Choosing the Right Fixed Frequency Buck Regulator Control Strategy

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How Do You Choose?

Part A

- Buck regulator basics
  - Basic functions
  - Filter design
  - Fixed frequency vs. variable
- Fixed frequency control
  - Voltage mode control
  - Current mode control
  - Emulated current mode control

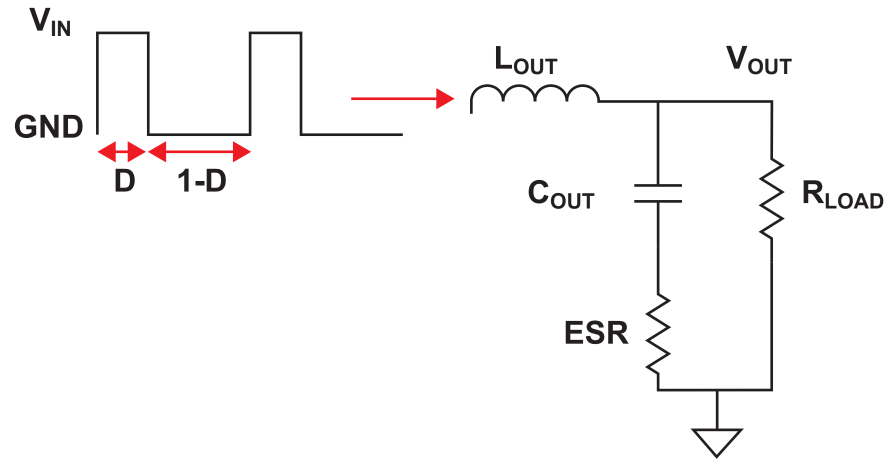
Part B

- Variable frequency control

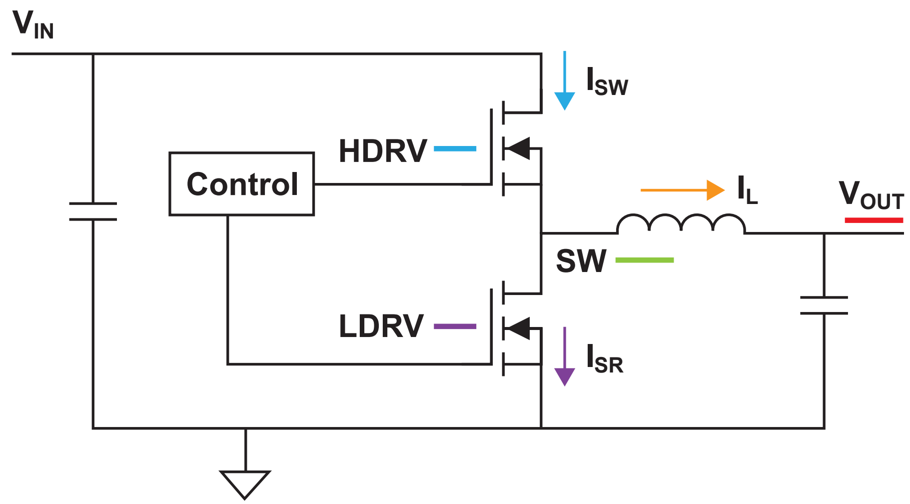
Buck Regulator

- Step down only
- "Chop up" the input voltage
- Send to averaging filter

$$V_{OUT} = \text{Duty Cycle} \times V_{IN}$$



Pretty simple – right?



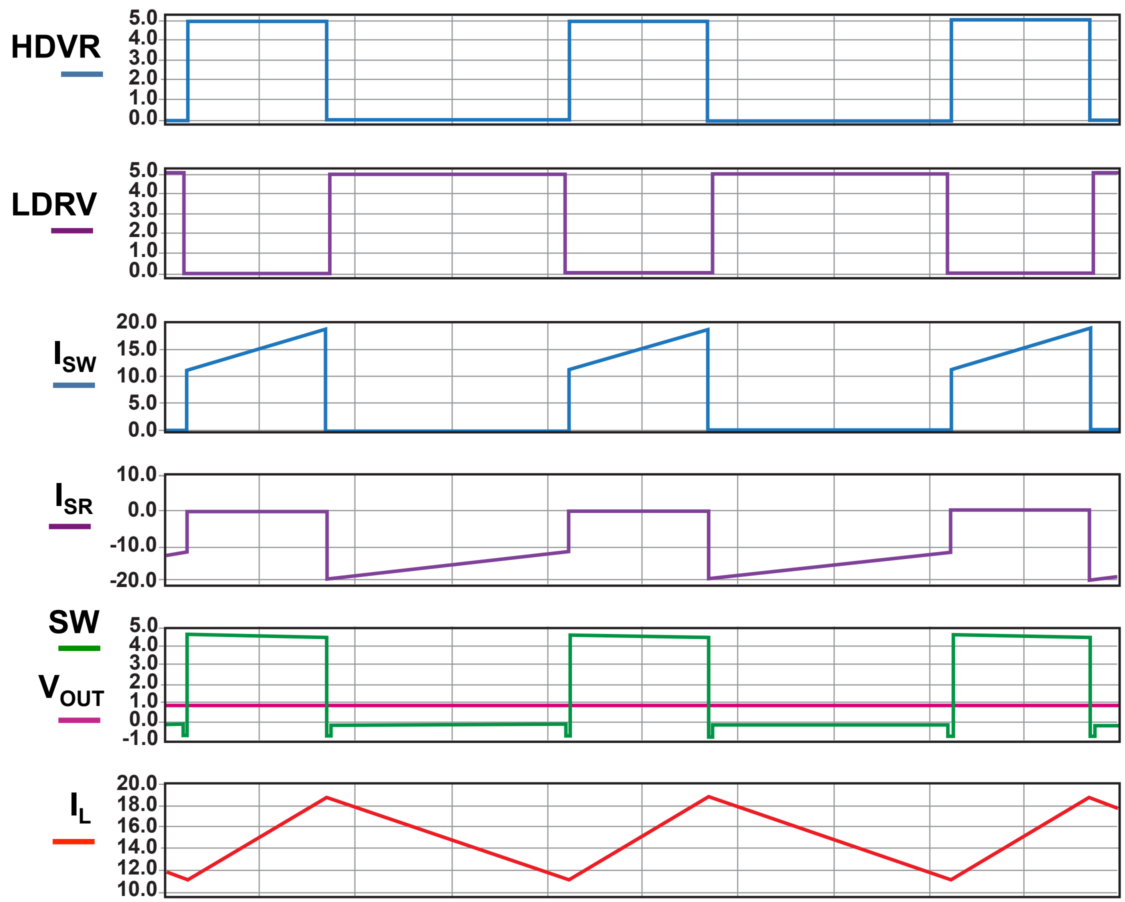
Synchronous Buck Waveforms

Continuous
Conduction
Mode

- Inductor current flow is continuous during the switching cycle

$$\text{Duty Cycle}_{CCM} = \frac{t_{ON}}{t_{ON} + t_{OFF}}$$

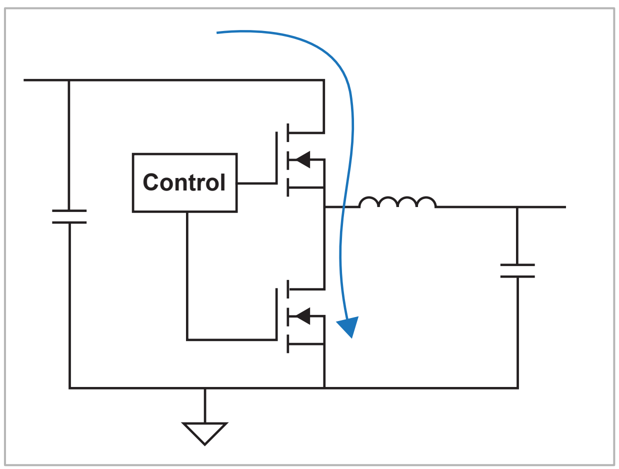
$$\text{Duty Cycle}_{CCM} = \frac{t_{ON}}{T_S}$$

