Constant-On-Time, Peak Current Mode, or Zero Delay PWM: How to Make the Right Decision?

POWER LIKE A BOSS Seminar

-Monolithic Power Systems/WE

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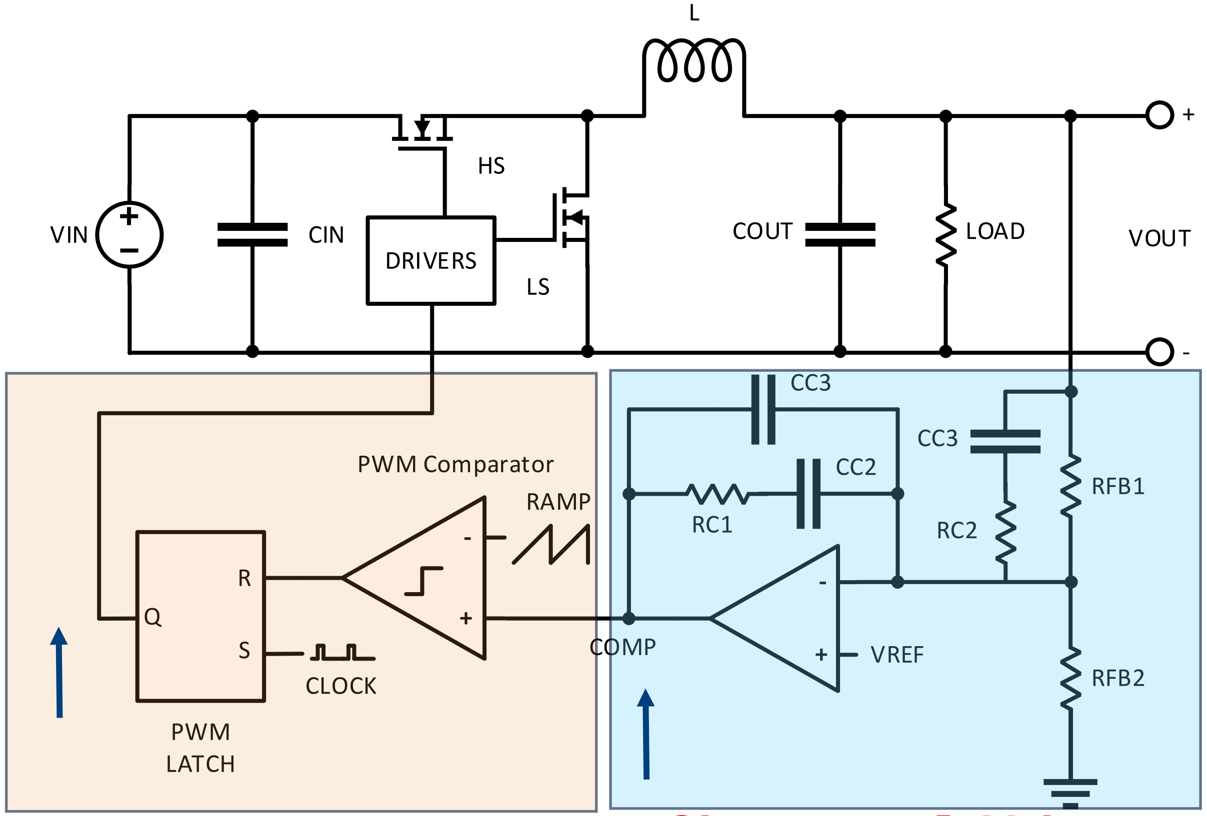
Voltage Mode Control – Method of Operation

Legend
Fast Change: ↑
Slow change: ↑

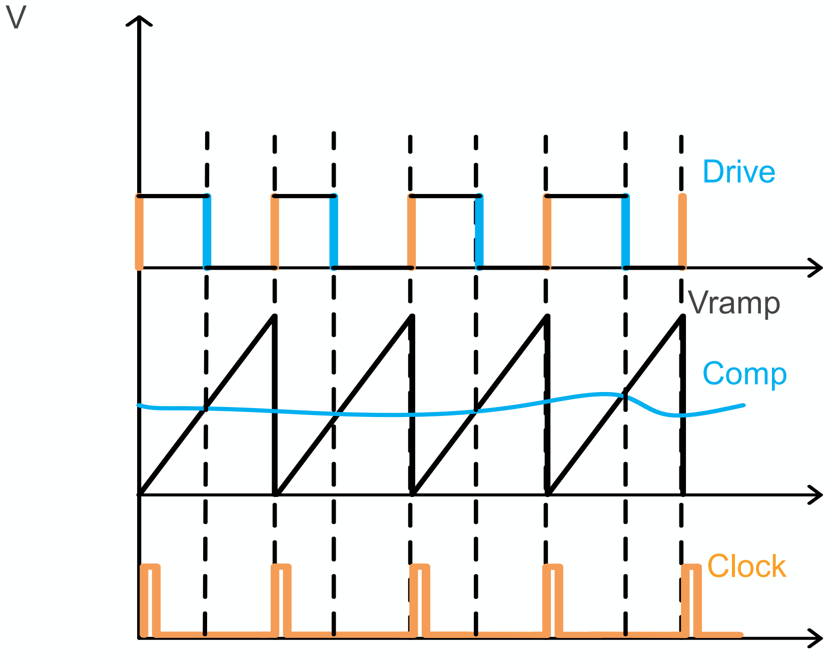


1. Sudden load current increase causes VOUT to drop

Slow Loop → Voltage

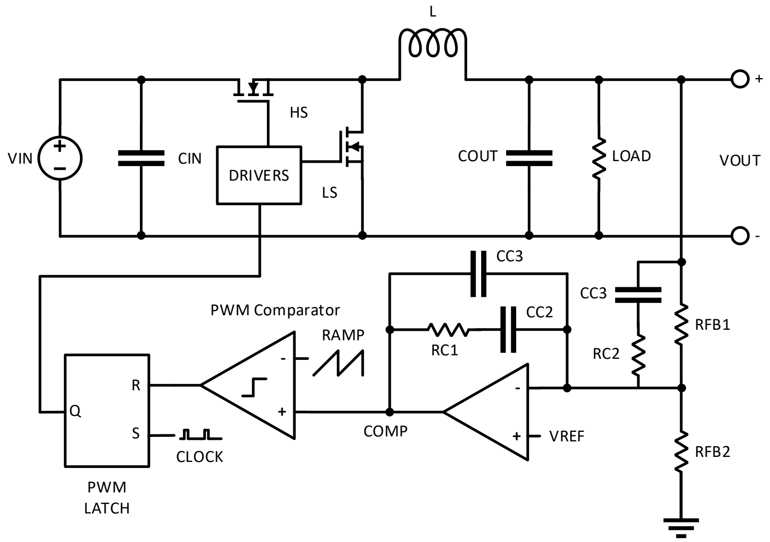
2. VOUT drop causes COMP to increase

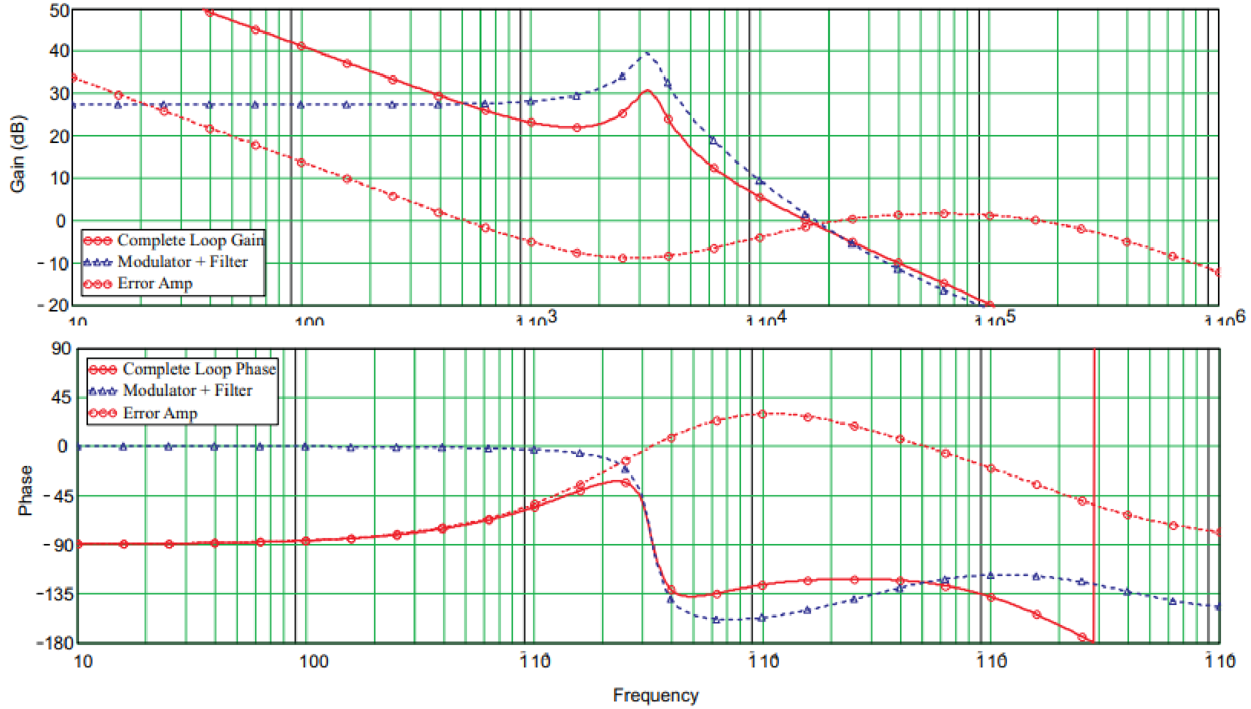
3. COMP increases causes duty cycle to increase



Stability is sensitive to Vin, Cout, and Iout!!!

Voltage Mode Control – Pros and Cons



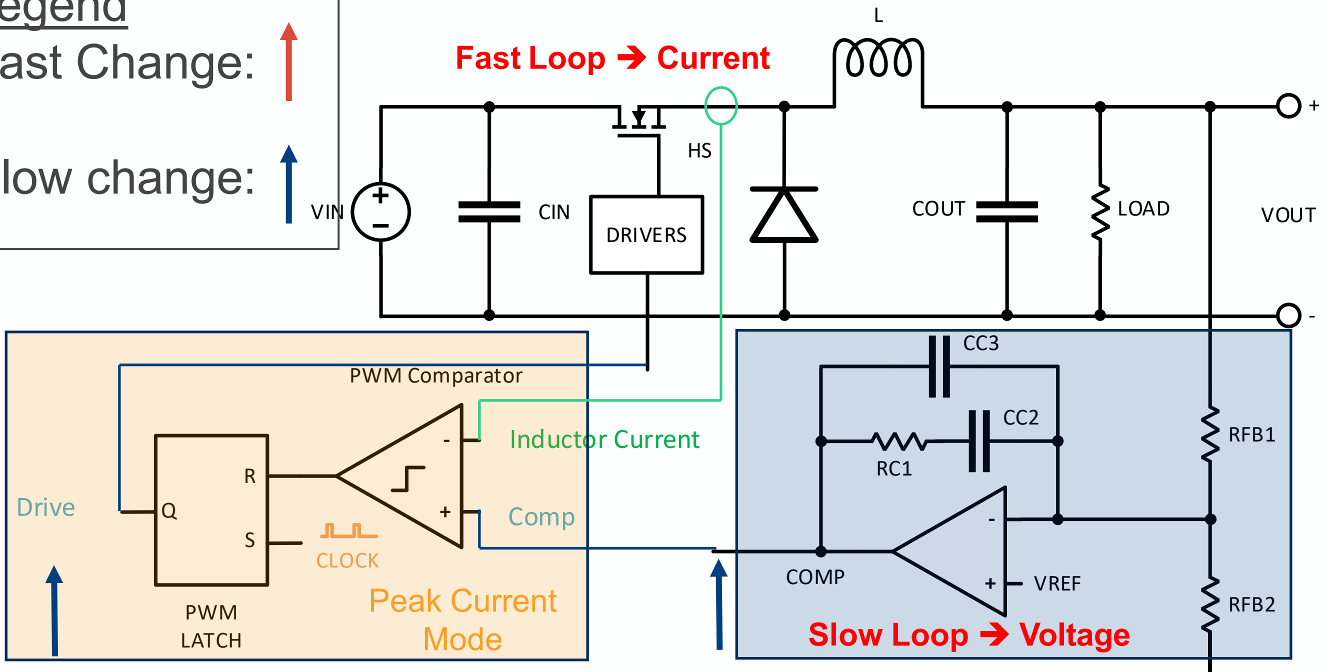


- \+ Simplest Control Method ☺
- \+ Good noise immunity ☺
- \- Due to undamped LC output filter, requires high ESR capacitors or type III compensation ☹
- \- Control loop gain is inversely proportional to VIN, so crossover gain will shift as VIN change. ☹
- \- Line transient performance is poor. Load transient performance is okay ☹

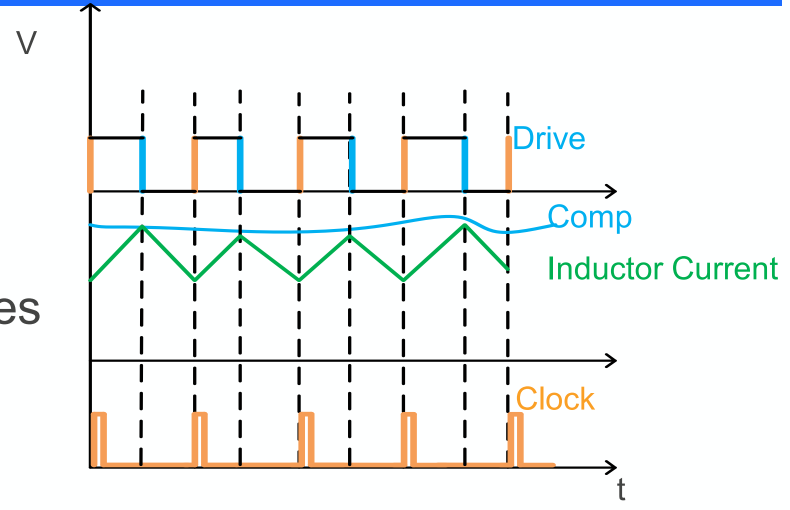
Control loop gain and line transient performance can be mitigated if ramp is made proportional to VIN.

