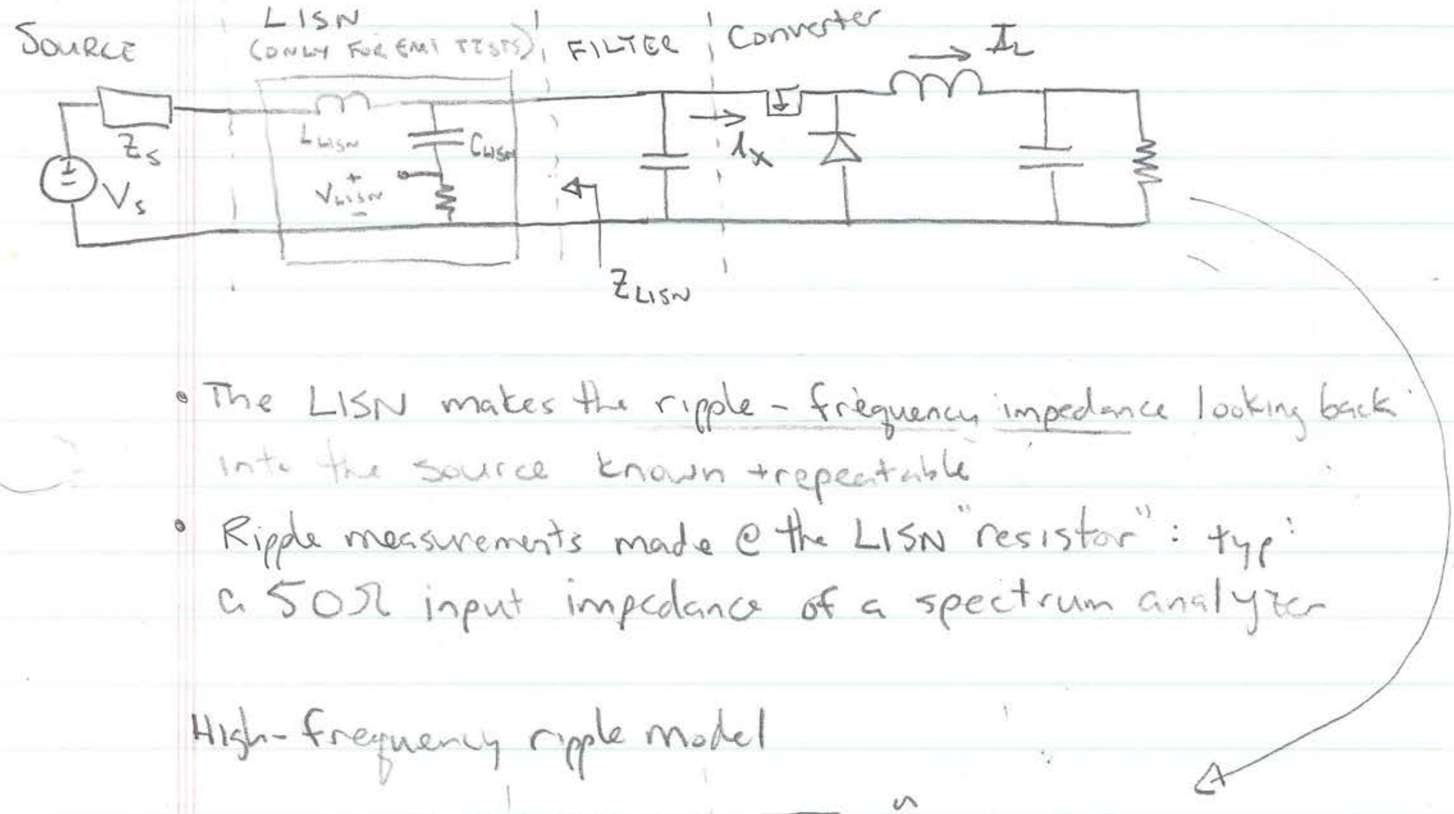
6.334 Lecture Notes EMI FILTERS #2

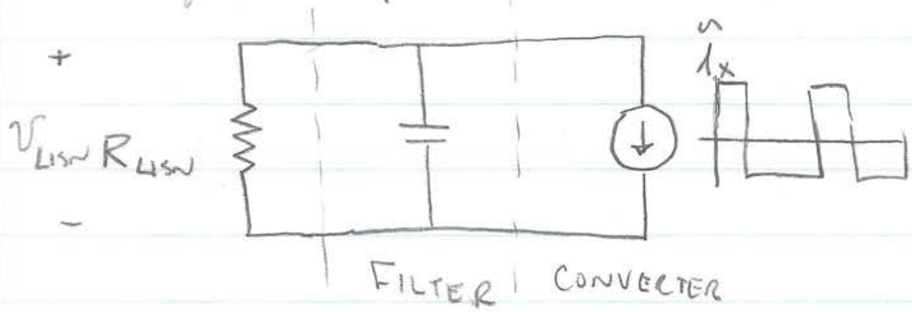
REVIEW:

- Filters are needed to achieve large attenuation of ripple
- To make measurements REPEATABLE a LISN is often specified for making EMI measurements:



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

High-frequency ripple model



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

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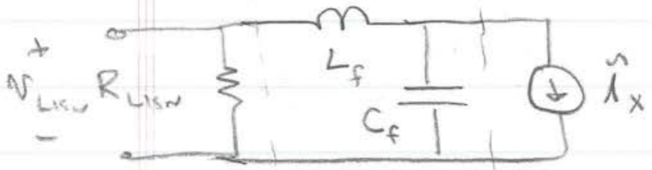
