Power Integrity Boot Camp for Designers

Section 3
Selecting and Modeling the Voltage Regulator Module (VRM)
Voltage Regulator Modules (VRM)
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
SIMULATED vs MEASURED

IMPROVED DESIGN

9mΩ + 4.2nH

IMPEDELANCE (OHMS)

FREQUENCY (Hz)
Flat Z at lower frequencies reduces the package/DUT anti-resonance at higher frequencies!

Reference Design does not fit an R/L Model!

R/L model assumes a flat PDN design!
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!
Inductor
Polymer Capacitor
Ceramic Capacitor
Extension Resistor Setup

DUT
KEYSIGHT ENA5061B
PICOTEST J2160A

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?
STATE SPACE AVERAGED MODEL

Duty = Ton\_SW1 \cdot Fsw

Vout = Vin \cdot Duty

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

State 1: SW1 = On and SW2 = Off

State 2: SW1 = Off and SW2 = On
STATE SPACE AVERAGED MODEL

\[ \text{Duty} = T_{on\_SW1} \cdot F_{sw} \]

\[ V_{out} = V_{in} \cdot \text{Duty} \]

\[ I_{out} = k \frac{V_c}{R_i} \]
Nominal Impedance is the same, Voltage Mode is very sensitive to tolerances

\[
R_{out\_CM} = \frac{R_i}{1 + A_v}
\]

\[
R_{out\_VM} = DCR_{lo} + RDS_{on.bot} + (RDS_{on.top} - RDS_{on.bot}) \cdot \frac{V_o}{V_{in}}
\]

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**

\[
Av_{series} = \frac{R_3 \cdot (Gm \cdot R_2 - 1)}{R_1 + R_3 + Gm \cdot R_1 \cdot R_3} = 3.215
\]

\[
\frac{\delta Av_{series}}{\delta Gm} = \frac{R_2 \cdot R_3}{R_1 + R_3 + Gm \cdot R_1 \cdot R_3} \cdot \frac{R_1 \cdot R_3^2 \cdot (Gm \cdot R_2 - 1)}{(R_1 + R_3 + Gm \cdot R_1 \cdot R_3)^2} = 2.58 \cdot 10^3
\]

**SHUNT FEEDBACK**

\[
Av_{shunt} = \frac{R_3 \cdot Gm \cdot R_{2_{shunt}}}{R_1 + R_3} = 3.215
\]

\[
\frac{\delta Av_{shunt}}{\delta Gm} = \frac{R_3 \cdot R_{2_{shunt}}}{R_1 + R_3} = 6.3 \cdot 10^3
\]

---

**Gfs Error Amp**

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

[Graph showing error and sensitivity]
Voltage Mode with Shunt Feedback

Impractical to make flat PDN impedance!

Voltage Mode Series vs Shunt

Error Amp Gain Slope (dB)

FREQUENCY (Hz)

Output Impedance (Ohms)

FREQUENCY (Hz)

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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!

<table>
<thead>
<tr>
<th>Mode</th>
<th>PSRR</th>
<th>Rout</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>Poor</td>
<td>Poor</td>
<td>Large tolerance impact</td>
</tr>
<tr>
<td>Current</td>
<td>Excellent*</td>
<td>Excellent</td>
<td>Small tolerance impact</td>
</tr>
</tbody>
</table>
Switching Transients

Pulse Width Modulated Switch

Large Signal Output Switching Ripple Transients

PDN Bulk Capacitor and Load

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Adding EM
Complete DC-DC Converter Model

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

LM25116 Example

Averaged Small Signal Output
(AC Sweep PDN Impedance)

Slope Compensation

Feedback Buffered (OTA)

PDN Bulk Capacitor and Load

Large Signal Output
Switching Ripple Transients

PDN Bulk Capacitor and Load

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Exploring the DC-DC Converter Model Performance

Explore Cramp Impact on PSRR

![Graph showing dB(PSRR) with m3 peak at Cramp=450.000, dB(PSRR[1])=117.267 Peak.](image)
...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