

# Choosing the Right Fixed Frequency Buck Regulator Control Strategy

Brian Cheng

Eric Lee

Brian Lynch

Robert Taylor

# 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

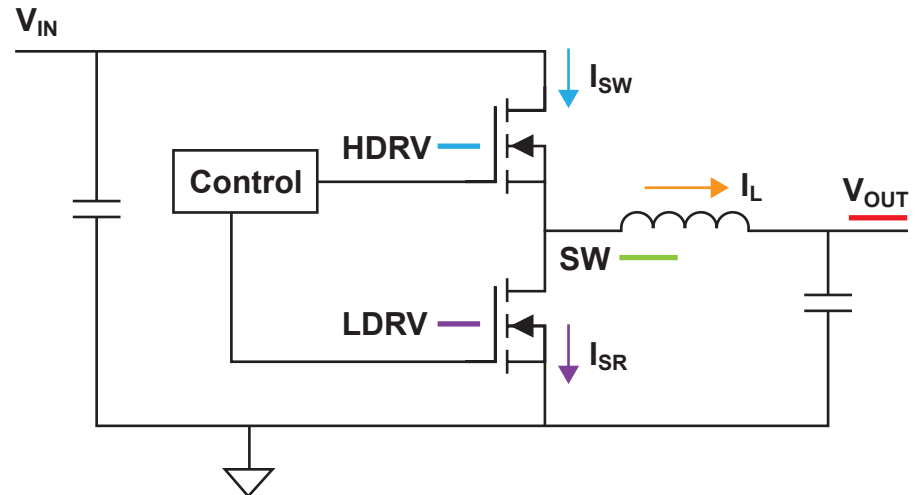
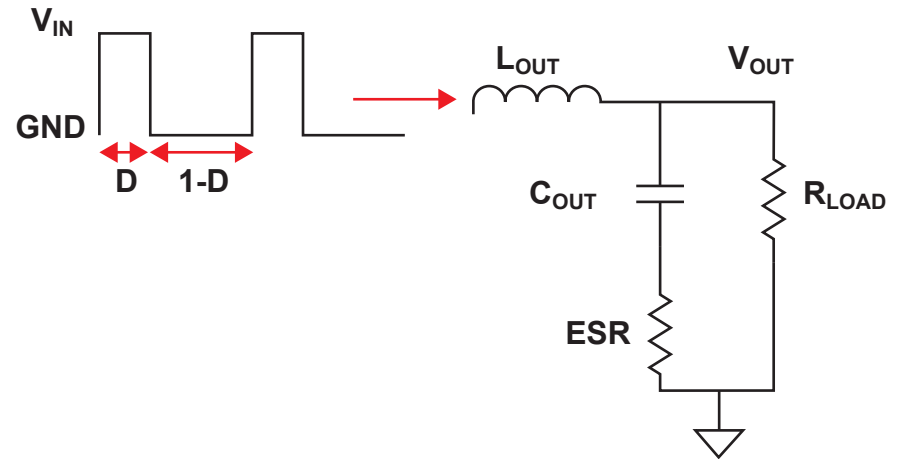


# Buck Regulator

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

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

Pretty simple – right?



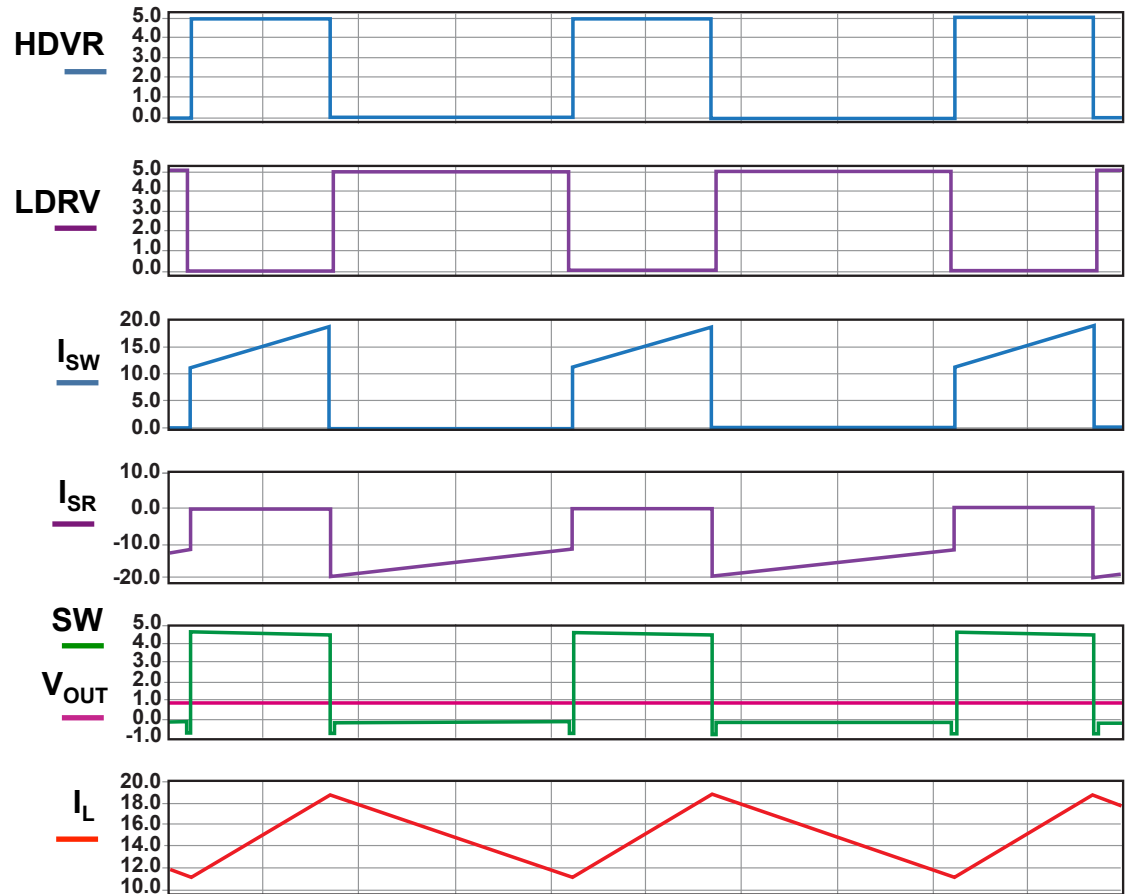
# Synchronous Buck Waveforms

## Continuous Conduction Mode

- Inductor current flow is continuous during the switching cycle

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

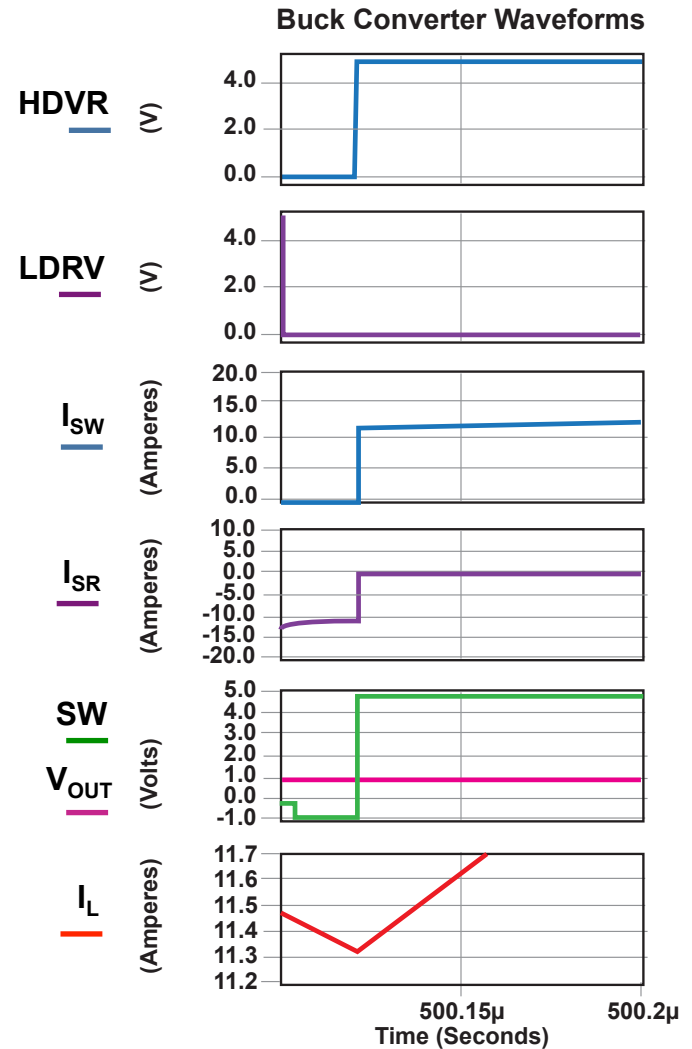
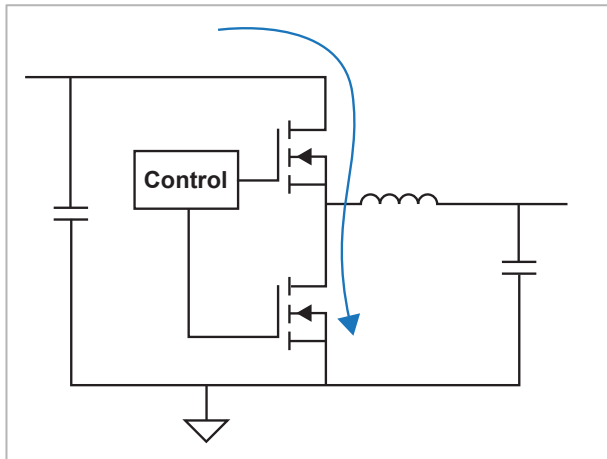
$$\text{Duty Cycle}_{\text{CCM}} = \frac{t_{\text{ON}}}{T_s}$$



# Synchronous Buck Waveforms

## Continuous Conduction Mode

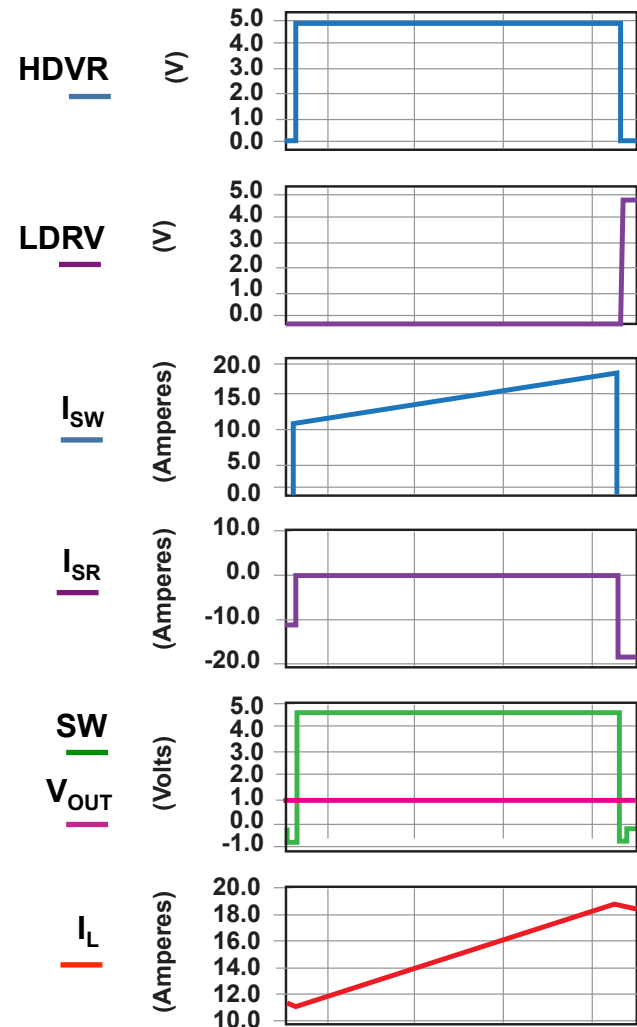
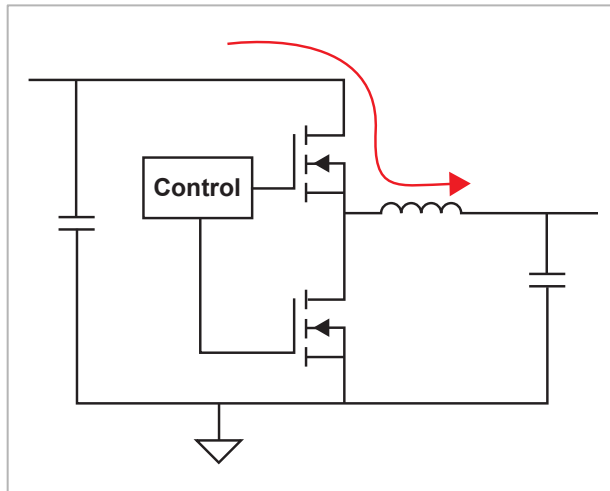
Switch turn ON



# Synchronous Buck Waveforms

## Continuous Conduction Mode

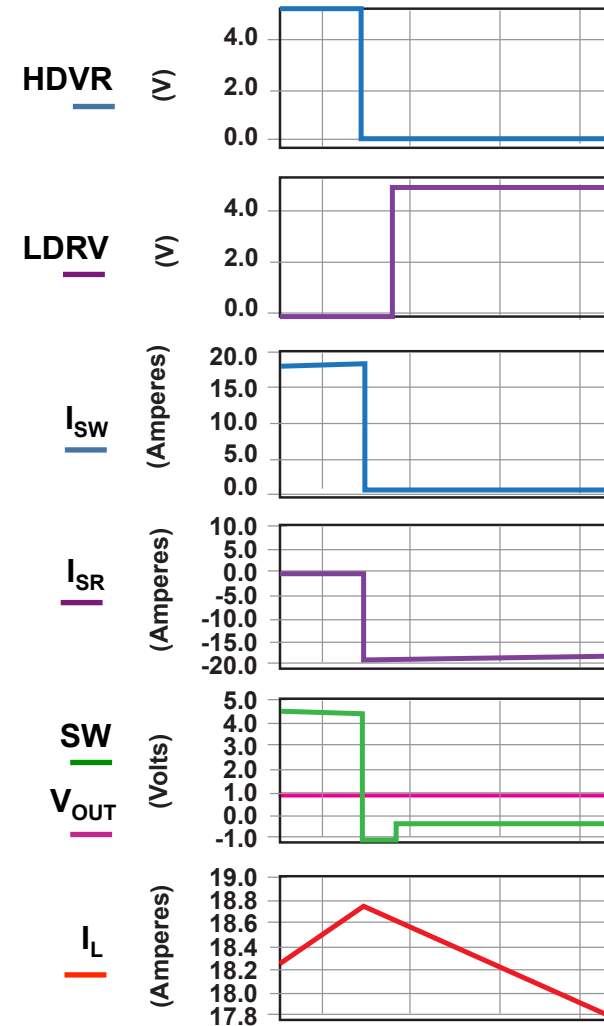
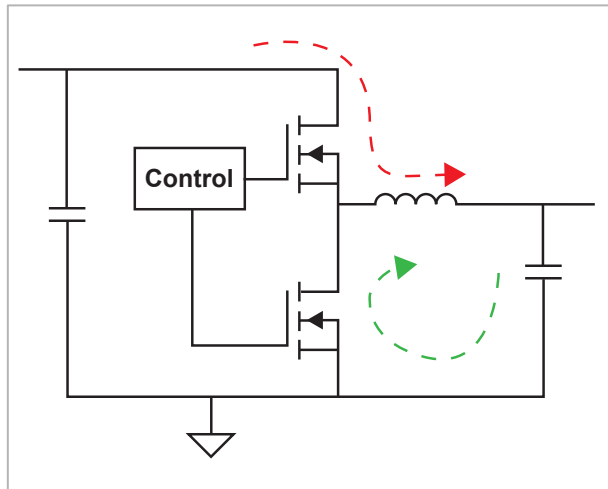
Power transfer



# Synchronous Buck Waveforms

## Continuous Conduction Mode

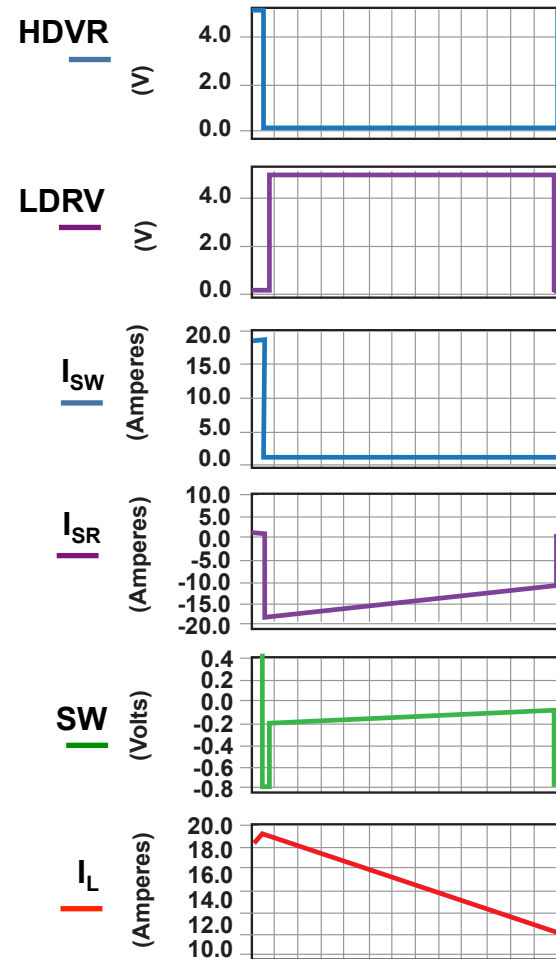
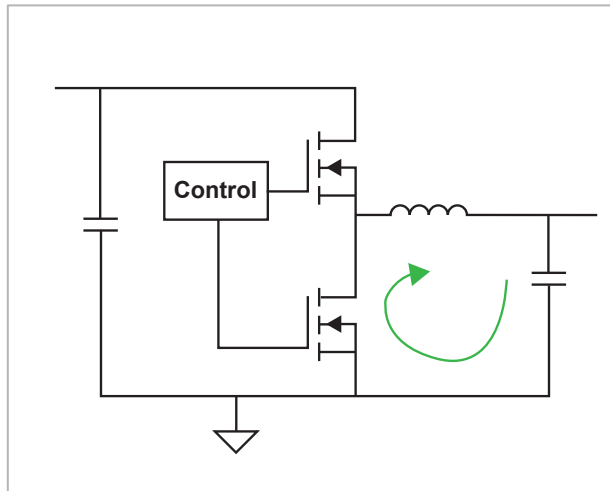
Switch turn OFF transition to SR turn ON



