

How to Build a VRM Model for Tuning PSRR and Output Z

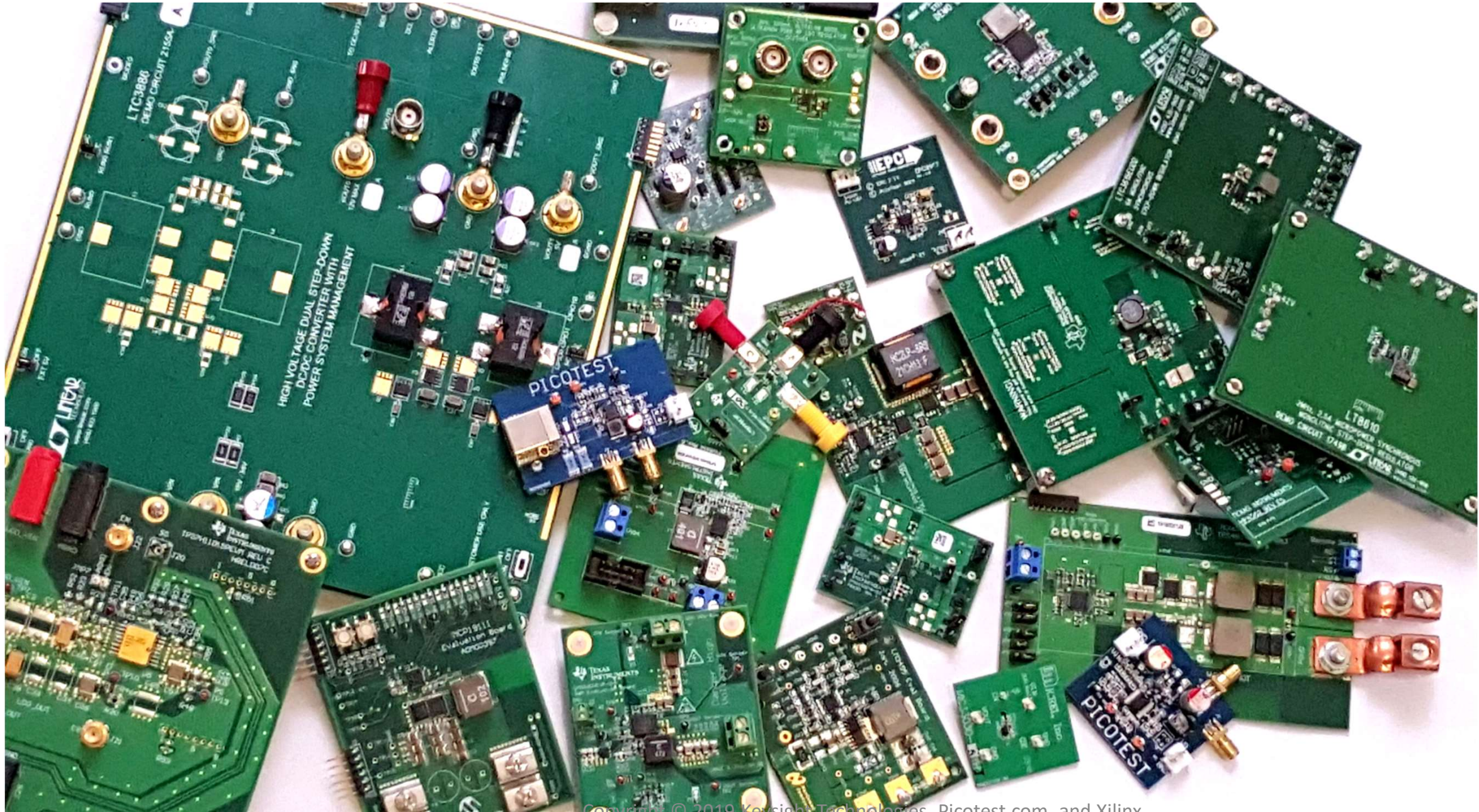
Heidi Barnes

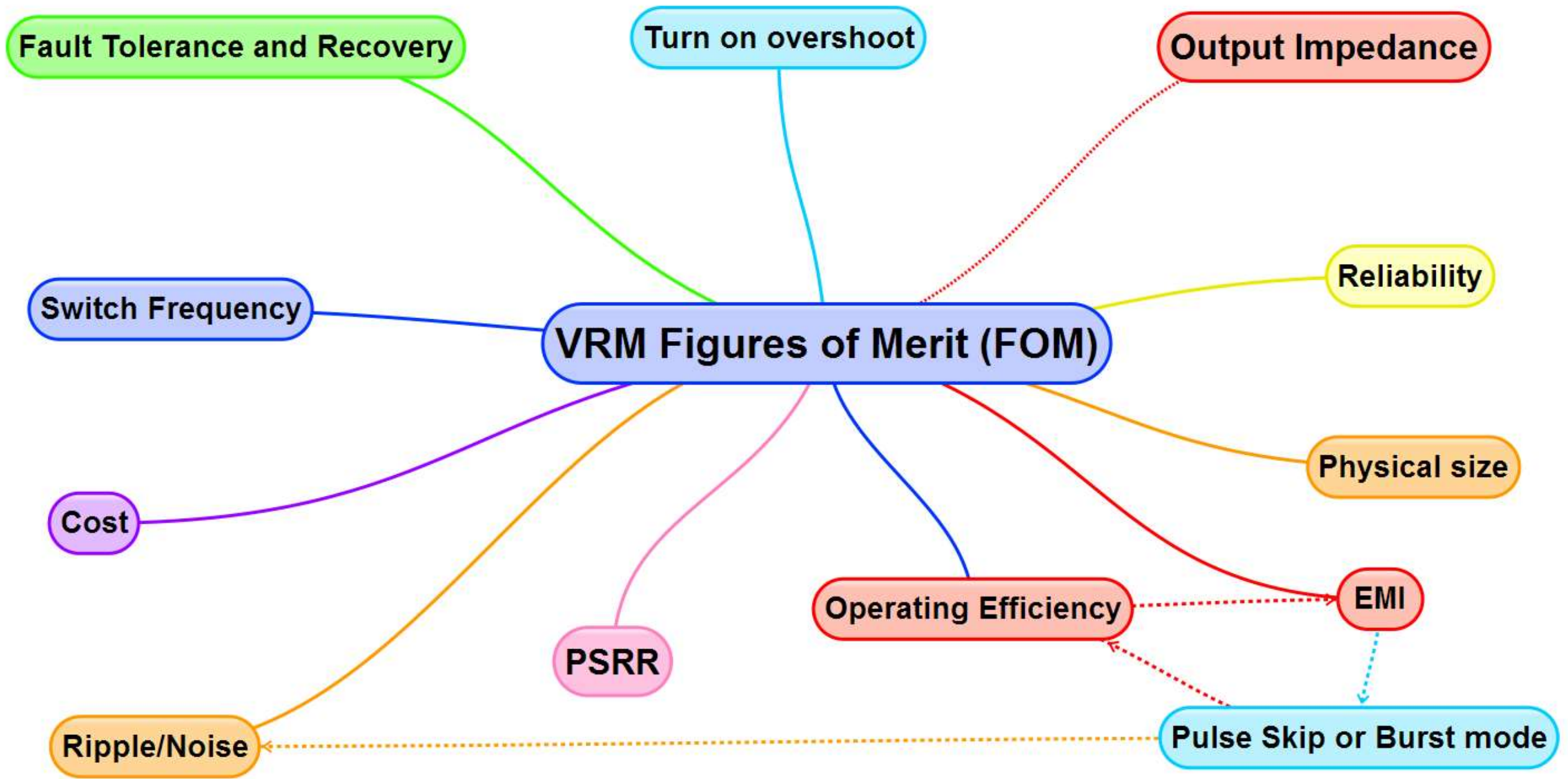
2020.3.12

Keysight Power Integrity Applications Expert



Voltage Regulator Modules (VRM)



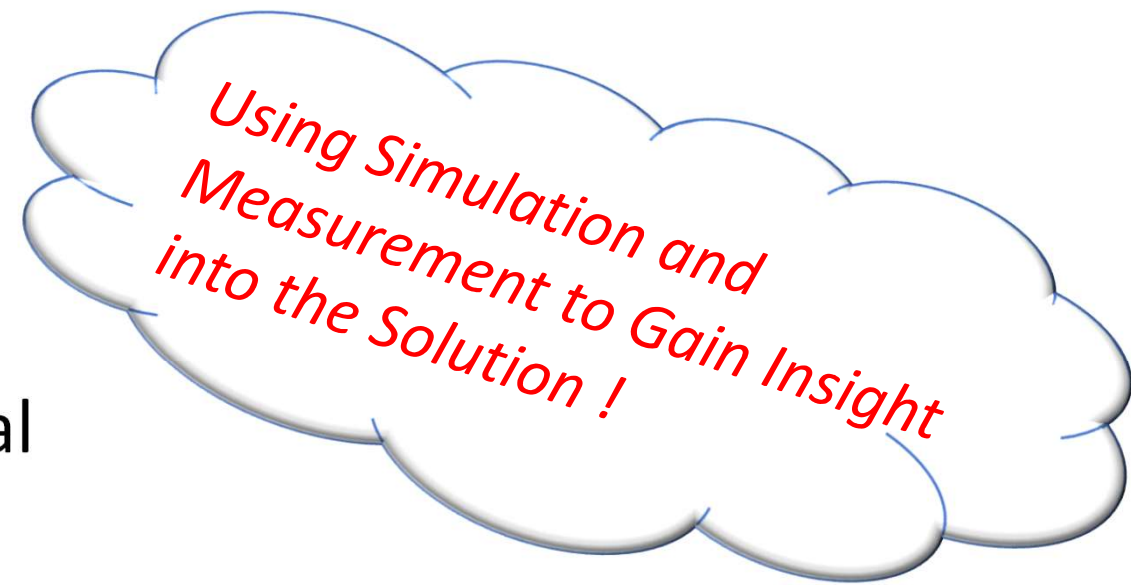


Key Topics

1. Flat impedance is the PDN design goal

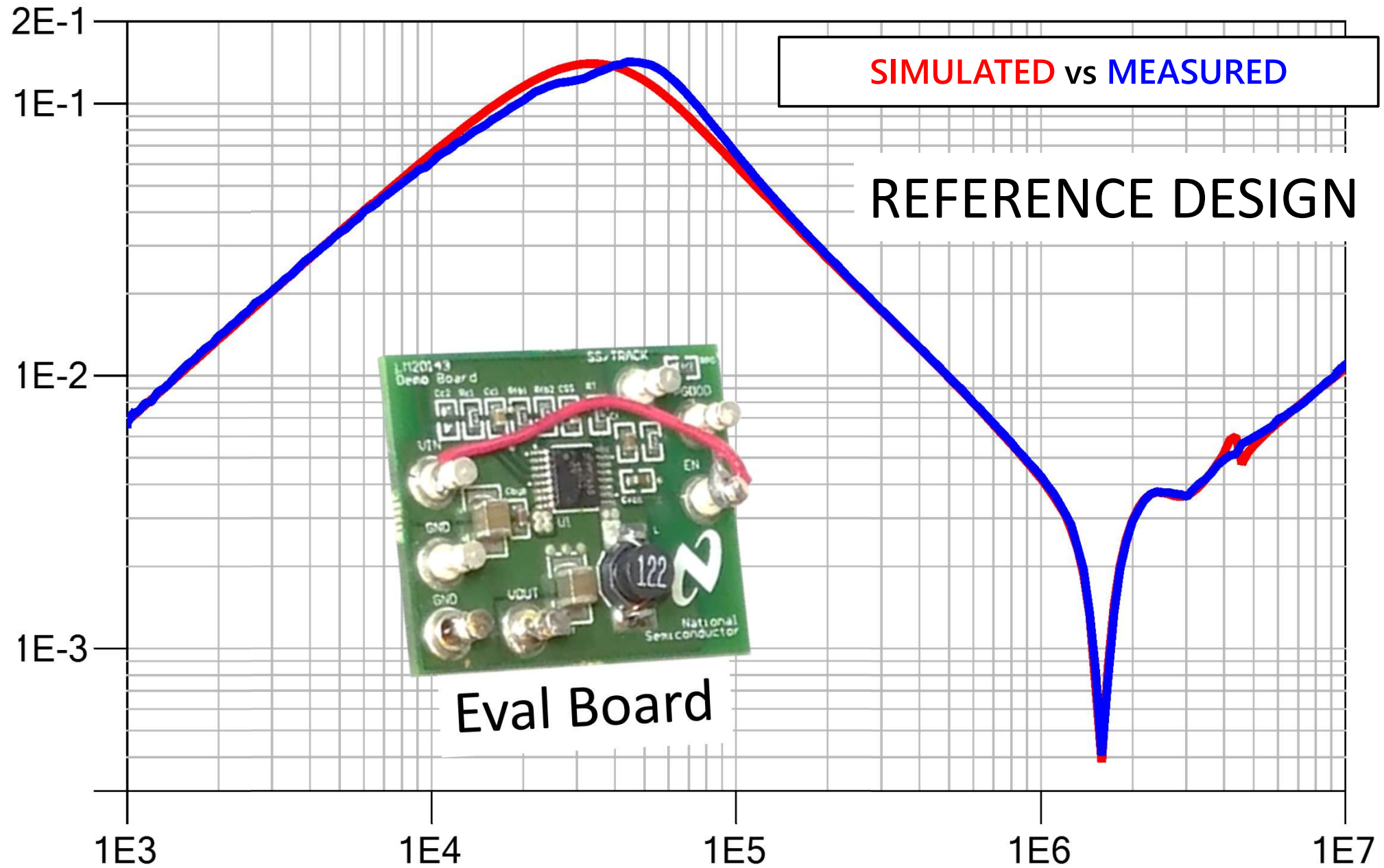
2. VRM selection is not arbitrary:

- VRM voltage mode vs. current mode control
- VRM shunt feedback vs series feedback for transconductance amplifiers



IMPEDANCE (OHMS)

