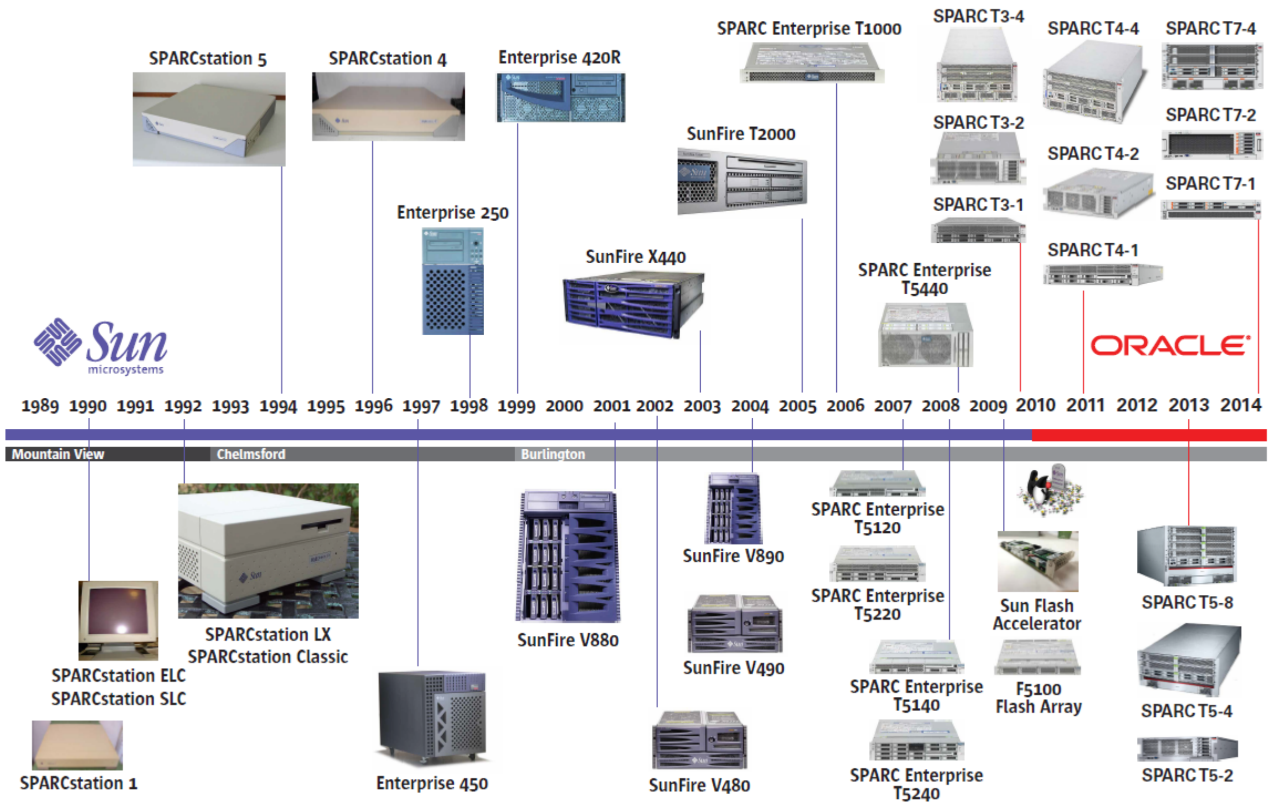


# A Little EMC Background

EMC monitoring in 2020:

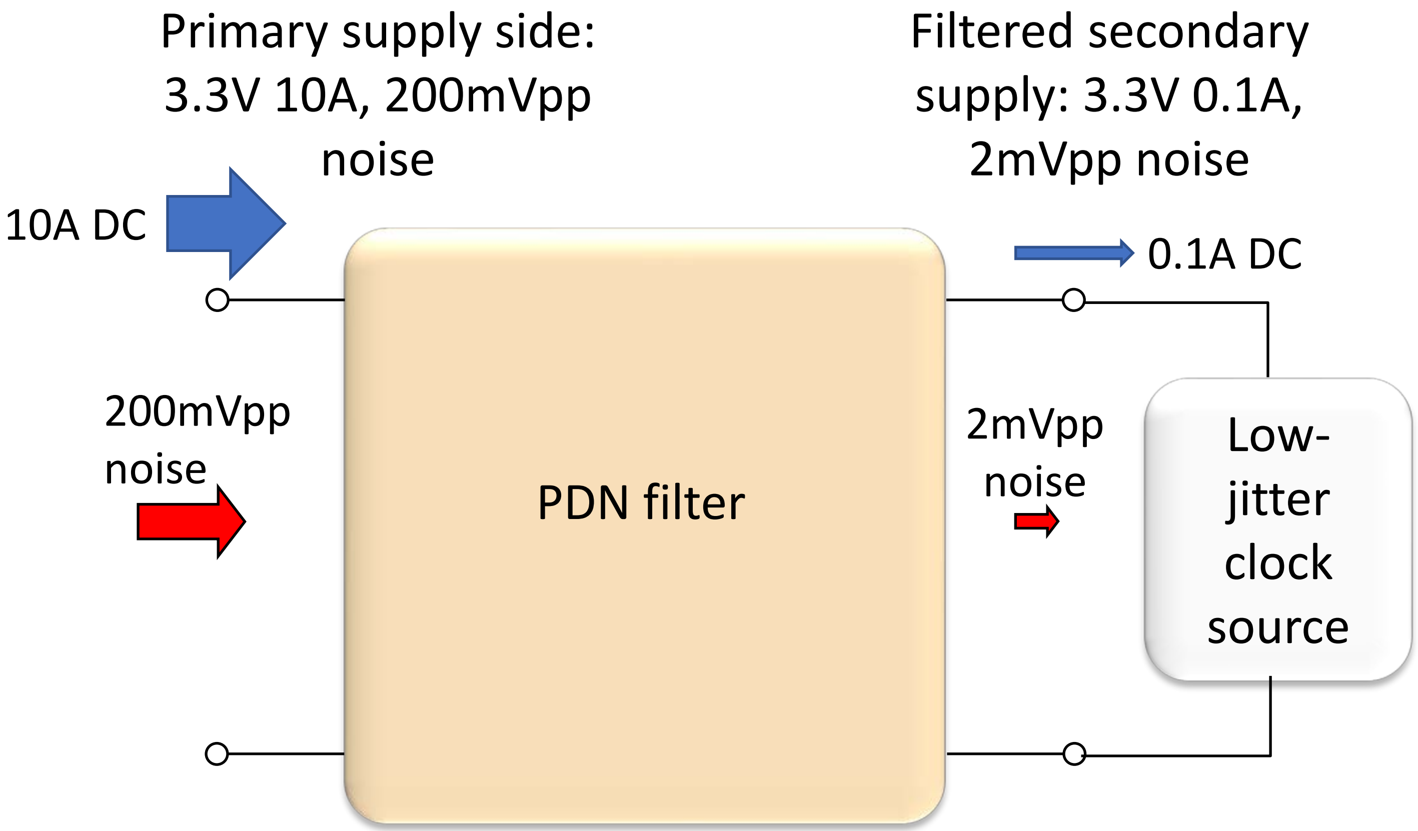

EMC monitoring station in the 70s:

Product portfolio commemorating Jeff Elsmore's career at SUN Microsystems – Oracle:



# When We Need a Filter

## To feed a sensitive low-current load

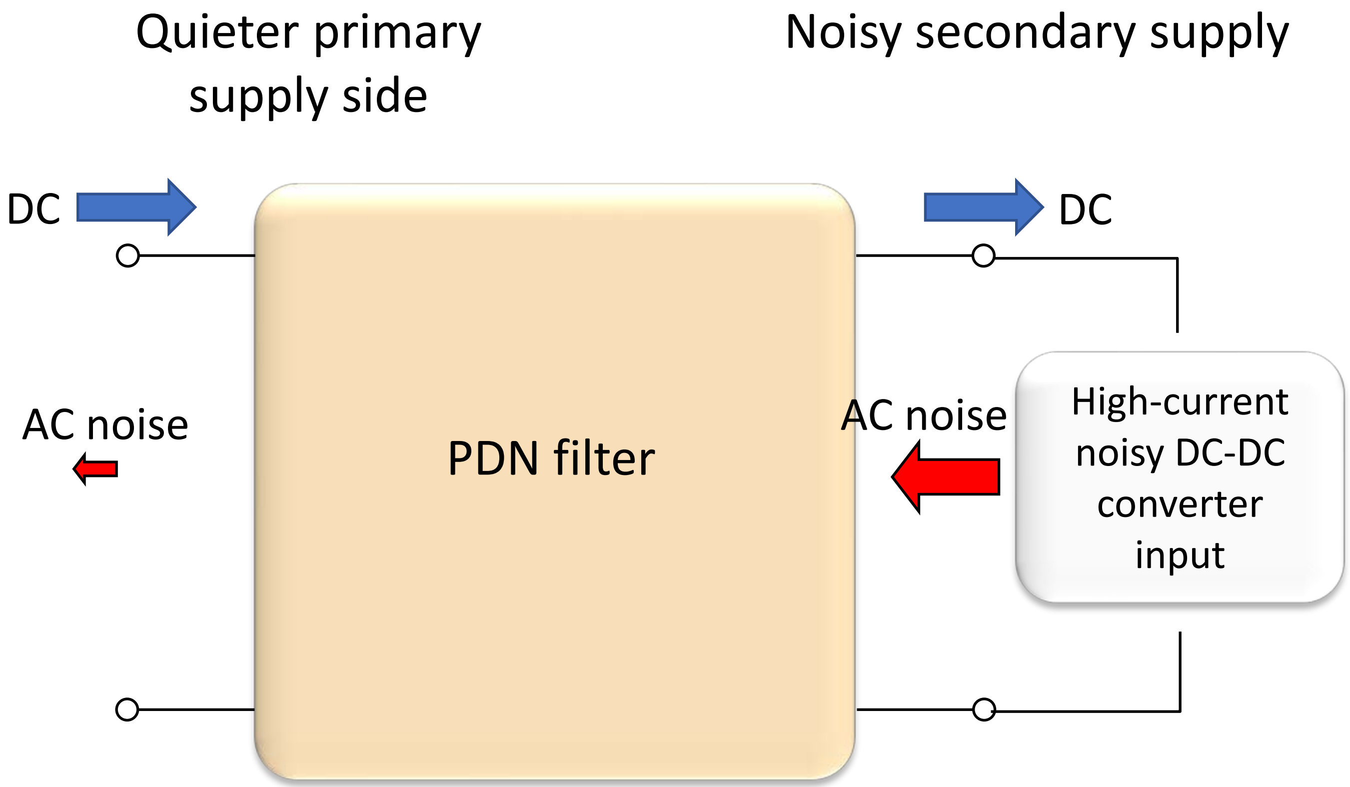



**Always ask yourself: Do we need a filter or not?**

It is easier to filter for a low-current rail than quiet a high-current rail.

