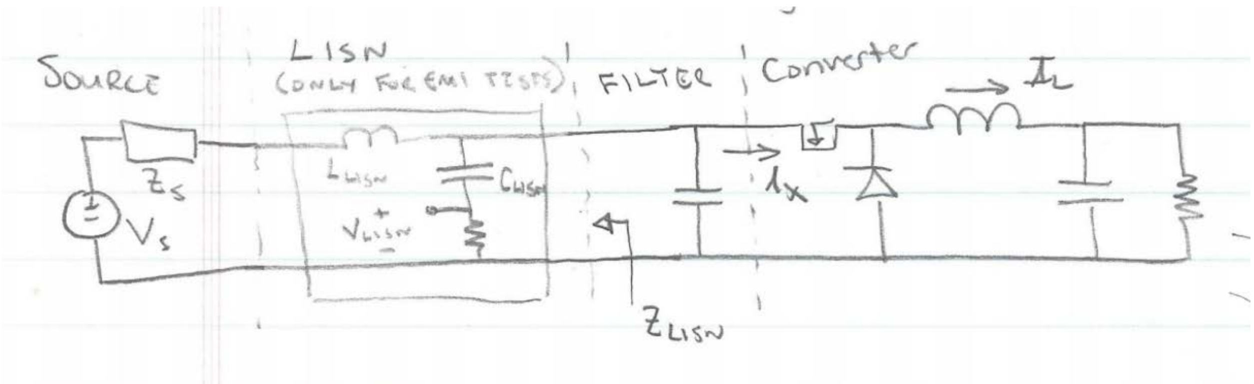
6.622 Power Electronics *Prof. David Perreault*

Lecture 29 - EMI Filtering 2

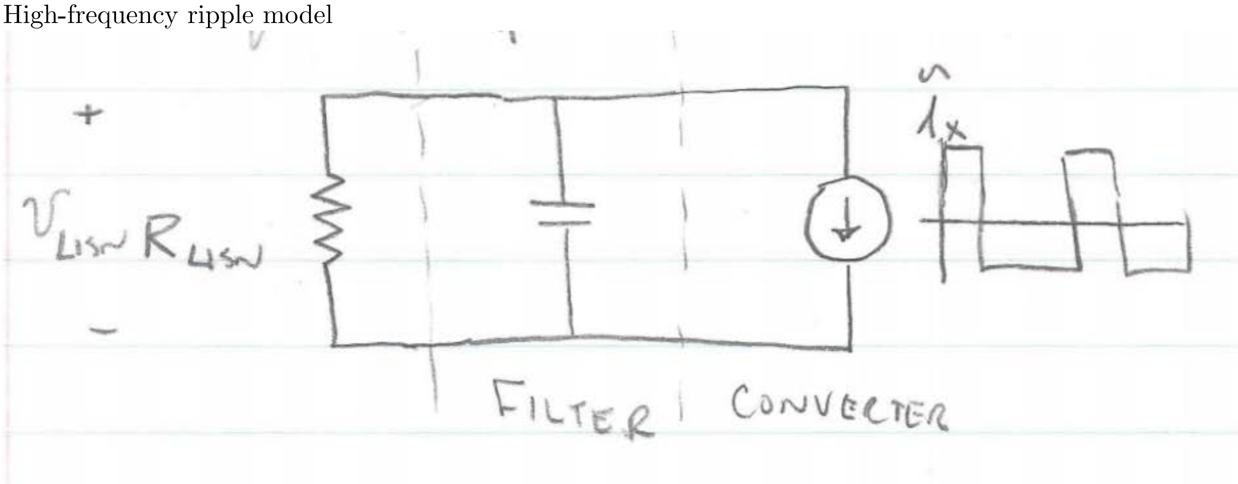
1 Review

- Filters are needed to achieve long attentuation of ripple
- to make measurements REPEATABLE a LISN is often specififed for making EMI measurements:

