Guidelines for Choosing the Right Buck Regulator Control Strategy (Part B)

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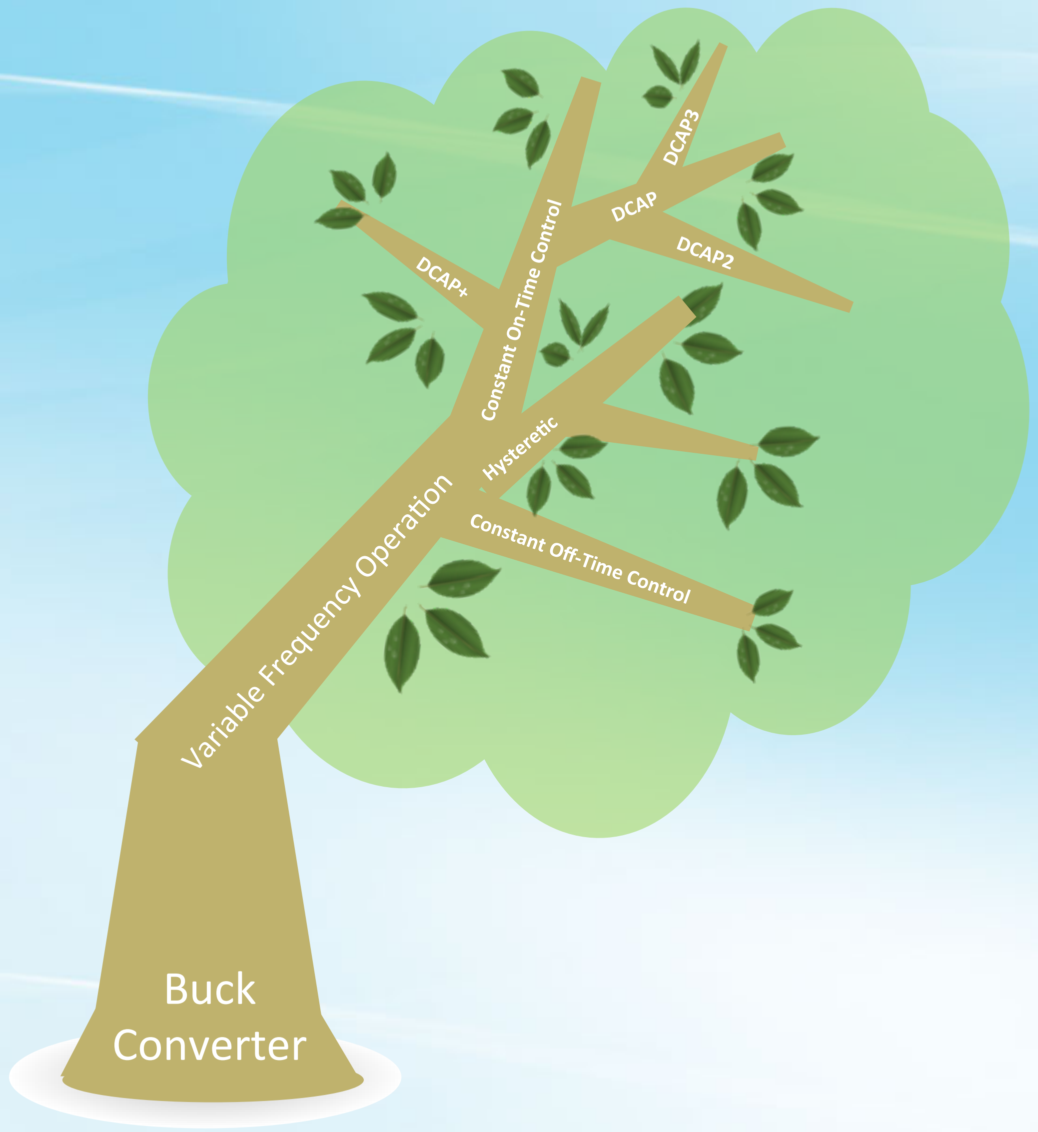
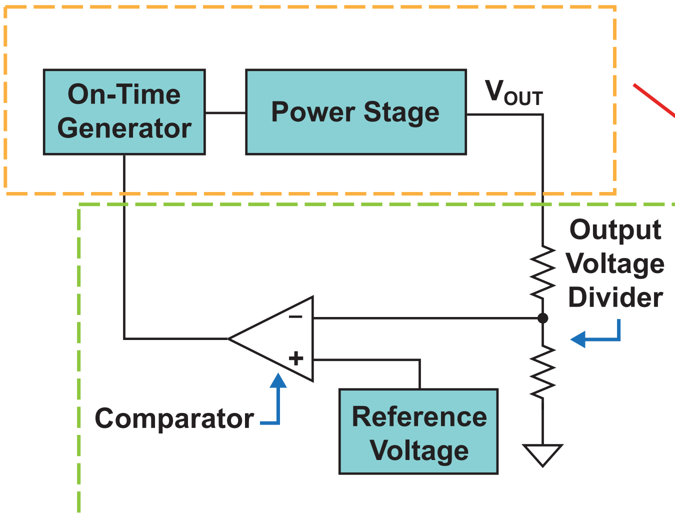
How Do You Choose?

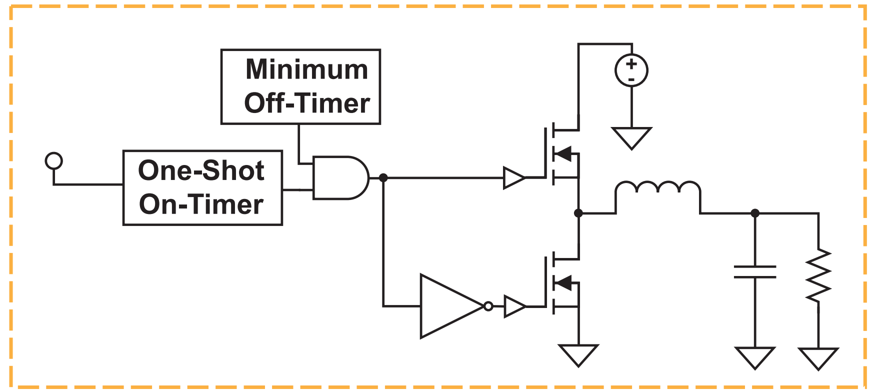
- **Part A**
  - Buck regulator basics
  - Fixed frequency control
- **Part B**
  - Variable frequency control
    - Constant on-time
    - Adaptive on-time
  - TI D-CAP™ families
    - D-CAP2™
    - D-CAP3™
    - D-CAP+™
  - Conclusions

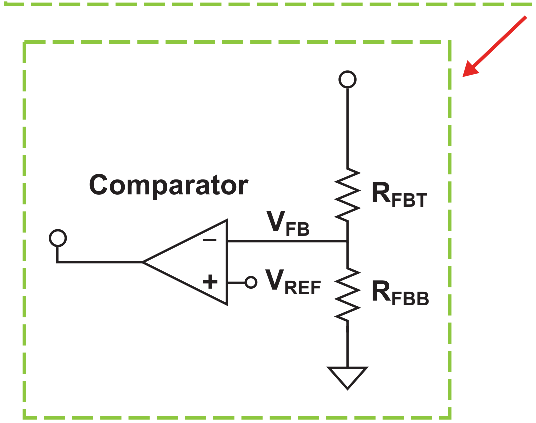
Variable Frequency Control



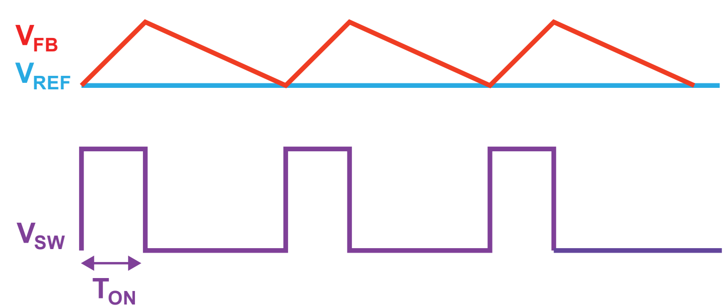
Constant On-Time Control – Basic Operation



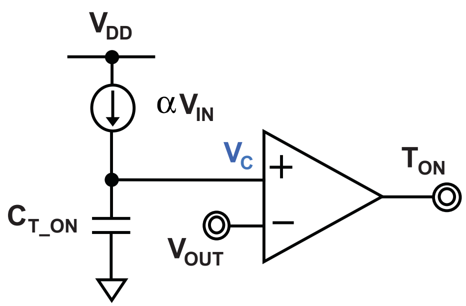


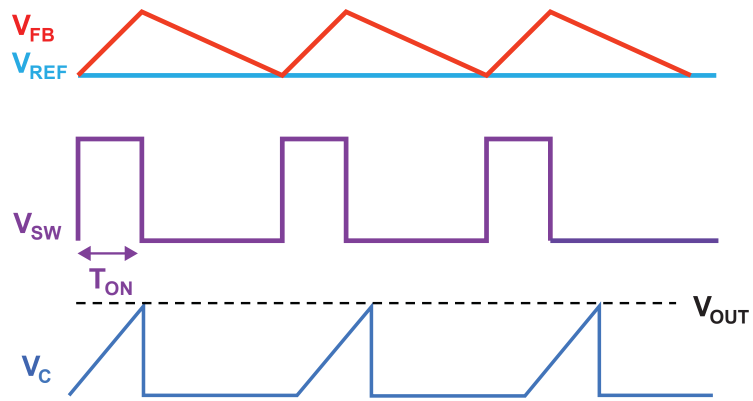


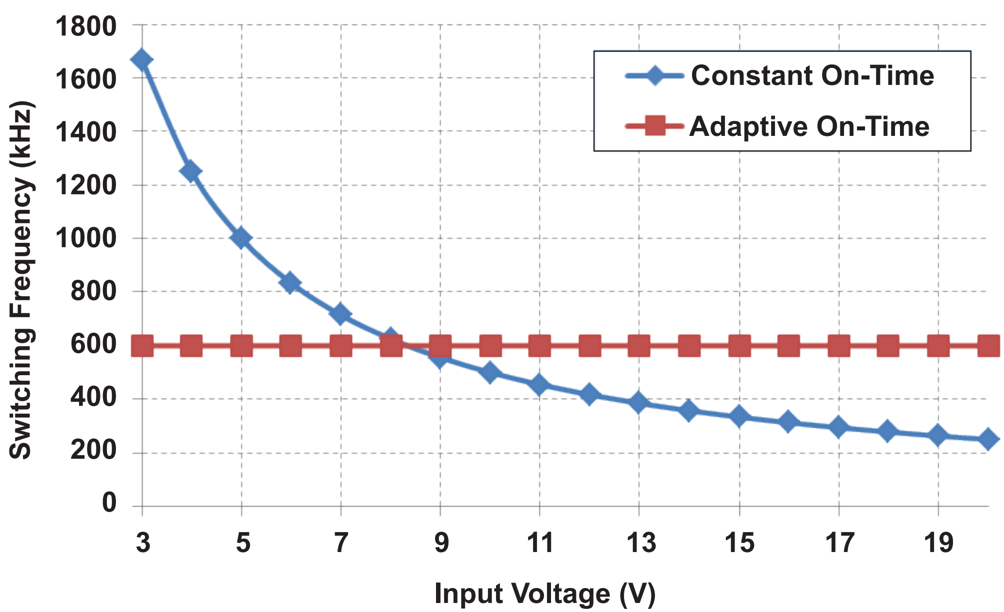
- Initiate fixed on-time when $V_{FB}<V_{REF}$
- On-time can be fixed or changed by input voltage



Adaptive On-Time Control – Frequency

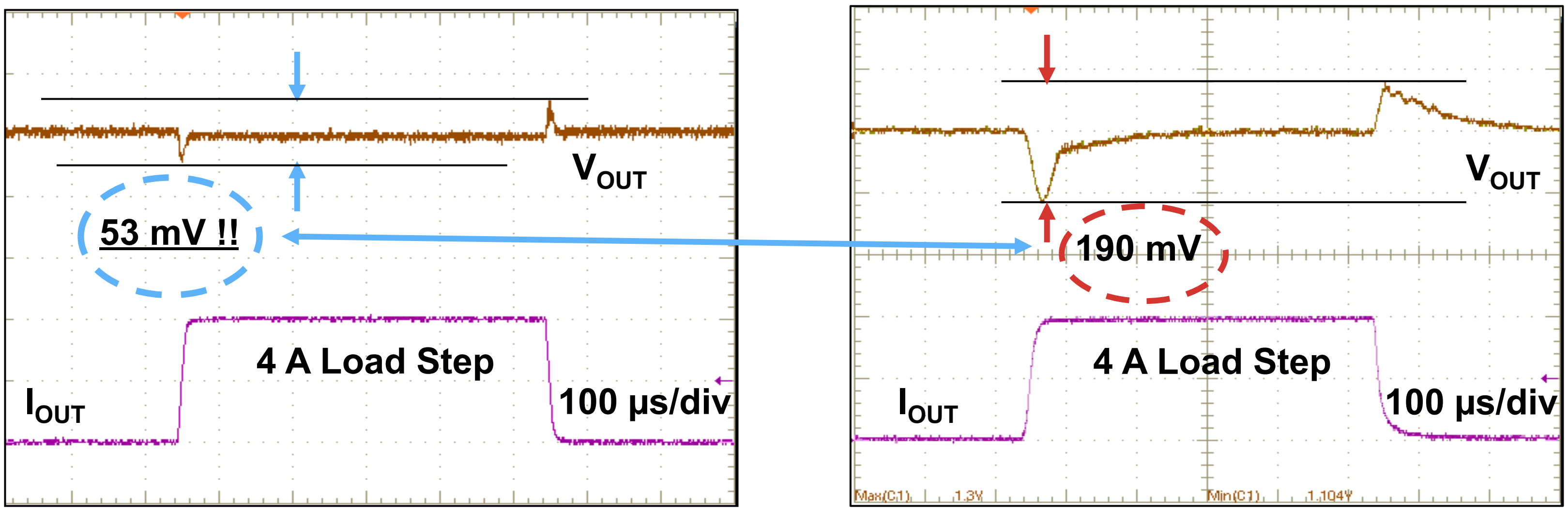






- Constant on-time has a fixed T_{ON}
- Adaptive on-time adjusts the T_{ON} based on the input voltage

