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Conference
January 31 – February 2, 2023

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February 1 – 2, 2023

Santa Clara Convention Center

VRM Modeling and Stability Analysis for the Power Integrity Engineer

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Benjamin Dannan, Northrop Grumman
Heidi Barnes, Keysight Technologies

Steve Sandler (Picotest), Benjamin Dannan (Northrop Grumman),
Heidi Barnes (Keysight Technologies), Christian Yots (Texas Instruments)

SPEAKERS

Steve Sandler

Managing Director, Picotest

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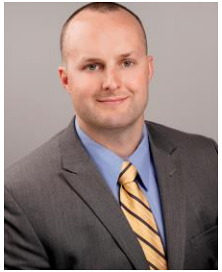
Steve Sandler has been involved with power system engineering for more than 40 years. The founder and CEO of Picotest.com, a company specializing in instruments and accessories for high-performance power system and distributed system testing



Benjamin Dannan

Technical Fellow, Northrop Grumman

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Benjamin Dannan is a Technical Fellow and an experienced signal and power integrity (SI/PI) design engineer, advancing high-performance ASICs and high-speed digital designs. He is a Keysight ADS Certified Expert with numerous publications on SI/PI-related topics and received the prestigious DesignCon best paper award in 2020.

Heidi Barnes

Power Integrity Applications, Keysight Technologies

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Senior Application Engineer in the PSS EDA Group of Keysight Technologies. Her recent activities include the application of electromagnetic, transient, and channel simulators to solve signal and power integrity challenges. Author of over 20 papers on SI and PI and recipient of the DesignCon 2017 Engineer of the Year.

Outline

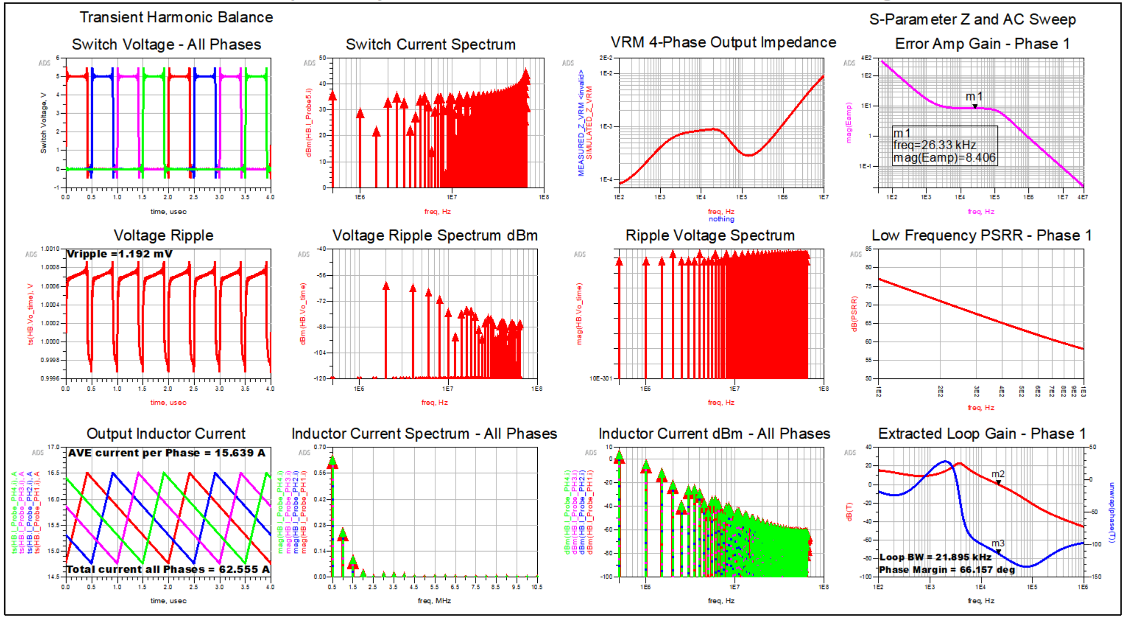
- **Why use a Sandler State-Space Average Model (SSAM)**
- **Populating the Sandler State-Space Model with design parameters and measurements**
- **Example: Building the TI TPS7H4003 SSAM**
- **The Digital Twin SSAM with PCB effects predicts measurement**
- **Results: TPS7H4003 SSAM vs. Simple L-R VRM SPICE model with and without PCB effects**
- **Call to action**
- **Summary**

Modeling a Switched Mode Power Supply

TI TPS7H4003 4-phase EVM

This model works for all forward VRM topologies

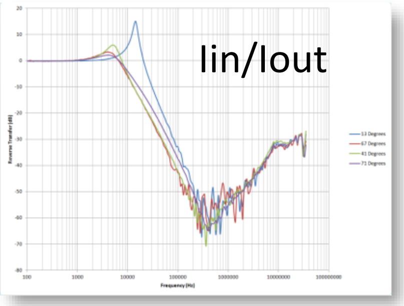
State Space Hybrid Model - TPS7H4003 4-PHASE Design



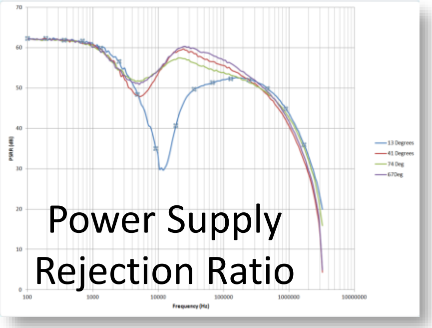
Modeling a 1-phase or N-phase Model is easy

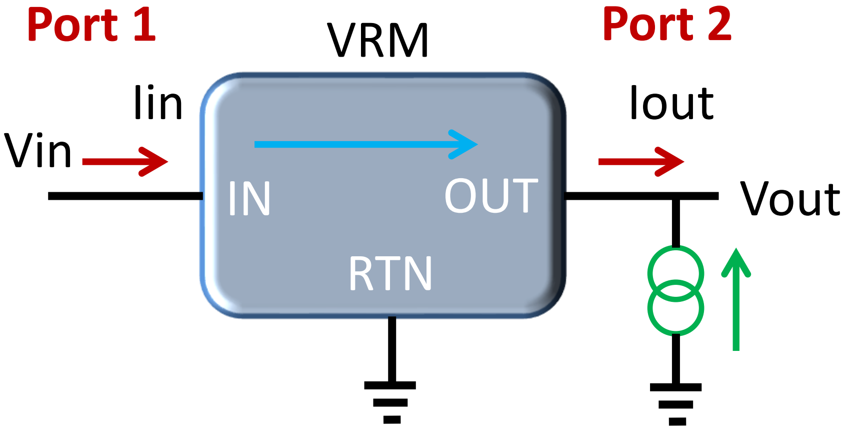
The Voltage Regulator Module (VRM) needs to consider <u>ALL</u> noise sources (large and small signal EMI)

Reverse Transfer - (S12)



PSRR - (S21)



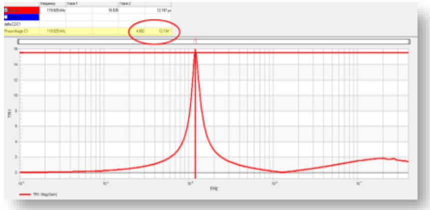


Input Impedance - (S11)

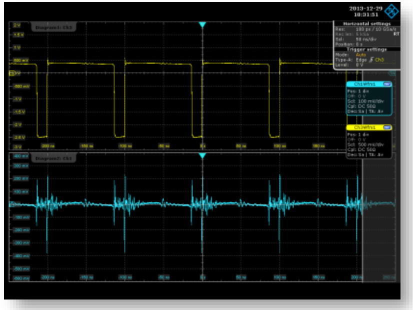
Input impedance can be NEGATIVE!

An R-L model only considers the output impedance

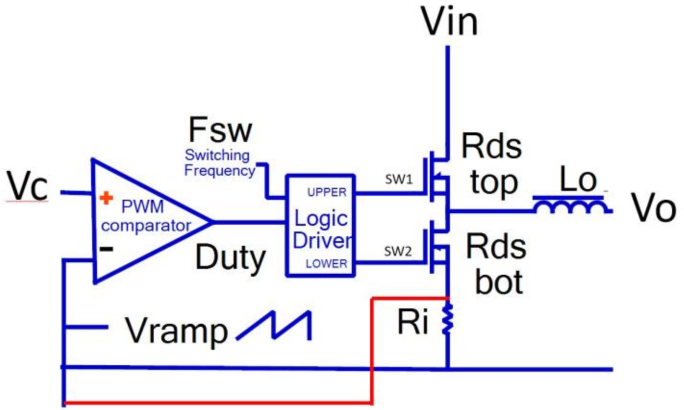
Output Impedance - (S22)

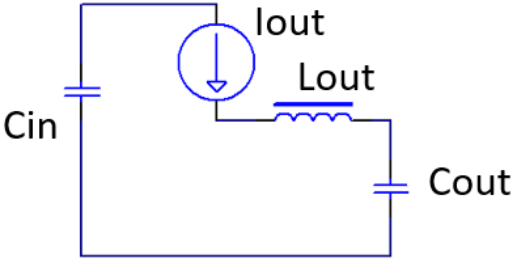


Output Noise/Spikes

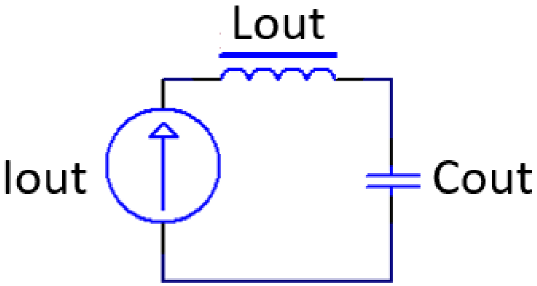


What is a State-Space Average (SSAM) VRM Model





State 1: SW1 = On and SW2= Off



State 2: SW1 = Off and SW2= On

STATE SPACE AVERAGED MODEL

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

$$Vout = Vin \cdot Duty$$

CURRENT MODE

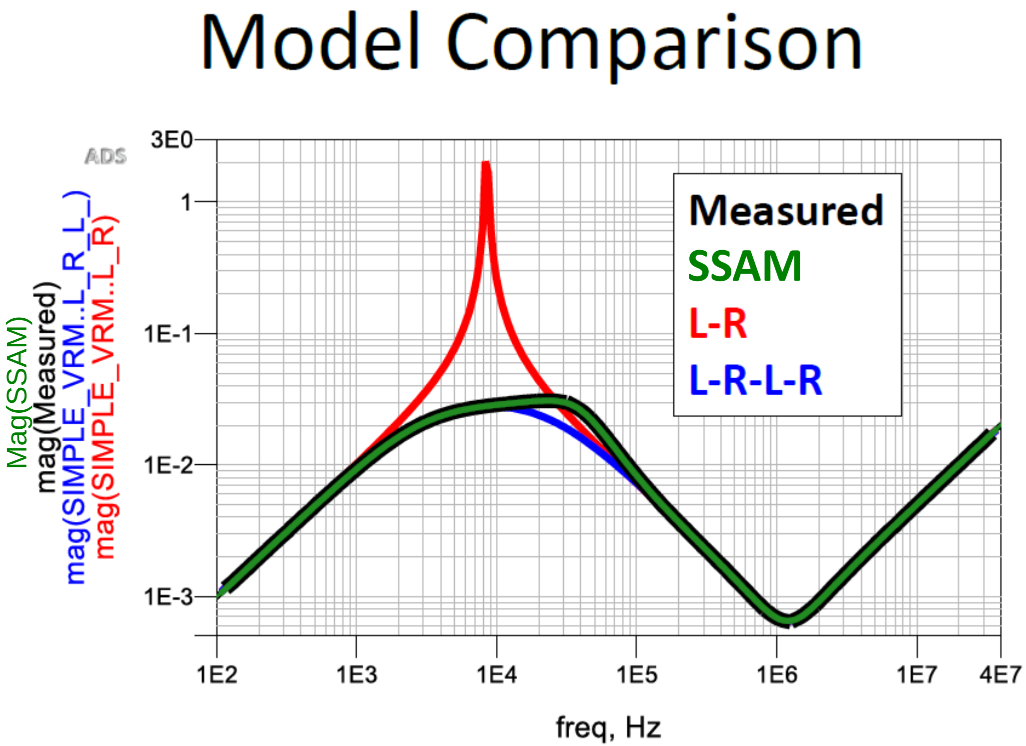
$$Iout = k\frac{Vc}{Ri}$$

Why a State-Space Average (SSAM) VRM Model is Better

- Ideal V_{source} has wrong output impedance
- R-L model only models output impedance and not with good accuracy
- RLC model only models output impedance with no information on switching noise, PSRR, stability, etc.
- State Space Average Model does it all and it is measure based and verified for the application.
  - ✓ The math is already done and free to use! Just add the parameters.

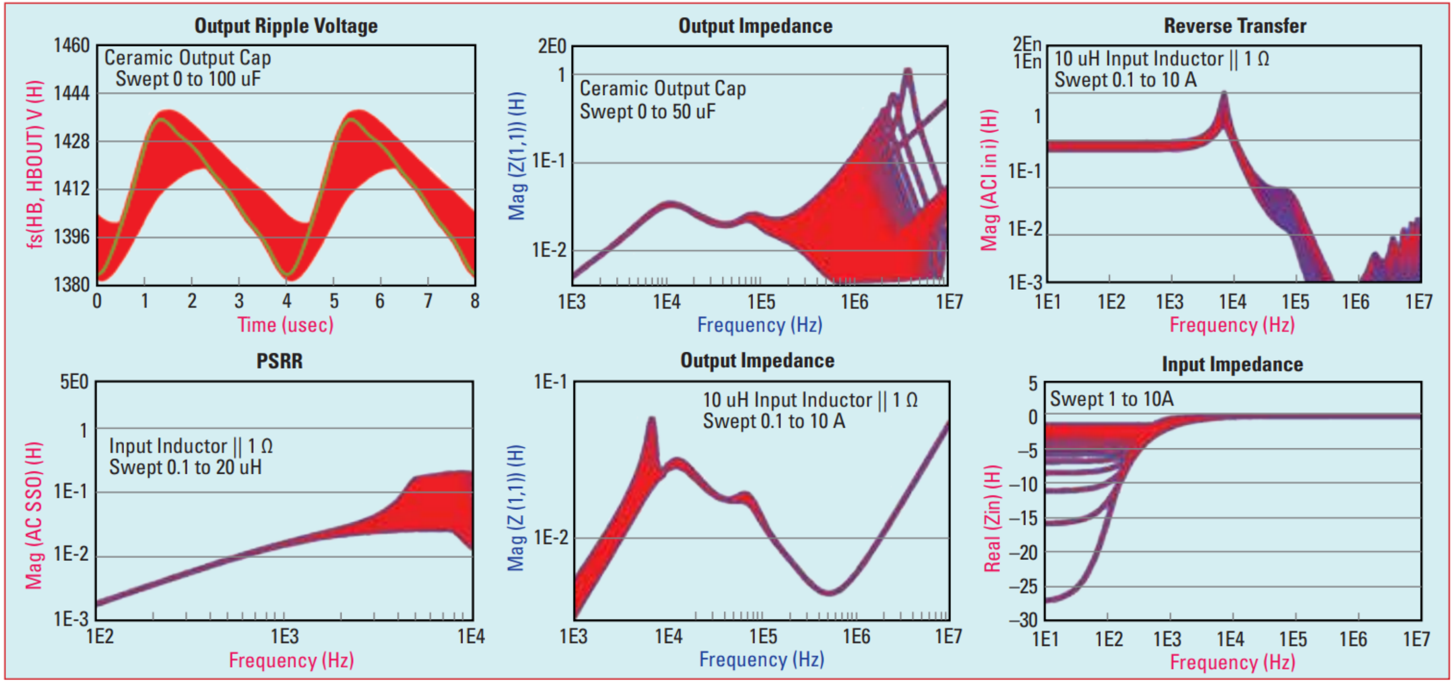
	V Source	L-R	L-R-L-R	SSAM
PDN Impedance	INCORRECT RESULT	NOT WELL	REASONABLY	Y
Switching ripple	N	N	N	Y
PSRR/Transients	N	N	N	Y
Negative resistance	N	N	N	Y
Input switching current	N	N	N	Y
Control loop stability	N	N	N	Y
Turn on overshoot	N	N	N	Y
Remote sense	N	N	N	Y

How Bad Can a Simple VRM Model Be?

