Input Filter Magic

Webinar February 23, 2023

Dr. Ray Ridley

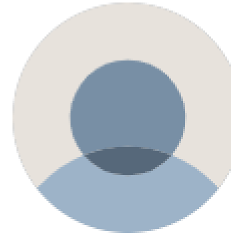
Input Filter Modeling – the Players

Dr. David Middlebrook presented the problem of the input filter interaction with a power supply as part of a bigger general impedance theorem.

Dr. Vlatko Vlatkovic found the issue with the feedforward solution to input filter interactions.

Arthur Nace –aerospace engineer and programmer who automated LTspice models for us and made this work possible. Our longest user of RidleyWorks.

Dr. Shriram S. Kelkar broke new ground by trying to control the effect of the input filter. He came close to getting it right. The important thing was the concept that you can control things outside of the converter cell.



Dr. Vatché Vorpérian – the best analytical mind in power electronics. Without his PWM switch model, none of this work would have happened.

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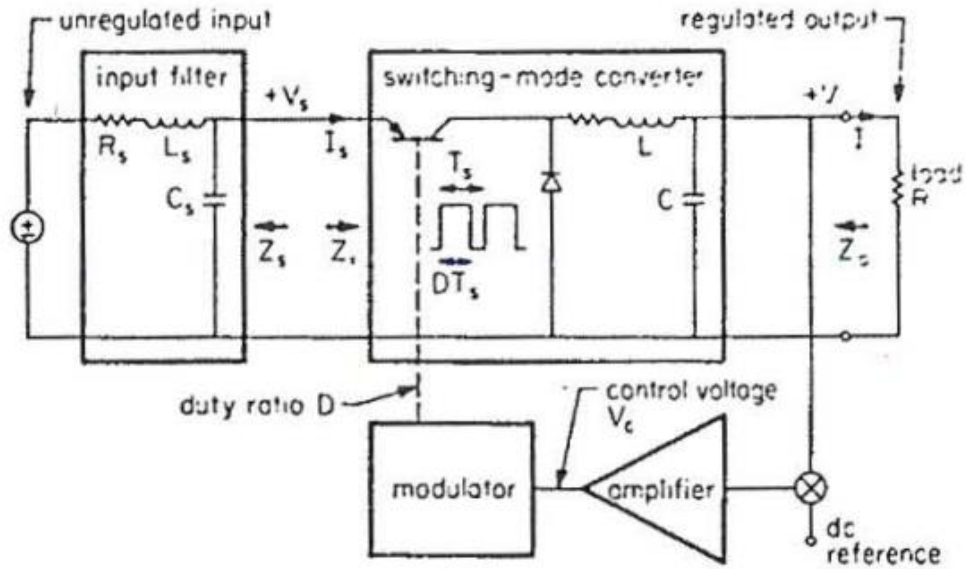
Part I

Basics of Input Filter Measurement and Design

Middlebrooks Input Filter Problem



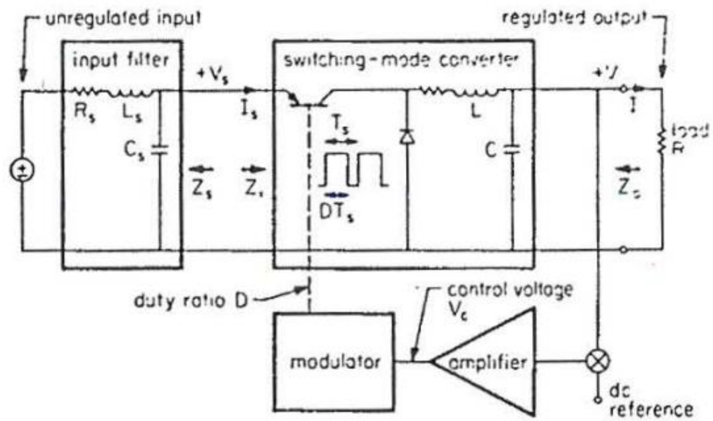
Middlebrook’s original problem description

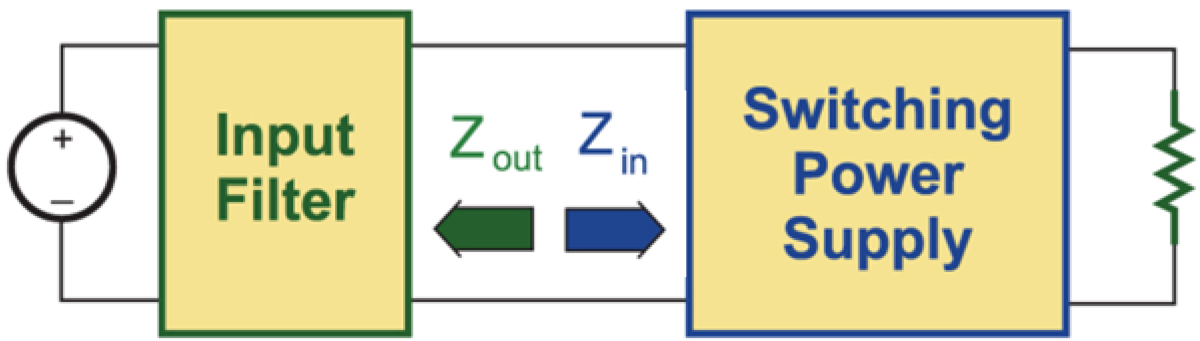
Practical considerations for system testing

Necessary measurements

InputFilterMiddlebrook1976

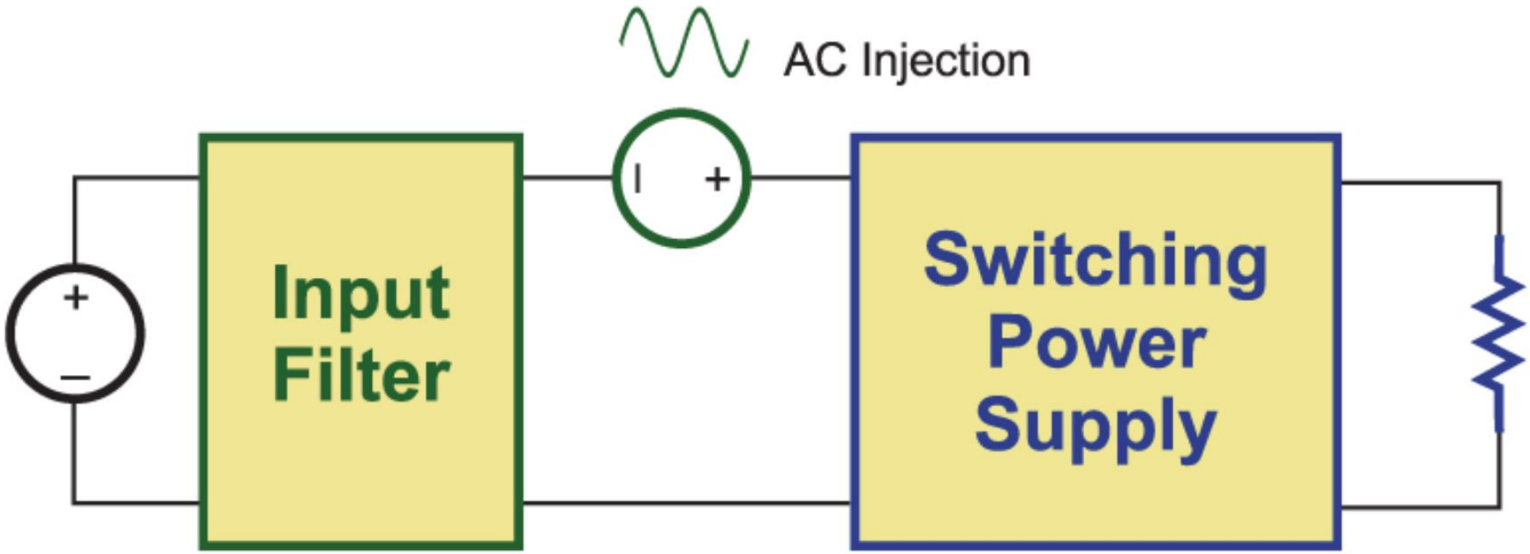
Middlebrooks Input Filter Problem



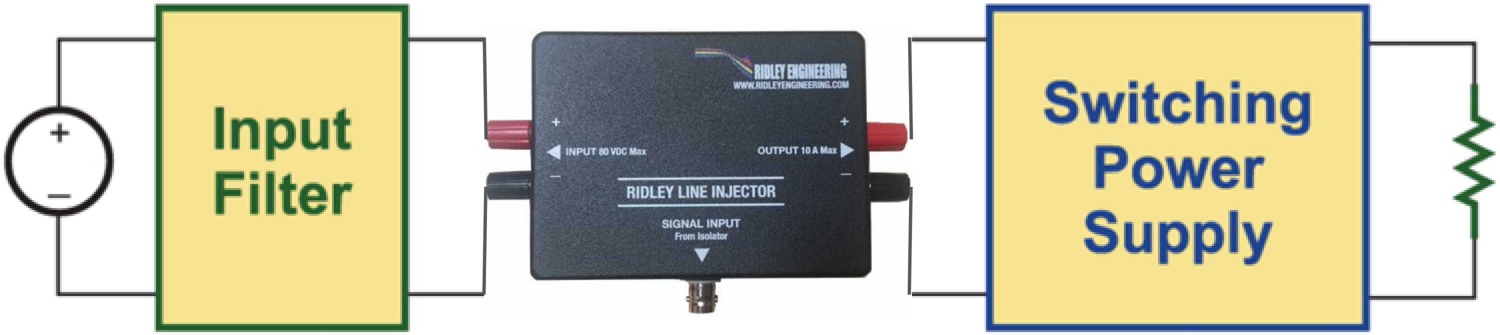


InputFilterMiddlebrook1976

Making Impedance Measurements



Making Input Impedance Measurements

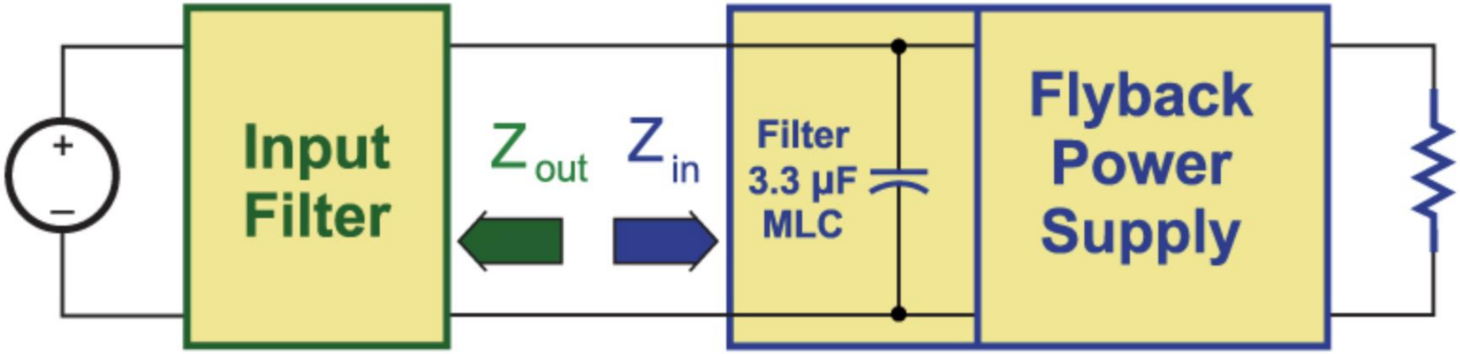


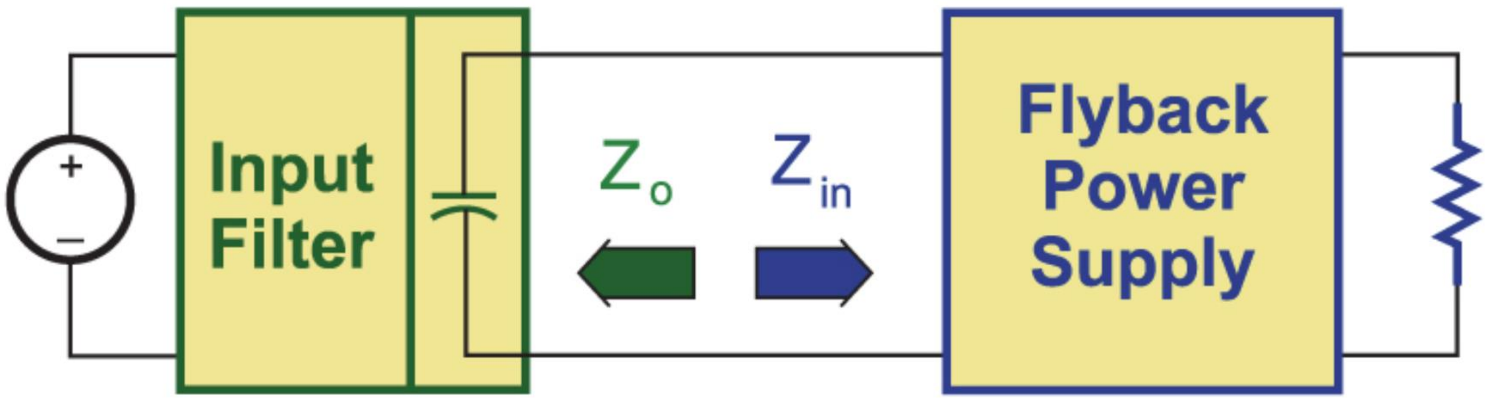
This is the most difficult of all transfer function measurements to make.

If you can avoid it – then avoid it!

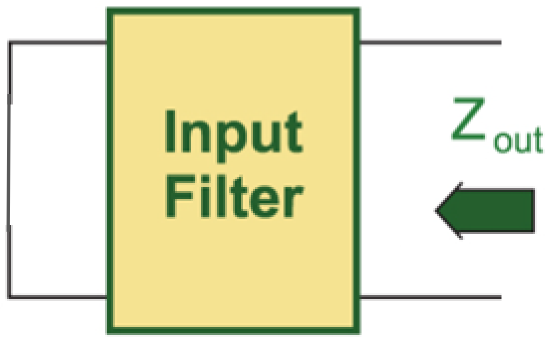
Even if you measure it successfully, it's probably wrong anyway!

Making Impedance Measurements





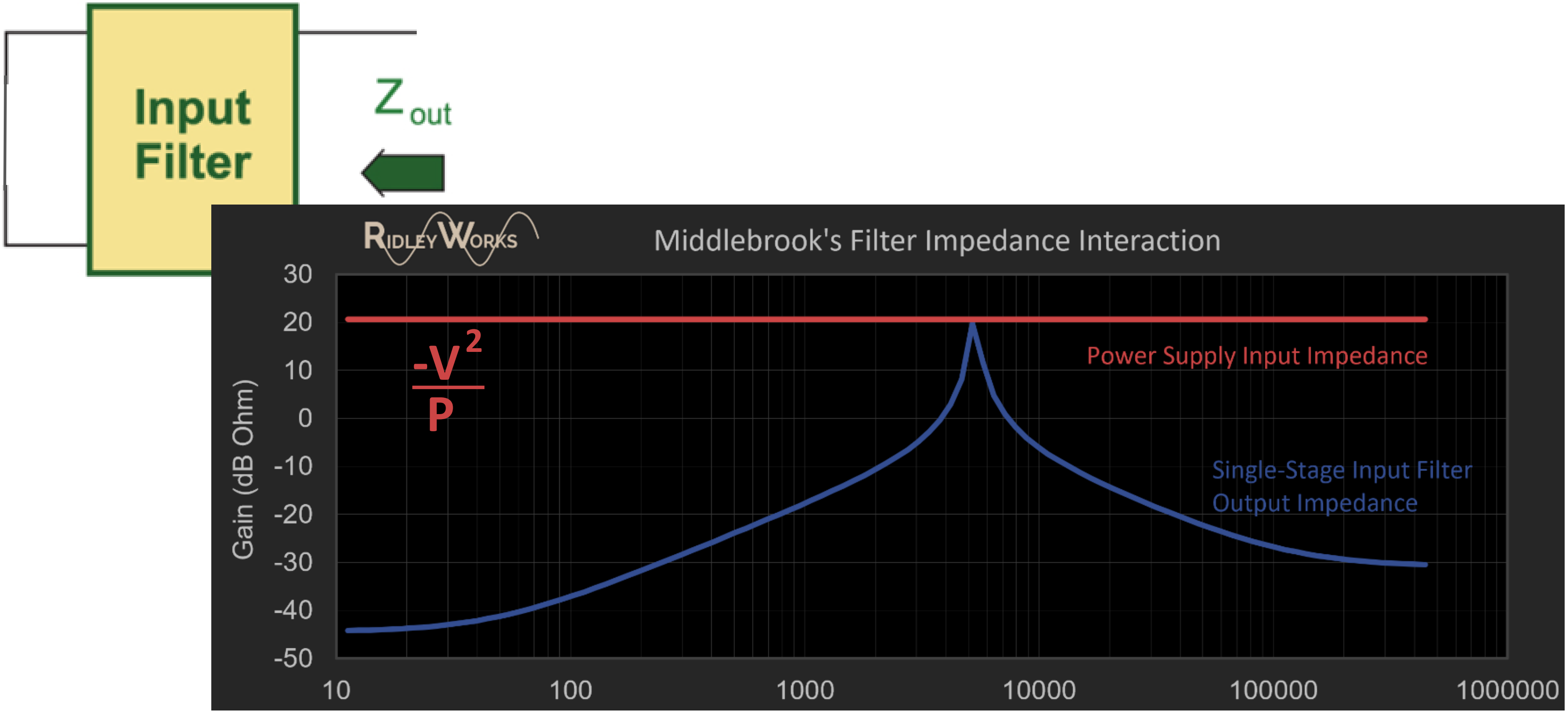
Making Filter Output Impedance Measurements



This measurement is easy. No need to power the input filter

Make sure you short the input of the filter for the measurement

Making Filter Output Impedance Measurements



This measurement is easy. No need to power the input filter

Make sure you short the input of the filter for the measurement.