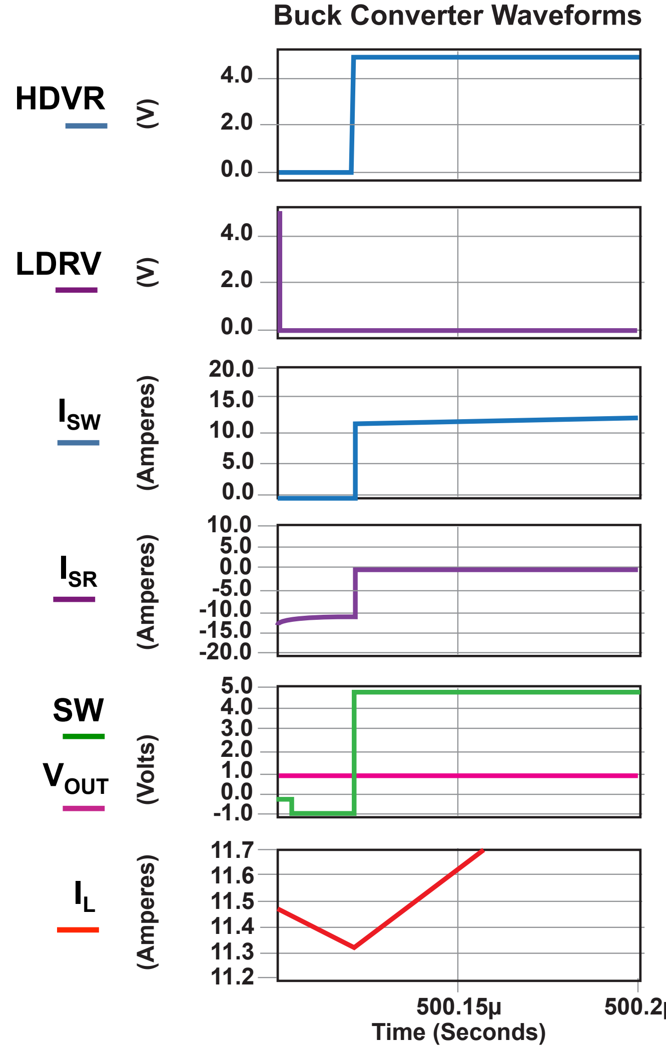


Synchronous Buck Waveforms

Continuous
Conduction
Mode

Switch turn ON

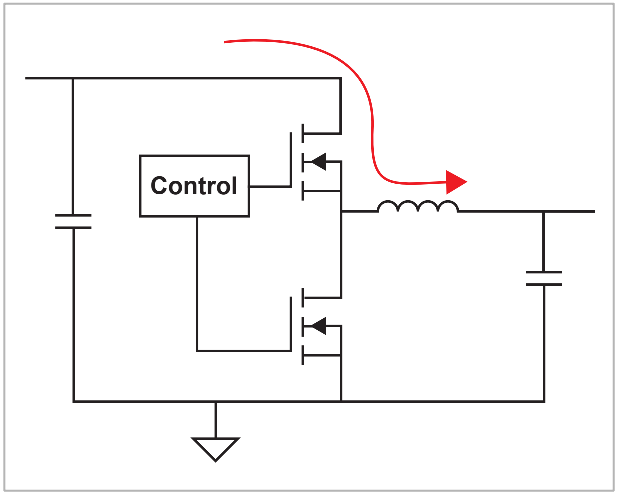


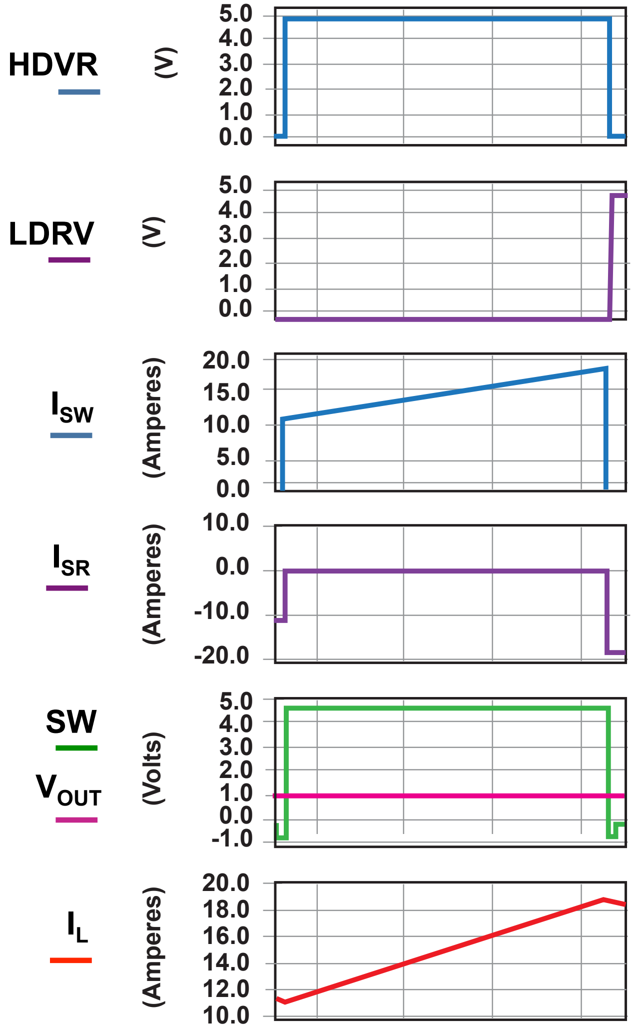


Synchronous Buck Waveforms

Continuous
Conduction
Mode

Power transfer

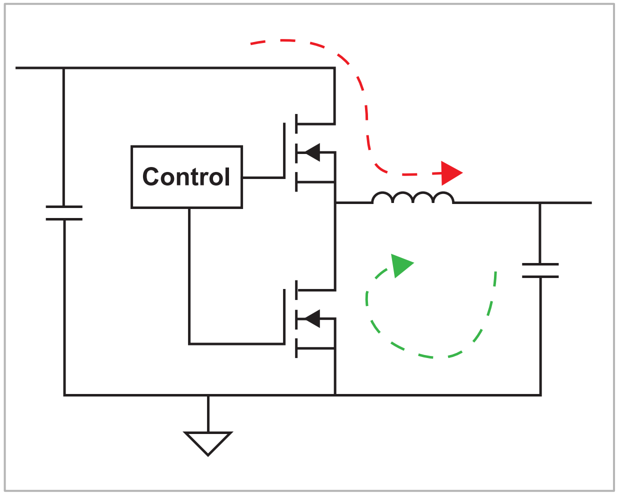


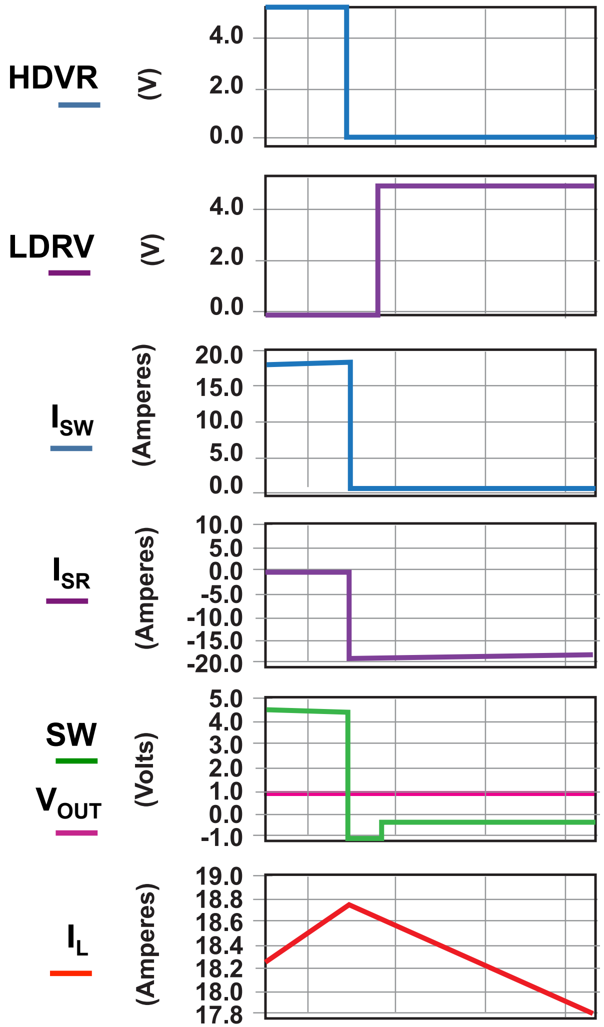


Synchronous Buck Waveforms

Continuous
Conduction
Mode

Switch turn OFF transition to SR turn ON

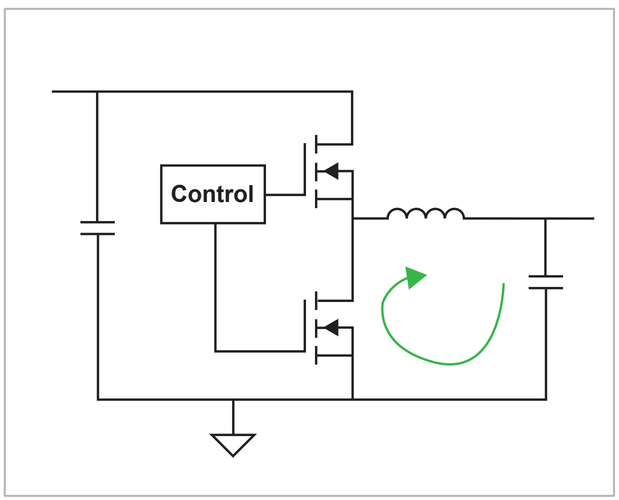


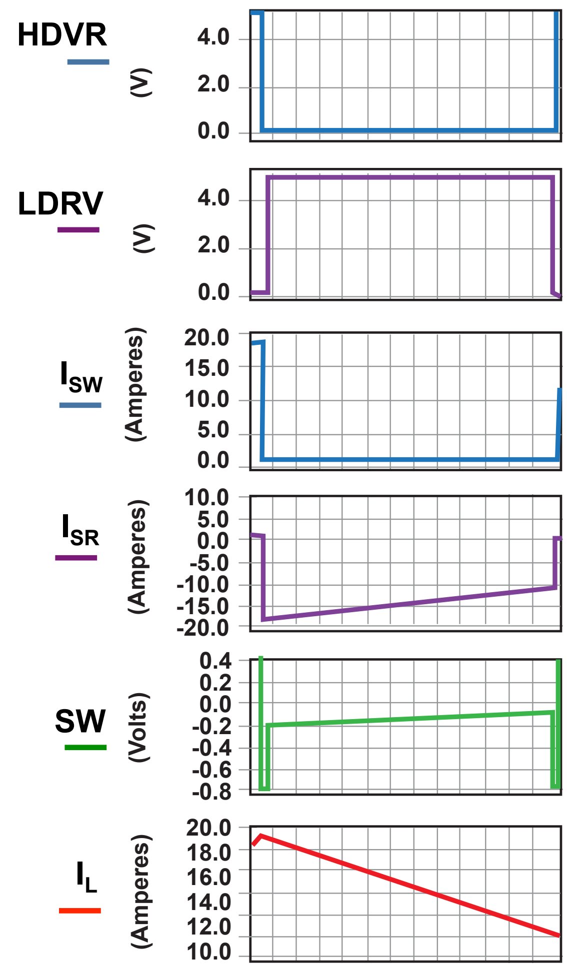


Synchronous Buck Waveforms

Continuous
Conduction
Mode

Inductor reset

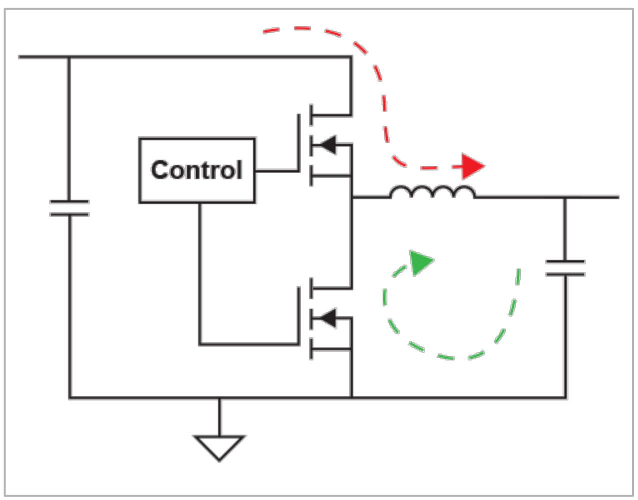


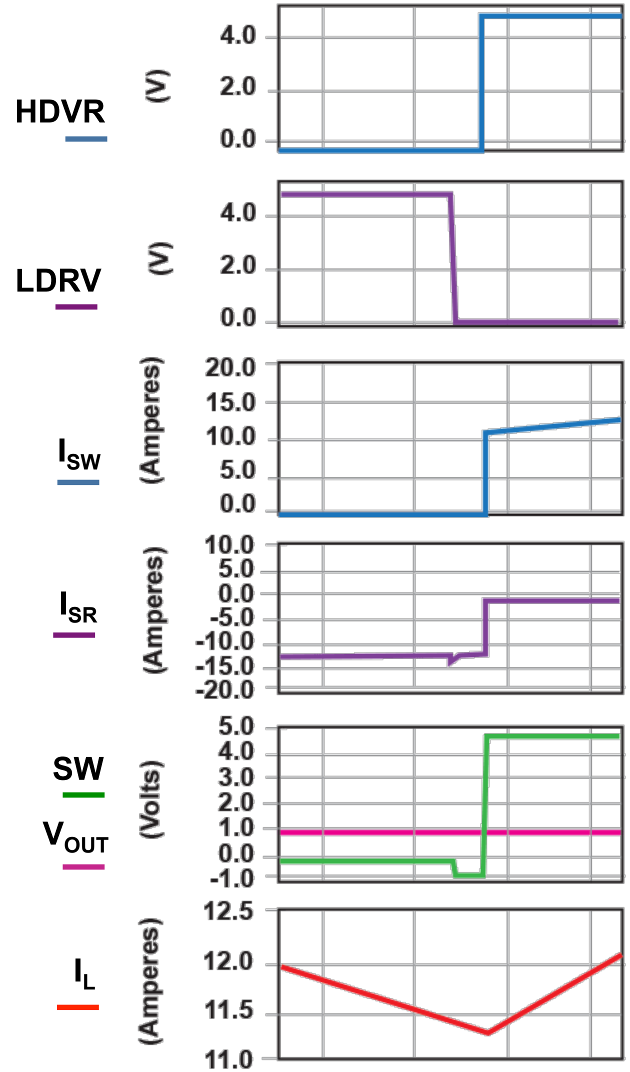


Synchronous Buck Waveforms

Continuous
Conduction
Mode

Transition for next cycle

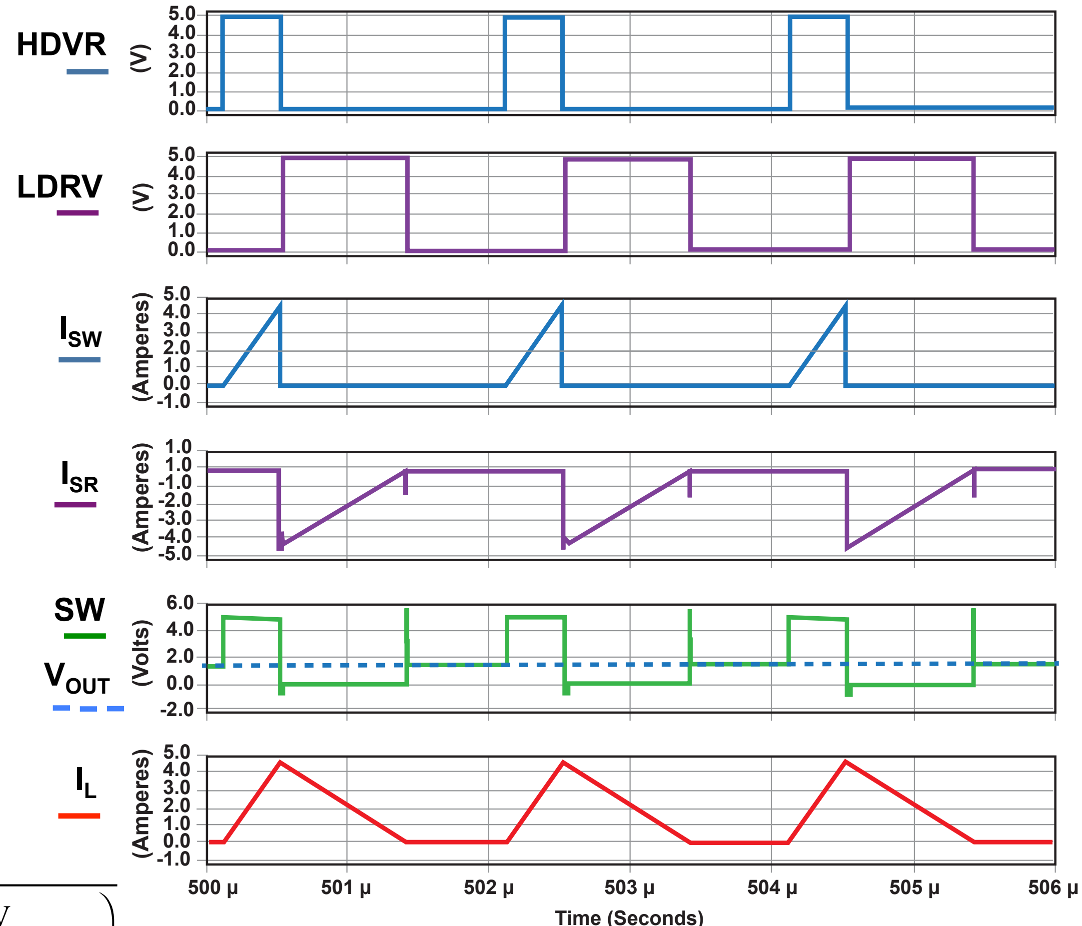




Synchronous Buck Waveforms

Discontinuous
Conduction
Mode

- Inductor current flow is discontinuous during the switching cycle



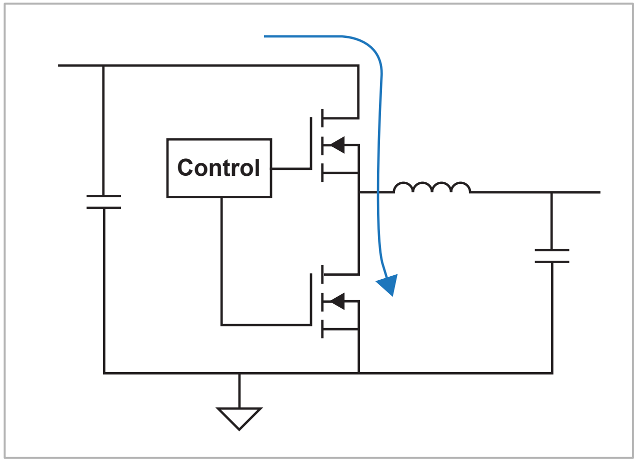
$$\text{Duty Cycle}_{DCM} = \frac{t_{ON}}{t_{ON} + t_{OFF} + t_{dead}}$$

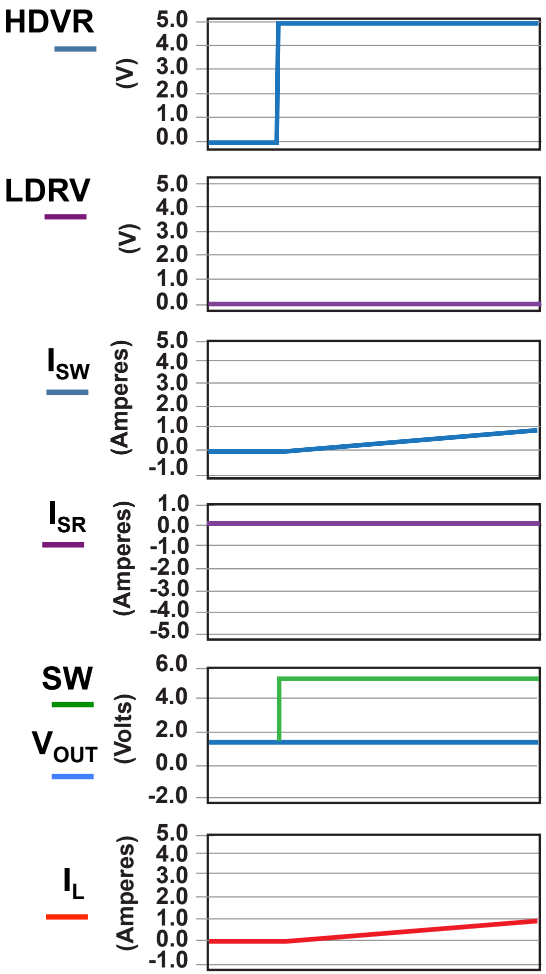
$$\text{Duty Cycle}_{DCM} = \sqrt{\frac{2 \times L \times I_{OUT}}{T_S \times V_{IN}} \times \left(\frac{V_{OUT}}{V_{IN} - V_{OUT}}\right)}$$

