Internally Compensated Advanced Current Mode (ACM) with the TPS543C20

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Agenda

- Introduction to Advanced Current Mode (ACM)
- ACM Overview
- ACM Small Signal Analysis
- TPS543C20 Overview
- ACM Comparison to other Control Modes
  - D-CAP3™
  - Voltage Mode with Voltage Feedforward
- Summary

Introduction to Advanced Current Mode (ACM)

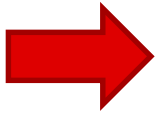
Motivation for Internally Compensated ACM

COT (D-CAPx™)

- ✓ No external compensation required
- ✓ Fast Transient Response
- ✓ Simple, easy to design with less BOM
- - No true fixed frequency
- - Higher jitter (during transients)
- - Inability to stack – no CLK sync
- - Challenge to employ traditional methods of gain-phase measurements

CMC/ VMC

- ✓ Proven methods to calculate/ measure bode plots to implement stable Designs
- ✓ True fixed frequency operation; ability to sync to external clock to eliminate beat noise and facilitate stacking
- ✓ Good, low-jitter performance
- - Requires external Type2/3 compensation
- - Larger BOM and more complex Designs
- - Tempered transient response

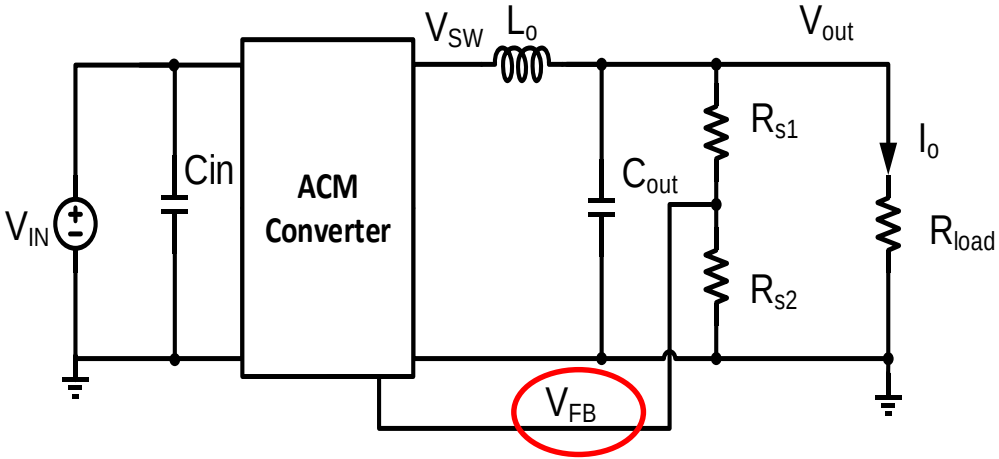


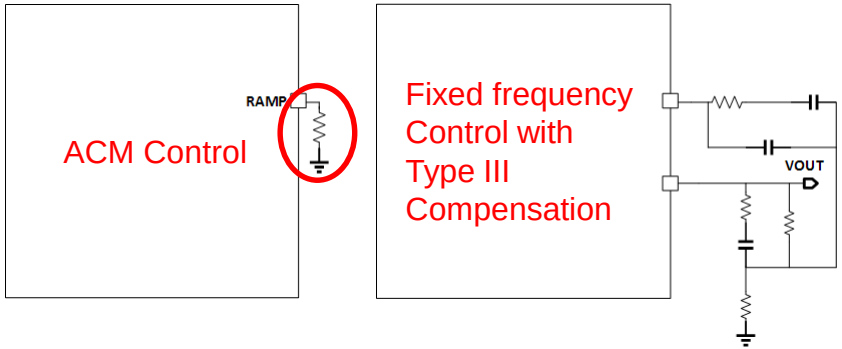
Internally Compensated ACM

- ✓ No external compensation required
- ✓ Fast Transient Response
- ✓ Simple, easy to design with less BOM
- ✓ Proven methods to calculate/ measure bode plots to implement stable Designs
- ✓ True fixed frequency operation; ability to sync to external clock to eliminate beat noise and facilitate stacking
- ✓ Good, low-jitter performance

ACM Control Introduction

- DC-DC Converter using ACM
  - Without external compensation, ACM converter only needs V_{FB} single for control loop.
  - The external passive components can be minimized to save total system cost and size.
  - Ease of use, no need to design the PID or PI compensation





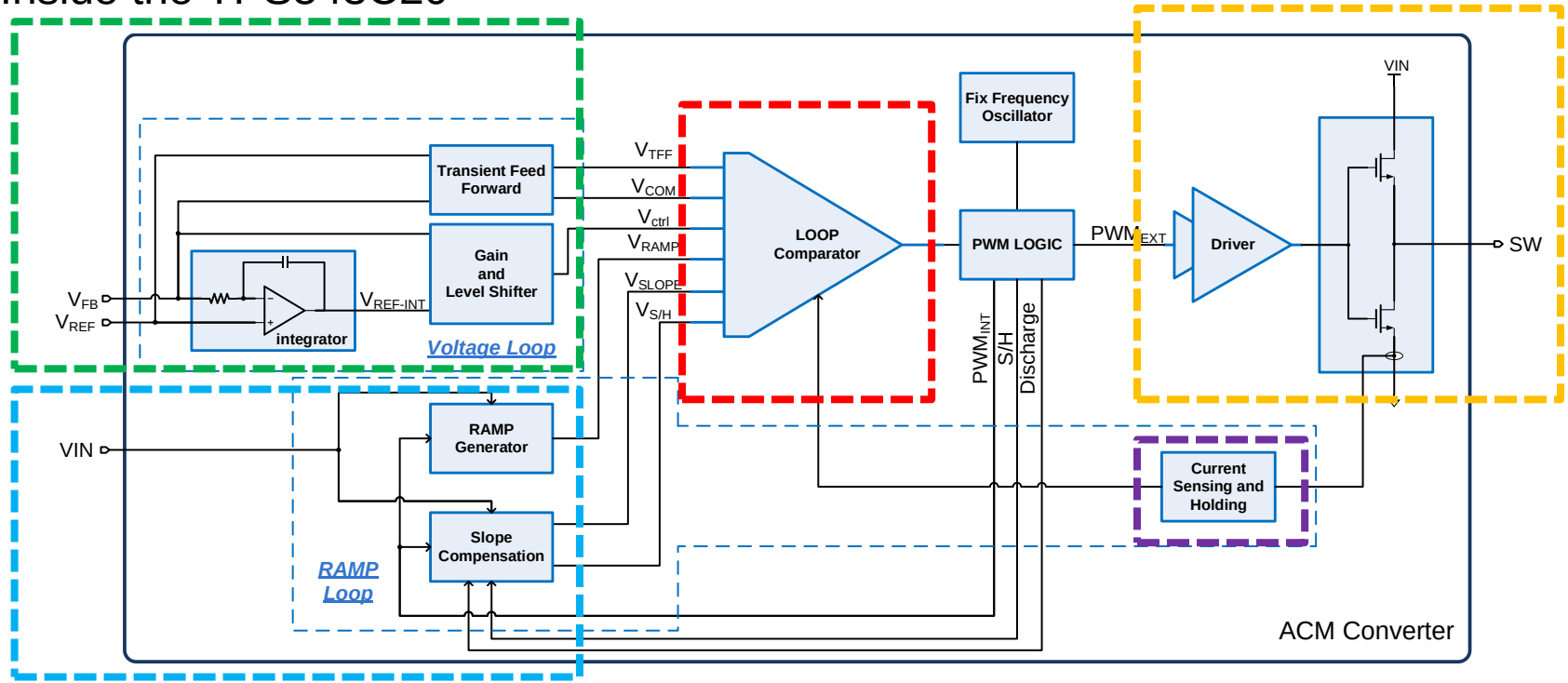
ACM Control Advantages Overview cont'd

True Fixed Frequency Modulation	Benefit
• Preset clock oscillator to determine switching frequency • Synchronization to external clock, enable easer stackability • Better jitter performance compare with various frequency	• Predictable EMI noise filtering • Power scaling to simplify design and layout • Low EMI noise
Internal Compensation with Fast Transient	**Benefit**
• Ease of use, without complicated compensation design • No external compensation components, reduce BOM and PCB area • Flexible loop optimization to cover wide L, C range	• Greatly reduce design to release cycle • Increase system power density • Design flexibility and tolerance for variations
Other Features	**Benefit**
• Large single to noise ratio by emulated ramp • Multi-mega Hz Switching • Asynchronous Pulse Insertion **(API)** and Body Braking • DC current feedback for resonant frequency damping	• Better switching jitter performance • Size reduction and fits automotive applications • Further improve transient performance • Supports huge output capacitance

ACM Control Overview

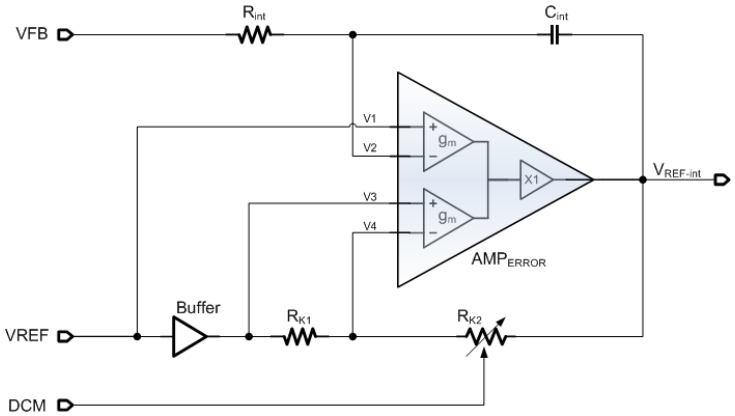
ACM Control Overview - Block Diagram

- Inside the TPS543C20



ACM Control Overview: Voltage loop – Integrator

- We used a four inputs error amplifier to do the integration. One pair of the input is doing the integration, while the other pair is controlling the gain of this integrator.
- The system diagram of this new internal integrator is shown below. V1 and V2 are used to do the feedback for integration and V3 and V4 are used to control the gain.



AC response of integrator:

$$V_{REF-int} = V_{REF} \cdot \frac{s + \frac{k \cdot (V_{REF} - V_{FB}) + V_{REF}}{(k+1) \cdot V_{REF} \cdot C_{int} R_{int}}}{s + \frac{1}{(k+1) \cdot C_{int} R_{int}}} \qquad Where, k = \frac{R_{K2} + R_{K1}}{R_{K1}}$$

VFB: This voltage is the feedback voltage of the DC-DC Converter

VREF: This is the reference voltage of the system.

DCM: DCM mode enable digital signal.

$V_{REF-INT}$: The output of the integrator

AMP_{ERROR}: Four input amplifier for the integrator

Buffer: The voltage buffer to separate the VREF from the loading of R_{K1} and R_{k2}.

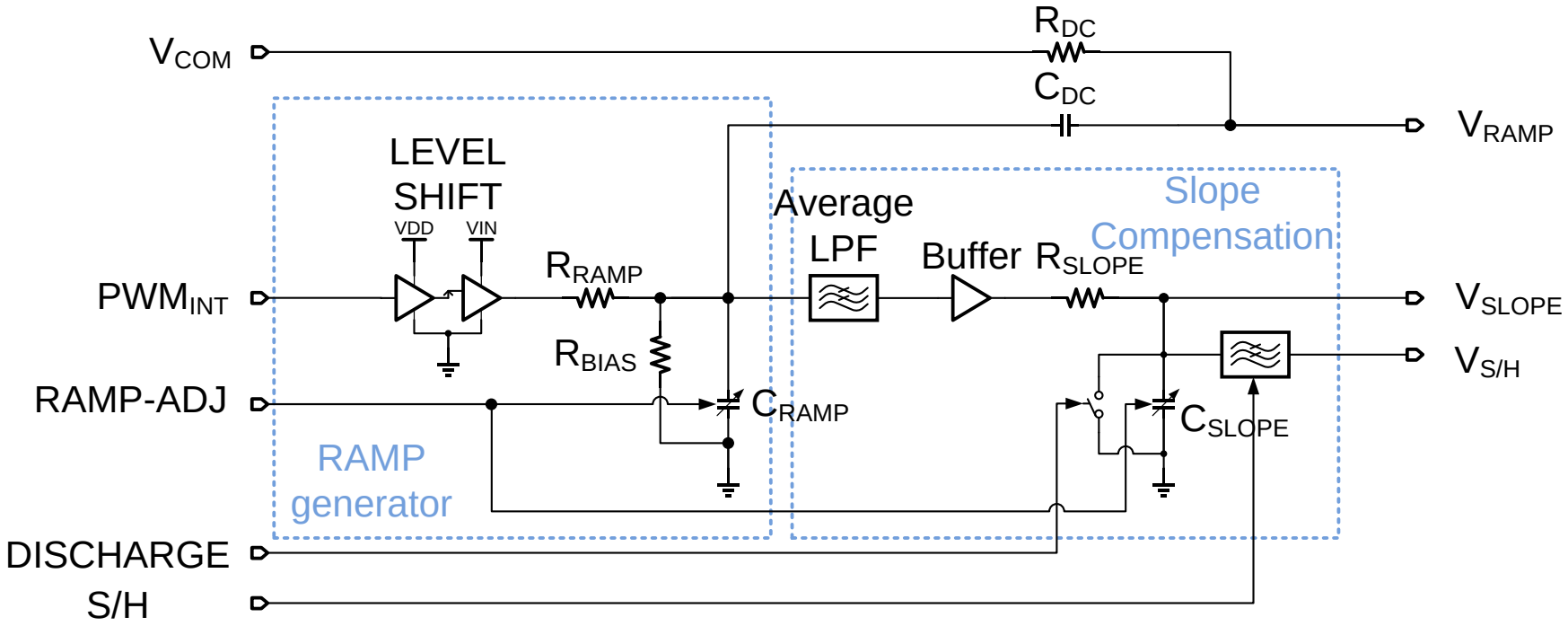
R_{int} and C_{int}: The resistor and capacitor providing the integration function.

