6.334 Power Electronics
Spring 2007

Power Electronics Notes - D. Perreault

★★ EMI Filtering

Input and output ripple / ElectroMagnetic Interference (EMI) filtering is important to prevent interference with other circuitry. (e.g. a power supply with an improperly designed EMI filter can easily interfere with radios, televisions, etc. in the vicinity.)

Requirements

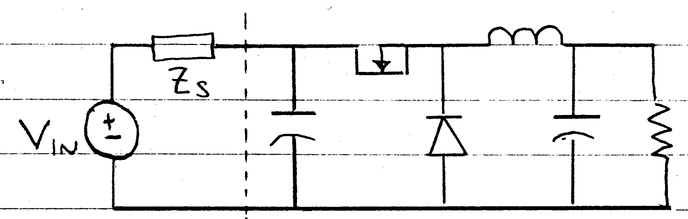
AC interfaced systems (FCC, VDE)

DC systems (MIL-STD 461, SAE J1113, CISPR)

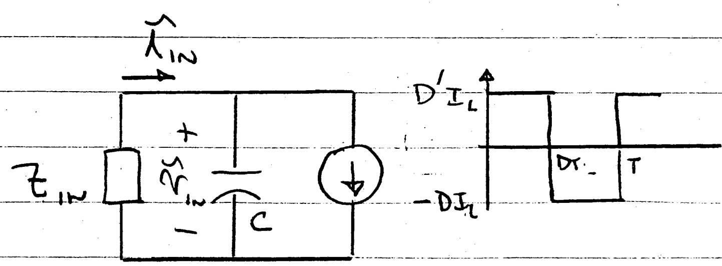
In general, ripple or EMI limits come in 2 flavors

1. Time-domain voltage or current ripple limits
2. Frequency-domain limitations (using LISN)

Consider simple case : buck converter input filter



AC-only model



ripple $\tilde{i}_{in}$ and $\tilde{v}_{in}$ depend on source impedance Z_s

→ $\tilde{v}_{IN}$ is worst for high Z_s

→ $\tilde{i}_{in}$ is worst for low Z_s

★ To properly design the input filter, we must know or control the source impedance (measurement specifications.)

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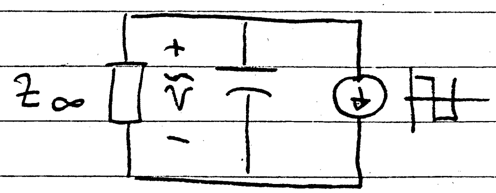
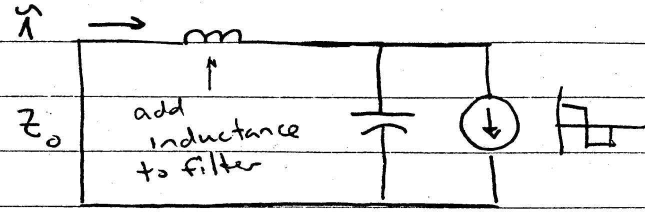
For time-domain ripple, we often assume the worst case



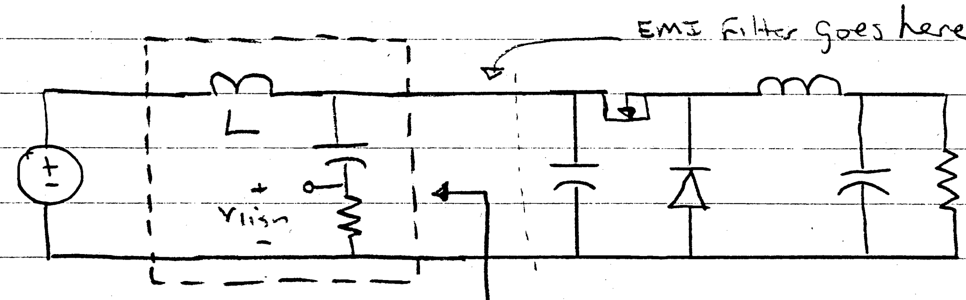
v ripple



i ripple

For frequency-domain limits (e.g. FCC), we <u>control</u> the ripple-frequency impedance to a known value for testing purposes (e.g. to meet specifications)
⇒ Otherwise results would vary

Line Impedance Stabilization Network (LISN)



LISN

Z_{lisn} @ dc $Z_{lisn} \to 0$
@ ripple freq $Z_{lisn} \to R$ (typ. 50Ω)