How Is The Control Method Evolving? – Peak Current Mode Control

Legend
Fast Change: ↑ (red)
Slow change: ↑ (blue)



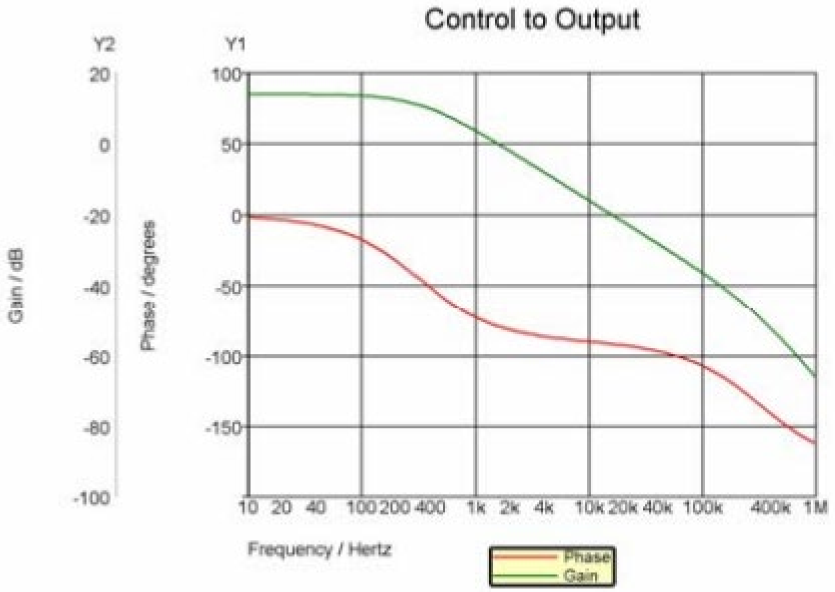
1. Sudden Current Increase causes output to drop



PWM Modulation Circuit

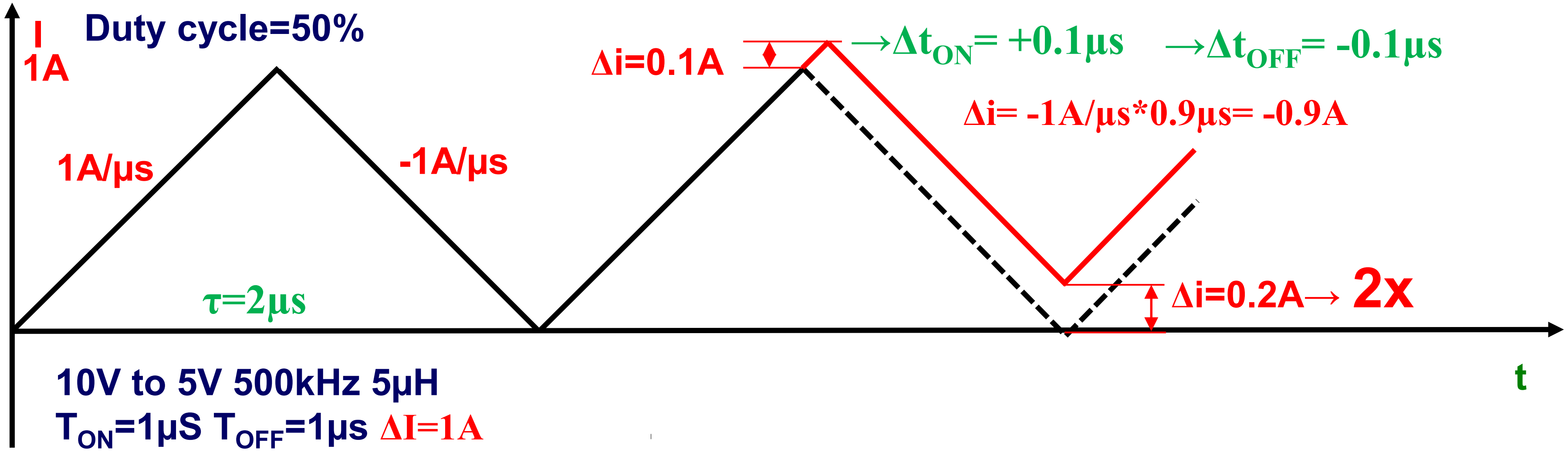
2. Output drop Linear Control causes comp to increase

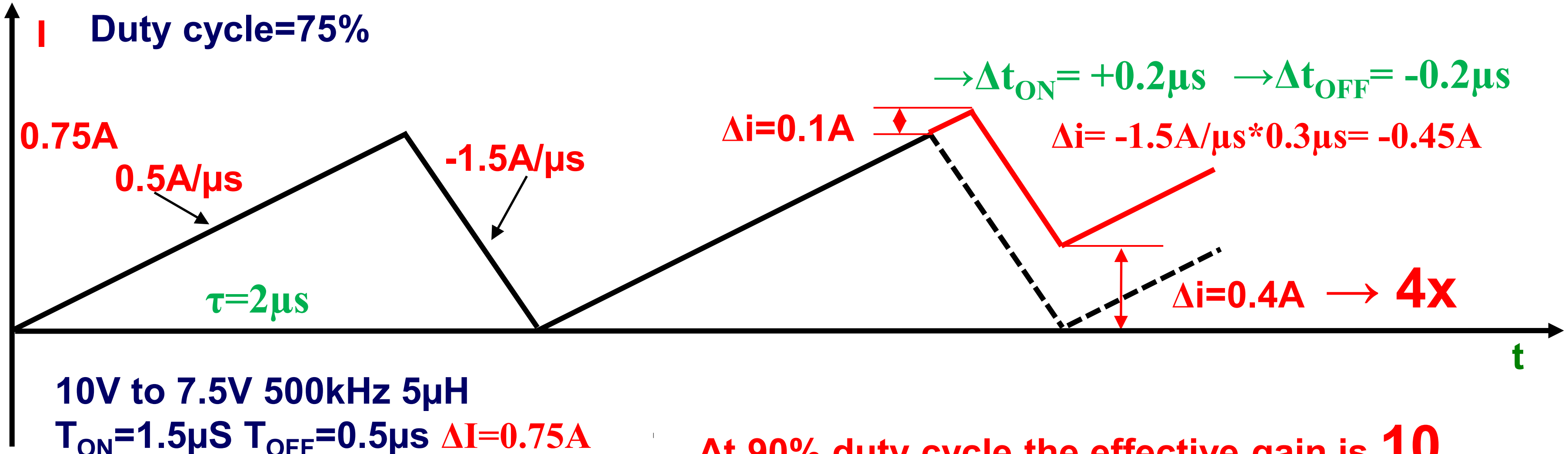
3. Comp increases causes duty cycle to increase



- Get rid of the double pole
- Power stage bode plot likes RC filter
- Stability is not sensitive to Vin, Cout and Iout

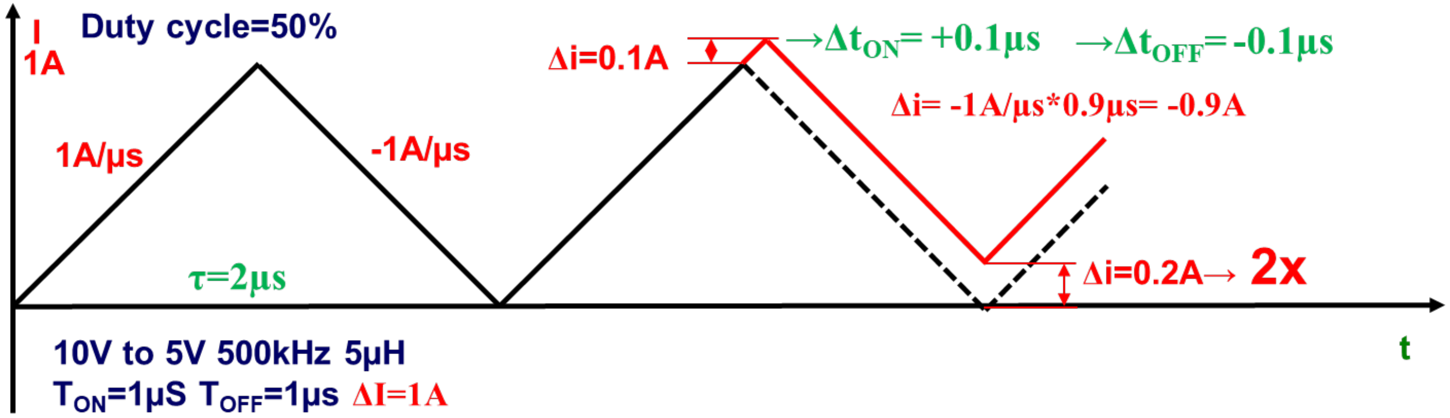
Slope Problem in fixed frequency peak Current Mode