R_{k1} and R_{k2}: the resistor pair to set the gain of the integrator. The resistance of R_{k2} is controlled by DCM

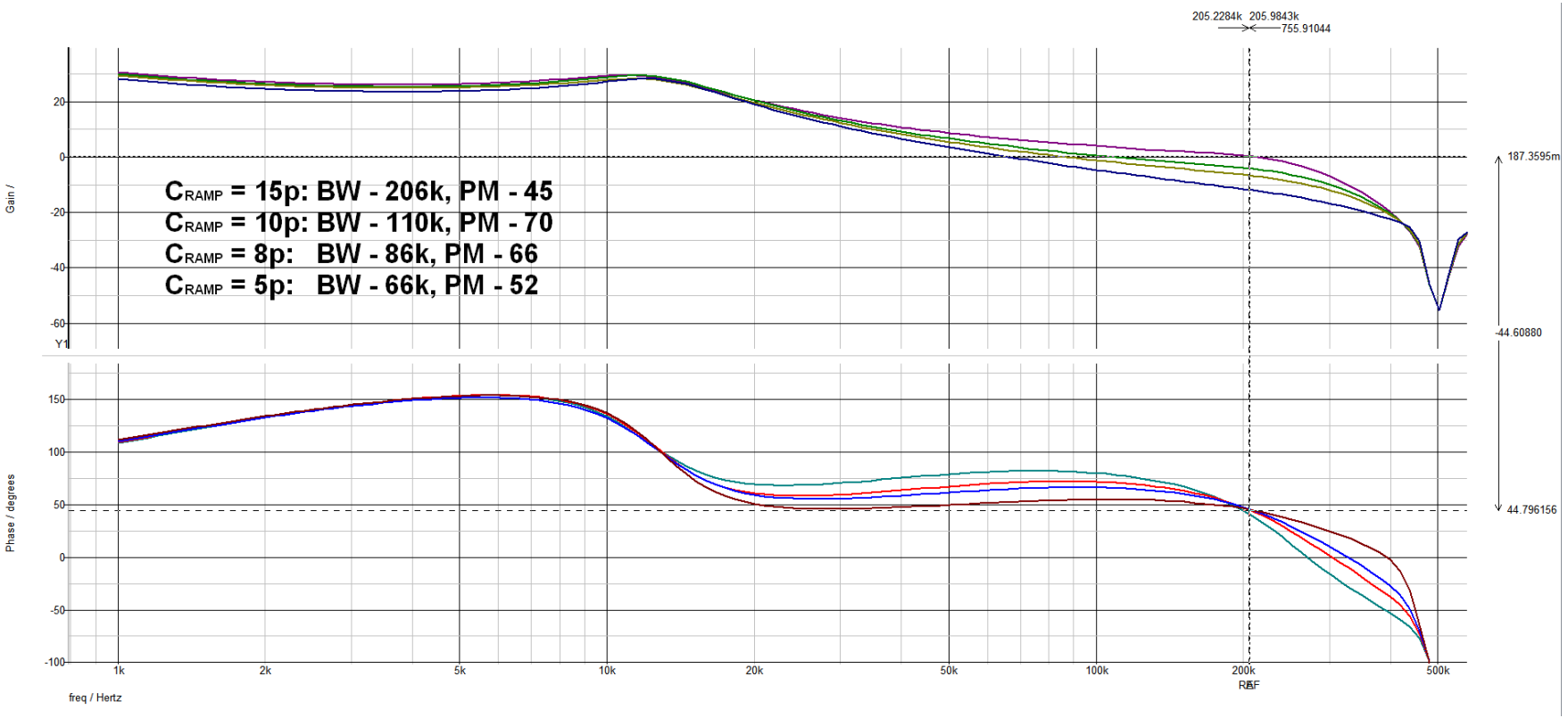
ACM Control Overview:

Ramp loop – RAMP Generator and slope compensation

- The RAMP generator and slope compensation is shown below

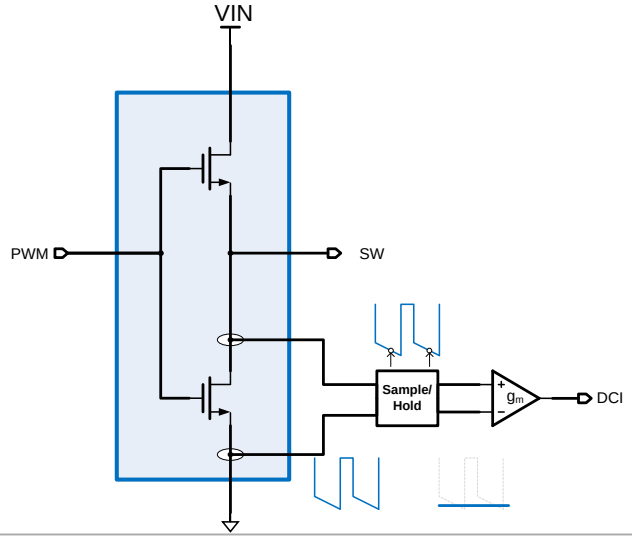


ACM Control Overview:
AC plot with different RAMP setting



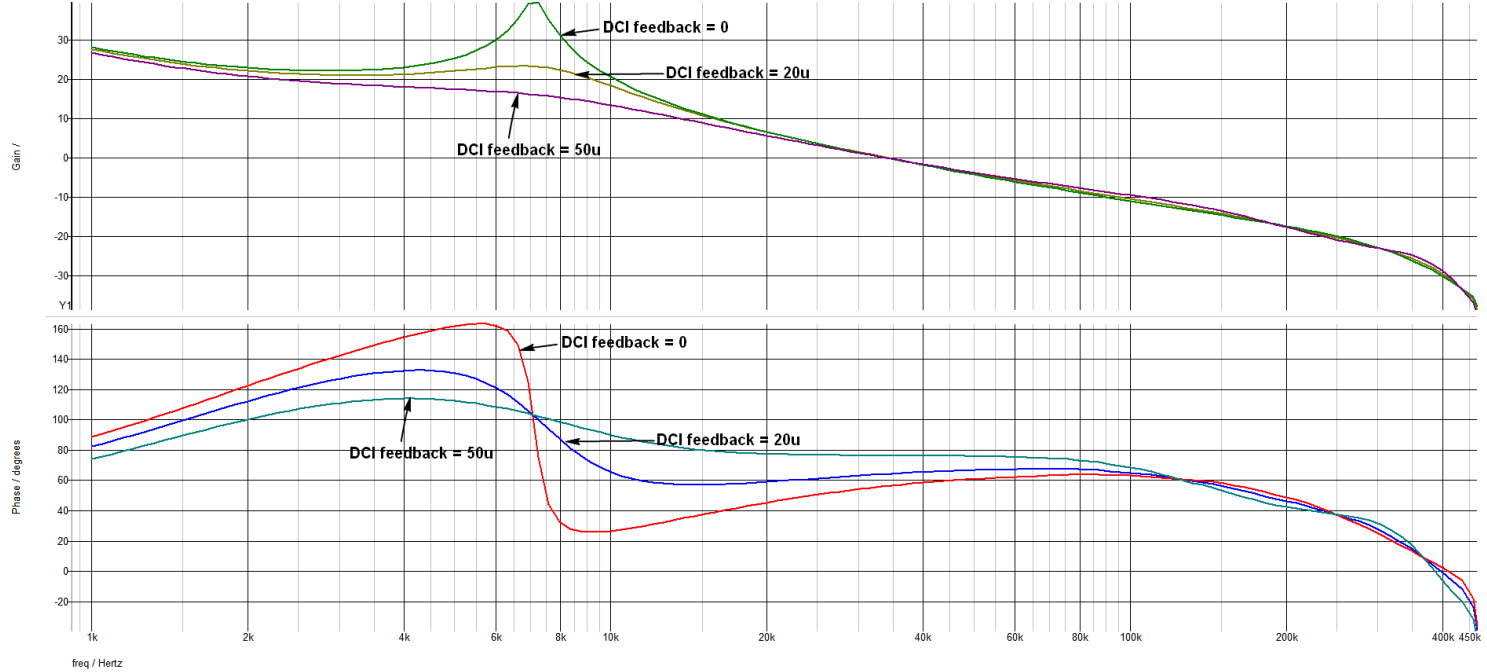
ACM Control Overview: DC Current Feedback Loop

- To decrease the Q value at the double pole frequency, a small DC current feedback is added to the loop.
- The current information is sensed from the power stage, for example from the low side FET. And it is sampled and hold at one point during off time, normally at the end of off time.
- A gm amplifier changes this S/H current information to current and feedback to the loop comparator.



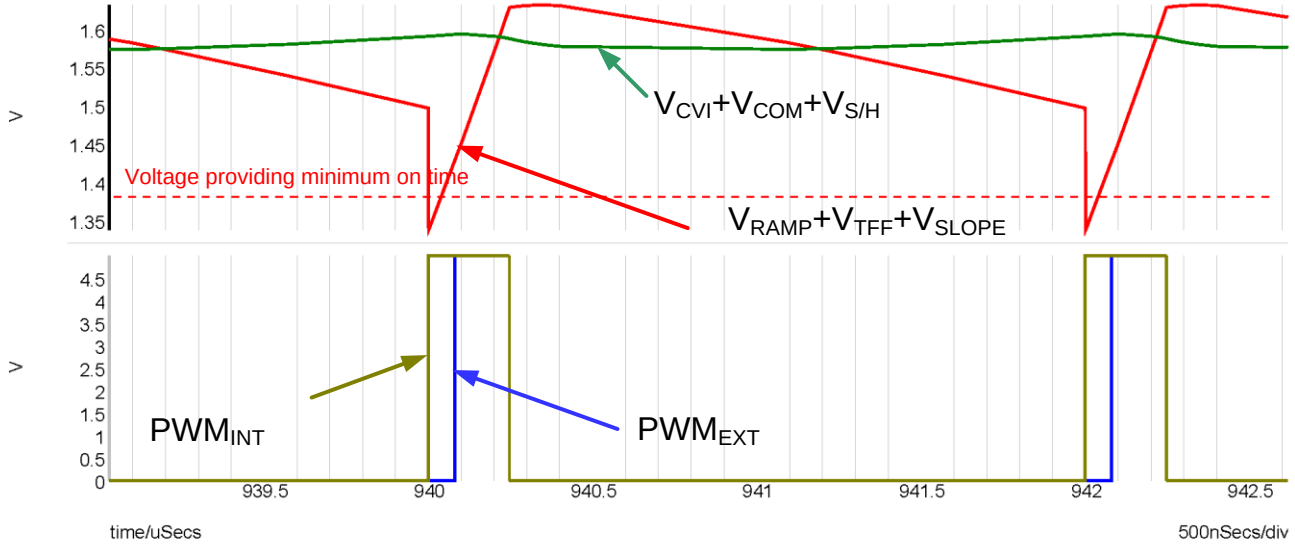
ACM Control Overview: DC Current Feedback Loop—cont.

- The bode plots with different DCI feedback value are compared below:



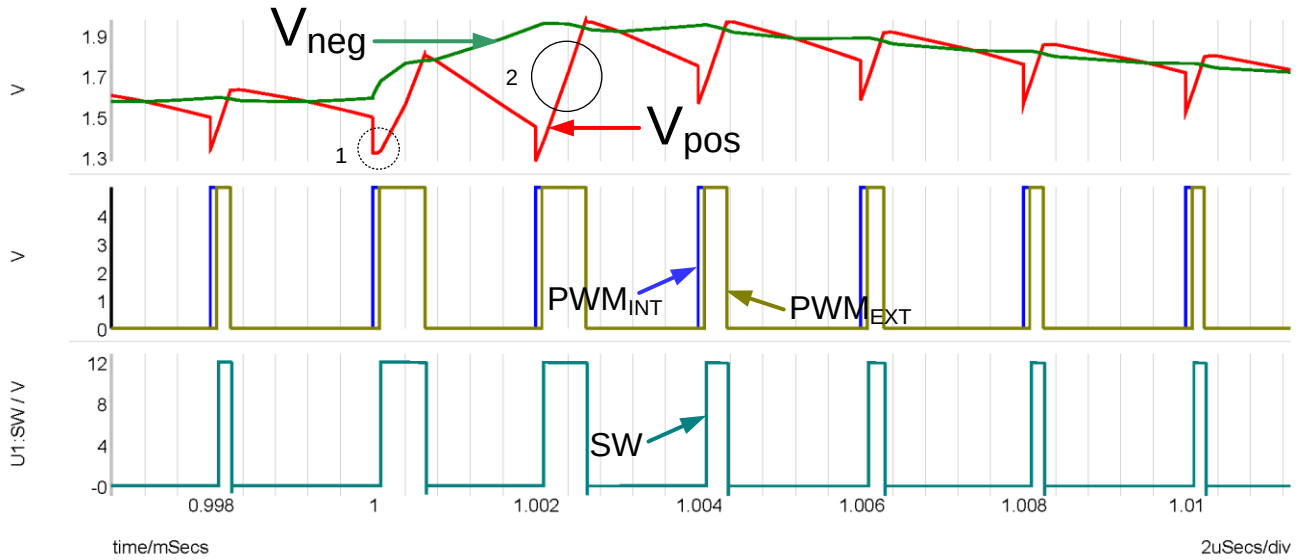
ACM Control Overview:
Control Signal Waveform—cont.

- We can add all of the positive inputs of the loop comparator together and compare it with all of the negative inputs. The waveform is shown below:



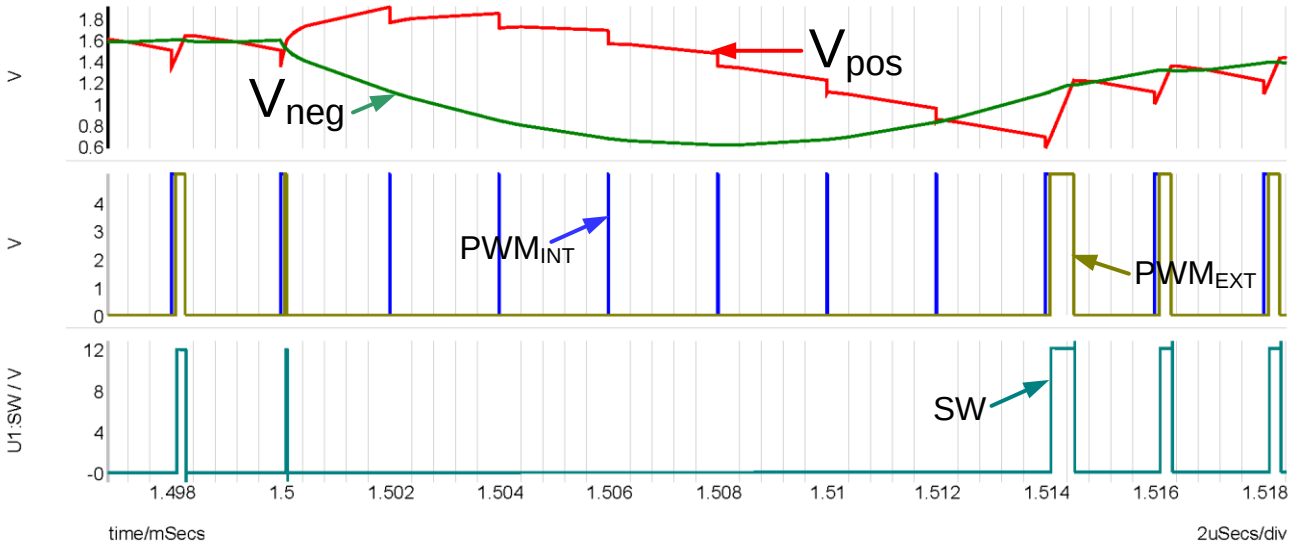
ACM Control Overview: Control Signal Waveform—cont.

- During load step up transient, Vout dips when the load increases. The V_{neg} (sum of negative inputs of the loop comparator) will increase and slope of the V_{pos} (sum of positive inputs of the loop comparator) will decrease. The duty cycle will be bigger to pull the Vout back to target. The waveform is shown below:



ACM Control Overview: Control Signal Waveform—cont.