ADS



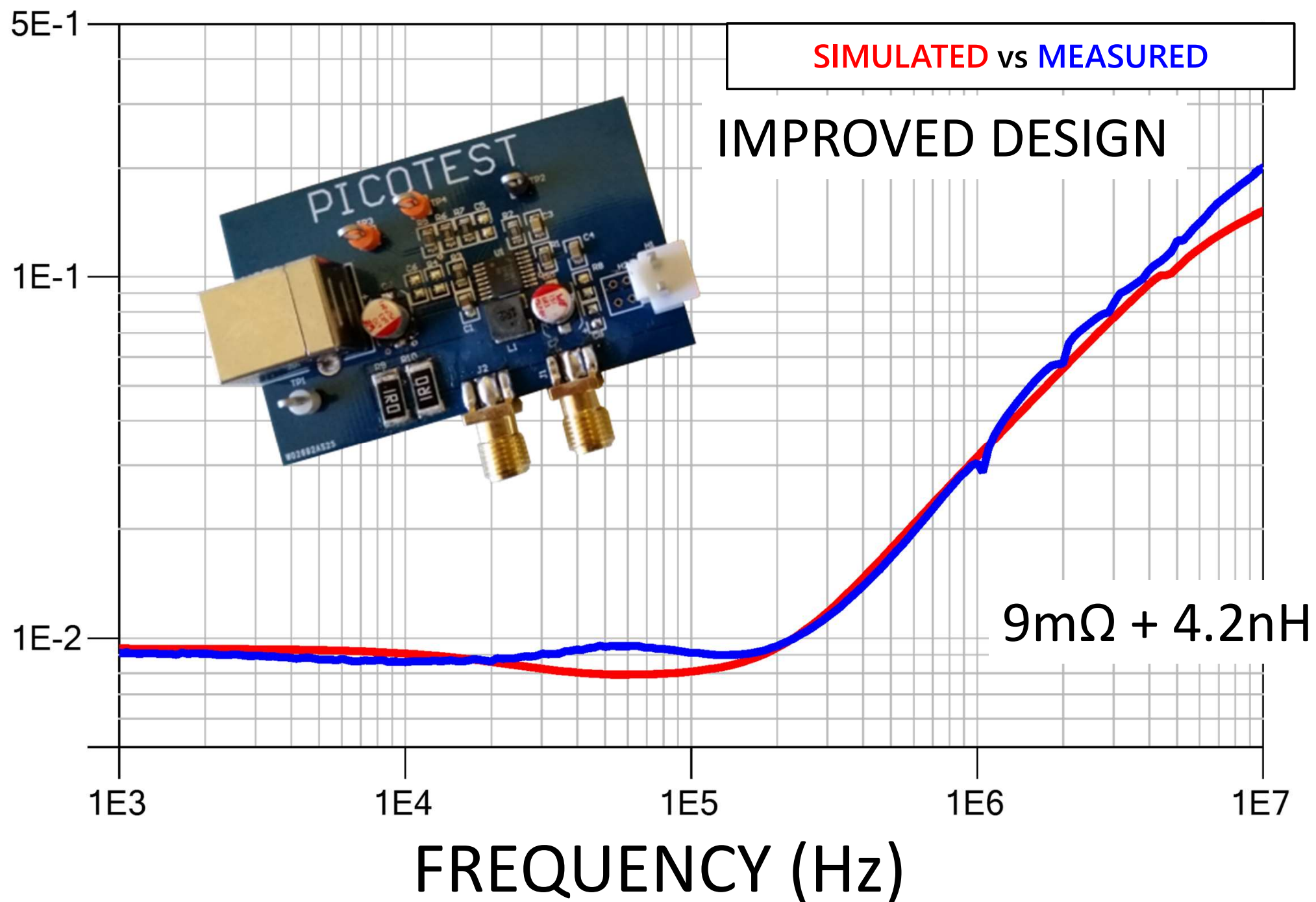
REFERENCE DESIGN

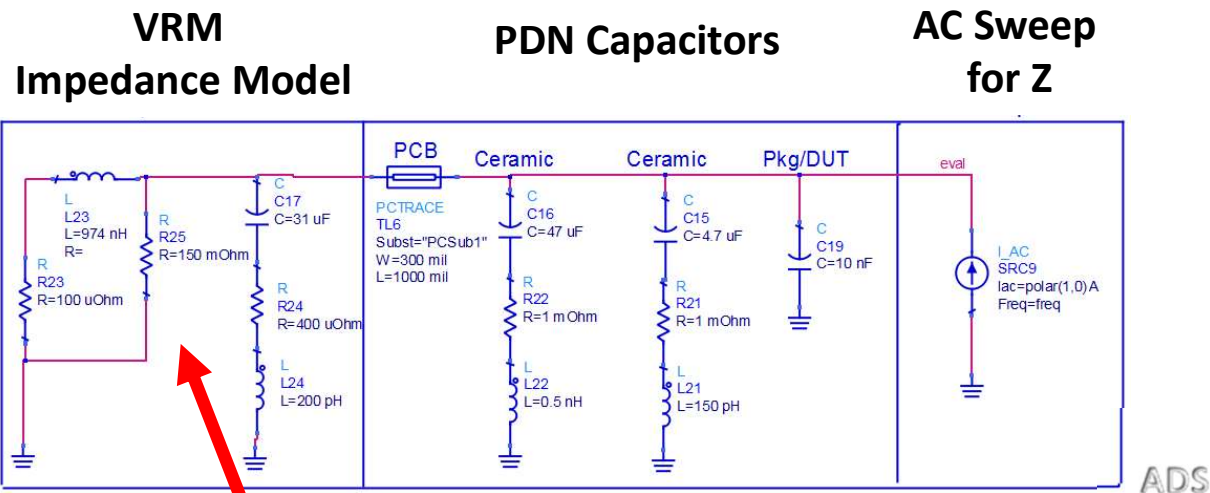
Eval Board

FREQUENCY (Hz)

IMPEDANCE (OHMS)

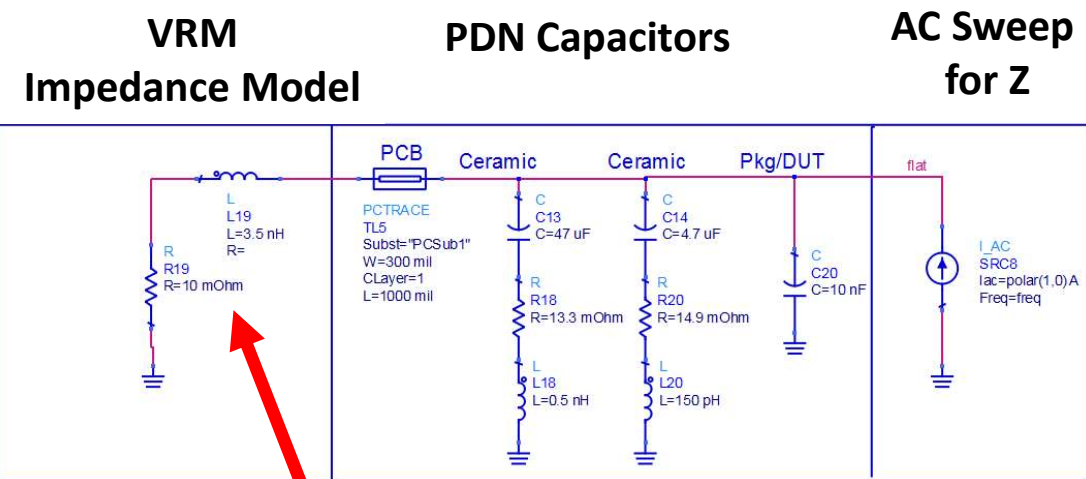
ADS



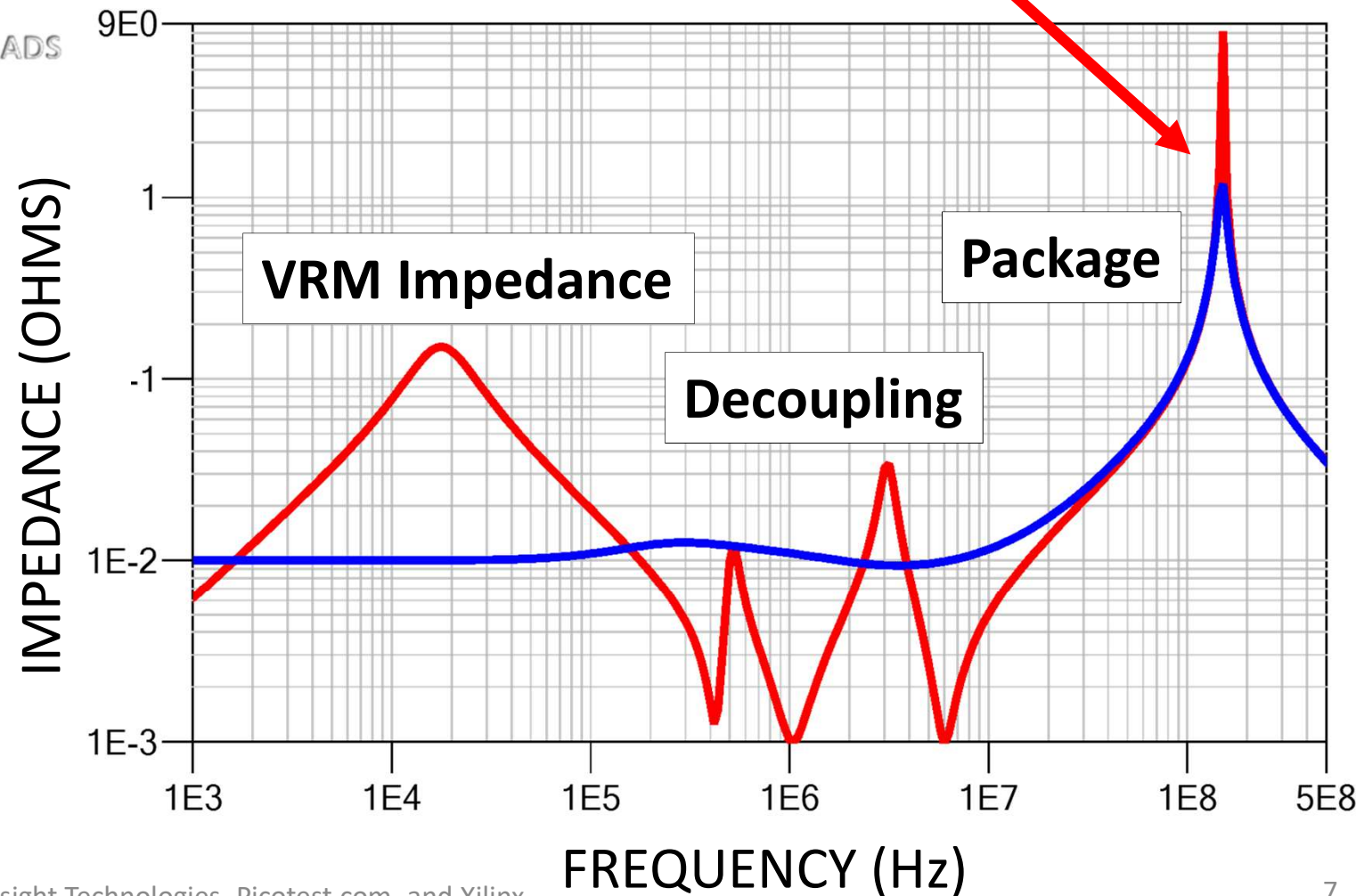


Reference Design does not fit an R/L Model!

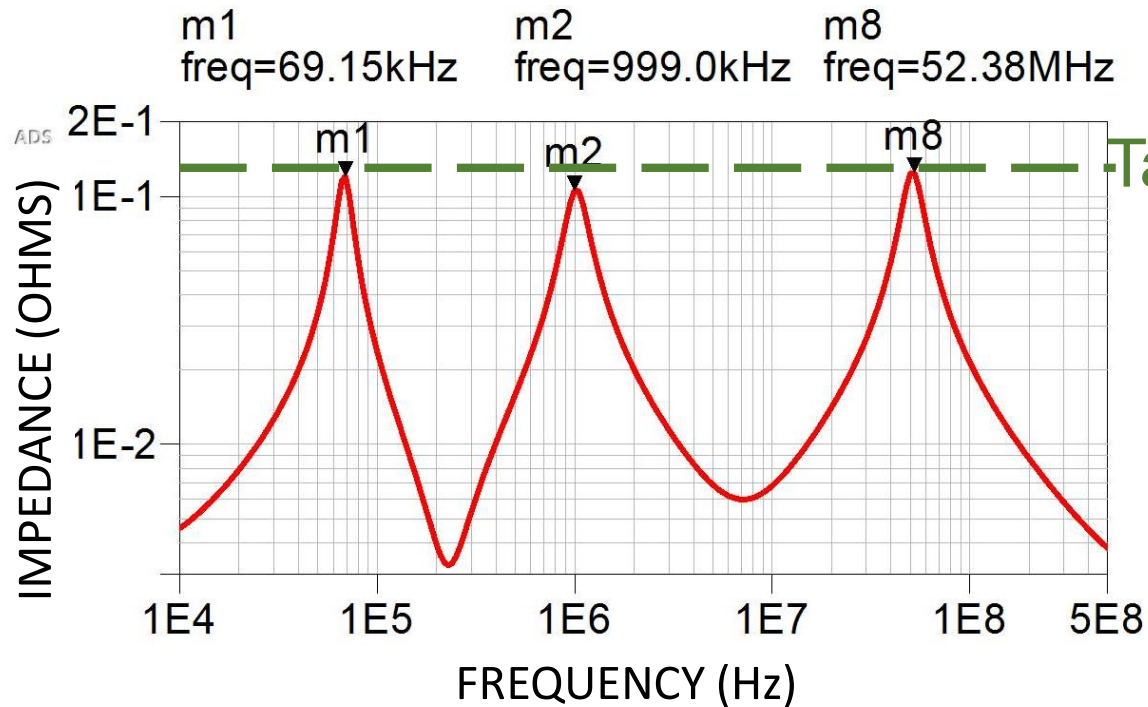
Flat Z at lower frequencies reduces the package/ DUT anti-resonance at higher frequencies!



R/L model assumes a flat PDN design!

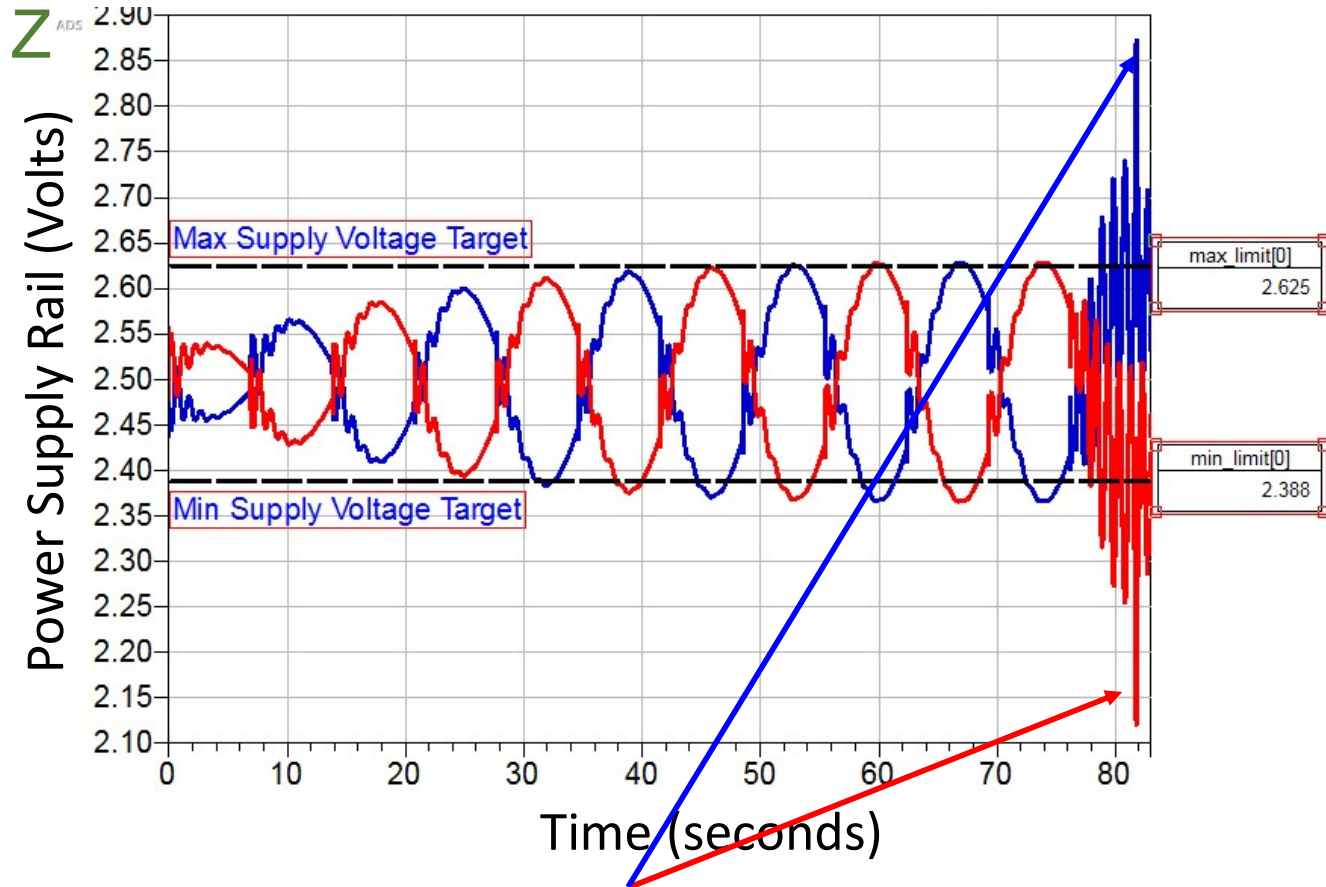


PDN Impedance vs Frequency



Power Supply Noise from Forced Response

Maximum and Minimum
Rogue Wave Response



Multiple resonances can
accumulate into a rogue wave!

