Start Time: January 17, 2024 | 5:00 PM CET | 8:00 AM PST | 11:00 AM EST

Constant-On-Time (COT) Control for FPGA High-Current Power Supplies

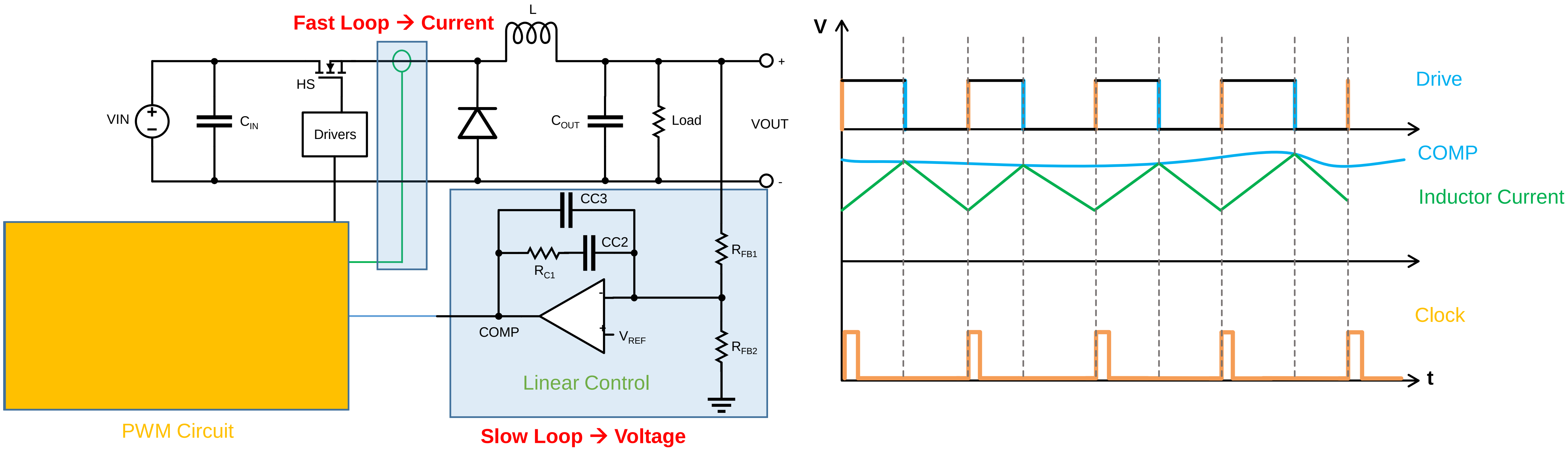
Tomas Hudson, Monolithic Power Systems, Inc.

January 17, 2024

Agenda

1. Peak Current Mode Control Basics
2. Peak Current Mode Control Basics: Subharmonic Oscillation
3. Constant-On-Time (COT) Control
4. COT Advantages and Challenges
5. MPS's Adaptive COT Control
6. MPS's COT Power Modules for FPGA
7. Using Power Modules to Simplify Hardware Design

Peak Current Mode Control Basics



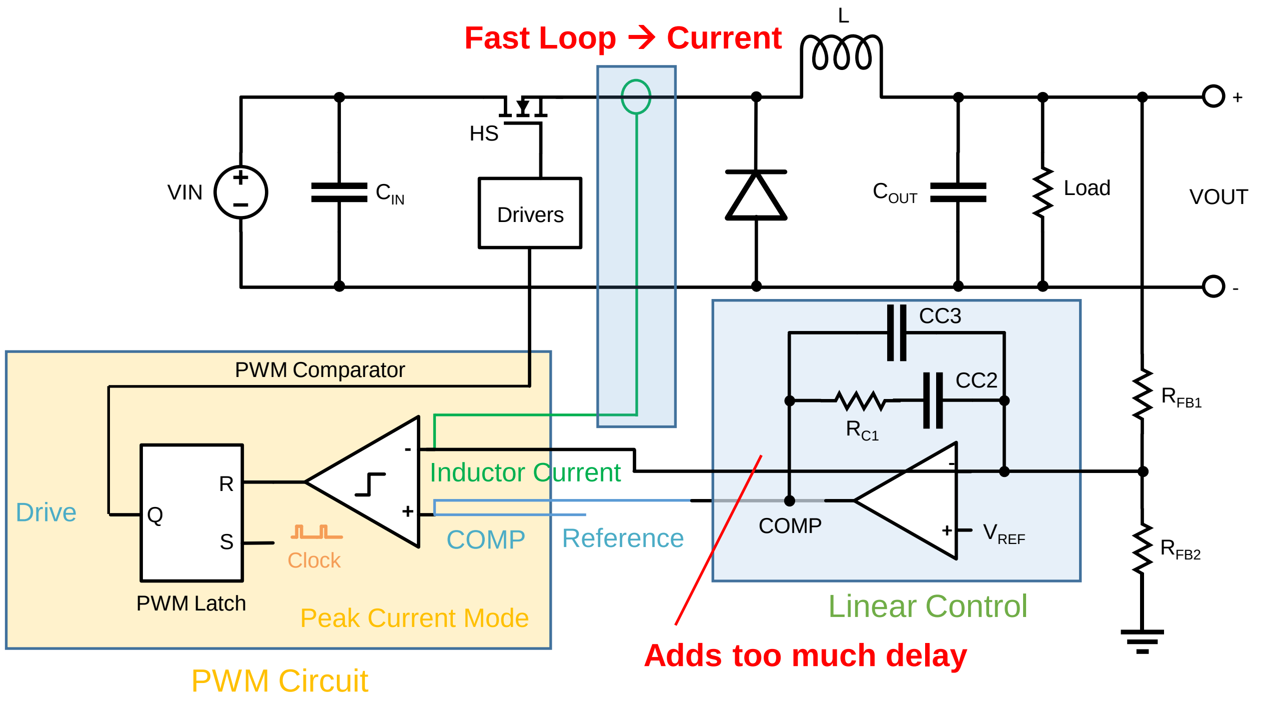
The error amplifier output (COMP) defines the peak current (I_{PK}) for the next cycle:

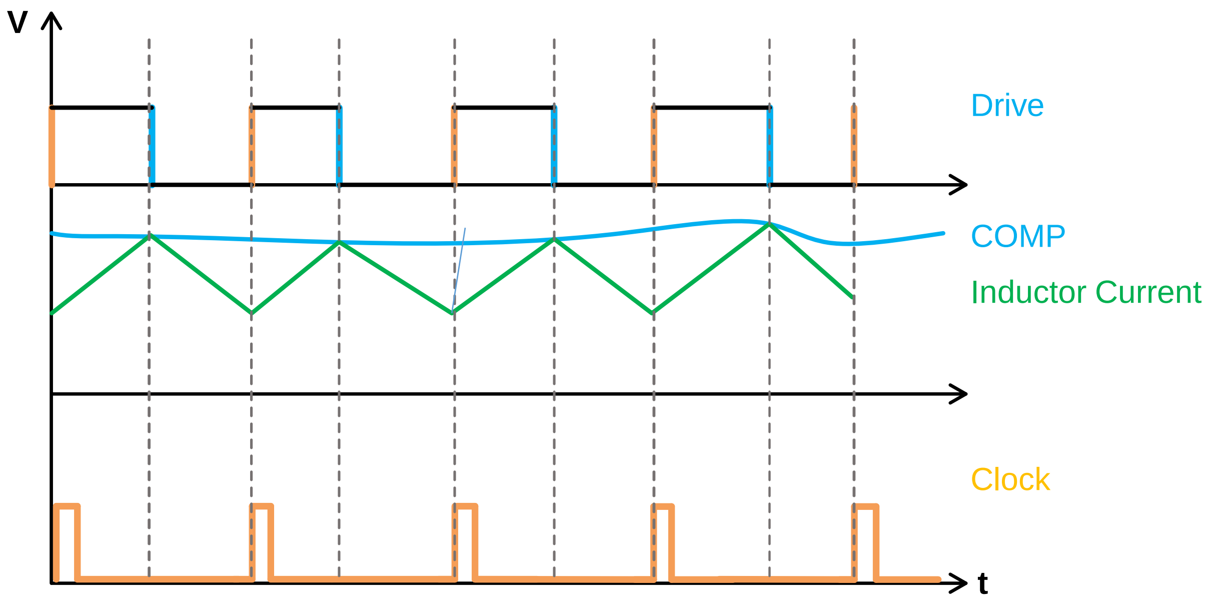
- If the compensation voltage (V_{COMP}) increases, then I_{PK} and the duty cycle increases
- If the input voltage (V_{IN}) drops, then the duty cycle increases until the required I_{PK} is reached, and the output voltage (V_{OUT}) is maintained

Peak Current Mode Control Is Not Sufficient for Certain Applications

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.





Constant-On-Time (COT) Control

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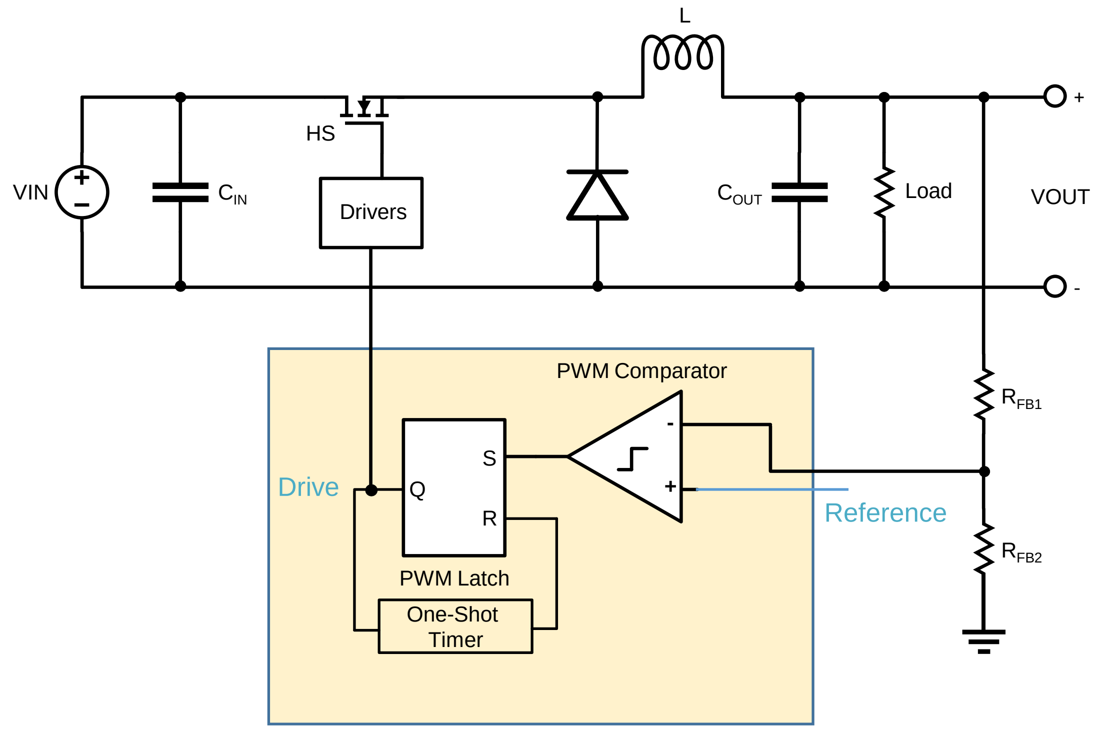
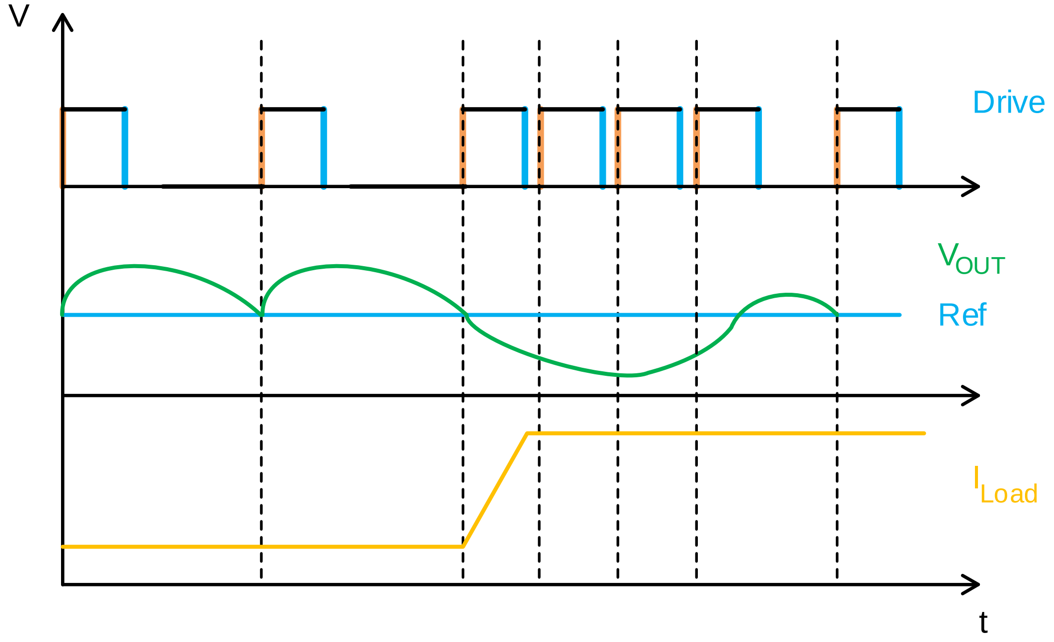