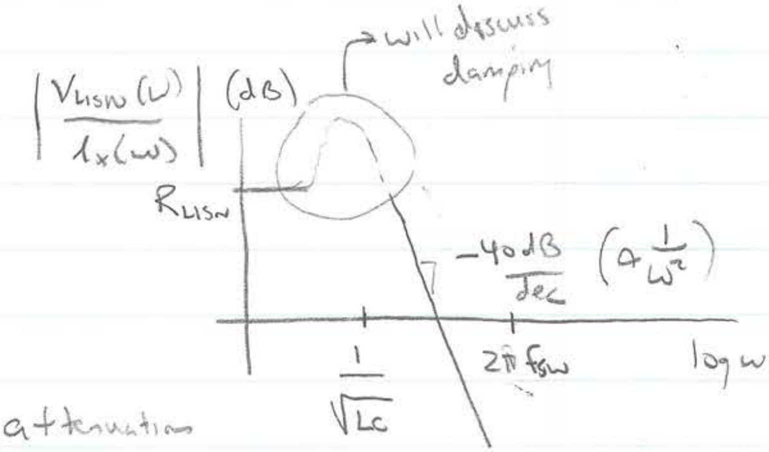
"L-section" Filter





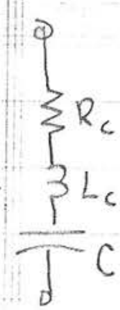
- We can get −40dB/decade attenuation above the cutoff
- Blocks dc voltage well (capacitor), carries dc current well (inductor)
- Can cascade L sections if needed.

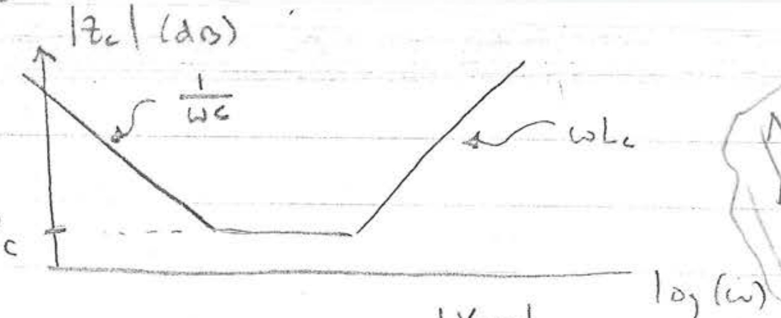
A second consideration is filter + component parasitics

PARASITICS

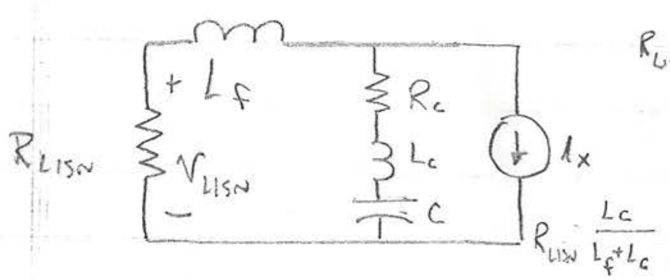
We must carefully consider component + Layout parasitics, as they limit H.F. performance!

