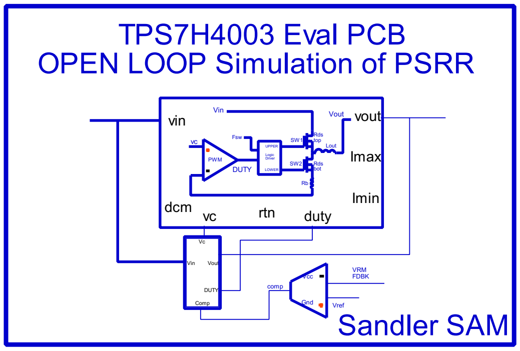
VRM Modeling and Stability Analysis for the Power Integrity Engineer

S. Sandler, H. Barnes, and B. Dannan, "VRM Modeling and Stability Analysis for the Power Integrity Engineer", DesignCon 2023.

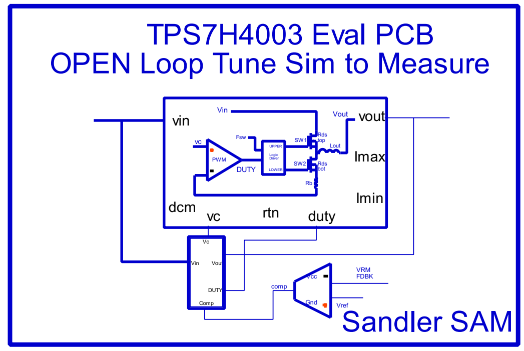
Building the TPS7H4003 SSAM Measured Behavioral Model

Step 1 - Simulate Data Sheet Values for OPEN Loop PSRR.



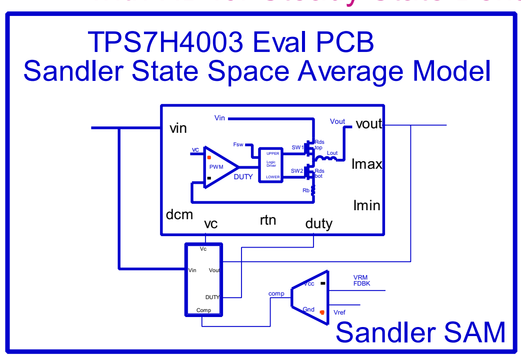
TPS7H4003_Simple_OpenLoop_MODEL
X1

Step 2 - Tune Ri and Vramp to match OPEN Loop PSRR Simulation to Measurement.



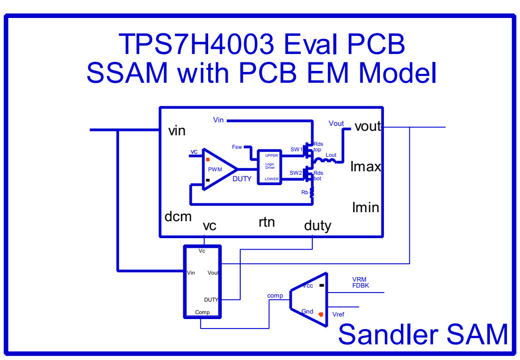
TPS7H4003_OpenLoop_MODEL
X2

Step 3 - Run the Tuned Sandler State Space Average Model (SSAM) with HB for Steady State Behavior



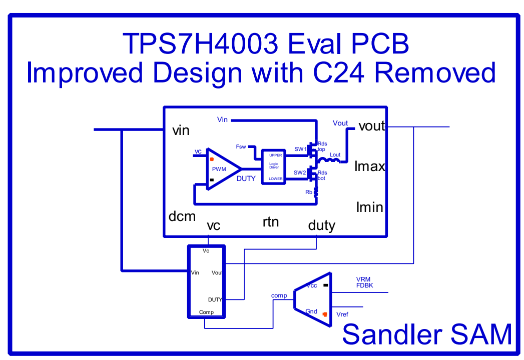
TPS7H4003_MODEL
X3

Step 4 - Matching with measurement requires PCB EM model to be added.



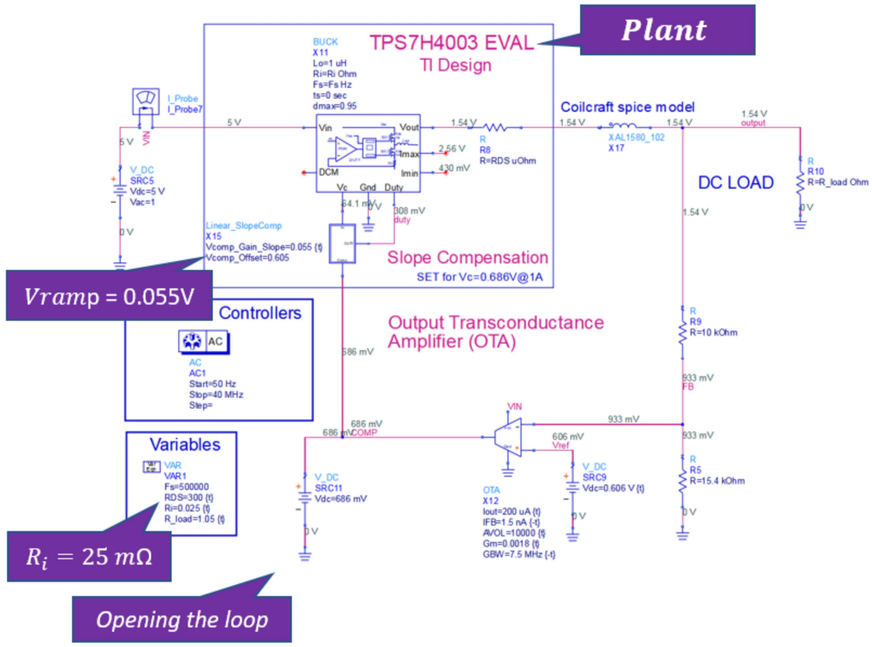
TPS7H4003_MODEL_PCB_SW
X4

Step 5 - Resonance at 1MHz is mitigated by removing C24.