COT Control – Transient Performance

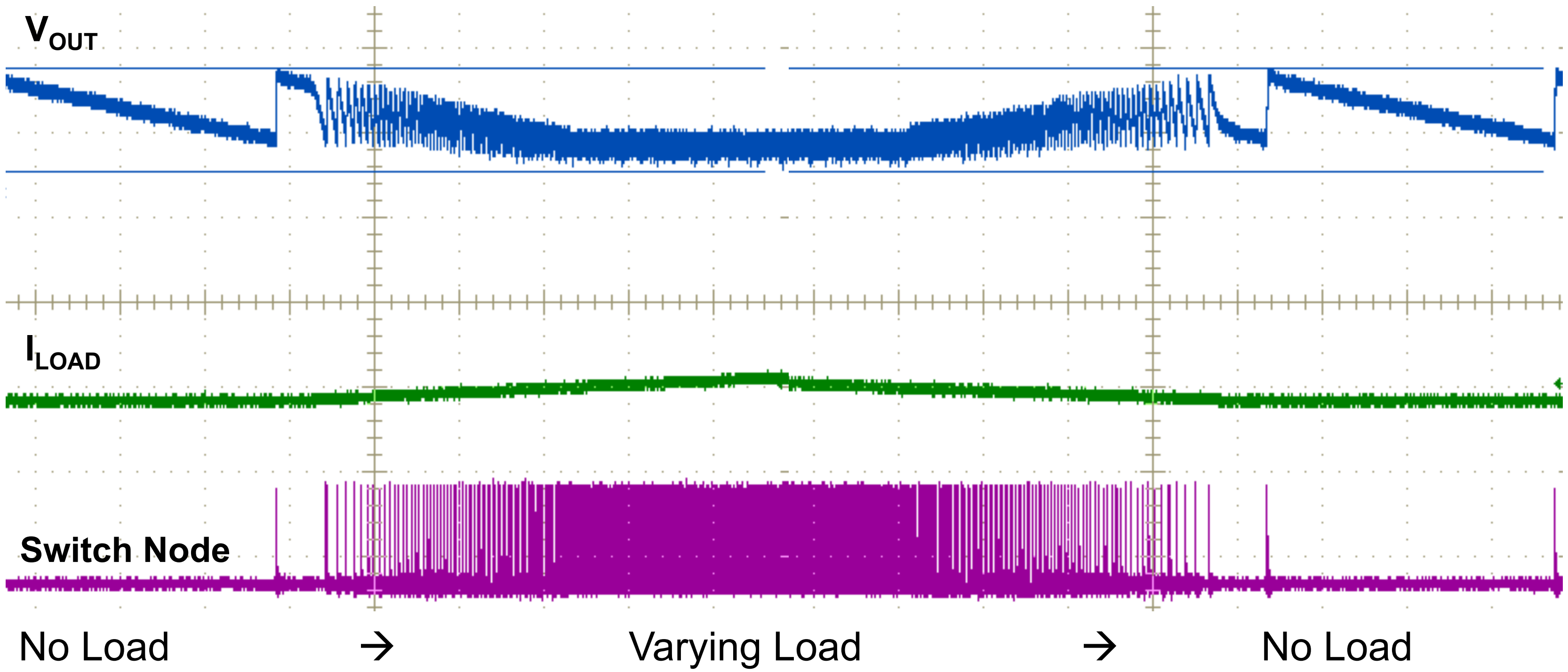


D-CAP™ Mode – Output Cap = 22 µFx3

Voltage Mode – Output Cap = 100 µFx4

- D-CAP™ mode: direct output capacitor voltage feedback
- D-CAP™ mode does not have an error amplifier or compensation

COT Control – Seamless DCM/CCM

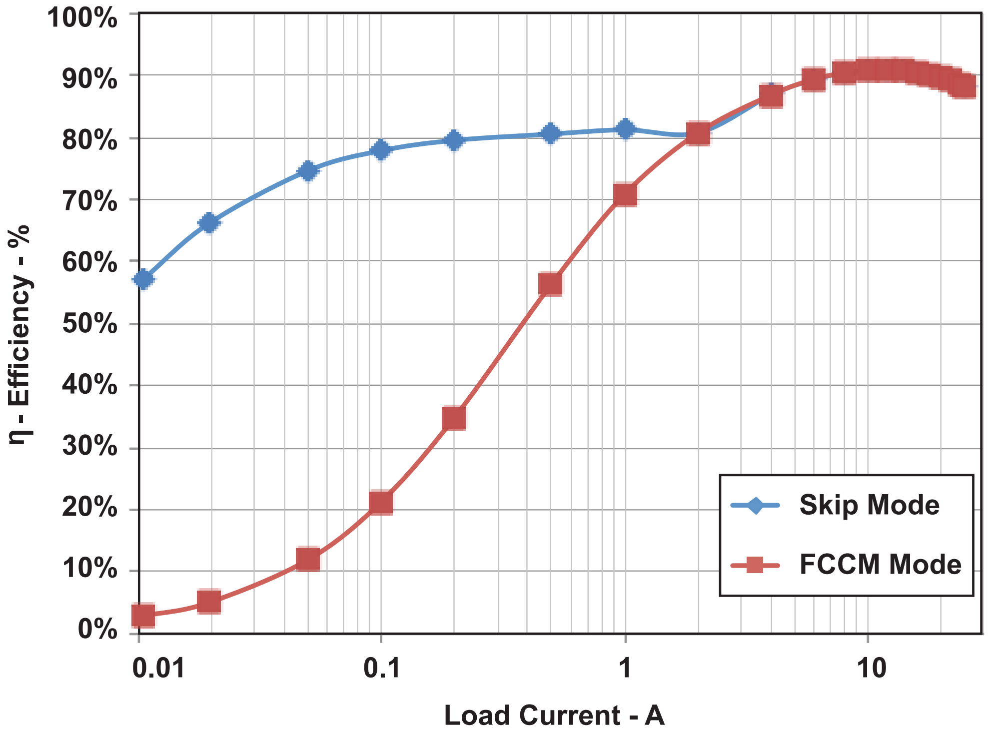


- The DCM/CCM transition is happening naturally without a mode change

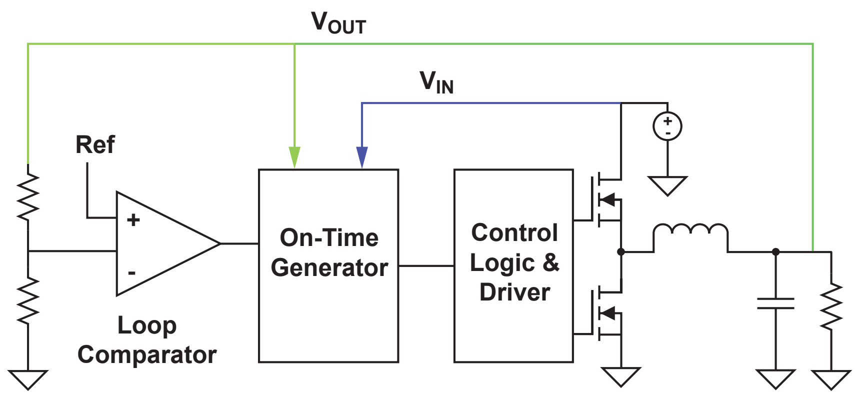
COT Control –
High Efficiency @ Light Loads

TPS53219 + CSD86350

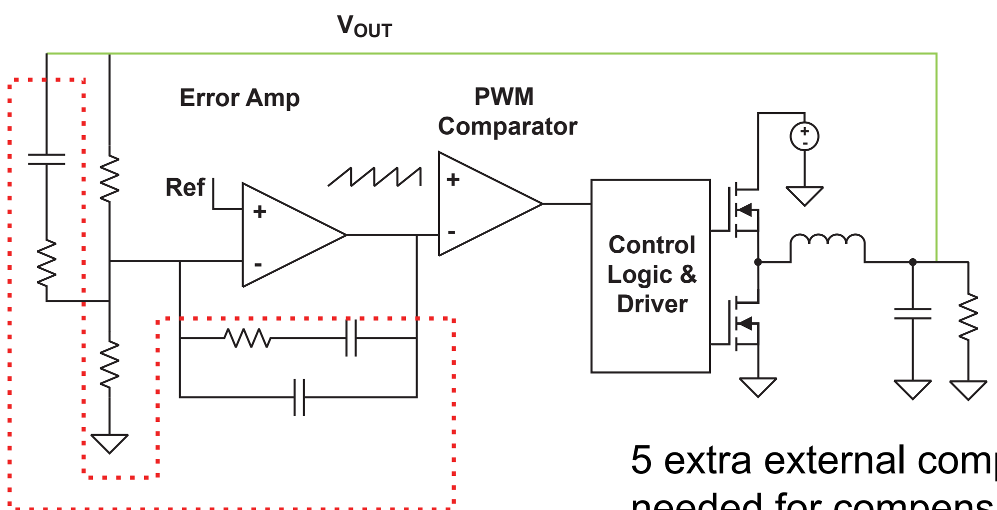
- Efficiency F_{SW} = 500 kHz, 12 V to 1.1 V
  - > 80% from 0.2 A to 25 A
  - > 55% efficiency in Skip mode at 10 mA



COT Control –
External Components



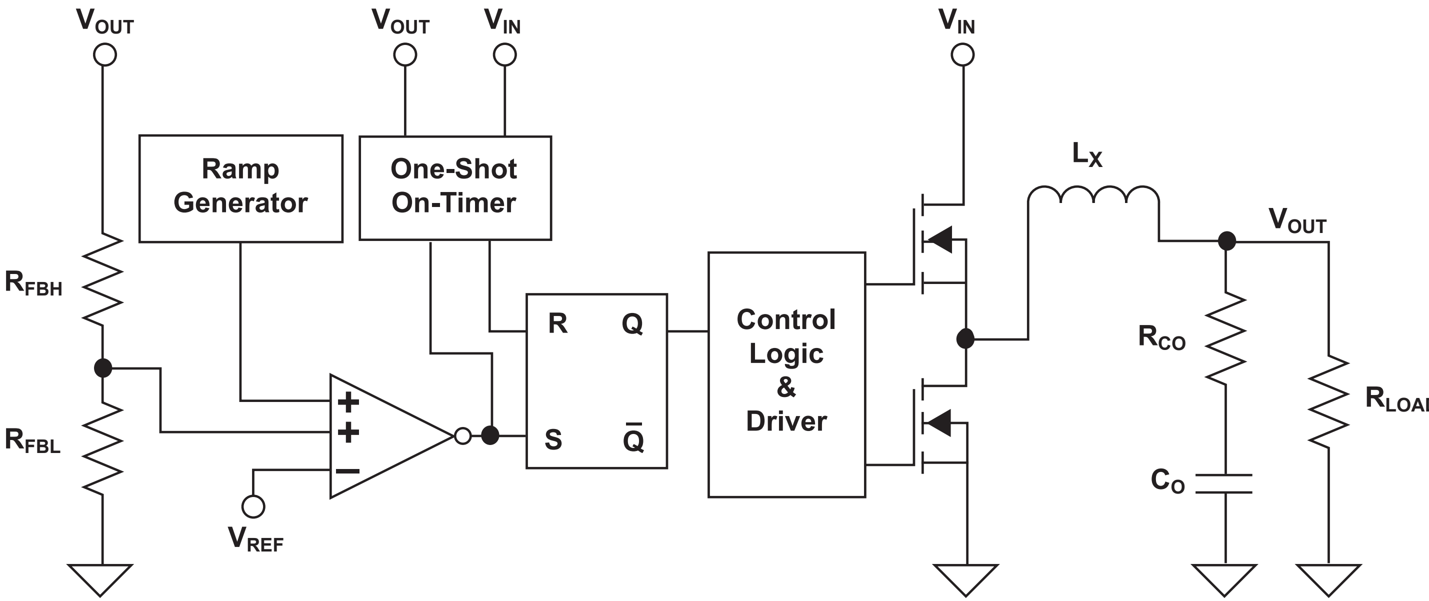
D-CAP™
Mode



Voltage
Mode

5 extra external components
needed for compensation!

TI D-CAP™ Control Architecture

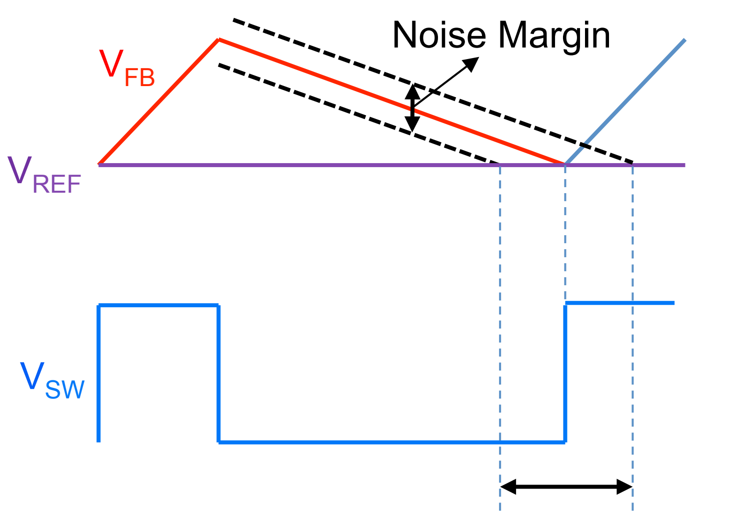


- Adaptive constant on-time $$T_{ON} = \frac{V_{OUT}}{V_{IN}} \times K$$
- Ramp is generated to improve the jitter performance

COT Control – Ramp Compensation

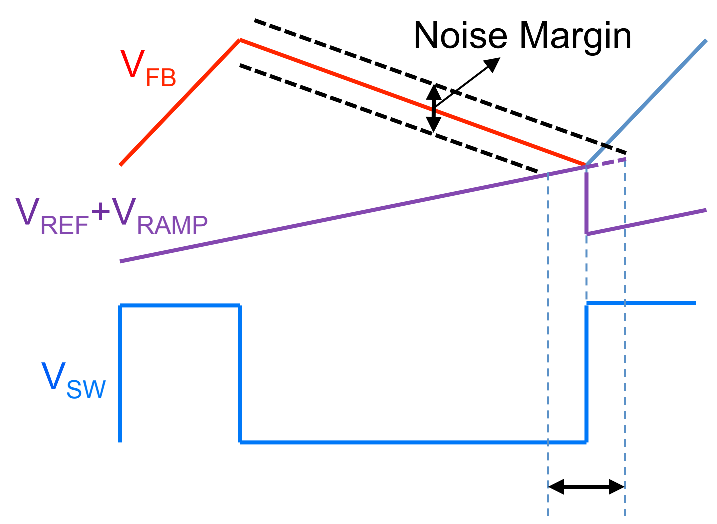
- Ramp compensation improves jitter performance by reducing the noise band
- Ramp compensation is built-in to most TI D-CAP controllers