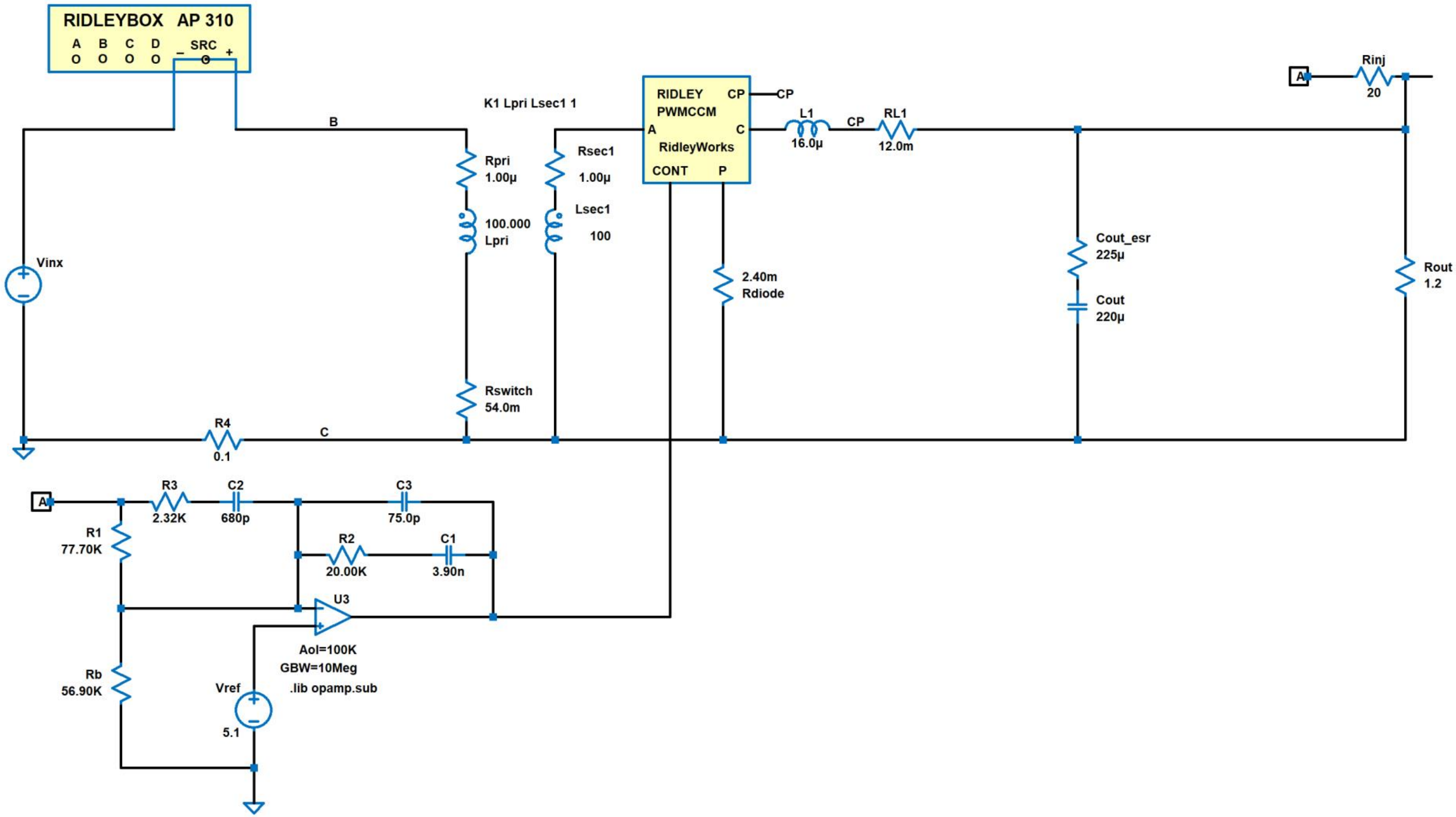
Making Filter Output Impedance Measurements

1. Identify the components of the input filter.
2. Identify the components of the switching power supply. Do NOT include filter components.
3. Place a short circuit on the input to the filter.
4. Measure unpowered filter output impedance with a device such at the AP310 or RidleyBox.
5. Plot the CALCULATED input impedance of the power converter on the same graph.
6. Ensure good separation between the two curves.
7. Check that the filter is well damped to prevent ringing.

Part II

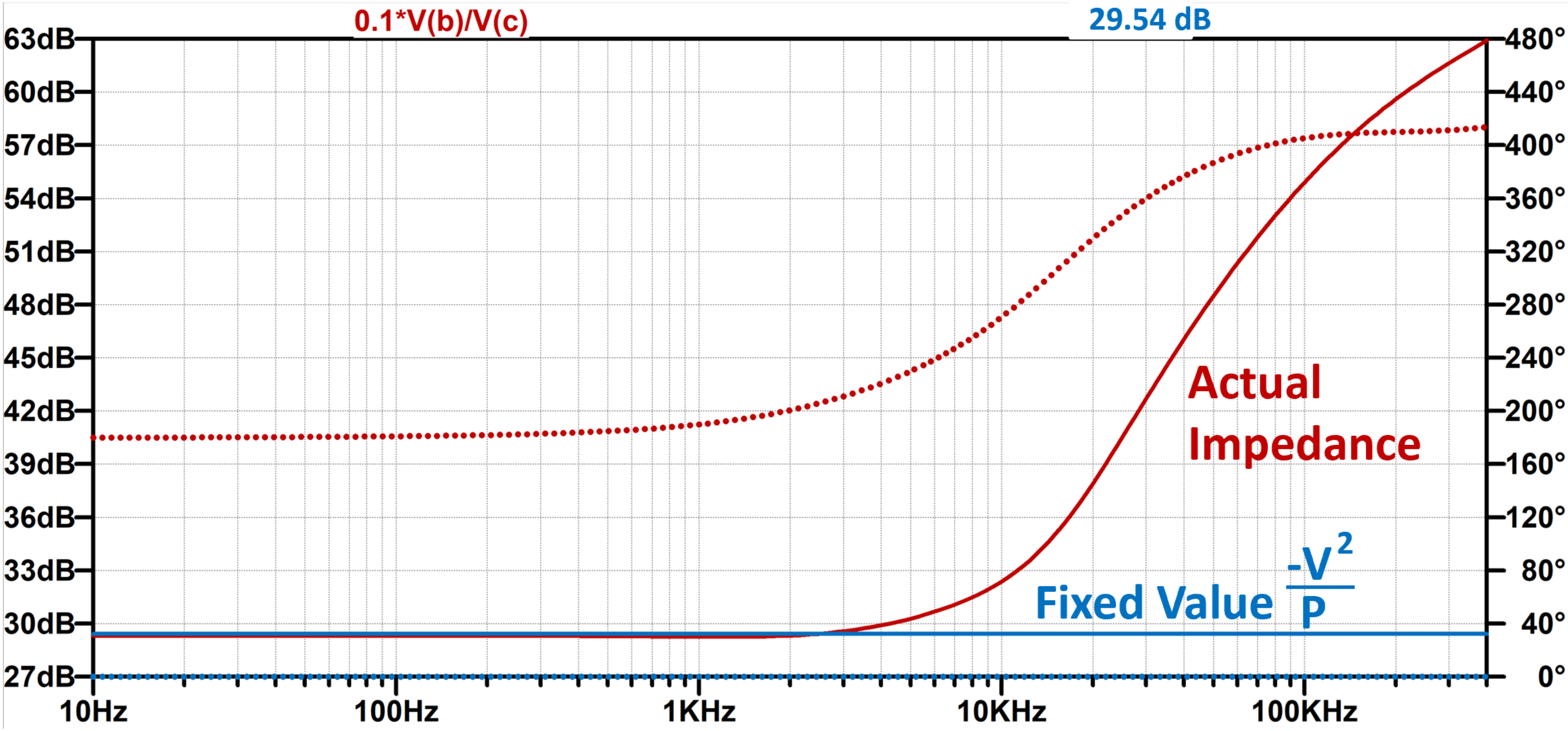
Going Deeper – Models and Loops

LTspice Model to Simulate Input Impedance Measurement



Circuit automatically generated from RidleyWorks

Calculating a Fixed Input Impedance is a Conservative Approach



Estimate the input impedance $\frac{-V^2}{P}$. Use low line for lowest value

Actual impedance will rise above the crossover frequency.

Going Deeper – Interaction with the OPEN-LOOP Input Impedance

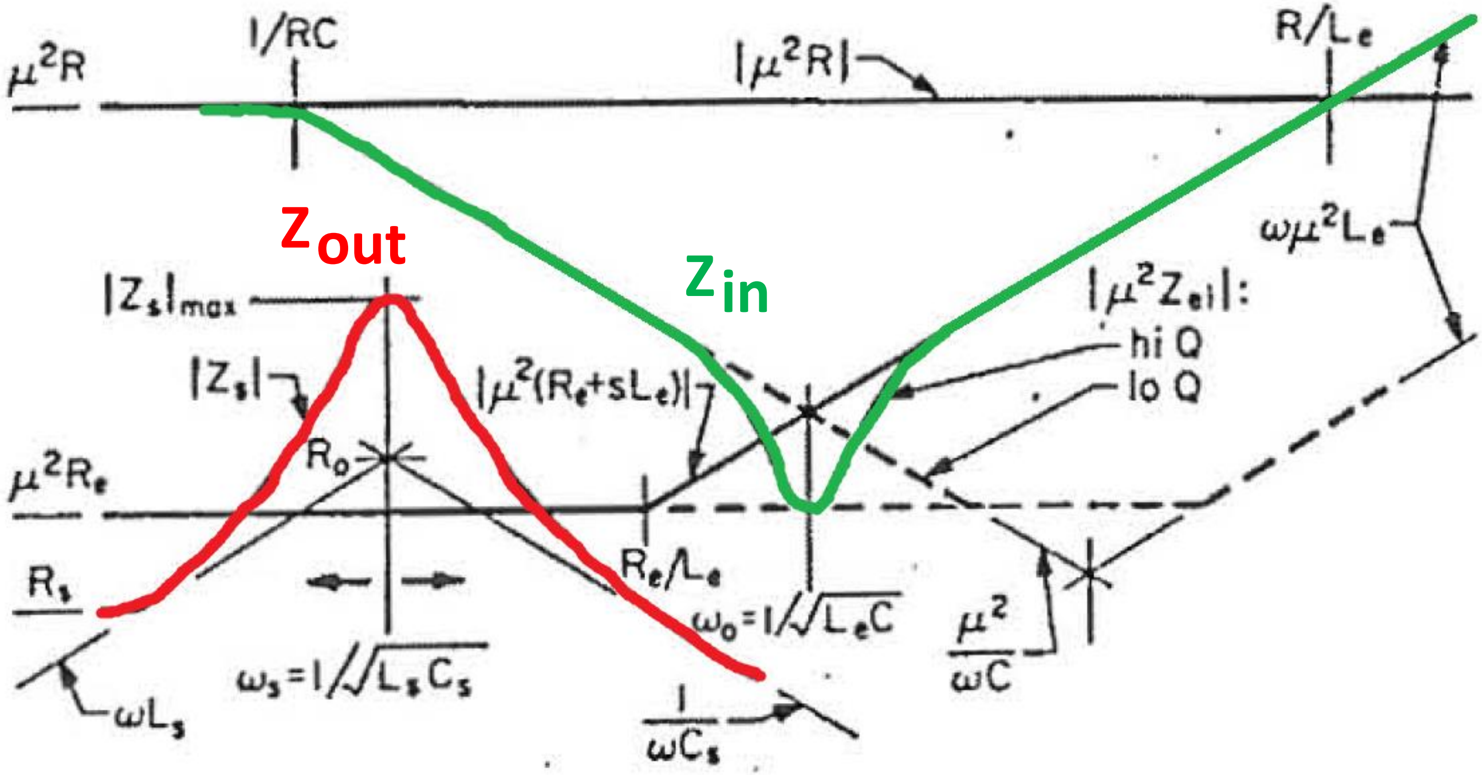
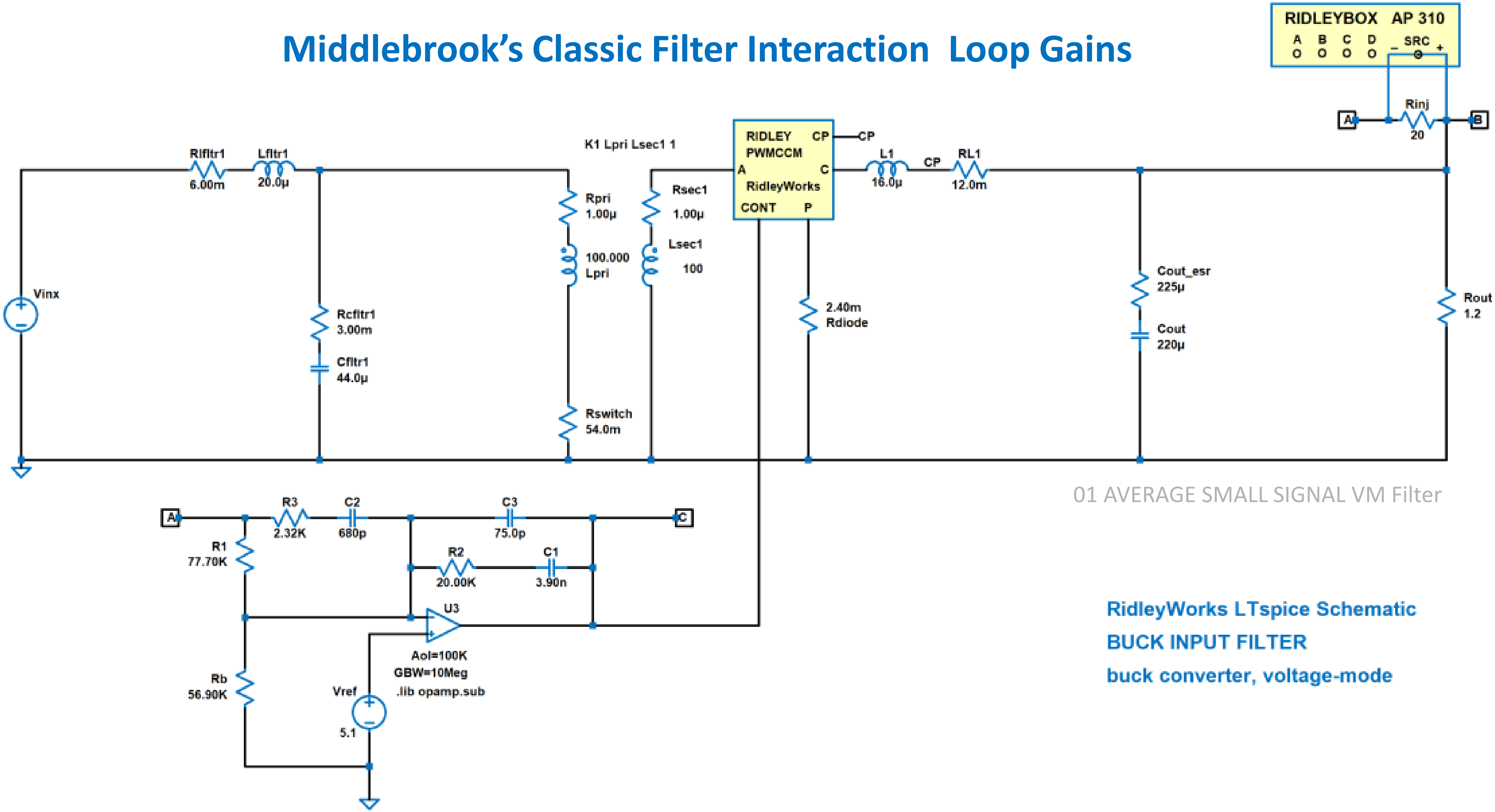


Fig. 7. Magnitude shapes of the regulator open-loop low-frequency input resistance |μ²R|,

Middlebrook talked about avoiding the open-loop input impedance of the power supply

This will mean that the transfer functions of the original power stage won't change significantly

