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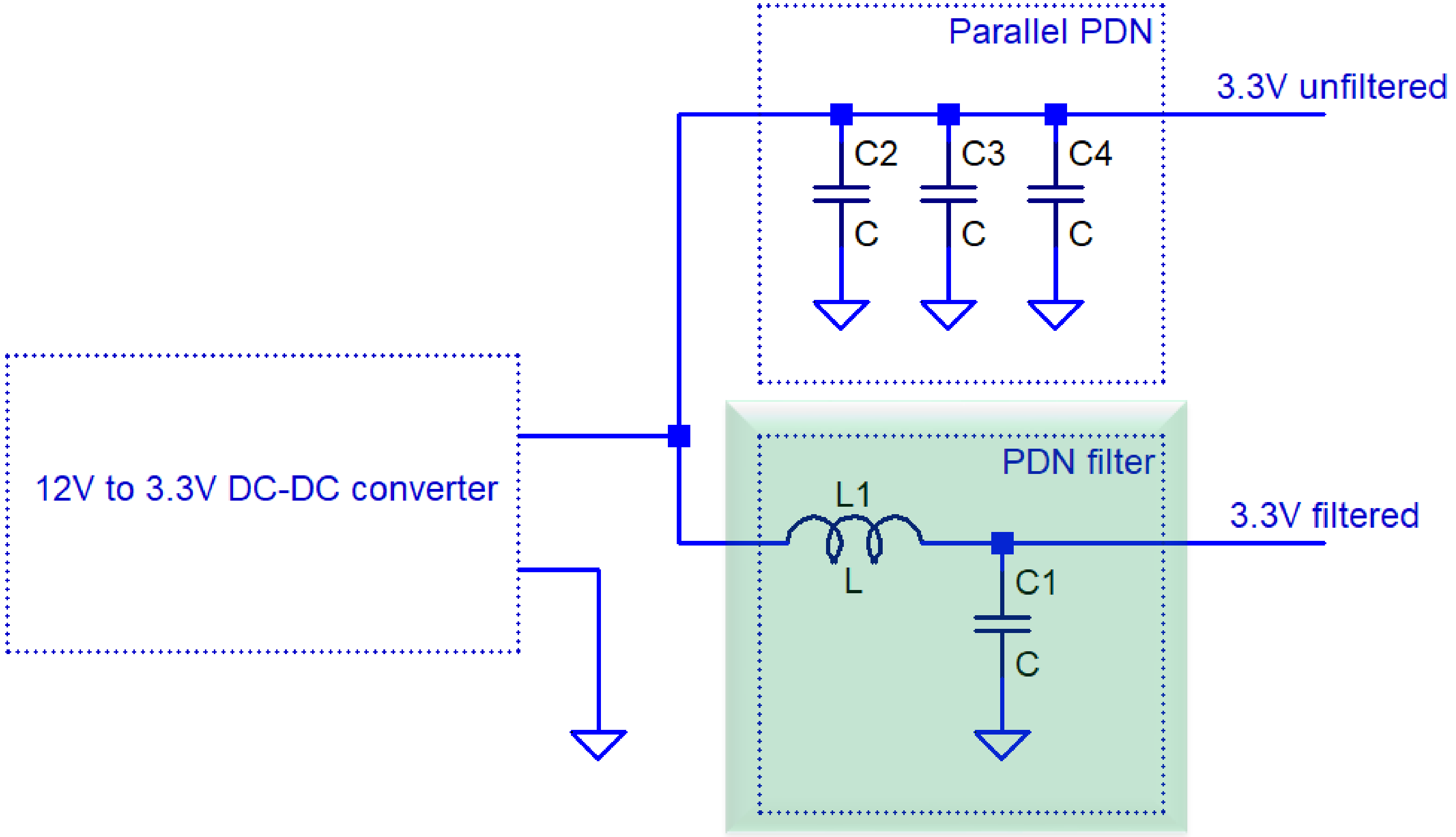
Using Ferrites and Inductors in Power Distribution Networks (PDN)

Presenter: Istvan Novak

Power Distribution Filters

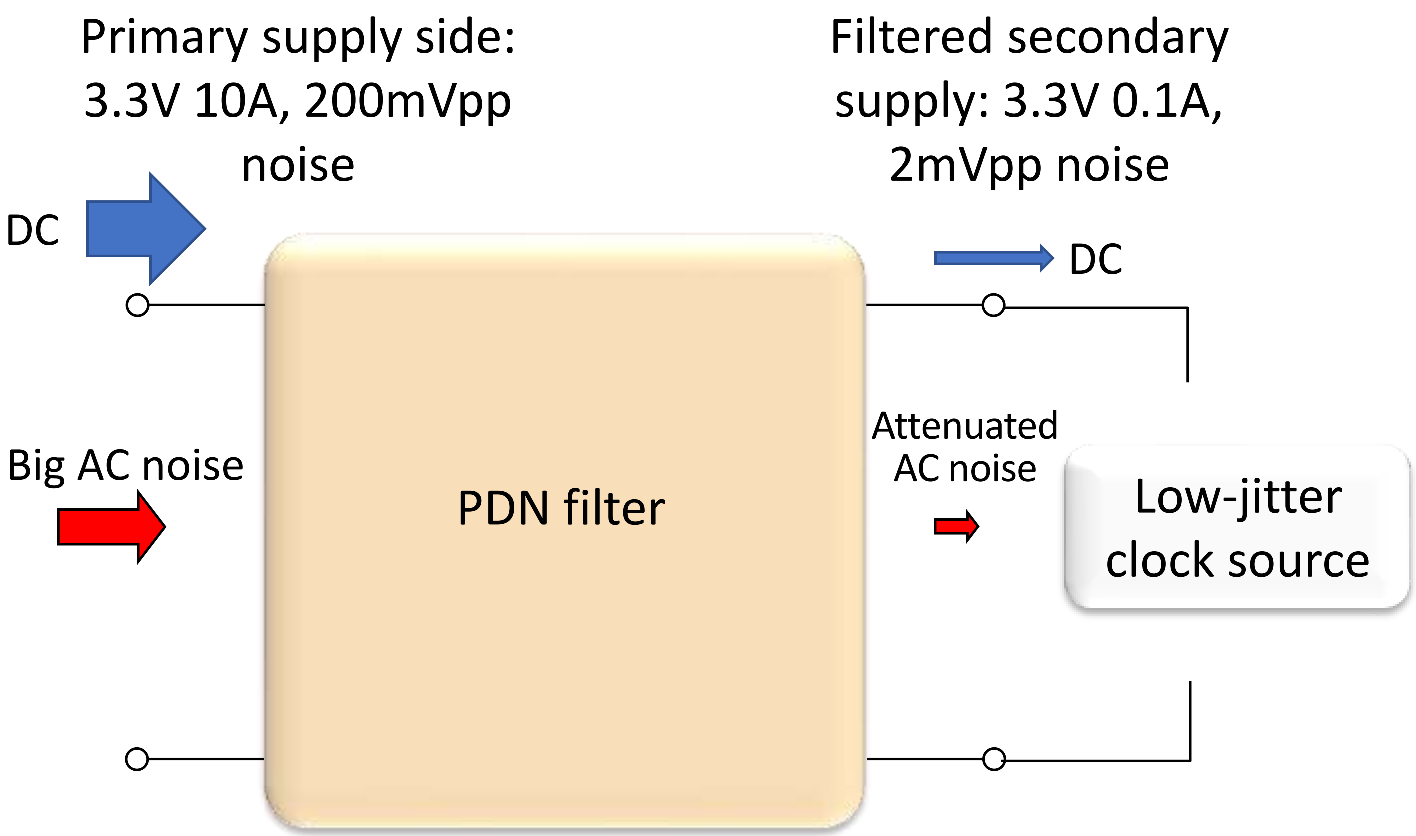
OUTLINE

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



When Do We Need a Filter?

