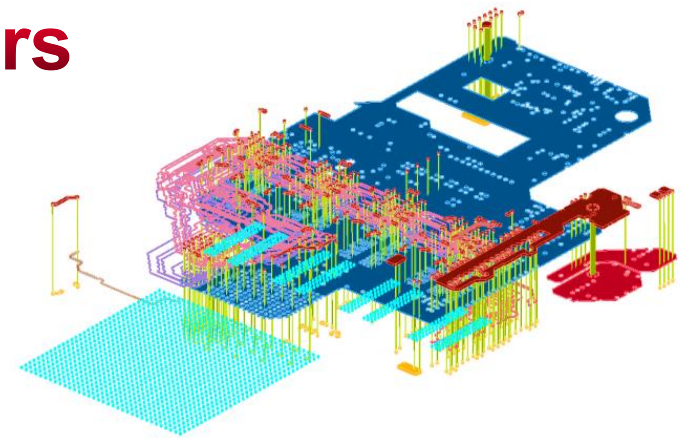
Power Integrity Boot Camp for Designers



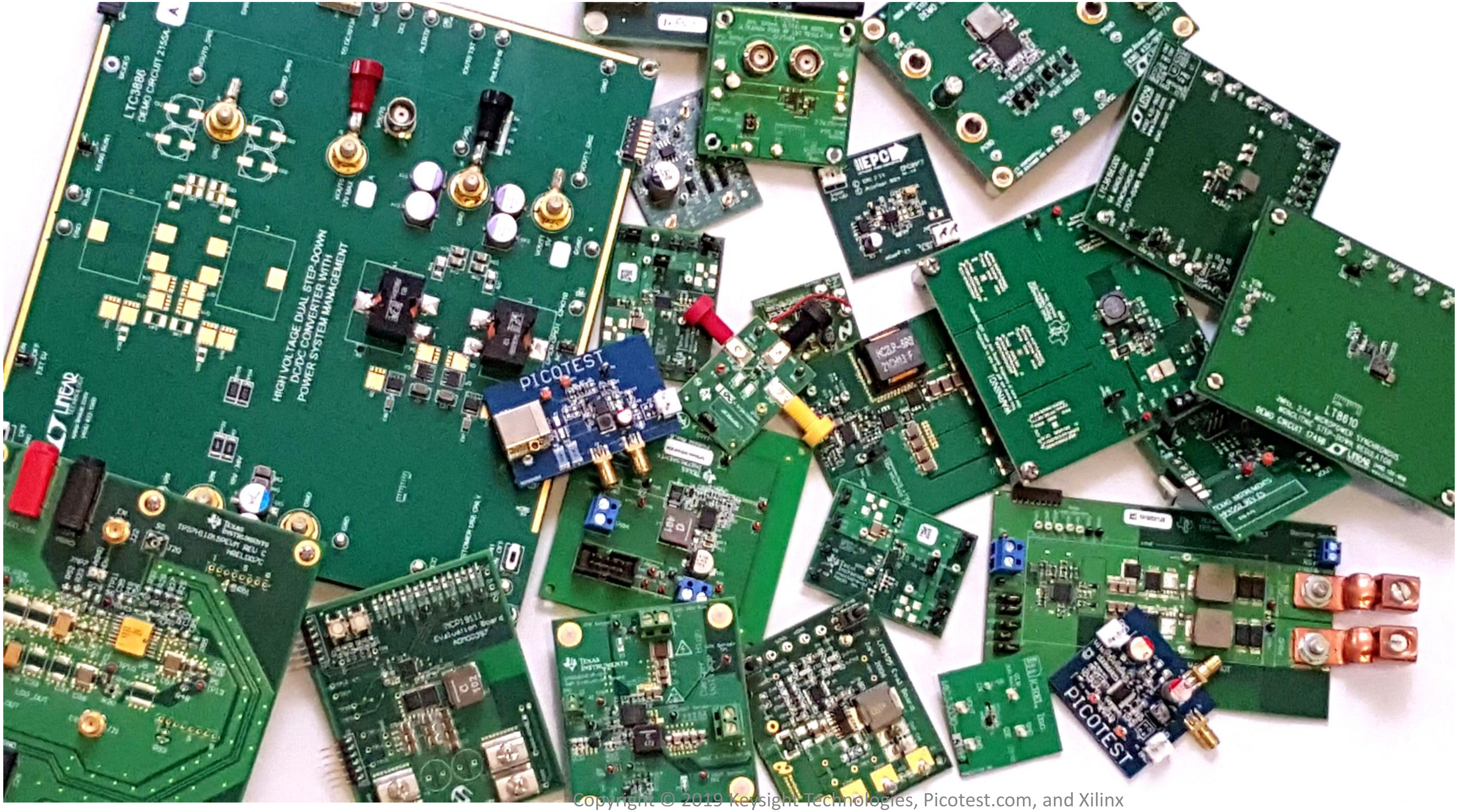
Section 3
Selecting and Modeling the Voltage Regulator Module (VRM)

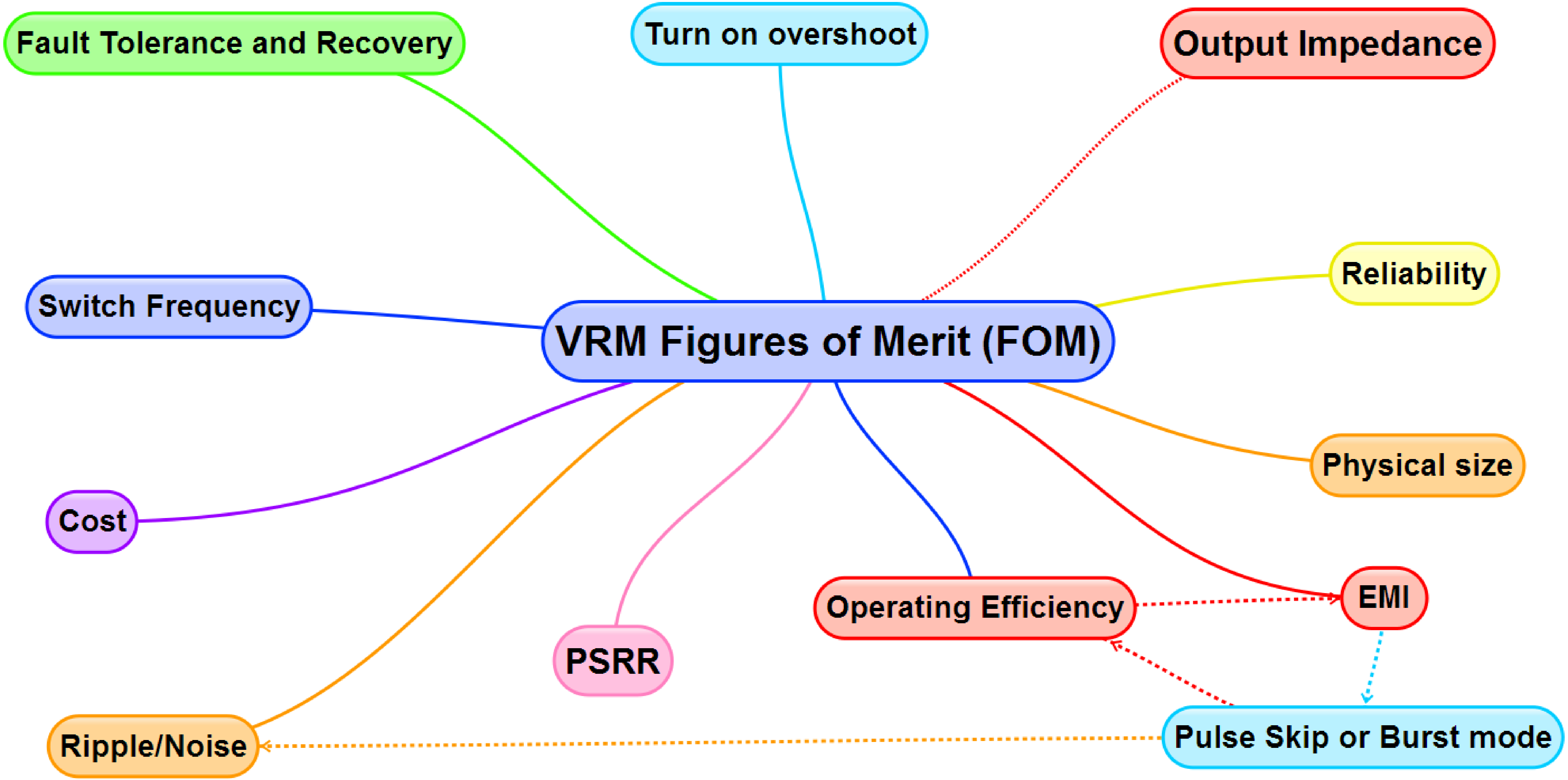
KEYSIGHT TECHNOLOGIES

with solutions partner

PICOTEST

Voltage Regulator Modules (VRM)




VRM Figures of Merit (FOM)
Fault Tolerance and Recovery
Turn on overshoot
Output Impedance
Reliability
Switch Frequency
Physical size
Cost
EMI
Operating Efficiency
PSRR
Ripple/Noise
Pulse Skip or Burst mode

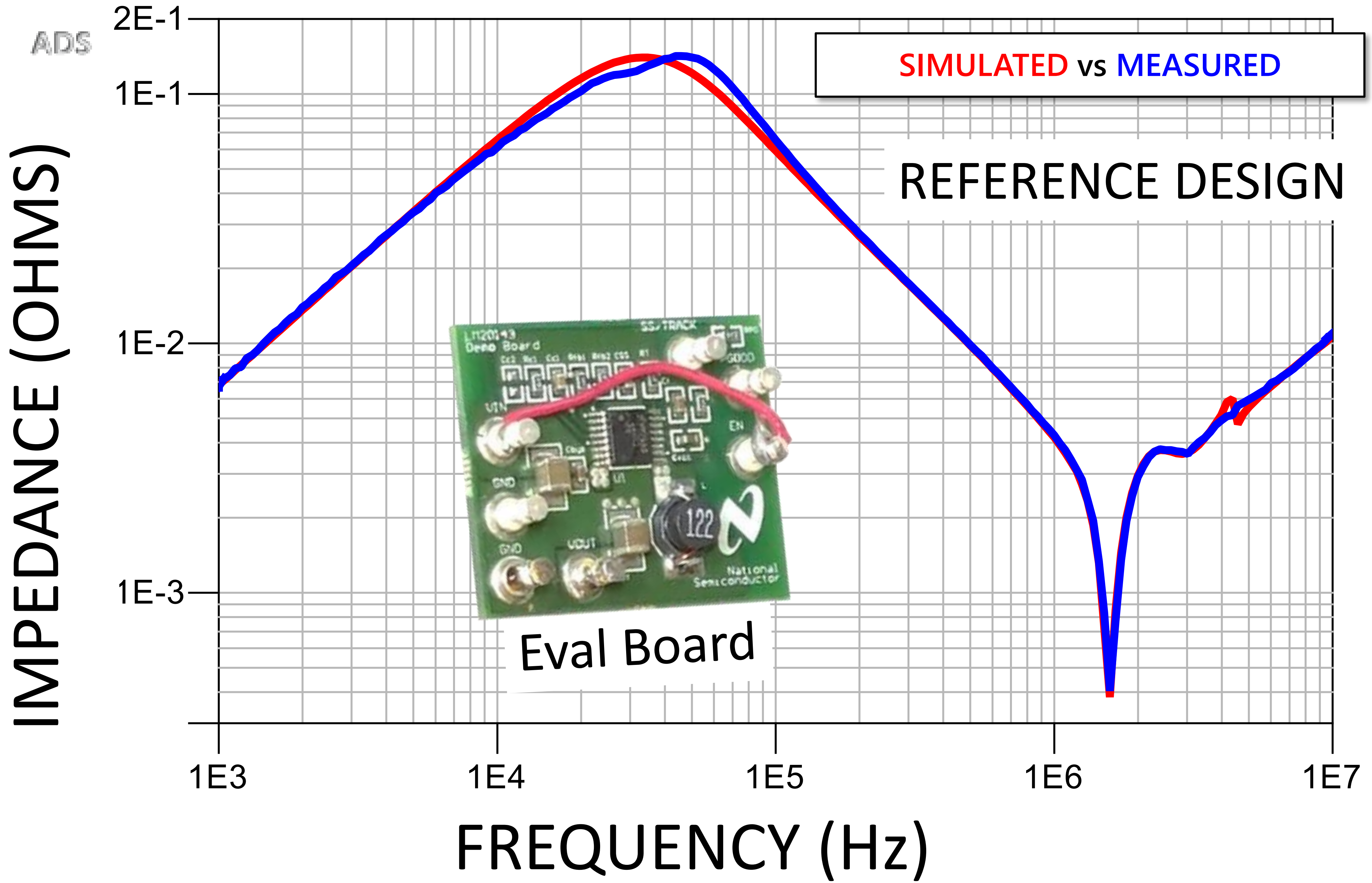
Key Topics

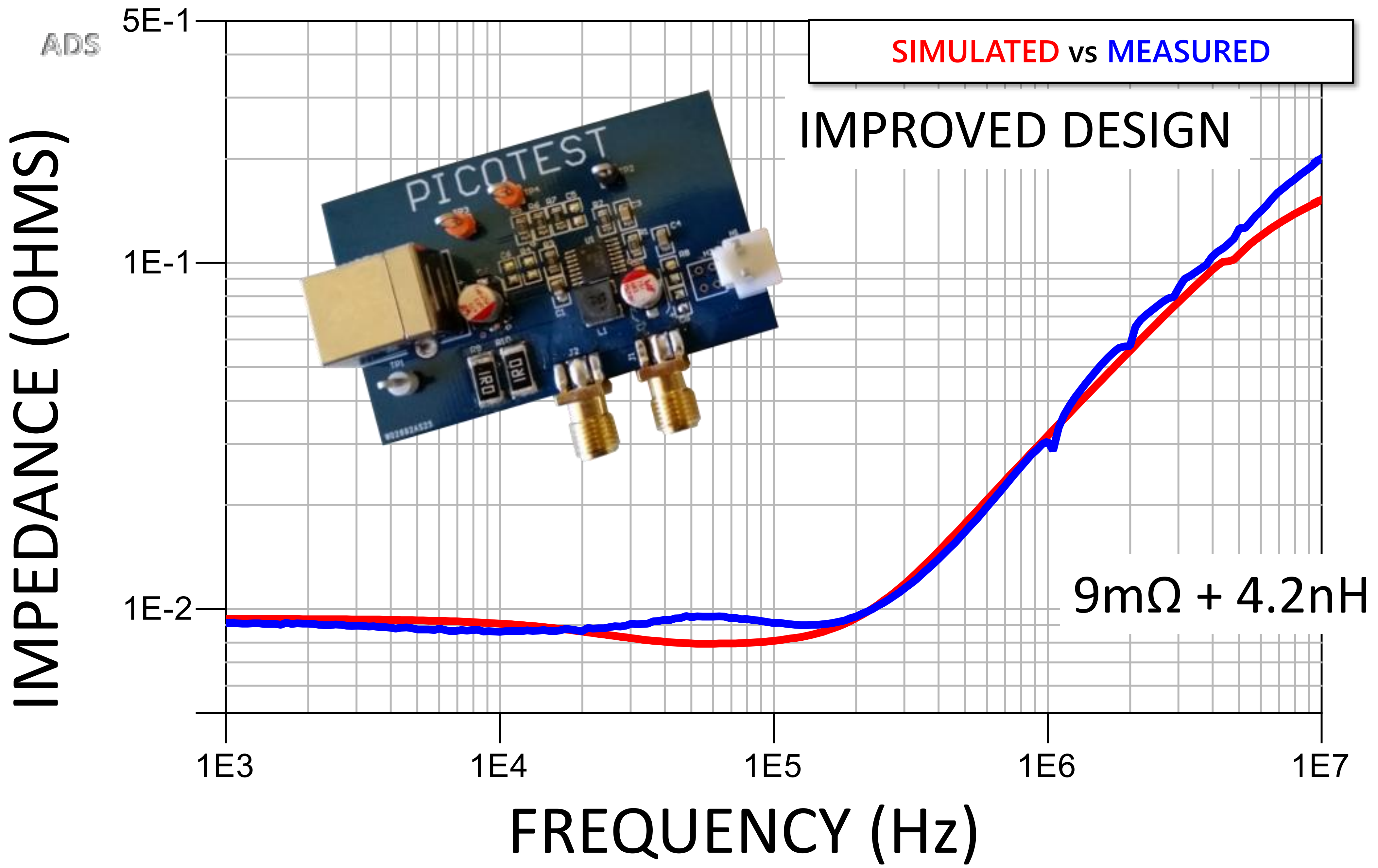
Using Simulation and Measurement to Gain Insight into the Solution !