The LISN, which controls the source impedance during testing, is specified as part of the test. Typically, we measure the voltage ripple across R and specify a limit on the frequency content of the ripple voltage (spectrum analyzer measurement)

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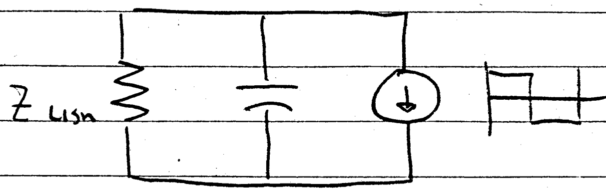
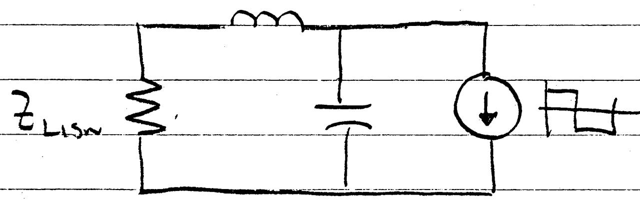
Look at frequency content of $\tilde{v}$



Add full EMI filter to obtain ripple reduction



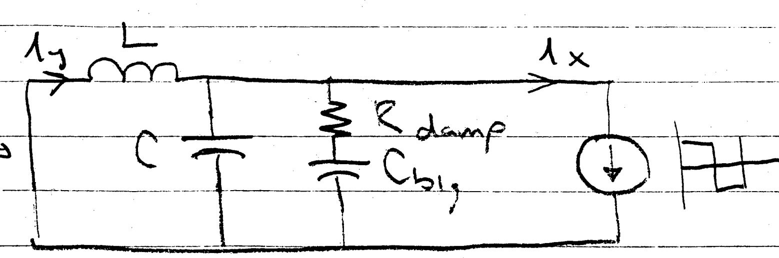
1-stage LC filter

- Note No resistance in dc path for filtering (dissipation)
- Could use multiple stages for very tight standards
  e.g. Automotive specs allow on the order of 100's of μA (only) in many cases.

However, we cannot assume that in reality we will have the LISN resistance there as damping! We must add our own to ensure that the filter doesn't ring.

Approach #1: Capacitor leg damping

Assume $Z_s = 0$ worst case for damping



@ corner frequency of LC (where damping is needed)

$$\frac{1}{sC_{big}} < R_{damp} \Rightarrow R_{damp} \text{ provides parallel damping but does not dissipate dc power.}$$

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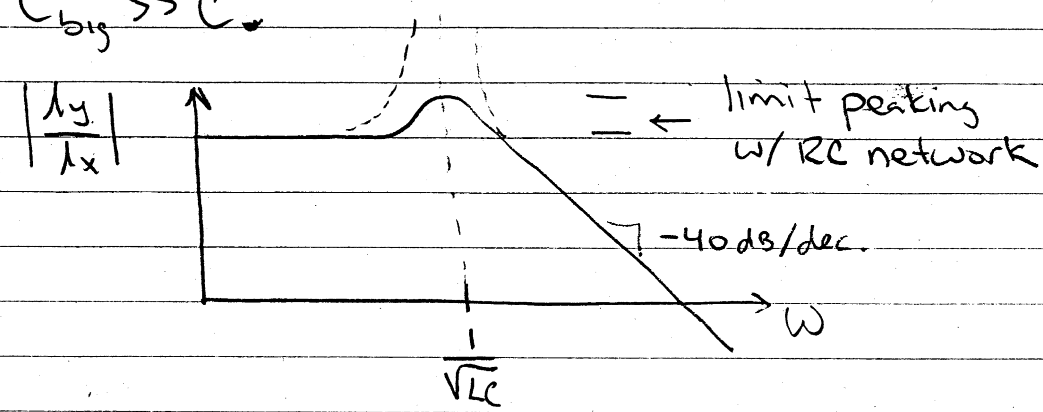
Alt.: C must take large AC ripple current, but C_{big} does not need to (because of R), but capacitance $C_{big} >> C$.