To feed a sensitive low-current load



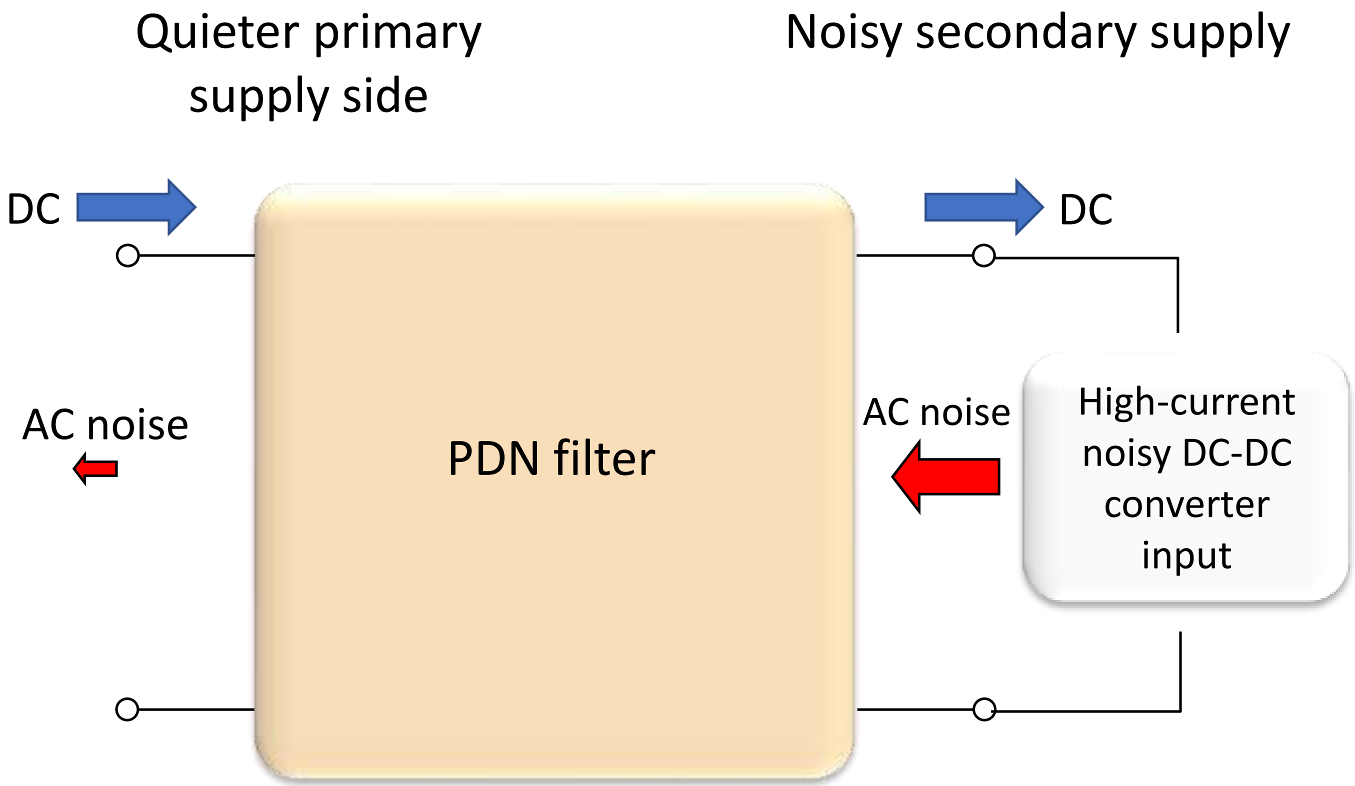
Always ask yourself: Do we need a filter or not?

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

How to Design a Good PDN Filter, http://www.electrical-integrity.com/Paper_download_files/DC19_Tutorial_SLIDES_HowToDesignGoodPDNFilter.pdf

When Do We Need a Filter?

To keep noise spilling out from noisy loads

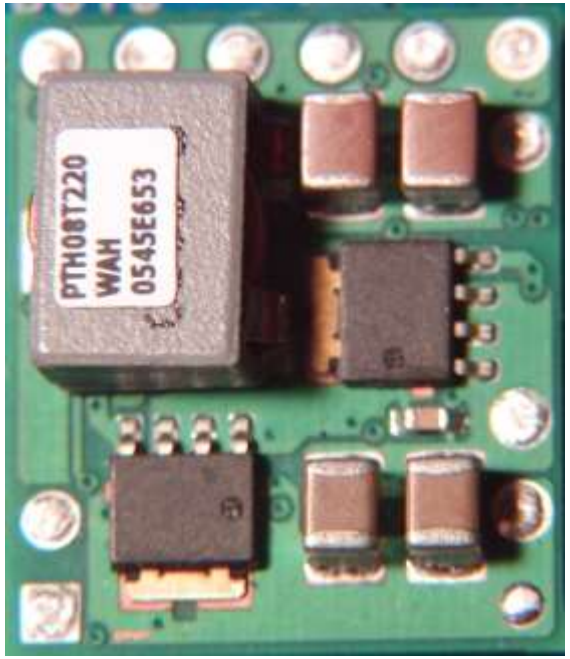


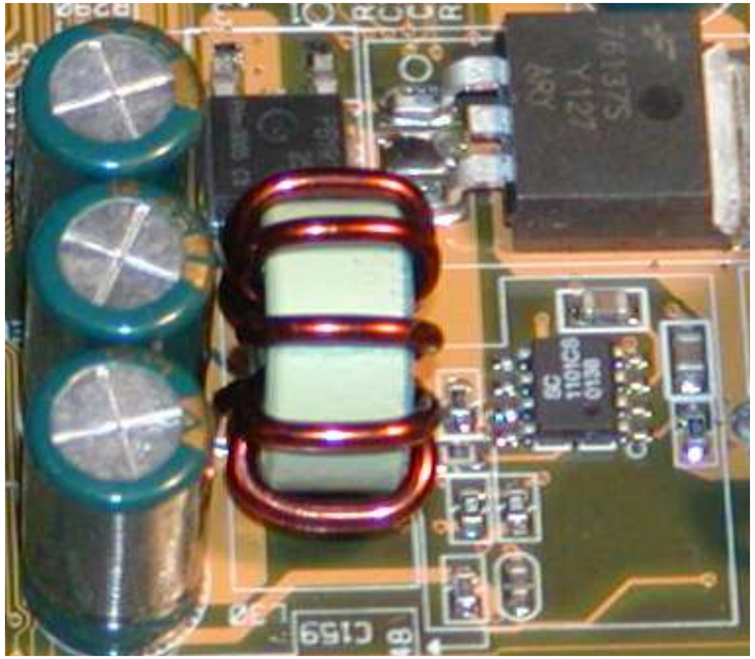
Always ask yourself: Do we need a filter or not?

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

A 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

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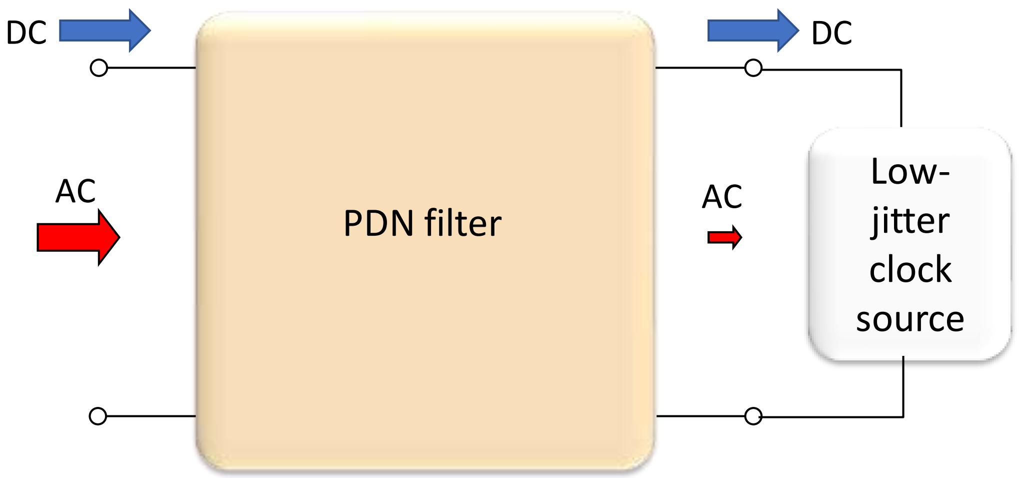
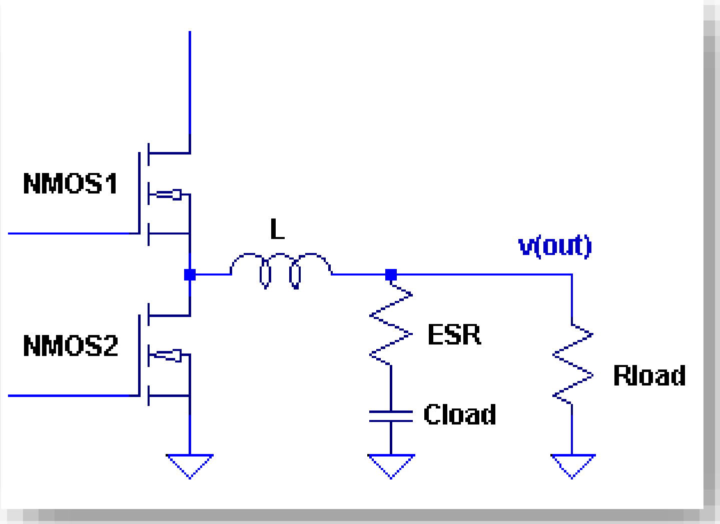
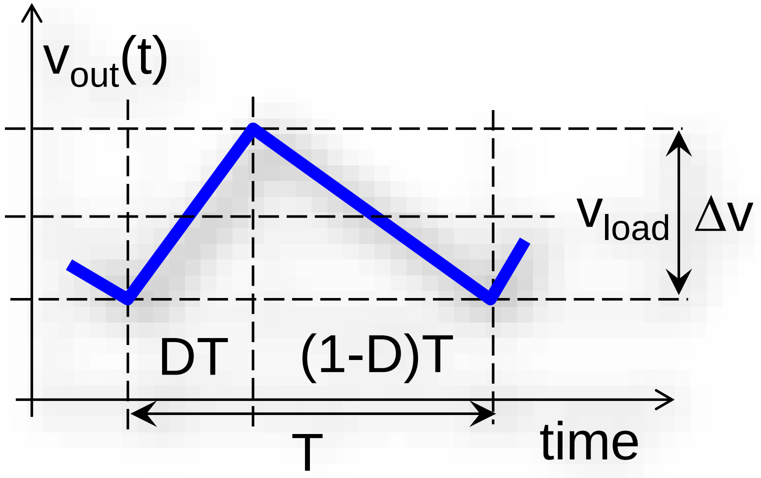
- The inductor ripple current flows through the output capacitor
- First-order mid-frequency capacitor model = ESR-only
- Output ripple voltage shape closely follows inductor ripple current