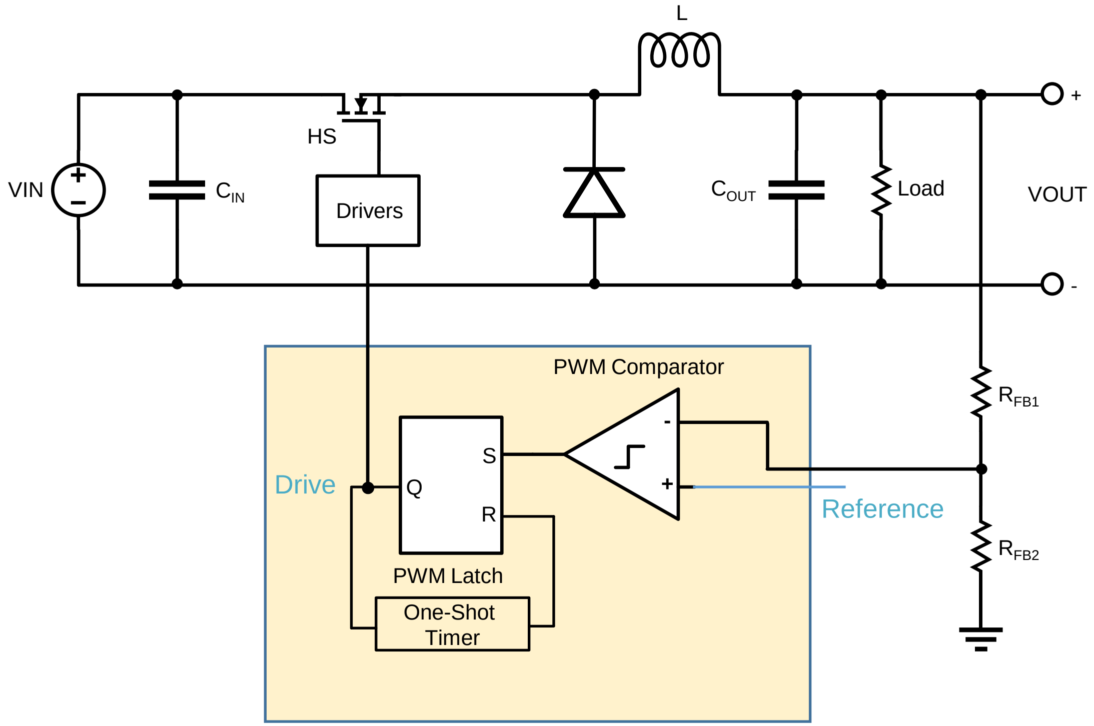
PWM Circuit



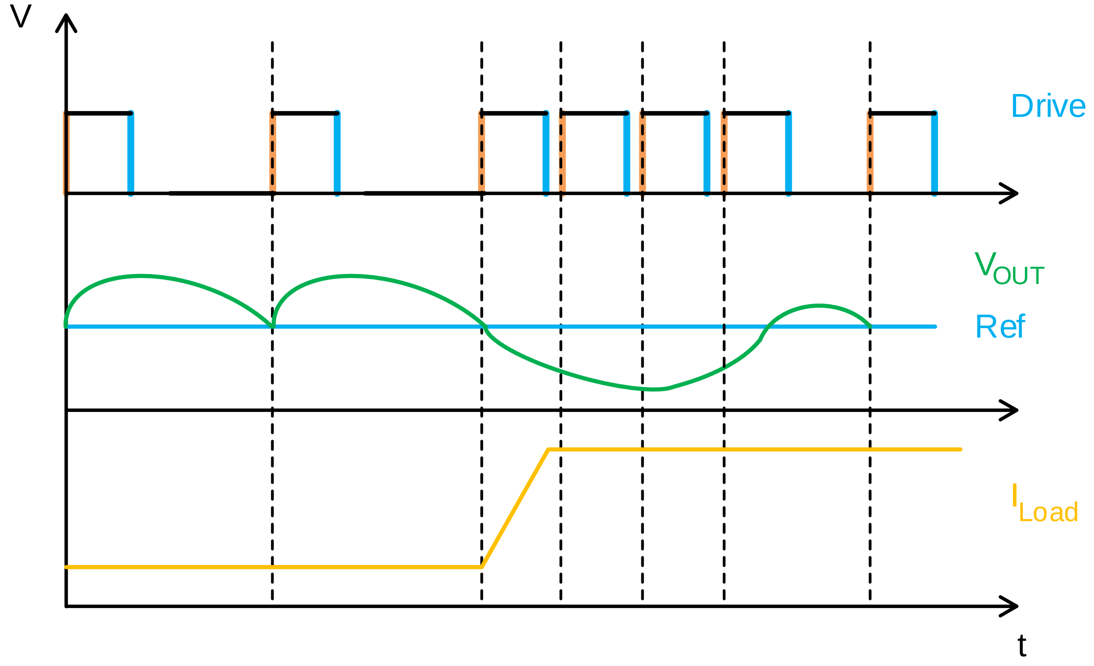
Constant-On-Time (COT) Control

COT control does not use a clock:

- When V_{OUT} falls bellow the reference voltage (V_{REF}), the high-side MOSFET turns on
- The on time is constant and determined by the one-shot timer, while the off time is variable