1. Flat impedance is the PDN design goal

2. VRM selection is not arbitrary:

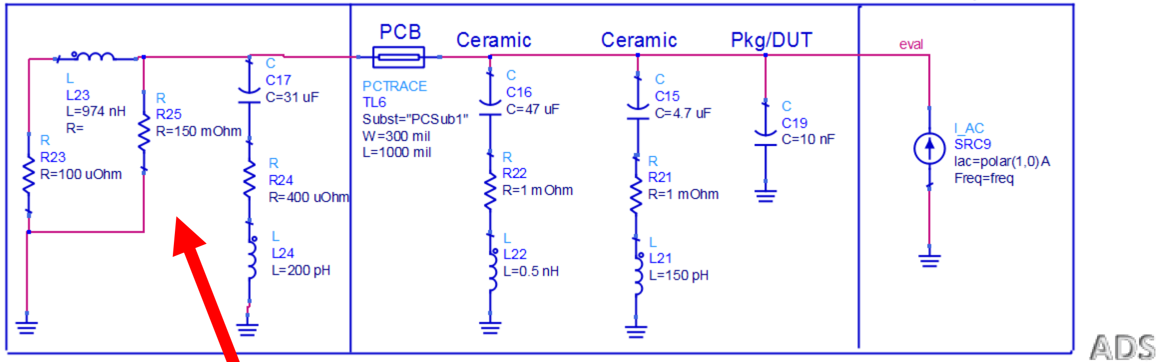
   - VRM voltage mode vs. current mode control
   - VRM shunt feedback vs series feedback for transconductance amplifiers


ADS
2E-1
1E-1
1E-2
1E-3
IMPEDANCE (OHMS)
SIMULATED vs MEASURED
REFERENCE DESIGN
Eval Board
1E3
1E4
1E5
1E6
1E7
FREQUENCY (Hz)



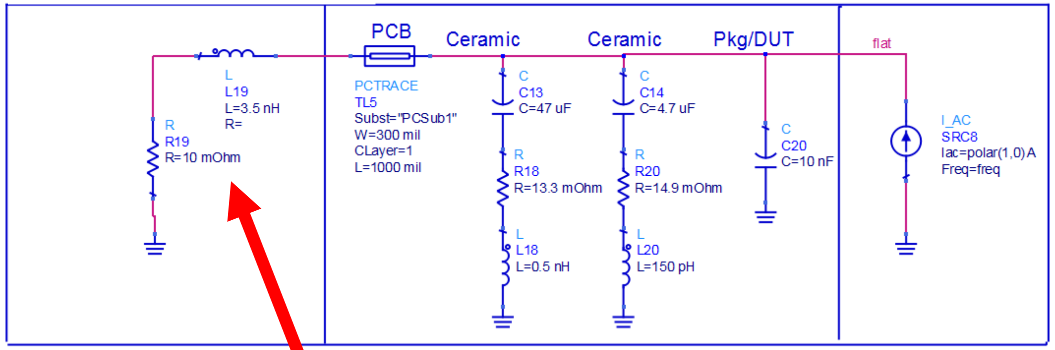
ADS
5E-1
1E-1
1E-2
SIMULATED vs MEASURED
IMPROVED DESIGN
PICOTEST
9mΩ + 4.2nH
IMPEDANCE (OHMS)
1E3
1E4
1E5
1E6
1E7
FREQUENCY (Hz)

VRM Impedance Model | **PDN Capacitors** | **AC Sweep for Z**



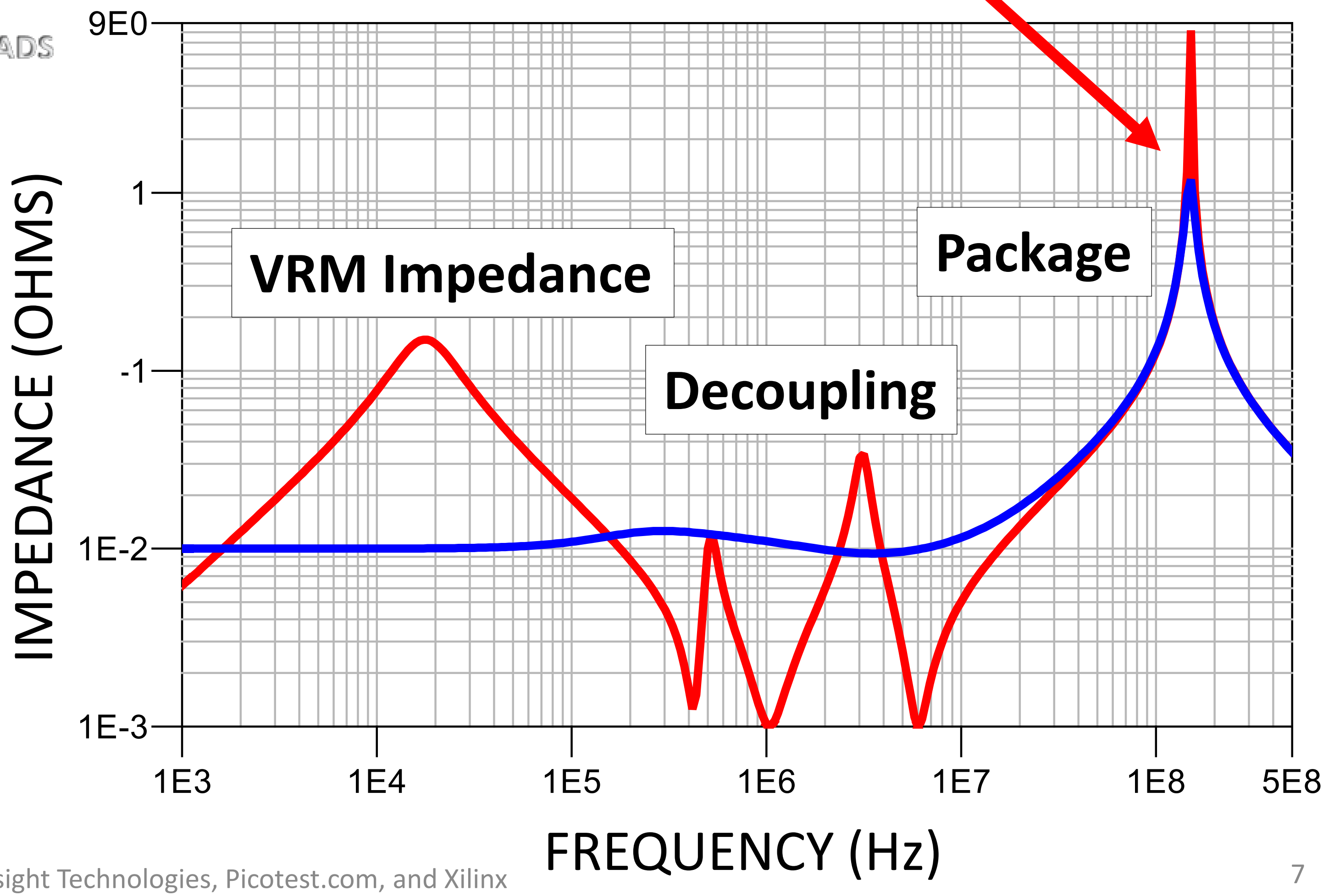
Reference Design does not fit an R/L Model!

VRM Impedance Model | **PDN Capacitors** | **AC Sweep for Z**

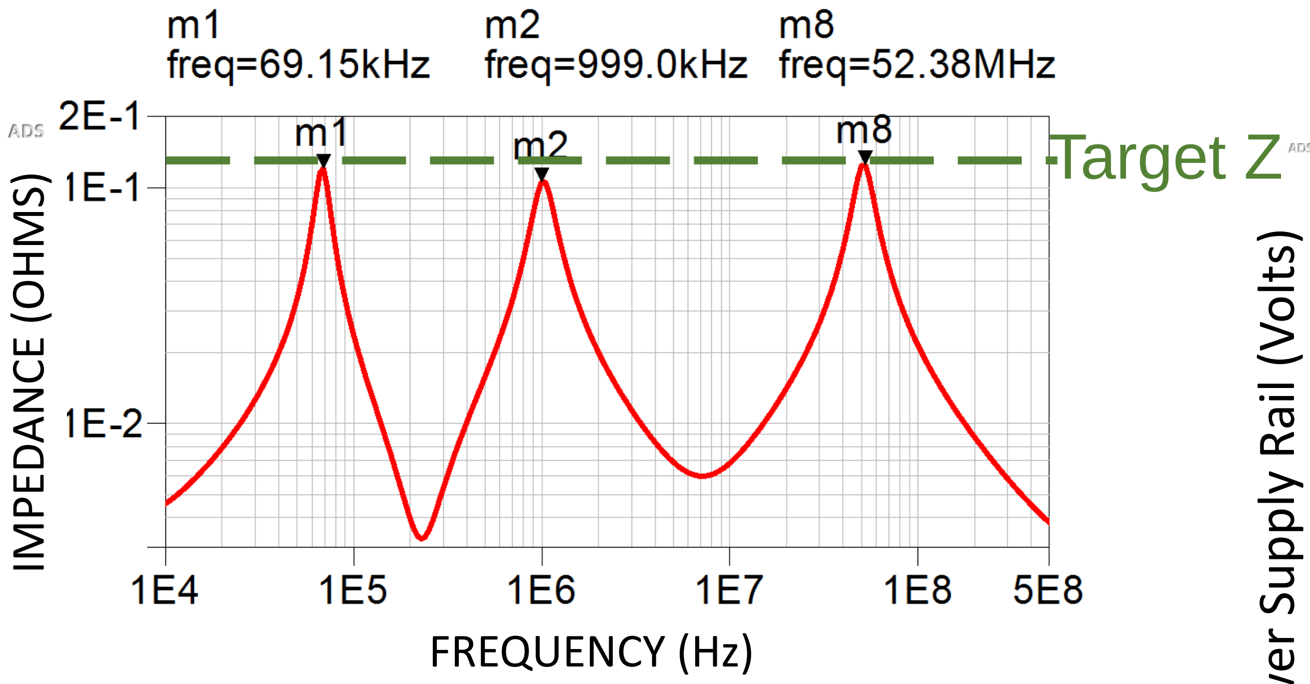


R/L model assumes a flat PDN design!