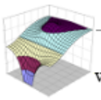
If Cload *ESR pole is below Fsw, the output ripple is:

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

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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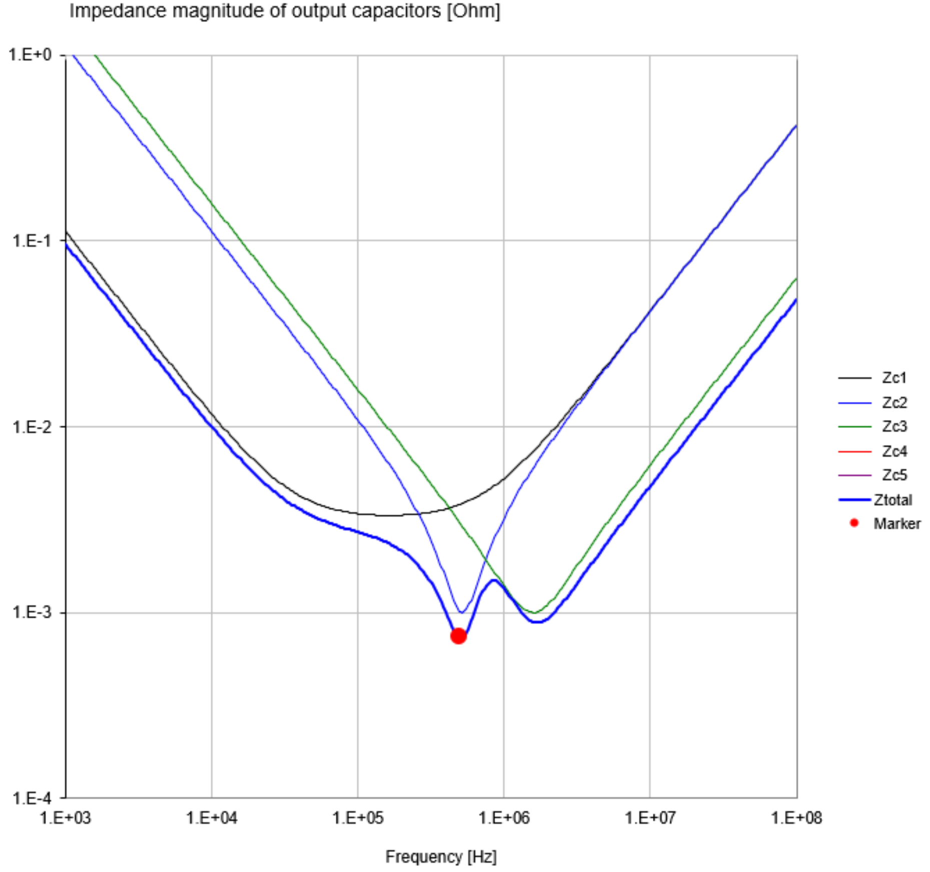
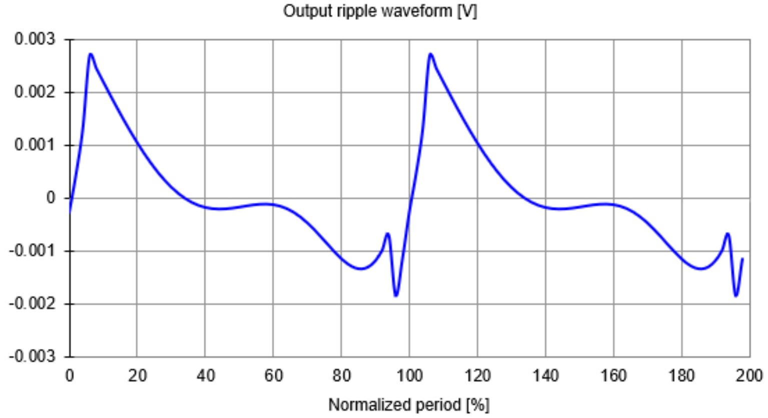
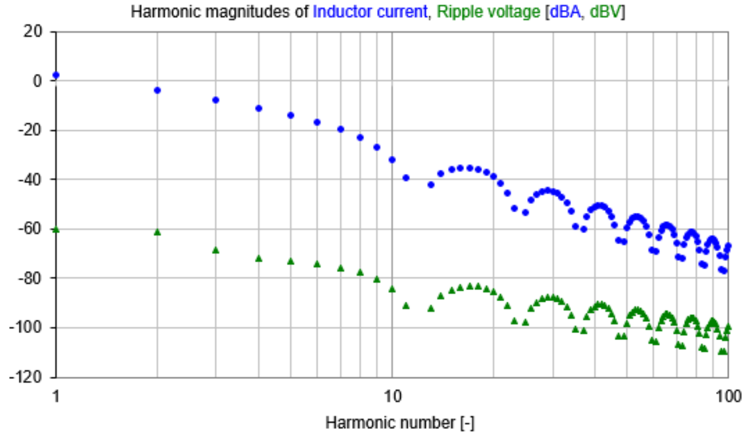
Number of periods
2





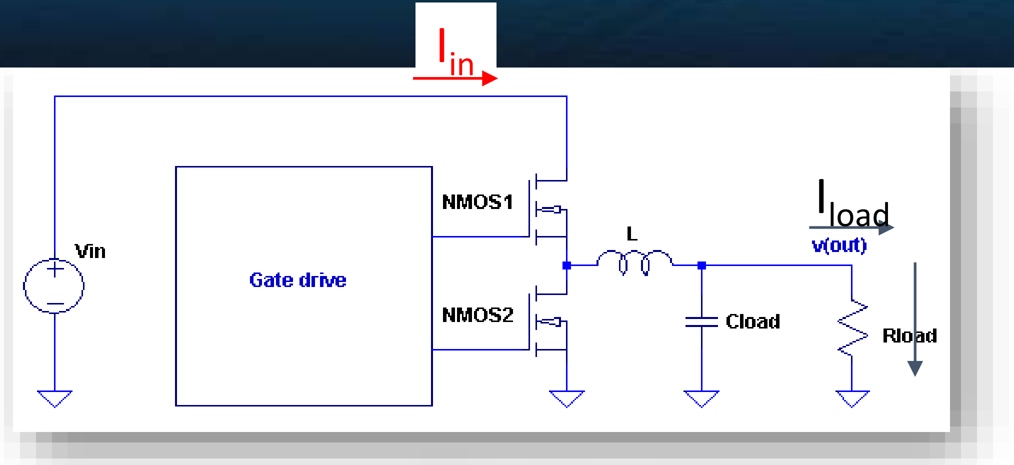


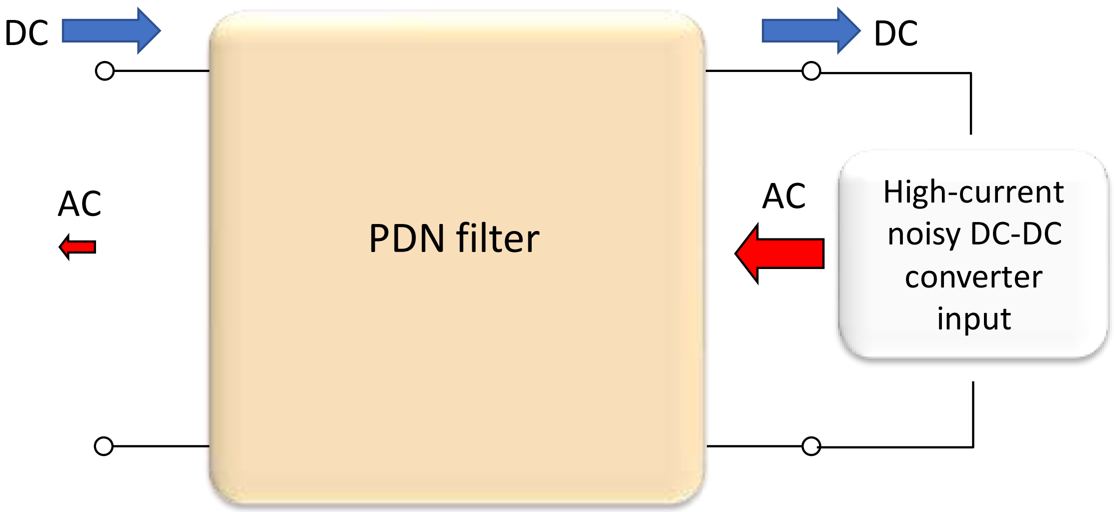
- The inductor ripple current flows through the output capacitor
- First-order mid-frequency capacitor model = ESR-only
- Output ripple voltage shape closely follows inductor ripple current