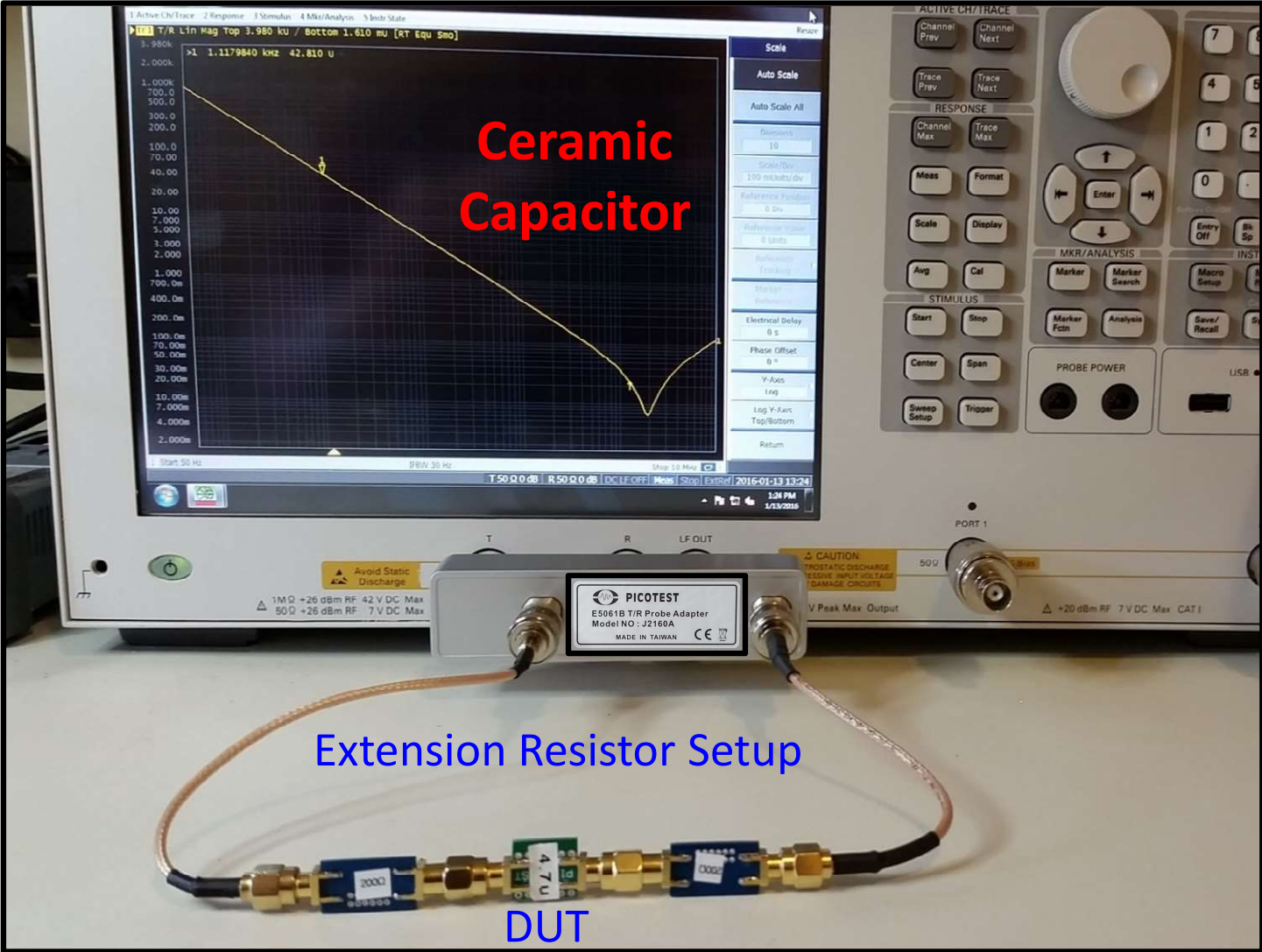
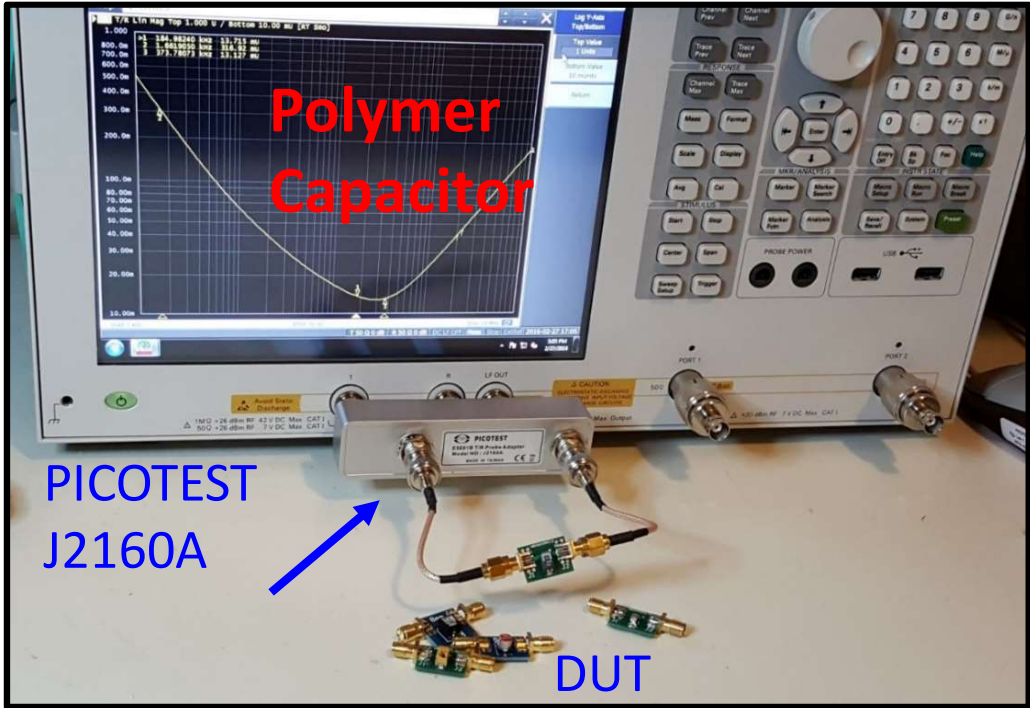
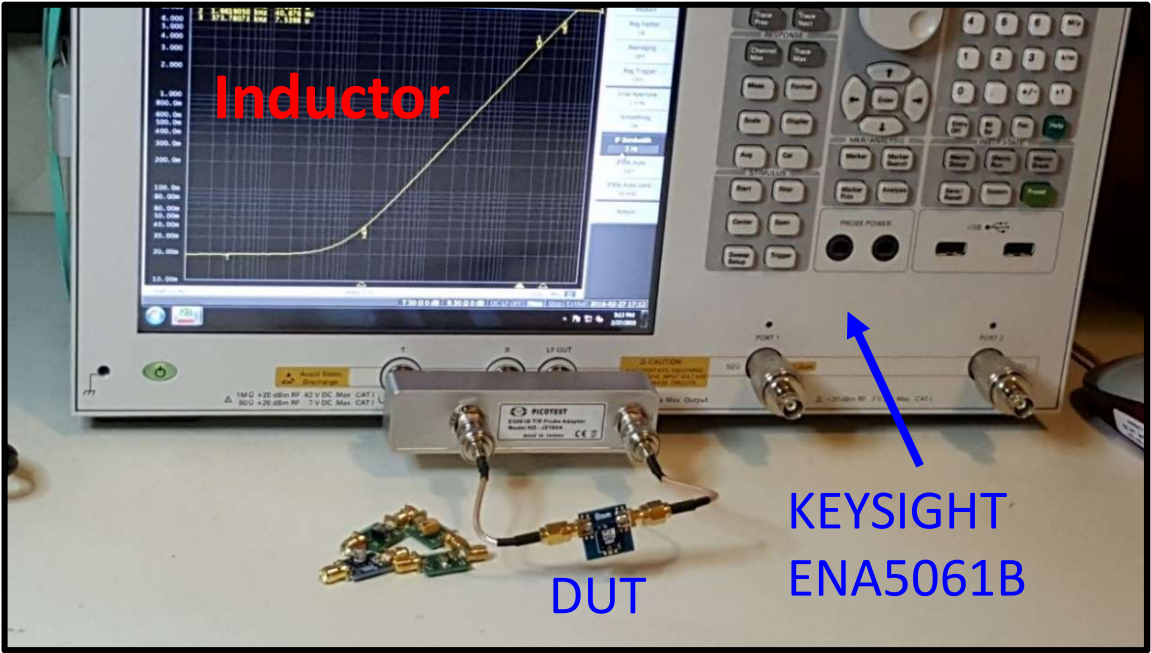
How to Design for Power Integrity:
Finding Power Delivery Noise Problems

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KEYSIGHT TECHNOLOGIES

How to Design for Power Integrity:
Finding Power Delivery Noise Problems

Search "YouTube Keysight How to PDN"

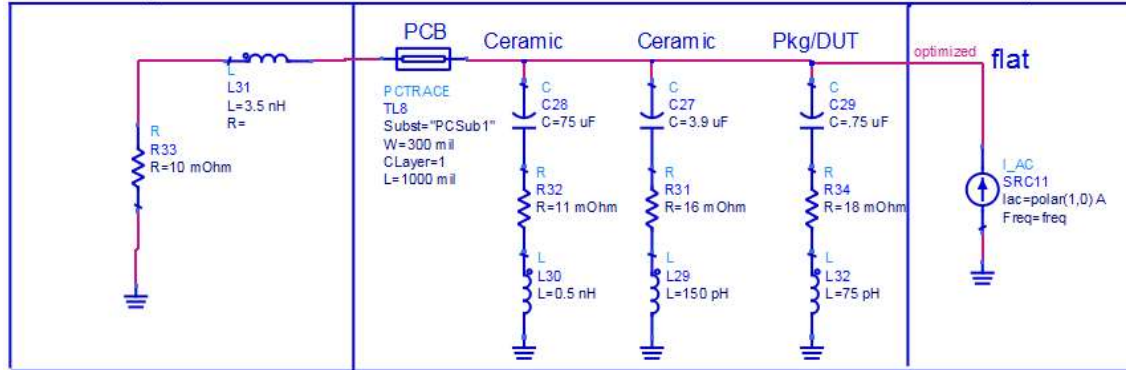


EDN
NETWORK

[Increase range in 2-port impedance measurements](#)

Steve Sandler - May 04, 2015

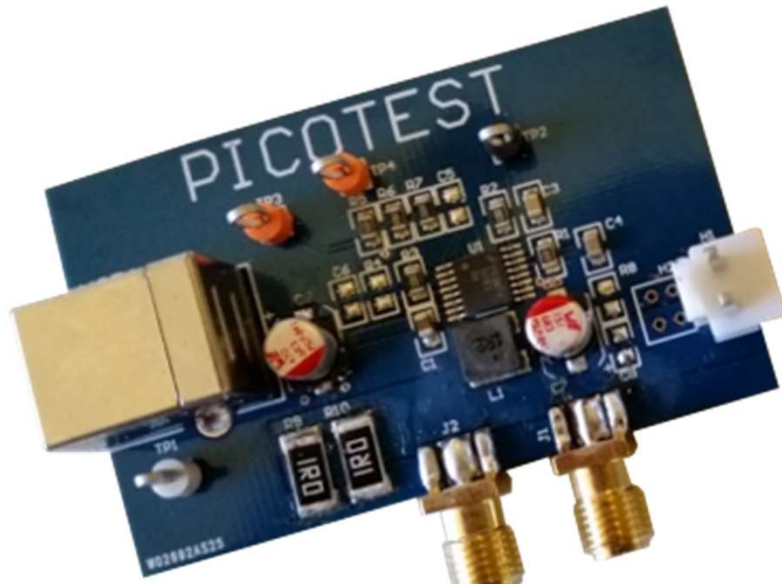
VRM Impedance Model



PDN Capacitors

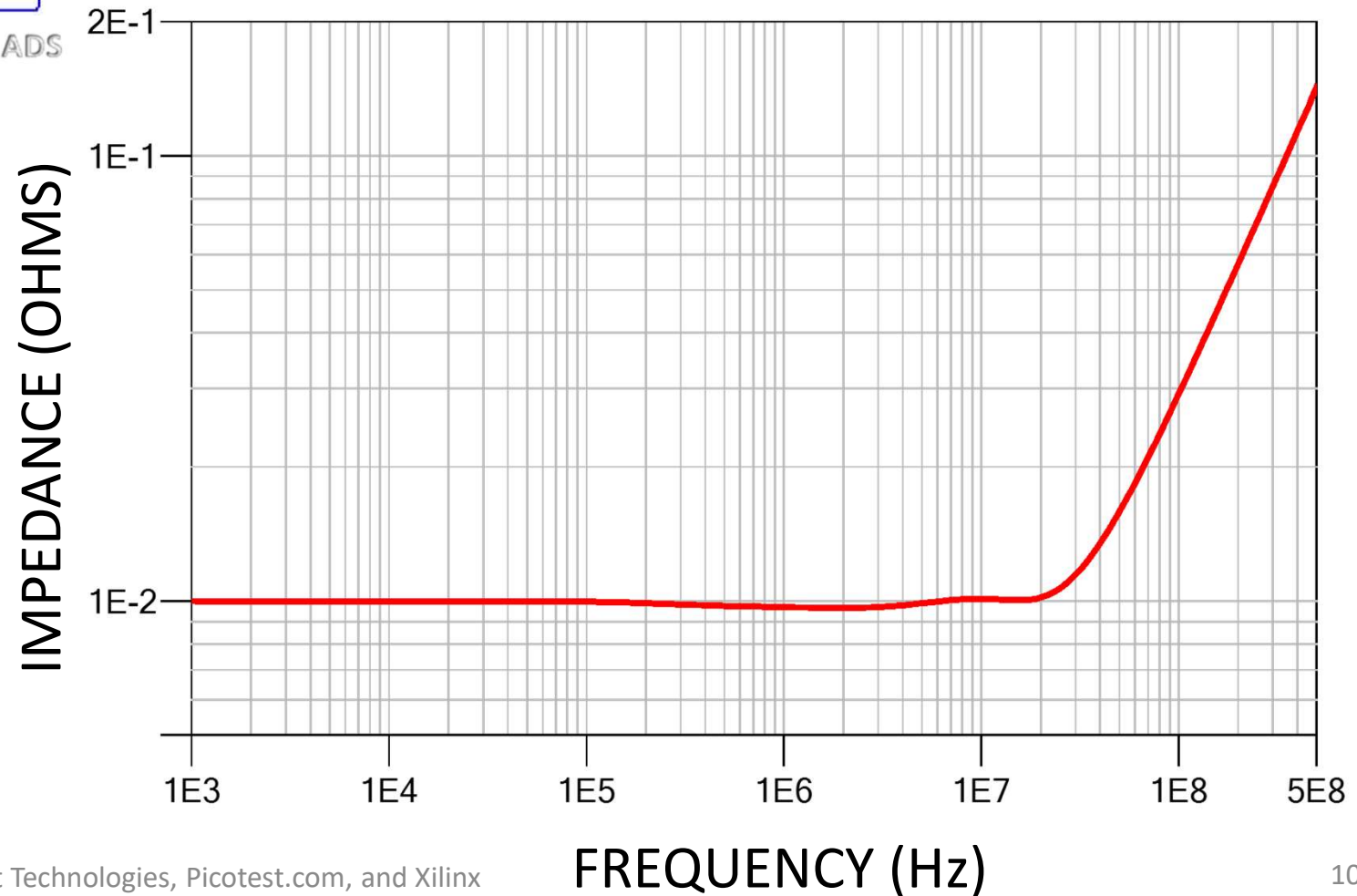
AC Sweep for Z

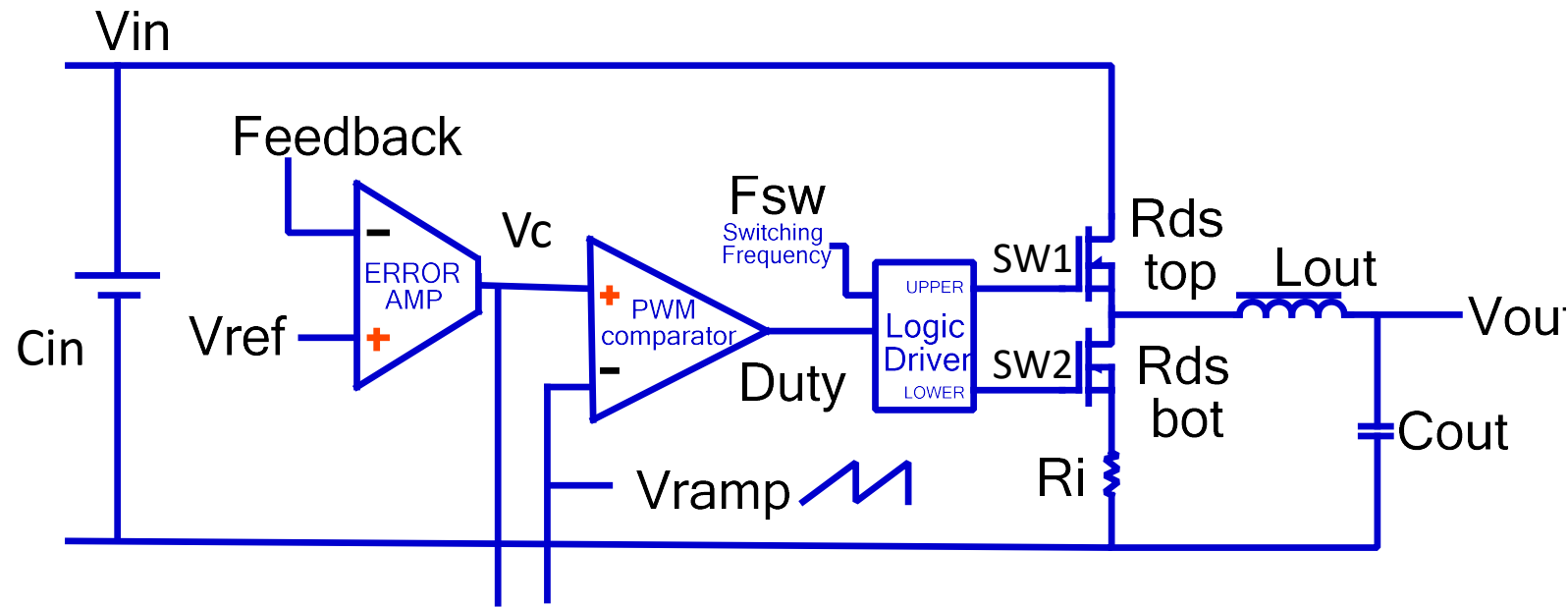
Many VRMs can be tuned for Flat Z.
So how do we choose the right one?