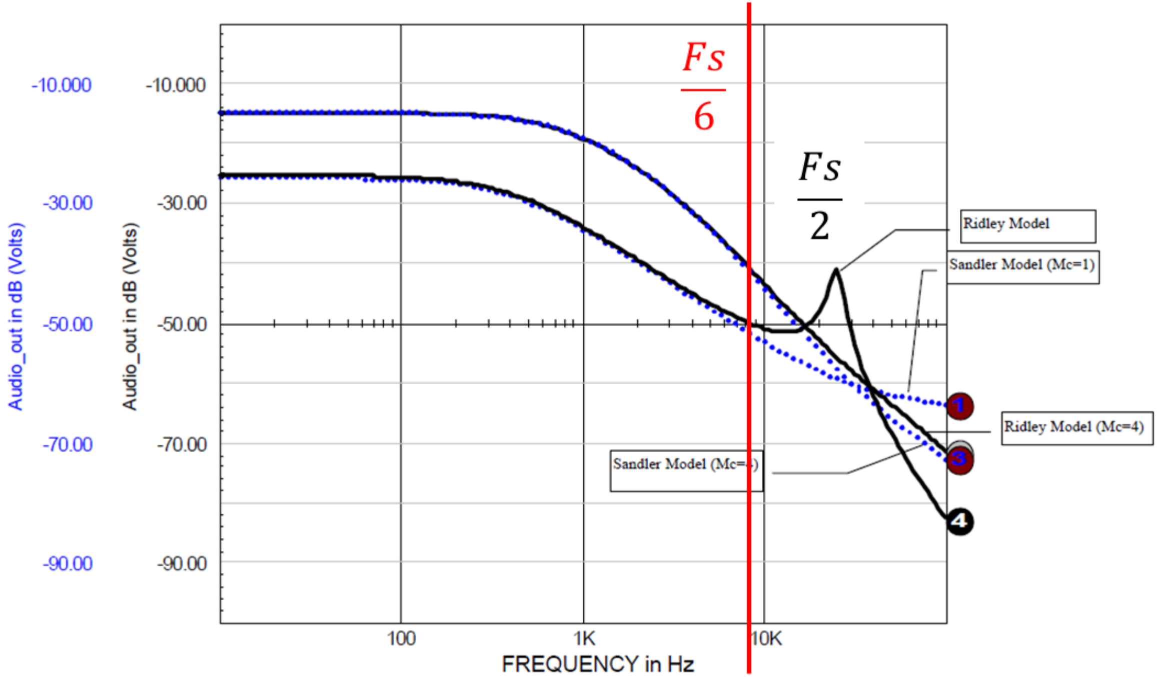


All Noise Sources with an SSAM VRM Model

State-space average behavioral VRM model predicts performance over process variations.

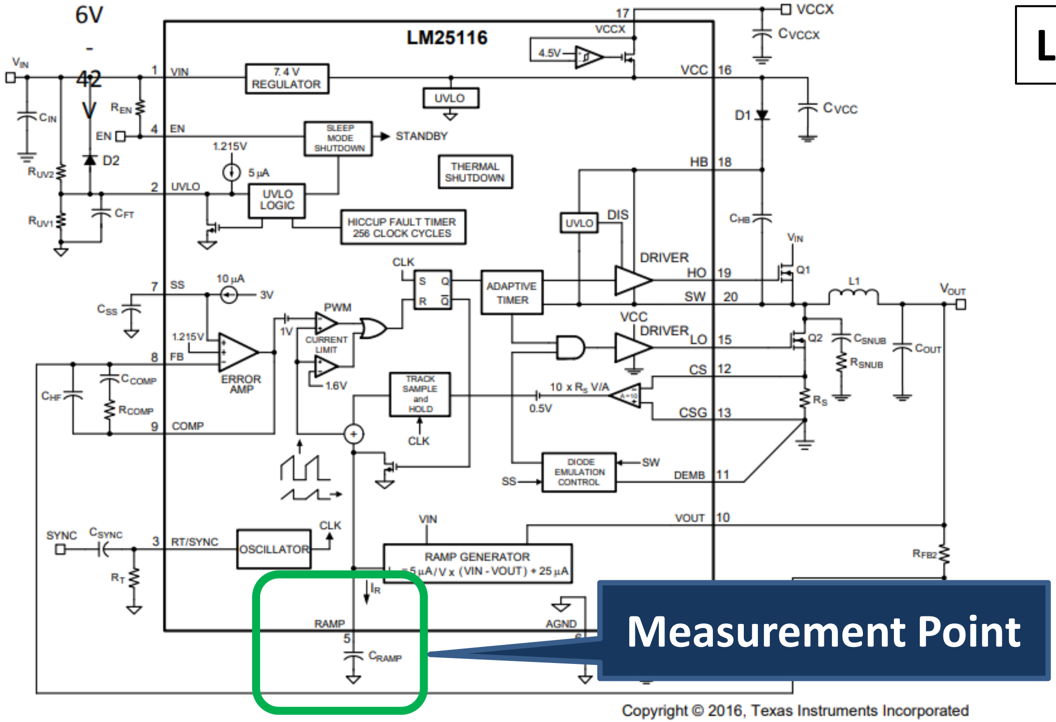


Sandler State-Space Average Model Accuracy:
Predicting Audio Susceptibility with Ridley vs. Sandler

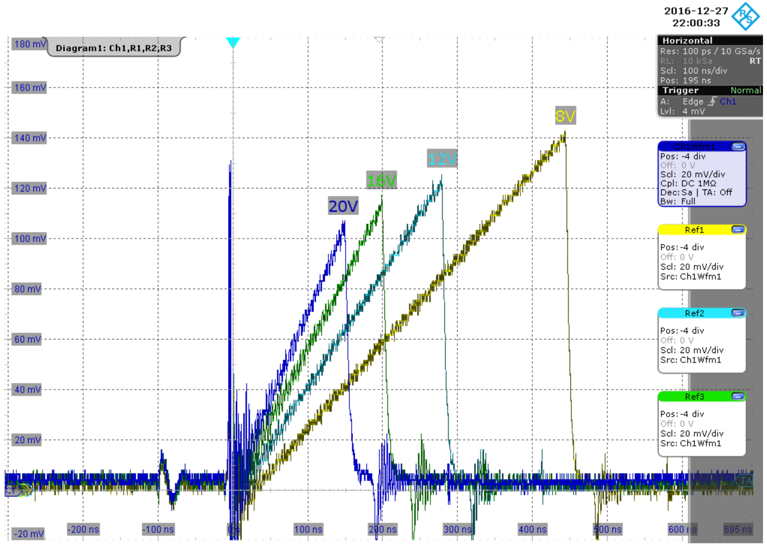


Accuracy is reduced for the Sandler State-Space Average VRM Model above Fs/6, but accurate where it matters!

SSAM Model Parameters: TI LM25116 VRM V_{RAMP}



LM25116 V_{RAMP} Measurements vs. Vin



It's not always this easy if you do not have access to V_{RAMP} on the VRM

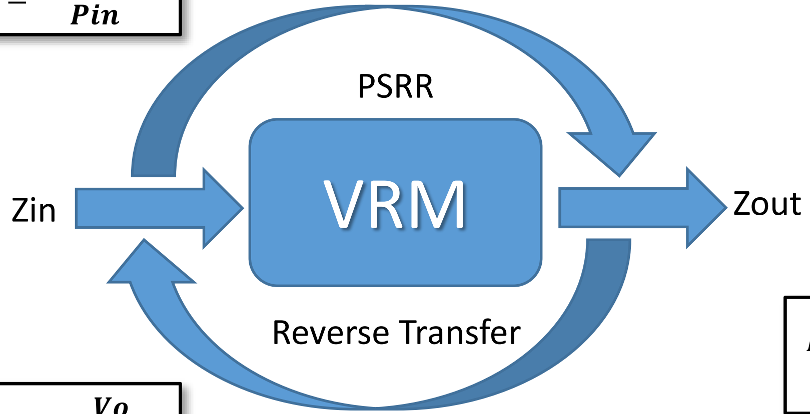
Sandler State-Space Average Model – Small Signal CCM

S. M. Sandler, *Switch-Mode Power Supply Simulation*, McGraw-Hill, 2005

$$PSRR\_dB = 20log\left[\left|\frac{Vo\cdot(Ri\cdot Vo - 2\cdot Fsw\cdot Lo\cdot Vramp)}{Ri\cdot Vin^2 - 2\cdot Ri\cdot Vo\cdot Vin + 2\cdot Fsw\cdot Lo\cdot Vin\cdot Vramp + 2\cdot Av\cdot Fsw\cdot Lo\cdot Vin}\right|\right]$$

$$Rin \cong -\frac{Vin^2}{Pin}$$

$$Rout = \frac{\frac{2\cdot Fs\cdot Lo\cdot Ri\cdot Vin}{Ri\cdot Vin - 2\cdot Ri\cdot Vo + 2\cdot Fsw\cdot Lo\cdot Vramp} + DCR + RDSon}{1 + Av\cdot\frac{2\cdot Fs\cdot Lo\cdot Vin}{Ri\cdot Vin - 2\cdot Ri\cdot Vo + 2\cdot Fsw\cdot Lo\cdot Vramp}}$$



$$L_{excess} = \frac{Lo}{1 + \frac{2\cdot Fs\cdot Lo\cdot Vin}{Ri\cdot Vin - 2\cdot Ri\cdot Vo + 2\cdot Fs\cdot Lo\cdot Vramp}\cdot Av} + \frac{Ro}{2\cdot\pi\cdot GBW}$$

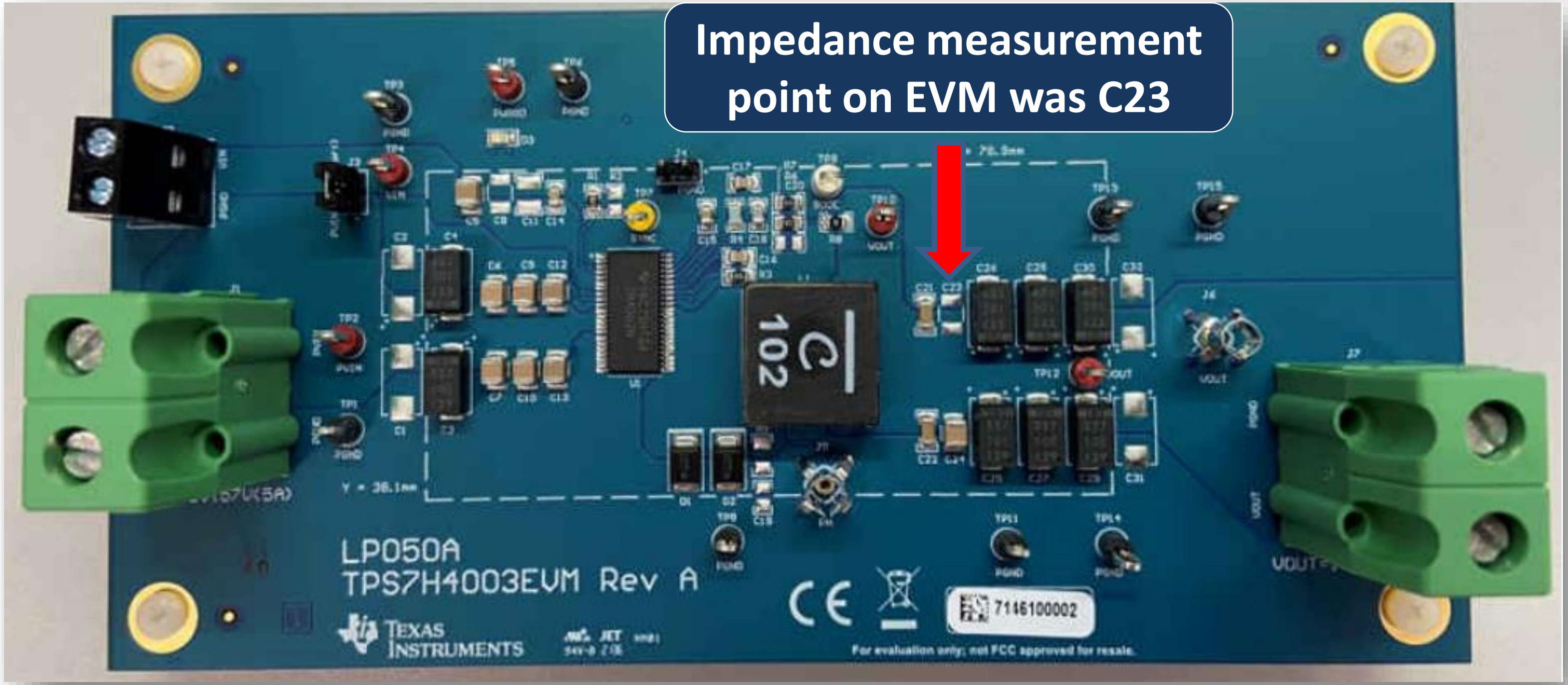
$$Reverse \cong \frac{Vo}{Vin}$$

$$\frac{Vo}{Vc} = \frac{2\cdot Fs\cdot Lo\cdot Vin}{Ri\cdot Vin - 2\cdot Ri\cdot Vo + 2\cdot Fs\cdot Lo\cdot Vramp}$$

Rin and Reverse are insensitive, so less attention is warranted

Now, let's show the process on an actual VRM of how to populate the SSAM model

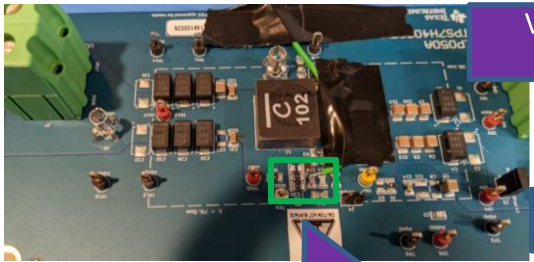
Measurement Platform – TI TPS7H4003 Evaluation Module