Synchronous Buck Waveforms

Discontinuous
Conduction
Mode

- First part is the same as CCM Mode
- High side switch turns ON

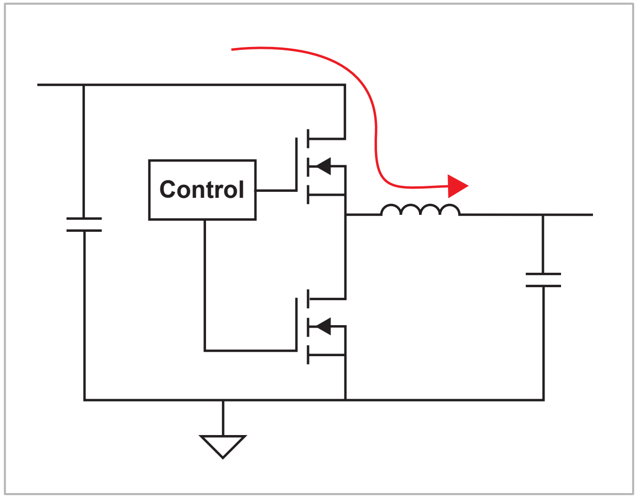


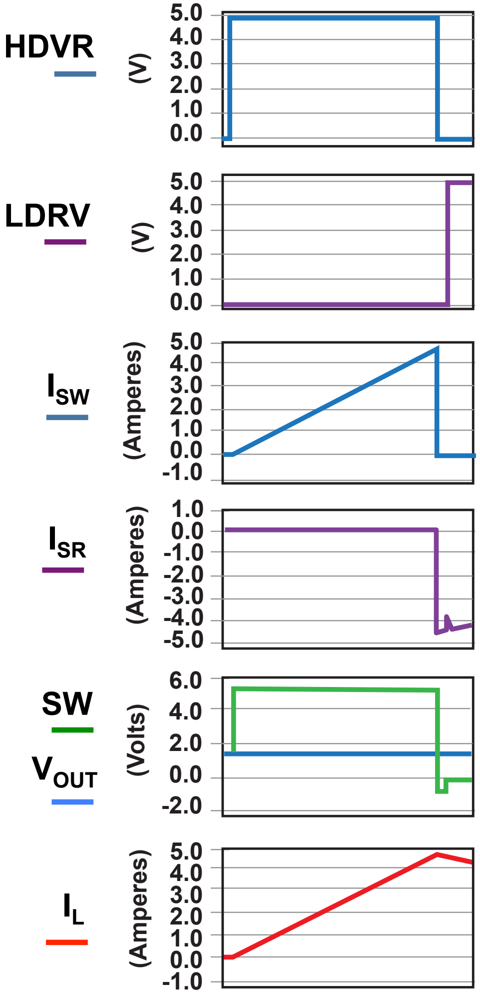


Synchronous Buck Waveforms

Discontinuous
Conduction
Mode

Switch ON

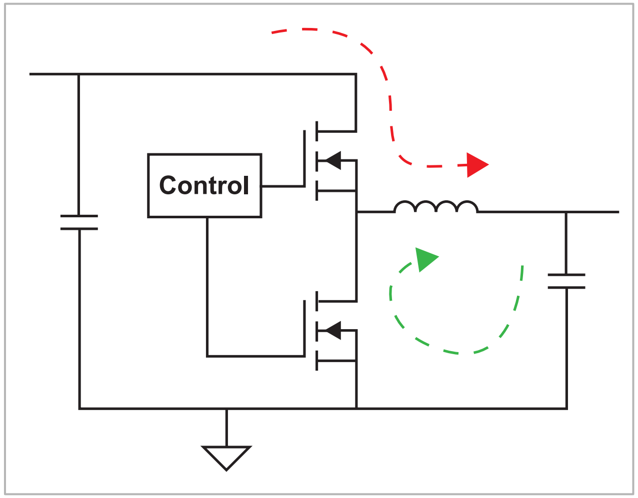


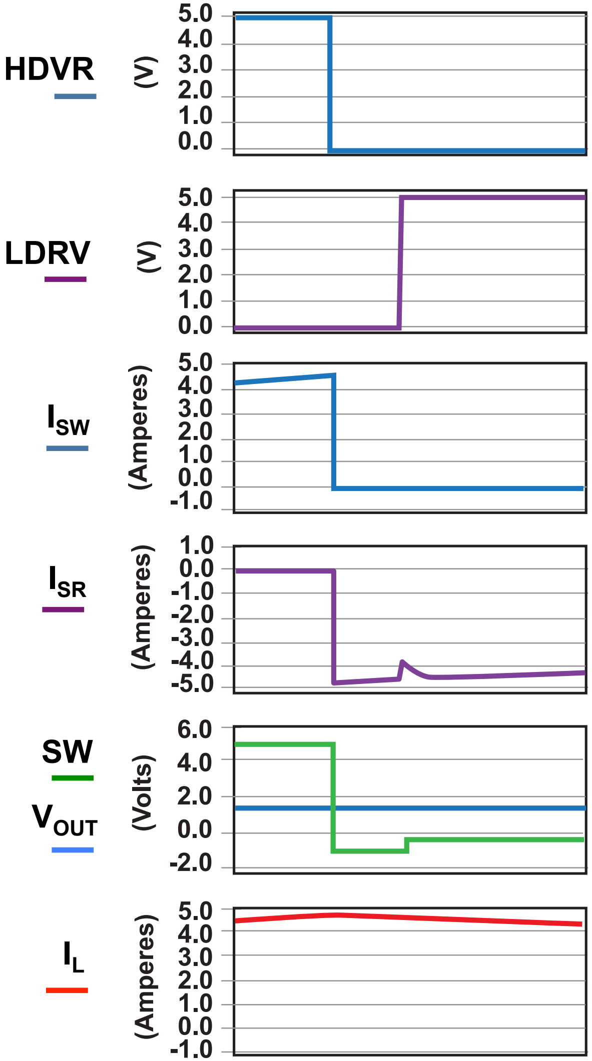


Synchronous Buck Waveforms

Discontinuous
Conduction
Mode

- Switch turn OFF
- SR turn ON

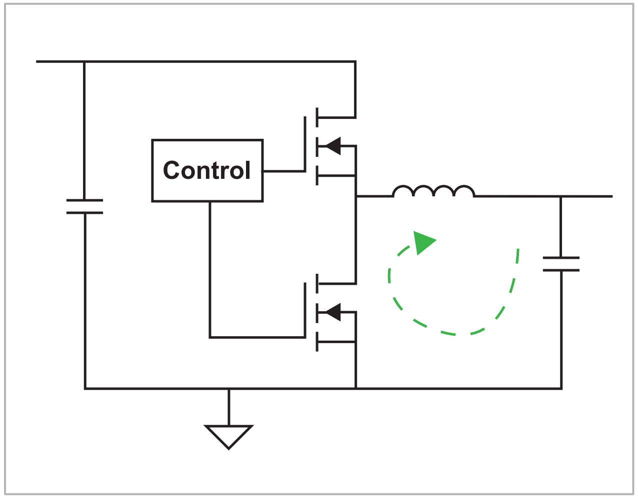


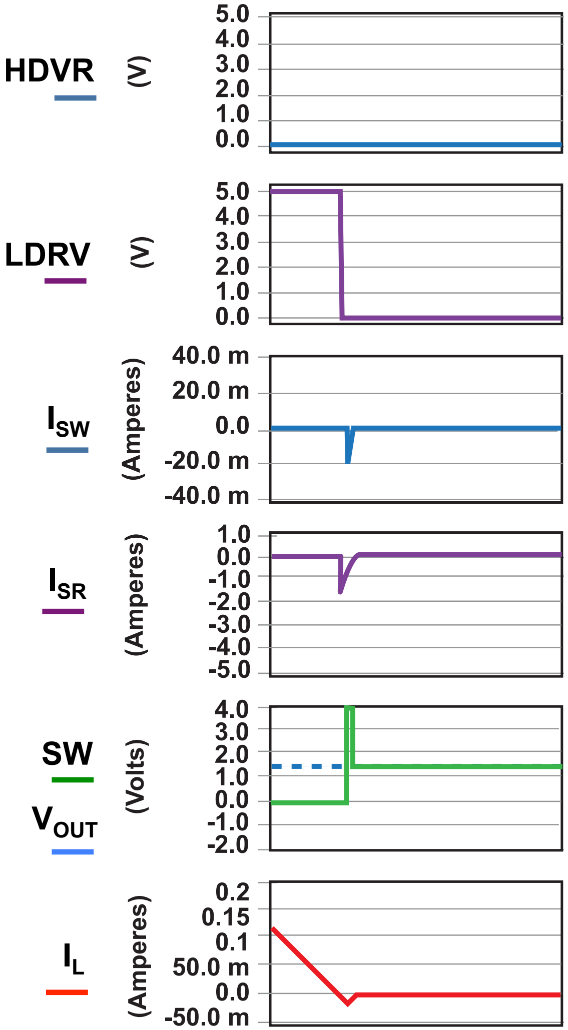


Synchronous Buck Waveforms

Discontinuous
Conduction
Mode

- SR turns OFF at zero current in inductor

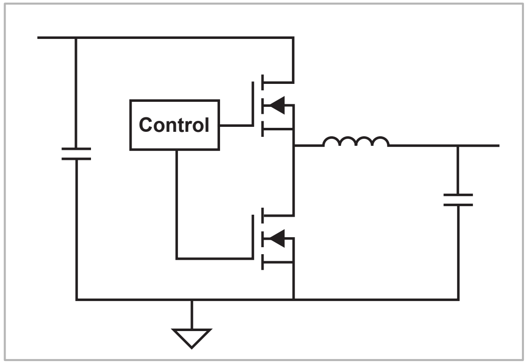




Synchronous Buck Waveforms

Discontinuous
Conduction
Mode

- Freewheeling interval



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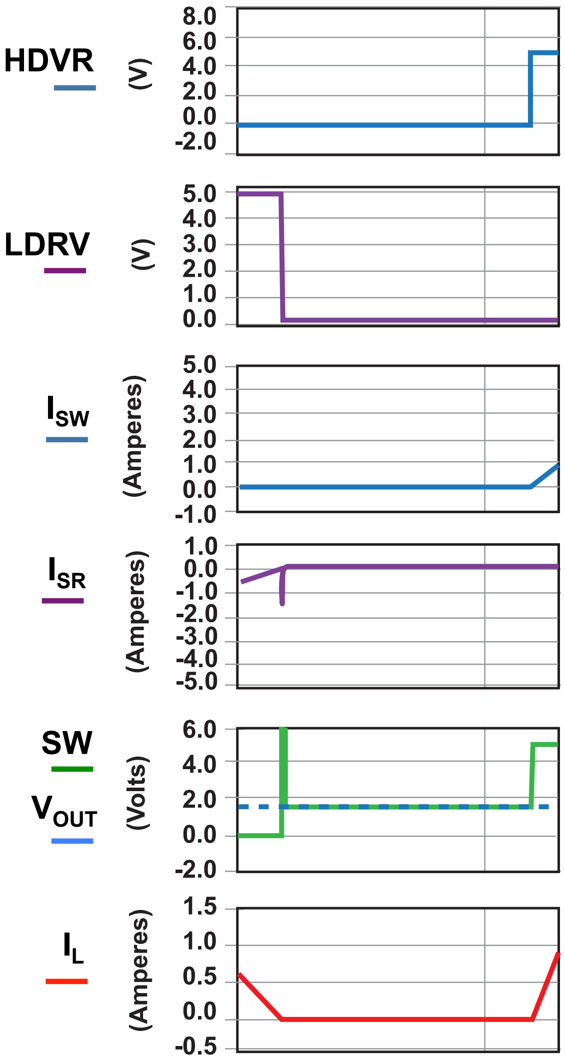
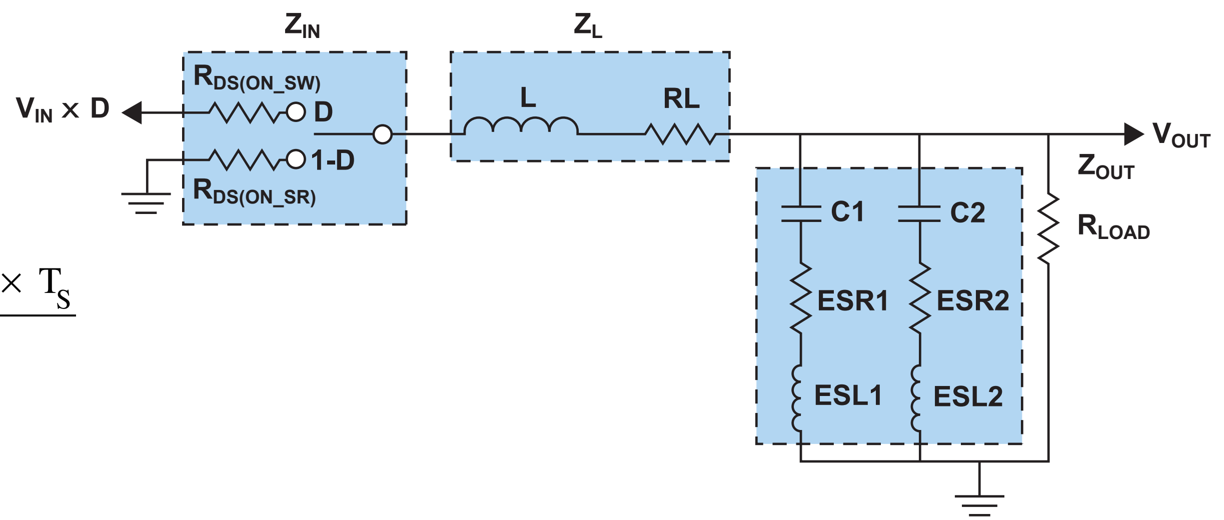
$$\text{Duty Cycle}_{DCM} = \sqrt{\frac{2 \times L \times I_{OUT}}{T_S \times V_{IN}} \times \left(\frac{V_{OUT}}{V_{IN} - V_{OUT}}\right)}$$



L-C Filter Design

- Inductor design for ripple current



$$\Delta I_L = \frac{(V_{IN} - V_{OUT}) \times D \times T_S}{L}$$

- Ripple current is generally 10% to 30% of full load current

- Capacitor selection for general purpose
  - Select TYPE based on ESR and ESL
  - Voltage ripple = impedance x inductor ripple
  - Select VALUE based on corner frequency of ~1/10 of desired crossover frequency

Output Capacitors

Output capacitors will determine output ripple, transient response and greatly impact the compensation

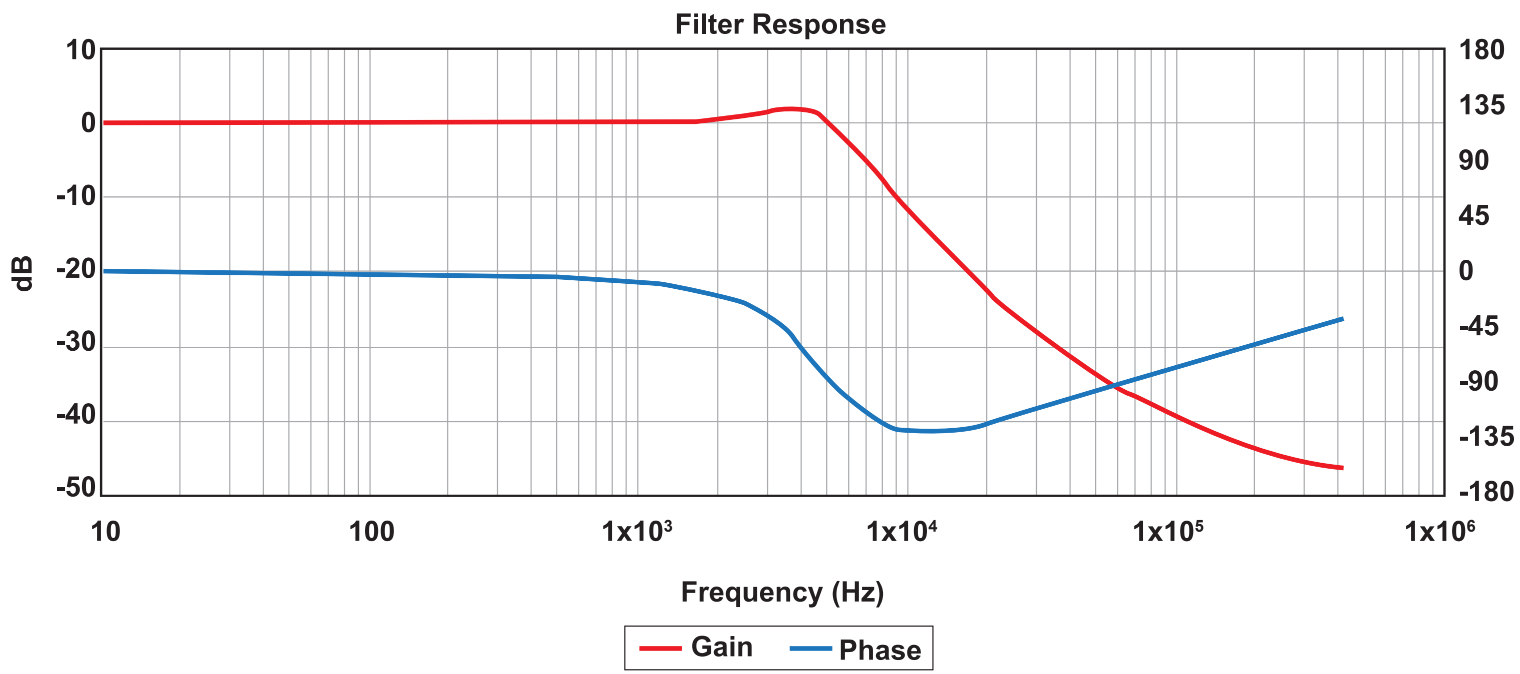
Type of Cap		Advantages	Disadvantages
Ceramic		Small size, low cost, low ESR, high ripple current rating	DC bias effects, low capacitance, cracking
Aluminum Electrolytic		High capacitance, low cost, good for high voltage	High ESR, low ripple current rating, temp issues, large size
Aluminum Polymer		High capacitance, low ESR, high ripple current rating	Expensive, fewer manufacturers, large size, voltage rating
Tantalum Polymer		High capacitance, low ESR, high ripple current rating, small size	Expensive, fewer manufacturers, voltage rating

Output Inductors

Output inductors will also determine output ripple, transient response and greatly impact the compensation

Type of Cap		Advantages	Disadvantages
Drum Core	 	Low cost, many vendors, high Isat, higher inductances	Can be unshielded, high core loss, high DCR, hard Isat
Molded Core		Very high Isat, easy to shape into many sizes, shielded, soft Isat	High core losses, low inductance range
Shaped Core		Low core loss, low DCR, high current, shielded, high inductance range	High cost, hard Isat, not suitable for low profile
Power Bead		Low core loss, low DCR, excellent for multiphase	Low inductance, hard Isat

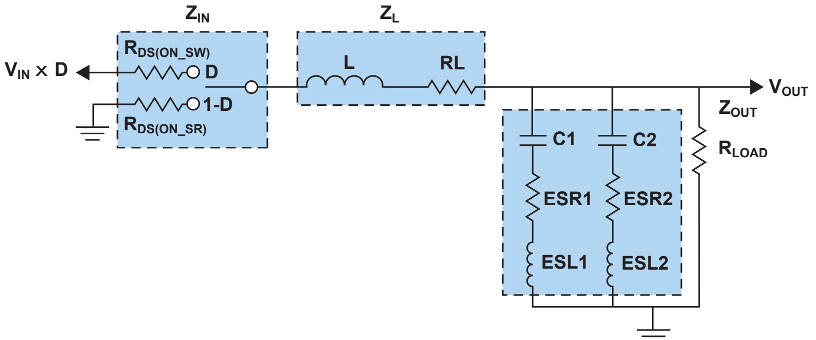
Filter AC Response



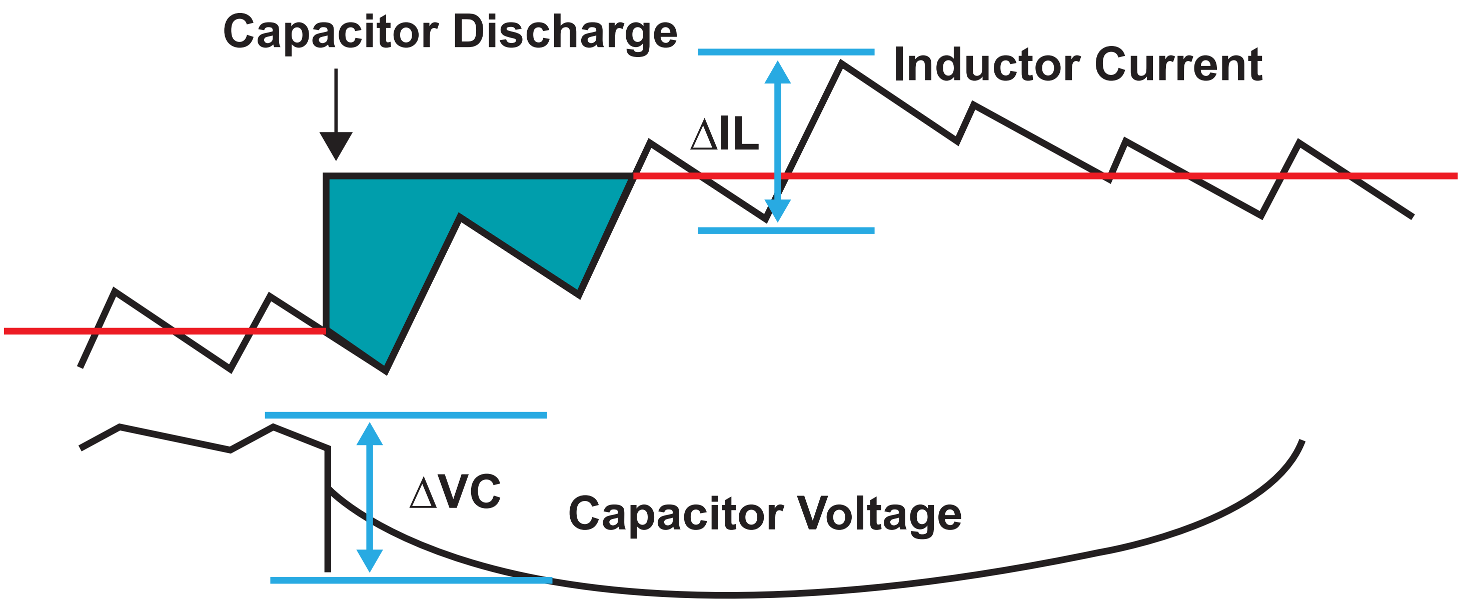
Corner frequency ~ 5 kHz

ESR zero ~ 21 kHz

ESL zero ~ 240 kHz



Filter Design for Transient Response



- Select L for current slew rate

$$\Delta I_L = \frac{(V_{IN} - V_{OUT}) \times D \times T_S}{L}$$

- Select capacitance VALUE based on support of output voltage while current is increasing

$$\Delta V_C = \frac{\Delta I^2}{2 \times (V_{IN} - V_{OUT})} \times \frac{L}{C}$$