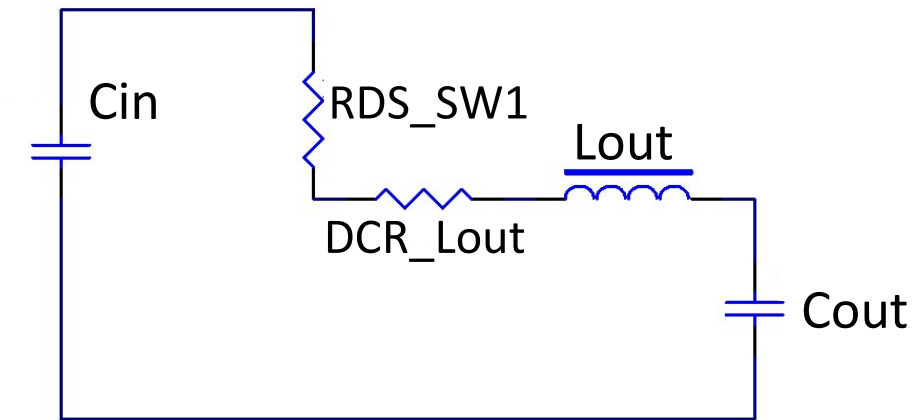
IMPROVED DESIGN

ADS





State 1: SW1 = On and SW2= Off

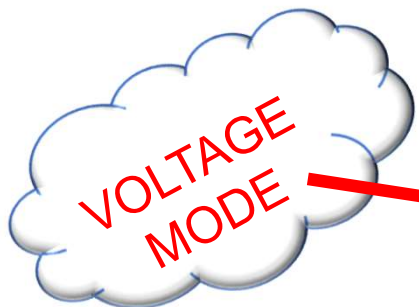


STATE SPACE AVERAGED MODEL

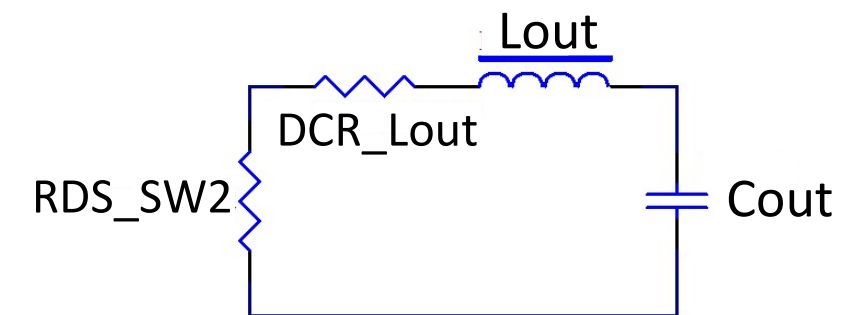
$$Duty = T_{on_SW1} \cdot F_{sw}$$

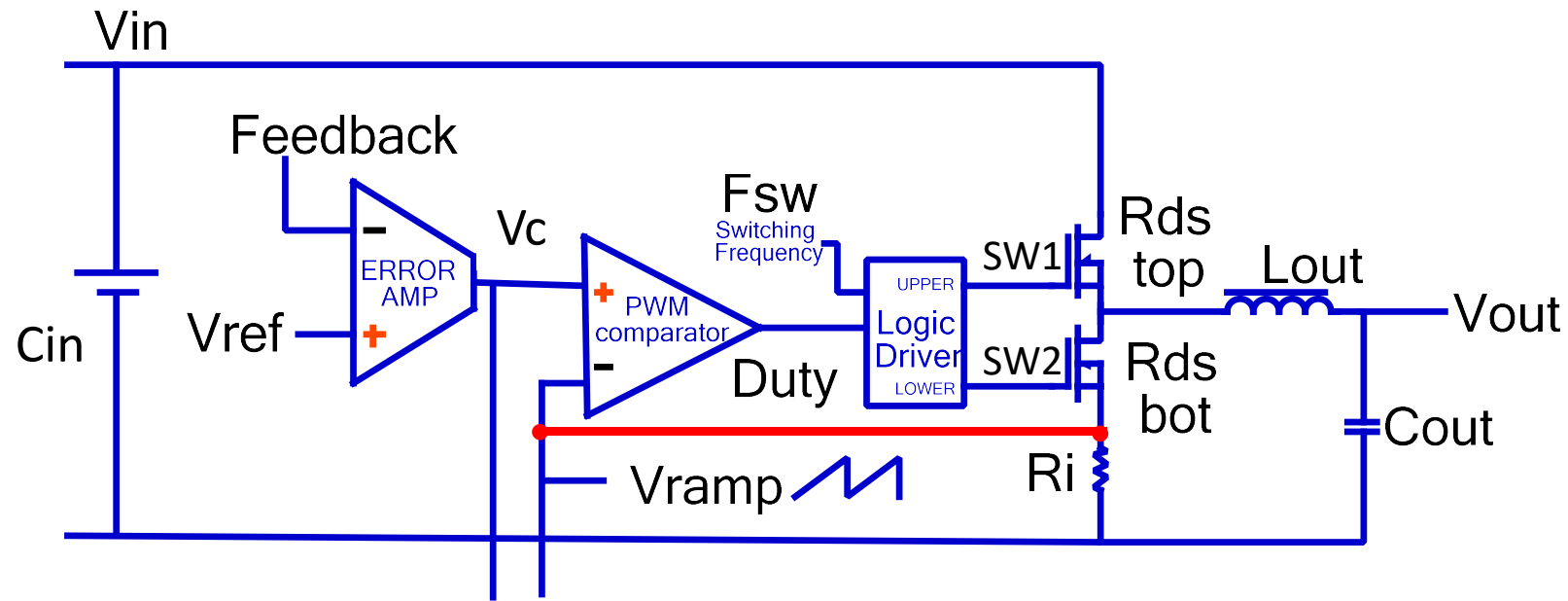
$$V_{out} = V_{in} \cdot Duty$$

$$V_{out} = V_{in} \cdot \frac{V_c}{V_{ramp}}$$

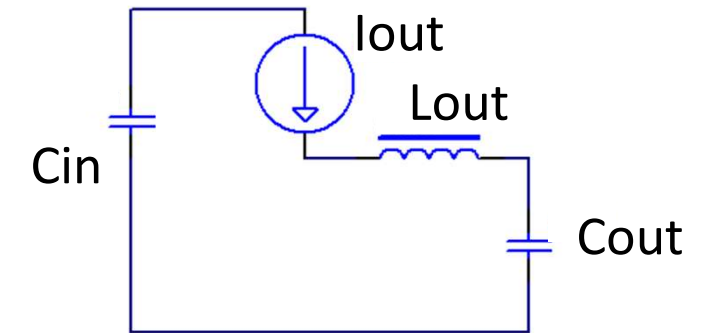


State 2: SW1 = Off and SW2= On





State 1: SW1 = On and SW2= Off

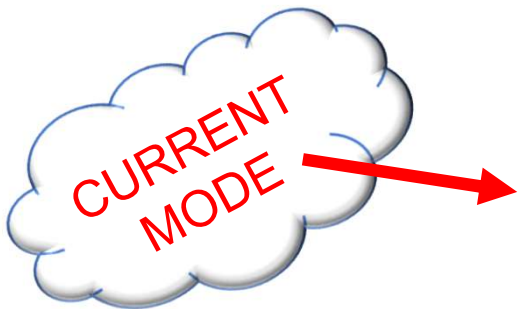


STATE SPACE AVERAGED MODEL

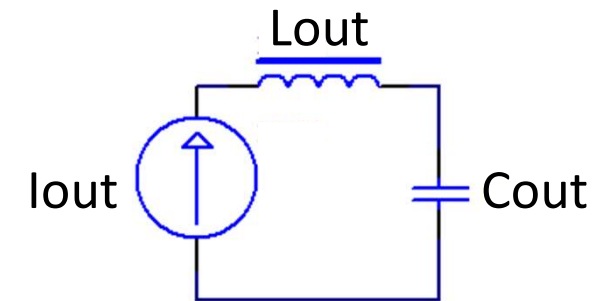
$$Duty = T_{on_SW1} \cdot F_{sw}$$

$$V_{out} = V_{in} \cdot Duty$$

$$I_{out} = k \frac{V_c}{R_i}$$



State 2: SW1 = Off and SW2= On

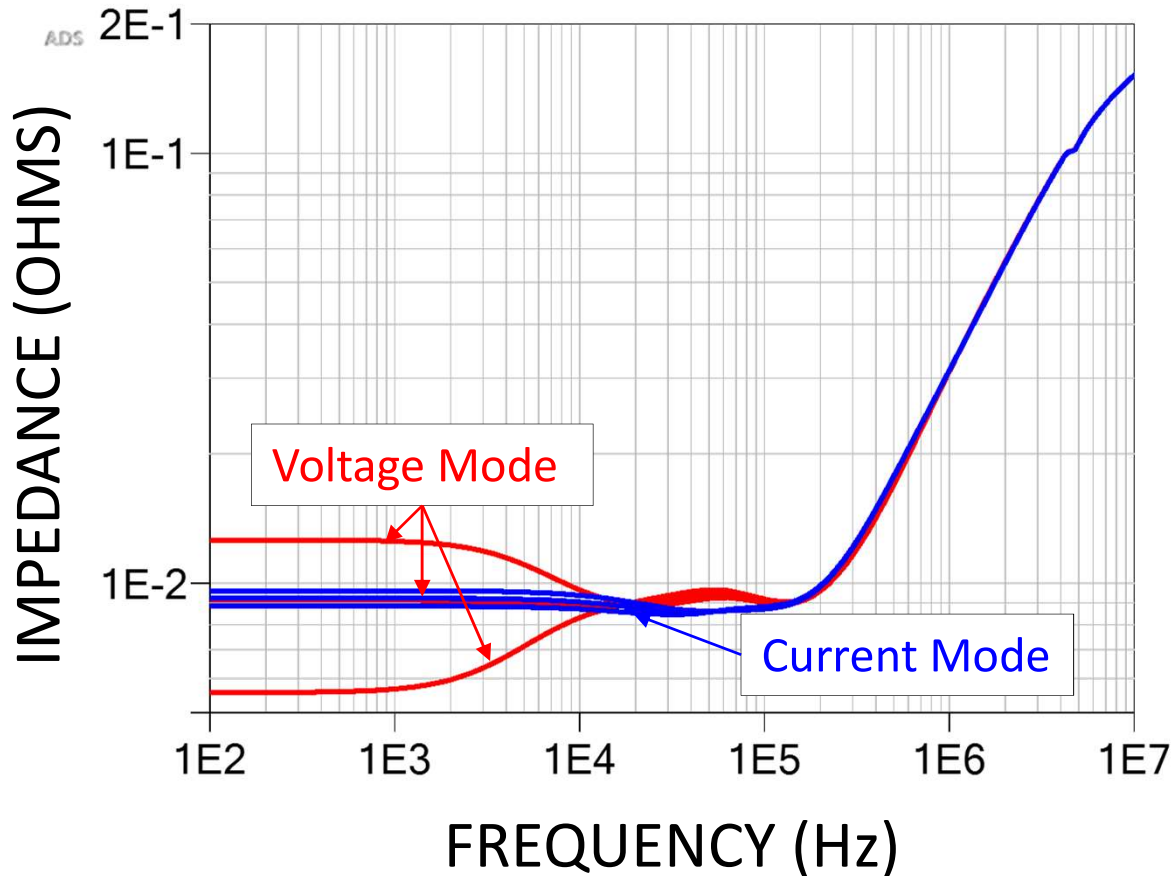


*Nominal Impedance is the same,
Voltage Mode is very sensitive to tolerances*

$$R_{out_CM} = \frac{R_i}{1 + A_v}$$

$$R_{out_VM} = \frac{DCR_{Lo} + R_{DSon_{bot}} + (R_{DSon_{top}} - R_{DSon_{bot}}) \cdot \frac{V_o}{V_{in}}}{1 + A_v \cdot \frac{V_{in}}{V_{ramp}}}$$

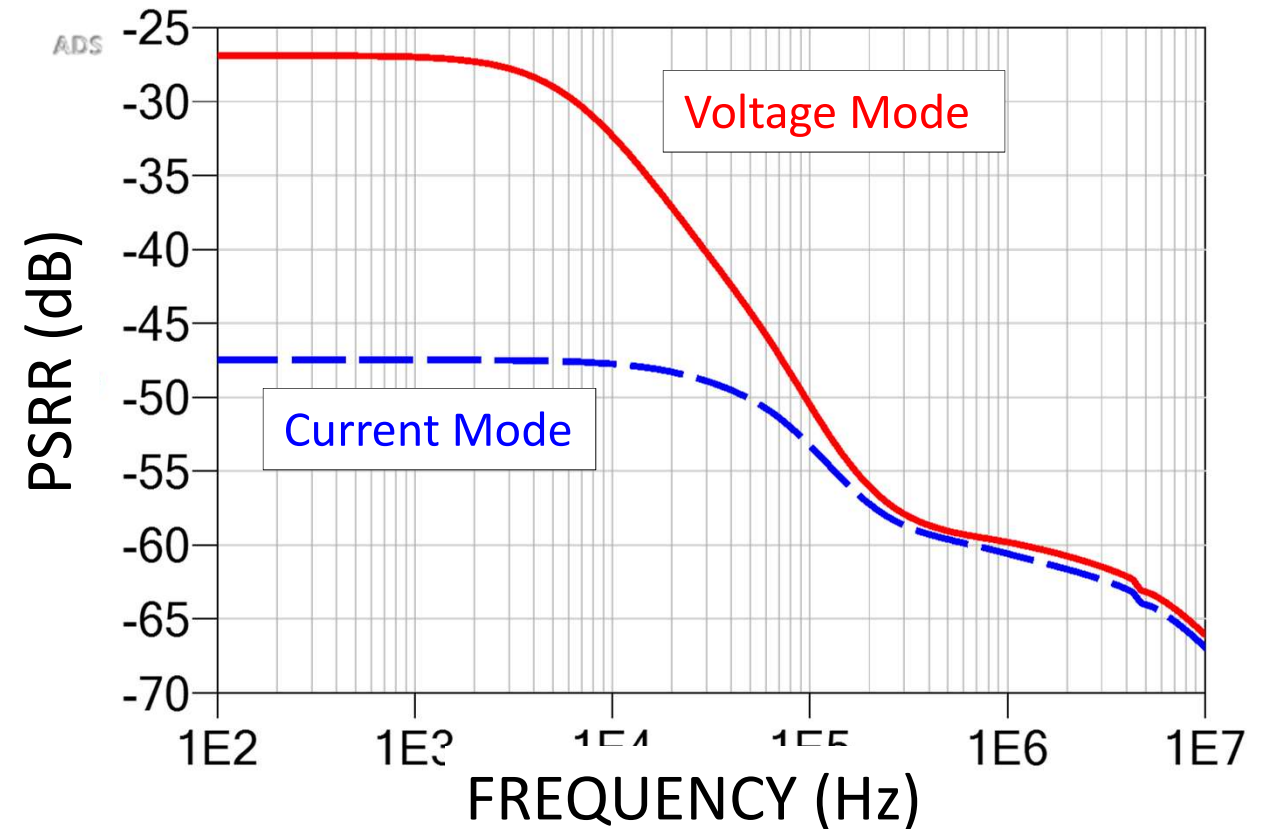
DCR_Lout +/- 45%



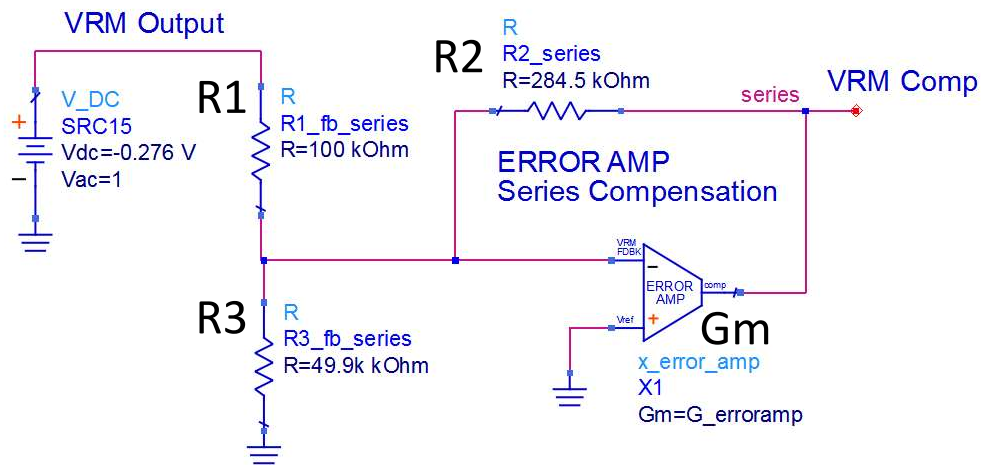
*Nominal PSRR is very different between
Current Mode and Voltage Mode*

$$PSRR = \frac{V_o(ac)}{V_{in}(ac)}$$

Power Supply Rejection Ratio (PSRR)

