Survey of Step-Down Regulator Control Architectures for TPS and LM Devices

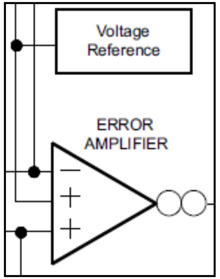
Presented by Josh Mandelcorn October 24, 2017 Tech Day
Modified from presentation by Rich Nowakowski August 2017

Agenda

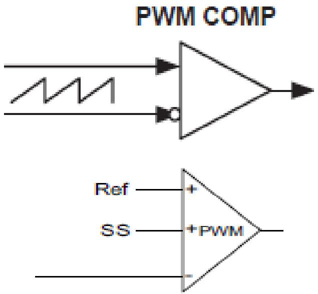
- Circuit Block Overview
- Linear Control Loop Architectures
- Non-Linear Control Loop Architectures
- “Best to Use When” Summary
- Additional Resources

Circuit Block Elements of Loop Control

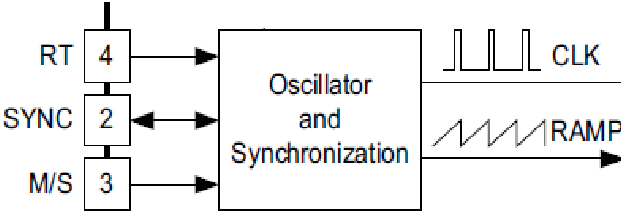
Error Amplifier



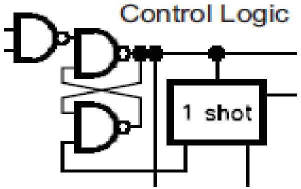
PWM Comparator



Oscillator



On Timer

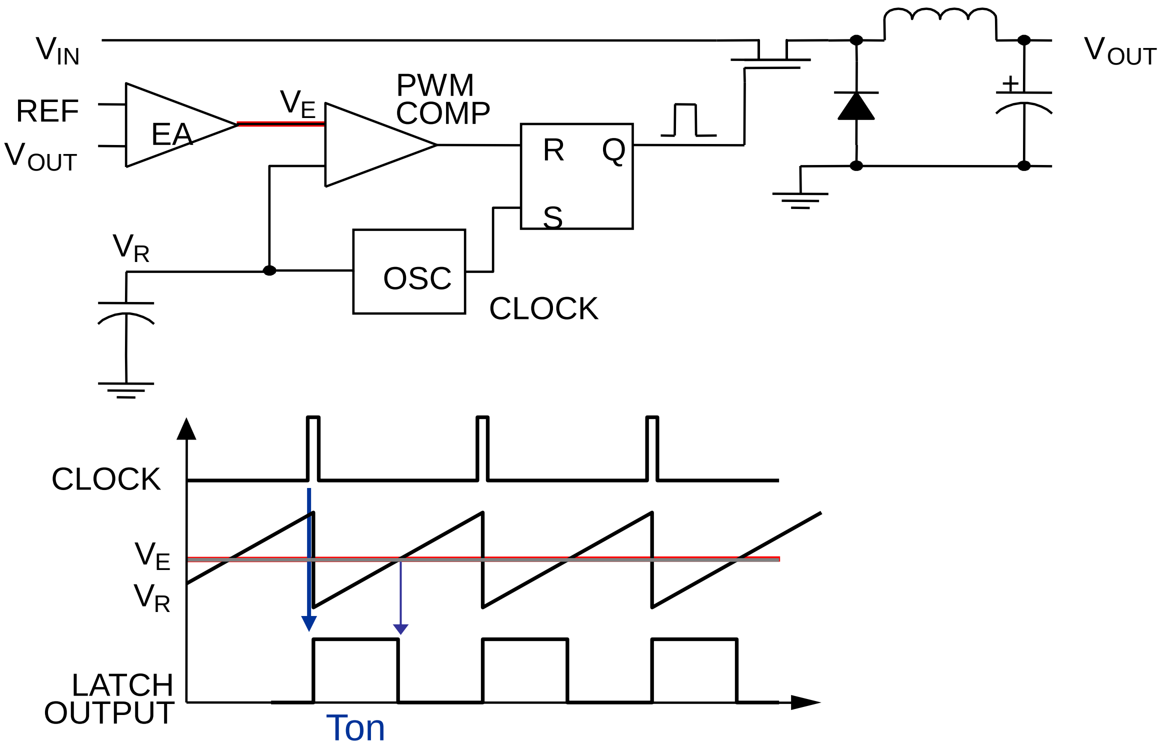


Control Architecture Summary

Linear Control Architectures

- Voltage Mode
- Voltage Mode with Voltage Feed Forward
- Current Mode
- Emulated Current Mode
- Internally Compensated Advanced Current Mode (ACM)

Voltage Mode Control



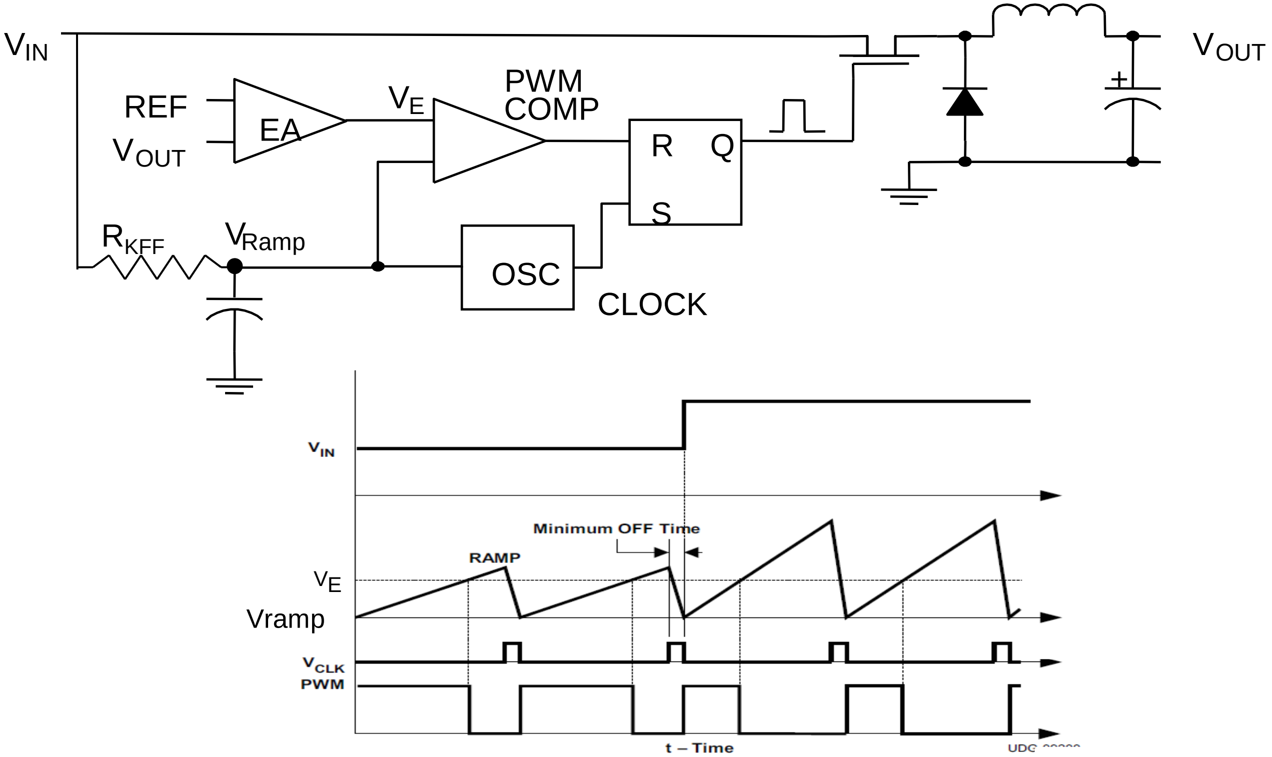
ADVANTAGES

- Single feedback loop
- Good noise margin with fixed ramp amplitude
- Voltage regulation is independent of current

DISADVANTAGES

- More difficult double-pole compensation
- Output caps affect compensation
- V_{IN} affects loop gain – modulator gain (Vin/ramp) not constant when Vin changes

