Characterizing and Selecting the VRM

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The Big Issues

VRMs and VRM controllers are often poorly characterized providing limited, poor quality, or incorrect data

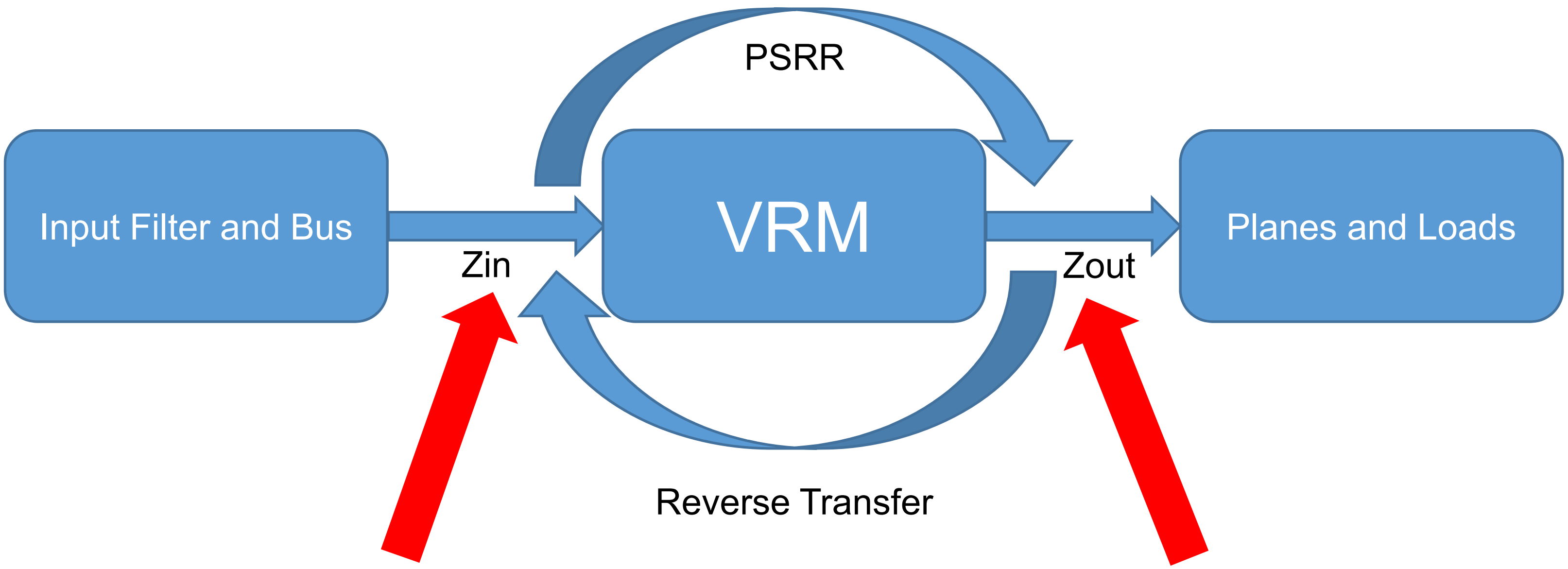
Figures of Merit are limited to a few general characteristics (i.e. voltage accuracy, efficiency, size)

In many cases, reference designs and manufacturer recommendations are poor or inappropriate

Evaluation boards are not constructed to support precise measurement or modification

In this session, we will define key VRM characteristics and provide tips on how to select one. We'll also show potential issues to look out for

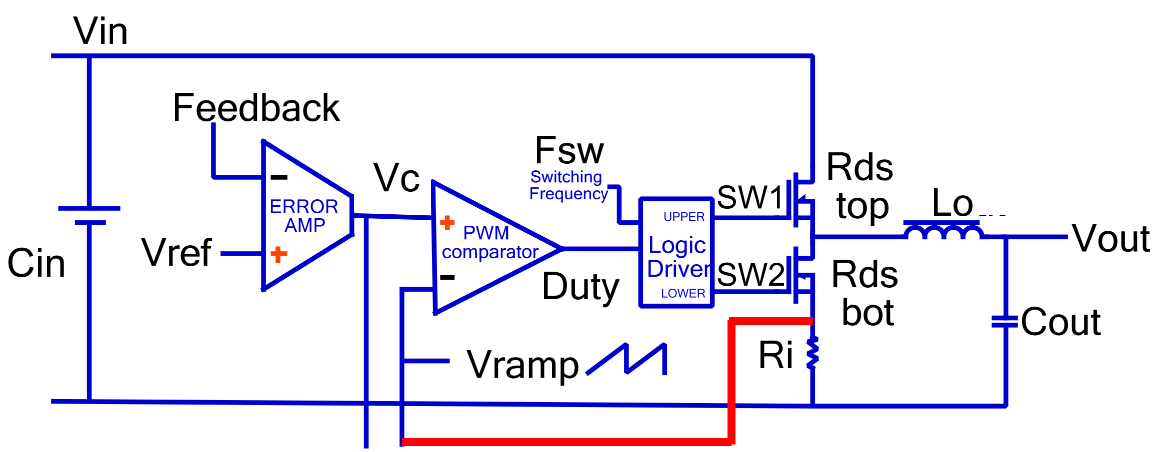
Small Signal System Interfaces



Stability concerns exist at both the input and the output

Unified State Space Average Model

Voltage Mode and Current Mode



The current mode control topology differs from the voltage mode topology **by the addition of a signal related to the inductor current.**

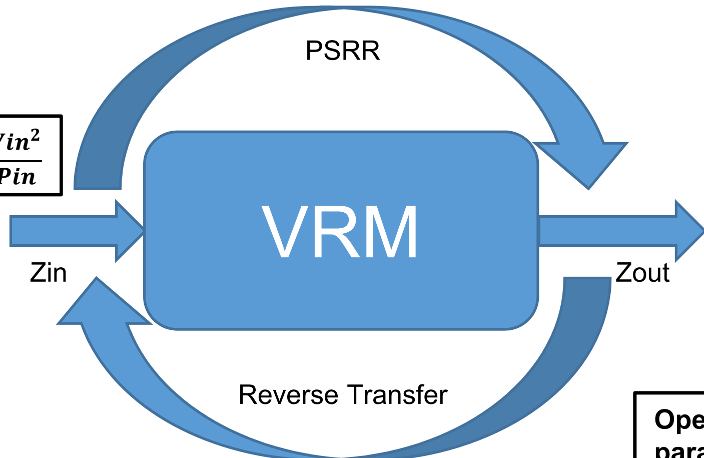
A model that includes both the current signal and the ramp signal, with the ability to proportion them, supports both modes of operation.

This unified model gives us a complete perspective of the operation and allows optimization of these common VRM topologies (and/or lack thereof)

Small Signal Responses (State Space Averaged)

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

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



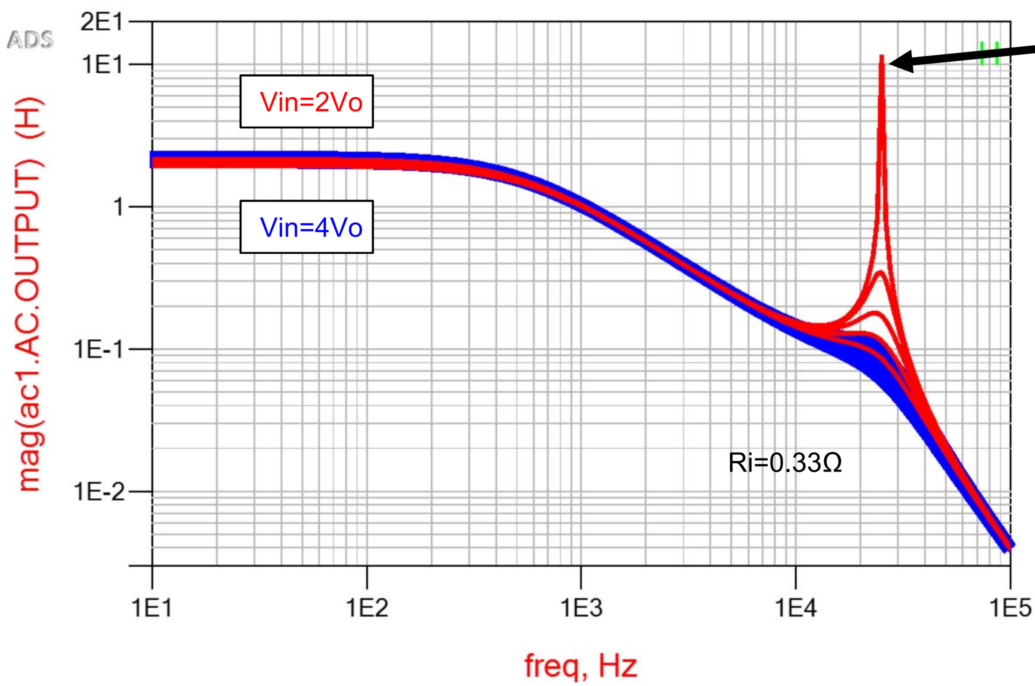
$$Rout = \frac{\dfrac{2\cdot Fs\cdot Lo\cdot Ri\cdot Vin}{Ri\cdot Vin-2\cdot Ri\cdot Vo+2\cdot Fsw\cdot Lo\cdot Vramp}+DCR+RDSon}{1+Av\cdot\dfrac{2\cdot Fs\cdot Lo\cdot Vin}{Ri\cdot Vin-2\cdot Ri\cdot Vo+2\cdot Fsw\cdot Lo\cdot Vramp}}$$

Open loop PSRR, Rout, and the Excess inductance are all functions of two parameters – Ri and Vramp. The closed loop functions add the feedback amplifier transfer function, Av

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

Rin and Reverse are less dependent, so less attention is warranted (for now)