# When We Need a Filter

## To keep noise spilling out from noisy loads

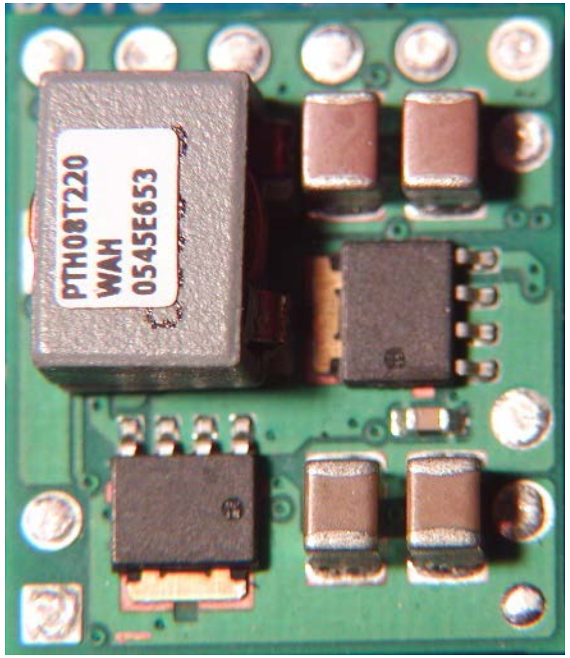


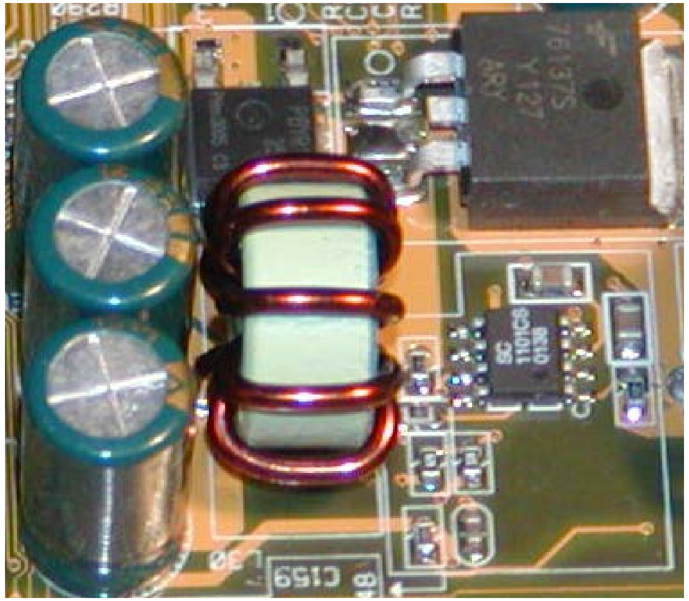

**Always ask yourself: Do we need a filter or not?**

It is easier to contain noise at its source. Main stress parameter is capacitor ripple current.

# Typical Noise Source

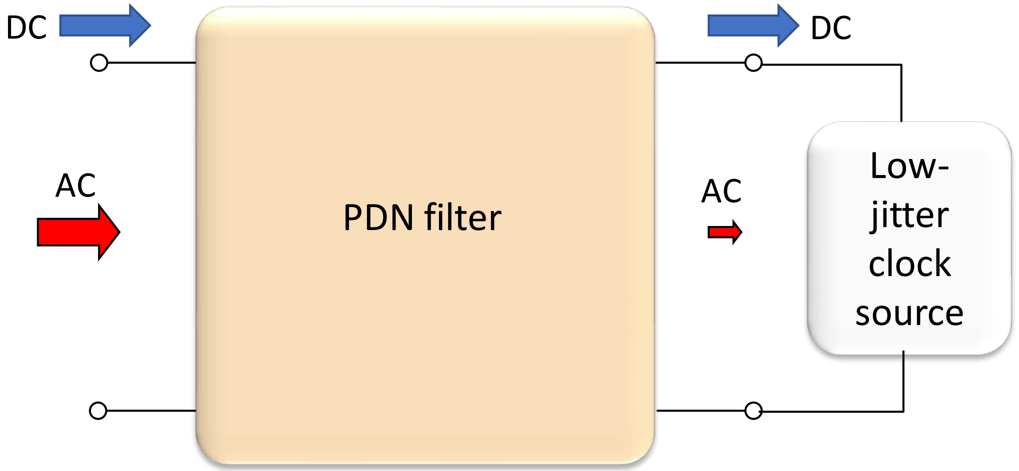
- DC-DC converters are popular and needed for their high efficiency
- They tend to generate a lot of noise

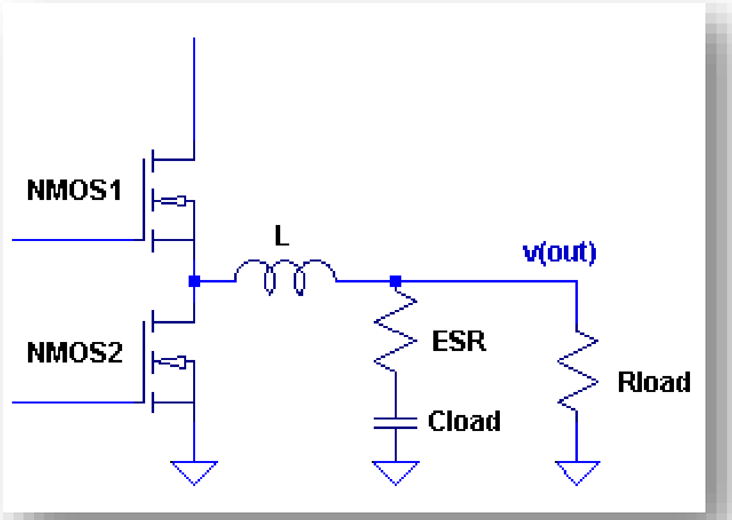



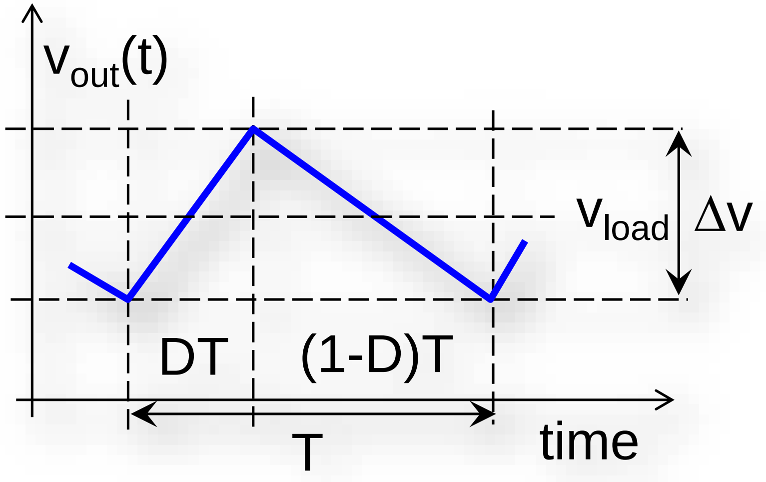



# DC-DC Converter Output Ripple Voltage

- The inductor ripple current flows through the output capacitor
- First-order mid-frequency capacitor model = ESR-only
- Output ripple voltage shape closely follows inductor ripple current



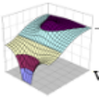

If Cload*ESR pole is below Fsw, the output ripple is:

$$\Delta v = ESR * \Delta I$$

# DC-DC Converter Output Ripple Voltage

**Time-domain harmonic composition of buck converter switching ripple**

| | OUTPUT CAPACITORS | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C1 | C2 | C3 | C4 | C5 | Fmin [Hz] | Vin [V] | Fsw Hz] | Sweep Min | D [%] | Ripple [mVpp] | m |
| C [F] | 4.70E-04 | 4.70E-05 | 1.00E-05 | 1.00E-06 | 3.00E-09 | 1.00E+03 | 12 | 5.00E+05 | 1 | 8.33 | 4.53 | 12.00 |
| R [Ohm] | 1.00E-02 | 3.00E-03 | 1.00E-02 | 1.00E+06 | 1.00E+06 | Fmax [Hz] | Vout [V] | L | Max | delta_I [A] | Ripple est [mVpp] | Ratio [-] |
| L [H] | 2.00E-09 | 2.00E-09 | 1.00E-09 | 1.00E-09 | 1.00E-10 | 1.00E+08 | 1 | 4.70E-07 | 10 | 3.9E+00 | 2.89 | 1.57 |
| N [-] | 3 | 3 | 10 | 0 | 0 | | | | | | | |



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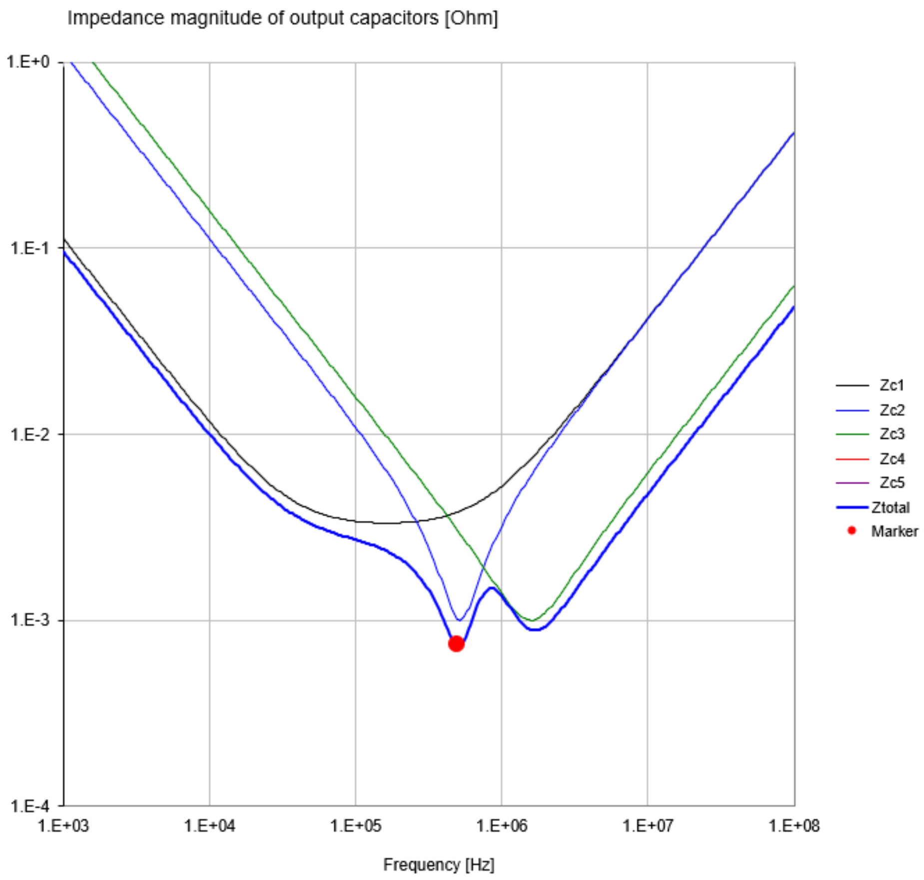
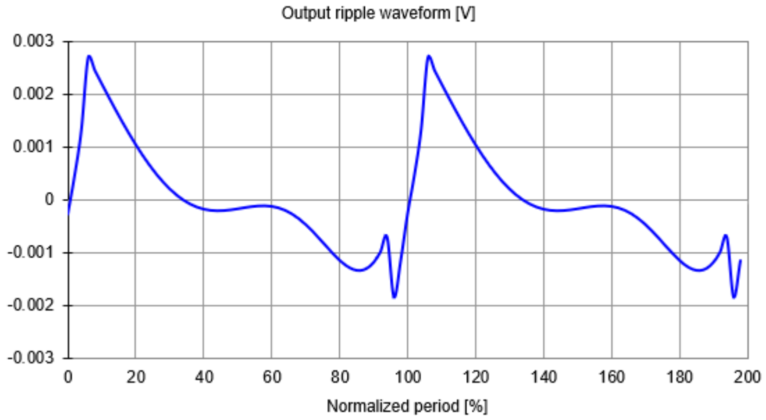
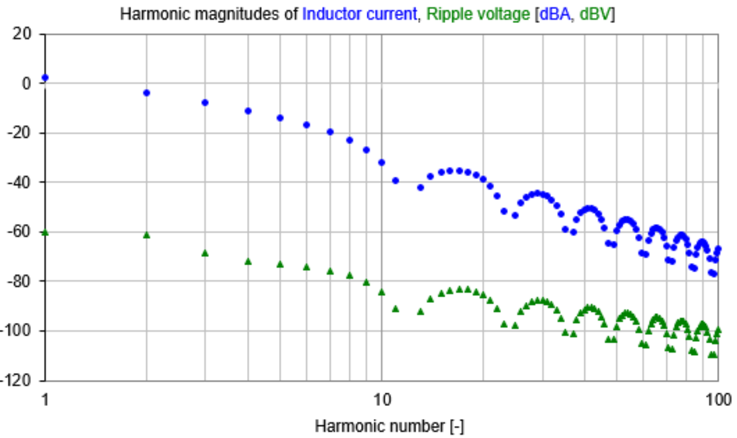
**Number of periods**
2