No Ramp Compensation



T1 : Jitter Due to Noise

With Ramp Compensation

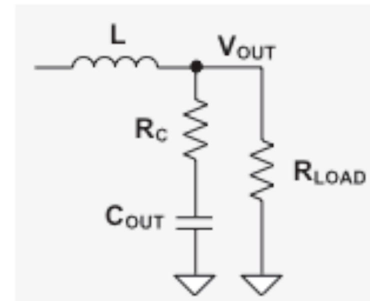


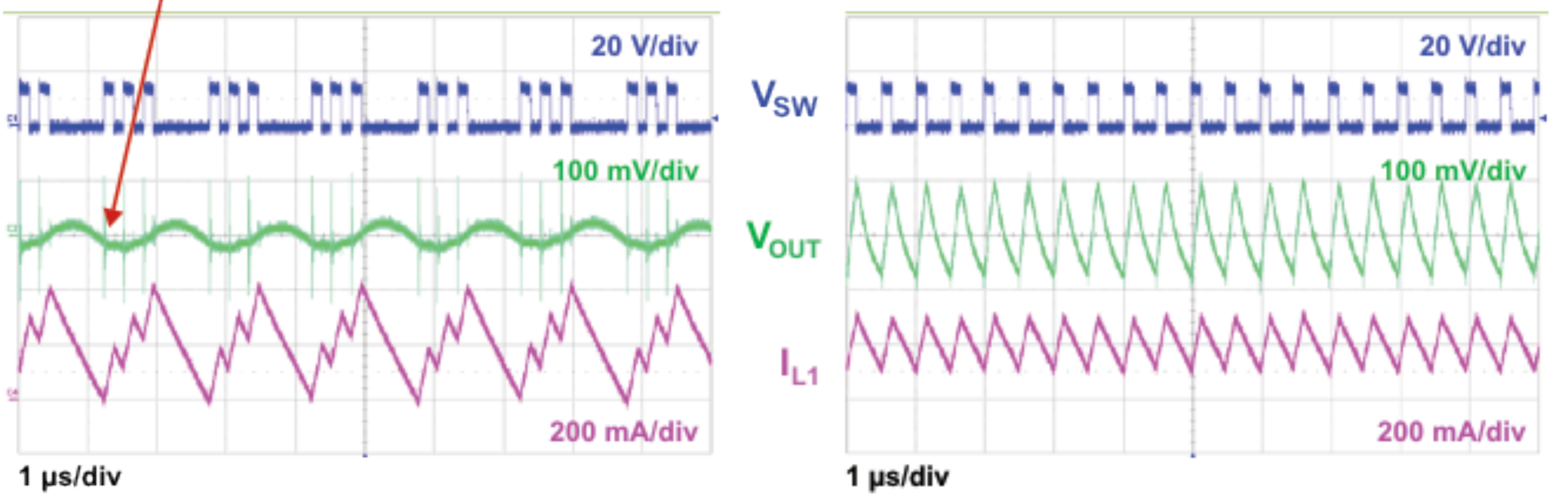
T2 : Jitter Due to Noise

TI D-CAP™ – Ripple Requirements

Feedback signal going down when it should be going up!!

$$\Delta V_{OUT} = \Delta I_L \times R_{Co} + \frac{\Delta I_L}{8 \times f_{SW} \times C_O} = V_{ESR} + V_C$$



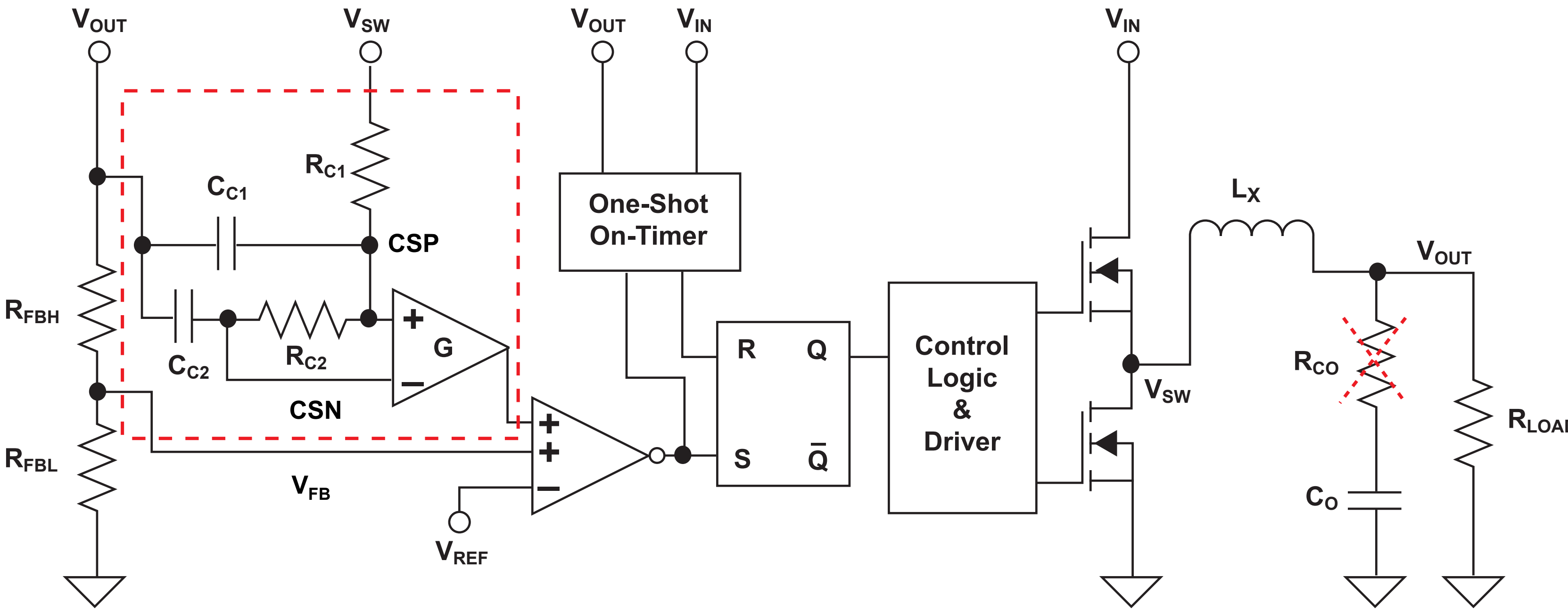


Without Series Resistor R_C **With Sufficient R_C**

TI D-CAP™ – Stability Measurement

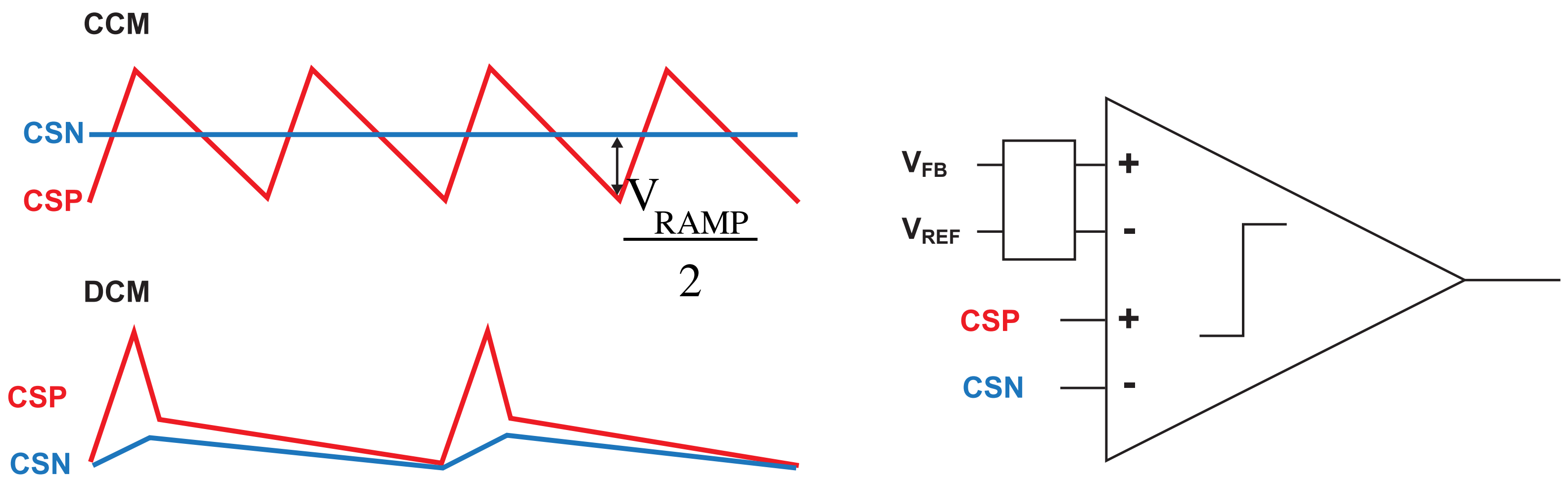
- Conventional open-loop Bode plot measurement is not applied to COT control architecture since output is directly fed back to PWM modulator
- Closed-loop frequency measurement used to indicate stability issue
- Due to inherent load feed-forward capability, bandwidth measured from small-signal analyses will not indicate large-signal load transient performance

TI D-CAP2™ Control Architecture



- Adaptive constant on-time $$T_{ON} = \frac{V_{OUT}}{V_{IN}} \times K$$
- Ripple injection is added to D-CAP2™
- This allows stability with low output ripple and ceramic output capacitors

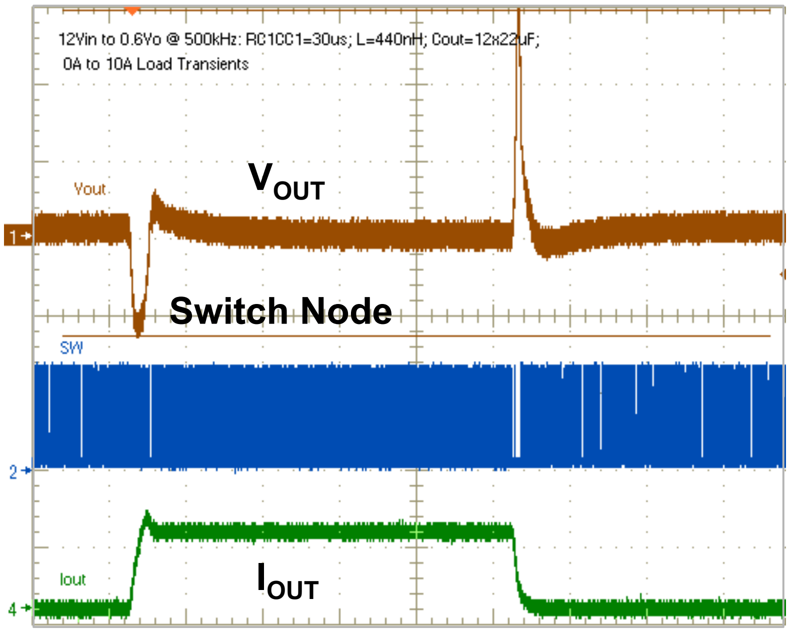
TI D-CAP2™ – Output Accuracy in DCM/CCM



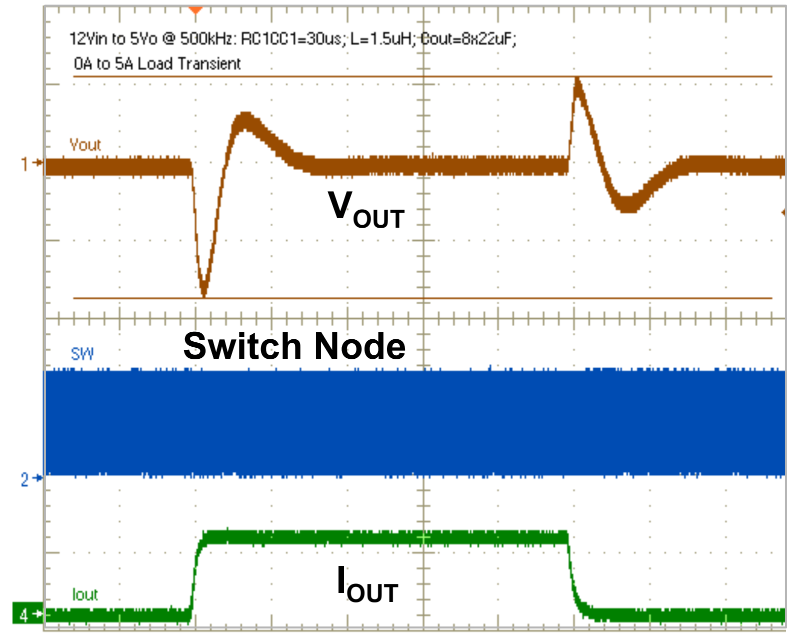
- Under CCM: $V_{FB} - V_{REF} \cong \frac{V_{RAMP}}{2}$
- Under deep DCM: $V_{FB} \cong V_{REF}$
- Offset is not constant in CCM and DCM