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



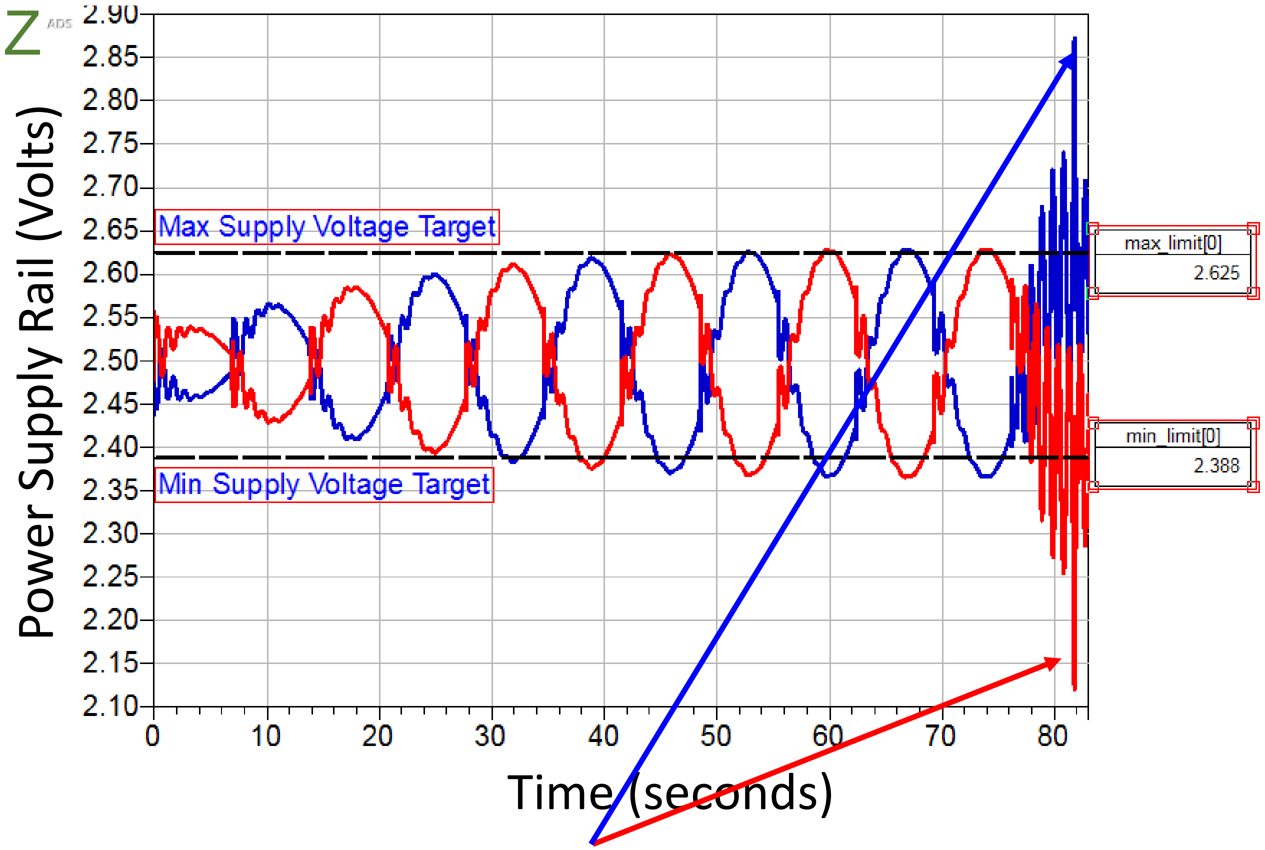
PDN Impedance vs Frequency

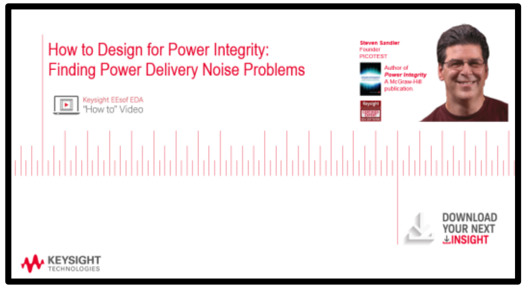


Power Supply Noise from Forced Response

Maximum and Minimum

Rogue Wave Response

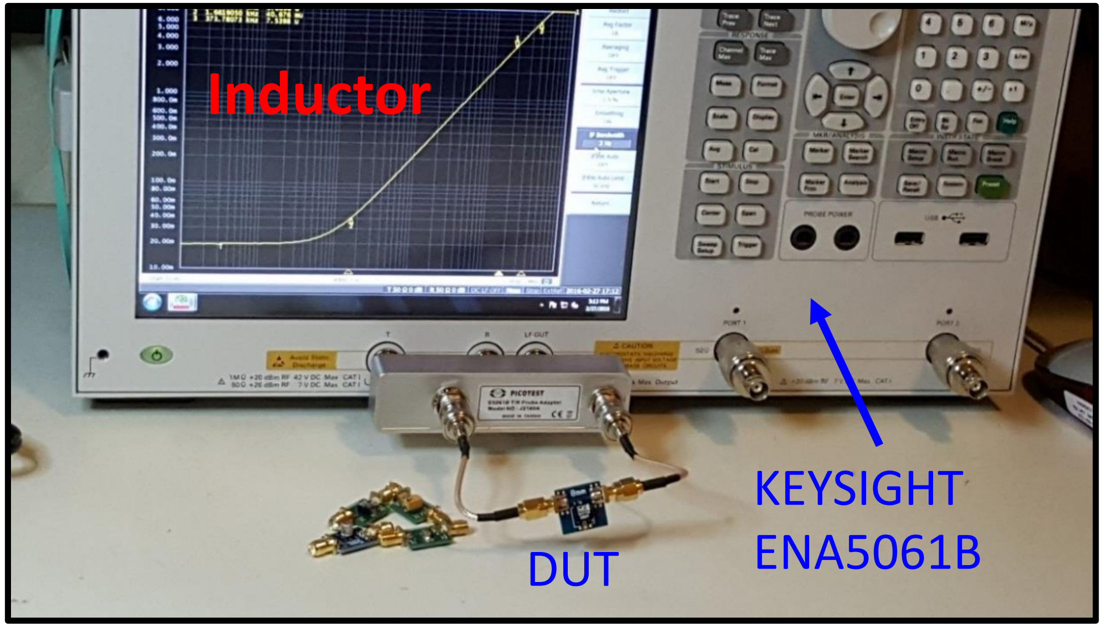


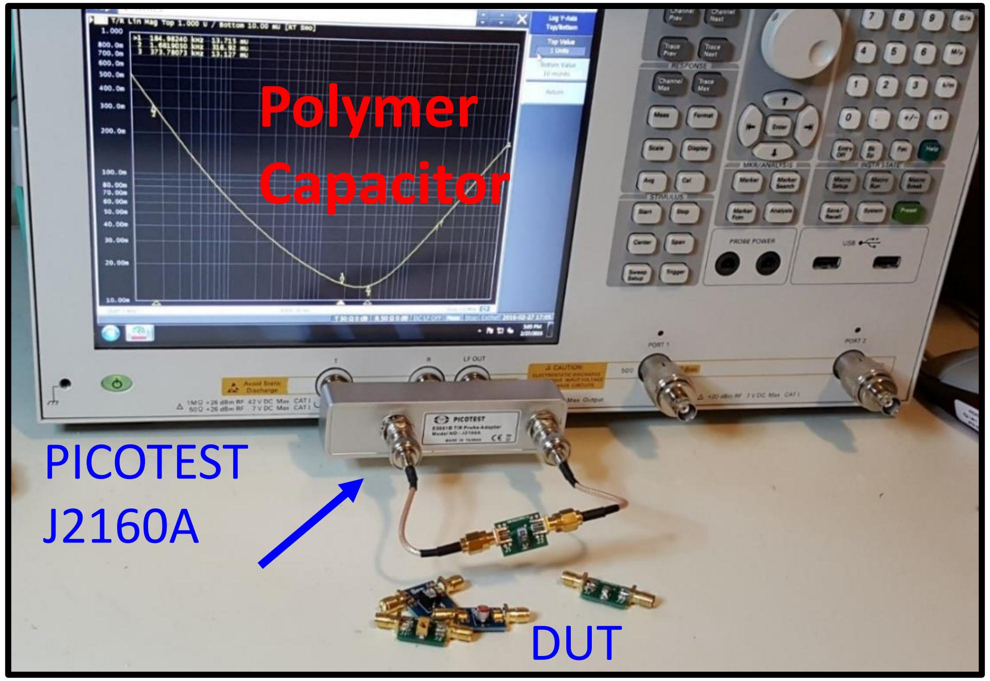


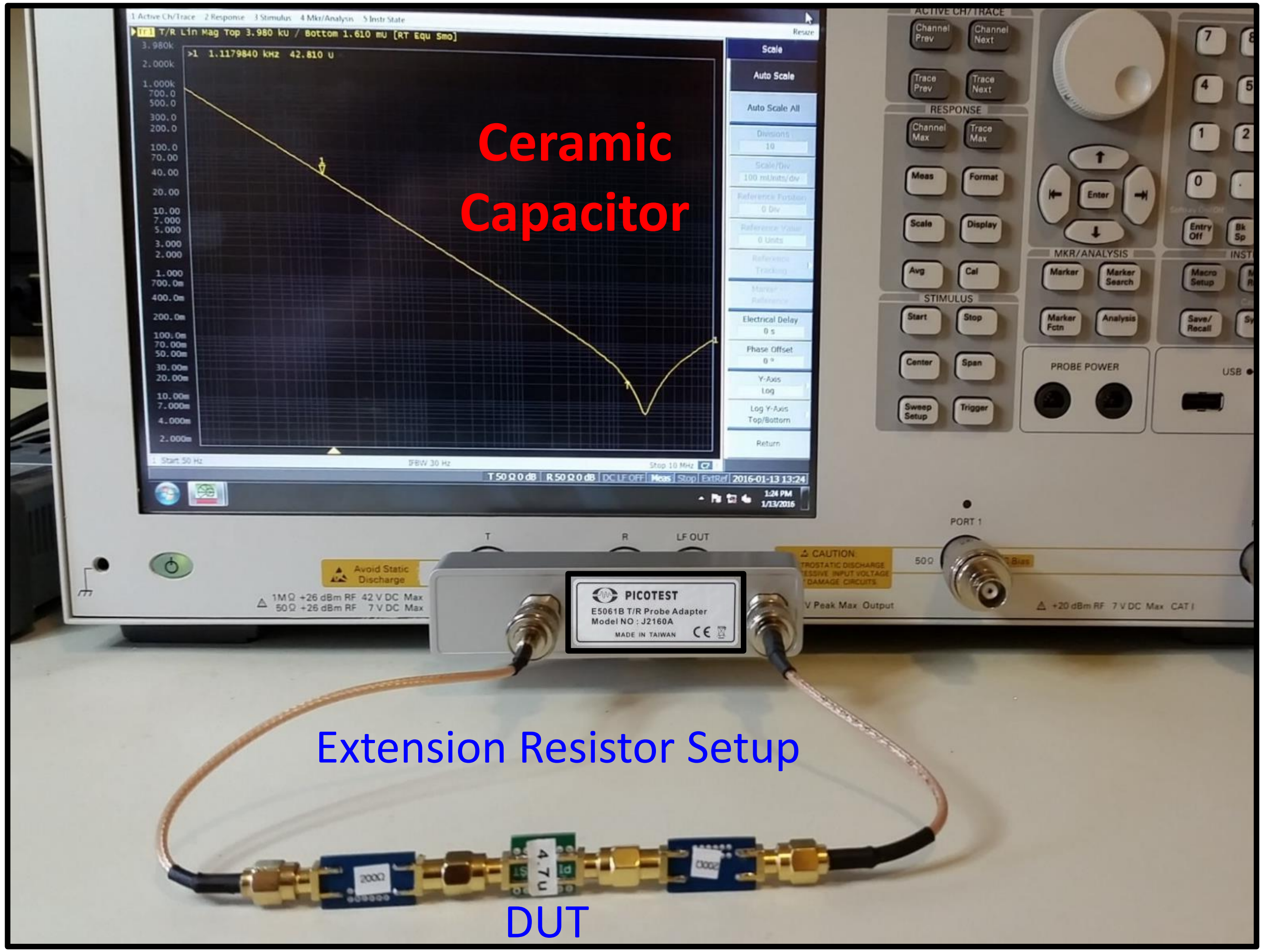
How to Design for Power Integrity: Finding Power Delivery Noise Problems

Search "YouTube Keysight How to PDN"

Multiple resonances can accumulate into a rogue wave!