Current Mode Subharmonic Resonance



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

Vramp (V):
0.000
0.125
0.250
0.375
0.500

$$Mc = 1 + \frac{Fs \cdot Lo \cdot Vramp}{Ri \cdot (Vin - Vo)}$$

Optimizing Vramp

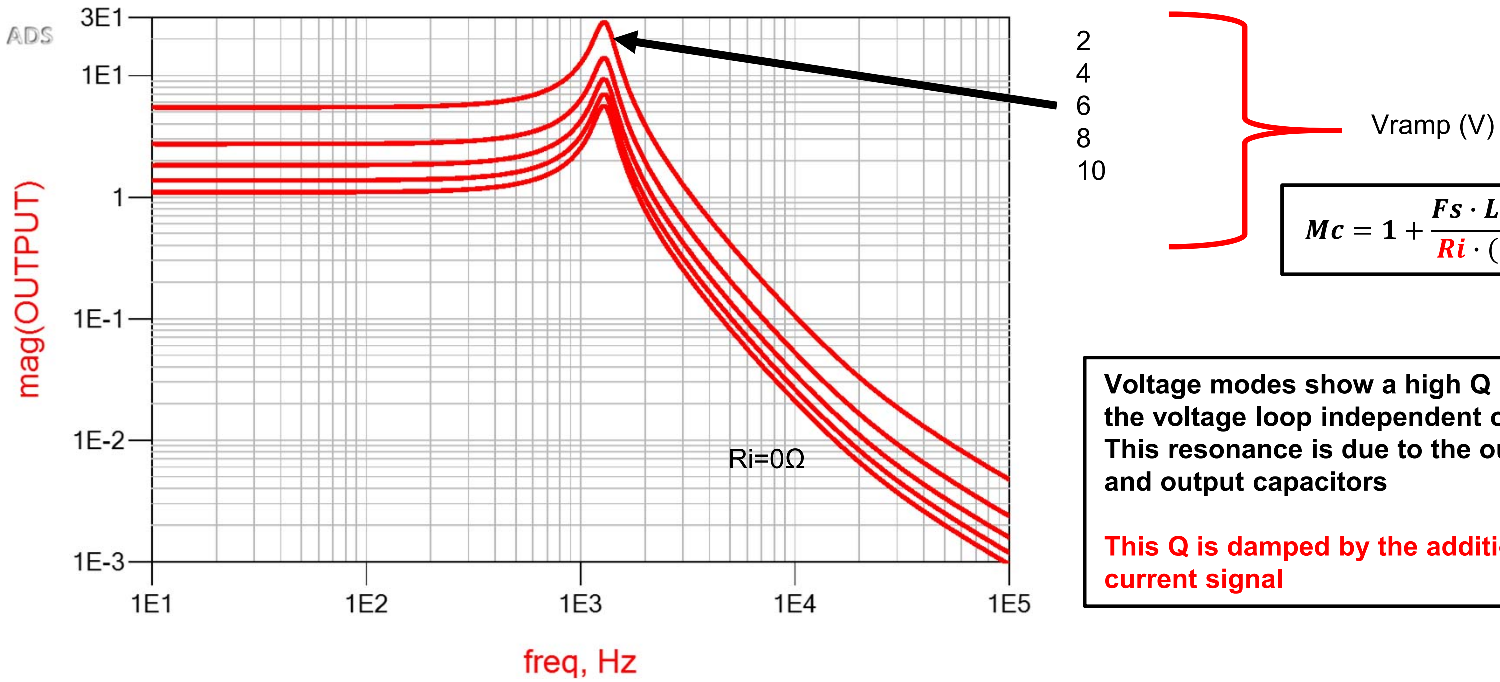
$$Vramp = \frac{Ri(Vo - Vin)}{Fs \cdot Lo \cdot Q} \cdot \frac{0.3183 + 0.5 \cdot Q}{\frac{Vo}{Vin} - 1} + Q$$

Most current modes show a high Q series resonance in the current loop near 50% duty cycle.

This Q is damped by the addition of a Vramp signal

Voltage Mode Filter Resonance

This resonance is shifted by external bulk capacitors

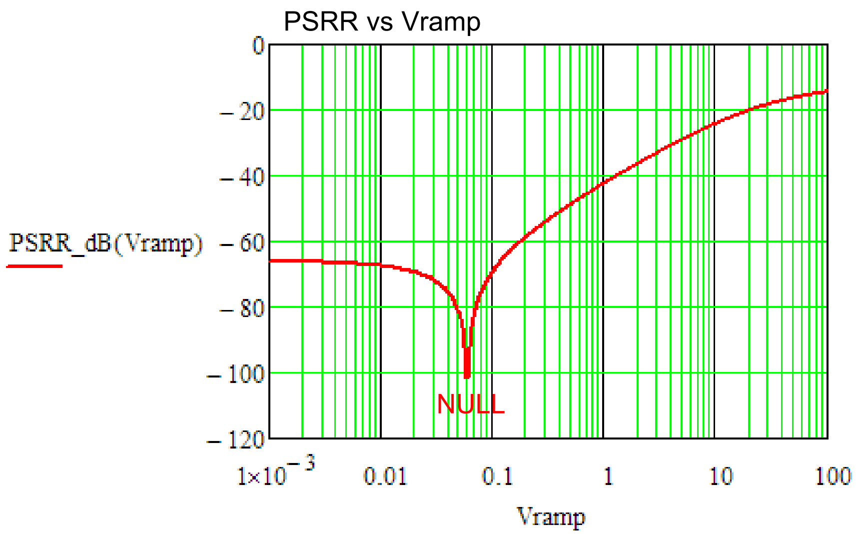


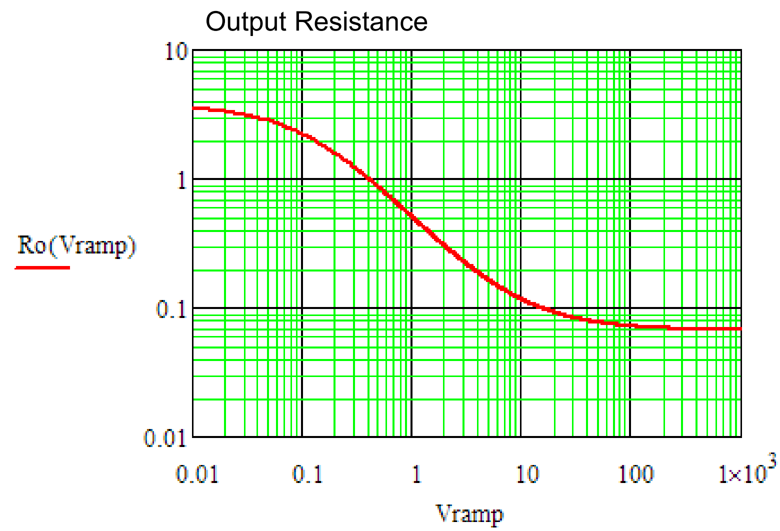
$$Mc = 1 + \frac{Fs \cdot Lo \cdot Vramp}{Ri \cdot (Vin - Vo)} = \infty$$

Voltage modes show a high Q resonance in the voltage loop independent of duty cycle. This resonance is due to the output inductor and output capacitors

This Q is damped by the addition of the current signal

Low Frequency Open Loop PSRR and Rout





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

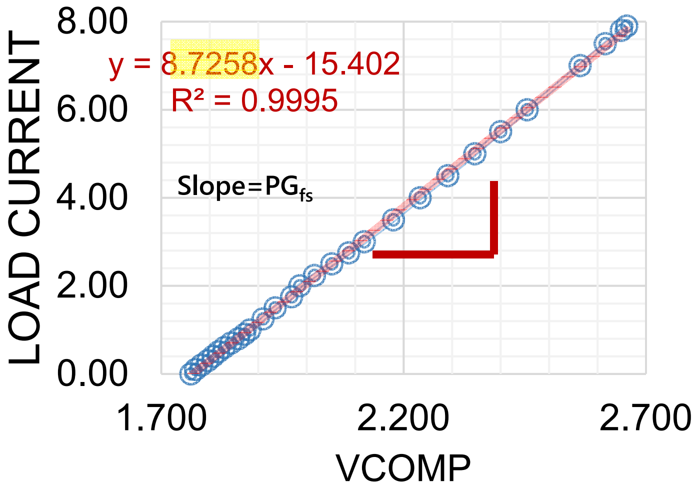
NULL

$$Vramp = \frac{Ri \cdot Vo}{2 \cdot Fs \cdot Lo}$$

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

Clearly Ri and Vramp are Both Critical

$$Ri = \frac{1}{8.7258} = 0.115\Omega$$



The measured value of Ri is 12% higher than expected due to DC PCB resistance despite the very short connections

LM25116 EVAL

$$Ri = A_{cs} \cdot R_{cs} = 0.1\Omega$$

Many controllers don't specify the Vramp characteristics at all, some do, though are not optimum, many offer less than this LM20143 excerpt

"What makes the LM20143 unique is the amount of slope compensation will change depending on the output voltage. When operating at high output voltages the device will have more slope compensation than when operating at lower output voltages. This is accomplished in the LM20143 by using a non-linear parabolic ramp for the slope compensation."