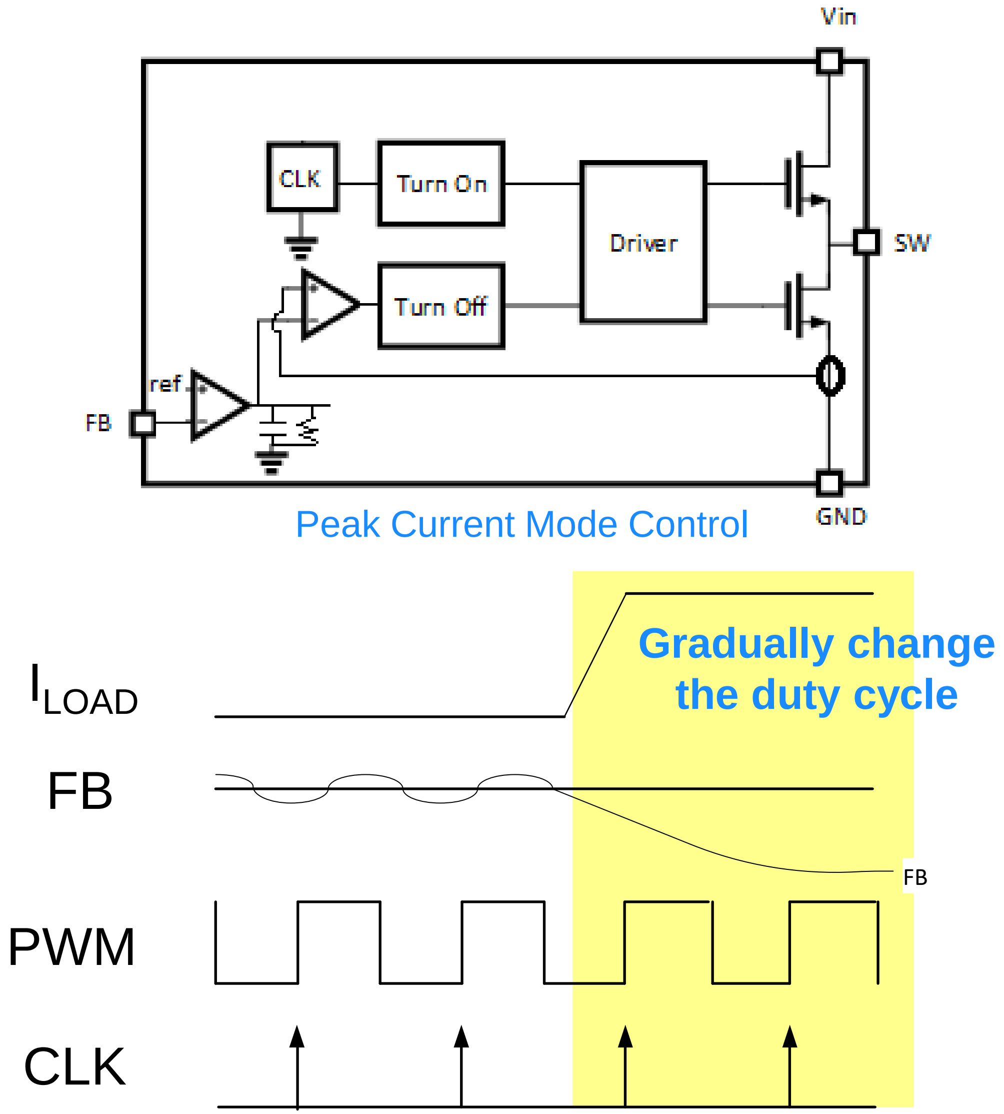
PWM Circuit

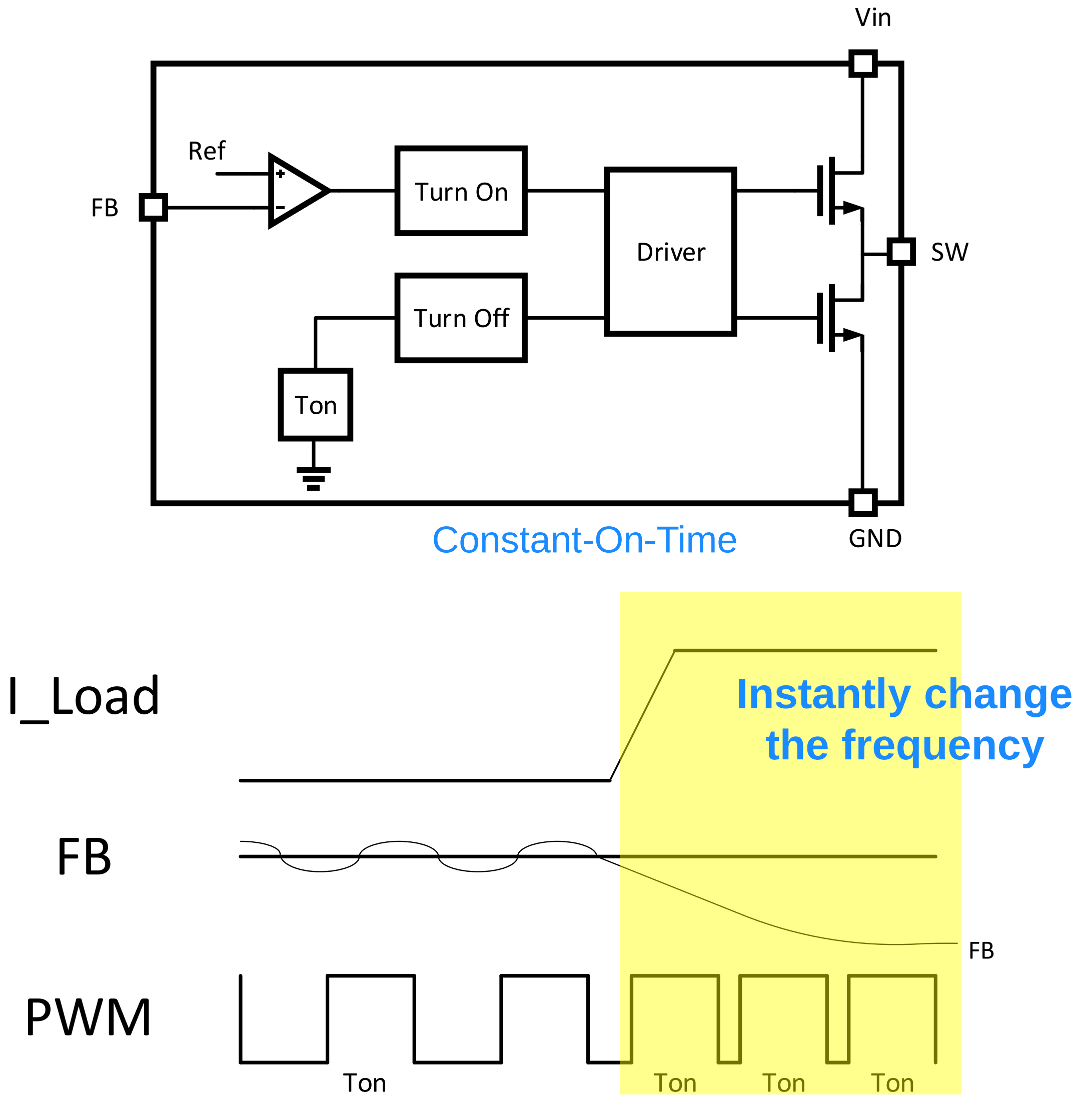


Constant-On- Time (COT) Control

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

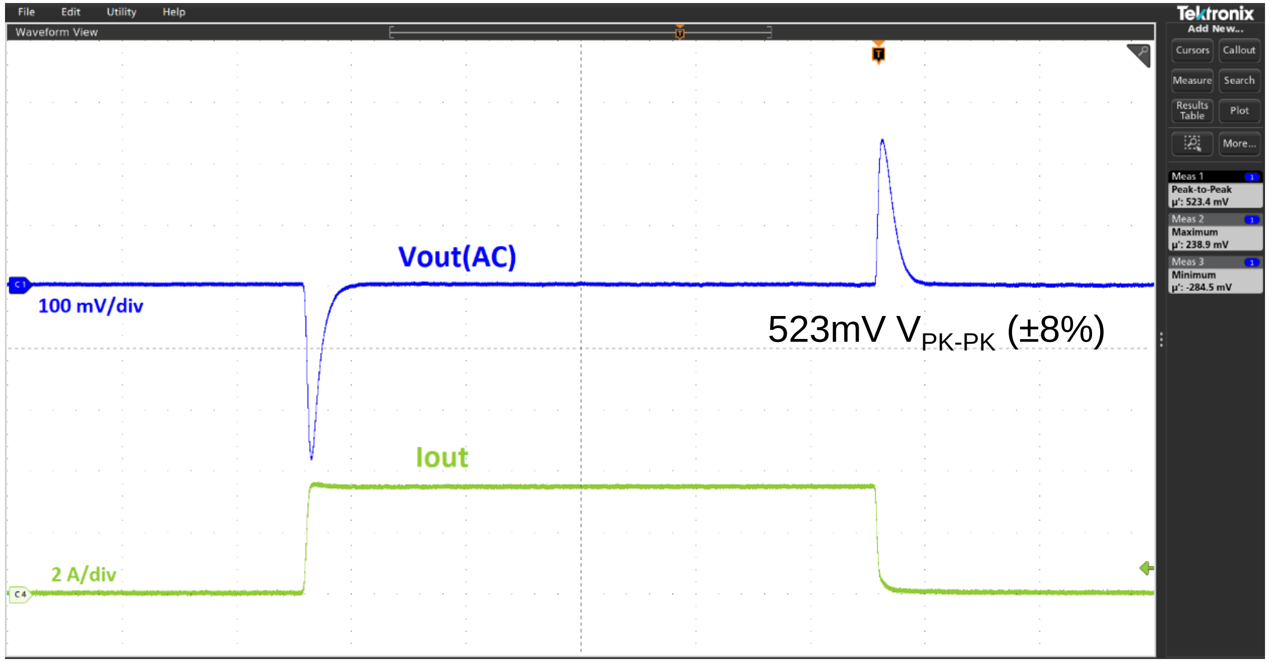
COT Advantages: Fast Transient Response



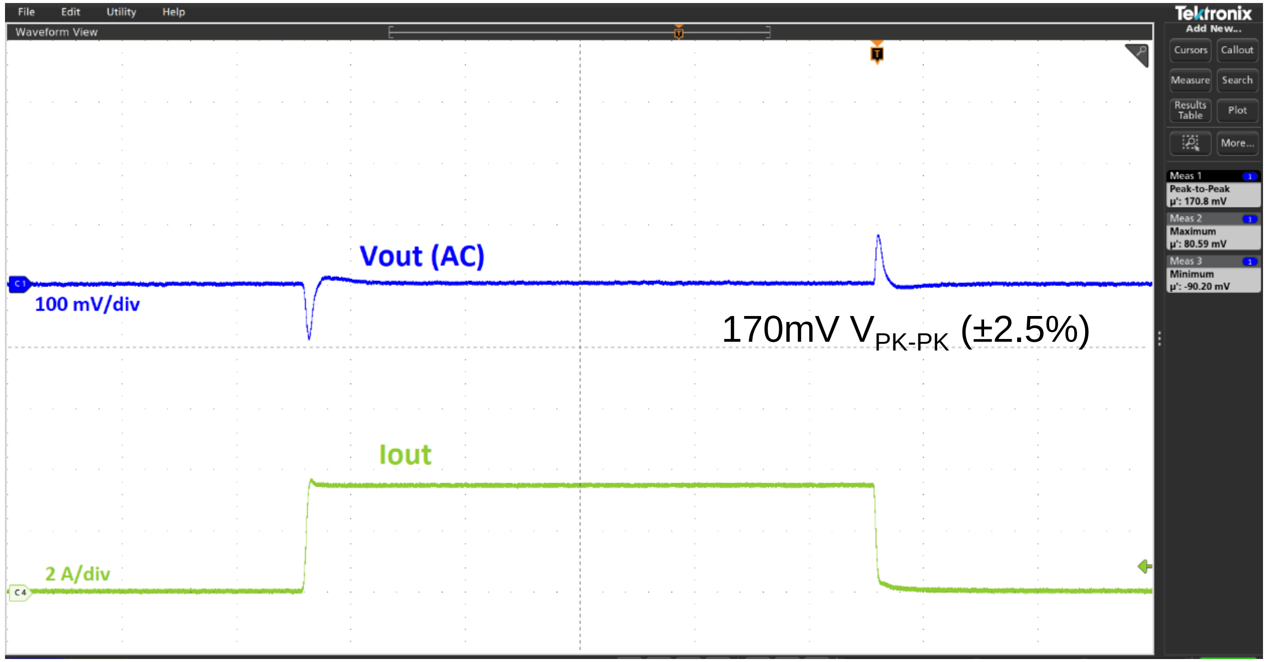


COT Advantages: Fast Transient Response

Peak Current Mode



Constant-On-Time



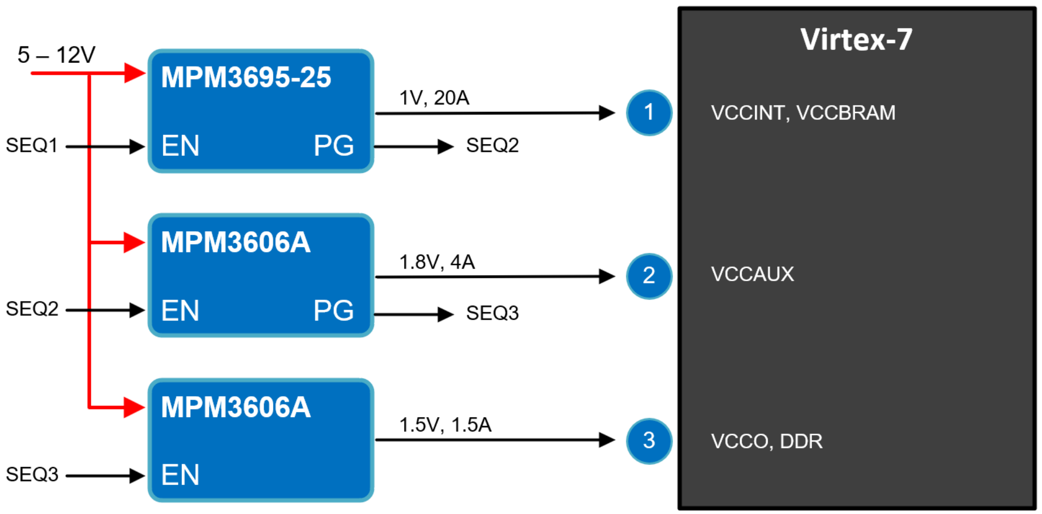
- 3x faster transient response compared to peak current mode with the same components and set-up:
  - 12V input, 3.3V output, 0A to 3.5A load step
  - 1µH L_{OUT}, 2x22µF C_{OUT}

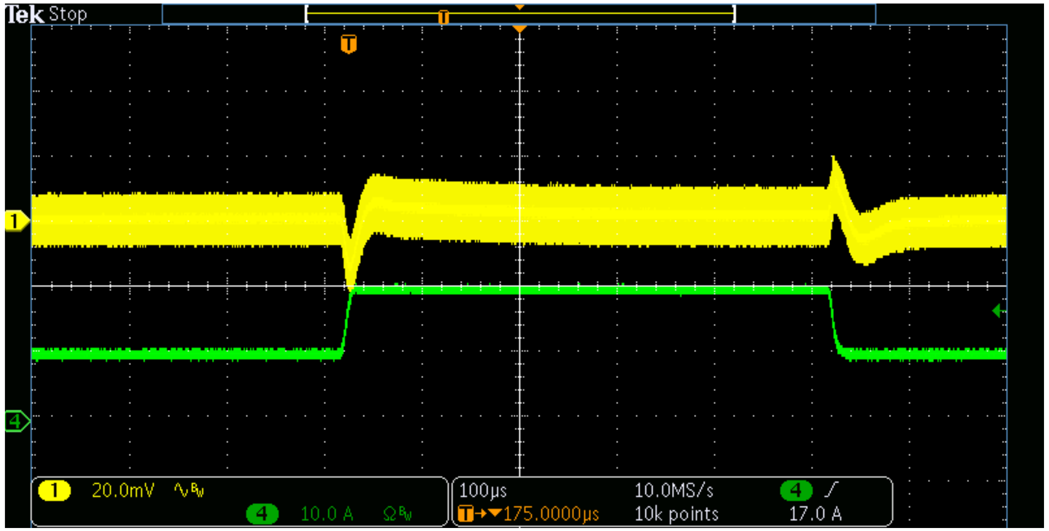
Example: Virtex-7

VCCINT Stability Requirement: 3% (30mV)

MPM3695-25

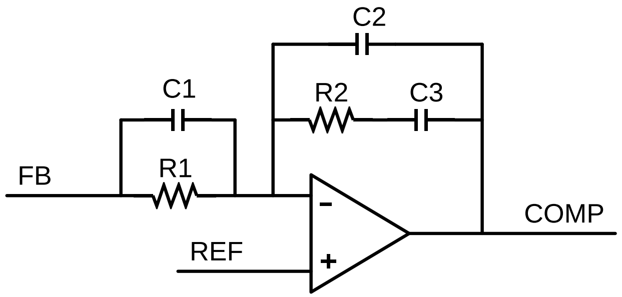
- 3V to 16V V_{IN} Range
- Continuous Output Current (I_{OUT}) Up to 20A
- Supports PMBus/I^2C for Monitoring and Control
- COT Control for Fast Transients
- 1% Reference Voltage (V_{REF}) across a 0°C to 70°C Temperature Range
- V_{OUT} Remote Sense
- Support Parallel Operation Up to 50A
- Available in a QFN-19 (10mmx12mmx4mm) Package