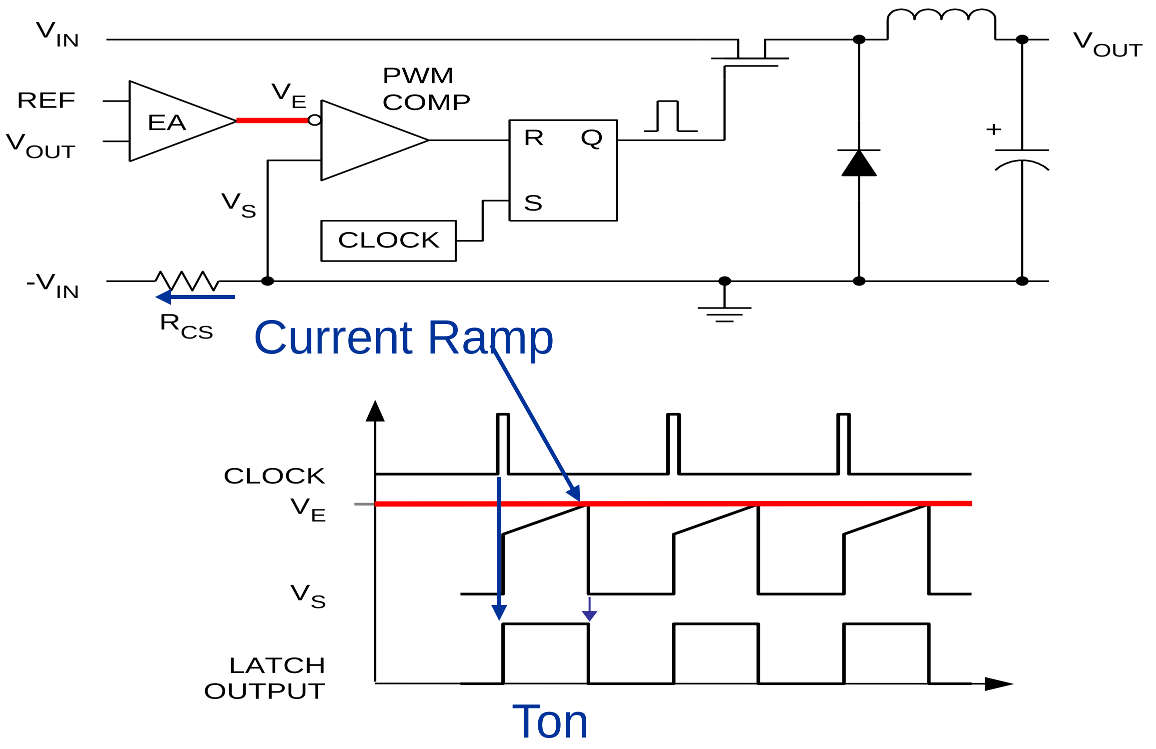
Voltage Mode w/ Voltage Feed-Forward



Ramp Generator Circuit

- Varies the PWM ramp slope with line voltage
- Excellent response to line variations. PWM does not have to wait for loop delays to change the duty cycle
- Useful when input voltage varies

Current Mode Control



ADVANTAGES

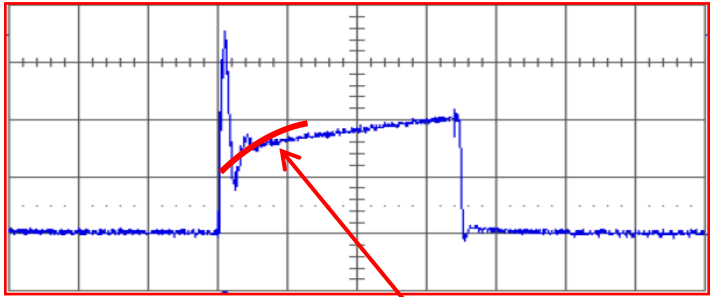
- Fast response to output current changes
- Single-pole compensation
- Inherent current limiting
- Inherent feed forward
- Multiple phase current-sharing possible

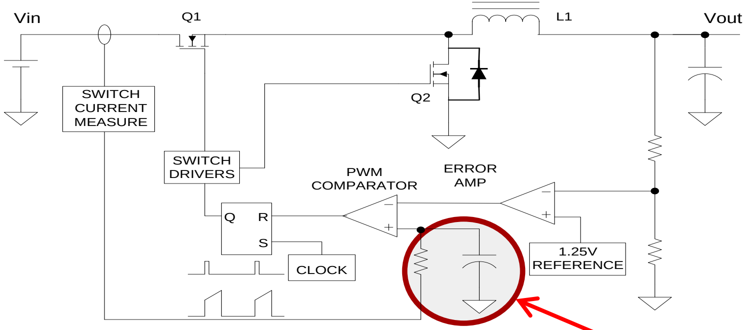
DISADVANTAGES

- Need for slope compensation to eliminate sub-harmonic oscillations
  - Occurs when L ripple current doesn’t return to initial value
- At low currents, current signal can become lost in noise
- Current limit “tail”
- Noise sensitivity due to leading edge current spike

Current Mode Leading Edge Spike

Filter out the leading edge spike with a RC filter



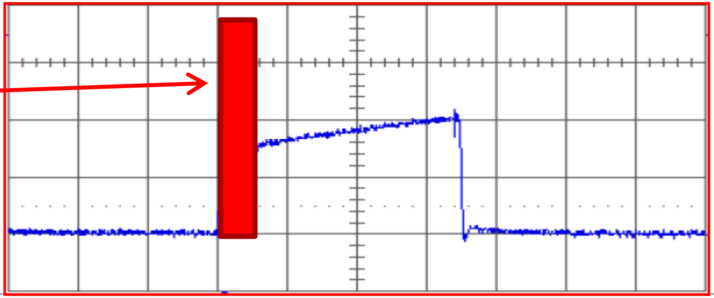


Waveform Distortion is a problem for small duty cycles

Filter

Use leading edge blanking

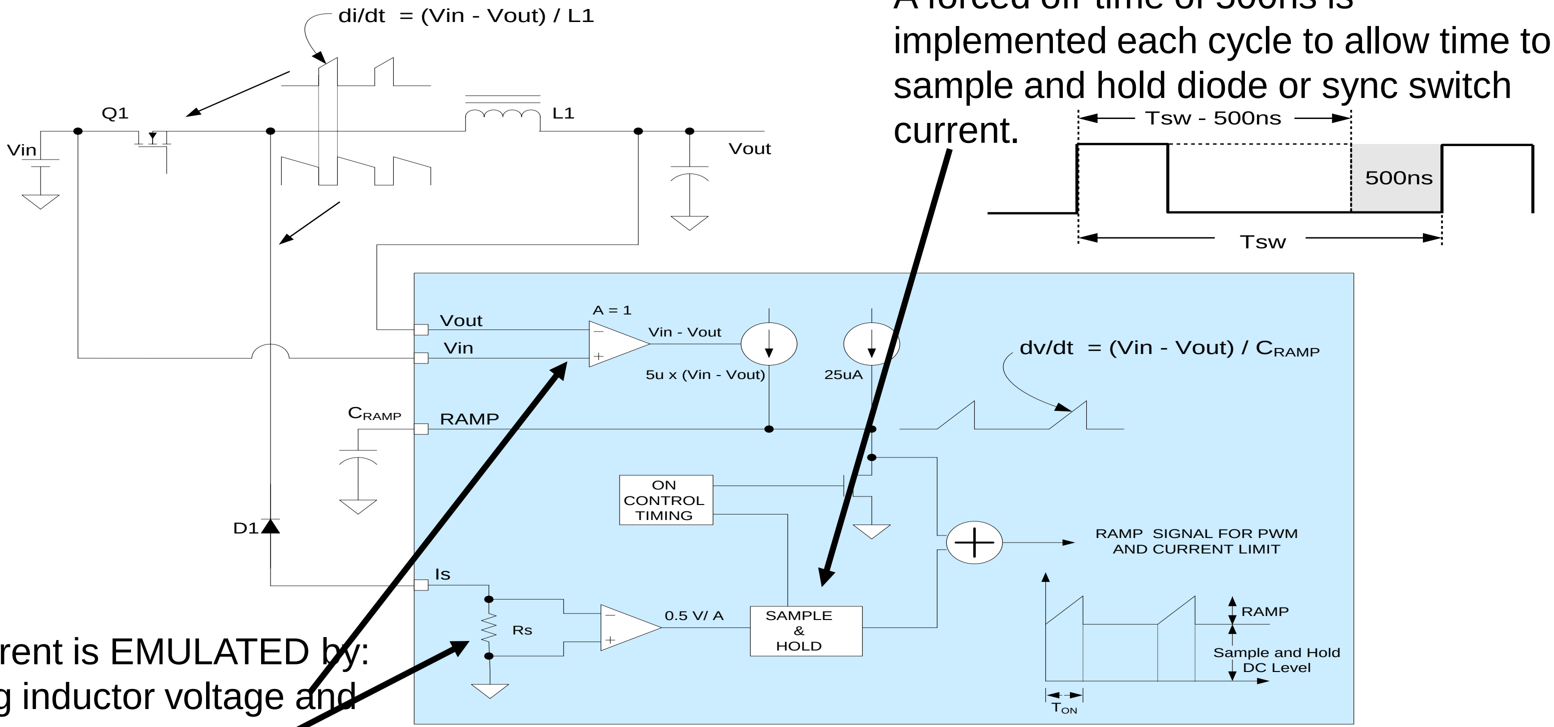
This portion of the duty cycle is un-available & precludes narrow pulses (high Vin to Vout ratios)



Emulated Current Mode Control

Sample and Hold

- A forced off-time of 500ns is implemented each cycle to allow time to sample and hold diode or sync switch current.