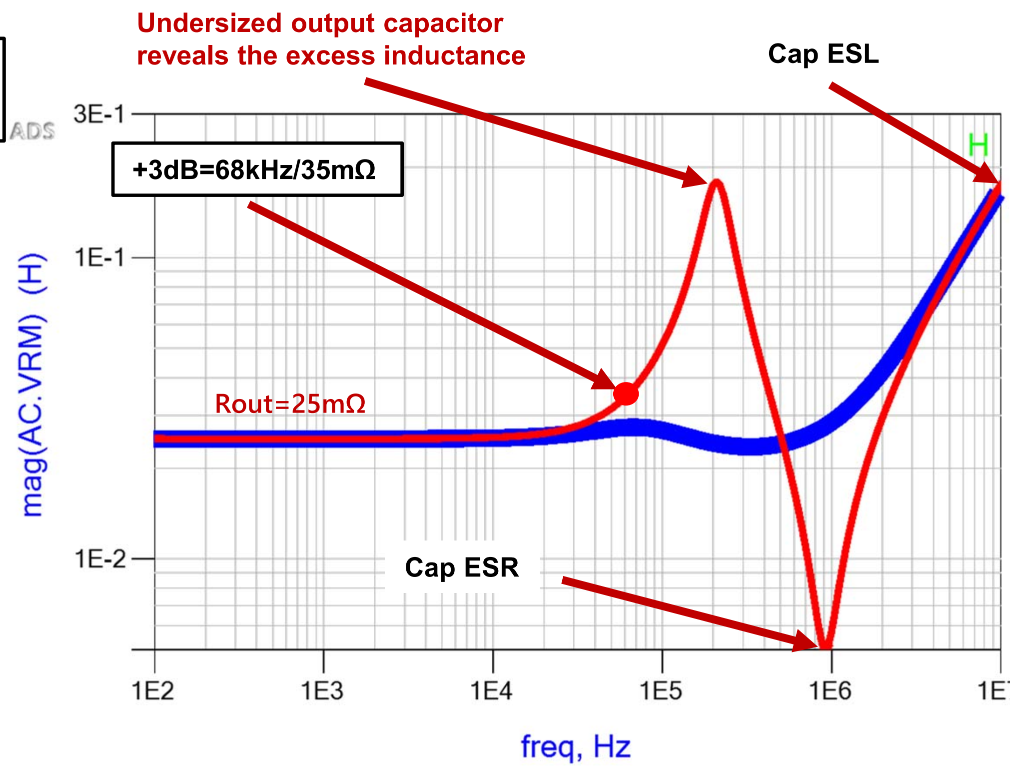
Output Inductance

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

The output inductance can best be directly measured by installing an undersized output bulk capacitor

$$L_{excess} = \frac{25m\Omega}{2\pi \cdot 68kHz} = 58.5nH$$

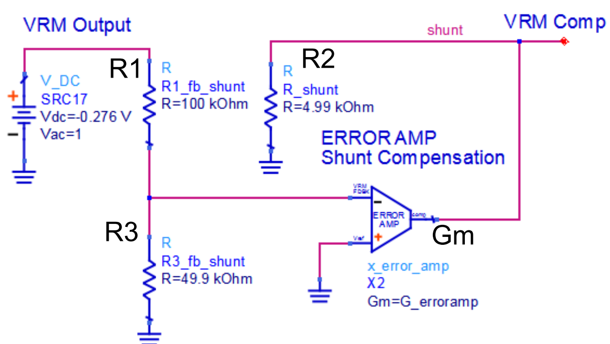
Lower inductance requires smaller output capacitors



Feedback Amplifiers

Many new devices use transconductance type error amplifiers

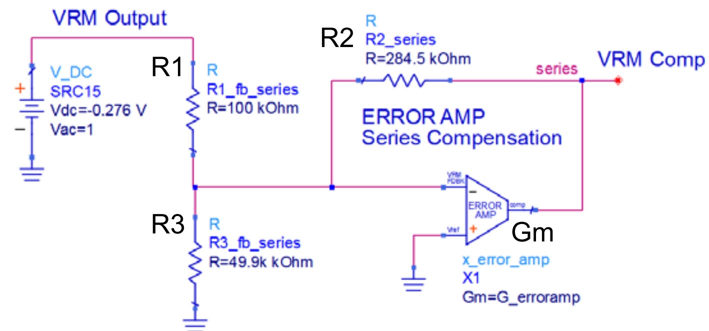
Manufacturer Suggested



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

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

Greatly Improved



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

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

Higher resistor values reduce this sensitivity

Gm tolerances are often poorly specified and tolerances can be very large. The manufacturer suggested feedback is often much more sensitive to this unspecified, large tolerance (aka BAD ADVICE).

Feedback Amplifier Data

MAX16932

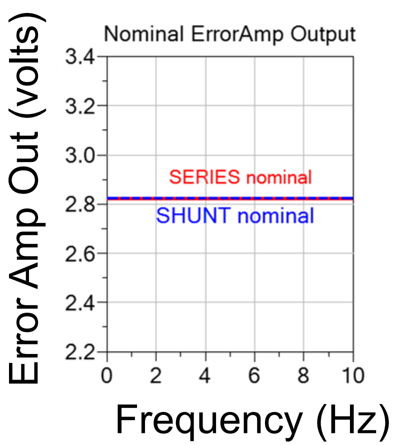
PARAMETER	SYMBOL	CONDITIONS	MIN	TYP	MAX	UNIT
Regulated Feedback Voltage	$V_{FB1,2}$		0.99	1.0	1.01	V
Feedback Leakage Current	$I_{FB1,2}$	T_A = +25°C		0.01	1	µA
Feedback Line Regulation Error		V_{IN} = 3.5V to 36V, V_{FB} = 1V		0.001		%/V
Transconductance (from FB_ to COMP_)	g_m	V_{FB} = 1V, V_{BIAS} = 5V		1200	2400	µS

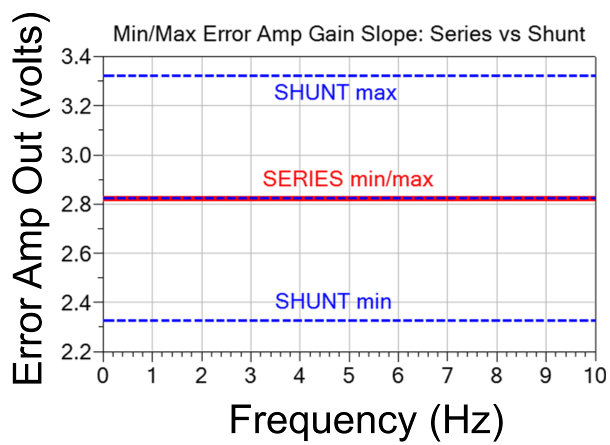
Does this suggest the minimum is 0?

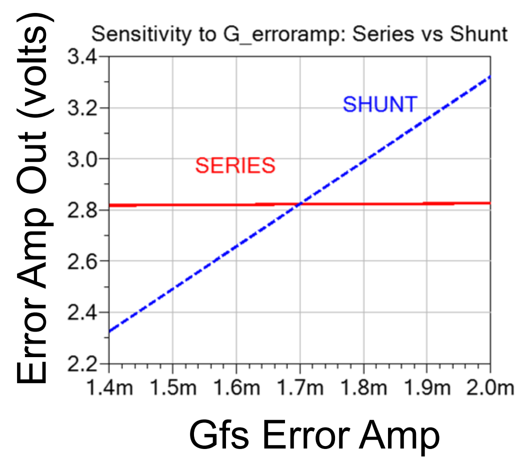
MIC2199

Error Amplifier					
Transconductance Error Amplifier GM			0.2		mS
Oscillator Section					

What about other parameters such as Gain Bandwidth? Source/Sink Current?







Gfs Error Amp

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

Measurements Offer Access To the Unknowns

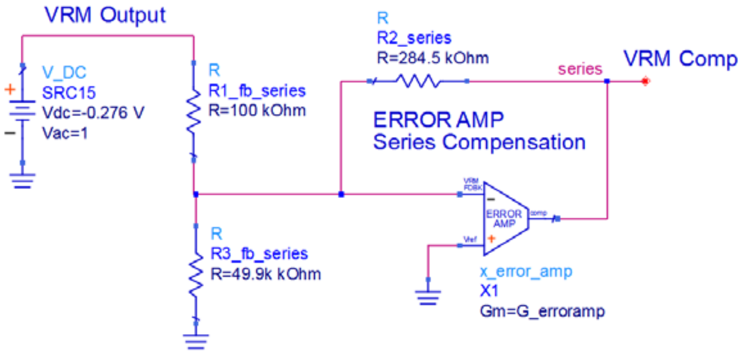
PSRR and Rout are both dependent on Vramp and Ri. A PSRR measurement and an Rout measurement provide two equations for the two unknowns, which is solvable

Output effective inductance is dependent on Vramp, Ri, and Av, which is further dependent on the error amplifier characteristics Gm and Gbw

$$Av = \frac{VRM\_Comp}{VRM\_Output} = \frac{R3 \cdot (Gm \cdot R2 - 1)}{R1 + R3 + Gm \cdot R1 \cdot R3}$$

$$Gm = \frac{R3 + Av \cdot (R1 + R3)}{R3 \cdot (R2 \cdot Av \cdot R1)}$$

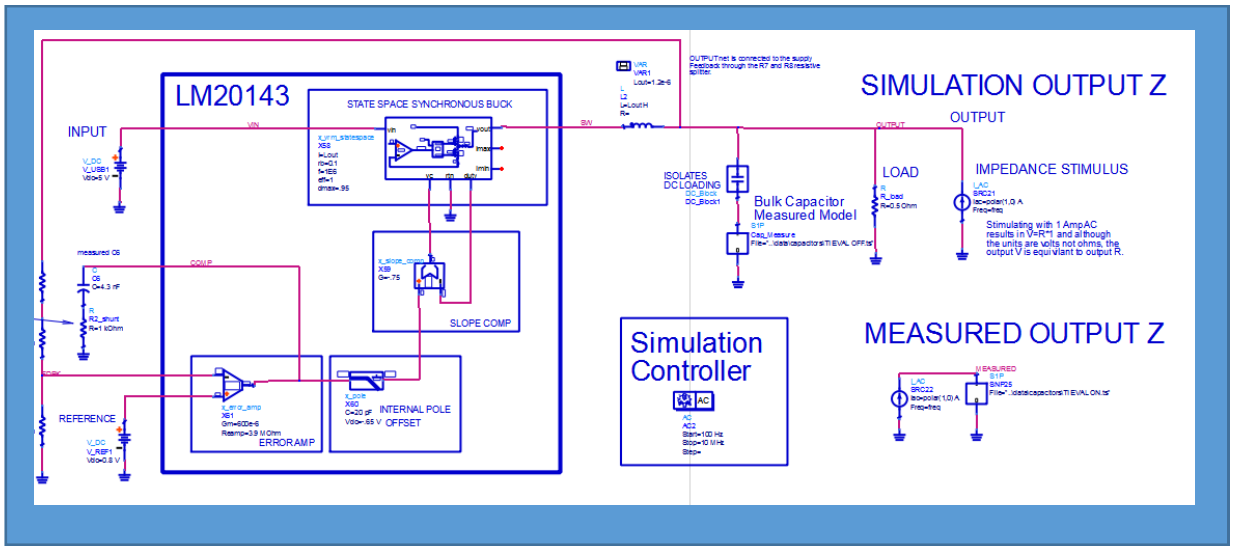
Unknown small signal error amplifier characteristics, Gbw and Gm, can be extracted from a closed loop gain measurement of the amplifier (if Vcomp is an available pin)



