Summary of Control Architectures for LM and TPS Families of DC/DC Step-Down Regulators

Agenda

- Elements of the Control Loop
- Loop Compensation Basics
  - Compensation schemes
  - Power Stages of Linear Architectures
  - Bode Plots
- Linear Control Loop Architectures
- Non-Linear Control Loop Architectures
- Popular Devices and “Best to Use When” Summary

Note – Intermediate level

- This presentation is a summary to briefly highlight the differences and similarities of various control architectures.
- This presentation does not explain the art of loop compensation

Control Architecture Summary

Linear

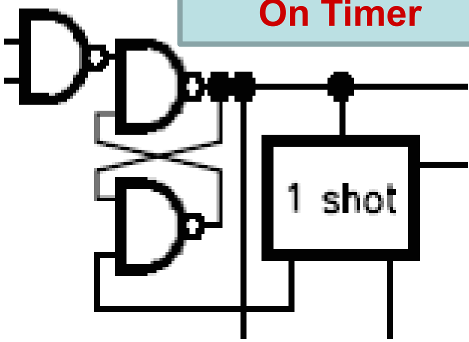
- Voltage Mode
- Voltage Mode with Voltage Feed Forward
- Current Mode
- Emulated Current Mode

Non-Linear

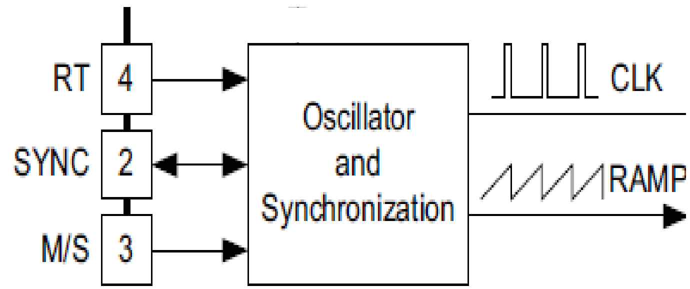
- Hysteretic
- DCAP™ – Adaptive On-Time
- Constant ON Time (COT)
- DCAP-2™ – Adaptive On Time
- Constant On Time with Emulated Ripple Mode
- DCS™ (Direct Control w/ Seamless transition to Power Save Mode)

Circuit Block Elements of Loop Control

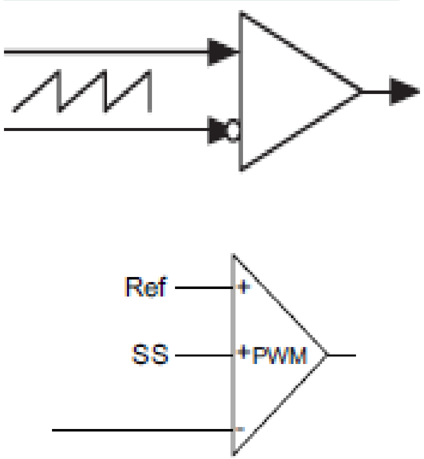
On Timer



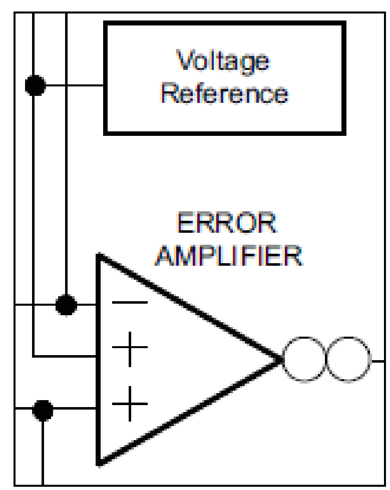
Oscillator



PWM Comparator



Error Amplifier

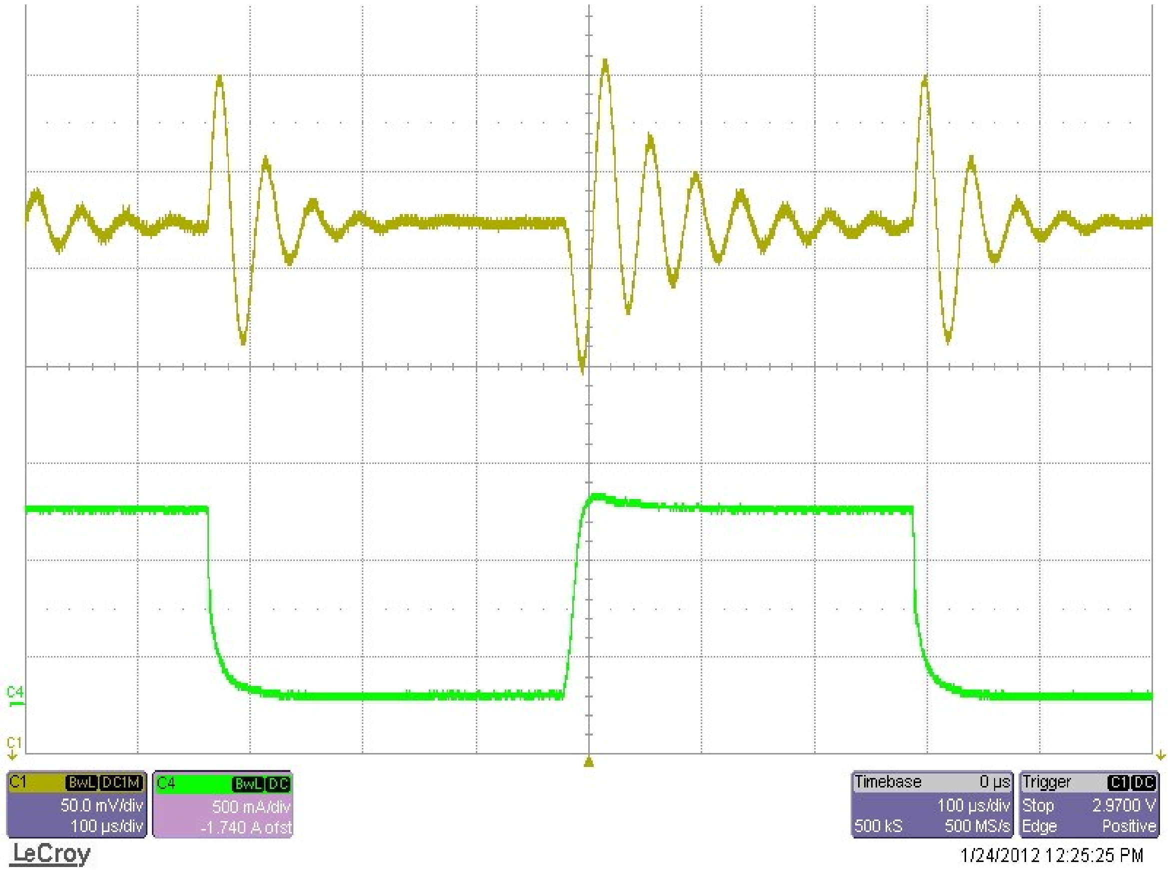


Control Architecture Summary

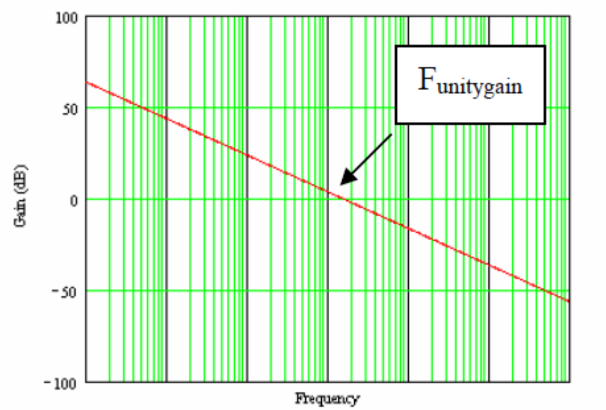
Linear Control Architectures

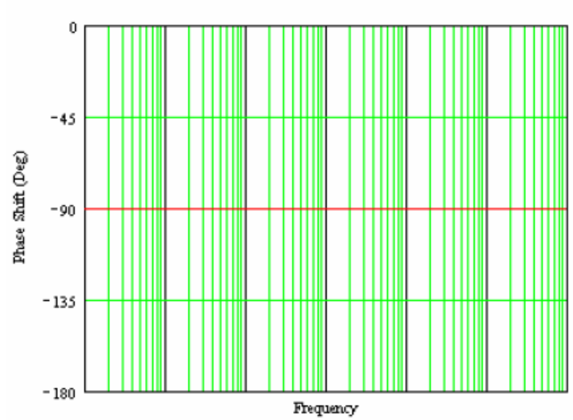
- Voltage Mode
- Voltage Mode with Voltage Feed Forward
- Current Mode
- Emulated Current Mode

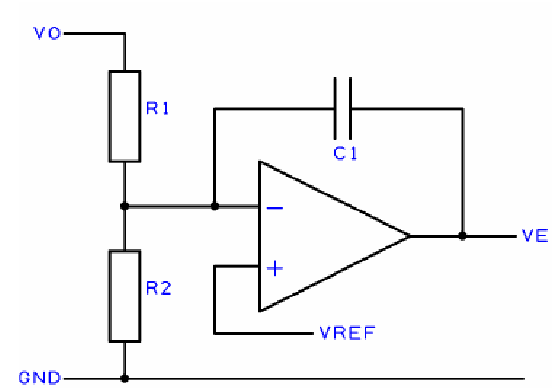
Why do we Compensate?