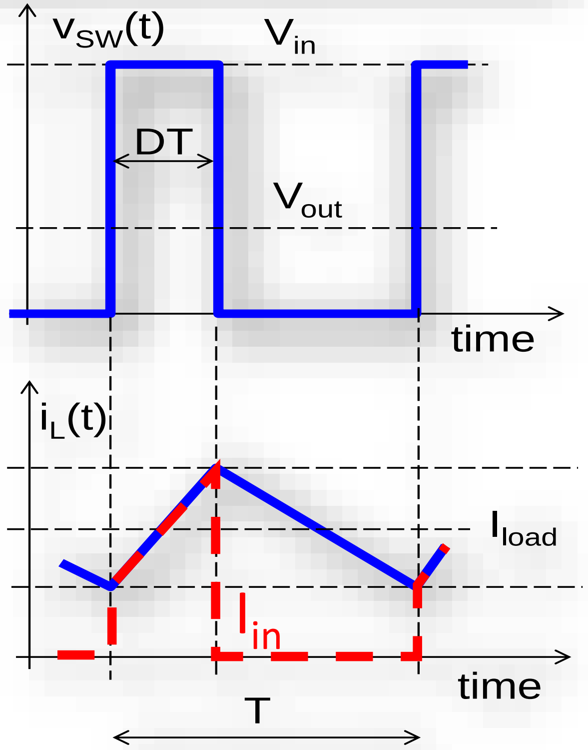
http://www.electrical-integrity.com/Tool_download_files/DC-DC_steady-state-ripple_WExcel2016-32-64b_v09.xlsm

DC-DC Converter Input

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

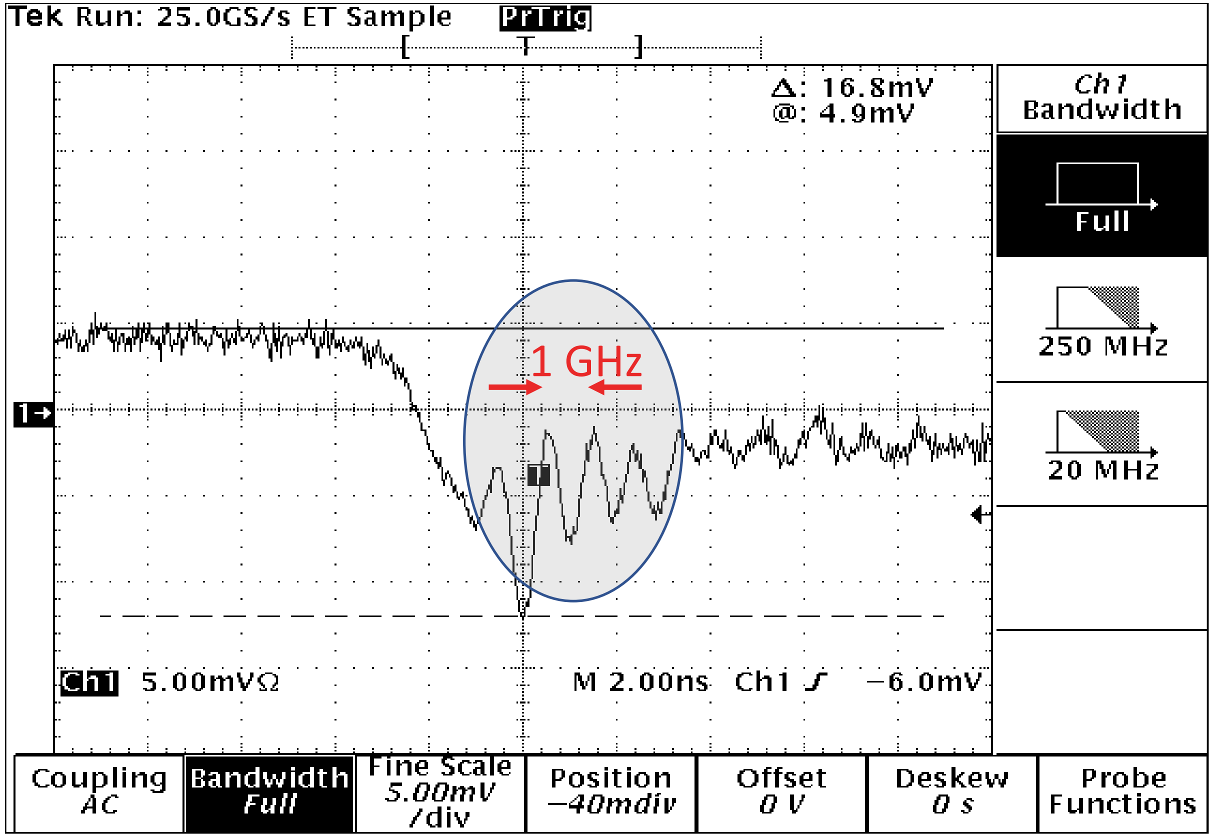




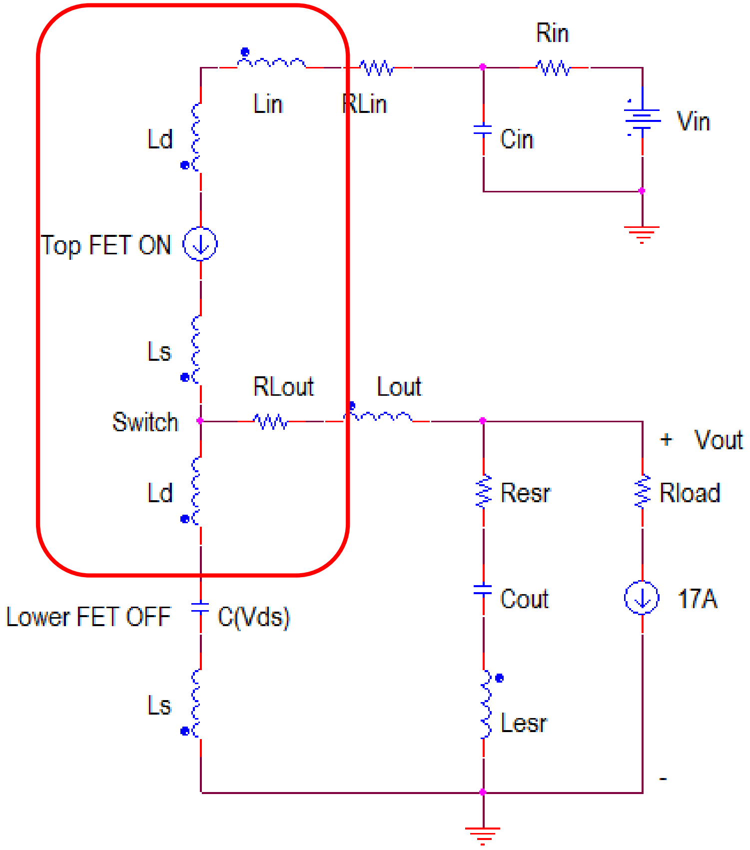


DC-DC Converter Ringing

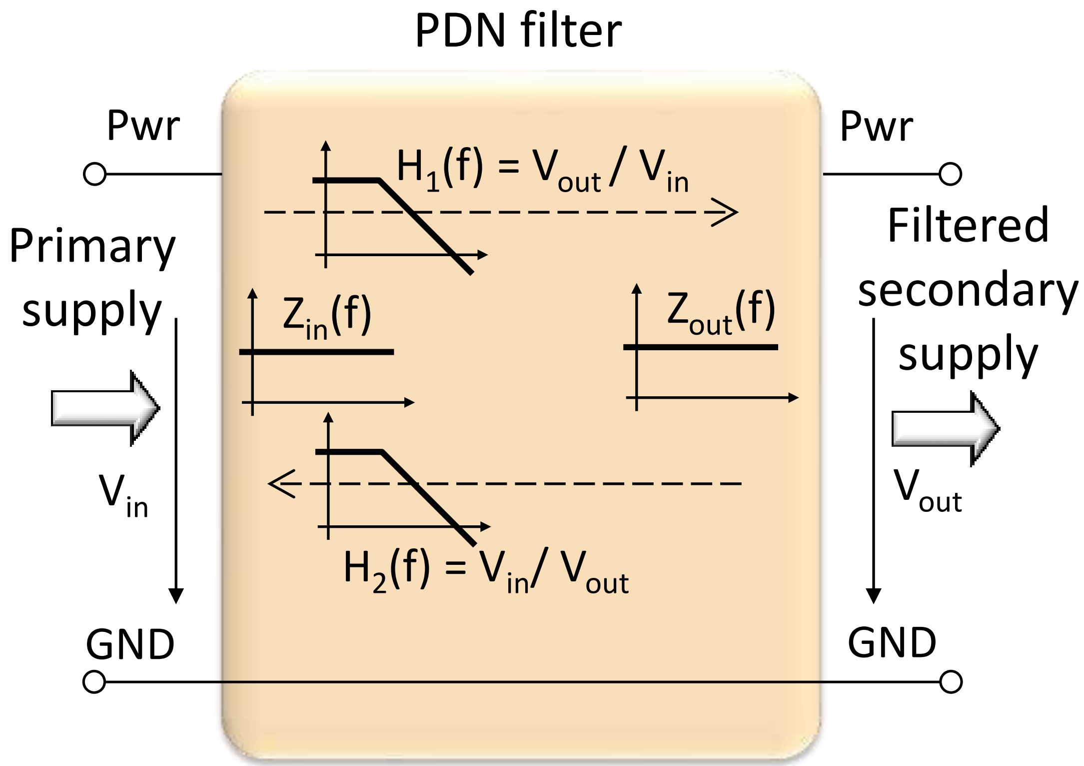
- The switching edges may have high-frequency transients
- Ringing frequency range today: 1 – 1000 MHz