# Synchronous Buck Waveforms

## Continuous Conduction Mode

Inductor reset

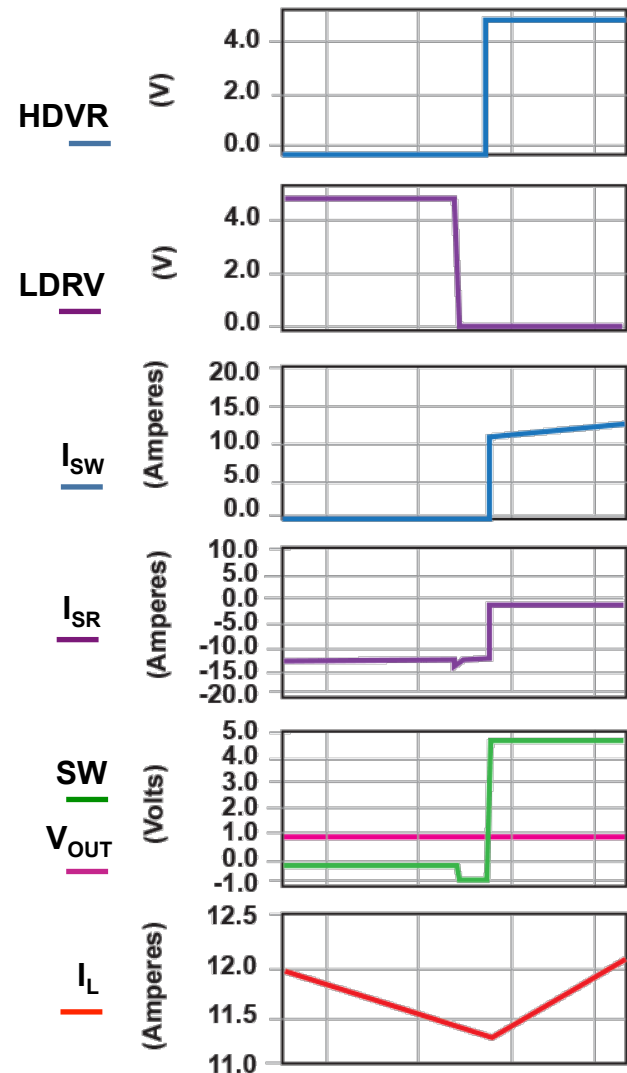
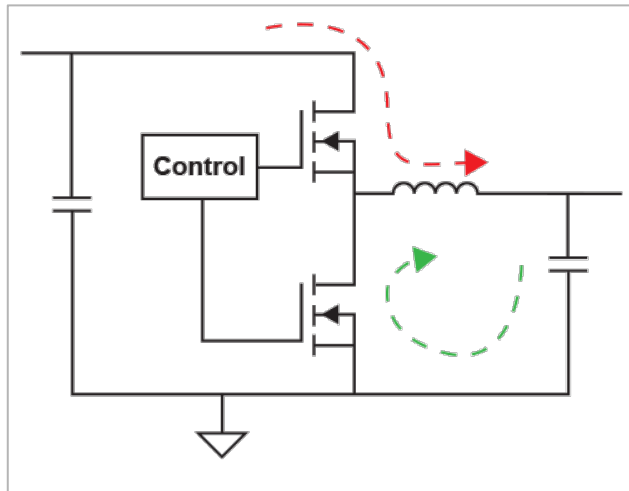




# Synchronous Buck Waveforms

## Continuous Conduction Mode

Transition for next cycle



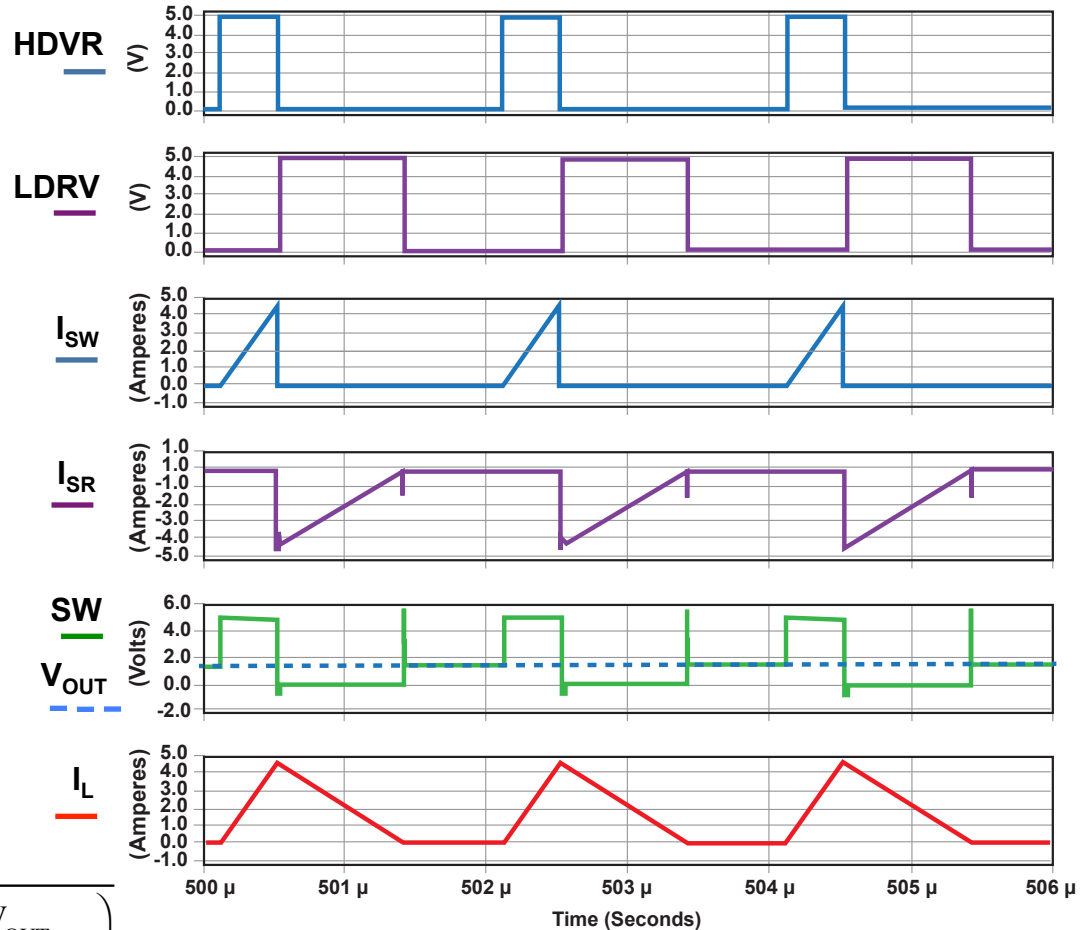
# Synchronous Buck Waveforms

## Discontinuous Conduction Mode

- Inductor current flow is discontinuous during the switching cycle

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

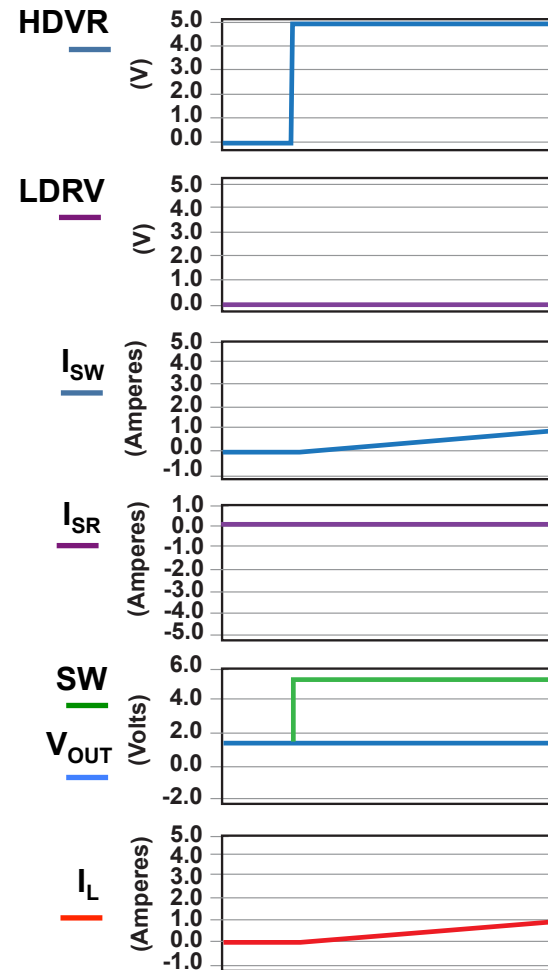
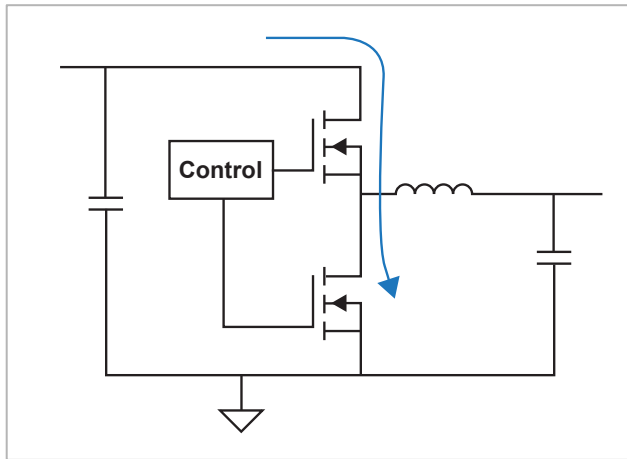
$$\text{Duty Cycle}_{\text{DCM}} = \sqrt{\frac{2 \times L \times I_{\text{OUT}}}{T_S \times V_{\text{IN}}}} \times \left( \frac{V_{\text{OUT}}}{V_{\text{IN}} - V_{\text{OUT}}} \right)$$



# Synchronous Buck Waveforms

## Discontinuous Conduction Mode

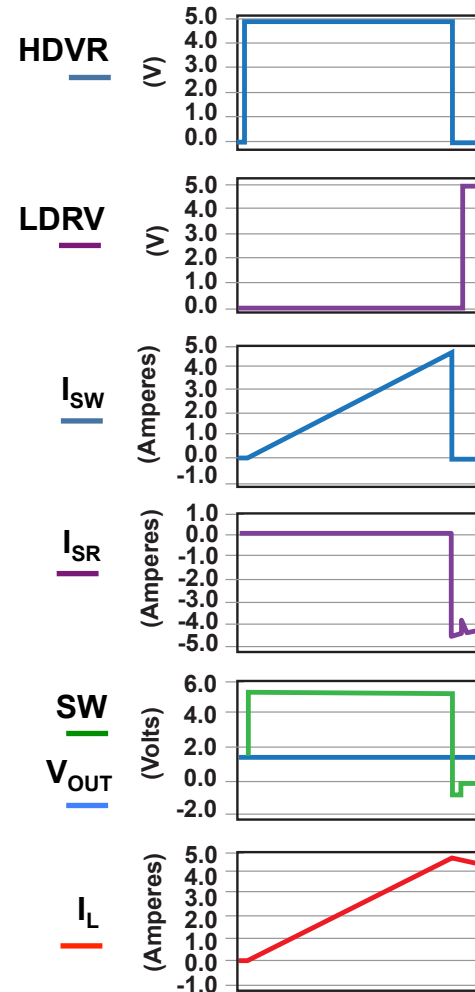
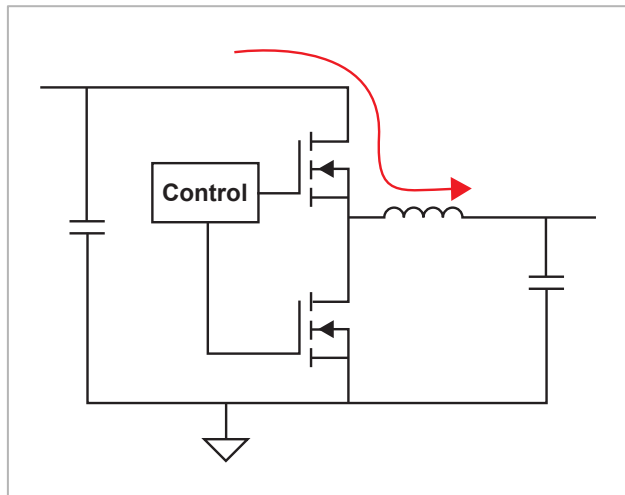
- First part is the same as CCM Mode
- High side switch turns ON



# Synchronous Buck Waveforms

## Discontinuous Conduction Mode

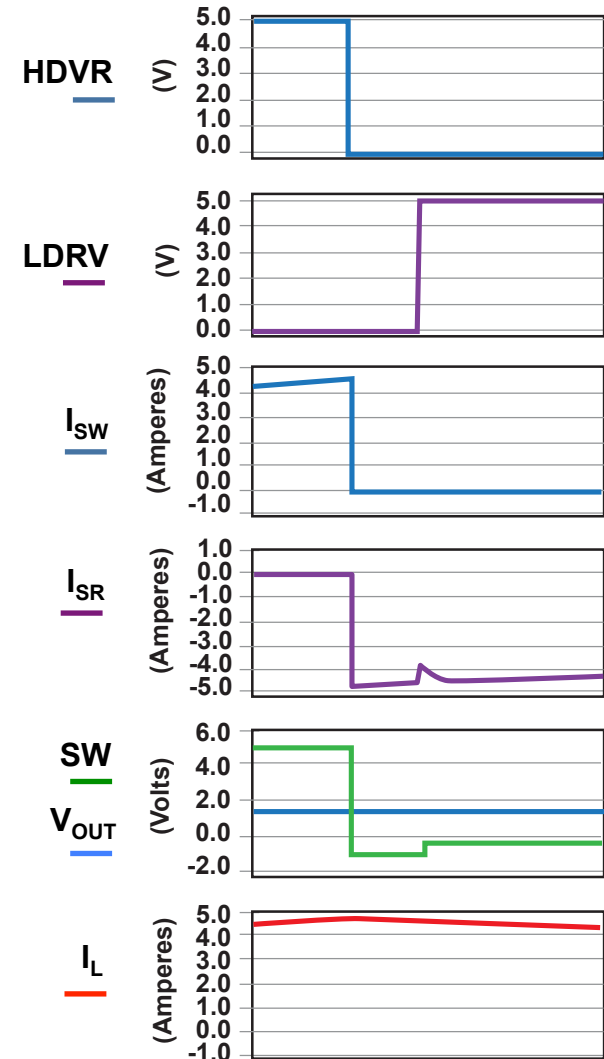
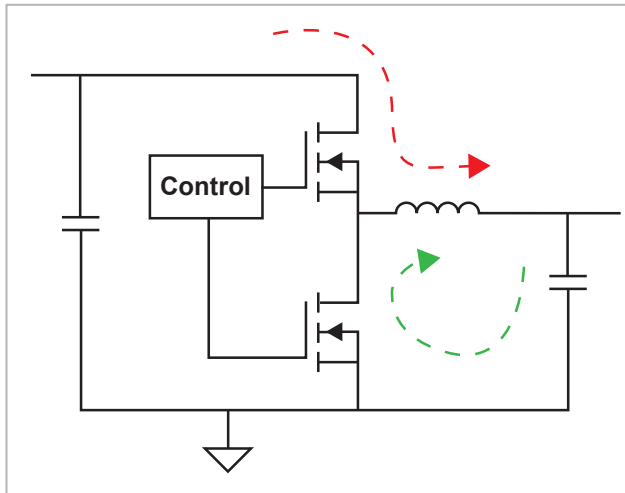
Switch ON



# Synchronous Buck Waveforms

## Discontinuous Conduction Mode

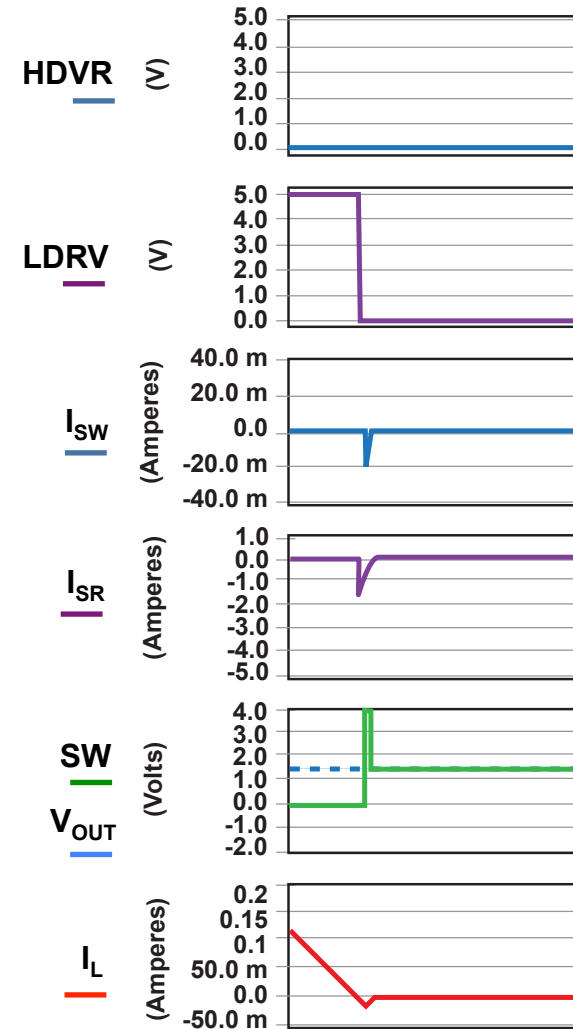
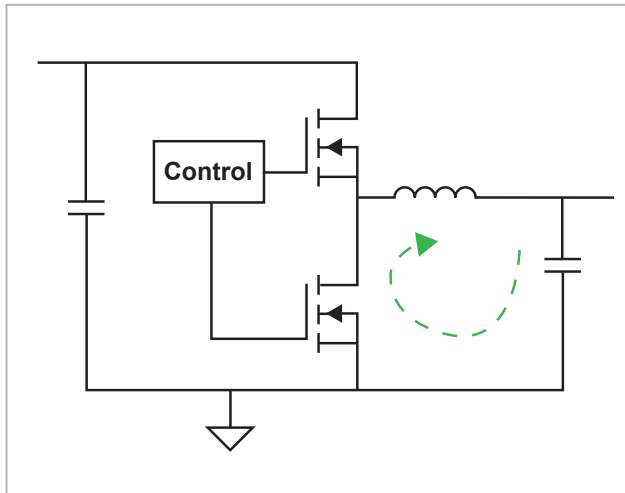
- Switch turn OFF
- SR turn ON