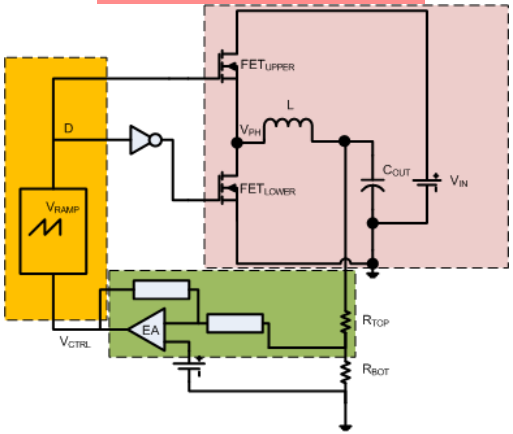
- During load step down transient, Vout rise when the load decrease. The V_{neg} will decrease and slope of the V_{pos} will increase. The duty cycle will be smaller to pull the Vout back to target. The waveform is shown below:



ACM Small Signal Analysis

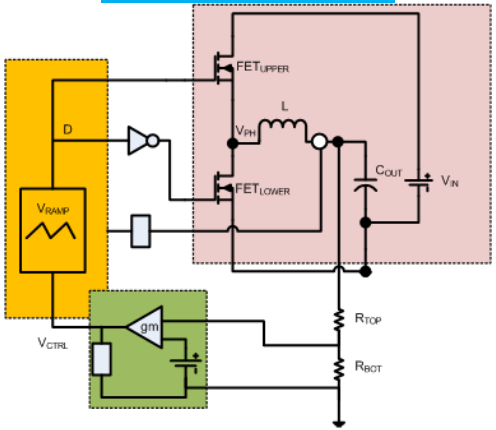
DC-DC Topology: Control vs Ramp

Voltage Mode



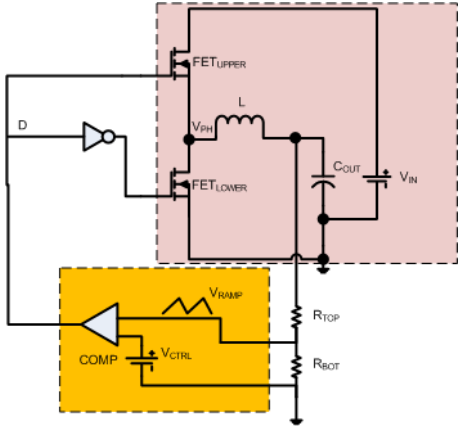
V_{RAMP} is saw tooth waveform
V_{CTRL} is EA output

Current Mode



V_{RAMP} is proportional to the inductor current
V_{CTRL} is gm output

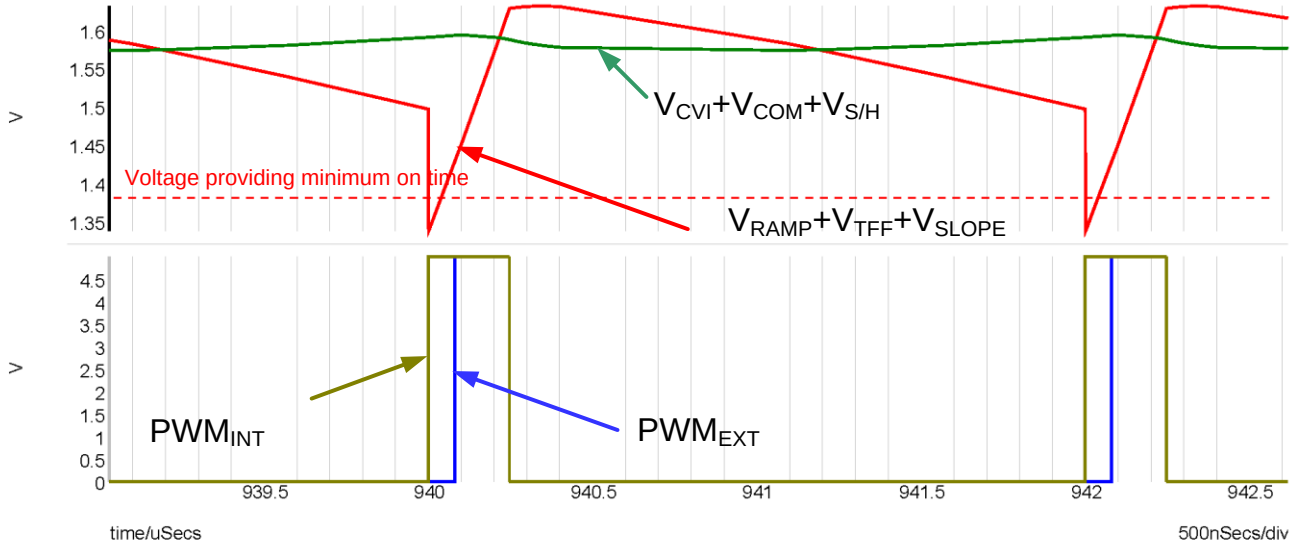
COT Mode



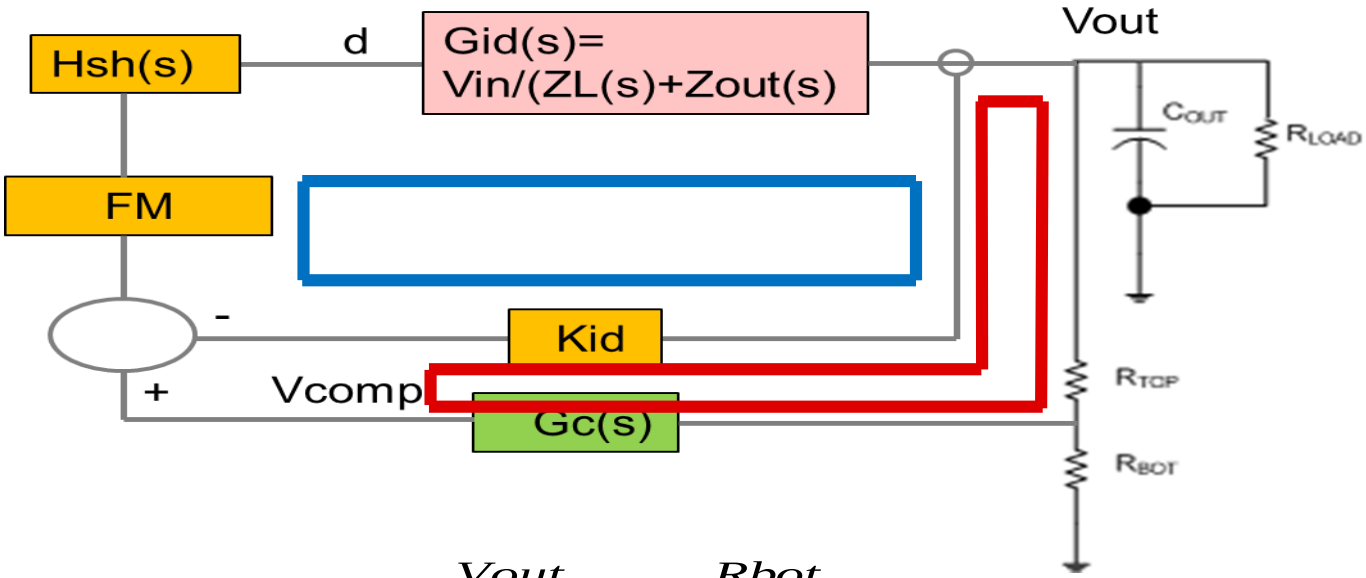
V_{RAMP} is proportional to the inductor current
V_{CTRL} is the reference voltage

ACM Control vs Ramp

- We can add all of the positive inputs of the loop comparator together and compare it with all of the negative inputs. The waveform is shown below:



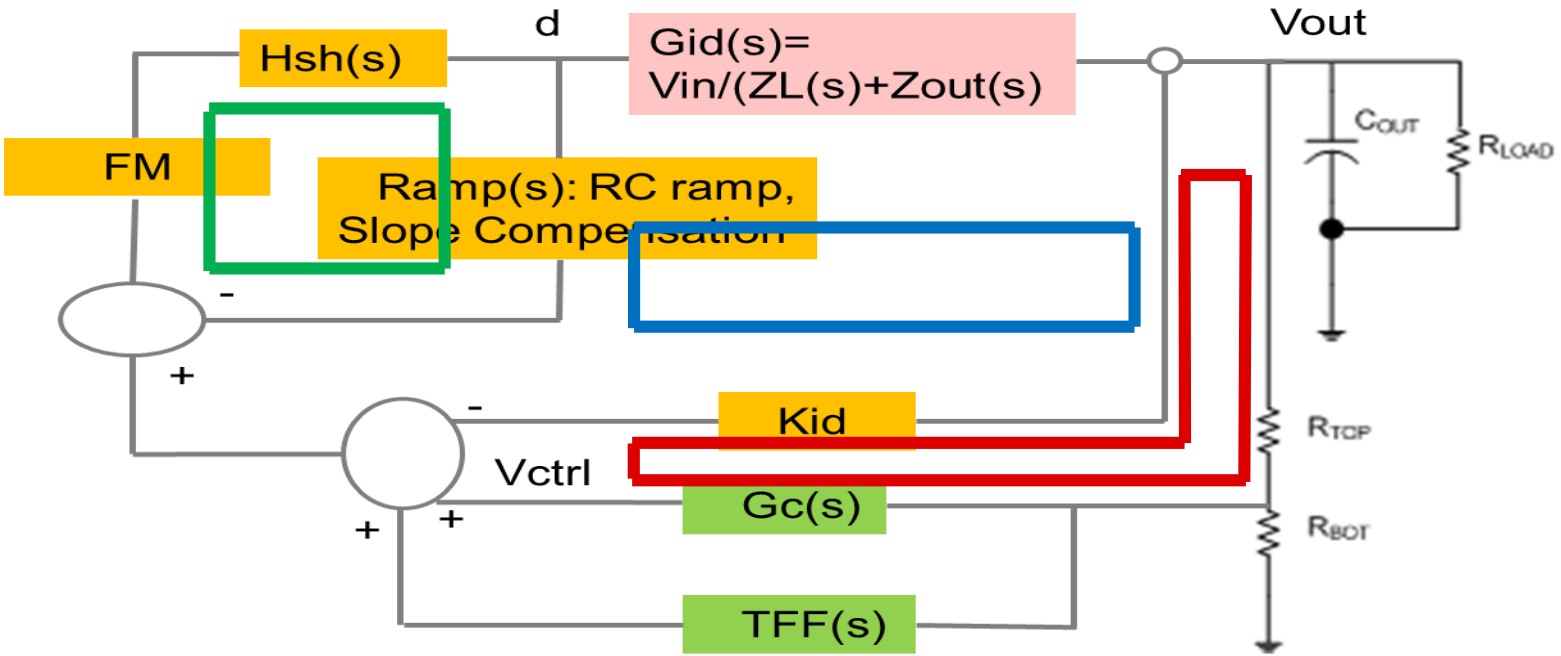
Convert Block Diagram to TF: Current Mode



$$LoopGain = \frac{Vout}{Vcomp} \cdot \frac{Rbot}{Rbot + Rtop} \cdot Gc$$

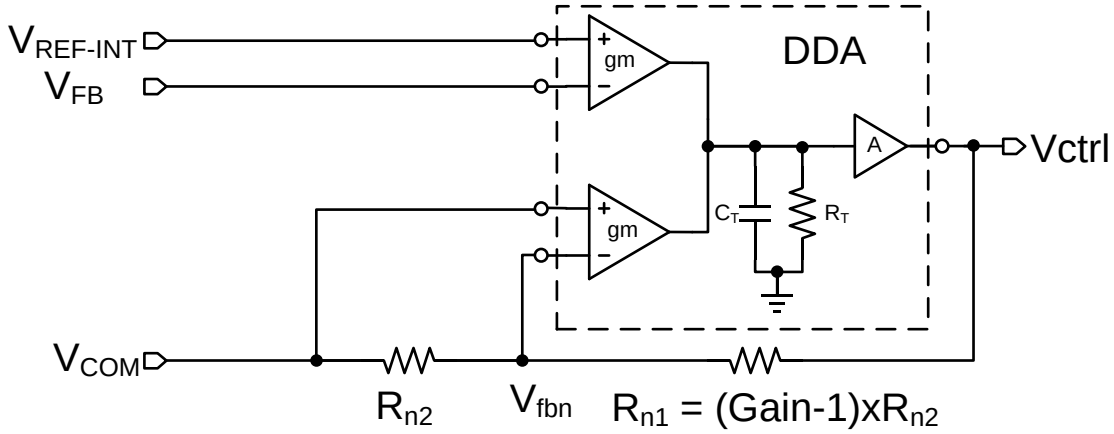
$$\frac{Vout}{Vcomp} = \frac{a}{1 + a \cdot b}$$

Block Diagram to TF: ACM



Next slides show the transfer function of each block and loop gain transfer function

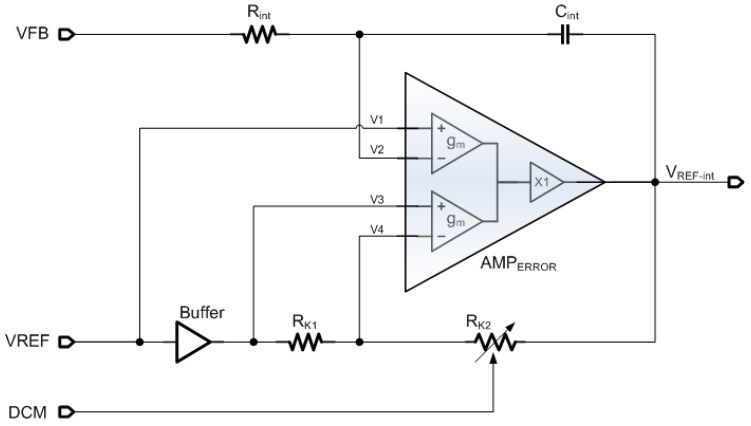
Control Voltage TF



- AC model: Set V_{COM} as zero

$$V_{ctrl} = \frac{R_{n2} + R_{n1}}{R_{n2}} (V_{REF-INT} - V_{FB})$$

Control Voltage TF: Con't



- AC model: Set V_{VREF} as zero

  V4 = - V2

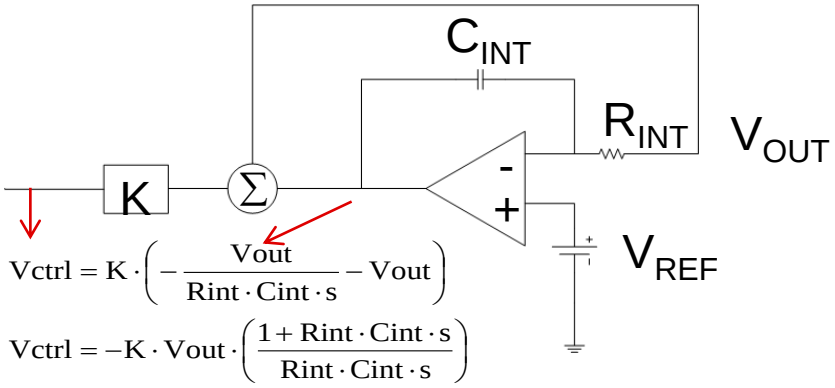
$$\frac{Rk1}{Rk2+Rk1}\cdot Vref\_int = -1\cdot\frac{VFB+s\cdot Cint\cdot Rint\cdot Vref\_int}{s\cdot Cint\cdot Rint+1}$$

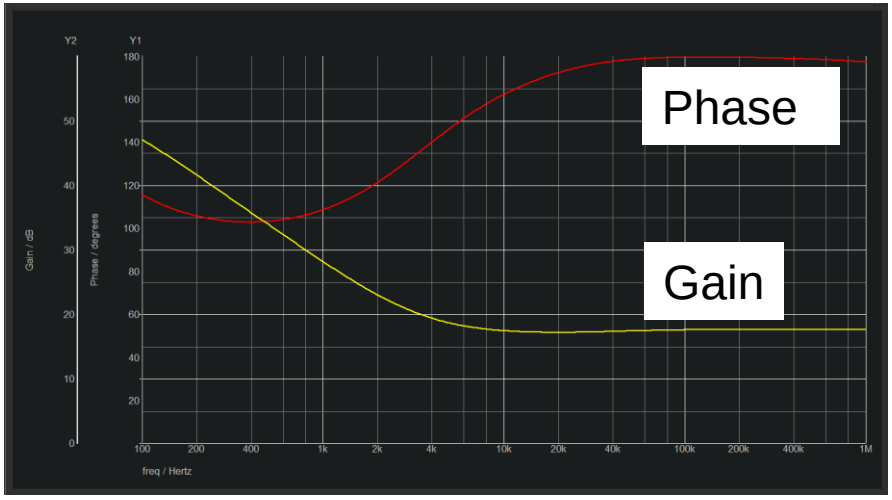
$$Vref\_int(s) := -\frac{H\cdot(Rk1+Rk2)}{Rk1+s\cdot Cint\cdot Rint\cdot(2\cdot Rk1+Rk2)}$$

How does V_{ctrl} effect the stability of the system?