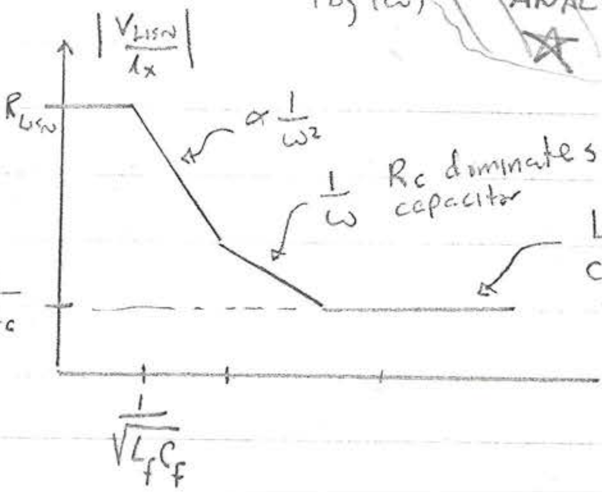
"real" capacitor





NOTE: SHOW DEMO W/ IMPEDANCE ANALYZER ☆





NOTE: UNDERSCORE LAYOUT PARASITICS ALSO!

Component parasitics are an important limitation / consideration in design!

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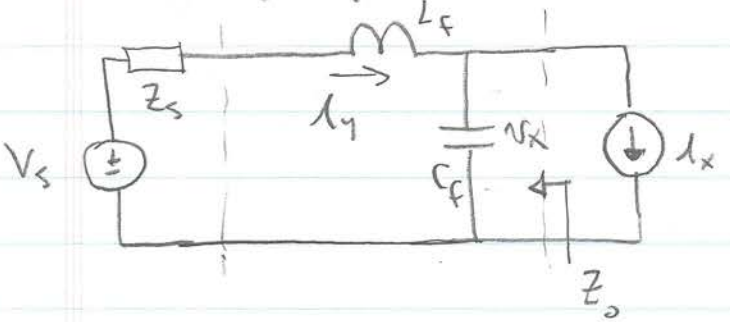
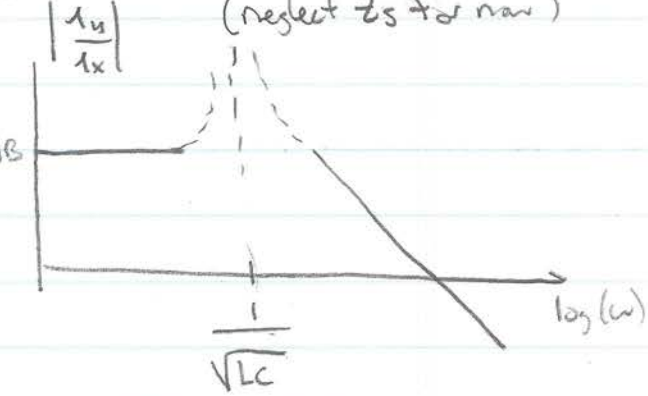
Another design issue is filter damping. (In practice, the LISN is not present, and we must have acceptable behavior across all frequency

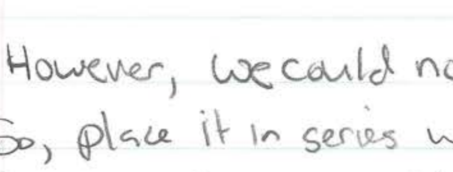
(neglect Z_s for now)



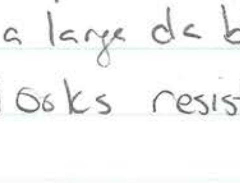


neglecting Z_s, setting $V_s \to 0$, the converter looks back into a parallel LC tank circuit. At resonance, this becomes a high impedance, + large resonant currents will flow! $\Rightarrow$ must damp to be acceptable.