# Synchronous Buck Waveforms

## Discontinuous Conduction Mode

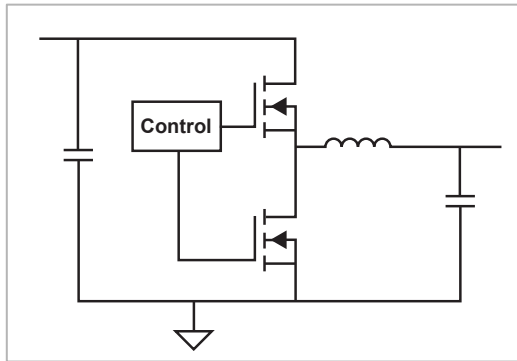
- SR turns OFF at zero current in inductor



# Synchronous Buck Waveforms

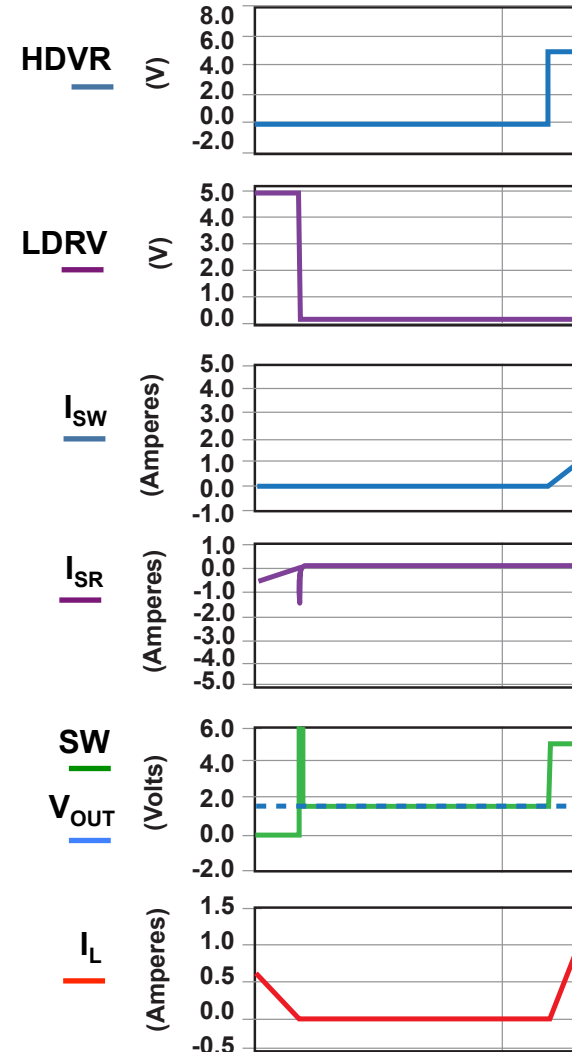
## Discontinuous Conduction Mode

- Freewheeling interval



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

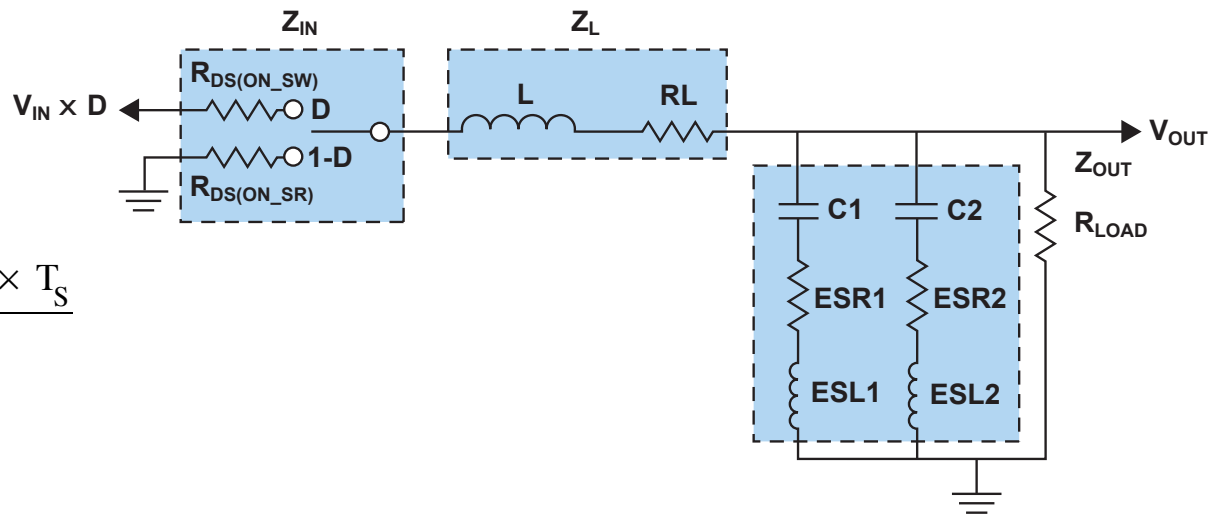
$$\text{Duty Cycle}_{\text{DCM}} = \sqrt{\frac{2 \times L \times I_{\text{OUT}}}{T_S \times V_{\text{IN}}}} \times \left( \frac{V_{\text{OUT}}}{V_{\text{IN}} - V_{\text{OUT}}} \right)$$



# 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  $\sim 1/10$  of desired crossover frequency







# Output Capacitors

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

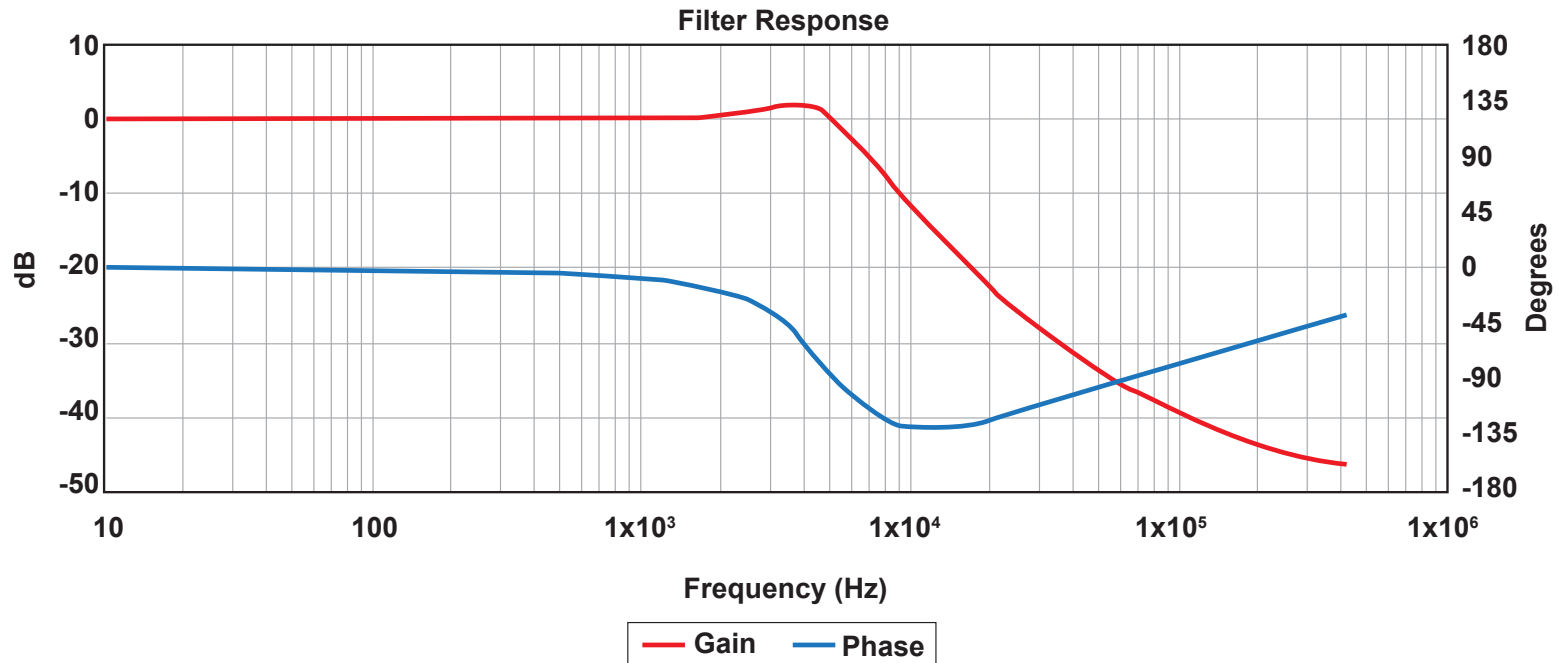
Type of Cap		Advantages	Disadvantages
<b>Ceramic</b>		Small size, low cost, low ESR, high ripple current rating	DC bias effects, low capacitance, cracking
<b>Aluminum Electrolytic</b>		High capacitance, low cost, good for high voltage	High ESR, low ripple current rating, temp issues, large size
<b>Aluminum Polymer</b>		High capacitance, low ESR, high ripple current rating	Expensive, fewer manufacturers, large size, voltage rating
<b>Tantalum Polymer</b>		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 $I_{sat}$ , higher inductances	Can be unshielded, high core loss, high DCR, hard $I_{sat}$
Molded Core		Very high $I_{sat}$ , easy to shape into many sizes, shielded, soft $I_{sat}$	High core losses, low inductance range
Shaped Core		Low core loss, low DCR, high current, shielded, high inductance range	High cost, hard $I_{sat}$ , not suitable for low profile
Power Bead		Low core loss, low DCR, excellent for multiphase	Low inductance, hard $I_{sat}$

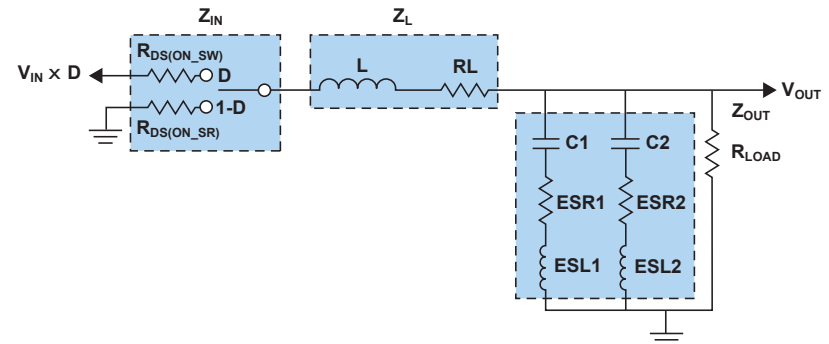
# Filter AC Response



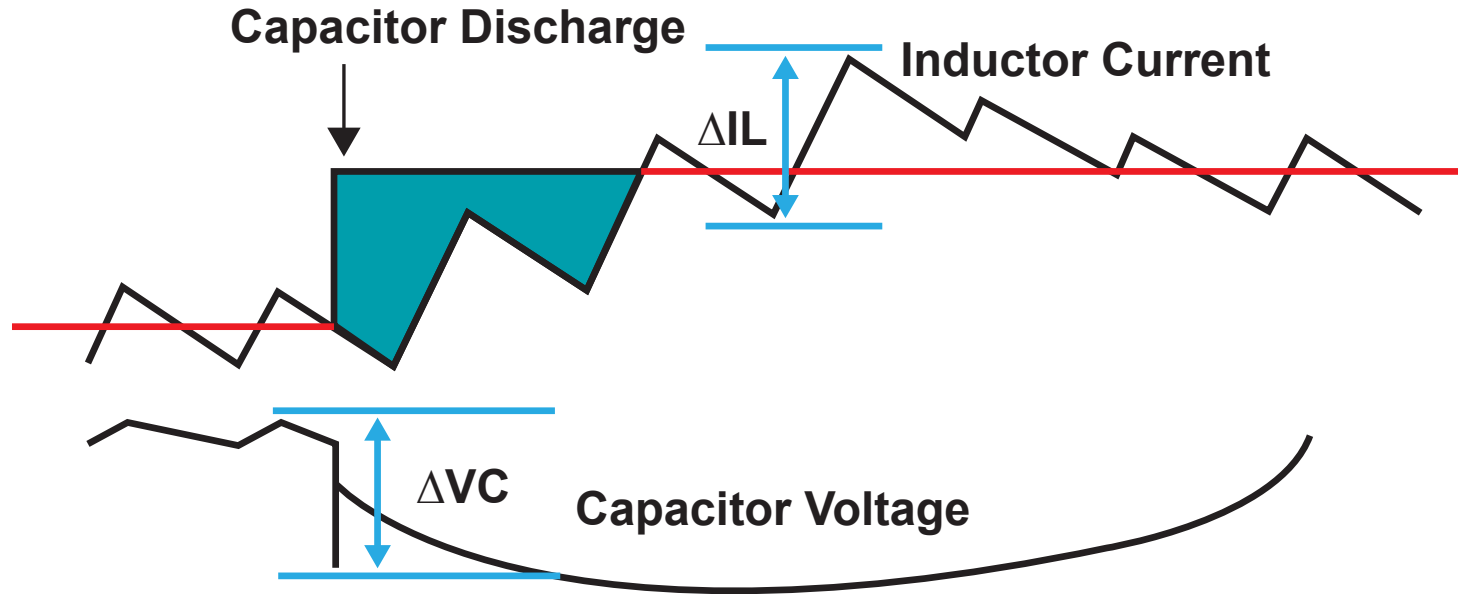
Corner frequency ~ 5 kHz

ESR zero ~ 21 kHz

ESL zero ~ 240 kHz



# Filter Design for Transient Response



- Select L for current slew rate
- Select capacitance VALUE based on support of output voltage while current is increasing

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

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

# Minimum Controllable On-Time

- Propagation delays limit the minimum controllable pulse width
- Below minimum controllable on-time, pulse skipping could occur

- $$T_{on\_MIN} \leq \frac{V_{OUT}}{V_{IN\_max} \times f_{max}}$$

- Example – TPS40170, min on-time is 100 ns max

- $V_{IN} = 60 \text{ Vmax}$
  - $V_{OUT} = 5 \text{ V or } 3.3 \text{ V}$
  - Frequency = 600 KHz (+10% shift)

$$T_{on\_MIN} \leq \frac{5 \text{ V}}{60 \text{ V} \times 600 \text{ kHz} \times 1.1} = 140 \text{ ns}$$

$$T_{on\_MIN} \leq \frac{3.3 \text{ V}}{60 \text{ V} \times 600 \text{ kHz} \times 1.1} = 91 \text{ ns}$$

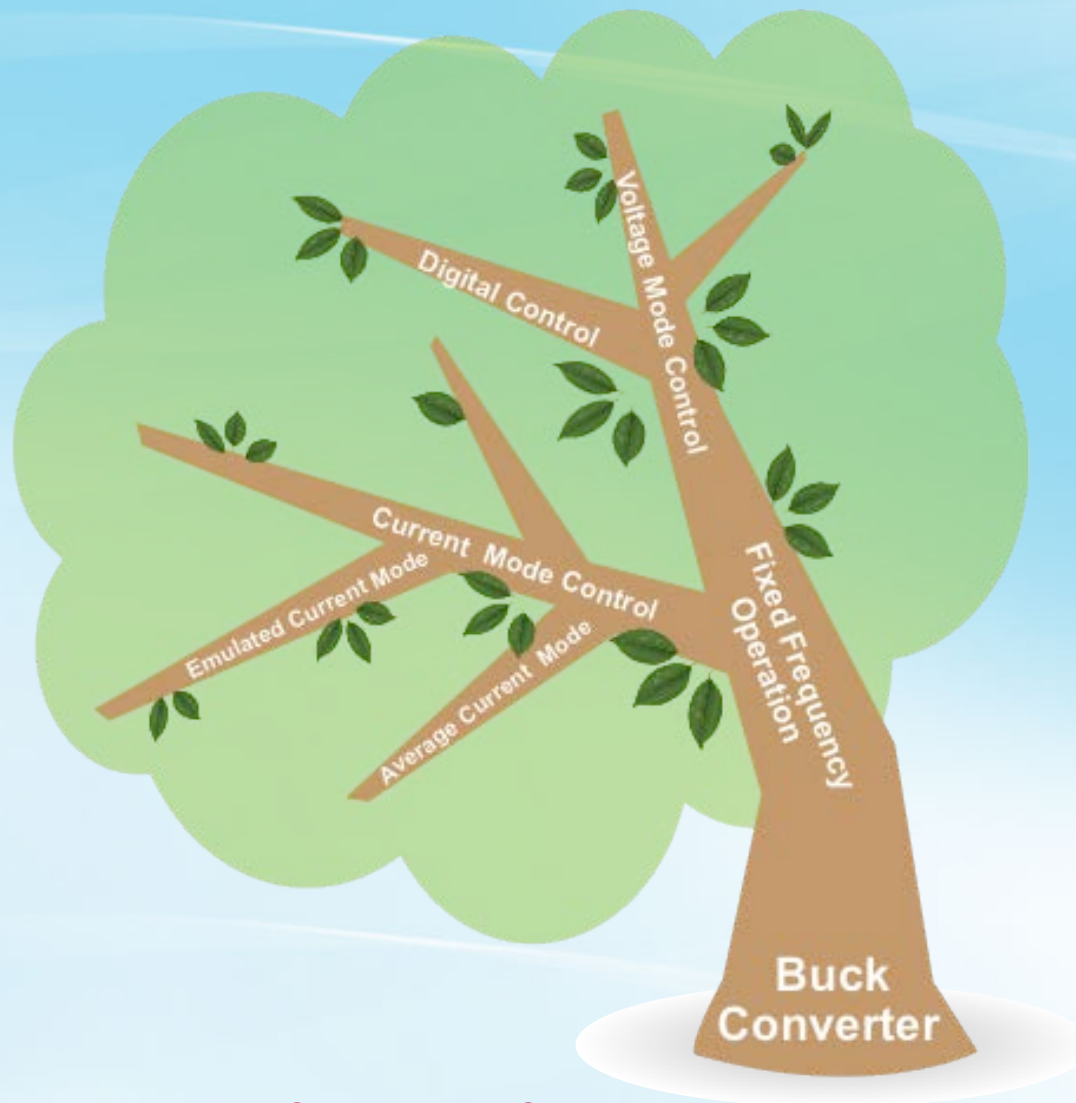


- For a 3.3 V output, the frequency would need to be lowered to ensure no pulse skipping