Middlebrook's Classic Filter Interaction Loop Gains



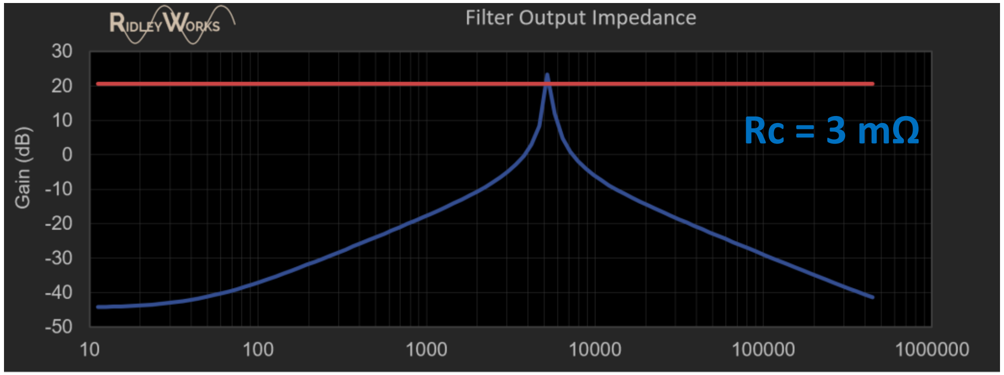
01 AVERAGE SMALL SIGNAL VM Filter

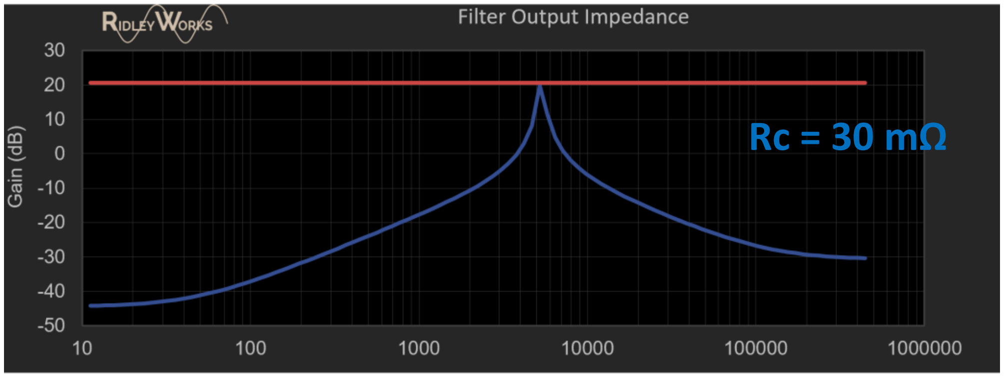
RidleyWorks LTspice Schematic

BUCK INPUT FILTER

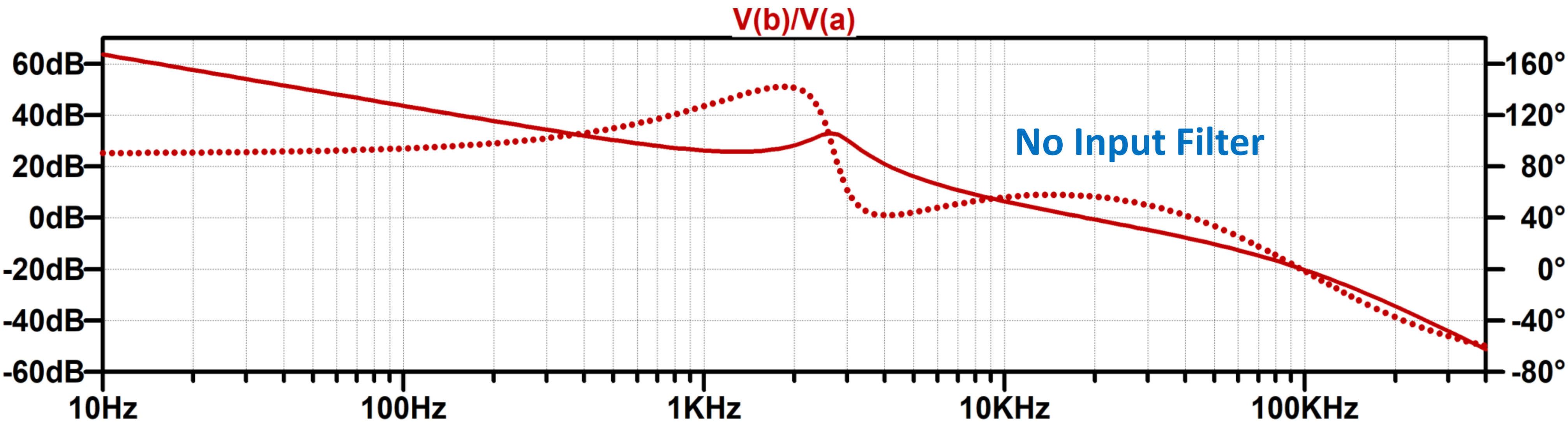
buck converter, voltage-mode

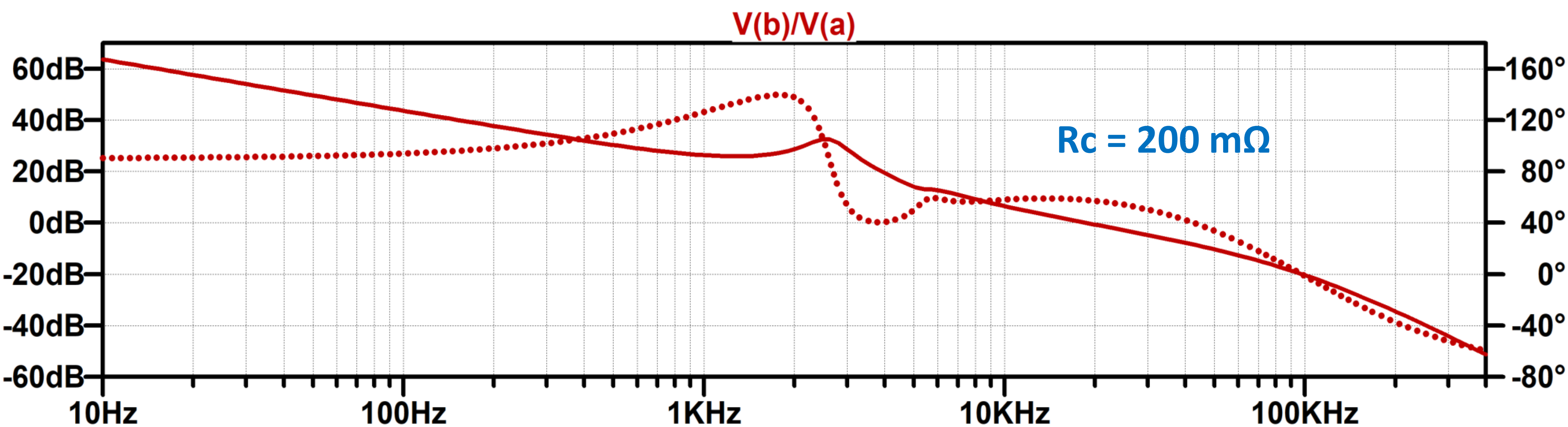
Input Filter Damping



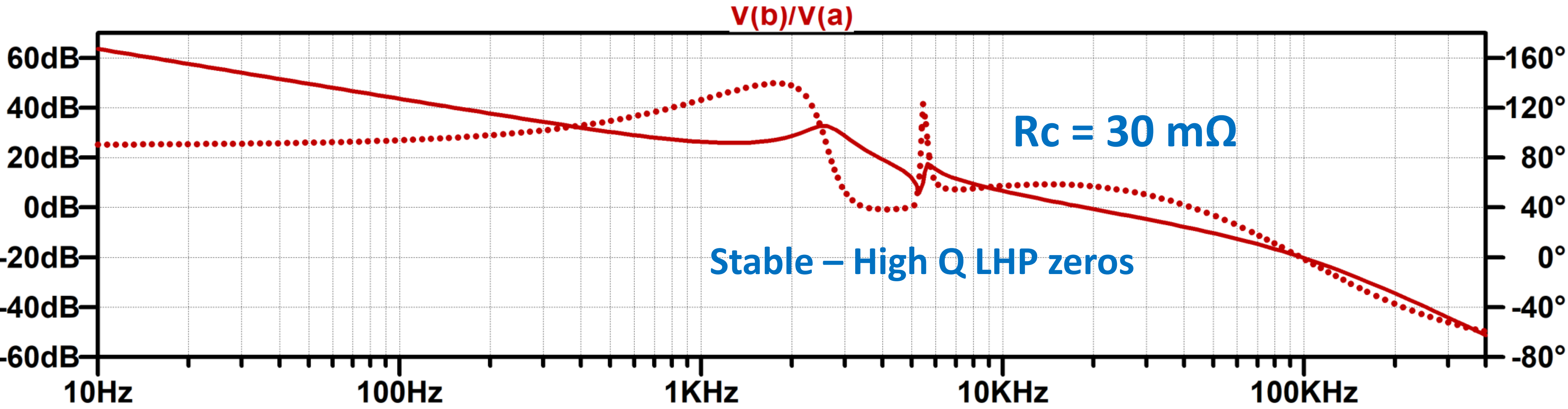


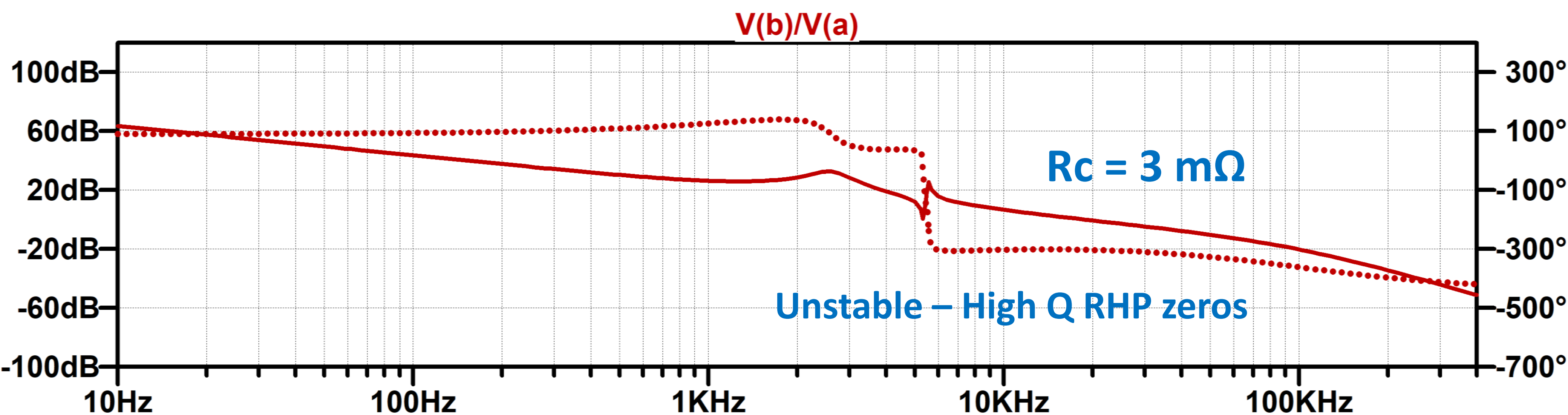
Filter Interaction Loop Gain



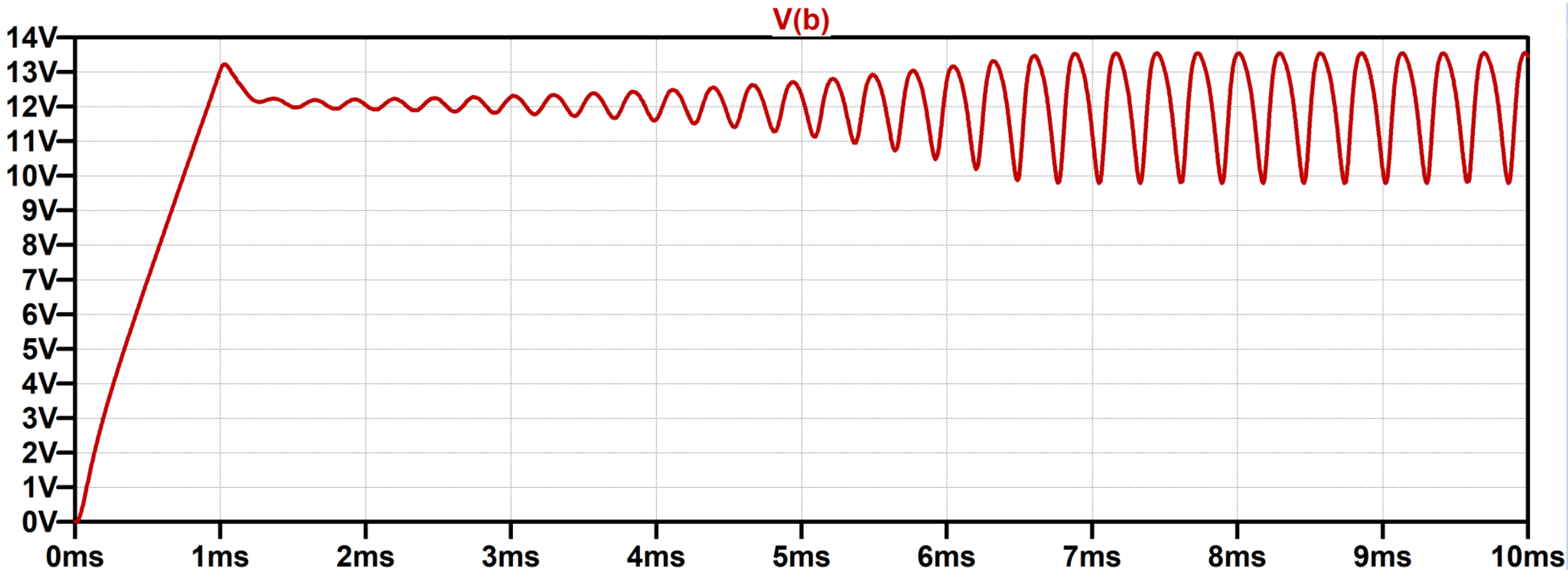


Filter Interaction Voltage-Mode Loop Gain





Unstable System Simulation



02 TRANSIENT VM Filter

Part III

Input Filter FeedForward (Feedback?)

Input Voltage Feedforward

INPUT FILTER COMPENSATION FOR SWITCHING REGULATORS

by

Shriram S Kelkar

Dissertation submitted to the Faculty of the

Virginia Polytechnic Institute and State University

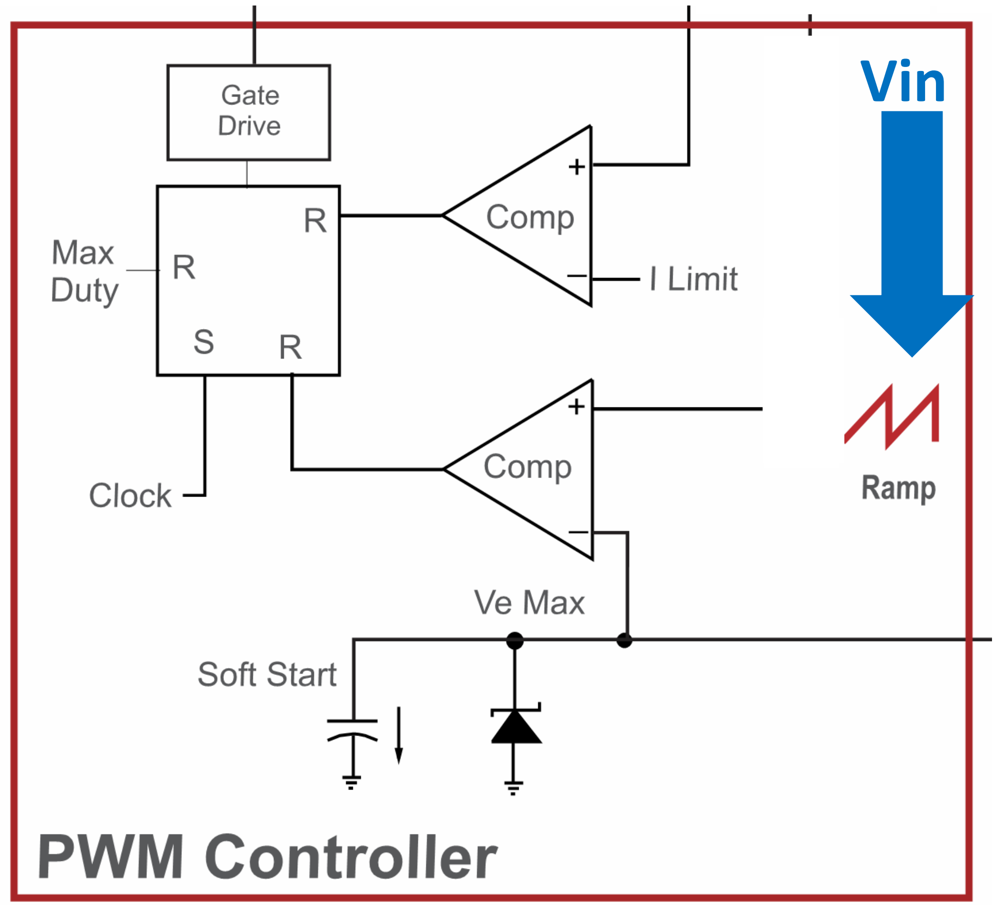
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Electrical Engineering

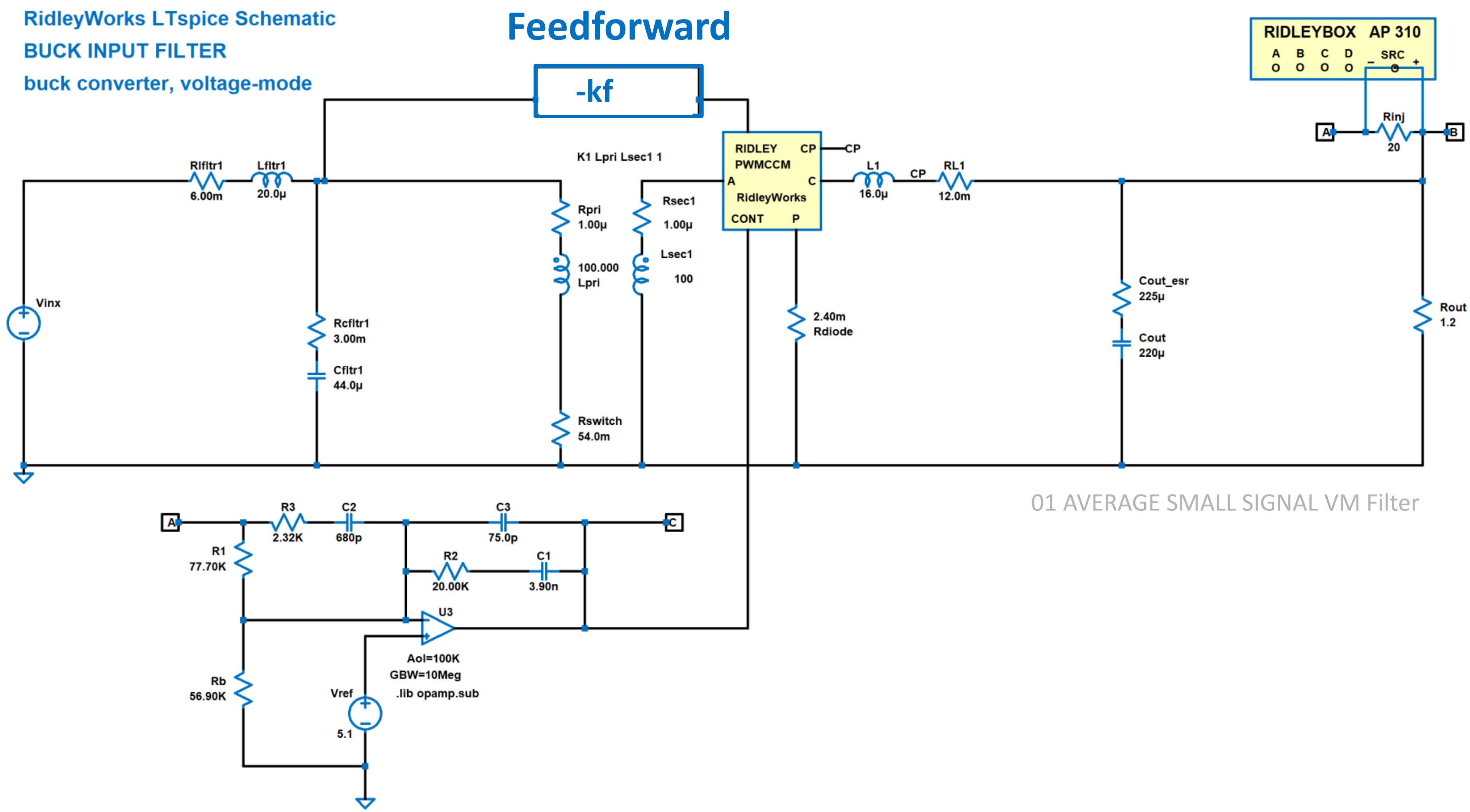
Input Voltage Feedforward



Ramp slope is determined by the input voltage

Input voltage goes up – duty cycle immediately goes down. (Feedforward)