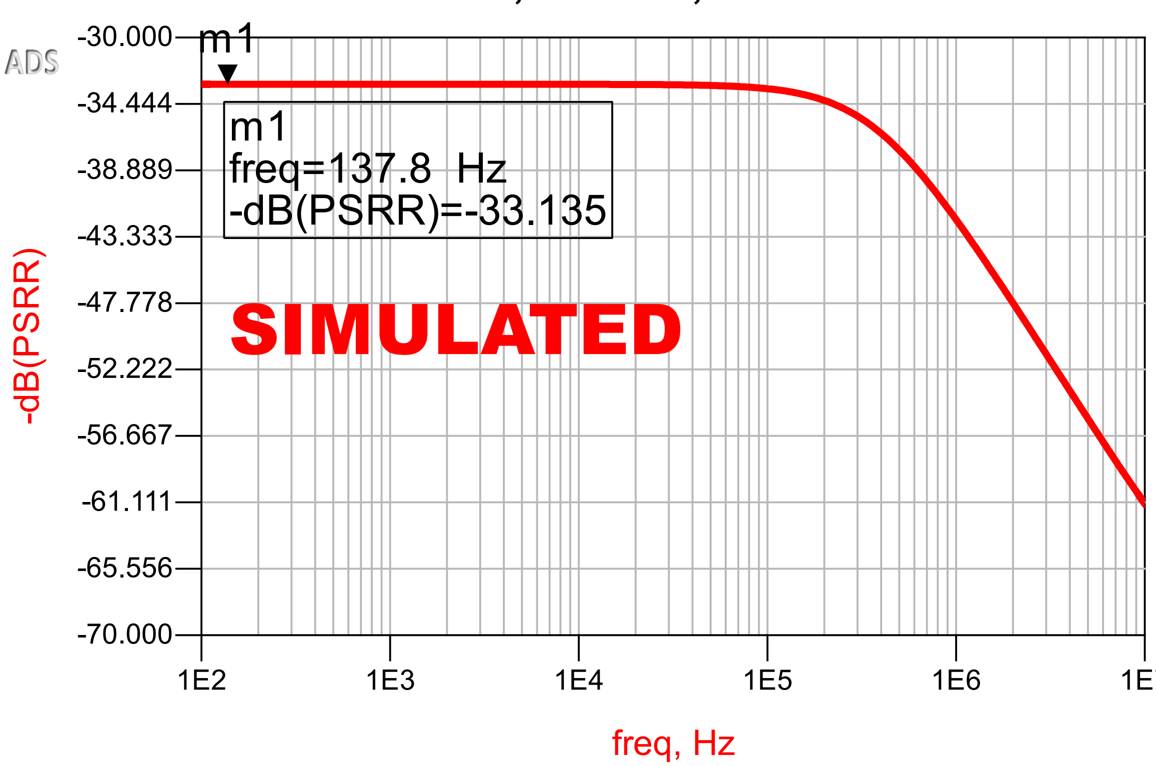
TPS7H4003_MODEL_PCB
X5

Showing Plant Open Loop Plant Gain using datasheet Vramp and Ri Values



TPS7H4003 Open Loop PSRR

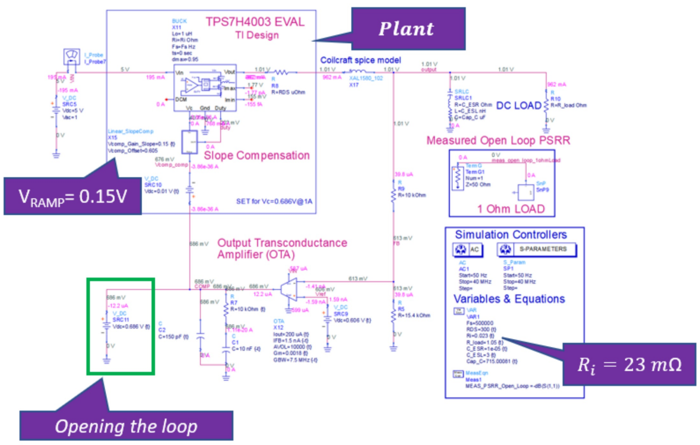
5Vin, 1Vout, 1A Load



NOTE:

Results shown include coilcraft inductor spice model

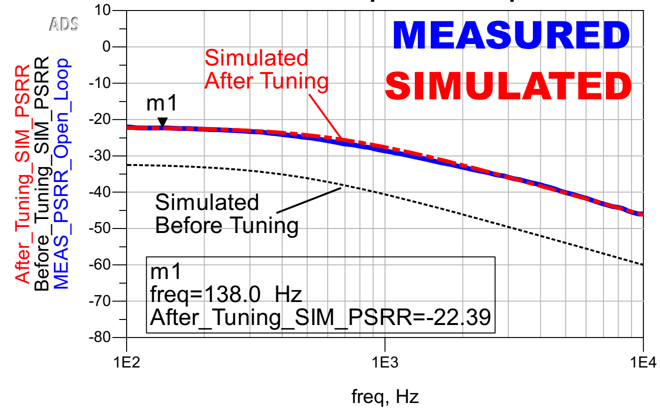
PSRR changes with load, so measure Open Loop