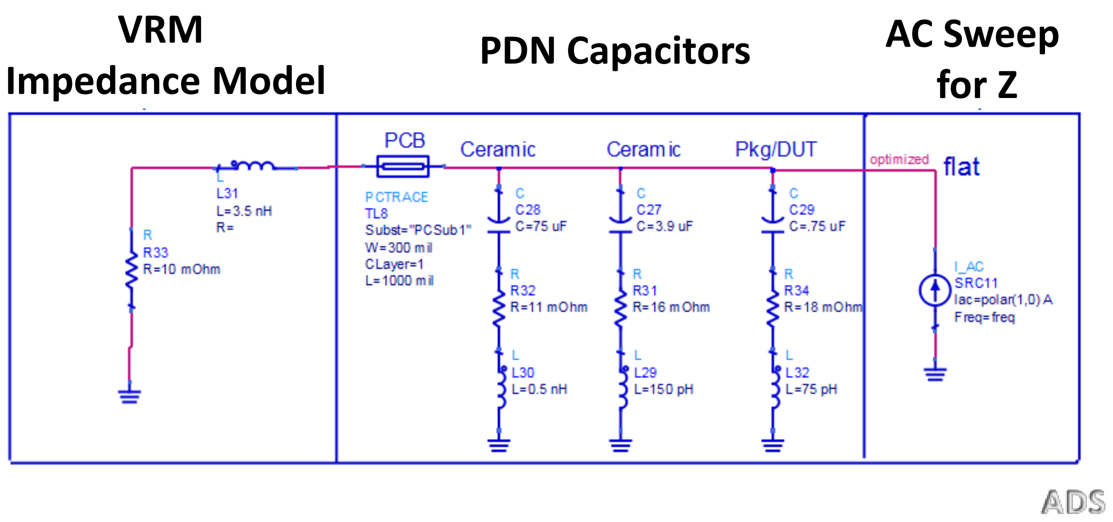




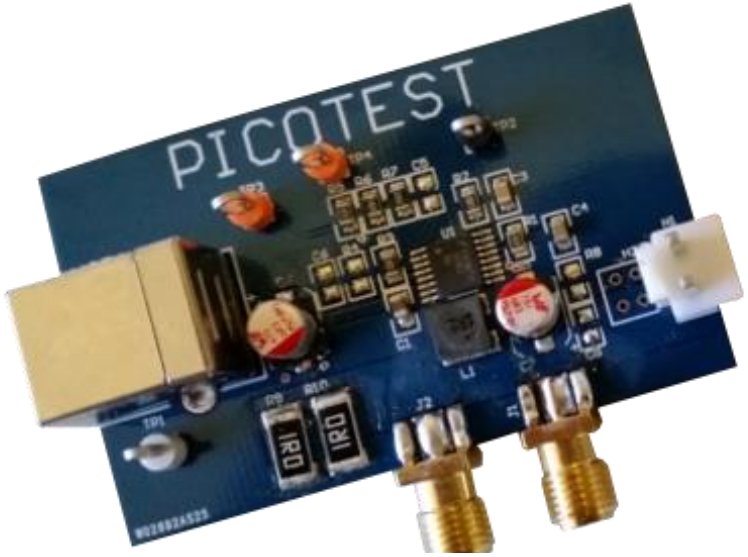
EDN NETWORK

Increase range in 2-port impedance measurements

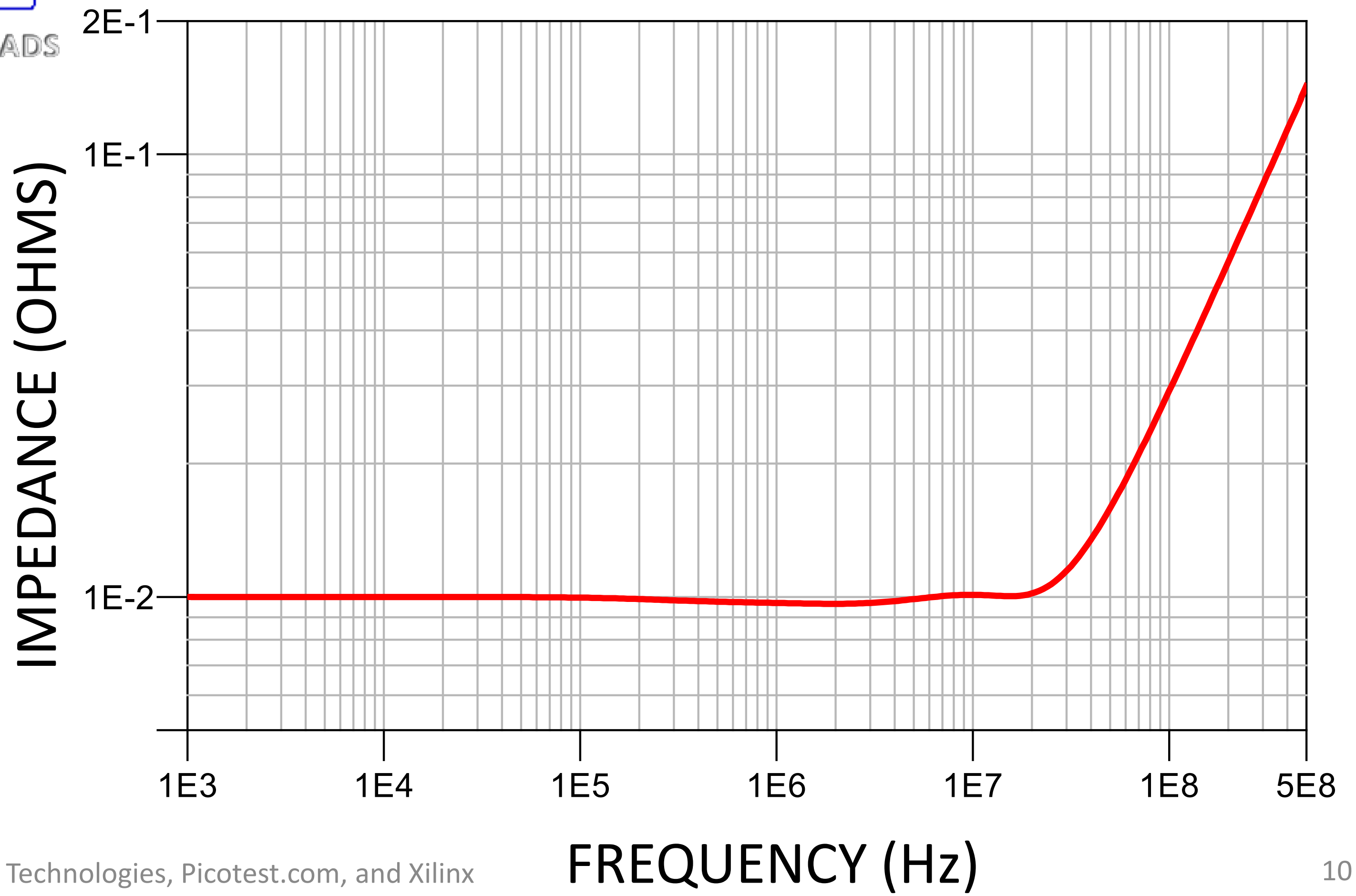
Steve Sandler - May 04, 2015

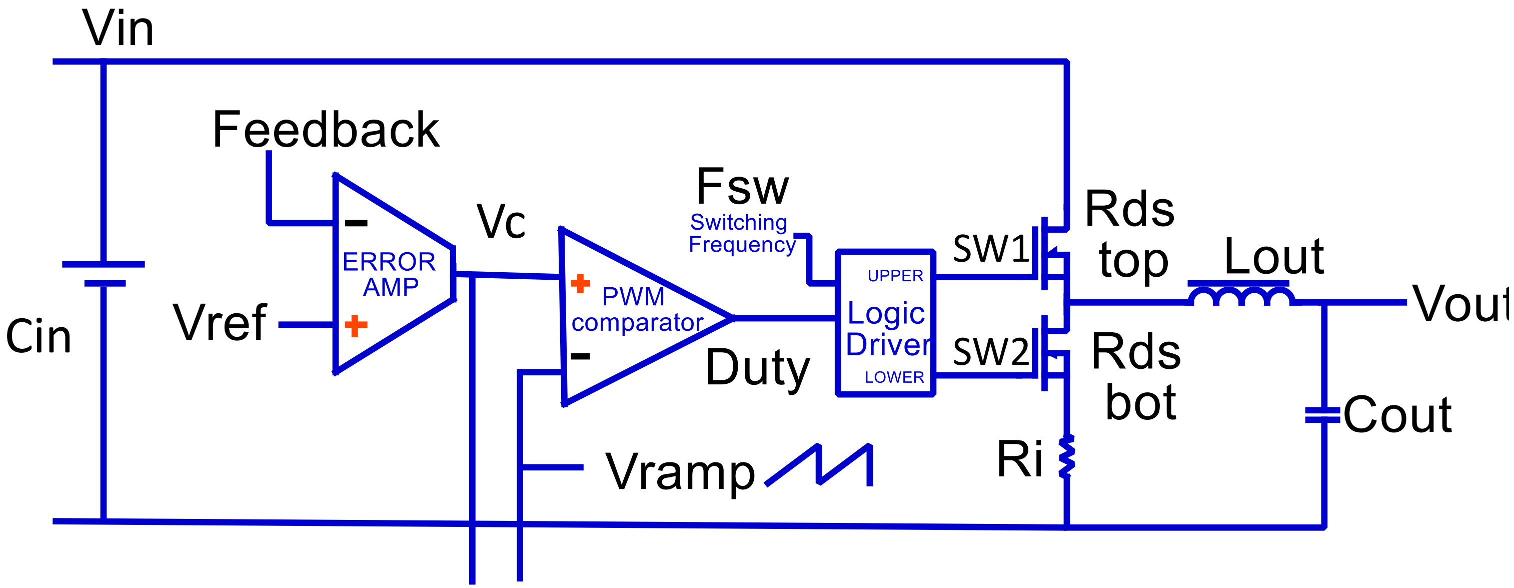


Many VRMs can be tuned for Flat Z. So how do we choose the right one?

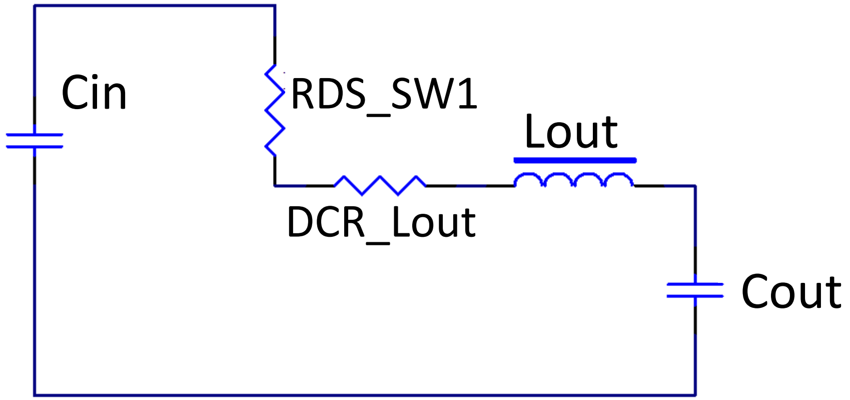


IMPROVED DESIGN





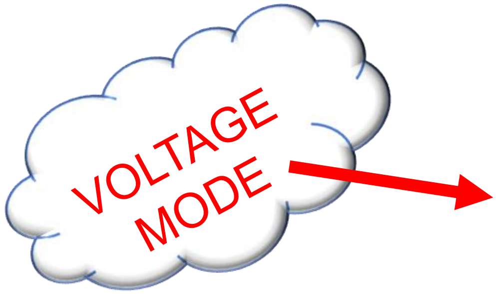
State 1: SW1 = On and SW2= Off



STATE SPACE AVERAGED MODEL

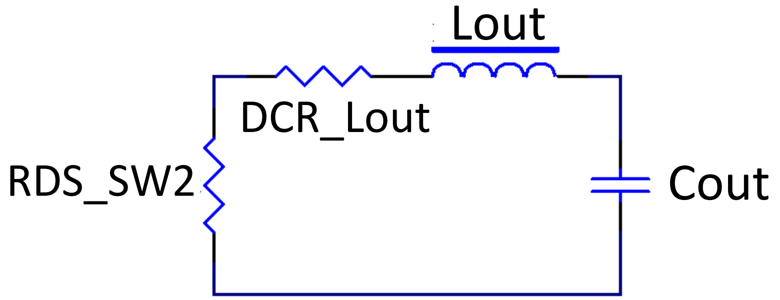
$$Duty = Ton\_SW1 \cdot Fsw$$

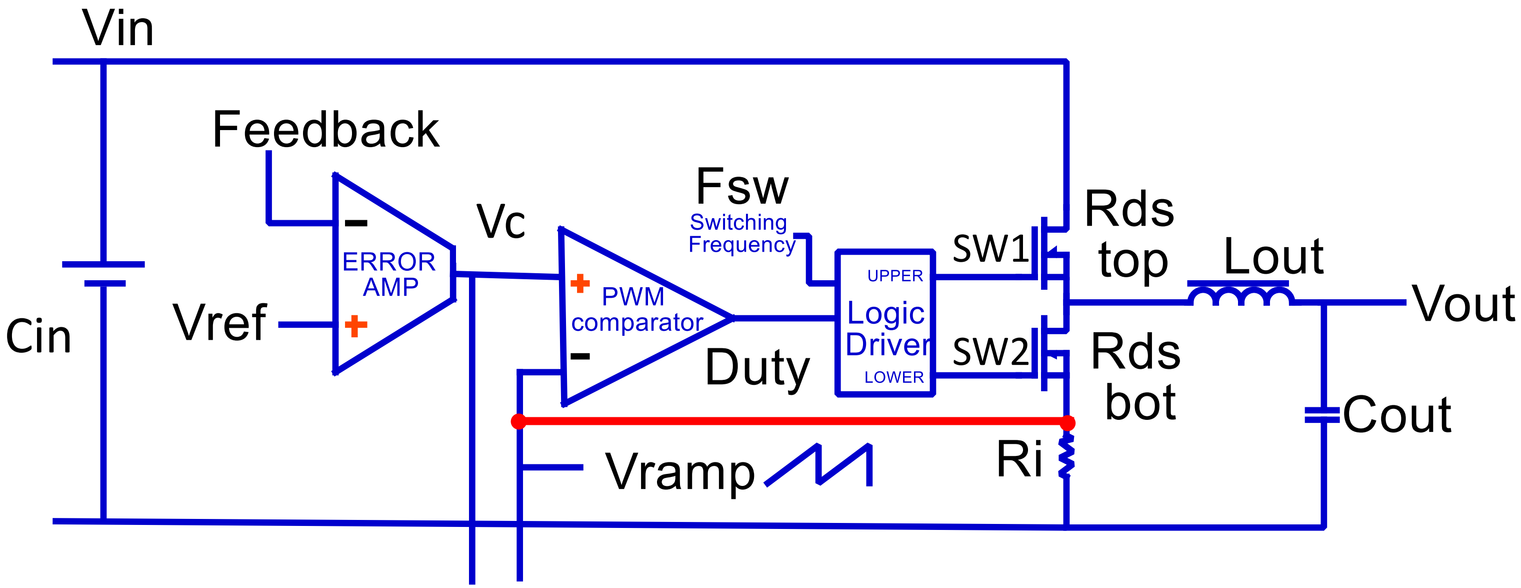
$$Vout = Vin \cdot Duty$$



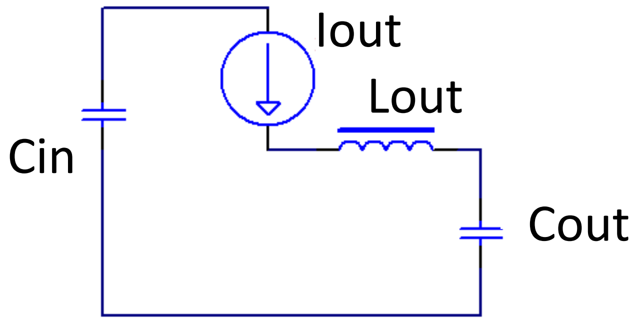
$$Vout = Vin \cdot \frac{Vc}{Vramp}$$

State 2: SW1 = Off and SW2= On





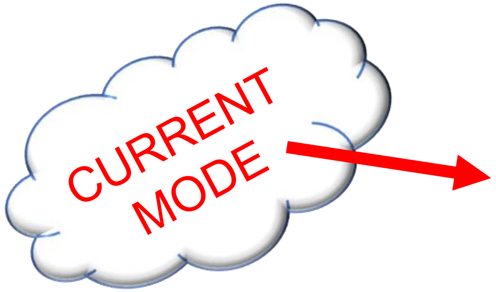
State 1: SW1 = On and SW2= Off



STATE SPACE AVERAGED MODEL

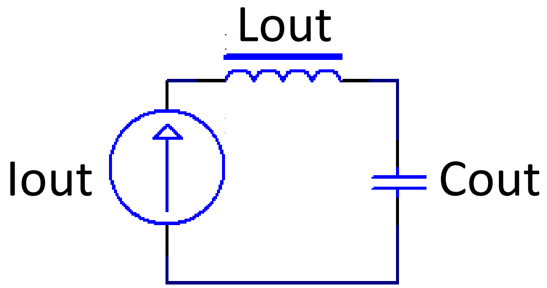
$$Duty = Ton\_SW1 \cdot Fsw$$

$$Vout = Vin \cdot Duty$$



$$Iout = k\frac{Vc}{Ri}$$

State 2: SW1 = Off and SW2= On

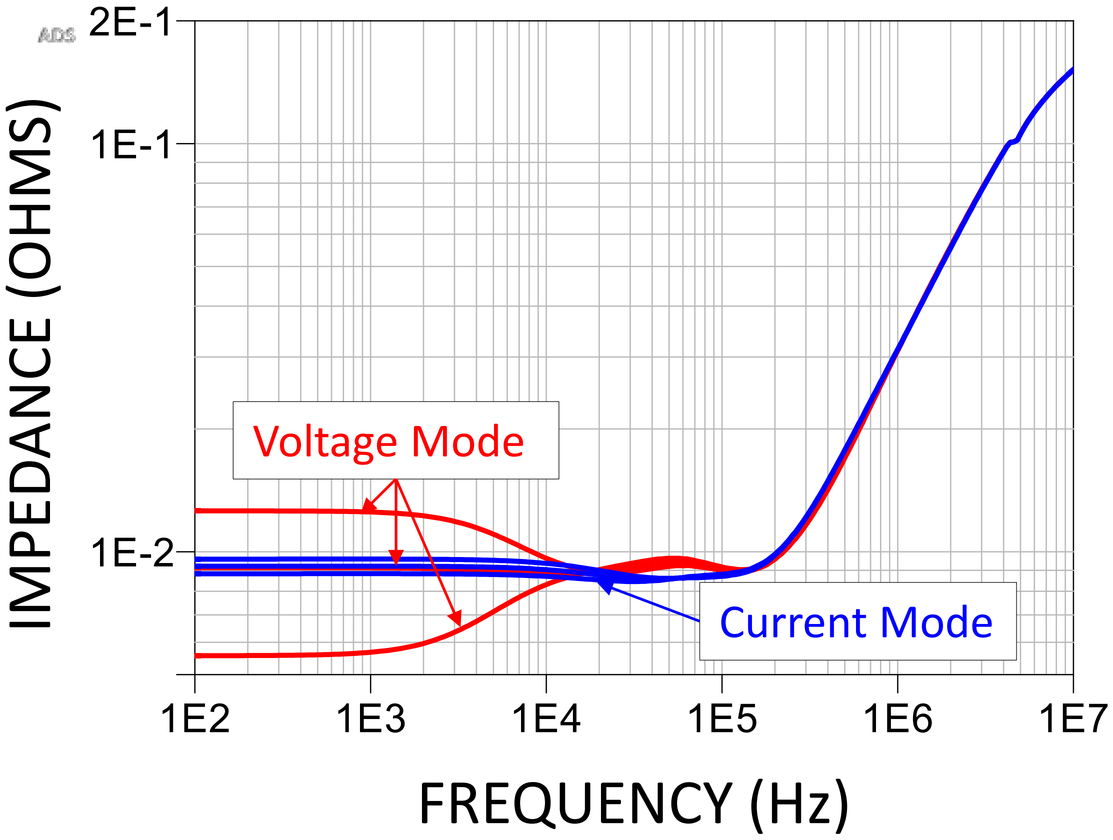


Nominal Impedance is the same,
Voltage Mode is very sensitive to tolerances

$$\mathbf{Rout\_CM} = \frac{Ri}{1 + Av}$$

$$\mathbf{Rout\_VM} = \frac{DCR_{Lo} + RDSon_{bot} + \left(RDSon_{top} - RDSon_{bot}\right) \cdot \frac{Vo}{Vin}}{1 + Av \cdot \frac{Vin}{Vramp}}$$