Impedance measurement point on EVM was C23

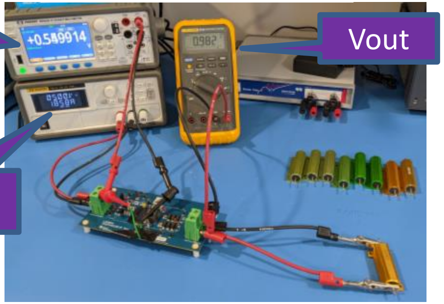
TPS7H4003 is a radiation tolerant VRM for LEO and GEO applications

Measure Ri Directly on TPS7H4003 VRM



Vcomp result

Measurement Setup



Vout

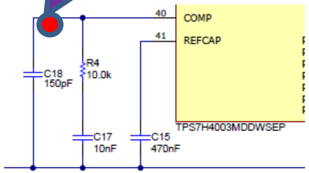
VRM Vin

Solder wire on VRM Vcomp pin

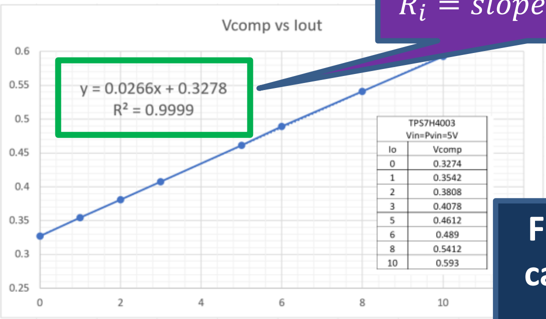
Io	Vcomp
0	0.3274
1	0.3542
2	0.3808
3	0.4078
5	0.4612
6	0.489
8	0.5412
10	0.593

Plot Vcomp vs. Iout results to determine R_i

Solder point @ C18



$R_i = slope = 26.6\ m\Omega$



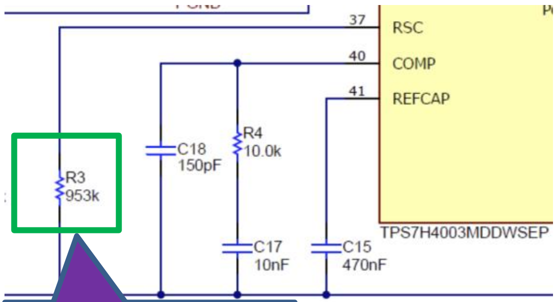
This measurement requires a VRM with external Vcomp access

For Ri we only care about the slope!

The measured result doesn't always agree with the datasheet

Estimating TPS7H4003 V_{RAMP}

From TPS7H4003 EVAL Schematic



RSC = 953k

From TPS7H4003 Datasheet

COMP to Iswitch gm[3]	COMP = 0.5 V	–55°C	28	38	49	S
		25°C	29	40	50	
		125°C	30	41	52	

$R_i = 1/40 = 25\ m\Omega$

Per TPS7H4003 Datasheet

$$RSC = \frac{24000}{f_{SW}} + \frac{1040}{SC} - 30$$

Solve for Slope Comp (SC)

TPS7H4003 f_{sw} = 500 kHz → SW_period = 2us period

$$SC = 1.1A/us \quad (1)$$

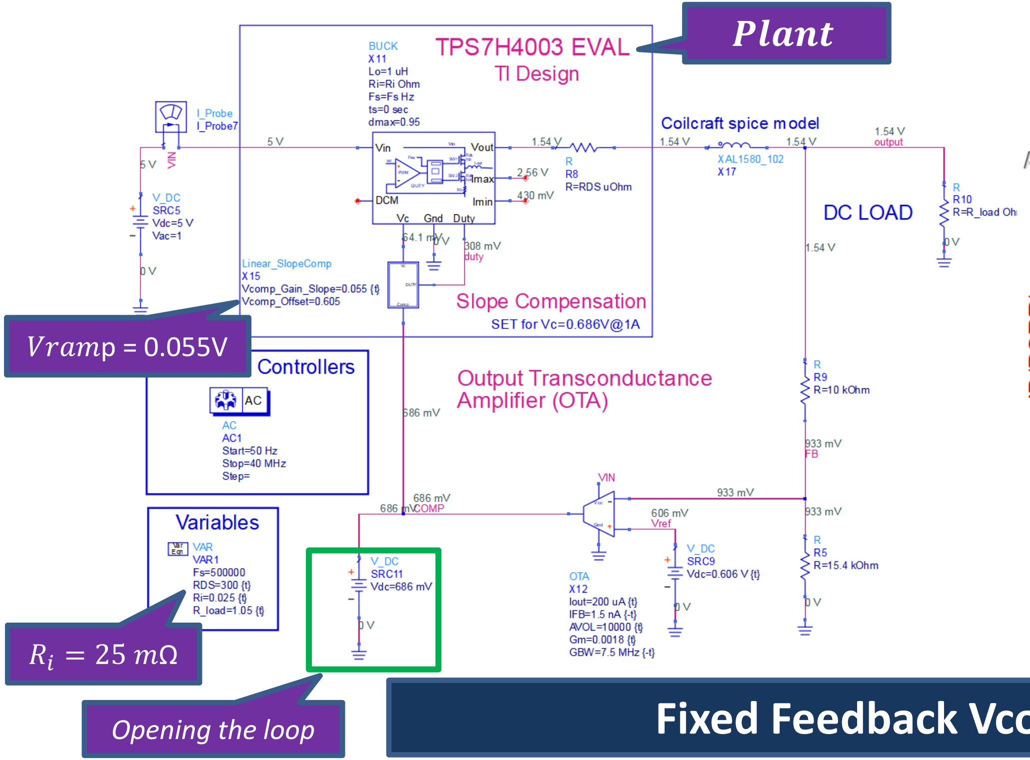
$$SC_{per\ duty\ cycle} = SC \cdot SW_{period} = 1.1A/us \cdot 2us = 2.2A/100\%\ duty\ cycle \quad (2)$$

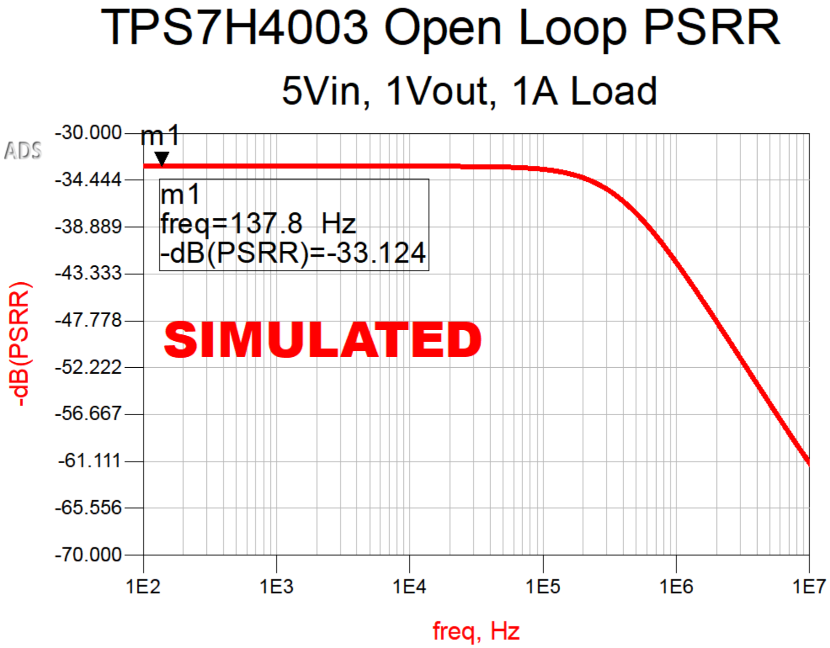
$$V_{RAMP} = SC \cdot R_i = 2.2A \cdot 0.025\Omega = 0.055V \quad (3)$$

VRM vendors do not always make this information available to populate the model

Simulating the Open Loop Plant Gain

Showing Plant Open Loop Gain using datasheet Vramp and Ri Values

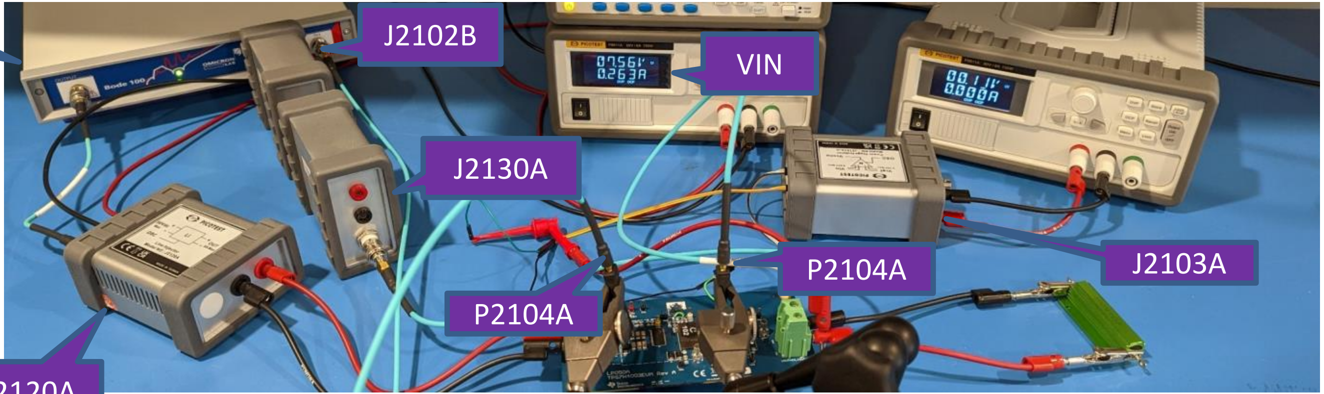




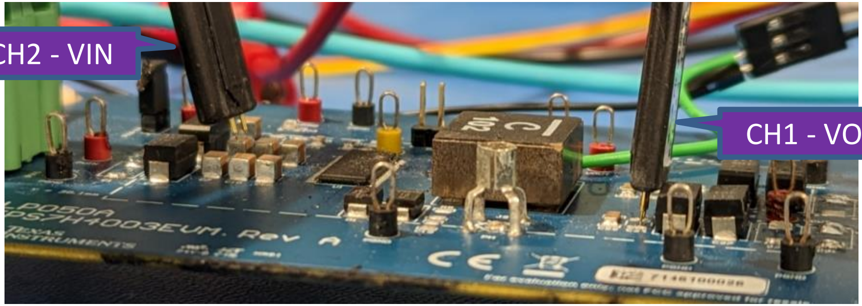
Fixed Feedback Vcomp for a given load

PSRR Setup with the TPS7H4003

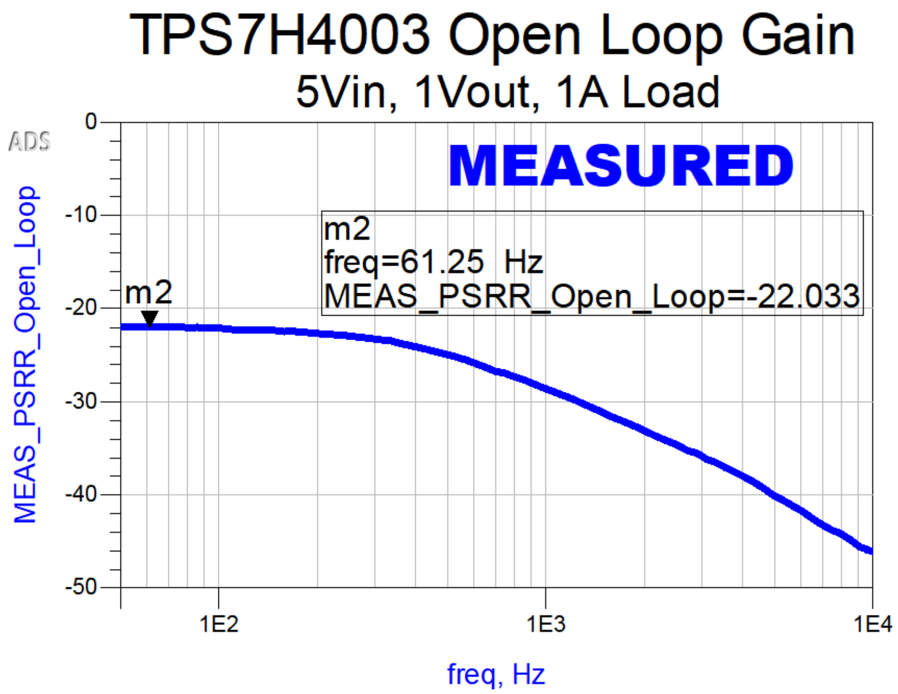
Let's measure the open loop plant gain and closed loop PSRR

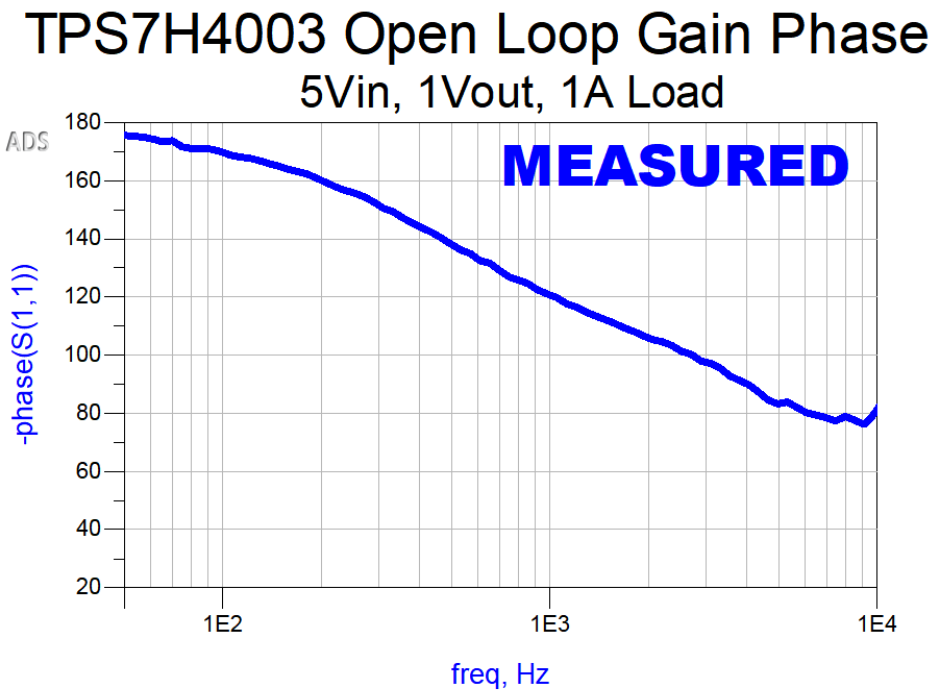


Now, let's measure this!