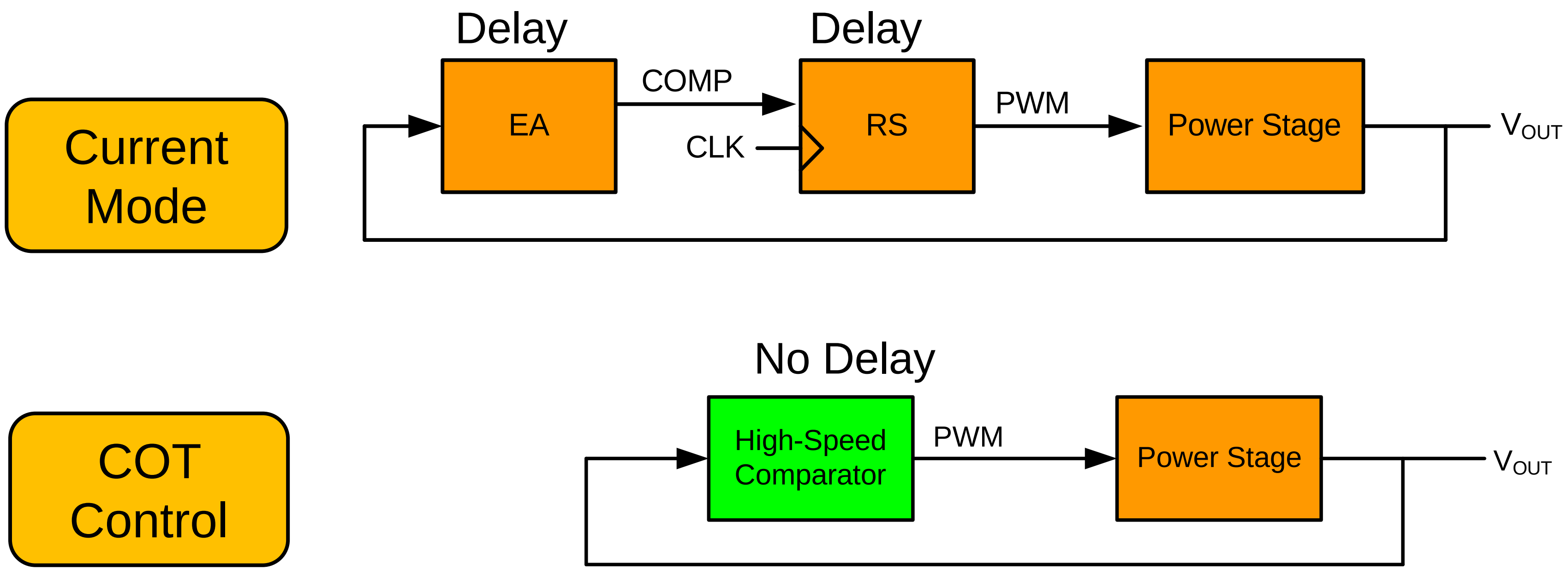




COT Advantages: Simple Architecture

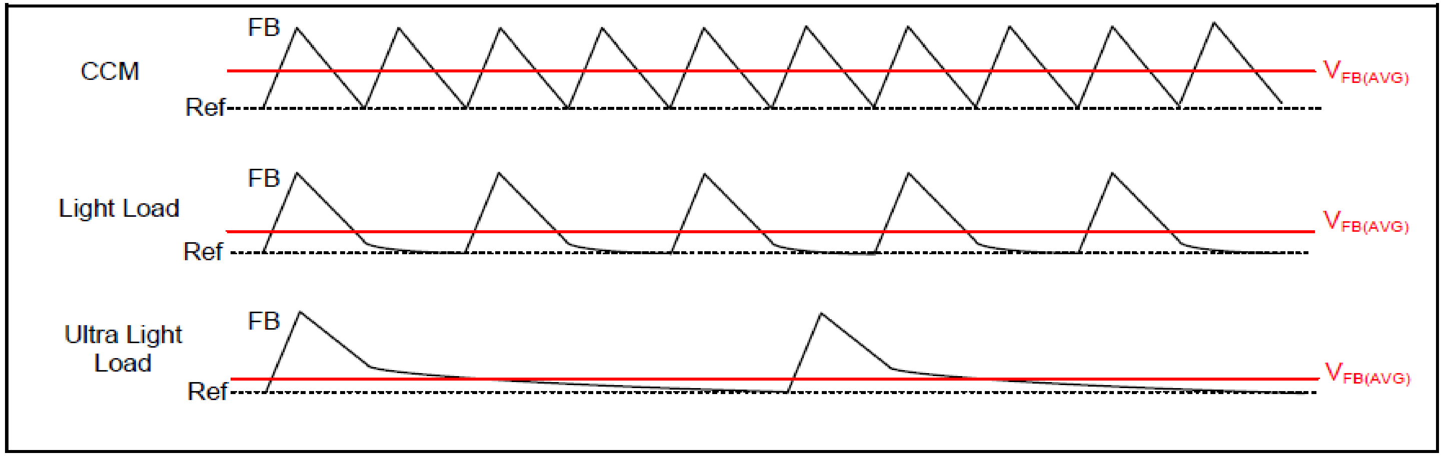
Since COT control does not require a compensator, no time is spent tuning the compensator parameters.

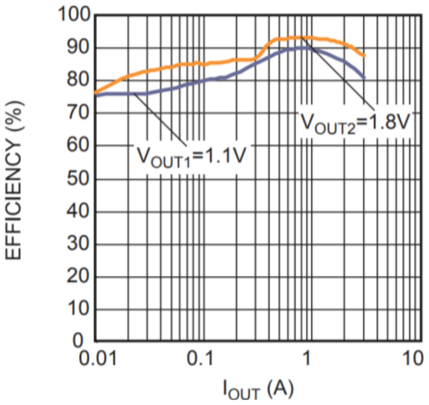




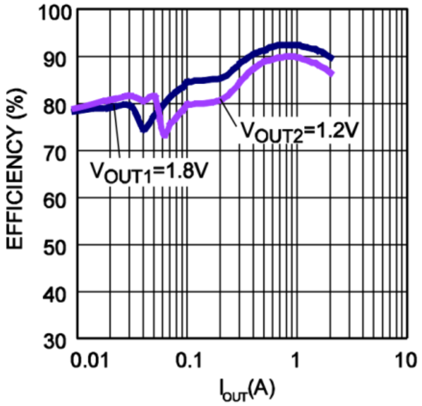
COT Advantages: Transition from Light Loads to Heavy Loads

Due to variable frequency, COT control provides intrinsic pulse-skipping capabilities, enabling a linear transition between light-load operation and continuous conduction mode (CCM).





COT Control

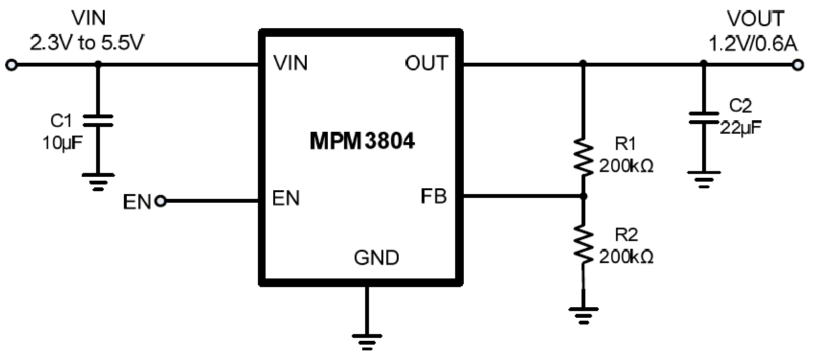


CMC

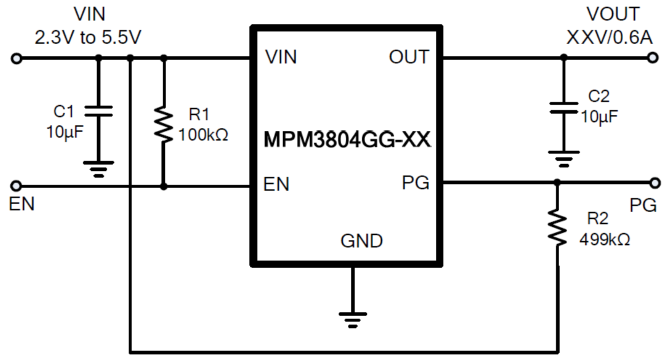
Low-Voltage Series: MPM3804, MPM3814C, MPM3824C, MPM3834C

MPM3804

- 2.3V to 5.5V V_{IN} Range
- Adjustable Output from 0.6V
- 100% Duty Cycle in Dropout
- 2.4MHz Switching Frequency (f_{SW})
- **Low Profile: 0.9mm**
- **QFN-10 (2mmx2mmx0.9mm) Package**
- **Best-in-Class Efficiency**
- **EN and PG for Sequencing**
- **COT Control**



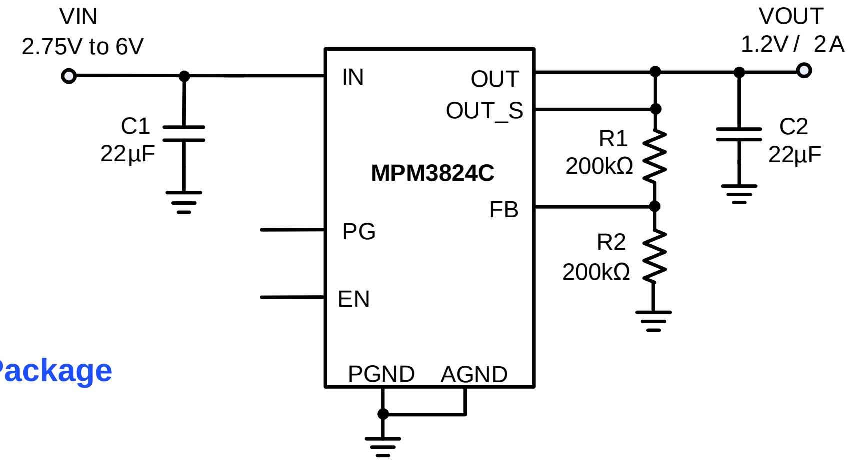
Total Solution Size: 3.7mmx3.7mm

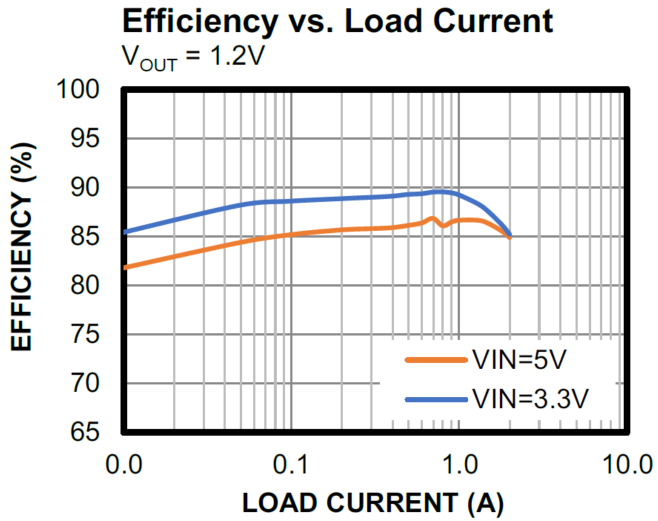


1.2V, 1.8V, 2.5V, 3.3V Fixed-Output Version Available

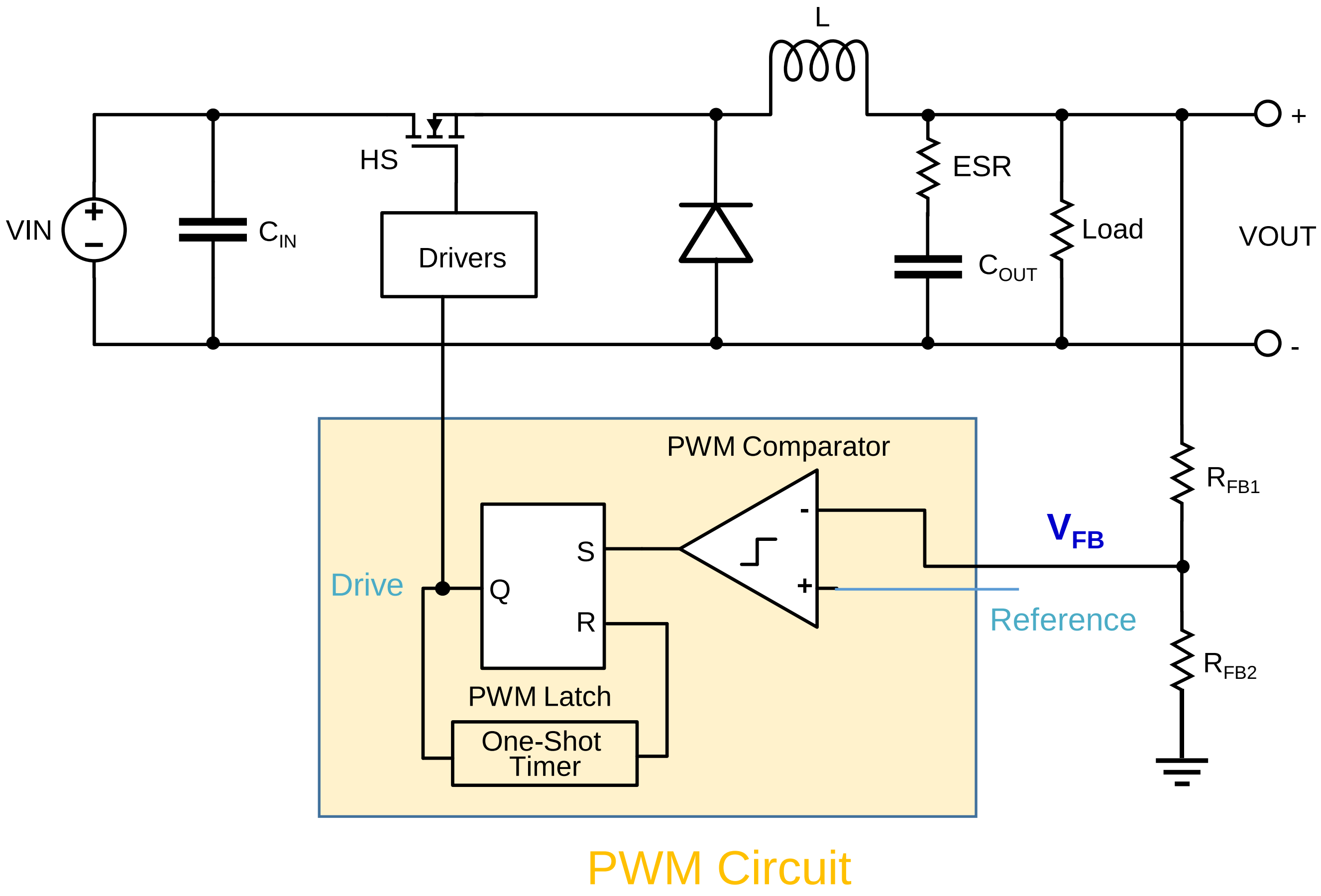
MPM3814C/24C/34C

- **1A/2A/3A Pin Compatible**
- 2.75V to 6V V_{IN} Range
- Adjustable Output from 0.6V
- **FCCM and DCM Available**
- **Low Profile: 1.2mm**
- **ECLGA-14 (2.5mmx2.5mmx1.2mm) Package**
- **Best-in-Class Efficiency**
- **COT Control**
- 100% Duty Cycle in Dropout