Minimum Controllable On-Time

- Propagation delays limit the minimum controllable pulse width
- Below minimum controllable on-time, pulse skipping could occur
- $Ton_{MIN} \le \frac{V_{OUT}}{V_{IN\_max} \times f_{max}}$
- Example – TPS40170, min on-time is 100 ns max
  - V_{IN} = 60 Vmax
  - V_{OUT} = 5 V or 3.3 V
  - Frequency = 600 KHz (+10% shift)

$$Ton_{MIN} \le \frac{5\ V}{60\ V \times 600\ kHz \times 1.1} = 140\ ns$$ ✓

$$Ton_{MIN} \le \frac{3.3\ V}{60\ V \times 600\ kHz \times 1.1} = 91\ ns$$ ✗

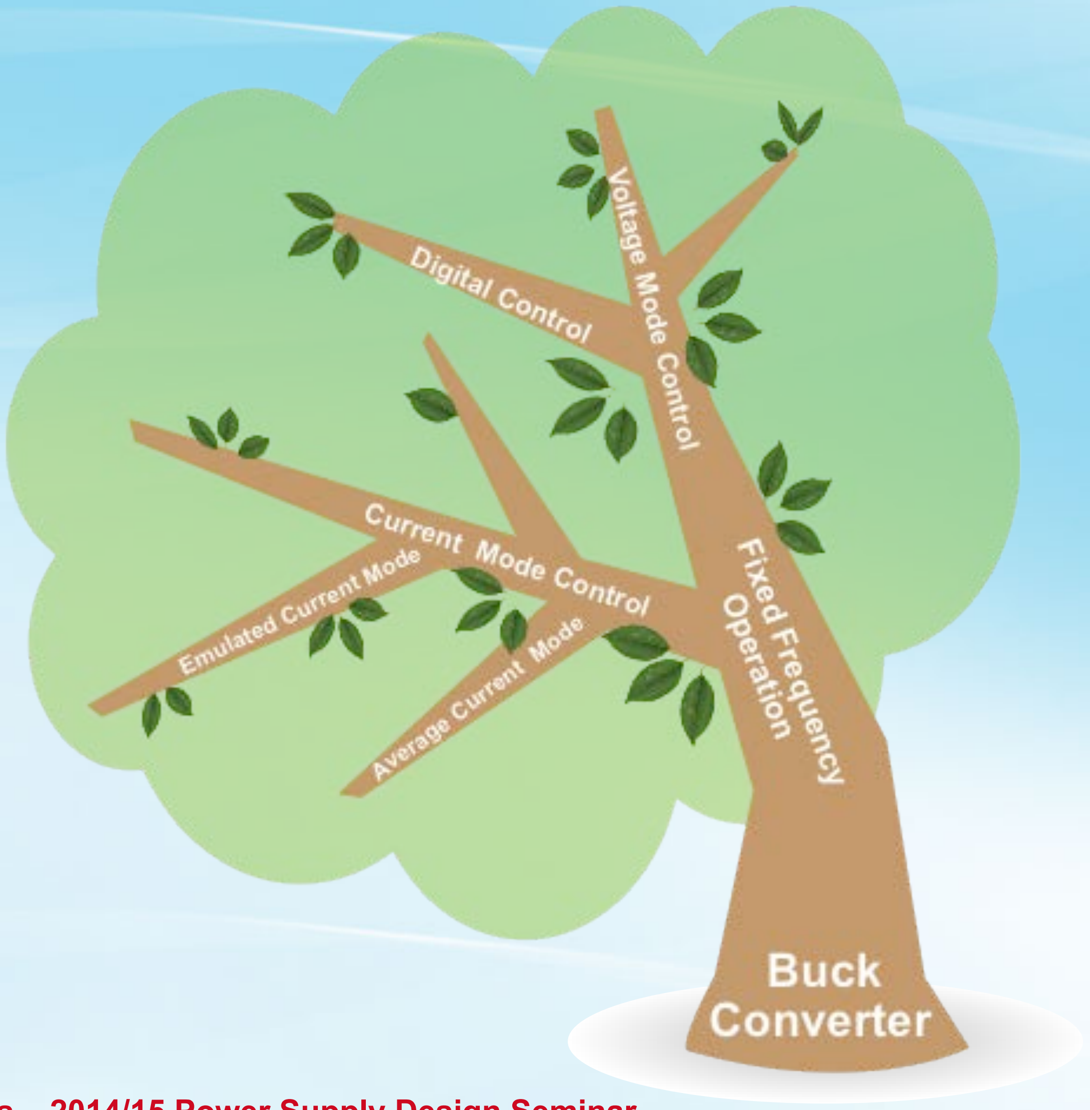
- For a 3.3 V output, the frequency would need to be lowered to ensure no pulse skipping

Fixed Frequency vs. Variable Frequency

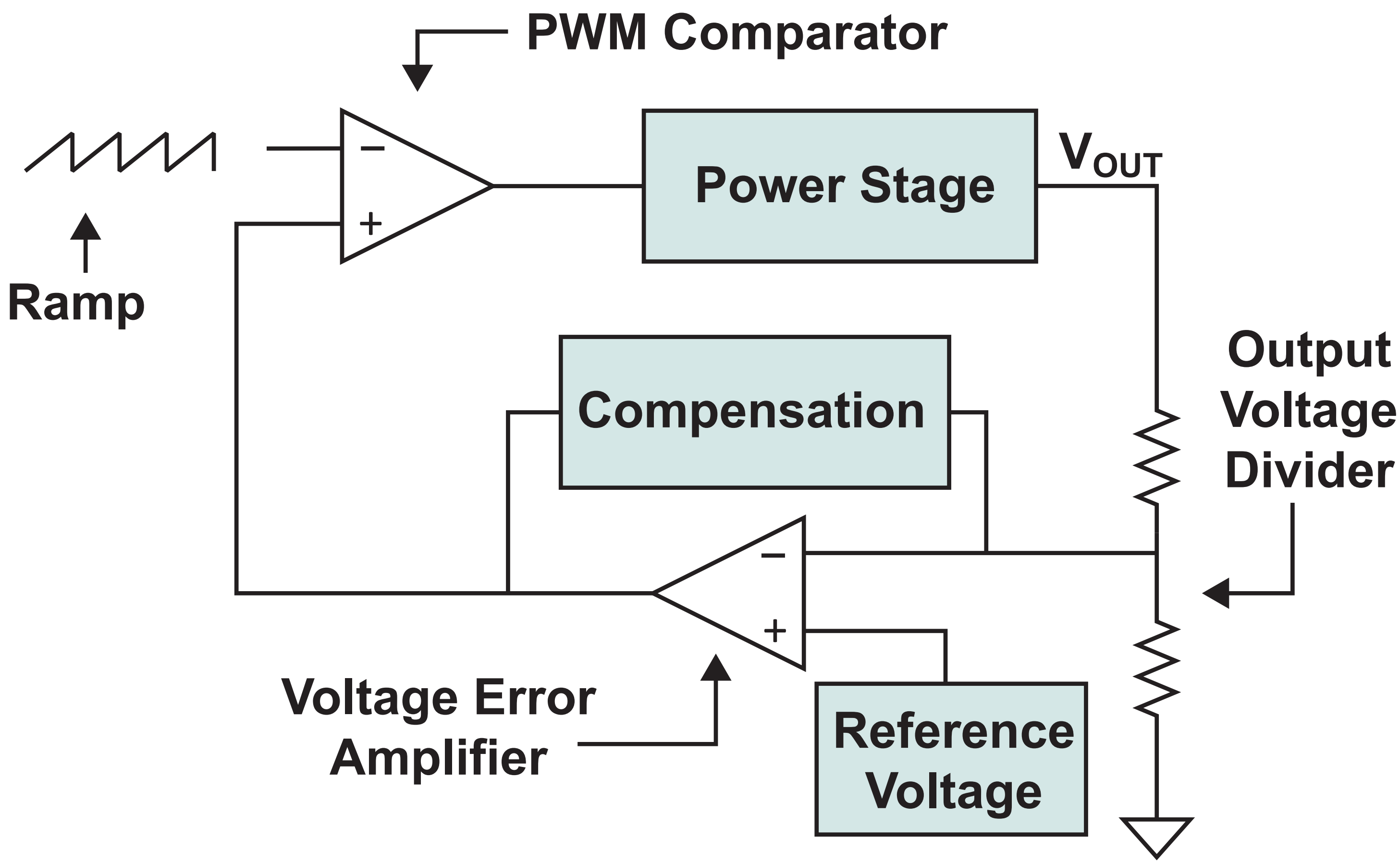
- Fixed frequency operation (Part A)
  - Synchronize multiple devices
    - Eliminate beat frequencies between multiple converters
    - Ripple cancellation to reduce losses in capacitors and PCB traces
  - EMI peaks consistent at any operating mode
  - Minimum controllable pulse width

- Variable frequency operation (Part B)
  - Easier to compensate
  - Lower peak EMI, higher average
  - Faster load transient response
  - Could be lower cost due to lower component count

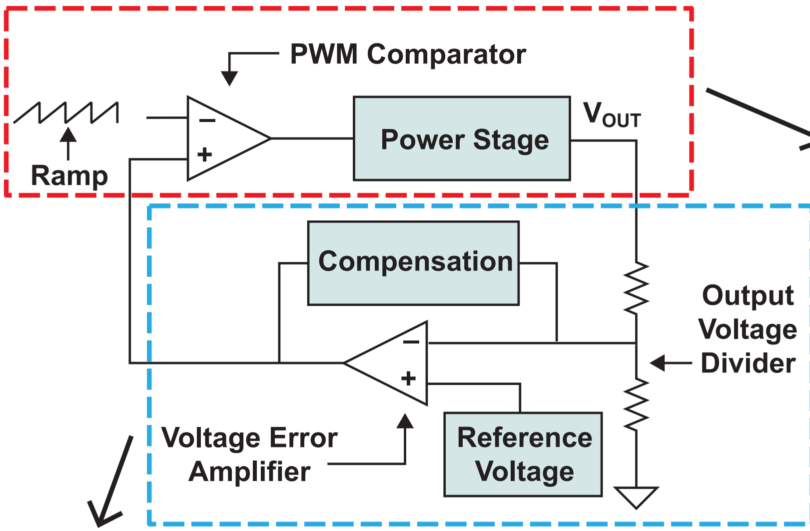
Fixed Frequency Control

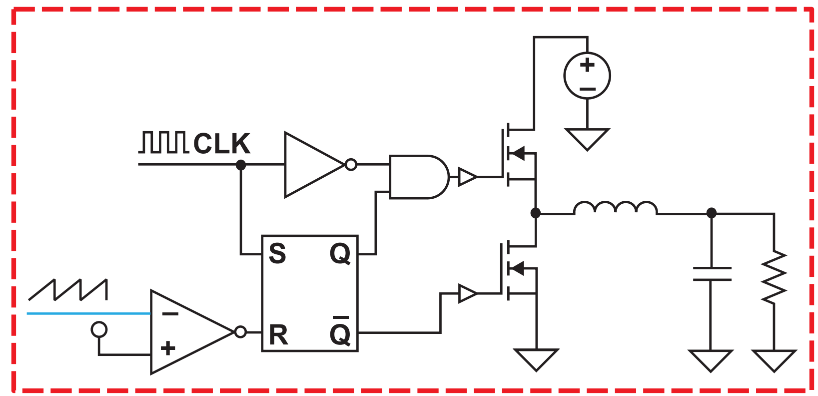


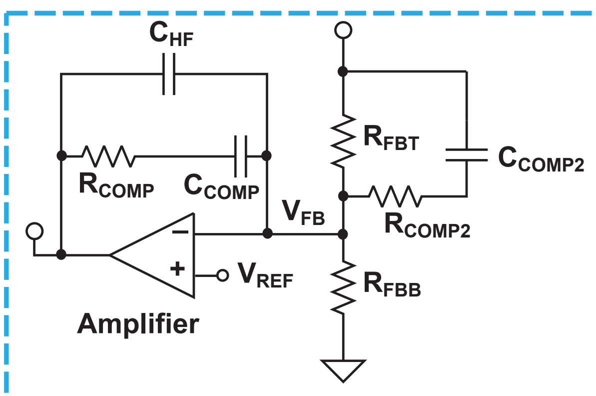
Voltage Mode Control Introduction



Voltage Mode Control – Basic Operation

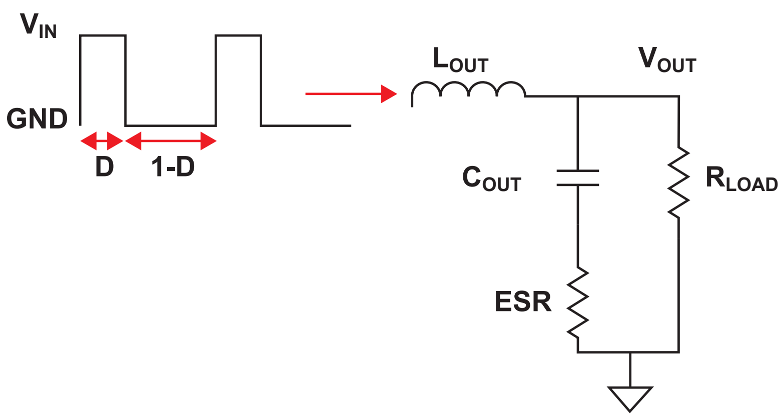


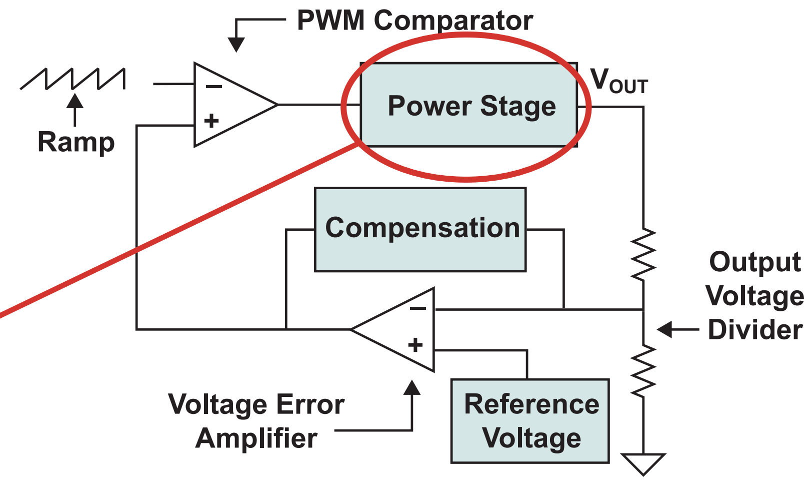


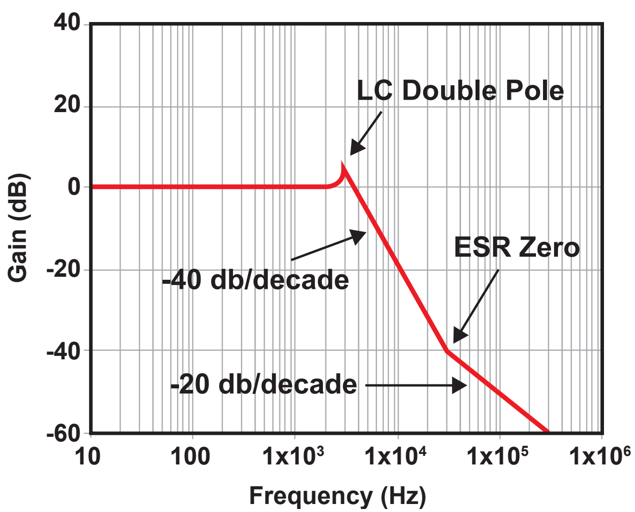


- Power switches generate a square wave
- Output inductor and output capacitor form a low pass filter
- $V_{OUT} = D \times V_{IN}$ (CCM)
- Type 3 compensator generally required

Voltage Mode Control – Power Stage

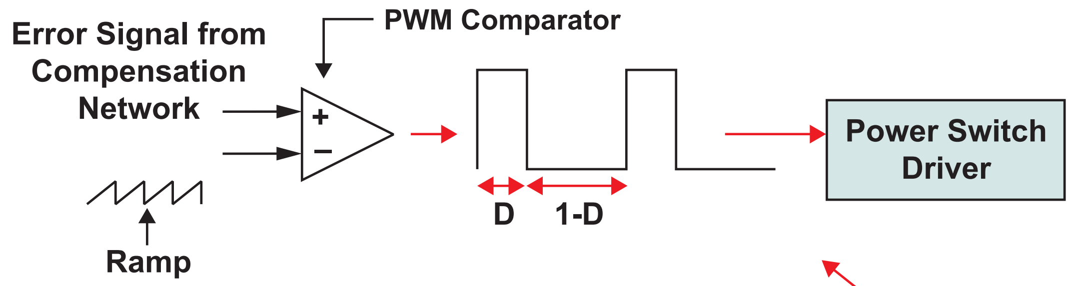


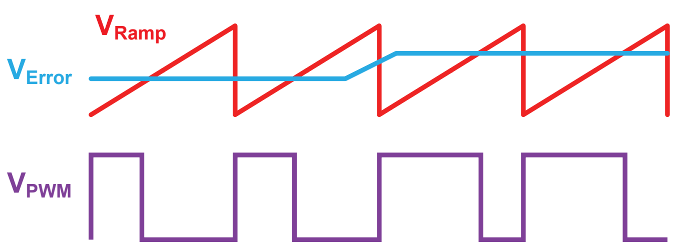


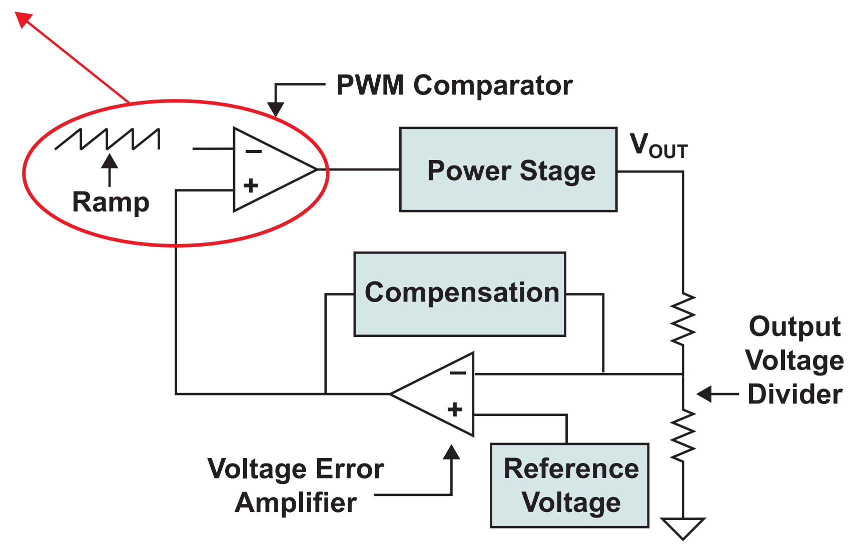


$$H_{PS}(s) = \frac{1 + (C_{OUT} \times R_{ESR})s}{1 + \left(\frac{L_{OUT}}{R_{OUT}} + R_{ESR} \times C_{OUT}\right)s + \left(\frac{R_{OUT} + R_{ESR}}{R_{OUT}}\right)L_{OUT} \times C_{OUT} \times s^2}$$