Statistical tolerances are extracted from measurements of several evaluation or characterization boards

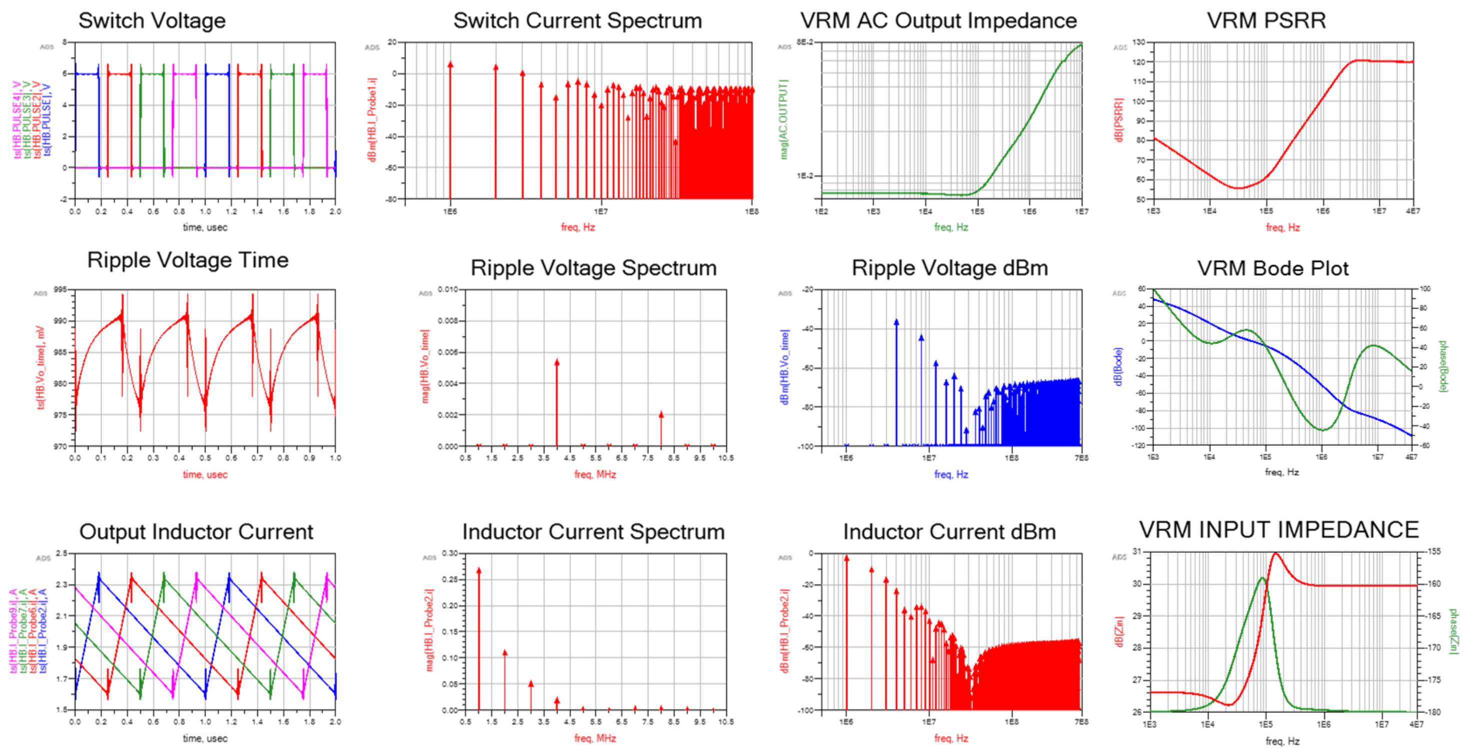
Solving the System of Equations

A few easy measurements and your favorite manual or automated multi-parameter equation solver provide a high fidelity model that supports optimization and worst case tolerance assessment



Var
Eqn
VAR
VAR1
Vramp=1.3
Fs=1E6
Lo=1E-6
Ri=0.1
Vos=0.43

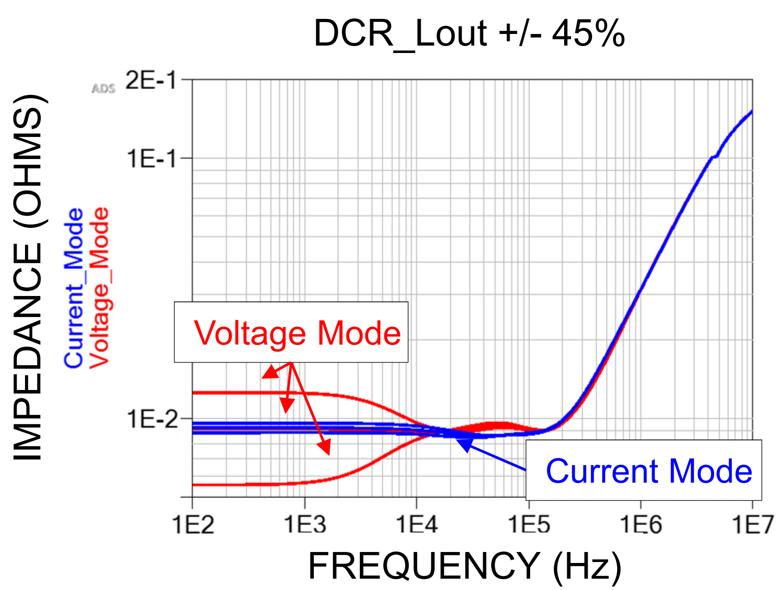
Results in an Accurate Simulation Model

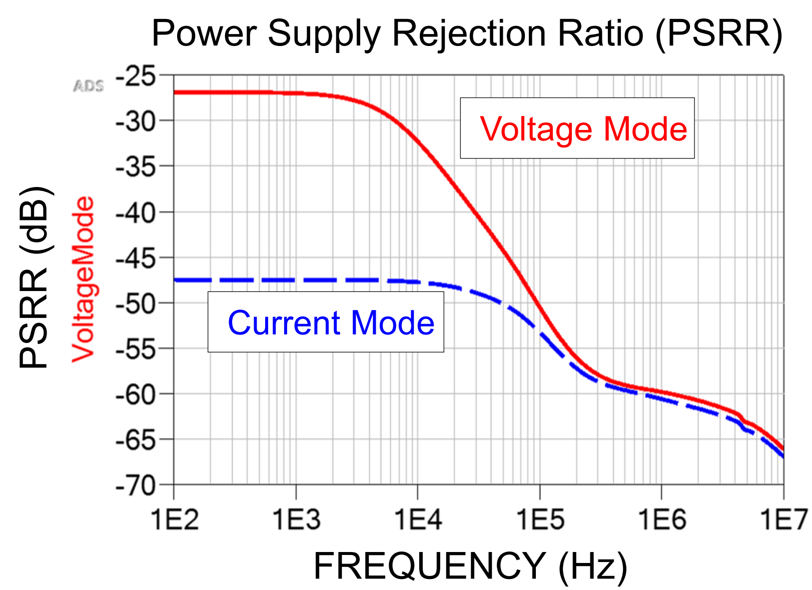


Current Mode is The Better Choice

$$Rout\_CM \cong \frac{Ri}{1 + Av}$$

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

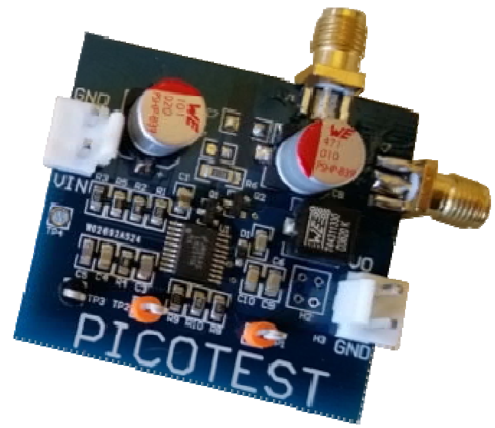


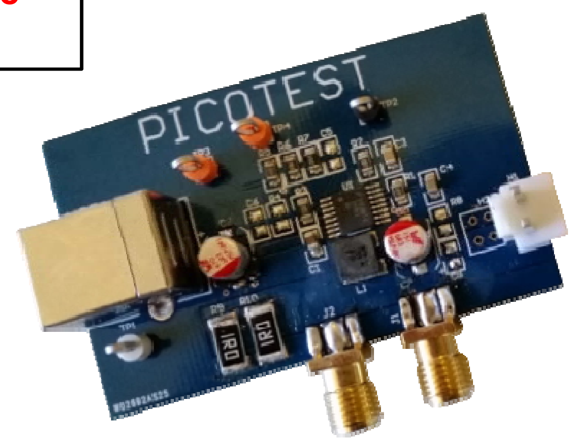


Small-Signal Figures of Merit

- *Topology (Current mode preferred)*
- *Controllable Vramp (characterized is better)*
- *Compensation pin accessible*
- *Ri (external preferred over DCR sense)*
- *Flat output impedance*
- *EA GFS characterized including tolerance!*
- *EA gain bandwidth - higher is better*
- *Any internal poles defined*