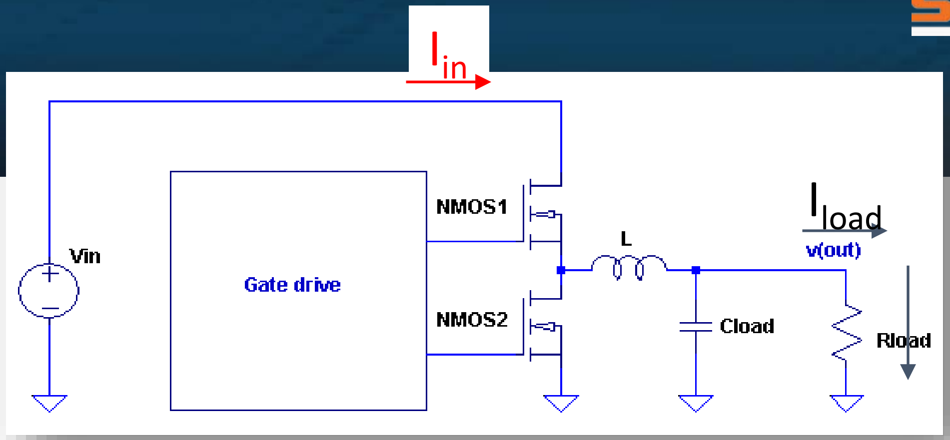



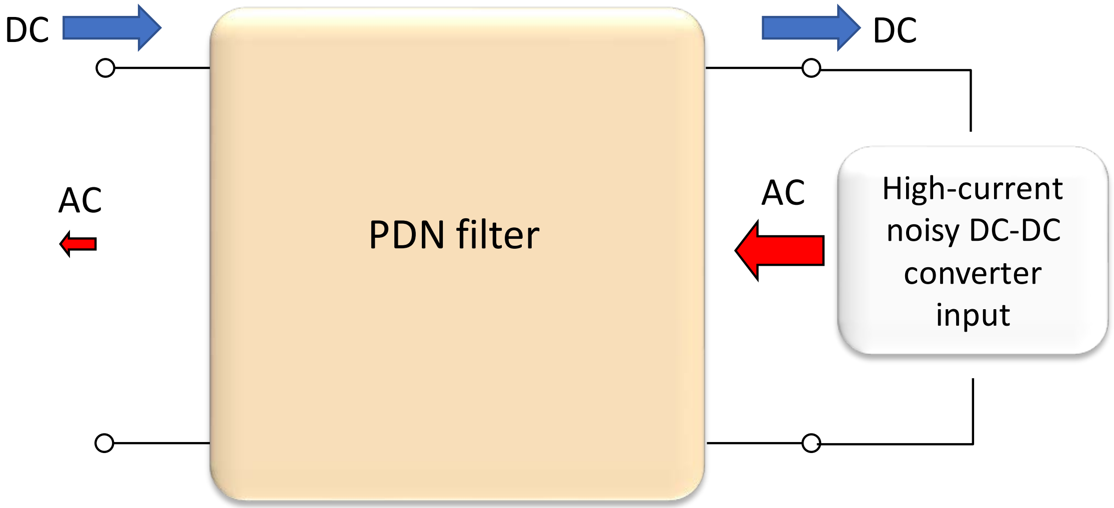

- The inductor ripple current flows through the output capacitor
- First-order mid-frequency capacitor model = ESR-only
- Output ripple voltage shape closely follows inductor ripple current

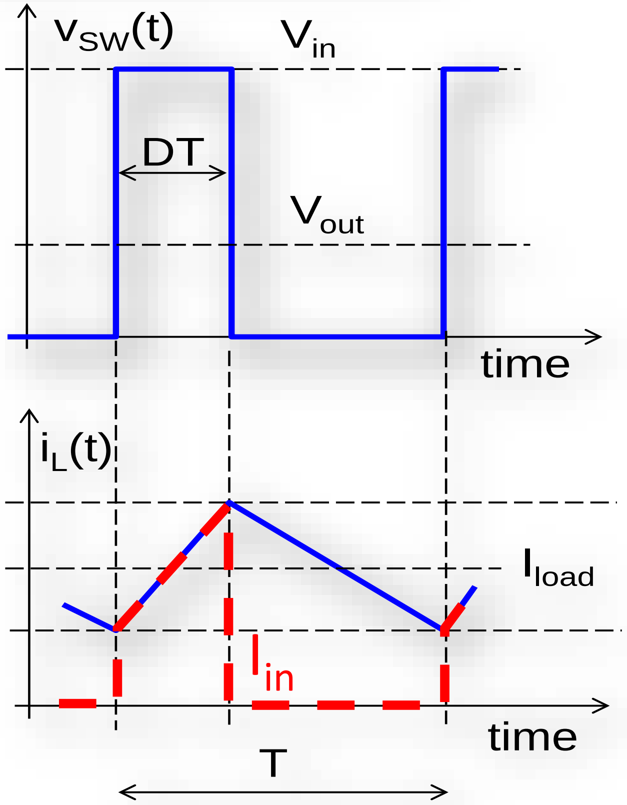
http://www.electrical-integrity.com/Tool_download_files/DC-DC_steady-state-ripple_WExcel2016-32-64b_v09.xlsm

# DC-DC Converter Input



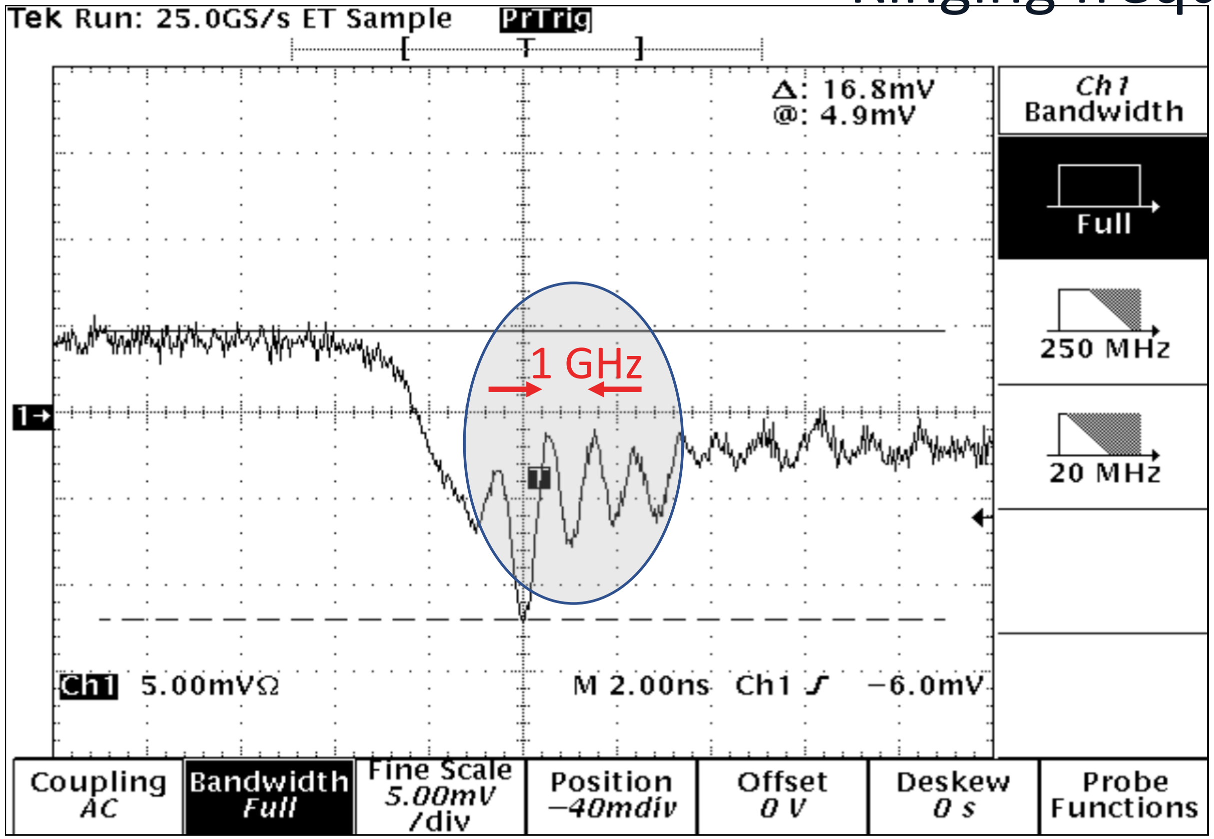

- The input voltage is chopped by the switches
- Inductor current is continuous
- Input current has large jumps

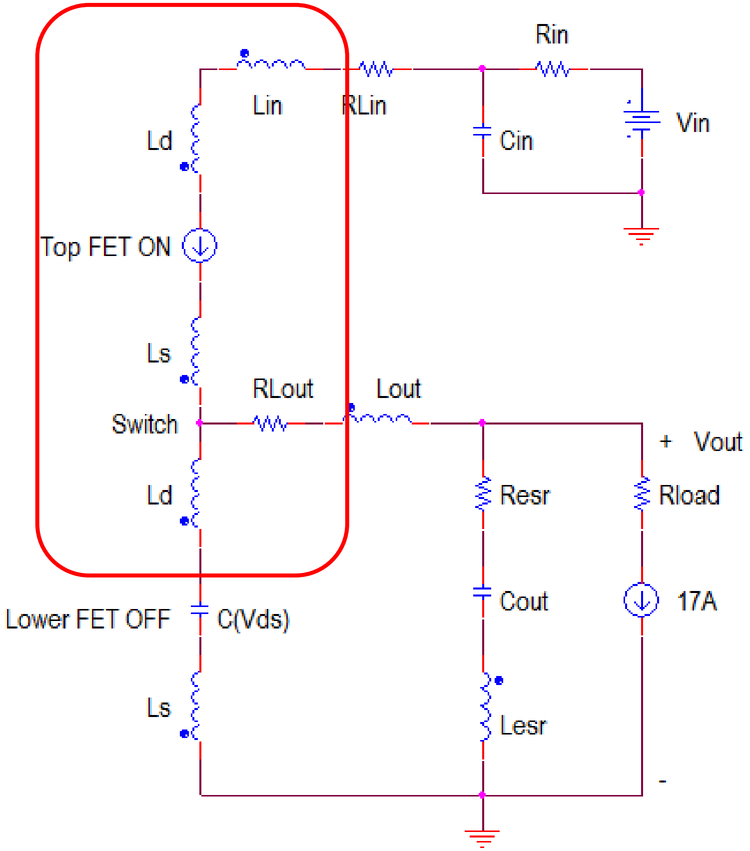


# DC-DC Converter Ringing

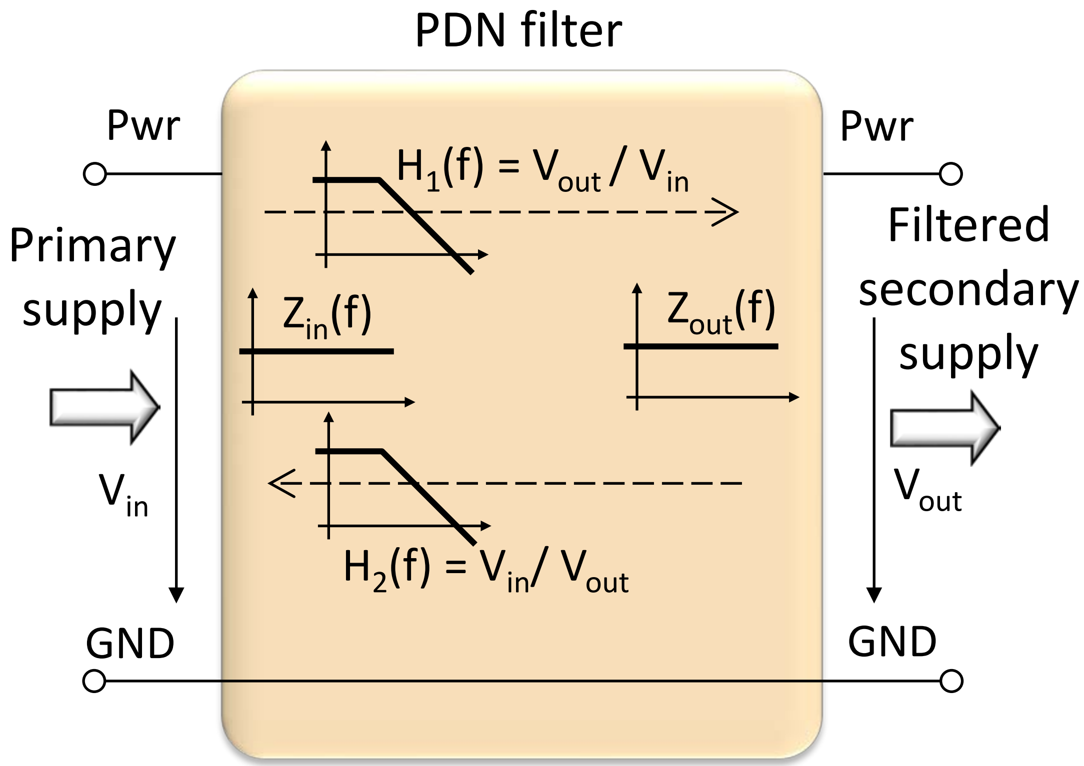
- The switching edges may have high-frequency transients
- Ringing frequency: 50 – 1000 MHz