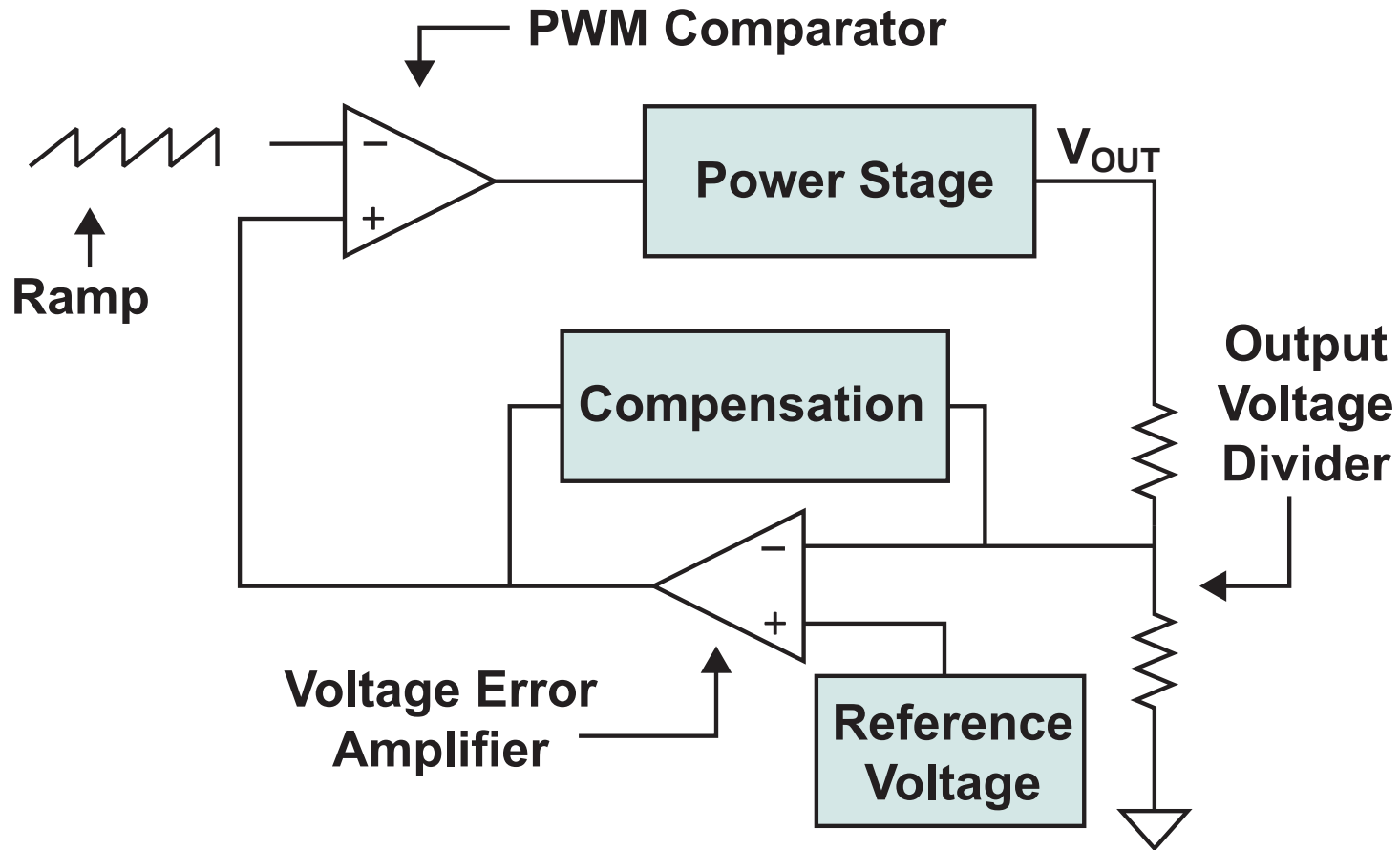
# Fixed Frequency vs. Variable Frequency

- 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

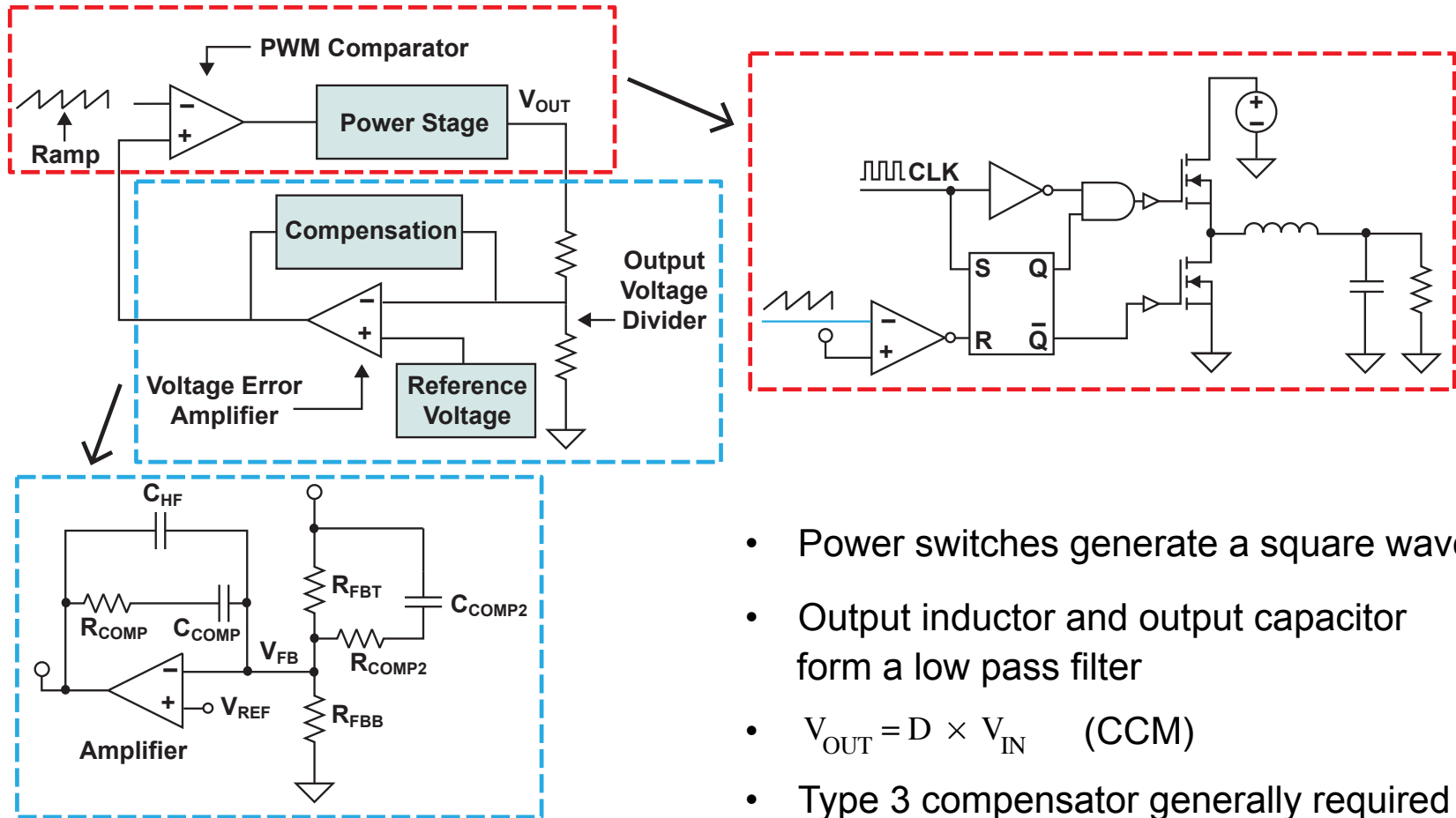


# Voltage Mode Control Introduction



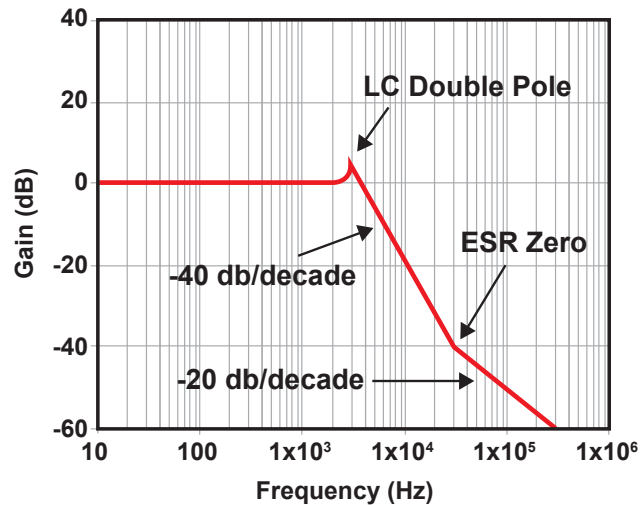
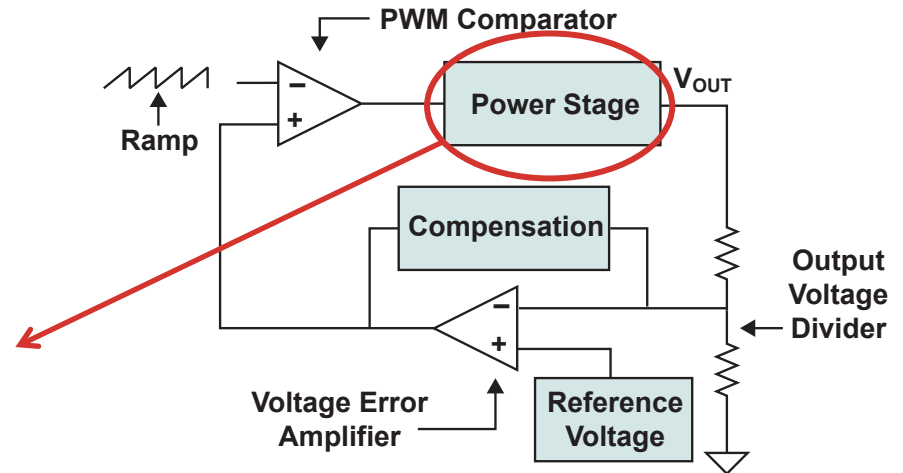
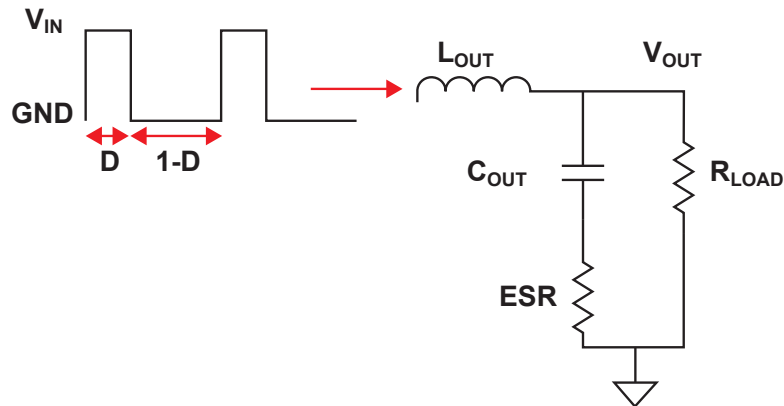


# Voltage Mode Control – Basic Operation



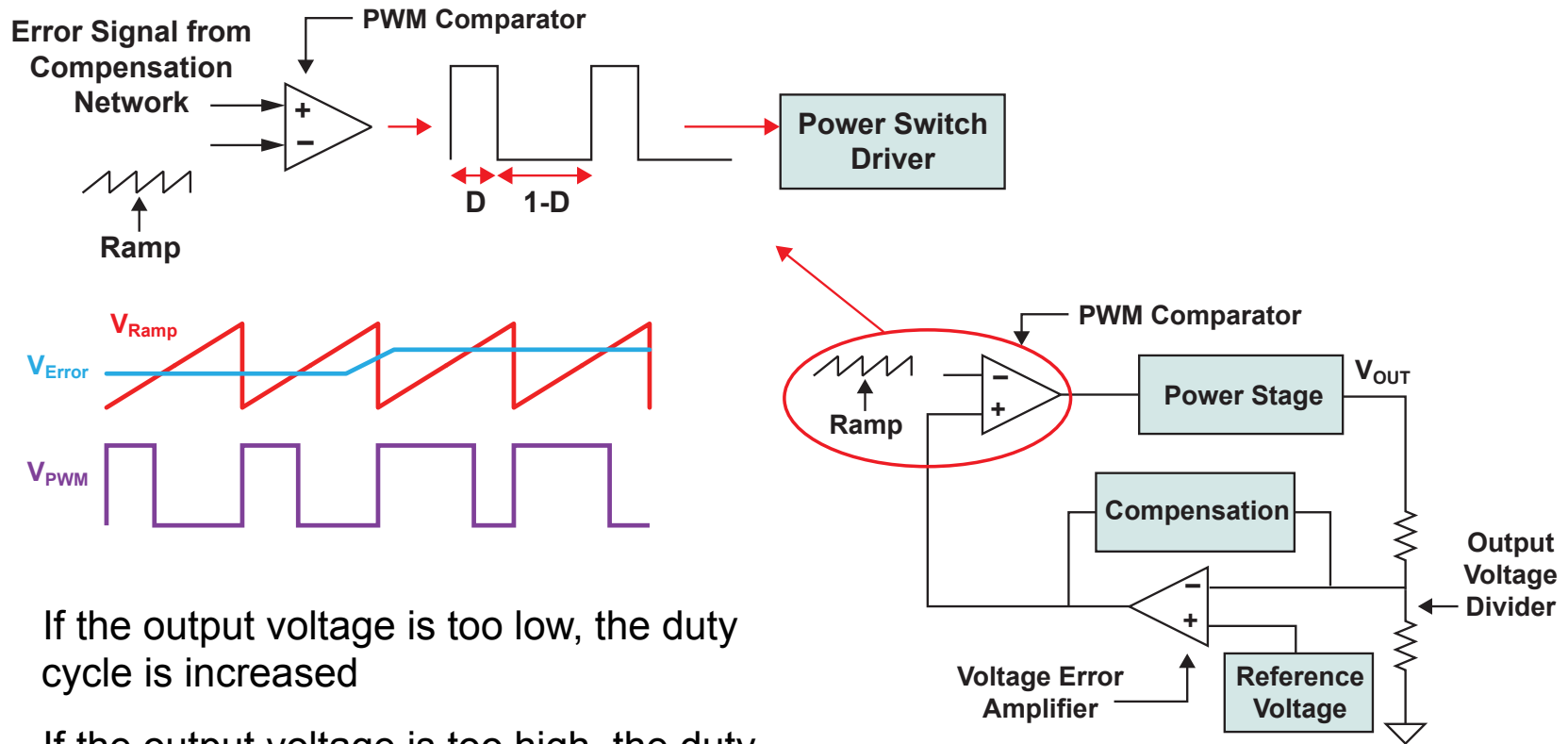
- Power switches generate a square wave
- Output inductor and output capacitor form a low pass filter
- $V_{OUT} = D \times V_{IN}$  (CCM)
- Type 3 compensator generally required

# Voltage Mode Control – Power Stage



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

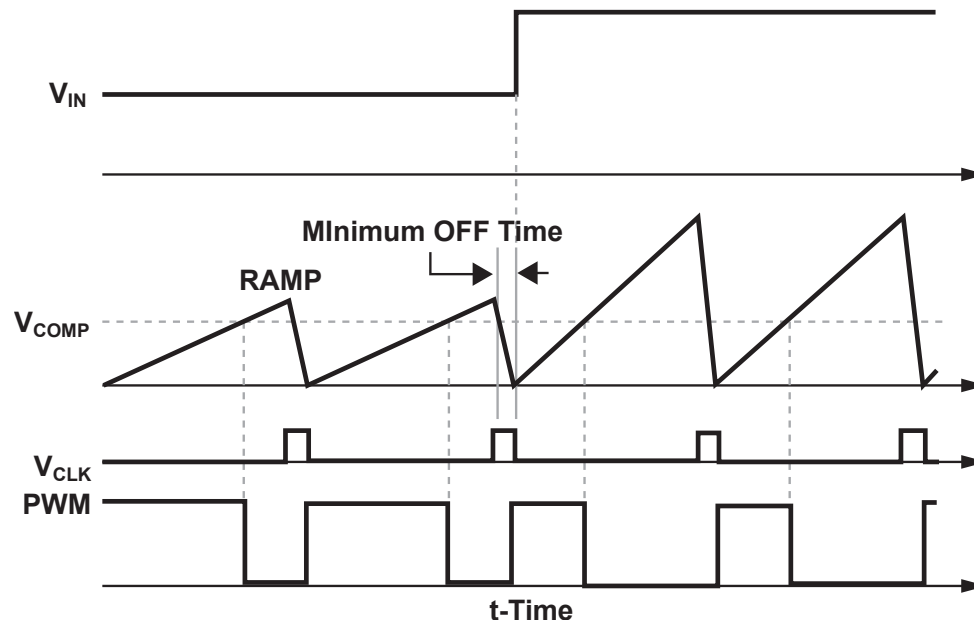
# Voltage Mode Control – Pulse Width Modulator