Input Voltage Feedforward



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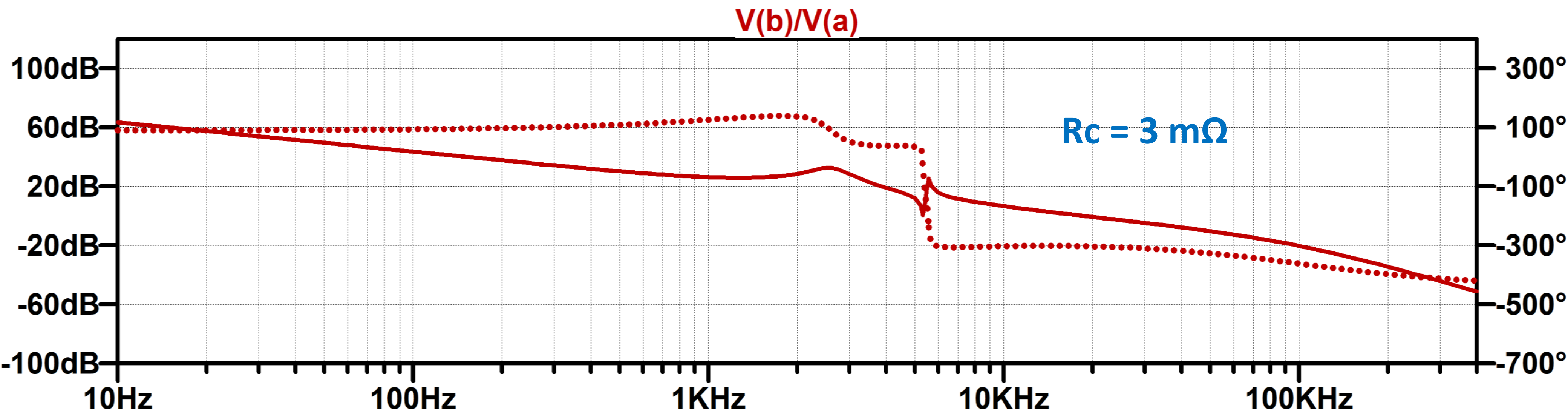
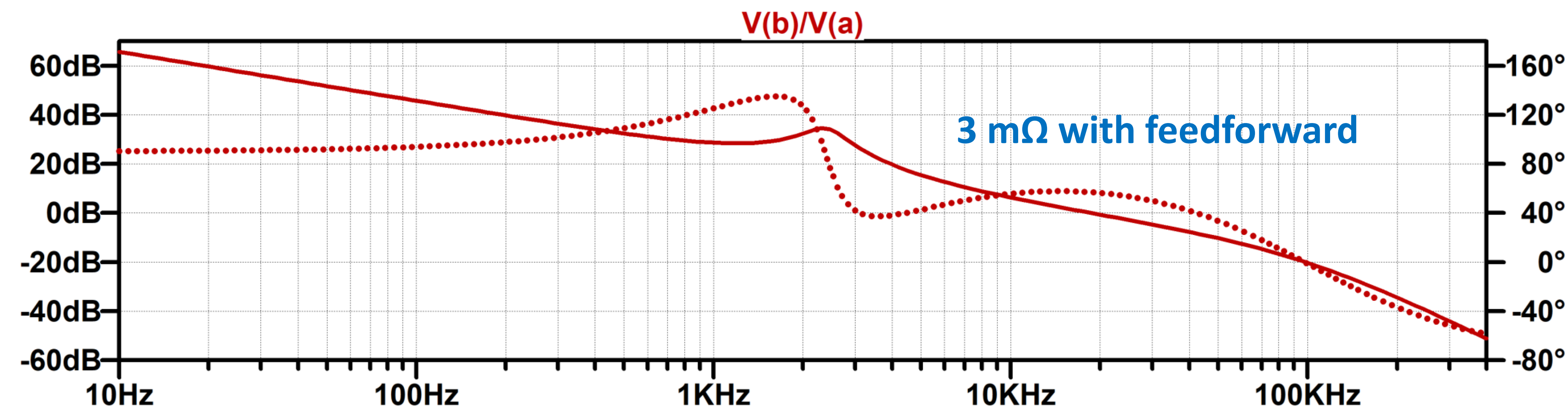
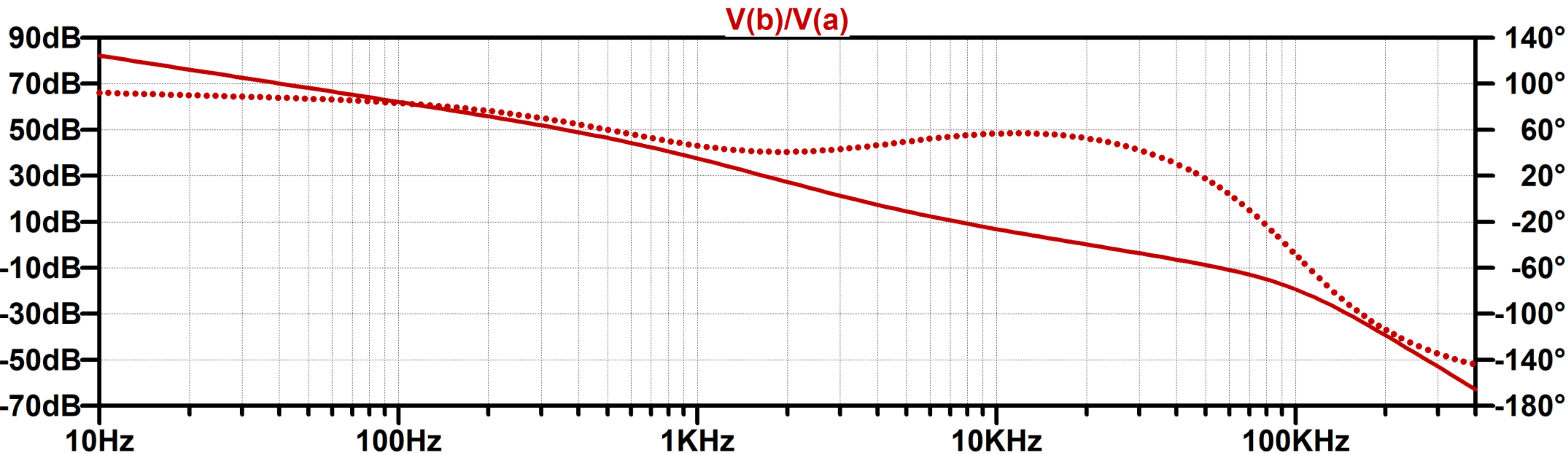
As the input voltage **increases**, the duty cycle **decreases**.

Effect of Input Voltage Feedforward





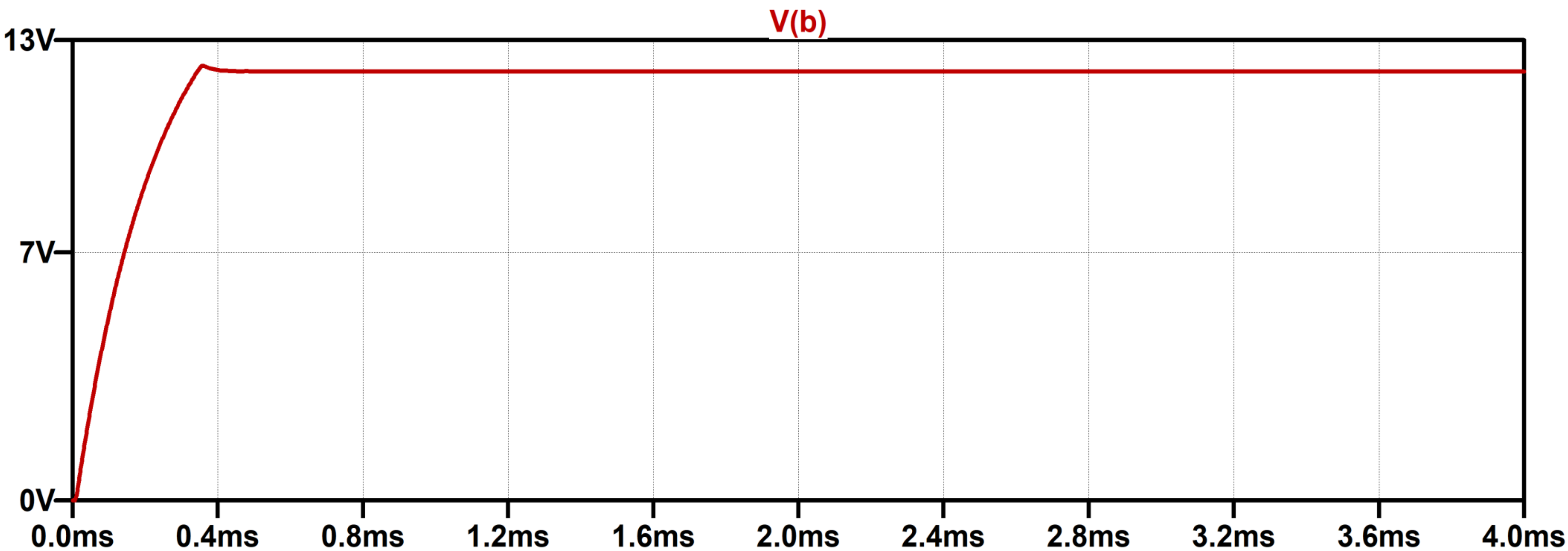
Current-Mode Loop Gain with Undamped Filter



03 AVERAGE SMALL SIGNAL CM Filter

Like FF voltage-mode, the loop is unaffected by the filter!

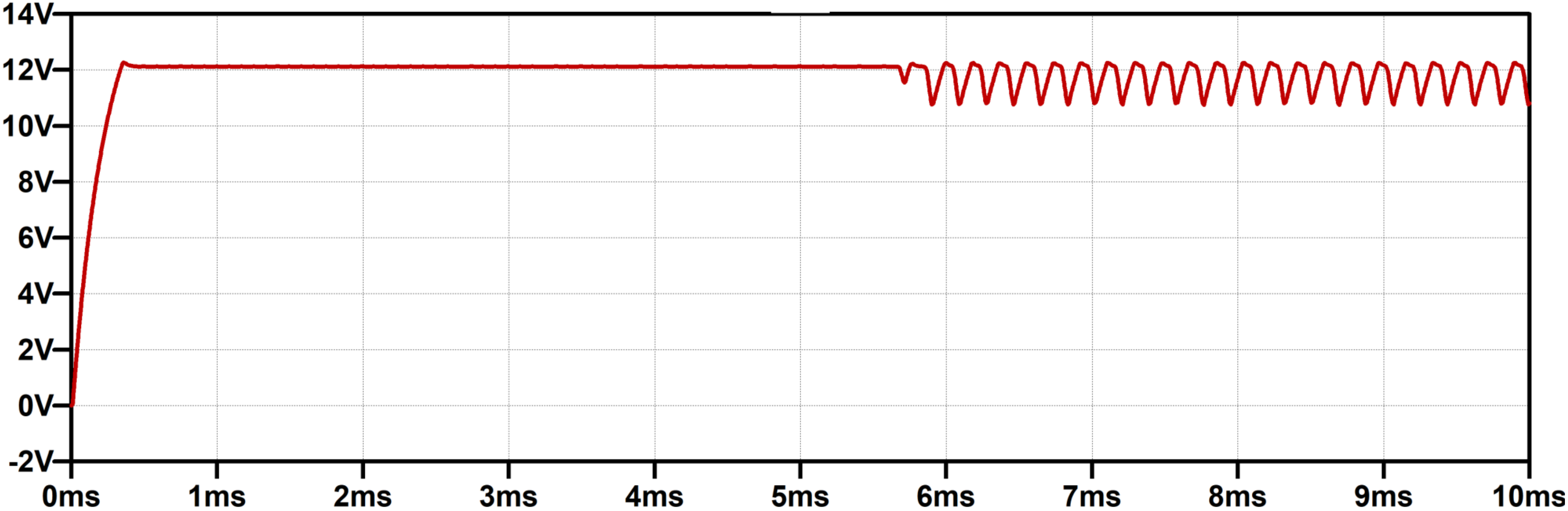
Transient Simulation with Undamped Filter



04 TRANSIENT CM Filter

Output voltage looks stable!

Transient Simulation with Undamped Filter

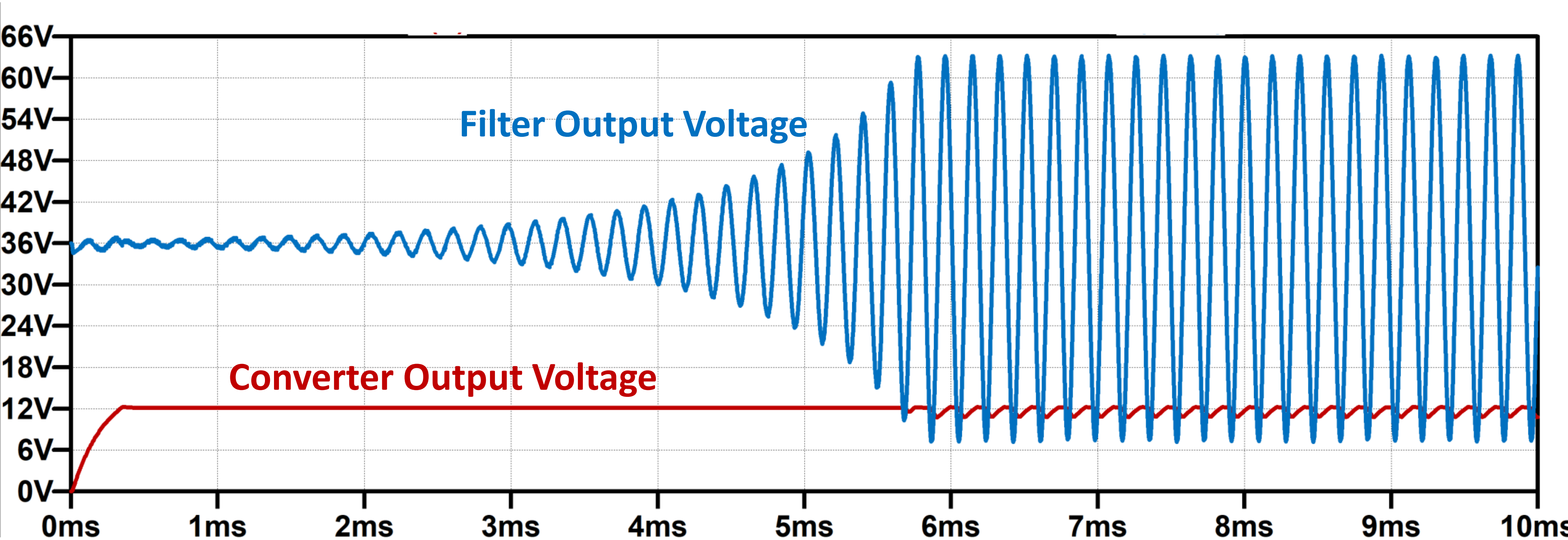


04 TRANSIENT CM Filter

Beyond 5.5 ms, the converter is clearly unstable.

Phase margin in loop is 60 degrees. But the system oscillates!