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

5Vin, 1Vout, 1A Load

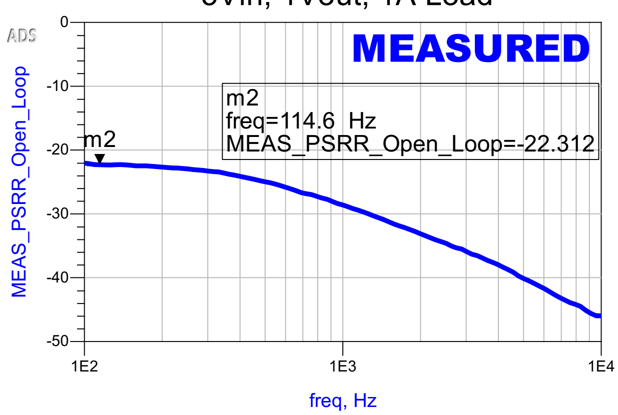
TPS7H4003 Open Loop PSRR



NOTE:
Results shown include coilcraft inductor spice model

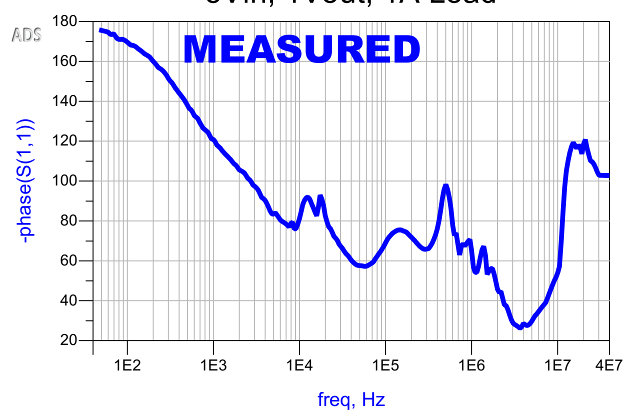
TPS7H4003 Open Loop Gain

5Vin, 1Vout, 1A Load



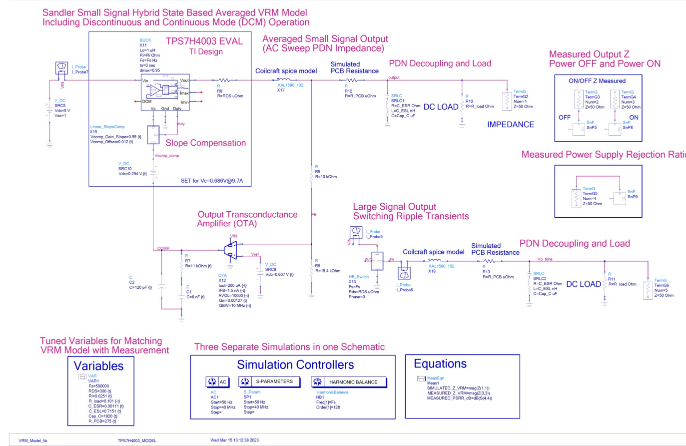
TPS7H4003 Open Loop Gain Phase

5Vin, 1Vout, 1A Load

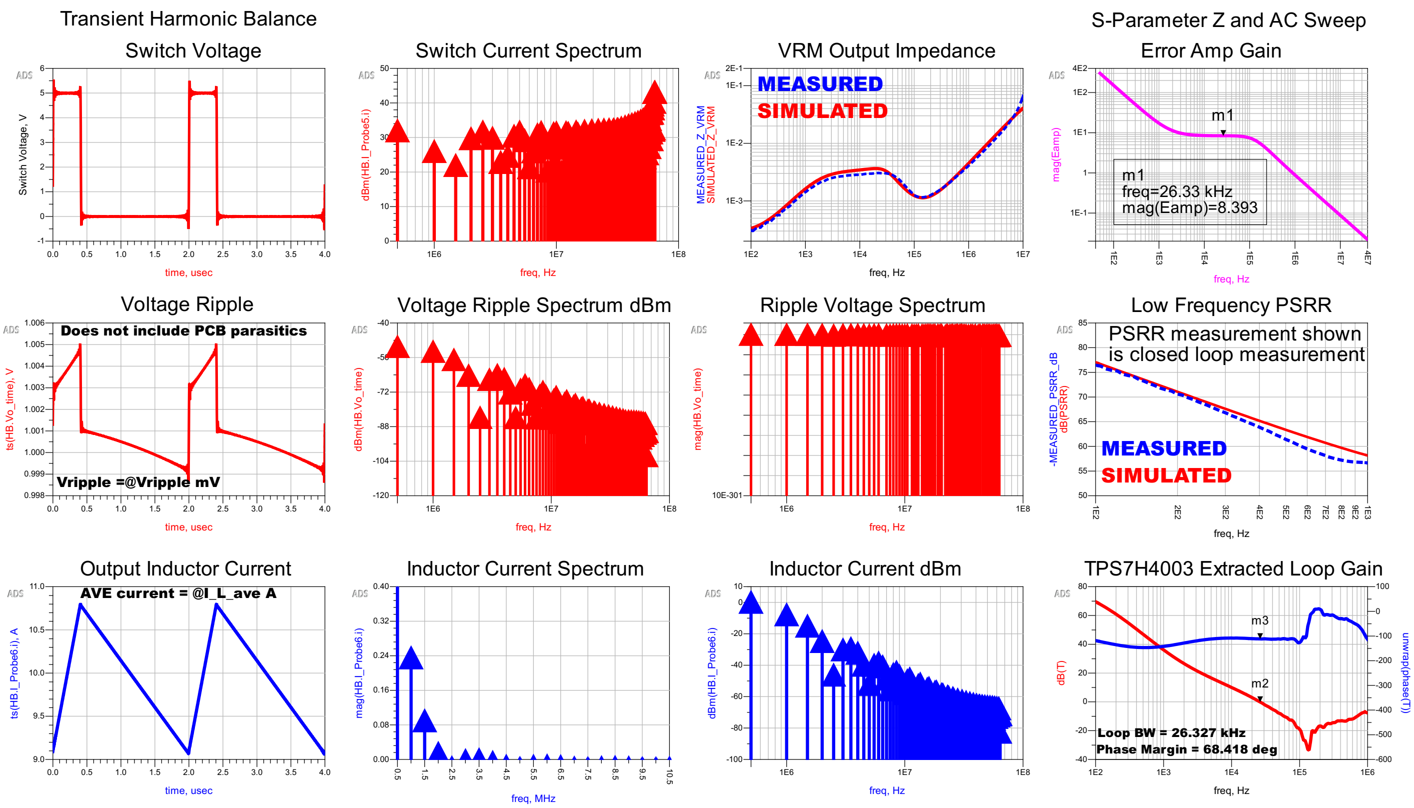


TPS7H4003 EVAL Board

This Hybrid State Space VRM Model enables fast simulation of PDN performance.
It is adjusted/tuned with measurements to capture actual design parasitics and tolerances.
This model enables accurate simulation of VRM active output impedance and control loop with the passive decoupling and dynamic load, as well as switching transients.
Simulation speed is less then 1 minute.



Sandler State Space Hybrid Model - TPS7H4003



NOTE:

Results shown include coilcraft inductor spice model

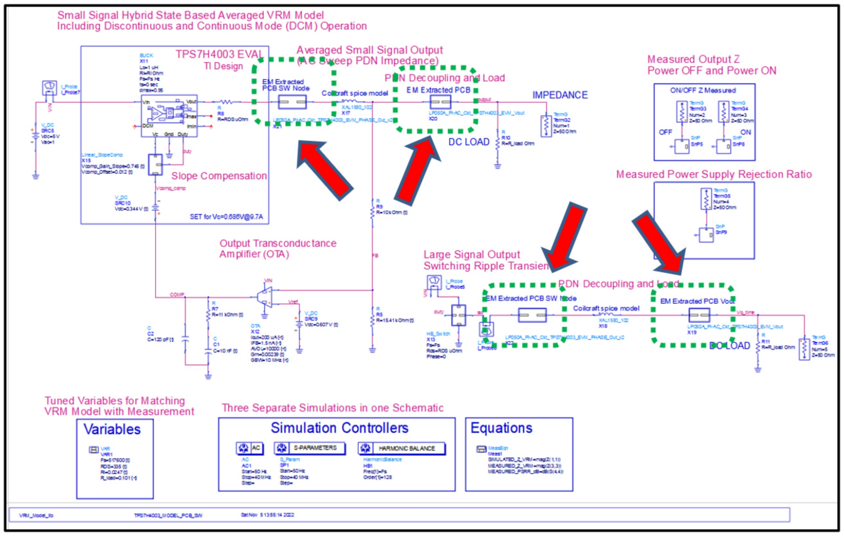
Eqn LoopBW=indep(m2)/1000

Eqn PM=180+m3

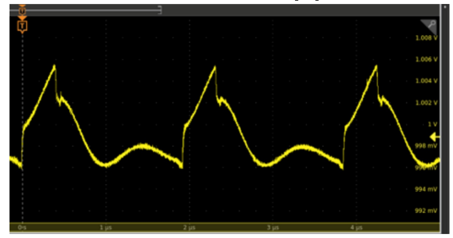
m2
freq=26.33 kHz
dB(T)=-140.7 m

m3
freq=26.33 kHz
unwrap(phase(T))=-111.582

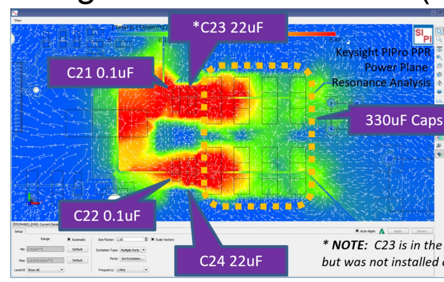
Adding PCB EM Model

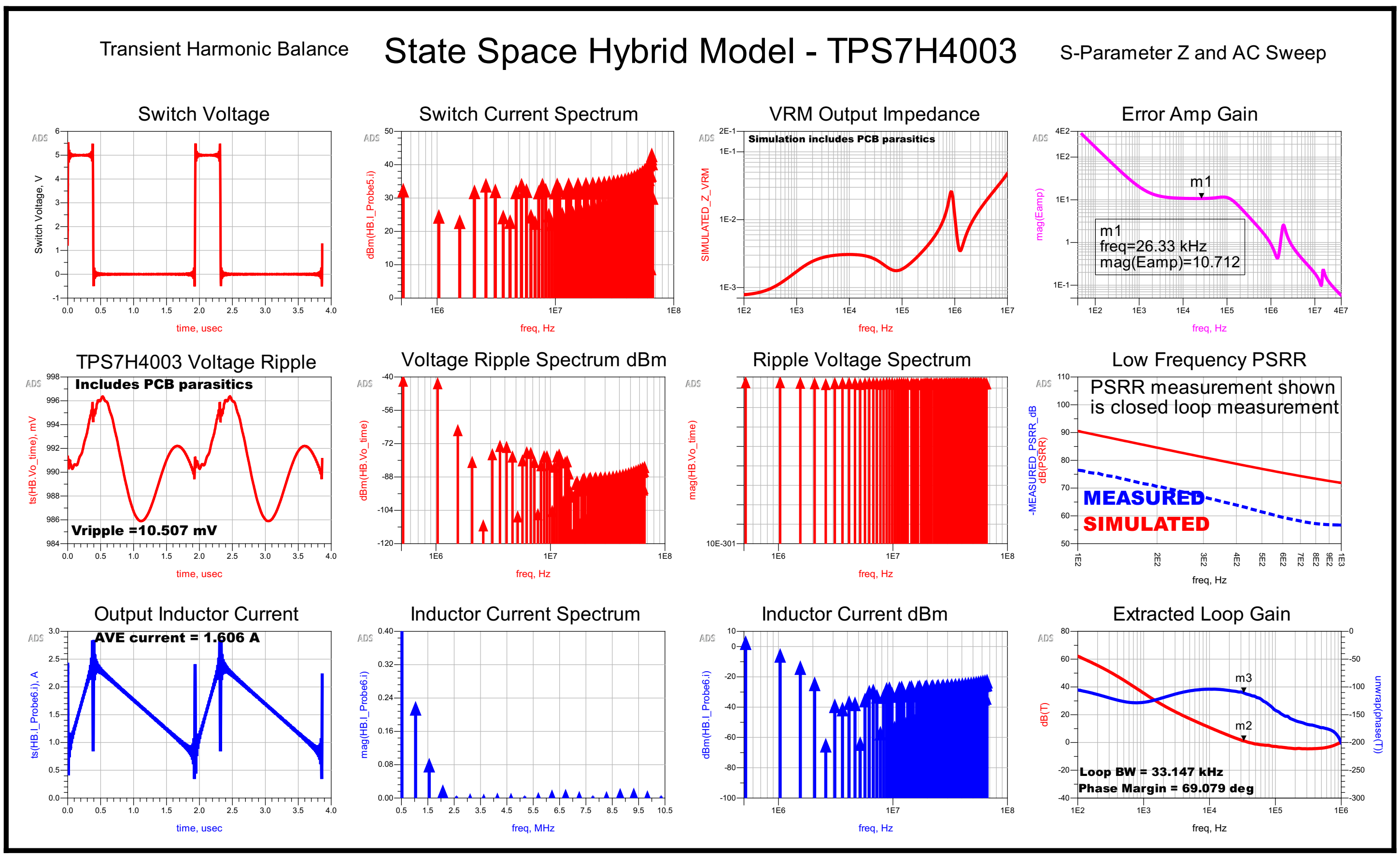


Measured Ripple



Locating 1 MHz Resonance (PIPro PPR)