Voltage Mode Control – Pulse Width Modulator



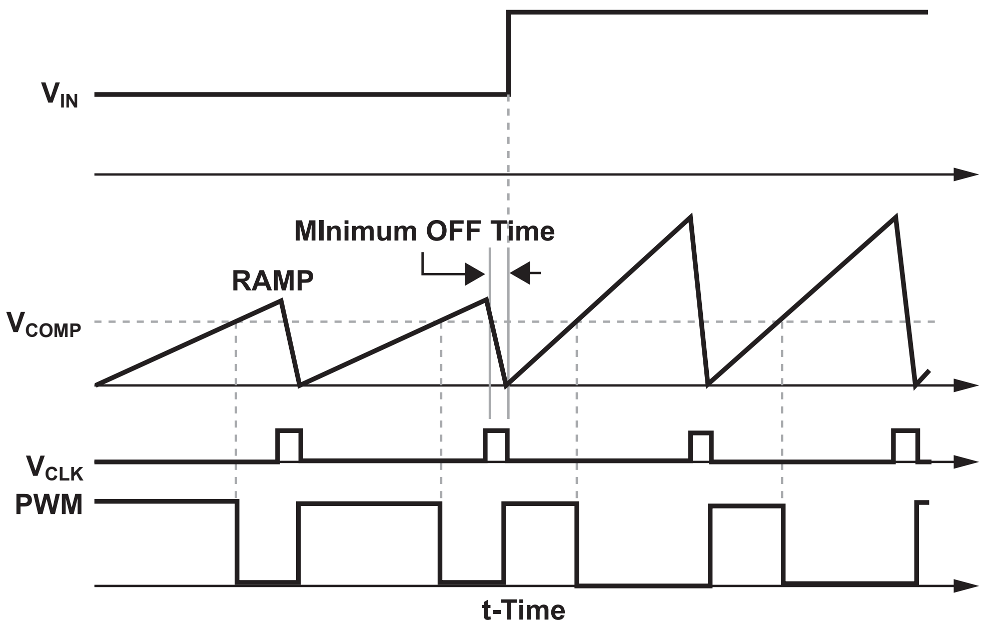




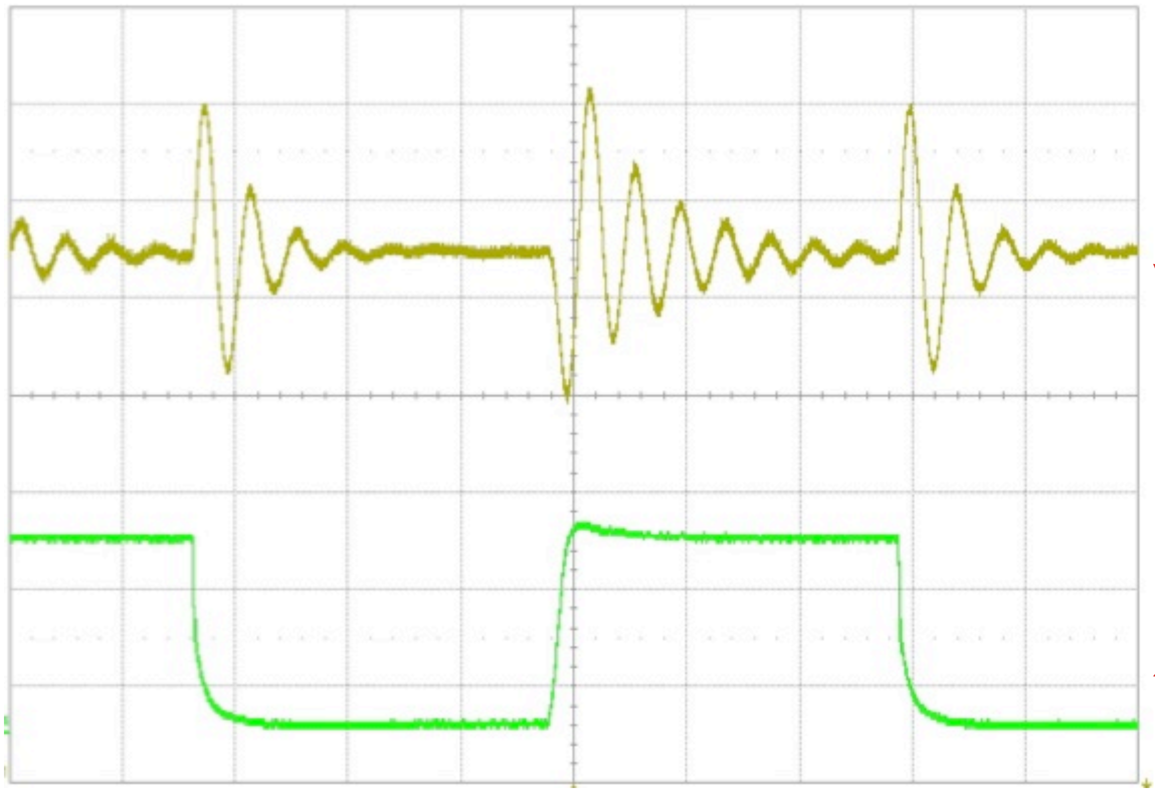
- If the output voltage is too low, the duty cycle is increased
- If the output voltage is too high, the duty cycle is reduced
- Gain of the modulator: $H_{Mod} = \frac{V_{IN}}{V_{Ramp}}$

Voltage Mode Control – Feed Forward

- As V_{IN} is increased, the gain increases. Not good for wide input voltage ranges. Voltage feed forward fixes this issue.
- Gain of the modulator: $H_{Mod} = \frac{V_{IN}}{V_{Ramp}} = \frac{V_{IN}}{K \times V_{IN}}$
- Feed Forward increases the ramp amplitude proportional to the input voltage



Why Do We Compensate?

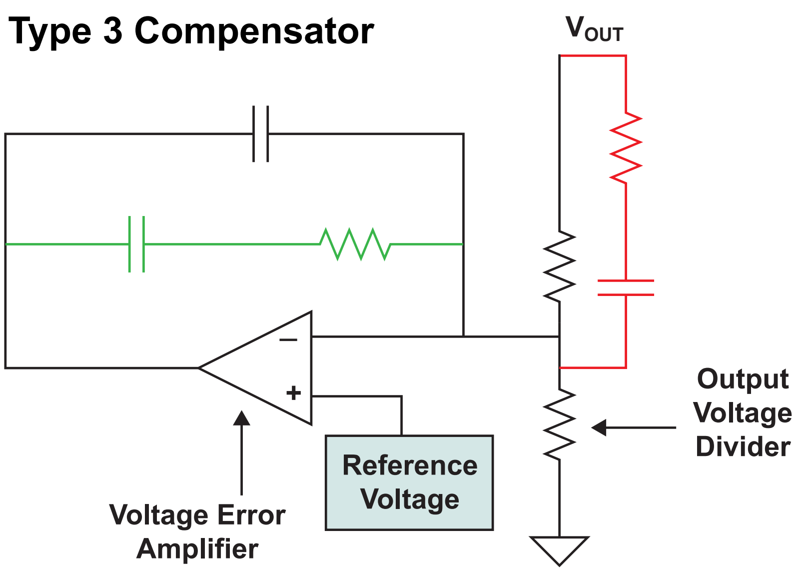


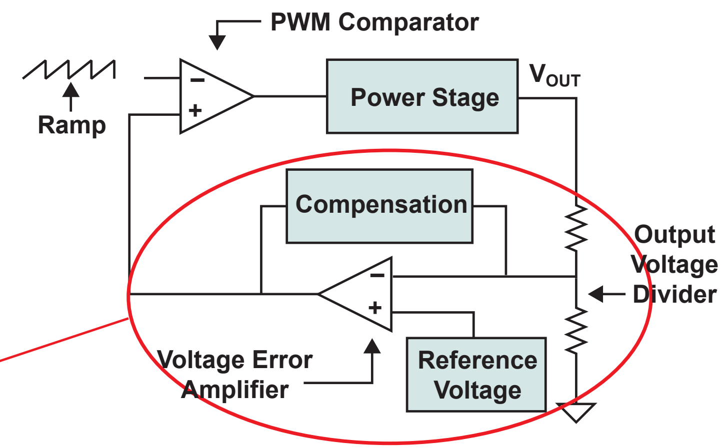
Output Voltage
(AC coupled)
50 mV/Division

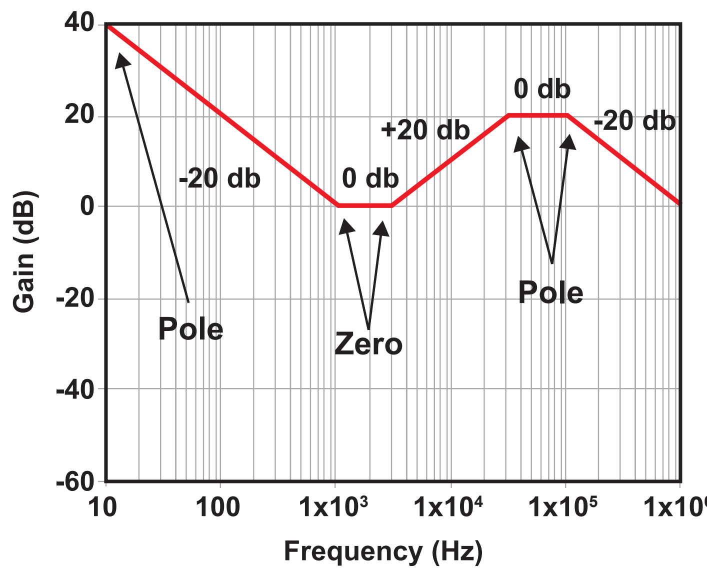
Output Current
500 mA/Division

100 μs/Division

Voltage Mode Control – Compensation



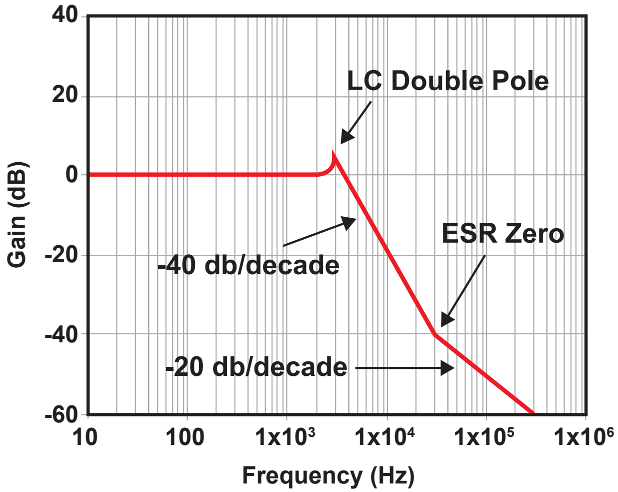




- Type 1 compensator – single dominant pole
- Type 2 compensator – two poles, one zero
- Type 3 compensator – three poles, two zeros

Voltage Mode Control Loop Compensation

Power Stage + Modulation



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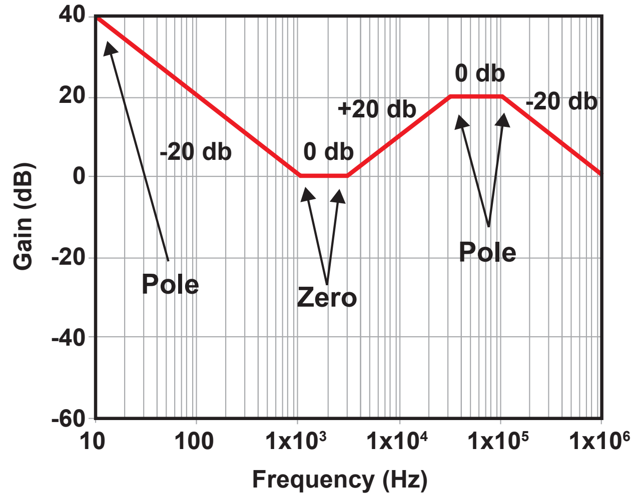
Type 3 Compensator



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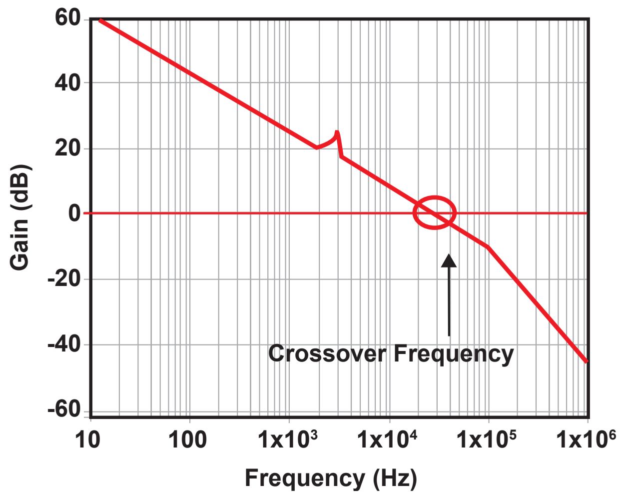
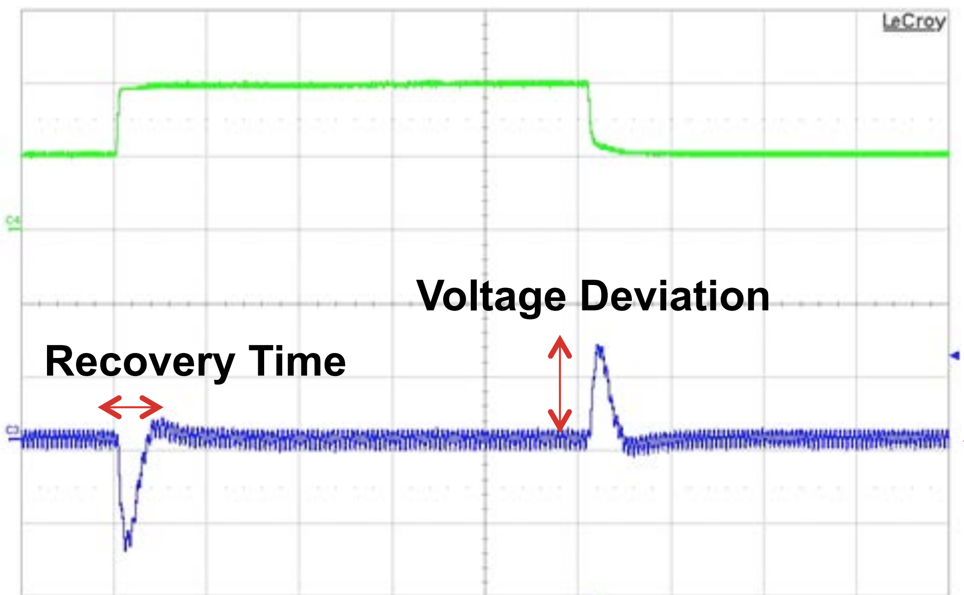


- Use double zero to cancel double pole
- Cross 0 dB with -20 dB/decade response
- Cross 1/10th to 1/4th below the switching frequency

Voltage Mode Control – Transient Response

- Output filter and loop compensation will impact the transient response
- Increasing the loop BW will lead to faster recovery time and lower voltage deviation
- Closed loop impedance of filter multiplied by load step can predict the voltage deviation



Output Current
10 A/Division

Output Voltage (AC Coupled)
500 mV/Division

200 µs/Division

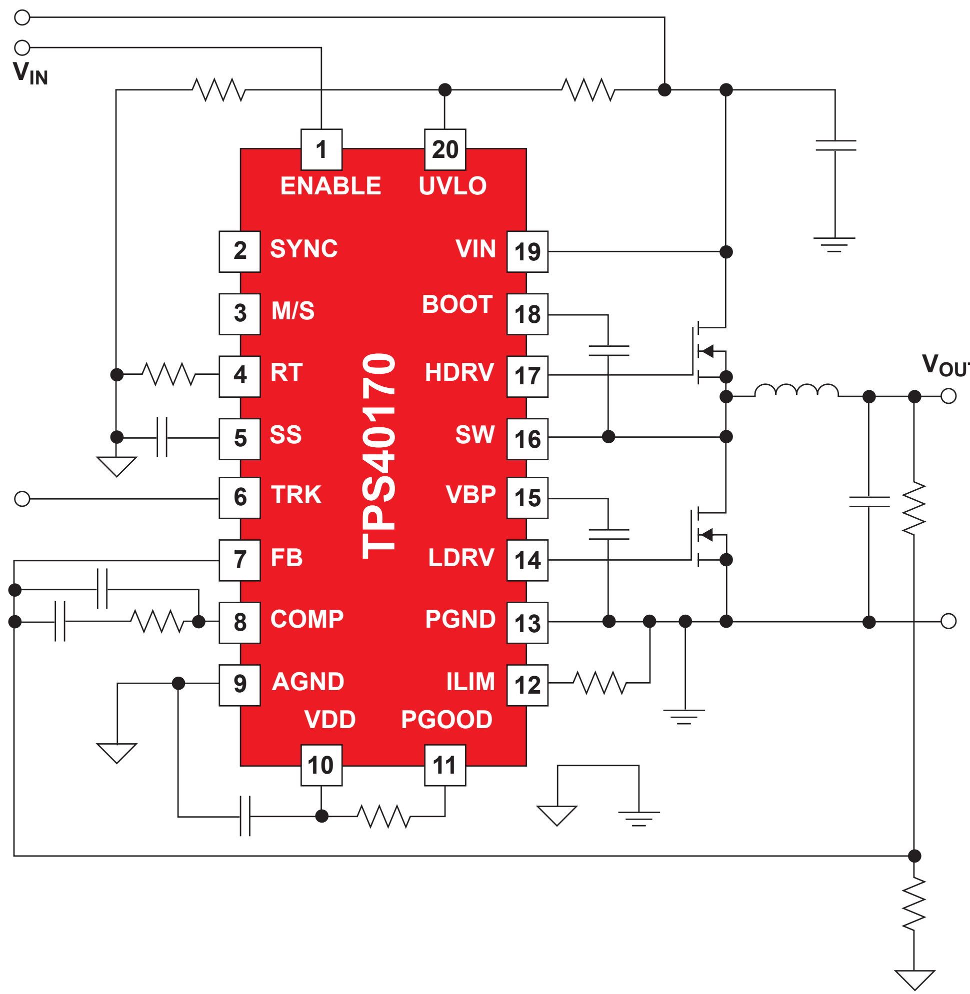
Voltage Mode Control

Advantages	Disadvantages
Fixed frequency operation	High bandwidth error amplifier required
Easy to synchronize to external clocks	Double pole compensation is more difficult
Voltage regulation is independent of current	Inductor value affects the compensation
Single feedback loop	V_{IN} affects loop gain (unless using feed forward)
Less susceptible to noise	Difficult to control light load efficiency modes
Good load regulation	Multiphase operation would require an extra current sharing loop