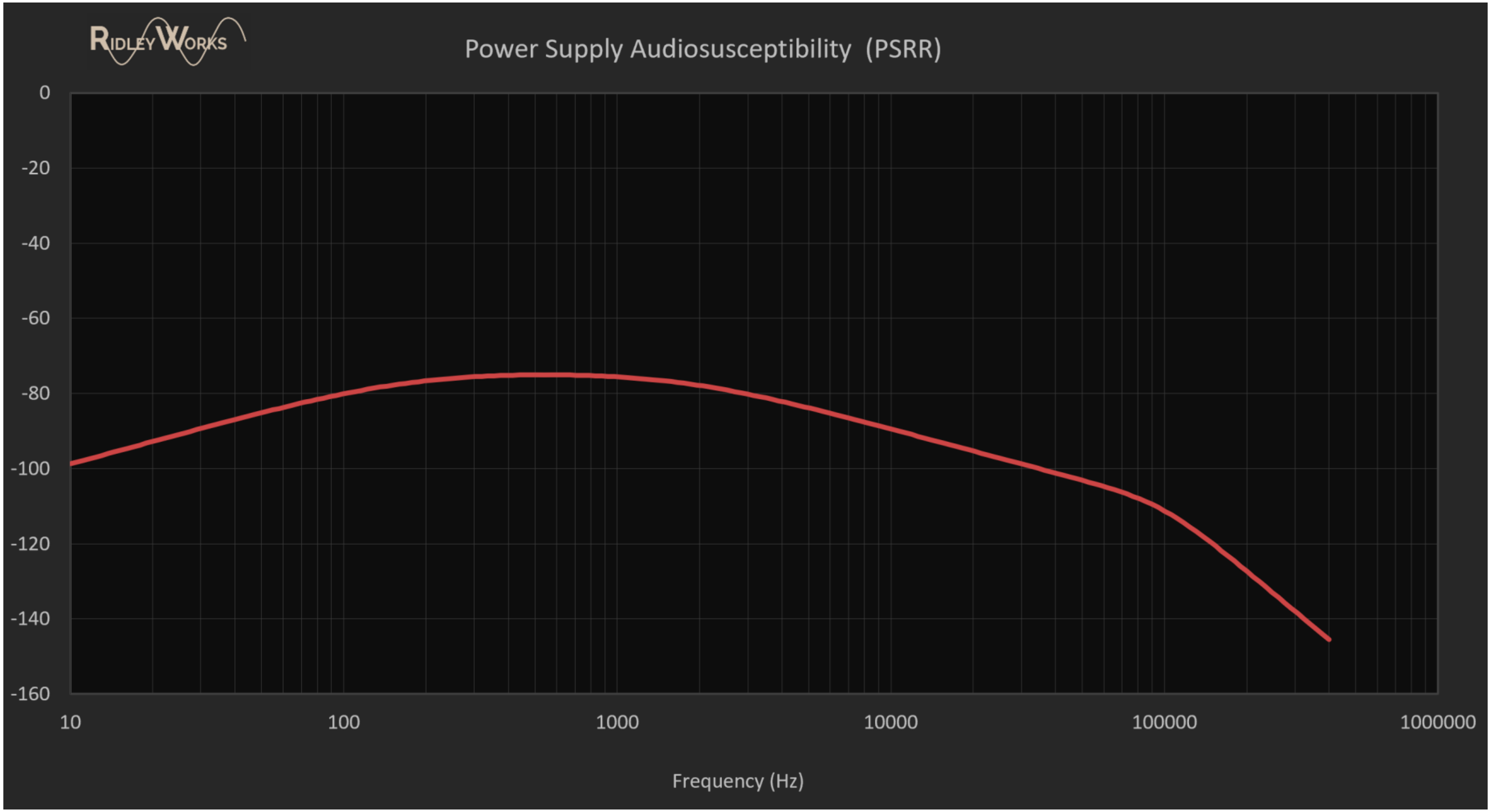
Transient Simulation with Undamped Filter



04 TRANSIENT CM Filter

The system is always oscillating – you just can't see it at first

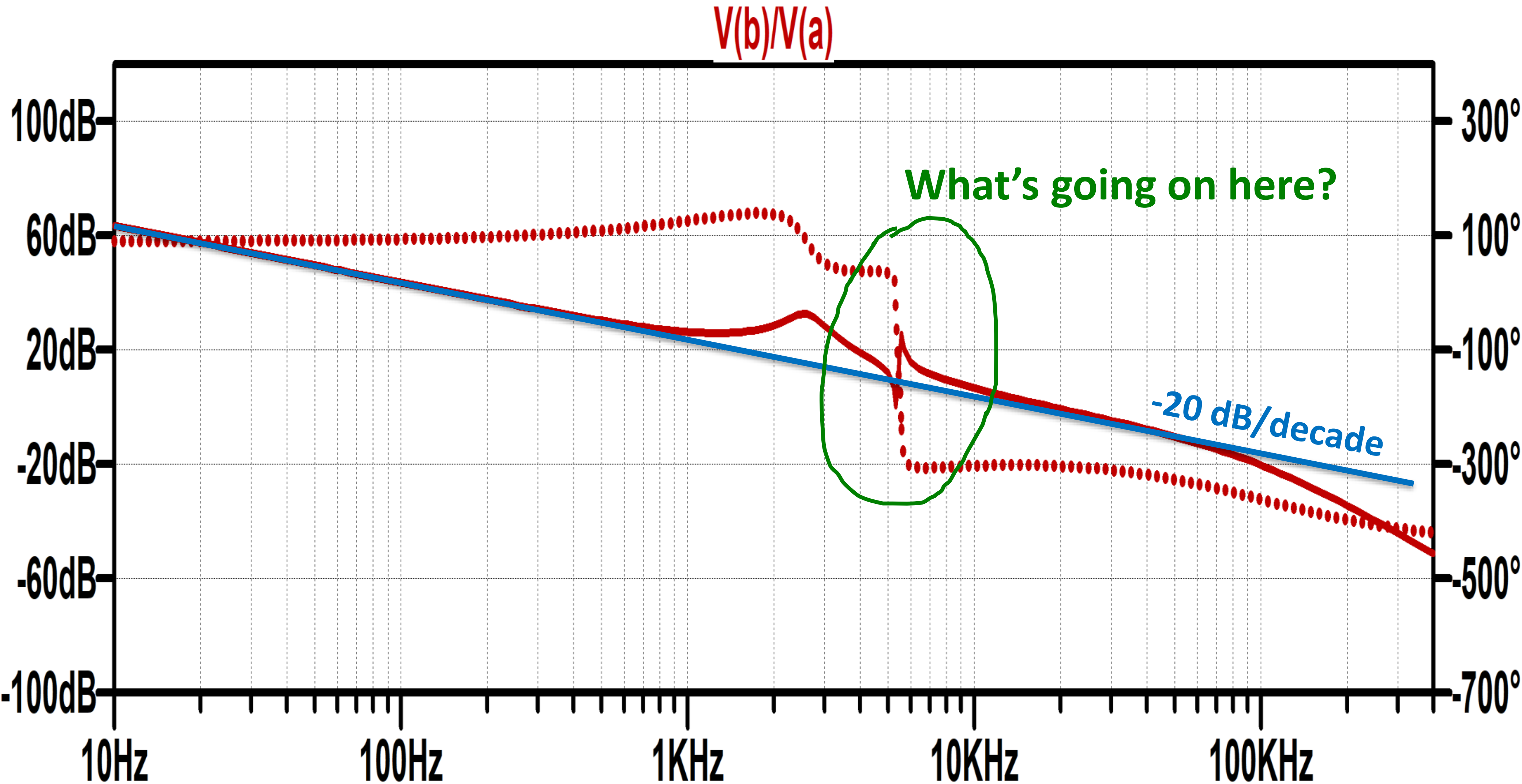
Unstable and Unobservable System



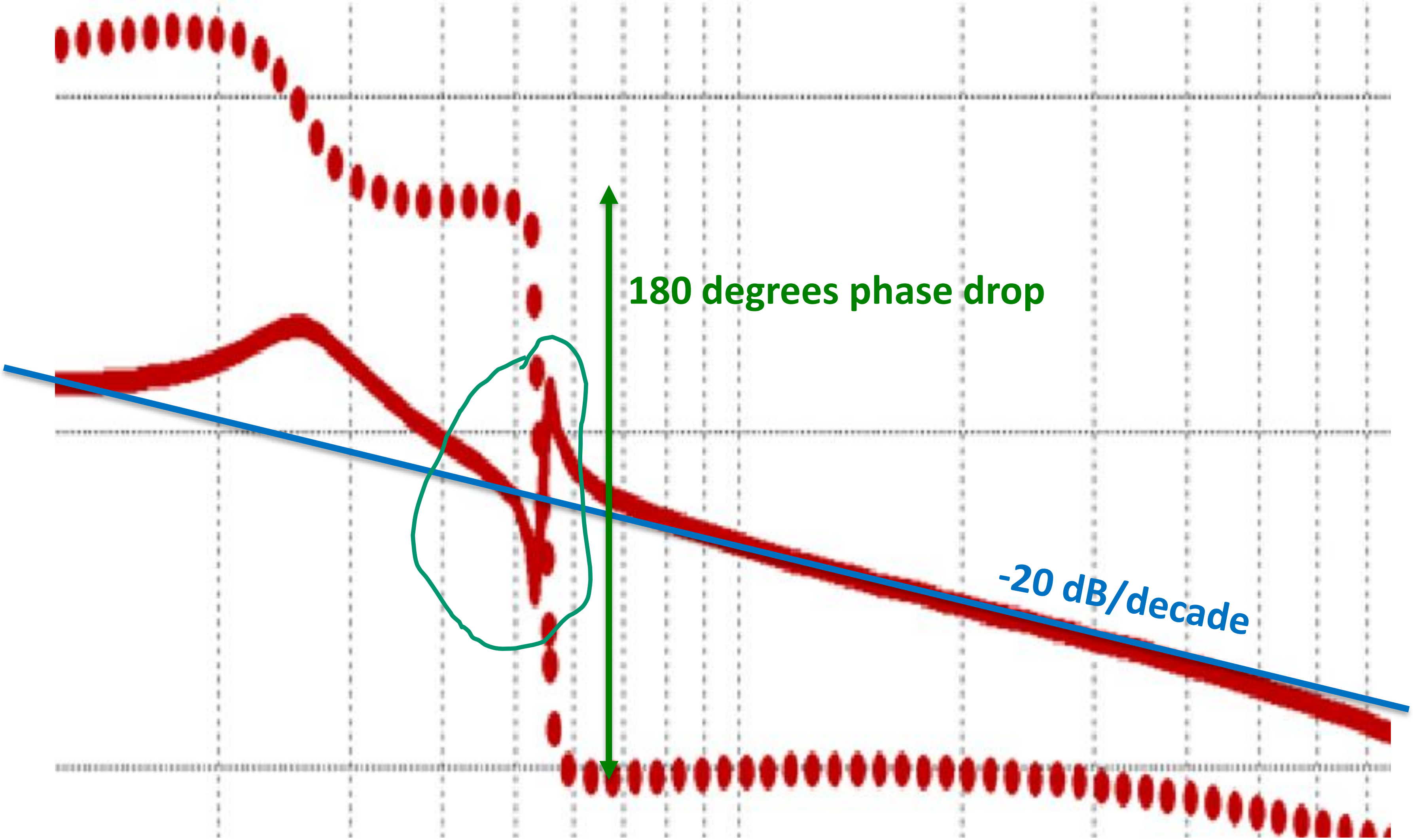
Very high rejection of input voltage due to feedforward

Oscillations on the filter cannot be seen on the output

Unstable Loop Gain Before Feedforward



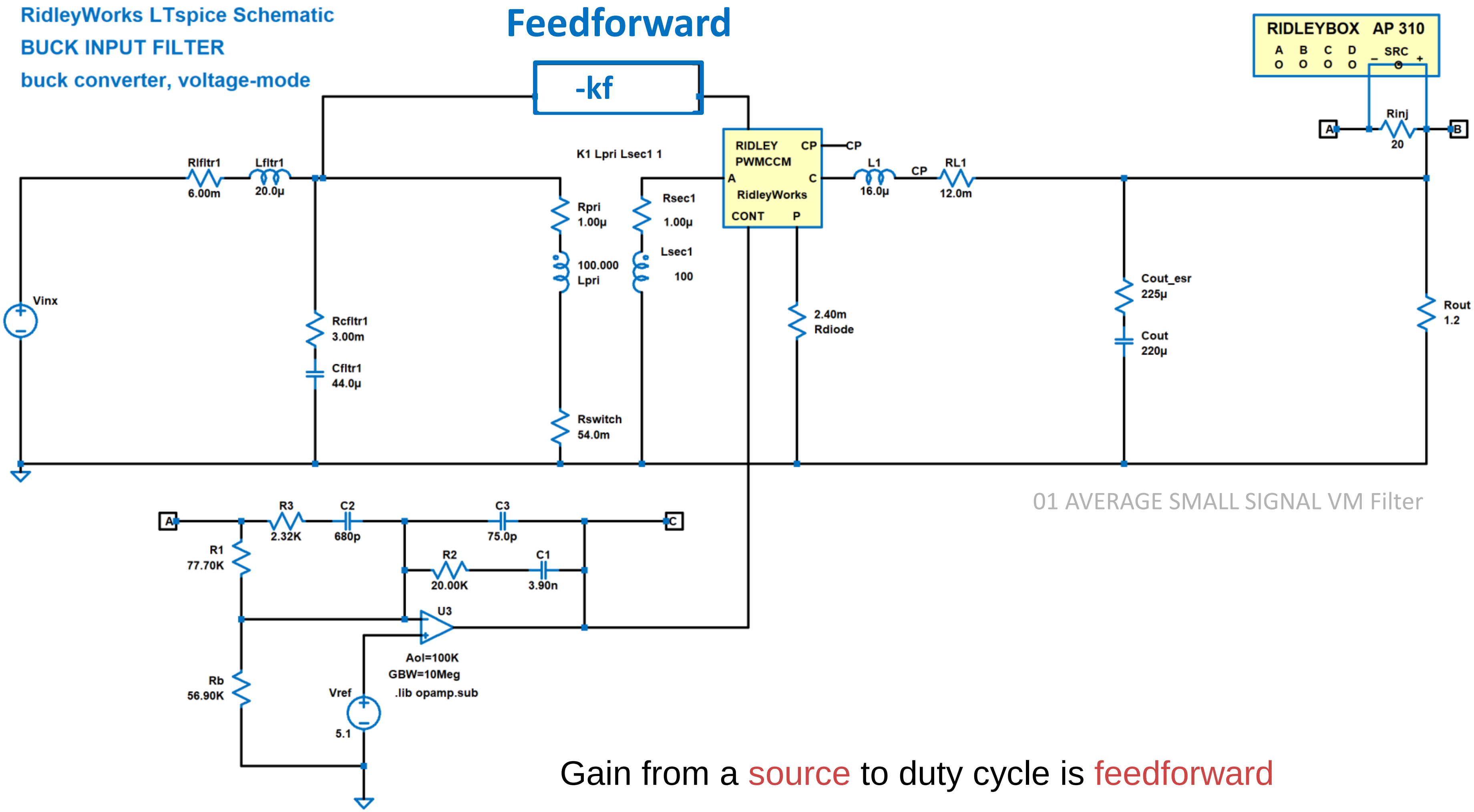
Unstable Loop Gain Before Feedforward



Two RHP zeros

Feedforward eliminates the two RHP zeros completely. How?

Feedforward is Actually Feedback!



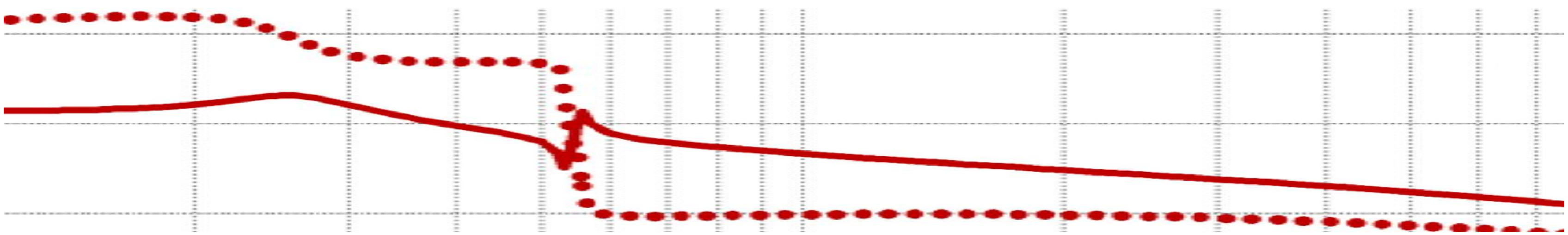
Gain from a source to duty cycle is feedforward

Gain from a state to duty cycle is feedback

Feedforward is Actually Feedback!

Feedforward will move the zeros of a transfer function

Feedback will move the poles of a transfer function



"I've seen this idea presented for the last three years at this conference. Something about it really bothers me, but I can't quite put my finger on it."   Middlebrook c.1984

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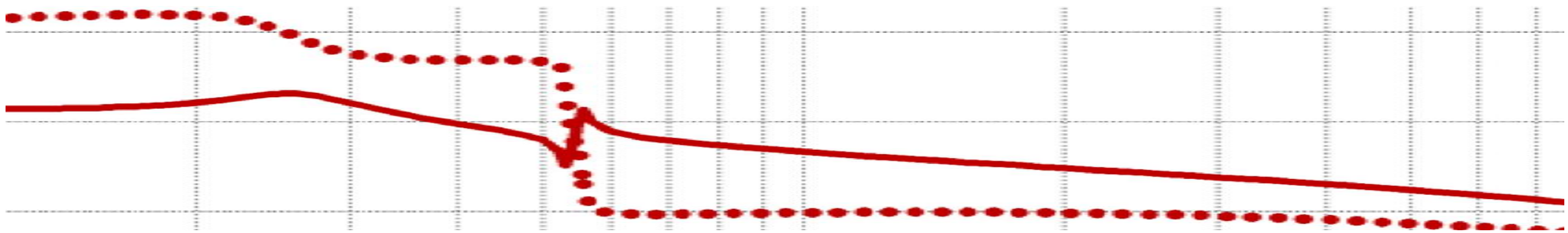
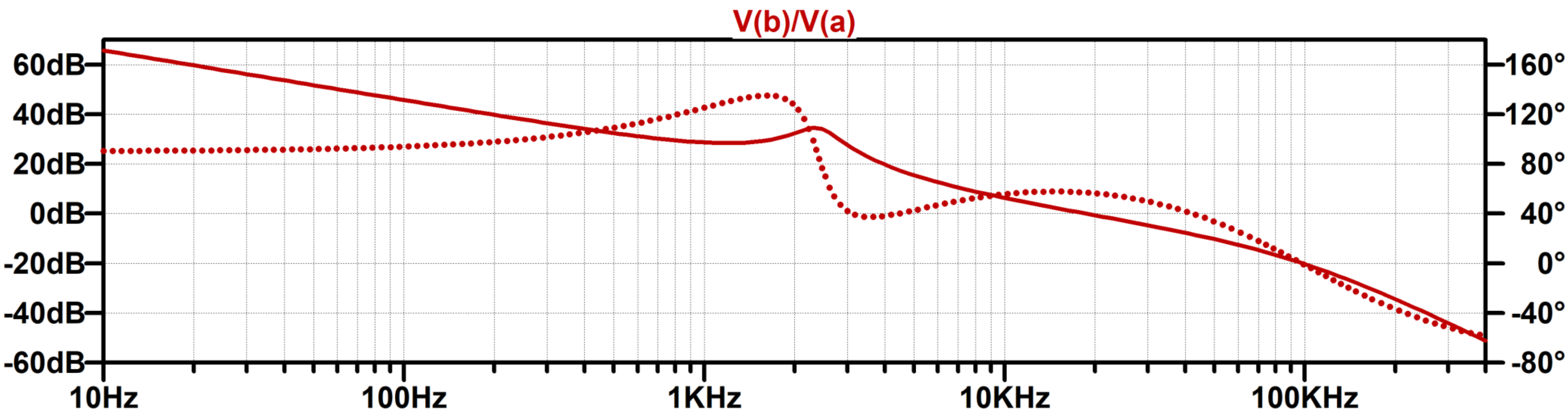
RHP Poles in the Transfer Function

Feedback will move the poles of a transfer function

Feedback can cancel two RHP zeros with two RHP poles right on top of them!