TI D-CAP2™ – Duty Cycle Dependency

12 V to 0.6 V

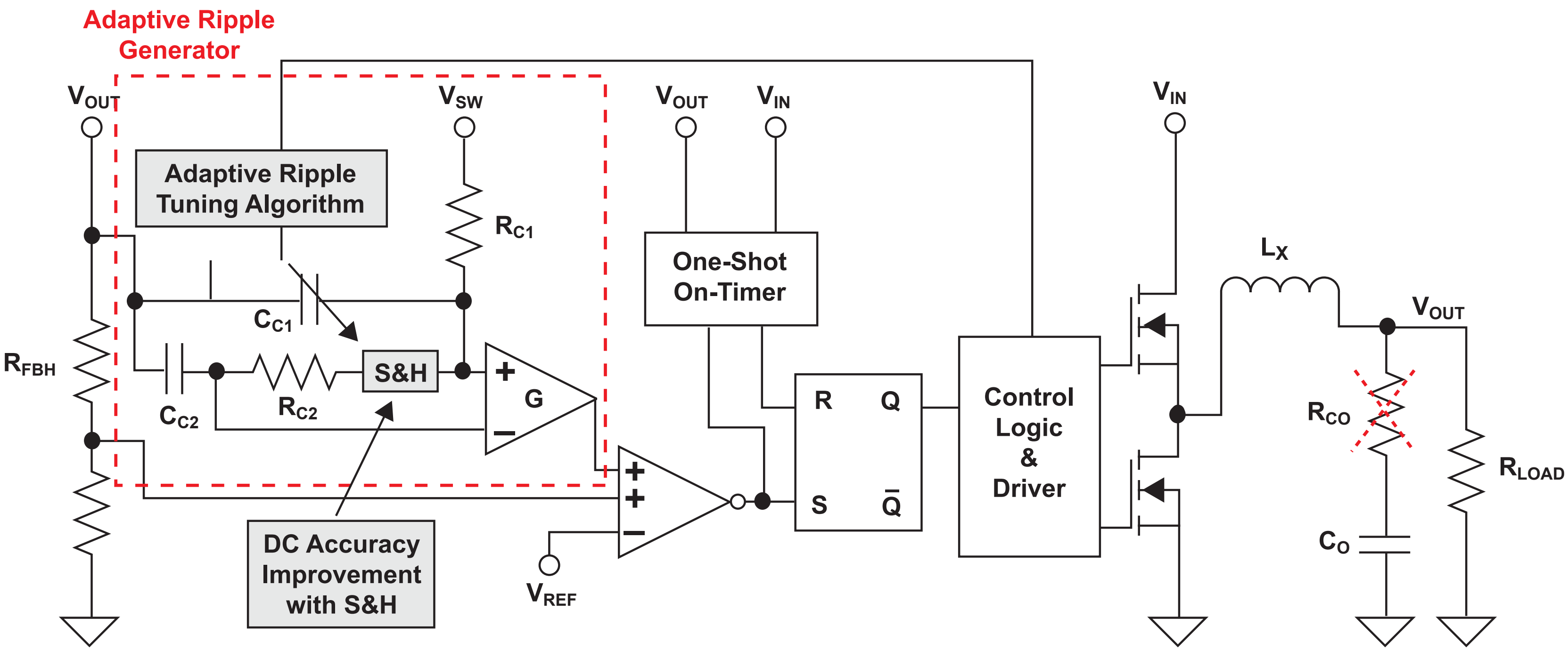


12 V to 5 V



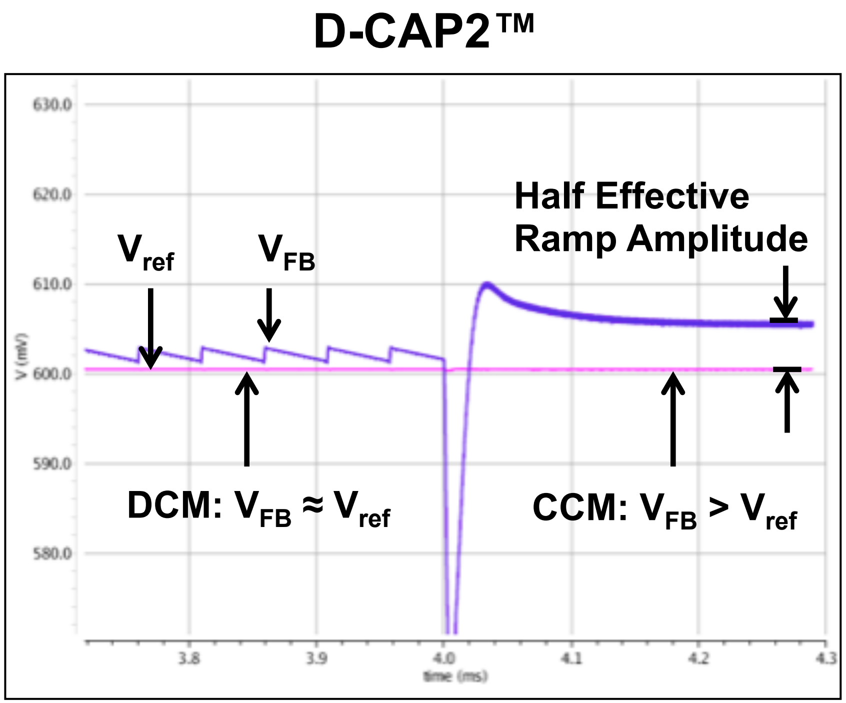
- Fixed $R_{C1}C_{C1}$ time constant = 30 µs for both outputs
- Transient performance is very different with different duty cycles

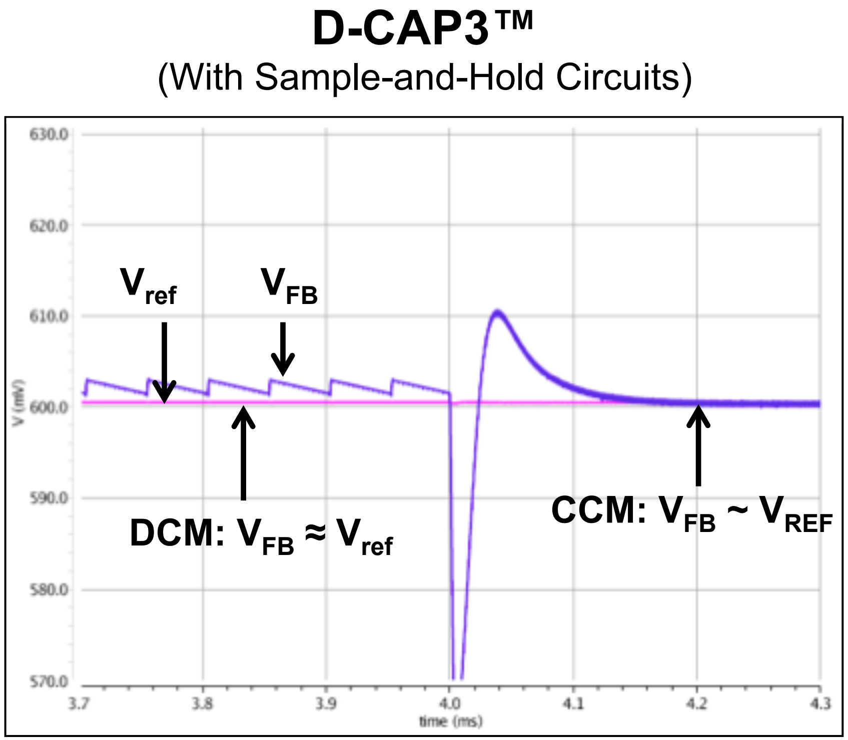
TI D-CAP3™ Control Architecture



- All of the benefits of D-CAP2™
- Adaptive ripple algorithm changes $R_{C1}C_{C1}$ time constant with V_{IN}, V_{OUT} and I_{OUT}
- Sample and hold circuit improves DC accuracy

TI D-CAP3™ – V_{OUT} Accuracy

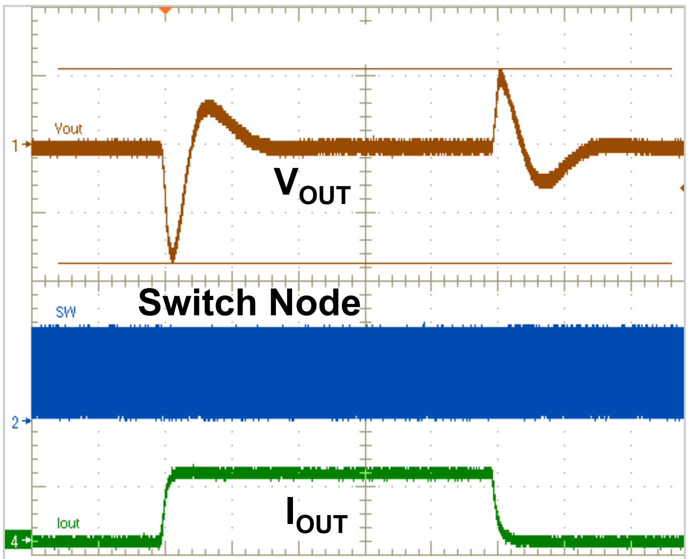




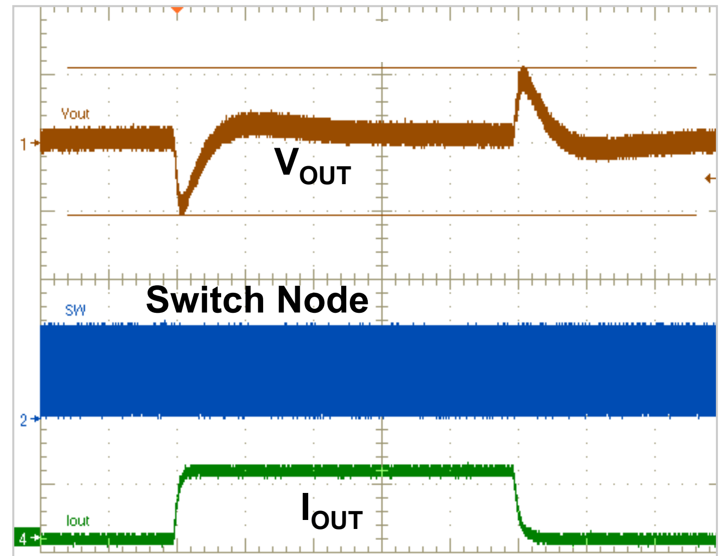
- DC accuracy is improved in CCM operation

TI D-CAP3™ – Adaptive Ripple Injection

D-CAP2™ 12 V to 5 V



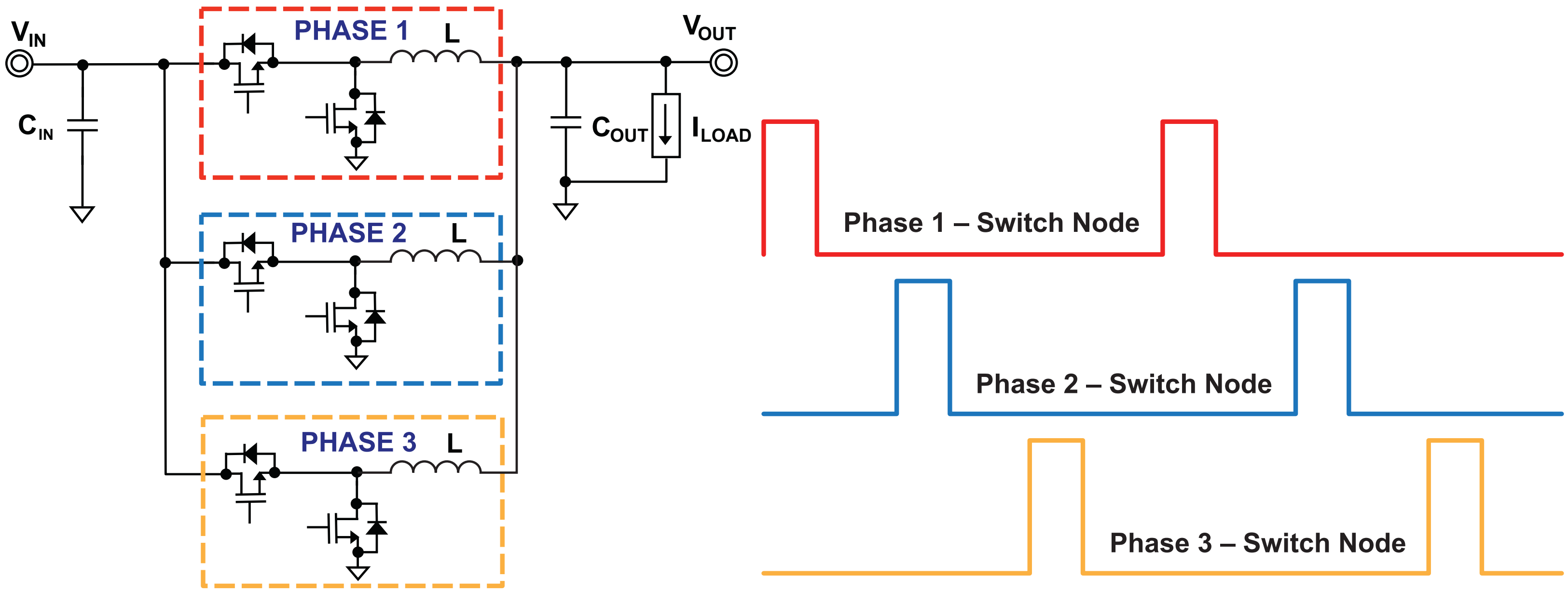
D-CAP3™ 12 V to 5V
(With Adaptive Ripple)



CH1 – Brown, 200 mV/Div **CH2 – Blue, 10 V/Div** **CH4 – Green, 5 A/Div**

- Time constant for D-CAP2™ = 30 µs
- Time constant for D-CAP3™ = 120 µs
- Adaptive ripple algorithm changes RC time constant with V_{IN}, V_{OUT} and I_{OUT}

Multiphase DC-DC Converter – Introduction

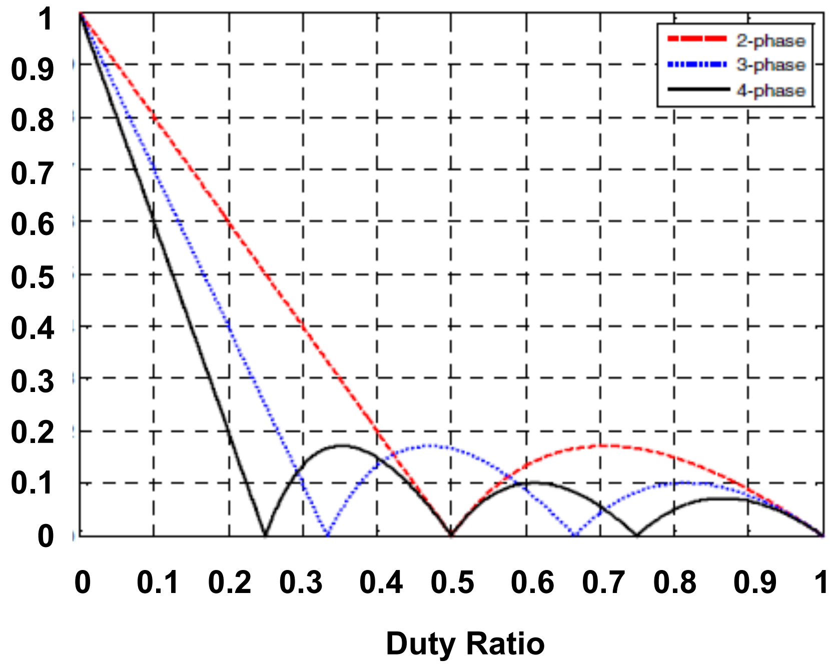


- Set of parallel converters
- Each power-stage is known as a ***phase***
- The phases operate equally spaced through the period