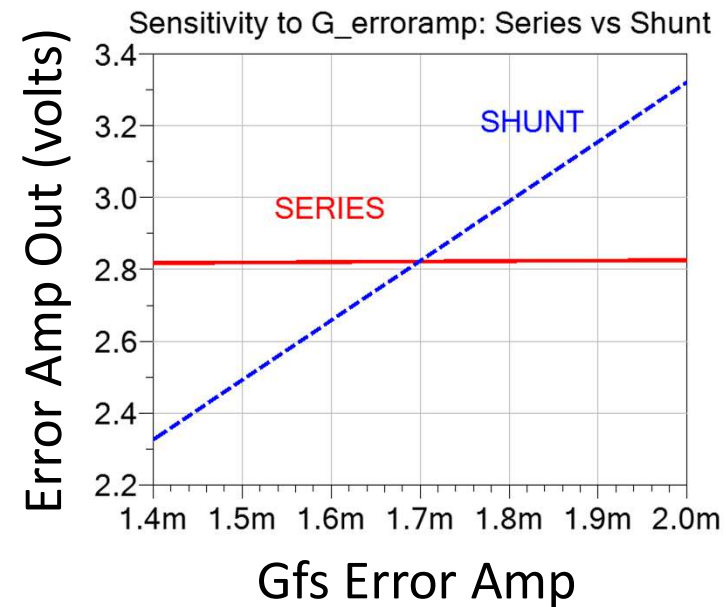
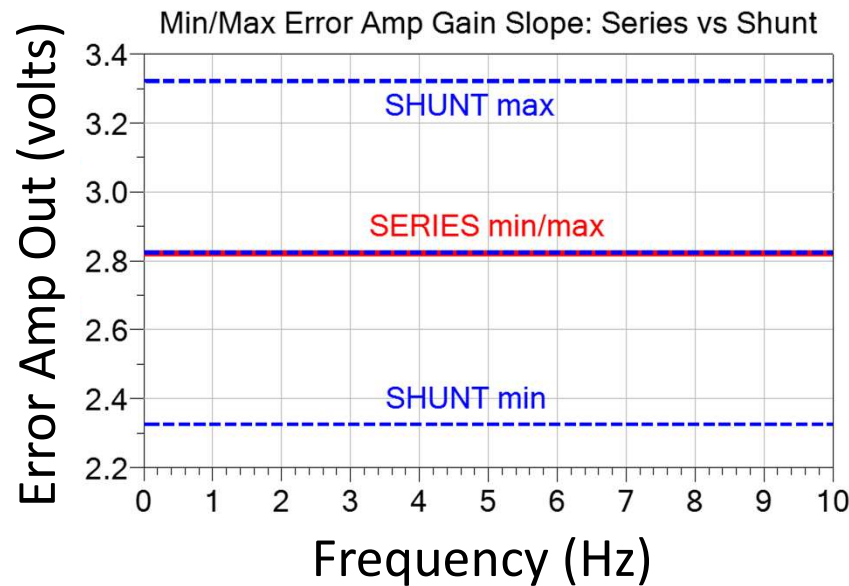
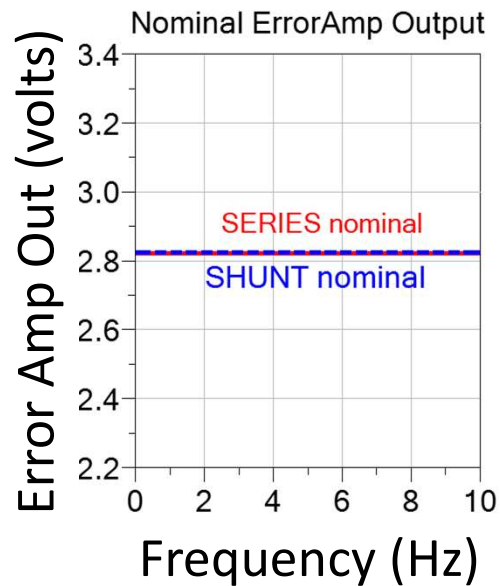


SERIES FEEDBACK



$$Av_{series} = \frac{R3 \cdot (Gm \cdot R2 - 1)}{R1 + R3 + Gm \cdot R1 \cdot R3} = 3.215$$

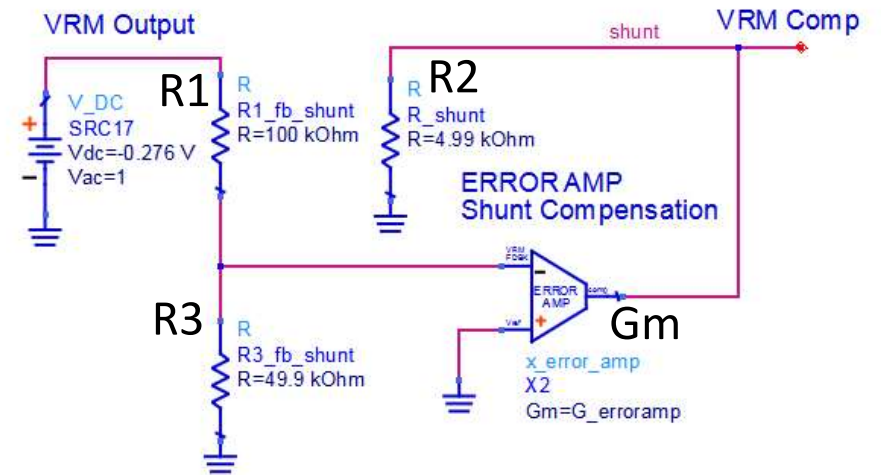
$$\frac{\delta Av_{series}}{\delta Gm} = \frac{R2 \cdot R3}{R1 + R3 + Gm \cdot R1 \cdot R3} - \frac{R1 \cdot R3^2 \cdot (Gm \cdot R2 - 1)}{(R1 + R3 + Gm \cdot R1 \cdot R3)^2} = 2.58 \cdot 10^3$$



Gfs Error Amp

Min = 1.4 e-3
Nominal = 1.7 e-3
Max = 2.0 e-3

SHUNT FEEDBACK



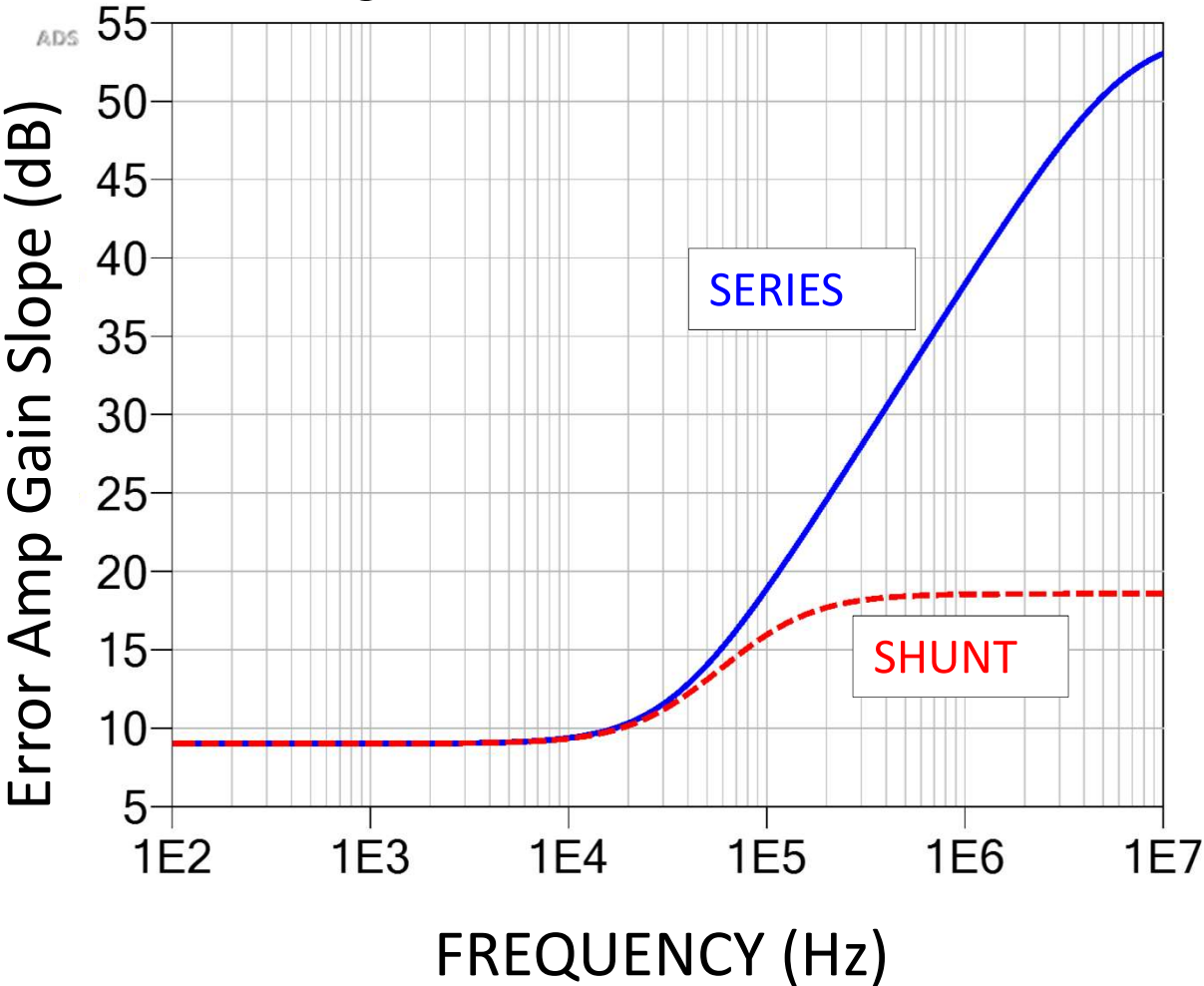
$$Av_{shunt} = \frac{R3 \cdot Gm \cdot R2shunt}{R1 + R3} = 3.215$$

$$\frac{\delta Av_{shunt}}{\delta Gm} = \frac{R3 \cdot R2shunt}{R1 + R3} = 6.3 \cdot 10^3$$

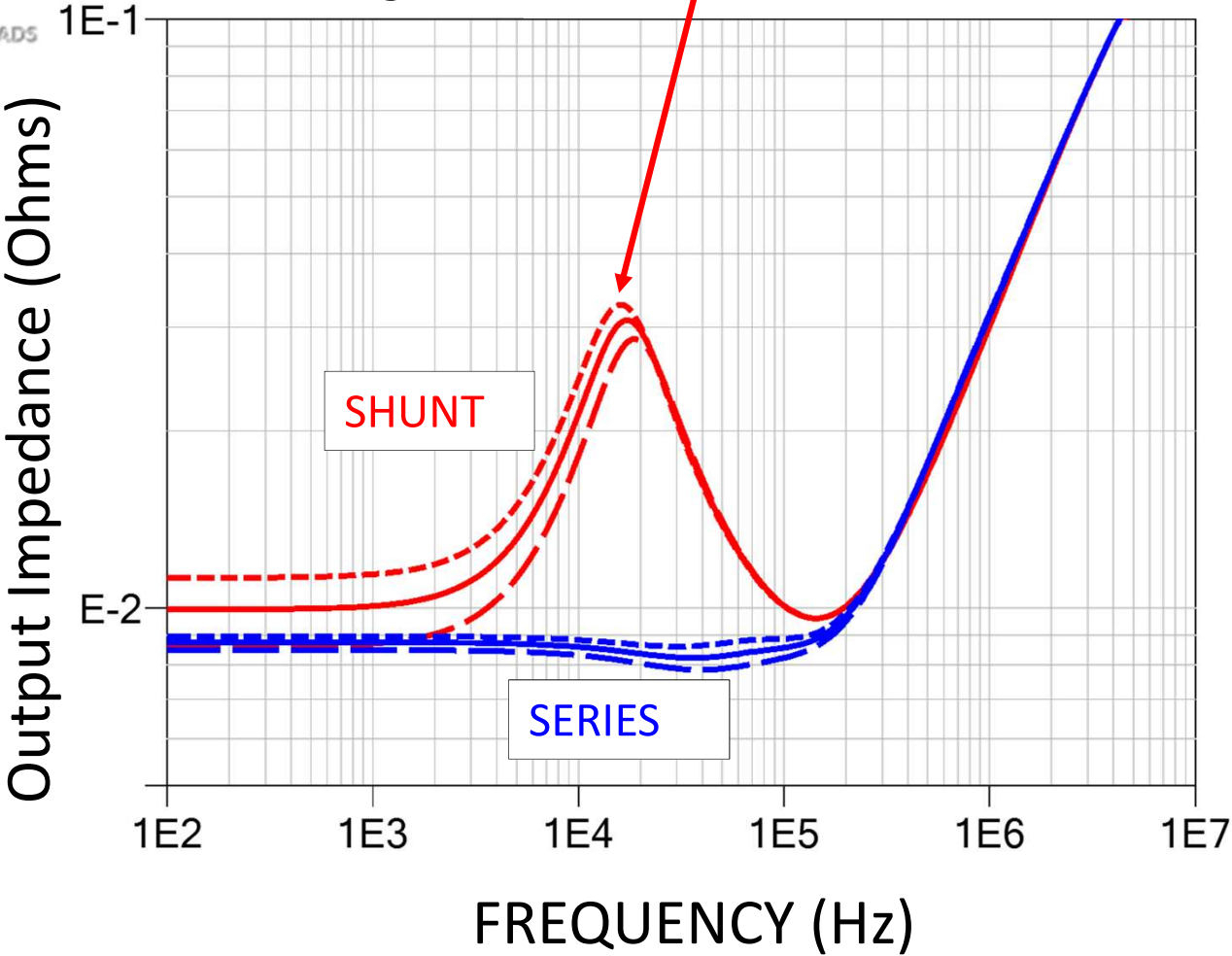
Voltage Mode with Shunt Feedback

Impractical to make flat PDN impedance!