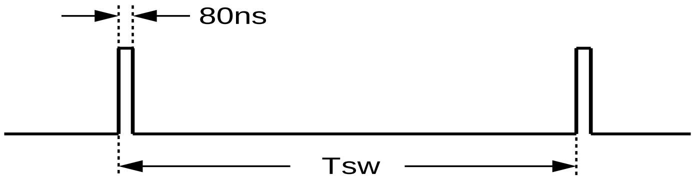
Inductor current is EMULATED by:

- Measuring inductor voltage and estimating current ramp
- Measuring diode current

Emulated Current Mode Control

Advantages

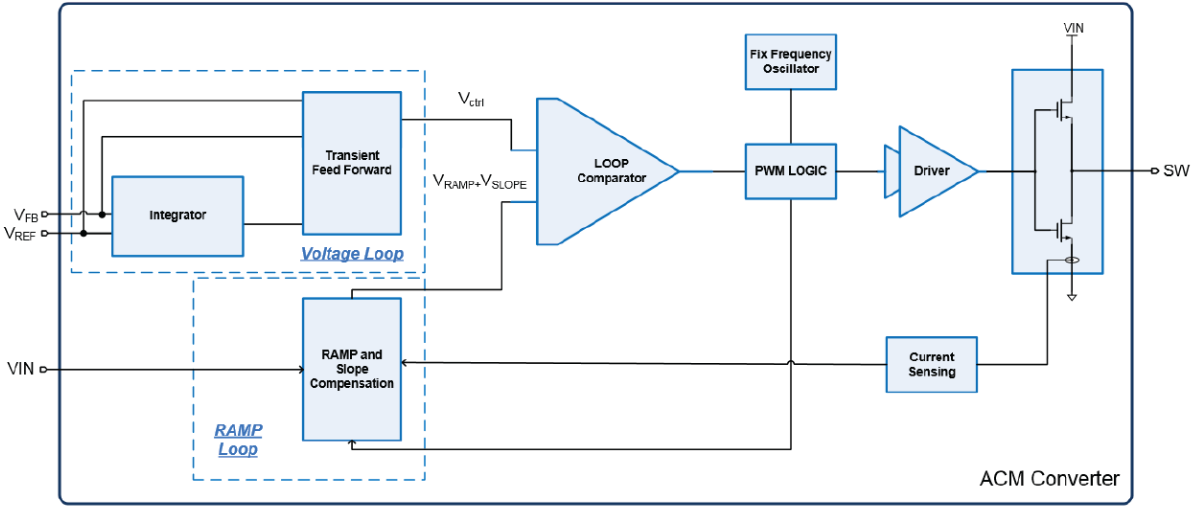
- Eliminates the leading edge spike
  - Allows much smaller duty cycles
  - Eliminates false triggering
- Ensures a clean current waveform when operating near the minimum on-time.
- The low current noise problem is much improved
  - Less need for a minimum load
- All the other advantages of current mode control remain



Disadvantages

- Maximum frequency and duty cycle is limited
  - Forced off-time is fixed and becomes a higher % of switching period
  - Less % of on-time is available at high frequency
  - Forced off-time needed for Sample and Hold current sensing circuit

Internally Compensated Advanced Current Mode (ACM)



- Voltage loop generates control voltage with true Vout error information
- Ramp loop includes pseudo inductor and DC current information
- Ramp loop processes VIN and PWM signal with slope compensation to create emulated peak current signal
- Loop comparator adds up all outputs from voltage and ramp loop
- PWM terminates when sum of positive inputs is higher than sum of negative inputs

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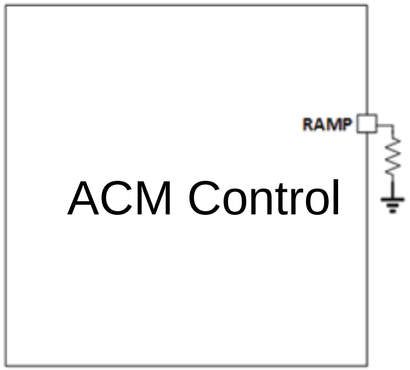
Advantages

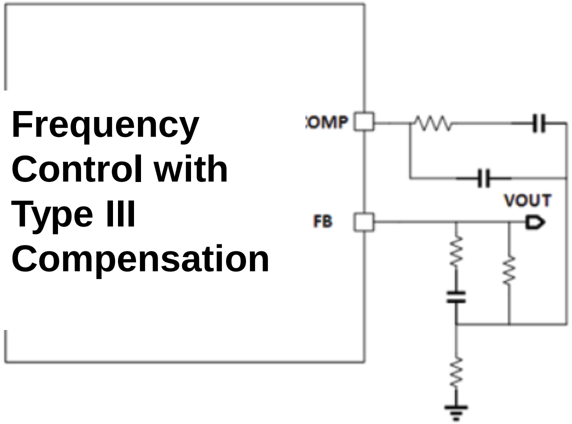
- True fixed frequency modulation
- No external compensation, with wide stability range
- Excellent stability with higher loop bandwidth and phase margin than peak current mode
- Large signal to noise ratio with high ramp voltage amplitude

Disadvantages

- Slower load transient response than Constant On Time or DCAP Control

Internally Compensated Advanced Current Mode (ACM)





- Internally generated ramp provides fixed frequency operation without external compensation
- RAMP pin adjusts the ramp level of the internal loop with a resistor to AGND to accommodate various inductor and capacitor selections
- RAMP resistor allows optimization of load transient response time and jitter
- ACM provides the advantages both of constant on-time (D-CAP™) and fixed frequency peak current mode control
  - ➢ No external compensation components or calculations – saves space and time
  - ➢ Fast load transient response
  - ➢ Predictable fixed frequency operation
  - ➢ Frequency synchronization