What are the meaning behind of this signal?

Control Voltage TF: Con't



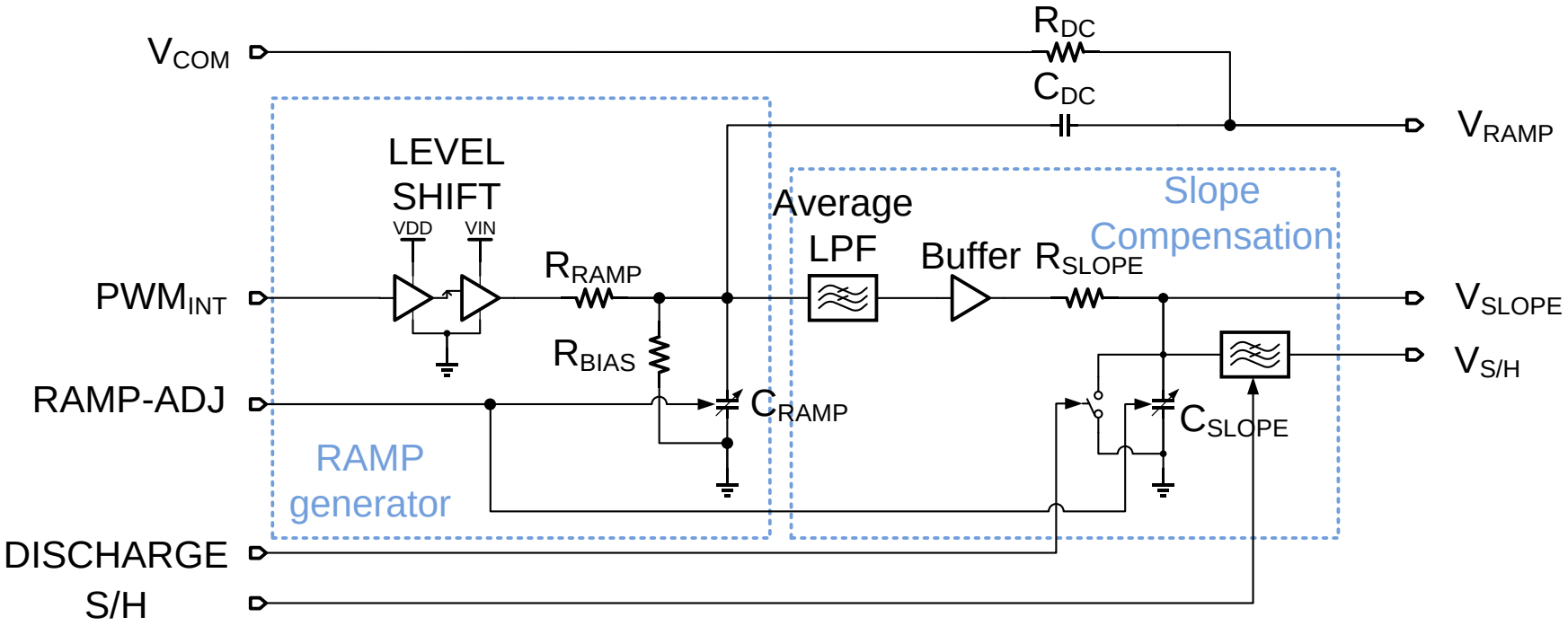


V_{ctrl} signal reveals:

1. A zero with constant gain, K at frequency > fz
2. Adjusting the gain, K, can affect the bandwidth
3. Set the settling time
4. Set the lowest LC corner frequency limit to design

RAMP Generator and Slope Compensation TF

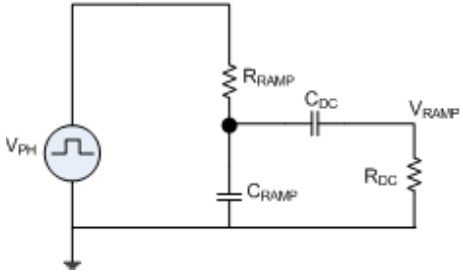
- The RAMP generator and slope compensation is shown below



RAMP and Slope Transfer Function:

Ramp TF:

$$Zp(s) := \frac{\frac{1}{s \cdot Cramp} \cdot \left(\frac{1}{s \cdot Cdc} + Rdc\right)}{\frac{1}{s \cdot Cramp} + \left(\frac{1}{s \cdot Cdc} + Rdc\right)} \rightarrow Vzp(s) := \frac{Zp(s) \cdot Vpwm}{Zp(s) + Rramp} \rightarrow Vramp(s) := \frac{Rdc \cdot Vzp(s)}{Rdc + \frac{1}{s \cdot Cdc}}$$



$$Vramp = \frac{s \cdot Cdc \cdot Rdc \cdot Vpwm}{Cdc \cdot Rdc \cdot Cramp \cdot Rramp \cdot s^2 + (Cdc \cdot Rdc + Cdc \cdot Rramp + Cramp \cdot Rramp) \cdot s + 1}$$

$$Vramp = \frac{Vpwm}{Cramp \cdot Rramp \cdot s + 1}$$

With: Cdc*Rdc > Cramp*Rramp and f>>1

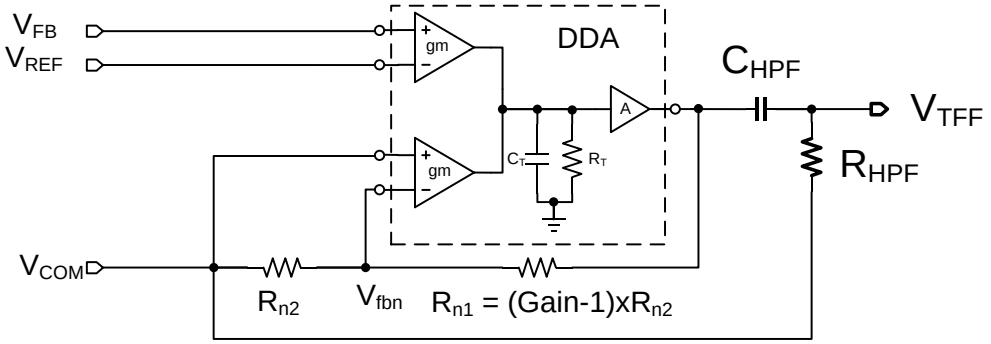
Slope TF:

$$Vslope = \frac{1}{s \cdot Csl \cdot Rsl + 1} \cdot \frac{Vpwm \cdot Ton}{2 \cdot Tsw}$$

When D is small, V_{RAMP} >> V_{SLOPE} ; V_{RAMP} dominates in the loop transfer function
Reveal the highest LC frequency at Cramp*Rramp

Transient Feed Forward TF

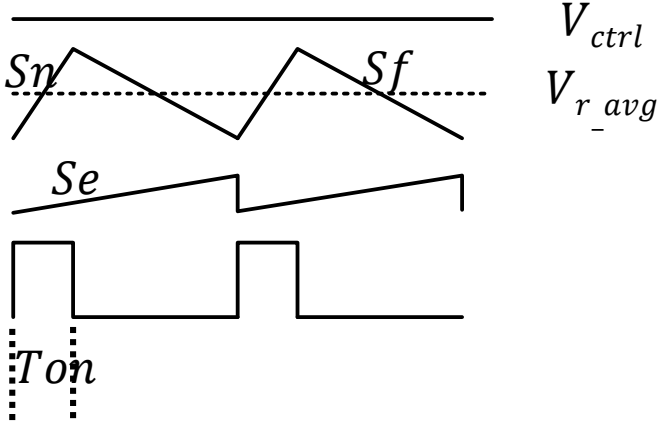
Implementation as V_{ctrl} and V_{COM}



$$Vtff(s) := \frac{Rn2 + Rn1}{Rn2} \cdot Kddap \cdot (-Vctrl(s)) \cdot \frac{s \cdot Rhpf \cdot Chpf}{s \cdot Rhpf \cdot Chpf + 1}$$

Kddap(1/5) is an internal gain of DDA

FM Gain Derivation



$$Vctrl = Vr\_avg + \frac{1}{2} Sn \cdot ton + Se \cdot ton$$

$$Sn = \frac{dVramp}{dt} = \frac{Vin - Vo}{Rramp \cdot Cramp} \qquad Se = Ksl \cdot Sf = Ksl \cdot \frac{dV}{dt} = Ksl \cdot \frac{Vo}{Rramp \cdot Cramp}$$

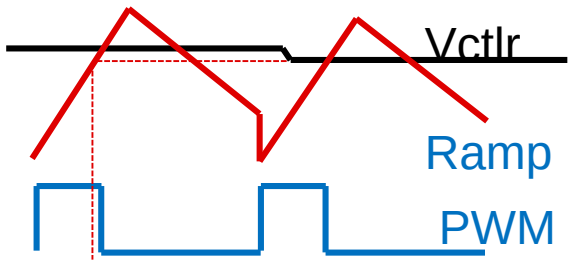
Perturbation and Linearization:

$$\mathrm{Vin} = \mathrm{VIN} + \hat{\mathrm{vin}}$$

$$\mathrm{d} = \mathrm{D} + \hat{\mathrm{d}}$$

$$FM = \frac{1}{\frac{1 \cdot Tsw}{Rramp \cdot Cramp} \cdot \left((0.5 - D) + 2 \cdot D \cdot Ksl \right)}$$

Sampling TF



- Sampling refers to only one D per switching cycle.
- Need to transform back to continuous-time representation by zero-order-hold:

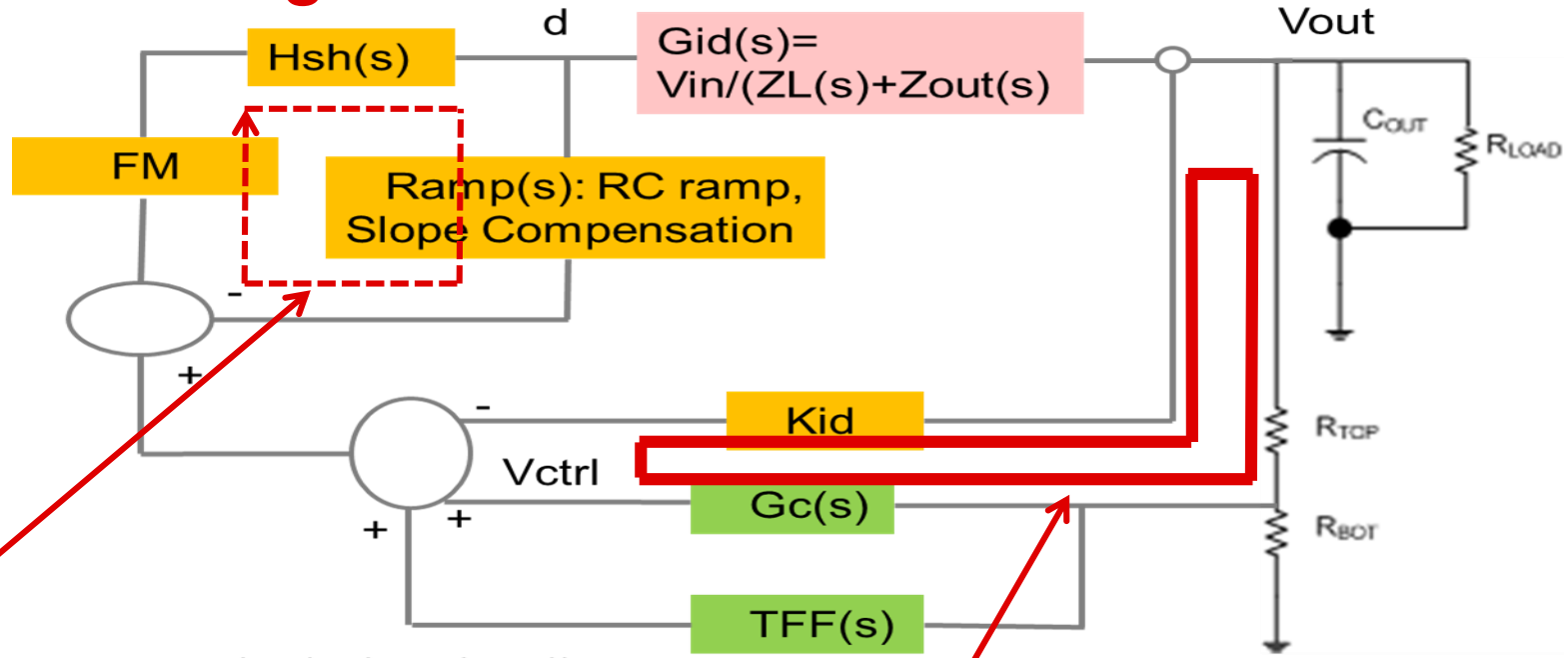
$$Hzoh(s) = \frac{1 - e^{-s \cdot Tsw}}{s \cdot Tsw}$$ ← Like PWM signal

$$\frac{FM \cdot Hsh}{1 + FM \cdot Vramp\_total \cdot Hsh} \cdot Vctlr = \frac{1 - e^{-s \cdot Tsw}}{s \cdot Tsw}$$

$$Hsh(s) = \frac{1 - e^{-s \cdot Tsw}}{\left(s \cdot Tsw + e^{-s \cdot Tsw} - 1\right)} \frac{\left(0.5 - D + 2 \cdot D \cdot Ksl\right) \cdot Tsw \cdot s}{Vpwm + 1.29 \cdot Vramp\_avg}$$

- Refer to Jiwei Fan's paper: Design and Characterization of DE-DRC for Step-Down Converter
- Refer to F. Dong Tan and R.D. Middlebrook paper: A Unified Model of Current Programmed Converters

ACM Block Diagram to TF



$$TFloop1(s,Vin) := \frac{(FM(Vin)\cdot Hsh(s,Vin))}{1+FM(Vin)\cdot Hsh(s,Vin)\cdot(Vramp(s)+Vslope(s,Vin))}$$