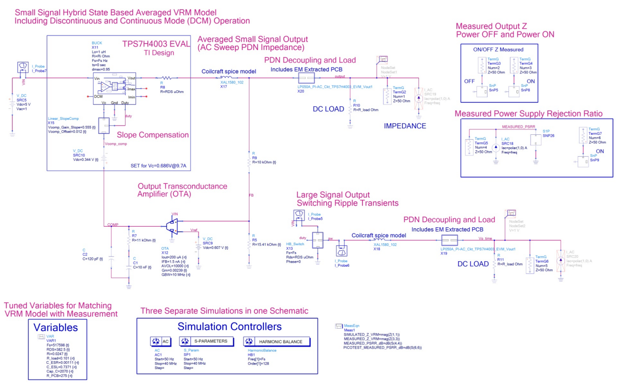
Eqn LoopBW=indep(m2)/1000   Eqn PM=180+m3

m2	m3
freq=33.15 kHz dB(T)=1.089	freq=33.15 kHz unwrap(phase(T))=-110.921

NOTE:

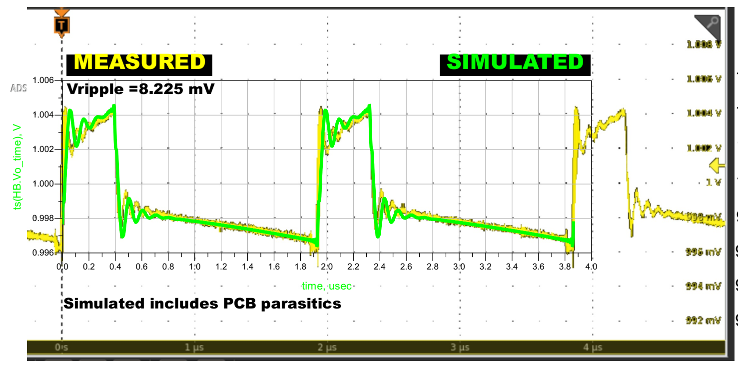
Results shown include coilcraft inductor spice model

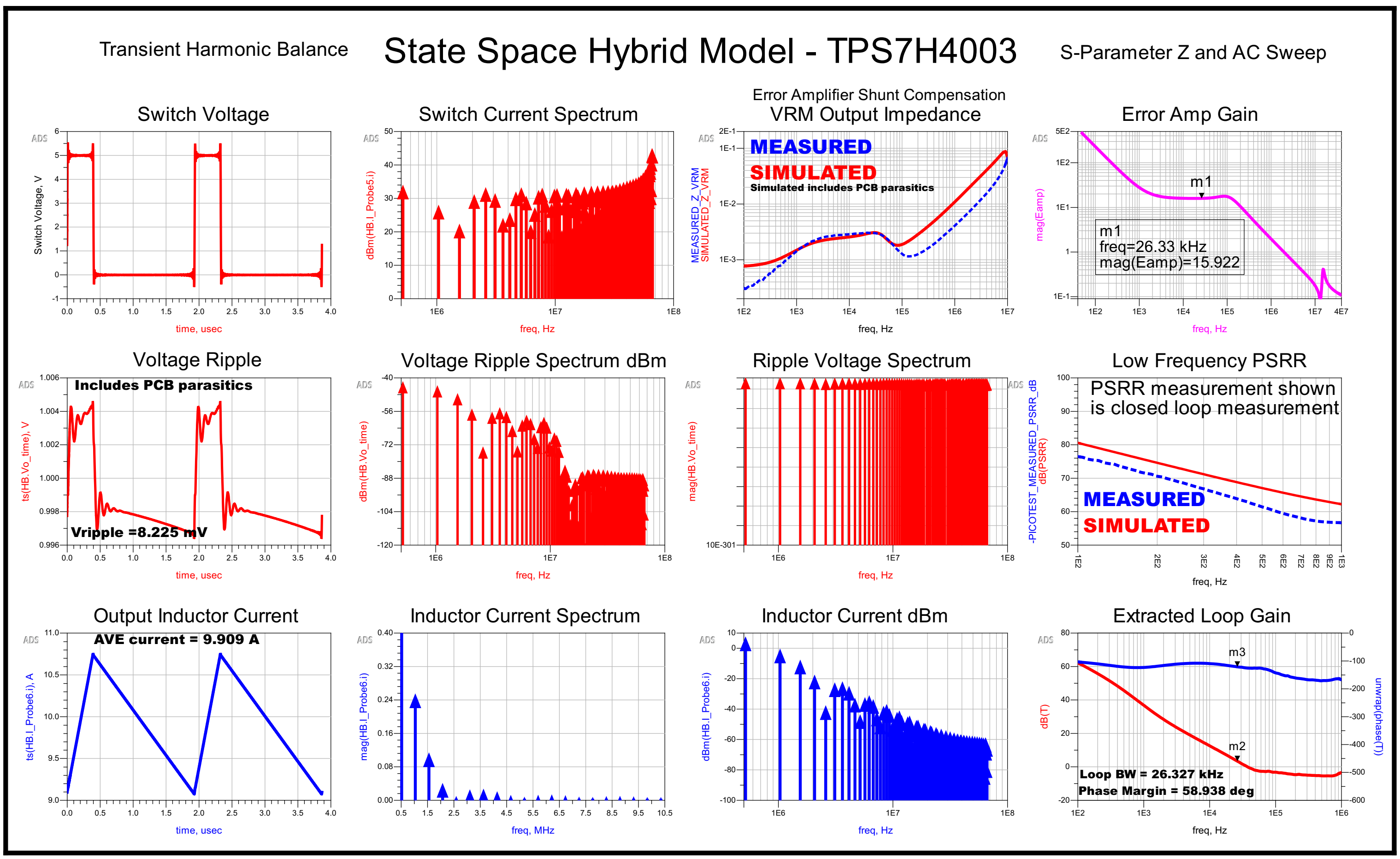
This Hybrid State Space VRM Model enables fast simulation of PDN performance.
It is adjusted/tuned with measurements to capture actual design parasitics and tolerances.
This model enables accurate simulation of VRM active output impedance and control loop with the passive decoupling and dynamic load, as well as switching transients.
Simulation speed is less then 1 minute.



TPS7H4003 VRM Evaluation Board

Measurement vs. Simulated State Space Average Model





NOTE:

Results shown include coilcraft inductor spice model

m2	m3
freq=26.33 kHz	freq=26.33 kHz
dB(T)=3.378	unwrap(phase(T))=-121.062

Eqn LoopBW=indep(m2)/1000

Eqn PM=180+m3

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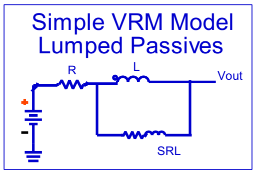
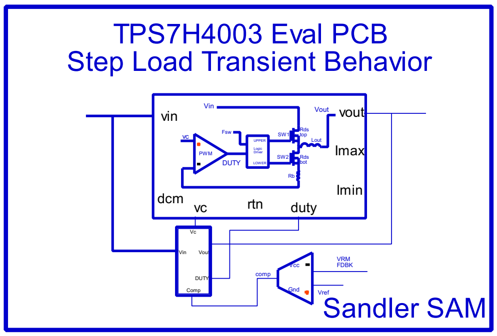
TPS7H4003 SSAM Model Compare



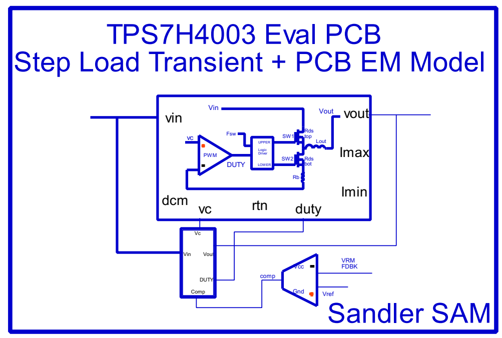
Comparing simple passive RLC models for the VRM vs. measurement.