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



Possible functions and requirements:

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

(*) Optional requirement

Passive filters may be physically symmetrical

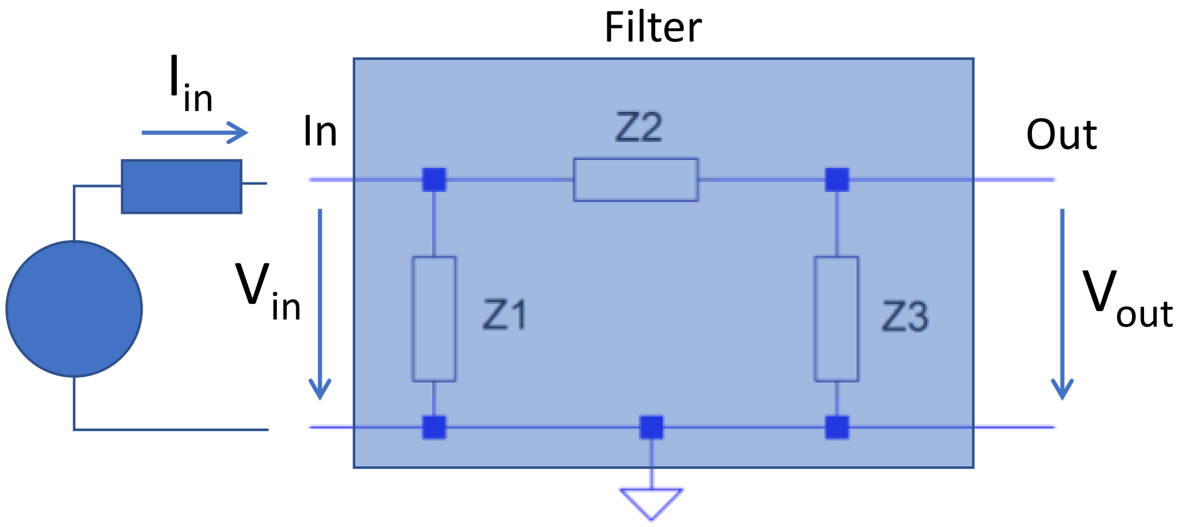
Relevant transfer functions are mostly not symmetric

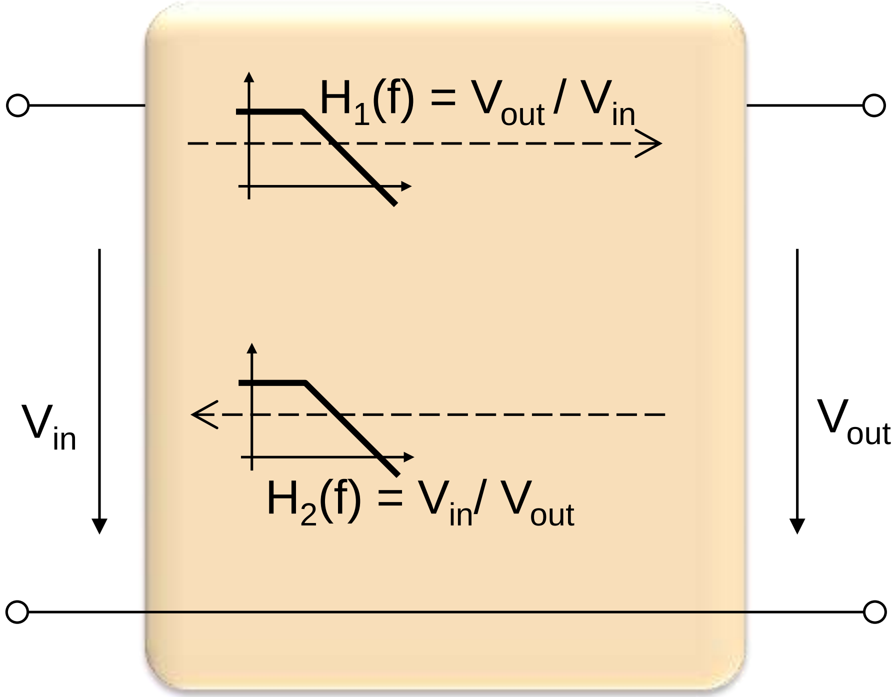
Watch DC voltage drops closely

Transfer Functions

What transfer function matters?

