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POWDER CORE SOLUTIONS

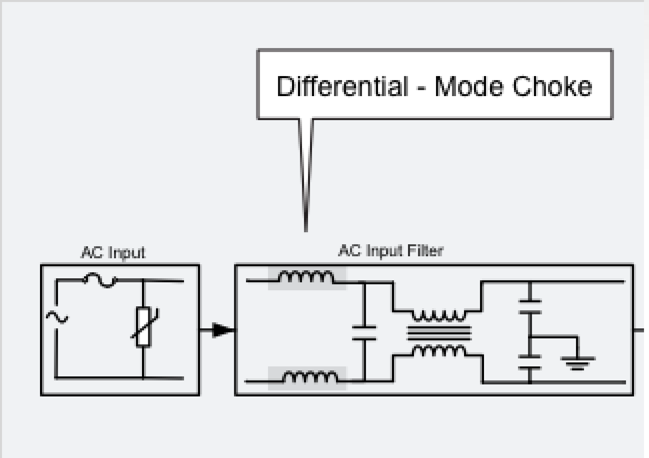
Low Q materials for differential mode EMI filters

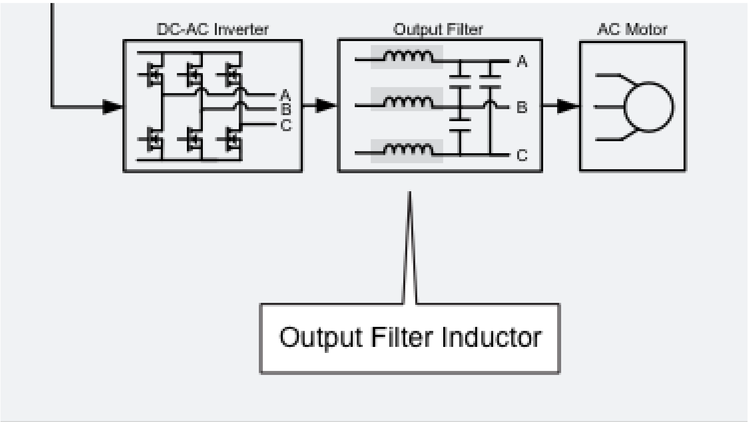
EMI filter - purpose

- Modern switch mode power supplies generate electromagnetic noise through a variety of mechanisms. This generated noise can cause interference in external devices
- Noise generated by other devices can generate a voltage/current ripple at the input of a power converter, interfering with its operation
- EMI filters are used to address both issues:
    - Reduce the amount of noise the power converter can inject into its in- and outputs below a mandated level. This helps insure the power converter doesn't interfere with other devices
    - Reduce any parasitic high frequency voltage ripple that might be present on the input from reaching the power converter

EMI filter – types and structure

- There are two types of noise:
  - Common mode noise
  - Differential mode noise
- Both types of noise can be suppressed using cascaded stages of LC filters
- Powdered materials are **not** suitable for common mode chokes at frequencies below 100s of MHz
- Focus here will be on differential mode filters





EMI filter – parameters and normalization

- A single stage EMI filter can be described by the following parameters:
  - Cut off frequency:

$$f_c = \frac{1}{2\pi\sqrt{L_f C_f}}$$

  - Output impedance:

$$Z_0 = \sqrt{\frac{L_f}{C_f}}$$

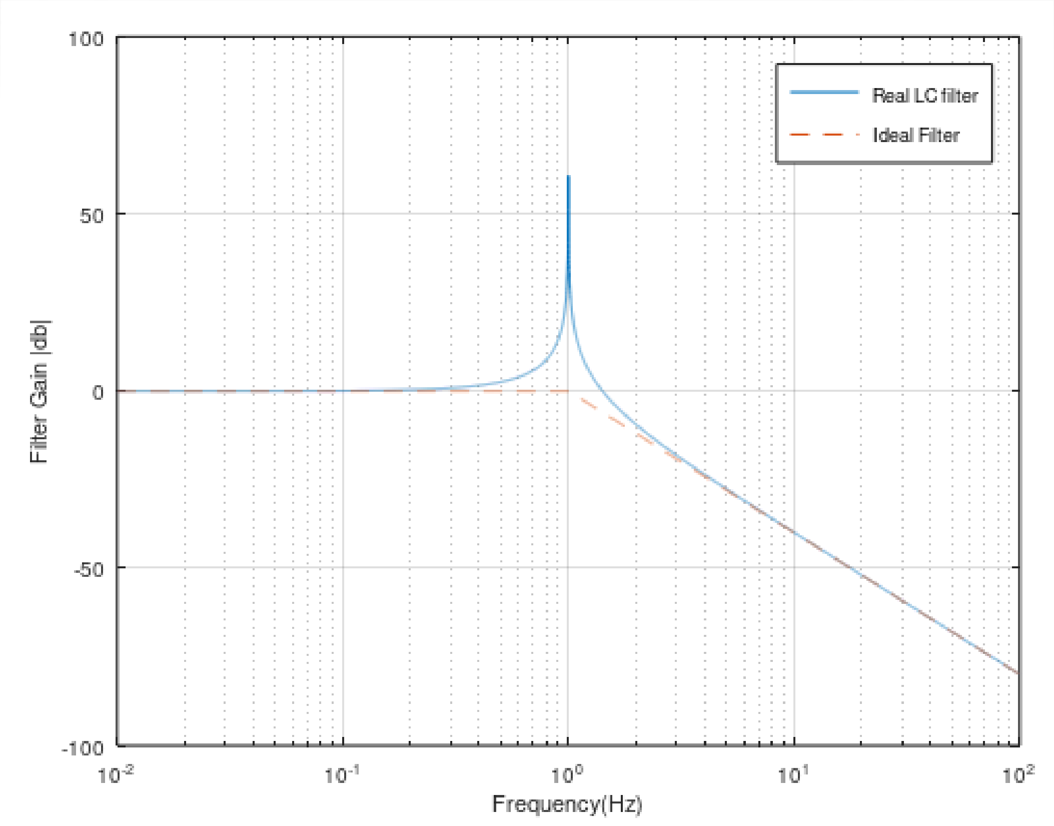
- Filters can be analyzed in a “normalized” fashion by describing all frequencies in relation to the cut-off frequency and all impedance in relation to the output impedance