Design Example #1
Voltage Mode – Design Specifications

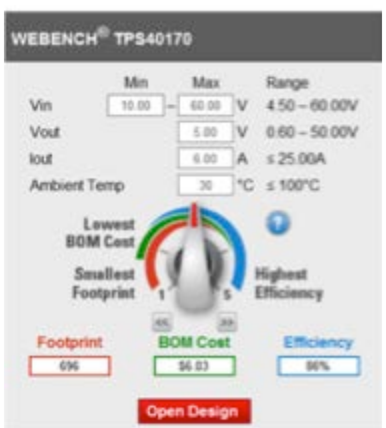
Design Specifications	
Input voltage range	10 V to 60 V
Target output voltage	5 V
Output current range	0 A to 6 A
Switching frequency	300 kHz
Controller	TPS40170

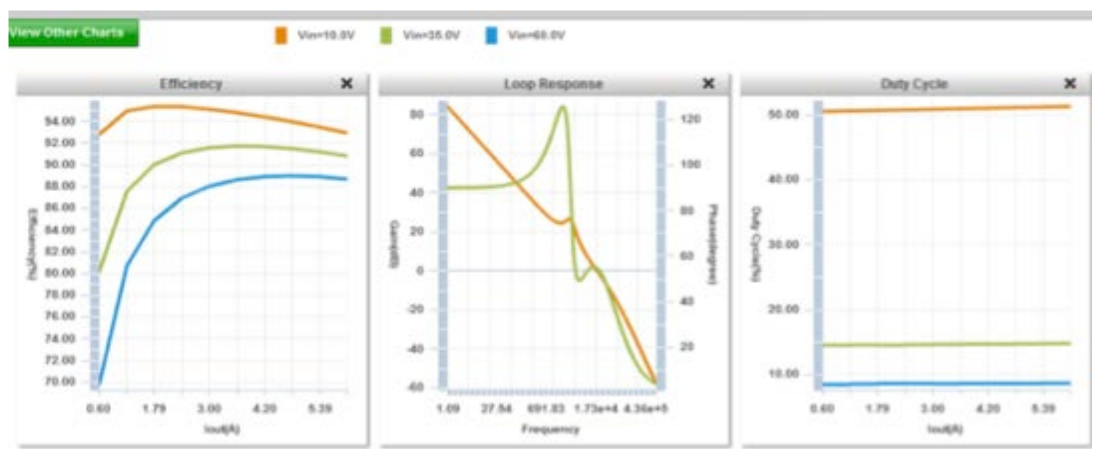
Operating Values (Theoretical)	
Minimum duty cycle	0.083
Minimum on-time	0.277 µs
Maximum duty cycle	0.500
Maximum on-time	1.667 µs



Design Example #1
Voltage Mode – Design Procedure

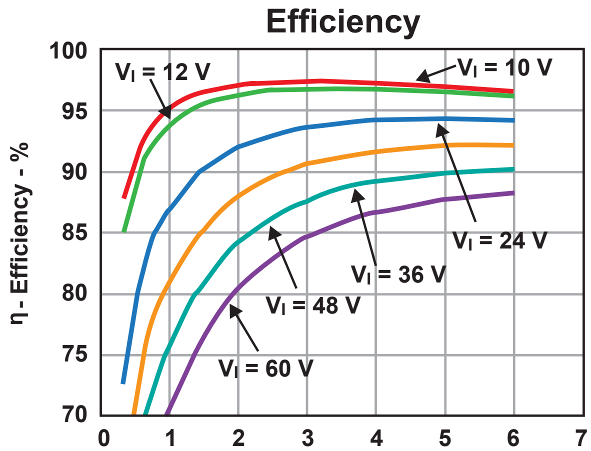
- Choose switching frequency first
- Calculate the output filter components (L and C)
- Calculate the power stage components (FETs)
- WEBENCH®
  - Helps calculate all of specific values for design
  - Allows optimization based on design goals
  - Gives estimates for loop response and efficiency
  - Provides a complete schematic and bill of materials

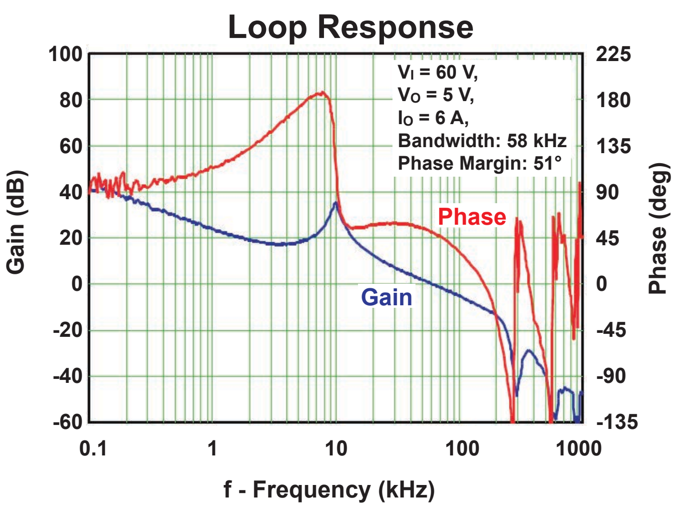


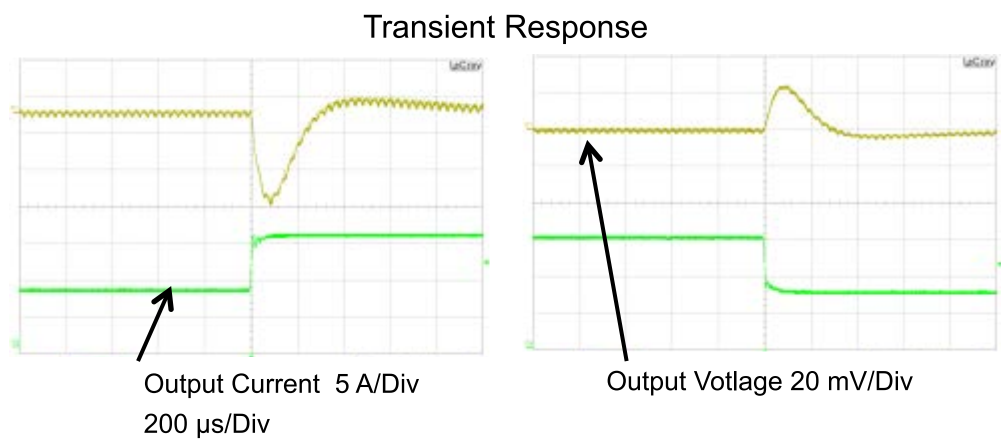


Design Example #1
Voltage Mode – Performance Graphs

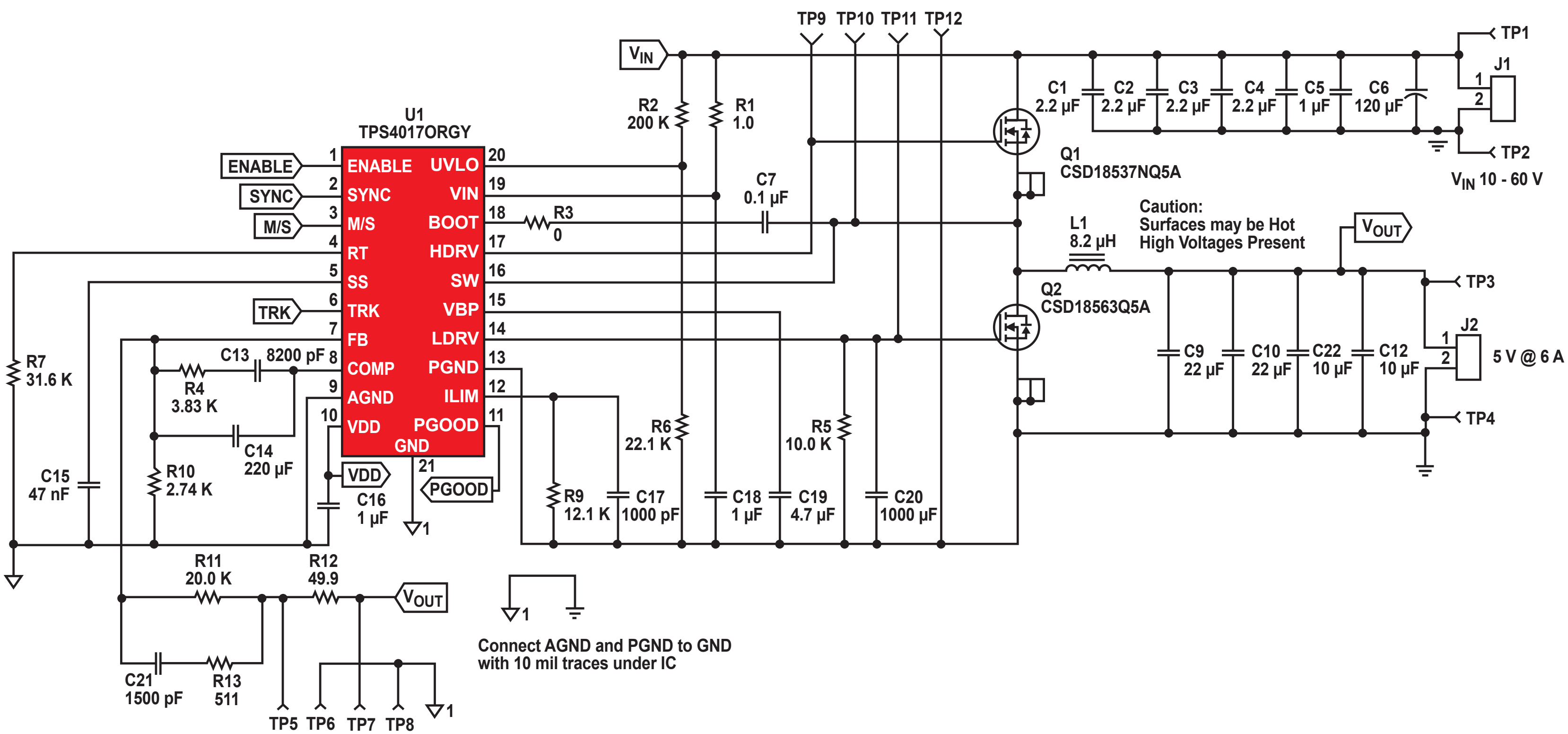
Data is taken with TPS40170 EVM (HPA578)



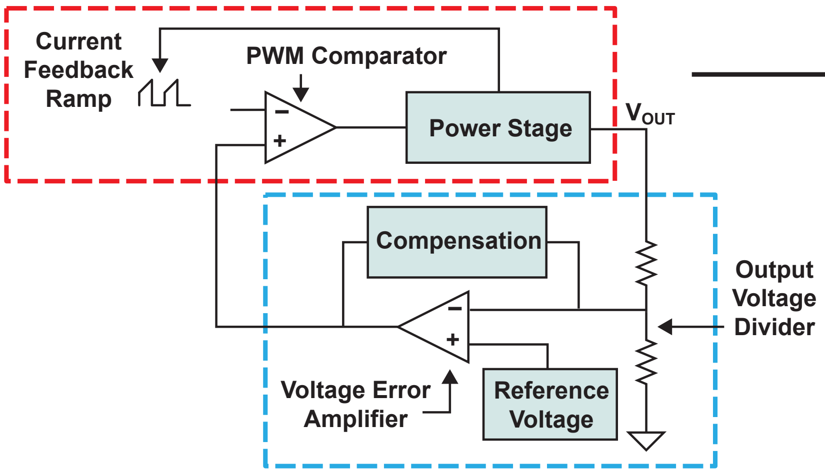


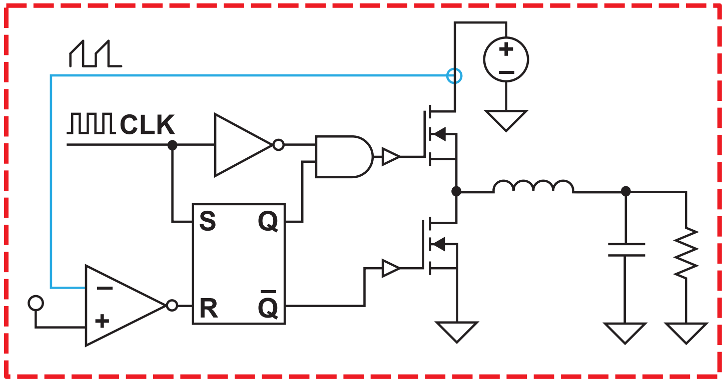


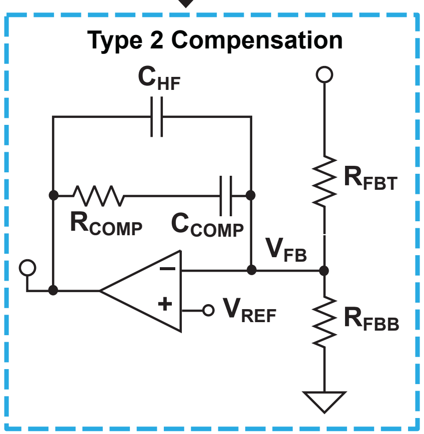
Design Example #1
Voltage Mode – Schematic (HPA578)



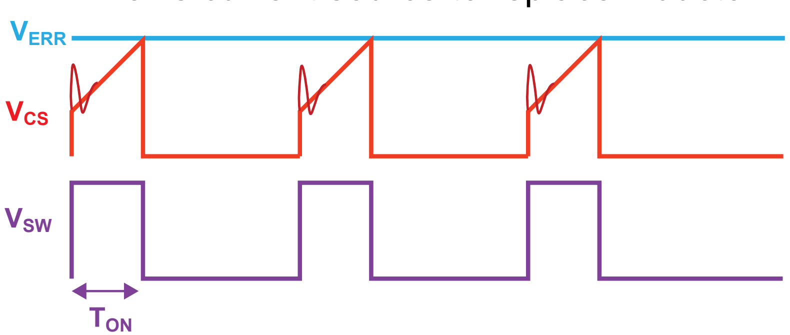
Current Mode Control
Basic Operation





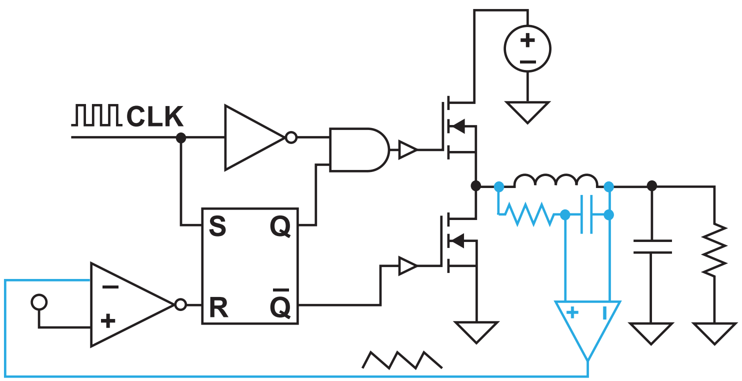


- Peak current mode is more popular than valley
- Outer voltage loop + inner current loop
- High-side / DCR current sensing
- Error amp output controls peak inductor current
- Allows current source to replace inductor