Control Architecture Summary

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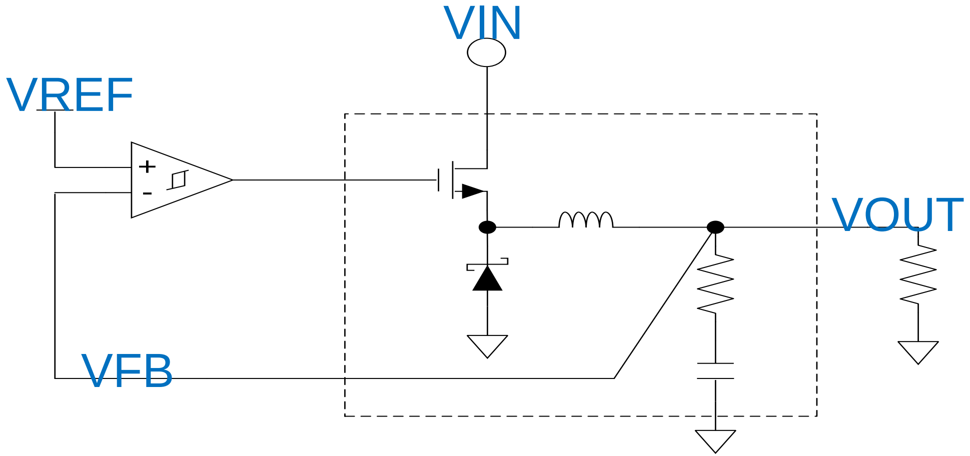
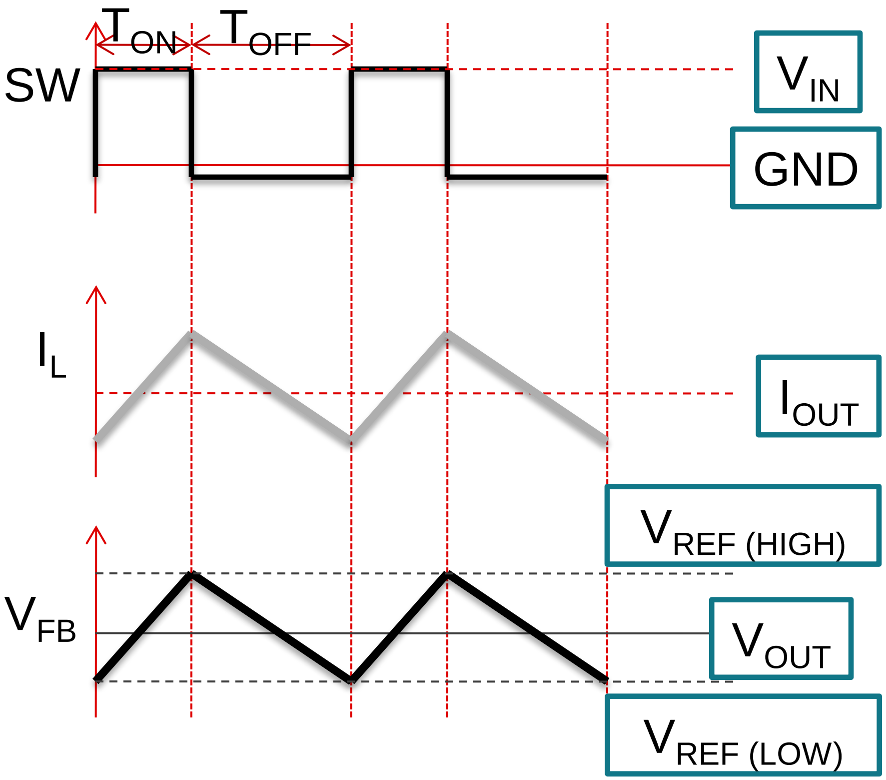
Non- Linear Control Architectures

- Hysteretic
- Constant On Time (COT)
- COT with Emulated Ripple Mode
- D-CAP™ (Direct Connect to the Capacitor)
- D-CAP2™
- D-CAP3™
- DCS™ (Direct Control w/ Seamless transition to Power Save Mode)

Hysteretic Control Scheme





TON - Terminated by VFB > $V_{REF\ (HIGH)}$

TOFF - Terminated by VFB < $V_{REF\ (LOW)}$

Hysteretic Control

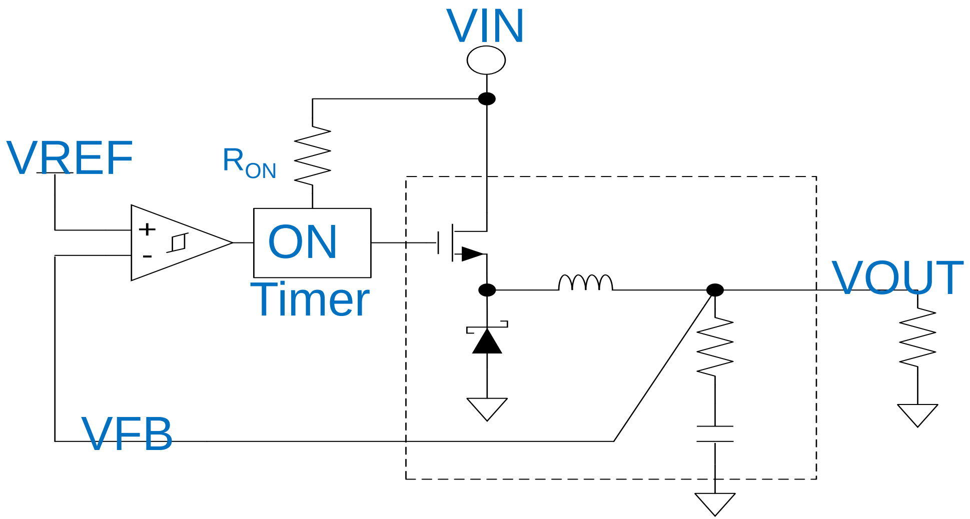
ADVANTAGES

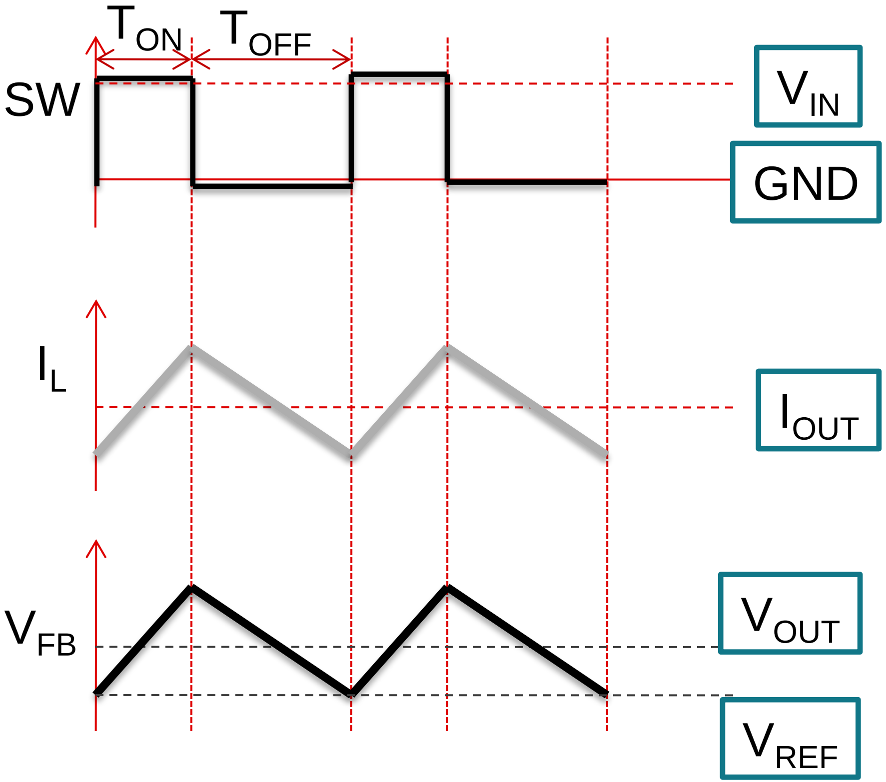
- Simple controls - bang/bang system
- No loop compensation
- Fastest response to load changes
- High light load efficiency

DISADVANTAGES

- Variable switching frequency
- Needs protection against magnetic saturation
- Requires some output ripple - ESR
- Sensitive to output noise
- Circuit delays limit maximum frequency

Constant-On-Time (COT)