EMI filter – attenuation

- At sufficiently high frequencies, the attenuation of a single stage EMI filter can be described using the following equation:

$$Att = F^2_{att,norm}$$

- But the LC circuit in the filter is still a resonant circuit, therefore it will go into resonance around its cutoff frequency
- Instead of attenuating it will amplify a signal at this frequency



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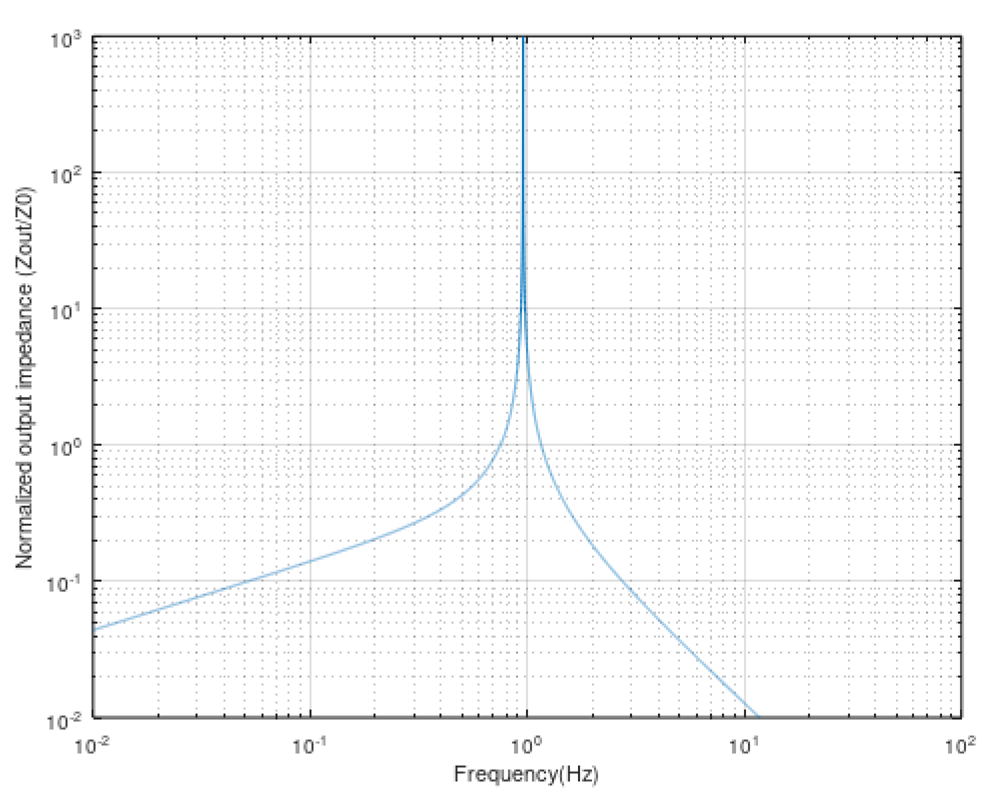
EMI filter – output impedance

- The LC filter will also introduce an impedance between the power converter and power source.
- Ideally, this impedance is low. However, around the cut off frequency, the impedance peaks due to parallel resonance between the filter components
- As predicted by Middlebrook's extra element theorem, the filter output impedance will change the control to output transfer function, potentially destabilizing the control loop



$$H = H_0 \frac{1 + \frac{Z_{out}}{Z_N}}{1 + \frac{Z_{out}}{Z_D}}$$

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EMI filter – negative resistance oscillator