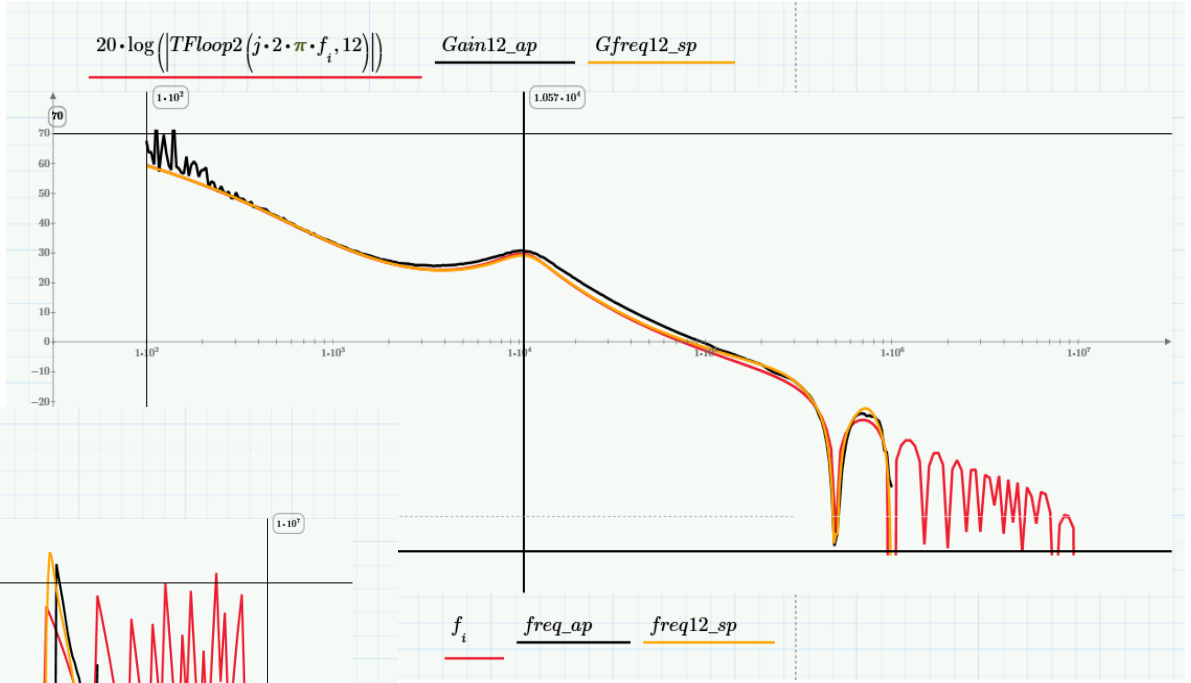
$$TFloop2(s,Vin) := \frac{TFloop1(s,Vin)\cdot Gid(s,Vin)\cdot Zout(s)}{1+TFloop1(s,Vin)\cdot Gid(s,Vin)\cdot Kid}\cdot((Vctrl(s)-Vtff(s)))$$

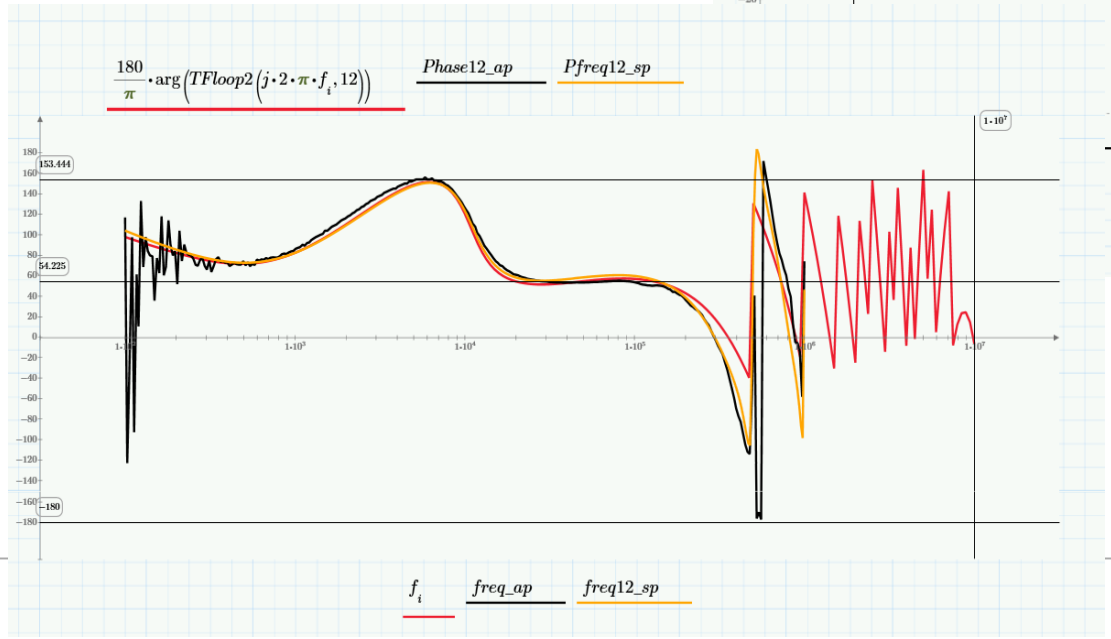
Comparison

Lab Data by AP

Simplis Data

Model





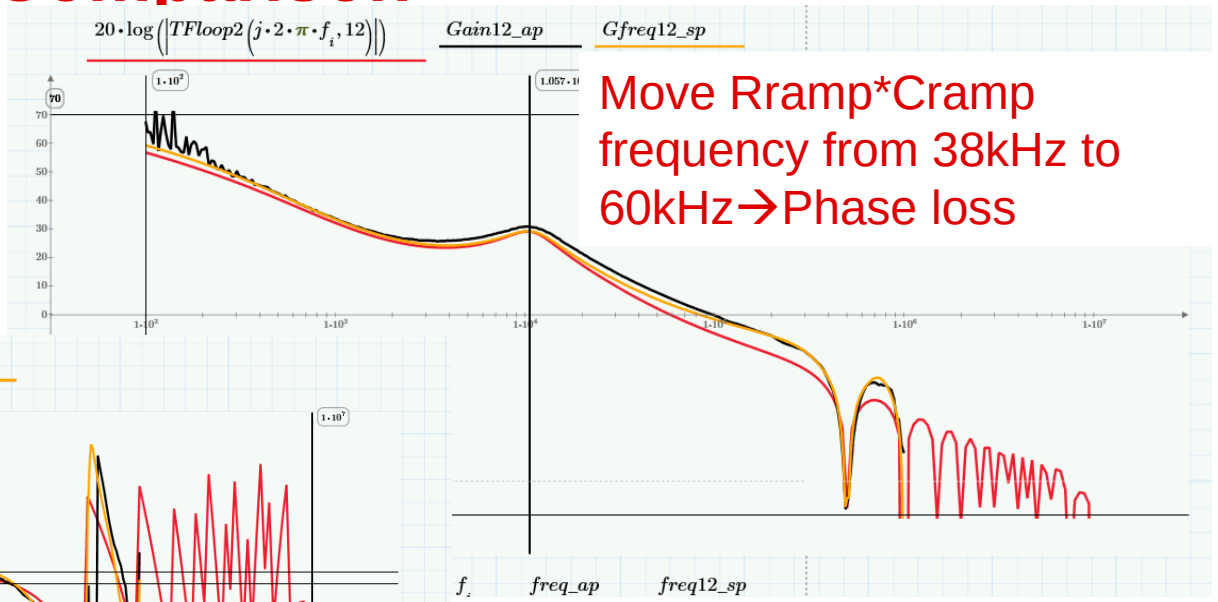
Vin = 12V, 0.9Vout, 500kHz,
470nH/0.16mOhm, 1x330uF(1.5mOHm)+
150uF (0.7mOhm)
Cramp = 14.1pF

Cramp Parameter Comparison

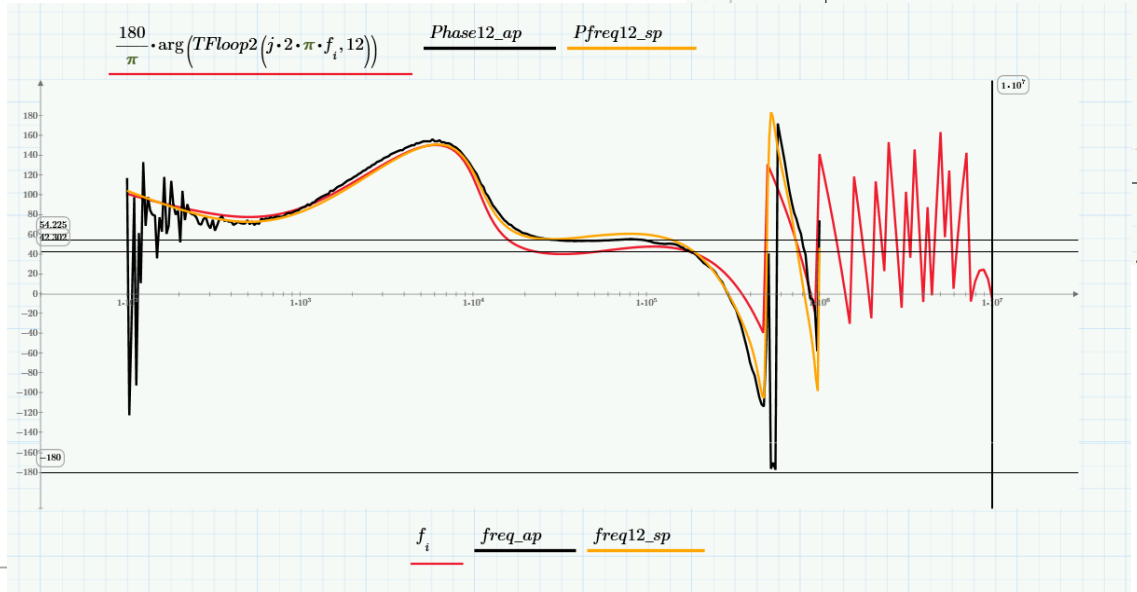
Lab Data by AP : Cramp = 14.1pF

Simplis Data: Cramp = 14.1pF

Model: Cramp = 8.91pF



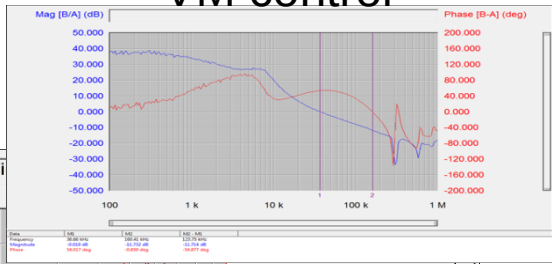
Move Rramp*Cramp frequency from 38kHz to 60kHz→Phase loss



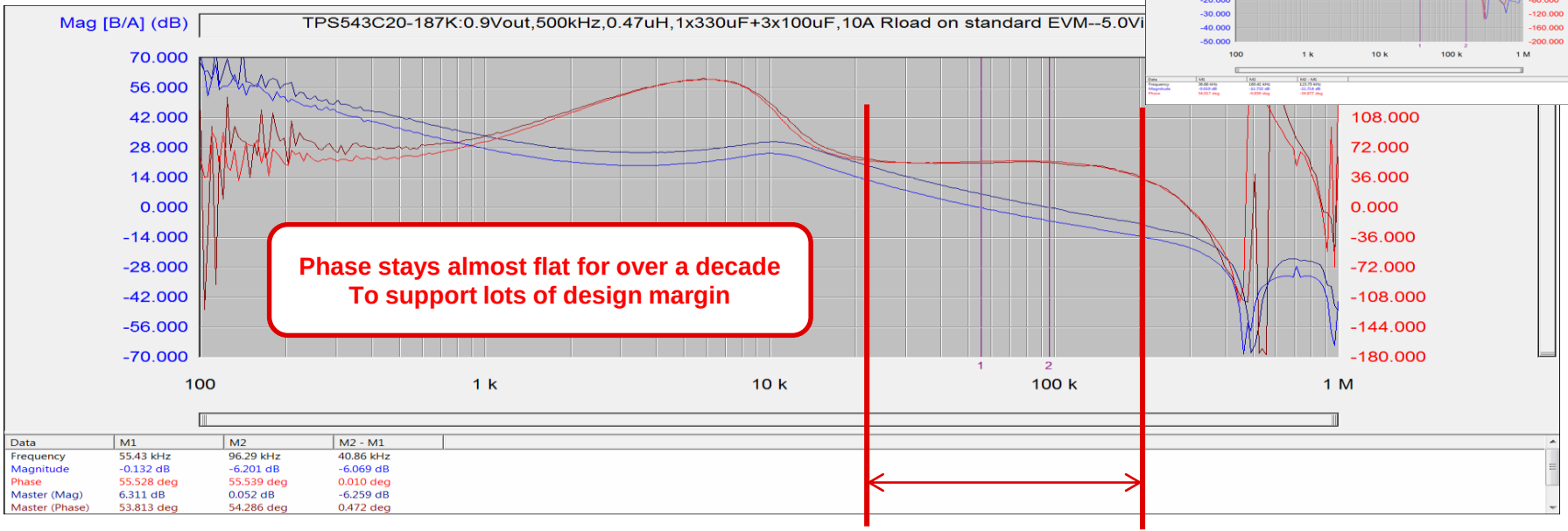
Vin = 12V, 0.9Vout, 500kHz,
470nH/0.16mOhm,
1x330uF(1.5mOHm)+ 150uF (0.7mOhm)
Cramp = 14.1pF
Cramp = 8.91pF (Model)