01 AVERAGE SMALL SIGNAL VM Filter

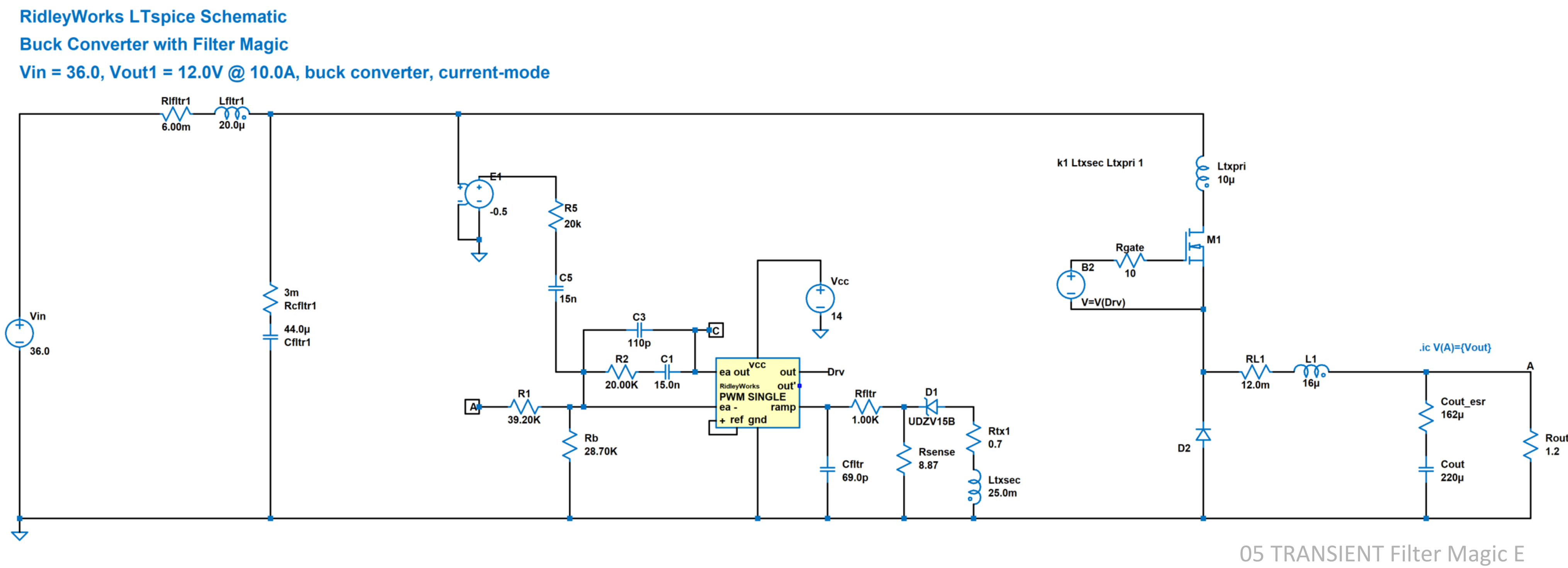
RHP poles in the transfer function!

Nyquist must encircle the -1 point as many times as there are RHP poles

Part IV

Design the Feedback System Properly

Input Voltage Feedback



Notice the polarity – Input voltage goes **UP** and error signal goes **UP**

Opposite to feedforward technique from Kelkar and others.

Everybody missed this!

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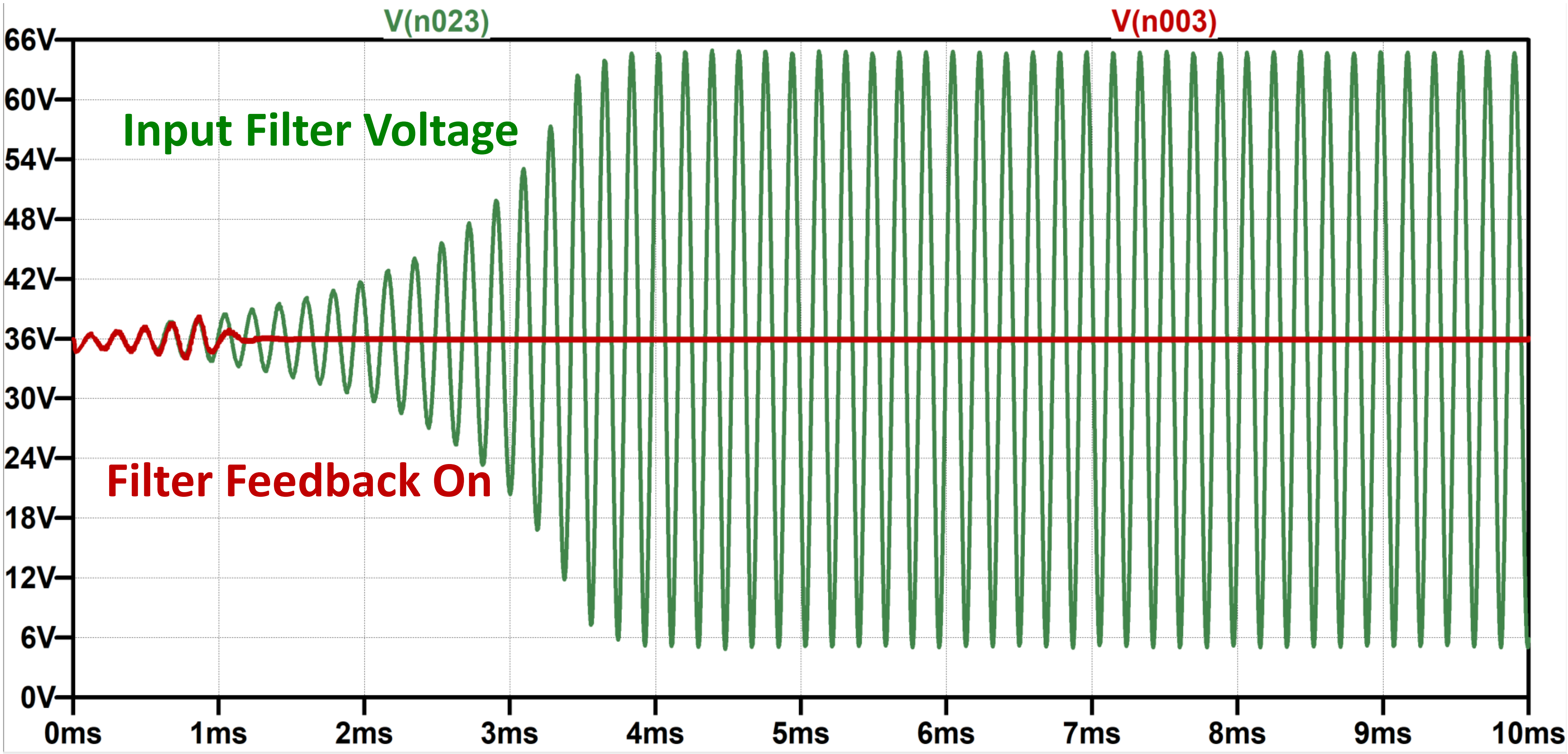
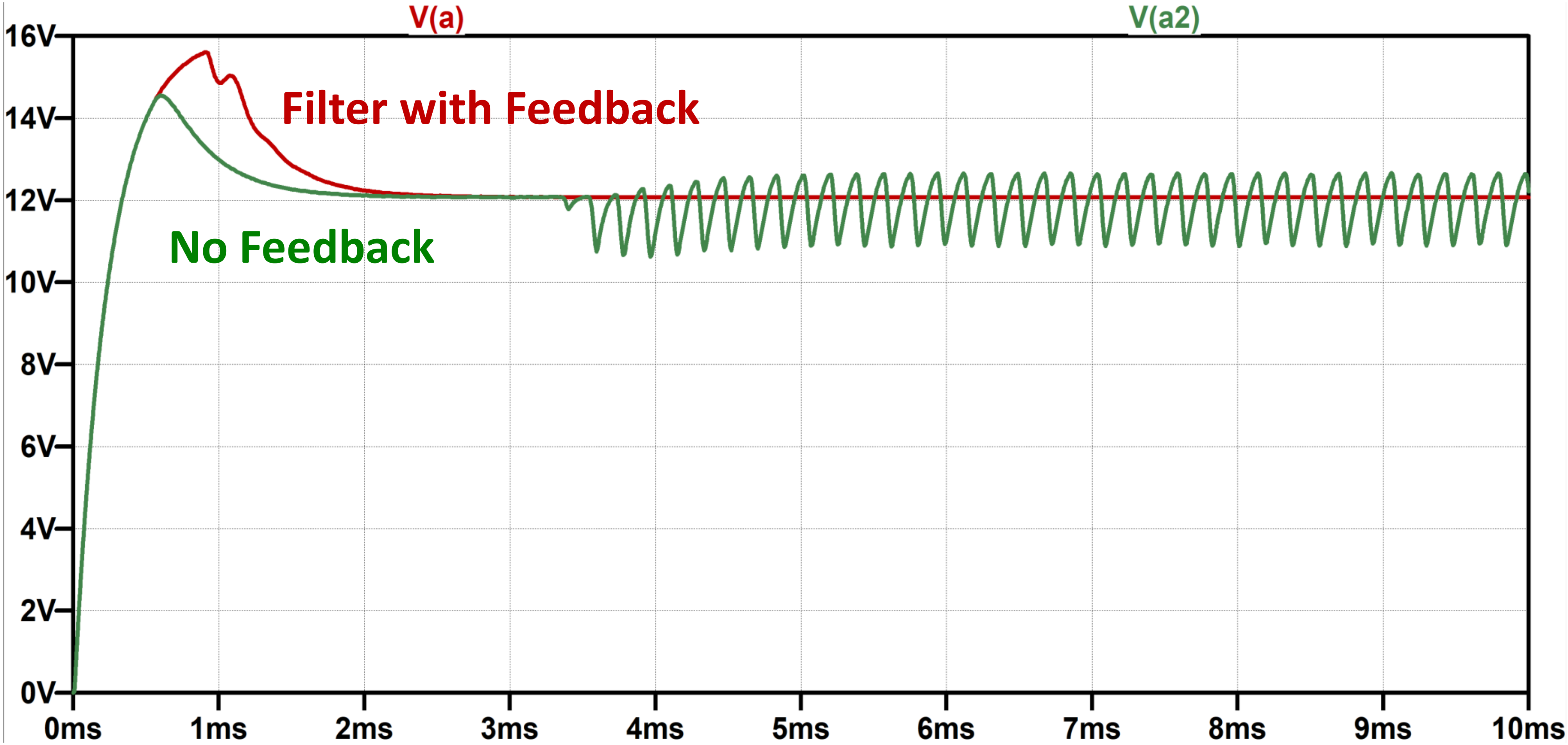
Turning the Magic ON



05 TRANSIENT Filter Magic E

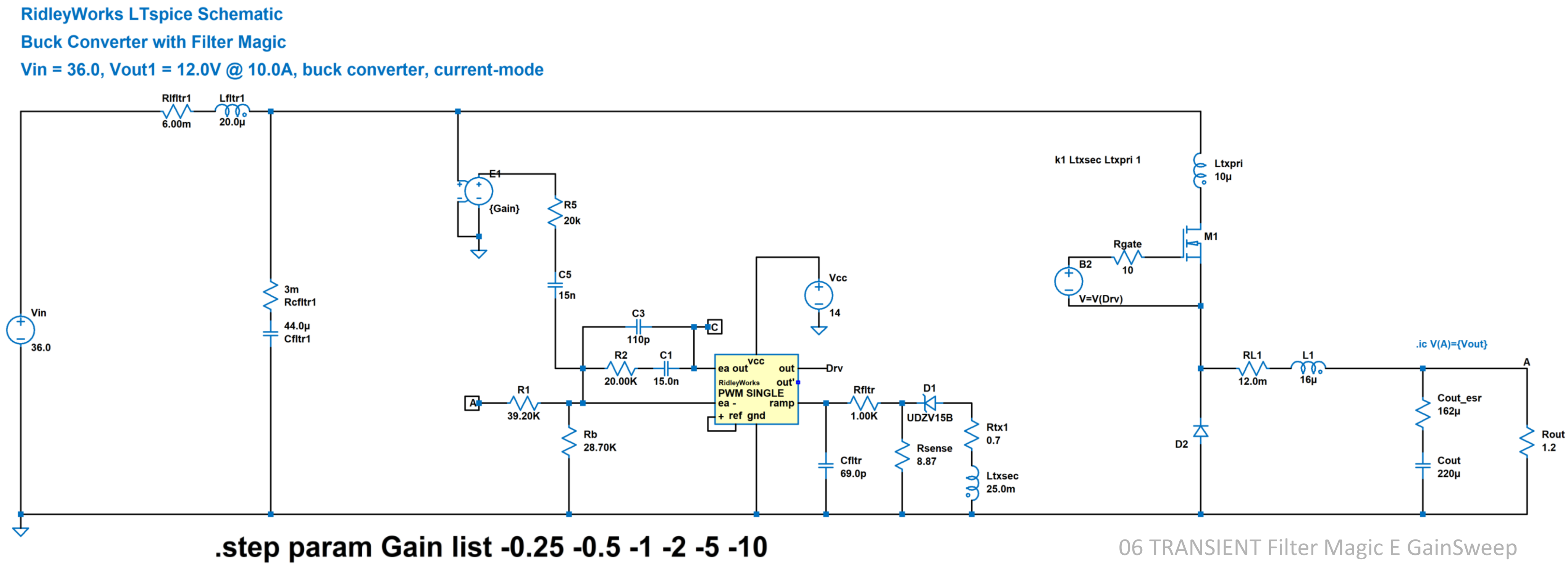
Filter feedback circuit perfectly controls the oscillation

Output Voltage Startup Simulation



05 TRANSIENT Filter Magic E

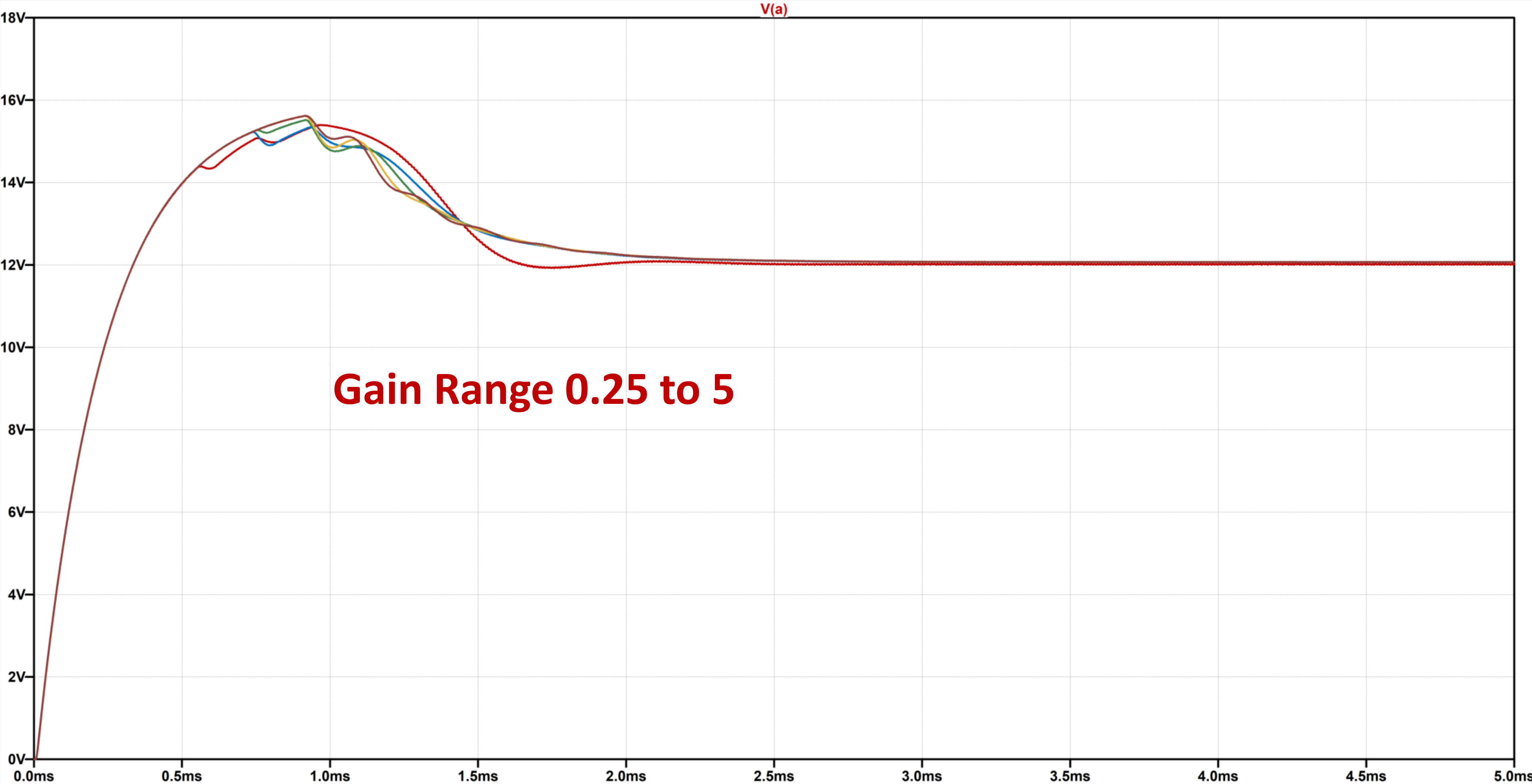
Input Voltage Feedback Gain



Optimize the gain through simulation (with knowledge of the Bode plots)

The compensation shape can also be experimented with or analyzed. (7^{th} order system)