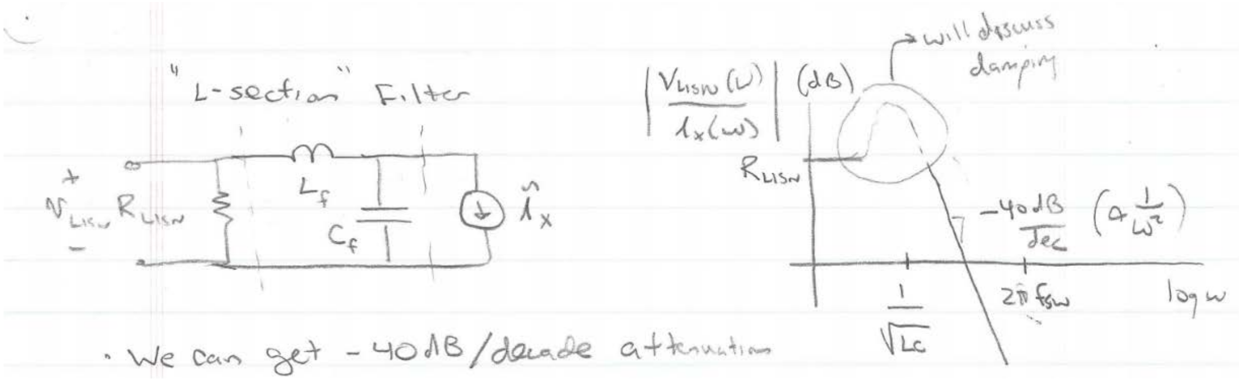


- The LISN makes the ripple-frequency impedance looking back into the source known + repeatable
- Ripple measurements made @ the LISN "resistor": typically a 50Ω input impedance of a spectrum analyzer

High-frequency ripple model



To achieve sufficient attenuation, a capacitor often insufficient. A higher-order filter is needed. The filter should pass dc current w low loss, and accept dc voltage with low loss