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

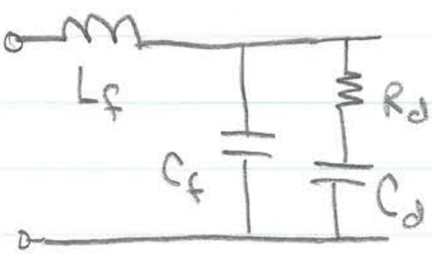


If $R_d \leq \sqrt{\frac{L_f}{C_f}}$ we will be damped!



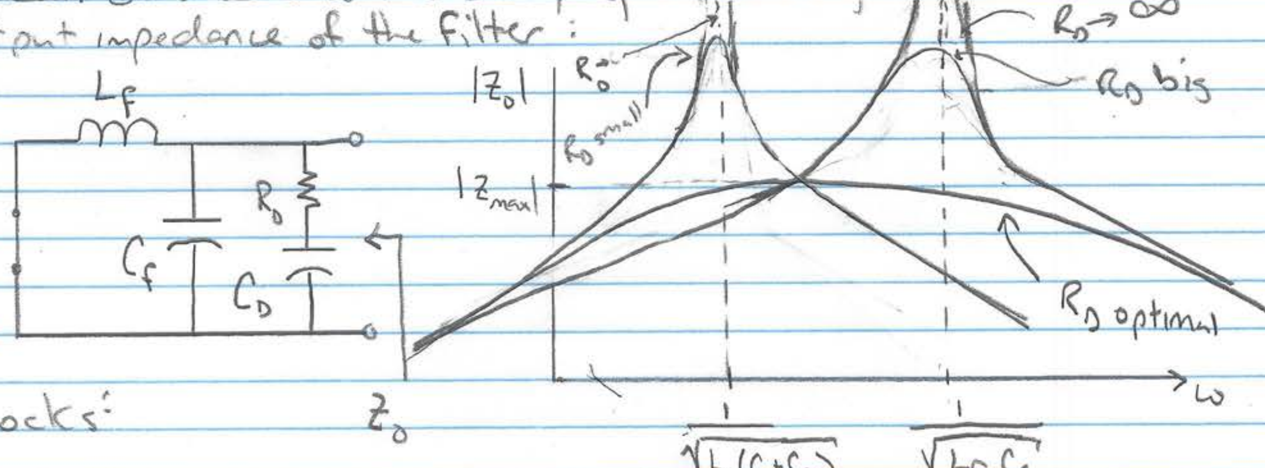
However, we could not accept the dc dissipation of R_d! So, place it in series with a large dc blocking capacitor C_d, such that $R_d - C_d$ combination looks resistive @ $\omega = \frac{1}{\sqrt{L_f C_f}}$

typ $C_d \sim 2\text{-}10\times C_f$



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

Lets consider selection of the damping resistor R_D for a given choice of damping capacitor $C_D = nC_f$ (where $n \geq 1$). We can characterize the damping by looking at the output impedance of the filter:



Goldilocks:

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

⇒ It can be shown (as in Erickson + Maksimovic) that the peak of the $|Z_o|$ curve for an optimal damping resistor that minimizes $\max_{\omega}\{|Z_o|\}$ is exactly the intersection point of the $|Z_o|$ curves for $R_D \to 0$ and $R_D \to \infty$.

★ ⇒ choose a "goldilocks" value of R_D to achieve this minimum peaking. Can find by simulation sweep, or analytically as

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

and we get a maximum output impedance: $|Z_{max}| = R_o \frac{\sqrt{2(2+n)}}{n}$

Note that in our filter design we choose $n = \frac{C_D}{C_f}$. The bigger the multiple n, the smaller 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_D value (bigger damping capacitor)