Source:
- Mid-Frequency Noise Coupling between DC-DC Converters and High-Speed Signals, DesignCon 2016
- What is New in DC-DC Converters; An OEM's Perspective, DesignCon 2012

# Analog Supply Noise Filter (1)




Possible functions and requirements:

- Low-pass filtering from main to secondary
- Low-pass filtering from secondary to primary
- Output impedance for the load (*)
- Input impedance for the source (*)

(*) Optional requirement

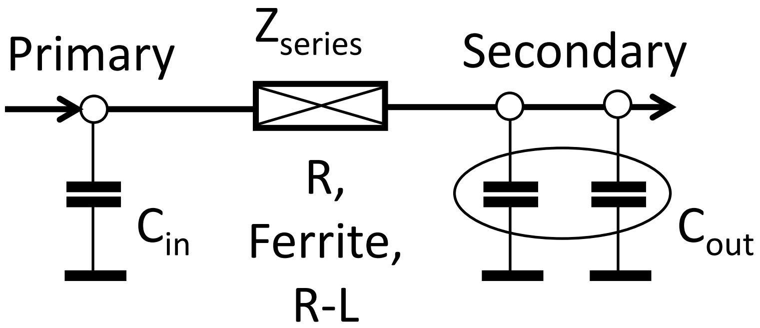
Passive filters may be physically symmetrical

Relevant transfer functions are mostly not symmetric

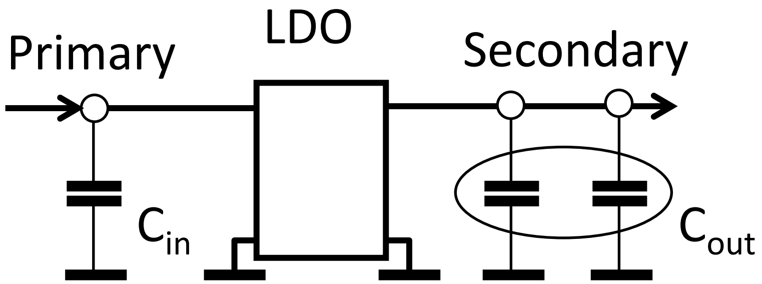
Watch DC voltage drops closely

# Analog Supply Noise Filter (2)

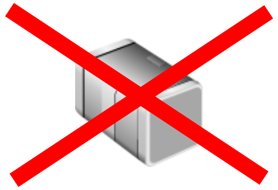
- Use low-Q inductors or ferrites, or

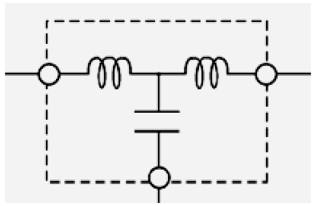



- Low Dropout Regulators




- DO NOT use Hi-Q filters

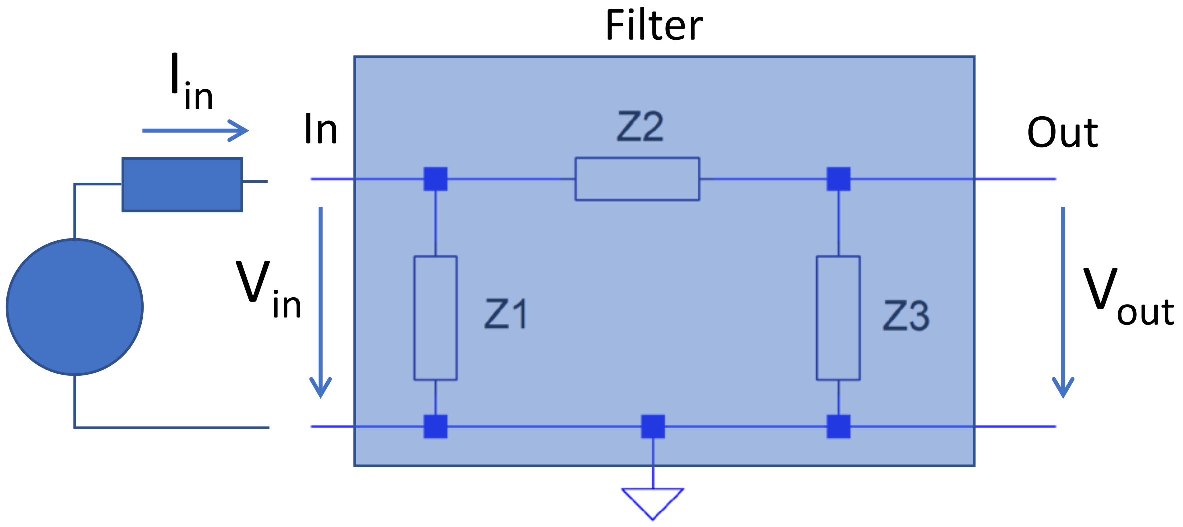


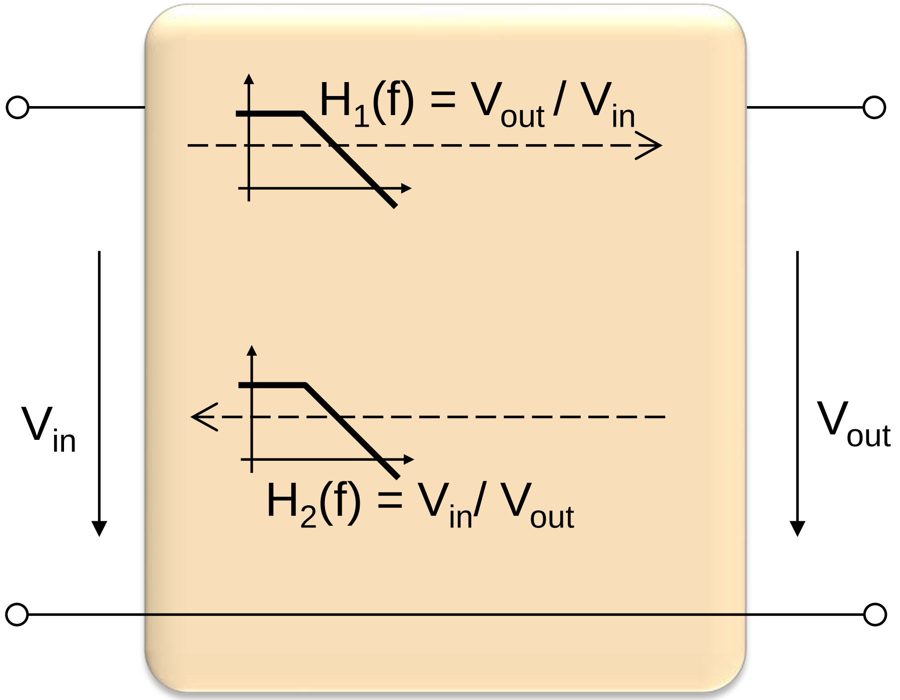


# Transfer Functions

What transfer function matters?

- $Z_{21}$ or $S_{21}$?
- Something else?



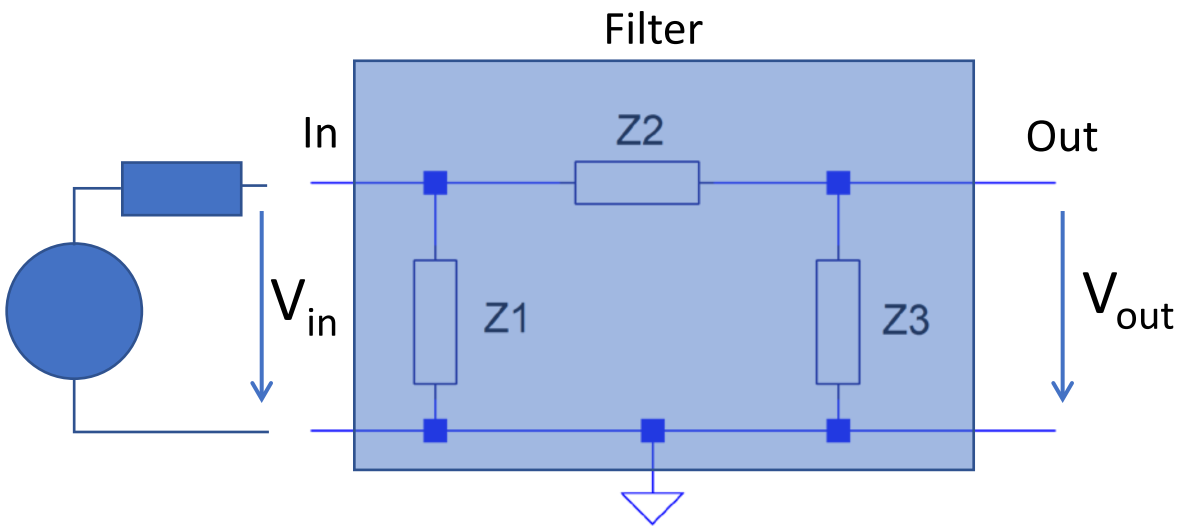




$$Z_{21} = V_{out}/I_{in}$$

$$S_{21} = wave_{out}/wave_{in}$$

# Transfer Functions

For filters from a high-current to a low-current rail we need the *unloaded voltage transfer function: $V_{out} / V_{in}$*