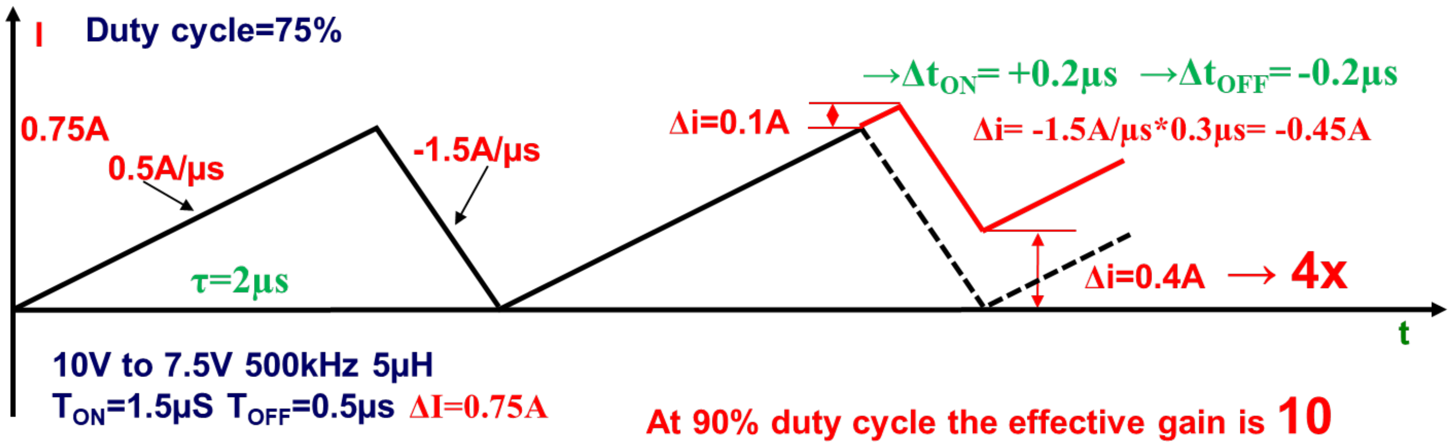


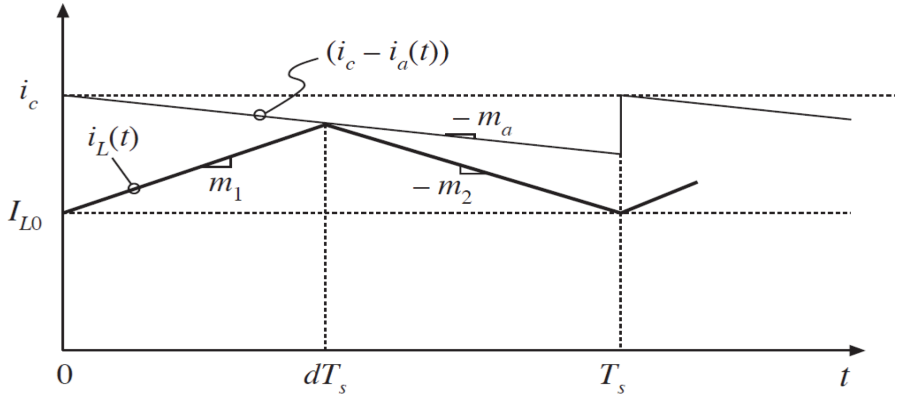


At 90% duty cycle the effective gain is **10**

Slope Problem in fixed frequency peak Current Mode

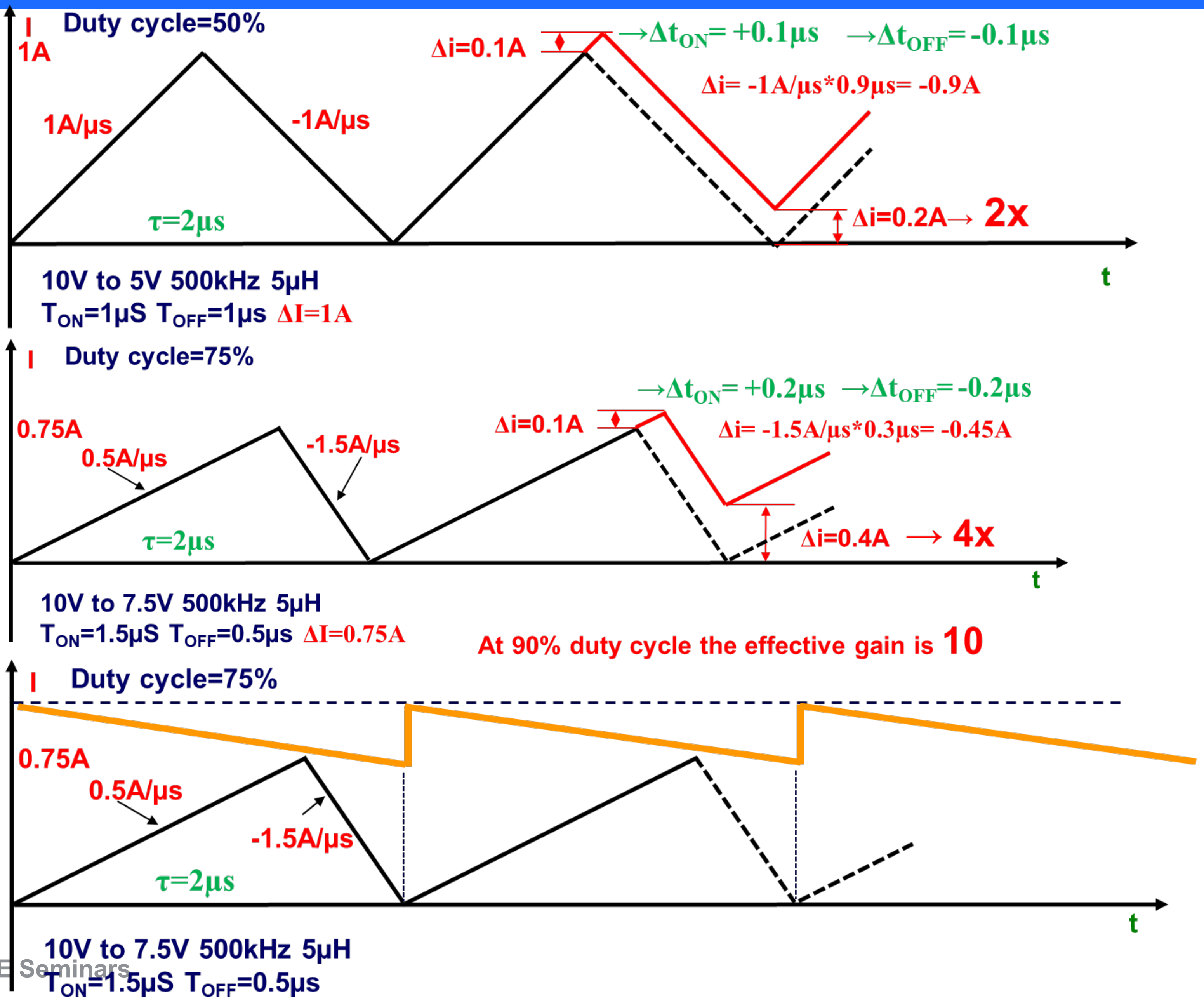




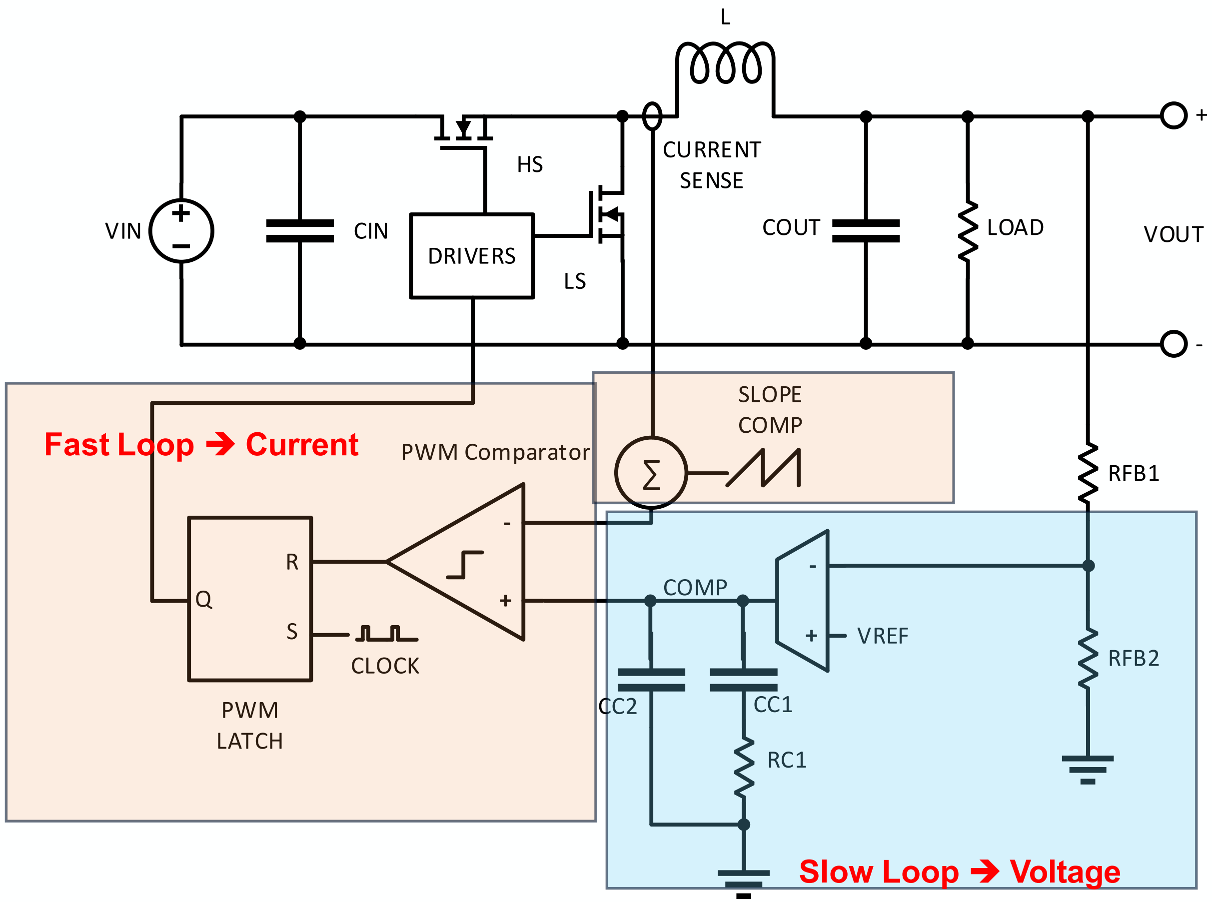


At 90% duty cycle the effective gain is **10**

Slope Problem in fixed frequency peak Current Mode



Peak Current Mode Control – Pros and Cons

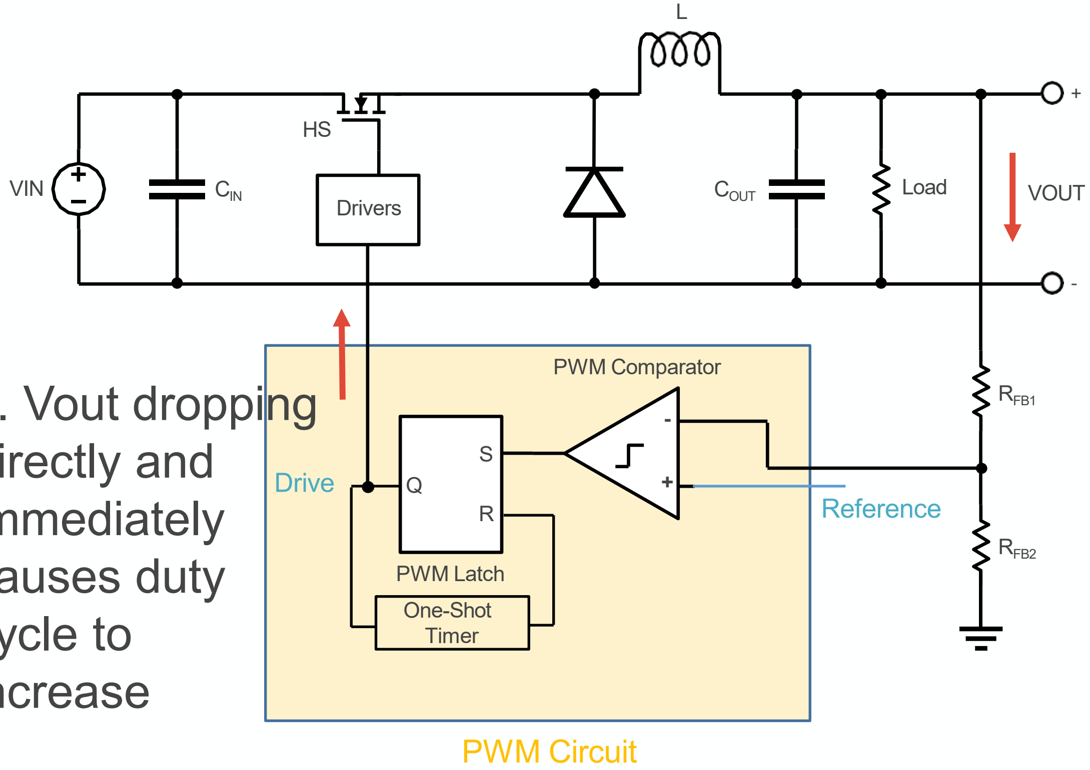


+ Current feedback acts a lossless resistor damping the output LC filter, so only type II compensation is required. ☺
+ Stable crossover with Vin ☺
+ Good line transient performance ☺
- Okay load transient performance ☹
- Requires current sensor ☹
- Requires slope compensation for >50% duty cycle ☹
- Large min on time limits minimum conversion ratio ☹

Constant-On-Time (COT) Control

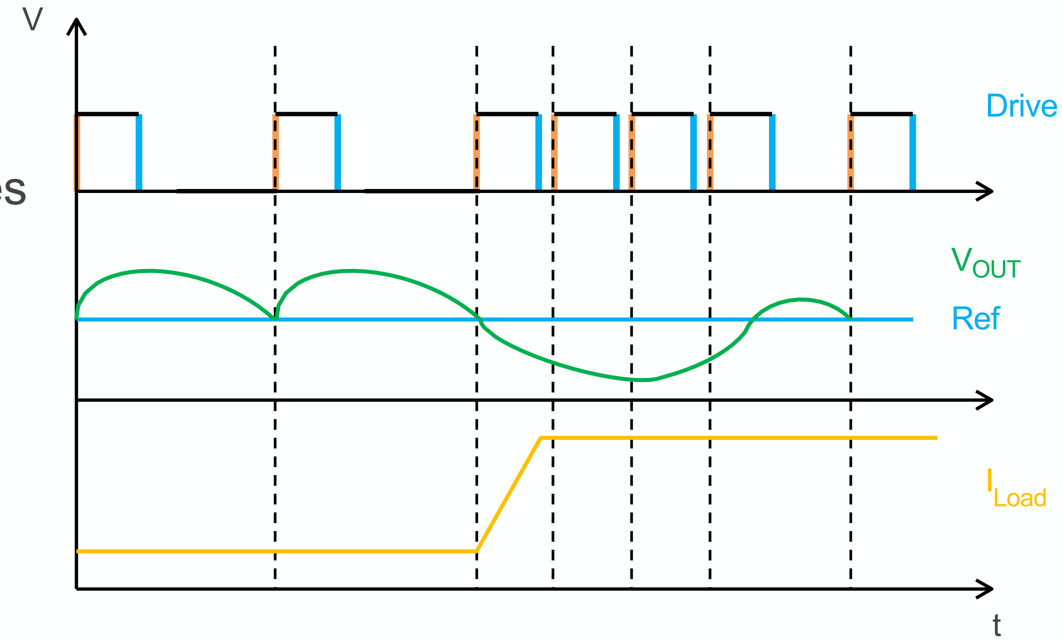
For applications where fast transient responses are required, current mode control is not fast enough.

- **Goal**: Faster transient response
- **Thought Process**: Transient response can be improved by not waiting for the clock.
- **Solution**: Use constant-on-time (COT) control to fix the on time while allowing the frequency to change.



2. Vout dropping directly and immediately causes duty cycle to increase

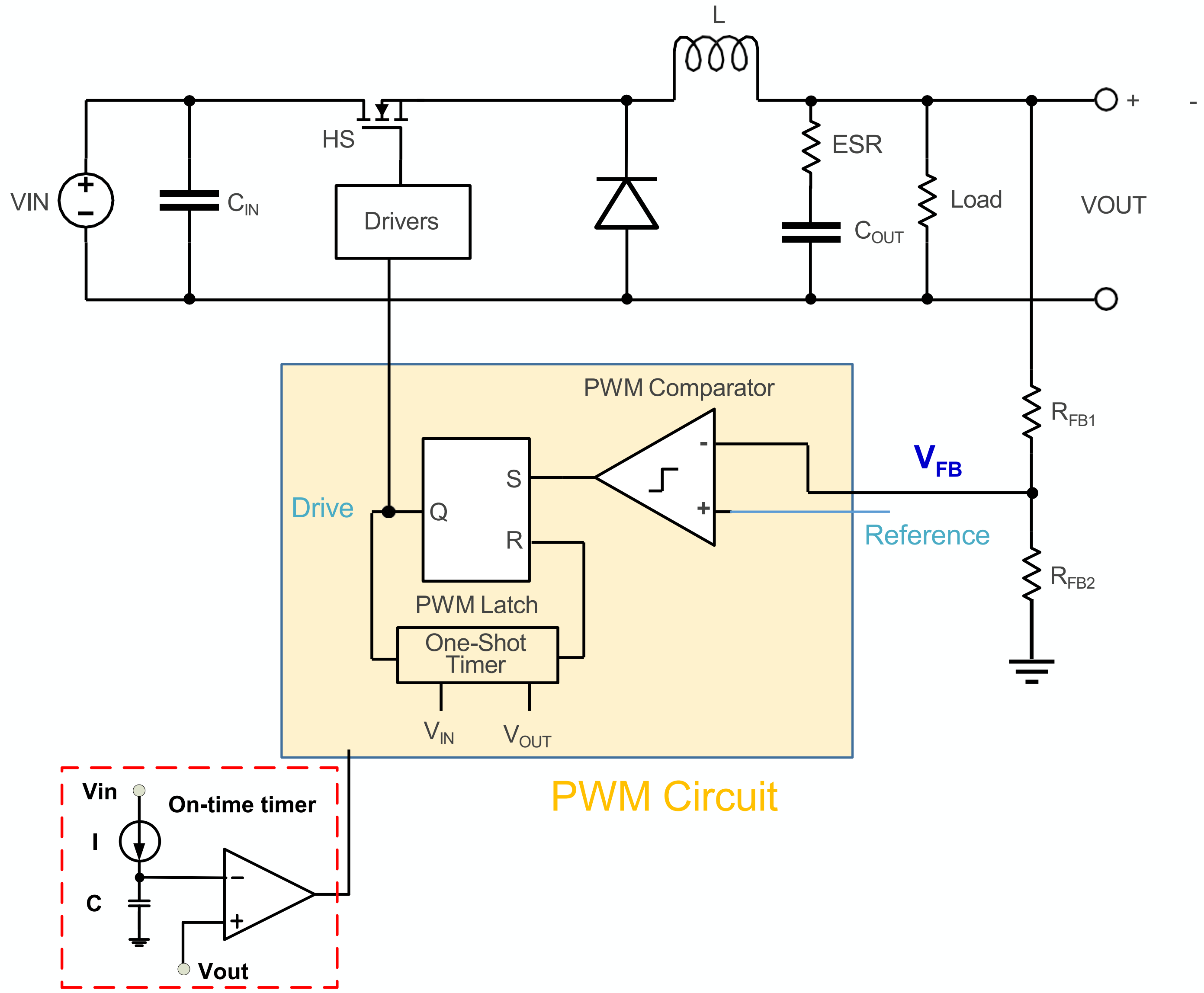
1. Sudden Current Increase causes output to drop



Constant-On- Time (COT) Control

Advantages	Disadvantages
• Excellent load transient performance: ○ About 4x faster compared to fixed-frequency current mode • Simple architecture does not require compensation • Seamless transition between light loads and heavy loads • Does not require an internal oscillator	• Must generate a slope on FB (e.g. using COUT_ESR) • The switching frequency (f_{SW}) is not constant due to variations in the off time • Output filter design is difficult and undesired in many sensitive systems

Solution: Adaptive COT Control

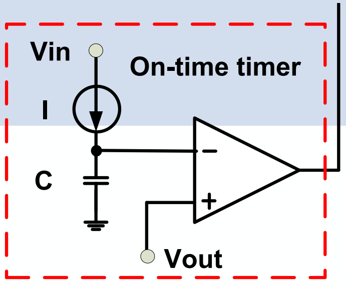


Adaptive COT control uses the conversion ratio (V_{OUT}/V_{IN}) to adjust the one-shot timer that sets the on time (t_{ON}).

This enables a steady f_{SW} during steady state, without affecting the converter's ability to immediately change the frequency when faced with a load step.

Constant-On- Time (COT) Control

Advantages	Disadvantages
• Excellent load transient performance: ○ About 4x faster compared to fixed-frequency current mode • Simple architecture does not require compensation • Seamless transition between light loads and heavy loads • Does not require an internal oscillator • Quasi-stable frequency during state-state operation	• Must generate a slope on FB (e.g. using COUT_ESR) • ~~**The switching frequency (f_{SW}) is not constant due to variations in the off time**~~ • Output filter design is difficult and undesired in many sensitive systems

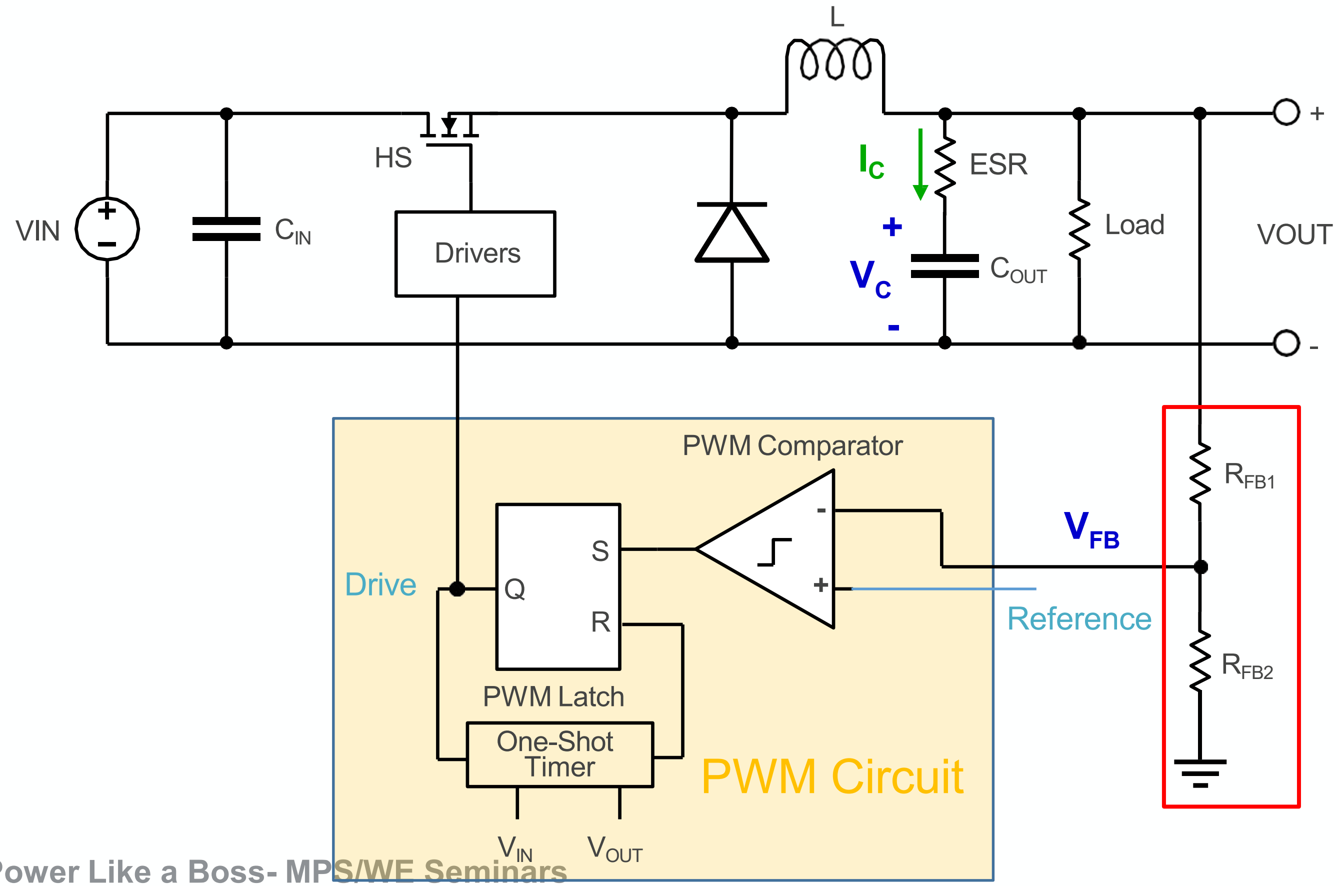


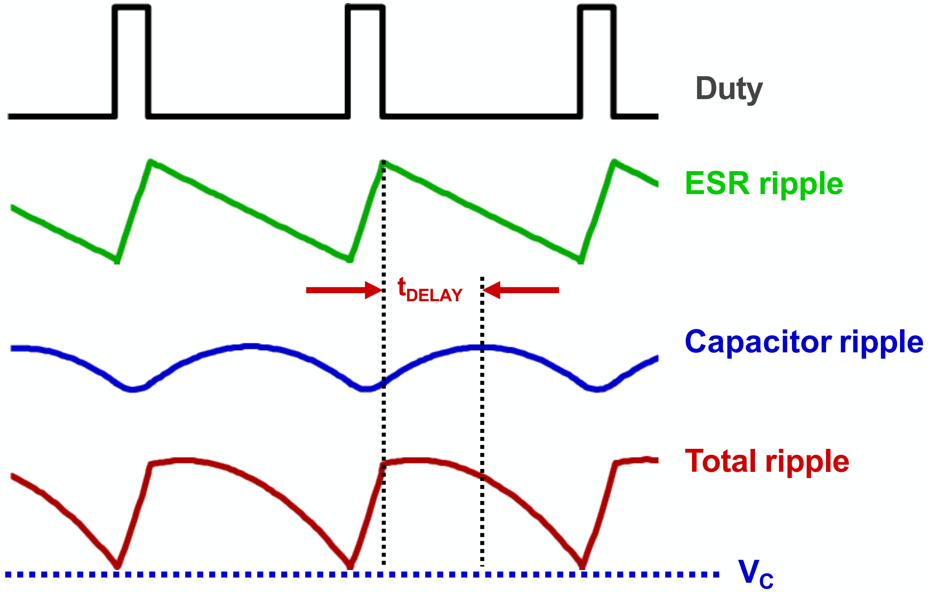
COT Challenge: Stability Is Dependent on ESR

COT control compares the feedback voltage to a set reference voltage.