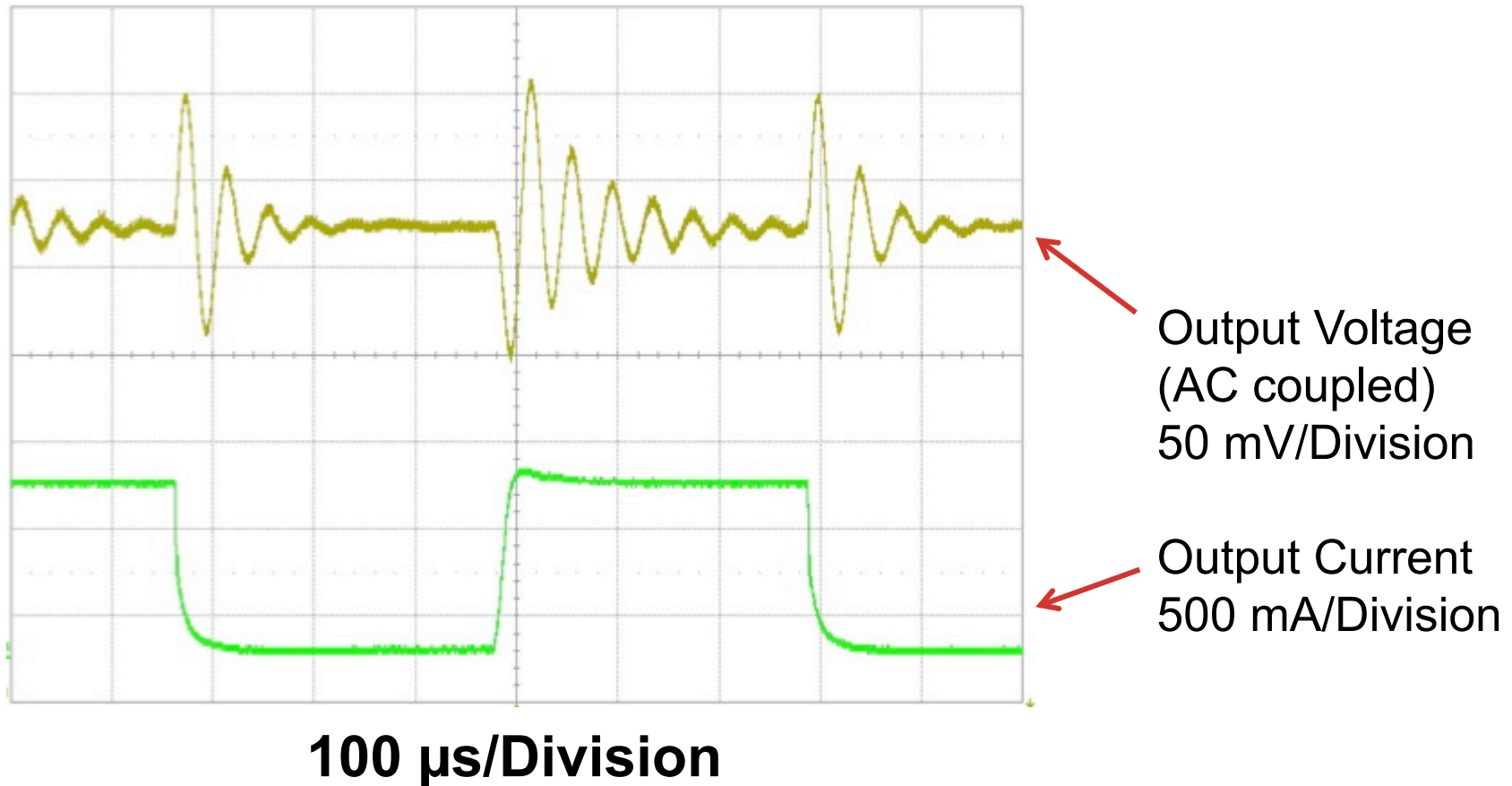
- If the output voltage is too low, the duty cycle is increased
- If the output voltage is too high, the duty cycle is reduced
- Gain of the modulator:  $H_{Mod} = \frac{V_{IN}}{V_{Ramp}}$

# 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

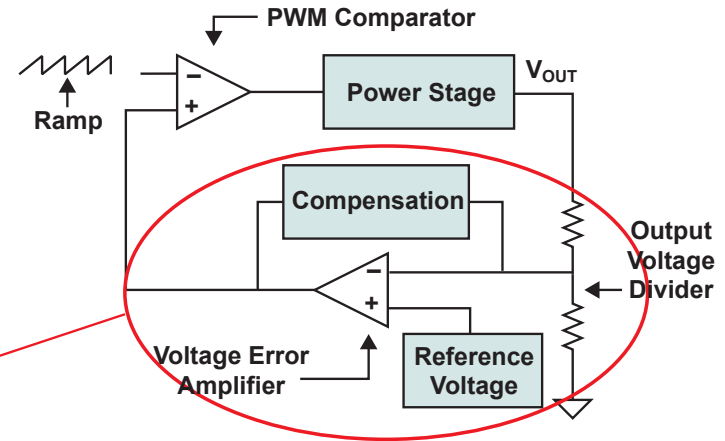
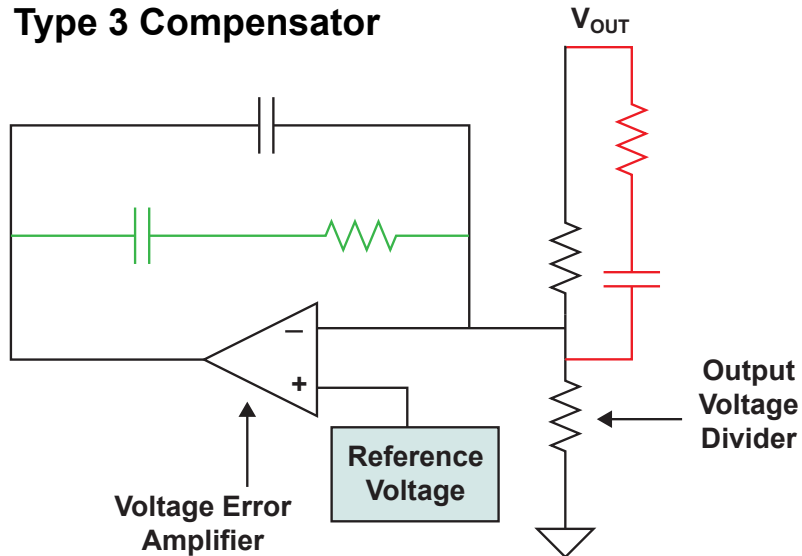


# Why Do We Compensate?

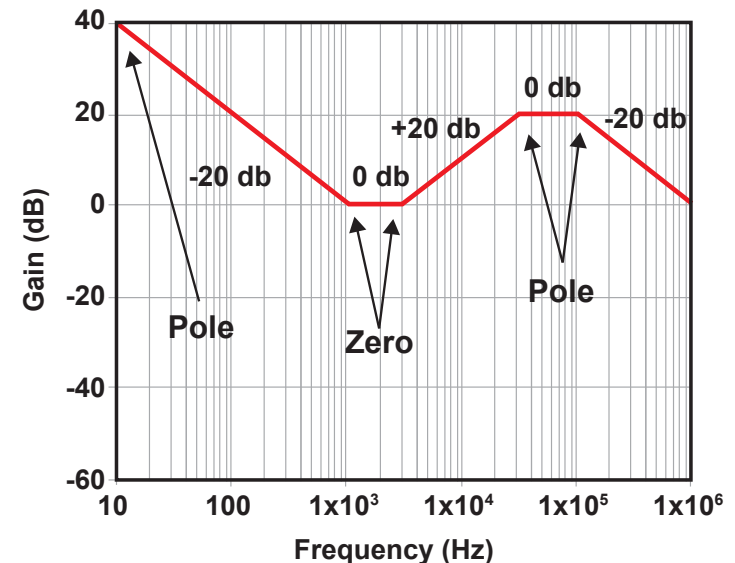


# Voltage Mode Control – Compensation

## Type 3 Compensator

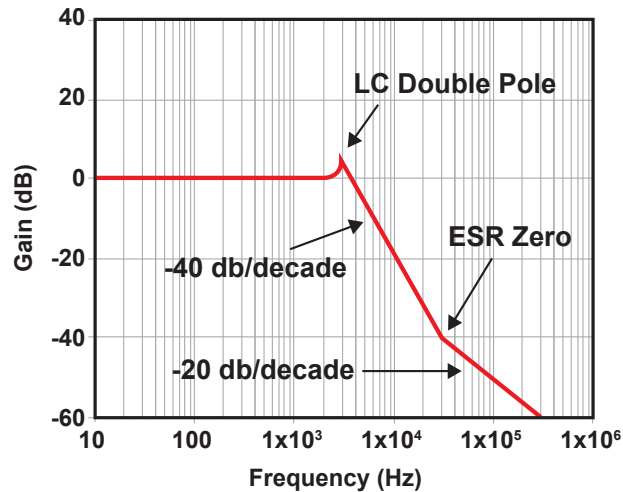


- Type 1 compensator – single dominant pole
- Type 2 compensator – two poles, one zero
- Type 3 compensator – three poles, two zeros

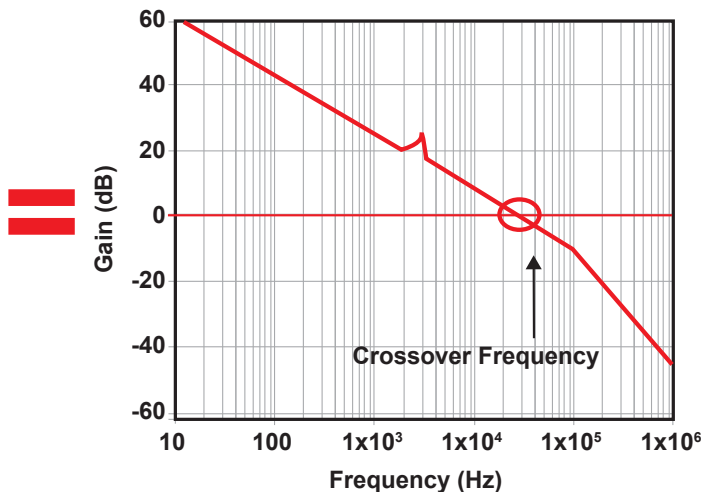
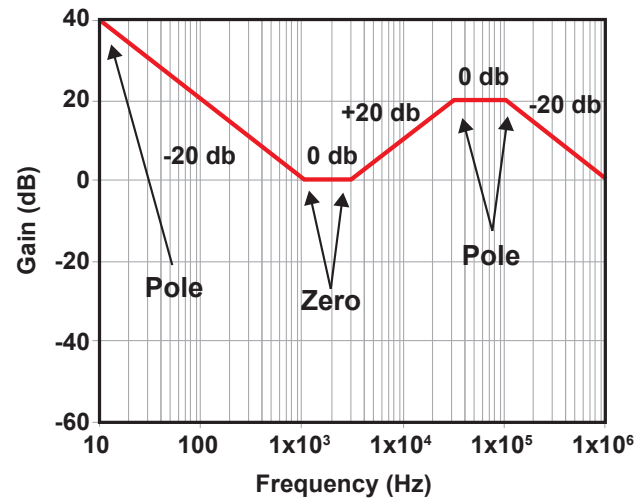


# Voltage Mode Control Loop Compensation

Power Stage + Modulation



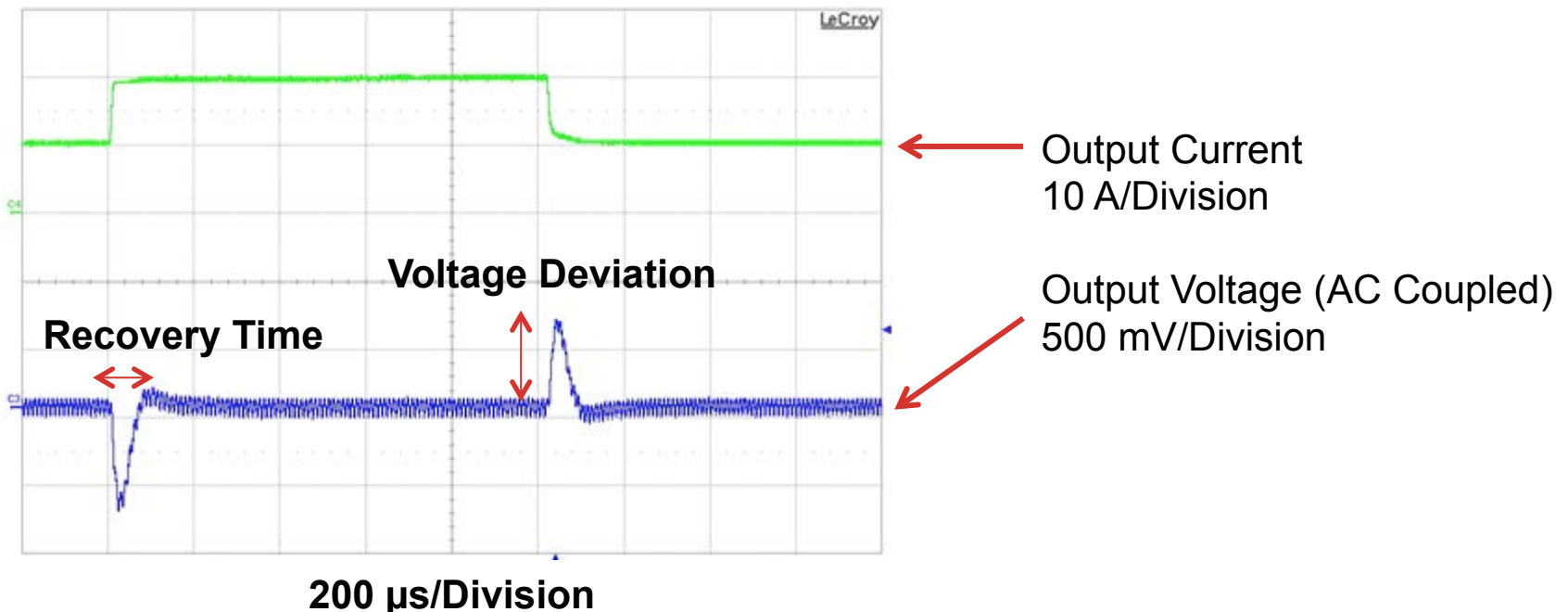
Type 3 Compensator



- Use double zero to cancel double pole
- Cross 0 dB with -20 dB/decade response
- Cross  $1/10^{\text{th}}$  to  $1/4^{\text{th}}$  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





# 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

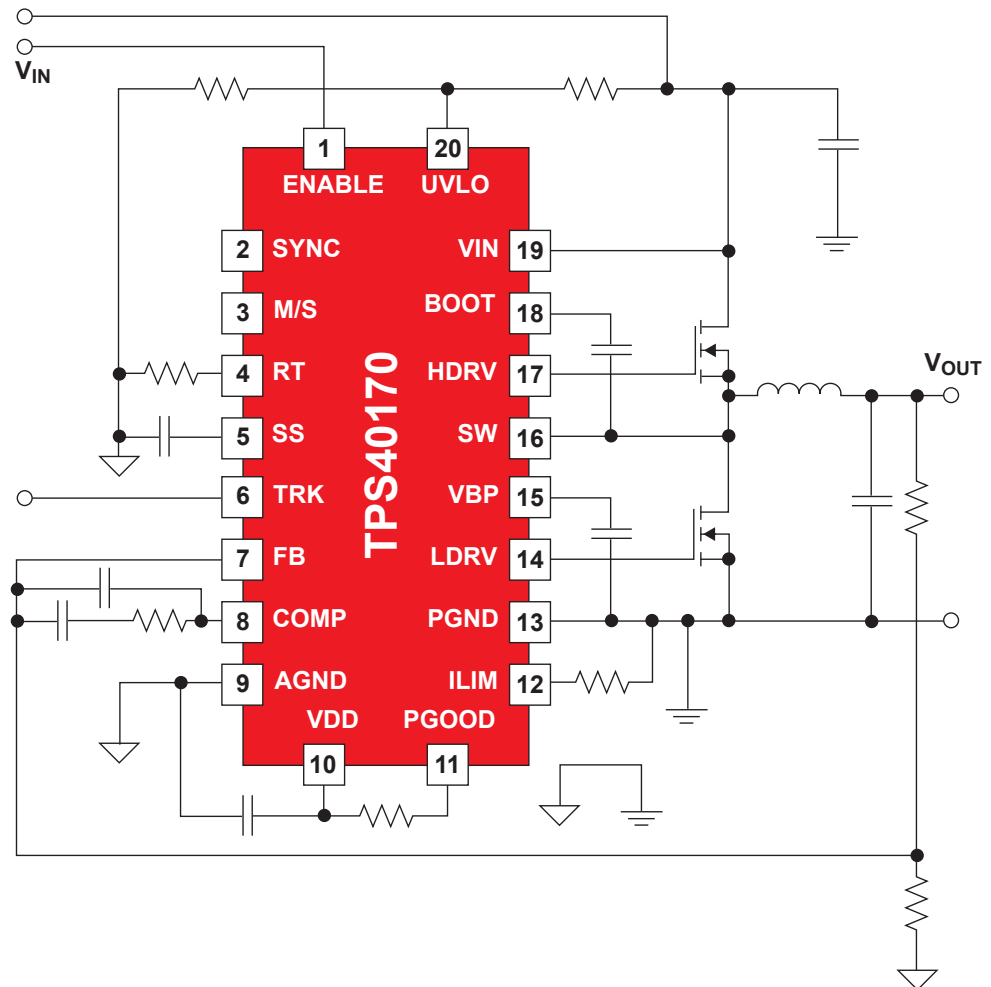
## Voltage Mode – Design Specifications

### 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)

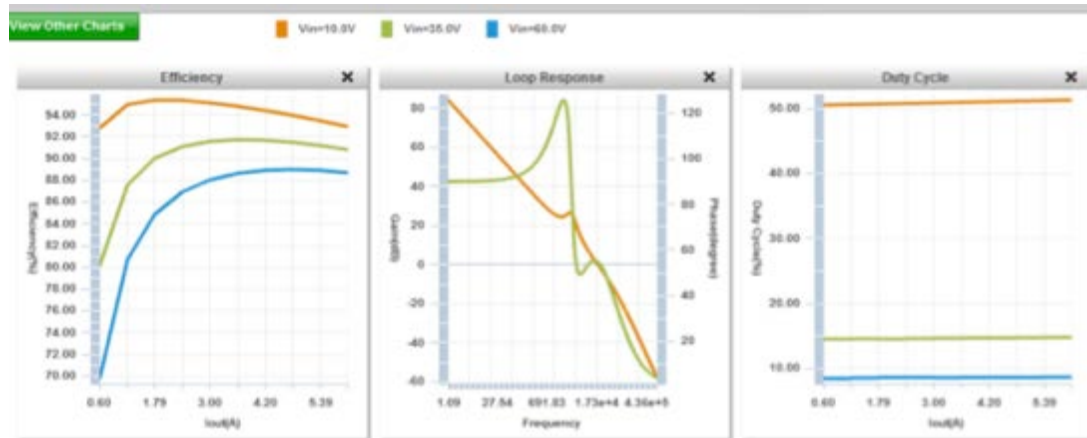
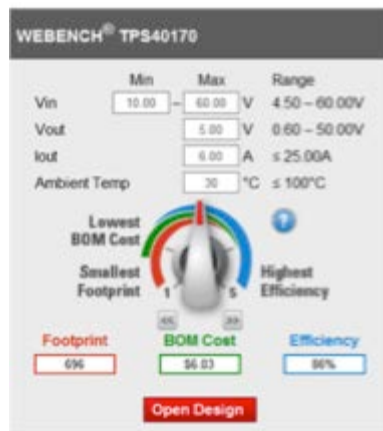
Minimum duty cycle	0.083
Minimum on-time	0.277 $\mu$ s
Maximum duty cycle	0.500
Maximum on-time	1.667 $\mu$ s