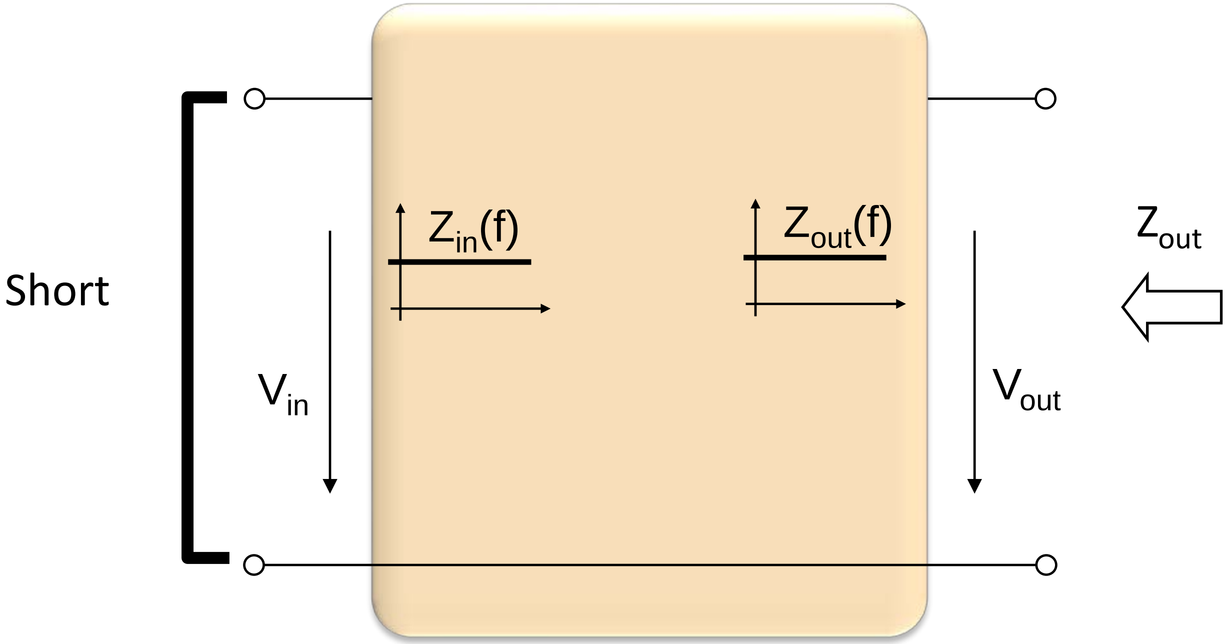


# Impedances

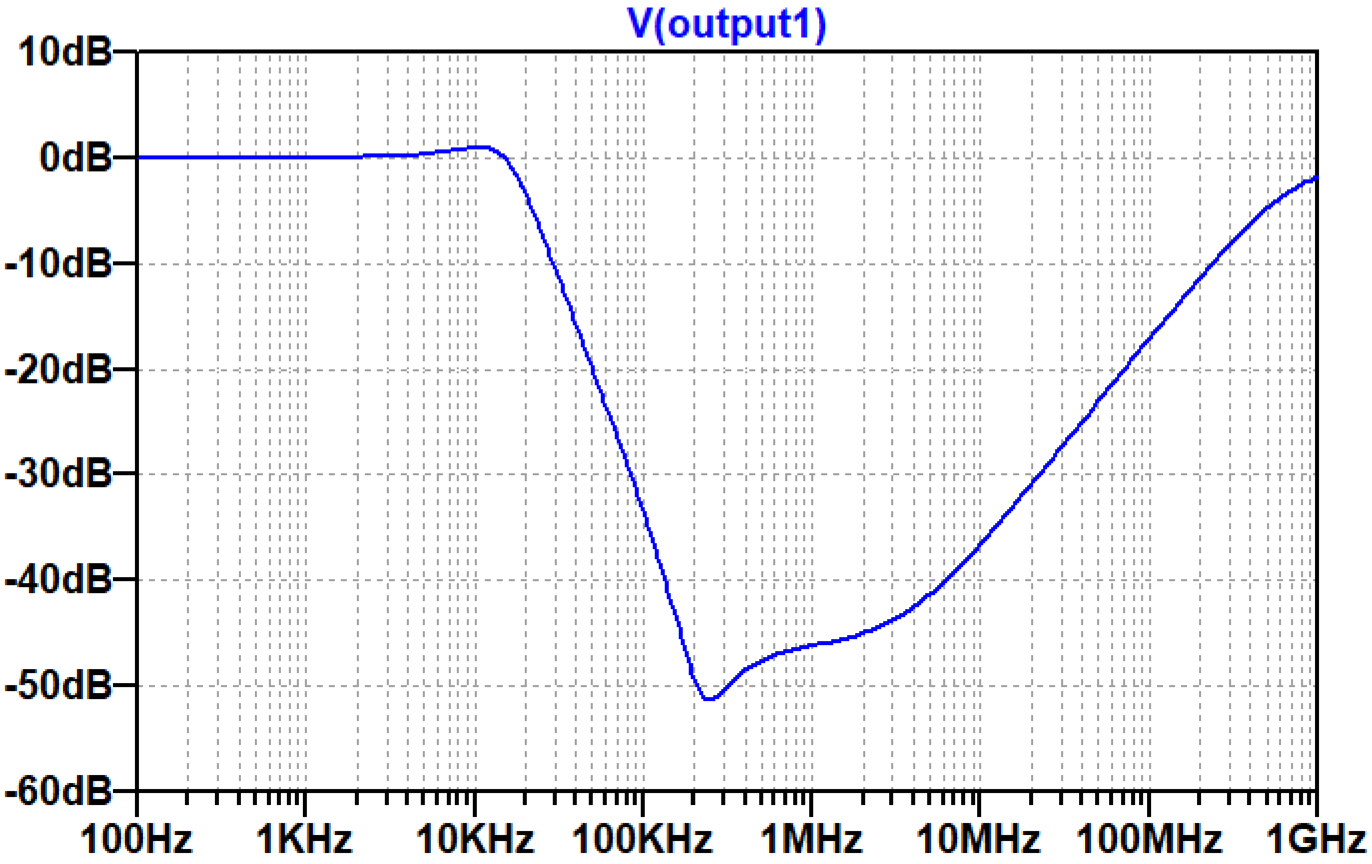
What filter impedance function matters?

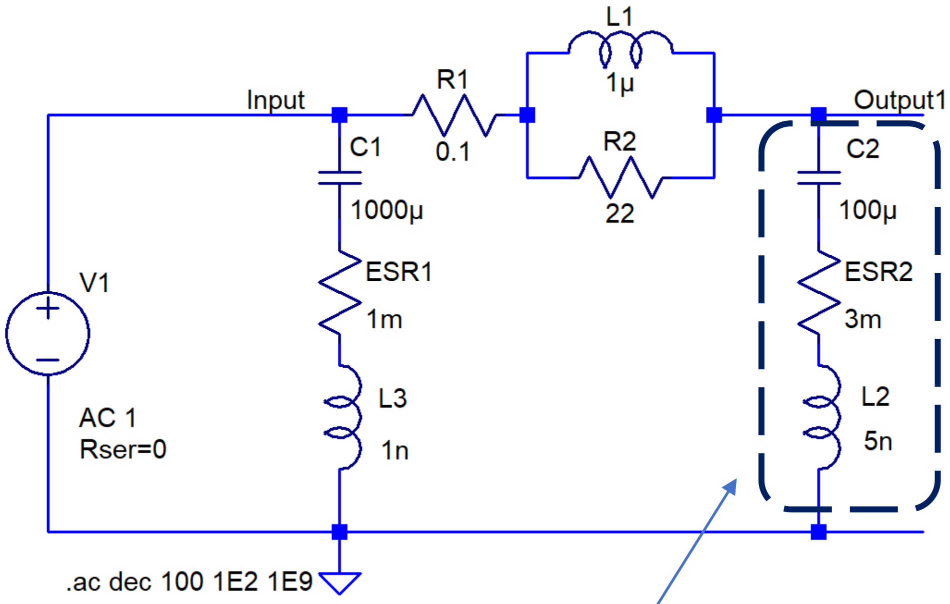
- $Z_{11}$, or $Z_{22}$?
- Something else?

For filters from a high-current to a low-current rail: *Output impedance with shorted input and input impedance with open output*