ACM's Constant Phase Character

VM control

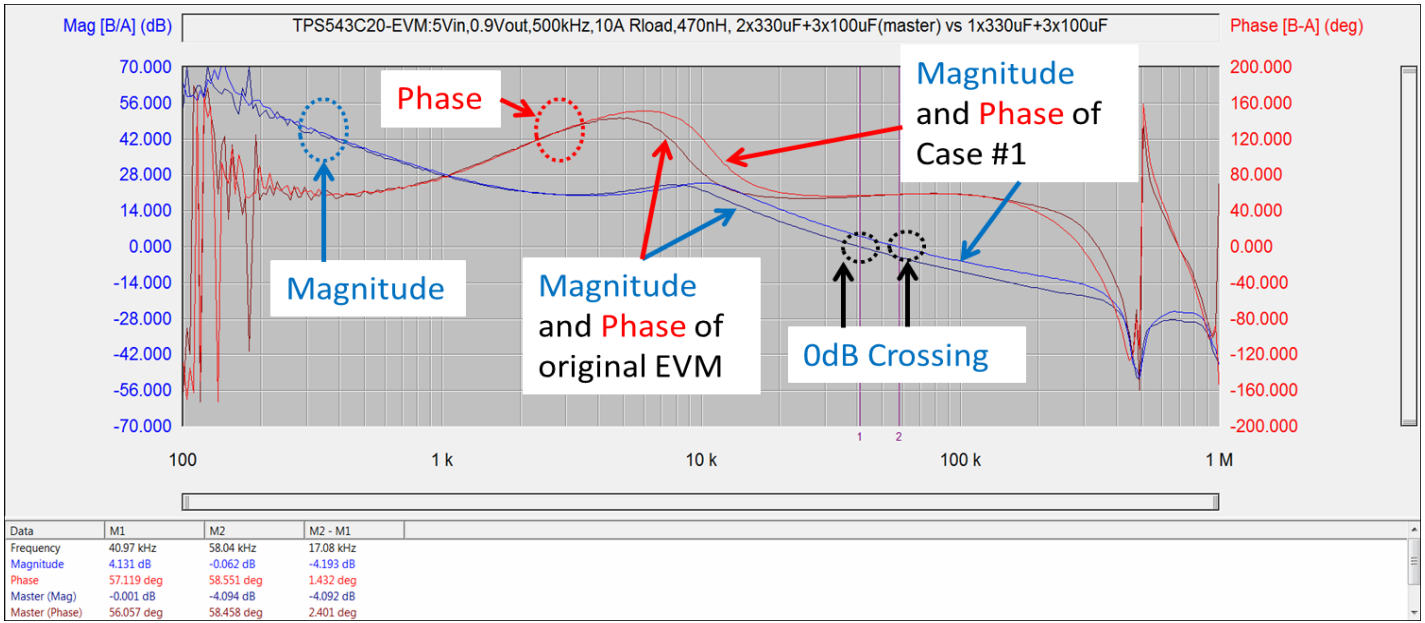


0.9V, 500kHz, 10A Load and Vin = 5V vs. 12V



ACM's Constant Phase Character

5Vin, 0.9Vout, 500kHz, 10A Load: 1/3 Output Capacitor Reduction

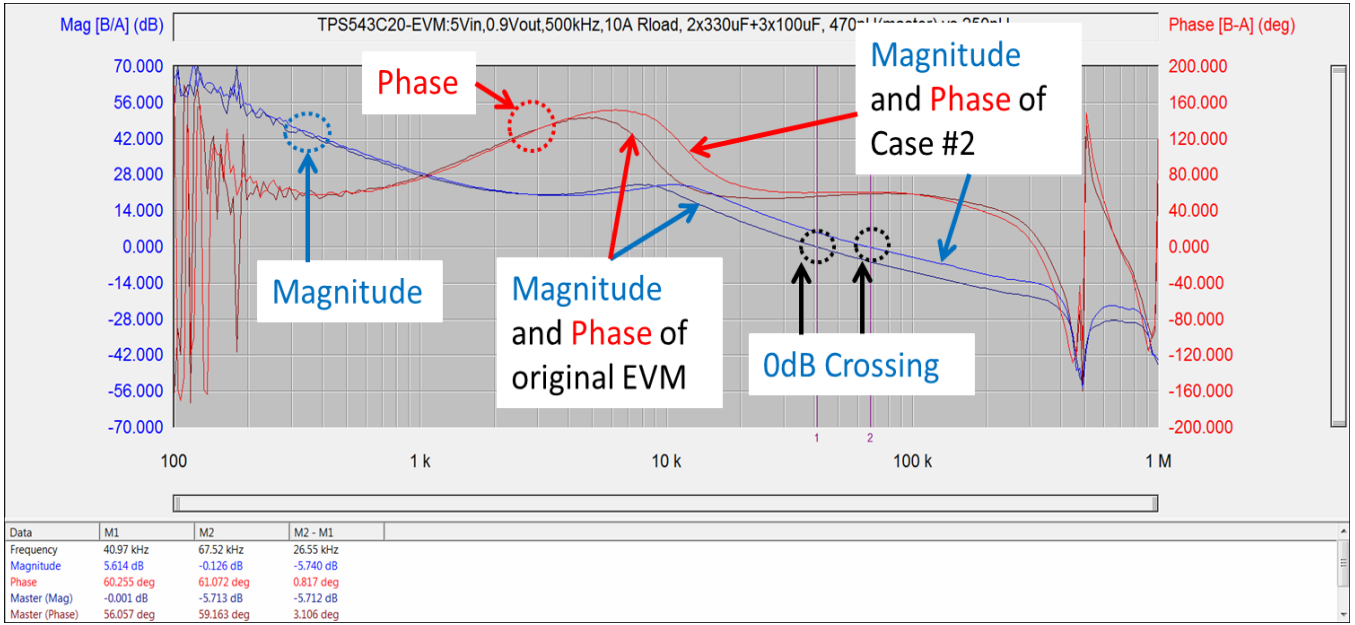


Original Configuration: L=470nH, Cout=2x330uF + 3x100uF

Case 1 Configuration: L=470nH, Cout=**1**x330uF + 3x100uF

ACM's Constant Phase Character

5Vin, 0.9Vout, 500kHz, 10A Load: 1/2 Output Inductor Reduction

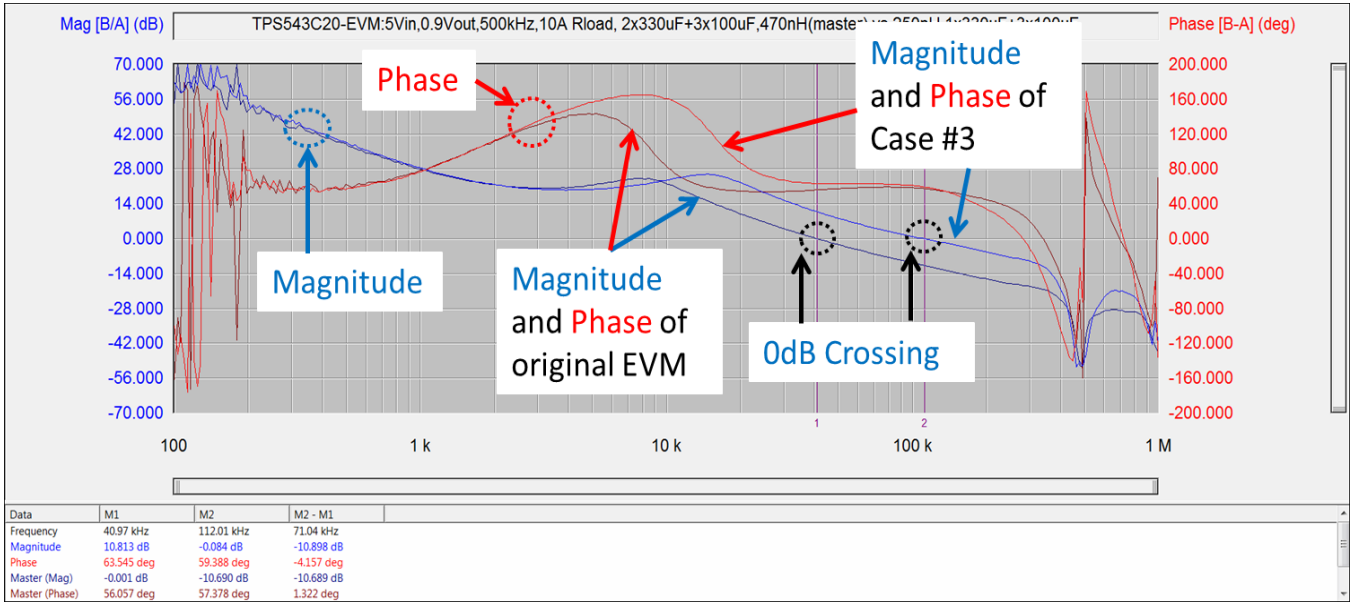


Original Configuration: L=470nH, Cout=2x330uF + 3x100uF

Case 2 Configuration: **L=250nH**, Cout=2x330uF + 3x100uF

ACM's Constant Phase Character

5Vin, 0.9Vout, 500kHz, 10A Load: 1/2 Output Inductor and 1/3 Cout Reduction



Original Configuration: L=470nH, Cout=2x330uF + 3x100uF

Case 3 Configuration: **L=250nH**, Cout=**1**x330uF + 3x100uF

TPS543C20 Overview and Comparison

TPS543C20

4.0Vin to 16Vin, 40A Stackable, Fixed-Fsw Synchronous Step-Down SWIFT™ Converter

NEW!

Features

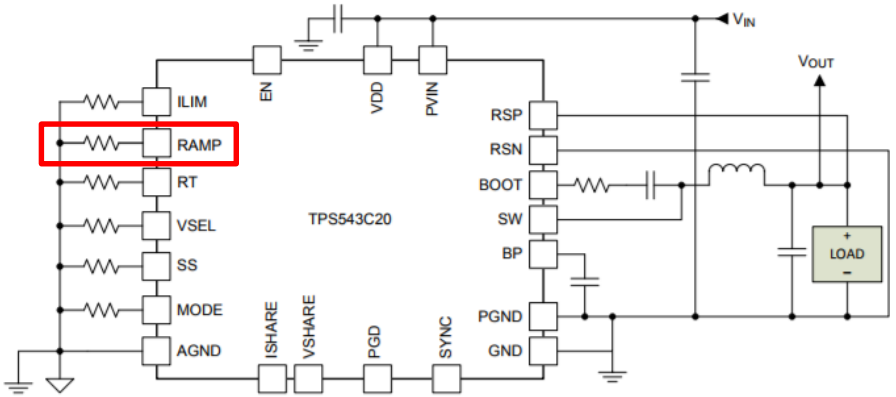
- Output Voltage Range 0.6V to 5.5V
- **Advanced Current Mode (ACM) True Fixed Frequency with CLK Synchronization**
- Low Rdson: ~**3.0/0.9mΩ**;
- **2-phase stackable** with Ishare, Vshare, Fsync
- **Fully Differential Remote Voltage Sense**
- 10 Vref choices: 0.6V; 0.7 to 1.1V in 50mV steps
- 10 SS choices: 0.5, 1, 2, 4, 5, 8, 12, 16, 24, 32ms
- Adj. Fsw: 300Khz to 2MHz (1Ph) /1MHz (2+ Ph)
- **High accuracy Over Current Limit (Hiccup I-lim)**
- **Asynchronous Pulse Injection (API) / Body Braking**
- 5x7x1.5mm, 0.5mm pitch 40 pin Stacked Clip QFN

Applications

- Communications RRU, Switches, Routers
- Enterprise Computing, Servers, Datacom
- ASIC, SoC, FPGA, DSP core and I/O Voltage Rails
- High-Power Programmable Logic Controllers

Benefits

- Fixed Frequency with No External Compensation for a wide range of switching frequencies
- 90+% efficiency over a wide load range
- Up to 80A POL needs with flexible sync positions
- +/-0.5% setpoint accuracy over temperature
- High accuracy for multiple Vout
- Optimize for efficiency or BOM size by adjusting frequency
- +/-10% I-lim Accuracy over temp & process
- Option to better manage undershoot/ overshoot



TPS543B20

4.0Vin to 18Vin, 25A Stackable, Fixed-Fsw Synchronous Step-Down SWIFT™ Converter

NEW!

Features

- Output Voltage Range 0.6V to 5.5V
- **Advanced Current Mode (ACM) True Fixed Frequency with CLK Synchronization**
- Low Rdson: ~**4.1/1.9mΩ**;
- **2-phase stackable** with Ishare, Vshare, Fsync
- **Fully Differential Remote Voltage Sense**
- 10 Vref choices: 0.6V; 0.7 to 1.1V in 50mV steps
- 10 SS choices: 0.5, 1, 2, 4, 5, 8, 12, 16, 24, 32ms
- Adj. Fsw: 300Khz to 2MHz (1Ph) /1MHz (2+ Ph)
- **High accuracy Over Current Limit (Hiccup I-lim)**
- **Asynchronous Pulse Injection (API) / Body Braking**
- 5x7x1.5mm, 0.5mm pitch 40 pin Stacked Clip QFN

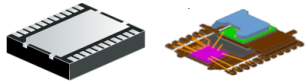
Applications

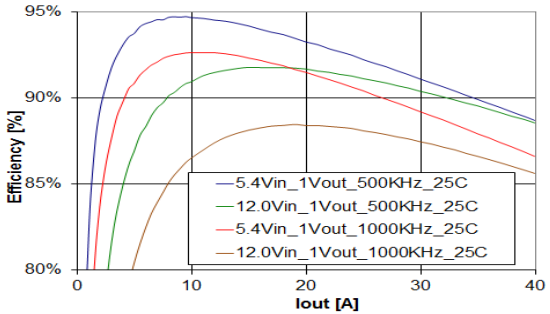
- Communications RRU, Switches, Routers
- Enterprise Computing, Servers, Datacom
- ASIC, SoC, FPGA, DSP core and I/O Voltage Rails
- High-Power Programmable Logic Controllers

Benefits

- Fixed Frequency with No External Compensation for a wide range of switching frequencies
- 90+% efficiency over a wide load range
- Up to 80A POL needs with flexible sync positions
- +/-0.5% setpoint accuracy over temperature
- High accuracy for multiple Vout
- Optimize for efficiency or BOM size by adjusting frequency
- +/-10% I-lim Accuracy over temp & process
- Option to better manage undershoot/ overshoot

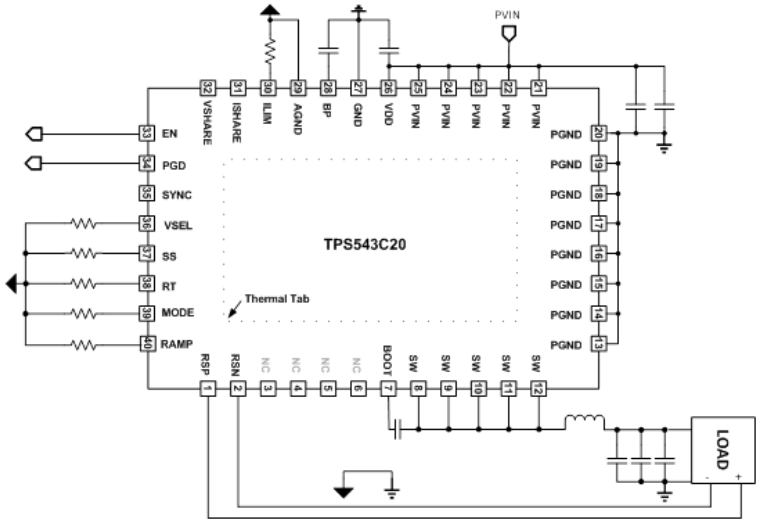
(2-phase stackable)