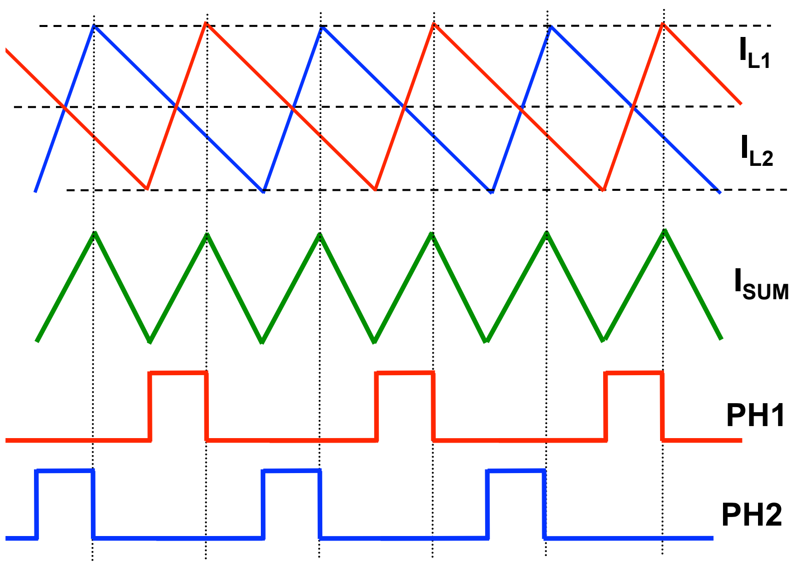
Multiphase DC-DC Converter – Output Ripple

Reduced output ripple current → Lower output capacitance to maintain same voltage ripple

Normalized Output Current Ripple

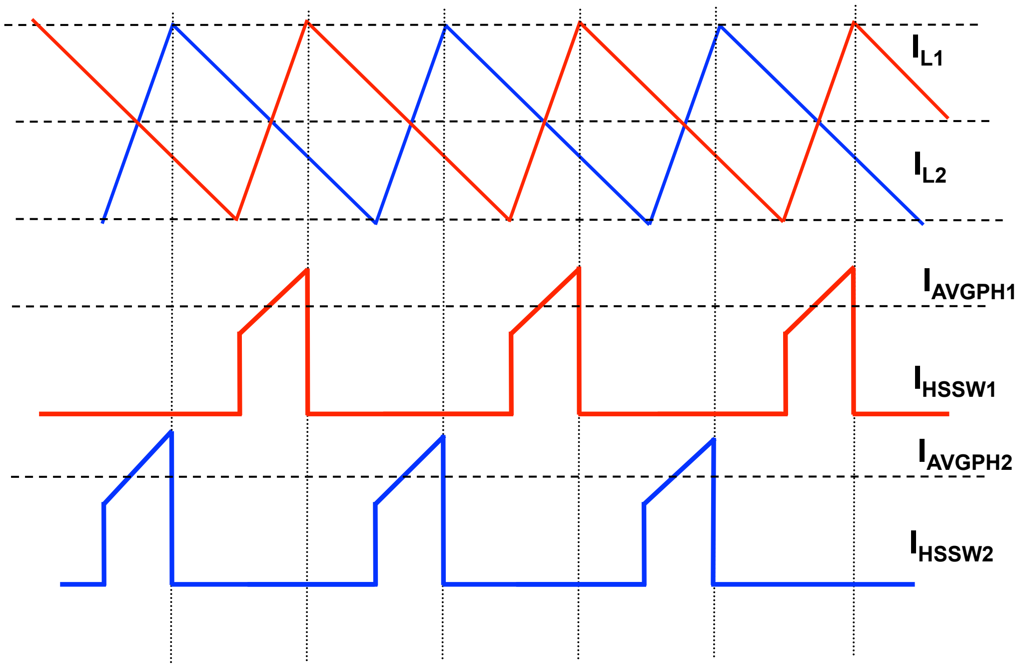


Example – Two-Phase System



Multiphase DC-DC Converter – Input Ripple

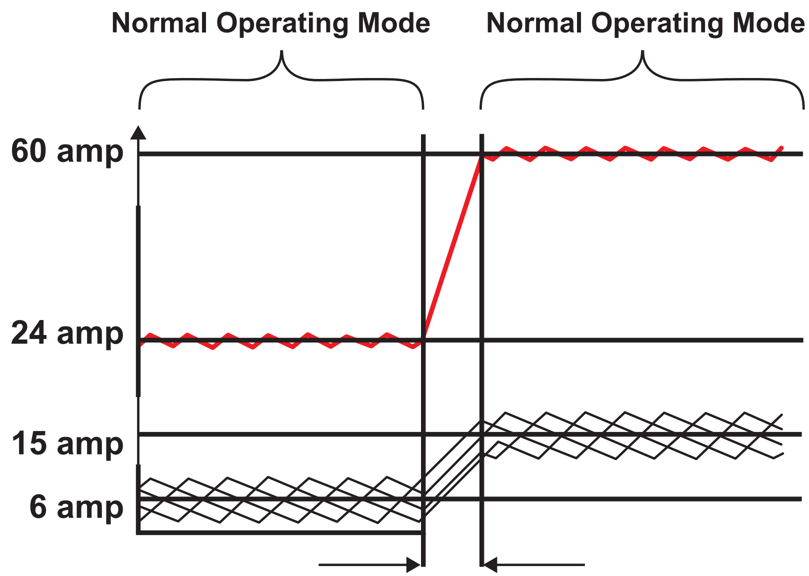
Reduced switch current → Distributed power loss and better thermal performance



Lower input RMS current → Smaller capacitance, lower ESR power loss, reduced self heating

Multiphase DC-DC Converter – Load Transients

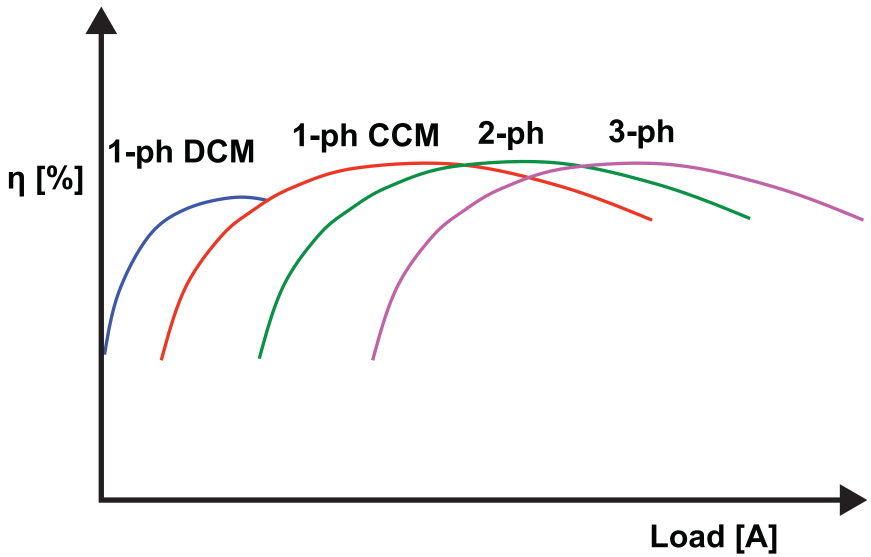
Improved transient with pulse overlap → Lower output capacitance



- During load insertion, all the phases (N) are turned on
  - If L is the inductor of each phase, effective inductance is L/N
  - Ability to deliver current to the output capacitor is N times higher than single-phase

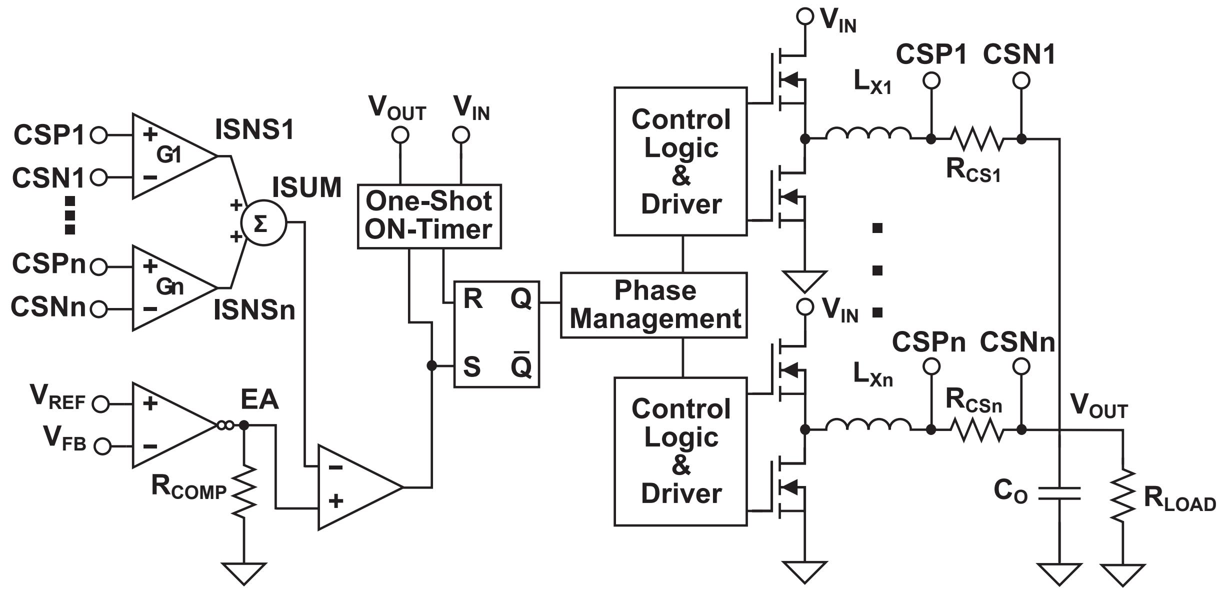
Multiphase DC-DC Converter – High Efficiency

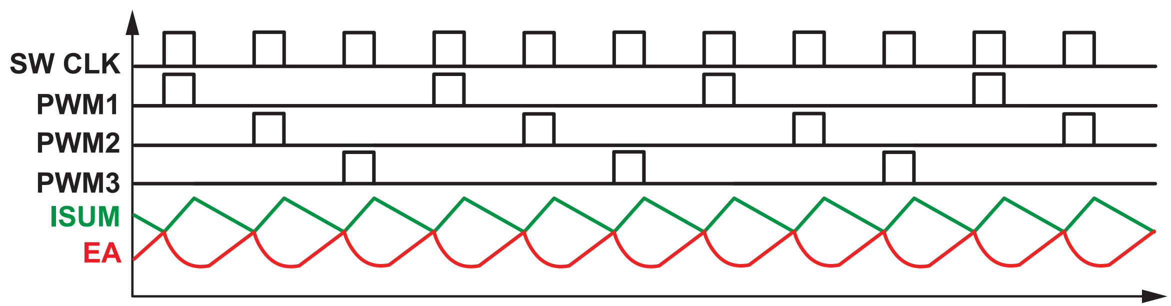
High Efficiency Over Wide Load Range



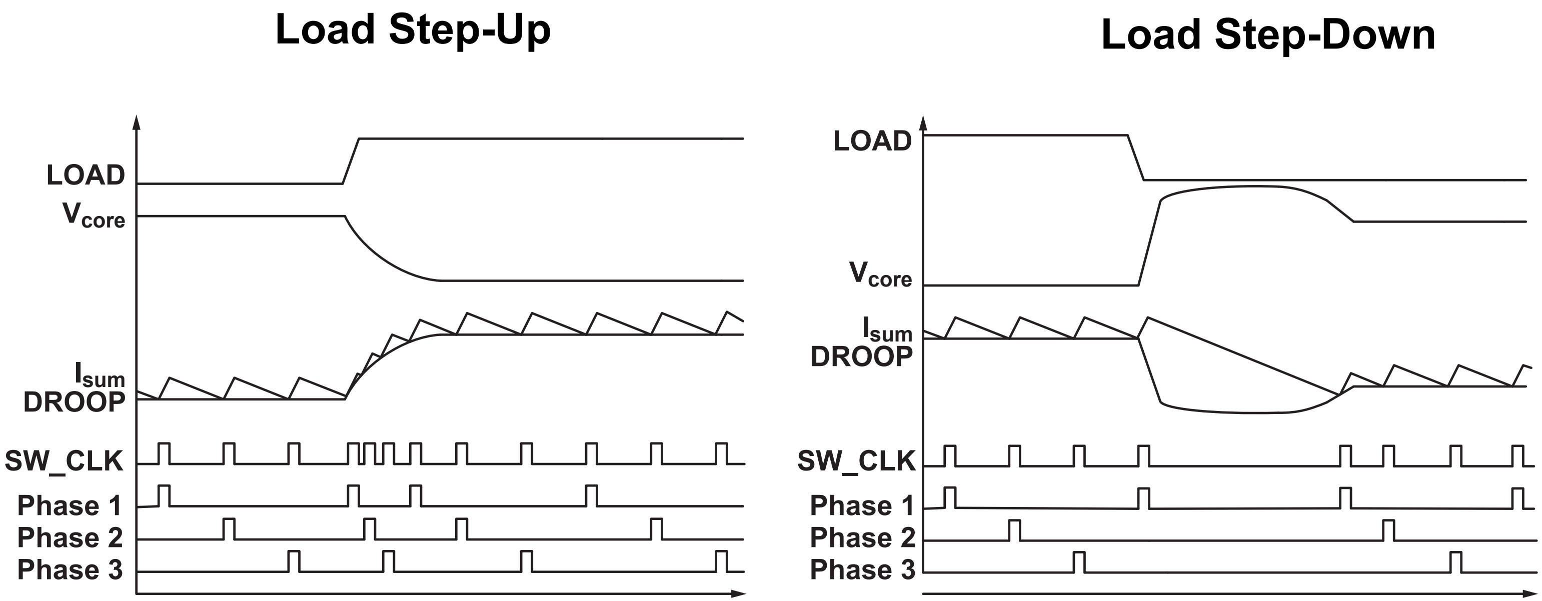
- Dynamic phase management is integral to achieve high-efficiency over wide loading conditions
  - Higher load current, more phases
  - As load current is reduced, there is a trade-off between switching and conduction losses — dropping phases can optimize the efficiency
  - At extreme light load, the power supply transitions to single-phase discontinuous conduction mode (DCM)