# Filter Illustrations



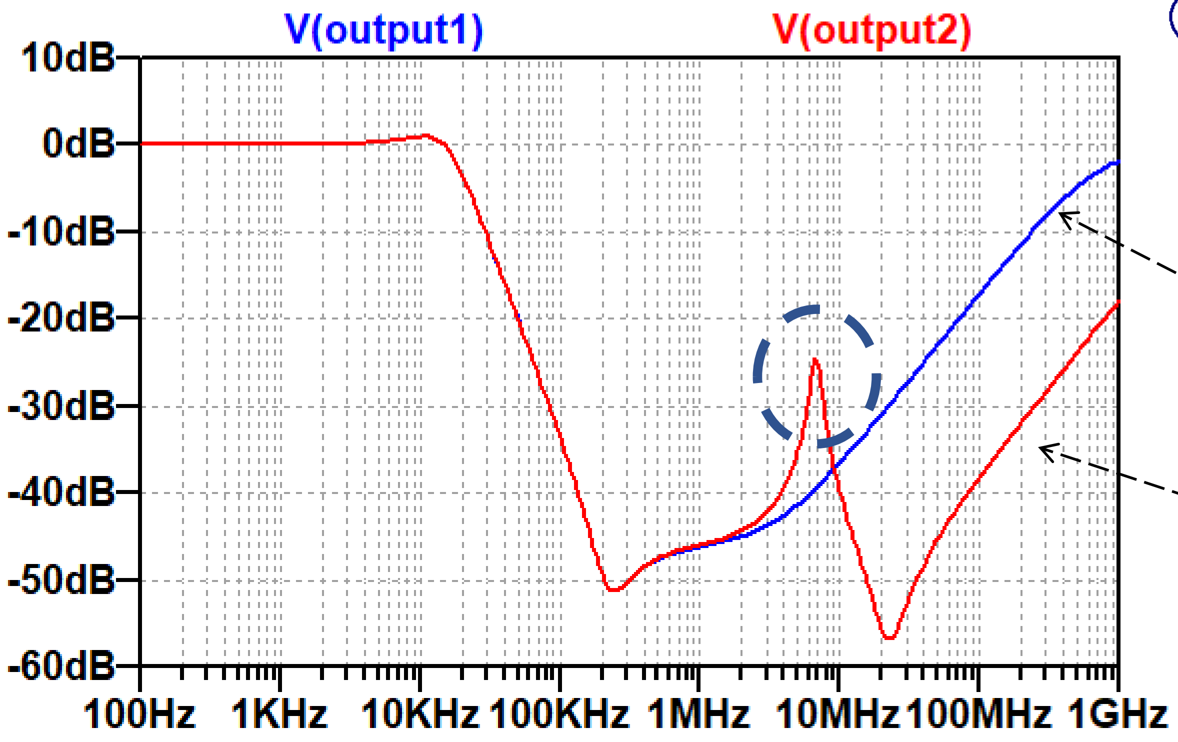



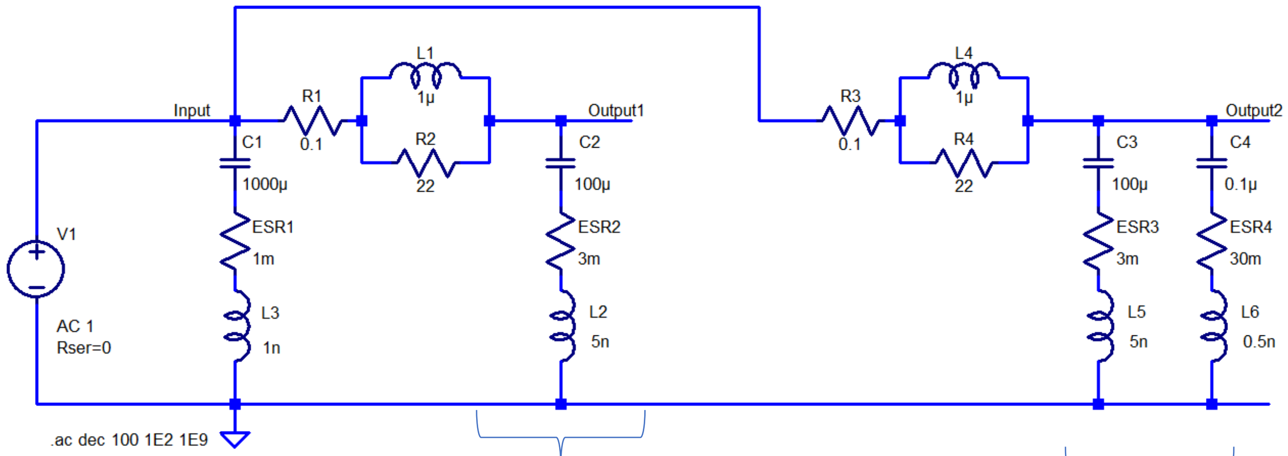

$C_{out}$=C2

100 µF 0.003 ohm 5 nH

# Filter Illustrations, When More is Less

Got better at high frequencies,
but we also got a peak



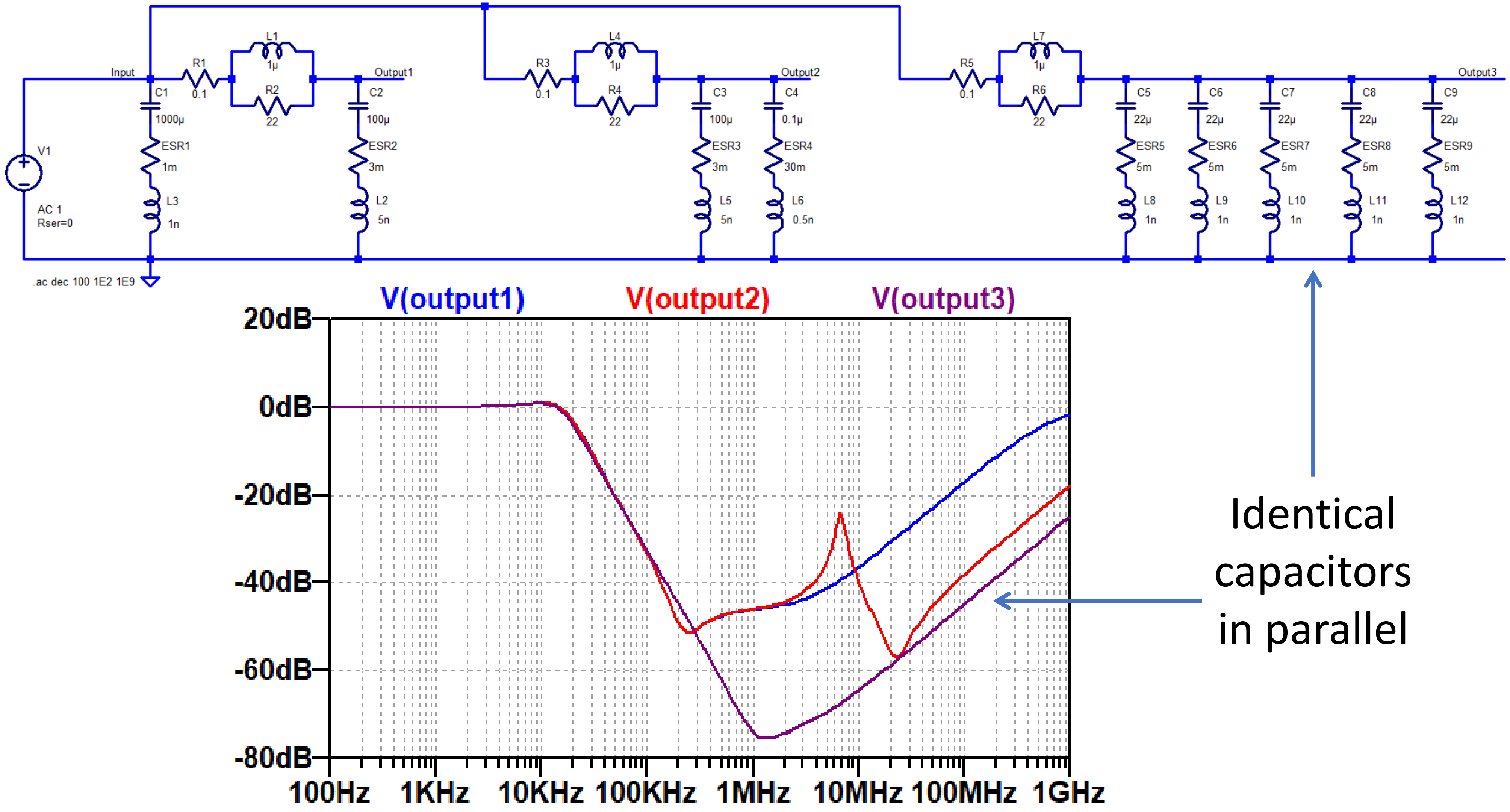

Case 1 $C_{out}$

Case 2 $C_{out}$

Case 1 $C_{out}$
100 µF 0.003 ohm 5 nH

Case 2 $C_{out}$
100 µF 0.003 ohm 5 nH
0.1 µF 0.03 ohm 0.5 nH

# Filter Illustrations, The Best



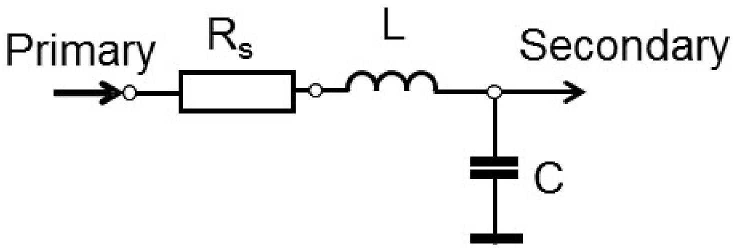

Identical capacitors in parallel

# The Filter Design Process

Collect input requirements

- Offending frequency components (frequency, magnitude) to filter
- Necessary attenuation
- Set design parameters:
- Filter cutoff frequency $f_c$ and Q

Design the inductance and bulk capacitance based on:




$$f_c = \frac{1}{2\pi\sqrt{LC}}, \quad Q = \frac{\sqrt{\frac{L}{C}}}{R_S}$$

Or use a circuit simulator to quickly iterate component values…

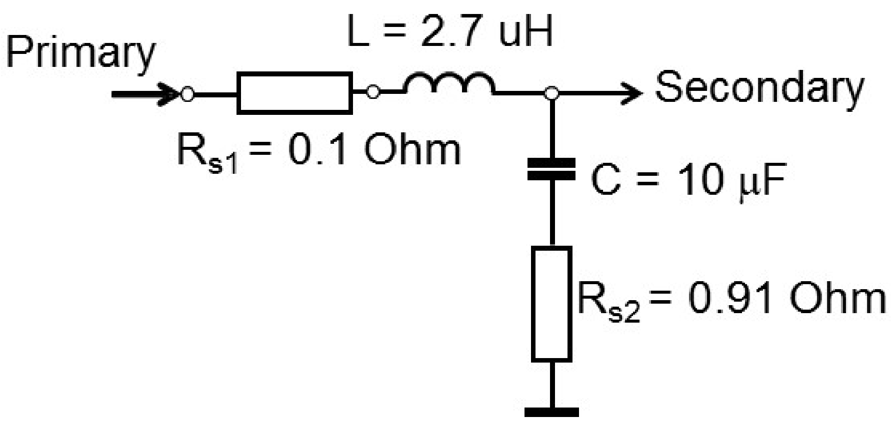
# Low-Current Filter Example (1)

Design requirements for low-current filter

* Cutoff frequency $f_c$ = 100 kHz (DC-DC converter running at 1MHz)
* Q = 0.5

Assume $R_s$ = 1 Ohm

$$f_c = \frac{1}{2\pi\sqrt{LC}}, \quad Q = \frac{\sqrt{\frac{L}{C}}}{R_S}$$



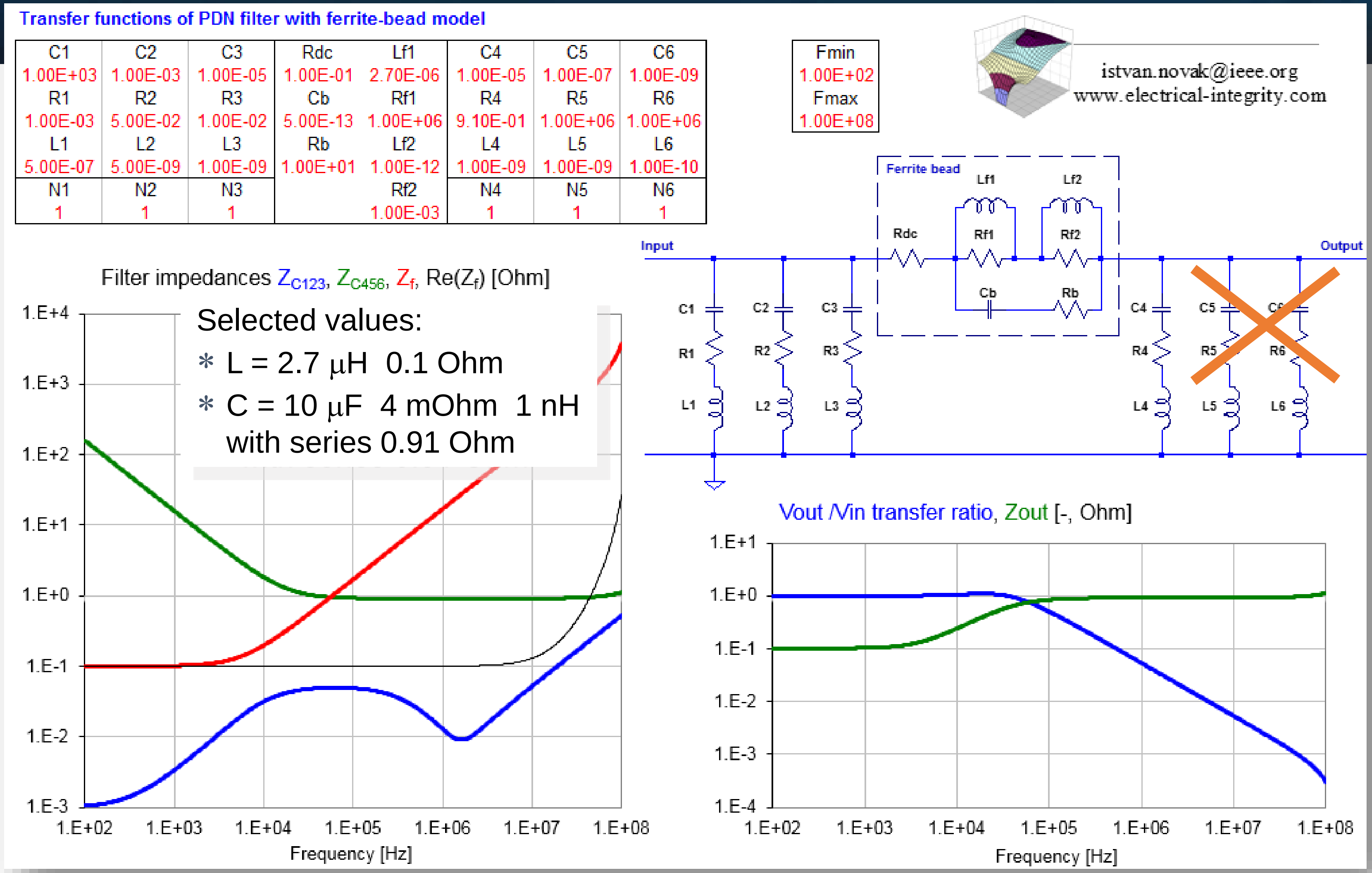

Calculated values:

* L = 2.7 µH
* C = 10 uF

Select:

* L = 2.7 µH 0.1 Ohm
* C = 10 µF + 0.91 Ohm

# Low-Current Filter Example (2)

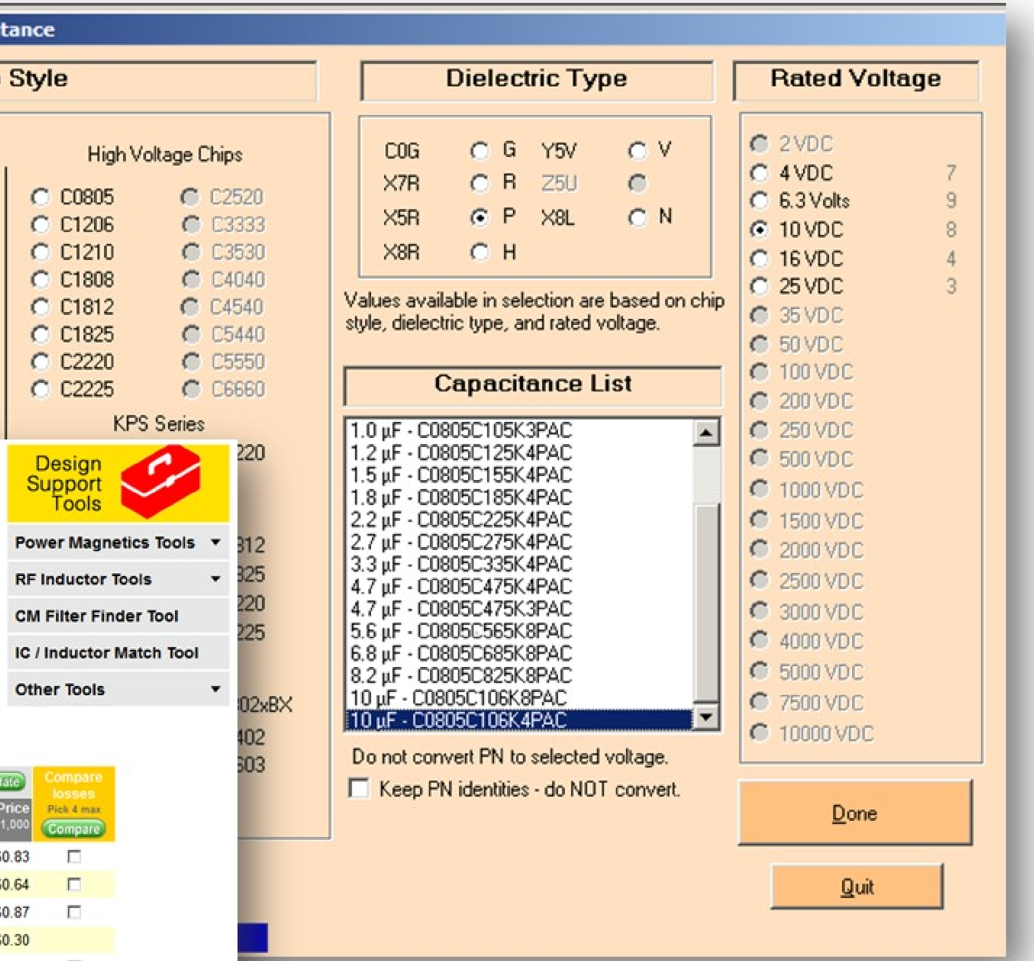


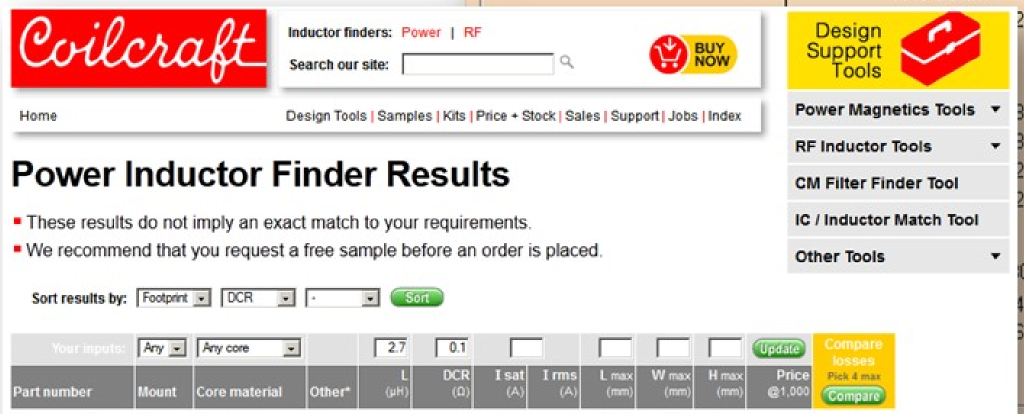

http://www.electrical-integrity.com/Tool_download_files/PDN-filter_WExcel2016-32-64b_v06.xlsm

# Low-Current Filter Example (3)

Selected components:

* Coilcraft 181PS-272 L = 2.7 μH 0.08 Ohm
* Kemet C0805C106K4PAC C = 10 μF 4 mOhm 1 nH



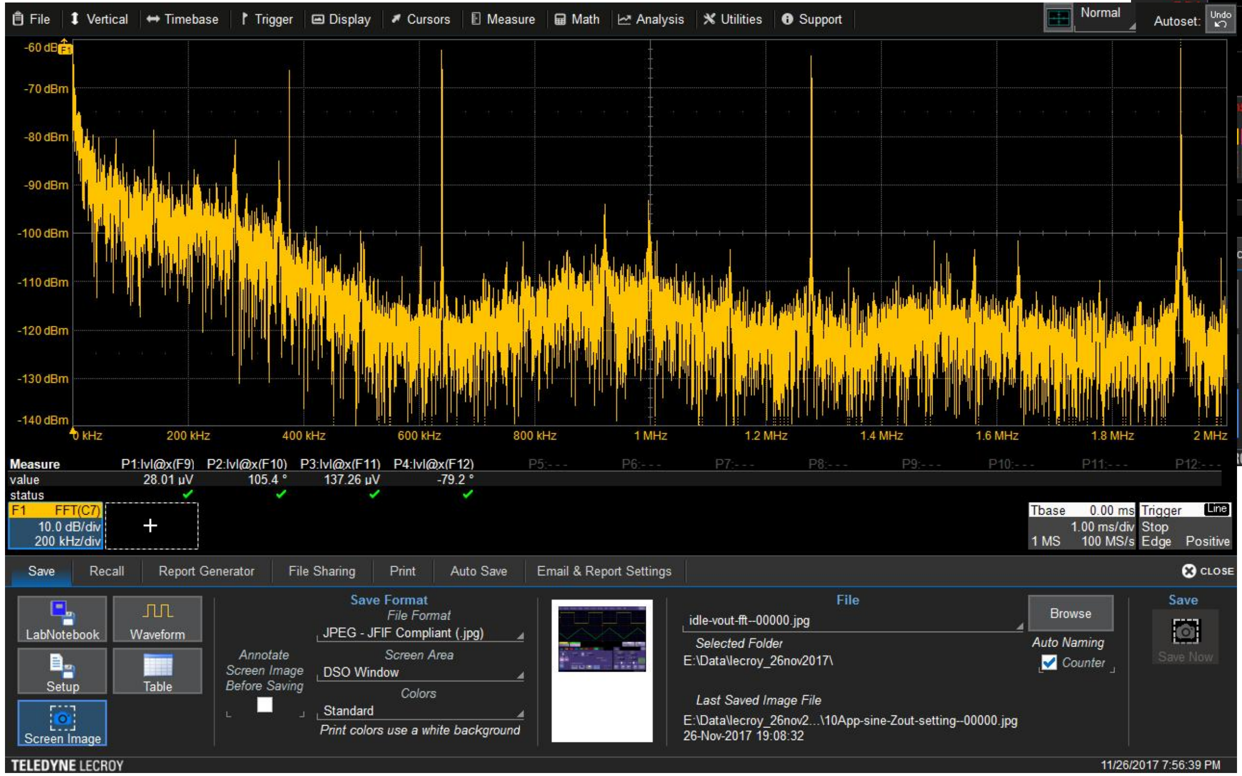

| Part number | Mount | Core material | Other* | L (µH) | DCR (Ω) | I sat (A) | I rms (A) | L max (mm) | W max (mm) | H max (mm) | Price @1,000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1812PS-272 | SM | Ferrite | S | 2.7 | 0.0800 | 1.4 | 2.3 | 5.87 | 4.98 | 3.81 | $0.83 |
| DO1608C-272 | SM | Ferrite | | 2.7 | 0.0800 | 2.1 | 2.45 | 6.60 | 4.45 | 2.92 | $0.64 |
| XAL7030-272 | SM | Composite | S | 2.7 | 0.0173 | 12.8 | 11.4 | 8.00 | 8.00 | 3.10 | $0.87 |
| RFB0807-2R7 | Leaded | Ferrite | | 2.7 | 0.0140 | 5.5 | 6.54 | 8.80 | 8.80 | 7.50 | $0.30 |
| MSS1038T-252 | SM | Ferrite | S | 2.5 | 0.0100 | 9.26 | 6.65 | 10.50 | 10.20 | 4.00 | $0.55 |

# Be Aware

- All filter components may be impacted by bias stress
  - Capacitance loss due to voltage bias
  - Inductance loss due to current bias
- The filter has to pass DC current and therefore very low frequency noise can not be eliminated
  - Sub-harmonic converter ripple
  - Out-of-band spurious signals
  - Low frequency random noise
- Series resistive loss maintains second-order filtering; resistance in the parallel path approaches first-order filtering
- Check the DC-DC converter operating frequency before you switch to a different converter!

# Be Aware

- Random wander of current sharing
- 600 kHz switching frequency
- Six-phase 12V to 0.9V regulator



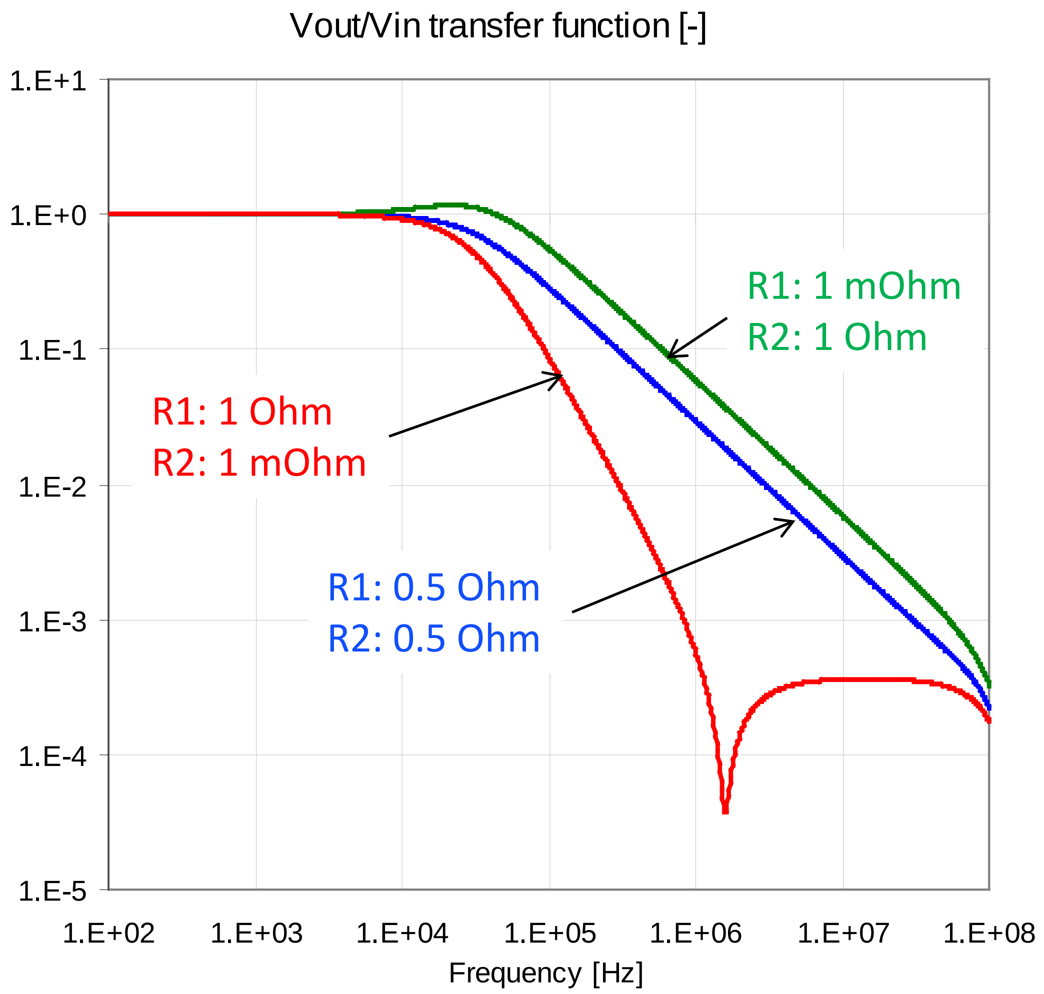


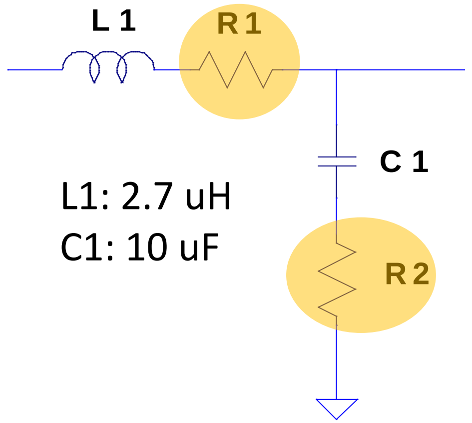
Current sharing among phases in the time domain

Spectrum of output voltage

http://www.electrical-integrity.com/Paper_download_files/DC18_PAPER_MeasuringCurrentAndSharing_corrected_v3.pdf