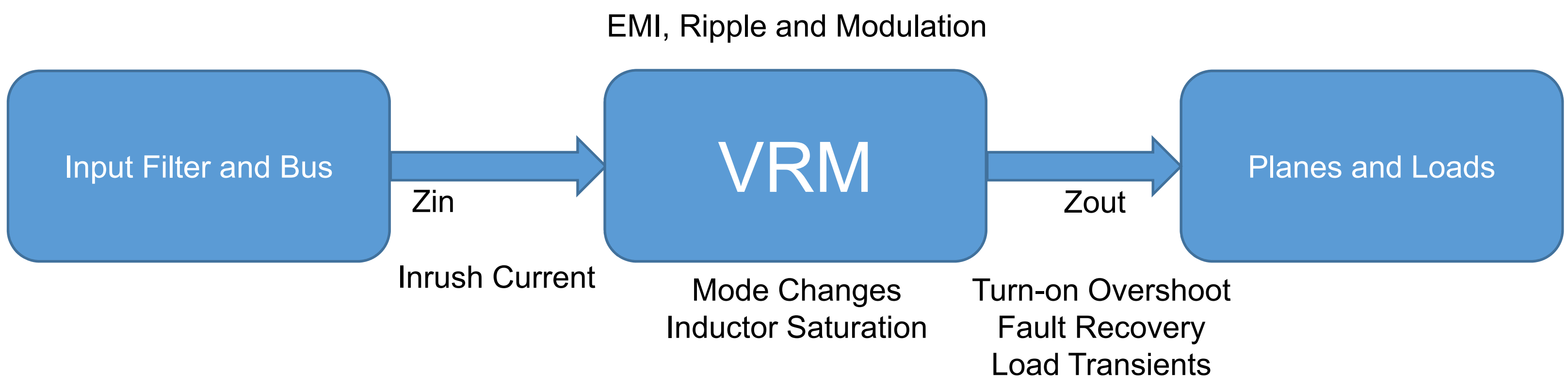
It's often best to create your own MEASURABLE test board and acquire the data yourself





NOTE THAT FLAT IMPEDANCE AUTOMATICALLY ASSURES STABILITY ☺

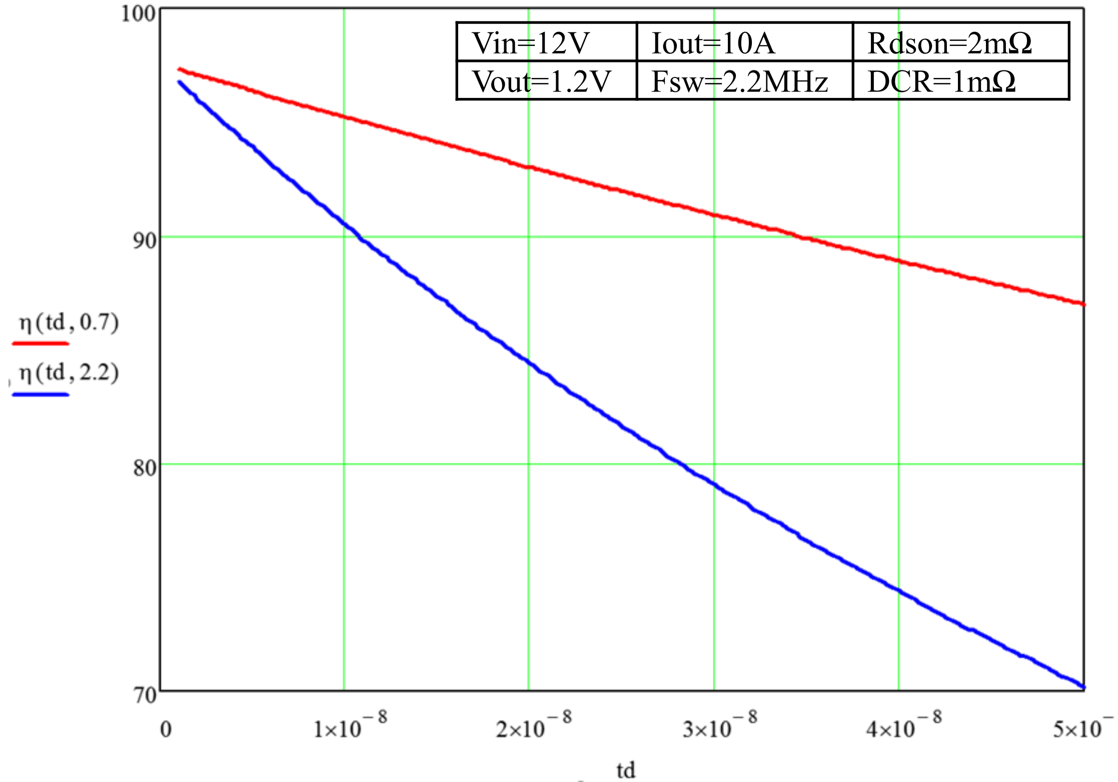
Additional Considerations



Power Losses

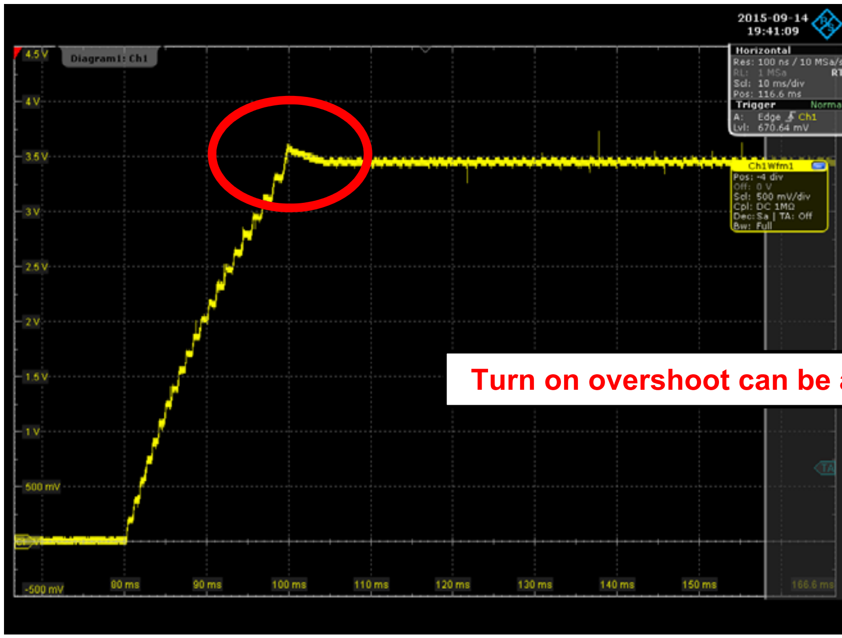
A significant portion of the total power loss is due to the switch deadtime. This impact increases rapidly with increasing switching frequency and also with body diode forward voltage

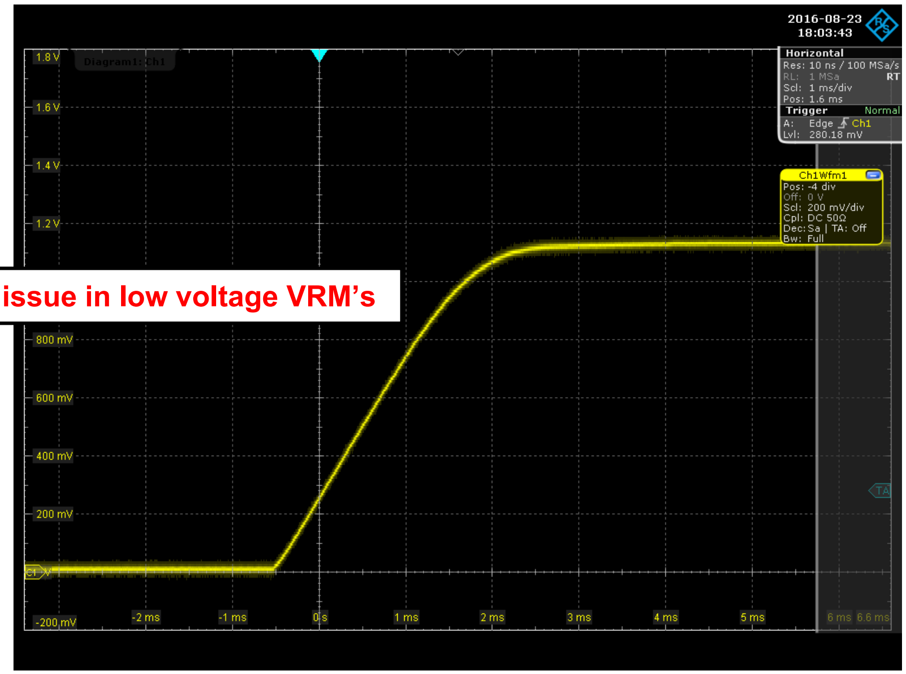
Most manufacturers only provide typical deadtime, if that



$$Ploss = Iout \cdot \left(Iout \cdot Rds + 2 \cdot Fsw \cdot Vf \cdot td \cdot \left(1 - \frac{Iout \cdot Rds}{Vf} \right) + Iout \cdot DCR \right)$$