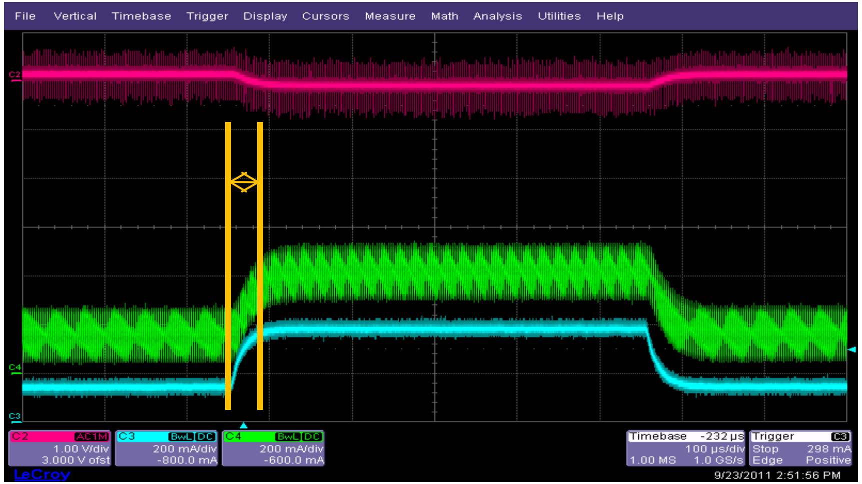


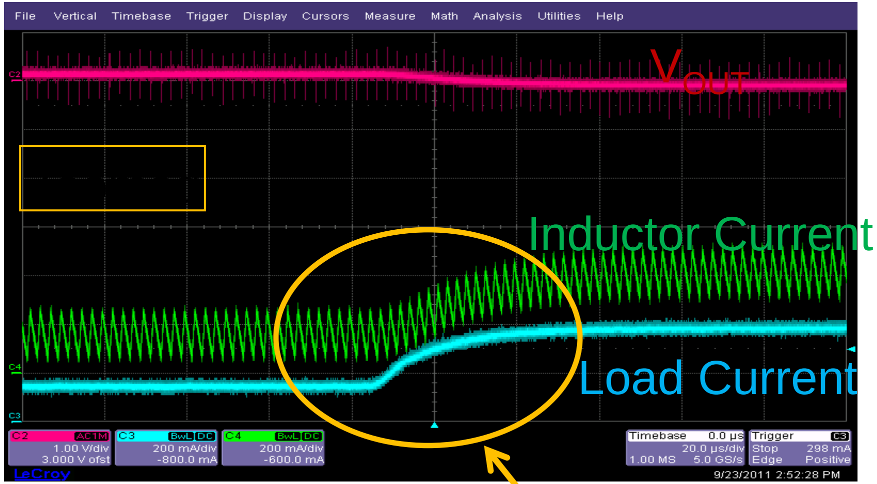
TON - **Terminated by On-Timer**

TOFF - **Terminated by $V_{FB} < V_{REF}$**

COT Fast Transient Response

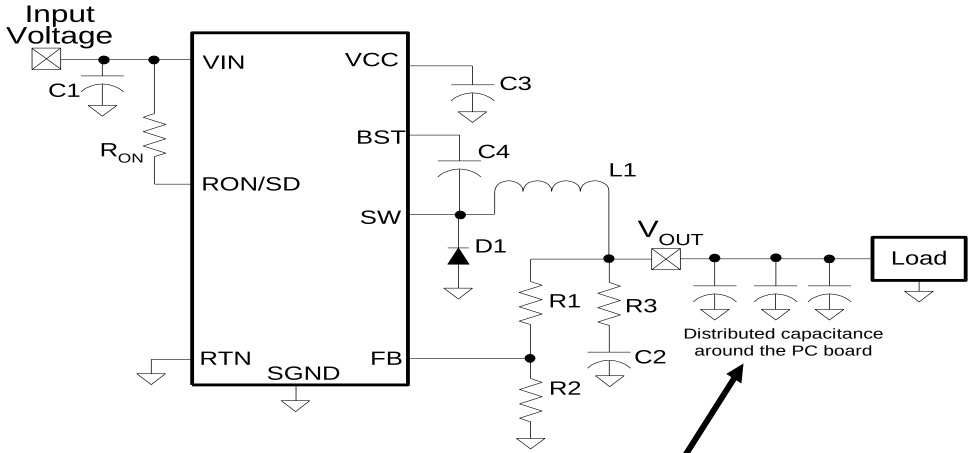
- **COTs have no error amplifier and compensation to limit the bandwidth**
- **This results in very fast response to load/line transients.**



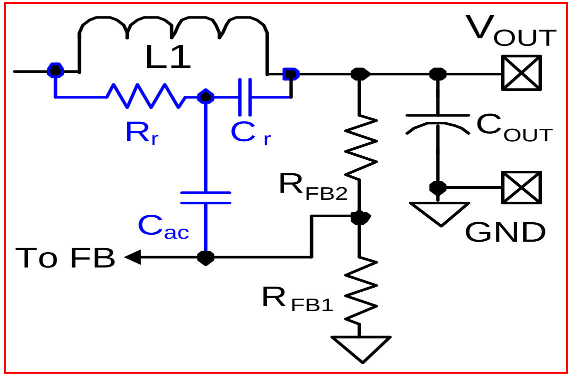


Fast 30us Response

COT Ripple Requirement



A BIG NO-NO!

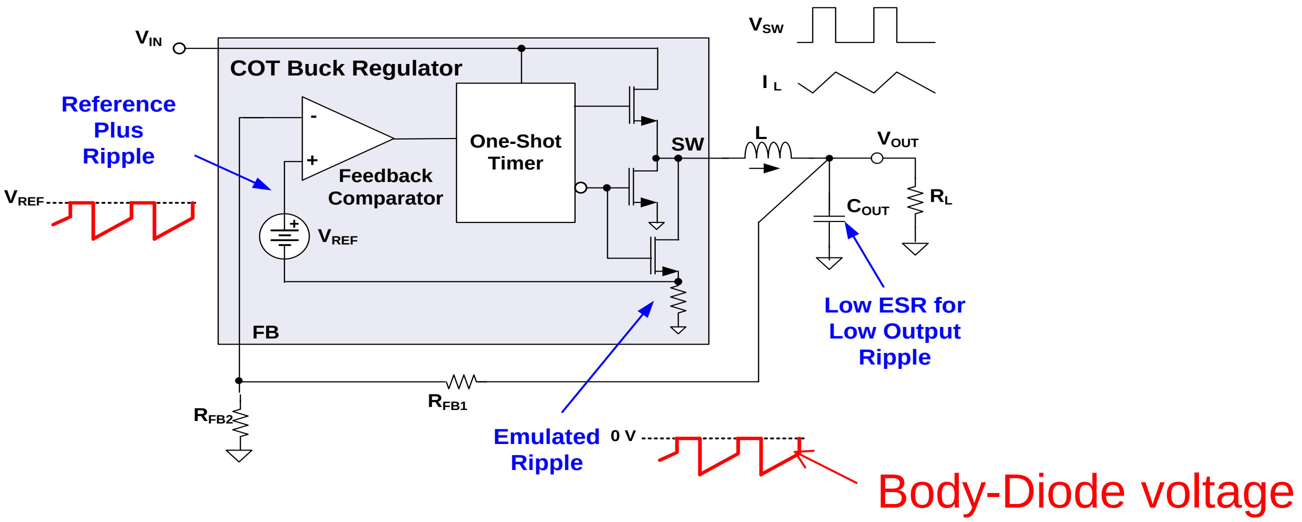


An external ripple injection circuit can be used to help generate a new on-pulse

COT w/ Emulated Ripple Mode (ERM)

Patented ERM technology satisfies ripple requirements of COT control:

- Emulated Ripple is coupled internally to feedback comparator from low-side switch of buck power stage
- No ripple required at regulator output (clean Vout)



COT Advantages and Disadvantages

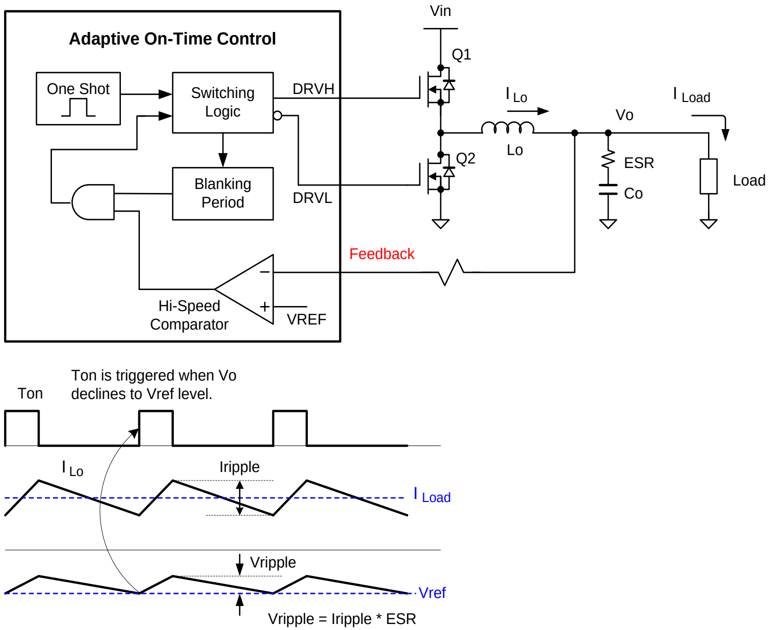
Advantages

- Simple design
- No compensation required
- Excellent transient response
- Works for high step-down ratios
- Minimizes frequency shift compared to hysteretic

Disadvantages

- Requires ripple at feedback node for stability (ESR)
  - ERM or injection circuit solves this
- No oscillator for fixed frequency (or Synchronizable) operation
- Sensitive to output noise as it translates to feedback ripple

D-CAP™ Mode (Adaptive On-time)