The feedback voltage ripple has two main components:

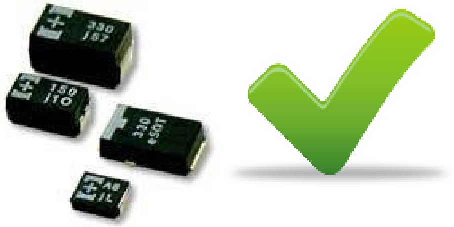
1. ESR ripple: Directly proportional to the inductor current (I_L), with no delay/phase difference
2. V_{CAP} ripple: Caused by charging/discharging the output capacitor, and is delayed with respect to I_L

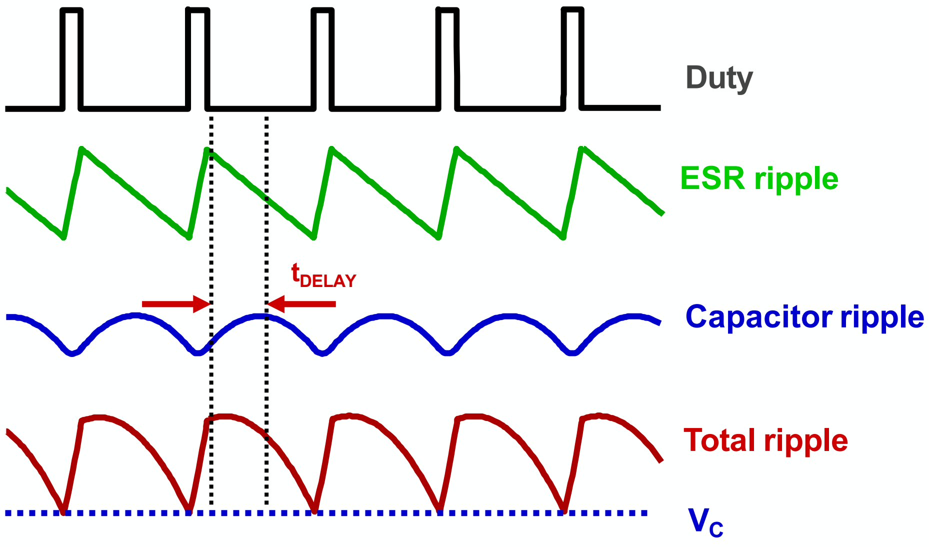




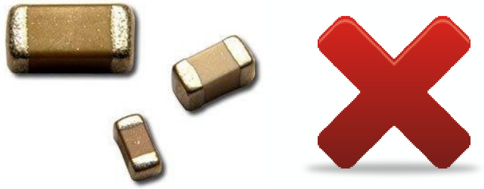
Solution 1: Stability Is Dependent on ESR- Solution 1

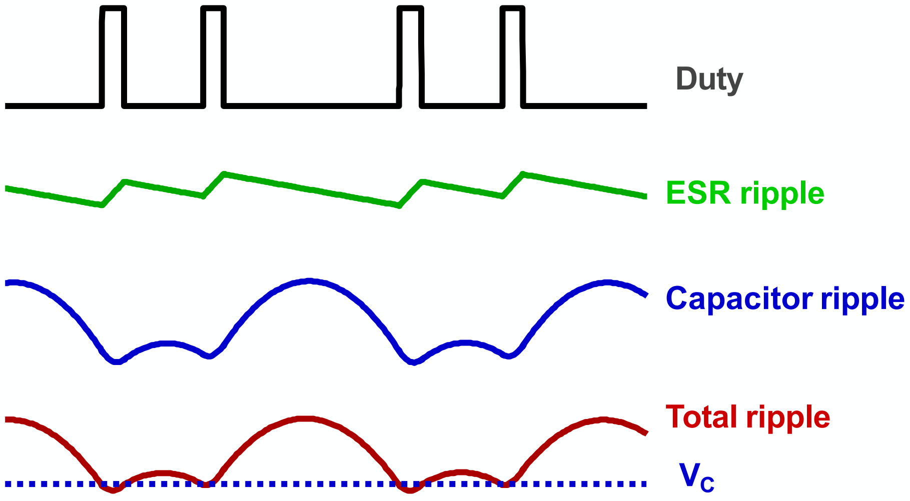
If the ESR ripple dominates, the V_{OUT} ripple is in phase with I_L, and the circuit operates correctly.





If the V_{CAP} ripple dominates, the V_{OUT} ripple is out of phase with I_L, and the circuit can enter subharmonic oscillation.

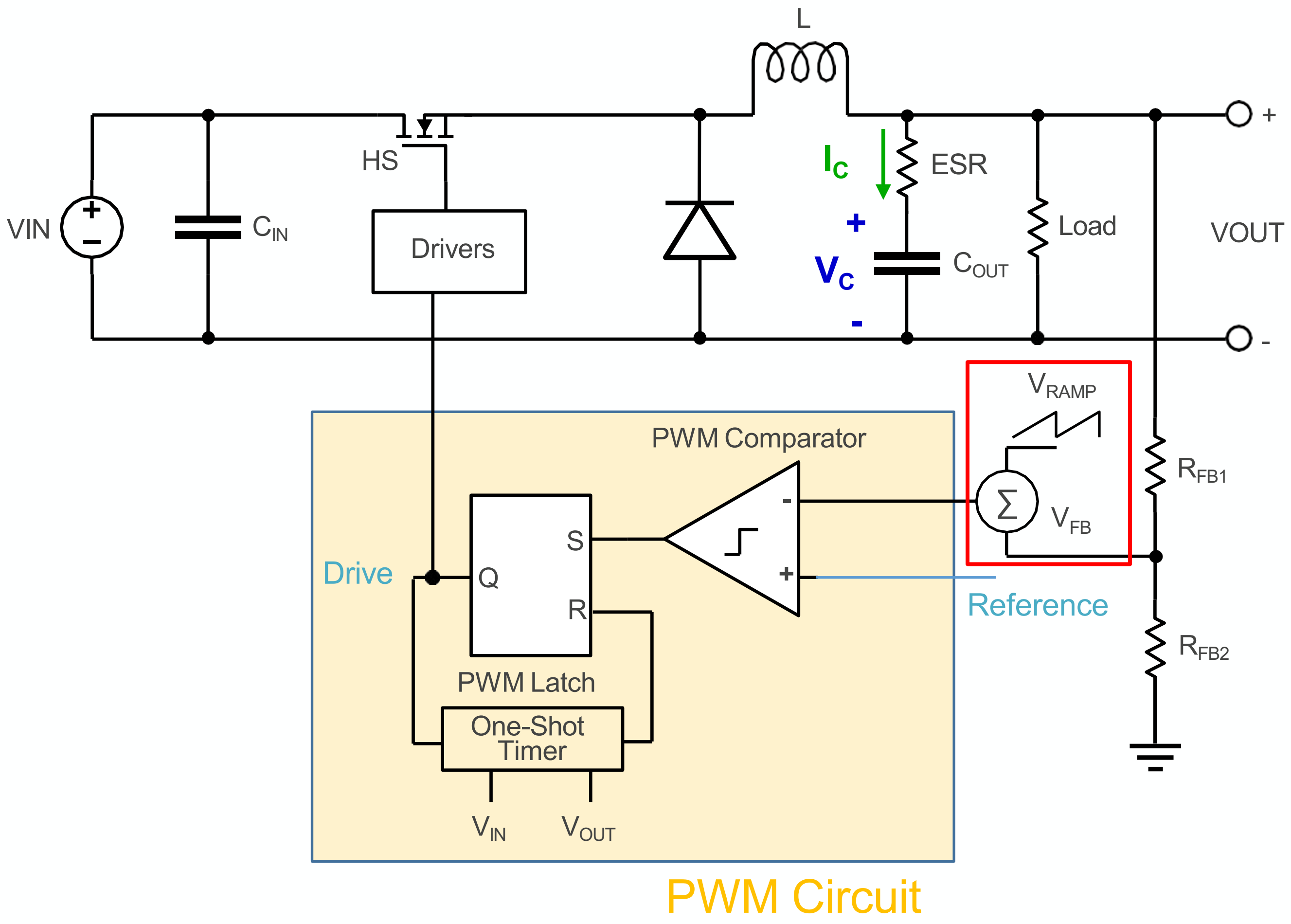


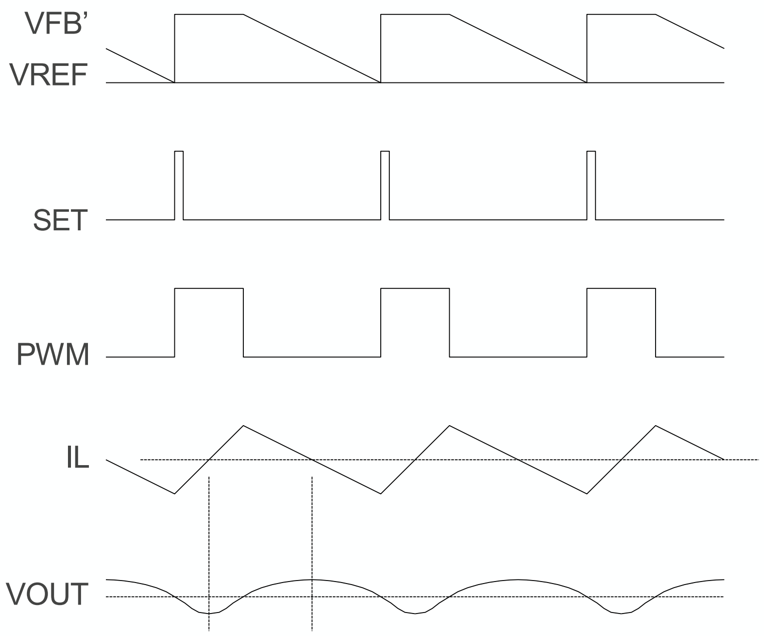


COT requires output capacitors (C_{OUT}) with large ESR for stability.
If low-ESR capacitors are used (e.g. MLCC), the circuit may become unstable.

MPS Solution 2: Current Ripple Injection

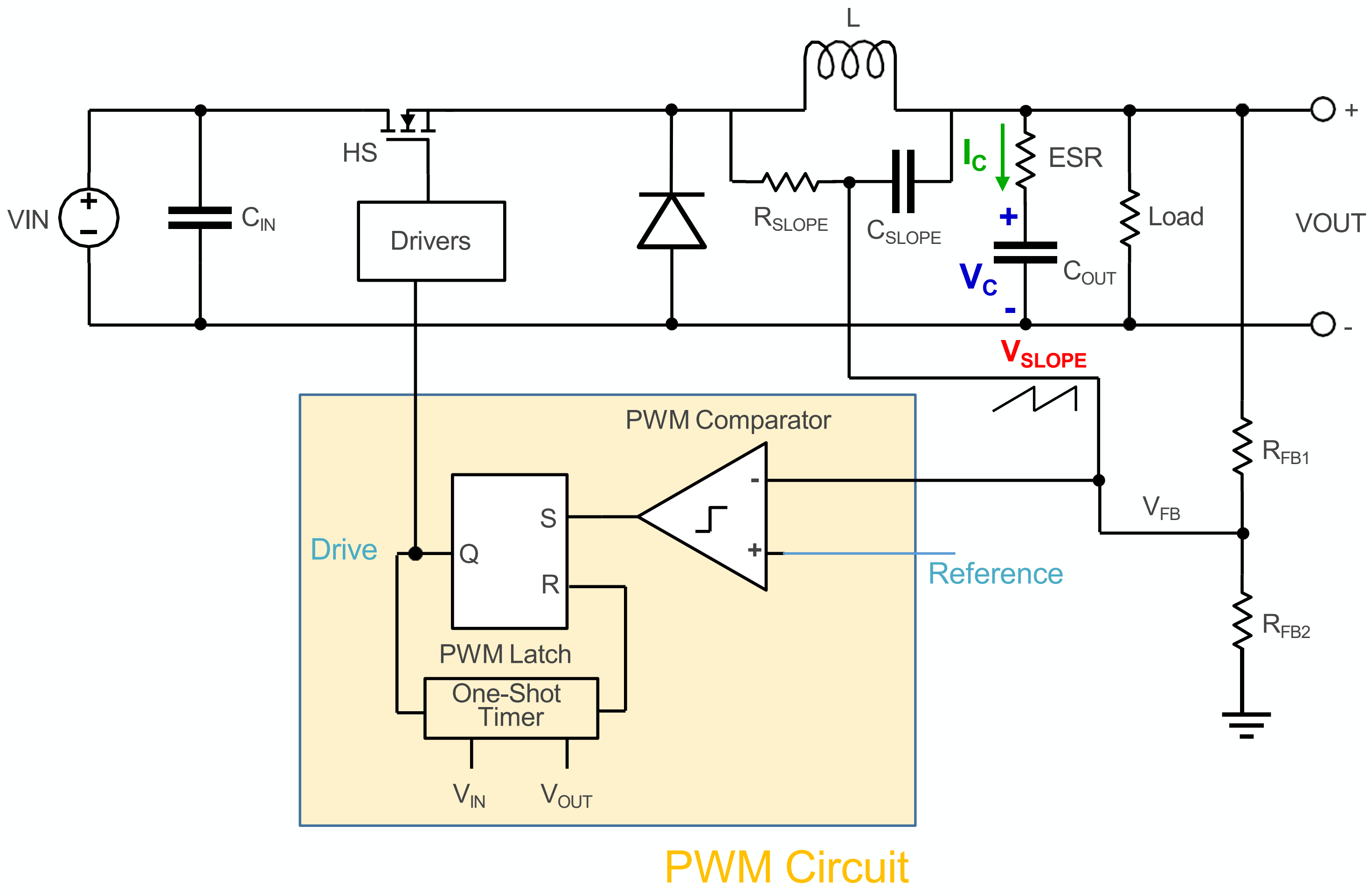
Option 2: Add an external ramp

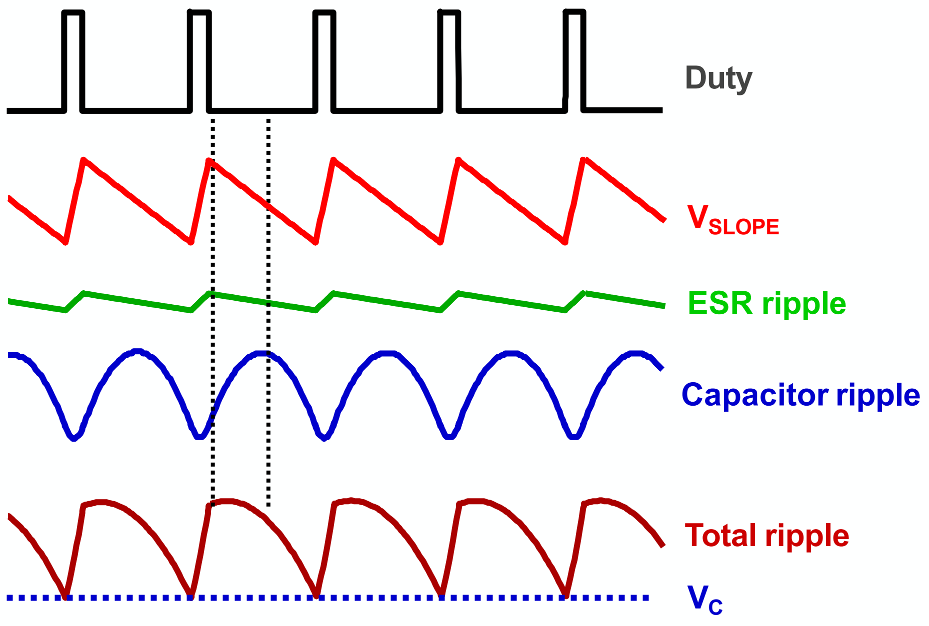




MPS Solution 3: Current Ripple Injection

Option 3: Use the RC circuit to generate a slope voltage and ensure that the FB ripple is in phase with I_L



