Power Supply Design Seminar

Topic 1 Presentation:

# Choosing the Right Fixed Frequency Buck Regulator Control Strategy

Reproduced from
2014 Texas Instruments Power
Supply Design Seminar SEM2100,
Topic 1
TI Literature Number: SLUP318



Power Seminar topics and online power training
modules are available at:
ti.com/psds

Texas Instruments

# Choosing the Right Fixed Frequency Buck Regulator Control Strategy

Brian Cheng
Eric Lee
Brian Lynch
Robert Taylor

# How Do You Choose?

## Part A

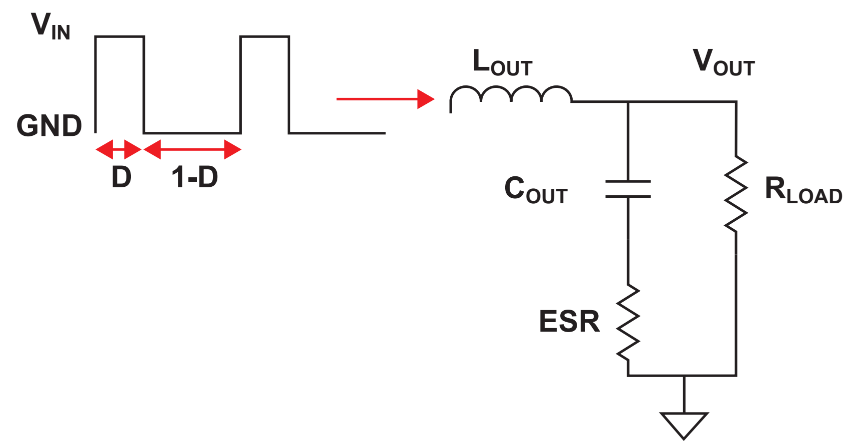
- Buck regulator basics
  - Basic functions
  - Filter design
  - Fixed frequency vs. variable
- Fixed frequency control
  - Voltage mode control
  - Current mode control
  - Emulated current mode control

## Part B

- Variable frequency control

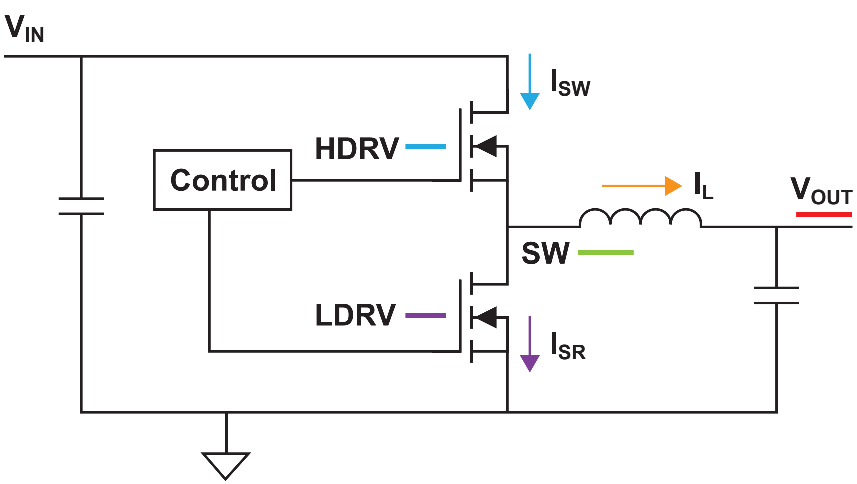
# Buck Regulator

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




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

Pretty simple – right?