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



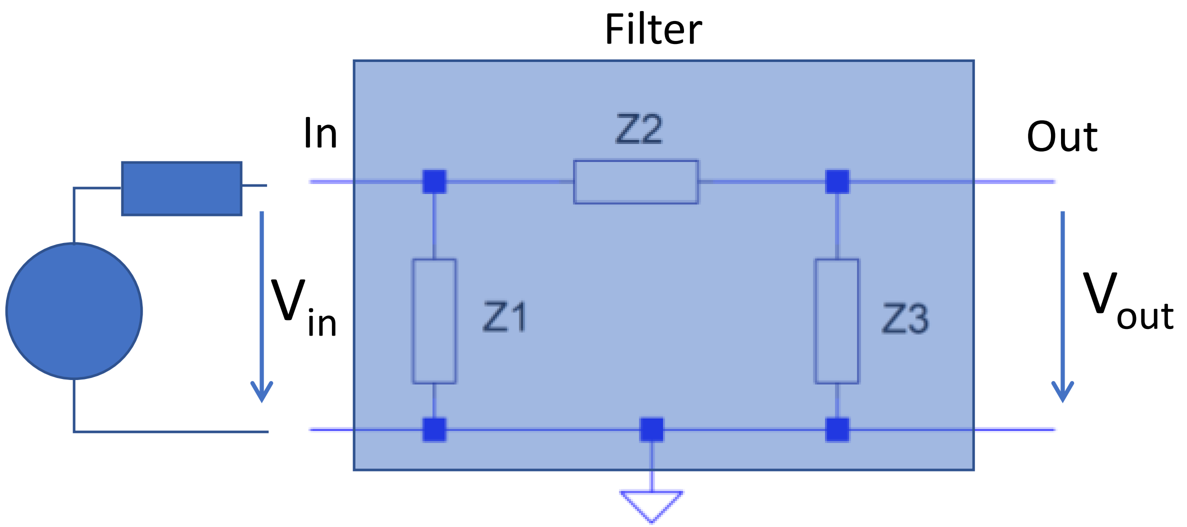


$$Z_{21} = V_{out}/I_{in}$$

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

Transfer Functions

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



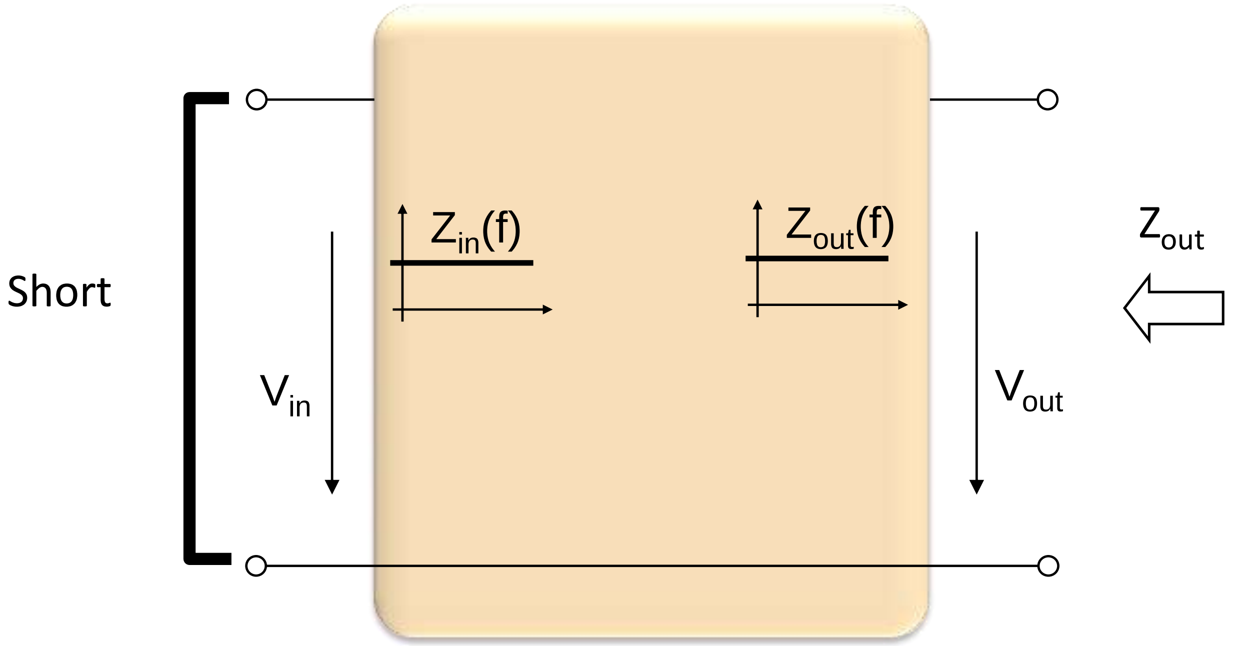
Impedances

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

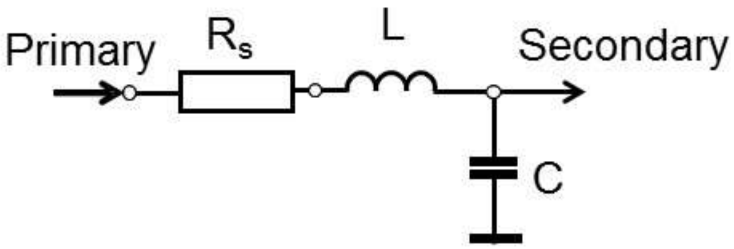


The Filter Design Process

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…

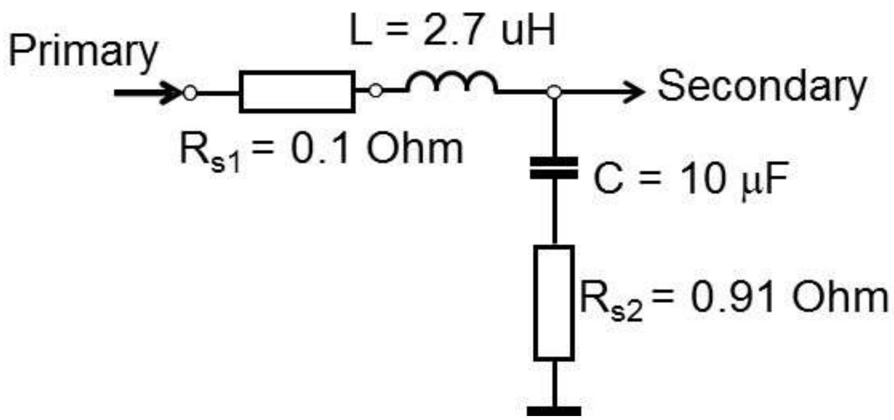
Low-Current Filter Example (1)

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)

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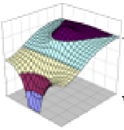
Transfer functions of PDN filter with ferrite-bead model

C1	C2	C3	Rdc	Lf1	C4	C5	C6
1.00E+03	1.00E-03	1.00E-05	1.00E-01	2.70E-06	1.00E-05	1.00E-07	1.00E-09
R1	R2	R3	Cb	Rf1	R4	R5	R6
1.00E-03	5.00E-02	1.00E-02	5.00E-13	1.00E+06	9.10E-01	1.00E+06	1.00E+06
L1	L2	L3	Rb	Lf2	L4	L5	L6
5.00E-07	5.00E-09	1.00E-09	1.00E+01	1.00E-12	1.00E-09	1.00E-09	1.00E-10
N1	N2	N3		Rf2	N4	N5	N6
1	1	1		1.00E-03	1	1	1

Fmin
1.00E+02
Fmax
1.00E+08



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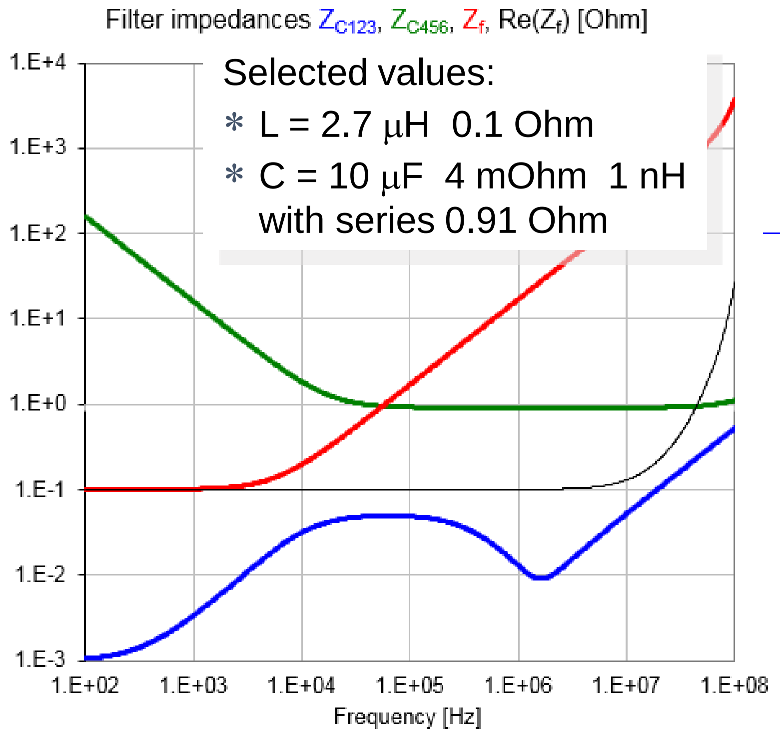
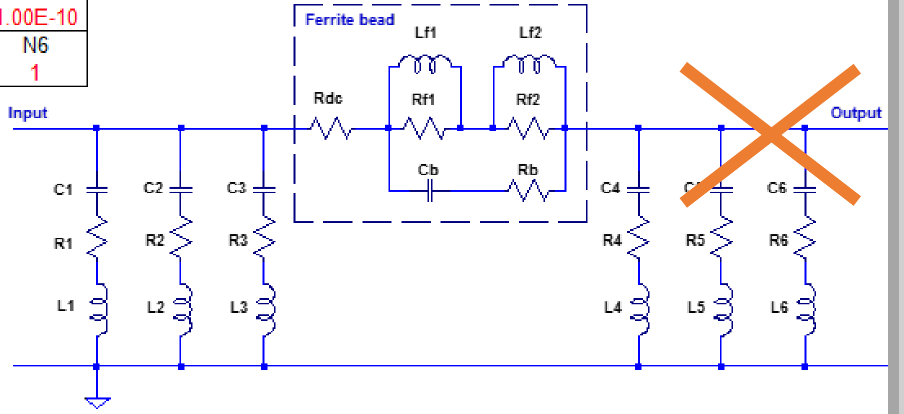
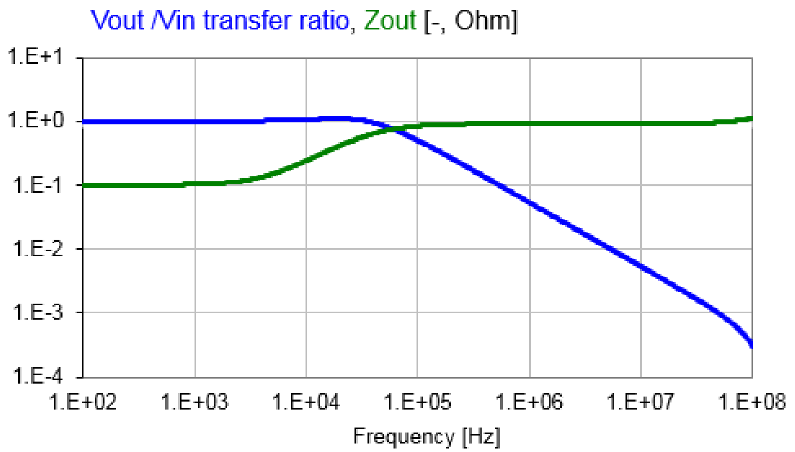


Selected values:

- L = 2.7 µH 0.1 Ohm
- C = 10 µF 4 mOhm 1 nH with series 0.91 Ohm



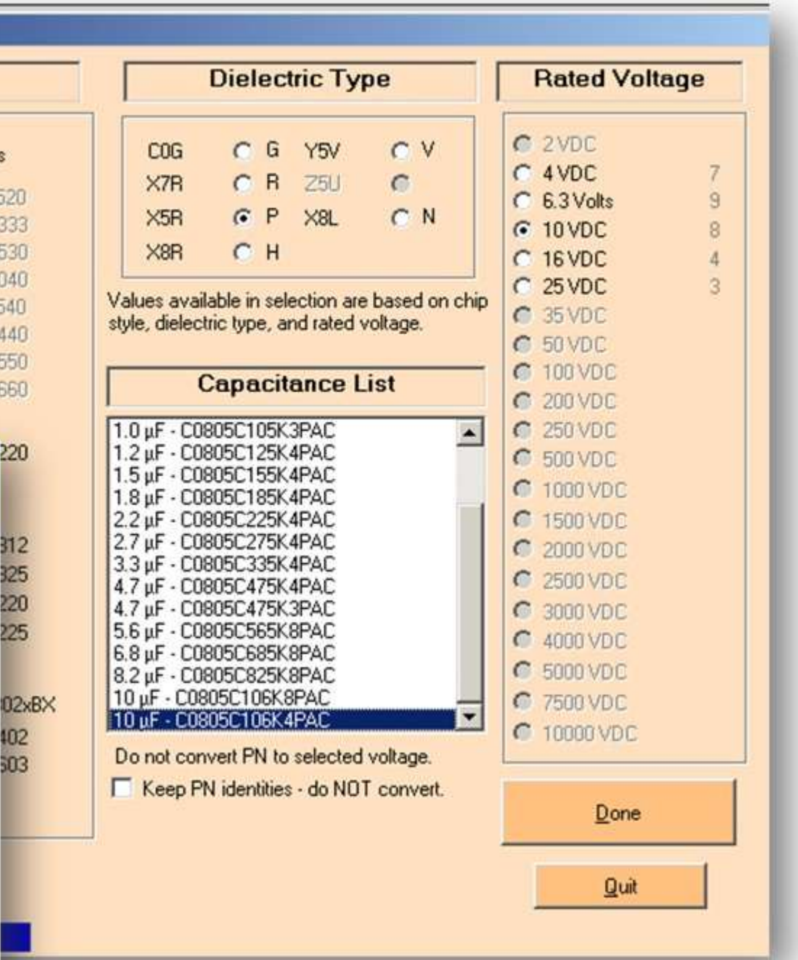


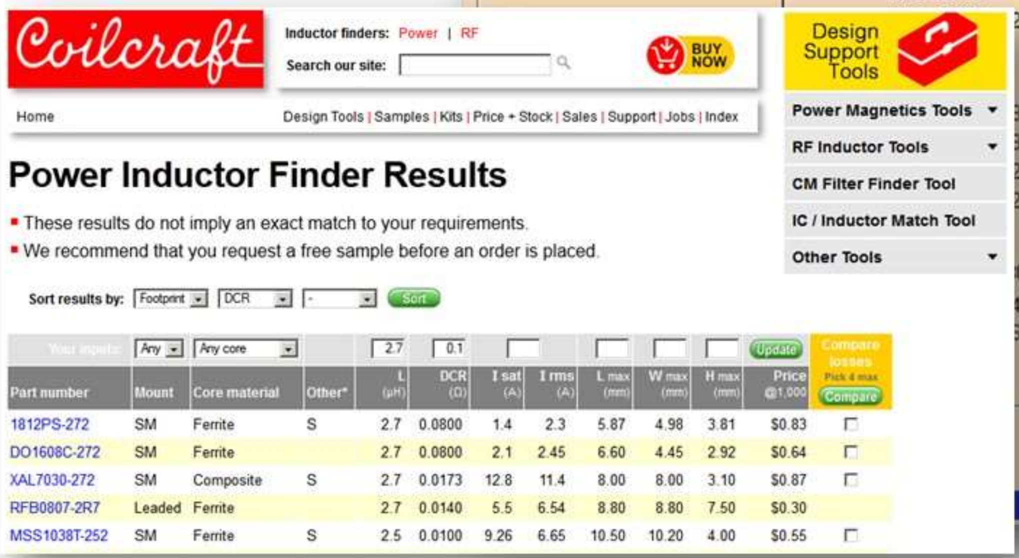
http://www.electrical-integrity.com/Tool_download_files/PDN-filter_WExcel2016-32-64b_v06.xlsm

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



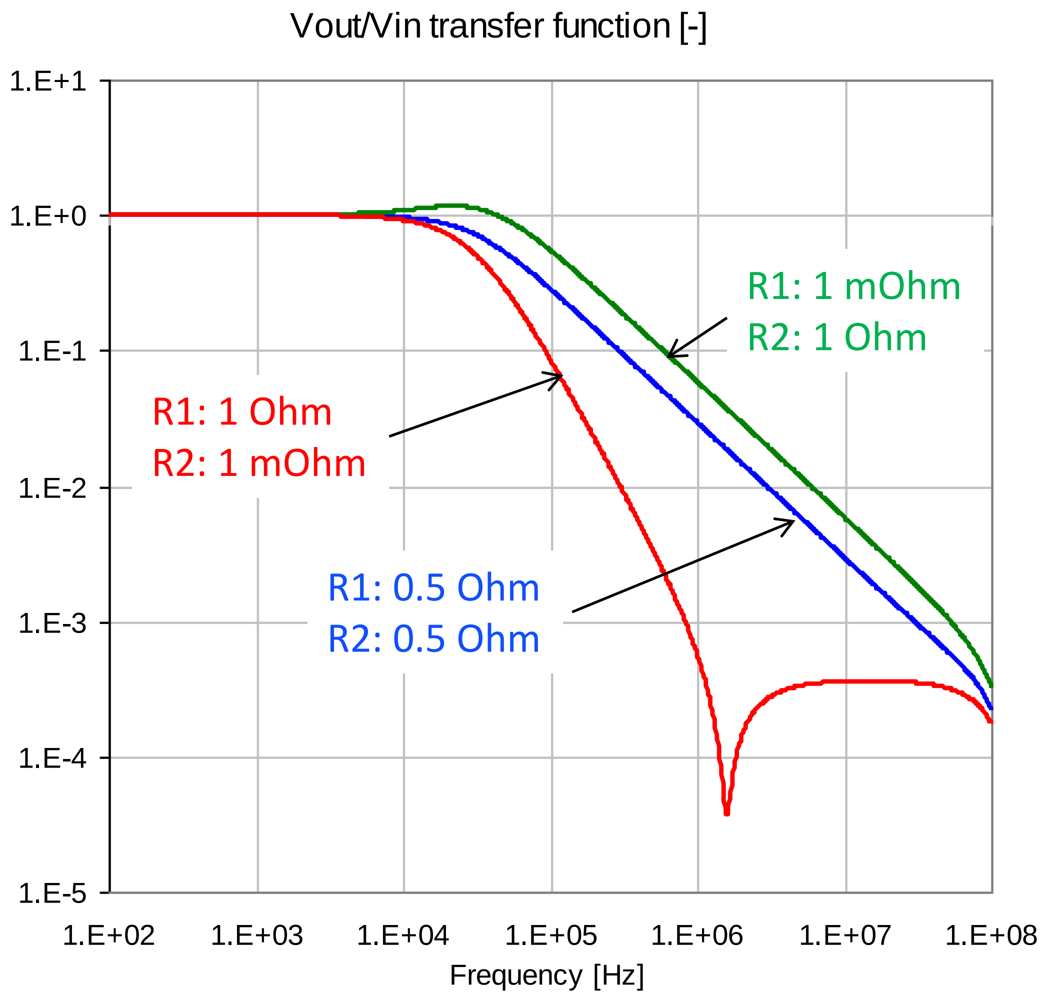


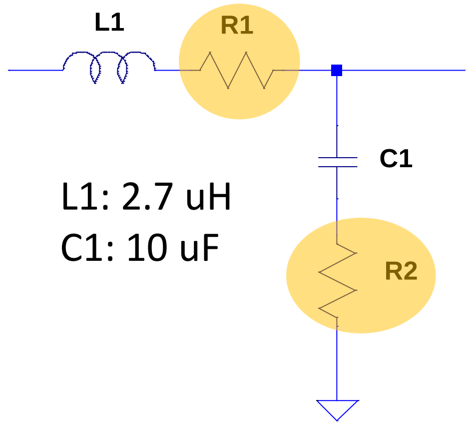
Part number	Mount	Core material	Other*	L (µH)	DCR (Ω)	I sat (A)	I rms (A)	L max (mm)	W max (mm)	H max (mm)	Price @1,000
1812PS-272	SM	Ferrite	S	2.7	0.0800	1.4	2.3	5.87	4.98	3.81	$0.83
DO1608C-272	SM	Ferrite		2.7	0.0800	2.1	2.45	6.60	4.45	2.92	$0.64
XAL7030-272	SM	Composite	S	2.7	0.0173	12.8	11.4	8.00	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

- Series resistive loss maintains second-order filtering; resistance in the parallel path approaches first-order filtering
- 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 with LC low-pass filters
  - Sub-harmonic converter ripple
  - Out-of-band spurious signals
  - Low frequency random noise
- Check the DC-DC converter operating frequency before you switch to a different converter!