TI D-CAP+™ Control Architecture



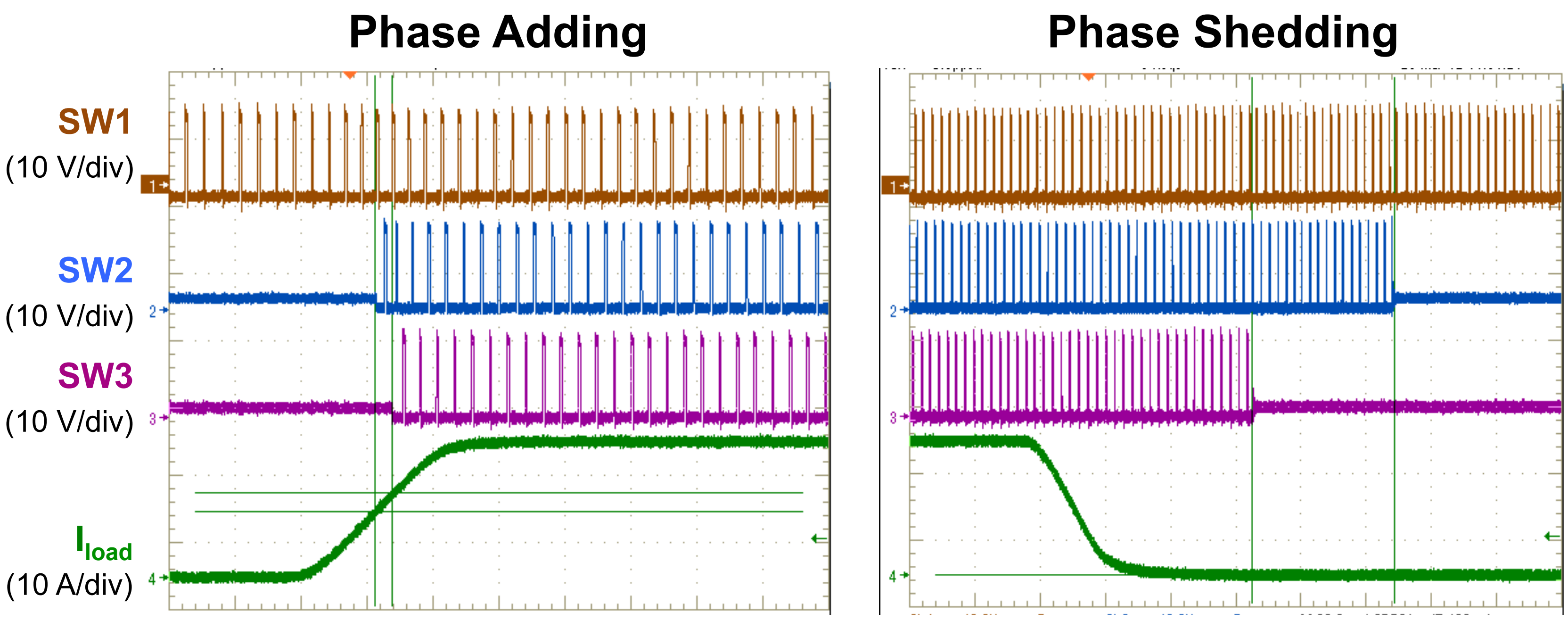


TI D-CAP+™ – Illustrated Transient Waveforms



- Pseudo constant switching frequency at steady state without internal clocks
- Variable switching frequency during load transients
- Dynamic current sharing during load transients

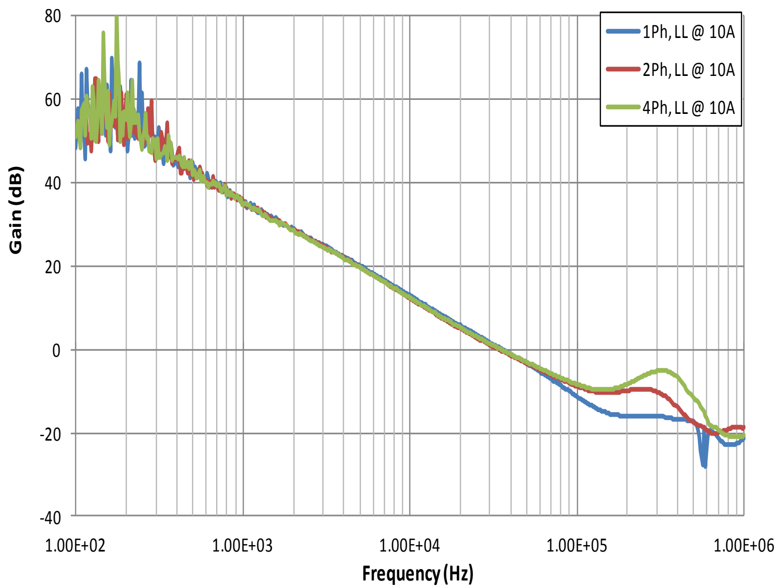
TI D-CAP+™ –
Dynamic Phase Shedding

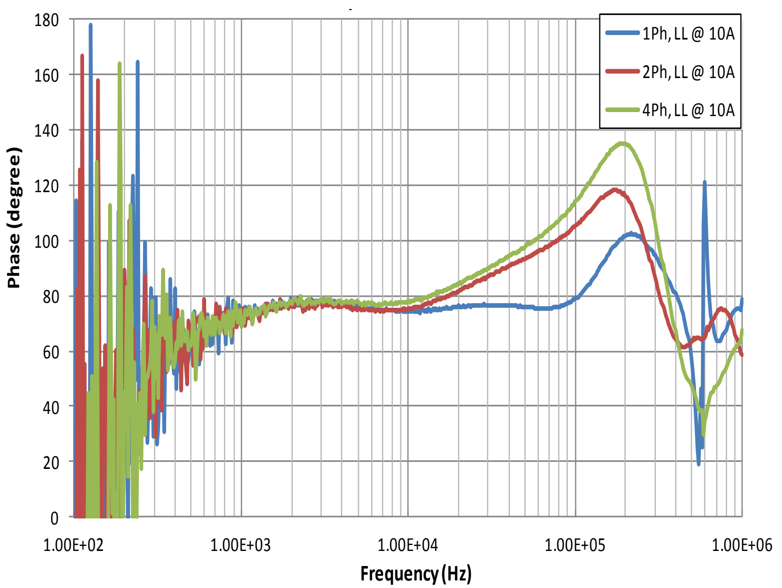


- Phase adding/shedding is determined based on the instantaneous ISUM
- Consists of both current and time hysteresis for phase shedding

TI D-CAP+™ –
Loop Gains with Different Phases

TPS53640 with 12 V_{IN} to 1.7 V_{OUT} @ 600 kHz, 10 A load and 1 mΩ loadline

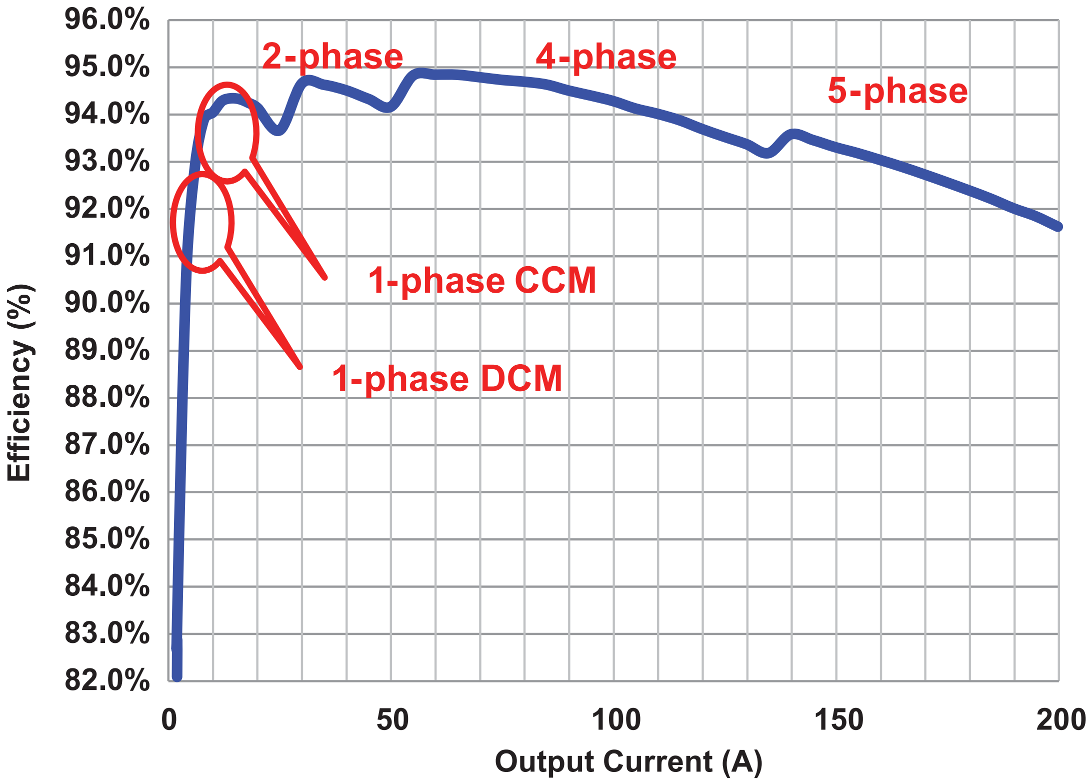




Loop Gain is Insensitive to the Number of Phases

TI D-CAP+™ – High Efficiency

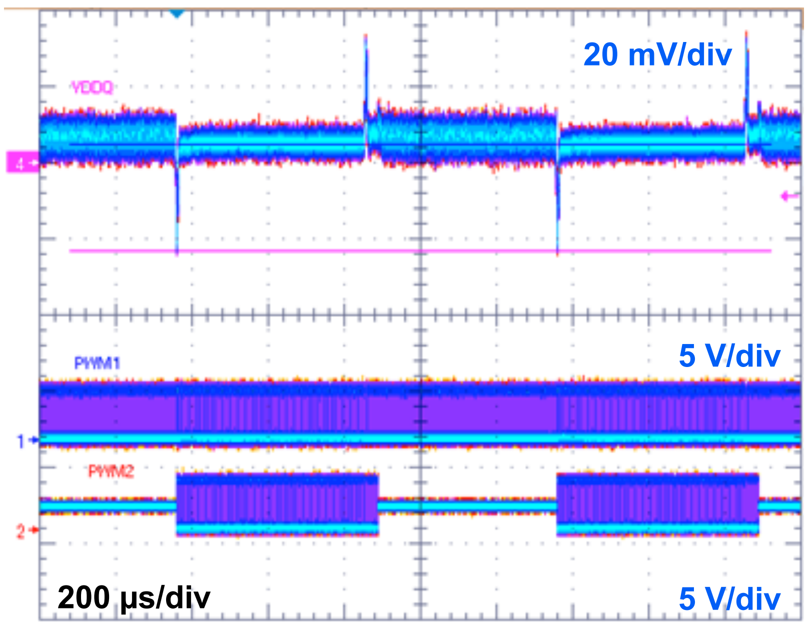
TPS53661 + CSD95372B with 12 V_{IN} to 1.8 V_{OUT} @ 600 kHz, 150 nH

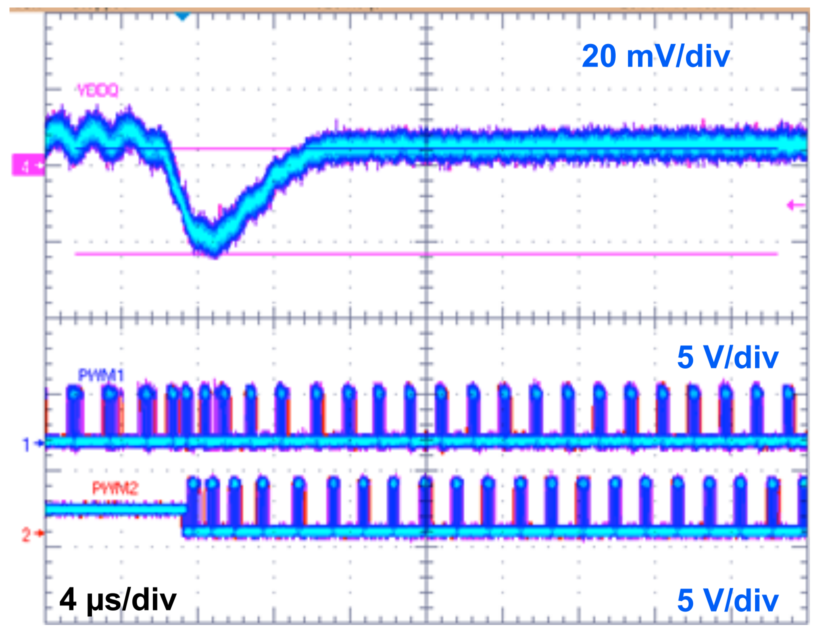


TI D-CAP+™ – Fast Phase Adding

120 nH @ 500 kHz with 2x470 µF/4.5 mΩ + 8x22 µF/DIMM

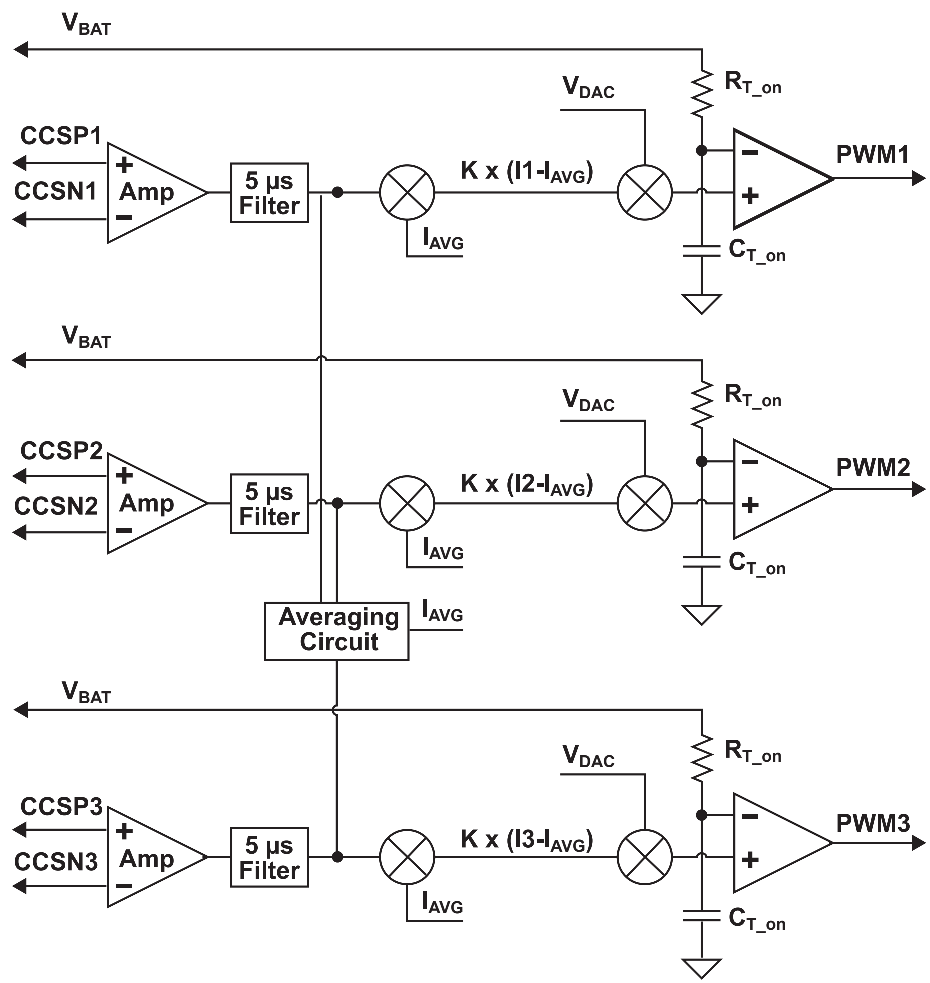
LF RR @ 1 kHz, 50% duty cycle (@ sensing point) 14.2 A-59.5 A @ 11.3 A/µs