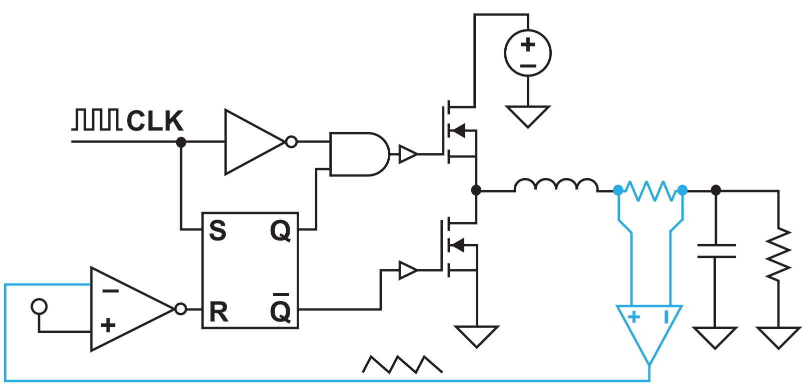


Current Mode Control
Other Considerations

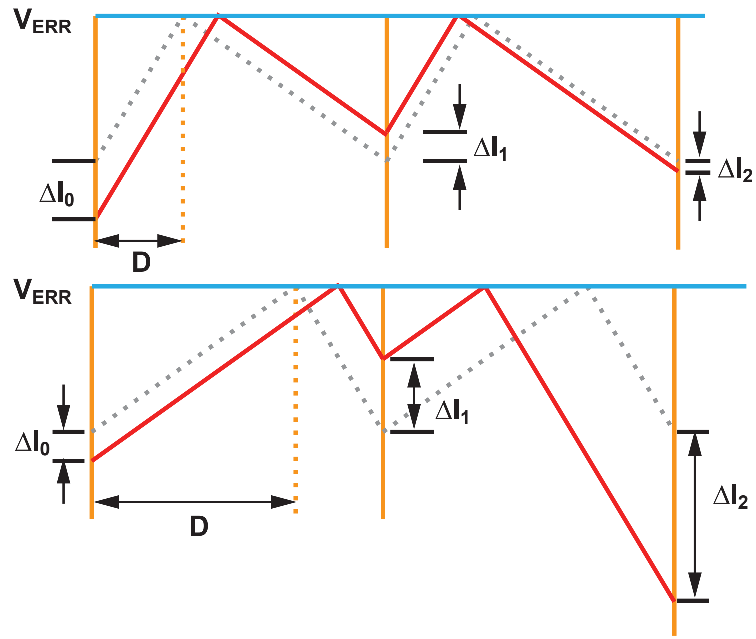
DCR Sensing



Resistor Sensing

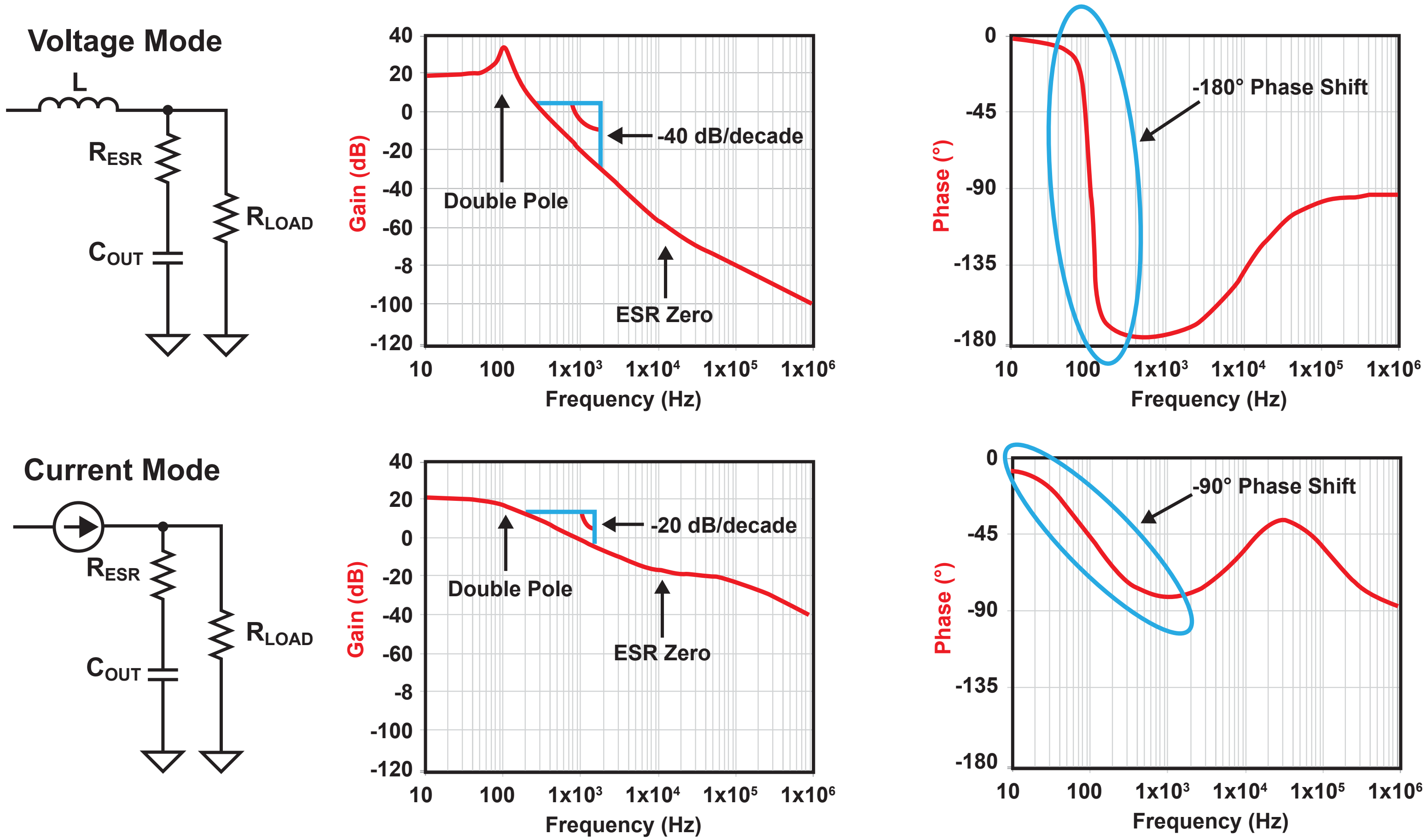


Sub-Harmonic Oscillation

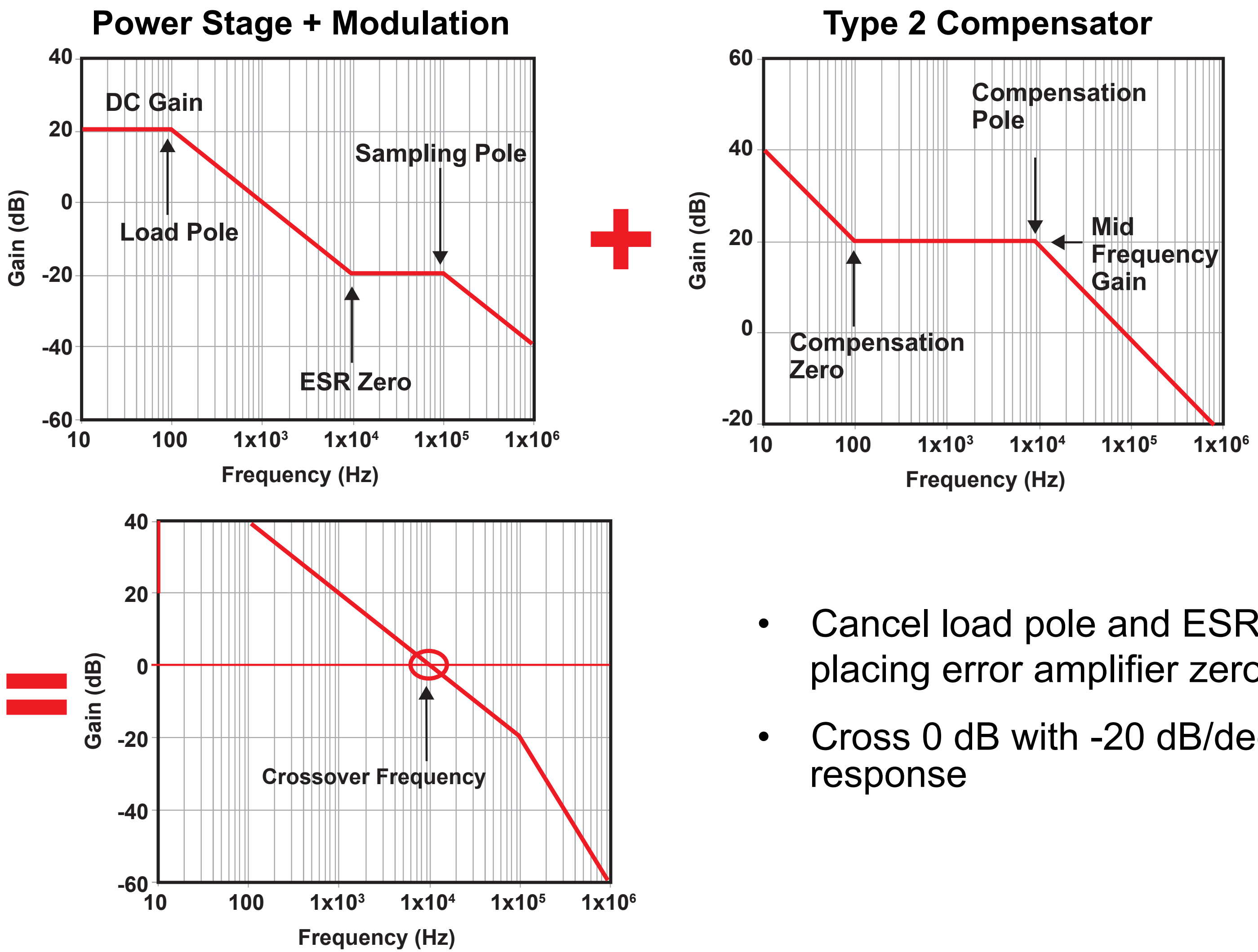


- $\Delta I_0 > \Delta I_1 > \Delta I_2$ when $D < 0.5$
- $\Delta I_0 < \Delta I_1 < \Delta I_2$ when $D > 0.5$ (sub-harmonic Oscillation)
- Requires slope compensation to be stable

Current Mode Control
Power Stage + Modulation



Current Mode Control Loop Compensation

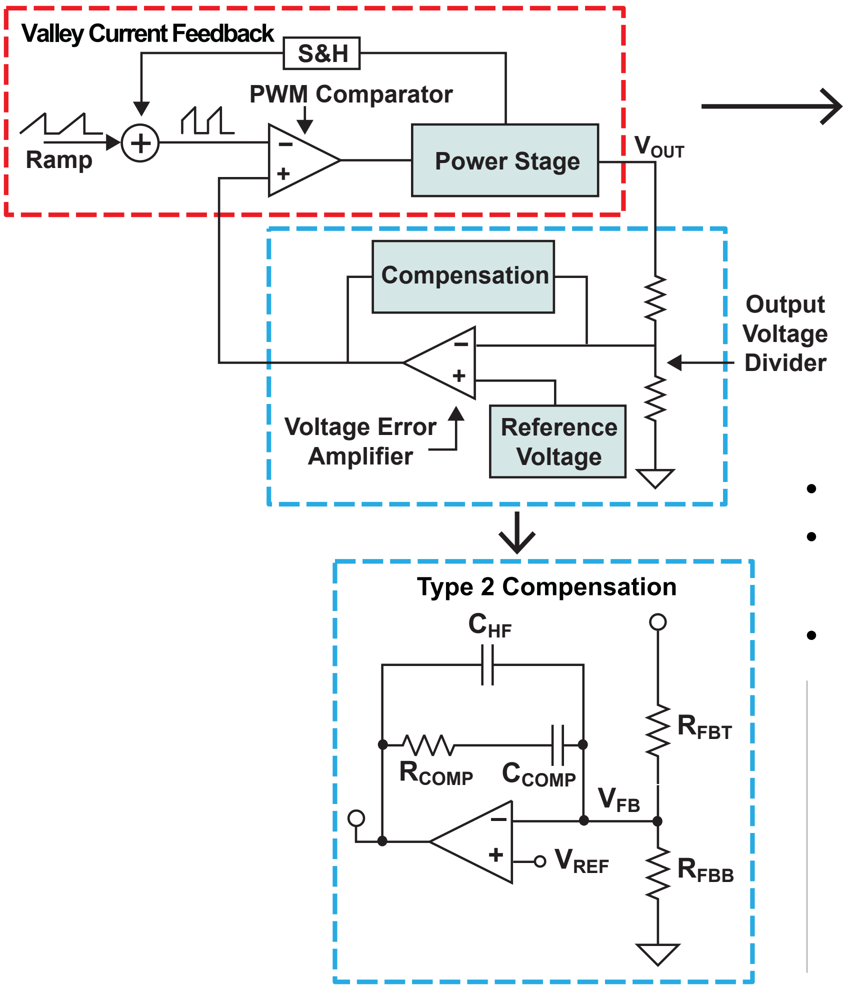


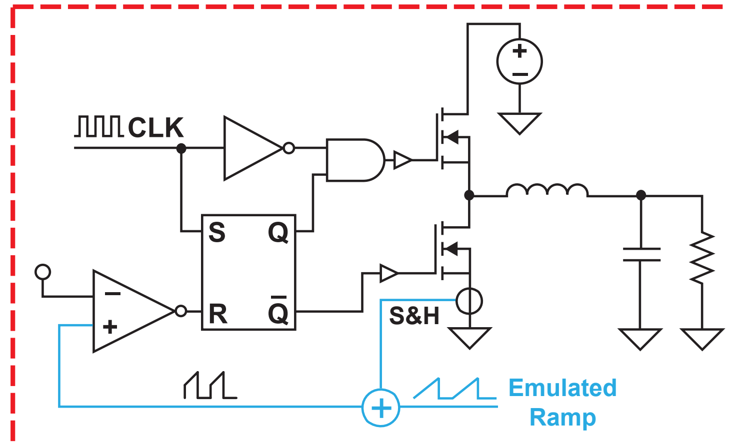
- Cancel load pole and ESR zero by placing error amplifier zero and pole
- Cross 0 dB with -20 dB/decade response

Current Mode Control

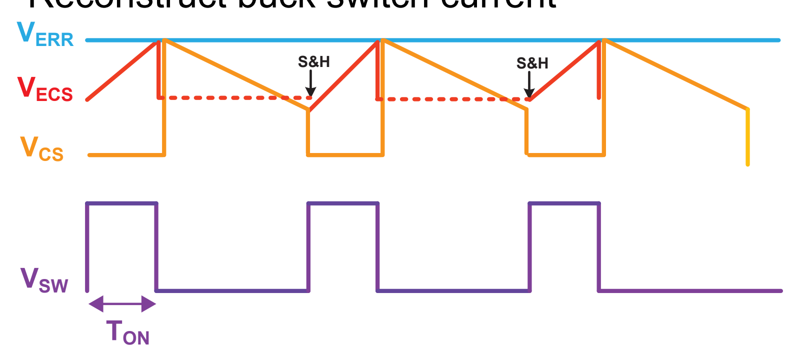
Advantages	Disadvantages
Single pole system allows simple Type 2 compensation	Need for slope compensation to eliminate sub-harmonic oscillation
Inherent feed forward improves line transient performance	Noise sensitivity at leading edge spike
Easy implementation of cycle-by-cycle current limit	Need for relatively long minimum on-time (peak current mode)
Easy current share across multiple converters	

Emulated Current Mode Control Basic Operation





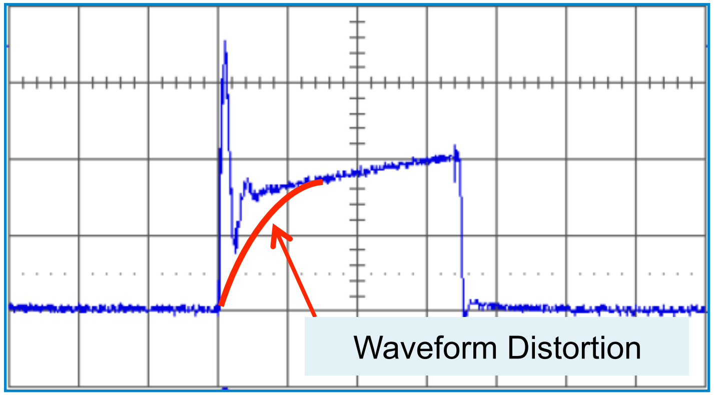
- Low-side current sensing during free-wheeling
- Sample & hold valley current before high-side switch turns on
- Reconstruct buck switch current



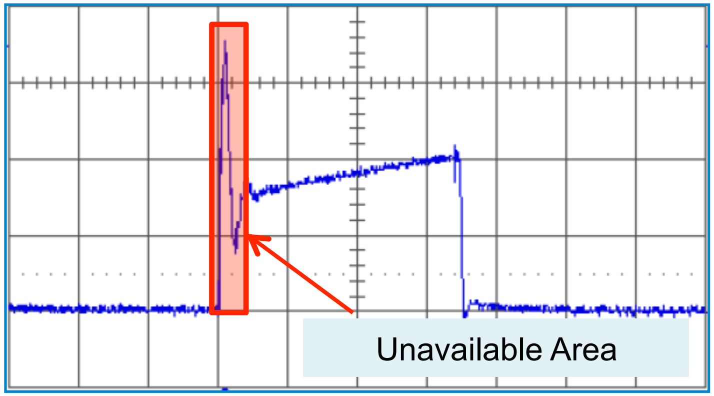
Emulated Current Mode Control
Leading Edge Spike

- The on-time of conventional peak current mode controller is limited by the leading edge spike
- R-C filtering distorts the waveform
- Leading edge blanking limits the minimum on-time
- Emulated current mode ensures a clean current waveform during high-side switch on-time

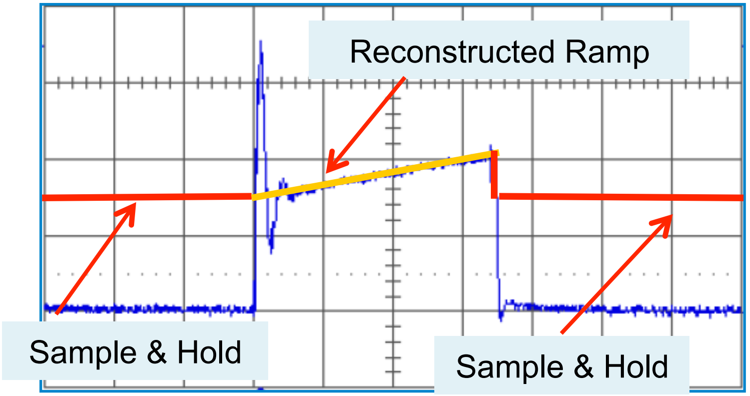
R-C Filter



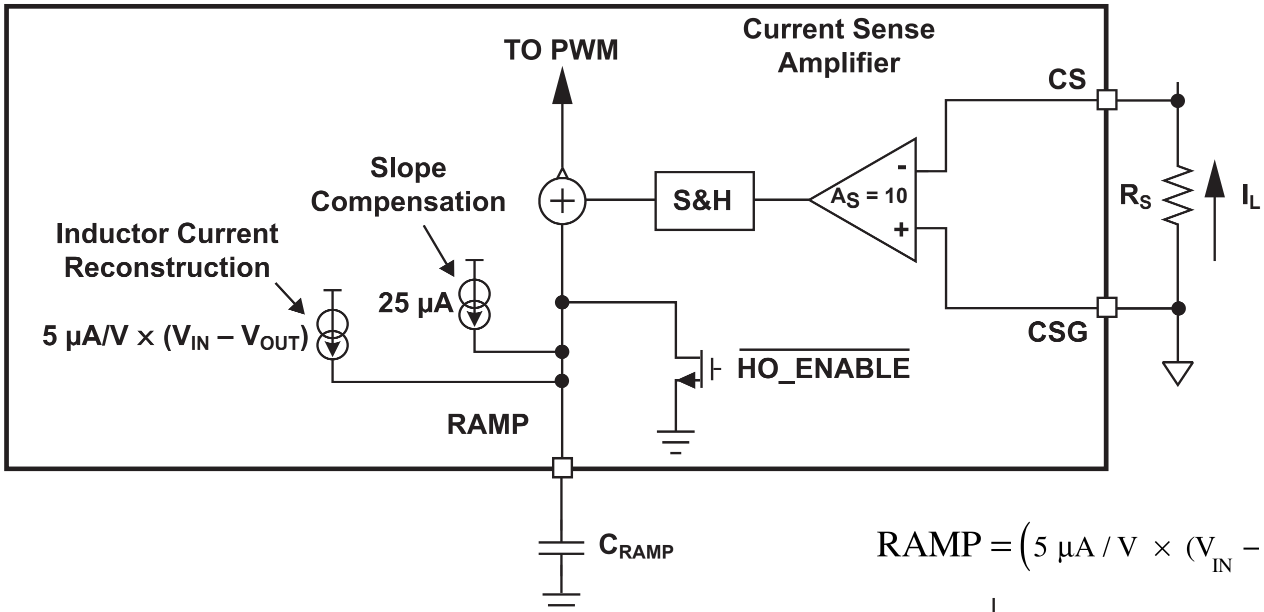
Leading Edge Blanking



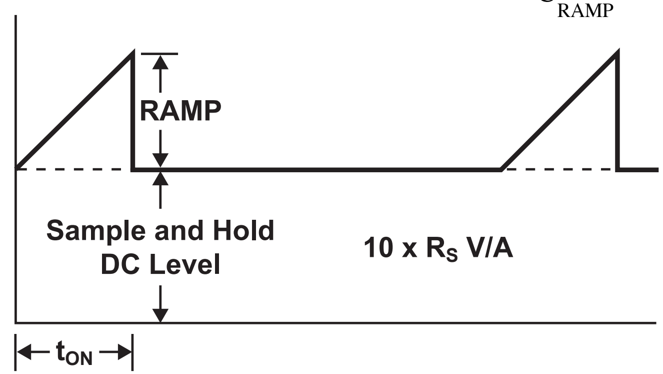
Emulated Current Mode



Emulated Current Mode Control Ramp Reconstruction



$$\text{RAMP} = \left(5\ \mu\text{A}/\text{V} \times (V_{IN} - V_{OUT}) + 25\ \mu\text{A}\right) \times \frac{t_{ON}}{C_{RAMP}}$$