Turn-On and Fault Recovery

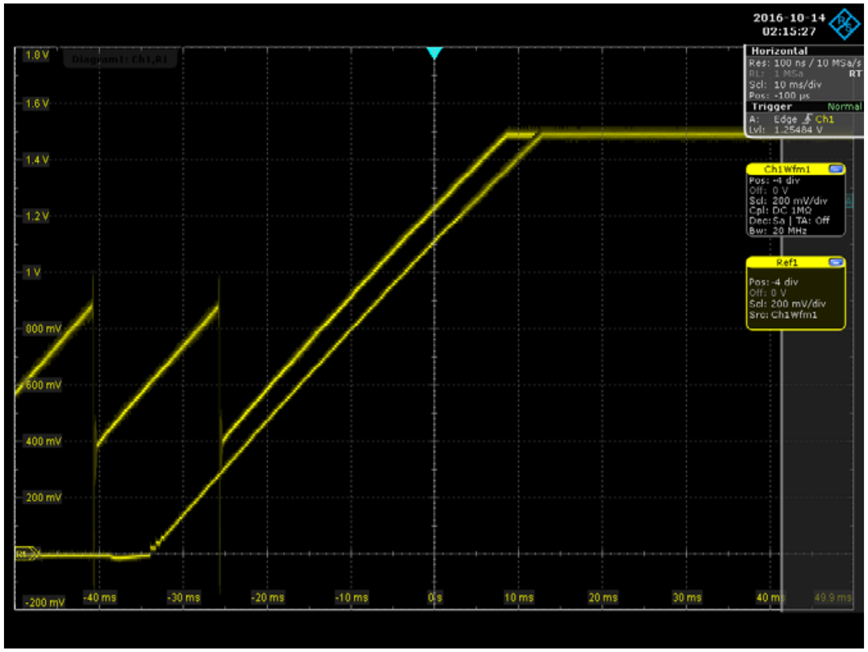




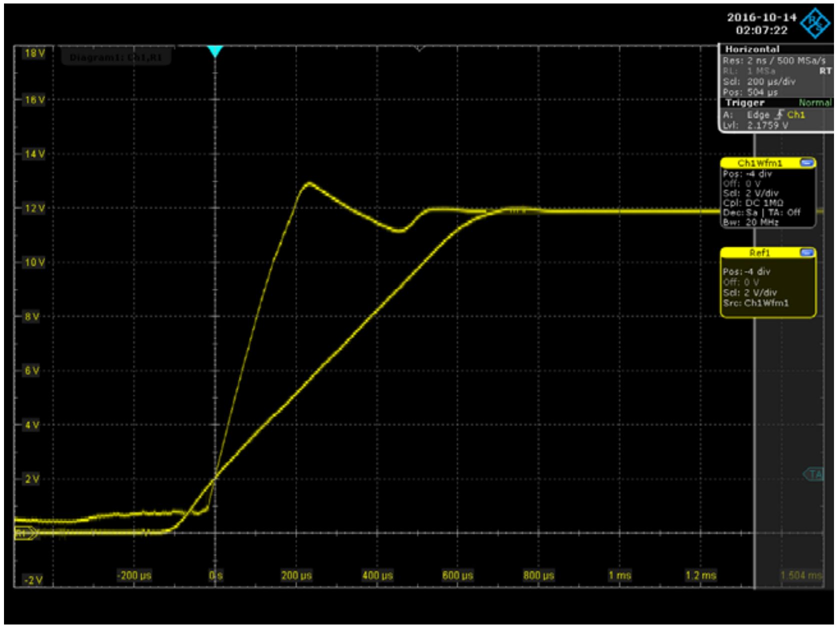
Turn on overshoot can be an issue in low voltage VRM's

There is an associated inrush current due to the dv/dt on the bulk capacitors

Fault Recovery Often Bypasses Soft-Start



There is a larger inrush current due to the dv/dt on the bulk capacitors, as well as, the overshoot

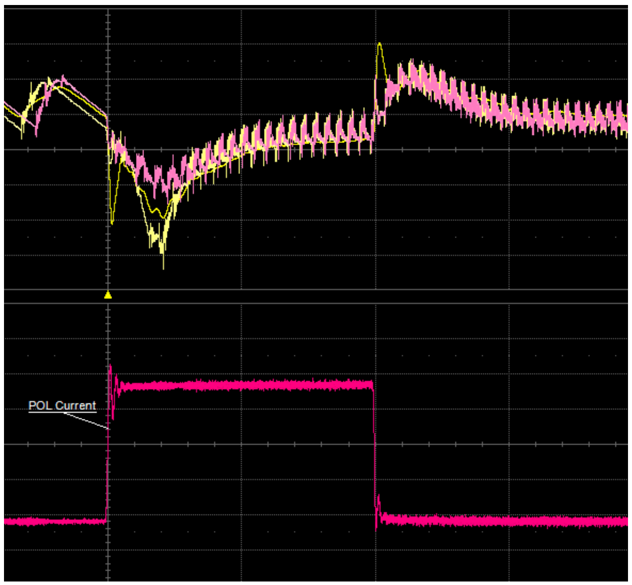


Large Signal Response

$$\Delta Vo = \frac{\sqrt{Co^2 \cdot Vo^2 + Lo \cdot Co \cdot IL^2 - Lo \cdot Co \cdot dIL^2}}{Co} - Vo$$

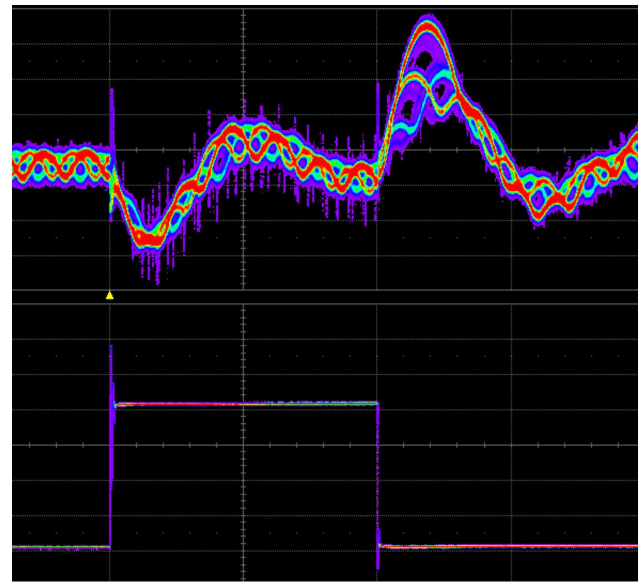
High duty cycle converters show large signal effects on the increasing current

Low duty cycle converters show large signal effects on the decreasing current

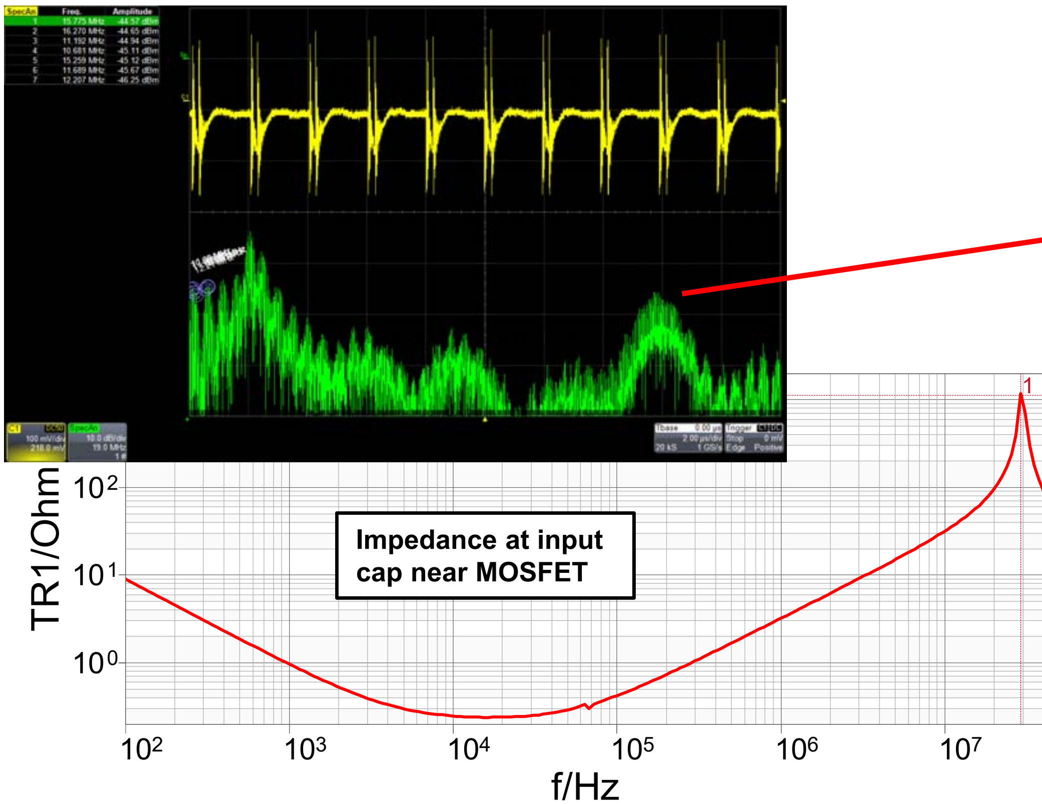


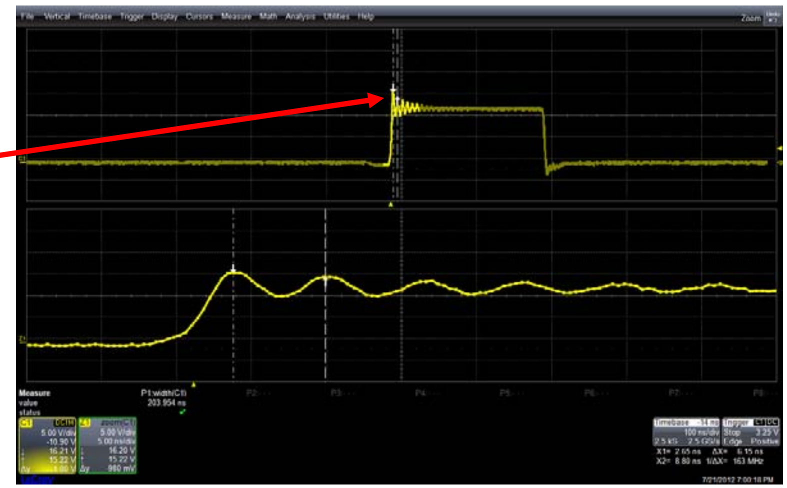
Step load response can be easily influenced by where in the switching cycle it occurs, so do not average! Use a digital filter or color persistence to highlight the responses if you need to

These measurements are performed with a 10ns, 15nF current injector so as not to interfere with the measurement