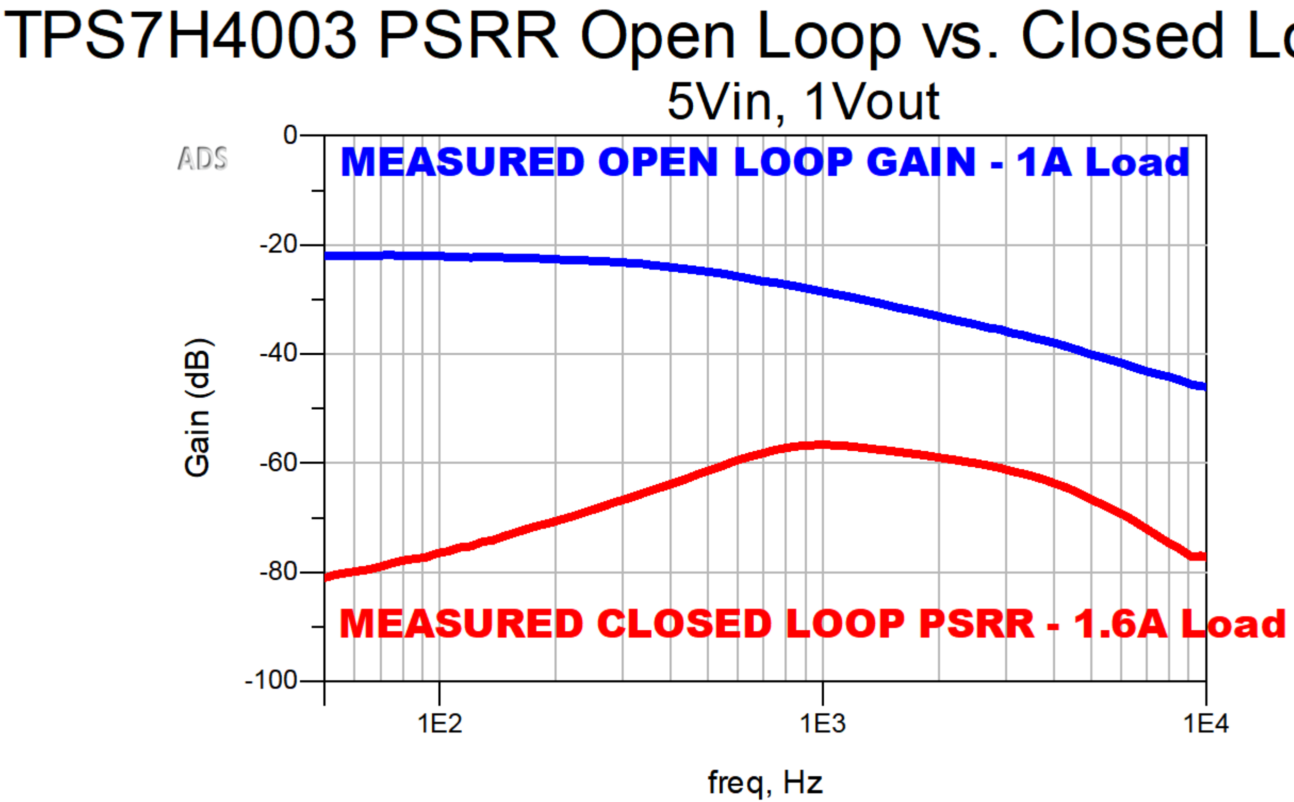


Open Loop PSRR – TPS7H4003 Gain Magnitude and Phase

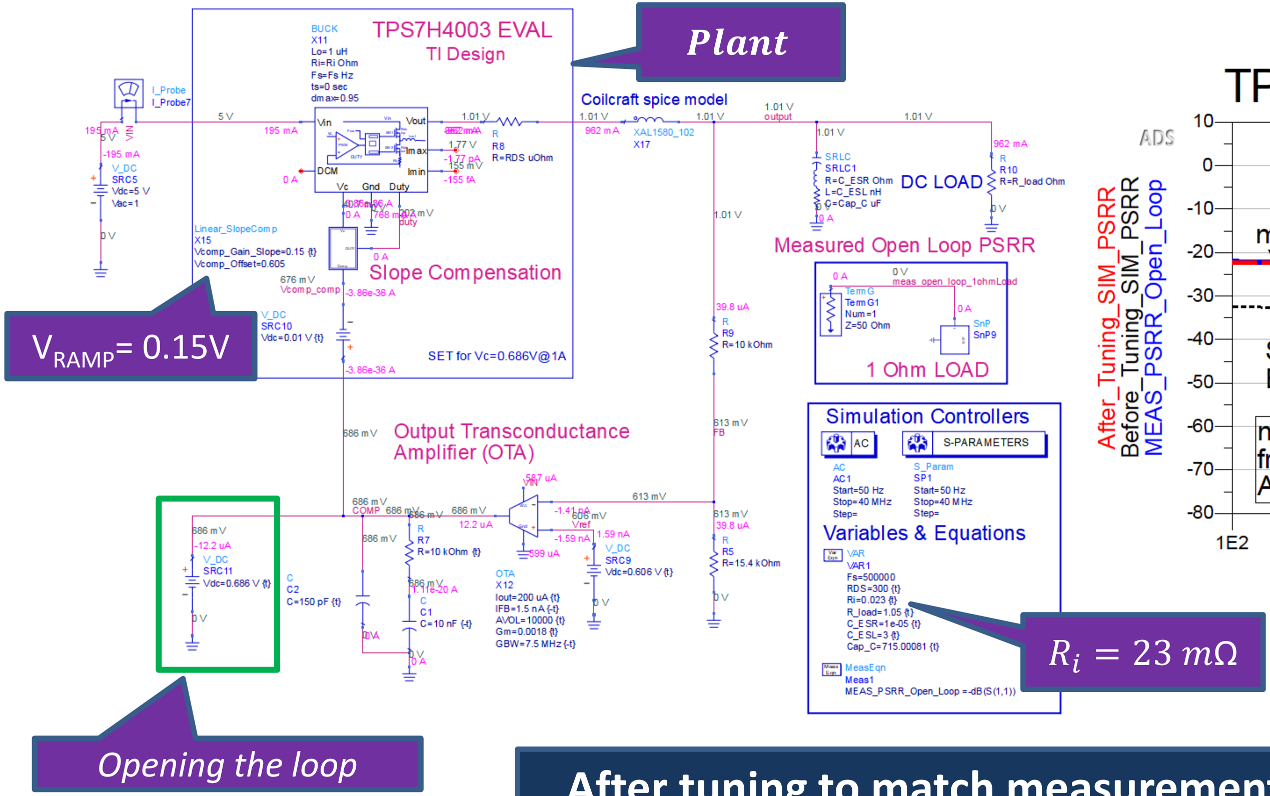


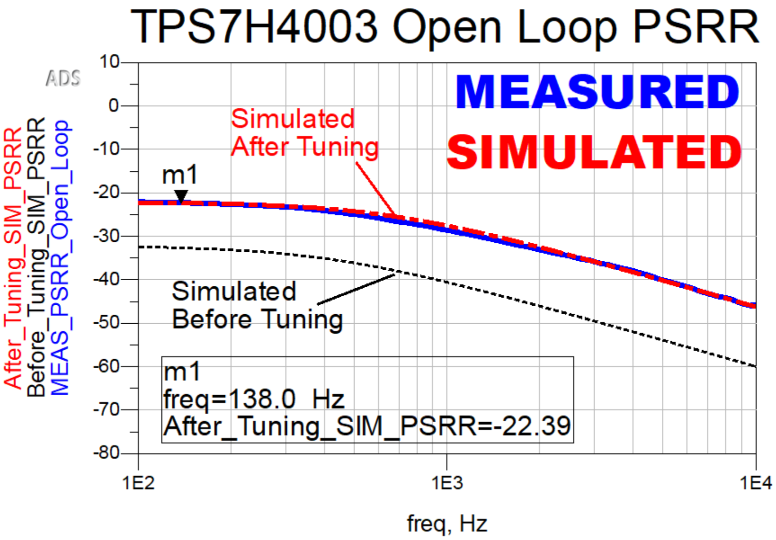


Measuring PSRR TPS7H4003 Open and Closed Loop



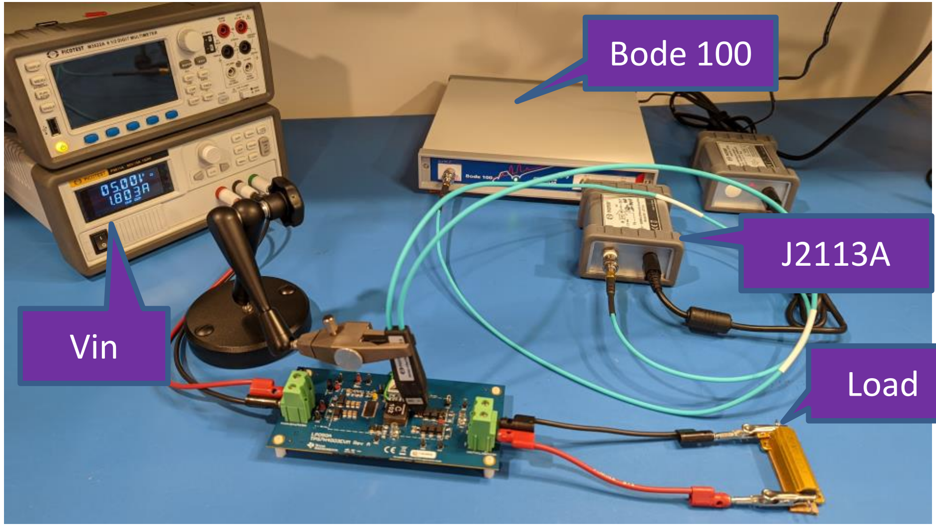
PSRR changes with load, so measure Open Loop

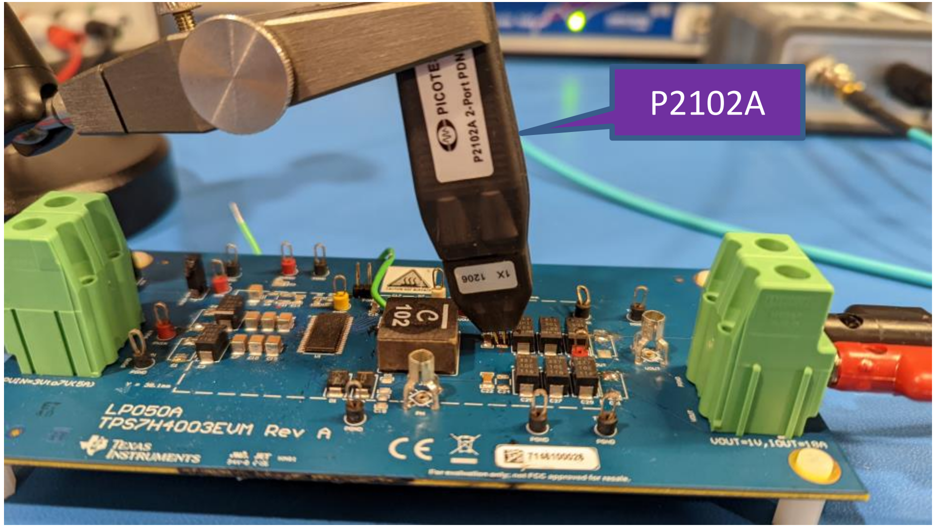




After tuning to match measurement, V_{RAMP} = 0.15V

Measuring VRM Output Impedance





Measure the VRM ON and OFF impedances

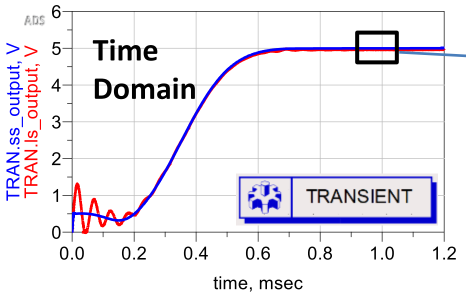
When doing a 2-port impedance measurement, it is important to remove the capacitor to prevent AC coupling between the 2 ports on the probe, which can cause measurement error

Why use the Harmonic Balance Simulator with SSAM

- Fourier Theory says time domain waveforms are made up of frequency domain waveforms.
- Solving a circuit in the Frequency Domain can be much faster since it limits the frequencies and jumps to steady state.

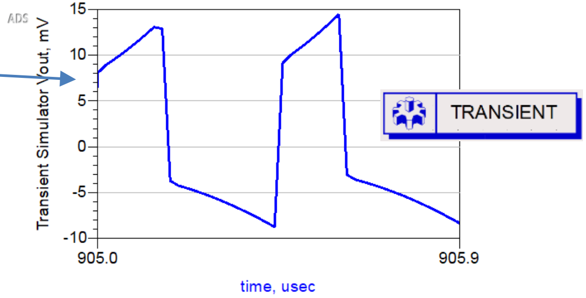
Simulator Results

Transient must reach steady state to measure ripple.
50,000 time-steps!

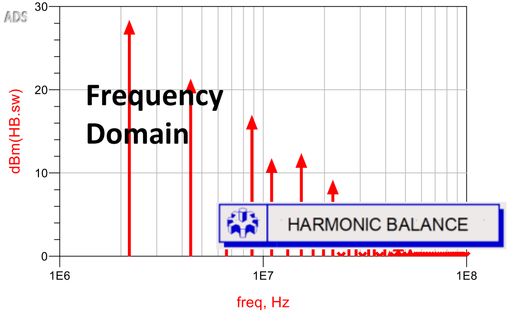


Time Domain
Transient Sim
Wait for Steady State
Minutes, Hours, **Days**

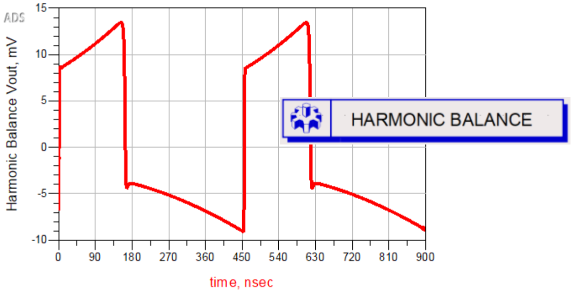
Steady State Ripple vs. Time



Harmonic Balance simulates harmonics of the switching frequency.
Only 255 Frequencies for steady state ripple!