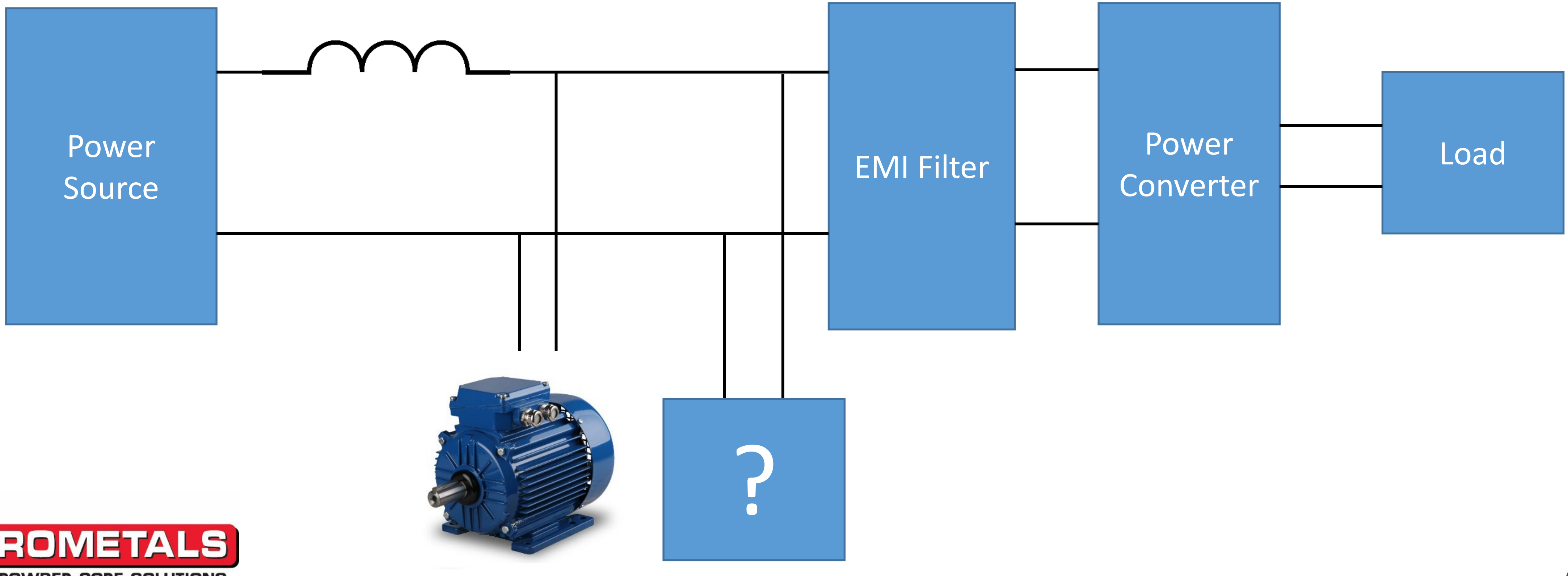
- Ideally a DC/DC power converter supplies a constant output voltage, regardless of a change in its input voltage.
- Therefore, if the load of the DC/DC converter is constant and the control loop gain is high, the input impedance of the converter will be:

$$\hat{Z_{in,CL}} = -\frac{\hat{V_{in}}^2}{P_{in}}$$

- The **negative** input impedance from the power converter in parallel with the LC resonant circuit now forms a **negative resistance oscillator**
- Any type of noise from any point in the entire system can now cause the filter to oscillate, potentially destabilizing the distributed power system

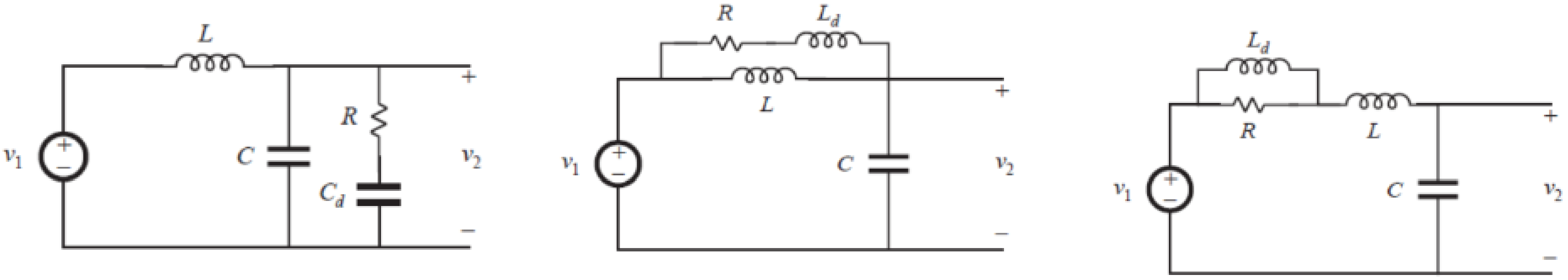
EMI filter – distributed power system

- Many different loads connected to the same system, other loads can interfere or excited resonances in an EMI filter
- EMI filter has to be stable on its own to insure a robust overall system



EMI Filter – How to fix this issue?