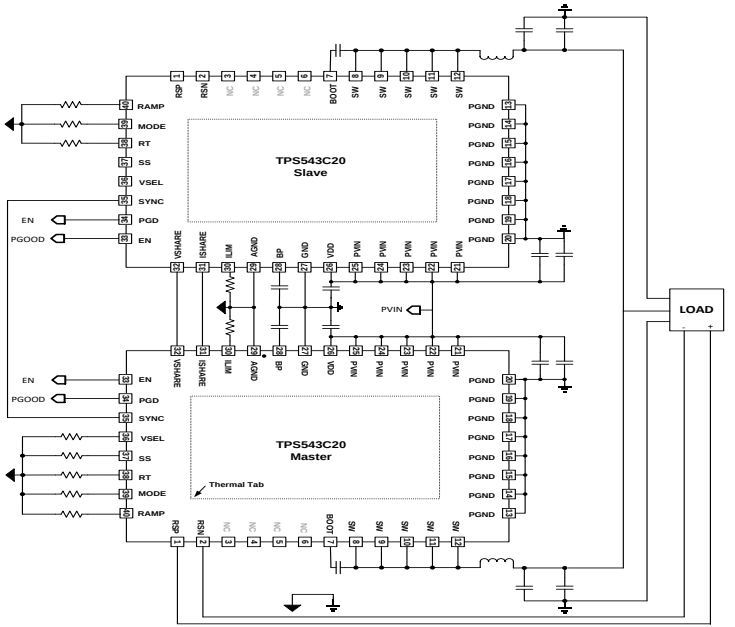
Simplified Application Schematic

Stand-alone Configuration



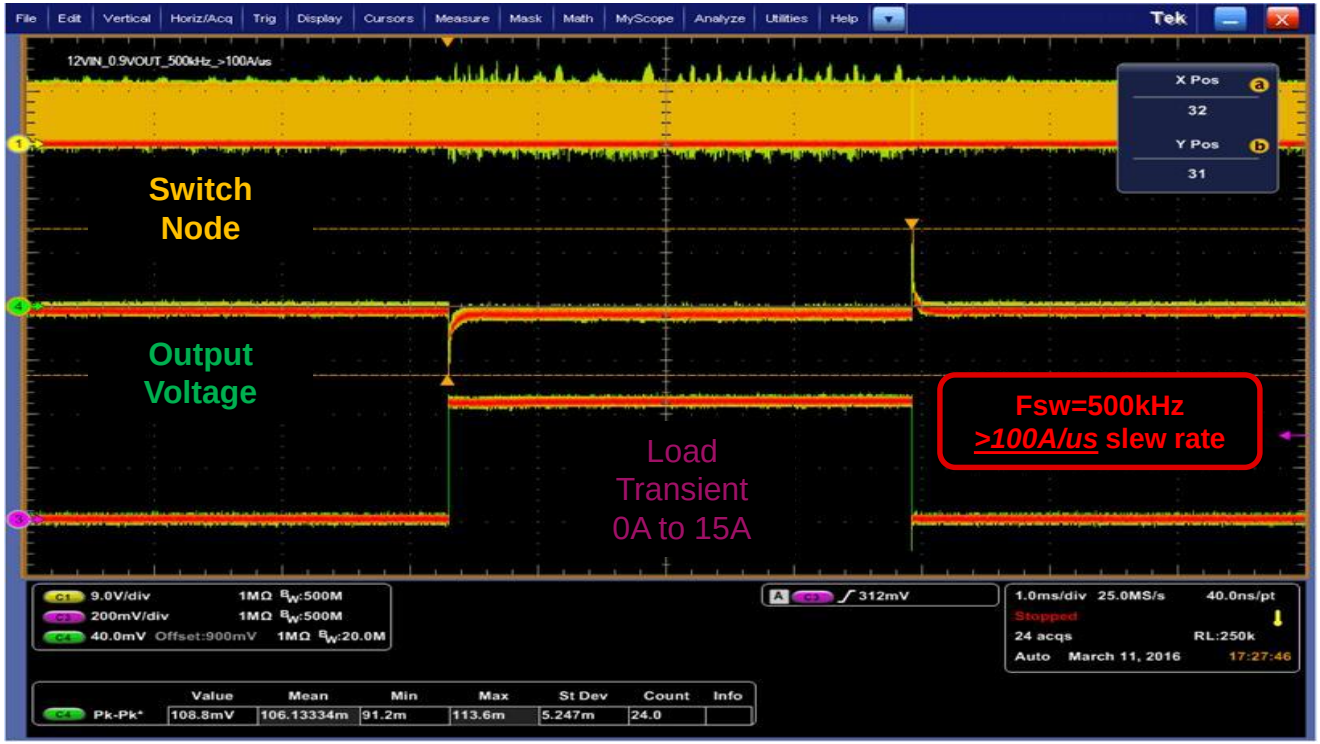
- No external compensation, Ramp pin sets internal compensation
- Adjustable Vref, SS, OC, Fsw by pin-strapping

Stackable Configuration



- Two phase interleaving, reduce input/output filters
- Layout friendly for two devices
- Pin-strap only programed on Master

Fast Load Transient Response



High Switching Frequency Operation

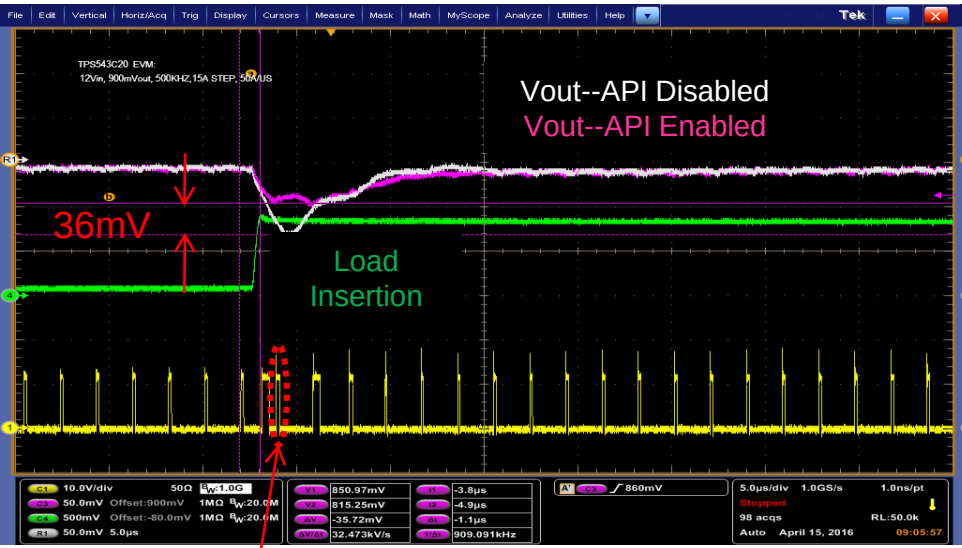
12Vin, 0.9Vout, 20A load, **2M**Hz switching frequency

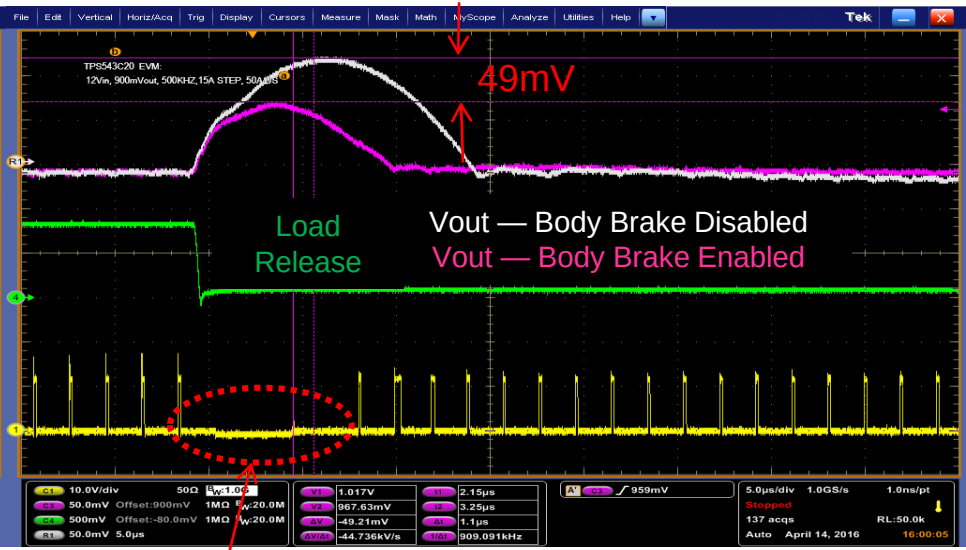
37.5ns Ton

Very Small Switching Jitter

Asynchronous Pulse Injection and Body Brake

Further Improving Transient Performance





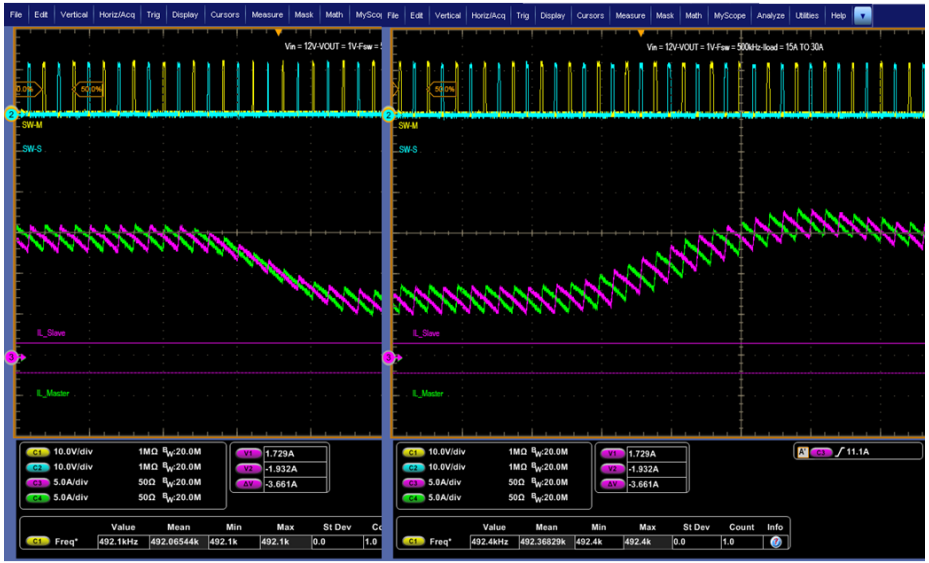
API—Undershoot Reduction

Body Brake—Overshoot Reduction

Current Balancing in a Stackable Application

12Vin, 0.9Vout, 40A load, 500kHz switching frequency

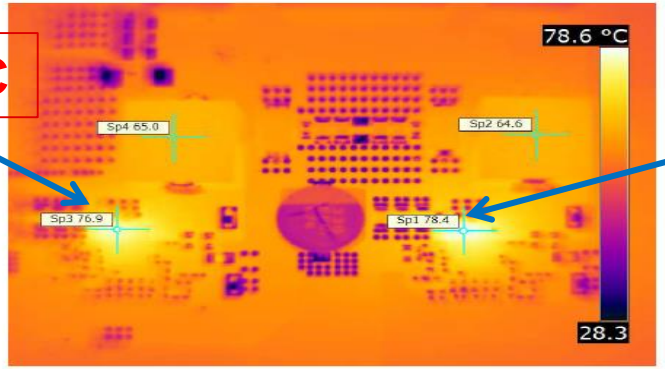
Current balance during steady state



Current balance during transient

2-Phase Stackable Thermal: 275Watts Output

76.9 ^{0} C



78.4 ^{0} C

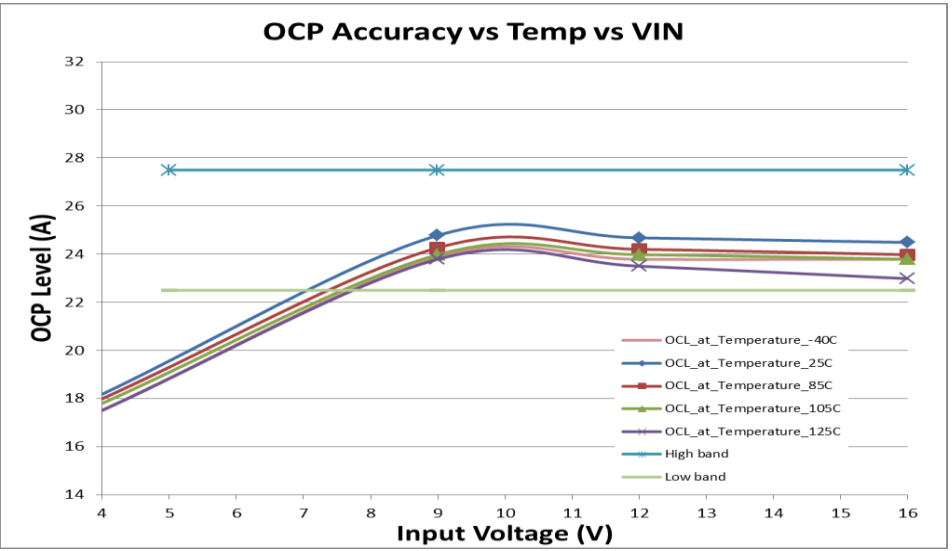
Image and Object Parameters	
Camera Model	FLIR T300
Image Date	11/9/2016 11:35:06 PM
Image Name	IR_0208.jpg
Emissivity	0.95
Reflected apparent temperature	20.0 °C
Object Distance	1.0 ft

Text Comments	
Sp1=IC1	78.4C
Sp2=Inductor1	64.6C
Sp3=IC2	76.9C
Sp4=Inductor2	65C

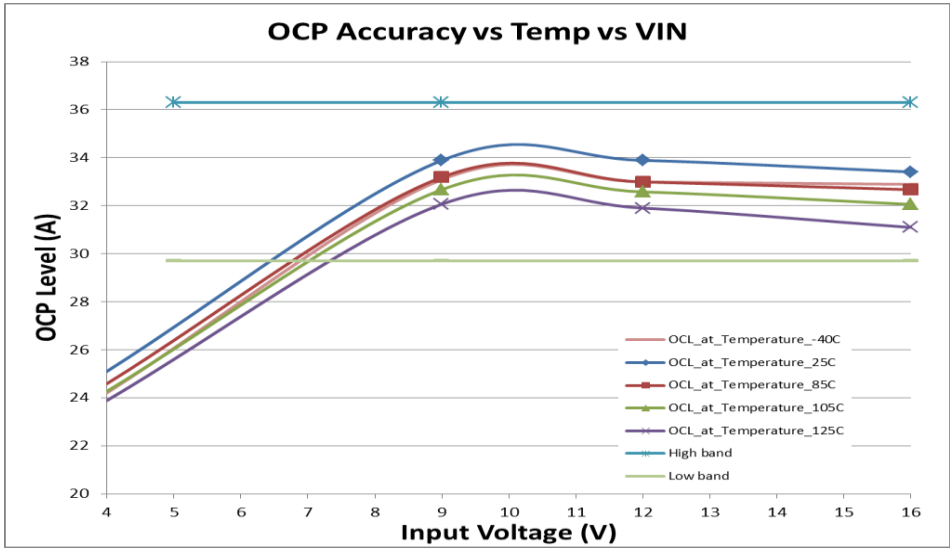
Description
Vin=12V, Vout=5V, Iout=55A, Fsw=500kHz, Ta=room

TPS543C20 Over Current Protection Accuracy

Tight current limit accuracy over temperature



24A Load Accuracy



33A Load Accuracy

Control Mode Comparison

TPS548D22

Overview

- V_{IN} 4.5 – 16V
- I_{OUT} 40A
- Rdson: 2.9-mΩ/1.2-mΩ
- FSW: 425/50/875/1050kHz
- Control Mode: D-CAP3™

Advantages

- No external compensation required
- Fast transient response

Disadvantages

- Frequency jitter
- Limited V_{OUT} range: 0.6 – 5.5V

Applications

- **Enterprise and Server**
  where there are fewer noise-sensitive analog components
- Low voltage processors that need **high accuracy** and **fast load transients**.