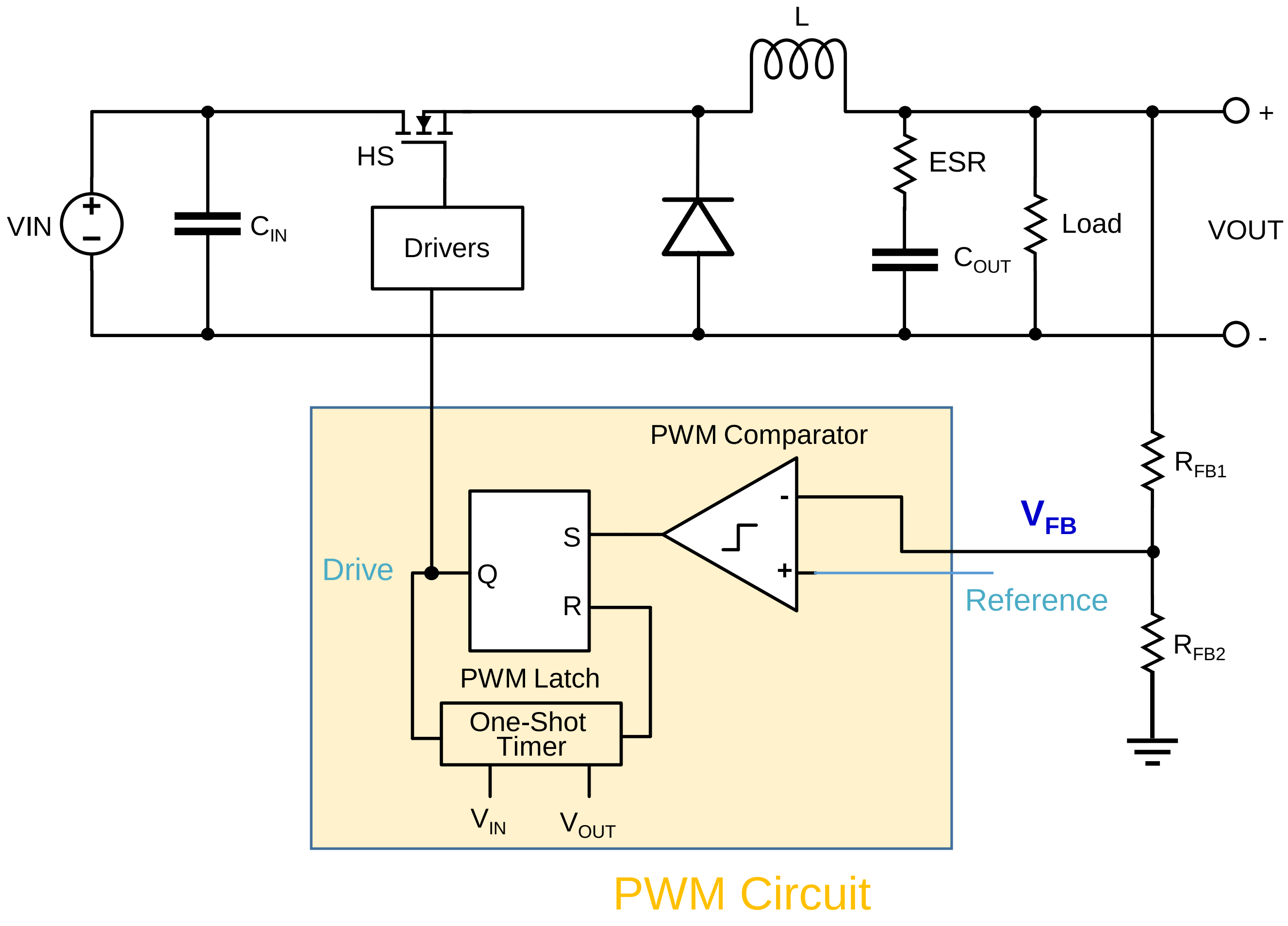
COT Challenges: Variable Frequency in Steady State



Since there is no clock, the COT converter's f_{SW} heavily depends on V_{IN}, V_{OUT}, and I_{LOAD}.

A stable f_{SW} at steady state (stable I_{LOAD}) may be difficult due to variations in V_{IN}, which is problematic for certain applications.

MPS 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}).

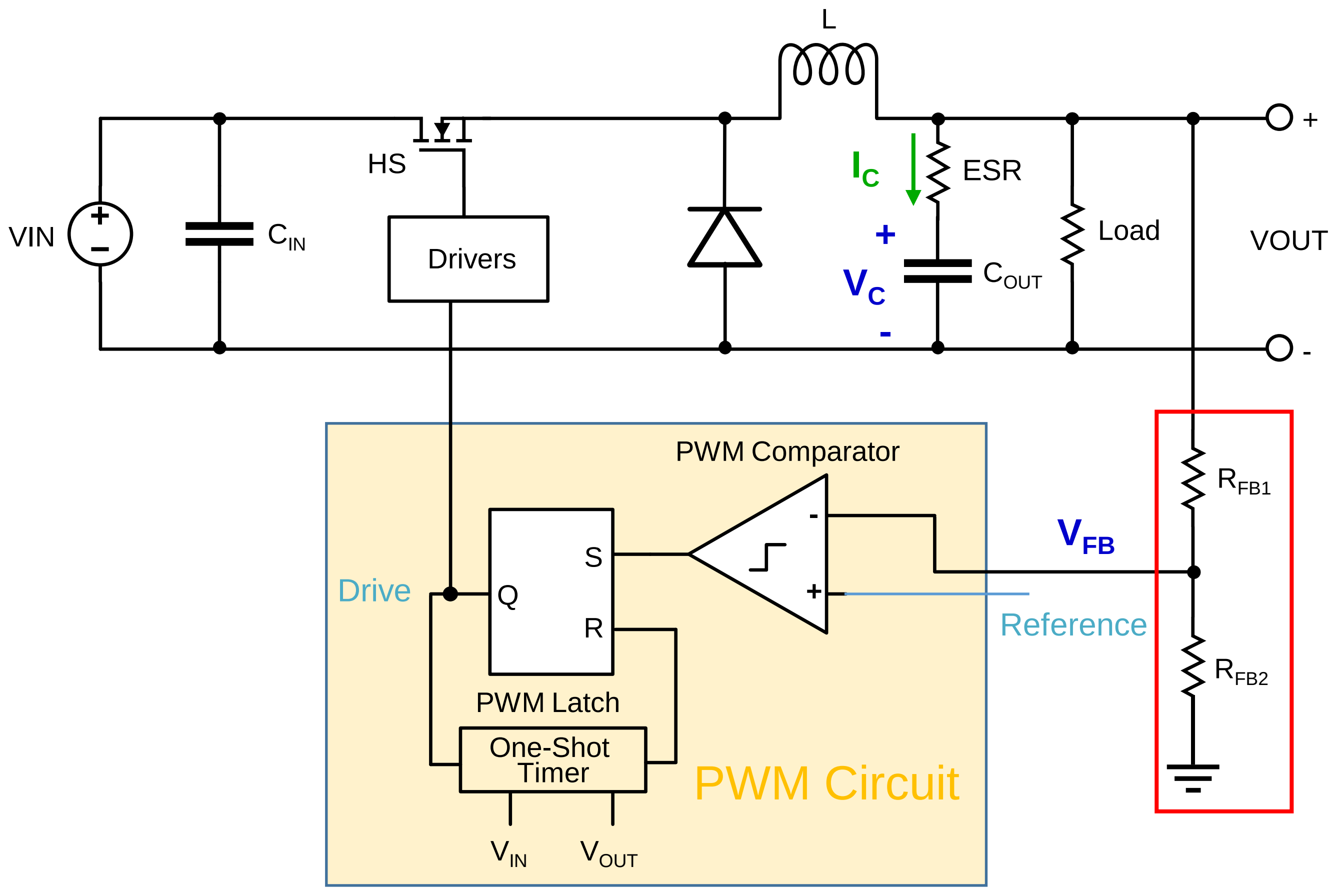
This enables a steady f_{SW} during steady state, without affecting the converter's ability to immediately change the frequency when faced with a load step.

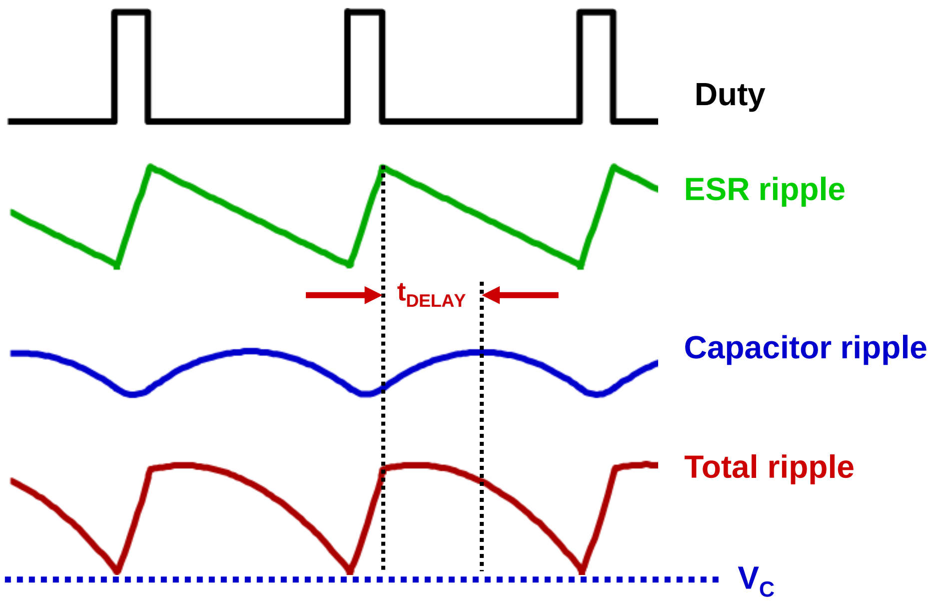
COT Challenge: Stability Is Dependent on ESR

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

The feedback voltage ripple has two main components:

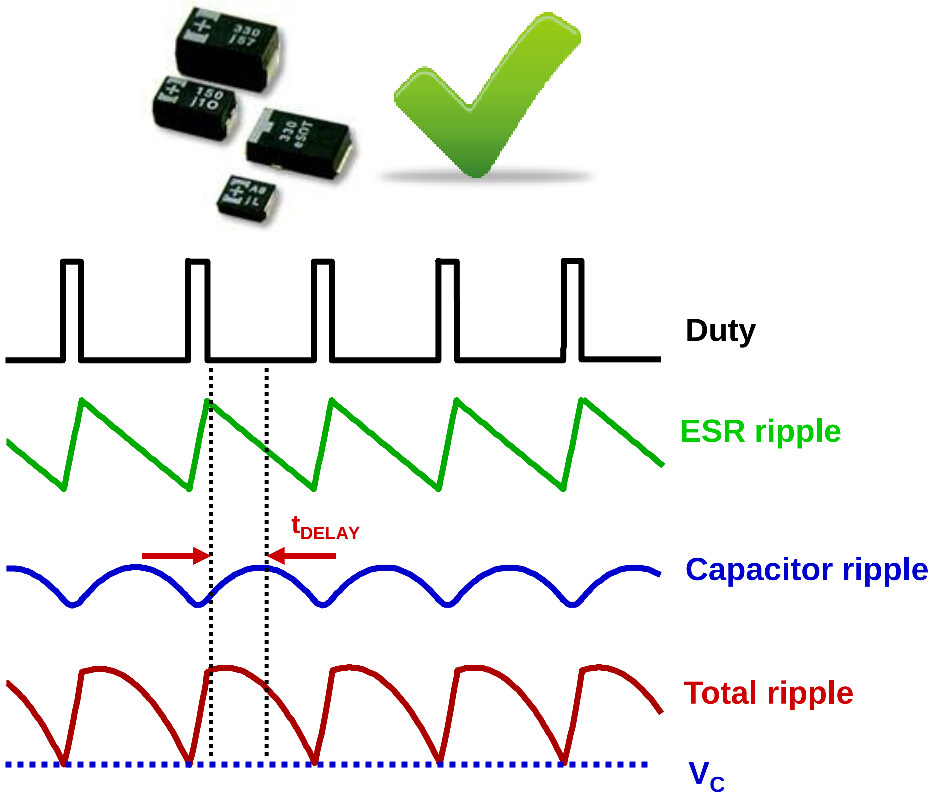
1. ESR ripple: Directly proportional to the inductor current (I_L), with no delay/phase difference
2. V_{CAP} ripple: Caused by charging/discharging the output capacitor, and is delayed with respect to I_L