- The resonance in the LC circuit has to be damped to reduce the peak output impedance and suppress the peak in the transfer function
- There are a variety of damping networks that can be utilized:

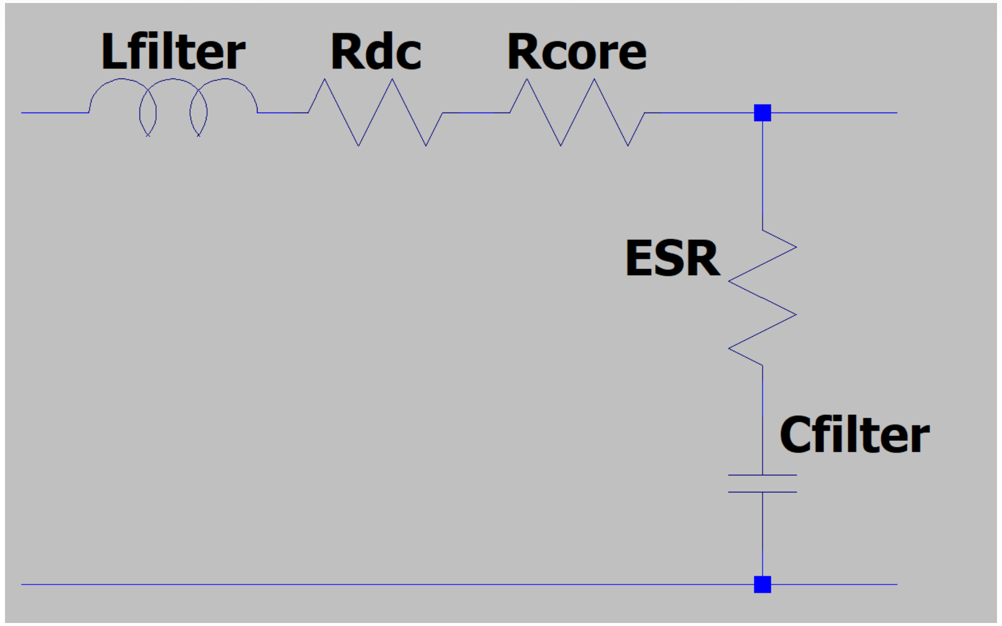


(a) C_d-R Damping (b) Parallel L_d-R (c) Series L_d-R Damping

- While all these damping networks can be effective, they add extra components to the circuit, increasing cost/size

EMI Filter Damping – A different way

- Instead of adding an external damping network, it is desirable to add a damping element into the existing LC filter.
- Increasing ESR of filter capacitors will greatly increase losses and degrade high frequency filter performance
- Increasing DC resistance of inductor will greatly increase conduction losses
- The core losses of the magnetic material can be increased without increasing losses in the filter for the applied DC or low frequency AC signal



EMI Filter Damping – Evaluating material loss

- Comparing externally damped parameters vs. "direct" damping:

Parallel Ld damped filter:

$$H_{peak;Ld,damped} \approx \frac{n+2}{n}$$

$$Z_{out,peak;Ld,damped} \approx Z_0\sqrt{2n \times (1+2n)}$$

$$L_d = n \times L_{filter}$$

"Direct" damped filter:

$$H_{peak} \approx Q$$

$$Z_{out,peak} \approx Q_L Z_0 + jZ_0$$

$$Q \approx Q_L = \frac{\mu'}{\mu''}$$

- "n" tends to be between 0.25-1, therefore Q should be at least less than 10, but the lower the better. A Q = 3 gives the same damping performance as n=1 for the transfer function

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Material Q - Evaluation

- The maximum Q of the filter is determined by the Q of the material. The Q of the material depends on the complex permeability:

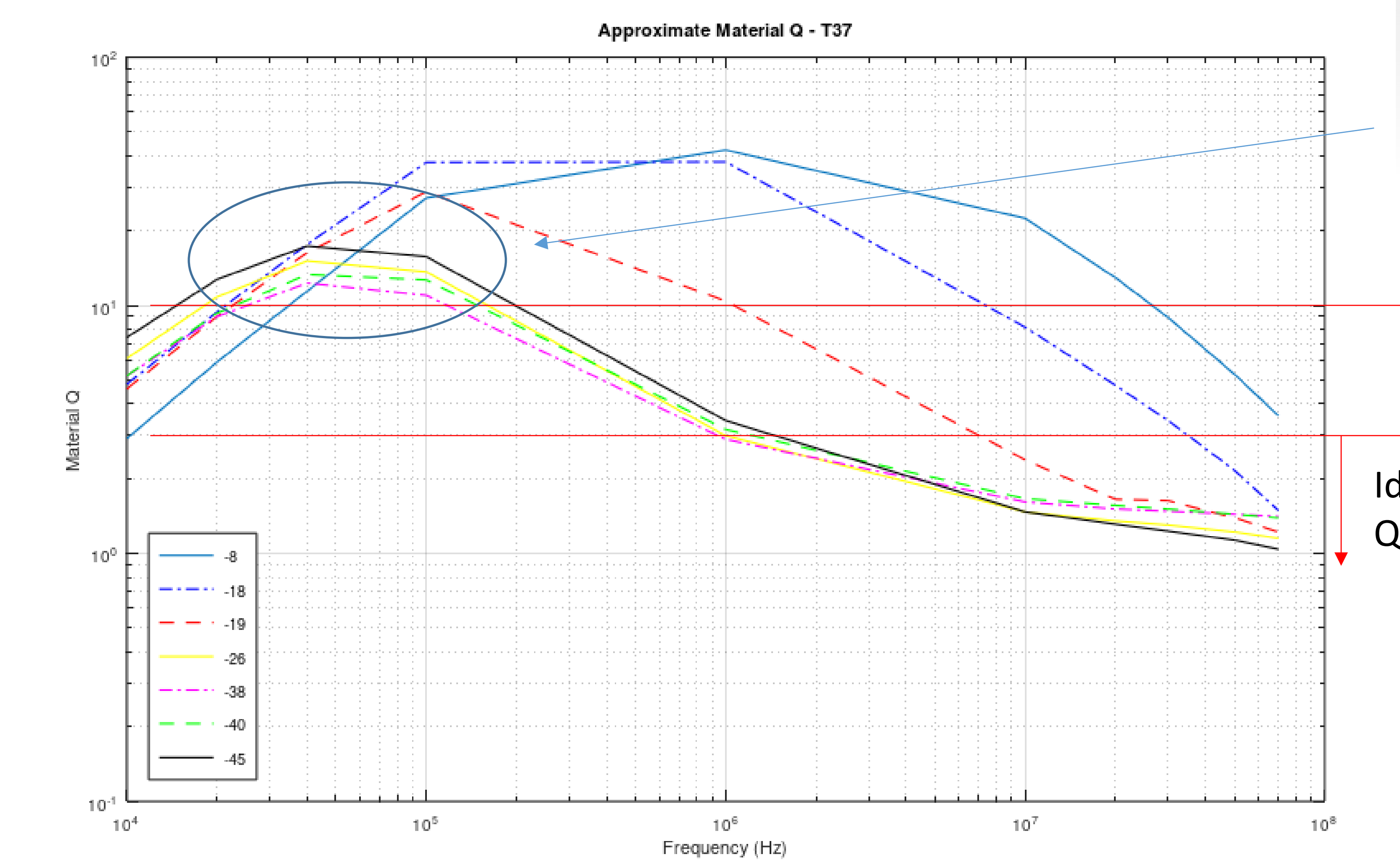
$$Q \approx Q_L = \frac{\mu'}{\mu''}$$

- The complex permeability can also be related to the core loss of the material using:

$$\mu" \approx \frac{\mu_0 \mu'^2(f) P_{core}(f, B_p)}{\pi B_p^2}$$

- Therefore a material with a high core loss/high u" around the cutoff frequency of the filter is desired

Standard Material Overview – Q



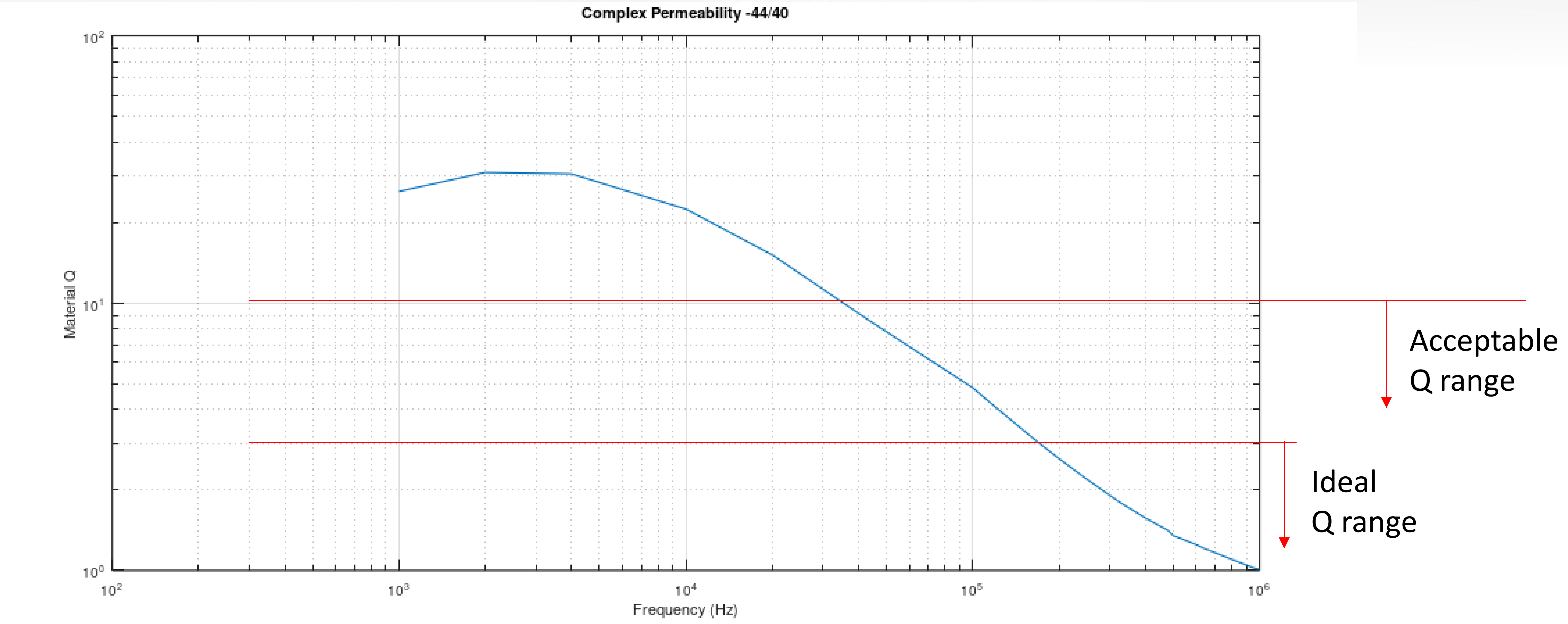
Q too high for direct damping below 100kHz, but high loss can still help reduce size of external damping network