# Design Example #1

## Voltage Mode – Design Procedure

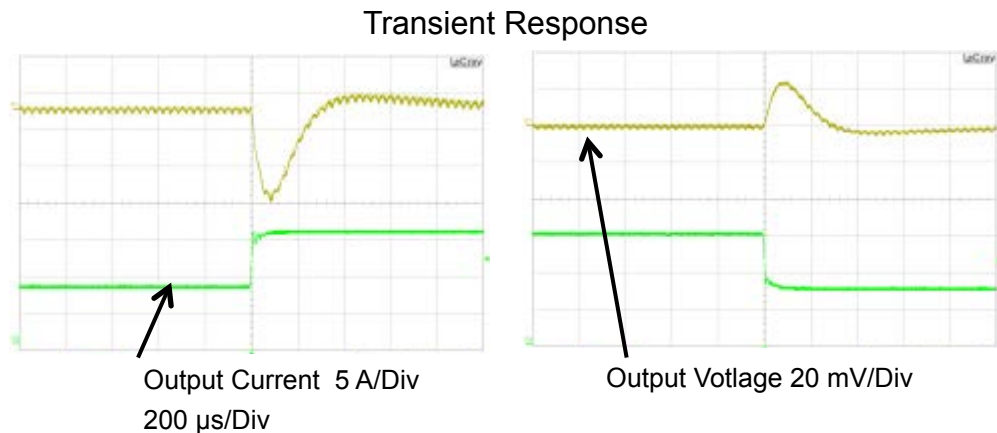
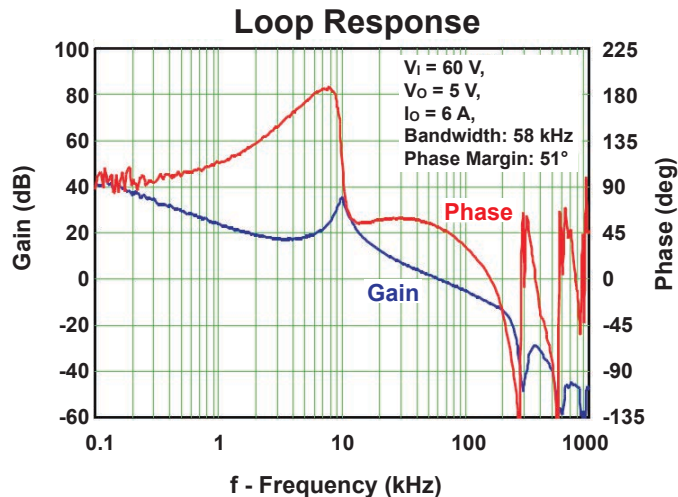
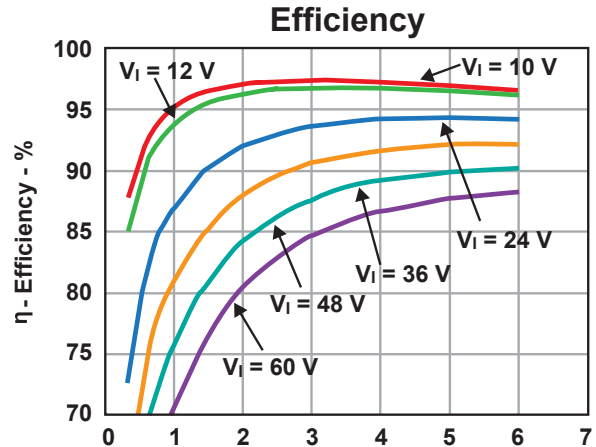
- Choose switching frequency first
- Calculate the output filter components (L and C)
- Calculate the power stage components (FETs)
- WEBENCH®
  - Helps calculate all of specific values for design
  - Allows optimization based on design goals
  - Gives estimates for loop response and efficiency
  - Provides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



# Design Example #1

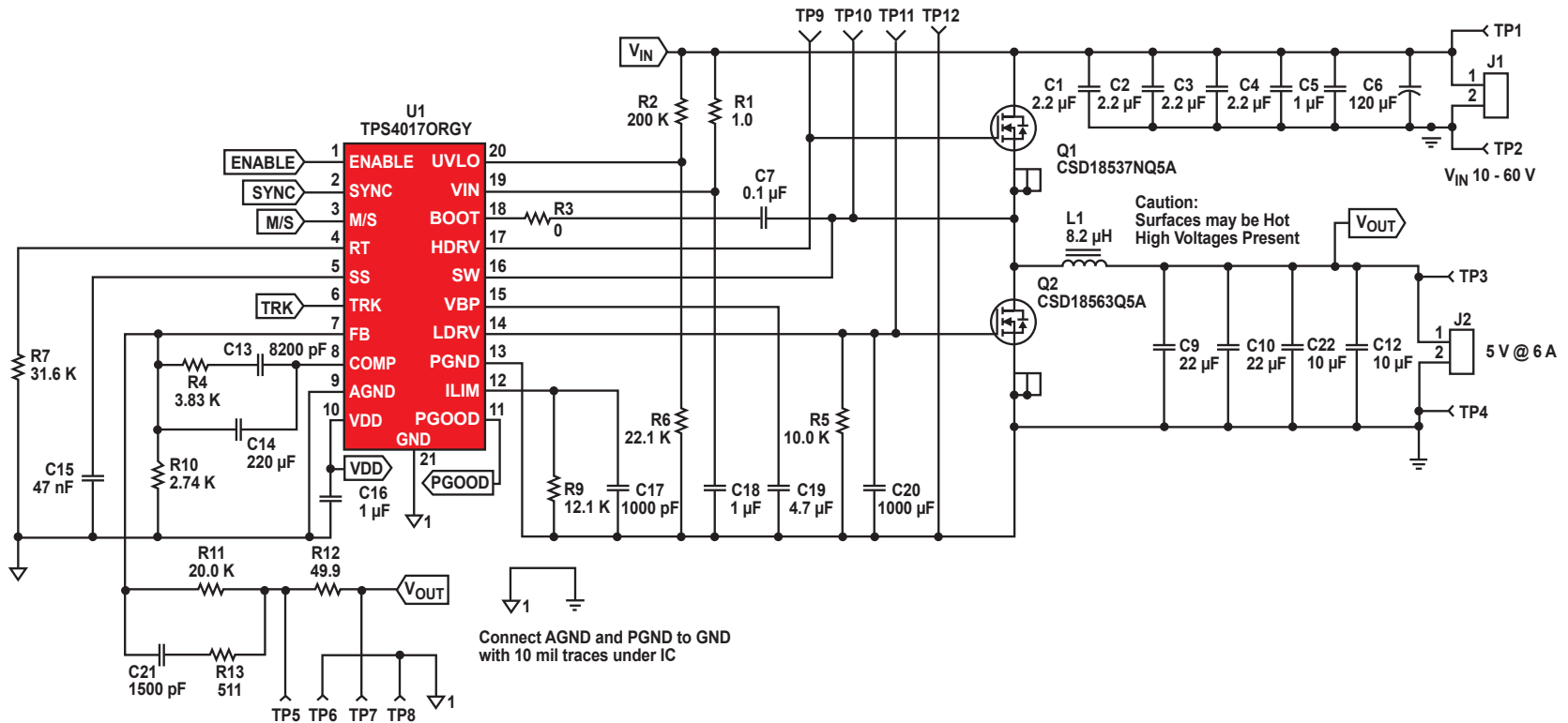
## Voltage Mode – Performance Graphs

Data is taken with TPS40170 EVM (HPA578)



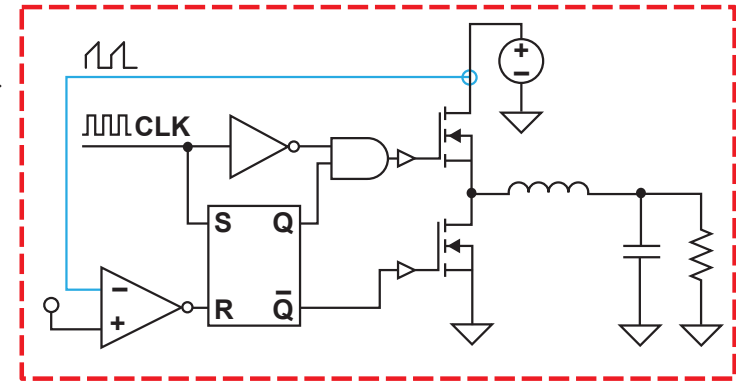
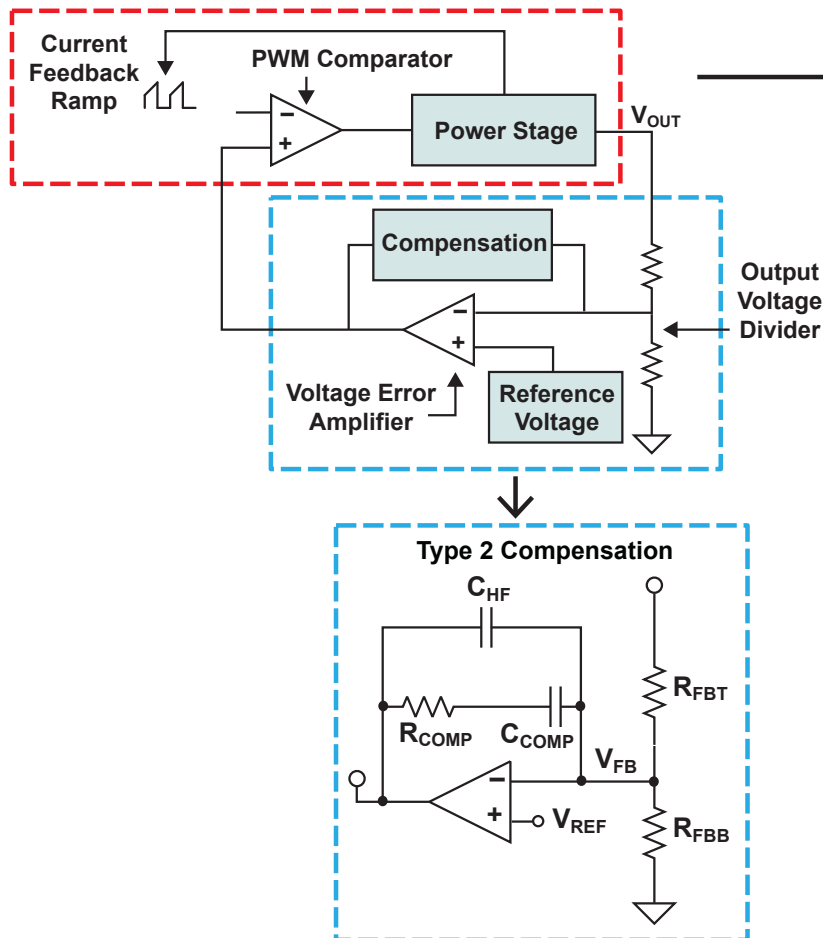
# Design Example #1

## Voltage Mode – Schematic (HPA578)

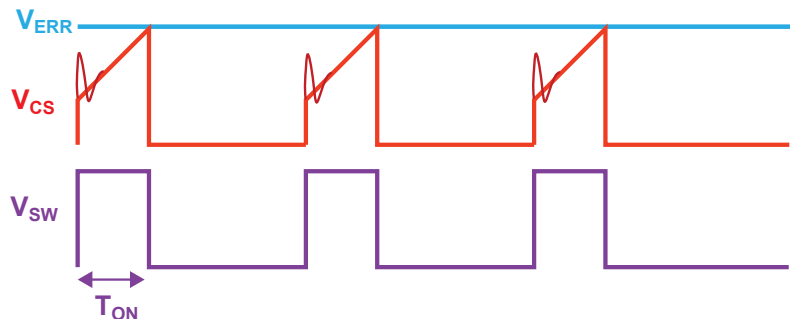


# Current Mode Control

## Basic Operation



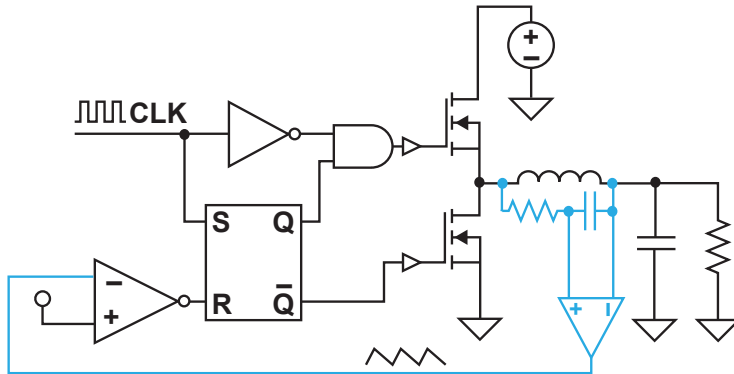
- Peak current mode is more popular than valley
- Outer voltage loop + inner current loop
- High-side / DCR current sensing
- Error amp output controls peak inductor current
- Allows current source to replace inductor