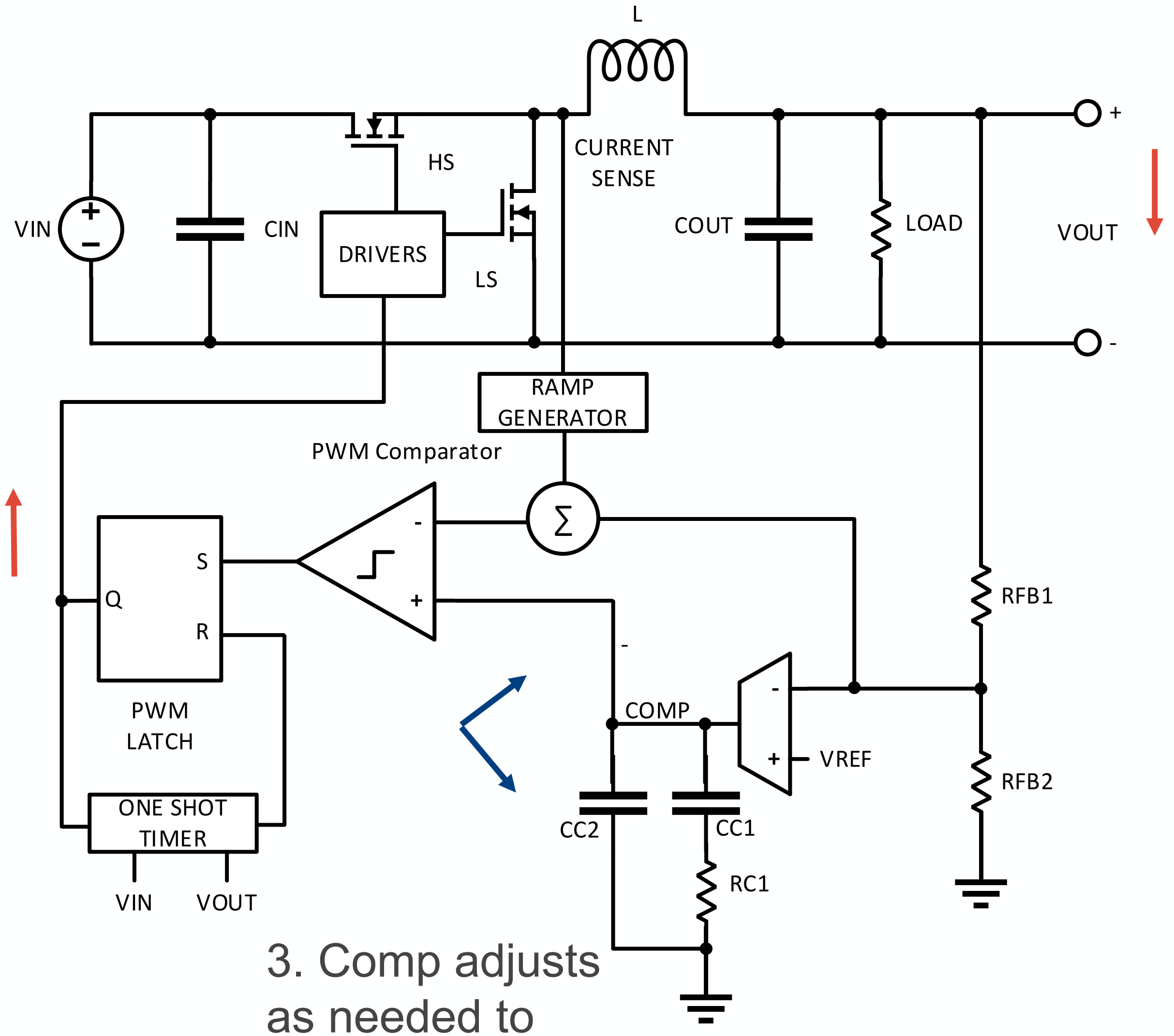


Constant-On- Time (COT) Control

Advantages	Disadvantages
• Excellent load transient performance: ○ About 4x faster compared to fixed-frequency current mode • Simple architecture does not require compensation • Seamless transition between light loads and heavy loads • Does not require an internal oscillator • Quasi-stable frequency during state-state operation • Integrated slope generator to keep the converter stable, even with low ESR	• ~~Must generate a slope on FB (e.g. using COUT_ESR)~~ • ~~The switching frequency (f_{SW}) is not constant due to variations in the off time~~ • Output filter design is difficult and undesired in many sensitive systems

Constant On-time Control - Operation
(w/ Offset Cancellation & Synthetic Ramp)

Legend
Fast Change:
Slow change:



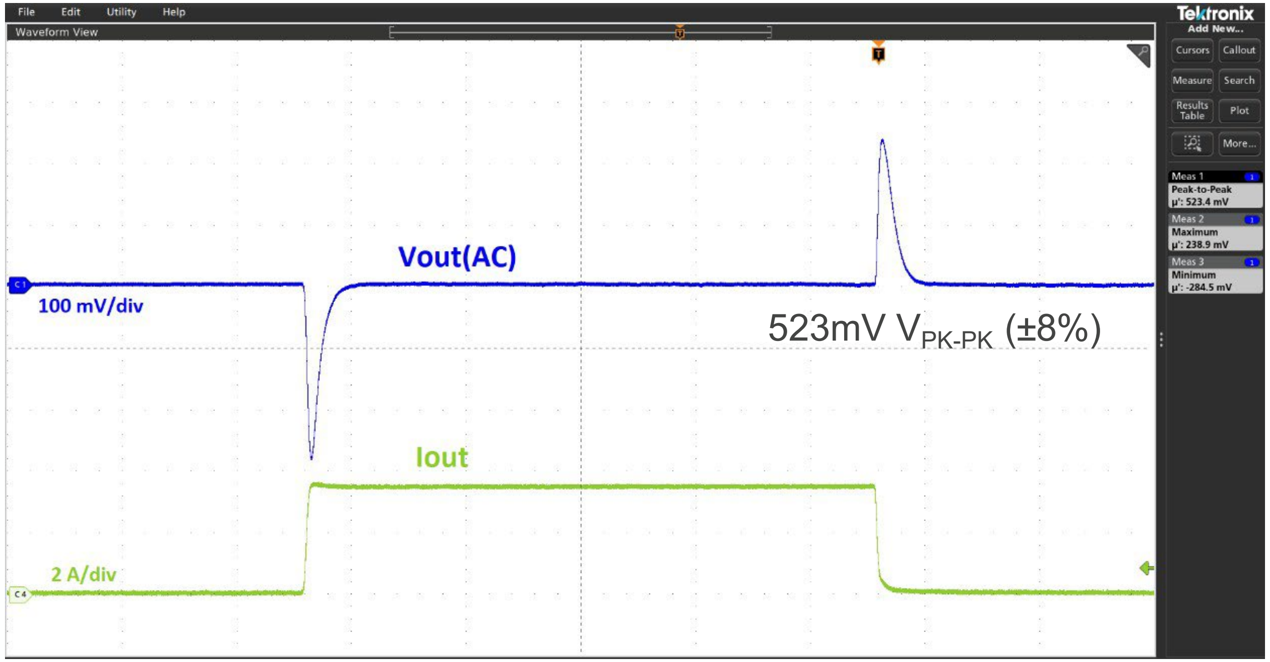
1. Sudden Current Increase causes output to drop

2. Vout dropping directly and immediately causes duty cycle to increase

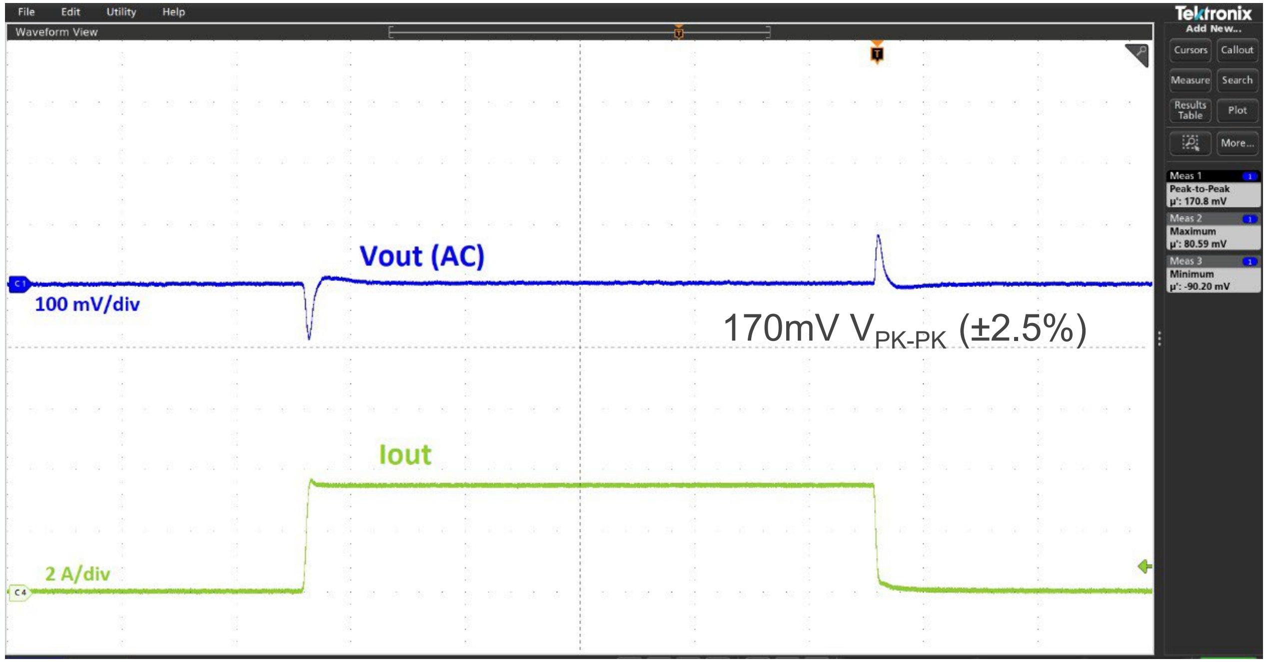
3. Comp adjusts as needed to maintain DC regulation

COT Advantages: Fast Transient Response

Peak Current Mode

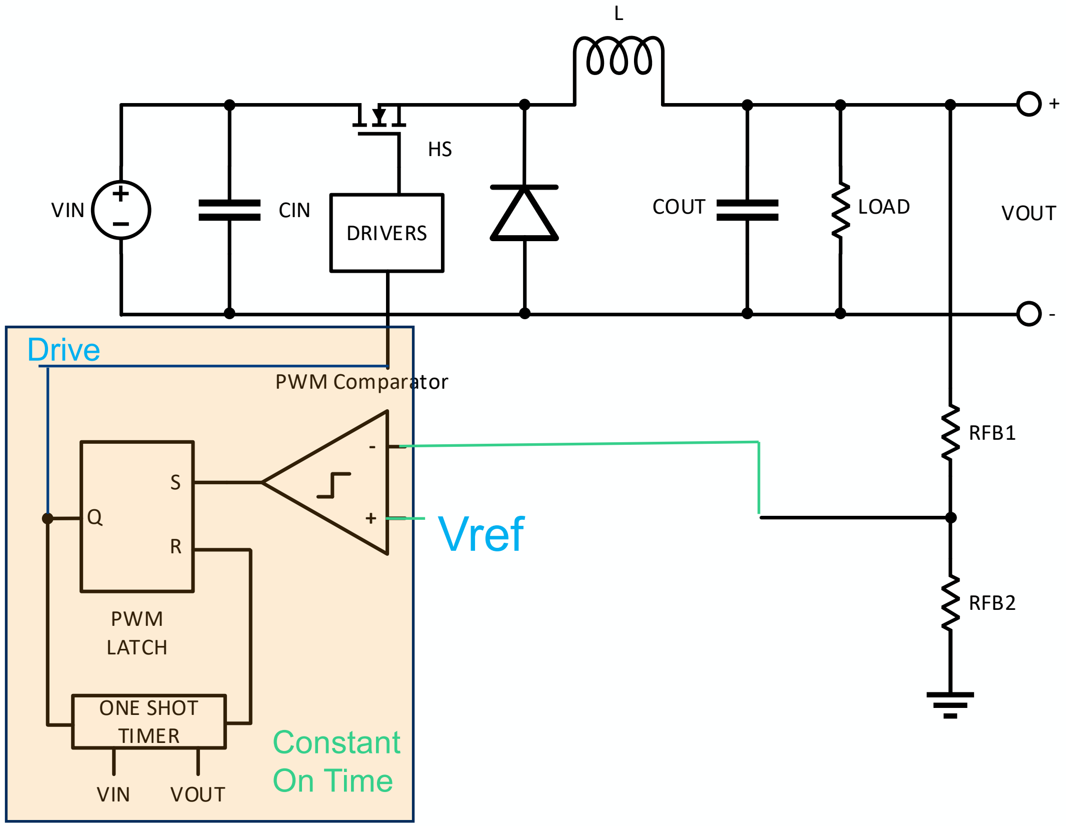


Constant-On-Time

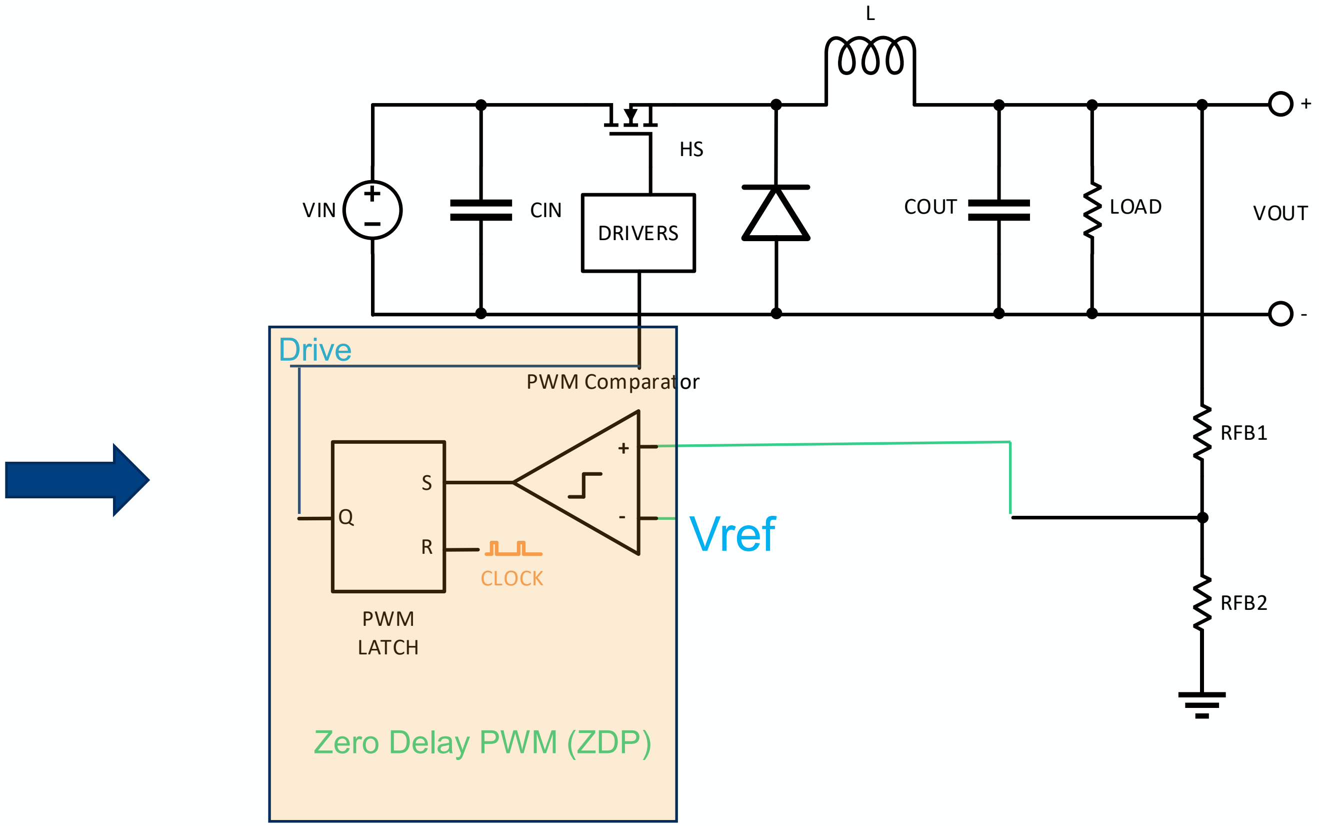


- 3x faster transient response compared to peak current mode with the same components and set-up:
  - 12V input, 3.3V output, 0A to 3.5A load step
  - 1µH L_{OUT}, 2x22µF C_{OUT}