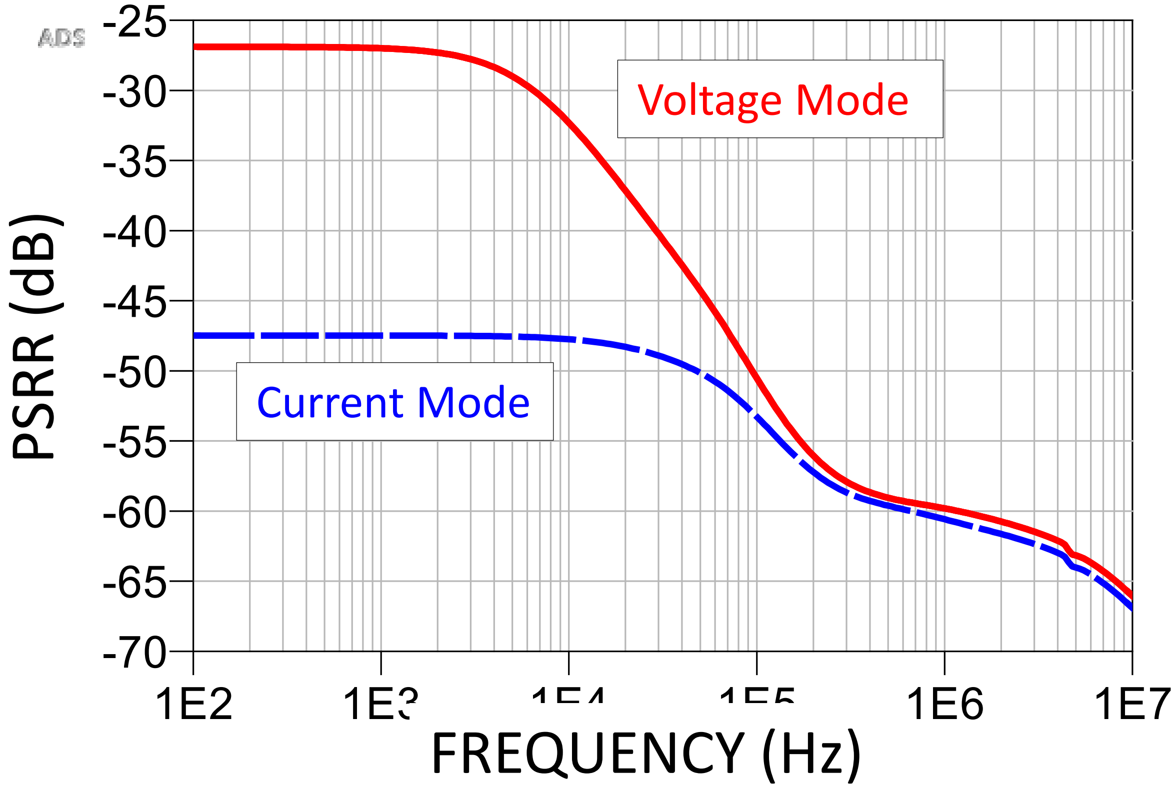
DCR_Lout +/- 45%



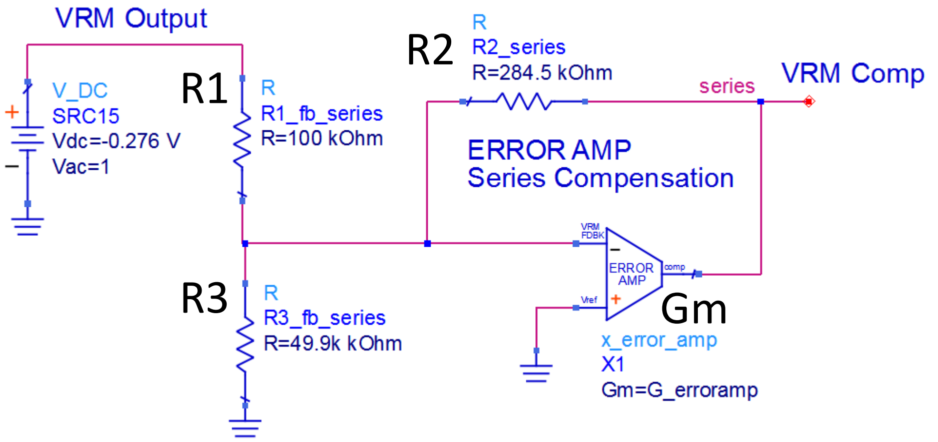
Nominal PSRR is very different between Current Mode and Voltage Mode

$$\mathrm{PSRR} = \frac{Vo\ (ac)}{Vin\ (ac)}$$

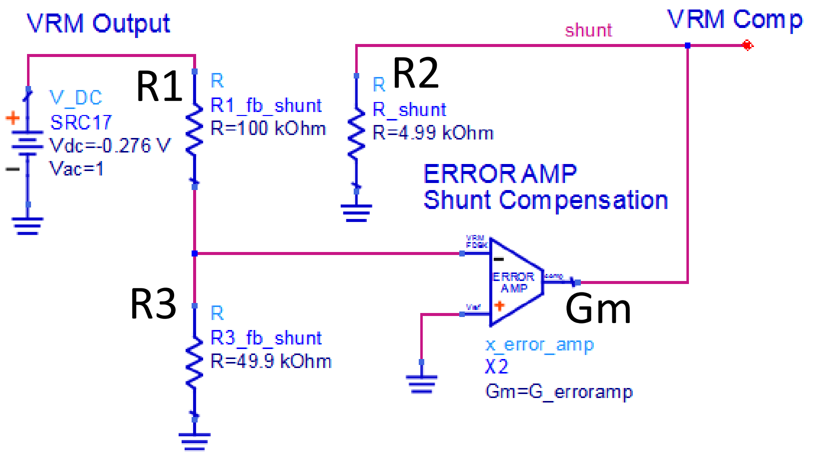
Power Supply Rejection Ratio (PSRR)



SERIES FEEDBACK



SHUNT FEEDBACK

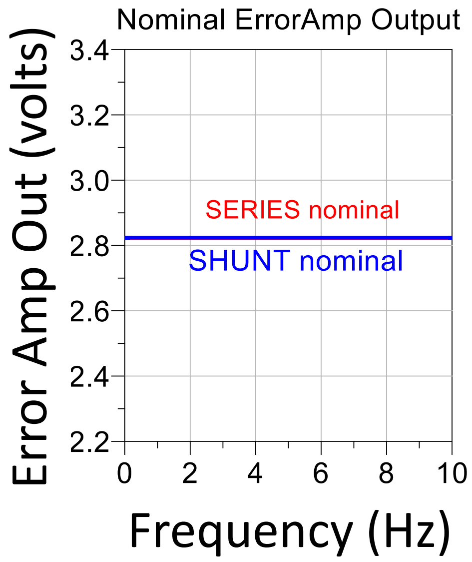


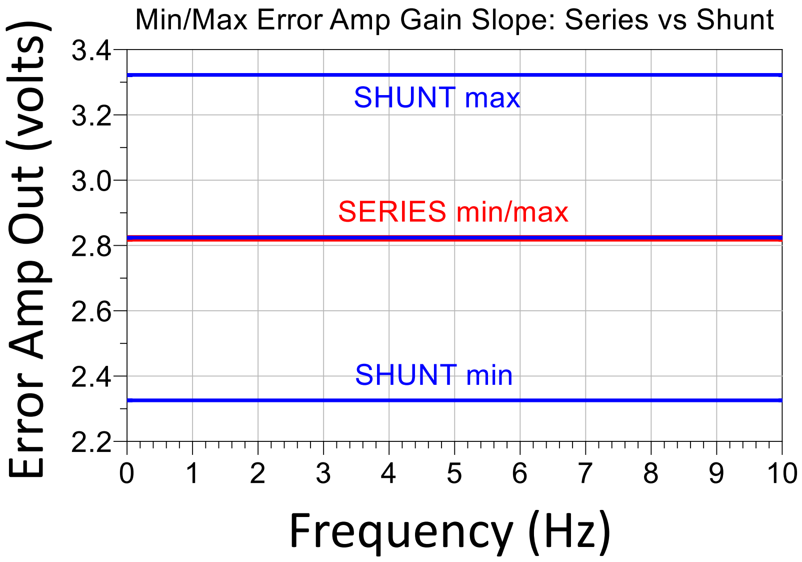
$$Av\_series = \frac{R3 \cdot (Gm \cdot R2 - 1)}{R1 + R3 + Gm \cdot R1 \cdot R3} = 3.215$$

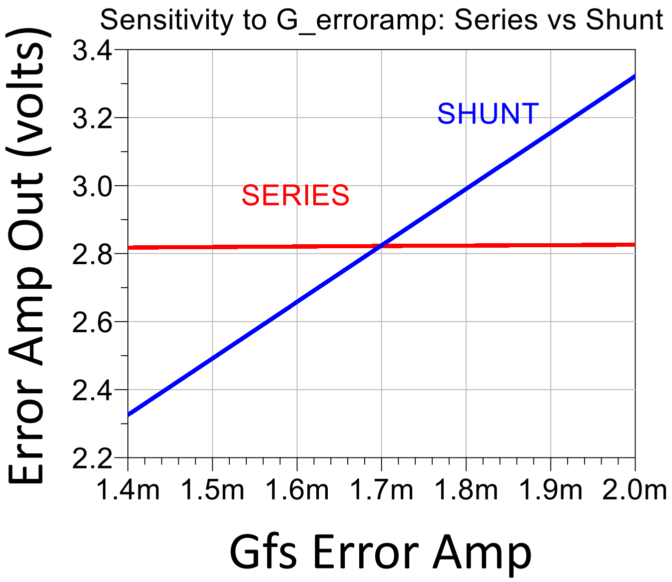
$$Av\_shunt = \frac{R3 \cdot Gm \cdot R2shunt}{R1 + R3} = 3.215$$