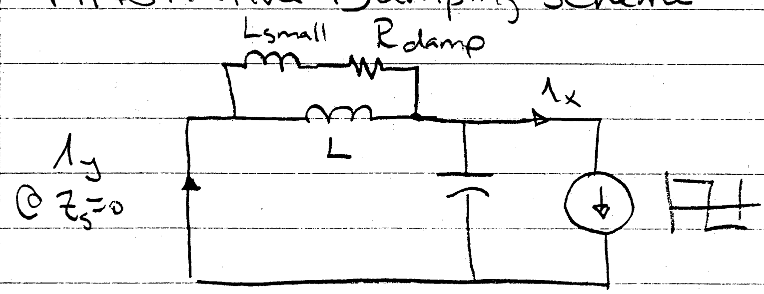


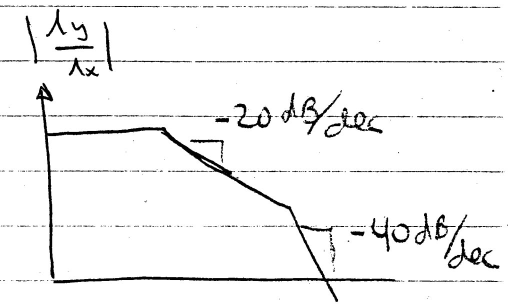
$\frac{1}{\sqrt{LC}} << 2\pi f_{sw}$ for attenuating switching ripple

→ Choose $\frac{1}{\sqrt{LC}}$ low enough to provide sufficient attenuation at f_{sw} and beyond

→ choose damping leg for limiting peaking near cutoff.

Alternative Damping Scheme:





Near cutoff make $|\omega L_{small}| << R$

$|\omega L_{small}| << \omega L$

∴ 1^{st} order rolloff near $\omega = \frac{1}{\sqrt{LC}}$ ≈ Rdamp -20 dB/dec

2^{nd} order rolloff @ high frequencies ≈ Lsmall $-40\frac{dB}{dec}$

⇒ Lsmall carries no dc current, so physically small

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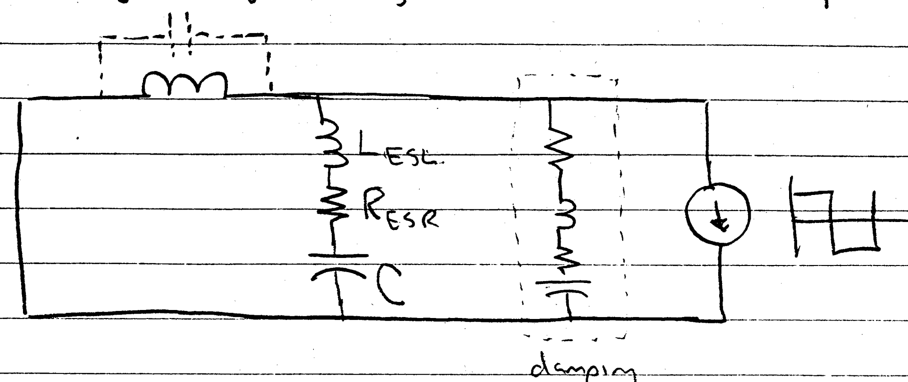
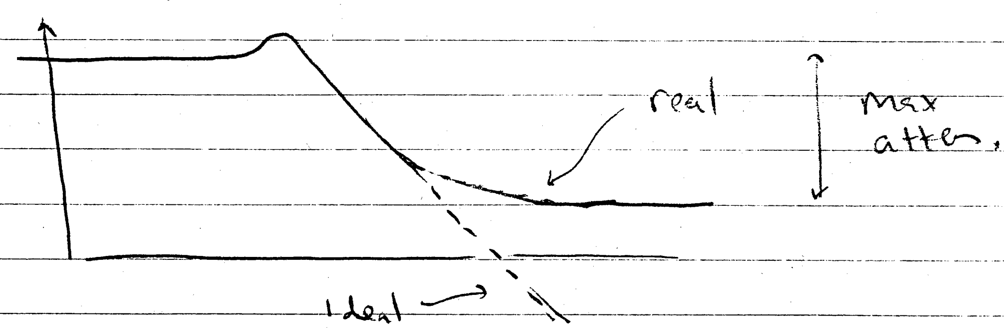
Note: since EMI filters must work to very high frequencies, we must consider parasitics



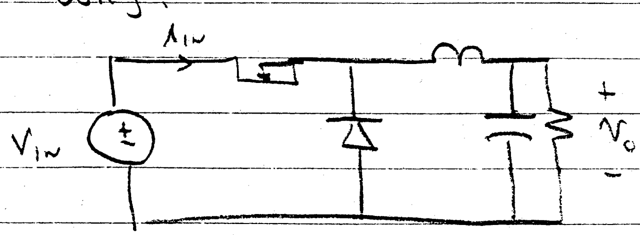
Capacitor ESR / ESL is most significant, but also must pay attention to capacitance across inductors (interturn capacitance).