Type 1 Compensation





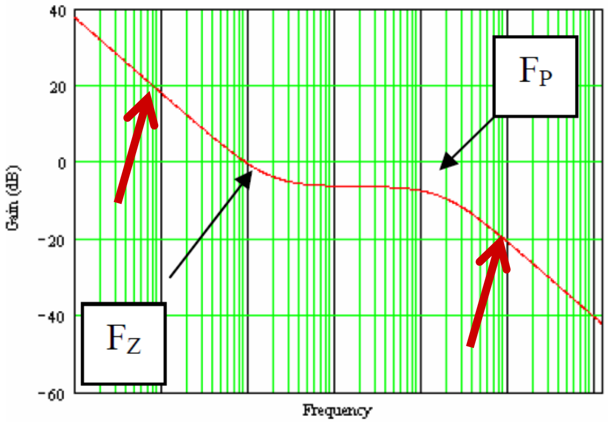


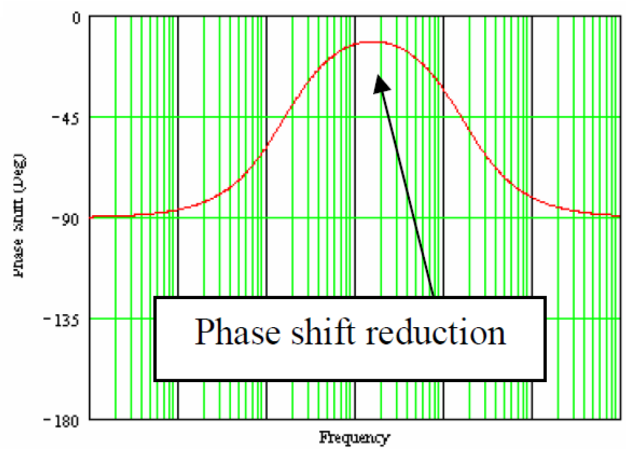
Slope is -20dB/decade

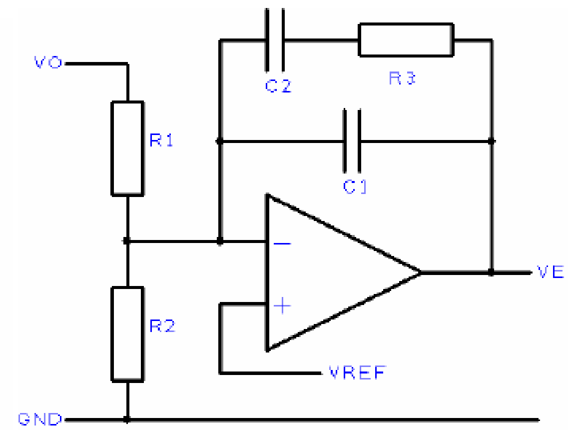
Type 1 Compensation (Dominant Pole Compensation)

- Minimum number of external components to get needed phase margin
- Adjust phase margin by choosing unity gain cross over frequency
- Poor transient response time since cross-over frequency is low
- Good load regulation due to high DC gain.
- Gain falls at a uniform -20dB per decade and phase is shifted by 90°
- Useful for troubleshooting - easy to stabilize by making C1 big enough.

Type 2 Compensation





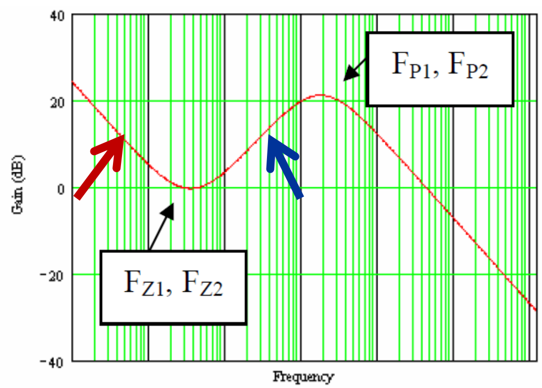


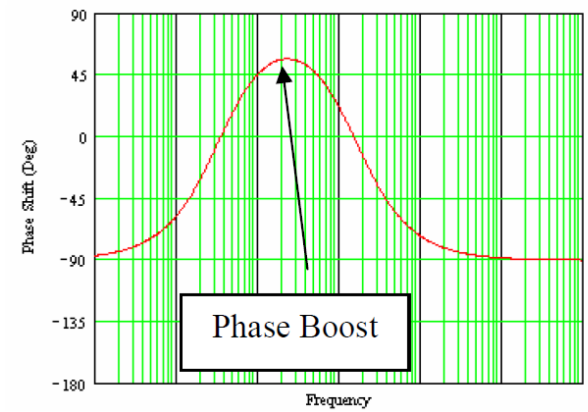
Slope is -20dB/decade

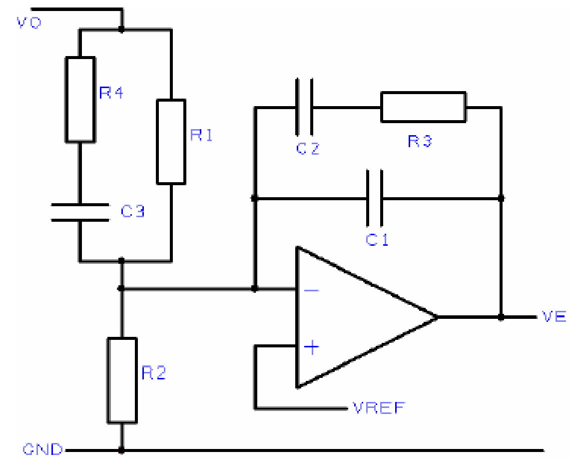
Type 2 Compensation

- A zero is added to cancel the low frequency dominate pole of the power stage
- A pole is added to cancel the ESR zero of the output capacitor
- Reduces compensation network phase shift at cross-over frequency
- Allows for higher cross-over frequency than type 1 – Better transient response
- Useful in Current Mode controlled buck converters
- Gives 180 degrees of phase shift at the peak

Type 3 Compensation







-20dB/decade

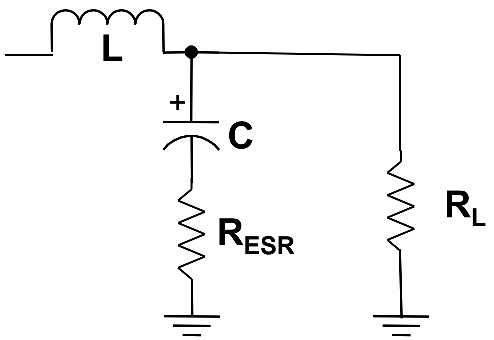
20dB/decade

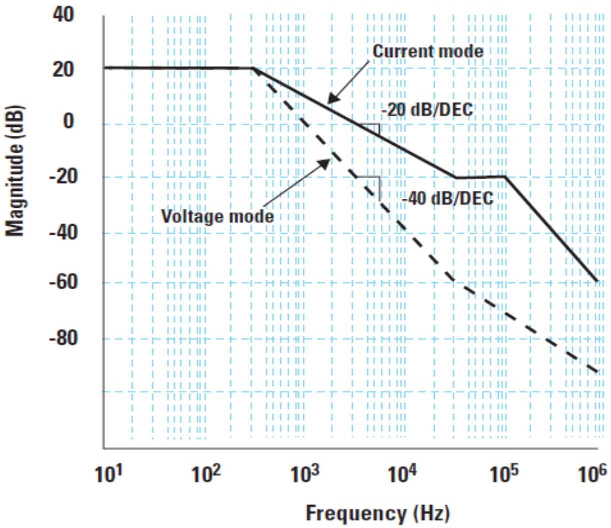
Type 3 Compensation

- More external components required
- Adds another pole and zero to type 2 for enhancement and provides another 90° phase boost (270 degrees total) for a higher cross-over frequency
- Useful in Voltage Mode controlled buck converters (-40dB / decade roll off above the poles of the output filter and -180° phase shift)