Fastest Fix Frequency Control – ZDP



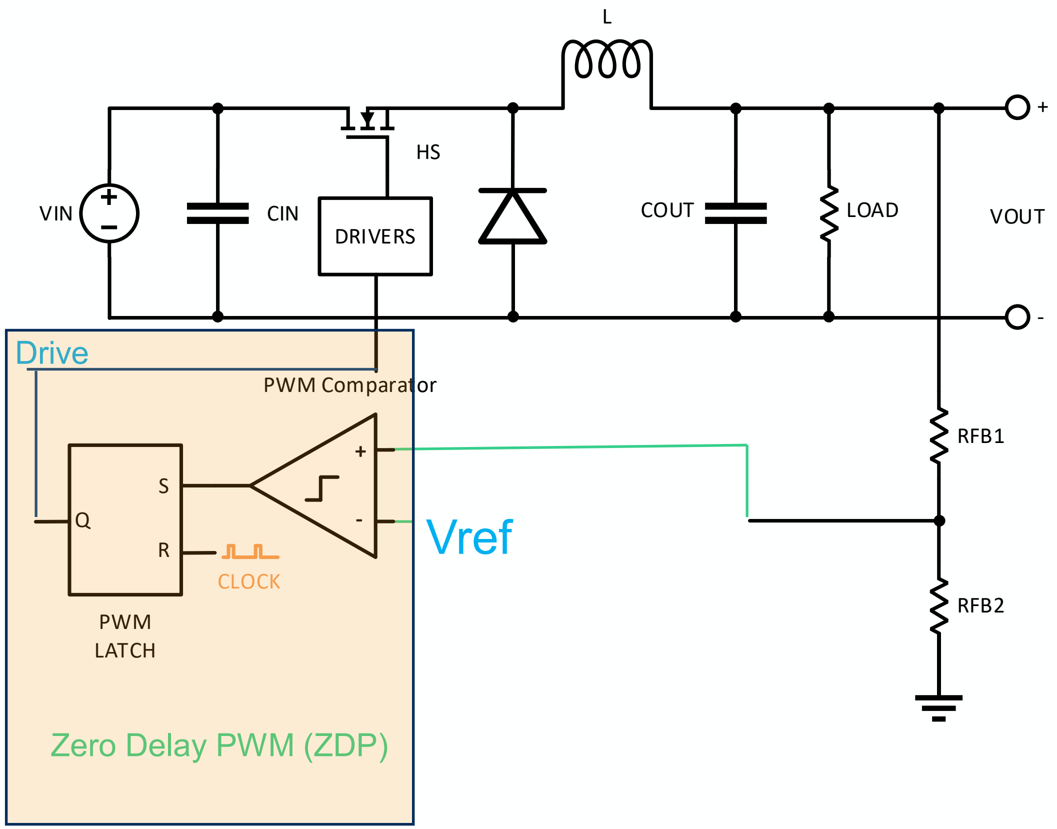
PWM Modulation Circuit



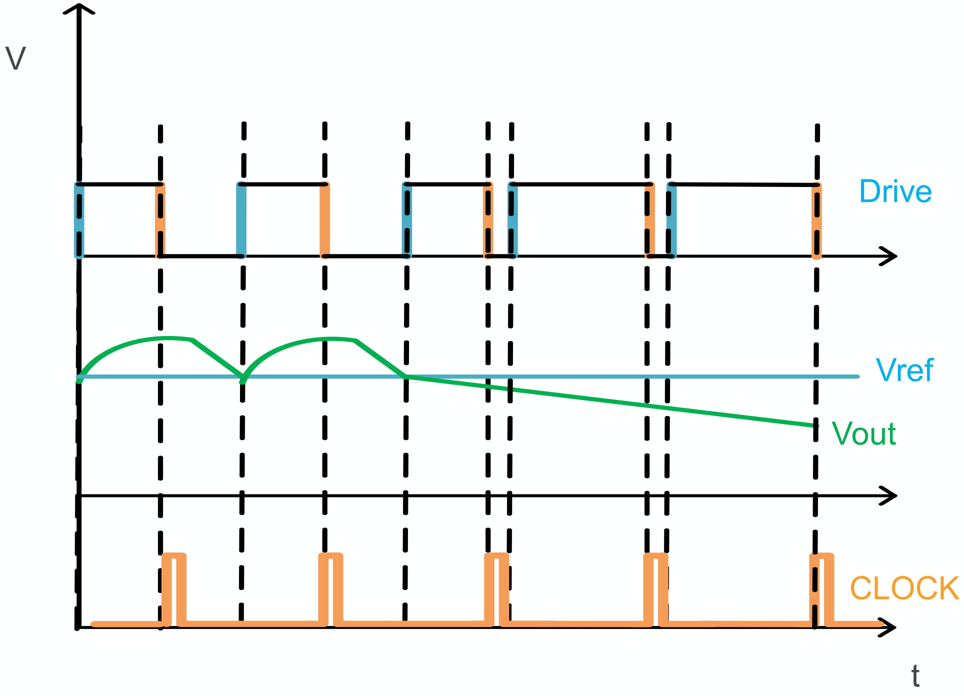
PWM Modulation Circuit

- Use clock to set the fix frequency for turn off
- Turn on immediately when Vo is lower than Vref
- As the result, duty cycle is changed instantly to response the transient

ZDP Control

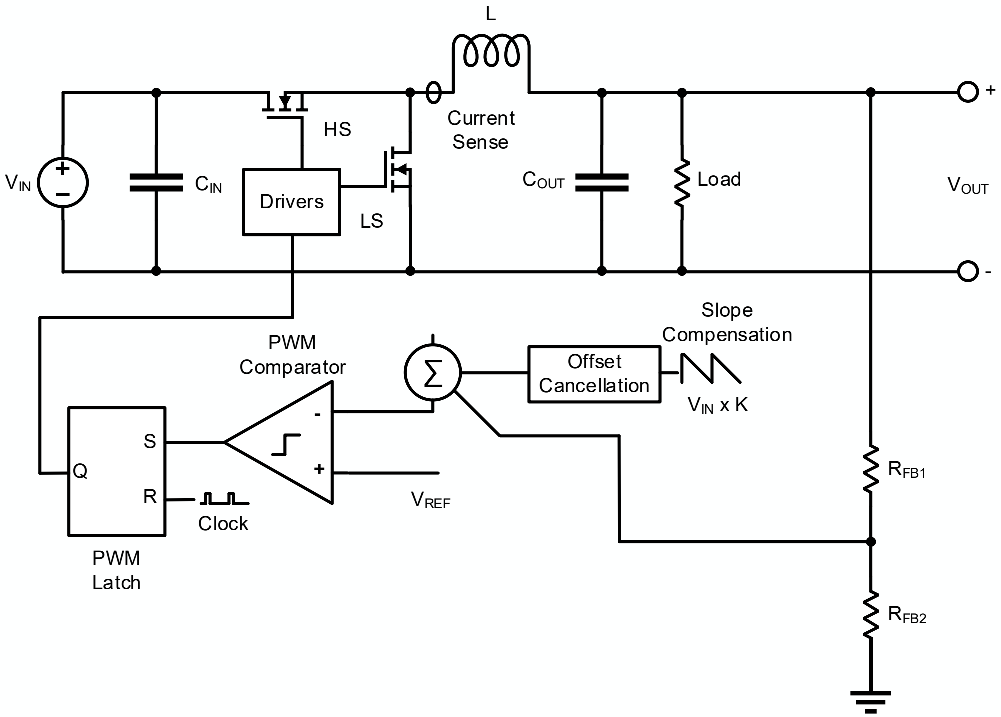


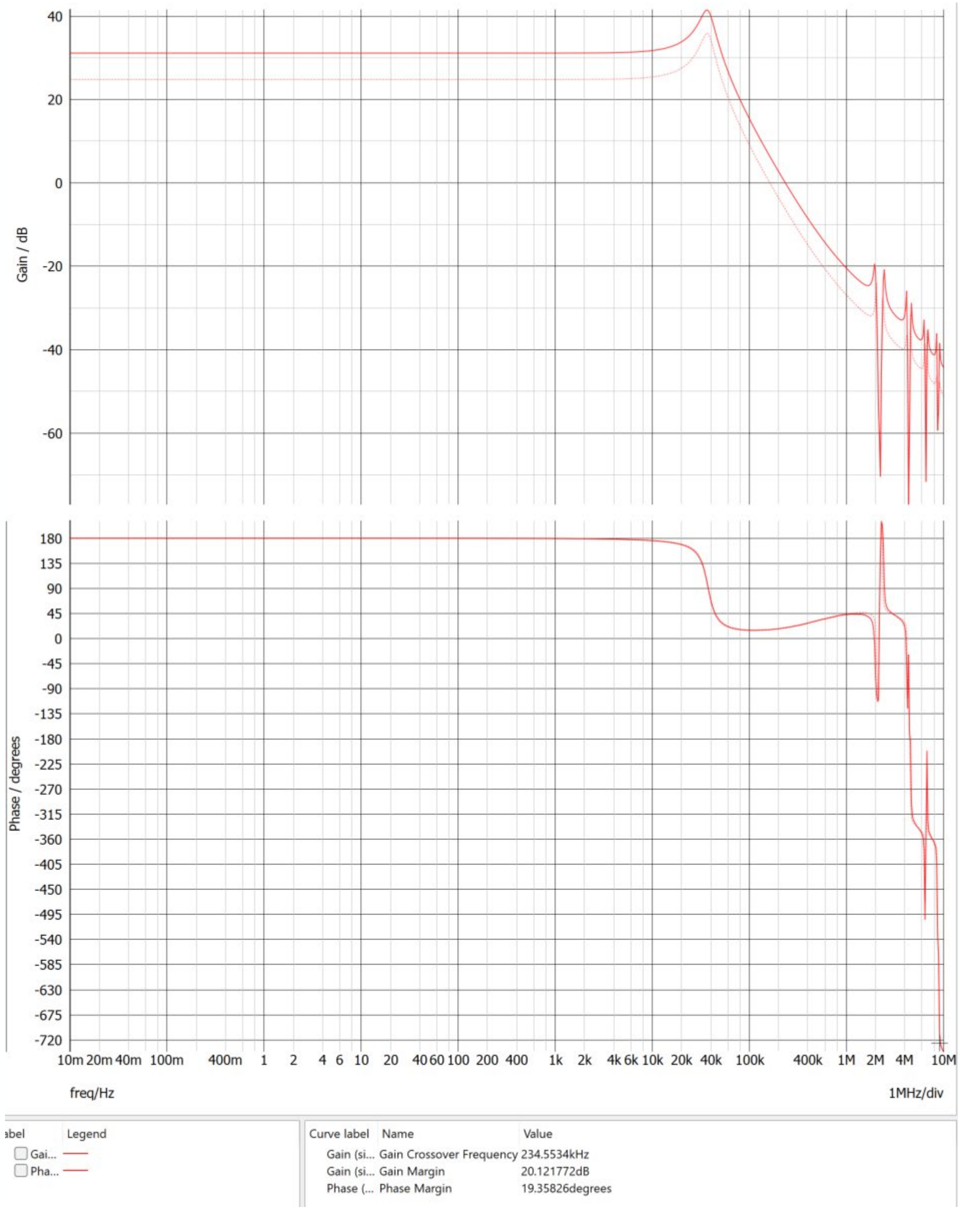
PWM Modulation Circuit



- Fastest Fixed Frequency Control because the duty cycle instantly change
- No linear control loop delay

Barebone ZDP in Frequency domain





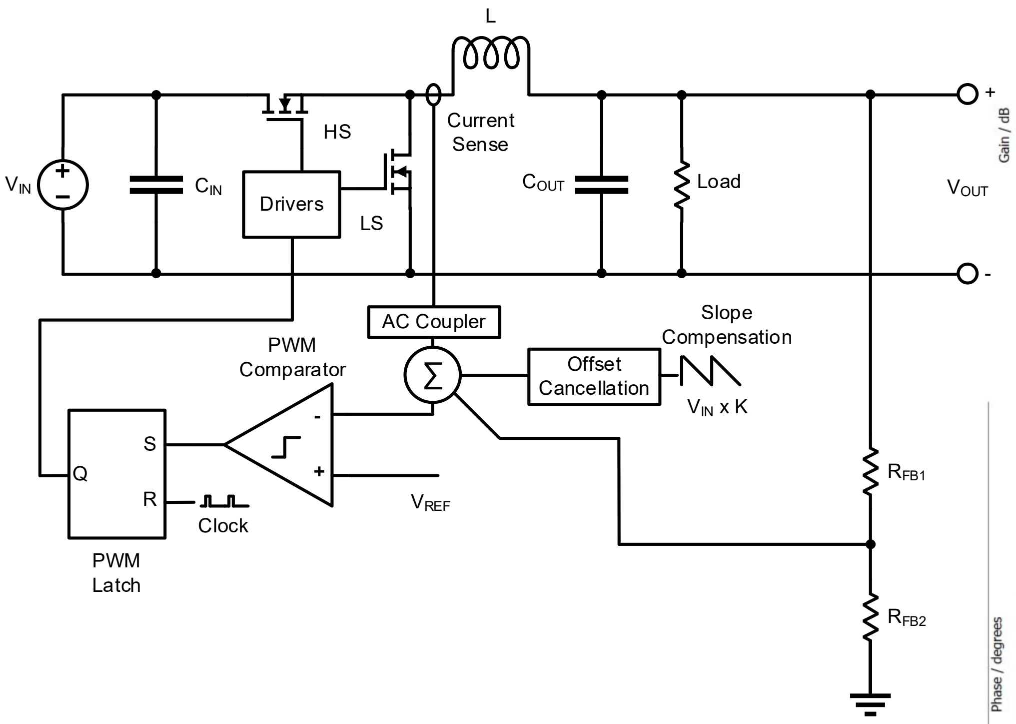
1x Ramp (K)

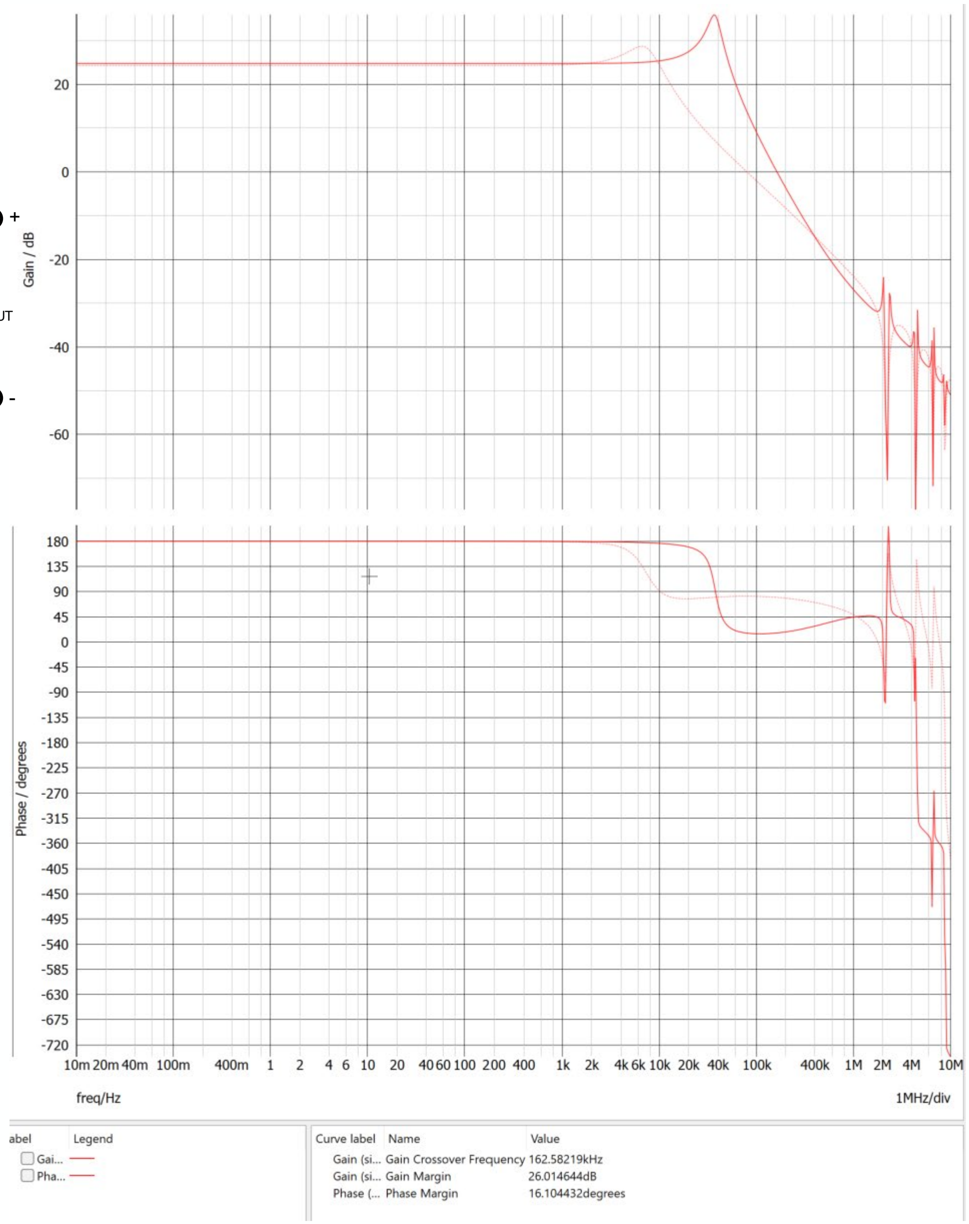
- Crossover Frequency: 234kHz
- Gain Margin: 20dB
- Phase Margin: 19 degrees

2x Ramp (K)