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

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







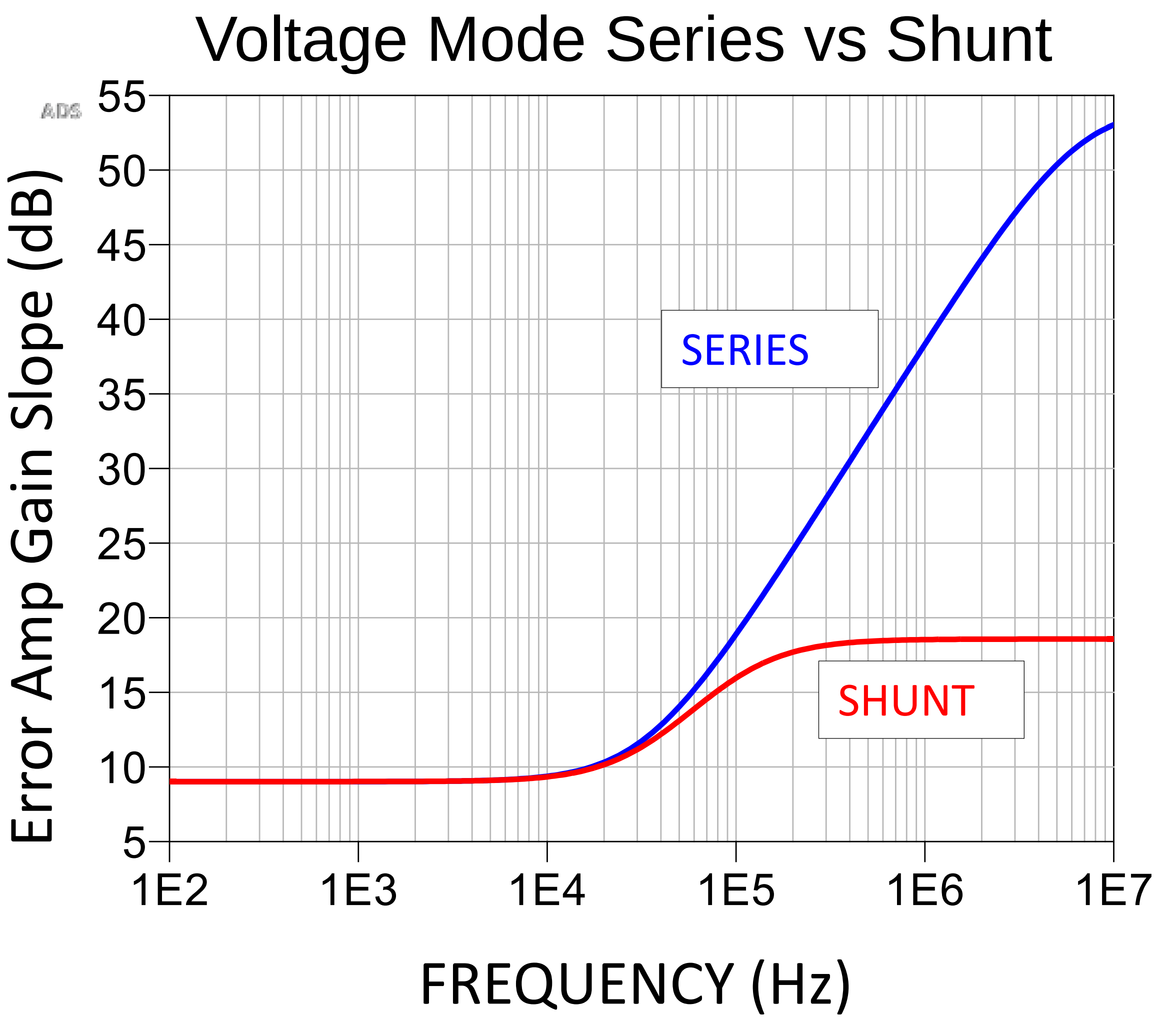
Gfs Error Amp

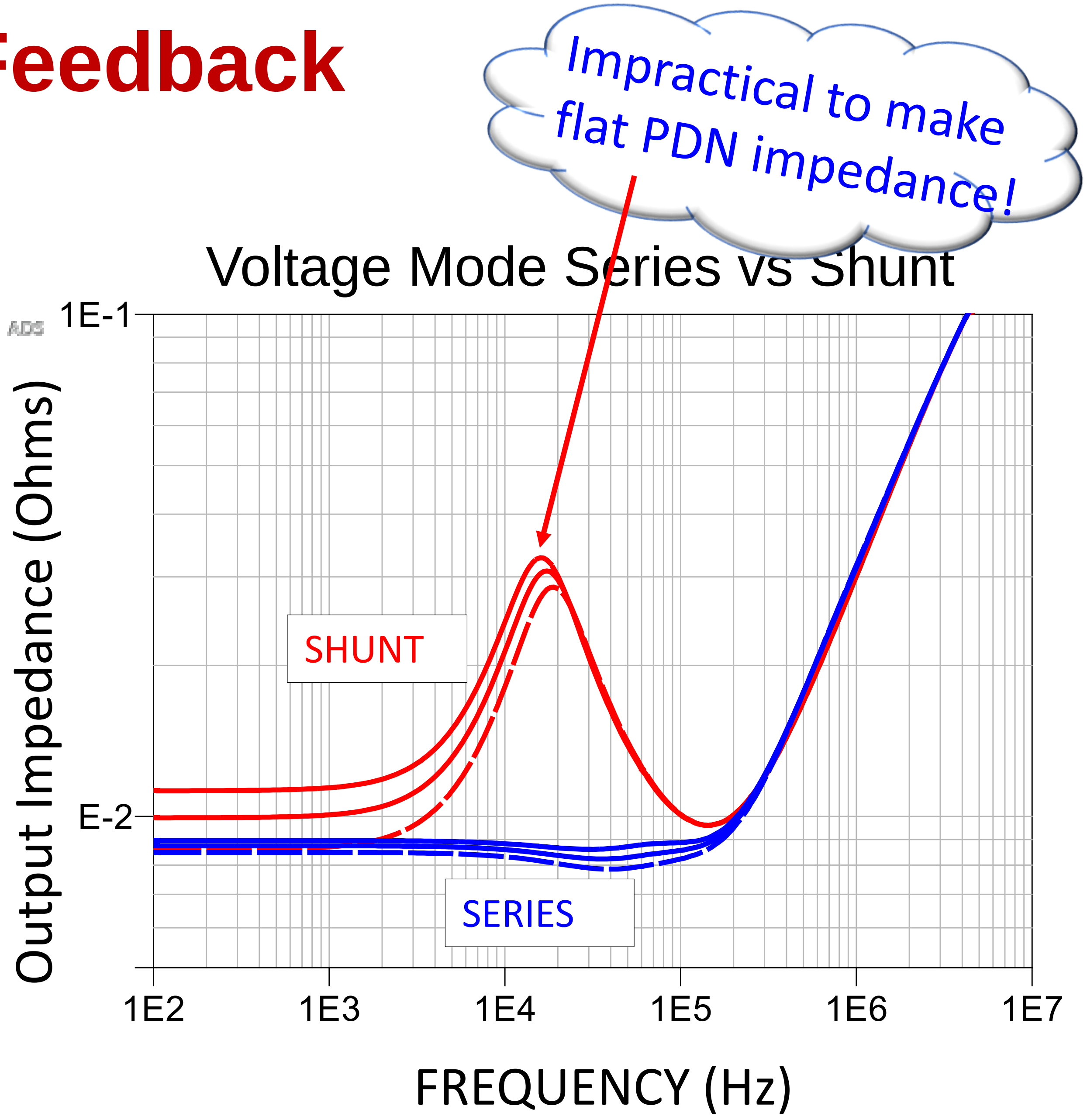
Min = 1.4 e-3

Nominal = 1.7 e-3

Max = 2.0 e-3

Voltage Mode with Shunt Feedback





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%

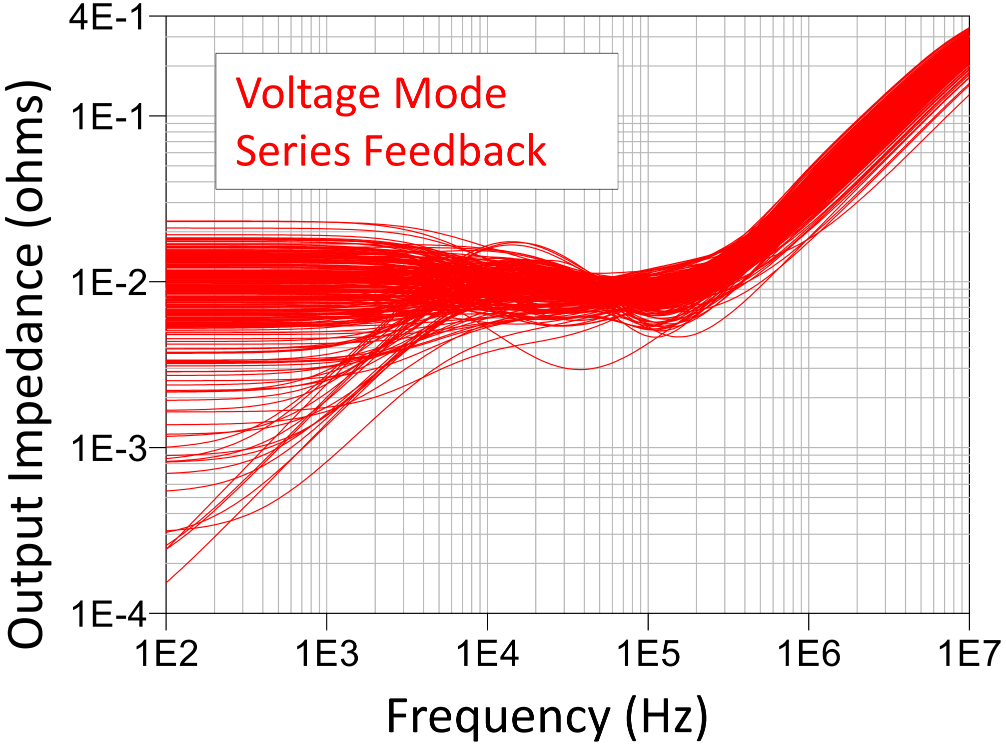
Cbulk_ESR=20%

Cbulk_ESL=20%

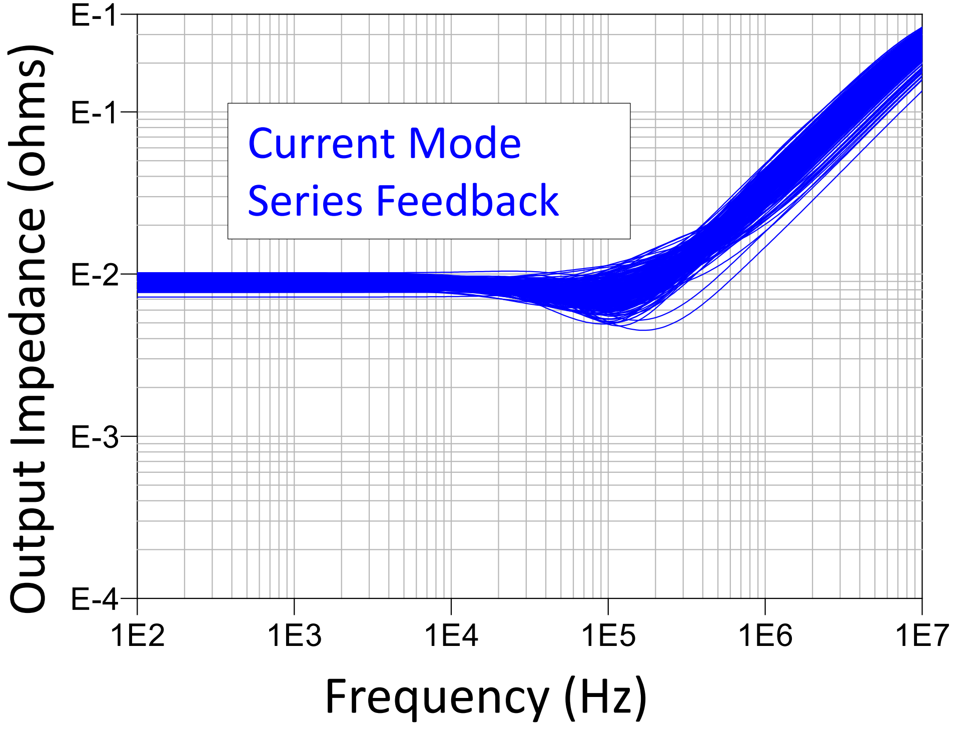
Current Mode with Series Feedback is the winner!

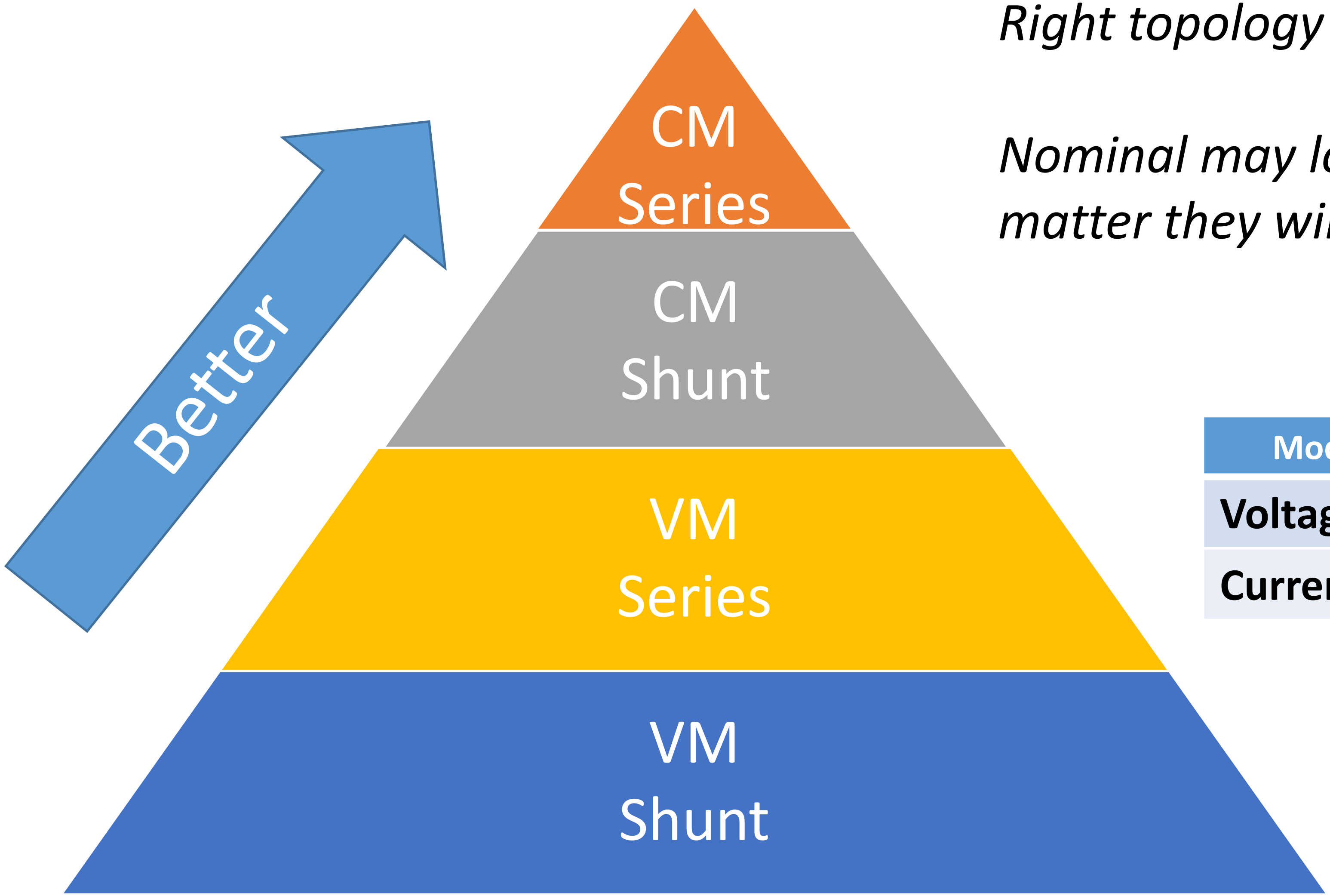
Monte Carlo of Voltage Mode vs Current Mode

Voltage Mode with Series Feedback - Monte Carlo



Current Mode with Series Feedback - Monte Carlo





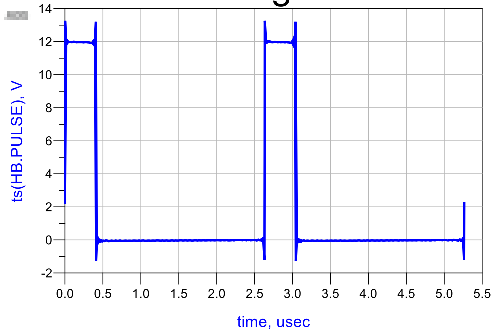
Right topology or the answer can be very wrong.

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

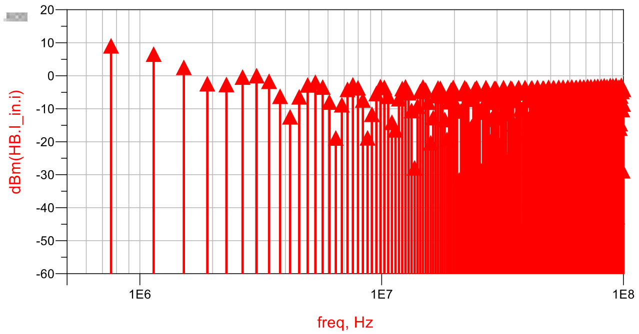
Mode	PSRR	Rout	Comments
Voltage	Poor	Poor	Large tolerance impact
Current	Excellent*	Excellent	Small tolerance impact