Input Voltage Feedback Gain Optimization

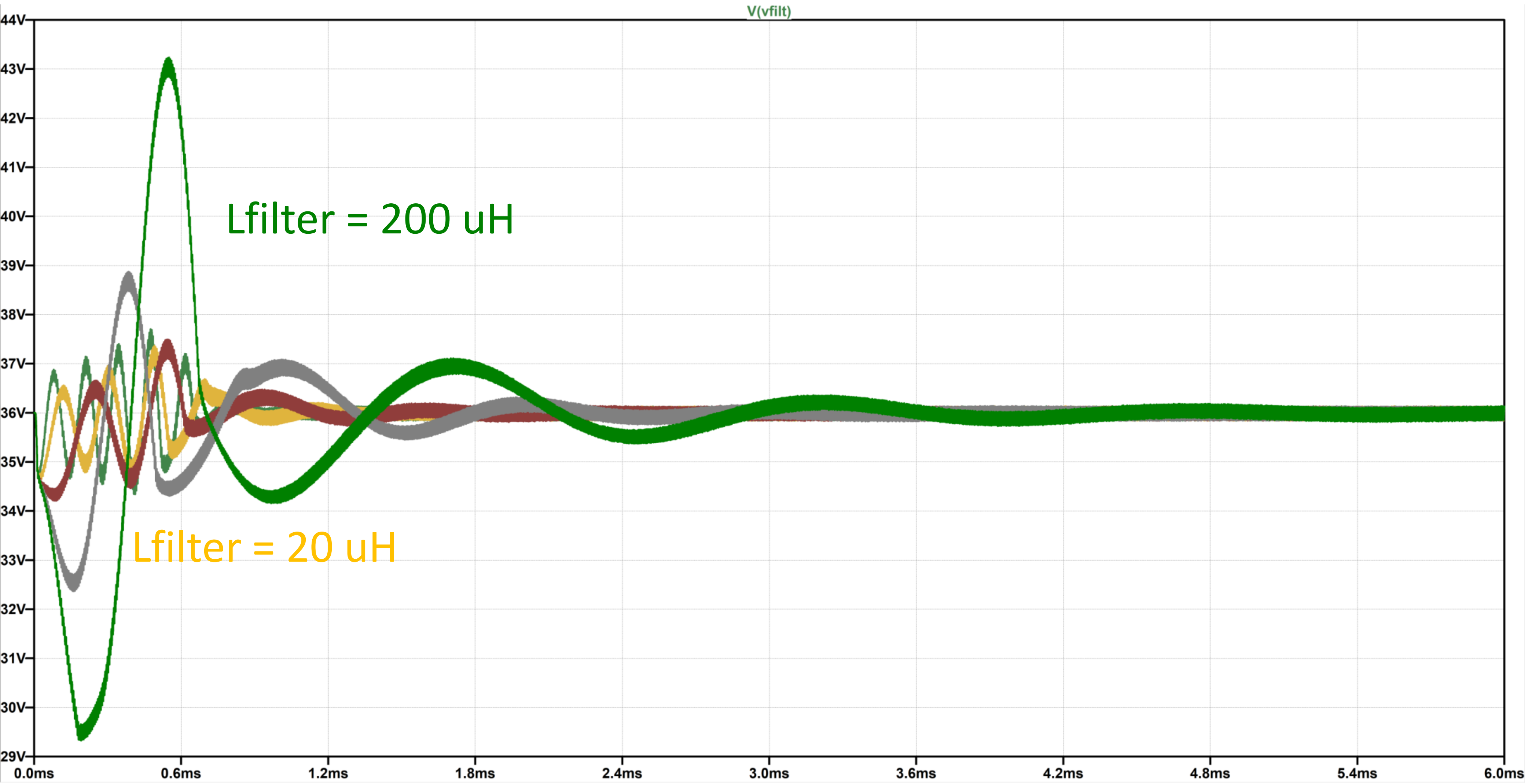


06 TRANSIENT Filter Magic E GainSweep

It's a complex response

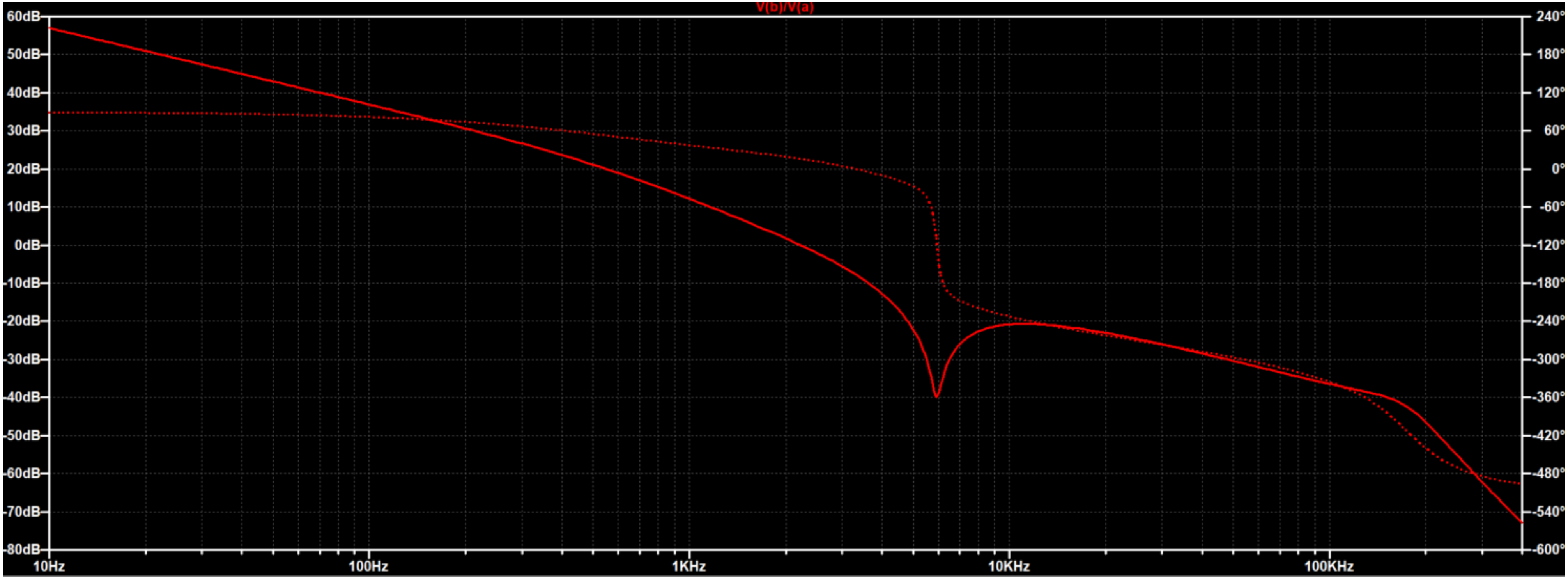
Gain of about 2 "feels" right

Adaptation to Input Filter Inductor



07 TRANSIENT Filter Magic E LfiltSweep

Filter Magic Loop Gain



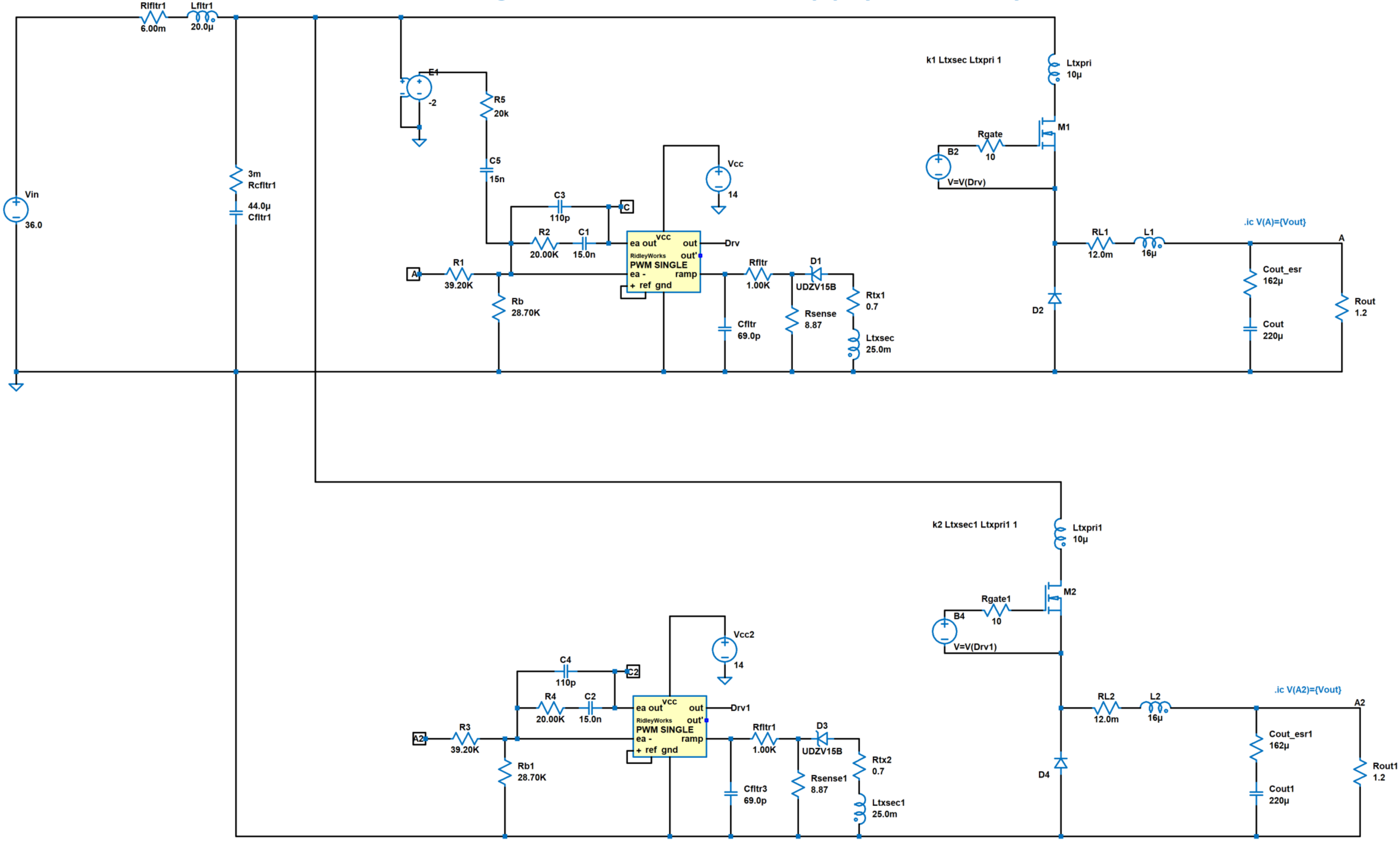
08 AVERAGE SMALL SIGNAL magic loop

This is a strange characteristic.

The dip should be beyond the loop crossover.

Much work to be done – what are the other transfer functions like?

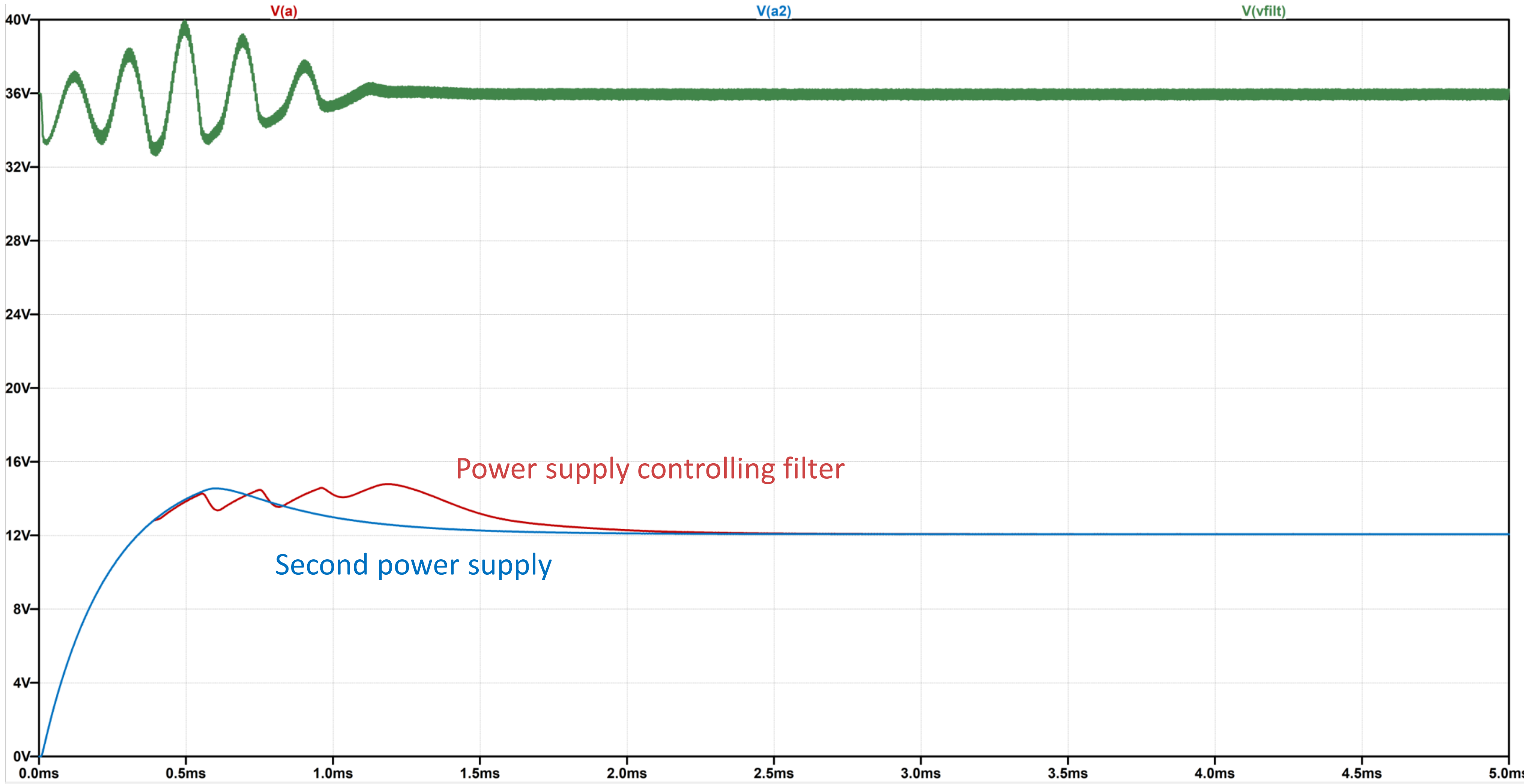
Adding Another Power Supply to the System



09 TRANSIENT Filter Magic Two Supplies

11^{th}-order system – easy analysis!

Adding Another Power Supply to the System Works Perfectly!

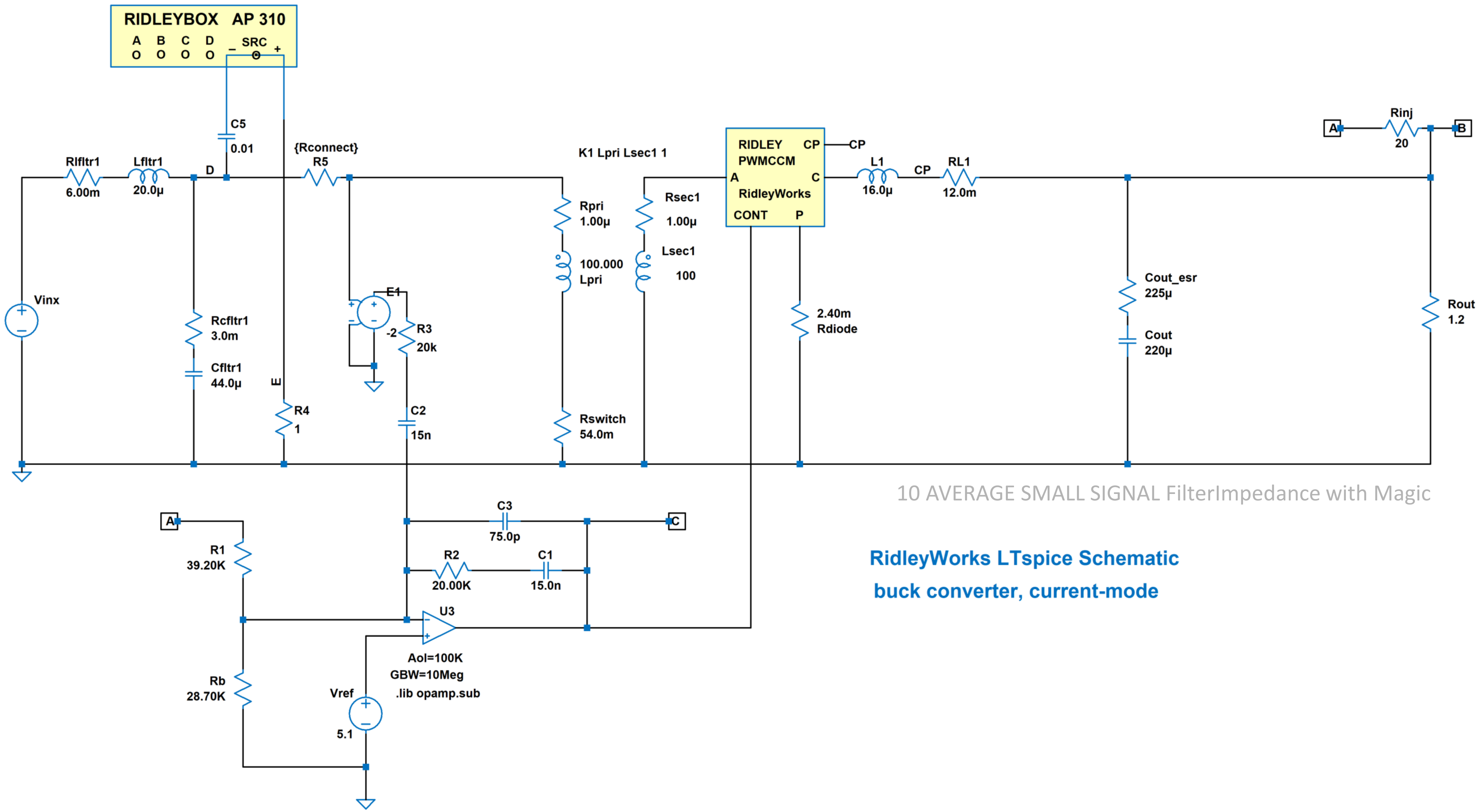


09 TRANSIENT Filter Magic Two Supplies

Perfect example of Middlebrook's work in action

Look at the impedances to know if this is a rugged system – don't reanalyze!