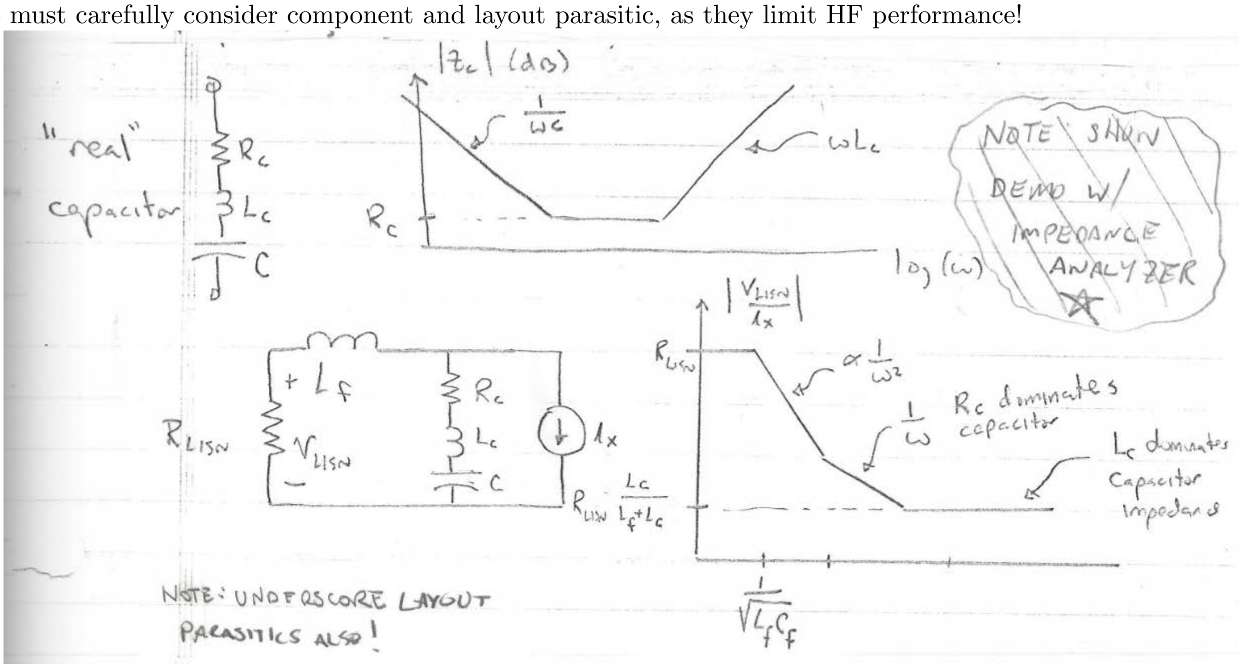


- We can get -40dB/decade attenuation above the cutoff
- blocks dc voltage well (capacitor), carries dc current well (inductor)
- can cascade L sections if needed

A second consideration is filter and component parasitics

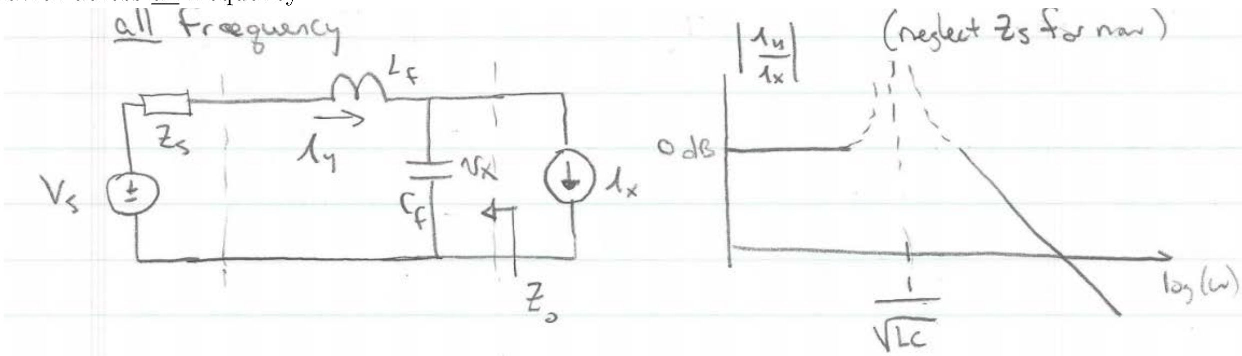
2 Parasitics

We must carefully consider component and layout parasitic, as they limit HF performance!



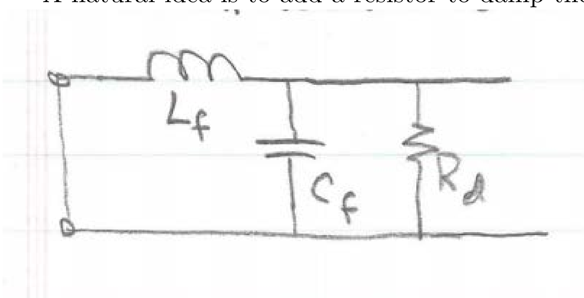
Component parasitics are an important limitation/consideration in design

Another design issue is filter damping. (In practice, the LISN) is not present, and we must have acceptable behavior across all frequency



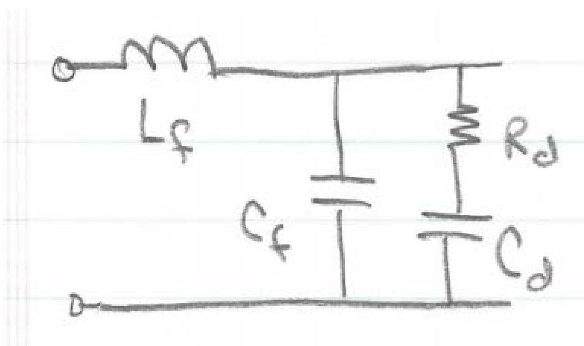
Neglecting Z_s, setting $V_s \to 0$, the converter looks back into a parallel LC tank circuit. At resonance, this becomes a high impedance + large resonant currents will flow! $\Rightarrow$ must damp to be acceptable.