STATE SPACE AVERAGE MODEL for IMEDANCE, TRANSIENTS, HARMONICS

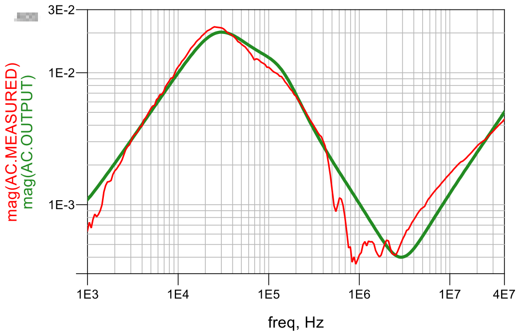
Switch Voltage



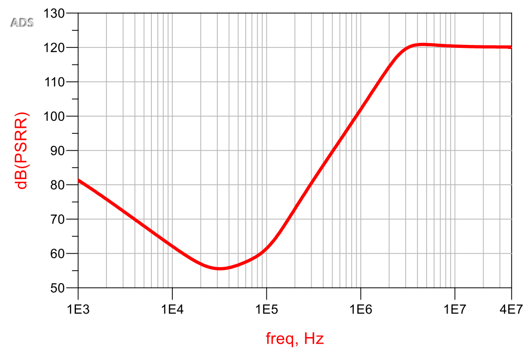
Switch Current Spectrum



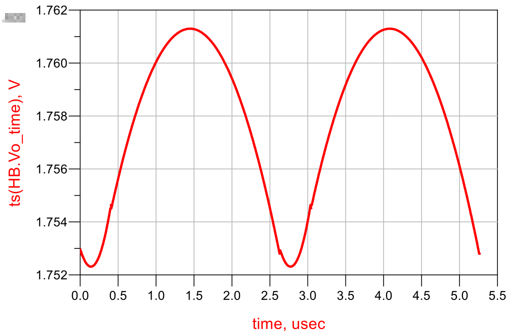
VRM AC Output Impedance



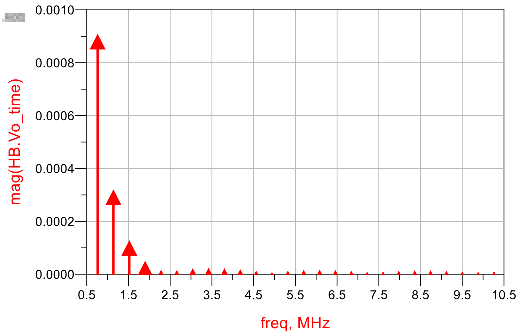
VRM PSRR



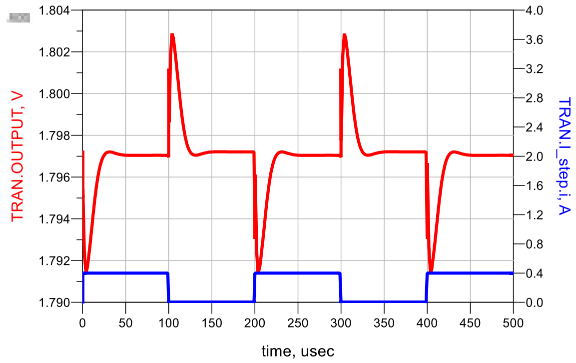
Ripple Voltage Time



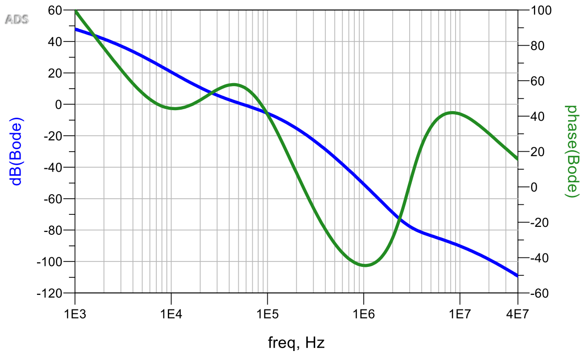
Ripple Voltage Spectrum



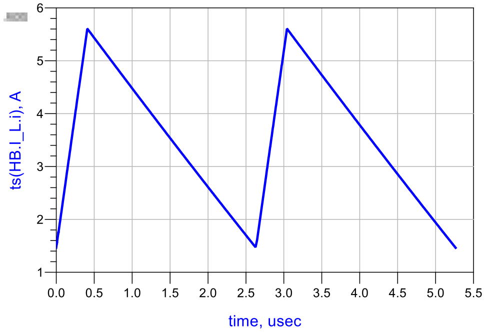
VRM Load Transient



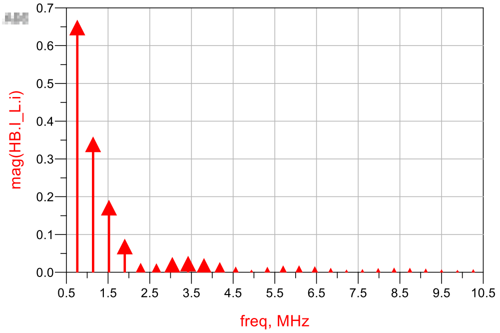
VRM Bode Plot



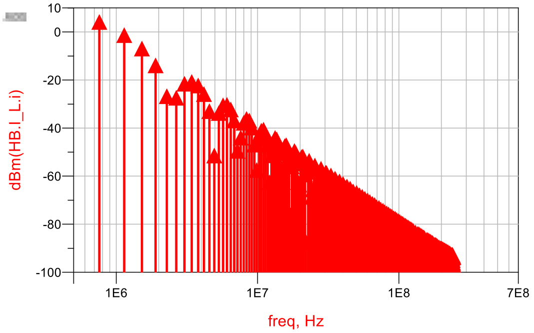
Output Inductor Current



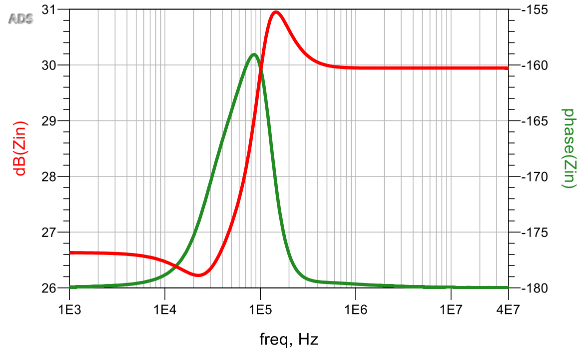
Inductor Current Spectrum



Inductor Current dBm

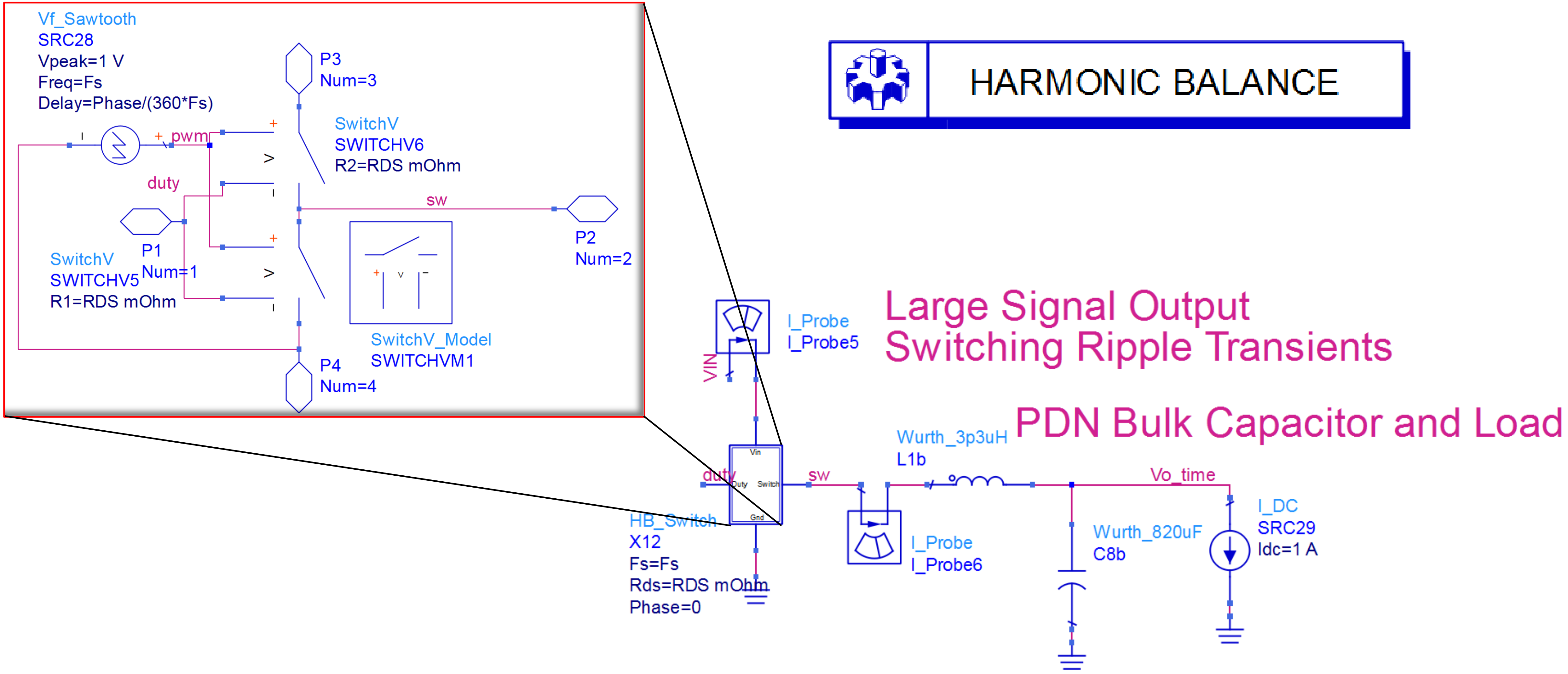


VRM INPUT IMPEDANCE

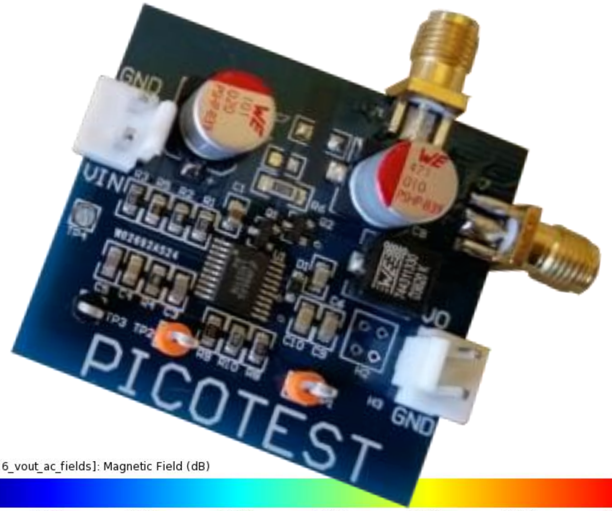


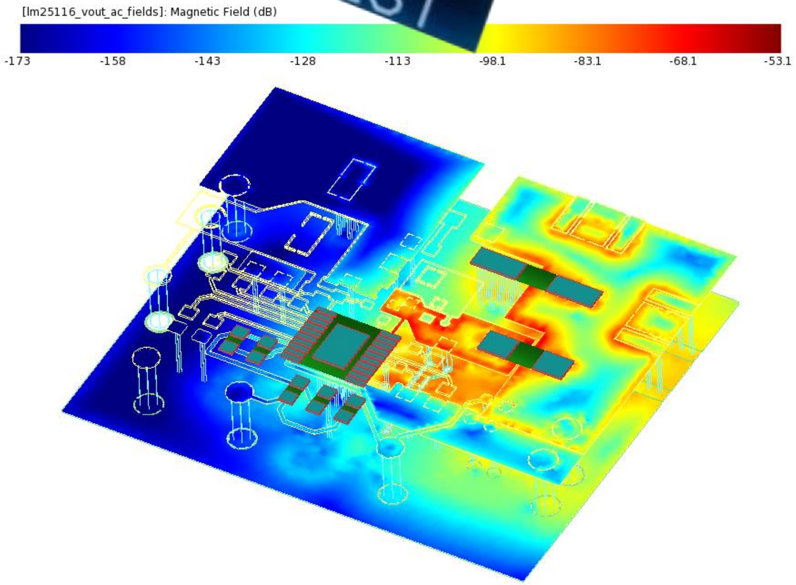
Switching Transients

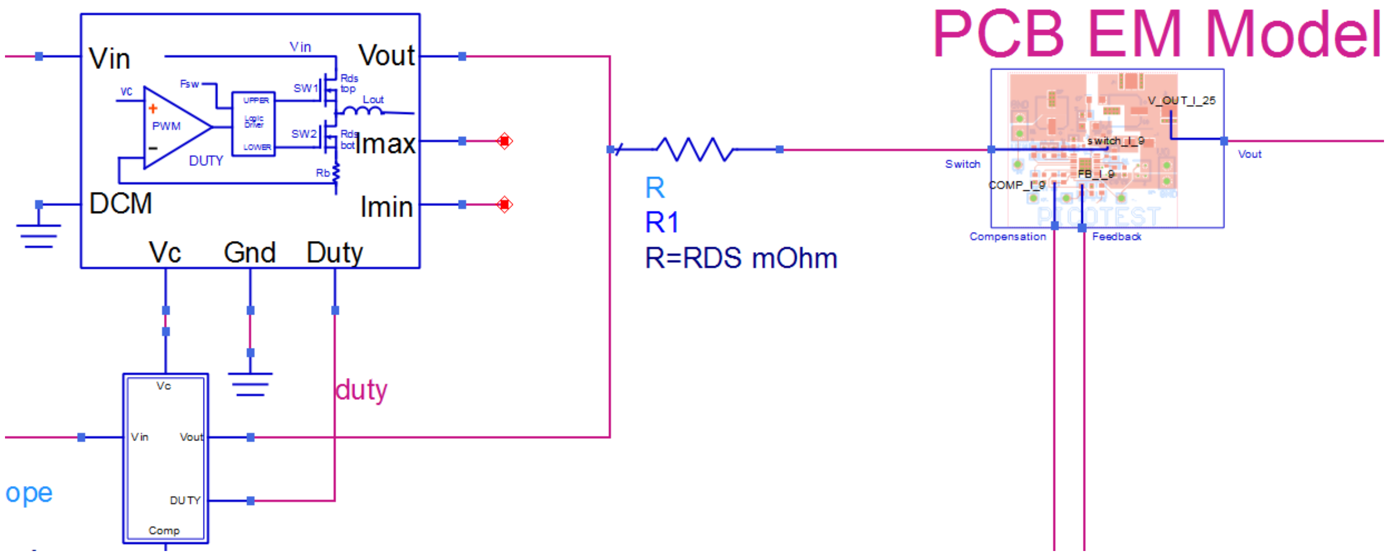
Pulse Width Modulated Switch

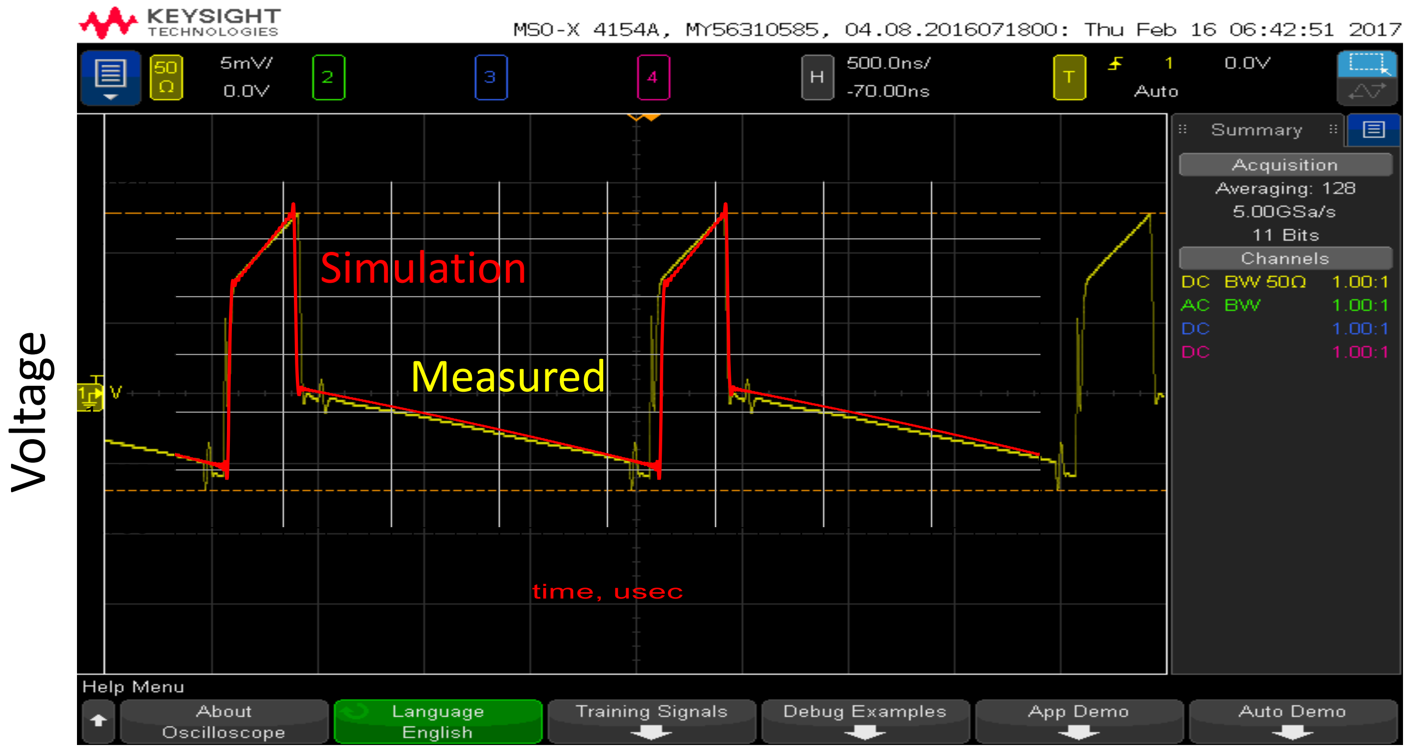


Adding EM

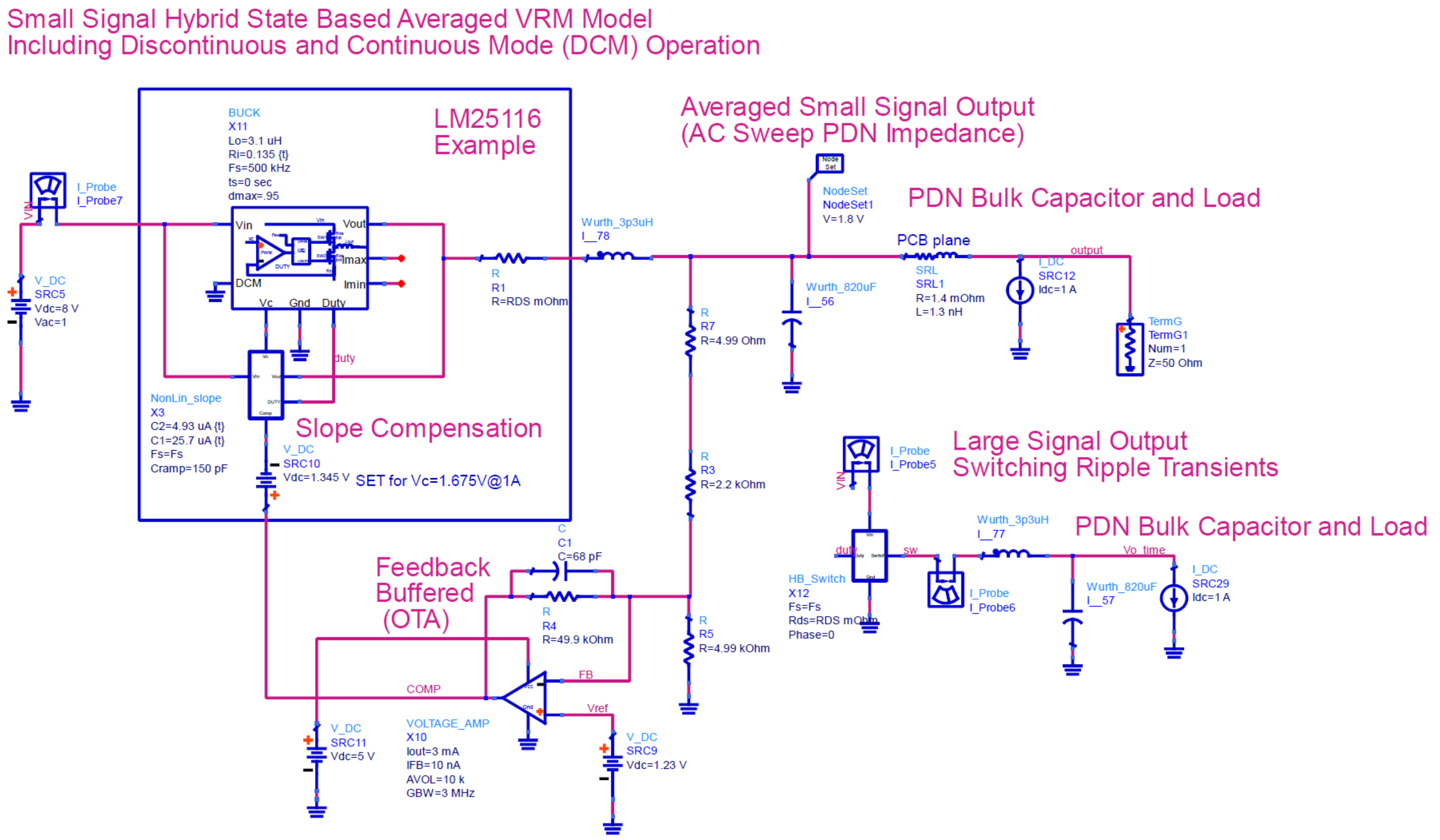

PICOTEST
GND
VIN


[lm25116_vout_ac_fields]: Magnetic Field (dB)