Effects of parasitics on Attenuation:



Other consideration: power converter interactions:
→ dc/dc converter w/ closed-loop control looks like negative incremental impedance at low freq.

Why?



$$\langle v_{in} i_{in} \rangle = \langle V_o I_o \rangle = P_o$$

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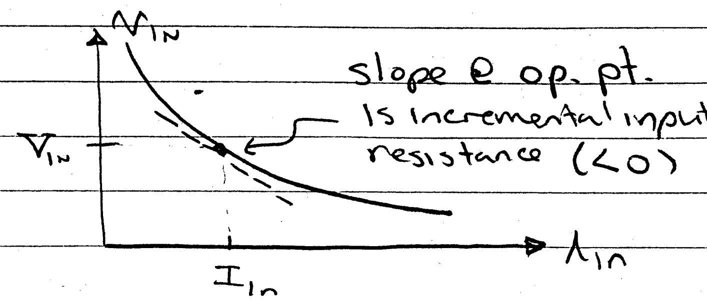
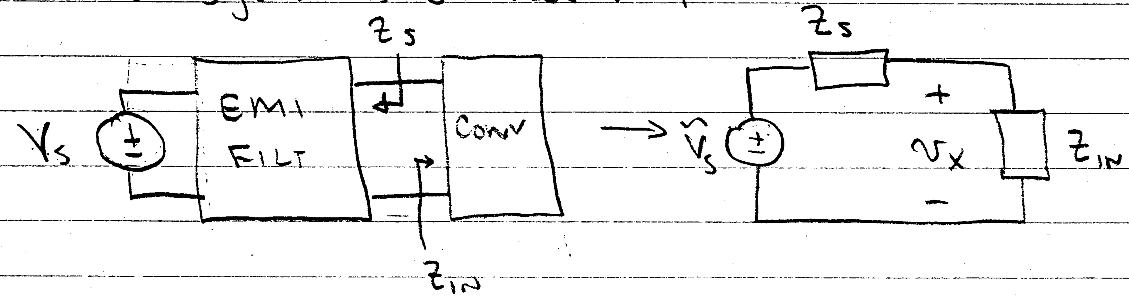
So $$i_{in} = \frac{P_o}{v_{IN}}$$

$$v_{IN} = \frac{P_o}{i_{in}}$$

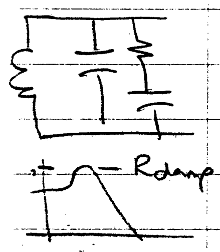


$$r_e = \left.\frac{\partial v_{IN}}{\partial i_{IN}}\right|_{V_{IN}, I_{IN}} = -\frac{P_o}{I_{IN}^2}$$

So, we must design EMI filter output impedance so the net system is stable. (keep Rdamp small)



Z_s is EMI filter output impedance
Z_{IN} is converter input impedance
} Linearized about op. pt.



$$\frac{v_x}{v_s} = \frac{Z_{IN}}{Z_{IN} + Z_s} \longrightarrow \boxed{\text{Poles @ } 1 + \frac{Z_s}{Z_{IN}} = 0}$$

$|Z_s|_{max} = R_{damp}$

$Z_{s,max} \cong R_{damp}$ @ filter resonance $\therefore$ need $|R_{damp}| \ll |r_e|$

For more info see:

D.M. Mitchell, "Power Line Filter Design Considerations for DC/DC converters", IEEE Industry Applications Magazine Nov/Dec 1999, pp 16–26

TK Phelps and W.S. Tate "Optimizing Passive Input Filter Design", Powercon 6, may 1979, pp G1-1 - G1-10