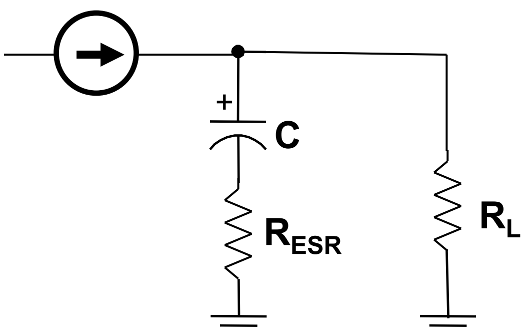
Voltage and Current Mode Power Stages

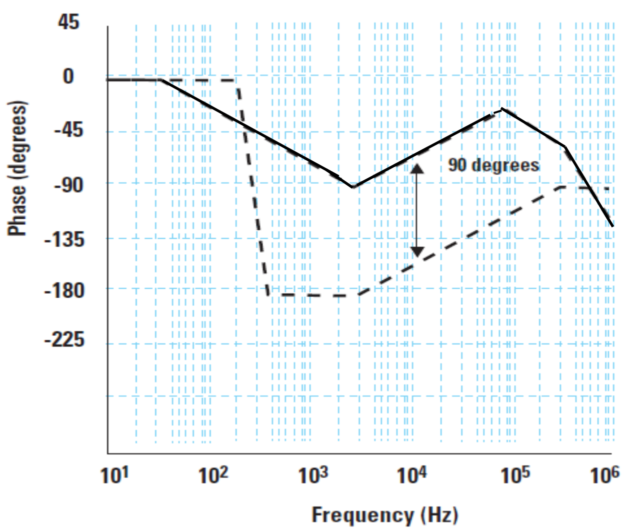
Voltage Mode



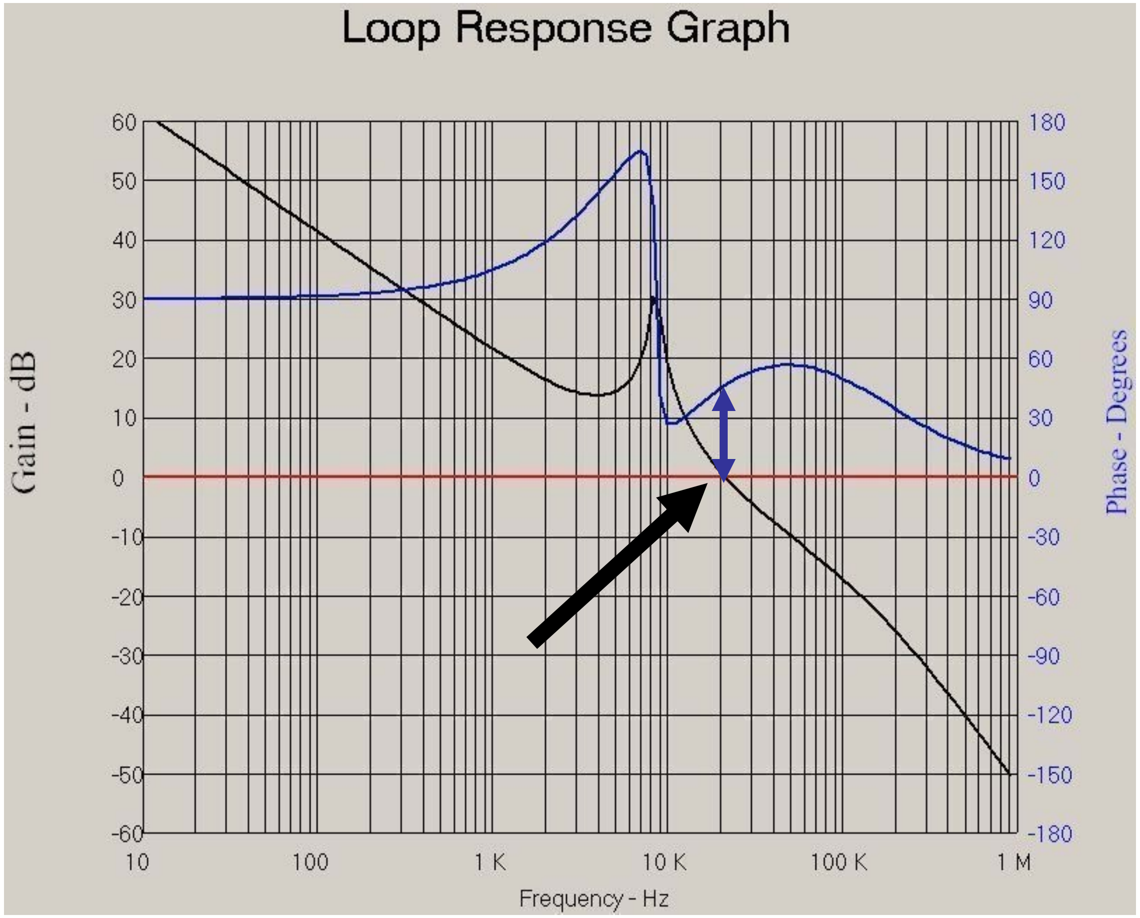


Current Mode





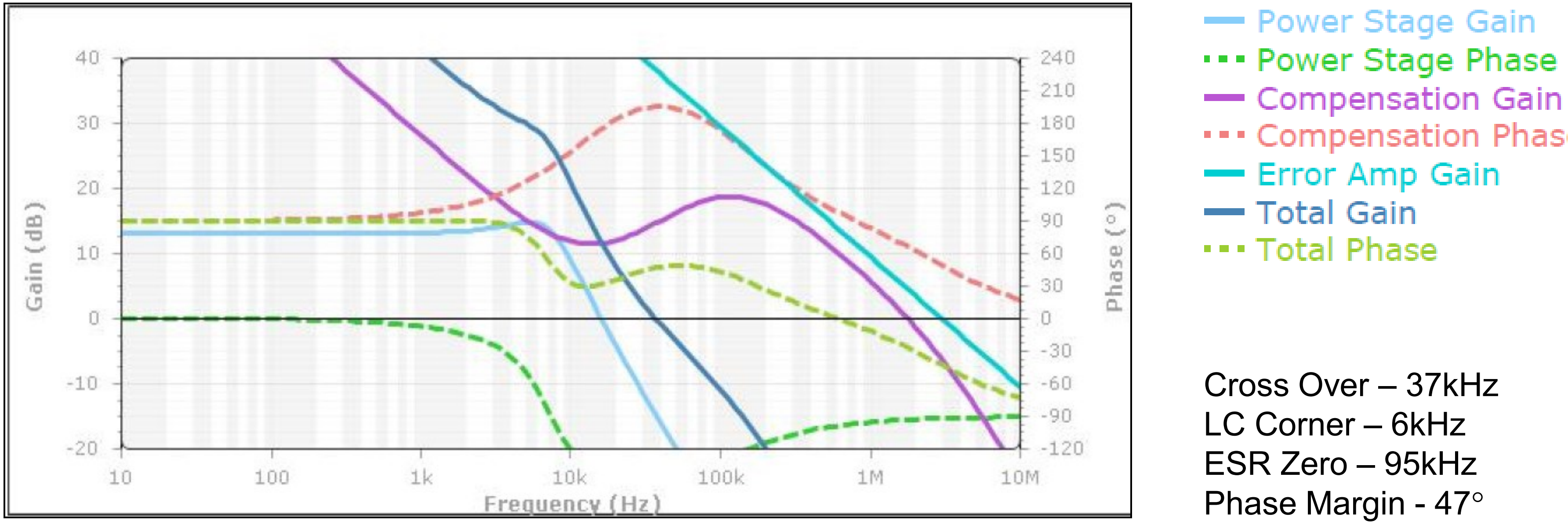
Basic Stability Criterion Example



Reading Bode Plot

1) **Find Cross Over Frequency at 0dB**
   - **21 kHz Cross Over**
2) **Find Phase Margin at the Cross Over Frequency**
   - **45° at 21kHz**
3) **Goal is to have Phase Margin in between 45° and 90° to maintained a well-damped transient response**

Bode Plot Example



Cross Over – 37kHz
LC Corner – 6kHz
ESR Zero – 95kHz
Phase Margin - 47°

When in dB, log A + log B = Log (AxB) & log C – log D = log(C/D)

- Start with the Power Stage gain and phase. What's the Control Mode?
- Add the Compensation gain to Power Stage gain to get Total Gain
- Add the Compensation phase to Power Stage phase to get Total Phase

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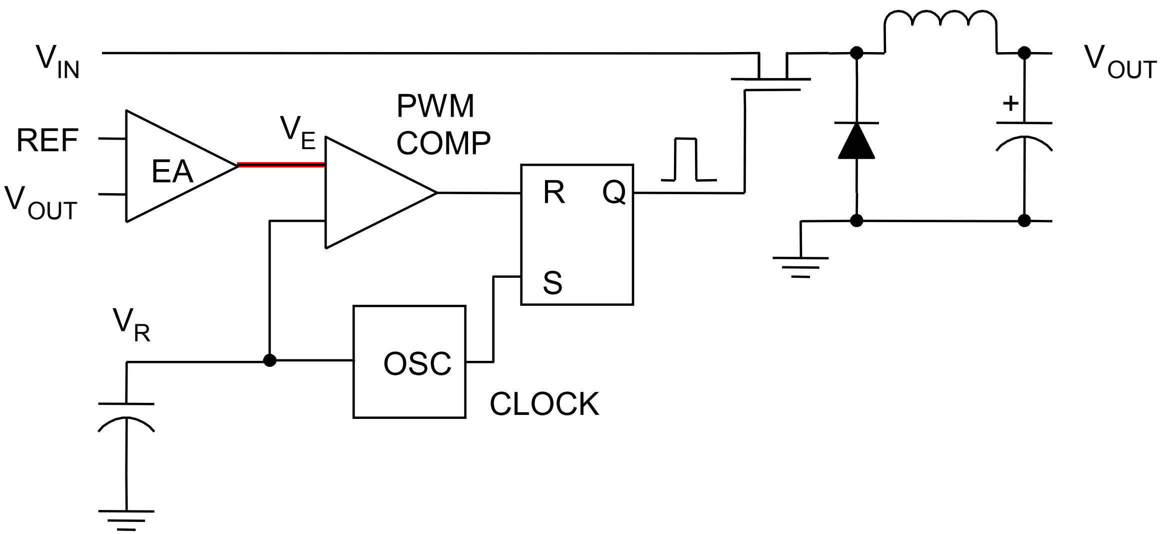
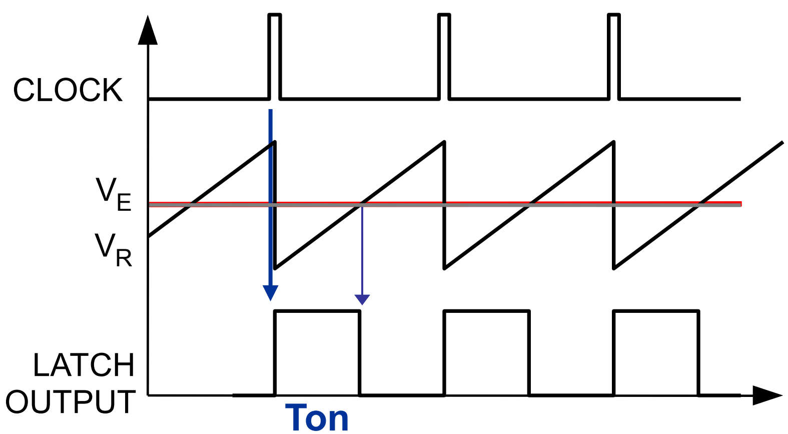
Voltage Mode Control