-173 -158 -143 -128 -113 -98.1 -83.1 -68.1 -53.1


PCB EM Model
Vin
Vout
PWM
DUTY
DCM
Imax
Imin
Vc
Gnd
Duty
R
R1
R=RDS mOhm
duty
ope
Vin
Vout
DUTY
Comp
Switch
Vout
Compensation
Feedback

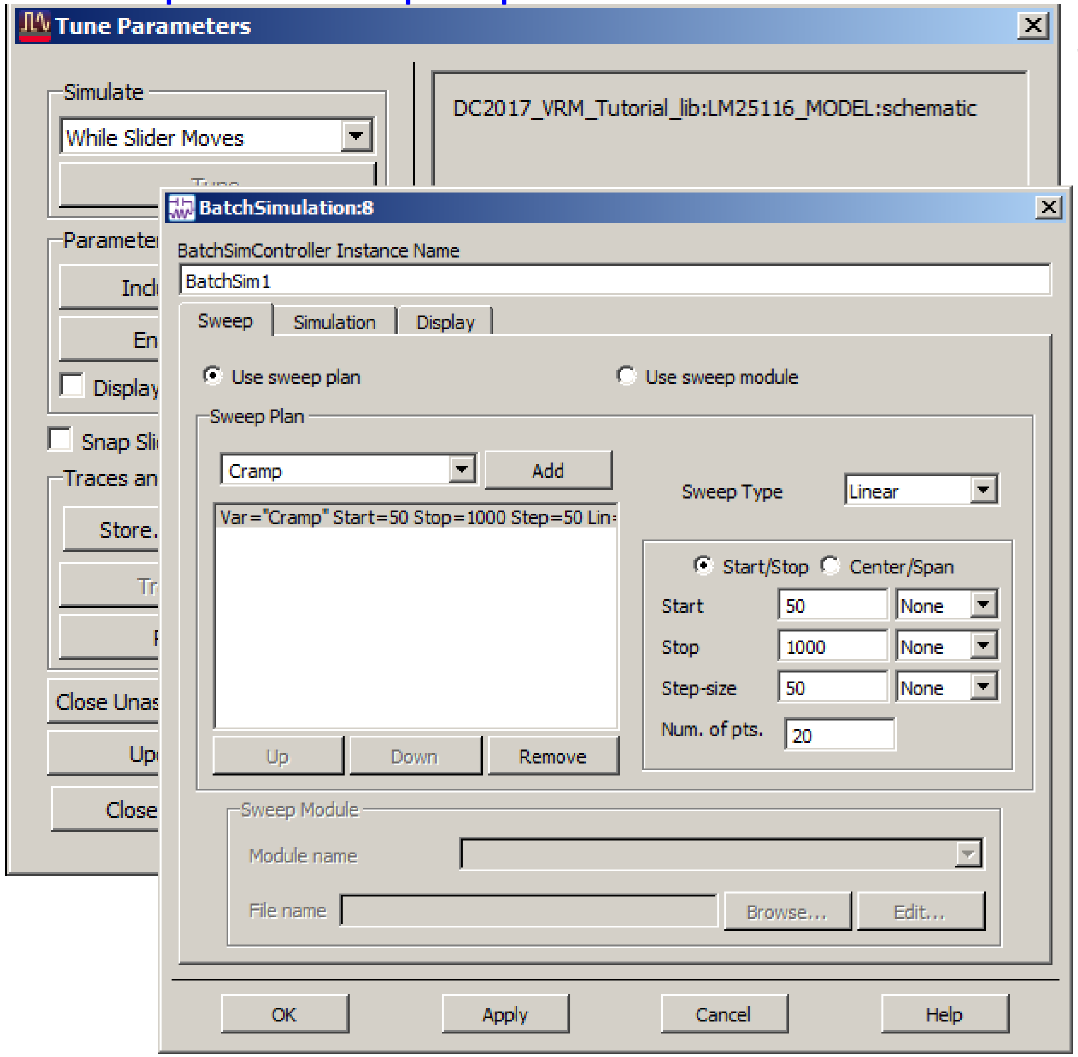

KEYSIGHT TECHNOLOGIES
MSO-X 4154A, MY56310585, 04.08.2016071800: Thu Feb 16 06:42:51 2017
5mV/
0.0V
500.0ns/
-70.00ns
Auto
Summary
Acquisition
Averaging: 128
5.00GSa/s
11 Bits
Channels
Simulation
Measured
Voltage
time, usec
Help Menu
About Oscilloscope
Language English
Training Signals
Debug Examples
App Demo
Auto Demo

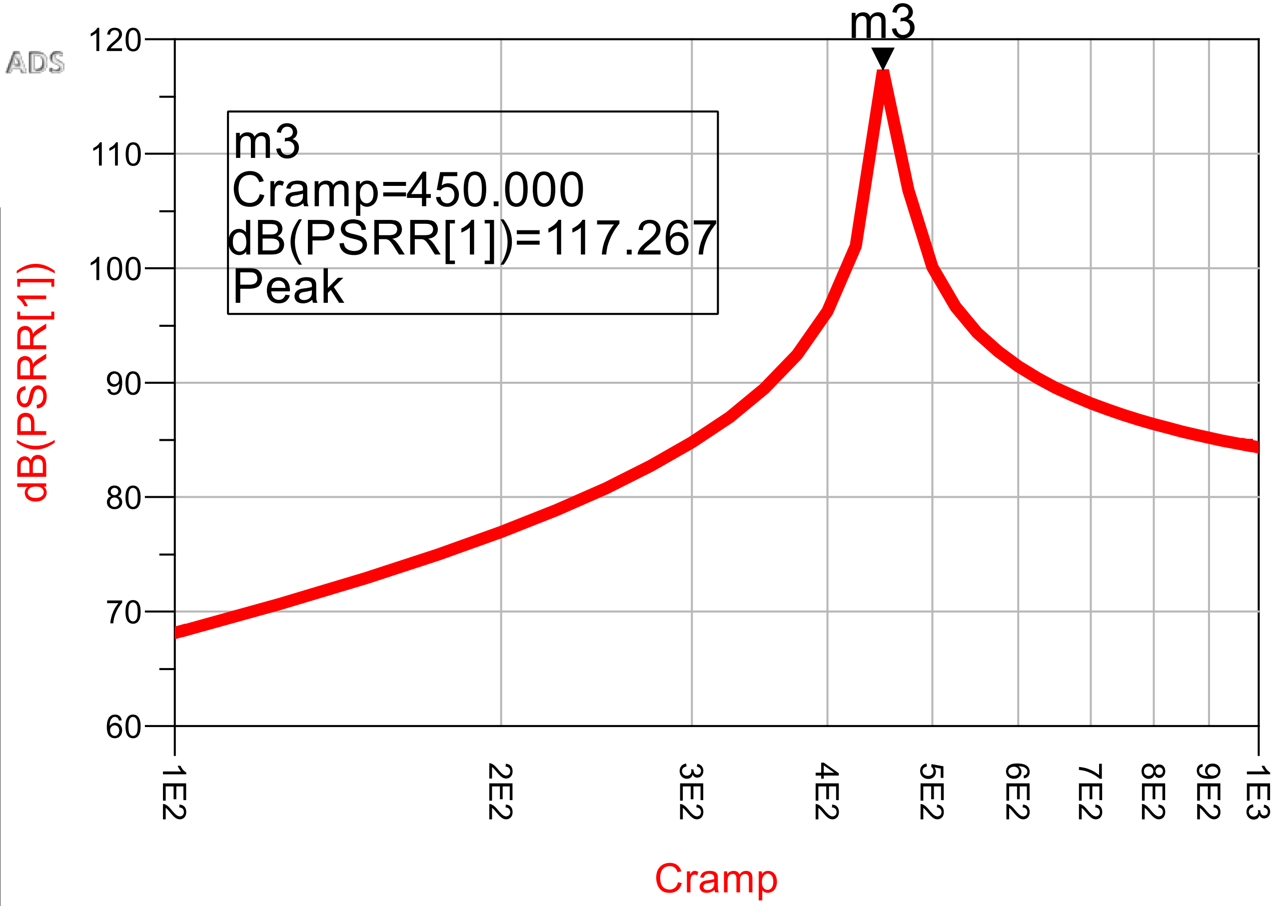
Complete DC-DC Converter Model



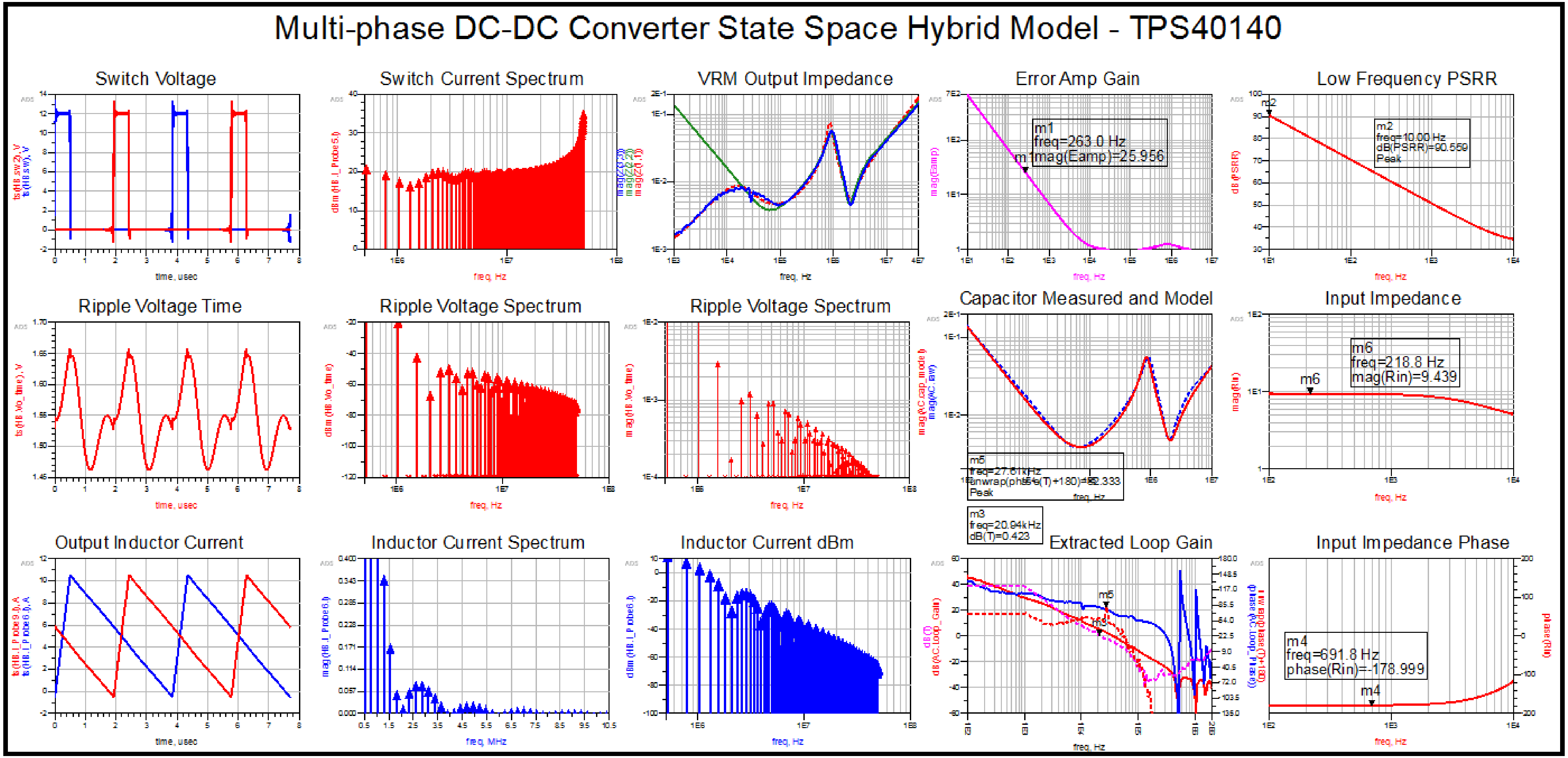
Exploring the DC-DC Converter Model Performance

Explore Cramp Impact on PSRR





…and it works for Multi-Phase



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

Big Screen Measurement Demo

- E5061B Network Analyzer Impedance Measurement Demo of a VRM: Not Flat vs. Flat

Hands-On Lab: 190219_Lab3a_VRM_Select_Z_wrk.7zads

Basics – Instructor Led Demo

Reading the VRM Impedance – Flat vs. Not Flat

Explore –

VRM State Space Average Model

Advanced –

Tolerance Analysis with Monte Carlo