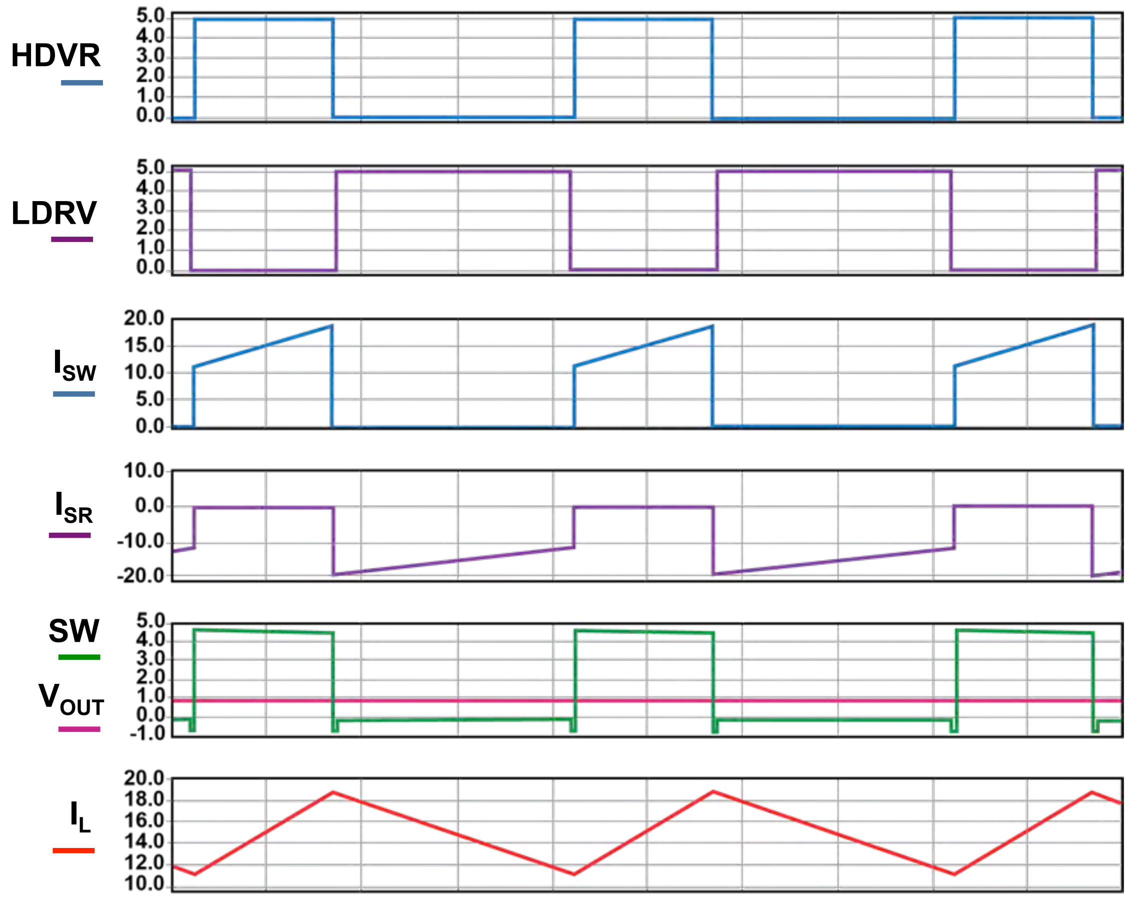
# Synchronous Buck Waveforms

## Continuous Conduction Mode

- Inductor current flow is continuous during the switching cycle

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

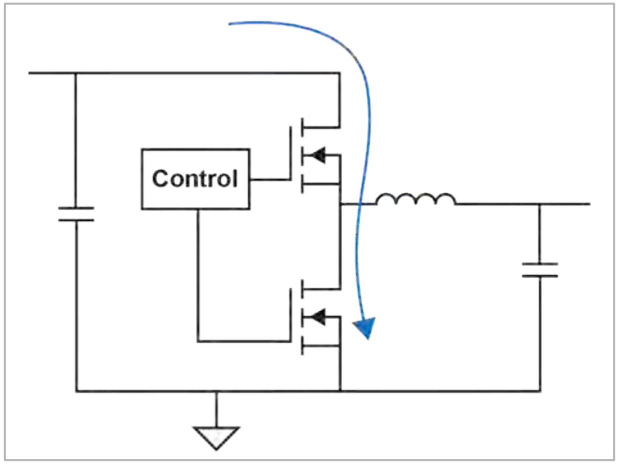
$$\text{Duty Cycle}_{CCM} = \frac{t_{ON}}{T_S}$$