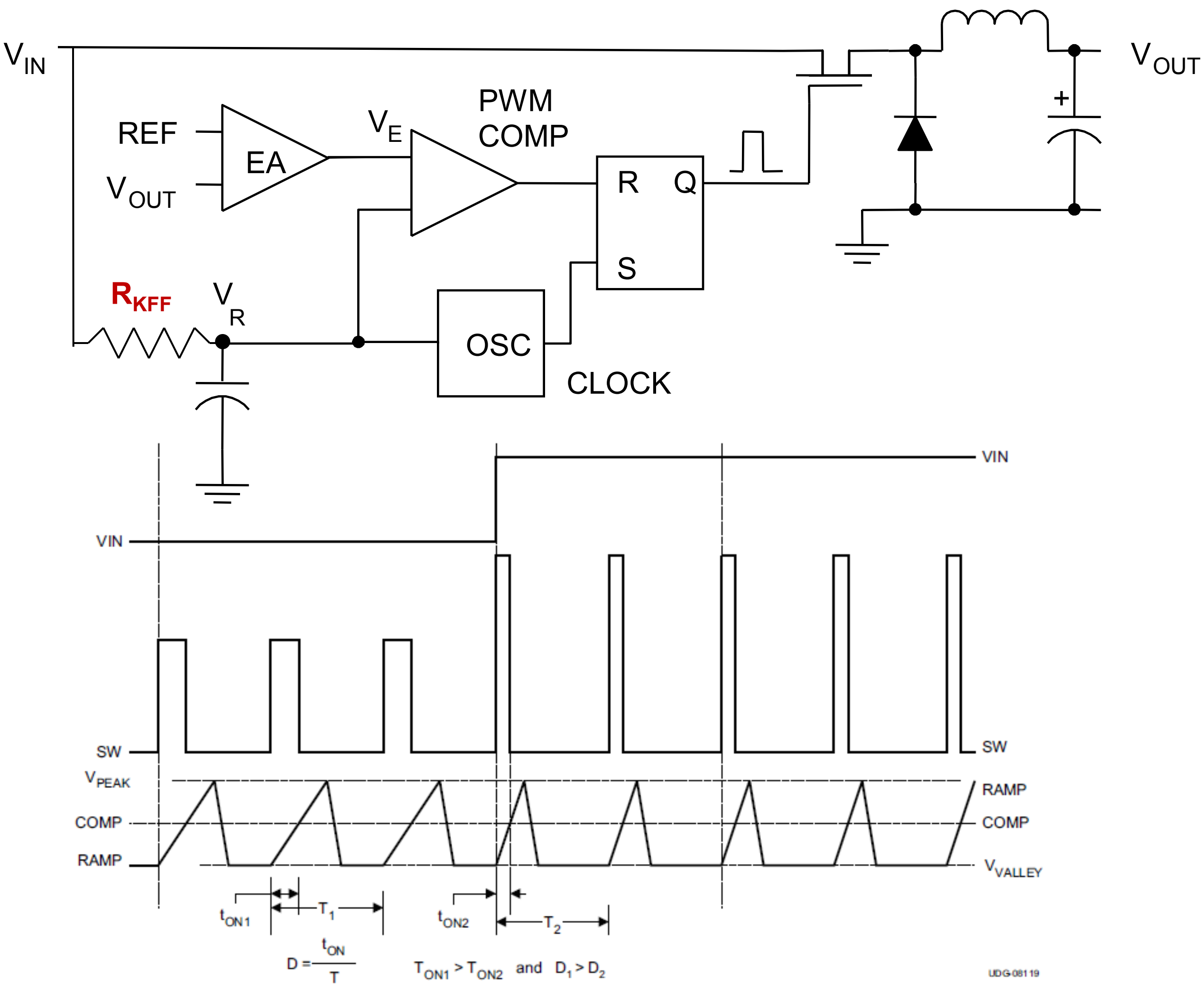
ADVANTAGES

- Single feedback loop
- Good noise margin
- Voltage regulation is independent of current

DISADVANTAGES

- High BW EA required
- More difficult double-pole compensation
- Output caps affect compensation
- V_{IN} affects loop gain

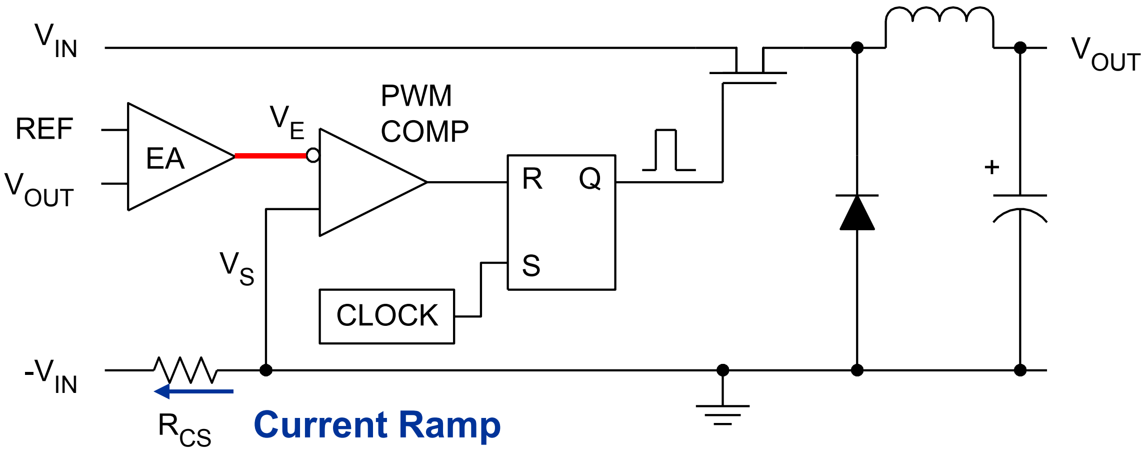
Voltage Mode w/ Voltage Feed-Forward



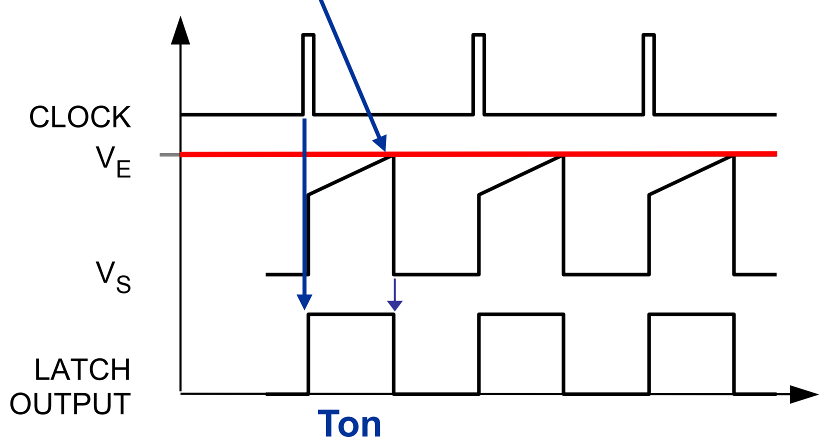
Ramp Generator Circuit

- Varies the PWM ramp with line voltage
- Maintains constant ramp magnitude
- 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



Current Ramp



ADVANTAGES

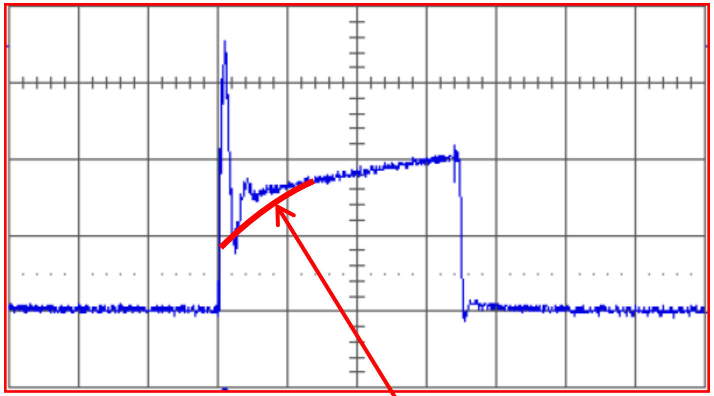
- Fast response to output current changes
- Single-pole compensation
- Inherent current limiting
- Inherent feed forward
- Multiple phase current sharing possible

DISADVANTAGES

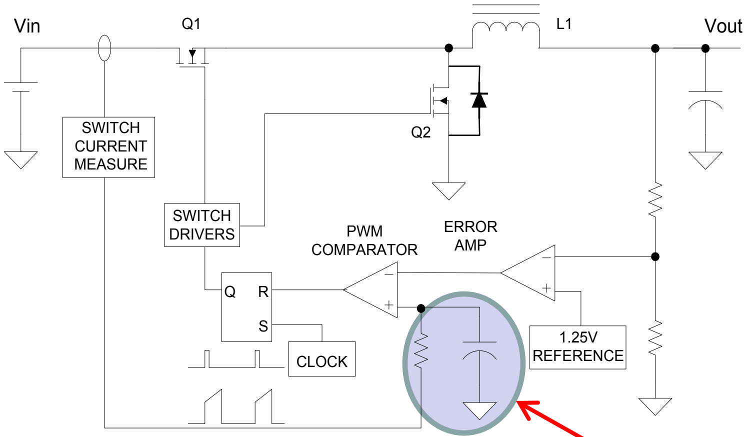
- Two feedback loops if a current amplifier is used
- Need for slope compensation
- Current limit "tail"
- Noise sensitivity due to leading edge current spike

Current Mode Leading Edge Spike

Filter out the leading edge spike with a RC filter



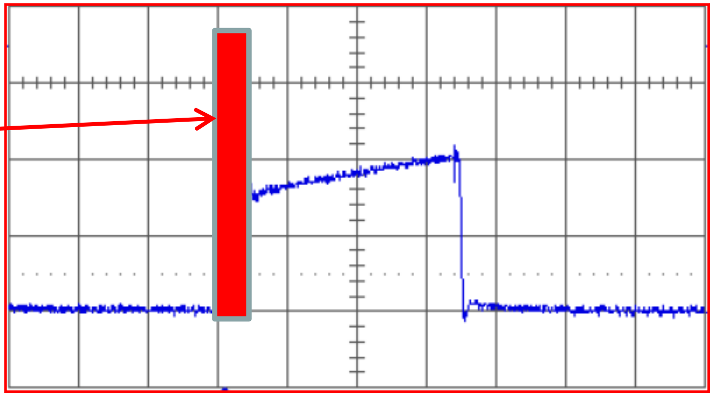
Waveform Distortion is a problem for small duty cycles