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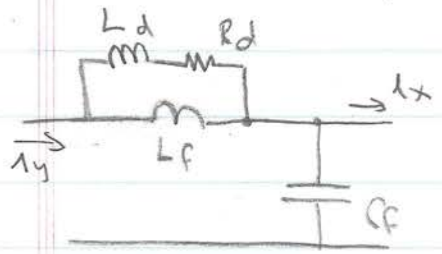
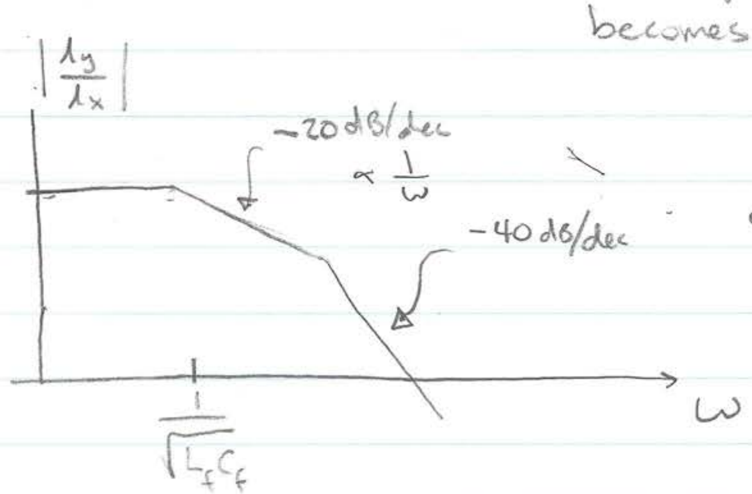
We could also put the damping leg in parallel with L_f



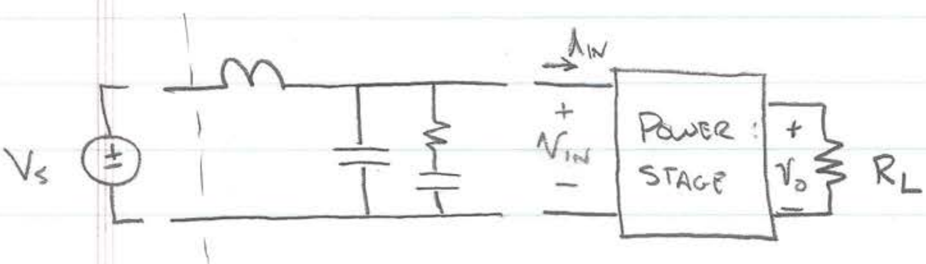
- L_d-R_d branch looks resistive @ $\frac{1}{\sqrt{L_f C_f}}$
  $\Rightarrow L_d < L_f$
- @ high frequencies, series branch becomes $L_{eq} = L_d \| L_f < L_f$



- high-frequency attenuation 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 + 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}!
  $\Rightarrow$ It is a constant-power load!

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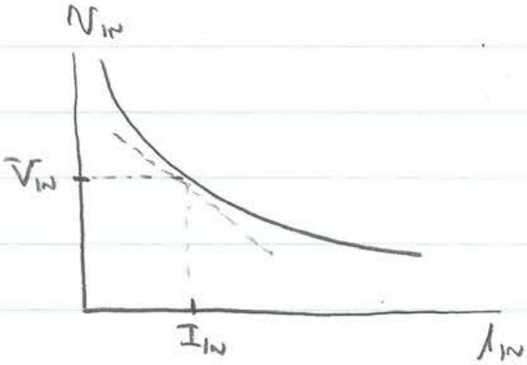
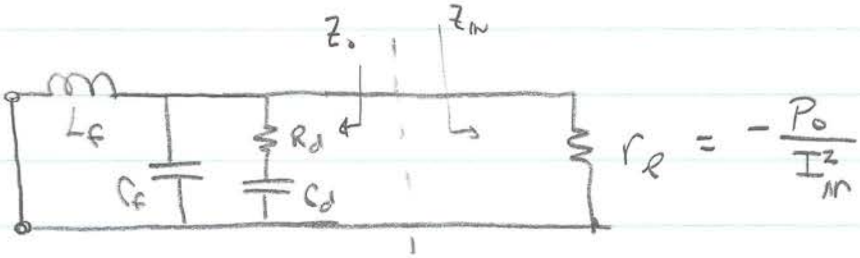
@ constant power P_o : $v_{IN} = \dfrac{P_o}{i_{IN}}$



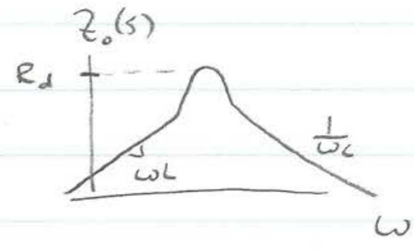
for variations in input voltage, we get variations in current

$$\left.\frac{\partial v_{IN}}{\partial i_{IN}}\right|_{op,pt} = -\frac{P_o}{I_{IN}^2} = r_\ell$$

So incrementally about the operating point, the converter looks like a <u>negative</u> <u>resistance</u>!