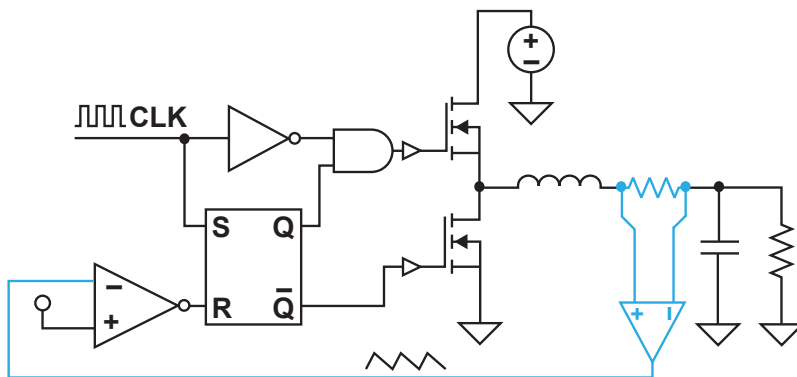
# Current Mode Control

## Other Considerations

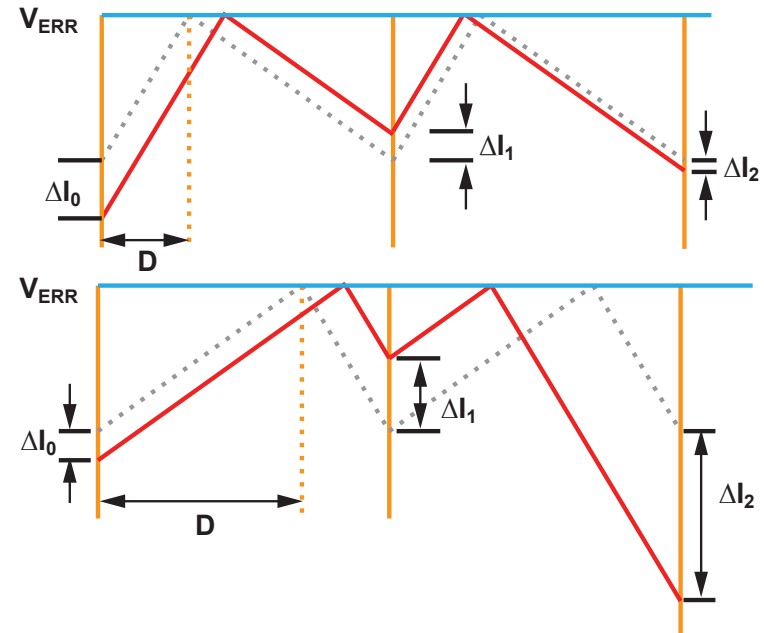
DCR Sensing



Resistor Sensing



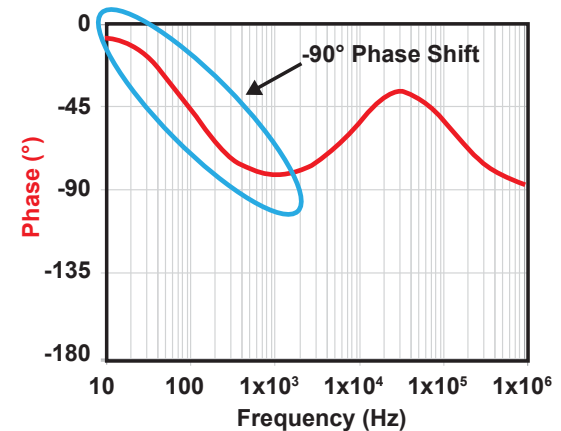
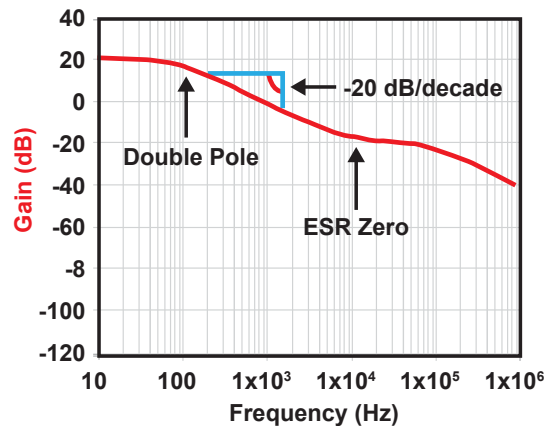
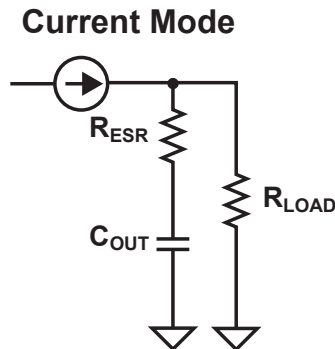
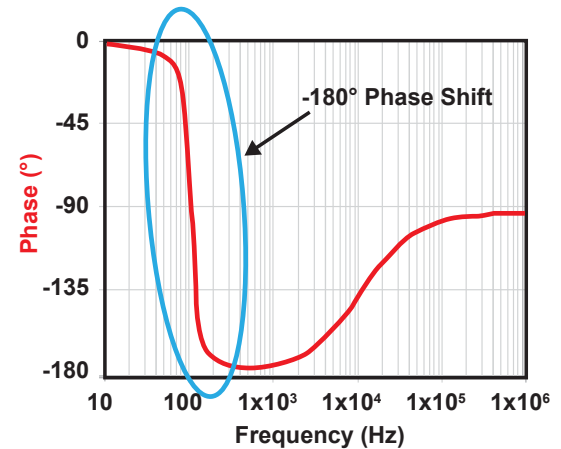
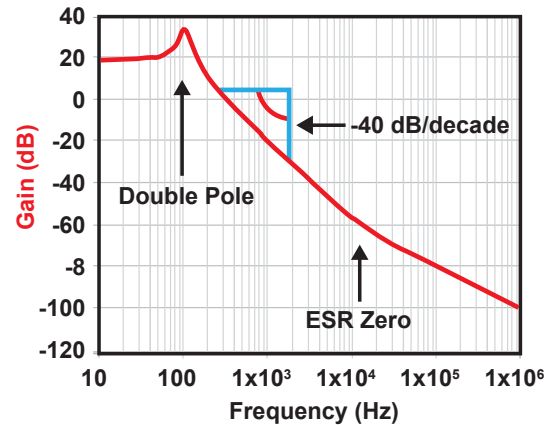
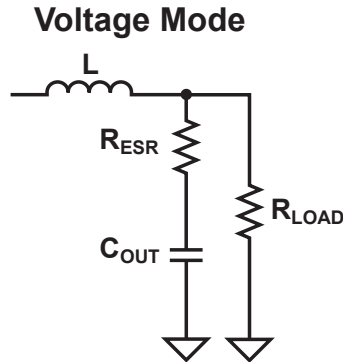
Sub-Harmonic Oscillation



- $\Delta I_0 > \Delta I_1 > \Delta I_2$  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

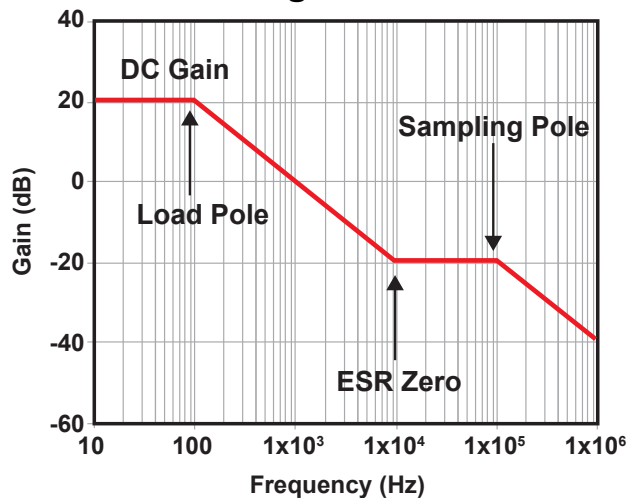
## Power Stage + Modulation





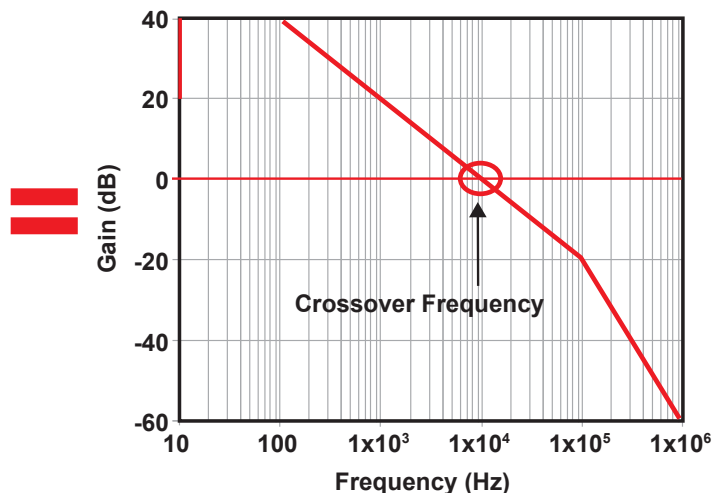
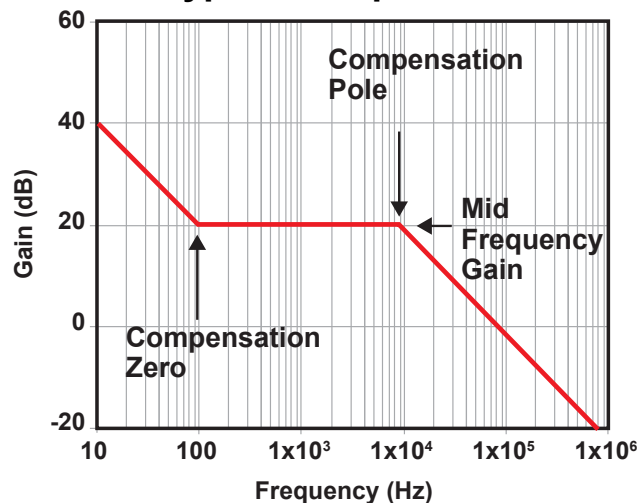
# Current Mode Control Loop Compensation

## Power Stage + Modulation



+

## Type 2 Compensator



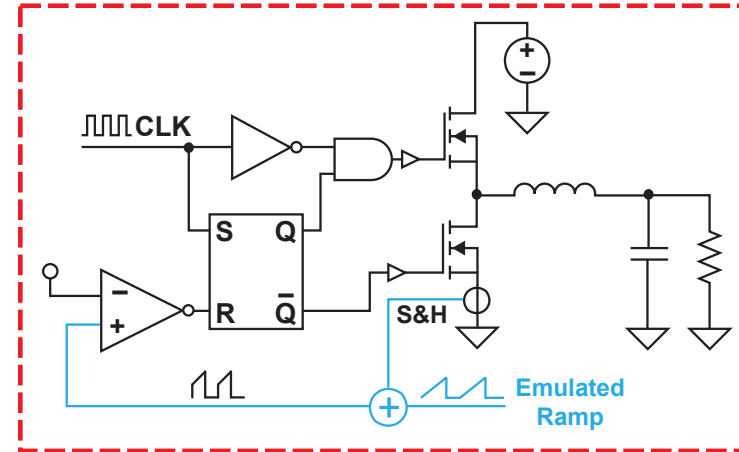
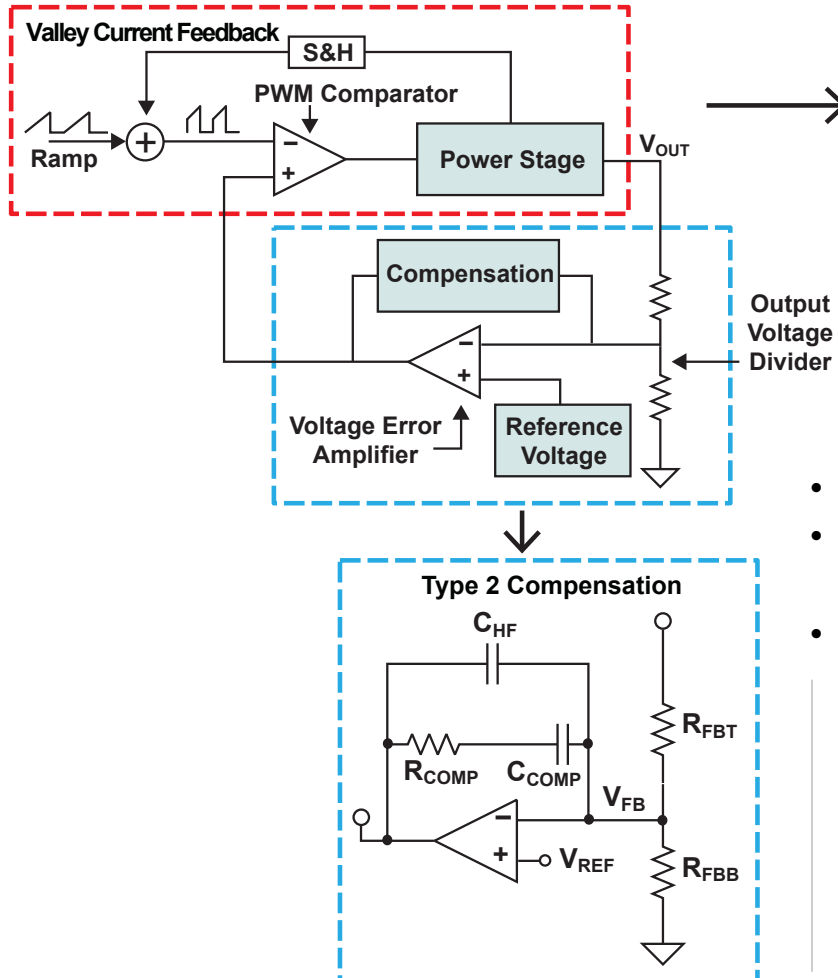
- Cancel load pole and ESR zero by placing error amplifier zero and pole
- Cross 0 dB with -20 dB/decade response

# Current Mode Control

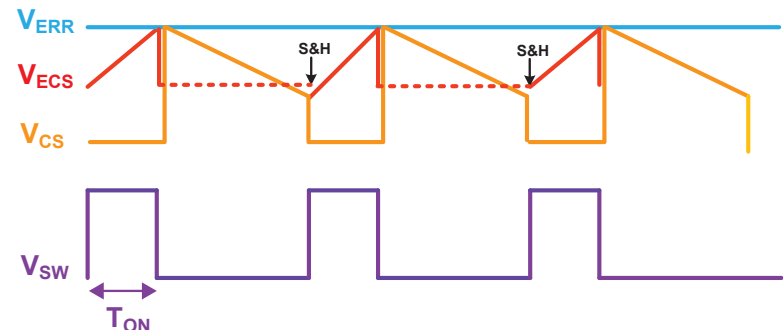
Advantages	Disadvantages
Single pole system allows simple Type 2 compensation	Need for slope compensation to eliminate sub-harmonic oscillation
Inherent feed forward improves line transient performance	Noise sensitivity at leading edge spike
Easy implementation of cycle-by-cycle current limit	Need for 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

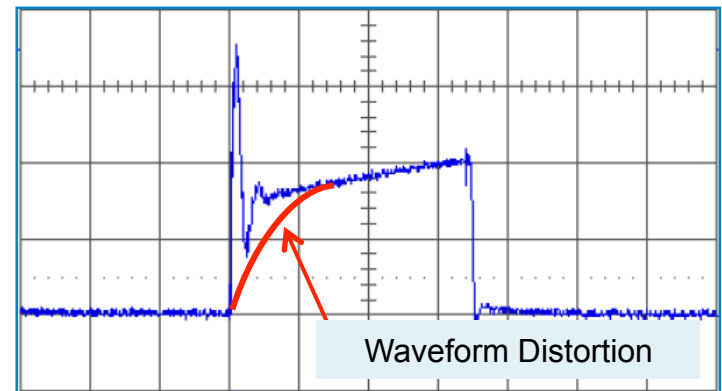


# Emulated Current Mode Control

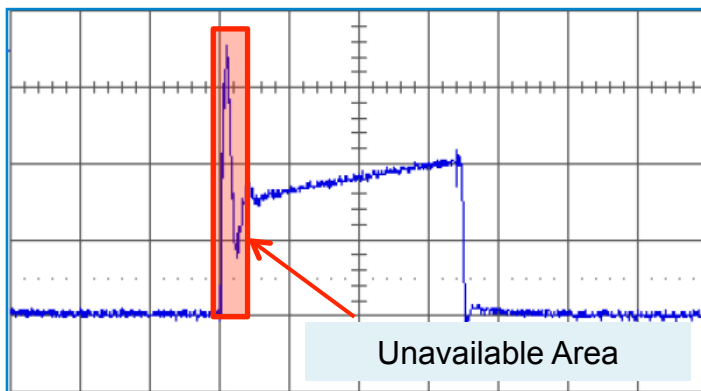
## Leading Edge Spike

- 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

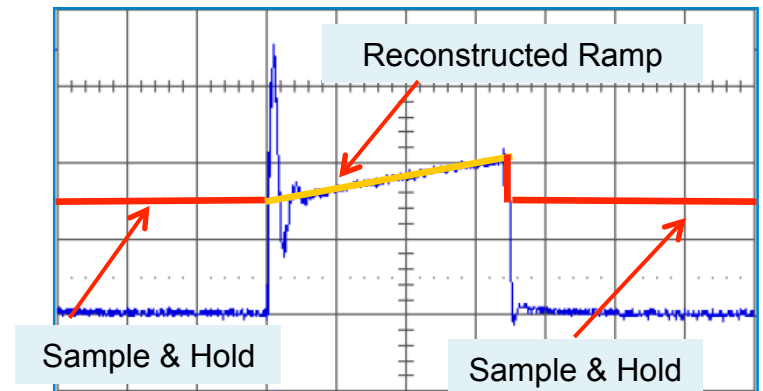
**R-C Filter**



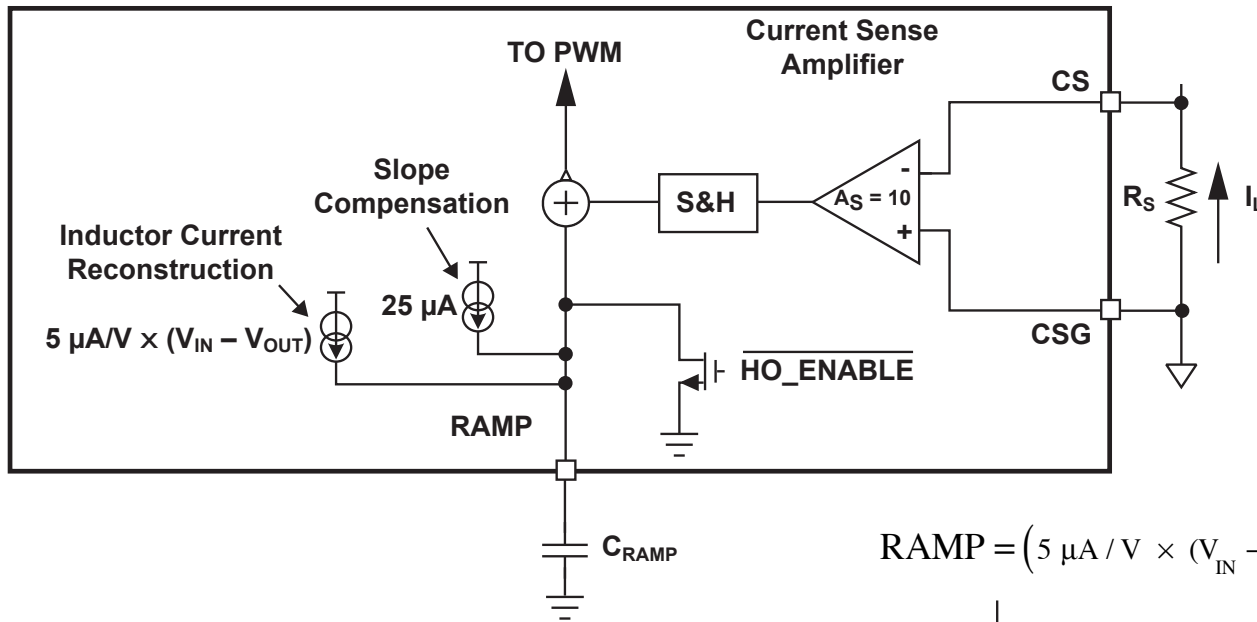
**Leading Edge Blanking**



**Emulated Current Mode**



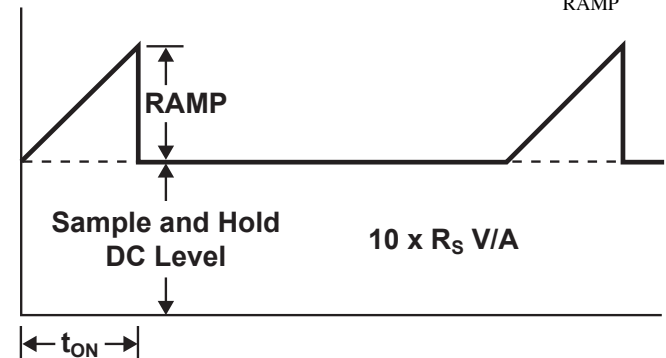
# Emulated Current Mode Control Ramp Reconstruction



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

- Proper selection of the RAMP capacitor ( $C_{\text{RAMP}}$ ) depends upon the value of the output inductor ( $L$ ) and the current sense resistor ( $R_S$ )