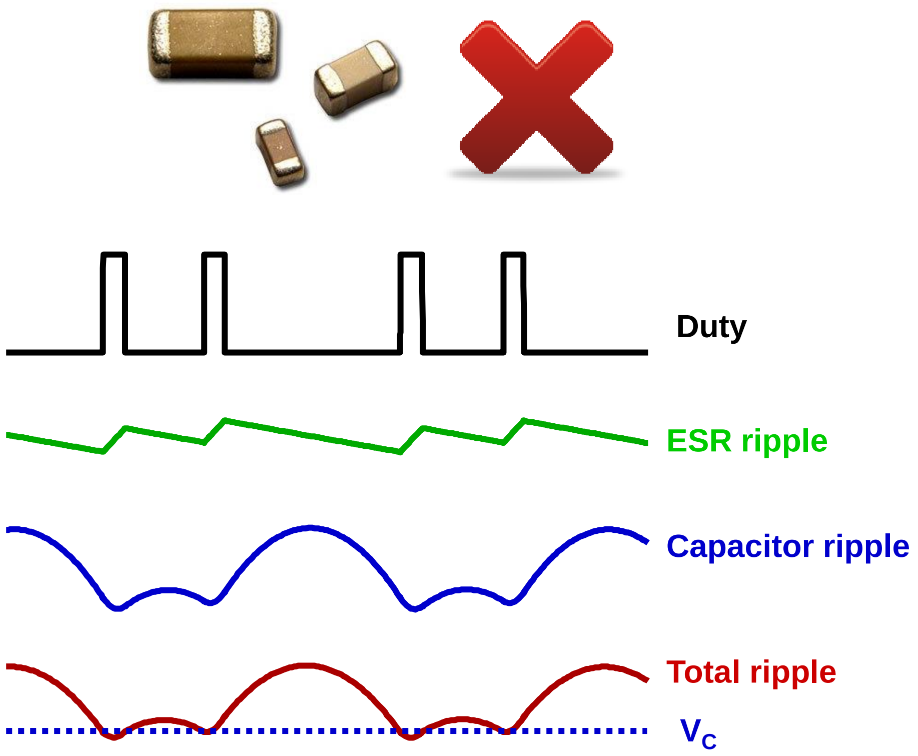


COT Challenge: Stability Is Dependent on ESR

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



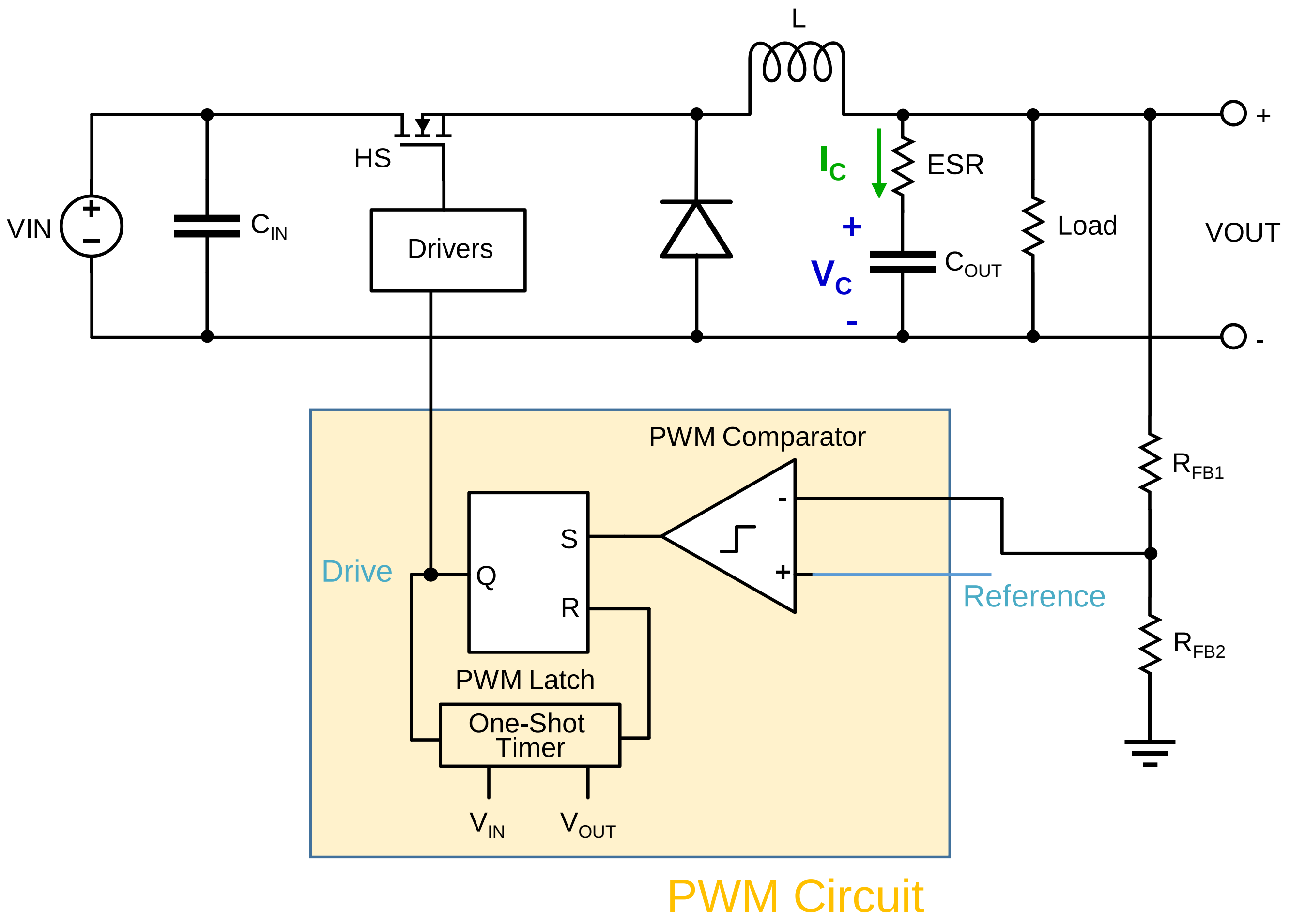
If the V_{CAP} ripple dominates, the V_{OUT} ripple is out of phase with I_L, and the circuit can enter subharmonic oscillation.

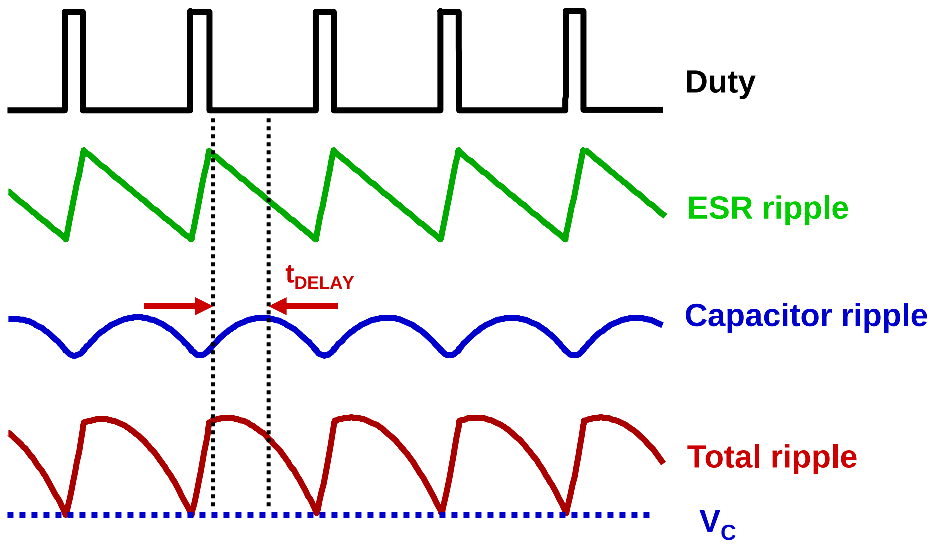


COT requires output capacitors (C_{OUT}) with large ESR for stability.
If low-ESR capacitors are used (e.g. MLCC), the circuit may become unstable.

MPS Solution: Current Ripple Injection

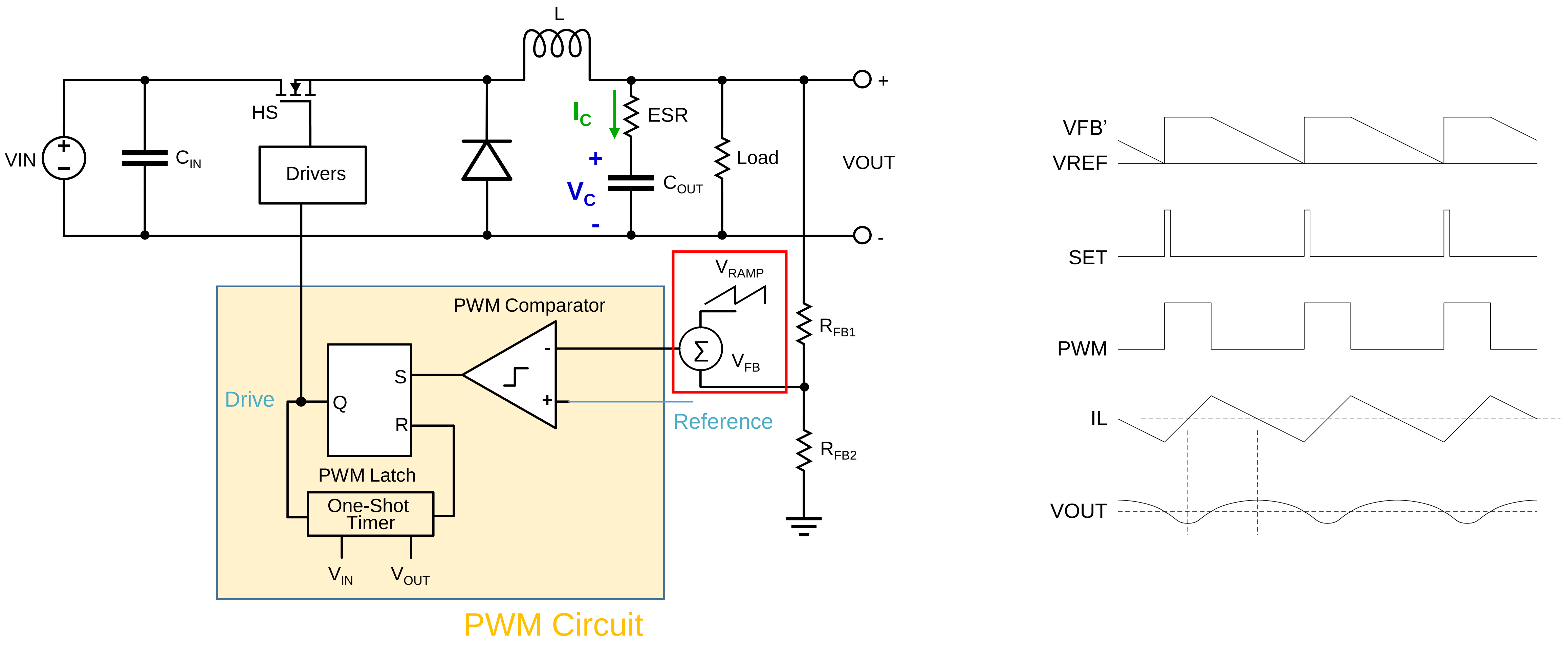
Option 1: Use C_{OUT} with sufficient ESR