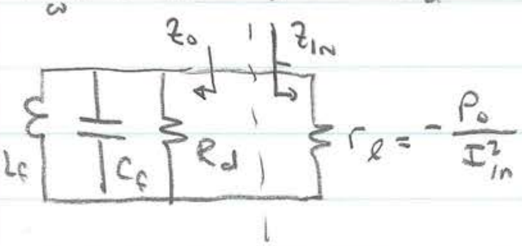
- we require that the system remain well damped despite the tendency of the negative resistance to undamp the system.



Simplified Approx: {neglects effects of C_d, but approximately true}

$\max_\omega (Z_o(\omega)) \approx R_d$

system approximation



we need $R_d \| r_\ell > 0$

$\dfrac{R_d r_\ell}{R_d + r_\ell} > 0$ for $R_d < |r_\ell|$ $\Rightarrow$ make $R_d \ll \left| -\dfrac{P_o}{I_{IN}^2} \right|$

for good damping!

In general: $\max_\omega \{Z_o\} \ll \left| -\dfrac{P_o}{I_{in}^2} \right|$!

{THERE ARE ALSO OTHER CONSIDERATIONS WE NEGLECT HERE!}

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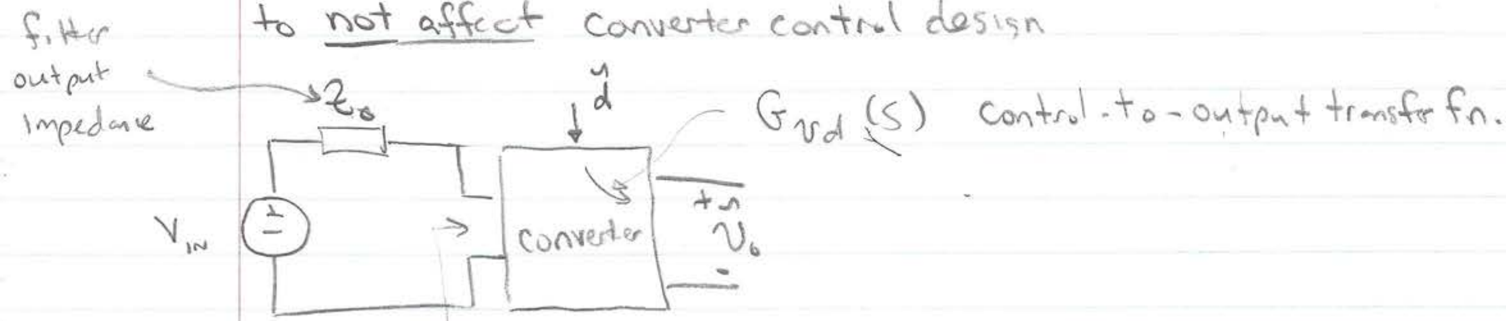
⇒ Show Demo of Input filter oscillations

If time permits: Show sufficient condition for input filter to not affect converter control design



Can prove (using Middlebrook extra element theorem)

$$G_{vd}(s) = \left(G_{vd}(s) \Big|_{Z_o(s)=0} \right) \cdot \left[\frac{1 + \frac{Z_o(s)}{Z_N(s)}}{1 + \frac{Z_o(s)}{Z_D(s)}} \right]$$

Transfer fn. with no filter

$Z_o(s)$ filter output impedance

$Z_N(s)$ converter input impedance w/ perfect control of output $\left(= -P_o/I_{IN}^2 \right)$

$Z_D(s)$ converter input impedance w/ CONSTANT duty ratio

Sufficient condition $|Z_o(s)| << Z_N(s)$ AND $Z_D(s)$

(see Erickson + Maksimovic chapter for details