Frequency Domain
Harmonic Balance Sim
FFT jumps to Steady State
Seconds, Minutes, Hours

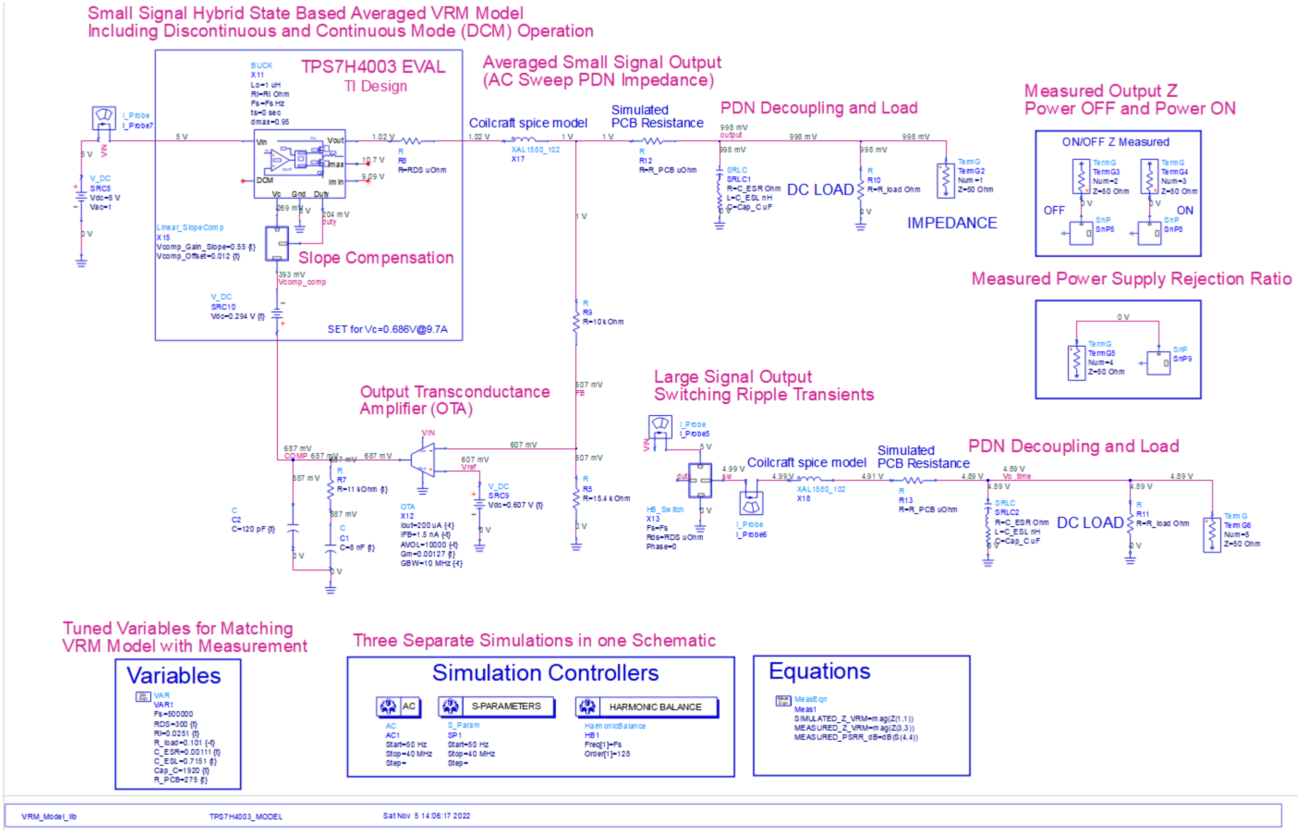


Data shown is for one VRM, typical PCB design has dozens of VRMs

State-Space Average Model TPS7H4003 EVM – TI Design

Does not include PCB effects

Put it all together in the Sandler SSAM VRM Model



TPS7H4003 State-Space Average Model Results

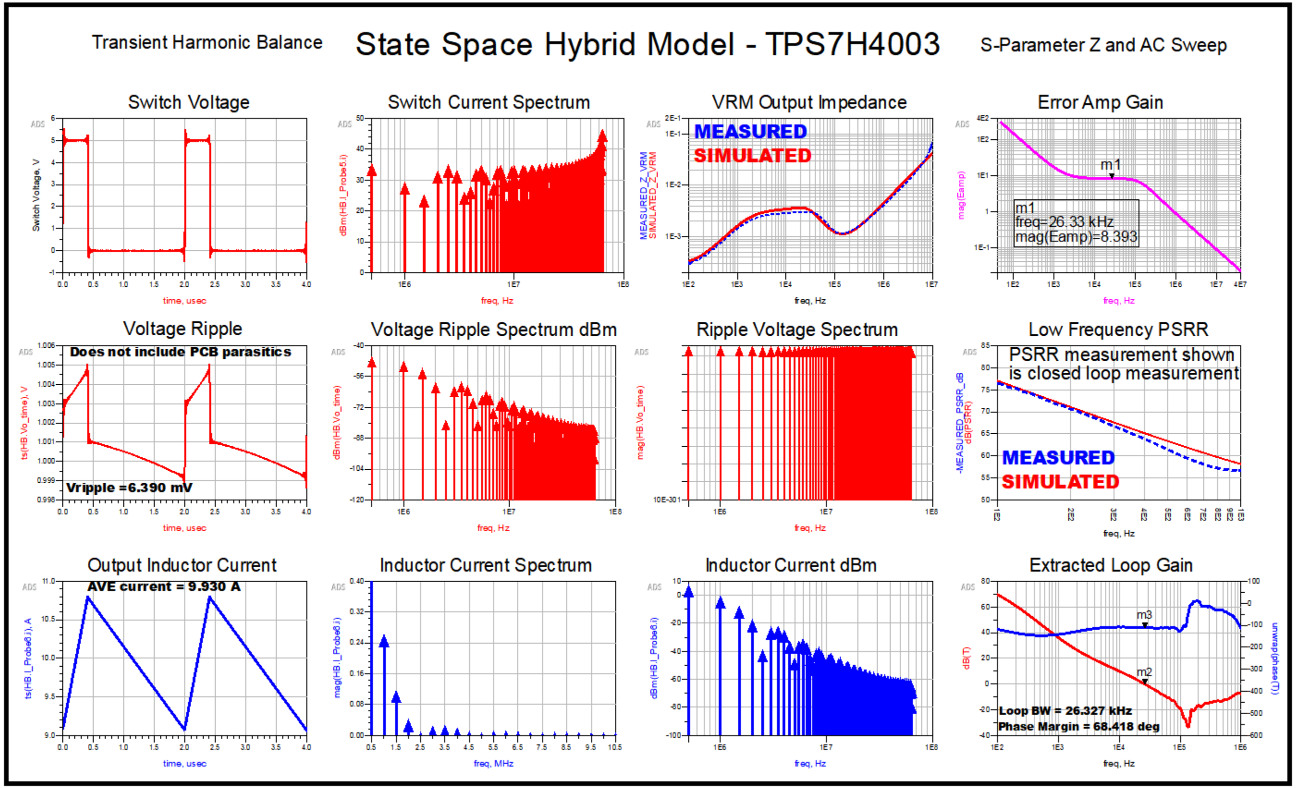
Does not include PCB effects

Simulation matches measurement…

Model is good!

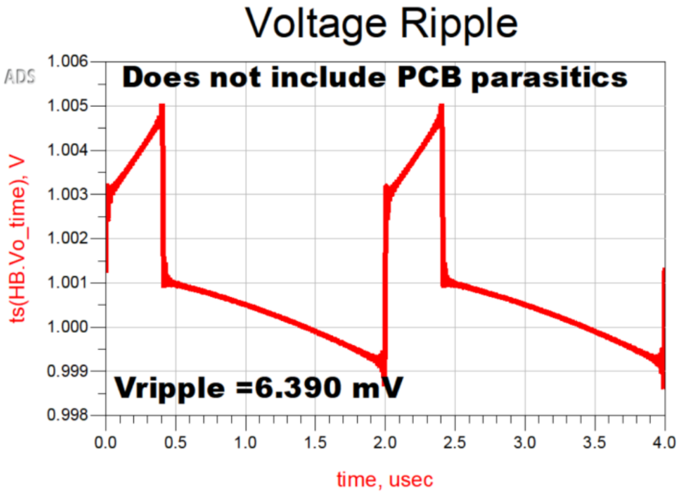
We're finished!

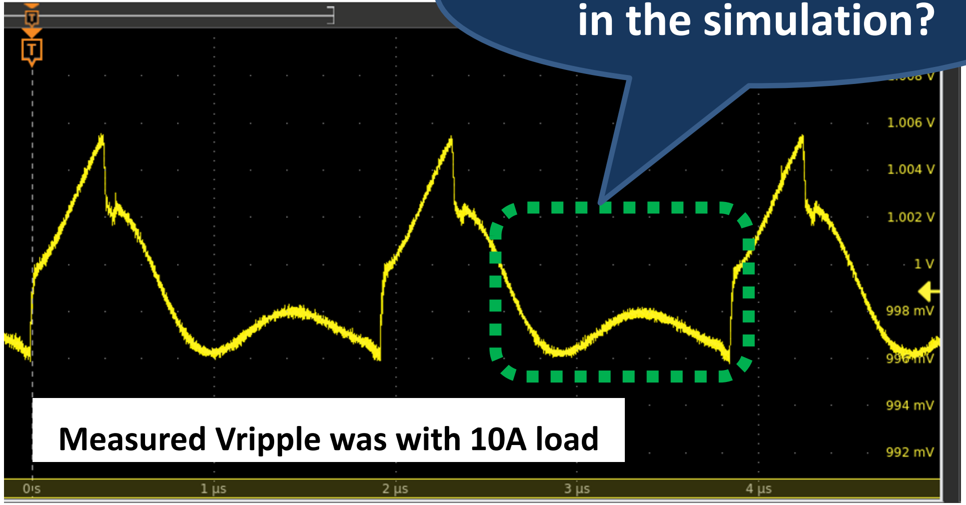
Or are we?



TPS7H4003 VRM Output Voltage Ripple

Simulation vs. Measurement





Why isn't this 1 MHz in the simulation?

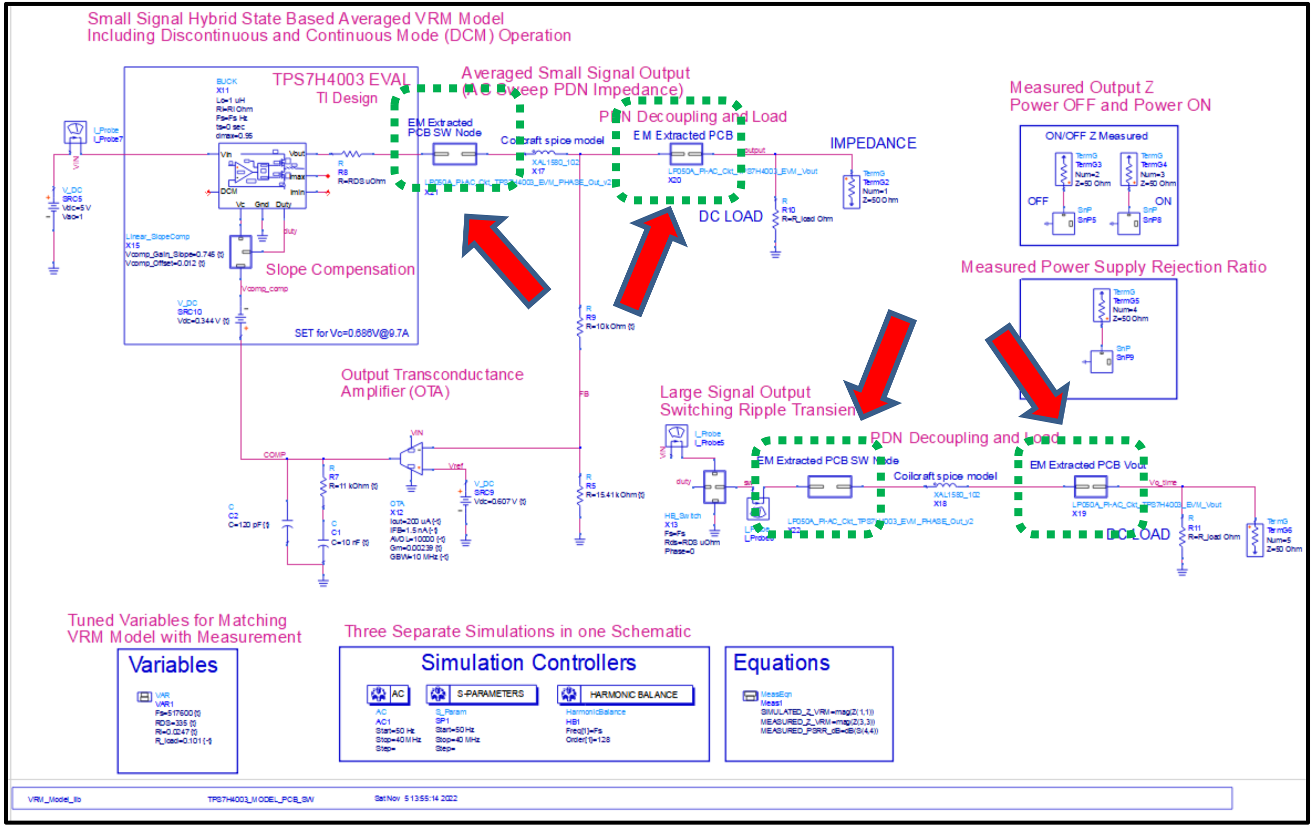
Measurement point

Comparing the simulated voltage ripple to the measurement

State-Space Average VRM Model TPS7H4003 EVM – TI Design

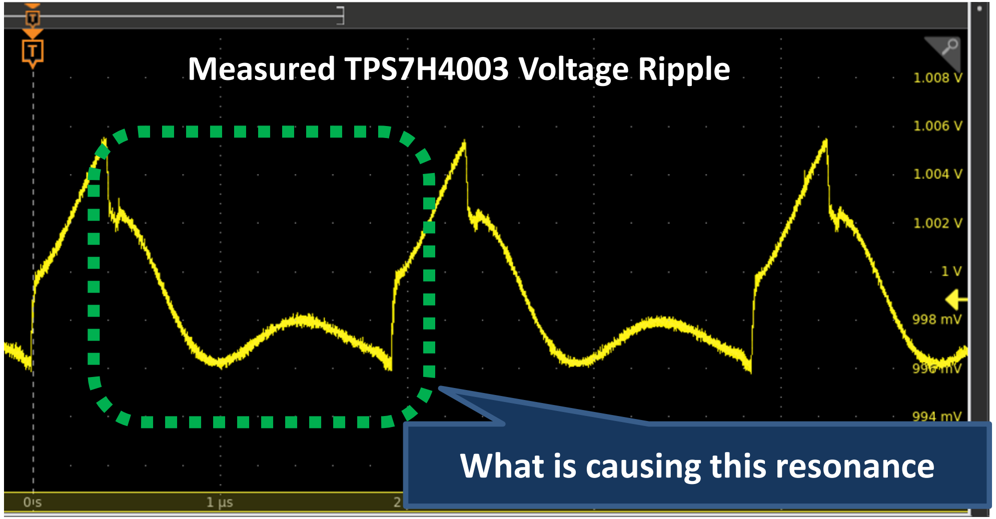
Does include PCB effects

Let's add the PCB effects to our model and see what happens to the voltage ripple