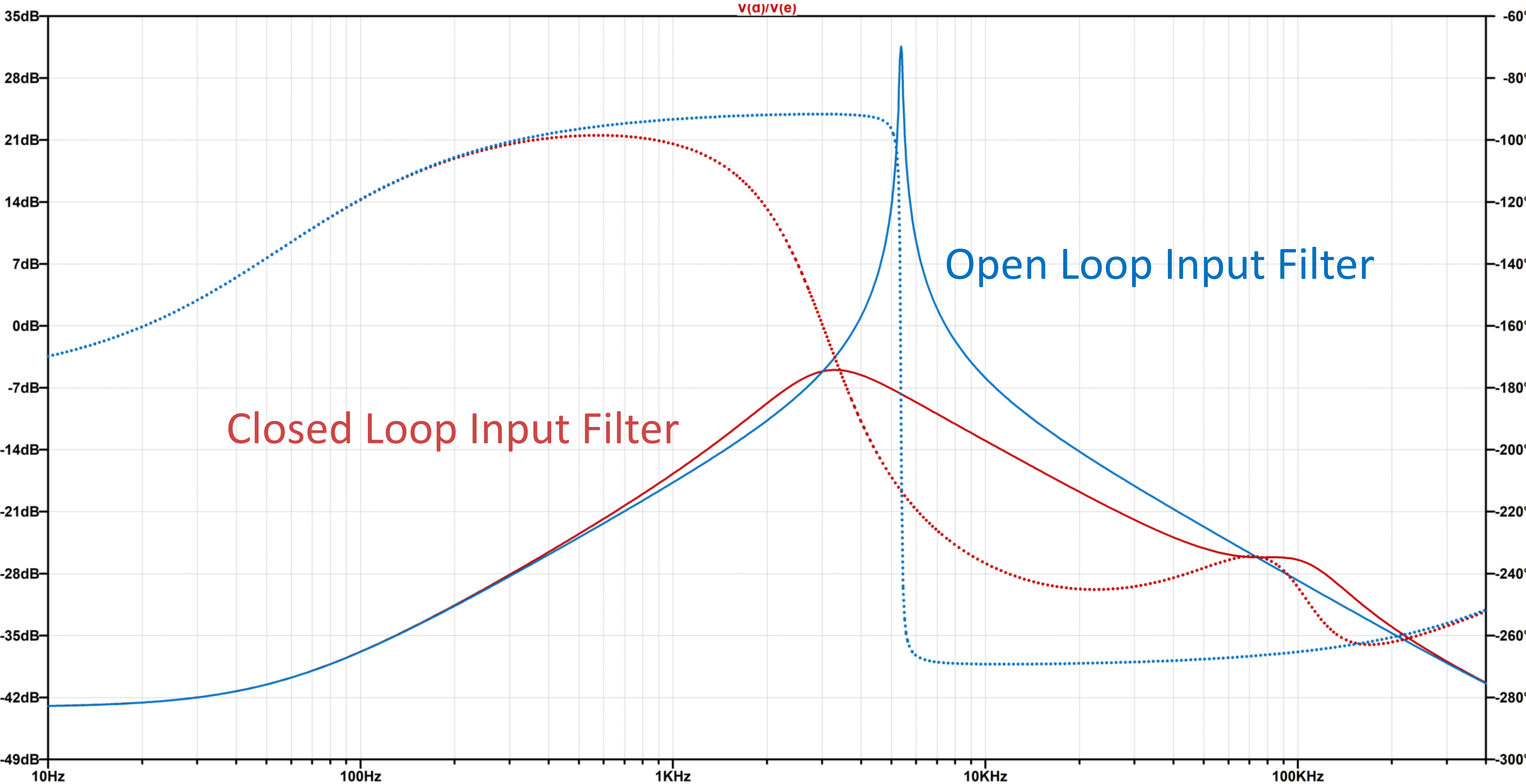
Filter Impedance After Control



RidleyWorks LTspice Schematic

buck converter, current-mode

Filter Impedance After Control



10 AVERAGE SMALL SIGNAL FilterImpedance with Magic

Lots of Work Remains

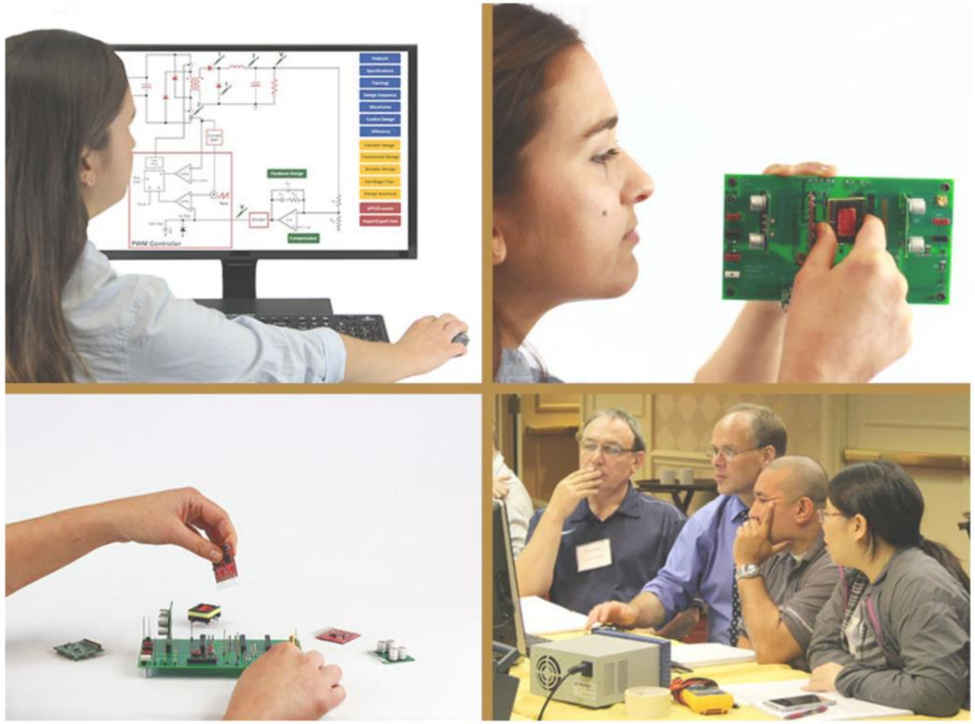
Students or bored engineers – please pick up the work from here. Call us.

There is enough material in this presentation for an MS/PhD dissertation. Just add equations!

Students – we are happy to work with you on this. (And Professors)

Ridley Engineering Products

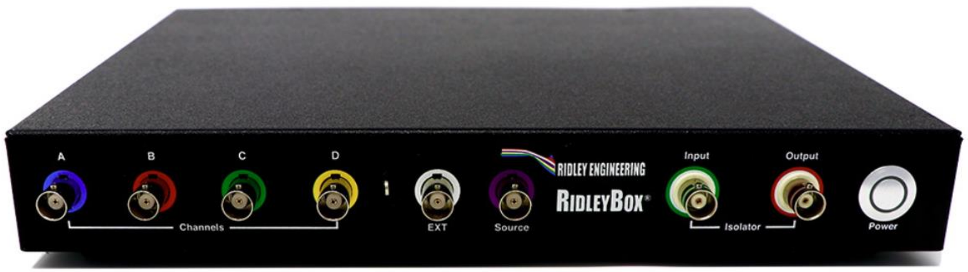
Come to our Hands-On Training Workshops

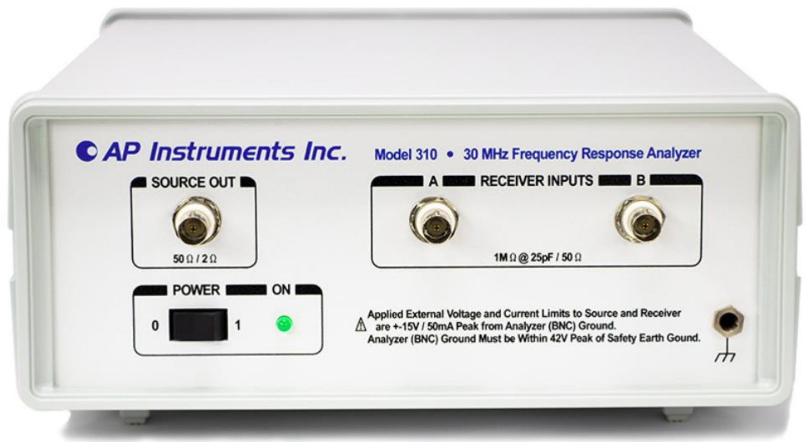


5-Day Workshop: JUN 12-16, 2023 in Camarillo, CA

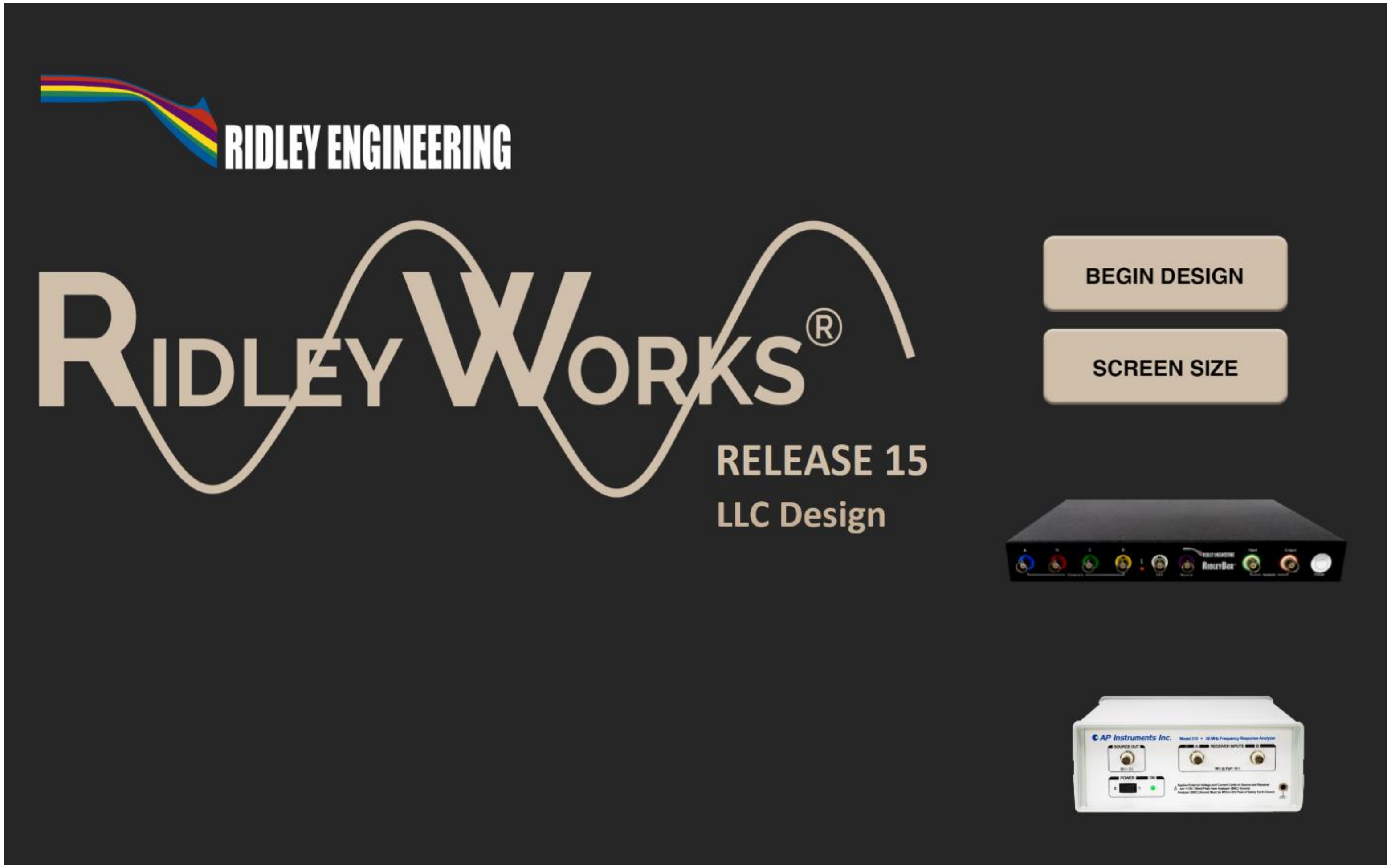
* One space is left for March

The Industry's Best Frequency Response Analyzers





The Industry's Best Power Supply Design Software

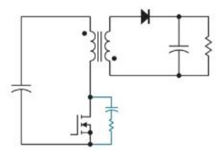


Learn From Our Power Supply Design Center

Articles and Webinar Series

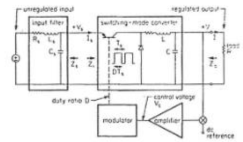
[A24] FLYBACK CONVERTER SNUBBER DESIGN

In this article, we will talk about practical design techniques for the most commonly used snubber and clamp circuits for the flyback converter.



MIDDLEBROOK1976

Middlebrook's original 1976 paper on input filter interactions. Make sure you design your filter properly to avoid interactions with your switching power supply.



S.S. KELKAR DISSERTATION

S.S. Kelkar's original 1982 dissertation on feedforward control. This is the first known attempt at controlling the input filter with the converter cell.


INPUT FILTER COMPENSATION FOR SWITCHING REGULATORS

by

Shriram S Kelkar

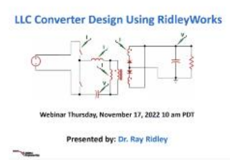
Dissertation submitted to the Faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY in Electrical Engineering

RIDLEYBOX PERFORMANCE MEASUREMENTS

Compare the RidleyBox Performance for frequency response measurements

LLC CONVERTER DESIGN USING RIDLEYWORKS

The design of the LLC converter is simple and straightforward when using RidleyWorks. No equations are needed, and the design process becomes a pleasure for the engineer rather than a chore.

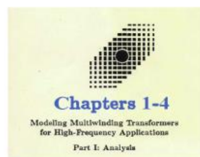


DUAL ACTIVE BRIDGE DESIGN USING SCALING LAWS

This unique presentation is by our guest speaker Nicola Rosano. The complex process of dual active bridge converter design is greatly simplified with the application of standardized curves combined with power and frequency scaling concepts.

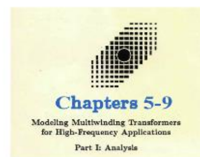
MAGNETICS AND DOWELL'S EQUATIONS CHAPTERS 1-4

This early report shows impressively detailed and complex application of Dowell's equations. Chapters 1-4 of the work.



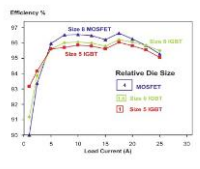
MAGNETICS AND DOWELL'S EQUATIONS CHAPTERS 5-9

Only 1% of engineers will ever attempt to use this work - will you be one of them? For the other 99%, RidleyWorks does all the hard work for you.



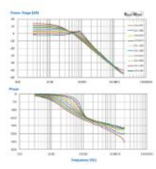
[A07] IGBTS CHALLENGE MOSFETS

Small die size makes IGBTs competitive in high frequency conversion.



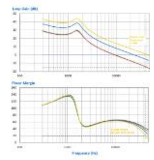
[115] SWEPT TRANSIENT FREQUENCY RESPONSE FOR THE LLC CONVERTER

Part III: Swept loops in LTspice® can be used for the LLC converter where no small-signal model exists.



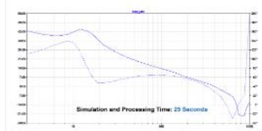
[114] TRANSIENT LOOP SWEEPS OUTPERFORM SMALL-SIGNAL MODELS

Part II: Swept loops in LTspice® provide more accurate and useful results than small-signal models.



[113] HIGH-PERFORMANCE LOOP SWEEPS IN LTSPICE

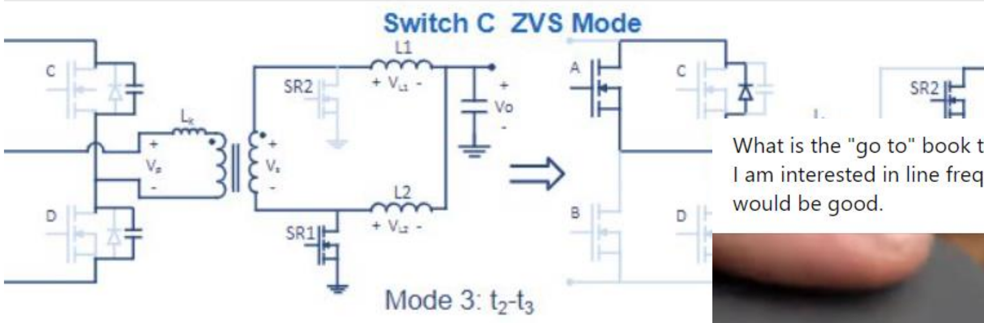
Part I: Learn how to emulate the RidleyBox and AP310 Analyzers in LTspice®.



Ridley Engineering

Power Supply Design Center Group on Facebook
6300 Members

I was going thru a design app note from Infineon for a PSFB converter. I was confused by the turn-off loss calculation.
At beginning of mode 3, switch D was conducting. Then it is turned off and the inductor current will discharge Switch C cap and charge Switch D cap. I thought that if Switch D is turned off fast, the charging capacitive current will not dissipate any heat loss on Switch D. It will just be part of the total system lossed.... **See more**



Since it's a ZVS converter, turn-on loss and output capacitance Cos

Turn-off time and loss are:

$$t_{off} = Q_{gd} \cdot \frac{R_g}{V_{pl}} + Q_{gs} \cdot \frac{V_{pl} - V_{th}}{V_{pl}} \cdot \frac{2 \cdot R_g}{V_{pl} + V_{th}}$$

$$= 22 \cdot 10^{-9} \cdot \frac{3}{6.4} + 7 \cdot 10^{-9} \cdot \frac{6.4 - 4}{6.4} \cdot \frac{2 \cdot 3}{6.4 + 4} = 11.83 \cdot 1$$

$$P_{S\,off} = 0.5 \cdot I_{L\,pk} \cdot \frac{N_s}{} \cdot V_{in} \cdot t_{off} \cdot f$$

What is the "go to" book that everyone has (and recommends) for transformer winding & design? I am interested in line frequency transformers but if the book also covers SMPS (kHz) types that would be good.