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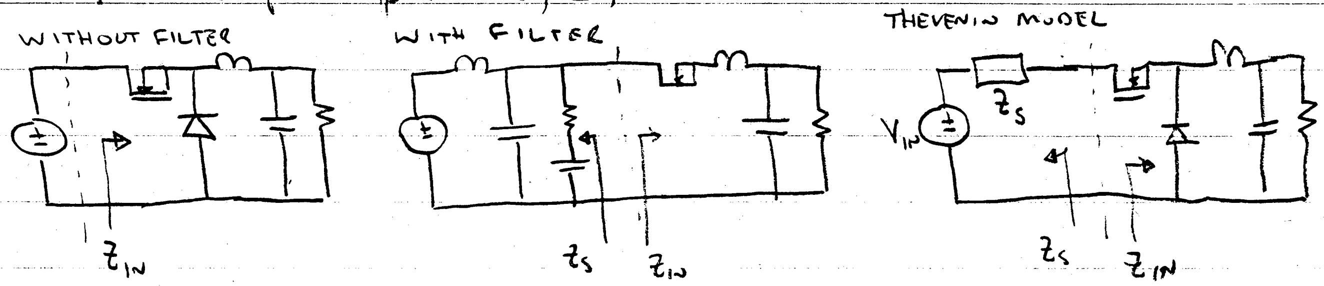
★ Control considerations of EMI Filters

So, we have seen that introducing an EMI filter can introduce instability, especially as the regulating converter tends to present a negative input impedance, reducing the filter damping. We can model the filter effects using the filter output impedance, e.g.



Keeping the filter damping sufficiently high ($|Z_s|$ low) so that $R_{damp} < |r_{in}|$ is necessary. However, is it sufficient?

⇒ The input filter can also change the control behavior of the converter, since the voltage at the converter input is no longer independent of what the converter is doing (due to filter interactions.)

⇒ we would like to know: for what kind of filter output impedance do we not change the converter control behavior by adding the filter.

This is treated in detail in "Fundamentals of Power Electronics, 2nd Ed" by Erickson + Maksimović, but we will summarize the considerations here.

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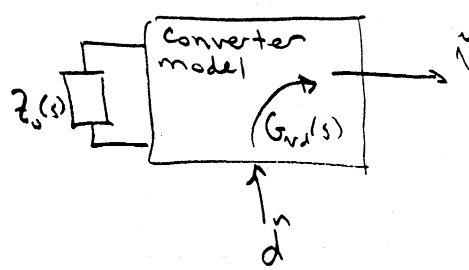
★ So the effect of adding in the filter may be modeled as introducing a new impedance (the filter output impedance) in between the source + the converter.

★ We may find the effect of this on the dynamics of the converter (e.g., the control to output xfer function) using the <u>Middlebrook Extra Element theorem</u>

~~(State + demonstrate the result first, then go back + prove it)~~:

Suppose we start with a converter having a linearized control to output xfer function $G_{vd}(s) = \frac{\hat{v}_o(s)}{\hat{d}(s)}$ and an input filter output impedance $Z_o(s)$. Then we may express

$$G_{vd}(s) = \underbrace{\left(G_{vd}(s)\Big|_{Z_o(s)=0} \right)}_{\text{Converter control to output xfer function with no input filter.}} \underbrace{\frac{\left(1 + \frac{Z_o(s)}{Z_N(s)}\right)}{\left(1 + \frac{Z_o(s)}{Z_D(s)}\right)}}_{\text{Correction factor for input filter dynamics, where}}$$



Converter control to output xfer function with <u>no</u> input filter.

Correction factor for input filter dynamics, where

$Z_o(s)$ is output impedance of input filter

$Z_D(s)$ $Z_i(s)\Big|_{\hat{d}=0}$ "converter Driving point" input impedance = <u>OPEN LOOP</u> INPUT impedance of the converter (D fixed @ op point)

Z_D

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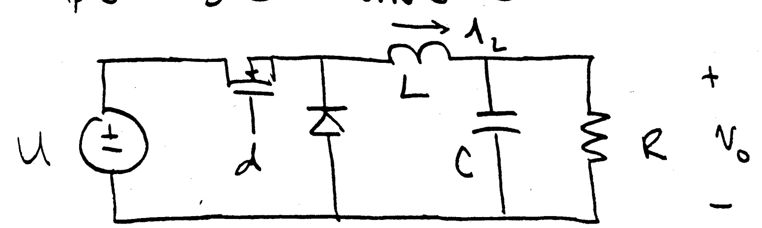
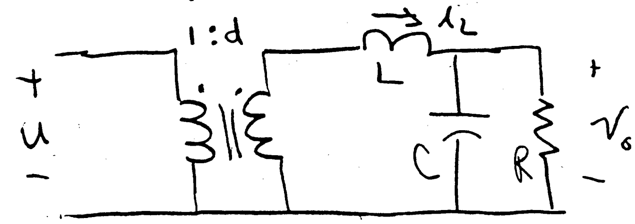
$Z_n(s)$ is $Z_i(s)\Big|_{\substack{\hat{d}(s) \text{ such that} \\ \hat{v}_o \to 0}}$ (output ripple nulled) $\to$ input impedance with a controller that perfectly regulates the output to no variation $\hat{v}_o(s) \to 0$