- Crossover Frequency: 163kHz
- Gain Margin: 26dB
- Phase Margin: 16 degrees

Damp the Double Pole to Reduce the Phase Drop





—— w/o AC coupler

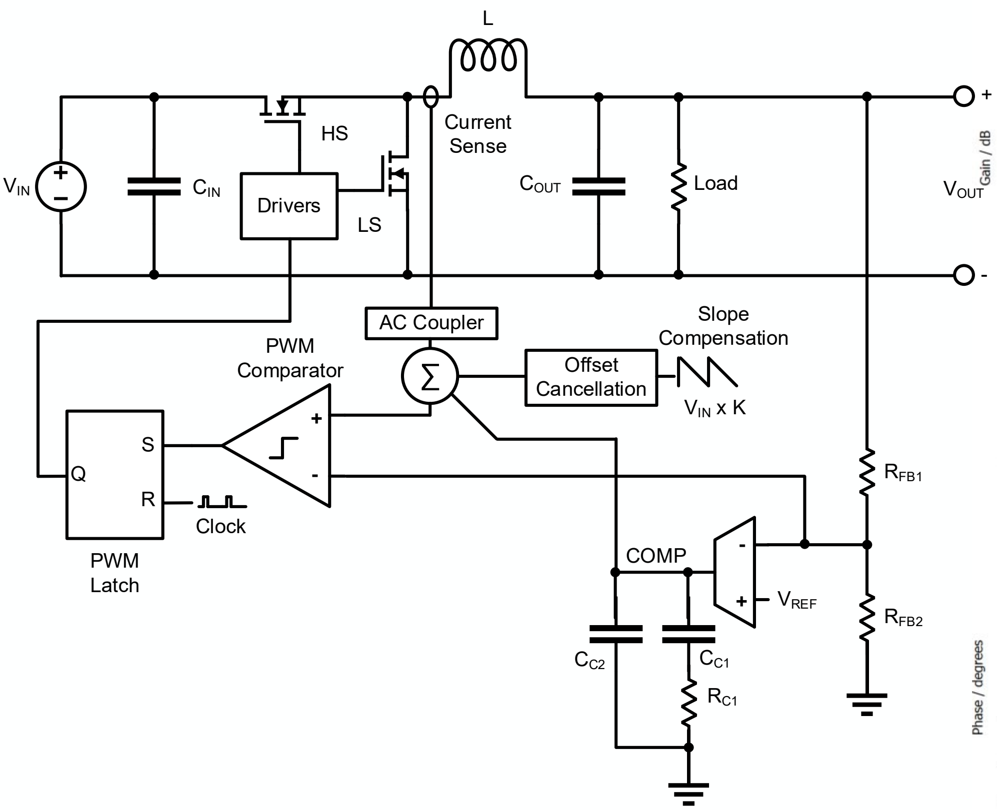
- Crossover Frequency: 163kHz
- Gain Margin: 26dB
- Phase Margin: 16 degrees

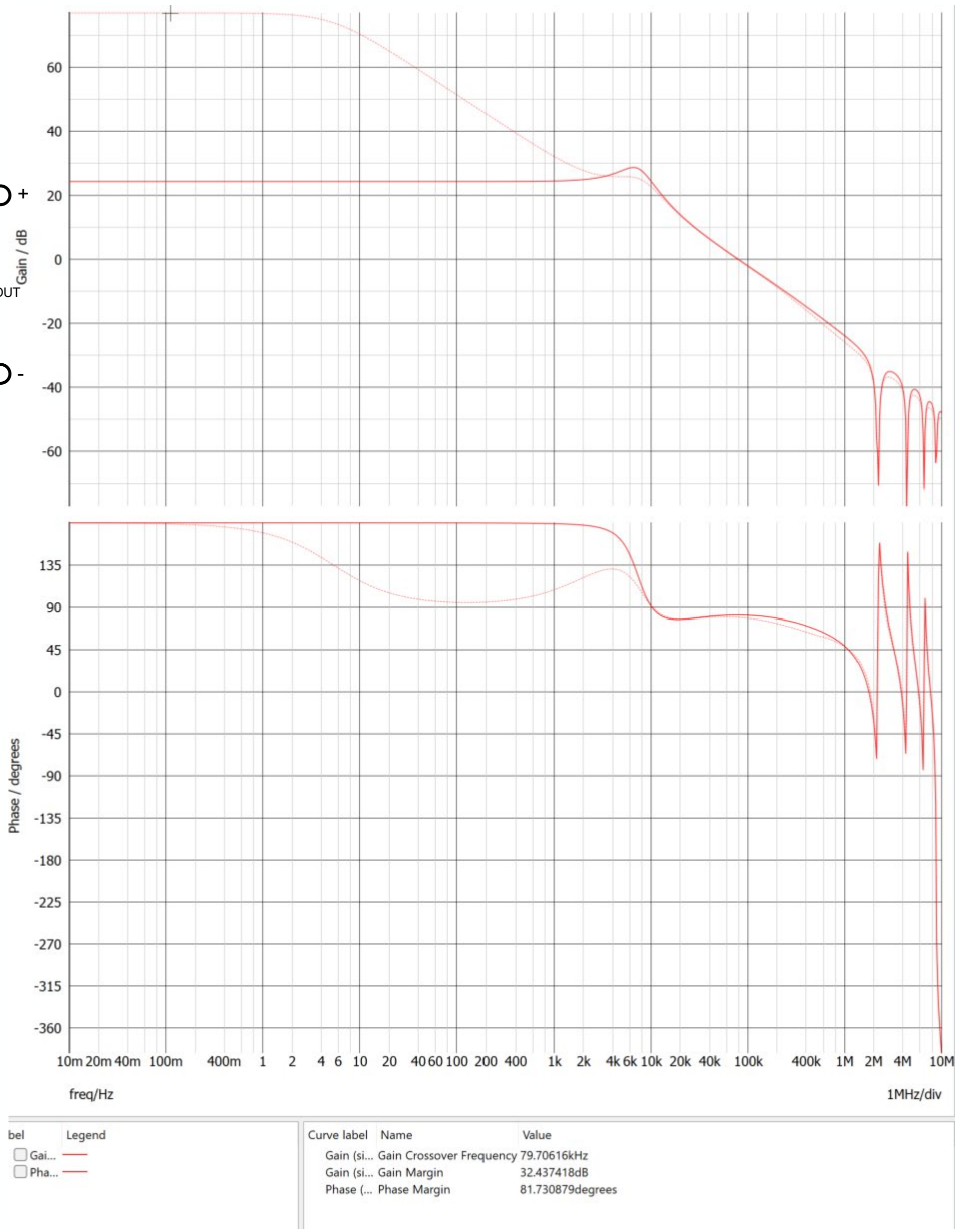
-------- with AC coupler

- Crossover Frequency: 85kHz
- Gain Margin: 32dB
- Phase Margin: 81 degrees

Double pole is damped

Add Integrator to Reduce the DC Offset





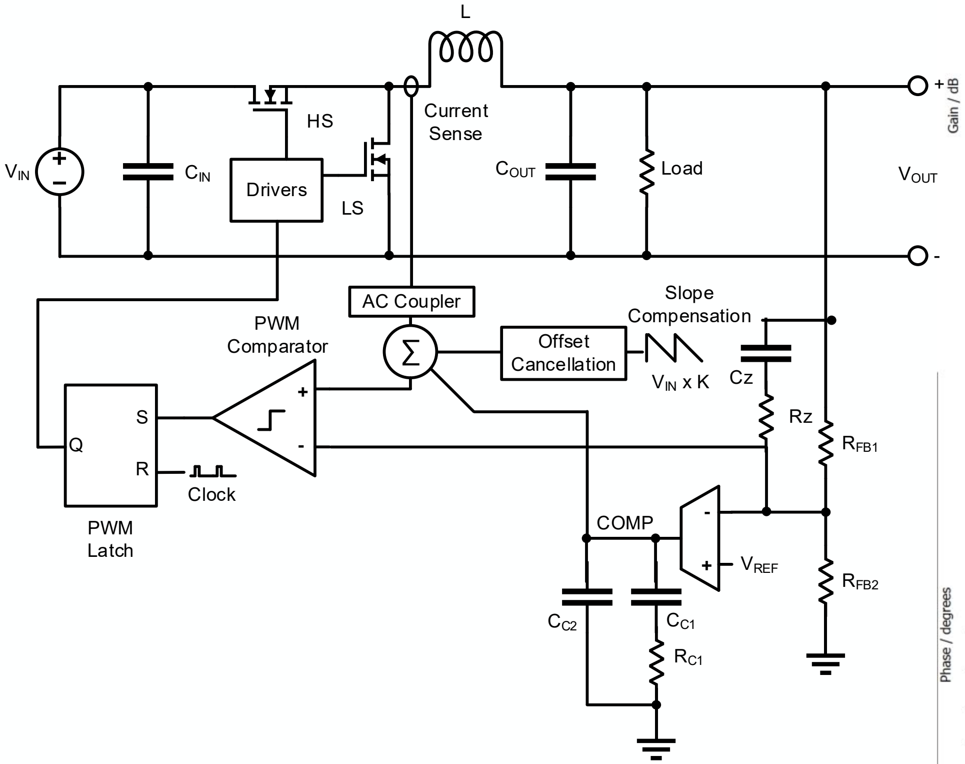
w/o Integrator

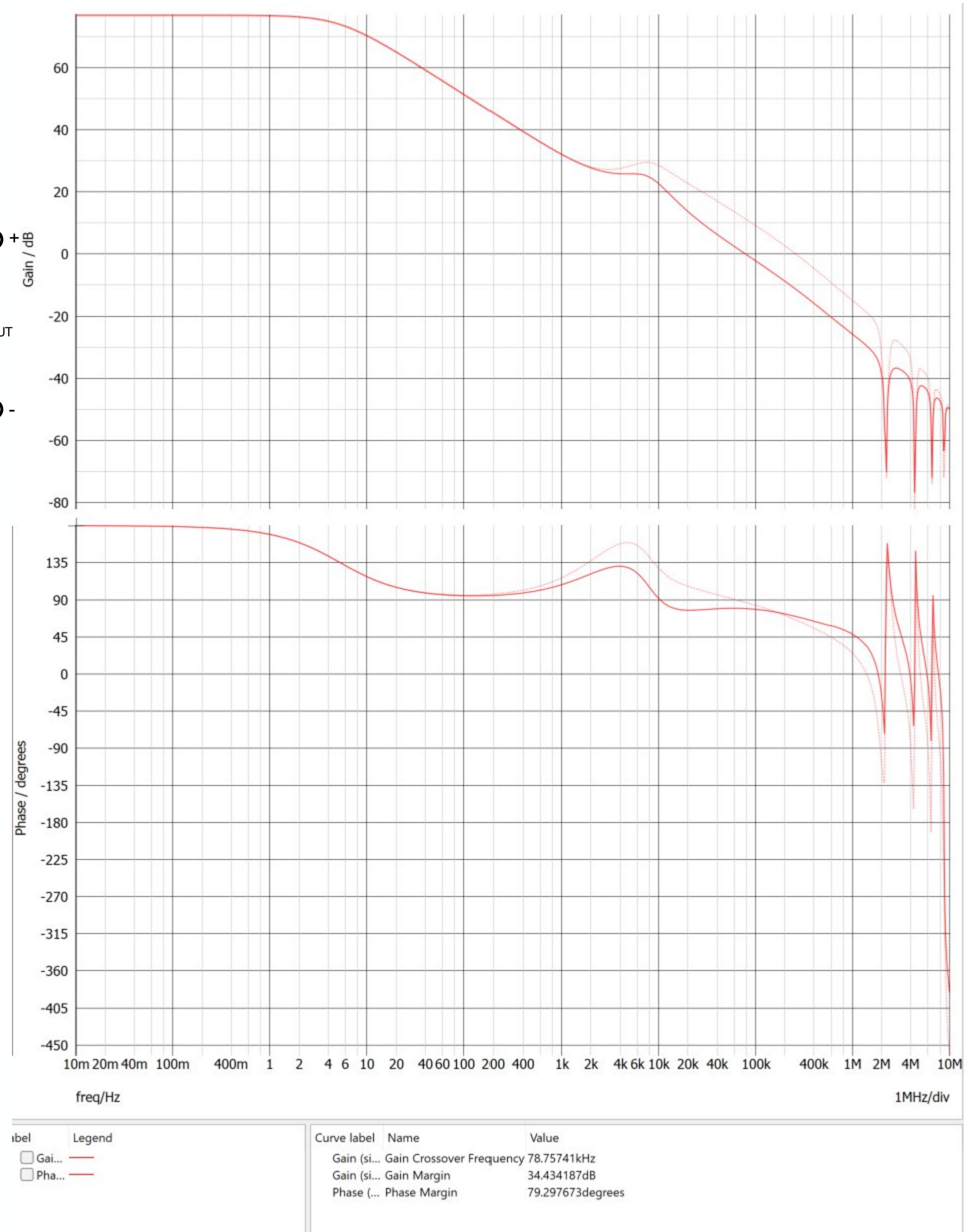
- Crossover Frequency: 85kHz
- Gain Margin: 32dB
- Phase Margin: 81 degrees

with Integrator

- Crossover Frequency: 80kHz
- Gain Margin: 32dB
- Phase Margin: 82 degrees

Add Zero to Further Increase the Bandwidth





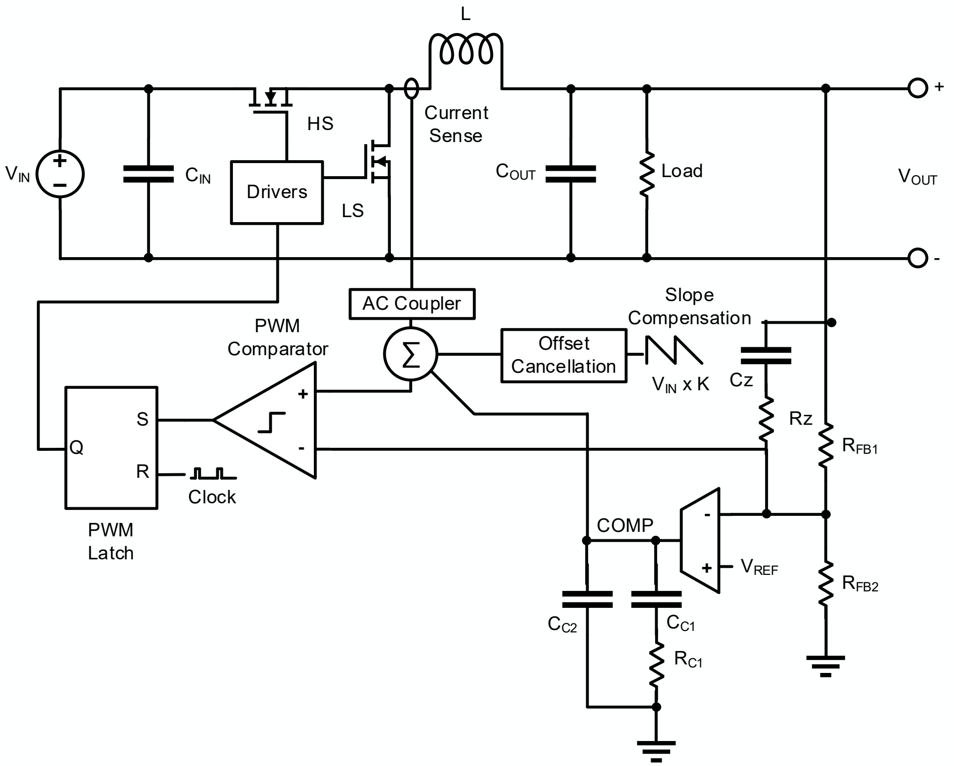
w/o zero

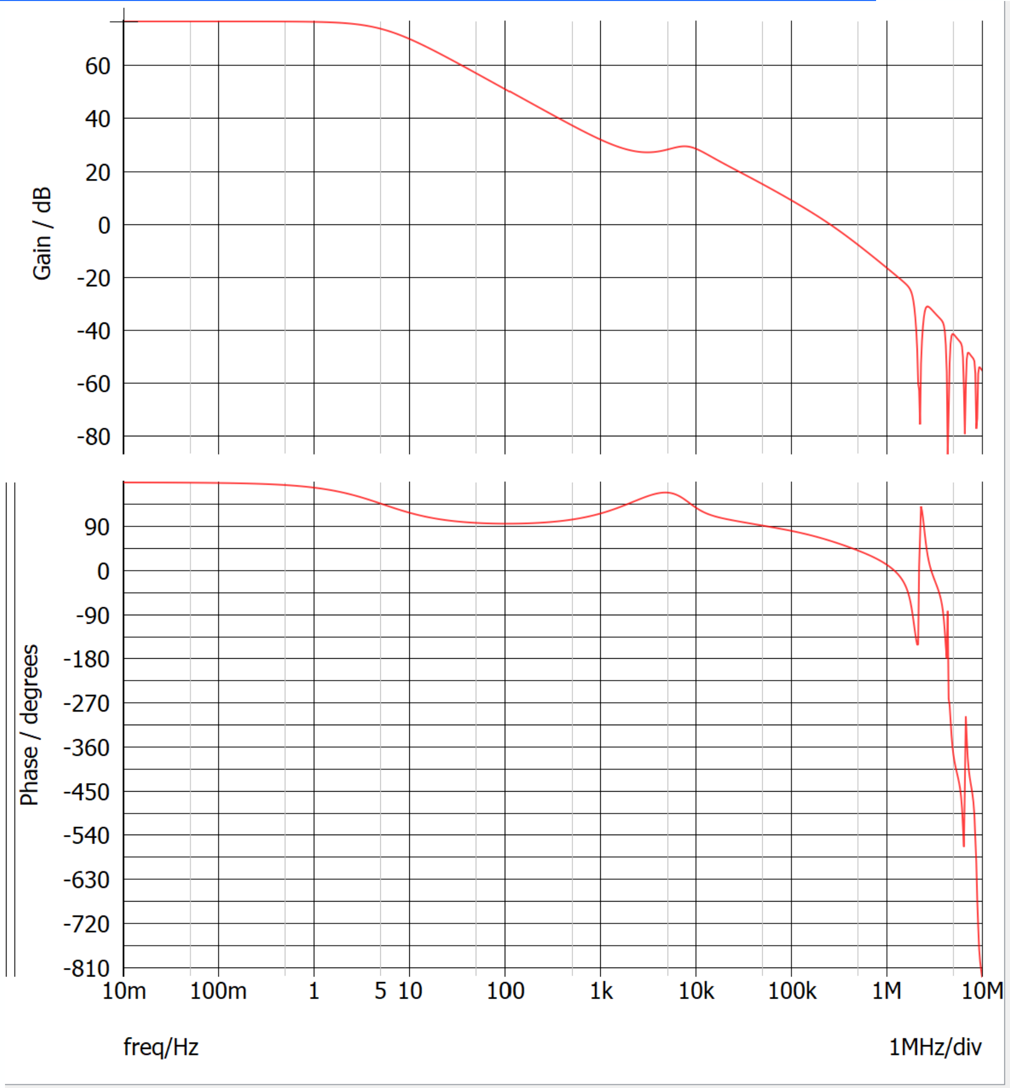
- Crossover Frequency: 80kHz
- Gain Margin: 32dB
- Phase Margin: 82 degrees