TPS7H4003_Fitted_Spice_Model
X4



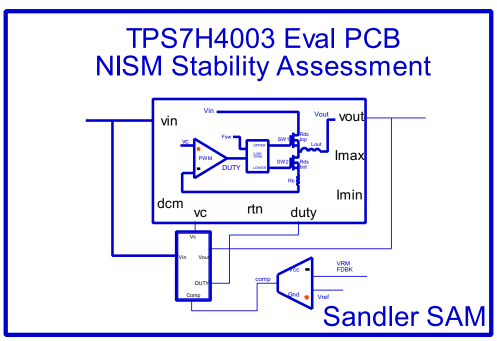
Transient step behavior without the PCB EM model.

TPS7H4003_MODEL_Step_Load
X6



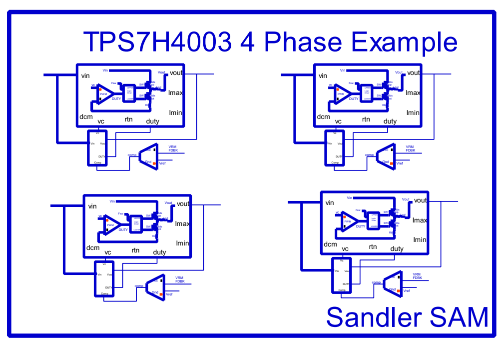
Transient step behavior with the PCB EM model.

TPS7H4003_MODEL_Step_Load_PCB
X7



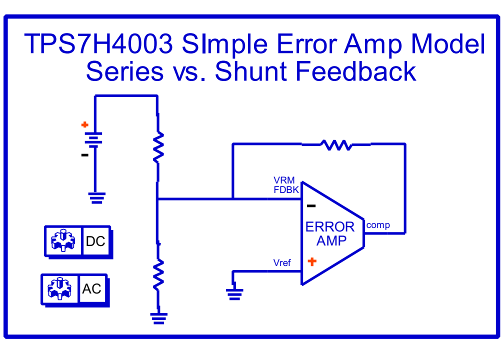
NISM stability assessment of the VRM control loop.

TPS7H4003_MODEL_NISM
X5



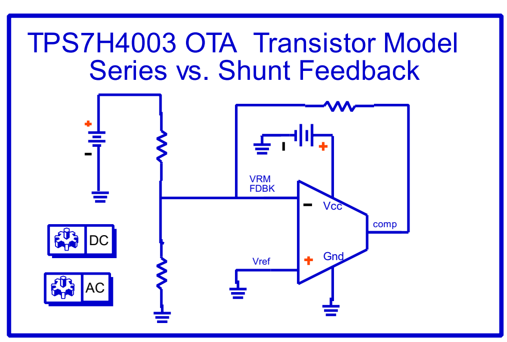
TPS7H4003 SSAM extended to a 4-phase model

TPS7H4003_4phase_MODEL
X1



Simple error amp behavioral model for VRM feedback

TPS7H4003_Error_amp_series_vs_shunt
X2



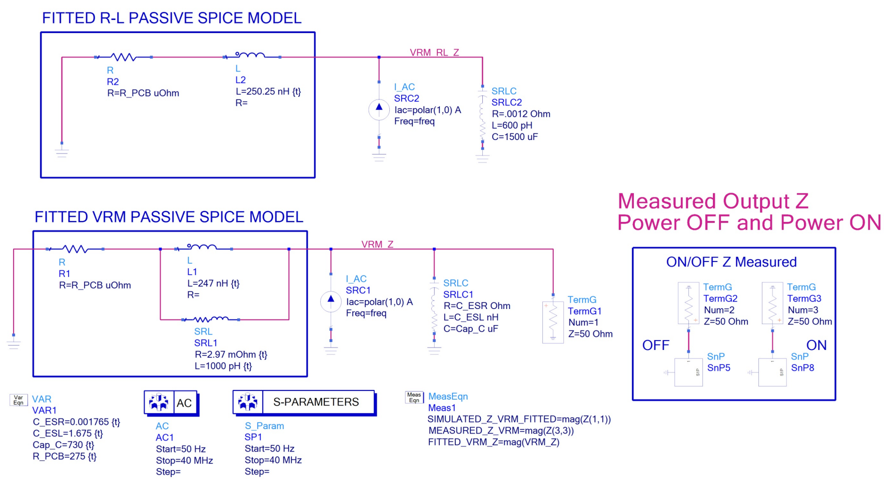
Operational Transconductance Amplifier transistor model for the VRM feedback.

TPS7H4003_OTA_series_vs_shunt_amp
X3

VRM_Model_lib

-readme_vrm_model_compare

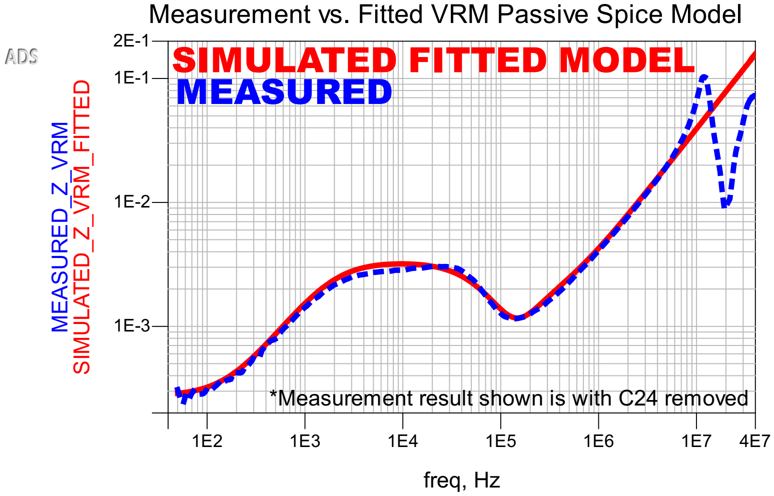
Thu Mar 16 14:50:45 2023

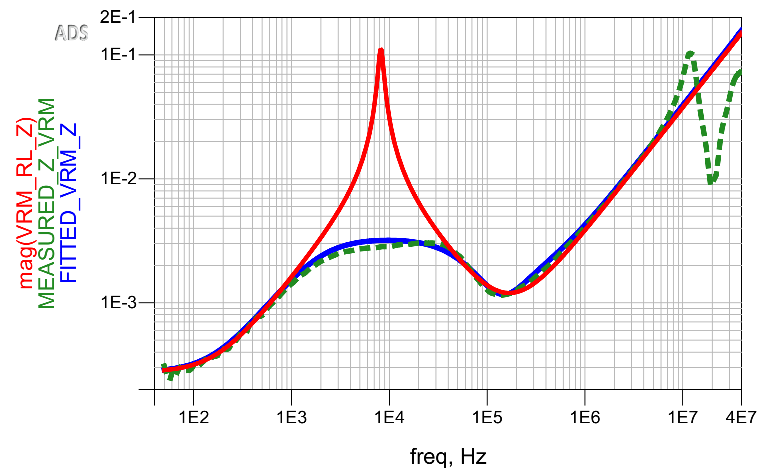


NOTE: The output impedance is equal to the output node voltage if the output AC load is set to 1 Amp. Alternatively, one can measure output impedance using an S-Parameter port.