EMI

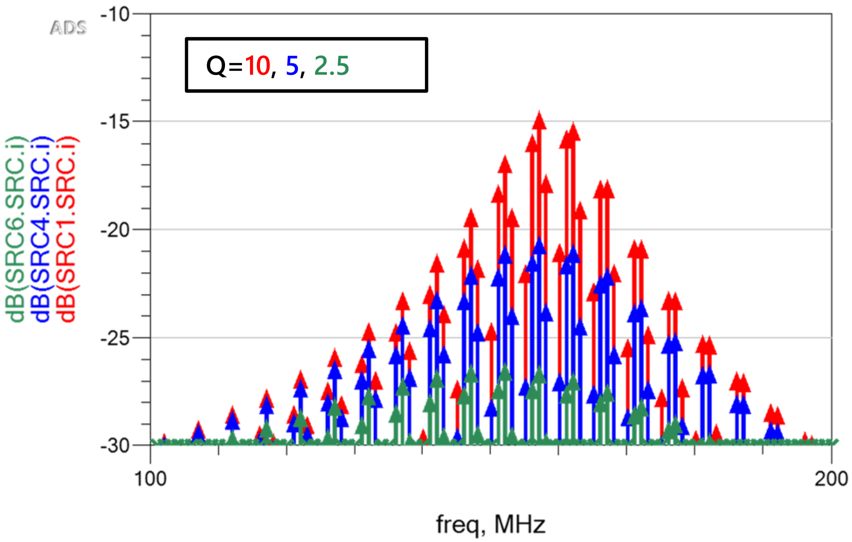


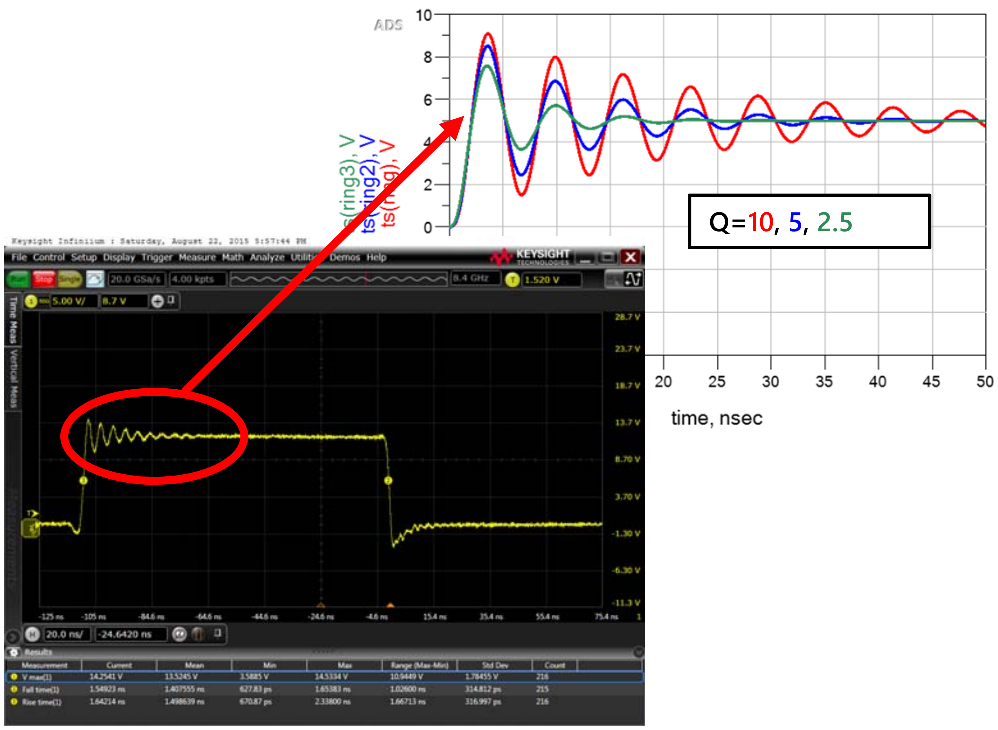


Resonant planes are often the source of EMI

EMI Damping Effect

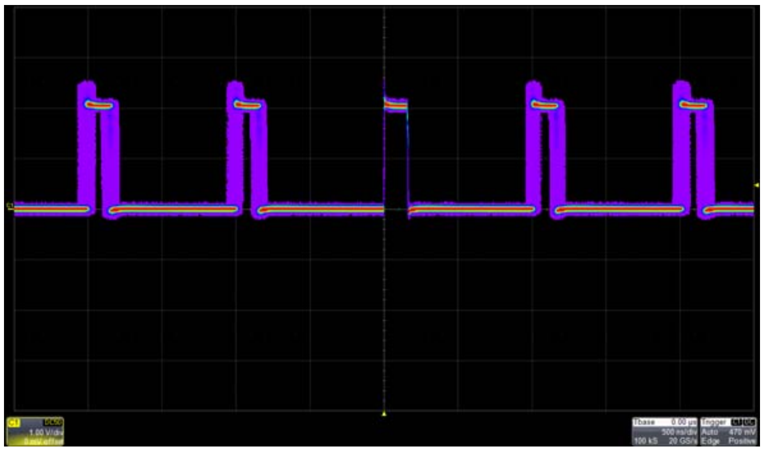
EMI is influenced mostly by the Q of the ring, not amplitude.
So look for good damping



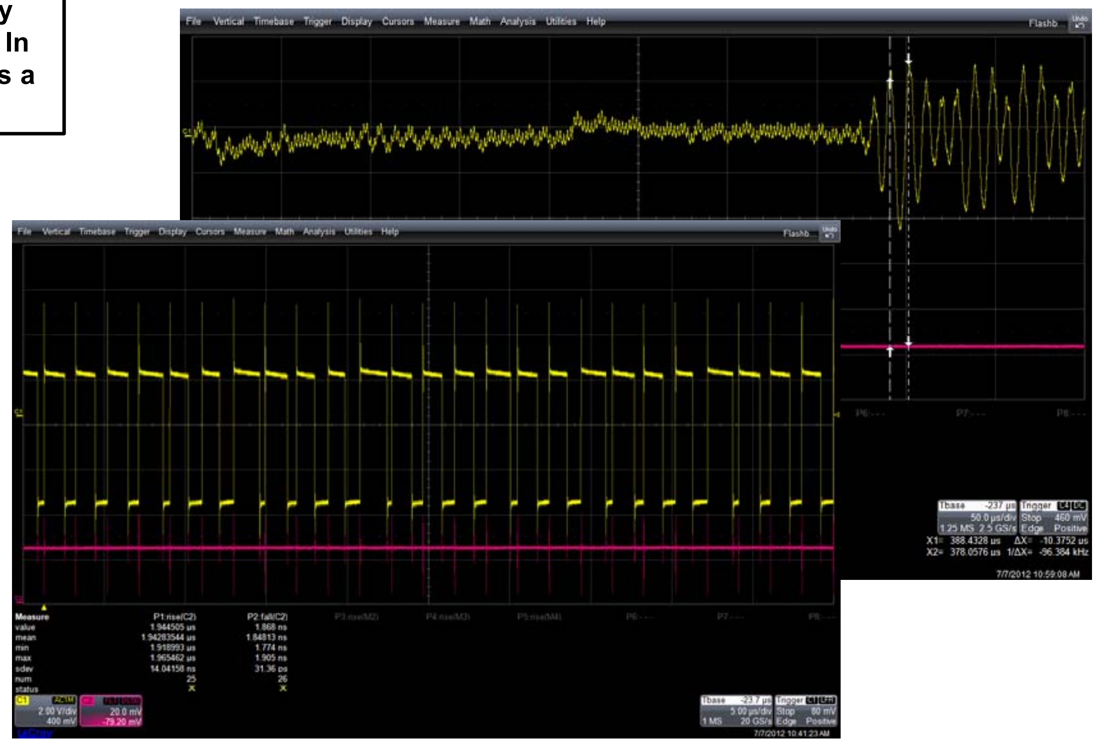


Modulated Noise Sources

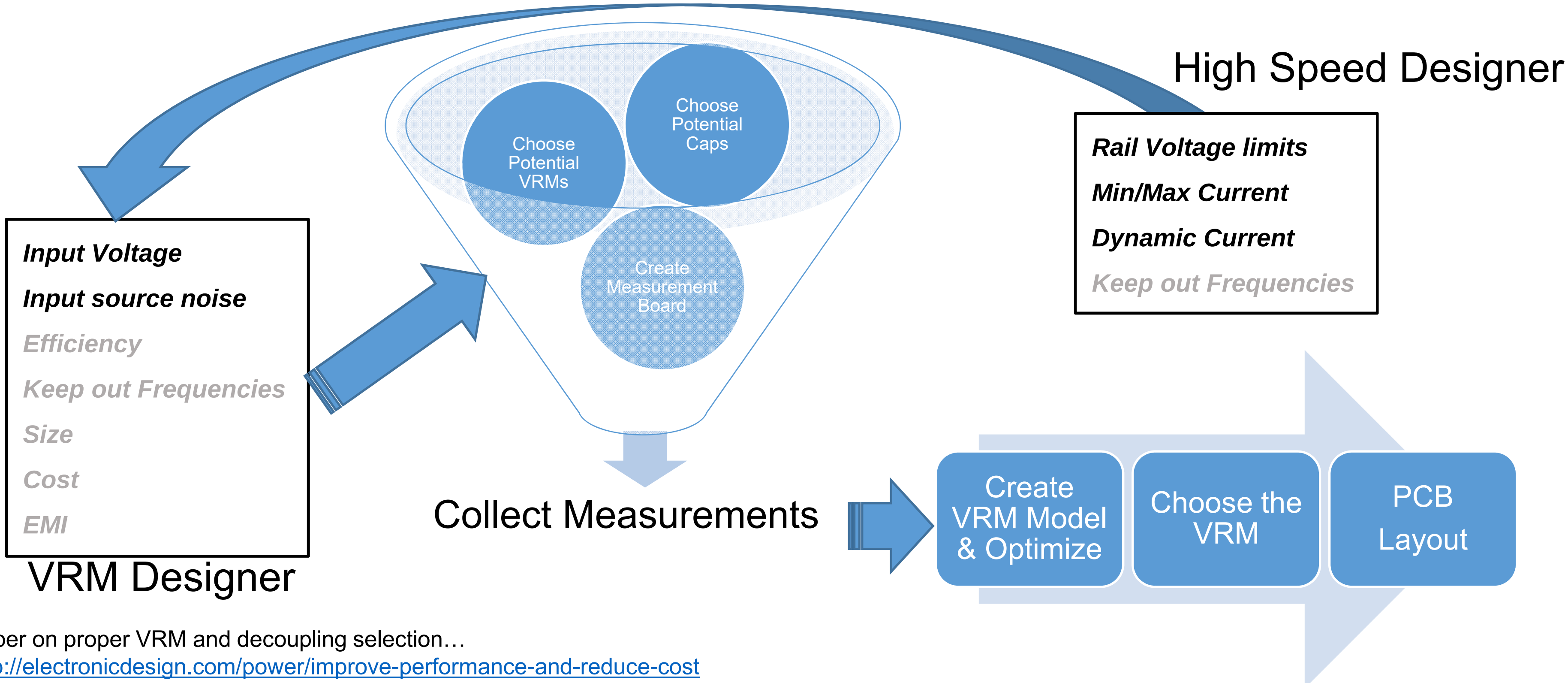
Some VRMs exhibit switching frequency modulation, which can be quite severe. In this example, the modulation introduces a time delay instability