- Proper selection of the RAMP capacitor (C_{RAMP}) depends upon the value of the output inductor (L) and the current sense resistor (R_S)
- $R_S \times A_S = \dfrac{5\mu \times L}{C_{RAMP}}$

Emulated Current Mode Control

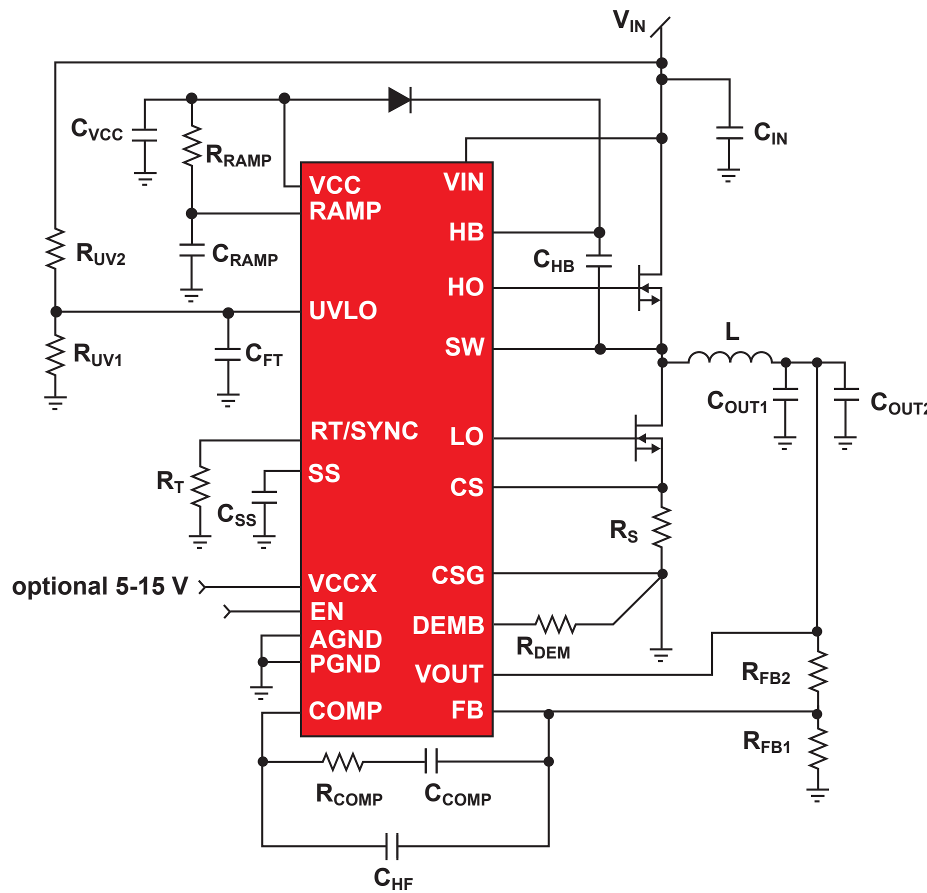
Advantages	Disadvantages
Single-pole system allows simple Type 2 compensation	Need for slope compensation to eliminate sub-harmonic oscillation
Inherent feed forward improves line transient performance	Need for relatively long minimum off-time than peak current mode
Easy implementation of cycle-by-cycle current limit	
Easy current share across multiple converters	
Noise immunity at leading edge spike	
Minimum on-time can be less than peak current mode	

All advantages of peak current mode control remain

Design Example #2
Design Specifications

Design Specifications	
Input voltage range	7 V to 60 V
Target output voltage	5 V
Output current range	0 A to 7 A
Switching frequency	250 kHz
Controller	LM5116

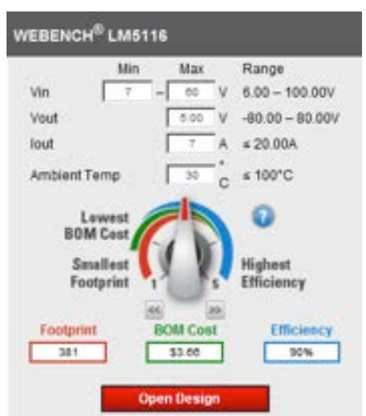
Operating Values (Theoretical)	
Minimum duty cycle	0.083
Minimum on-time	0.333 µs
Maximum duty cycle	0.714
Maximum on-time	2.857 µs

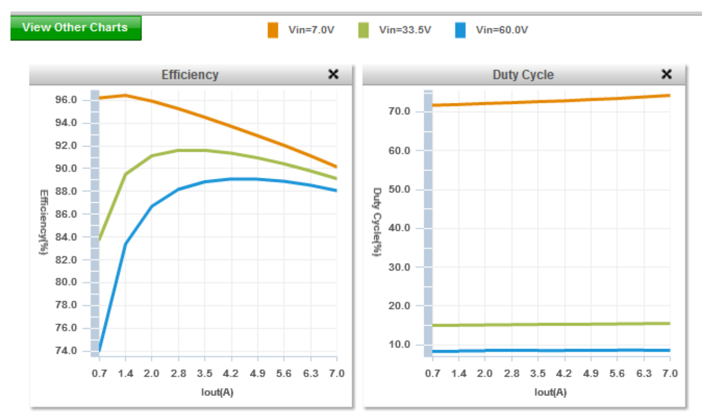


Design Example #2 – Calculation

- Choose switching frequency first
- Calculate the output filter components (L and C)
- Calculate the power stage components (FETs)

- WEBENCH®
  - Helps calculate all of specific values for design
  - Allows optimization based on design goals
  - Gives estimates for loop response and efficiency
  - Provides a complete schematic and bill of materials

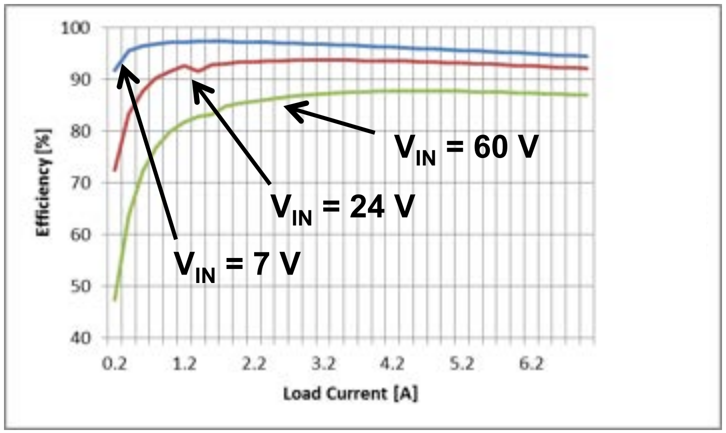




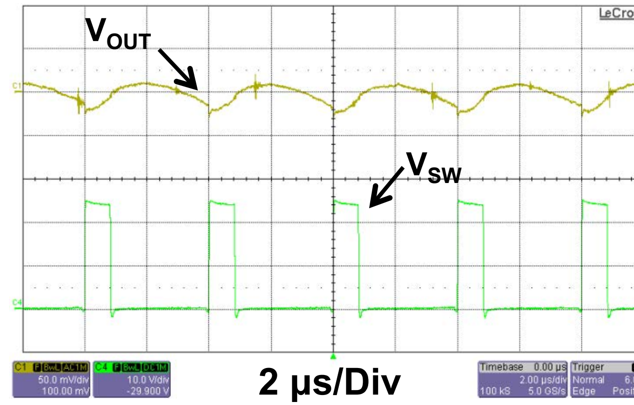
Design Example #2 – Performance Graphs

Data is taken with LM5116EVM

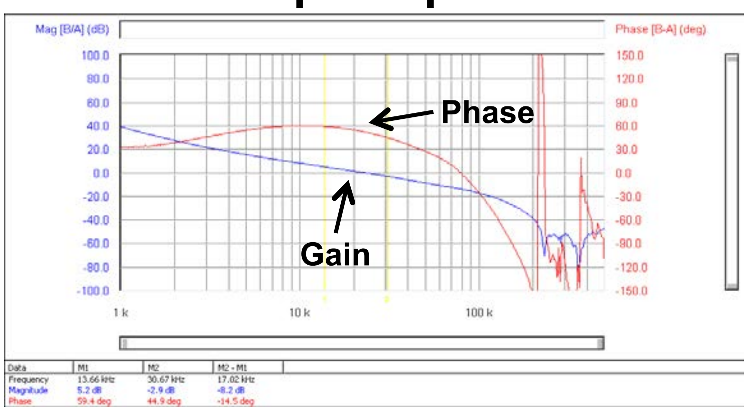
Efficiency



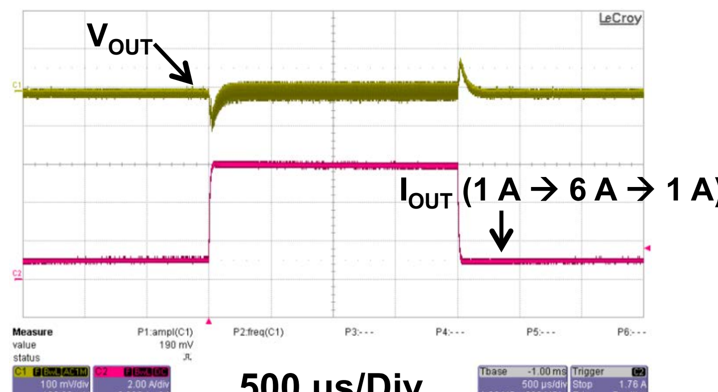
Switching Operation



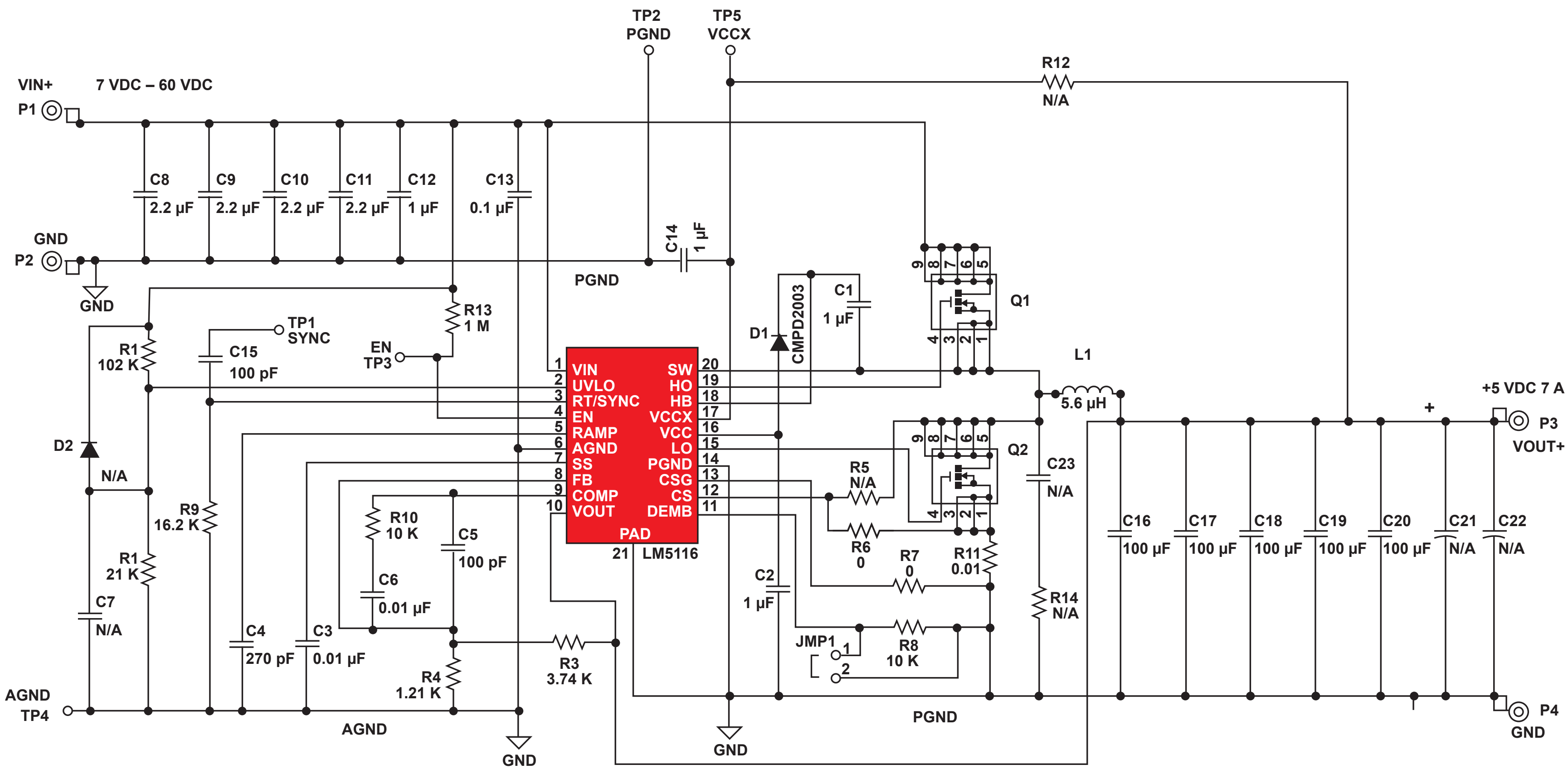
Loop Response



Transient Response

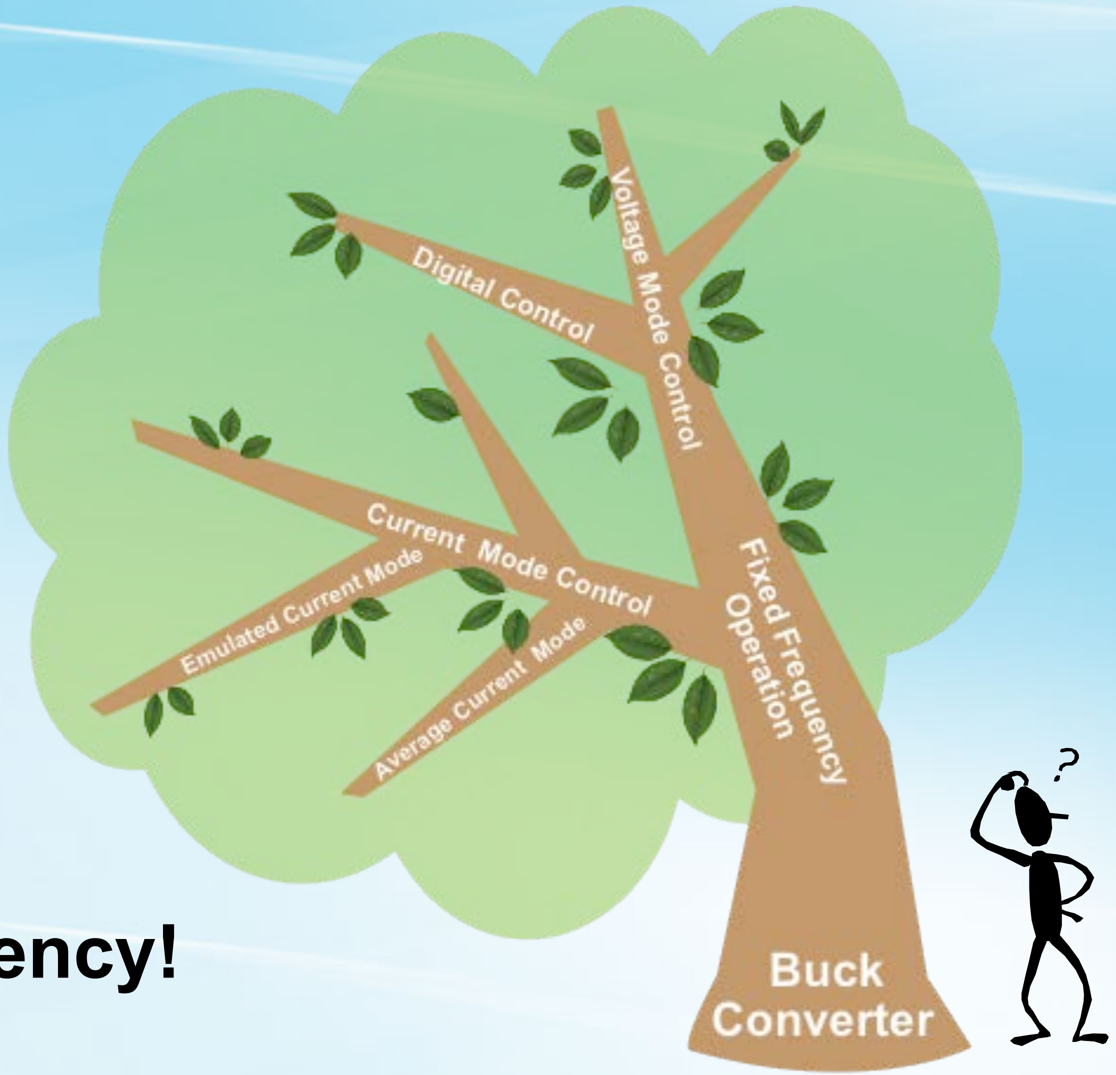


Design Example #2 - Schematic



Fixed Frequency Control

Questions?



Stay tuned for Variable Frequency!