Filter

Use leading edge blanking

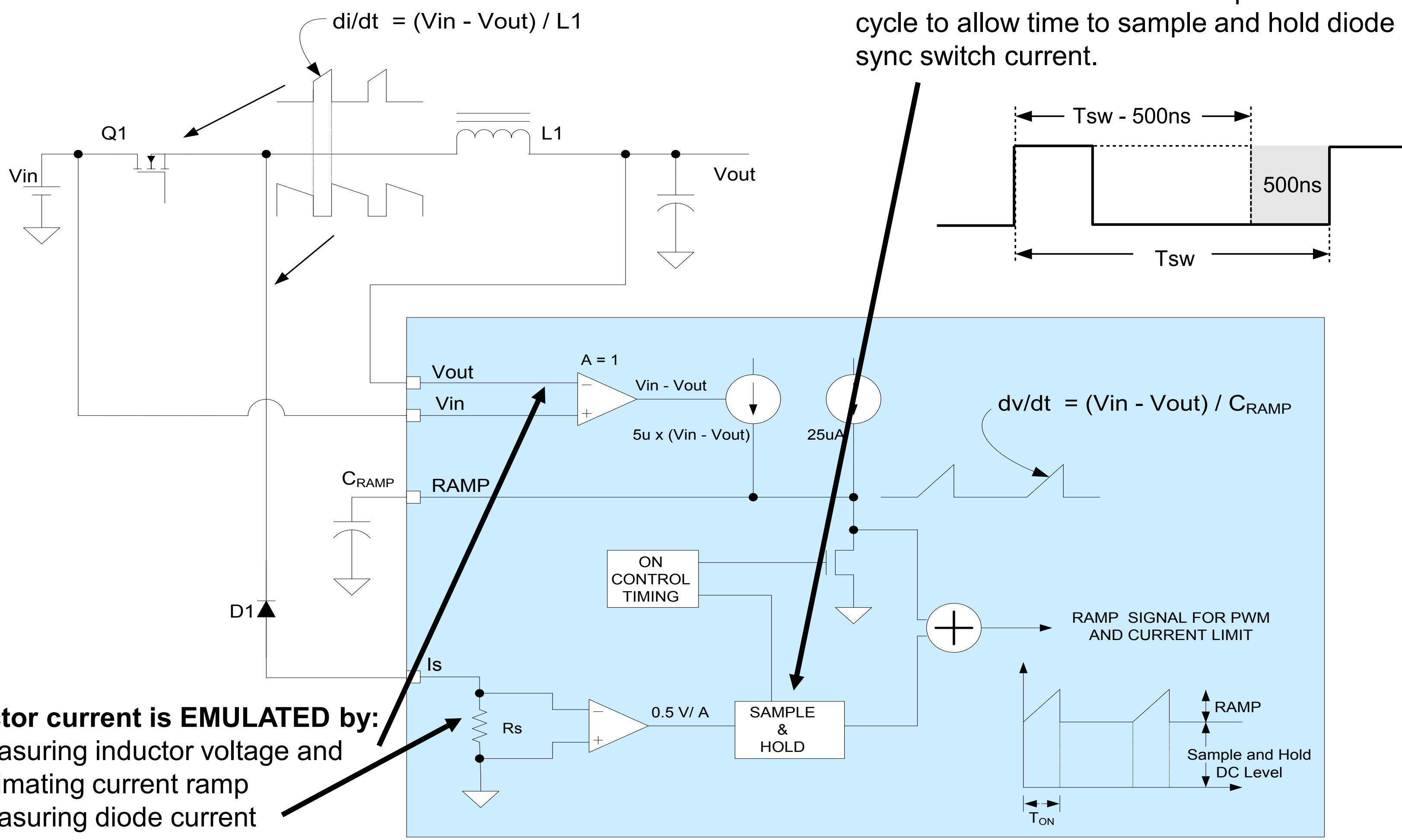
This portion of the duty cycle is un-available Precludes narrow pulses (high Vin to Vout ratios)



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

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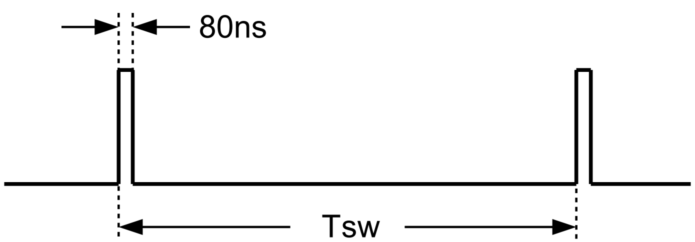
Emulated Current Mode

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



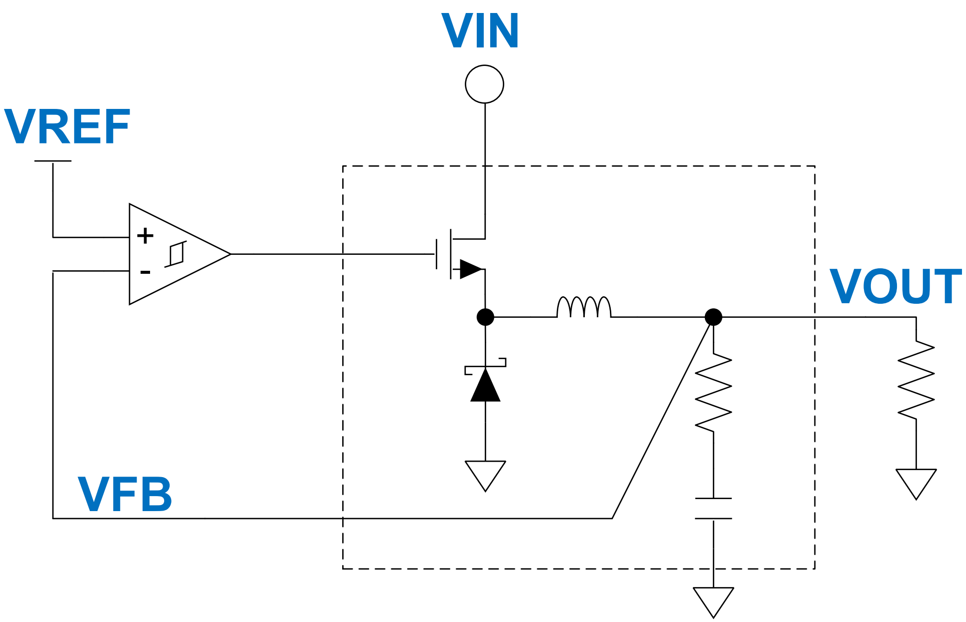
Disadvantages

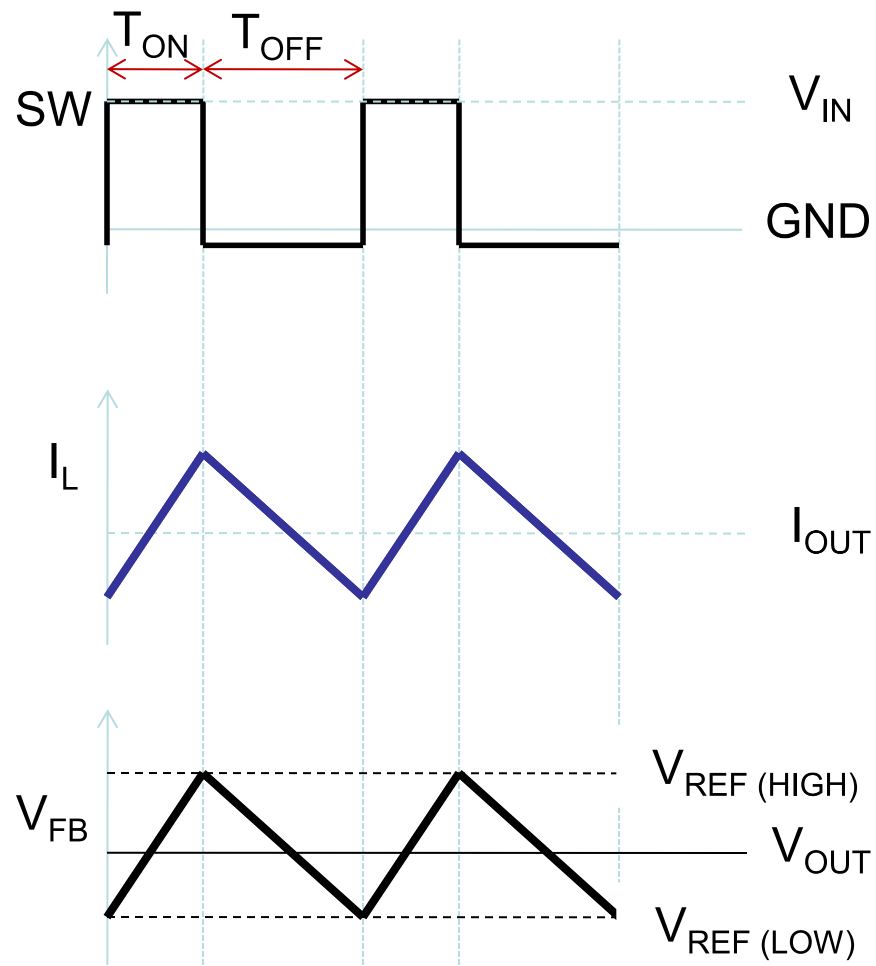
- Maximum frequency and duty cycle is limited
  - Forced off-time is fixed and becomes a higher % of switching period
  - Less % of on-time is available at high frequency
  - Forced off-time of ~500ns needed for Sample and Hold current sensing circuit

Non- Linear Control Architectures

- Hysteretic
- Constant On Time (COT)
- COT with Emulated Ripple Mode
- D-CAP^{TM} (Adaptive On Time)
- D-CAP2^{TM}
- DCS^{TM} (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