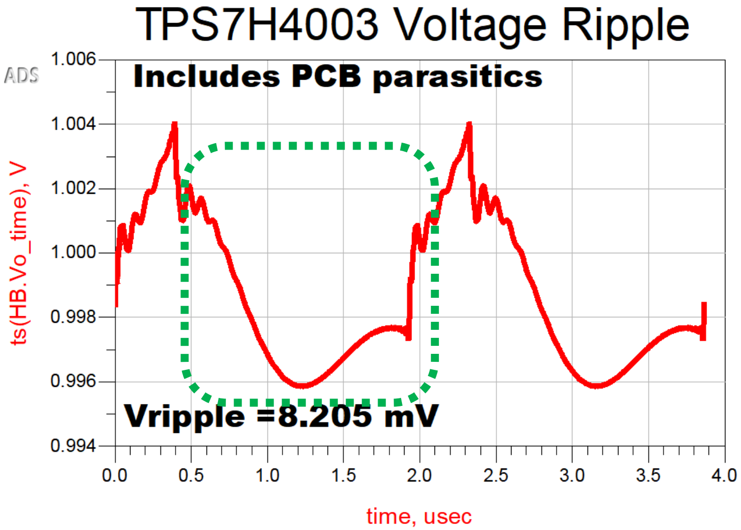


TPS7H4003 VRM Output Voltage Ripple

Measurement vs. Simulation with included PCB effects

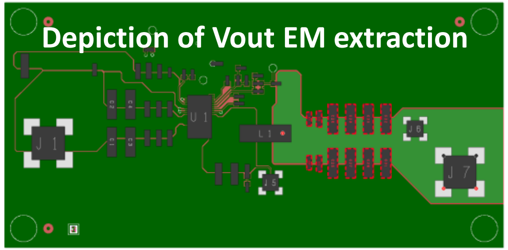


Simulated TPS7H4003 Voltage Ripple using State-Space Average VRM Model



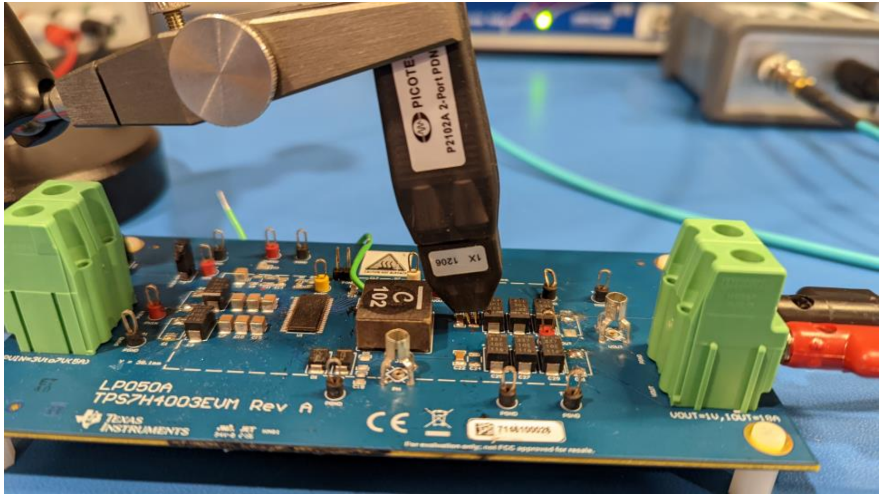
All extracted PCB artwork was from Keysight PathWave PIPro

Extracted PCB Artwork, the extracted Switch node is not depicted

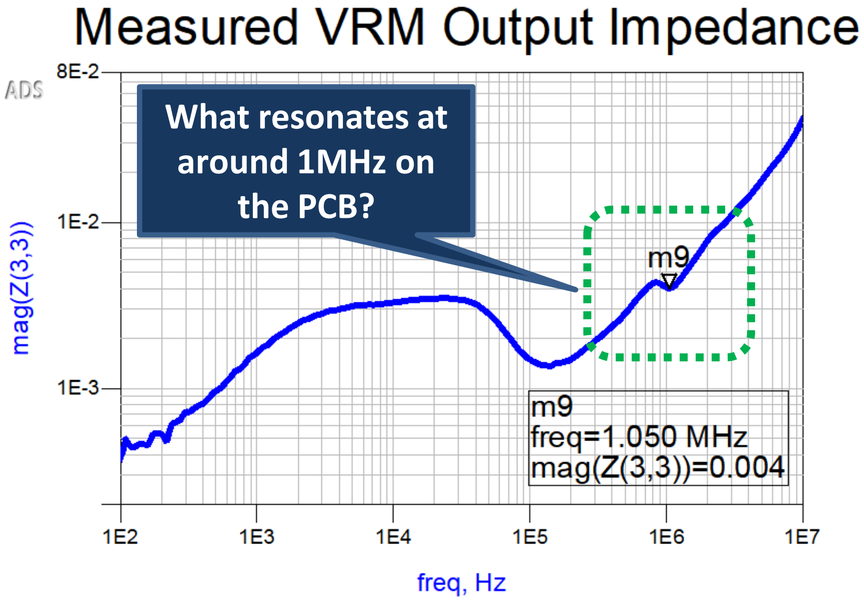


Exploring the PCB Effects seen in the Output Ripple

Output Impedance Measurement Setup with 2-port PDN Probe



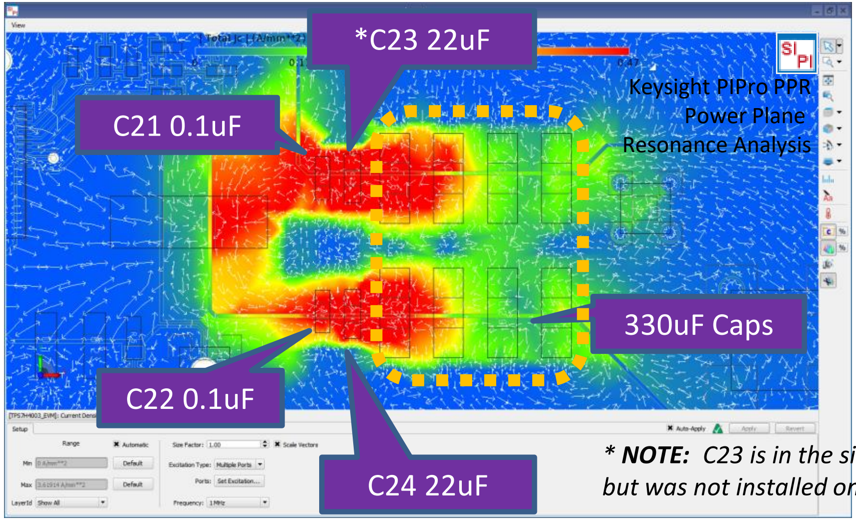
Measurement Point at C23



Output impedance measurement shows 1MHz resonance

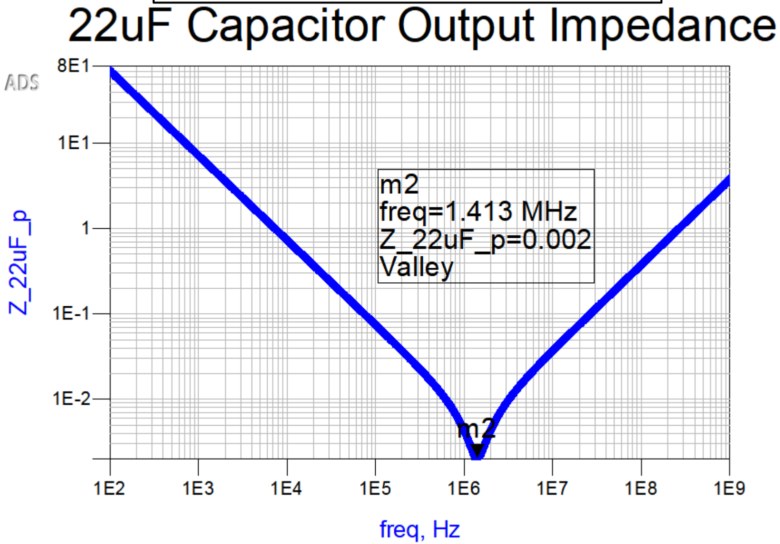
TPS7H4003 VRM – Investigating the Current Density on the PCB

Current Density Plot is created with 1MHz Resonance Frequency



*** NOTE:** *C23 is in the simulation, but was not installed on the PCB*

22 uF Cap resonances at 1 MHz!



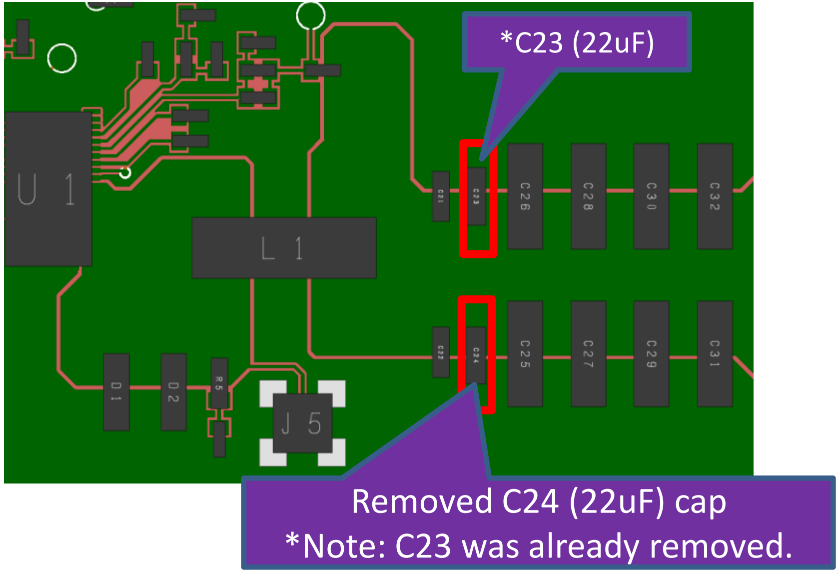
Multiple Caps are resonating at 1MHz, but only one is the culprit

Further Analysis 22uF vendor spice model confirms C24 is the potential resonance point on the PCB…..

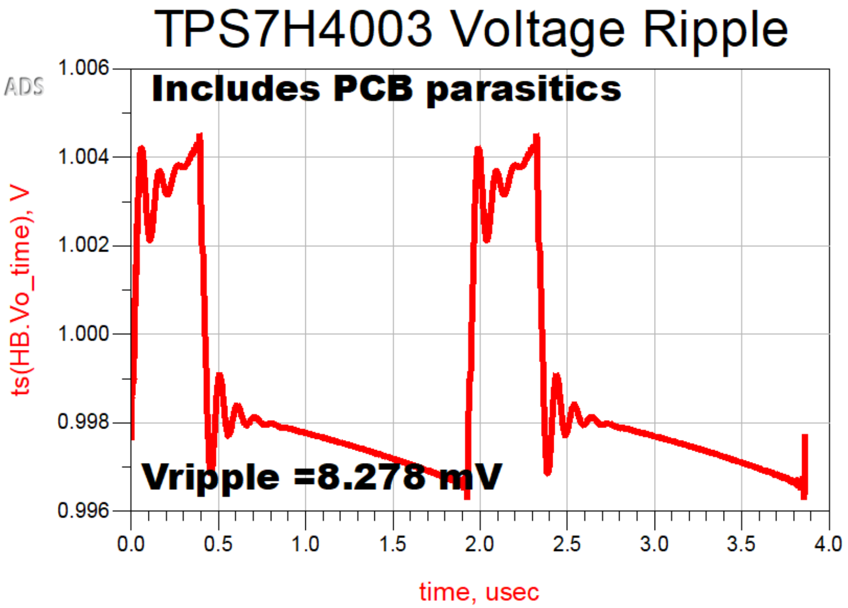
The 22uF Cap (C24) looks be our problem, right?

TPS7H4003 VRM – Removing the 22uF Capacitor

What happens if we remove the 22uF cap (C24)?



Simulated Vripple with 9.8A load



Removing a single capacitor removed the resonance seen in the output voltage ripple!

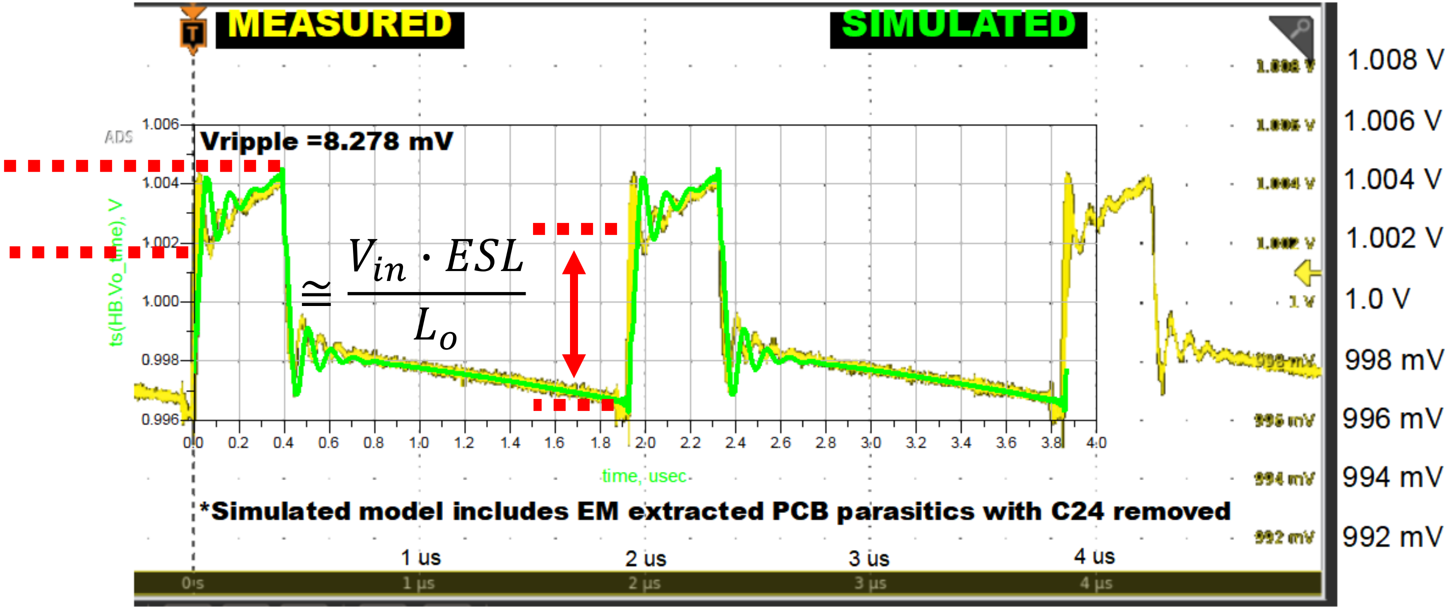
Simulating with PCB effects matters for getting the answer right.