A natural idea is to add a resistor to damp the filter



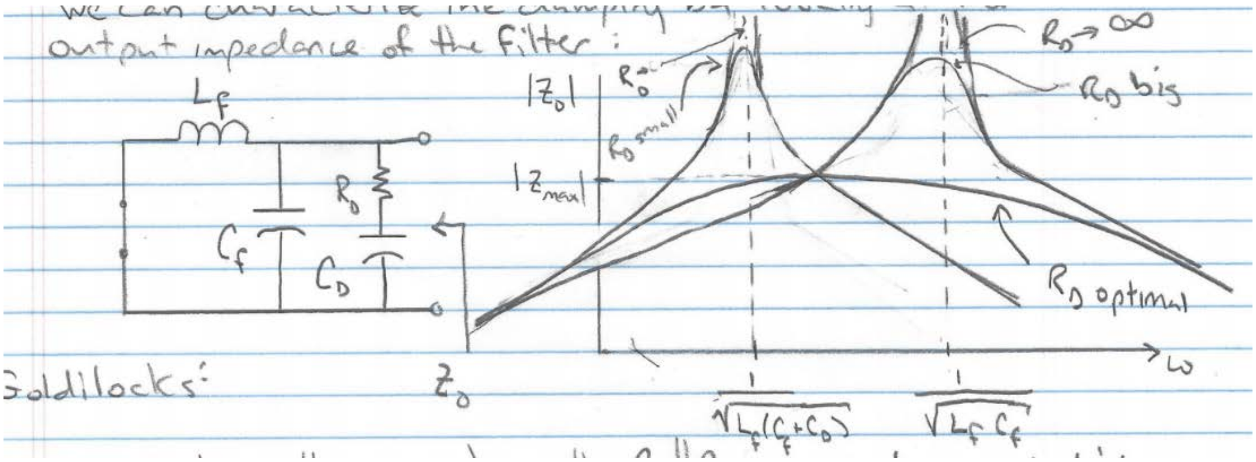
If $R_d \leq \sqrt{\frac{L_f}{C_f}}$ we will be damped!

However, we could not accept the dc dissipation of R_d! So, place it in series with a large dc blocking capacitor C_d, such that the $R_d - C_d$ combination looks resistive @ $\omega = \frac{1}{\sqrt{L_f C_f}}$



- we want $C_d >> C_f$ for effective performance, typically 2 to 10 times
- C_d needs to be big, but unlike C_f
  - It only carries low current
  - it can have big parasitics (only capacitive @ low freq $\frac{1}{\sqrt{L_f C_f}}$)

Let's consider selection of the damping resistor R_0 for a given choice of damping capacitor $C_0 = nC_f$ (where n≥1, usually 2-10). We can characterize the damping by looking at the output impedance of the filter:



3 Goldilocks

- If R_0 too small, L_f resonates with $C_0||C$ and impedance peaks high.
- If R_0 too big, L_f resonates with C and impedance peaks high.
- If R_0 "just right," we minimize peaking for that value of $C_D = nC_f$.

$\Rightarrow$ It can be shown (as in Erickson + Maksimovic) that the peak of the $|Z_0|$ curve for an optimal damping resistor that minimizes max $|Z_0|$ is exactly the intersection point of the $|Z_0|$ curves for $R_0 \to 0$ and $R_0 \to \infty$.

$\star$ Choose a "Goldilocks" value of R_0 to achieve this minimum peaking. Can find by simulation sweep or analytically as

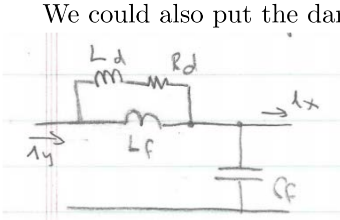
$$R_0 = \triangleq \sqrt{\frac{L_f}{C_f}}, n = \frac{C_d}{C_f}, R_D = R_0 \sqrt{\frac{(2+n)(4+3n)}{2n^2(4+n)}}$$