Voltage Mode Series vs Shunt



Voltage Mode Series vs Shunt



Monte Carlo Distribution of VRM Tolerances

Tolerance Distribution

DCR_Lo=30m 7%+0.4%/degC=50%

Transconductance Error Amplifier Gm=10%

Vin=10%

Vramp=10% (Gslope comp)

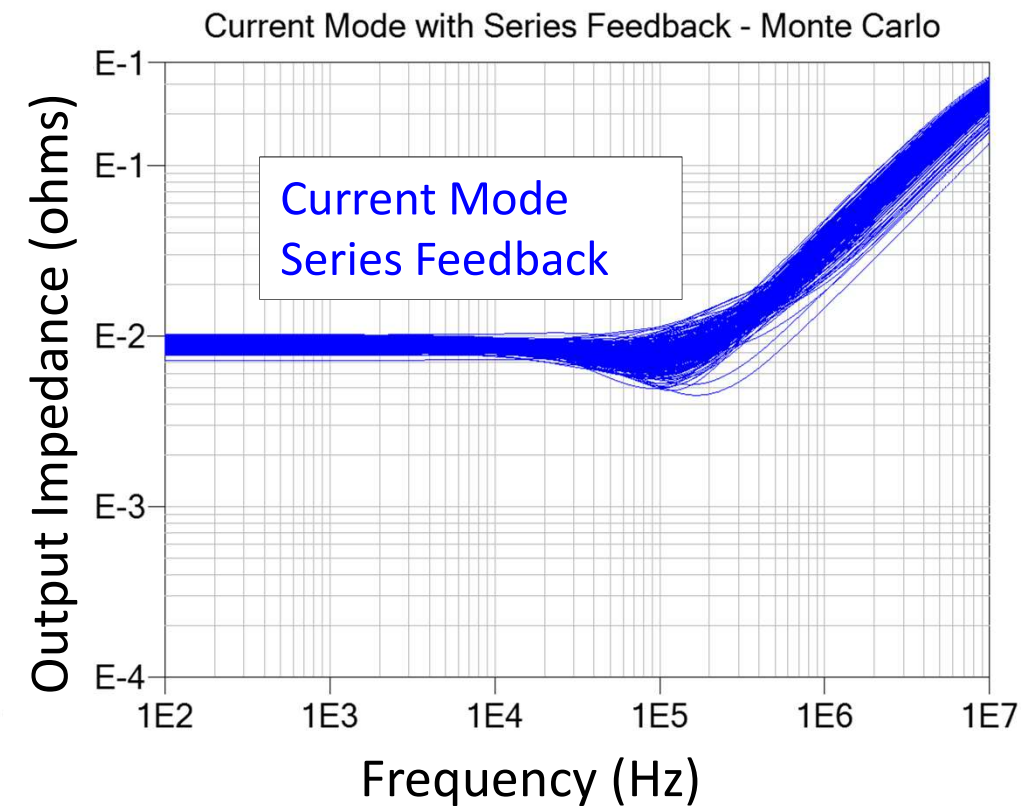
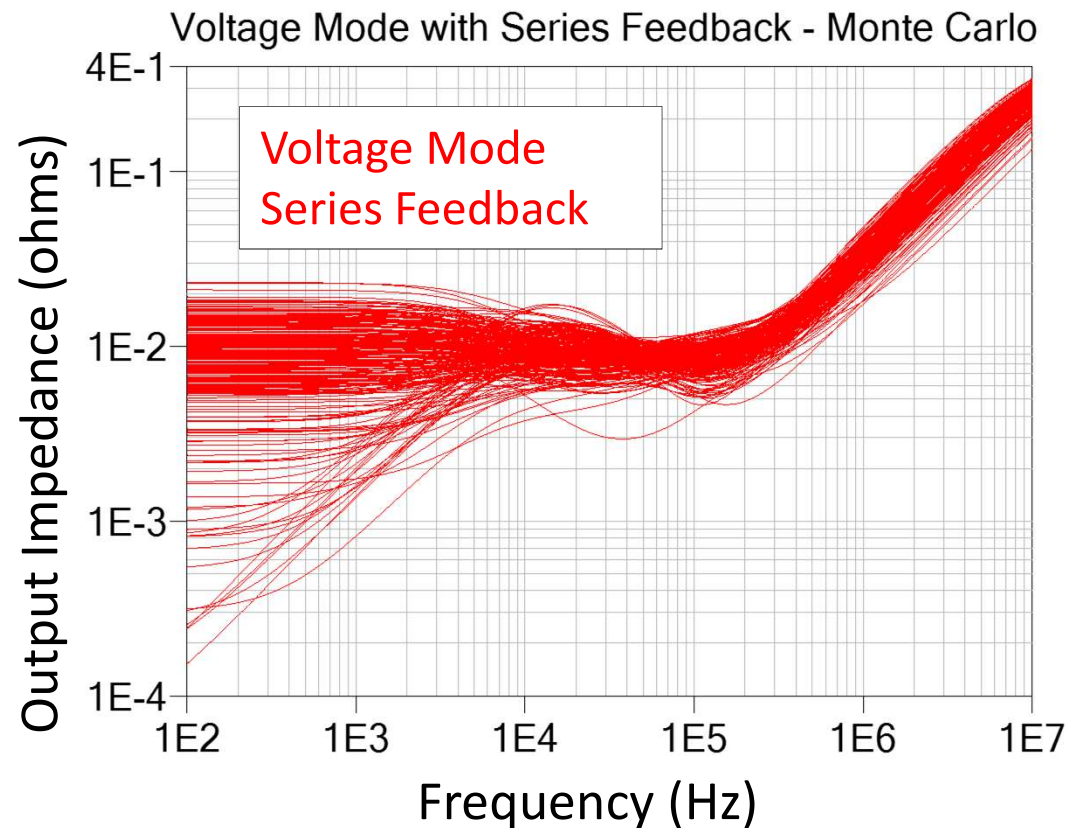
Lout=25%

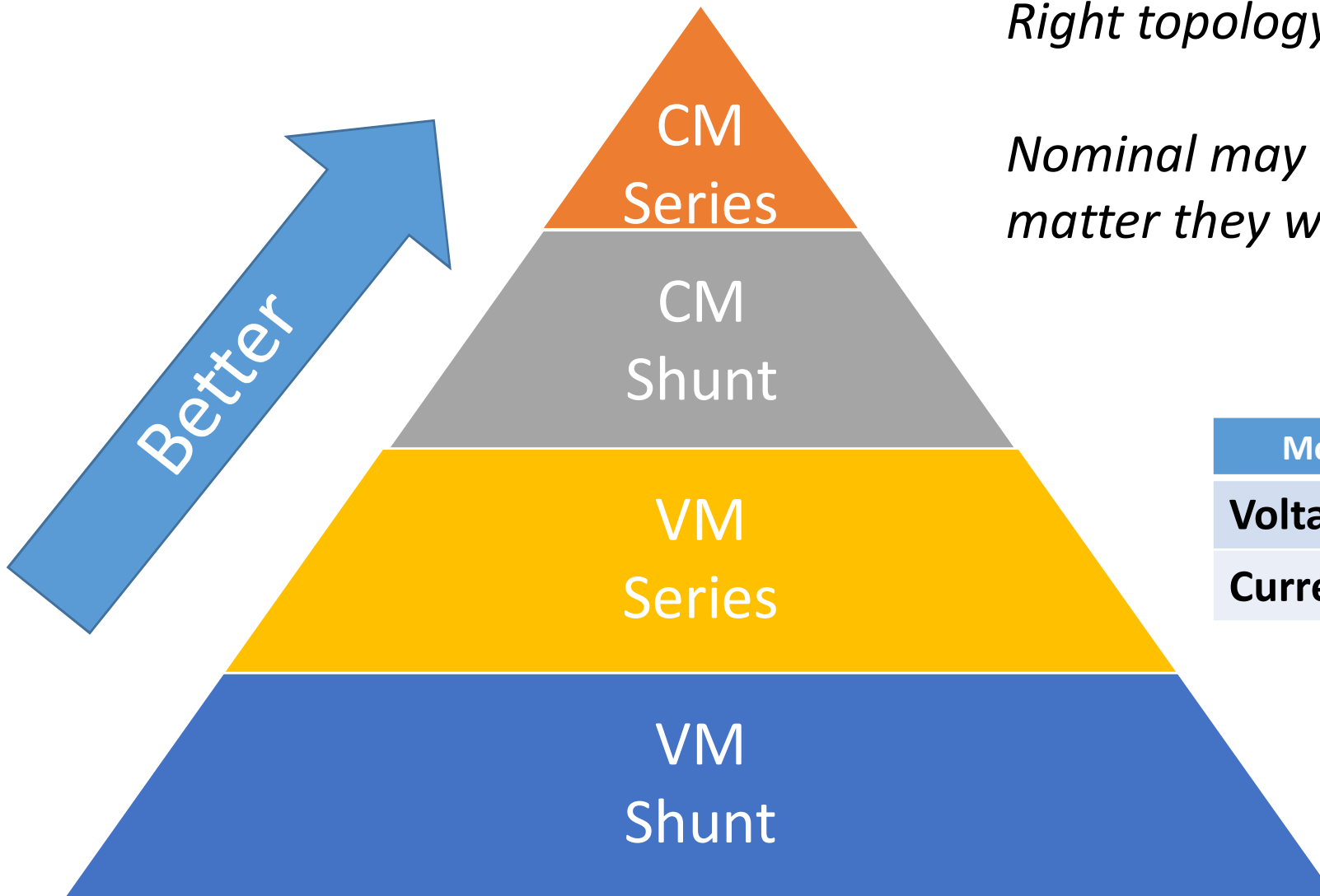
Cbulk_ESR=20%

Cbulk_ESL=20%

Current Mode with Series Feedback is the winner!

Monte Carlo of *Voltage Mode* vs *Current Mode*



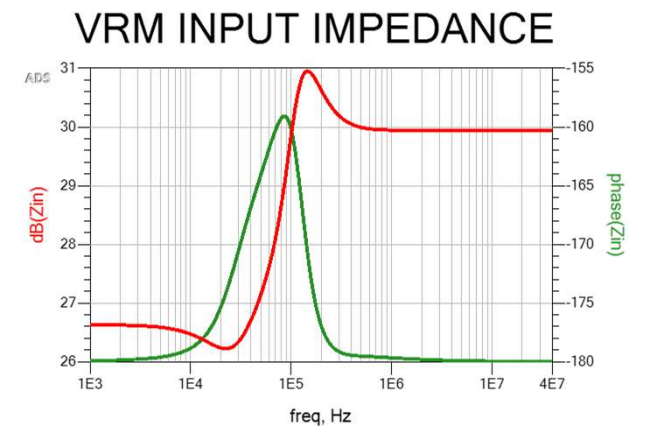
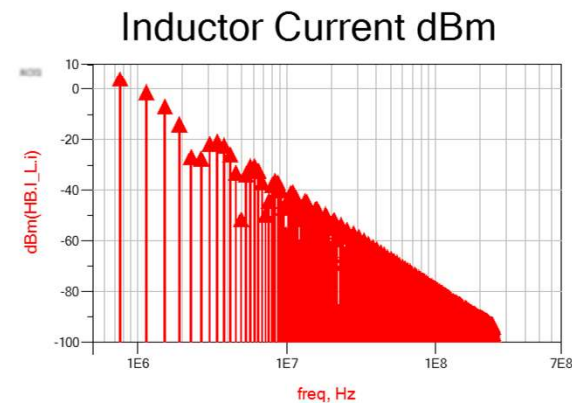
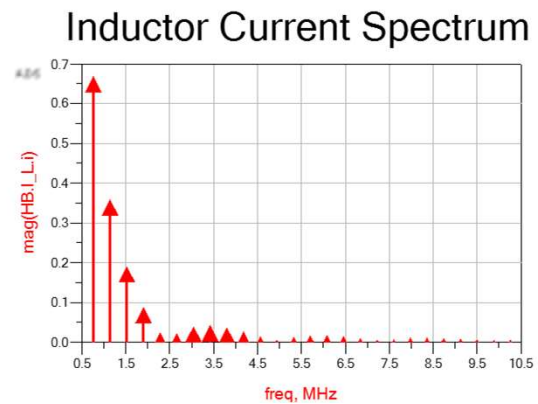
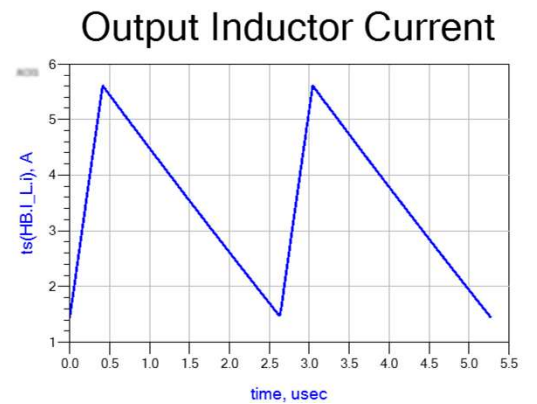
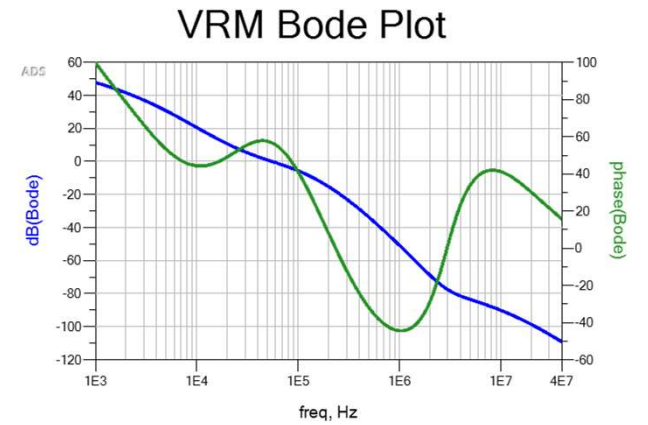
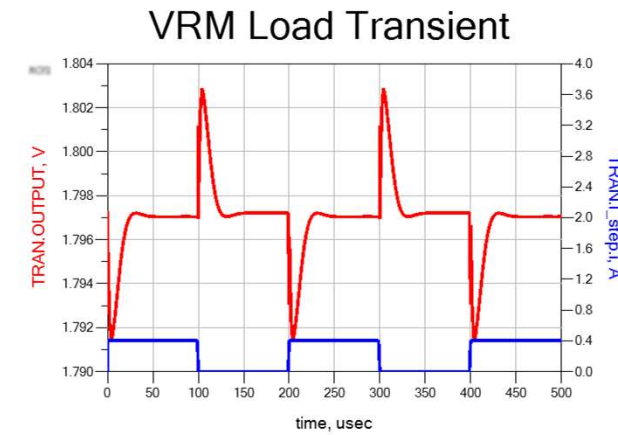
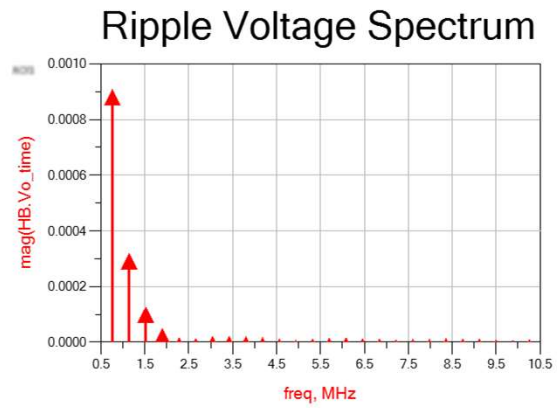
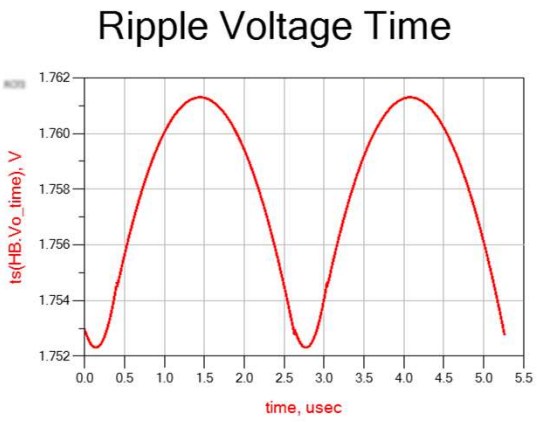
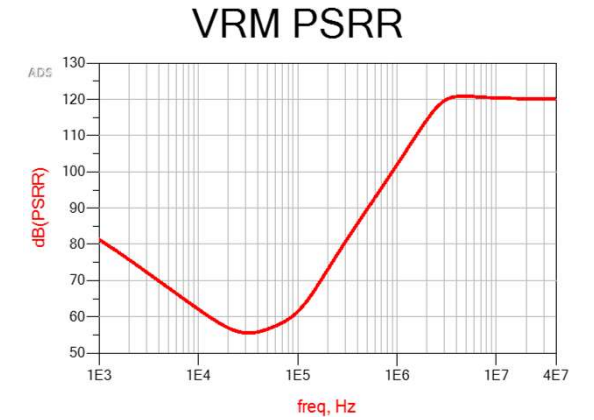
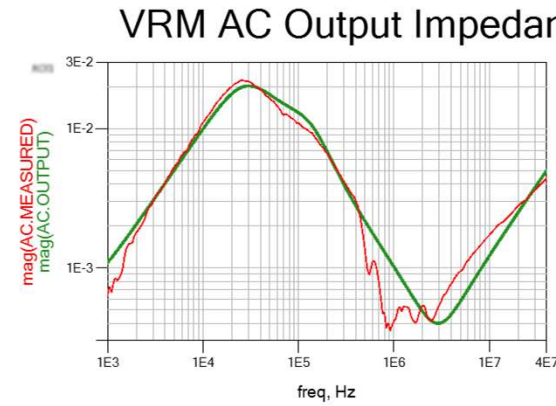
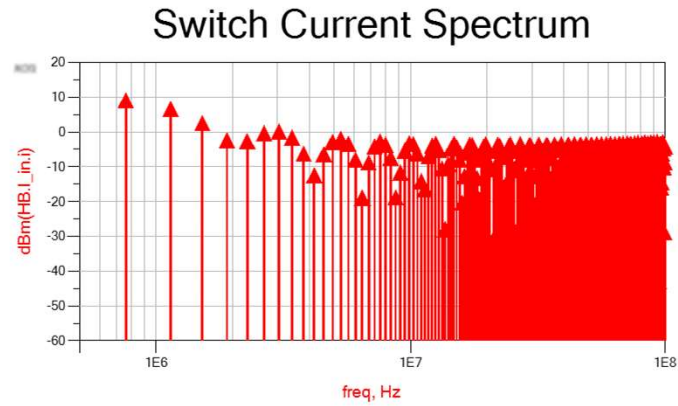
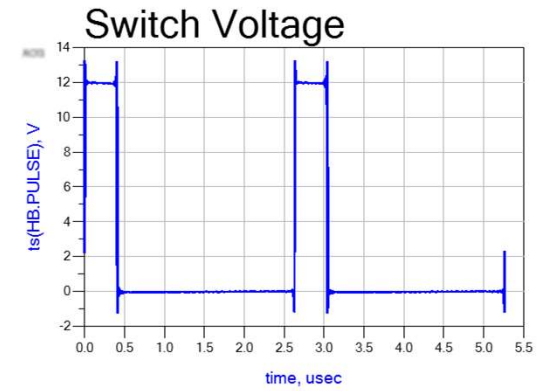