TPS7H4003 EVAL

Measurement vs. Fitted VRM Passive Spice Model

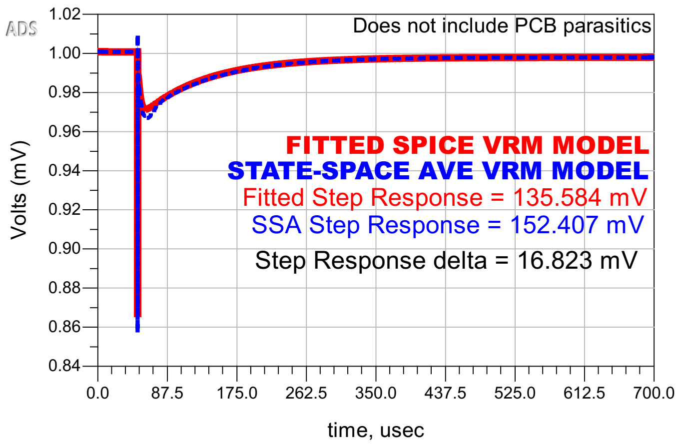


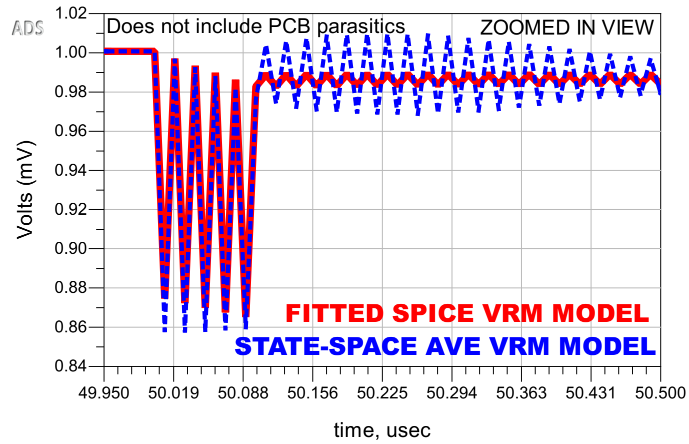


TPS7H4003 EVAL

VRM Step Load Response - State-Space Ave VRM vs. Fitted VRM Spice Model

Step Load = 10A, 100 nsec rise time



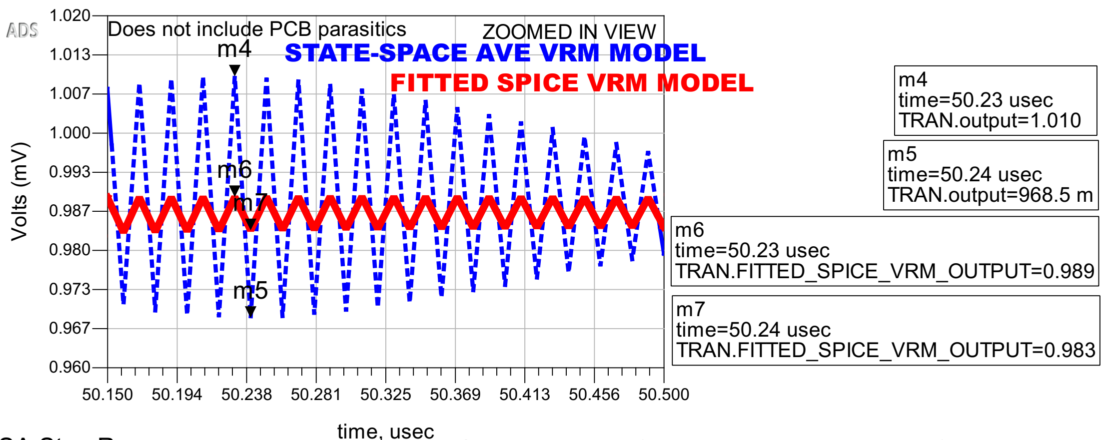


Step Reponse Analysis
50.15 usec to 50.5 usec

SSA Step Response = 41.135 mV

Fitted Step Response = 5.668 mV

Step Response delta = 35.467 mV

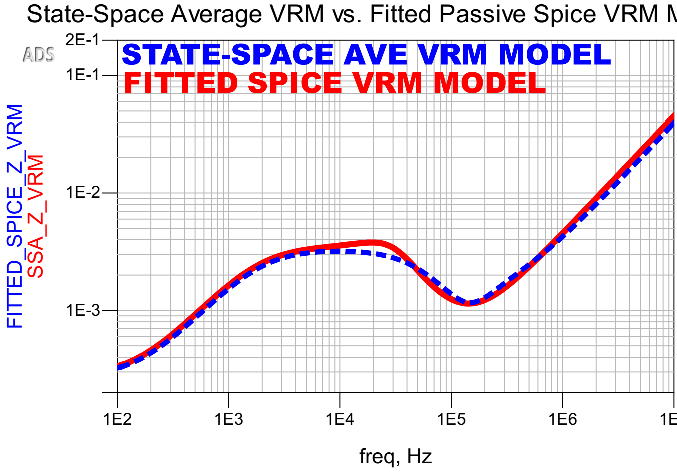


*State-Space Ave VRM Model = SSA Step Response

*Passive Fitted Spice VRM Model = Fitted Step Response

VRM Output Impedance

State-Space Average VRM vs. Fitted Passive Spice VRM Model



Eqn max_fitted=max(TRAN.FITTED_SPICE_VRM_OUTPUT)

Eqn min_fitted=min(TRAN.FITTED_SPICE_VRM_OUTPUT)

Eqn delta_fitted=(max_fitted-min_fitted)*1e3

Eqn max_ssa=max(TRAN.output)

Eqn min_ssa=min(TRAN.output)

Eqn delta_ssa=(max_ssa-min_ssa)*1e3

Eqn delta_step=(delta_ssa-delta_fitted)

Eqn delta_ssa_mk=(m4-m5)*1e3

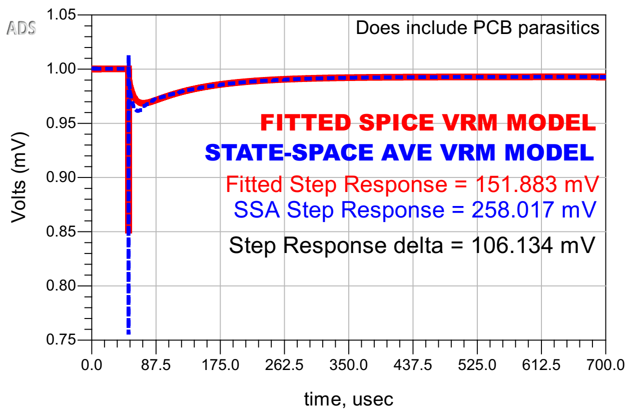
Eqn delta_fitted_mk=(m6-m7)*1e3

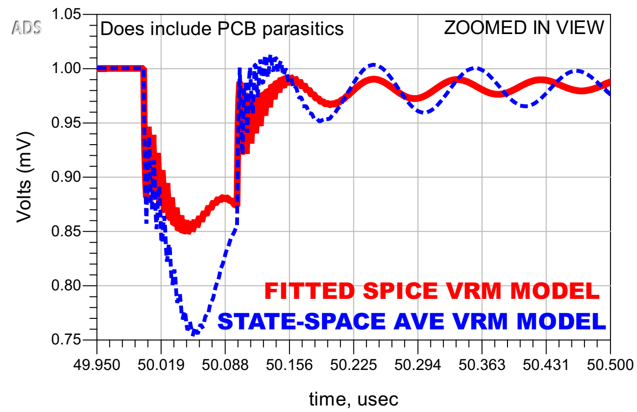
Eqn delta_step1=(delta_ssa_mk-delta_fitted_mk)