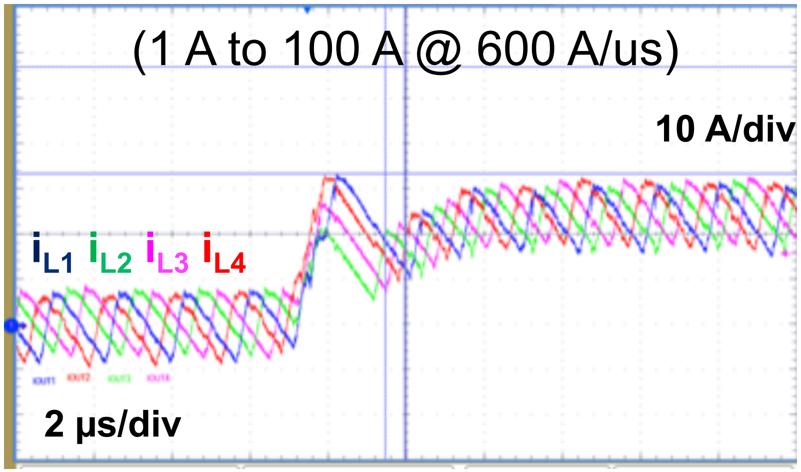


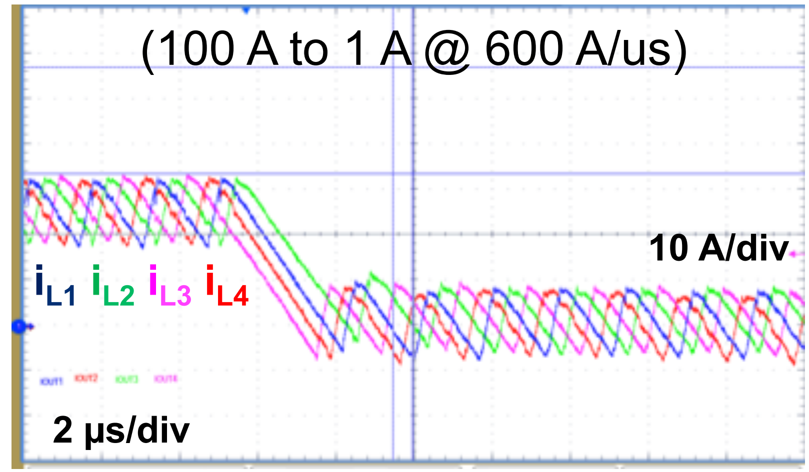
TI D-CAP+™ – Dynamic Current Sharing

- Currents are amplified, filtered and compared with average current
- At each on-time, the on-time reference (DAC) is “tweaked” by a voltage equivalent to K x (I_{IN} - I_{AVG})
- Since filtering is light (5 µs), system response is < 25 µs
- Current sharing loop analysis paper is available on request

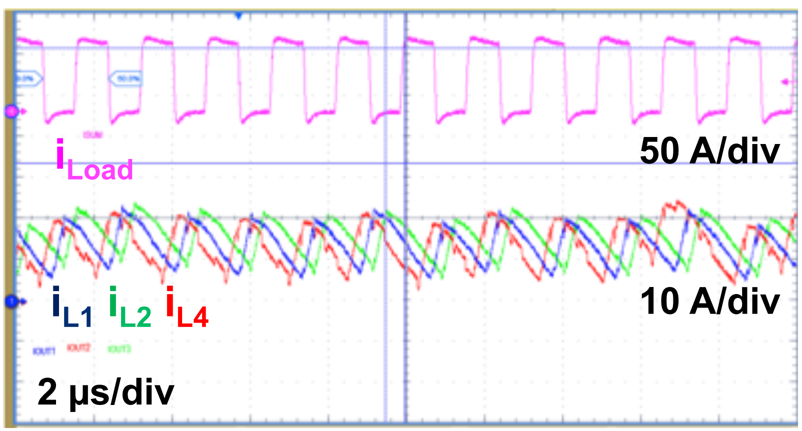


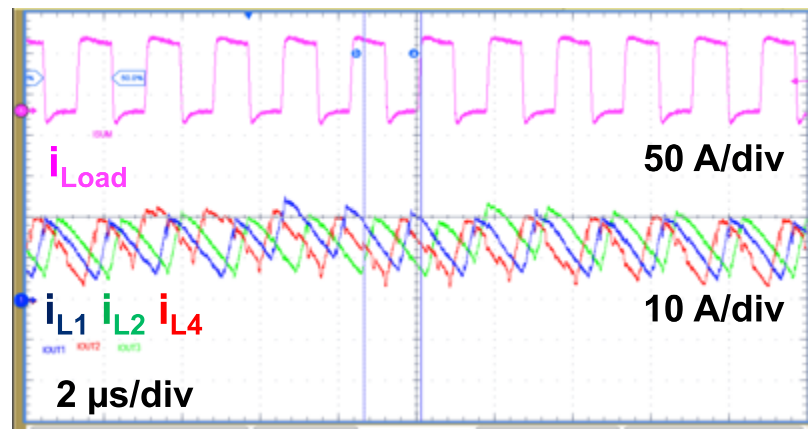
TI D-CAP+™ – Dynamic Current Sharing





(1 A to 100 A @ 600 A/µs and Load Frequency = Switching Frequency)





Comparisons of TI D-CAP™ Families

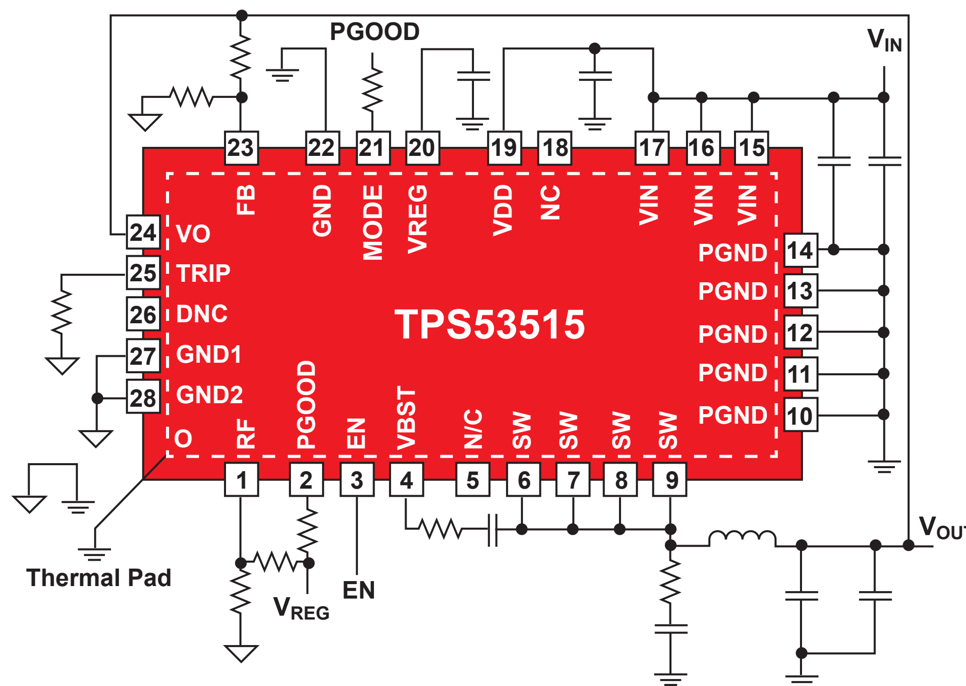
Control Architecture	Features
D-CAP™	• Adaptive on-time control • Fast load transient response • Ramp compensation built-in • High efficiency @ light loads
D-CAP2™	• Internal ripple compensation for MLCCs
D-CAP3™	• Sample-and-hold for DC accuracy improvement for CCM/DCM • Adaptive ripple compensation
D-CAP+™	• With actual current feedbacks • Extension to multi-phase applications • Dynamic current sharing • Dynamic phase shedding

COT Control – Advantages and Challenges

Advantages	Disadvantages
Simple design, no compensation required	Variable switching frequency (Solution: D-CAP/D-CAP2/D-CAP3/D-CAP+)
Excellent load transient response	Sensitive to PCB design for jitter (Solution: D-CAP/D-CAP2/D-CAP3/D-CAP+)
Excellent line transient response	Minimum ripple requirement or output capacitor type limitations (Solution: D-CAP2/D-CAP3/D-CAP+)
Seamless DCM/CCM transitions for good light-load efficiency	Poor load/line regulation (Solution: D-CAP3/D-CAP+)
	Not easy for multi-phase configurations (Solution: D-CAP+)

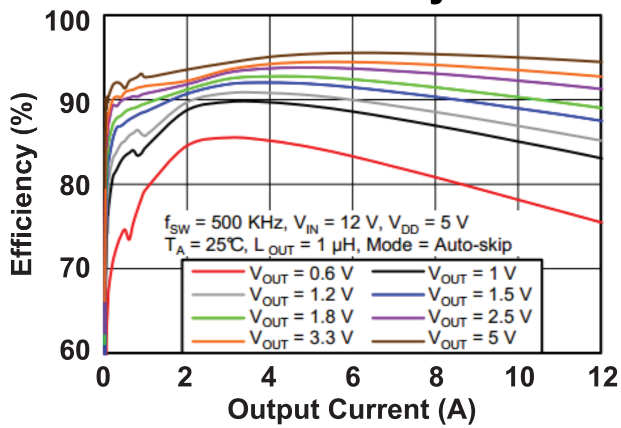
Design Example #3
COT Control – Design Specifications

Design Specifications	
Input voltage range	5 V to 18 V
Target output voltage	1.2 V
Output current range	0 A to 6.6 A
Switching frequency	500 kHz
Controller	TPS53515