And we get a maximum output impedance: $|Z_{max}| = R_0 \frac{\sqrt{z(z+n)}}{n}$

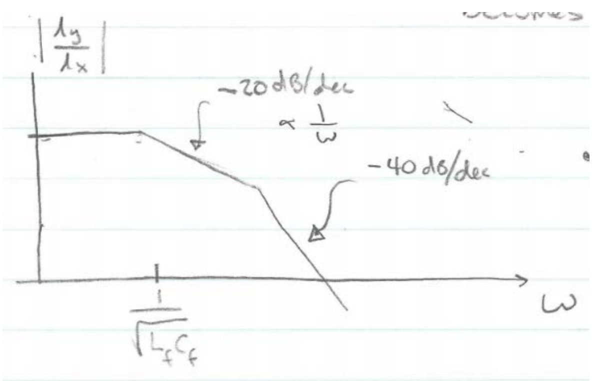
Note that in our filter design we <u>choose</u> $n = \frac{C_0}{C_f}$. The bigger the multiple n, the <u>smaller</u> we can make $|Z_{max}|$ or equivalently, the more damped we can make the filter for a given L_f, C_f.

We pay for a bigger n by requiring a higher C_0 value (bigger damping capacitor).

We could also put the damping leg in parallel with L_f



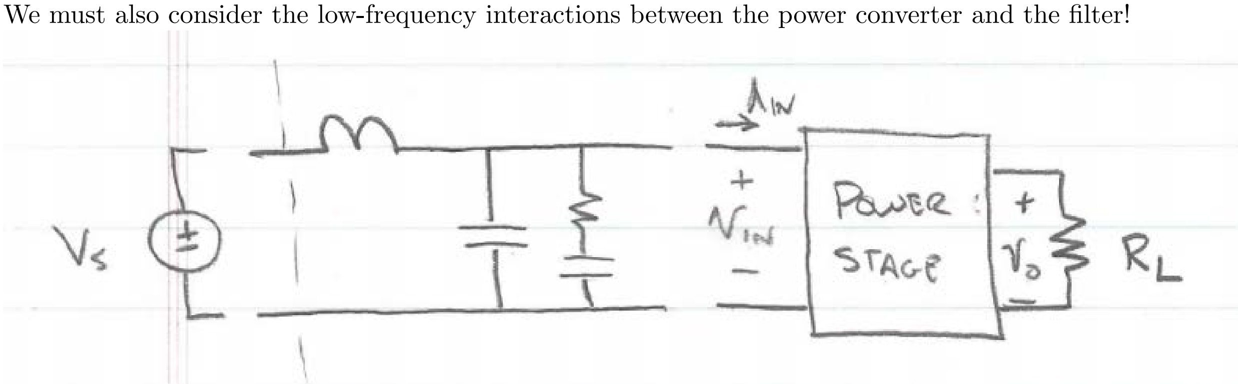
- $L_d - R_d$ branch looks resistive @ $\frac{1}{\sqrt{L_f C_f}} \Rightarrow L_d < L_f$
- @ high frequencies, series branch becomes $L_{eq} = L_d || L_f < L_f$



- high-frequency attentuation not as good as undamped $L_f C_f$. Move cutoff down to compensate.

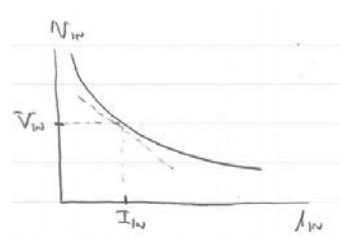
L_d can be small since it carries no dc current!

We must also consider the low-frequency interactions between the power converter and the filter!



To regulate the output to a specified voltage (controlled) the converter needs to draw a certain amount of power from the input, independent of voltage v_in!

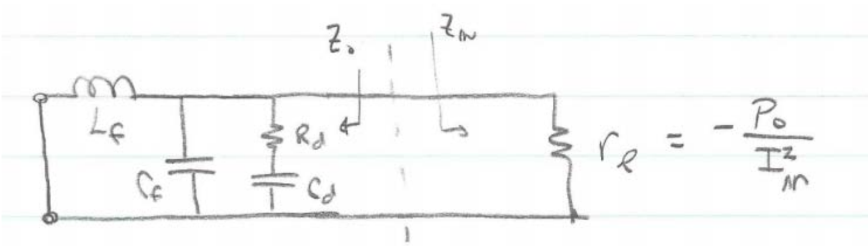
⇒ It is a constant-power load!