ADVANTAGES

- No loop compensation
- Fastest response to load changes

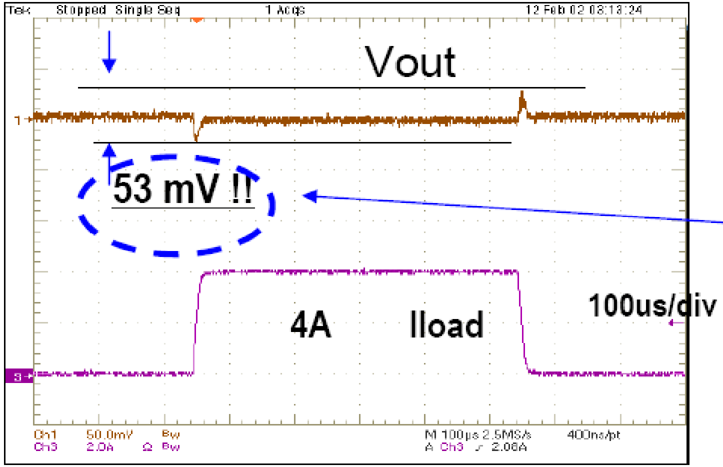
DISADVANTAGES

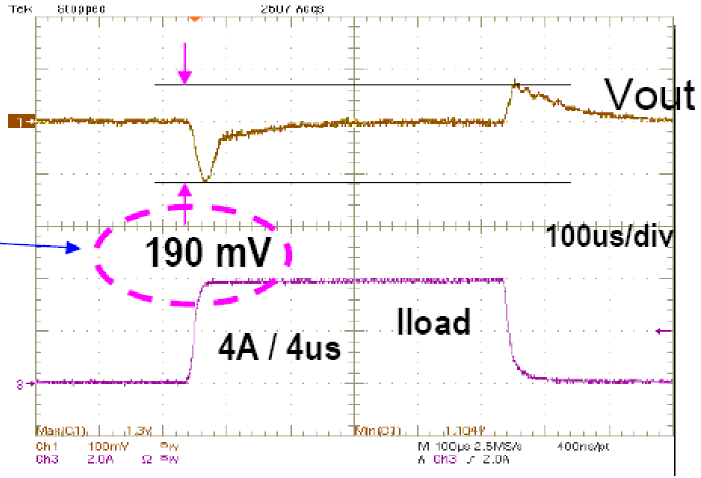
- Quasi fixed switching frequency
- Output voltage has a ripple component
- Ton and T jitter is expected, with smaller L and C
- Requires some output ripple (ESR)
- Sensitive to output noise

Direct Connect to the Capacitor (D-CAP)

- Each Ton pulse duration is calculated based upon Vin, Vout, nominal Fsw
- Each time the falling feed-back voltage equals Vref, a new ON pulse is generated
- There is no loop lag time. Pulse by pulse adjustment, comparator and the 'one shot block' lag are smaller

Compared Transient Response





D-cap mode transient response

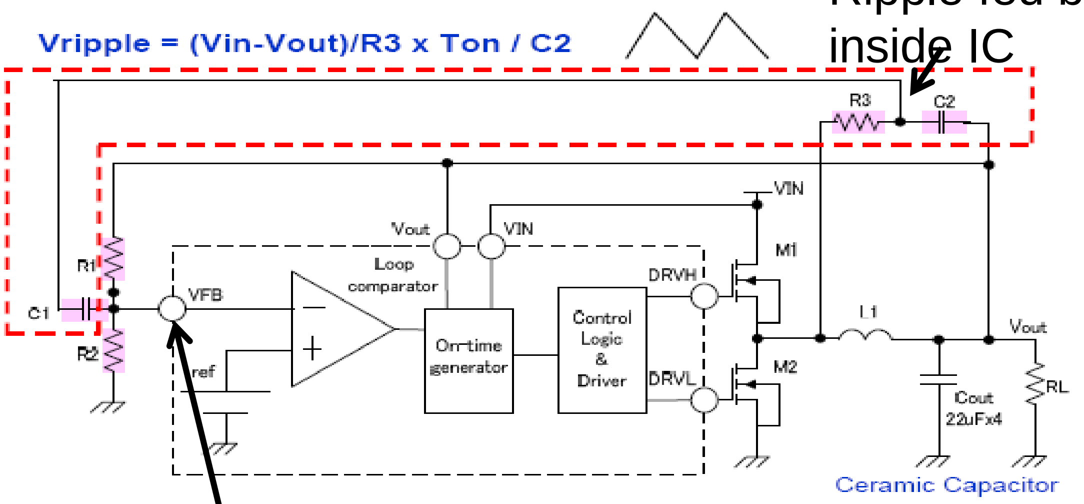
Voltage mode transient response

Cout=22uFx3 ⟷ Cout=100uFx4

D-CAP2TM Control Mode

Basically, D-CAP2TM is D-CAPTM plus internal ripple injection allowing for output ceramic capacitors use without added components

Ripple fed back inside IC



VFB ripple virtually zero

Vout ripple very small

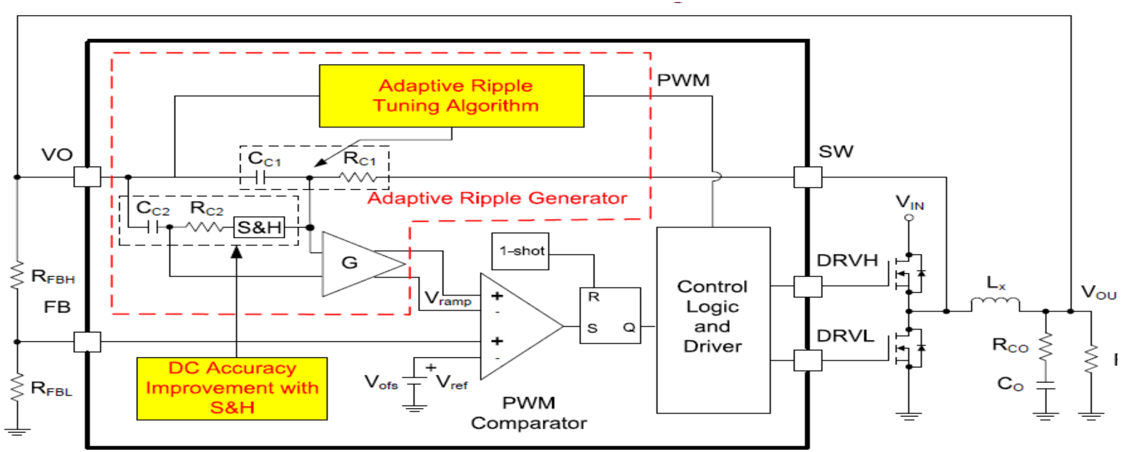
Advantage over DCAP

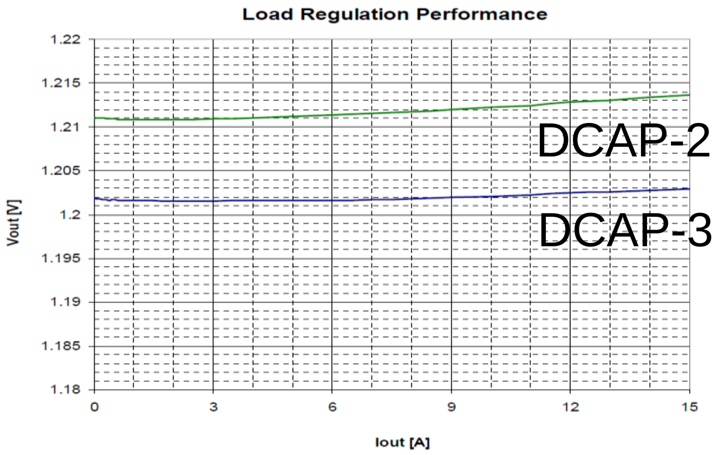
- Use when ceramic output caps are required: Less ripple than DCAP

Disadvantage

- Offset voltage generated from emulated ramp reduces Vout accuracy

D-CAP3™ Control Mode





- New ramp generation design has been implemented
- Sample and Hold circuit removes offset voltage from emulated ramp
- Offset caused by the ripple amplitude can be canceled
- Improved load regulation over D-CAP2