Right topology or the answer can be very wrong.

Nominal may look okay, but reality is tolerances matter they will change!

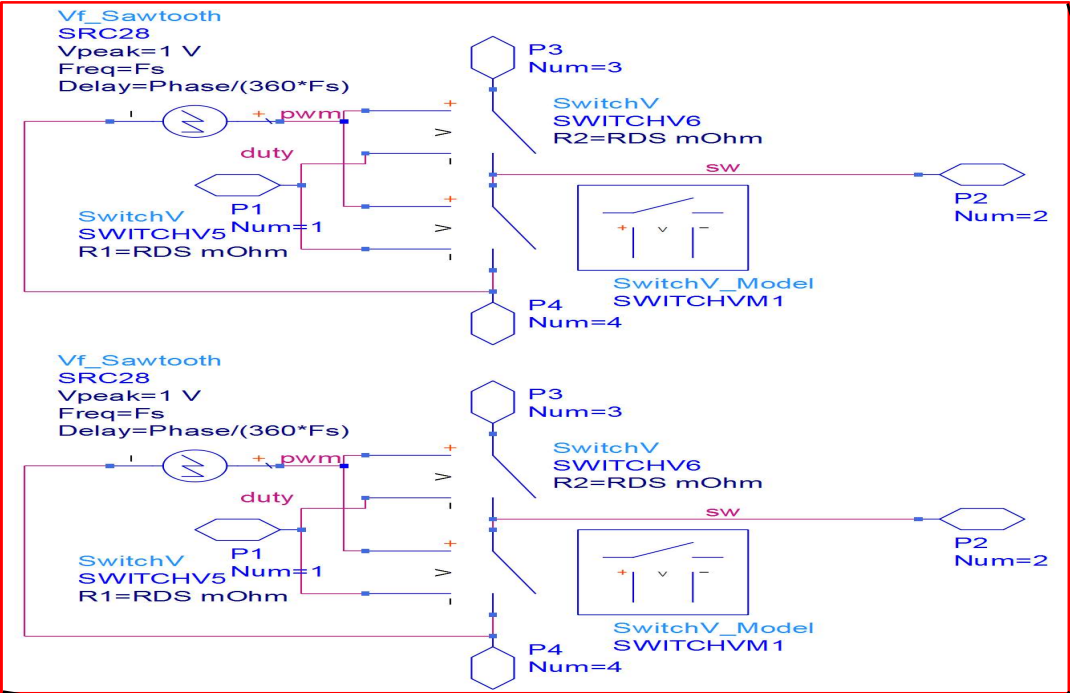
Mode	PSRR	Rout	Comments
Voltage	Poor	Poor	Large tolerance impact
Current	Excellent*	Excellent	Small tolerance impact

STATE SPACE AVERAGE MODEL for IMEDANCE, TRANSIENTS, HARMONICS



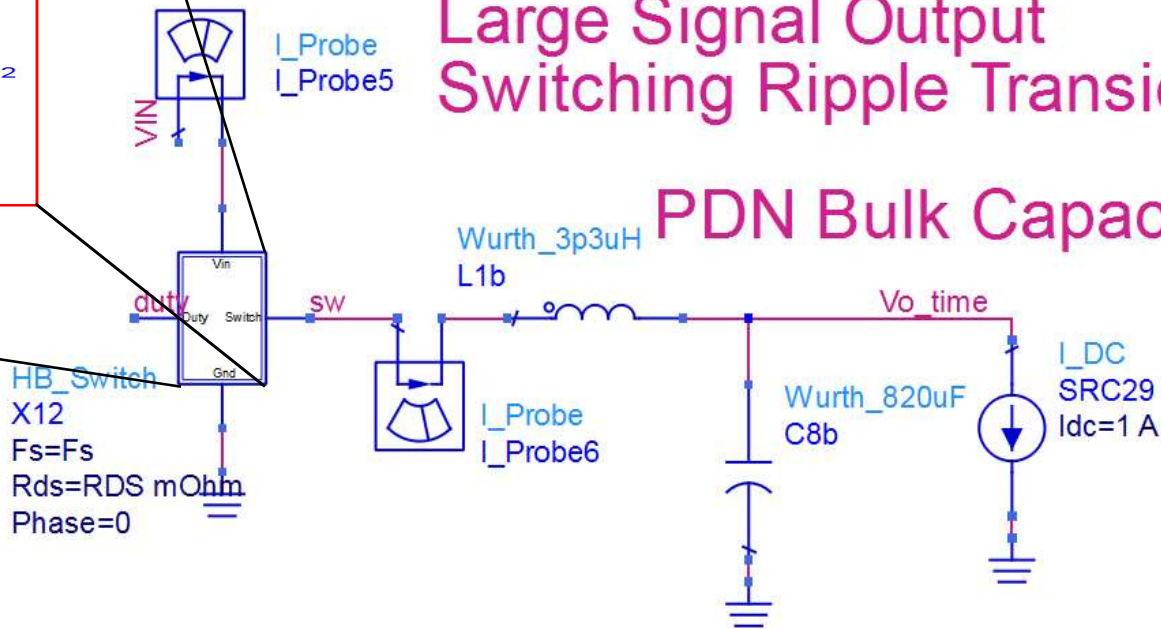
Switching Transients

Pulse Width Modulated Switch

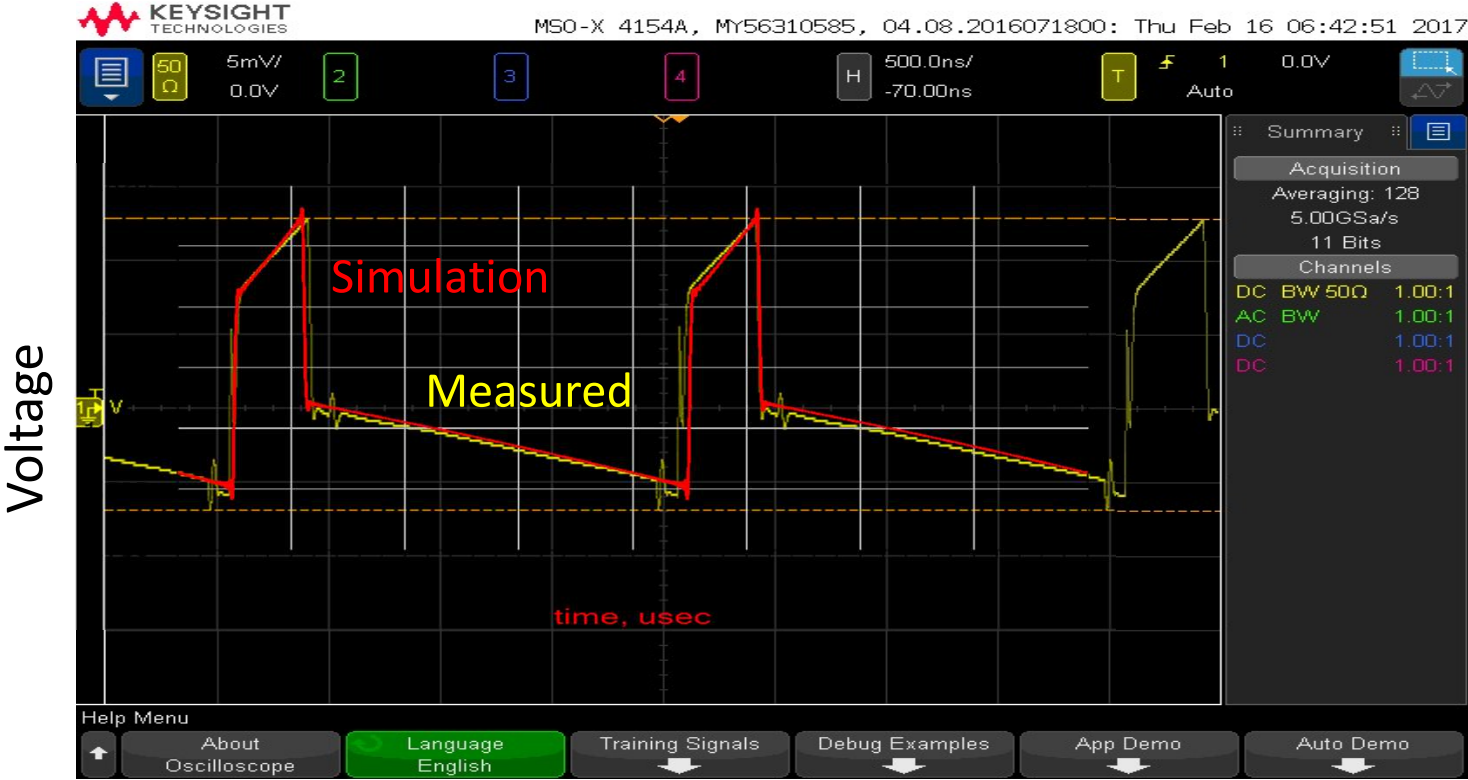
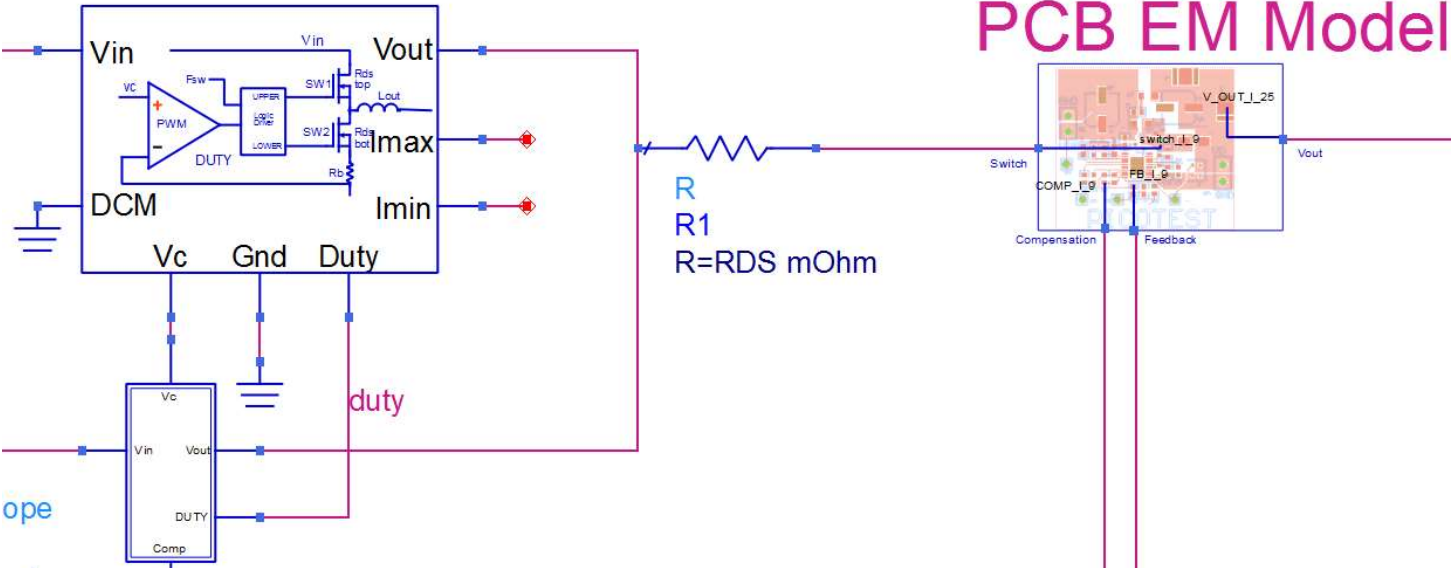
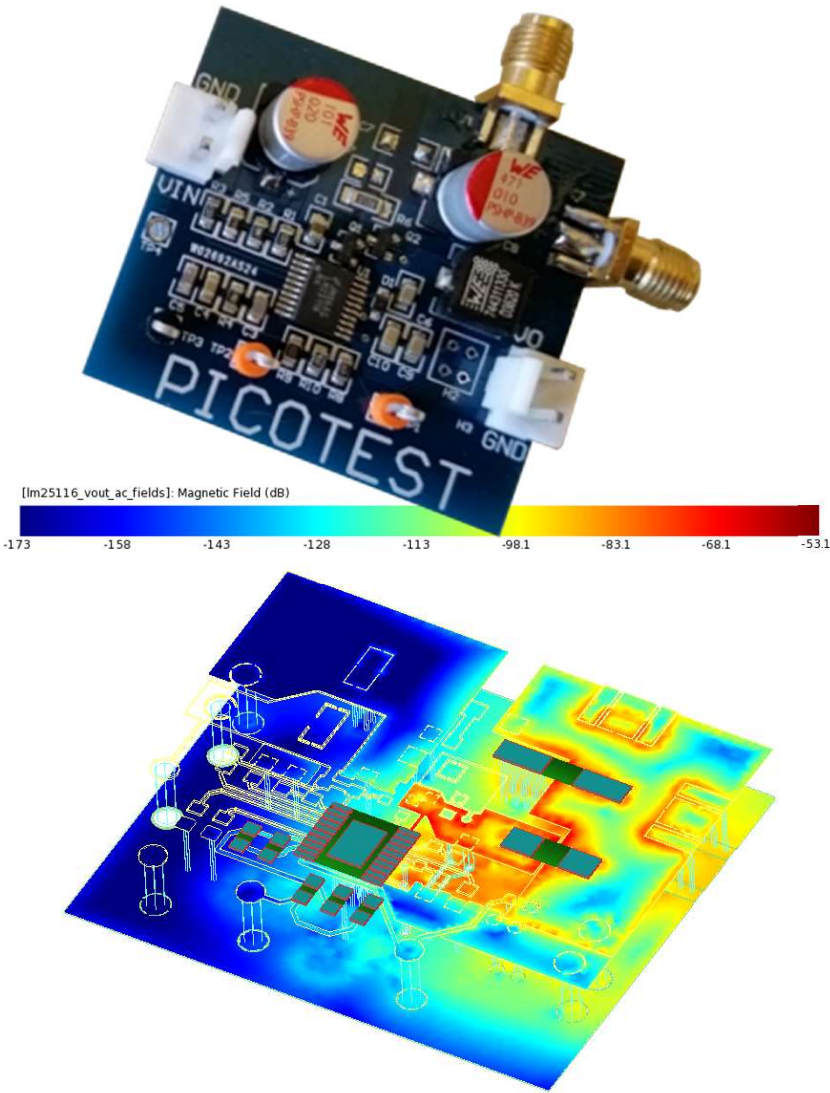