Fine Tuning the TPS7H4003 EVM SSAM VRM Model – Digital Twin

Voltage Ripple - TPS7H4003 VRM EVAL PCB

Measurement vs. Simulated State Space Average Model

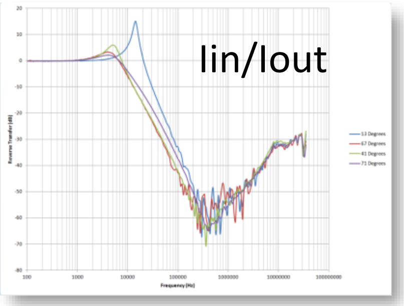
$$\cong \Delta I_L \cdot ESR$$



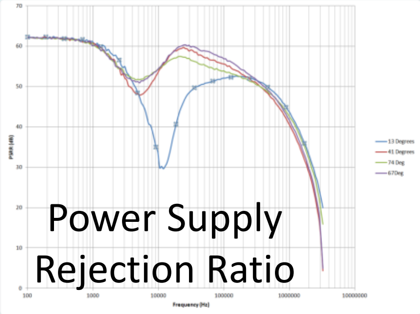
The model accurately matches the measurement

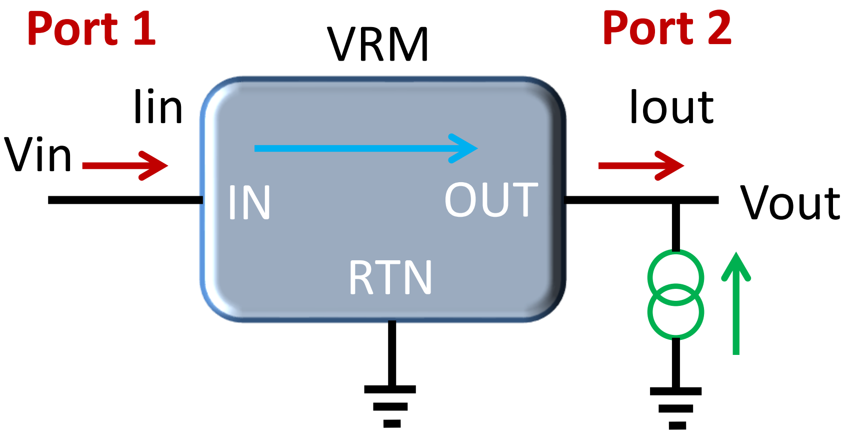
The Voltage Regulator Module (VRM) needs to consider <u>ALL</u> noise sources (large and small signal EMI)

Reverse Transfer - (S12)



PSRR - (S21)



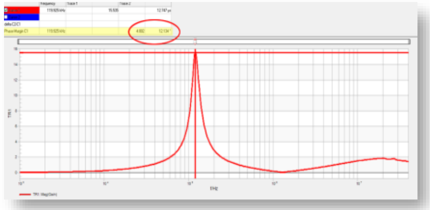


Input Impedance - (S11)

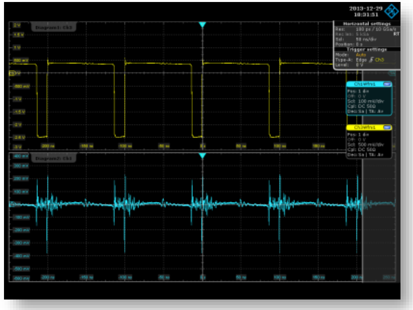
Input impedance can be NEGATIVE!

An R-L model only considers the output impedance

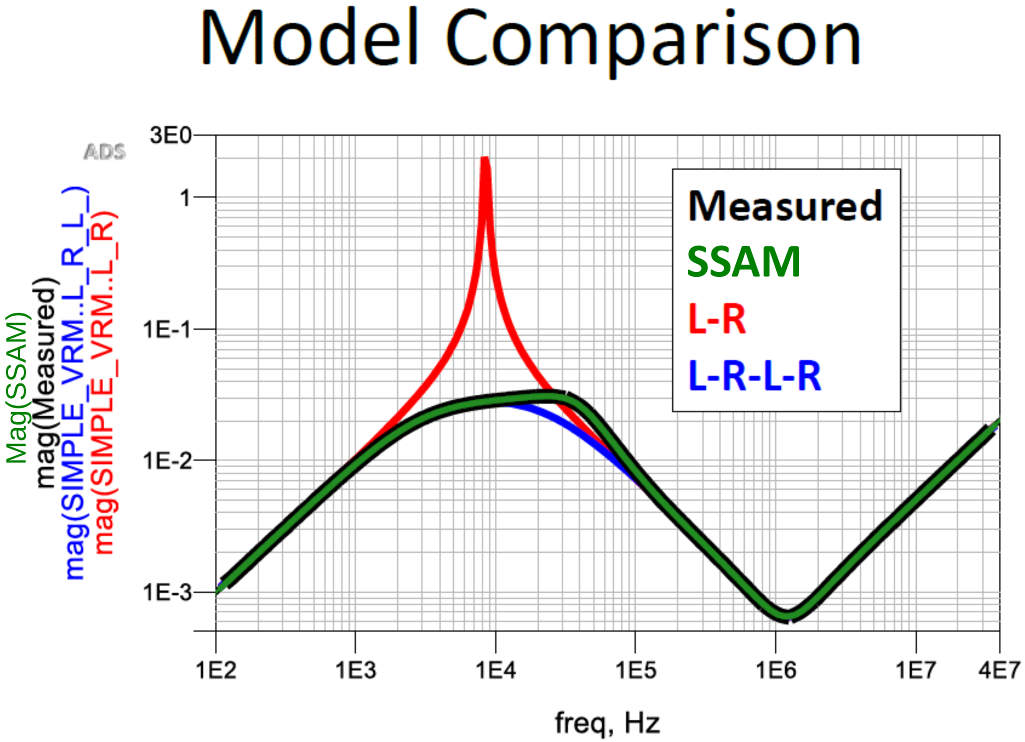
Output Impedance - (S22)



Output Noise/Spikes



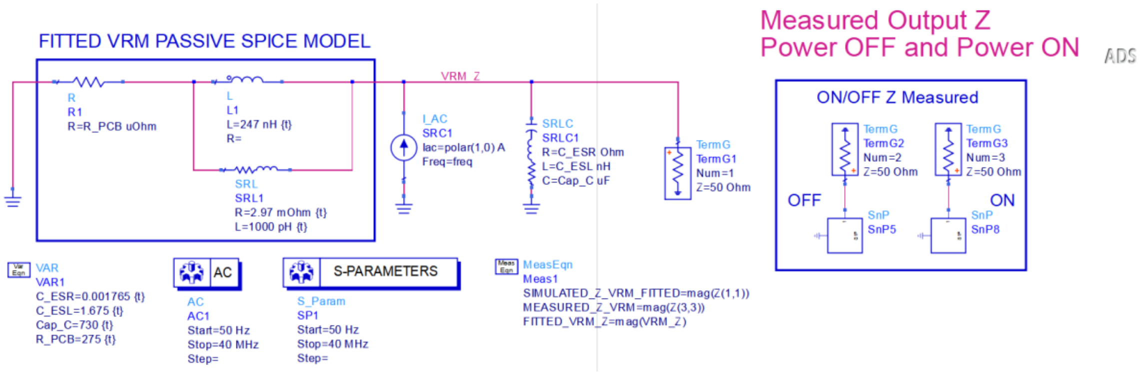
Evaluating the Results.. How much better is the SSAM VRM Model?

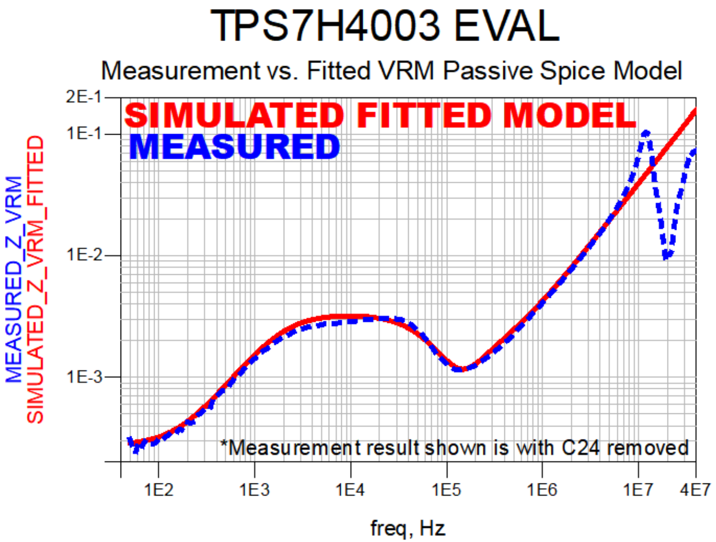


TPS7H4003 Measurement vs. Fitted Passive Spice Model

How much do we care about simulation with the PCB effects with the State-Space Average Model?

To answer that question, we need to first create a fitted passive spice VRM model

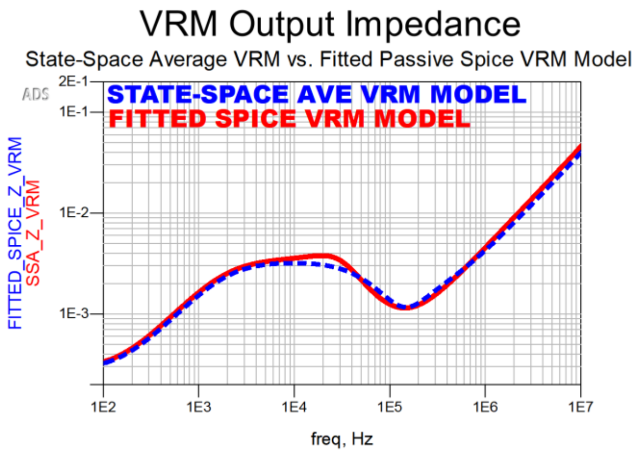




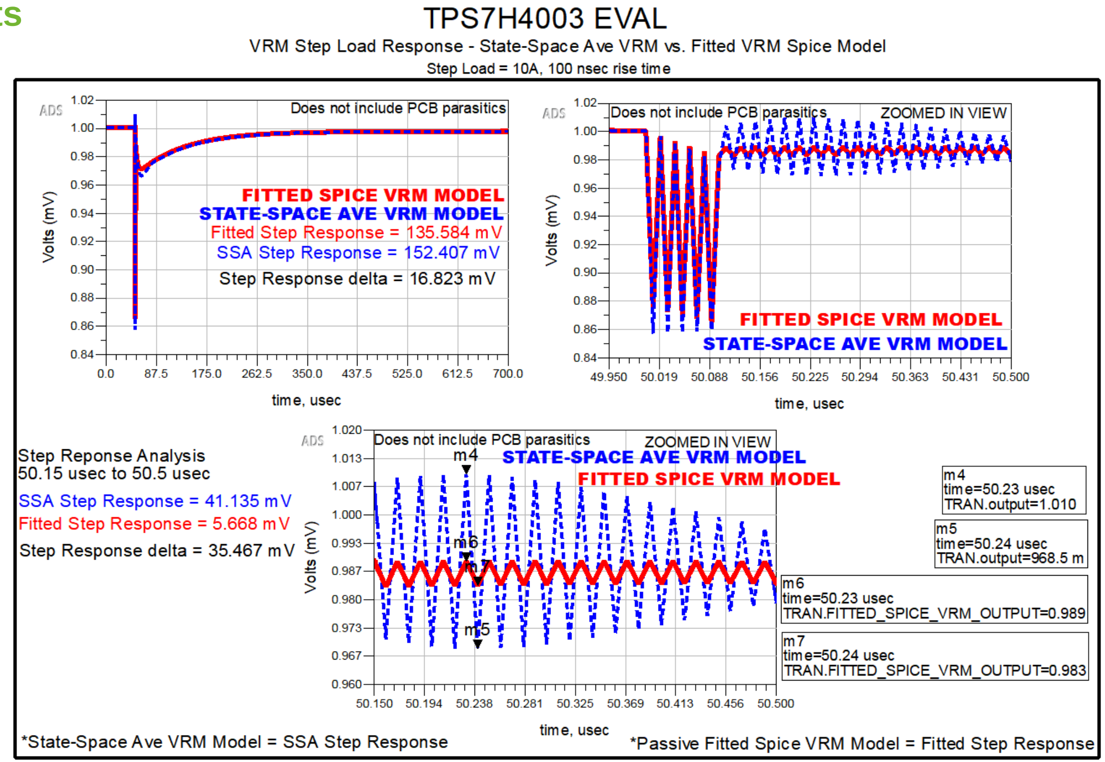
TPS7H4003 EVM with PCB SSAM vs. Fitted Passive SPICE Model Step Response

10A, 100nsec step load <u>without</u> PCB effects

Comparing the step response between the State-Space Average Model and the Fitted Passive Spice VRM model



Output Impedance Correlates between both models



86% Change in transient step response between both models *<u>without PCB Effects</u>*

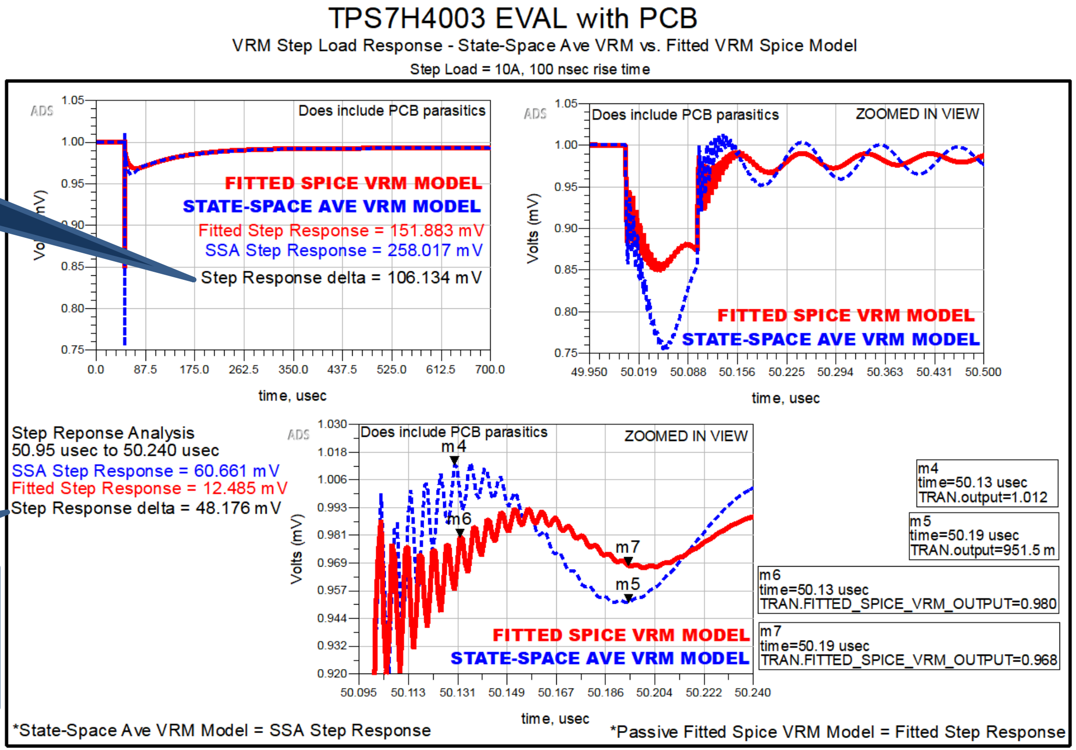
TPS7H4003 EVAL with PCB SSAM vs. Fitted Passive Spice Model Step Response