TPS7H4003 EVAL with PCB

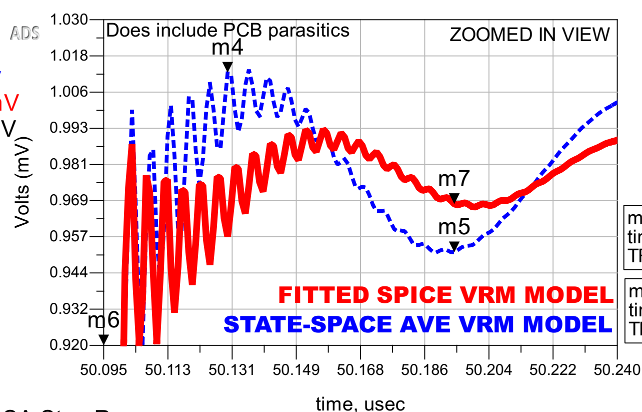
VRM Step Load Response - State-Space Ave VRM vs. Fitted VRM Spice Model

Step Load = 10A, 100 nsec rise time





Step Reponse Analysis
50.95 usec to 50.240 usec
SSA Step Response = 60.661 mV
Fitted Step Response = -89.775 mV
Step Response delta = 150.436 mV



m4
time=50.13 usec
TRAN.output=1.012

m5
time=50.19 usec
TRAN.output=951.5 m

m6
time=50.10 usec
TRAN.FITTED_SPICE_VRM_OUTPUT=0.878

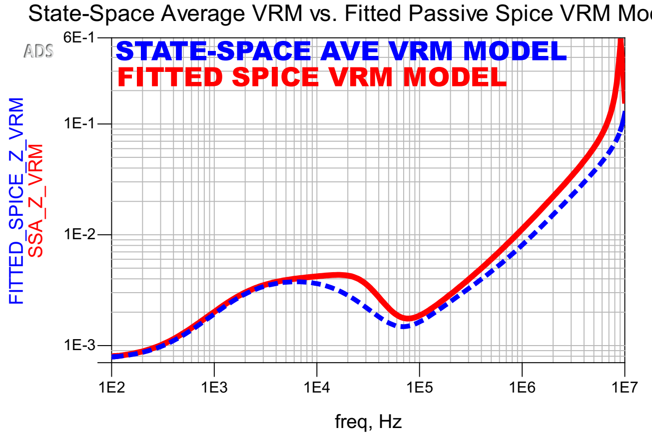
m7
time=50.19 usec
TRAN.FITTED_SPICE_VRM_OUTPUT=0.968

*State-Space Ave VRM Model = SSA Step Response

*Passive Fitted Spice VRM Model = Fitted Step Response

VRM Output Impedance

State-Space Average VRM vs. Fitted Passive Spice VRM Model



Eqn max_fitted=max(TRAN.FITTED_SPICE_VRM_OUTPUT)

Eqn min_fitted=min(TRAN.FITTED_SPICE_VRM_OUTPUT)

Eqn delta_fitted=(max_fitted-min_fitted)*1e3

Eqn max_ssa=max(TRAN.output)

Eqn min_ssa=min(TRAN.output)

Eqn delta_ssa=(max_ssa-min_ssa)*1e3

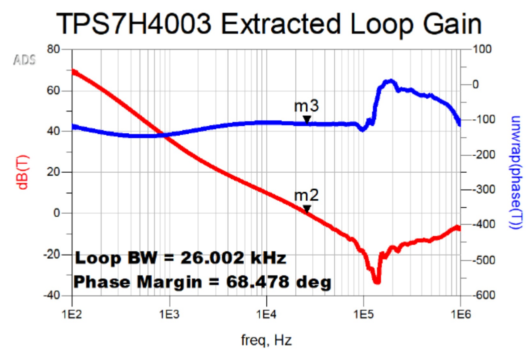
Eqn delta_step=(delta_ssa-delta_fitted)

Eqn delta_ssa_mk=(m4-m5)*1e3

Eqn delta_fitted_mk=(m6-m7)*1e3

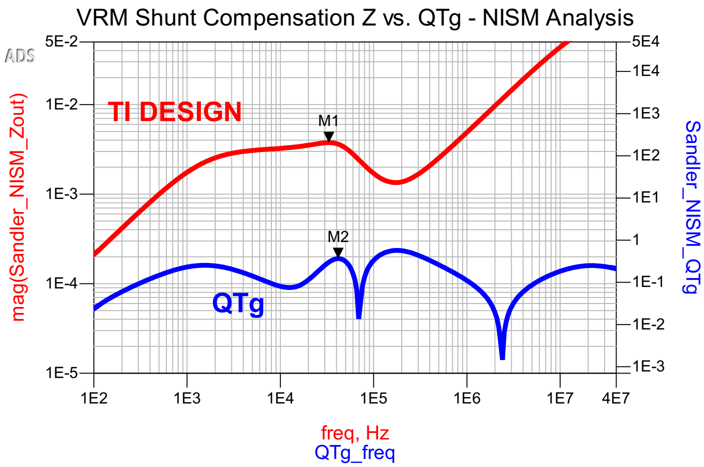
Eqn delta_step1=(delta_ssa_mk-delta_fitted_mk)

Traditional Bode Plot
Does not guarantee stability
Requires access to the feedback loop



Picotest Sandler Non-Invasive Stability Measurement (NISM)

TPS7H4003 EVAL



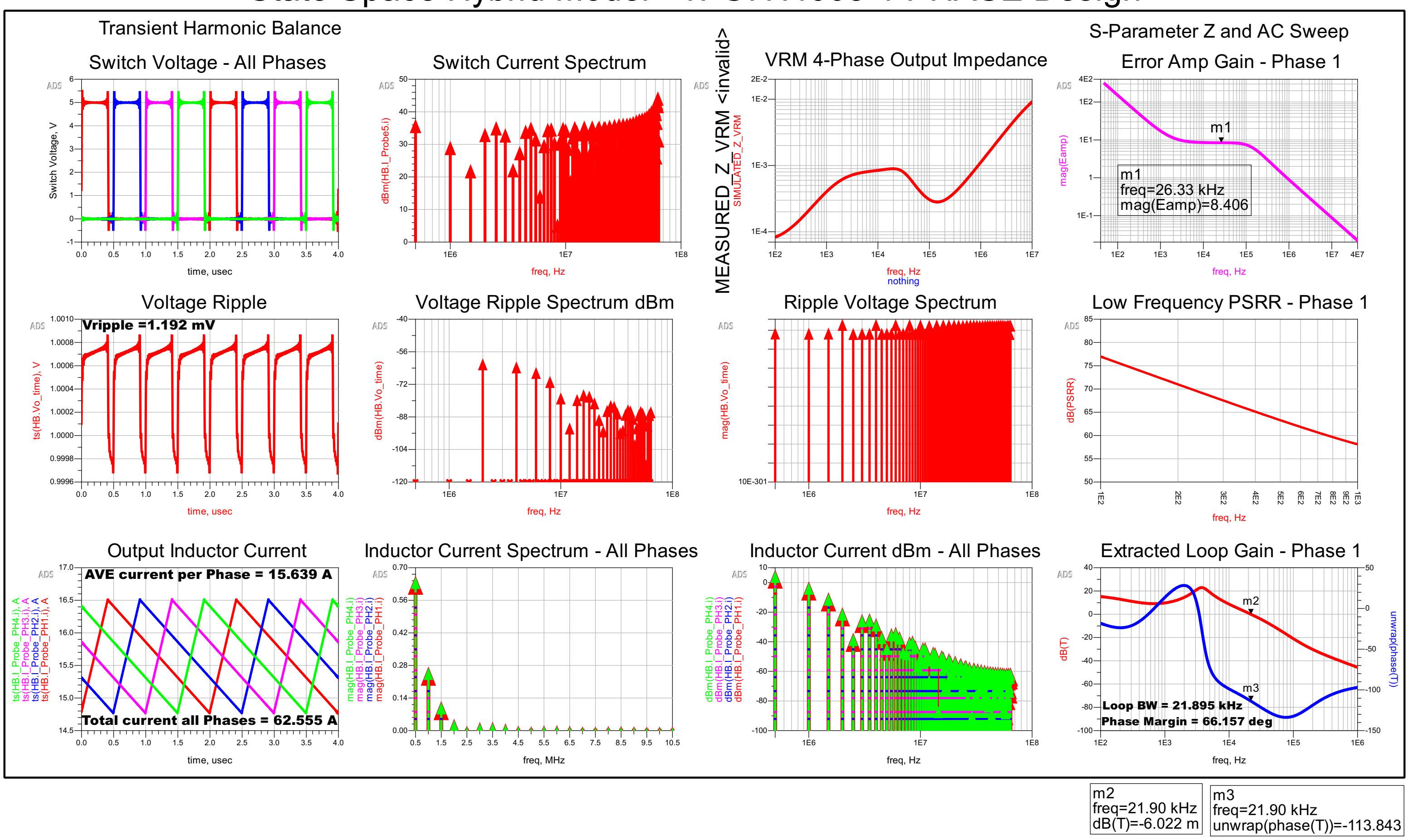
Sandler_NISM_PM: >71 degrees
Z Frequency: 33147.205 Hz
Q Frequency: 41734.891 Hz
Effective Q: 0.366