D-CAP3 Control Mode Comparison

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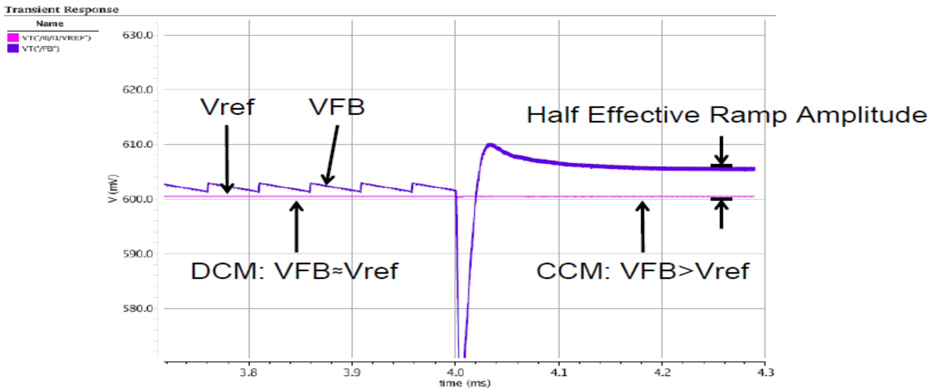
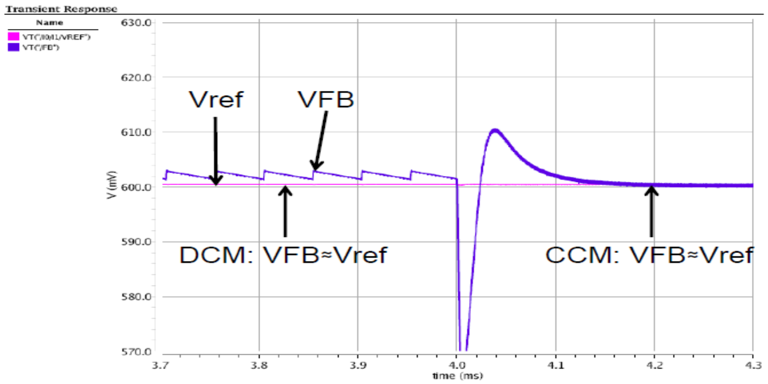
DCAP-2 Waveform



- In DCM, VFB≈Vref
- In CCM, VFB=Vref+Ramp/2>Vref
- Offset generated by ramp reduces Vout accuracy

DCAP-3 Waveform

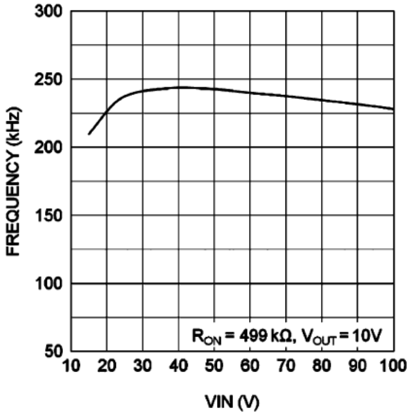


- In both DCM and CCM, VFB≈Vref
- Offset generated by Ramp is removed and Vout accuracy is improved

COT (LM5xxx) and D-CAP™ (TPS5xxxx)

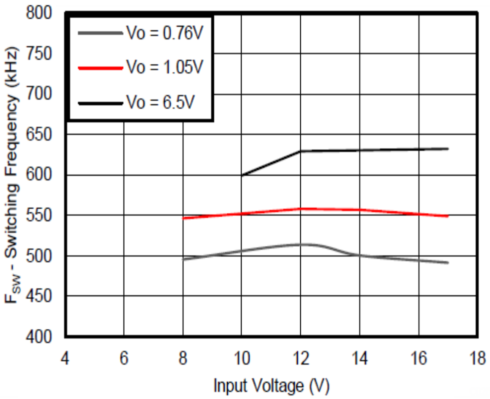
Constant On Time for LM Devices

- One Shot Timer set inversely proportional to Vin. Datasheet specifies the on-time.
- Provides nearly constant frequency for varying input voltage.



D-CAP for TPS5xxxx devices

- One Shot Timer set inversely proportional to Vin and proportional to Vout.
- Provides nearly constant frequency for varying input voltage.



Both methods achieve the same results to keep the frequency nearly constant

DCS-Control™

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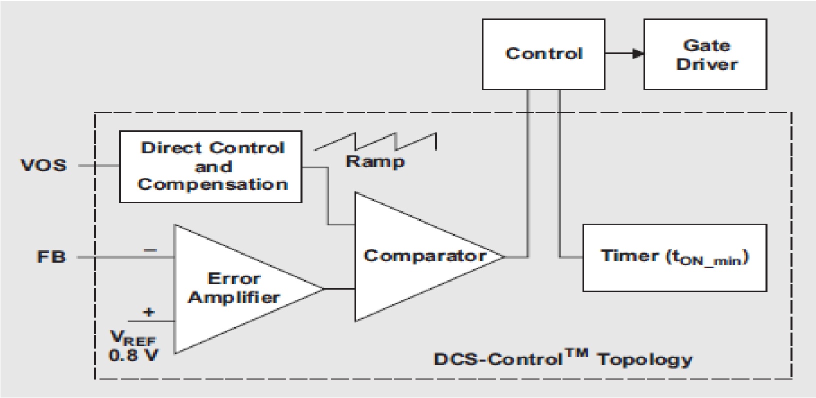
Proprietary Ramp Circuitry Feeds VOS (Vout) to Comparator



- **VOS pin connected to Vout at Cout**
- **Ramp Compared to Error signal from E/A like Voltage Mode**
- **Error Amplifier for Precise DC Regulation**
- **Hysteretic Comparator for Fast Response**
- **On Timer, set by Vin & Vout, for PFM mode and Constant Operating Frequency**

Advantages

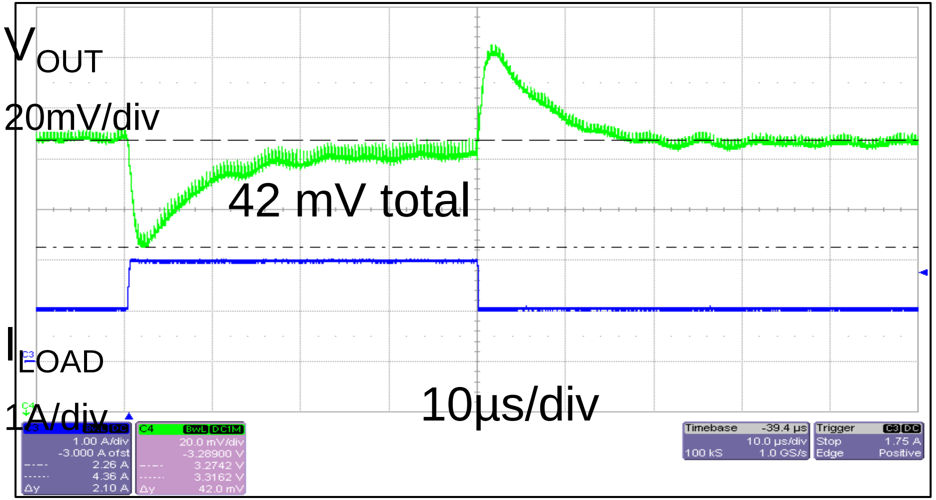
- **Fast transient response by direct path to output voltage (VOS).**
- **Additional voltage mode loop and E/A for high dc accuracy (FB).**
- **Seamless transition between PWM and Power Save Mode (single building block – no switch, no glitch).**
- **Supports low ESR output caps.**

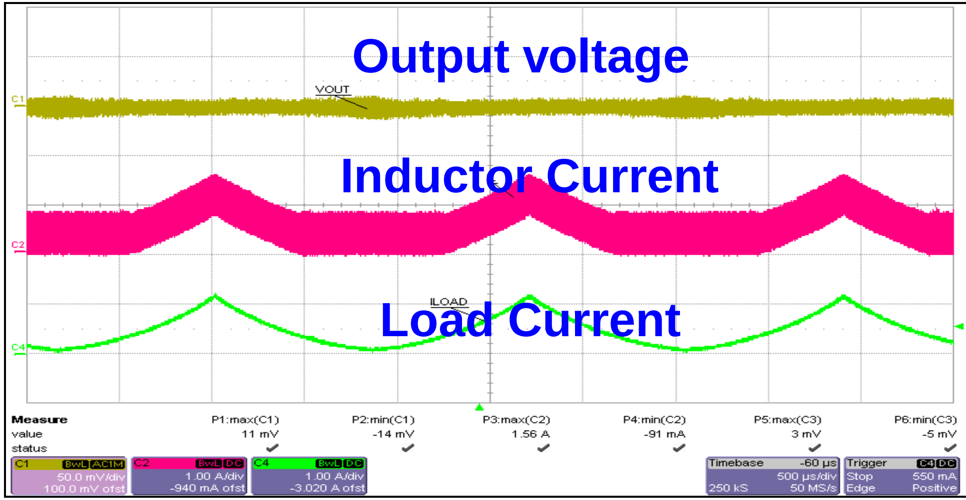
Disadvantages

- **VOS pin is noise sensitive**
- **Forced PWM mode at high duty cycles**

DCS Performance

CH1 – VOUT @ 50mV/div
CH2 – IL @ 1A/div
CH3 – ILOAD @ 1A/div





12V to 3.3V, 1A to 2A step with 2.2uH and 22uF

No disturbing bursts during the transition between PWM and Power Save Mode

High Level "Best to Use When" Summary (linear modes)

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Voltage Mode

- Use when synchronized / fixed switching frequency is needed. Usable for small input voltage variations and lighter loads.