with zero

- Crossover Frequency: 245kHz
- Gain Margin: 19dB
- Phase Margin: 61 degrees

ZDP Complete View in Frequency Domain





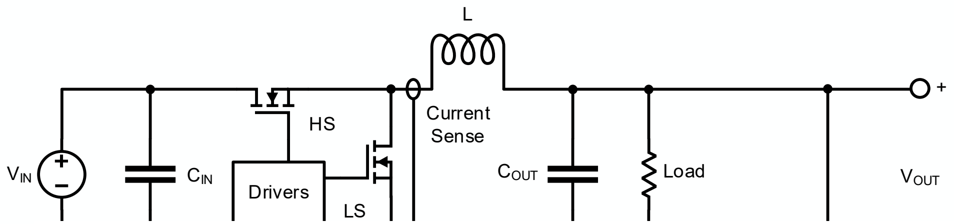
Label	Legend
Gain	—
Phase	—

Curve label	Name	Value
Gain	Gain Crossover Frequency	254.45439kHz
Gain	Gain Margin	18.791254dB
Phase	Phase Margin	60.914817degrees

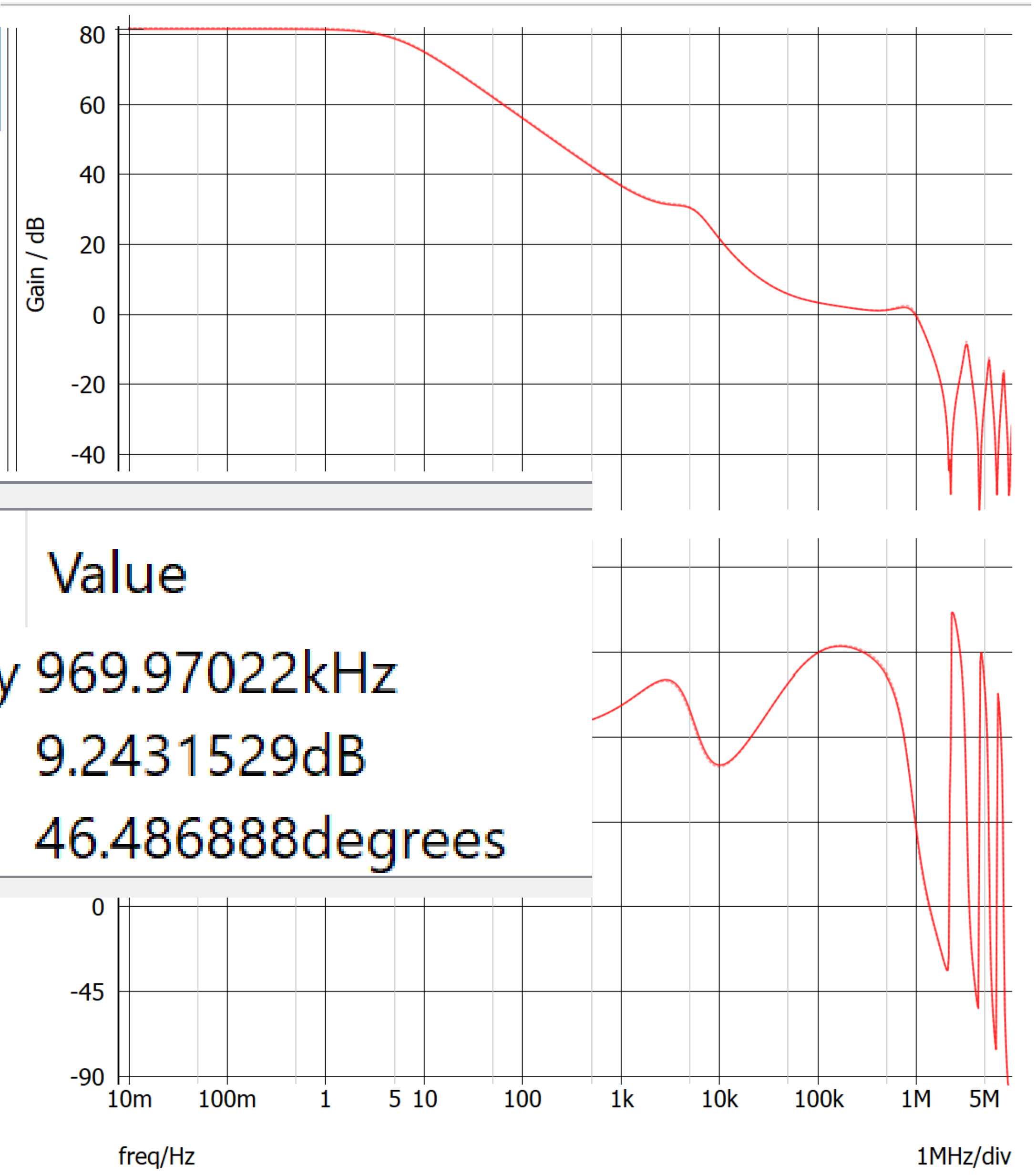
With any possible control method, the highest bandwidth a switching converter can achieve is ½ of switching frequency. This is limited by switcher.

How much ZDP can achieve?

Push the Bandwidth to the extreme



Curve label	Name	Value
Gain (si...	Gain Crossover Frequency	969.97022kHz
Gain (si...	Gain Margin	9.2431529dB
Phase (...	Phase Margin	46.486888degrees



Label	Legend
Gai...	—
Pha...	—

Curve label	Name	Value
Gain (si...	Gain Crossover Frequency	969.97022kHz
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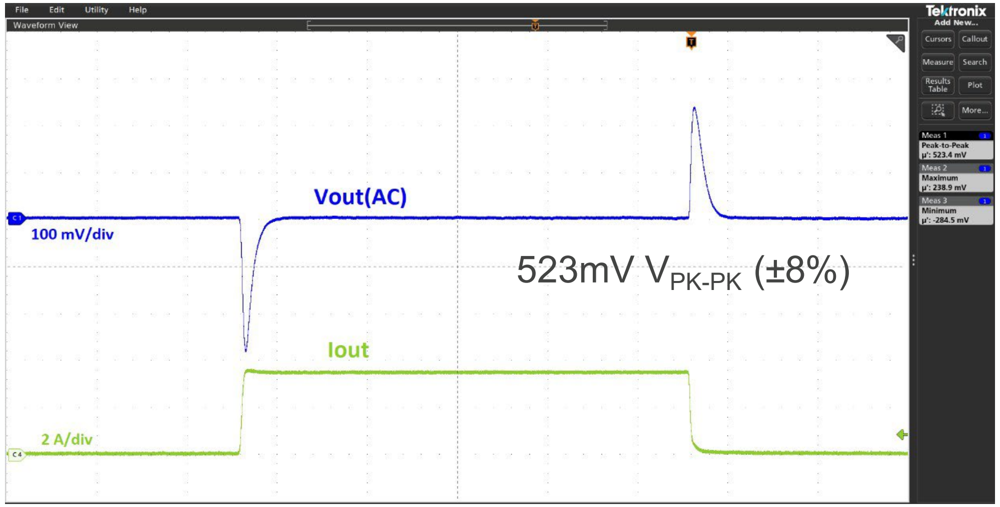
COT Advantages: Fast Transient Response

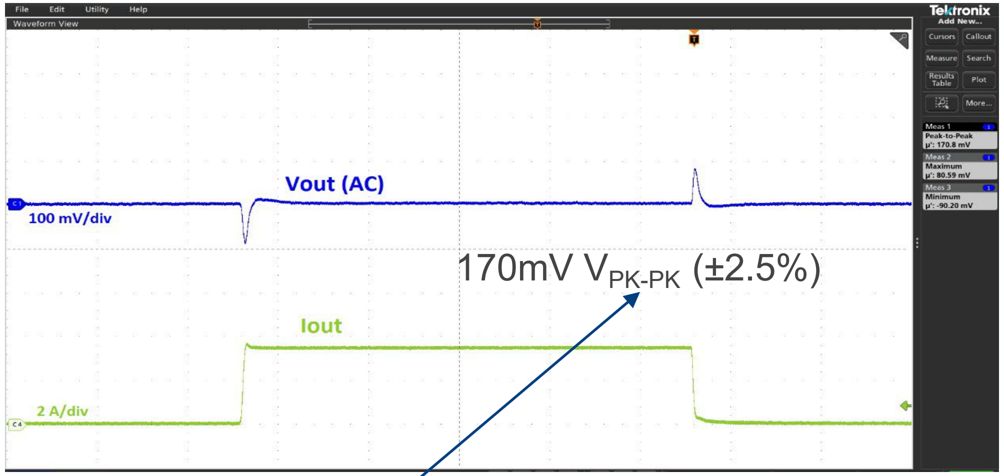
- 12V input, 3.3V output, 0A to 3.5A load step

1µH L_{OUT}, 2x22µF C_{OUT}

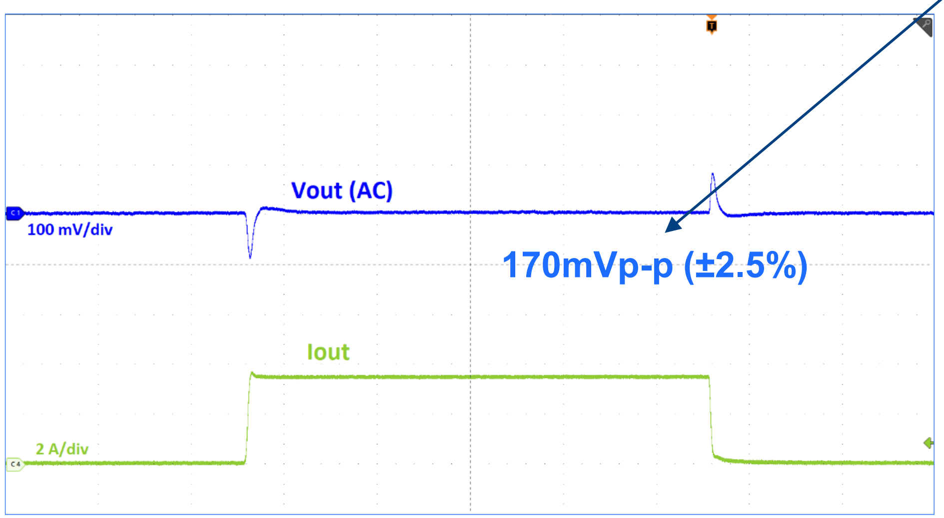
Peak Current Mode



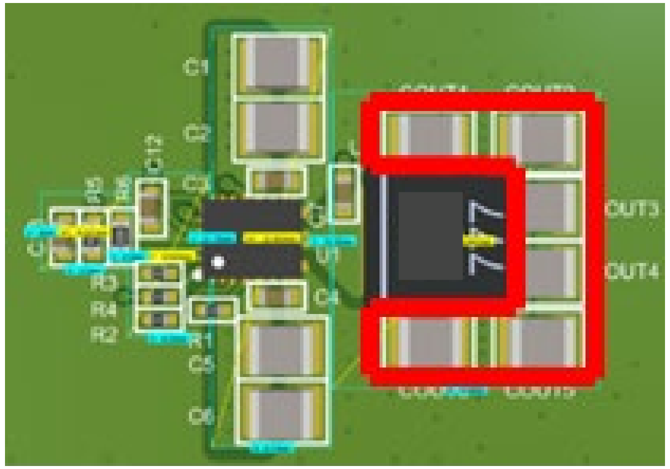
Constant-On-Time



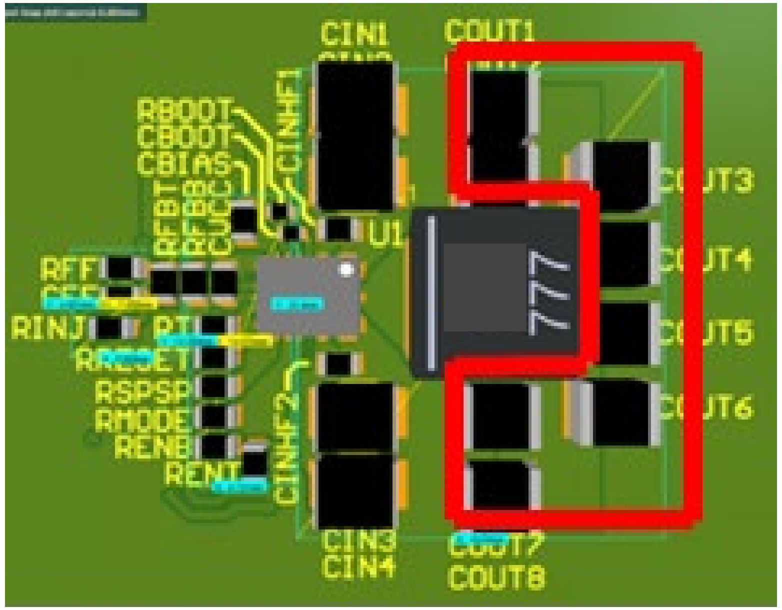
1µH L_{OUT}, 1x22µF C_{OUT}



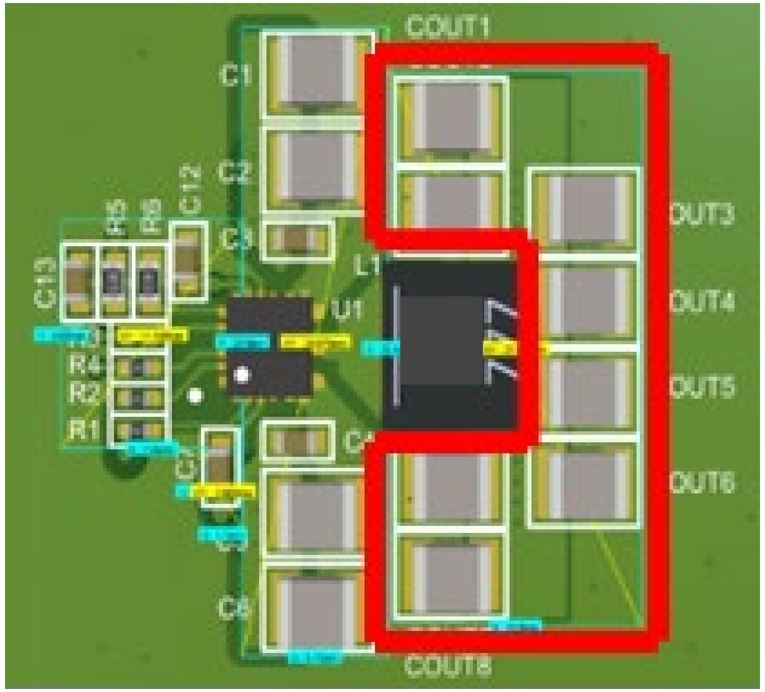
ZDP on a board



402mm²



444mm²



445mm²

Thank You