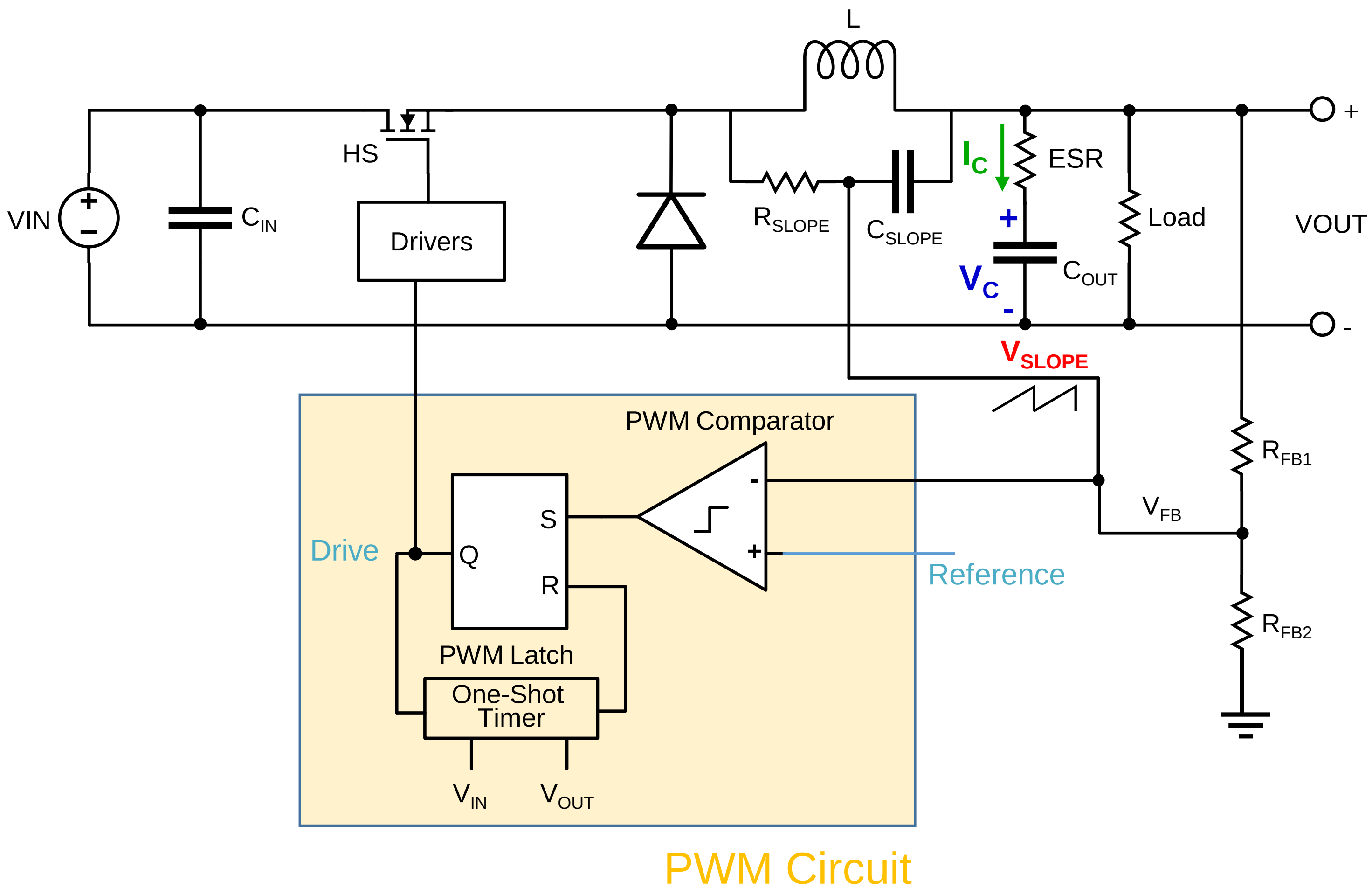
MPS Solution: Current Ripple Injection

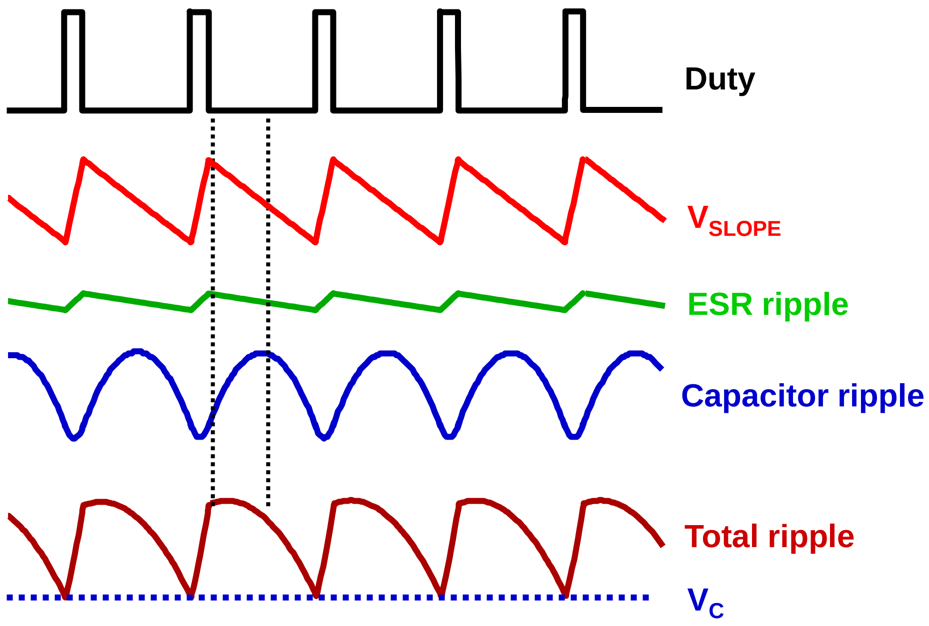
Option 2: Add an external ramp



MPS Solution: 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

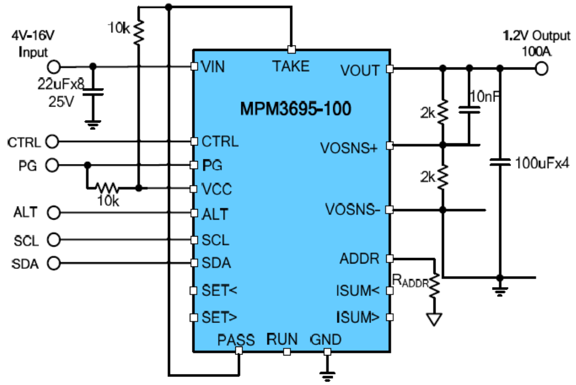


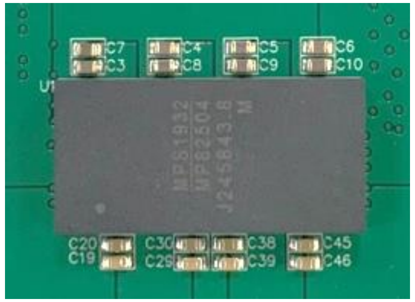


MPM3695-100: 100A Power Module

Key Advantages:

- 3V to 16V V_{IN} Range
- 0.5V to 3.3V V_{OUT} Range
- **100A of Continuous Current (60A for 3.3V V_{OUT})**
- **Parallel Up to 800A**

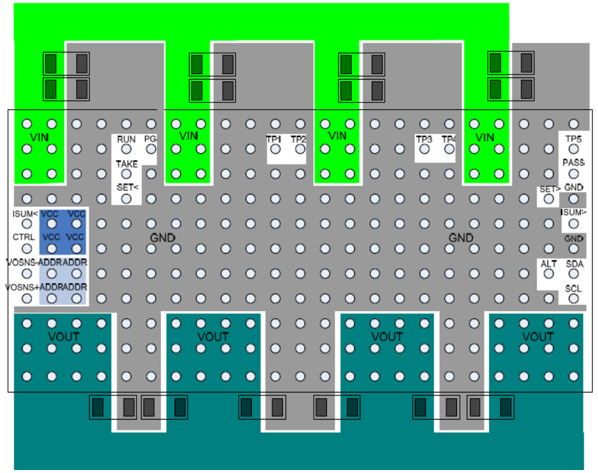




Available in a BGA (15mmx30mmx5.18mm) Package

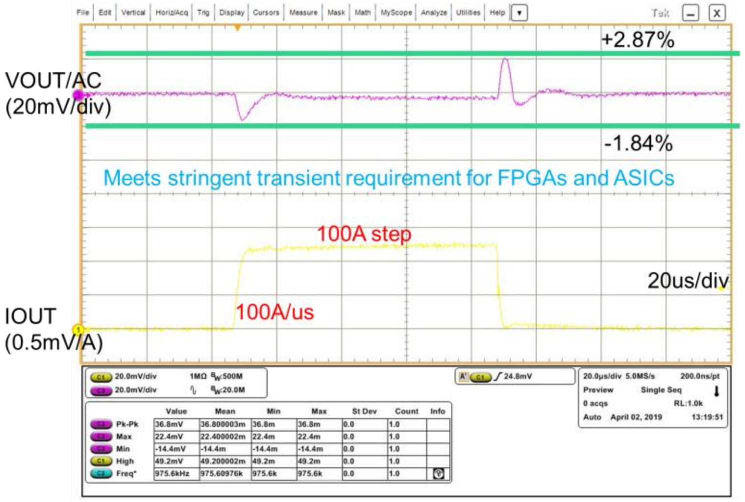
Small Size and Easy to Use

- Very simple 100A+ solutions
- Minimum external components
- Only three layers required for layout
- Saves board space: Allows for high-speed traces underneath



Fast Transients and Min C_{OUT}

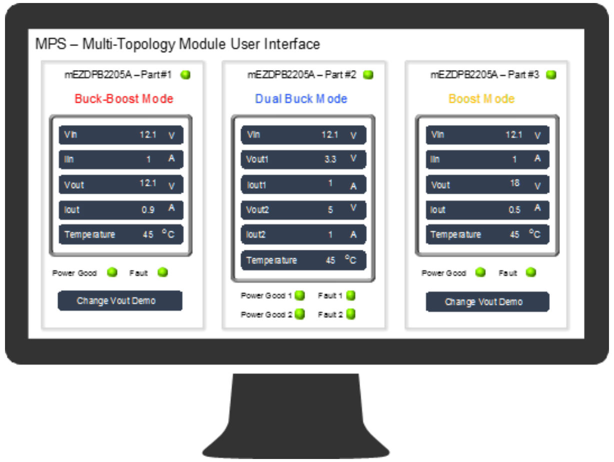
- Four phases interleaved inside
- Multi-phase COT (MCOT) for fast transients
- Saves up to 50% of C_{OUT} compared with competitor modules



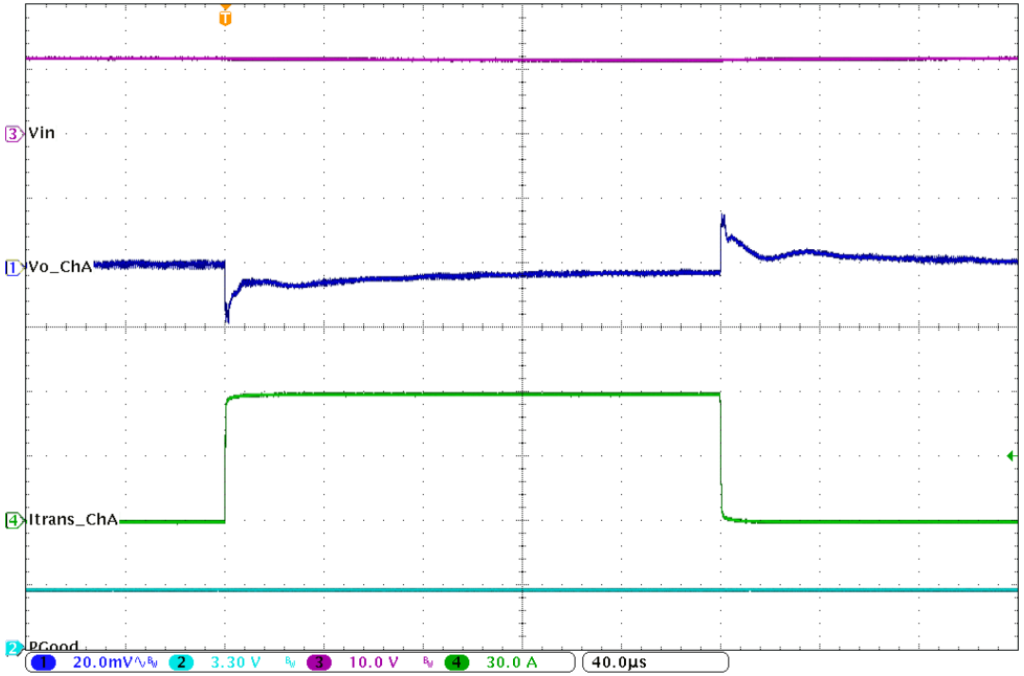
2x Modules, 100A Step, Peak to Peak ±3%, 2500µF C_{OUT}

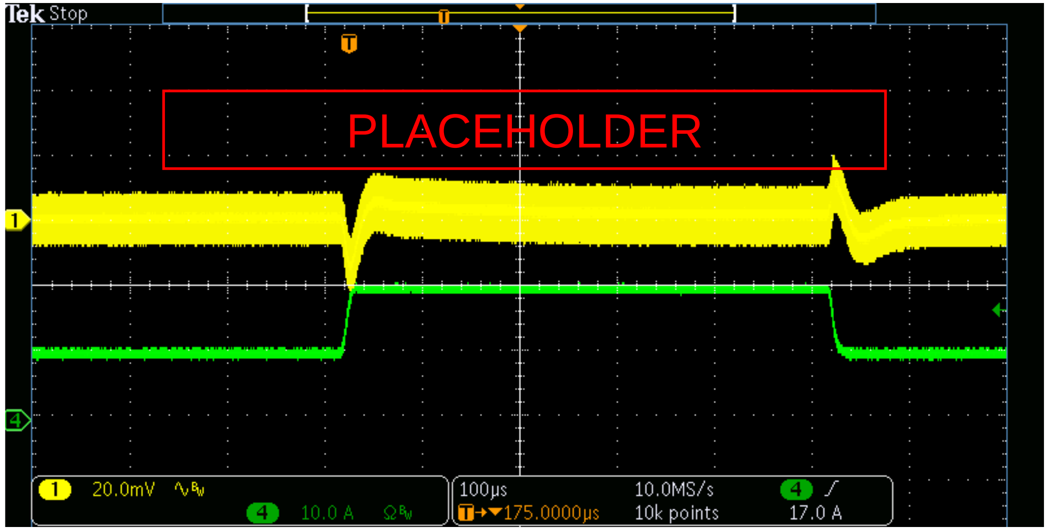
Diagnostics and Reliability

- BGA packages enhance mechanical and thermal stress as well as reliability
- I²C reports any system faults
- Individual module/phase faults can be detected