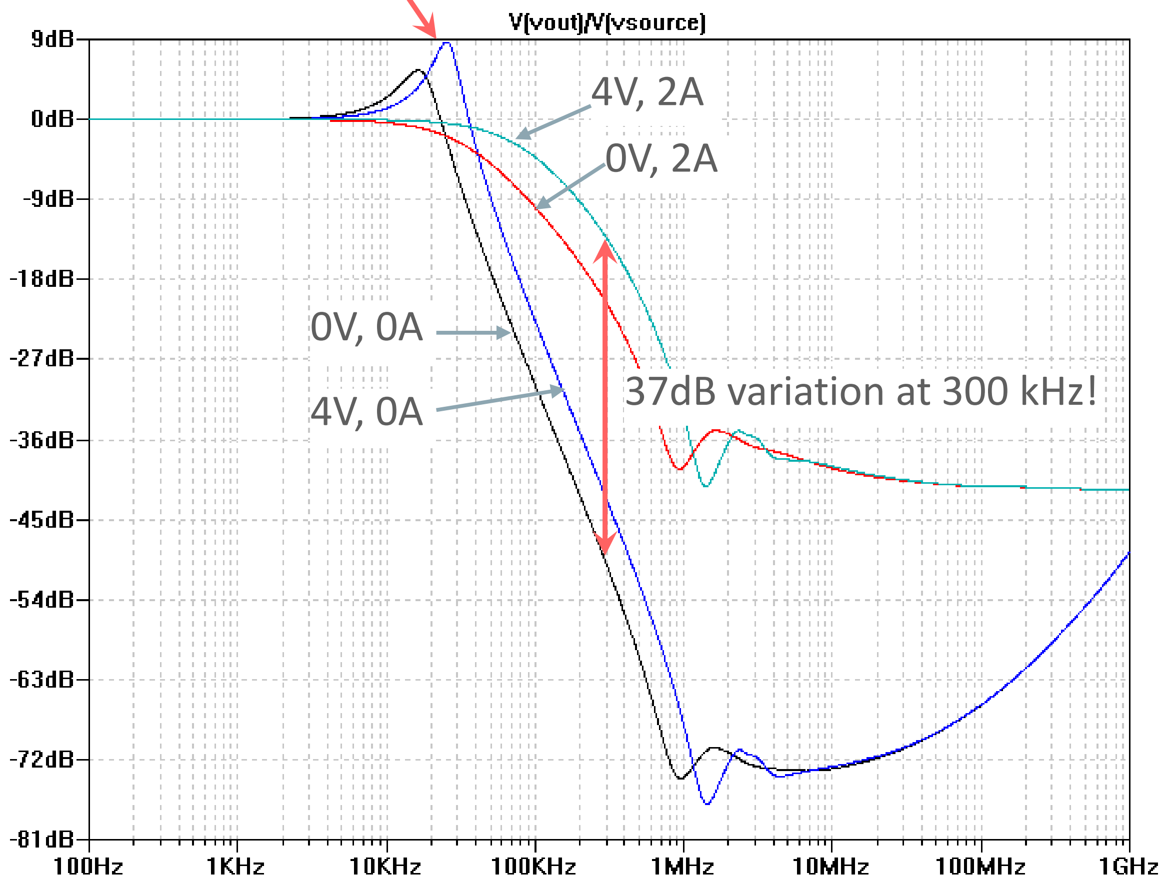
# Be Aware, Distribution of Losses

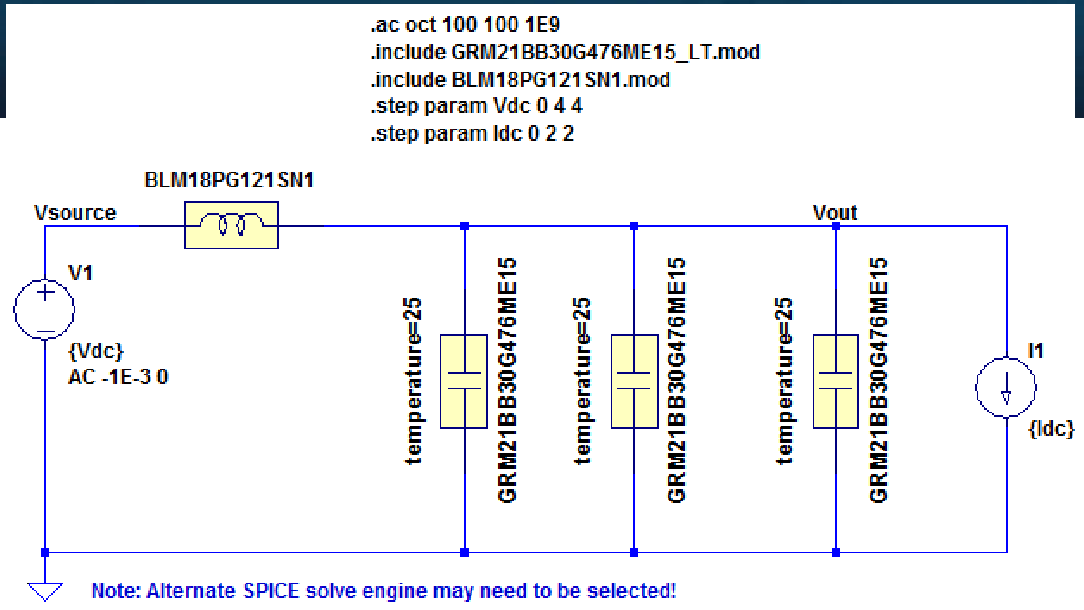


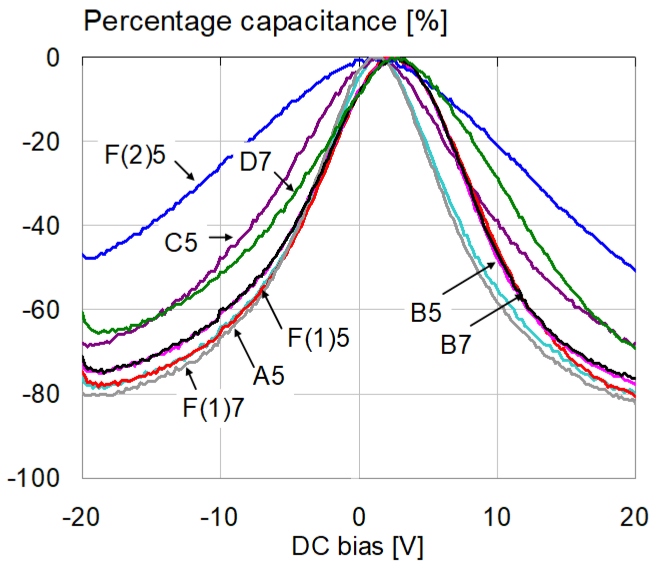




Series resistive loss maintains second-order filtering; resistance in the parallel path approaches first-order filtering

# Be Aware, Bias Effects




Source: "How Much Capacitance Do We Really Get?," QuietPower columns, http://www.electrical-integrity.com/Quietpower_files/QuietPower-40.pdf

# Loss of Capacitance in MLCCs

| | Percentage range [%] | Relative multiplier |
|---|---|---|
| Initial tolerance | +-10 | 0.9 … 1.1 |
| Temperature effect | +-15 | 0.85 … 1.15 |
| DC bias effect | +0 -70 | 0.3 … 1 |
| AC bias effect | +0 -30 | 0.7 … 1 |
| Aging (over 3 years) | +0 -7.5 | 0.925 … 1 |

***0.15*** ***1.27***

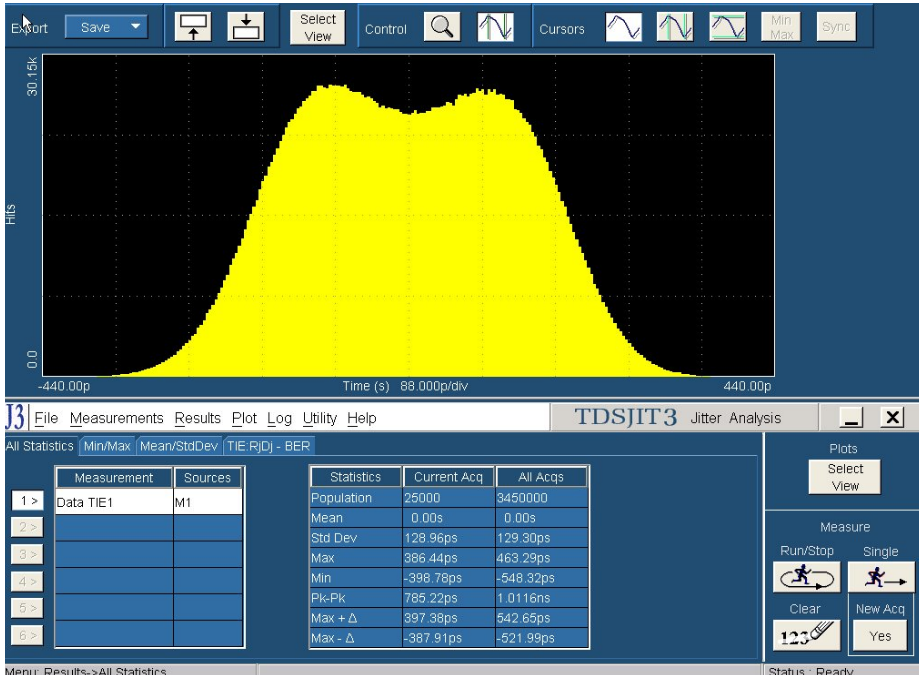
* For worst case, have to multiply all multipliers
* High CV ceramic capacitors can lose up to 85% of capacitance
* Highest impact is DC and AC bias voltage

Source: "How Much Capacitance Do We Really Get?," QuietPower columns, http://www.electrical-integrity.com/Quietpower_files/QuietPower-40.pdf

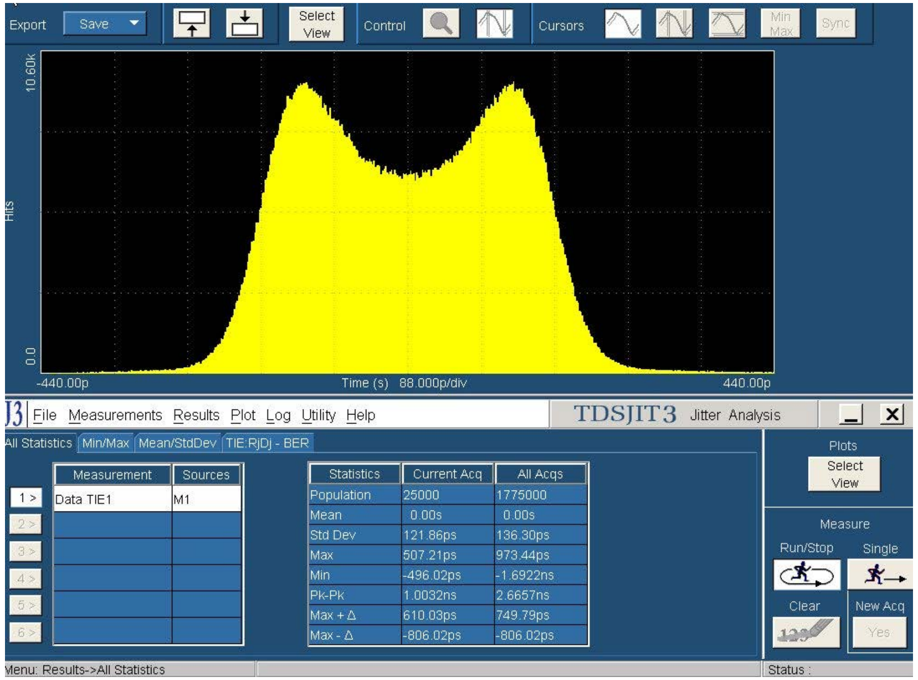
# In-System Interference

GbE jitter measured on a live system

Only the AC/DC power supply was changed




With PSU #1




With PSU #2

http://www.electrical-integrity.com/Paper_download_files/DC18_PAPER_MeasuringCurrentAndSharing_corrected_v3.pdf

# The First EMC-SMOG Map of Earth

Live interactive map is at

https://gnd.bme.hu/mb/site

Credit:

- Spectrum data from Hungarian SMOG-P nanosatellite, http://gnd.bme.hu/smog
- Visualization and data processing: Markotics Boldizsar and Takacs Donat, BME Cosmos Society, https://kozmosz.space/

# Summary

- Filters can effectively suppress noise propagating from
  - High-power source to low-power sensitive circuit
  - High-current load transients spilling back out to main supply rails
- Primary design goals for LC filters
  - Provide enough attenuation of the offending spectrum
  - Avoid peaking of transfer function that would amplify instead of attenuating the noise
- But
  - Series filter reactance must be balanced by capacitance after the filter
  - If the filter is not needed or incorrectly implemented, it can create problems
- Filter performance can be impacted by bias current (loss of inductance) and voltage (loss of capacitance)

# Further Resources

"How to Design Good PDN Filters," DesignCon 2019, January 29-31, 2019, Santa Clara, CA

http://www.electrical-integrity.com/Paper_download_files/DC19_Tutorial_SLIDES_HowToDesignGoodPDNFilter.pdf

"Do You Really Need that Ferrite Bead in the PDN?"

http://www.electrical-integrity.com/Quietpower_files/QuietPower-55.pdf

For illustration tools, papers, blogs, SI and PI courses, see

http://www.electrical-integrity.com/

# THANK YOU

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