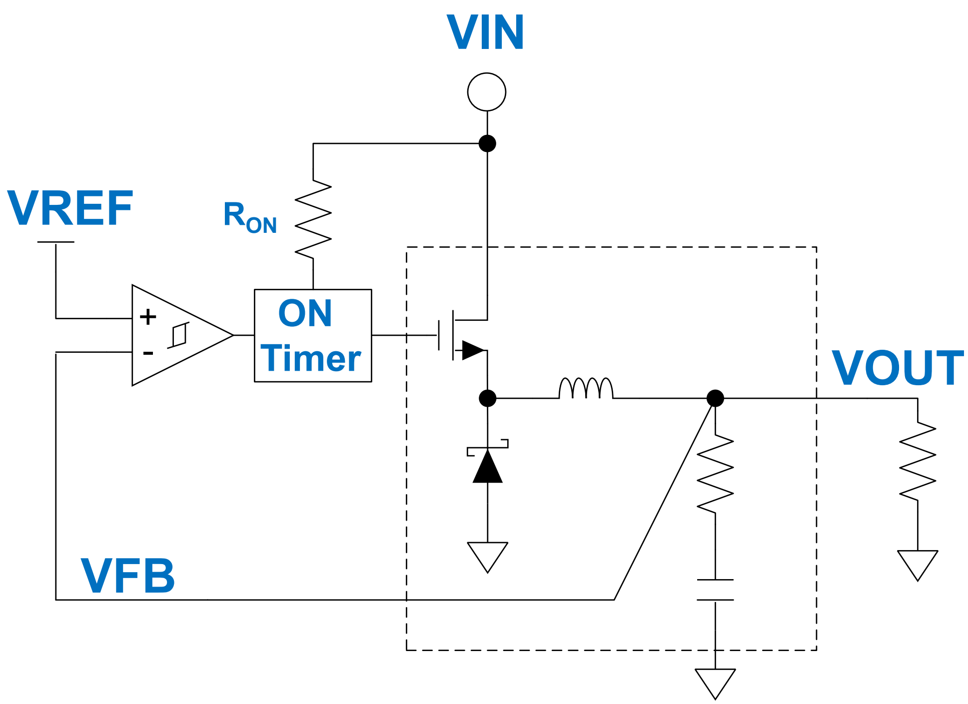
ADVANTAGES

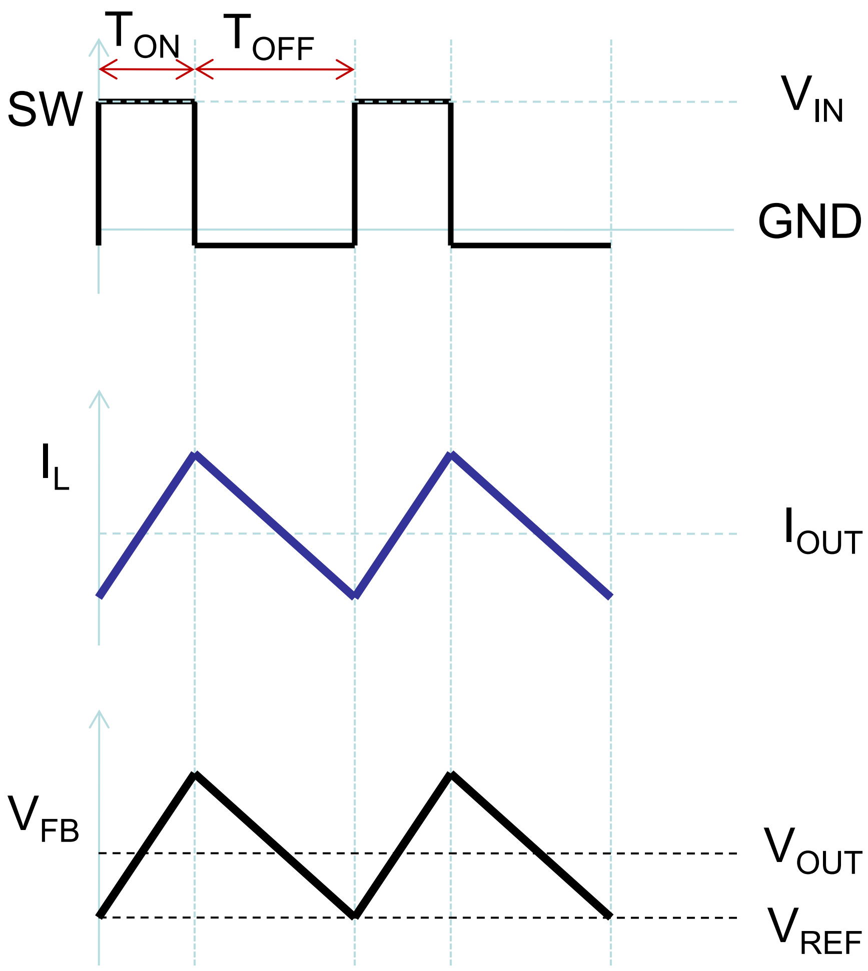
- Simple controls - bang/bang system
- No loop compensation
- Fastest response to load changes

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)



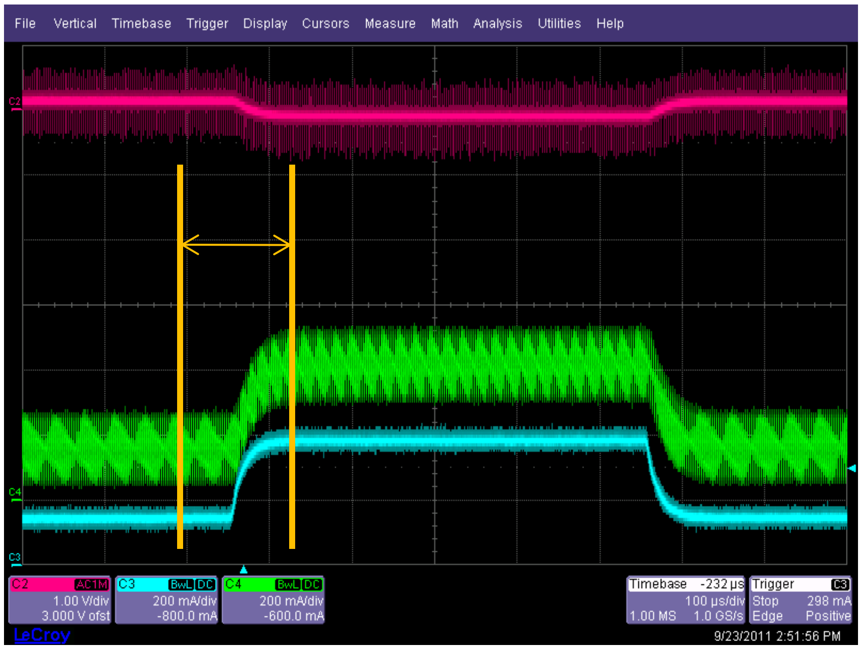


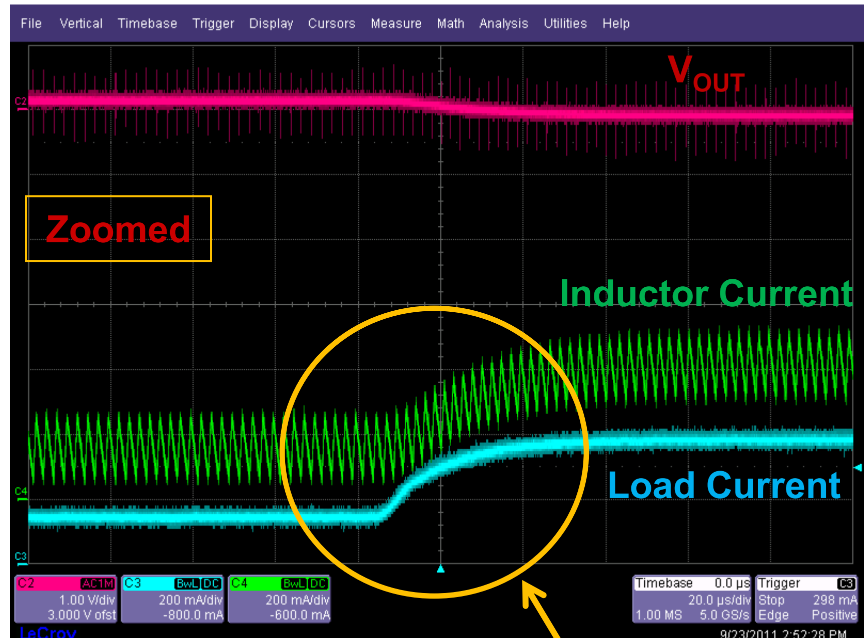
TON - Terminated by On-Timer

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

COT Fast Transient Response

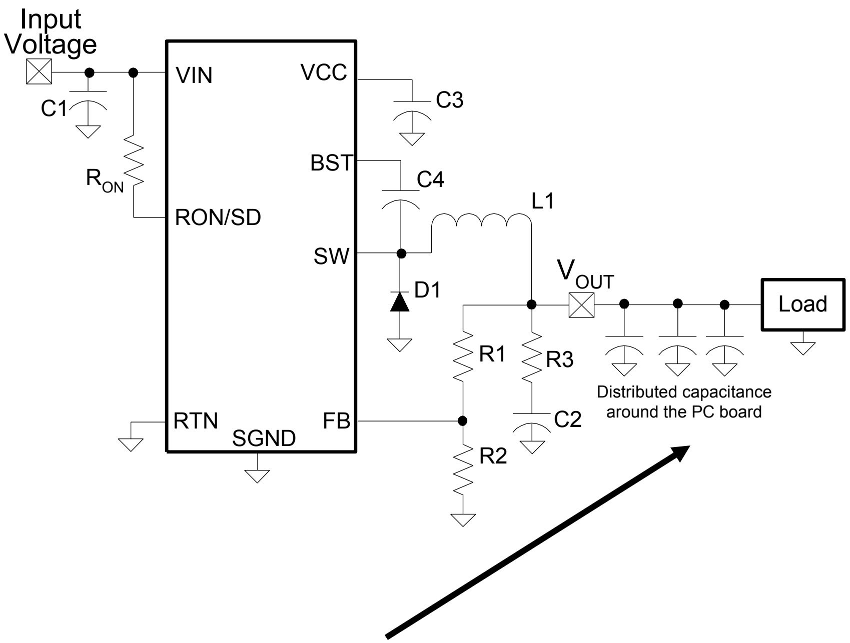
- COTs have no error amplifier and compensation to limit the bandwidth
- This results in very fast response to load/line transients.