@ constant power P_0: $v_{in} = \frac{P_0}{i_{in}}$
For variations in input voltage, we get variations in current

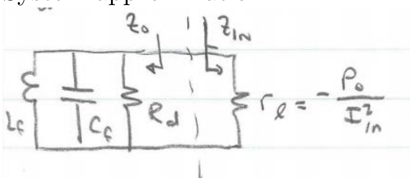
$$\frac{\partial v_{in}}{\partial i_{in}}|_{op,pt} = -\frac{P_0}{I_{in}^2} = r_l$$

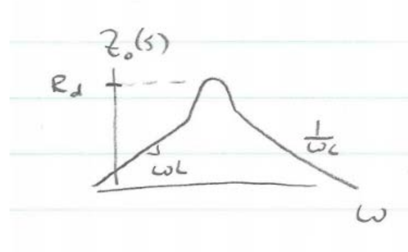
So incrementally about the operating point, the converter looks like a negative resistance!



We require that the system remain well damped despite the tendency of the negative resistance to undamp the system.

max$(Z_0(\omega) \approx R_d)$
System approximation



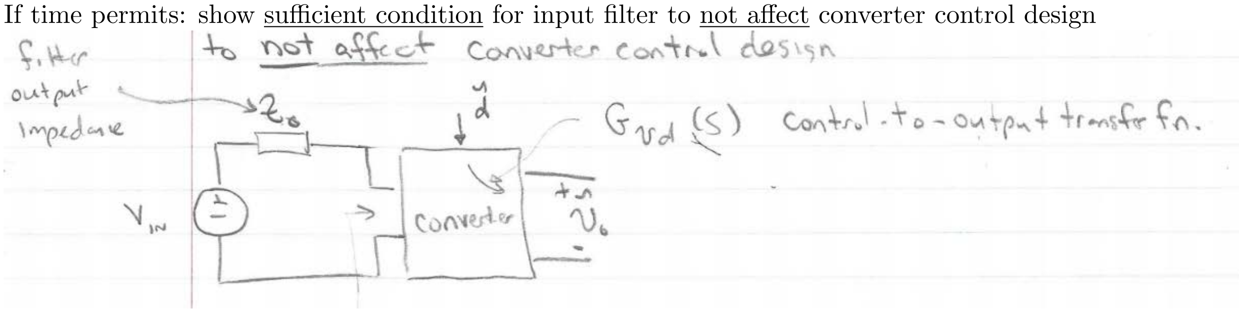


Simplified approximation: neglects effect of C_d, but approximately true
We need $R_d||r_l > 0$

$$\frac{R_d r_l}{R_d + r_l} > 0 \text{ for } R_d < |r_l| \Rightarrow \text{ make } R_d << |-\frac{P_0}{I_{in}^2}|$$

In general: $max(Z_0) << |-\frac{P_0}{I_{in}^2}|$! (There are also other considerations we neglect here!)
$\Rightarrow$ show demo of input filter oscillations

If time permits: show <u>sufficient condition</u> for input filter to <u>not affect</u> converter control design



Can prove (using Middlebrookextra element theorem)

$$G_{vd}(s) = (G_{vd}(s)|_{z(s)=0}) \cdot [\frac{1 + \frac{z_0(s)}{z_n(s)}}{1 + \frac{z_0(s)}{z_d(s)}}]$$

Where $G_{vd}(s)$ is a transfer function with <u>no</u> filter

- $z_0(s)$ filter output impedance
- $z_n(s)$ converter input impedance w/ perfect control of output (=-$\frac{P_0}{I_{in}^2}$)
- $z_d(s)$ converter input impedance w/ <u>constant</u> duty ratio

Sufficient condition $|z_0(s)| << z_n(s)$ <u>and</u> $z_d(s)$
(see Erickson and Maksimoniv chapter for details)