TPS543C20

Overview

- V_{IN} 4 – 14V
- I_{OUT} 40A
- Rdson: 3.0-mΩ/0.9-mΩ
- FSW: 300kHz – 2MHz
- Control Mode: ACM with Sync

Advantages

- Fast transient response
- Low jitter fixed frequency operation
- No external compensation required

Disadvantages

- Limited V_{OUT} range: 0.6 – 5.5V

Applications

- **Communications and Industrial** applications where many signal chain devices are used.
- **Enterprise and Server**
  high power density and fast transient

Competitive Voltage Mode

Overview

- V_{IN}: 5 – 21V
- I_{OUT}: 35A
- Rdson: 3.1-mΩ/1.27-mΩ
- FSW: 300kHz to 1.5MHz
- Control Mode: VM w/ VIN Feedforward

Advantages

- Low jitter fixed frequency operation
- Control loop is tunable adding flexibility for filter components
- Supports higher duty cycles

Disadvantages

- Lack of remote sense
- Requires external compensation

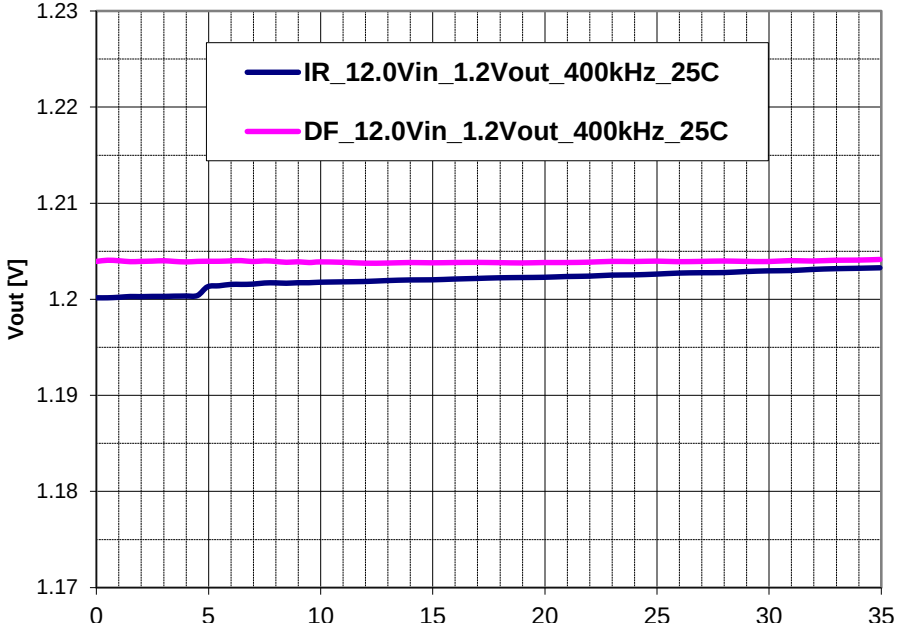
Applications

- **Communications and Industrial** applications where many signal chain devices are used.

TPS543C20 vs Competitive VM Comparison

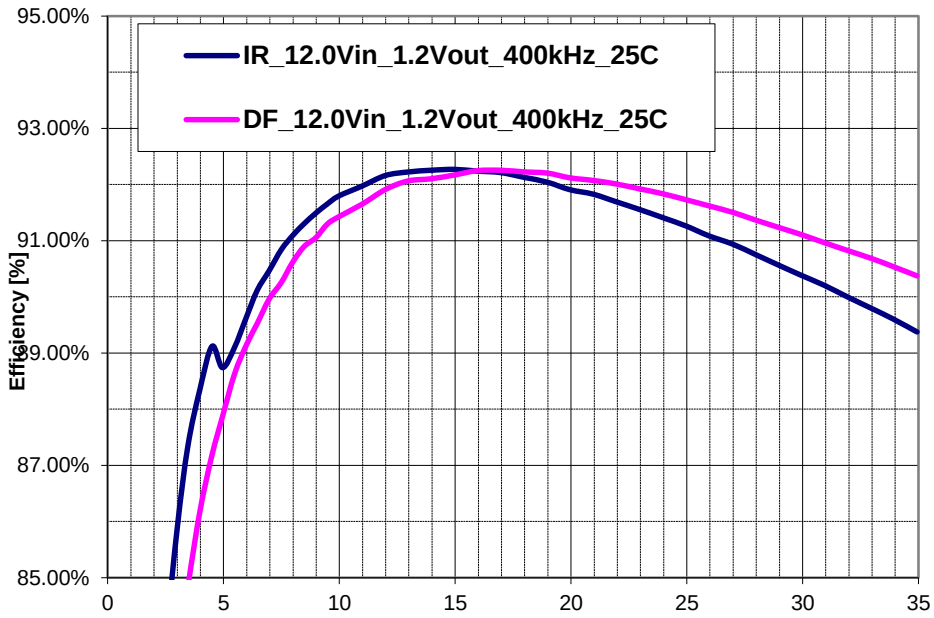
DC Performance: L=470nH, Cout=6x100uF

Load Regulation Performance



IR3846 doesn't have remote sense

Efficiency Performance

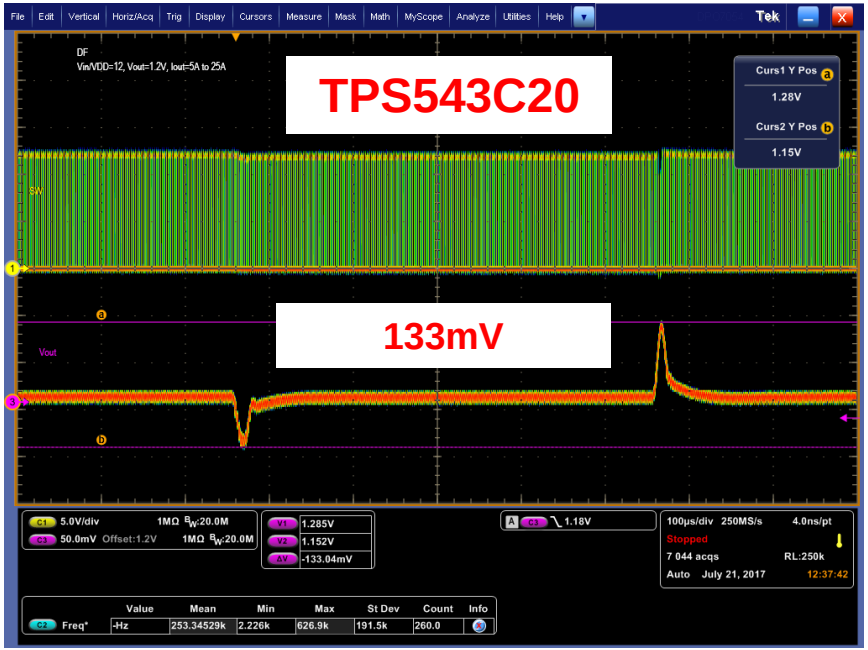


TPS543C20 has >1% higher efficiency at 35A
~0.4W

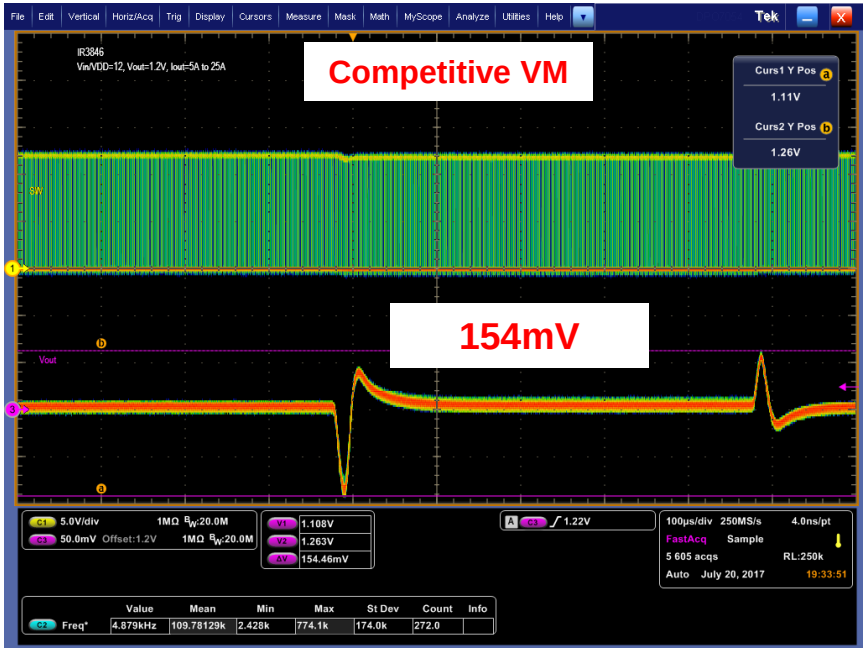
TPS543C20 vs IR3846 Comparison

Transient Performance

Vin=12V, Vout=1.2V, Fsw=400kHz, L=470nH, Cout=6x100uF, Iout=5A to 25A@2.5A/us

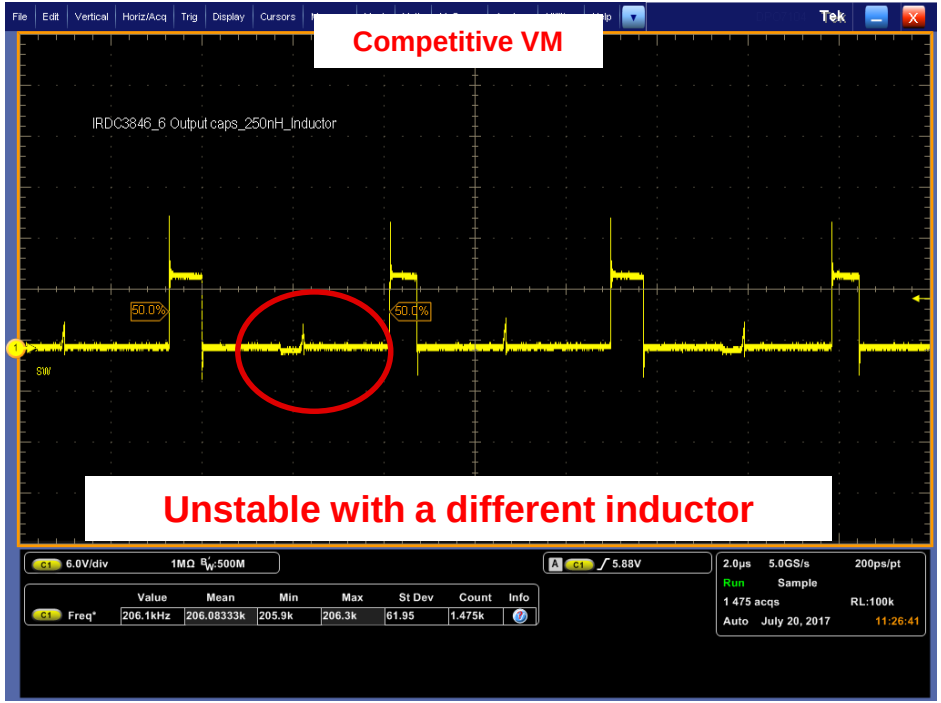


TPS543C20 only needs 1 resistor for internal compensation



Needs complicated TYPE III network

Low Tolerance on Components Variation



- The voltage mode controlled device showed instability when modifying the inductor from 470nH to 250nH. The compensation needs to be re-designed
- ACM tolerates design variations better without the need to change compensation

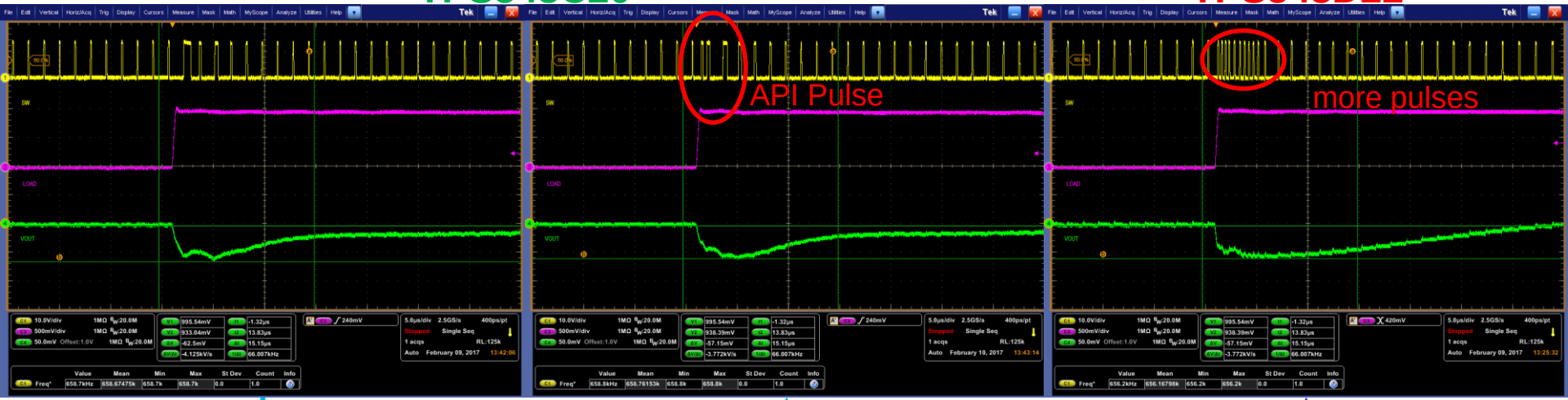
TPS543C20 vs TPS548D22 Comparison

Transient Performance—Undershoot

Vin=12V, Vout=1.2V, Fsw=650kHz, L=470nH, Cout=2x330uF+3x100uF, Iout=5A to 25A@50A/us

TPS543C20

TPS548D22



Without API: Undershoot = 62.5mV

With API: Undershoot = 57.2mV

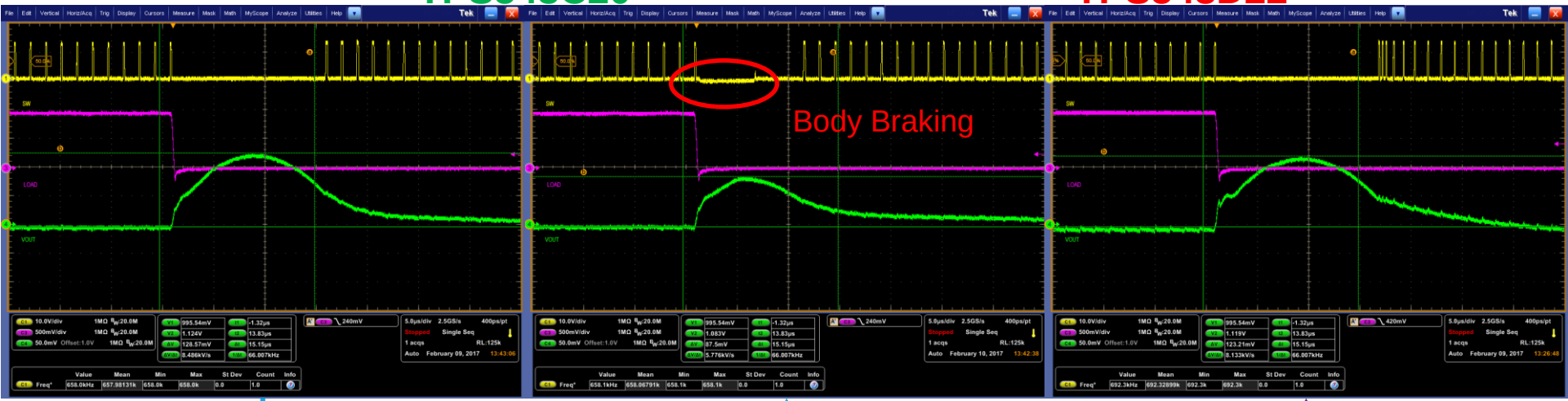
With API: Undershoot = 57.2mV

TPS543C20 vs TPS548D22 Comparison

Transient Performance—Overshoot

Vin=12V, Vout=1.2V, Fsw=650kHz, L=470nH, Cout=2x330uF+3x100uF, Iout=5A to 25A@50A/us

TPS543C20 | TPS548D22



Without API: Undershoot = 128.6mV

With API: Undershoot = 87.5mV

With API: Undershoot = 123mV

Summary

- ACM provides the fixed frequency advantage of Voltage Mode or Current Mode Control
- ACM does not need loop compensation, like constant on time or D-CAP converters
- ACM simulations compare well with actual lab measurements
- ACM will be used in future products from Texas Instruments to simplify a high performance point-of-load solution