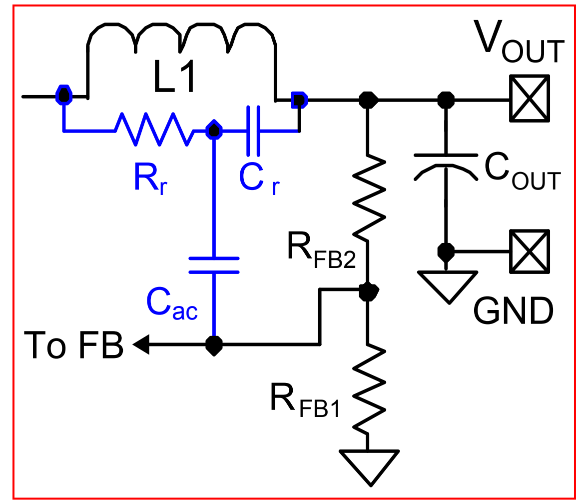


Fast Response

COT Ripple Requirement



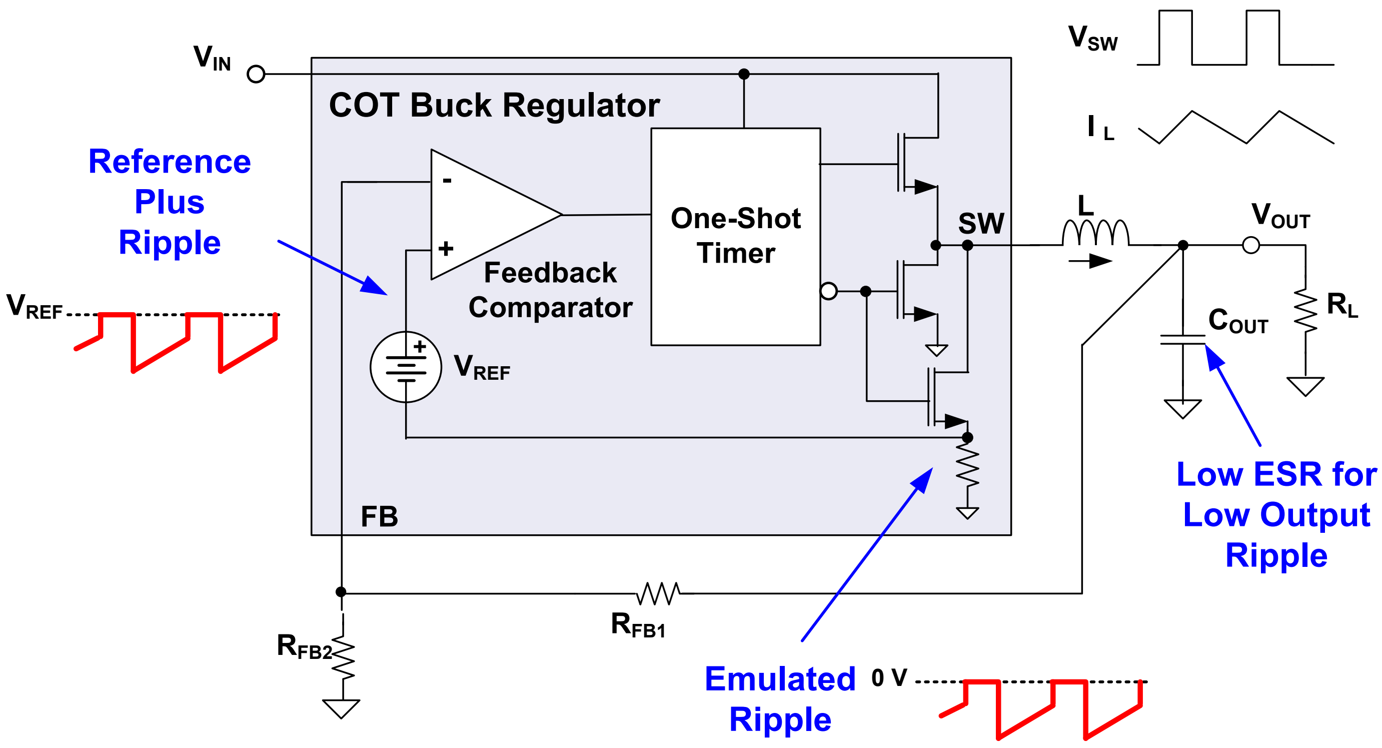
A BIG NO-NO! However……



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

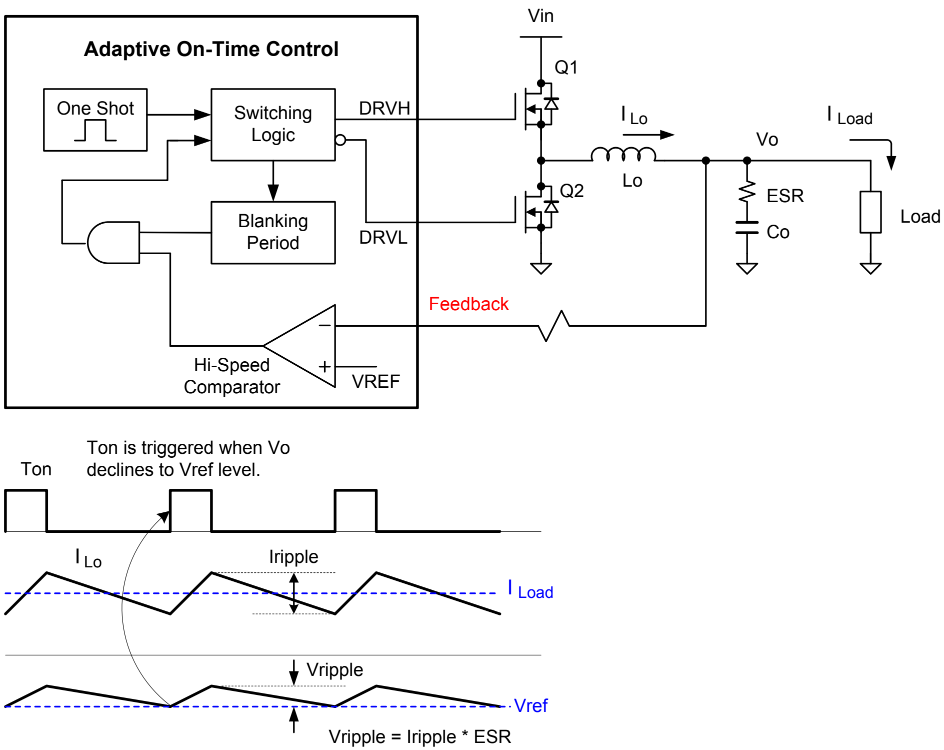
Advantages

- 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^{TM} Mode (Adaptive On-time)



ADVANTAGES

- No loop compensation
- Fastest response to load changes

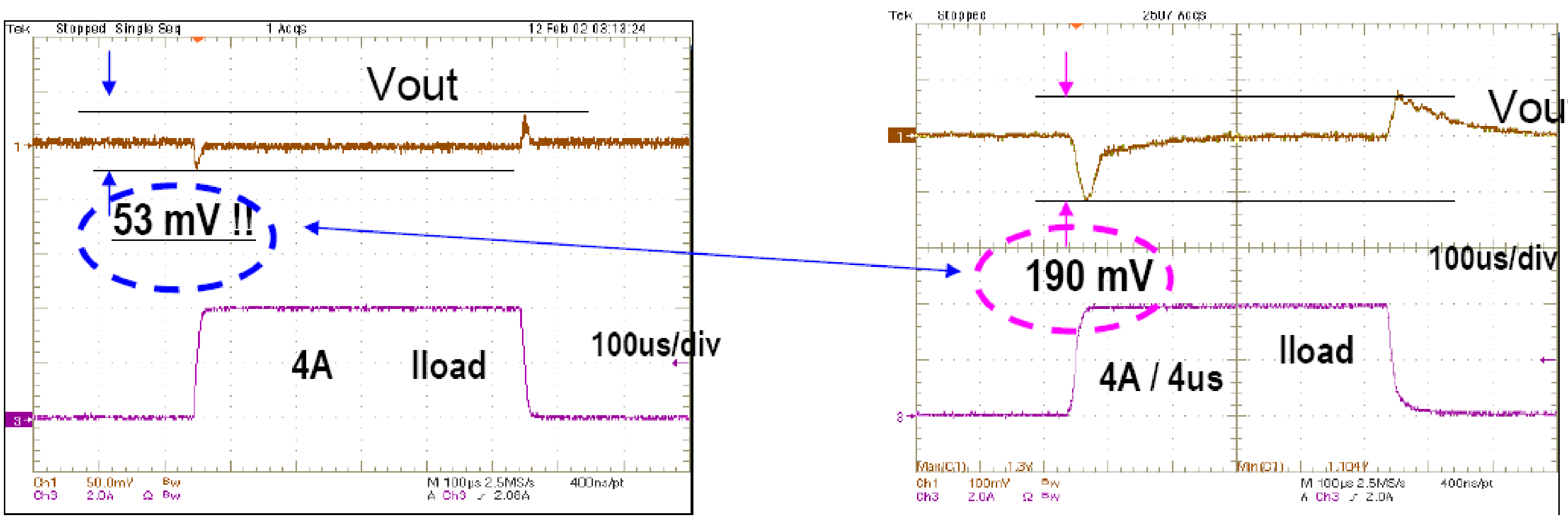
DISADVANTAGES

- 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 **Cap**acitor (D-CAP)

- Each Ton pulse duration is calculated based upon Vin, Vout, nominal fout
- 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



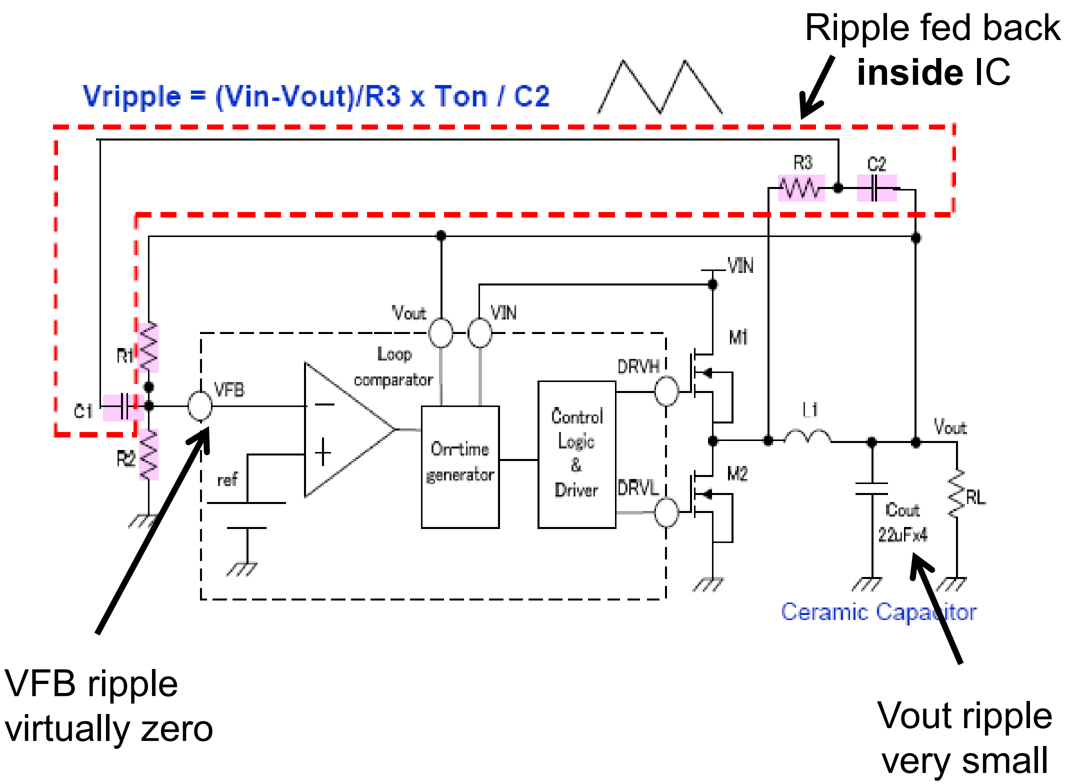
D-cap mode transient response

Voltage mode transient response

Cout=22uFx3 ⟷ Cout=100uFx4

D-CAP2^{TM} Control Mode

Basically, D-CAP2^{TM} is D-CAP^{TM} plus internal ripple injection allowing for output ceramic capacitors use without added components

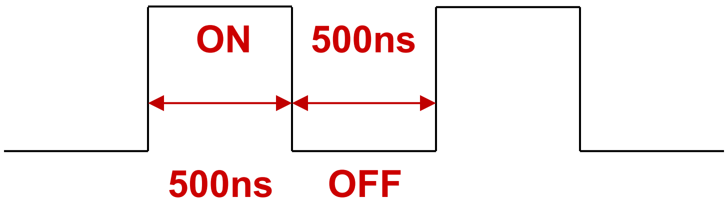


Advantages over DCAP

- Use when ceramic output caps are required: Less jitter but output voltage accuracy is degraded by emulated current information.