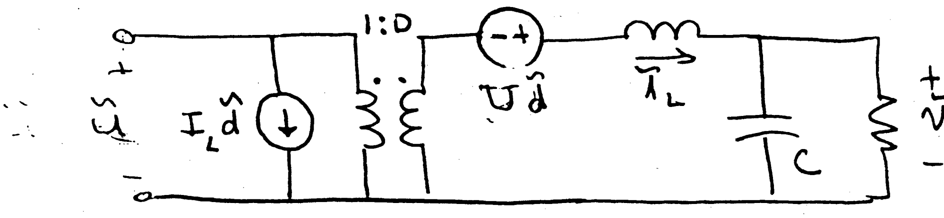
Example: Buck converter:



large-signal averaged circuit model

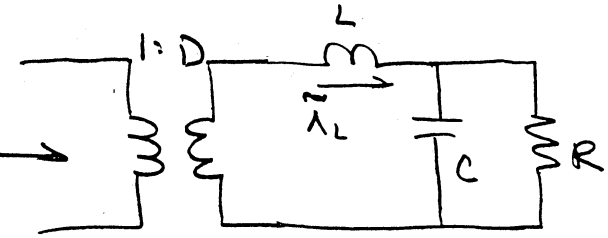


Small-signal model about U, I_L, V_o, D

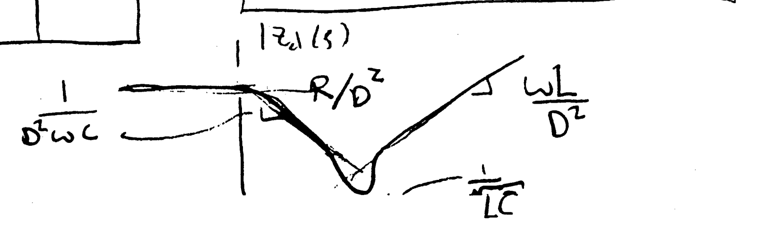


So to find $Z_d(s)$, we set $\hat{d} \to 0$

$Z_d(s) \longrightarrow$



$$\boxed{Z_d(s) = \frac{sL}{D^2} + \frac{R}{D^2(sCR+1)}}$$



$\frac{R}{sC}$ $\frac{R}{sCR}$

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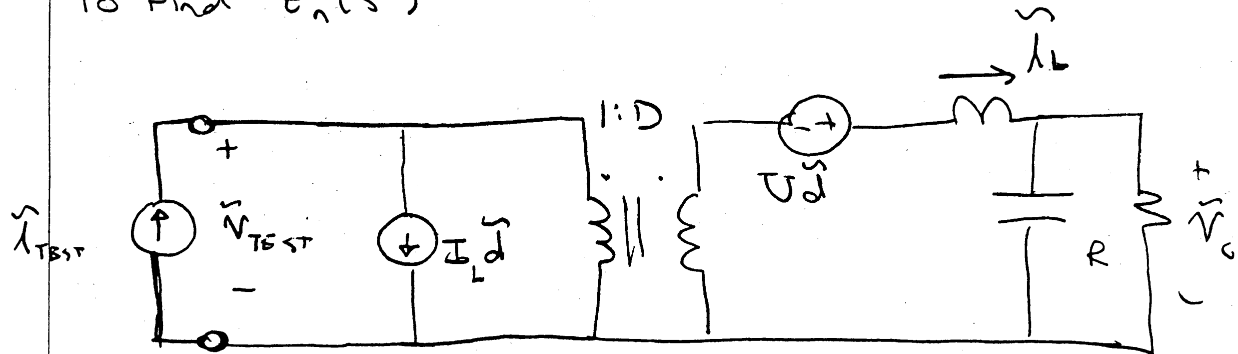
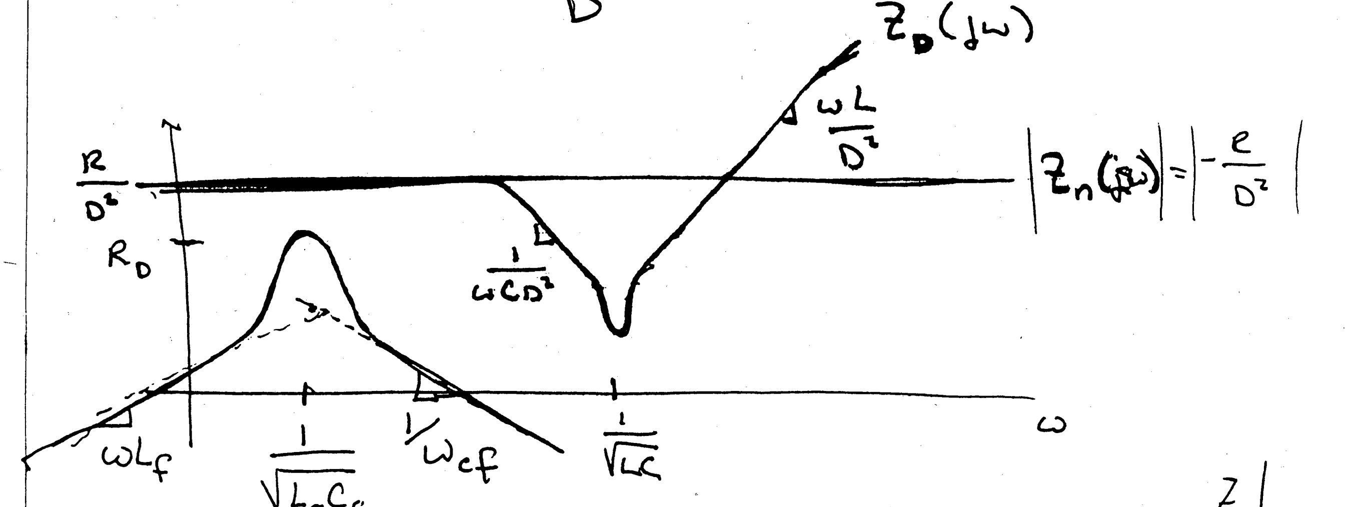