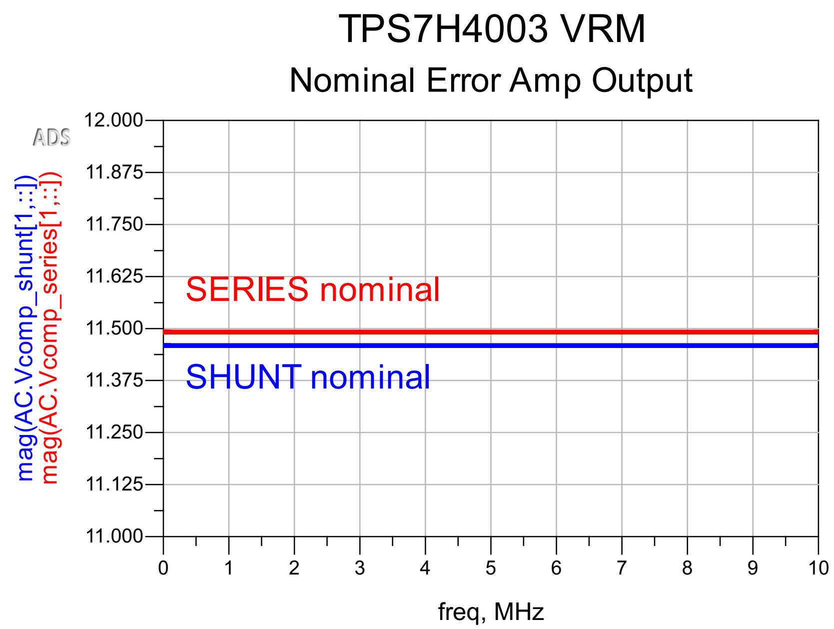
M1
freq=33.15 kHz
mag(Sandler_NISM_Zout)=3.757 m

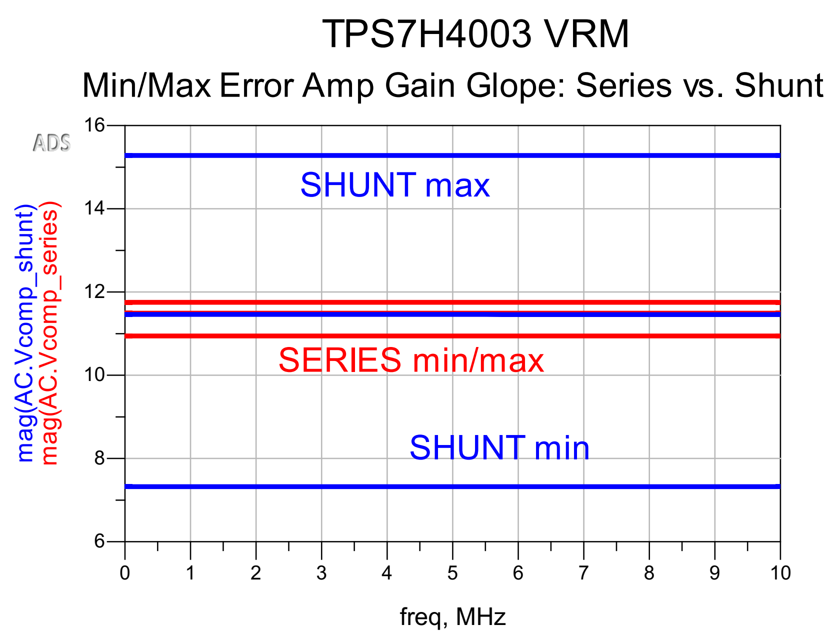
M2
indep(M2)=4.173E4
plot_vs(Sandler_NISM_QTg,QTg_freq)=0.366
Peak

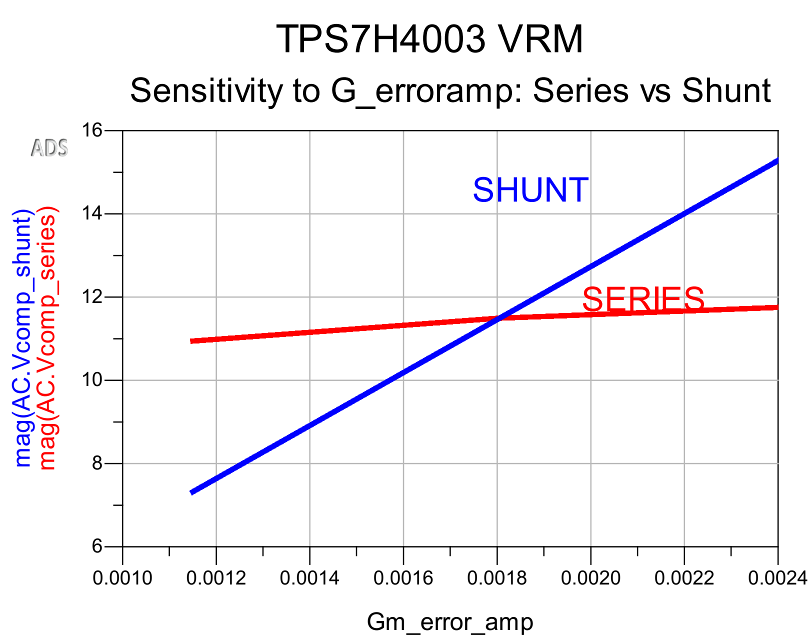
Eqn Sandler_NISM_Zout = Z(1,1)
Eqn QTg_freq=QTg_freq_function(Sandler_NISM_Zout)
Eqn Sandler_NISM_QTg=Sandler_NISM_QTg_function(Sandler_NISM_Zout)
Eqn Sandler_NISM_PM=Sandler_NISM_M1Z_M2Q_function(M1,M2)
Eqn Z_Frequency=indep(M1)
Eqn Q_Frequency=indep(M2)
Eqn Effective_Q=M2
Eqn Time_Stamp=date_time()

State Space Hybrid Model - TPS7H4003 4-PHASE Design




TPS7H4003 VRM
Nominal Error Amp Output
ADS
mag(AC.Vcomp_shunt[1,::])
mag(AC.Vcomp_series[1,::])
12.000
11.875
11.750
11.625
11.500
11.375
11.250
11.125
11.000
SERIES nominal
SHUNT nominal
0 1 2 3 4 5 6 7 8 9 10
freq, MHz


TPS7H4003 VRM
Min/Max Error Amp Gain Glope: Series vs. Shunt
ADS
mag(AC.Vcomp_shunt)
mag(AC.Vcomp_series)
16
14
12
10
8
6
SHUNT max
SERIES min/max
SHUNT min
0 1 2 3 4 5 6 7 8 9 10
freq, MHz


TPS7H4003 VRM
Sensitivity to G_erroramp: Series vs Shunt
ADS
mag(AC.Vcomp_shunt)
mag(AC.Vcomp_series)
16
14
12
10
8
6
SHUNT
SERIES
0.0010 0.0012 0.0014 0.0016 0.0018 0.0020 0.0022 0.0024
Gm_error_amp

batchNumber	INDEX	corner	Gm_error_amp
1	0.0000	min	1.150 m
2	1.000	nominal	1.800 m
3	2.000	max	2.400 m