- $$R_S \times A_S = \frac{5 \mu \times L}{C_{\text{RAMP}}}$$



# 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	

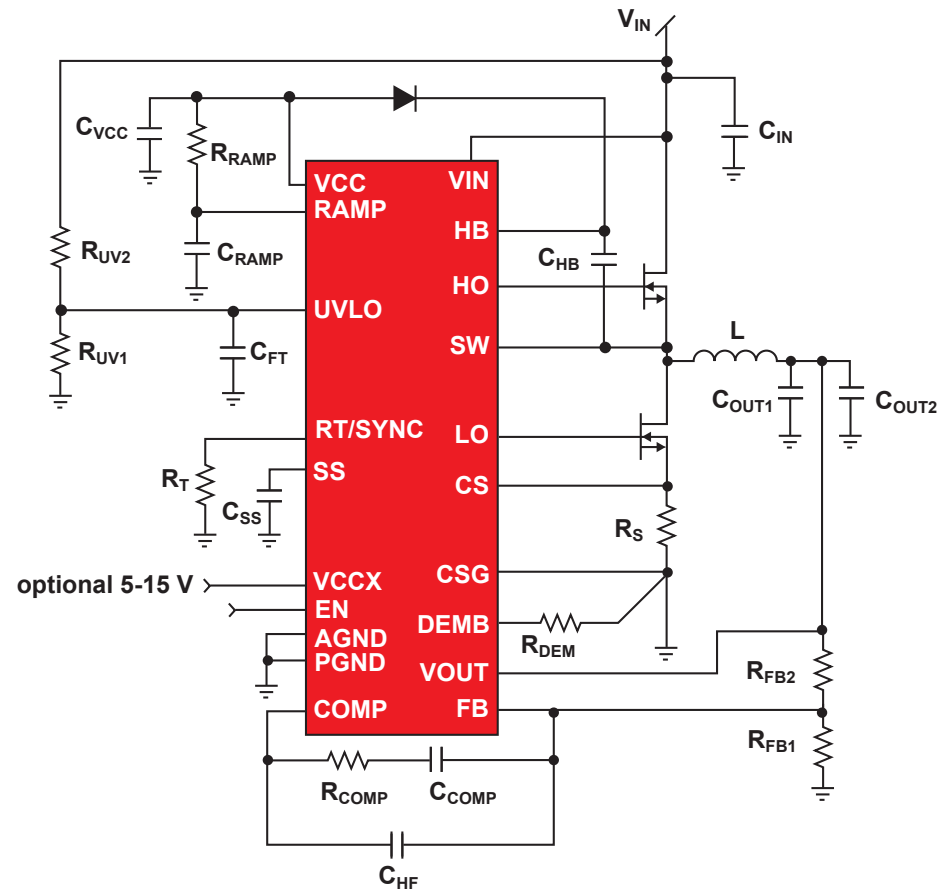
All advantages of peak current mode control remain

# Design Example #2

## Design Specifications

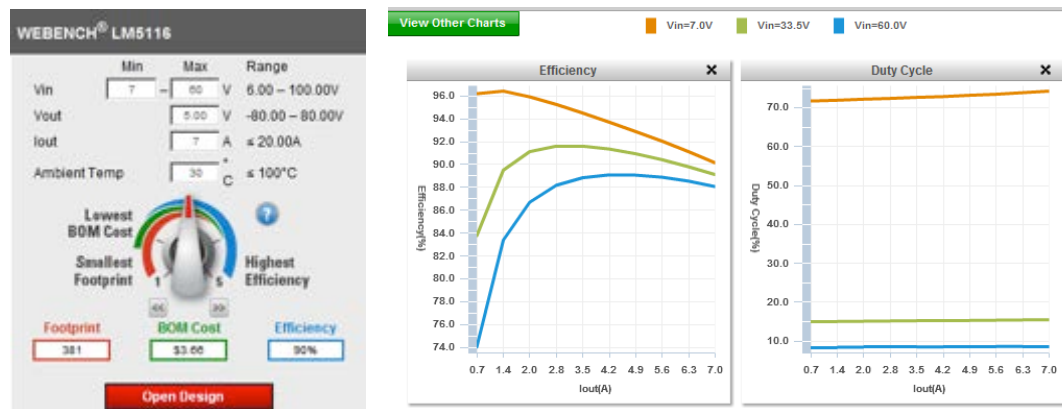
Design Specifications	
Input voltage range	7 V to 60 V
Target output voltage	5 V
Output current range	0 A to 7 A
Switching frequency	250 kHz
Controller	LM5116

Operating Values (Theoretical)	
Minimum duty cycle	0.083
Minimum on-time	0.333 $\mu$ s
Maximum duty cycle	0.714
Maximum on-time	2.857 $\mu$ s



# 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

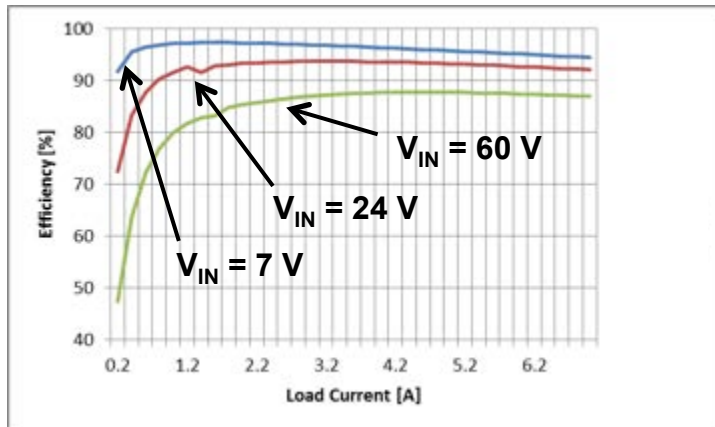




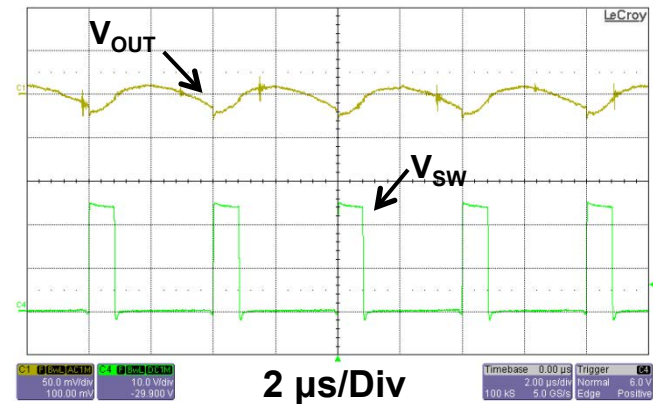
# Design Example #2 – Performance Graphs

Data is taken with LM5116EVM

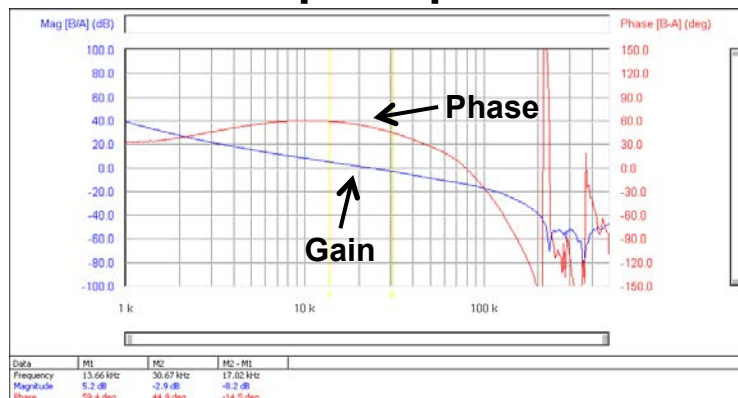
## Efficiency



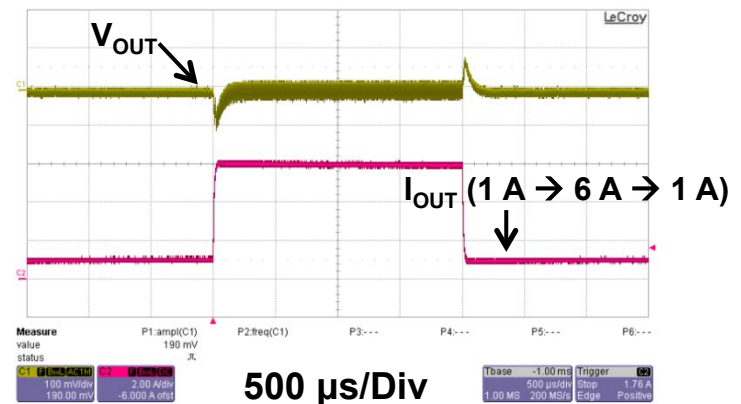
## Switching Operation



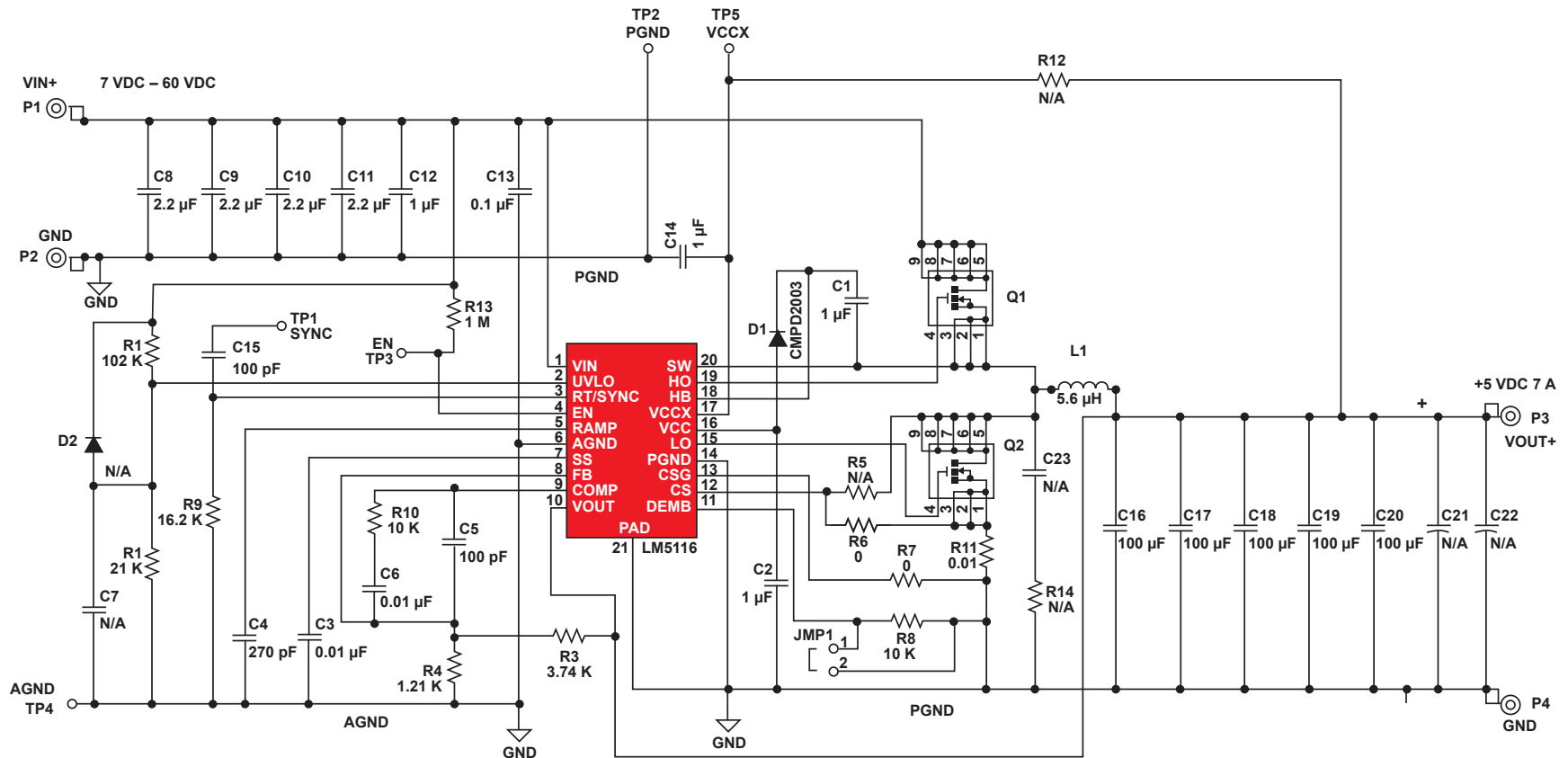
## Loop Response



## Transient Response



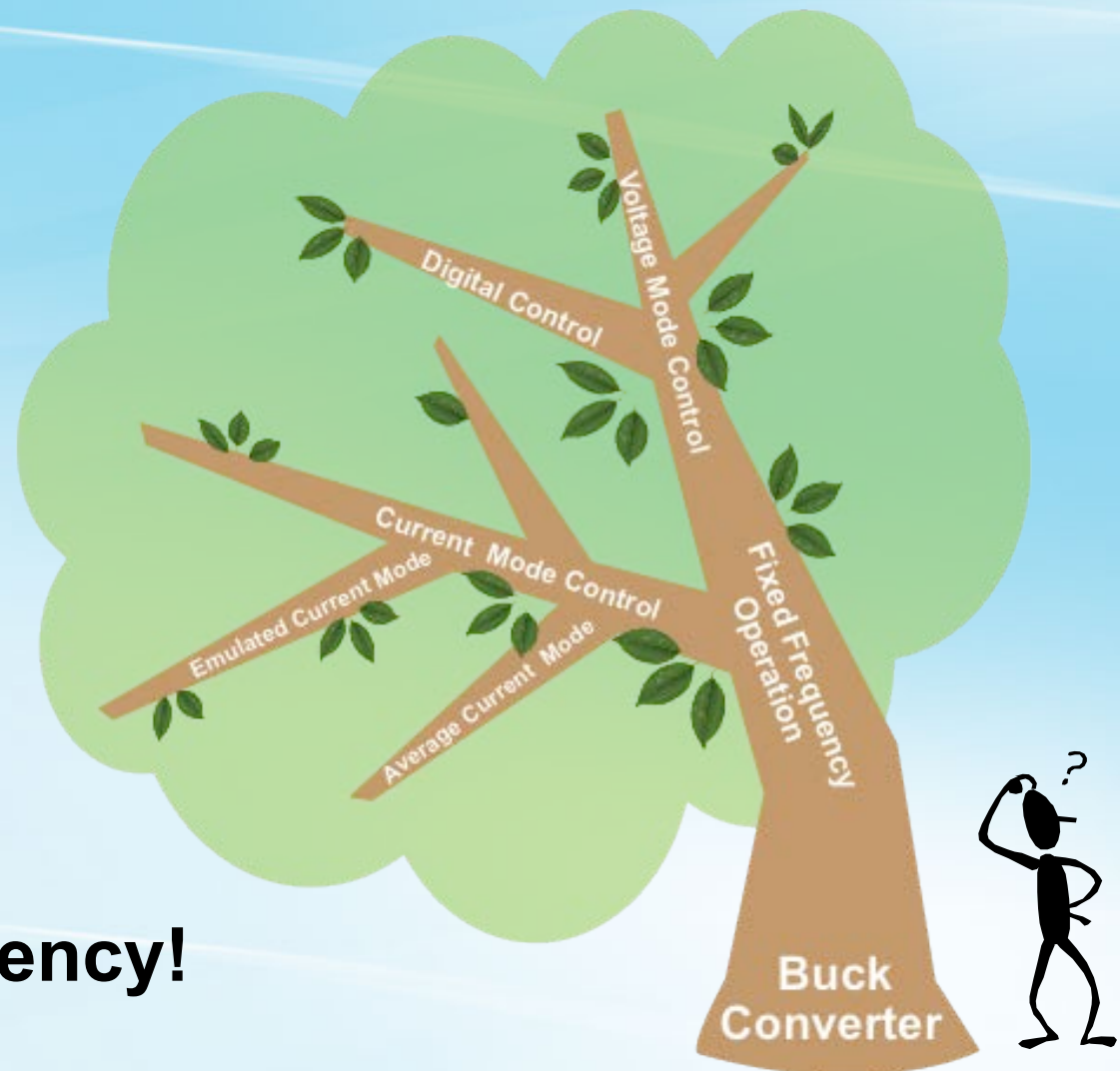
## Design Example #2 - Schematic



# Fixed Frequency Control

Questions?

Stay tuned for  
Variable Frequency!



## IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as "components") are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI's terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers' products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers' products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI's goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or "enhanced plastic" are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have **not** been so designated is solely at the Buyer's risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

### Products

Audio	<a href="http://www.ti.com/audio">www.ti.com/audio</a>
Amplifiers	<a href="http://amplifier.ti.com">amplifier.ti.com</a>
Data Converters	<a href="http://dataconverter.ti.com">dataconverter.ti.com</a>
DLP® Products	<a href="http://www.dlp.com">www.dlp.com</a>
DSP	<a href="http://dsp.ti.com">dsp.ti.com</a>
Clocks and Timers	<a href="http://www.ti.com/clocks">www.ti.com/clocks</a>
Interface	<a href="http://interface.ti.com">interface.ti.com</a>
Logic	<a href="http://logic.ti.com">logic.ti.com</a>
Power Mgmt	<a href="http://power.ti.com">power.ti.com</a>
Microcontrollers	<a href="http://microcontroller.ti.com">microcontroller.ti.com</a>
RFID	<a href="http://www.ti-rfid.com">www.ti-rfid.com</a>
OMAP Applications Processors	<a href="http://www.ti.com/omap">www.ti.com/omap</a>
Wireless Connectivity	<a href="http://www.ti.com/wirelessconnectivity">www.ti.com/wirelessconnectivity</a>

### Applications

Automotive and Transportation	<a href="http://www.ti.com/automotive">www.ti.com/automotive</a>
Communications and Telecom	<a href="http://www.ti.com/communications">www.ti.com/communications</a>
Computers and Peripherals	<a href="http://www.ti.com/computers">www.ti.com/computers</a>
Consumer Electronics	<a href="http://www.ti.com/consumer-apps">www.ti.com/consumer-apps</a>
Energy and Lighting	<a href="http://www.ti.com/energy">www.ti.com/energy</a>
Industrial	<a href="http://www.ti.com/industrial">www.ti.com/industrial</a>
Medical	<a href="http://www.ti.com/medical">www.ti.com/medical</a>
Security	<a href="http://www.ti.com/security">www.ti.com/security</a>
Space, Avionics and Defense	<a href="http://www.ti.com/space-avionics-defense">www.ti.com/space-avionics-defense</a>
Video and Imaging	<a href="http://www.ti.com/video">www.ti.com/video</a>

### TI E2E Community

[e2e.ti.com](http://e2e.ti.com)