Voltage Mode with Voltage Feed Forward

- Input voltage changes – Useful in Automotive, Battery Systems & Back up.

Current Mode

- Synchronized / fixed switching frequency is needed with lower parts count. Easier to design with type 2 compensator – no double complex pole.

Emulated Current Mode

- Low duty cycles versus traditional current mode, without current noise susceptibility.

High Level "Best to Use When" Summary (cont. – non linear)

Hysteretic

- Low cost – Few parts count. Fast transient response. Inherent light load efficiency

DCAP, Constant On Time

- Fast transient response when using POSCAP or medium ESR Cout. Psuedo-fixed Fsw

DCAP2, DCAP3, & Constant On Time with Emulated Ripple Mode

- Fast transient response when using ceramic Cout. Reduced parts count.

Advanced Current Mode - ACM

- Fast transient response, reduced parts count with predictable fixed frequency operation

DCS (Direct Control w/ Seamless transition to Power Save Mode)

- Light load efficiency is needed, fast transient response, reduced parts count.

Search on the Web for a Control Mode

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Products for Buck Converter (Integrated Switch)

Quick search

Vin nominal (V)

Vout nominal (V)

Iout (Max) (A) ≥ 0.05 ≤ 40

Iq (Typ) (mA) ≥ 0.0003 ≤ 100

Regulated Outputs (#) ≥ 1 ≤ 5

Package Group: Select

Search

Hide filters | Reset

844 total parts

- ☑ Vin (Min) (V)
- ☑ Vin (Max) (V)
- ☑ Vout (Min) (V)
- ☑ Vout (Max) (V)
- ☑ Iout (Max) (A)
- ☑ Regulated Outputs (#)
- ☑ Switching Frequency (Min) (kHz)
- ☑ Switching Frequency (Max) (kHz)
- ☑ Iq (Typ) (mA)
- ☑ Special Features
- ☑ Control Mode
- ☐ Duty Cycle (Max) (%)

Compare	Part Number (Filter by part number)	Vin (Min) (V)
☐	TPS543B20 - 4V to 19Vin, 25A Synchronous Step-down SWIFT™ Converter With Adaptive Internal Compensation - New	4
☐	LMR23615 - SIMPLE SWITCHER®, 36V, 1.5A Synchronous Step-Down Converter - New	4
☐	TPS549B22 - 1.5V to 18V Input, 25A SWIFT™ Synchronous Step-Down Converter With Full Differential Sense and PMBus - New	1.5
☐	TPS54308 - 4.5V to 28V Input, 3A Output, Synchronous 350kHz FCCM Step-Down Converter - New	4.5
☐	TPS65263-1Q1 - 4.5V-18V Input, Triple 3A/2A/2A Synchronous Buck Converter - New	4
☐	TPS561208 - 4.5V to 17V Input, 1A Output, Synchronous Step-Down Converter - New	4.5

☑ Control Mode

- ☐ Constant on-time (COT)
- ☐ Current Mode
- ☐ D-CAP
- ☐ D-CAP+
- ☐ D-CAP2
- ☐ D-CAP3

844 total parts

☐ Duty Cycle (Max) (%)

2300	0.6	Dynamic Voltage Scaling, Enable, Frequency Synchronization, Light Load Efficiency, Phase Interleaving, Power Good, Synchronous Rectification, UVLO Adjustable	Current Mode
580	0.4	Enable, Synchronous Rectification	D-CAP2
580	0.4	Enable, Light Load Efficiency, Synchronous Rectification	D-CAP2
2000	4.3	Adjustable Current Limit, Enable, Frequency Synchronization, N/A, Over Current Protection, Phase Interleaving, Power Good, Pre-Bias Start-Up, Remote Sense, Synchronous Rectification	Current Mode

Quick Reference Guide SLYT710

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Control-Mode Quick Reference Guide
Step-Down Non-Isolated DC/DC

Texas Instruments

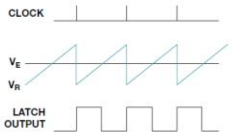
Overview

TI is active in the development of leading-edge control circuits to help engineers address specific design challenges. Since no control mode is optimal for every application, various control modes for non-isolated step-down controllers and converters are referenced with their advantages and how to learn more about each mode. The TI portfolio contains 12 types of control architectures for non-isolated TPS- and LM-series switching DC/DC converters and controllers.

Voltage Mode (VM)	Voltage Mode with Feedforward (VFF)	Peak Current Mode	Emulated Current Mode (ECM)	Internally-Compensated Advanced Current Mode (ACM)	Hysteretic
Constant On Time (COT)	COT with Emulated Ripple (COT with ERM)	D-CAP™	D-CAP2™	D-CAP3™	DSC Control™

Voltage Mode (VM)

Pulse-width modulation (latch output) is accomplished by comparing a voltage error signal (V_E) from the output voltage and reference voltage to a constant sawtooth-ramp waveform. The ramp is initiated by a clock signal from an oscillator. Good noise-margin performance is attained with a fixed ramp amplitude (V_R). Voltage regulation is independent of the output current. Voltage mode uses type-3 compensation addressing a double-pole power stage to support a wide range of output filter combinations for externally compensated devices.



When to use: When a fixed, predictable switching frequency is desired. Also useful when wide output-load variations are possible.

Popular devices: TPS54610, TPS40040, LM22670

Learn more: Switching Power Supply Topology Voltage Mode vs. Current Mode (SLUA119)

Download from www.ti.com. Search SLYT710

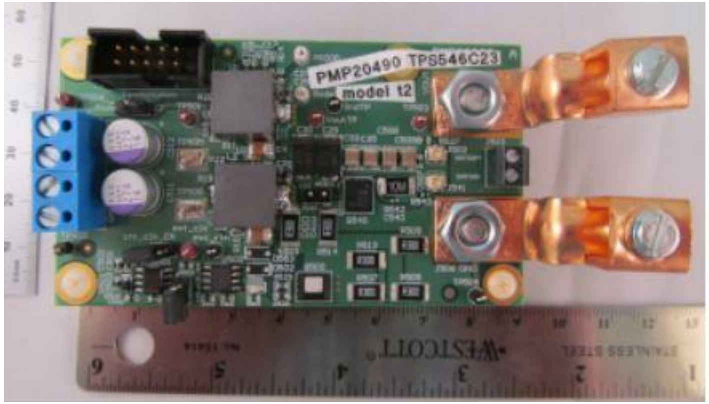
TI Design - EXAMPLE

High-Density 12Vin, 1.2Vout, 60A POL Reference Design with Stacked TPS546C20A PMBus DCDC Converters

Visit: **ti.com/tidesigns**

Part number: **PMP20490**

- **Description**
- The TPS546C23 provides a single IC for both control & the synchronous power stage for high current DC/DC applications and allows doubling of the current capability with use of two of the same part. Multi-phase also allows output ripple cancellation and effective higher bandwidth control for a given switching frequency. PMP20490 shows a high current two phase application with inductors on top of control ICs for smaller footprint and two on board dynamic loads. The test report shows performance and efficiency with two sources of inductors.
- **Features**
- Complete high current 2 phase DC/DC converter with all the advantages of phase interleaving using only two of the single phase parts
- Fixed frequency voltage mode control allows for user selection of switching frequency and synchronization to an external clock
- Inductors on top of controllers for small overall footprint
- Rich test interface including a self contained high speed dynamic test load and a Signal Generator driven dynamic test load
- Schematic, BOM, layout and test report focusing on efficiency & ripple performance with two sources for the inductors



Thank You!