Acceptable Q range

Ideal Q range

Low Q material - Example

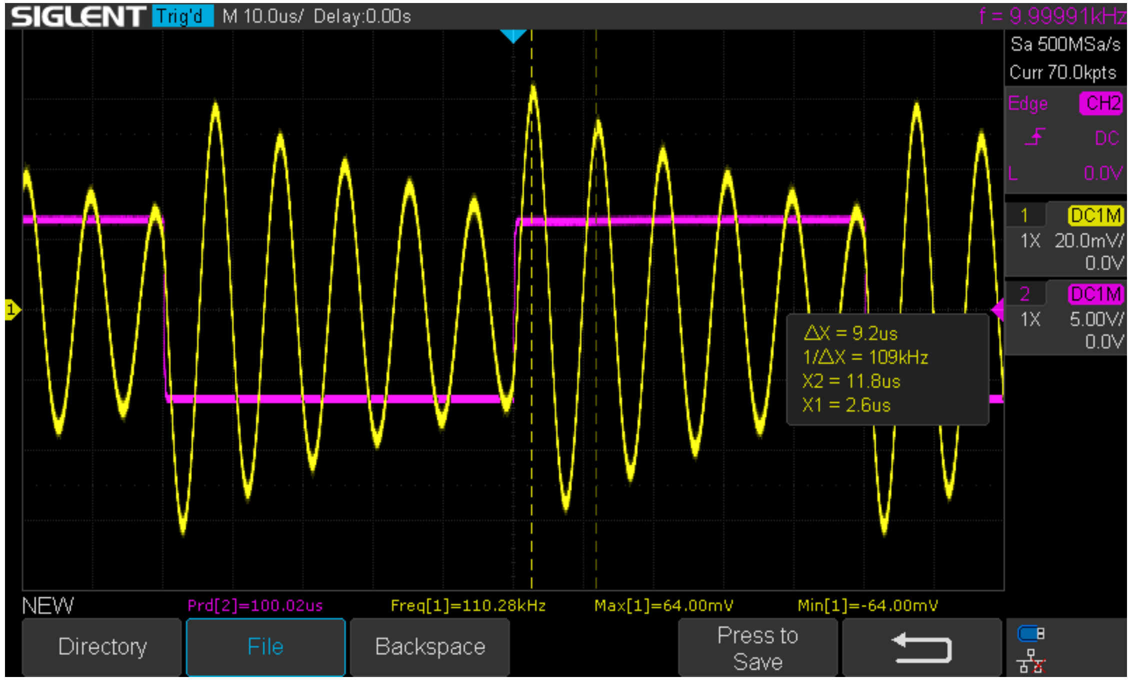
- Micrometals’ Mix 44 offer sufficiently low Q to directly damp EMI filter:



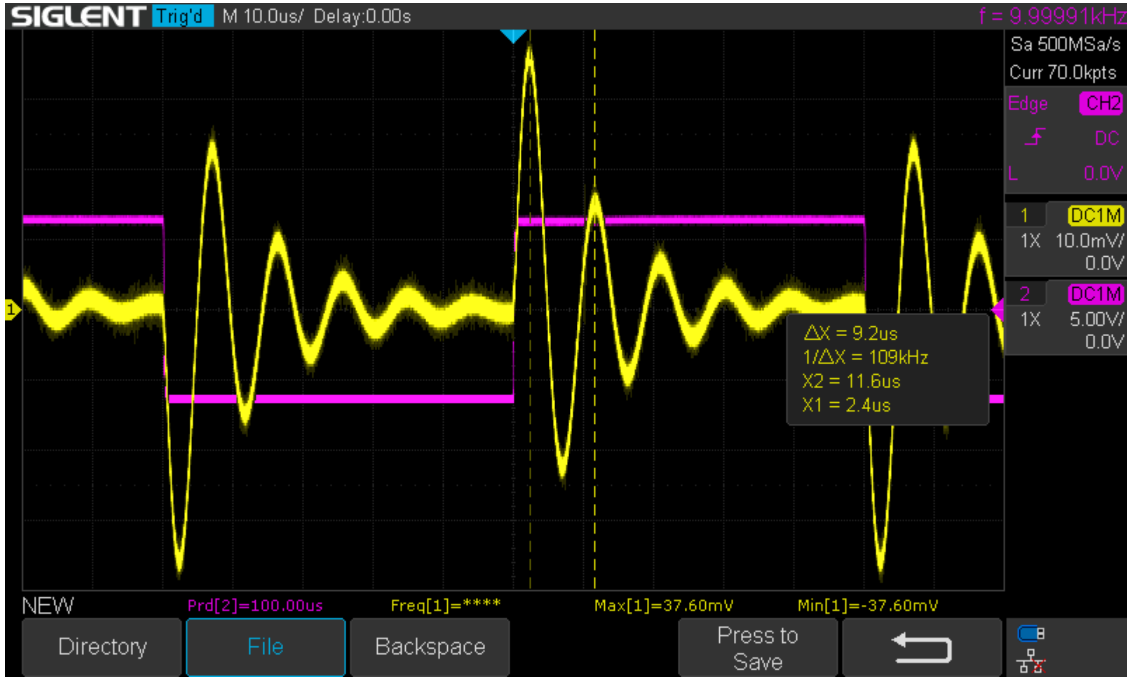
Measurements – is there really a difference?