10A, 100nsec step load with PCB effects

41% change in transient response from SSAM VRM model

Now let's include the PCB effects and compare the results again

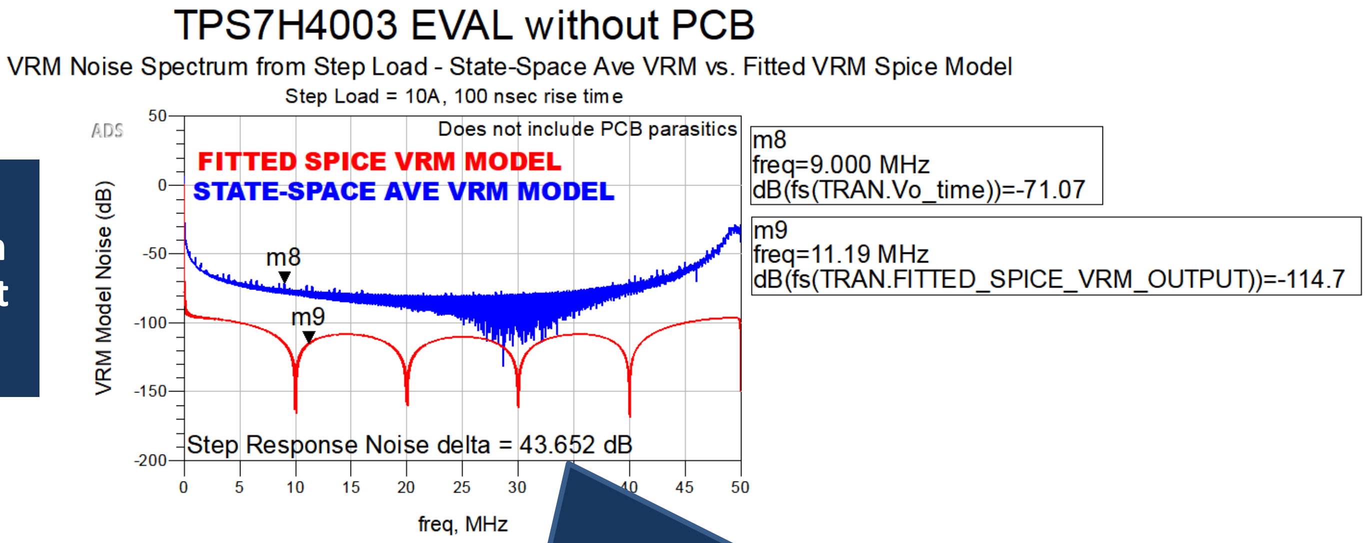
79% change in transient response from SSAM VRM model



79% Change in transient step response between both models *with PCB Effects*

TPS7H4003 EVM with PCB SSAM vs. Fitted Passive Spice Model Noise Spectrum from Step Response

10A, 100nsec step load without PCB effects



Let's compare the results in the noise spectrum without the PCB effects

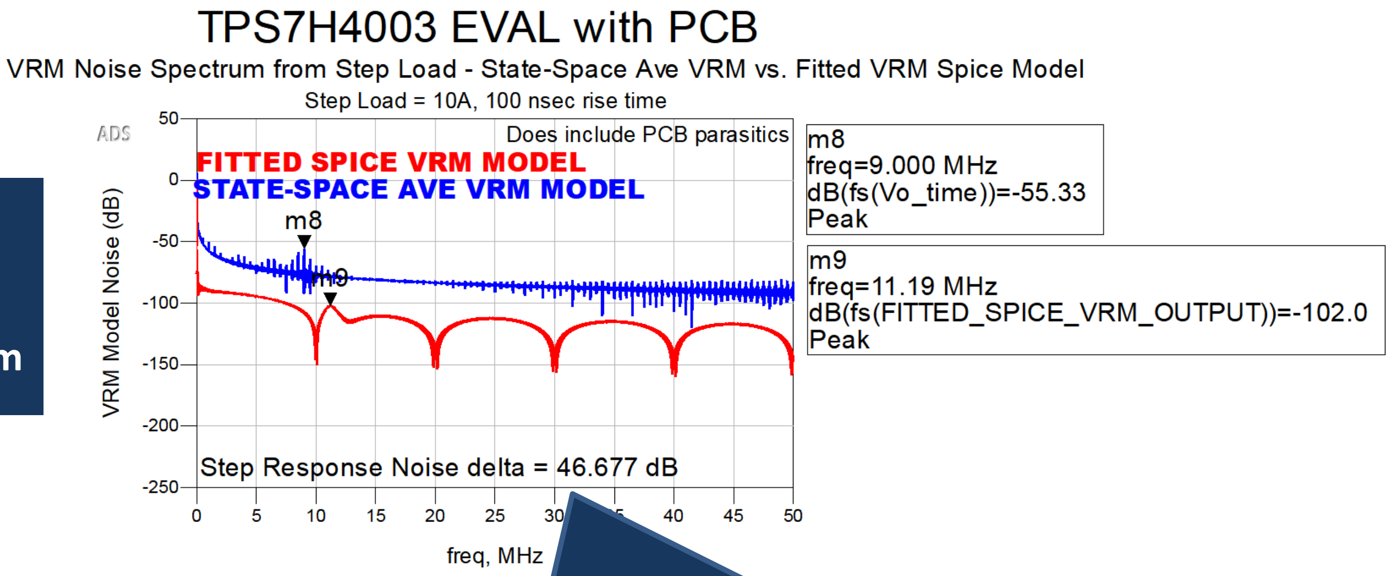
61.42% (44 dB) change in noise spectrum from SSAM

61% (44 dB) Change in transient step noise spectrum response between both models *without PCB Effects*

TPS7H4003 EVM with PCB SSAM vs. Fitted Passive Spice Model Noise Spectrum from Step Response

10A, 100nsec step load with PCB effects

Now let's include the PCB effects and compare the results in the noise spectrum



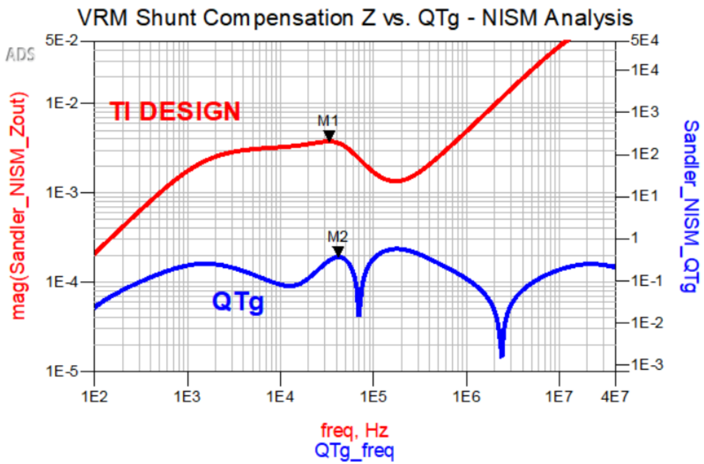
84% (47 dB) change in noise spectrum from SSAM

84% (47 dB) Change in transient step noise spectrum response between both models *with PCB Effects*

…..And Picotest NISM works in ADS also!

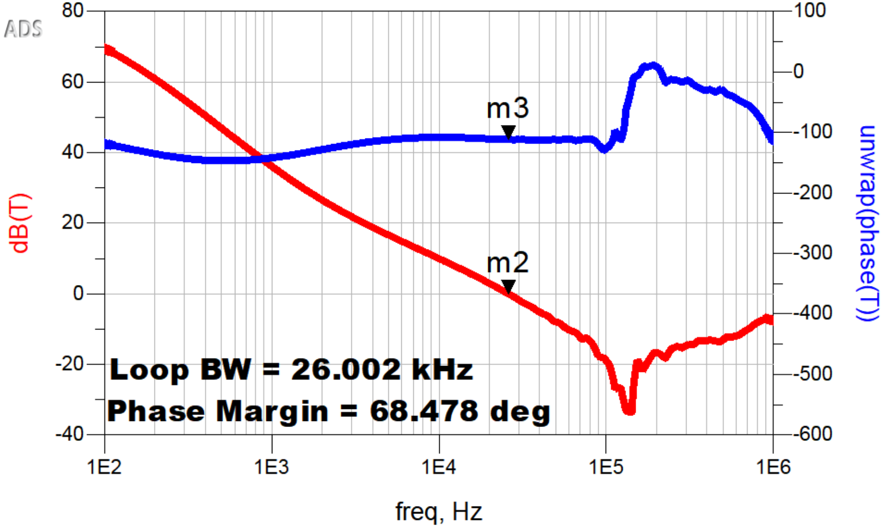
NISM* can be used for stability analysis of your VRM State-Space Average Model design with your PDN

TPS7H4003 EVAL



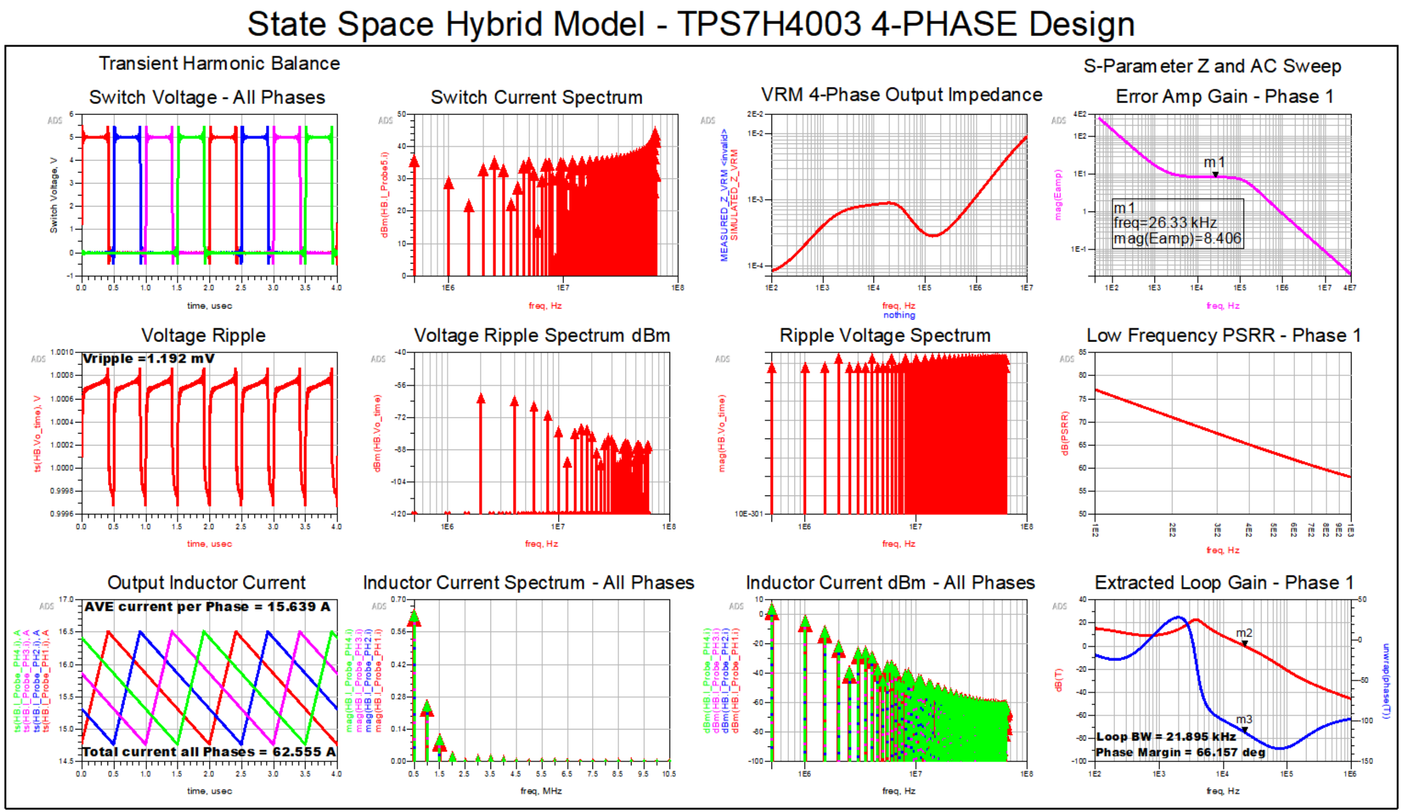
Sandler_NISM_PM: >71 degrees
Z Frequency: 33147.205 Hz
Q Frequency: 41734.891 Hz
Effective Q: 0.366

TPS7H4003 Extracted Loop Gain



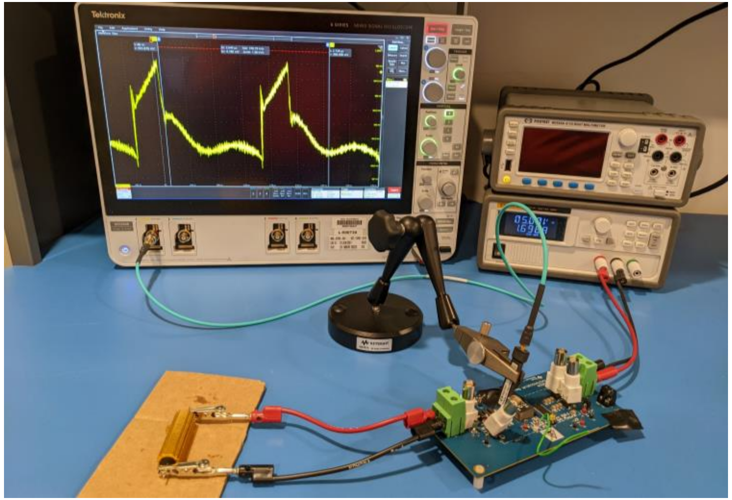
***Picotest Non-Invasive Stability Measurement (NISM)**

…. And it works for Multi-Phase and PMICs…



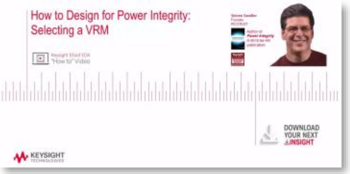
Call to Action

- **Designers need to stop using the L-R, L-R-L-R VRM SPICE models for PI simulations!**
    - The SSAM includes all 5 VRM noise sources for significantly higher fidelity
- **The delineation between Power Integrity and Power Electronics needs to end!**
    - PE designs need to include PCB EM with their VRM designs!
- **Learn to make these simple measurements and try this for yourself**
- **Download the ADS workspace to see the model and simulations**



https://www.picotestonline.com/Designcon2023

- **How to Design for Power Integrity: Selecting a VRM**



Conclusion and Summary

- **Accurate simulation results require a high-fidelity VRM model and the PCB effects!**
- **It takes 4 measurements to build an accurate Sandler State-Space Average VRM model**
    - However, these State-Space Average Models do not need to be perfect!
- **The Sandler State-Space Average VRM Model is…..**
    - Easy to populate for VRMs
    - Supports EM simulations
    - Supports many modes and multi-phase
- **A poor fidelity State-Space Average Model is significantly better than a good R-L VRM model**

Thank you for attending!

QUESTIONS?

References

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4. Techniques for Accurate PSRR Measurements
5. Measurement Based VRM Modeling
6. Picotest P2102A-1X 2-port PDN Transmission Line Probe
7. Application Note - 2-Port Impedance Measurement using the P2102A Probe and Bode 100 VNA
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9. Picotest J2102B Common Mode Transformer
10. Picotest BNC-BNC 0.25m PDN Cable
11. Picotest J2120A Line Injector
12. Bode 100 VNA
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18. Keysight PathWave PIPro – https://www.keysight.com/us/en/product/W3034E/pathwave-pipro.html