Be Aware, Distribution of Losses

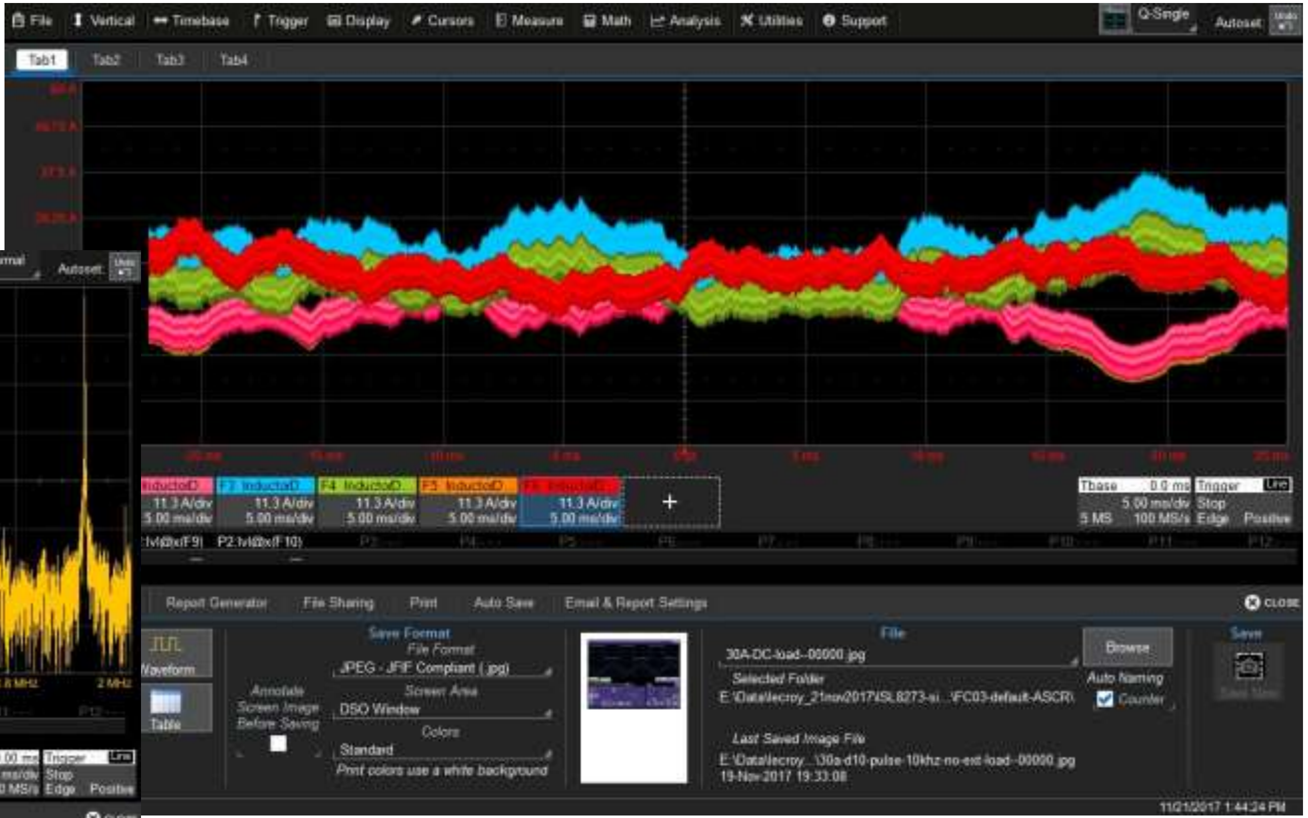


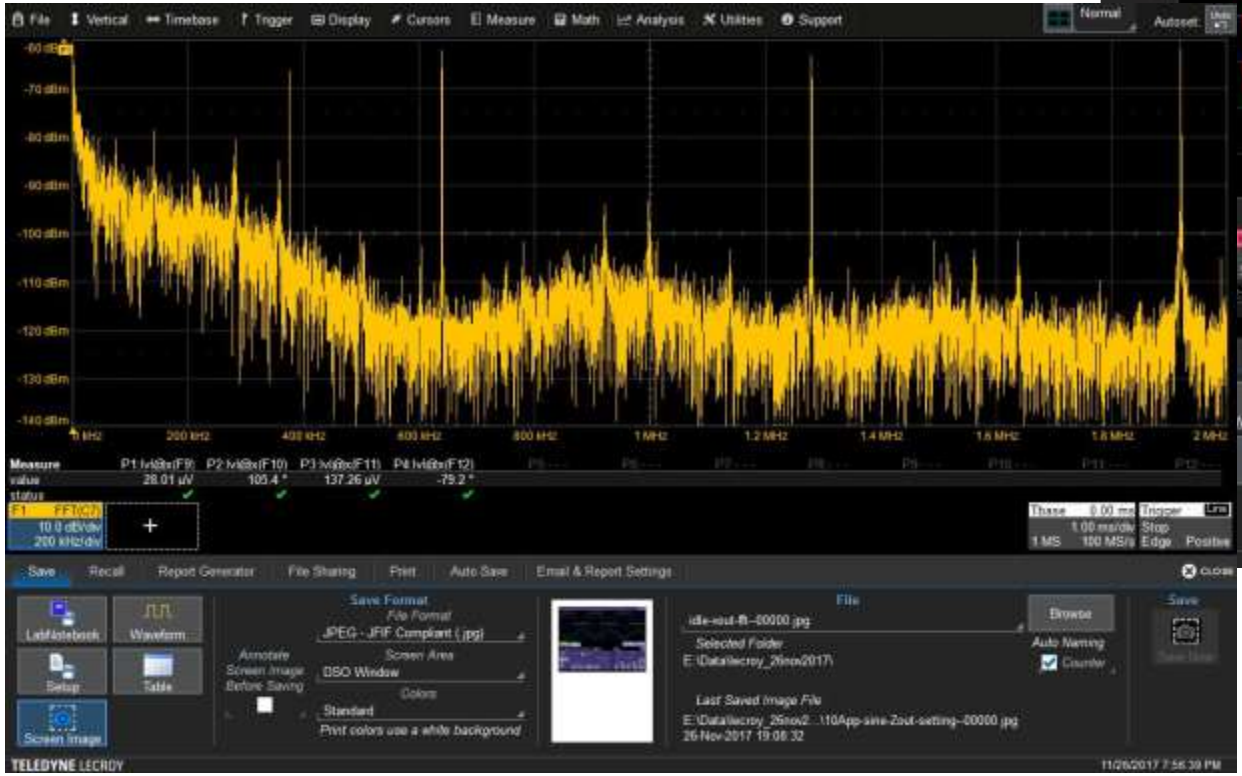


Series resistive loss maintains second-order filtering; resistance in the parallel path approaches first-order filtering

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

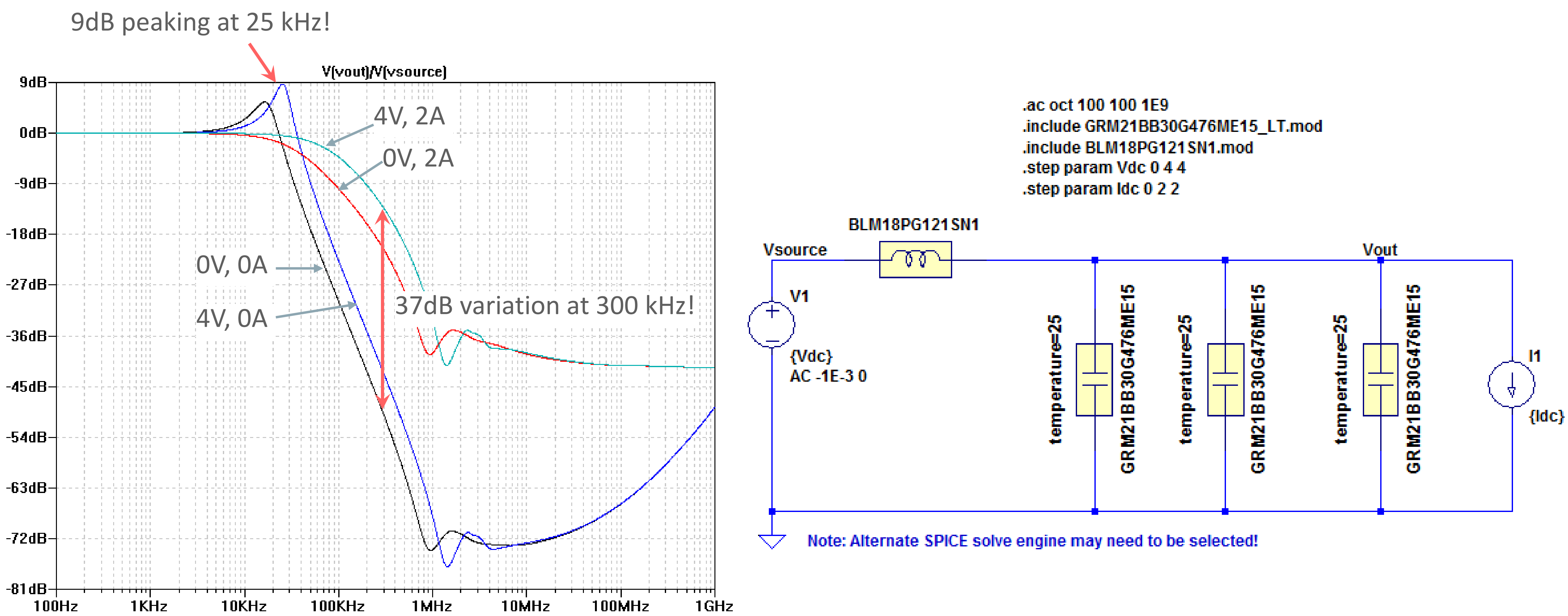
Loss of Capacitance in MLCCs

	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

Be Aware, Bias Effects



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

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