- Two EMI filters with a cut-off frequency of 110kHz (L=6.3uH) are subjected to a square wave current at 10kHz to visualize the output impedance. The only difference between the two is the core material:

Micrometals -52 material:



Micrometals -44/40 material:



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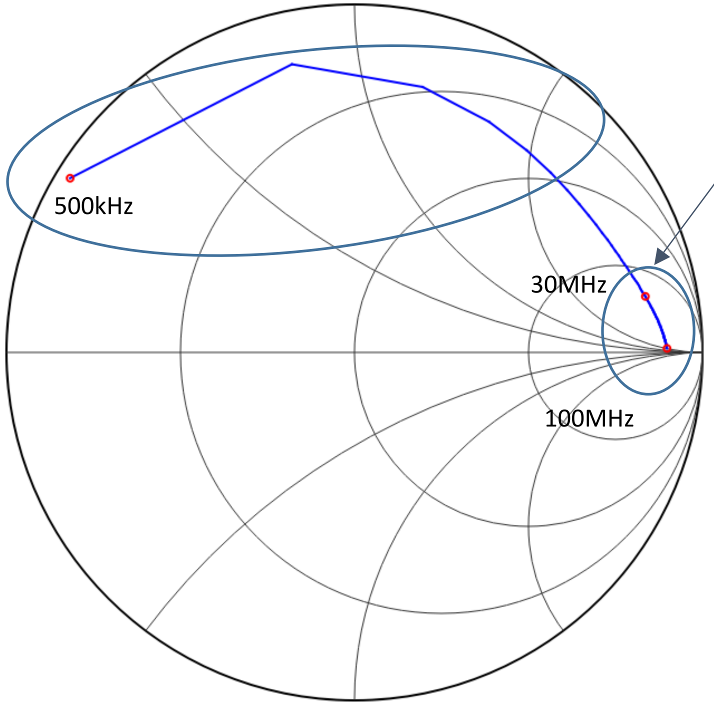
Measurements – is there really a difference?

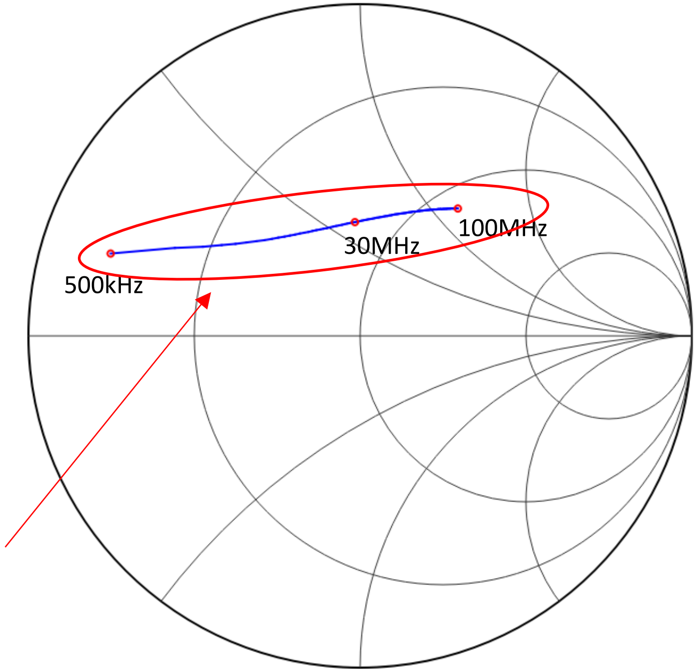
- Comparing the same inductors with a VNA between 0.5-100MHz shows differences in material characteristics as well:

Micrometals -52 material:



Material goes into resonance due to winding capacitance

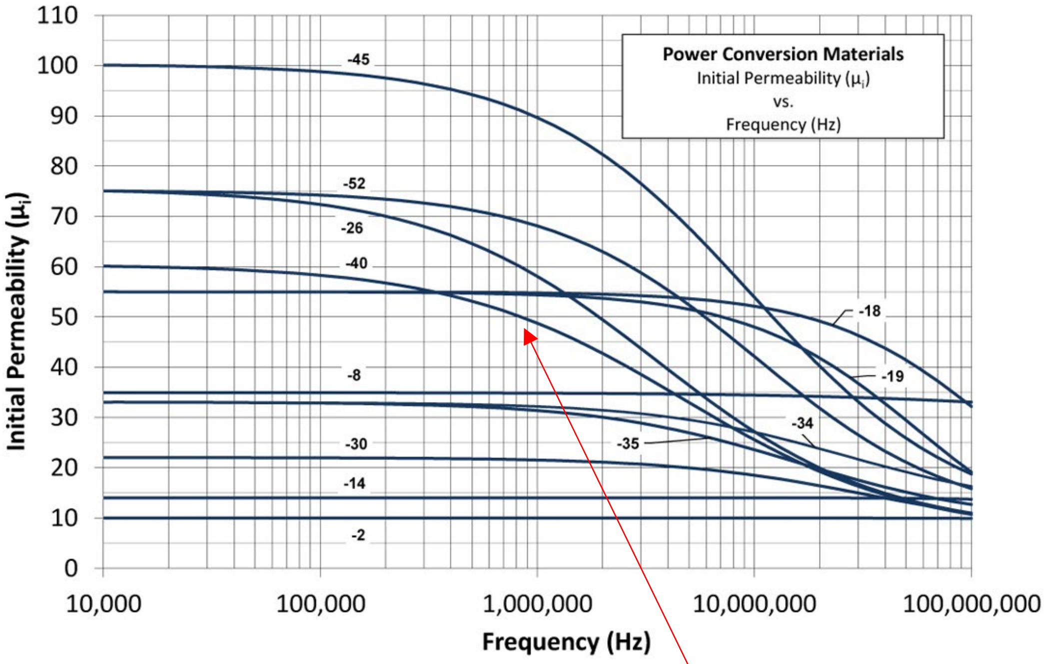
Micrometals -44/40 material:

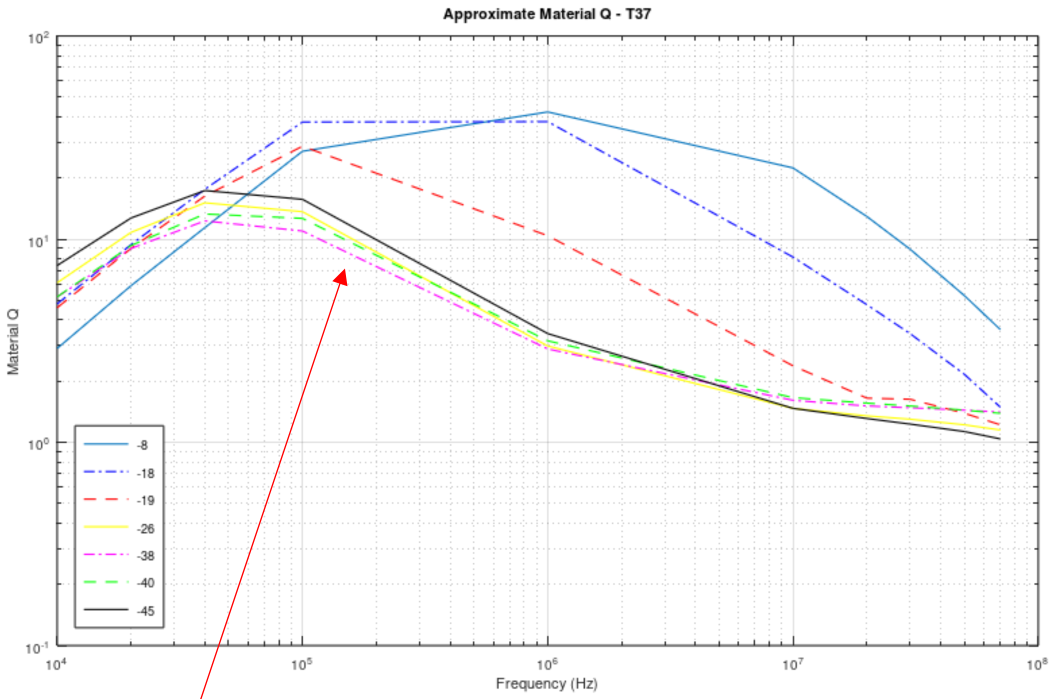


Q of inductor tracks close to 1 over the entire frequency range
Complex impedance is lower, but no resonance either

Low Q materials – aware of trade off

- As seen in the VNA measurement, the low Q material has a lower impedance at high frequencies compared to the higher Q material.
- This is generally true for most powdered materials:

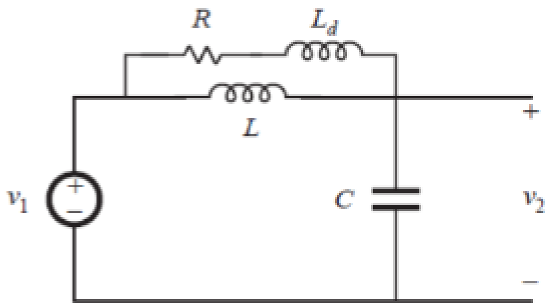




Low Q materials' real permeability drops quicker with frequency

Summary

- EMI Filters need to be dampened to insure stability in the power system
- Traditionally, additional resistors and inductors/capacitors are required to realize damping network increasing number of components, cost and size
- Using magnetic materials with a low Q factor allows the filter inductor to damp resonance directly, eliminating the need for external components



Eliminate extra damping components by using low Q powdered material