Low frequency modulation can result in low frequency EMI which is extremely difficult to filter



Design Flow - Working Ends Towards the Middle



Paper on proper VRM and decoupling selection…
http://electronicdesign.com/power/improve-performance-and-reduce-cost

Conclusions

GET YOUR OWN DATA-PREFERABLY ON YOUR OWN CHARACTERIZATION BOARD

1. ***Current mode control to optimize impedance***
2. ***External slope compensation to optimize PSRR***
3. ***External EA comp pin to acquire error amplifier data***
4. ***Controllable Soft-Start (no turn-on overshoot)***

New Video - "How to Design for Power Integrity: Selecting a VRM", Keysight YouTube, 5/5/2016,
https://www.youtube.com/watch?v=ejAApIv1cR8&feature=youtu.be

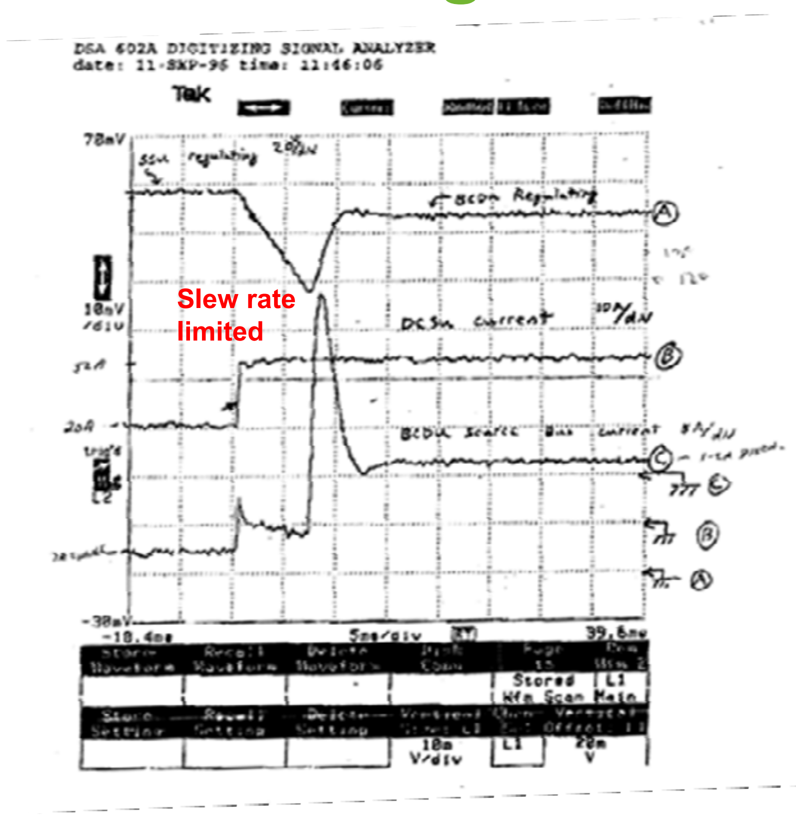
Articles
"Power Integrity: Measuring, Optimizing, and Troubleshooting Power Related Parameters in Electronics Systems", Steve Sandler, 7/29/2014, McGraw-Hill, ISBN: 0071830995,
"Three stability assessment methods every engineer should know about", Steve Sandler, 9/8/2016, https://www.signalintegrityjournal.com/articles/192-three-stability-assessment-methods-every-engineer-should-know-about
"Fix Poor Capacitor, Inductor, and DC/DC Converter Impedance Measurements", Steve Sandler, EEWeb, 10/2016, https://issuu.com/eeweb/docs/10-2016_modern_test___measure_1_pag
"This Misconception About Power Integrity Can Cost You Big", Steve Sandler, How2Power, 3/2016
"Improve Performance And Reduce Cost", Steve Sandler, 6/19/2014, Electronic Design, http://electronicdesign.com/power/improve-performance-and-reduce-cost
"How do I pick the best voltage regulator for my circuit?", Steve Sandler, 9/3/2013, Power Electronics, http://powerelectronics.com/community/how-do-i-pick-best-voltage-regulator-my-circuit
"Switch-Mode Power Supply Simulation: Designing with SPICE 3", Steve Sandler, 11/11/2005, McGraw-Hill, ISBN-10: 0071463267

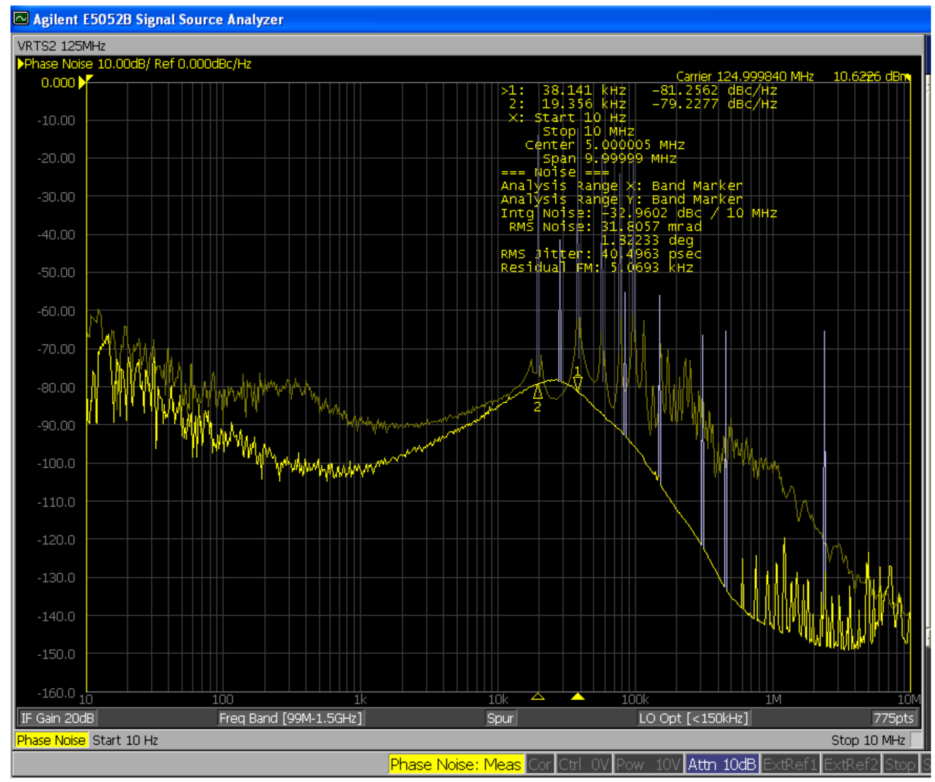
CAREFULLY LOOK FOR SIGNS OF AND CONSIDER IMPACTS OF:

- ***Turn-On Overshoot***
- ***Fault recovery (soft-start recovery)***
- ***Large Signal transients***
- ***Switching frequency modulation***
- ***EMI plane resonances and switch resonant Q***
- ***Chaotic behavior – parasitic SCR, saturation***
-

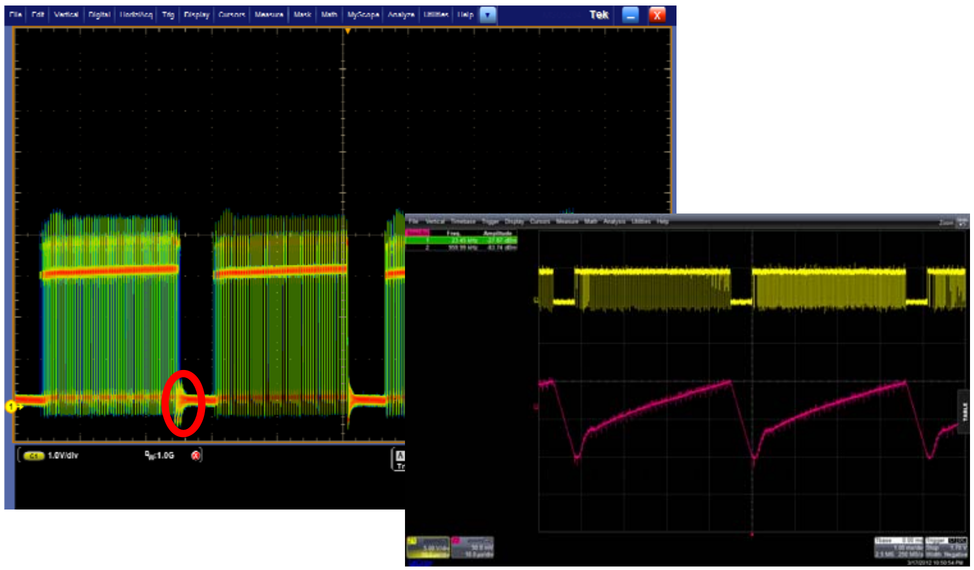
Mode Changes

While burst mode and pulse skipping modes can significantly improve efficiency, they can also result in time delay instabilities and increased noise. This clock phase noise plot shows the impact of burst mode





Other Noise Sources



Inductor saturation increases output ripple and EMI, but it can also impact small signal responses

Noise can conduct the substrate junction present in many controllers, which acts like a parasitic SCR, shutting down the VRM until the SCR releases. One result is greatly increased ripple at low frequency