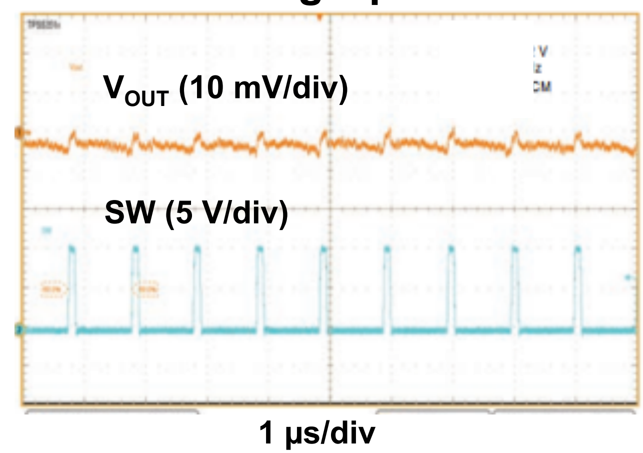


Design Example #3
COT Control – Performance Graph

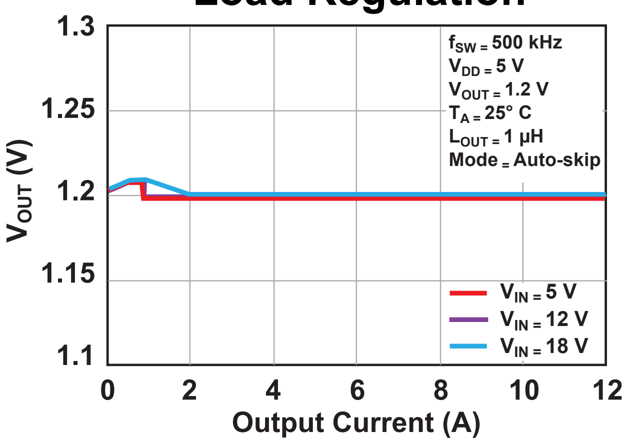
Efficiency



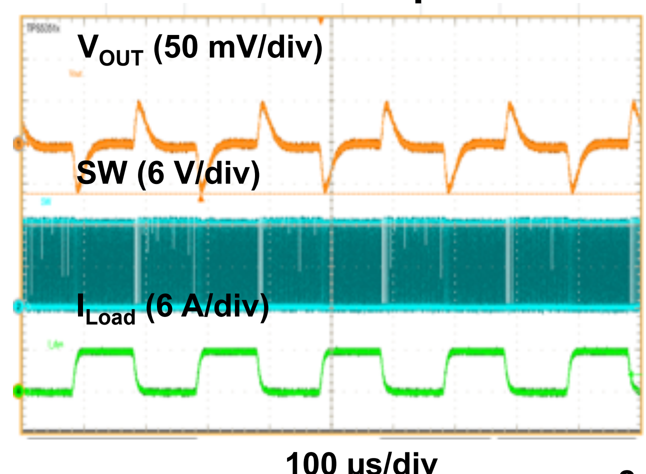
Switching Operation



Load Regulation

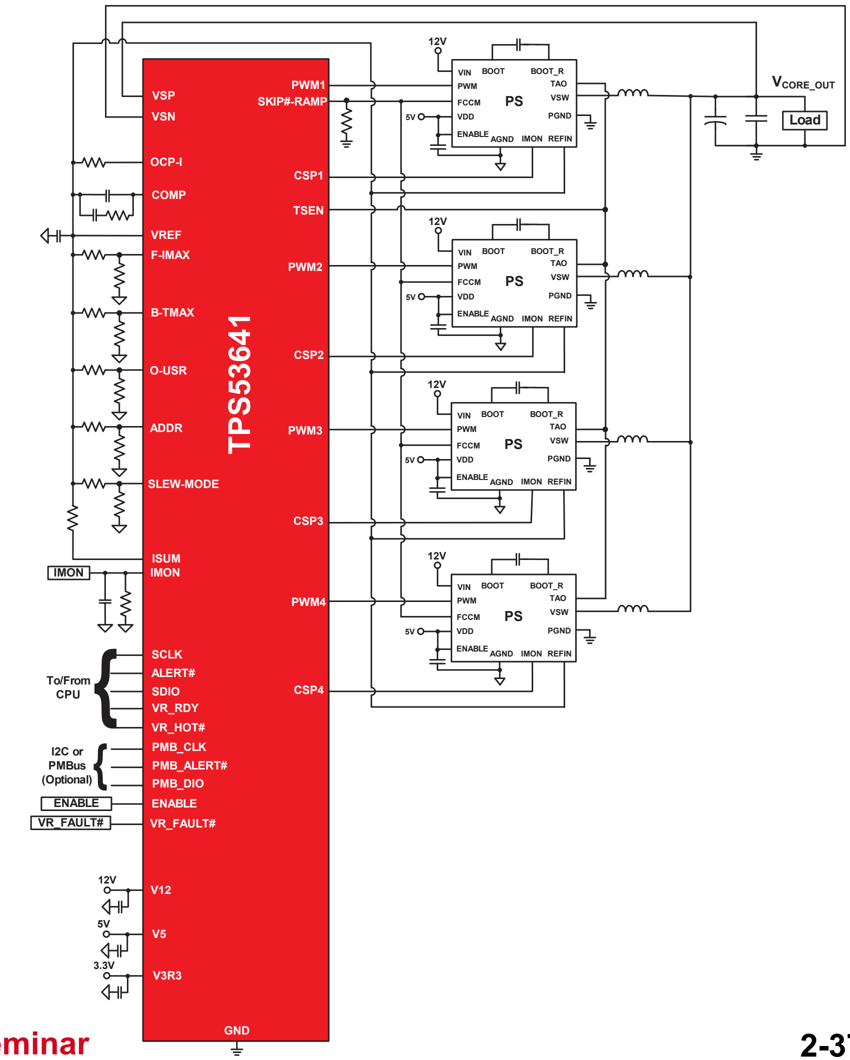


Transient Response



Design Example #4
D-CAP+ Design Specifications

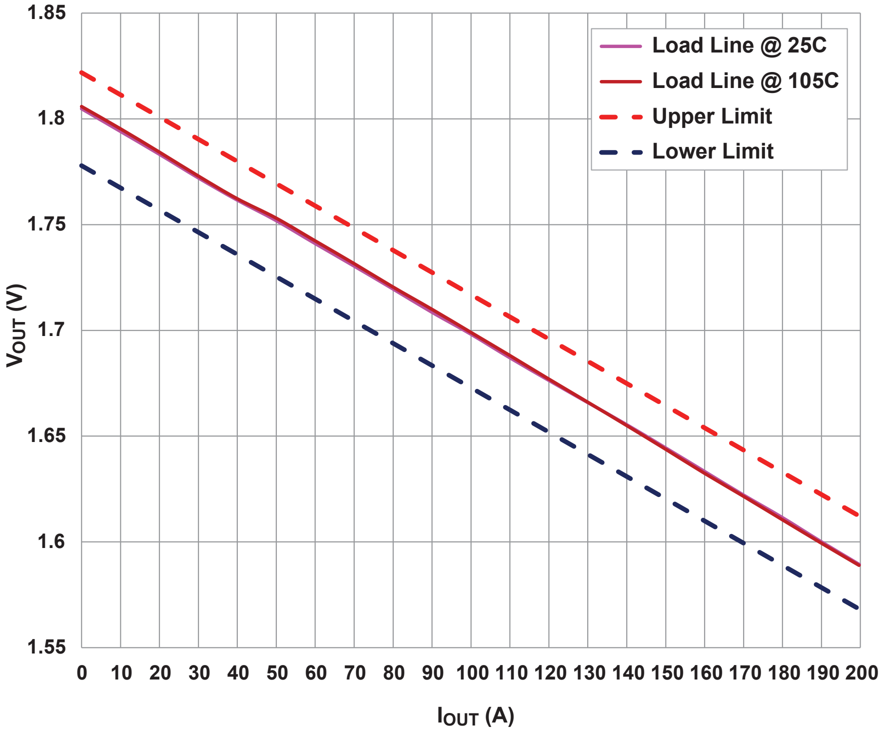
Design Specifications	
Input voltage range	12 V
Target output voltage	1.6 V-1.9 V
Output current range	0 A to 189 A
Switching frequency	600 kHz
Controller	TPS53641



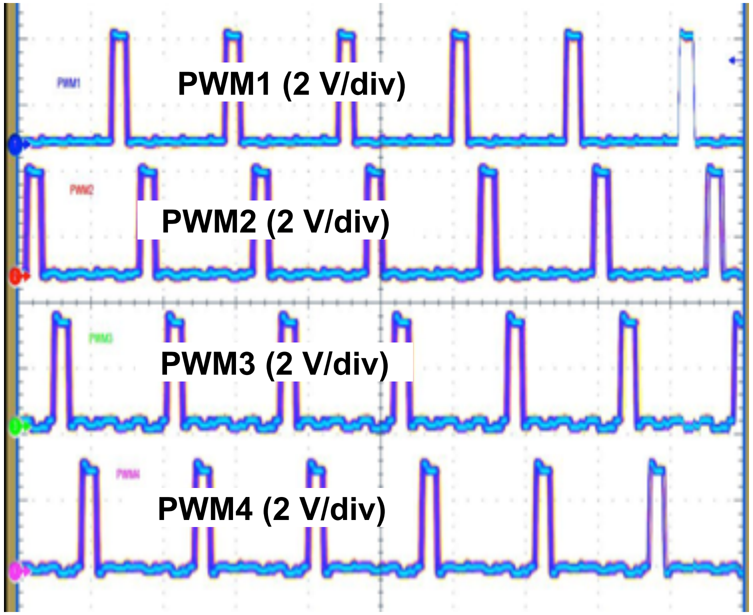
Design Example #4
D-CAP+ Performance Graph

12 V to 1.8 V with 4-phase operations @ 600 kHz, 150 nH, and 1 mΩ loadline

Loadline Regulation @ 25C and 105C



Phase Interleaving and Jitter @ 90 A

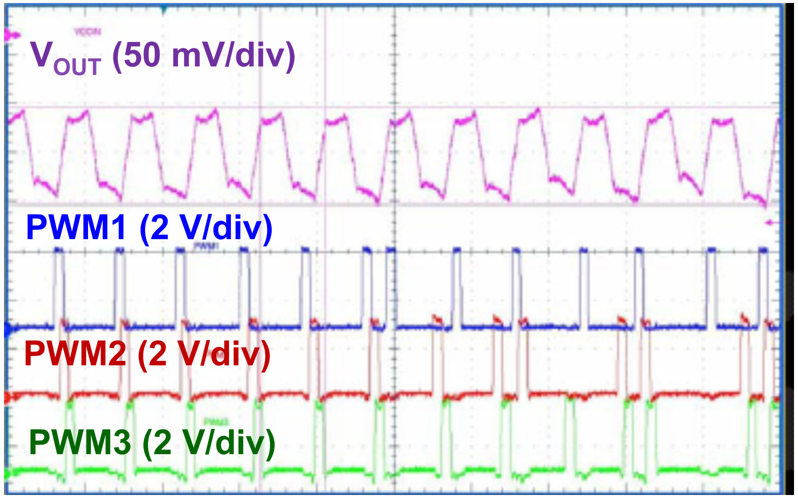


1 µs/div

Design Example #4
D-CAP+ Performance Graph (2)

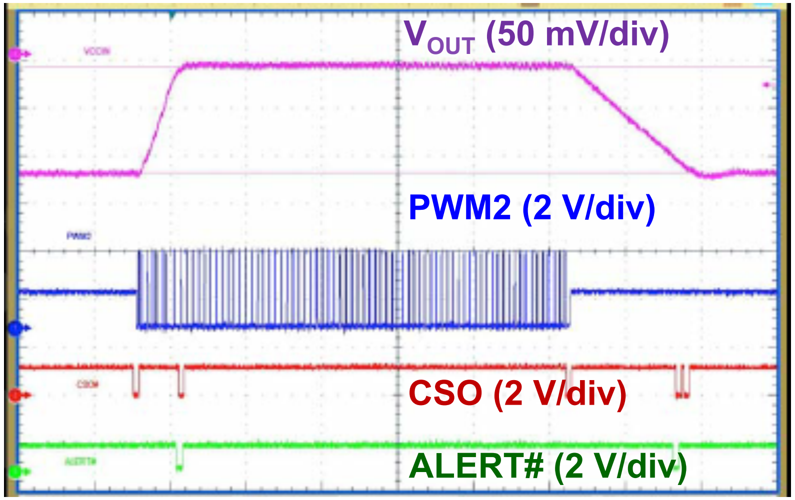
12 V to 1.8 V with 4-phase operations @ 600 kHz, 150 nH, and 1 mΩ loadline

High-Frequency Transient Response
(31 A to 189 A load @ 600 kHz)

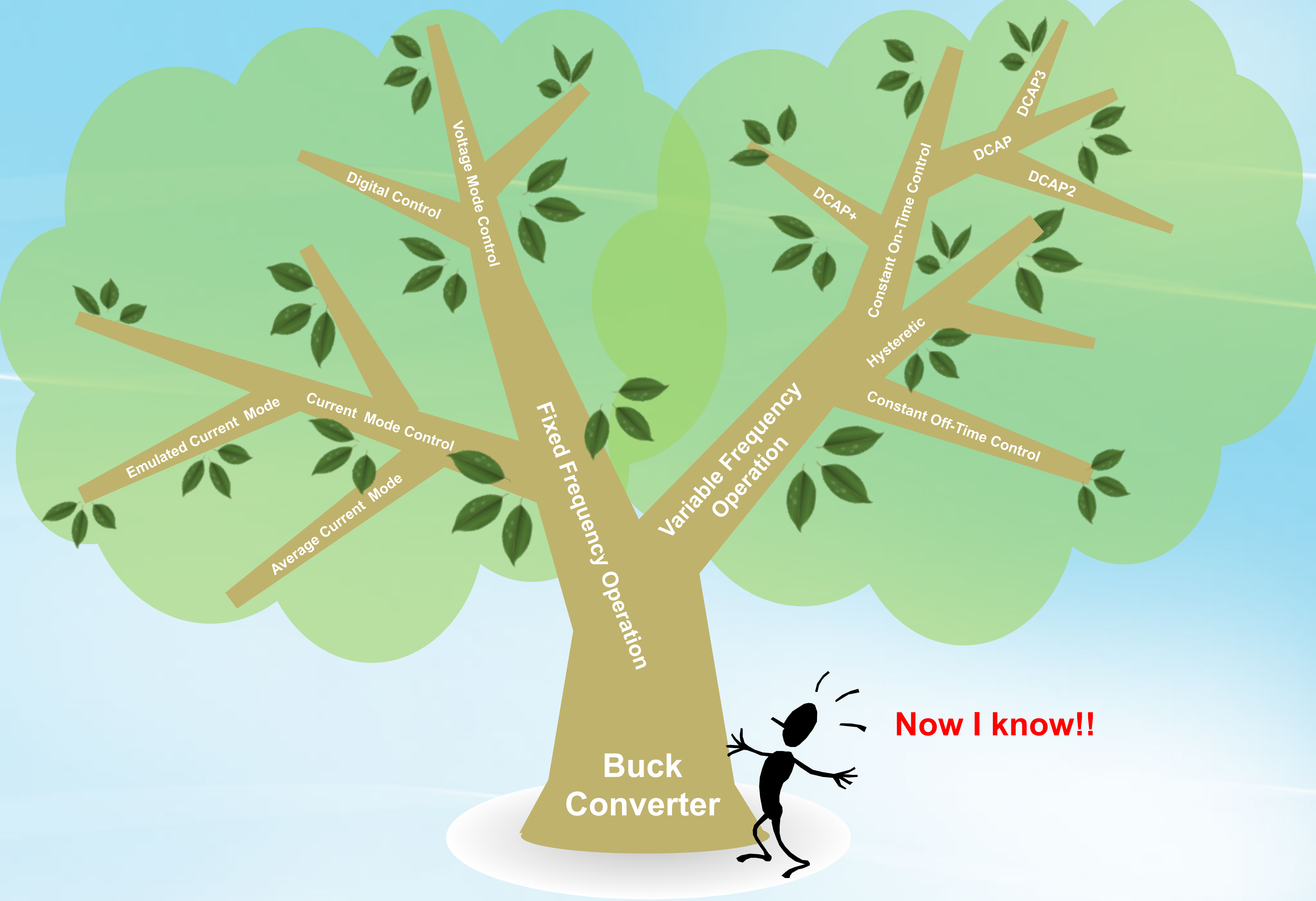


1 µs/div

Dynamic Voltage Change
(1.6 V to 1.82 V @ 5 A)



20 µs/div


Buck Converter
Fixed Frequency Operation
Variable Frequency Operation
Voltage Mode Control
Digital Control
Current Mode Control
Emulated Current Mode
Average Current Mode
Constant On-Time Control
DCAP+
DCAP
DCAP2
DCAP3
Hysteretic
Constant Off-Time Control
Now I know!!

References

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- SLVA301 - Loop Stability Analysis of Voltage Mode Buck Regulator with Different Output Capacitor Types – Continuous and Discontinuous Modes
- Easy Calculation Yields Load Transient Response
  - http://powerelectronics.com/site-files/powerelectronics.com/files/archive/powerelectronics.com/ar/502pet23.pdf
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- Switching Power Supply Topology Voltage Mode vs. Current Mode
  - http://www.ti.com/general/docs/litabsmultiplefilelist.tsp?literatureNumber=slua119
- Modeling, Analysis and Compensation of the Current-Mode Converter
  - http://www.ti.com/general/docs/lit/getliterature.tsp?baseLiteratureNumber=SLUA101&fileType=pdf

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