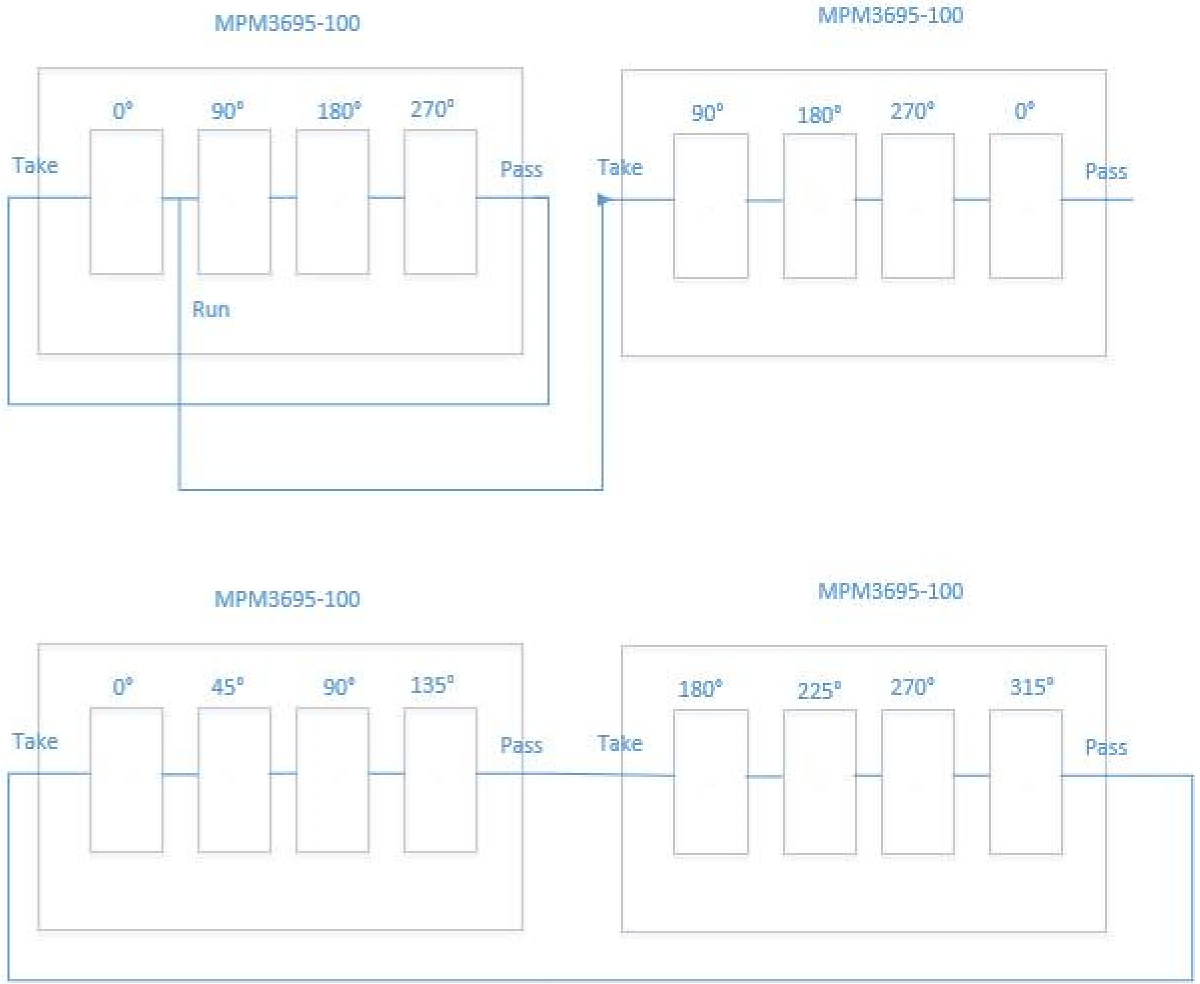
Save Up to 50% on External Components





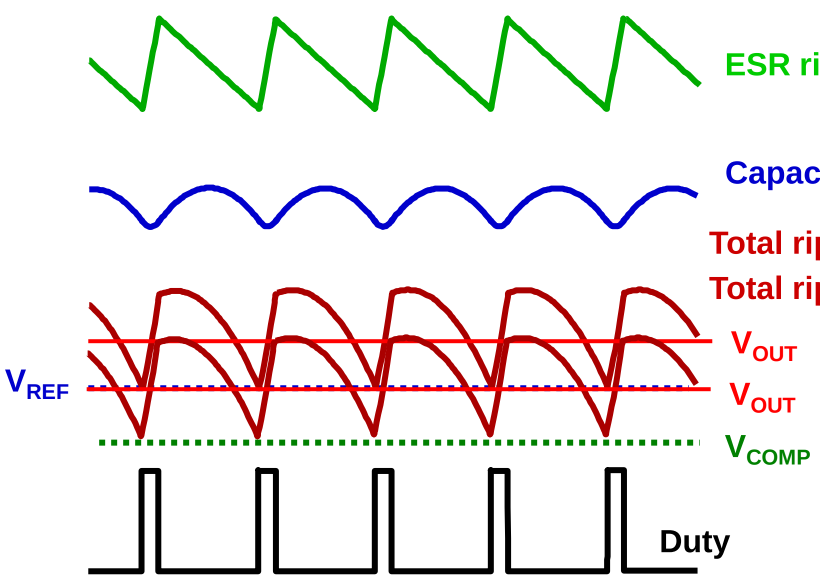
VOUTA 60-A load step 100 A/µsec

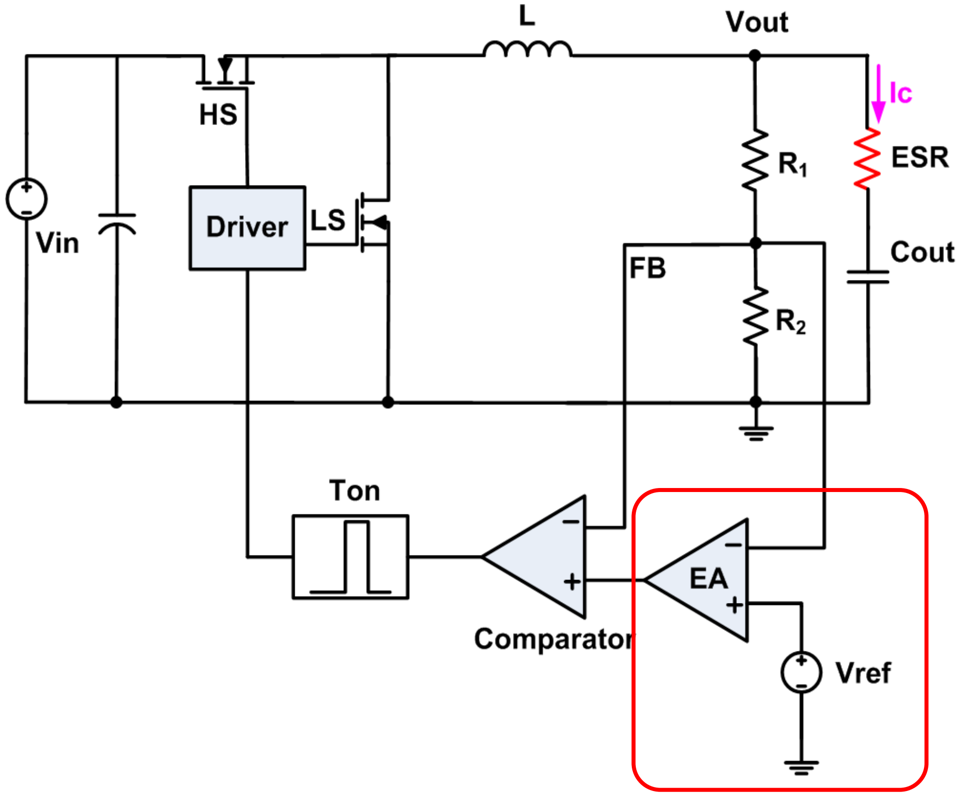
Auto-Interleaving COT



- MPS scalable power modules allow for up to 8-phase operation
- Active current balancing ensures equal current across all outputs
- Automatic master/slave detection and phase counting via the TAKE pin

COT Challenge: DC Offset Error





- Add an integrator to compensate the ½ (V_{OUT} ripple) influence
- The voltage loop is a slow-speed loop, which is used for DC regulation only
- Does not impact transient speed

MPS's Adaptive 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 • Integrated slope generator to keep the converter stable, even with low ESR • Quasi-stable frequency during state-state operation • Auto-interleaving for simple power scaling	• Must generate a slope on FB (e.g. using COUT_ESR) • f_{SW} is not constant due to variations in the off time • Output filter design is difficult and suboptimal in many sensitive systems

MPS's COT Power Modules for FPGA

V_{IN}

10A	20A	30A	50A	100A+
MPM3695-10 3.3V to 16V, 10A, 0.5V to 5V V_{OUT}, COT Control, LGA-45 (8mmx8mmx2mm)	**MPM3690-20A/B** 4V to 16V, A: Dual 13A, B: Single 26A, 500kHz to 1.6MHz, BGA (16mmx16mmx5.18mm)	**MPM3690-30A/B** 4V to 16V, A: Dual 18A, B: Single 36A, 500kHz to 1.6MHz, BGA (16mmx16mmx5.18mm)	**MPM3690-50A/B** 4V to 16V, 25A, A: Dual 25A, B: Single 50A, COT Control, BGA (16mmx16mmx5.18mm)	**MPM3698/99** 4.5V to 16V/3V to 16V, Single 120A, Dual 80A + 40A, Master/Slave, BGA (15mmx30mmx5.18mm)
MPM3683-10 2.7V to 16V, 10A, 0.6V to 5.5V V_{OUT}, COT Control, LGA-29 (7mmx7mmx4.4mm)	**MPM3683-20** 2.7V to 16V, 20A, 0.6V to 5.5V V_{OUT}, COT Control, LGA-29 (7mmx7mmx4.4mm)	**MPM81204** 4V to 16V, Dual 12A, Dual 5A, 0.6V to 5V V_{OUT}, BGA (9.5mmx16mmx4.98mm)	**MPM3690-50D** 3.2V to 16V, 12A, 5A, 0.5V to 3.6V V_{OUT}, COT Control, BGA (16mmx16mmx5.18mm)	**MPM3695-100** 3.2V to 16V, 100A, Parallel Up to 800A, Interleaved COT Control, BGA (15mmx30mmx5.18mm)
				MPM82504 3V to 16V, Quad 25A, Flexible Output Parallel, MCOT Control, BGA (15mmx30mmx5.18mm)

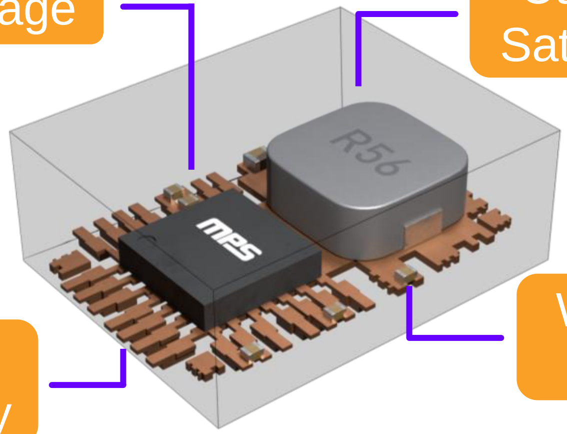
Multiple Outputs

Released

MPS Power Module: Key Advantages

Monolithic Power Stage

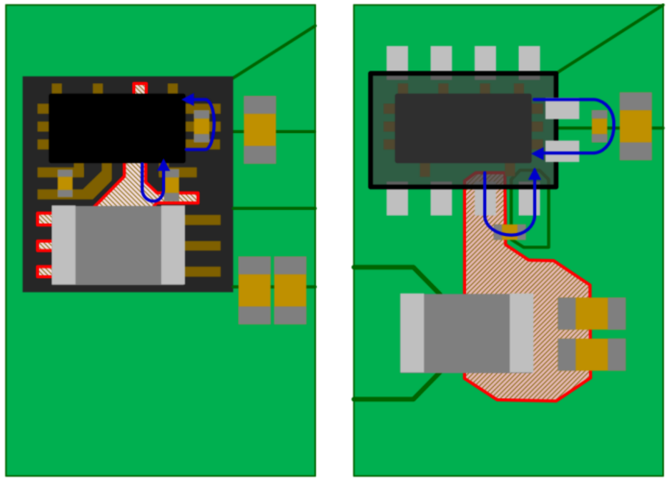
Customized, Soft Saturation Inductor



MeshConnect™ Packaging Technology

Wide Temperature Range Passives

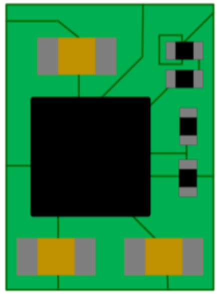
Improved EMI Performance



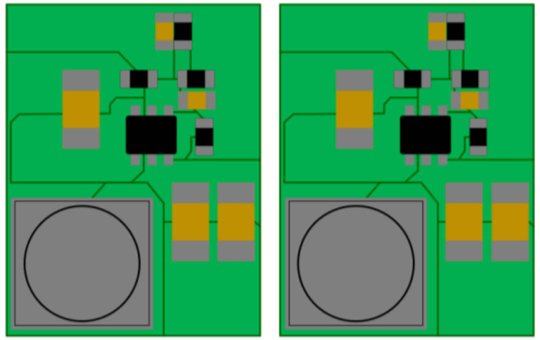
Module Layout Optimized for EMI:

- Smaller Switch Node
- Smaller Hot Loops
- Fast Time to Market
- Full Qualification as a Complete Power Supply

MPM38111



MP2152 x 2



- Small Solution Size
- Simplified Board Layout
- Minimum Components