To Find $Z_n(s)$

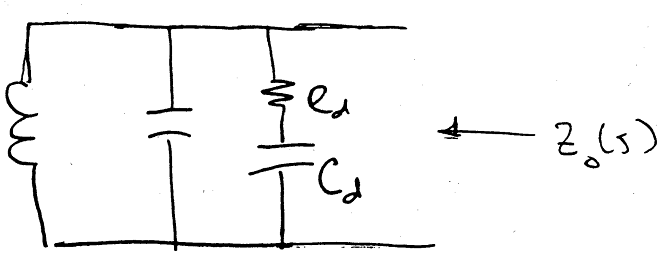


If $\hat{v}_o \to 0 \therefore \hat{i}_L \to 0$ $\qquad R = \frac{DU}{I_L}$

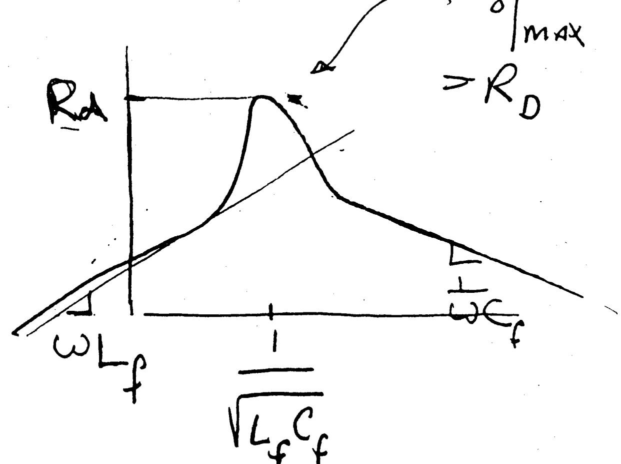
$$\left.\begin{aligned} \therefore\ I_L\hat{d} &= \hat{i}_{TEST} \\ \hat{v}_{TEST} &= -\frac{U\hat{d}}{D} \end{aligned}\right\} \quad Z_n(s) = \frac{\hat{v}_{TEST}}{\hat{i}_{TEST}} = -\frac{U}{DI_L} = -\frac{R}{D^2}$$



Filter



$Z_{o,max}$



So:

1. Keep $\frac{1}{\sqrt{L_f C_f}}$, $\frac{1}{\sqrt{LC}}$ apart
2. Keep $R_d \ll \frac{R}{D^2}$, (Z_d, Z_n across ω)