Large Signal Output
Switching Ripple Transients

PDN Bulk Capacitor and Load

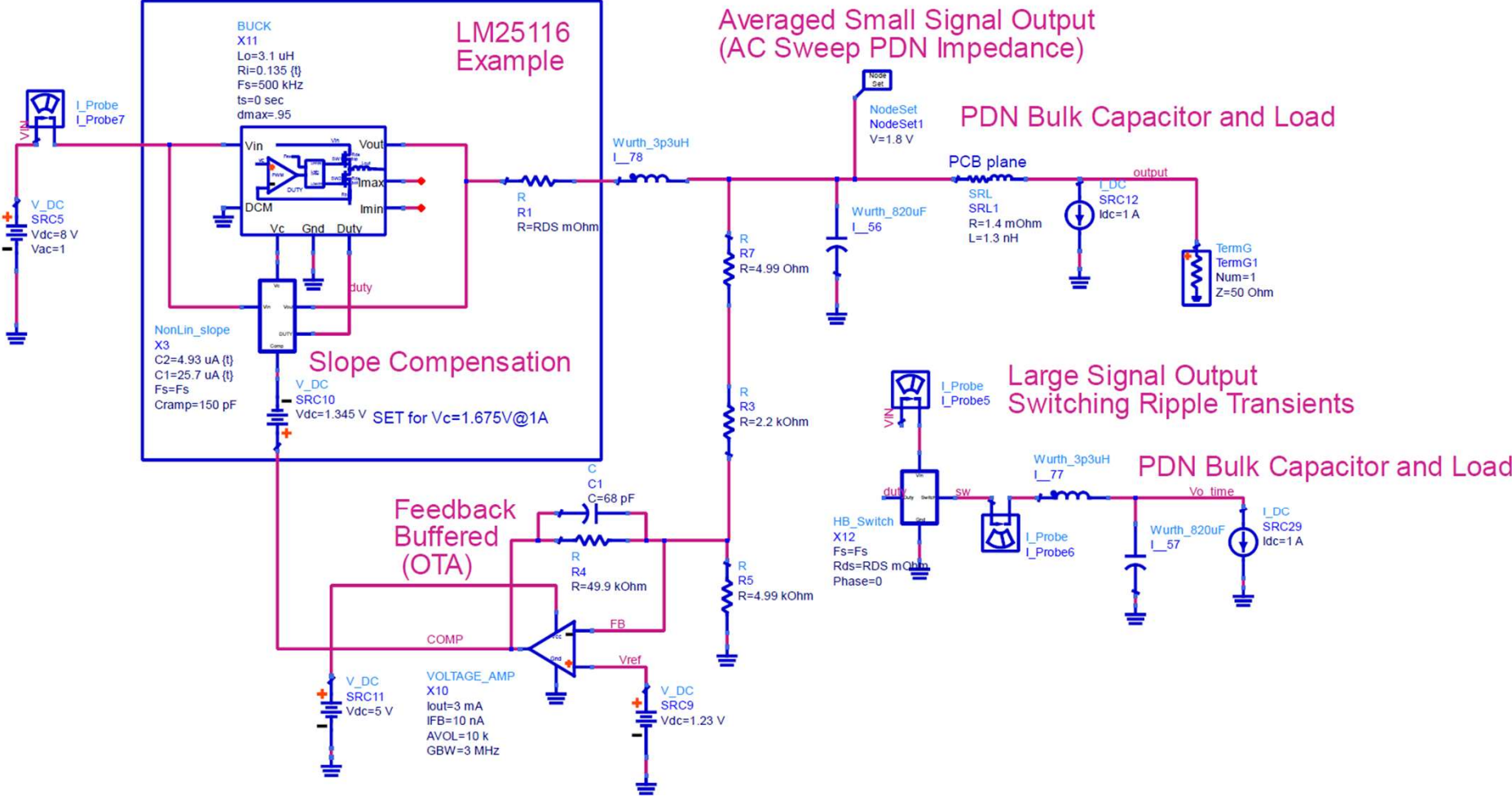


Adding EM



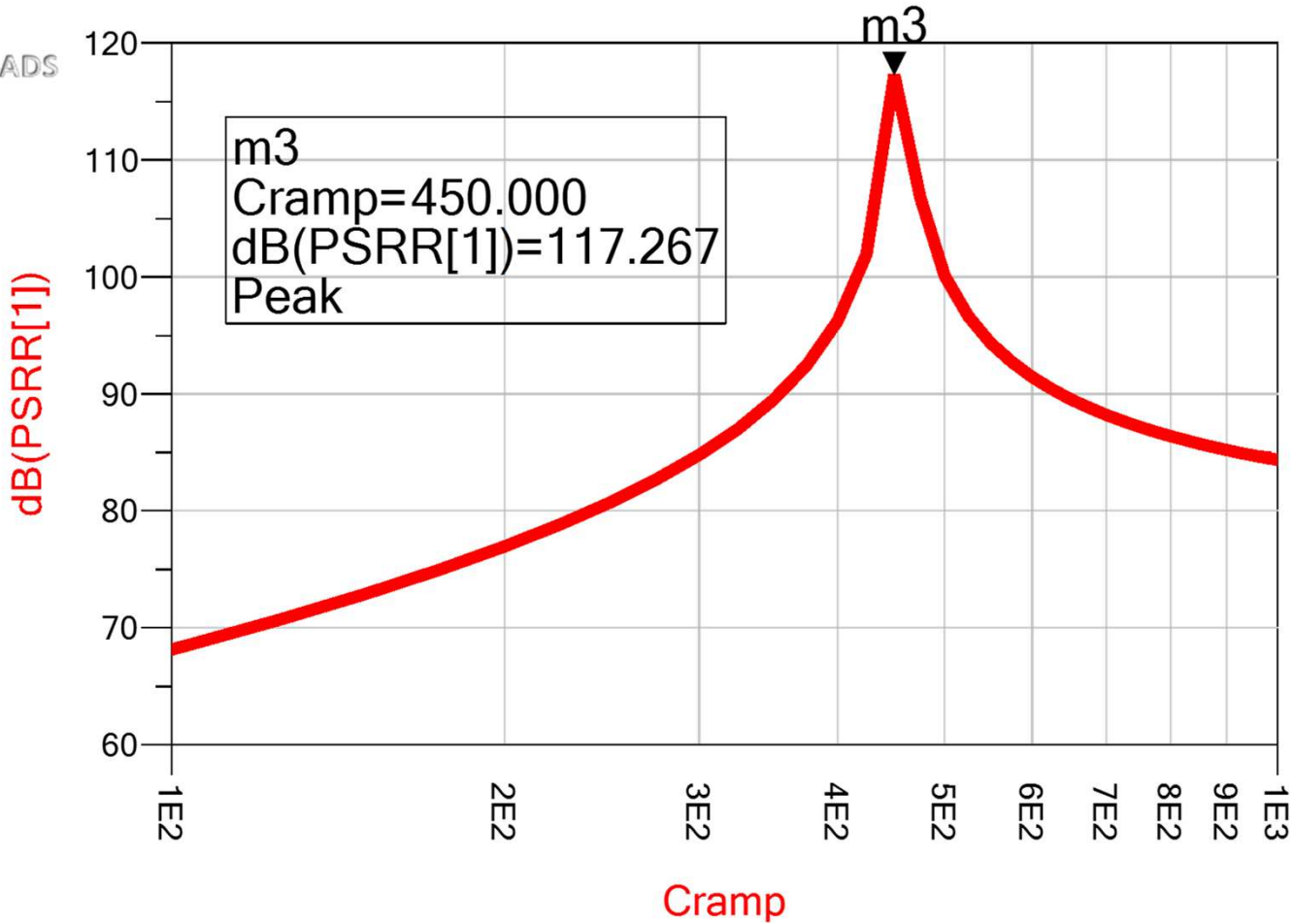
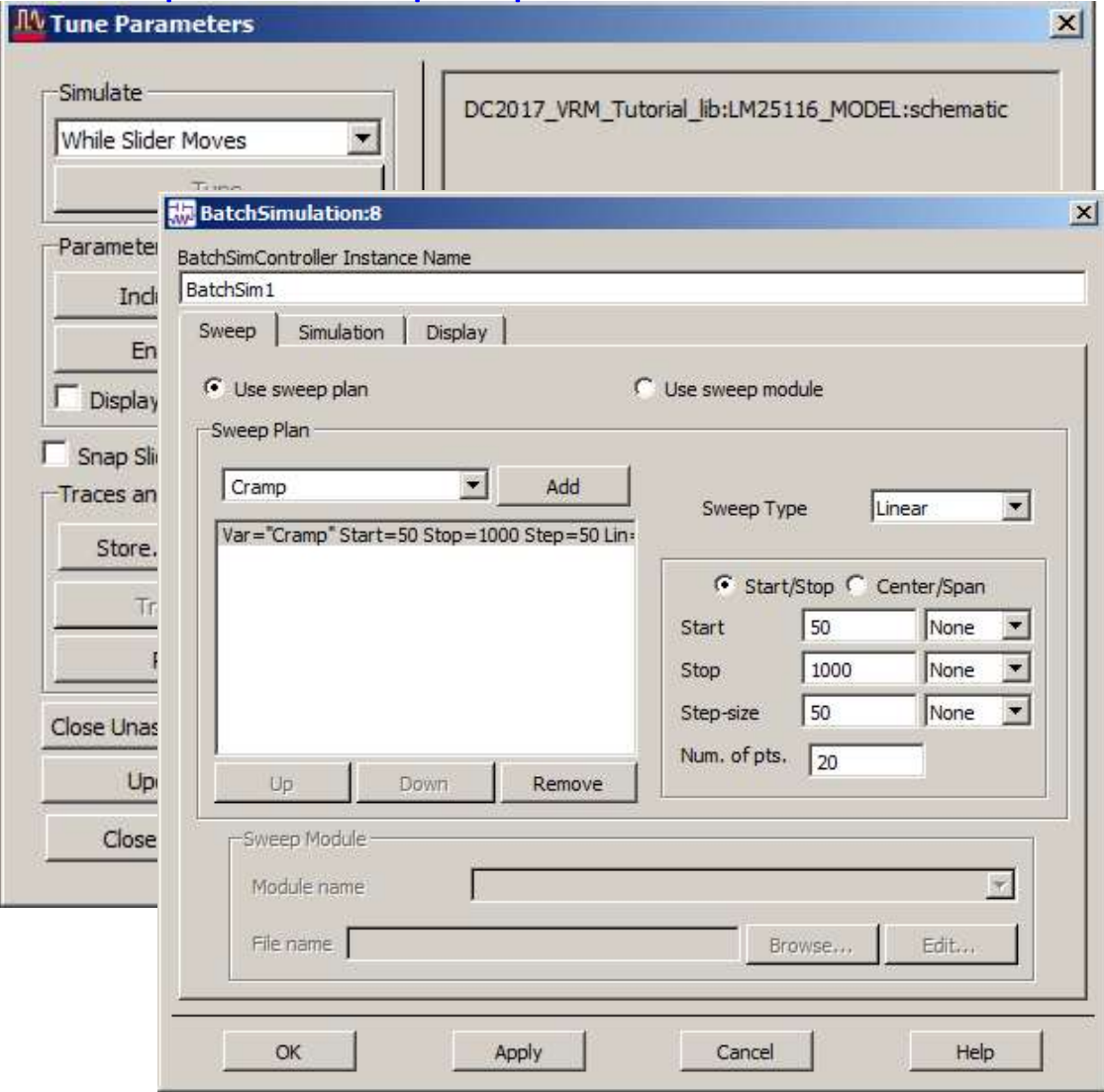
Complete DC-DC Converter Model

Small Signal Hybrid State Based Averaged VRM Model
Including Discontinuous and Continuous Mode (DCM) Operation



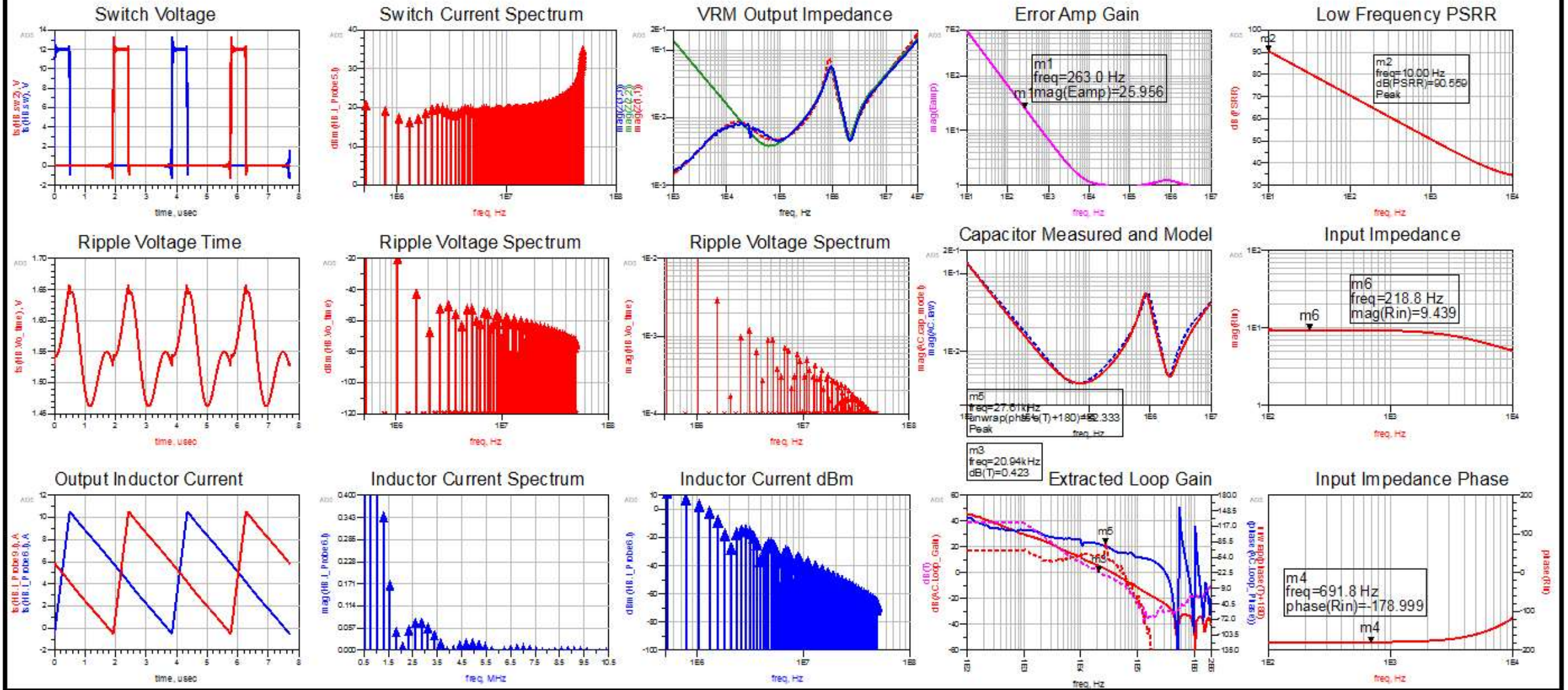
Exploring the DC-DC Converter Model Performance

Explore Cramp Impact on PSRR



...and it works for Multi-Phase

Multi-phase DC-DC Converter State Space Hybrid Model - TPS40140



Summary

- Why a VRM should have:
 - ✓ Current mode control
 - ✓ Series feedback for transconductance amplifiers
 - ✓ Flat impedance
- How tolerances impact voltage mode, feed-forward mode, and current mode VRMs

Hands-On Lab 3b:

200128_ADS_PI_Lab3b_Create_VRM_Model_wrk.7zads



Basics – Instructor Led Demo

VRM R-L Model Assumes Flat Impedance

Explore –

Explore - Measurement Based VRM Model with R_i and V_{ramp} and the sub components

Advanced –

Optimizing PSRR by adjusting the external C_{ramp} value

Thank You!

■ ■

Questions?