Constant versus Adaptive On-Time

10Vin, 5Vout, 1MHz

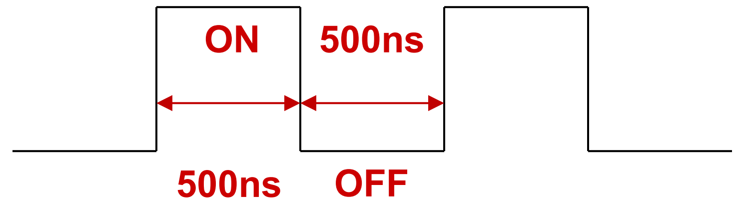


10Vin, 2.5Vout, 500kHz

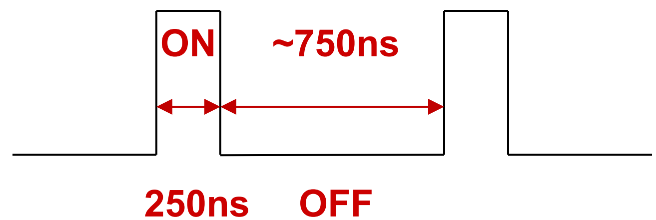
Constant On Time (COT)

- On Time is Fixed
- Off Time is Hysteretic
- Frequency Varies with Vin, Vout, and Iout (slightly)

10Vin, 5Vout, 1MHz



10Vin, 2.5Vout, 1MHz



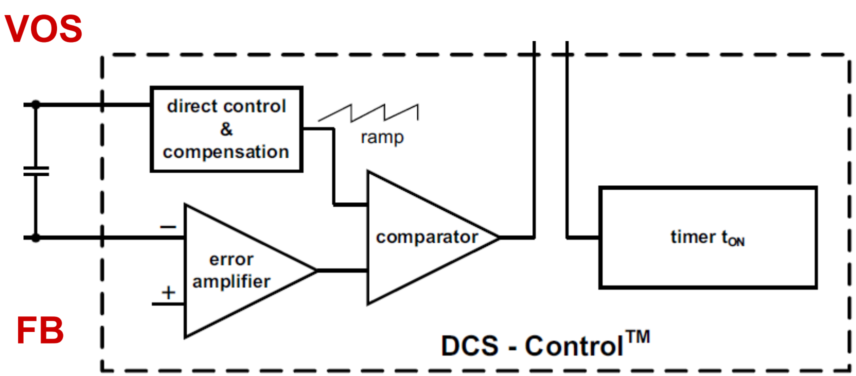
Adaptive On Time (D-CAP)

- On Time is function of Vin, Vout
- Off Time is Hysteretic
- Frequency less variable than COT since On-Time is dynamic with Vin, Vout, & Iout

Adaptive On-Time allows control of the switching frequency

DCS-Control™

Proprietary Ramp Circuitry Feeds VOS (Vout) to Comparator



- **Feed Forward Capacitor Required for PFM Mode Performance**
- **Error Amplifier for Precise DC Regulation**
- **Hysteretic Comparator for Fast Response to Changes in Output Voltage**
- **On Timer for PFM mode and Constant Operating Frequency**

Advantages

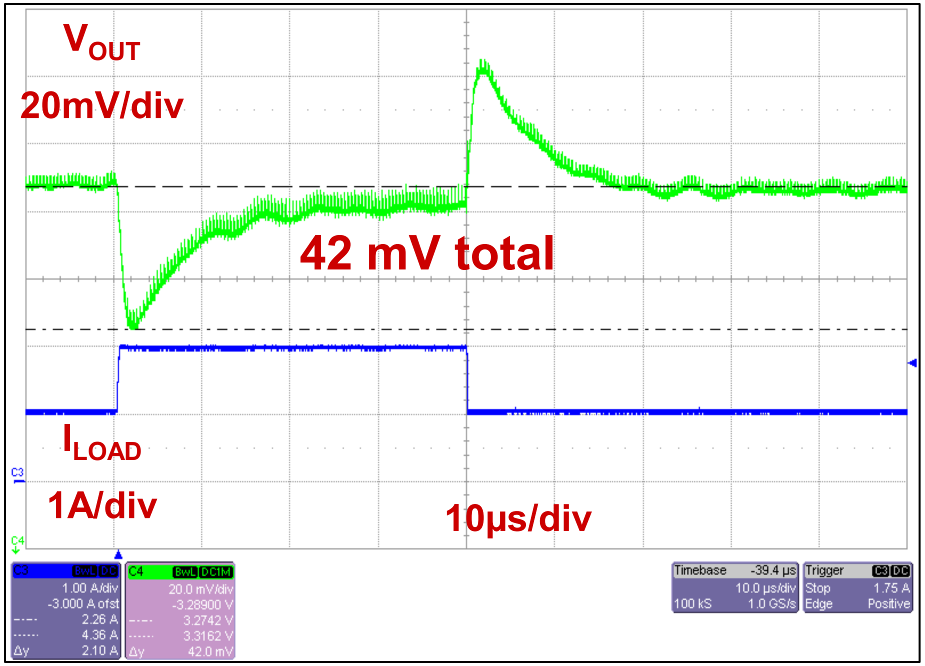
- Fast transient response by direct path to output voltage (VOS).
- Additional Voltage mode loop for high dc accuracy (FB).
- Seamless transition between PWM and Power Save Mode (single building block – no switch, no glitch).
- Supports low ESR output caps.

Disadvantages

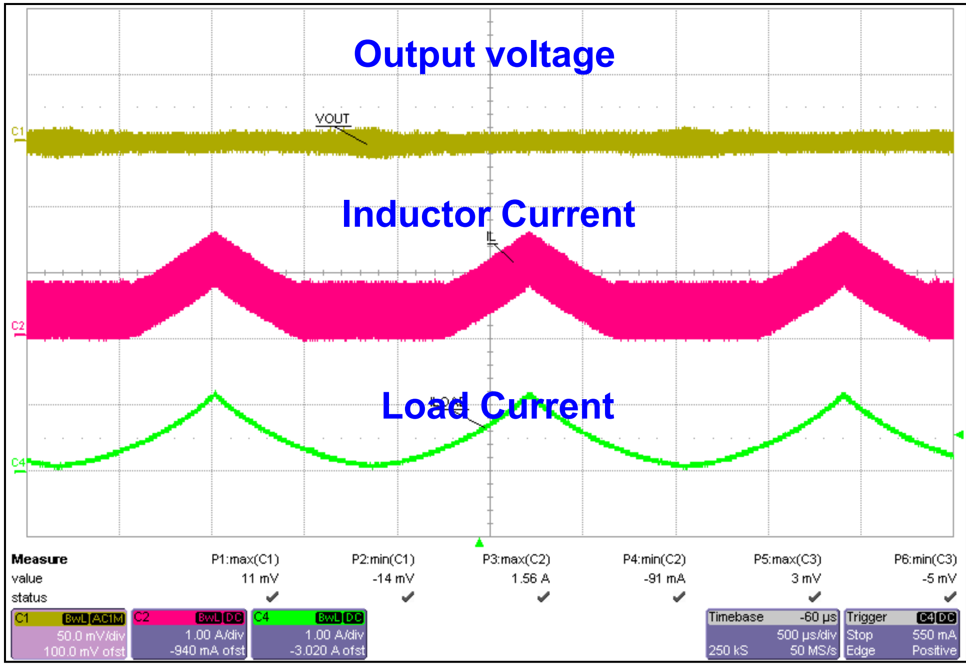
- Frequency variation at extreme duty cycles
- Forced PWM mode at high duty cycles

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

Popular Devices

Voltage Mode
- LM2267x , TPS5430, LM21215, TPS54610, LM285x

Voltage Mode with Voltage Feed Forward
- TPS40170, TPS4005x, TPS56221, TPS40400

Current Mode
- TPS54620, TPS54160, LM21305, TPS54618

Emulated Current Mode
- LM557x, LM2557x, LM5005, LM5117, LM5116, LM5119

Hysteretic
- LM5007, LM3485, LM3475

DCAP – Adaptive On-Time
- TPS51124, TPS51216, TPS53355, TPS53219

Constant ON Time
- LM2501x, LM5006, LM5007/8/9, LM310x

DCAP2 – Adaptive On Time
- TPS54327/8, TPS54527/8, TPS53114, TPS5312x

Constant On Time with Emulated Ripple Mode
- LM315x, LM310x, LM25011

DCS (Direct Control w/ Seamless transition to Power Save Mode)
- TPS62230, TPS62120/30/40/50

High Level "Best to Use When" Summary

Voltage Mode
- Use when synchronized / fixed switching frequency is needed. Better for higher duty cycles than current mode.

Voltage Mode with Voltage Feed Forward
- Input Voltage changes – Useful in Automotive, Battery Back up.

Current Mode
- Synchronized / fixed switching frequency is needed with lower parts count. Fast transient response when fixed frequency is needed.

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

Hysteretic
- Low cost – Few parts count. Fast transient response. Frequency not critical.

DCAP, Constant On Time
- Fast transient response when using POSCAP or medium ESR Cout, reduced parts count.

DCAP2, Constant On Time with Emulated Ripple Mode
- Fast transient response when using ceramic cap. Reduced parts count.

DCS (Direct Control w/ Seamless transition to Power Save Mode)
- Light load efficiency is needed, fast transient response, reduced parts count.

Thank You!