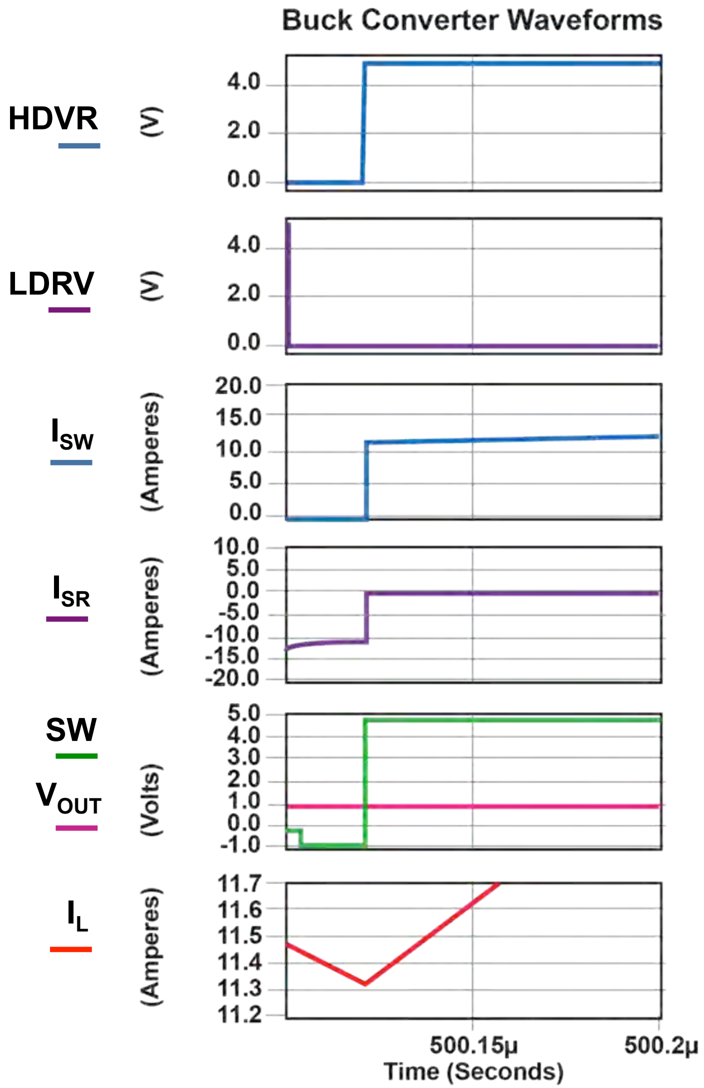


# Synchronous Buck Waveforms

**C**ontinuous
**C**onduction
**M**ode

Switch turn ON

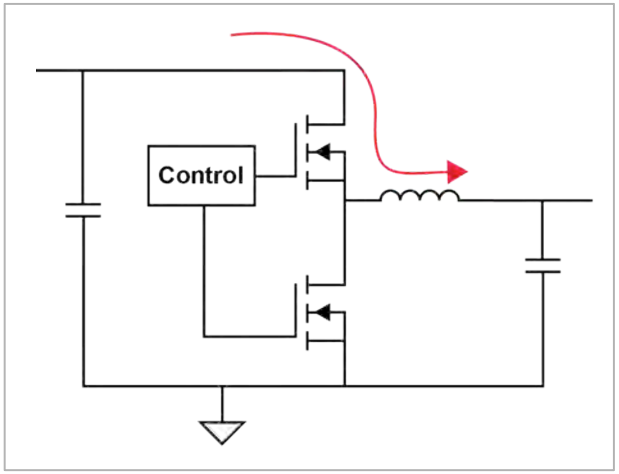


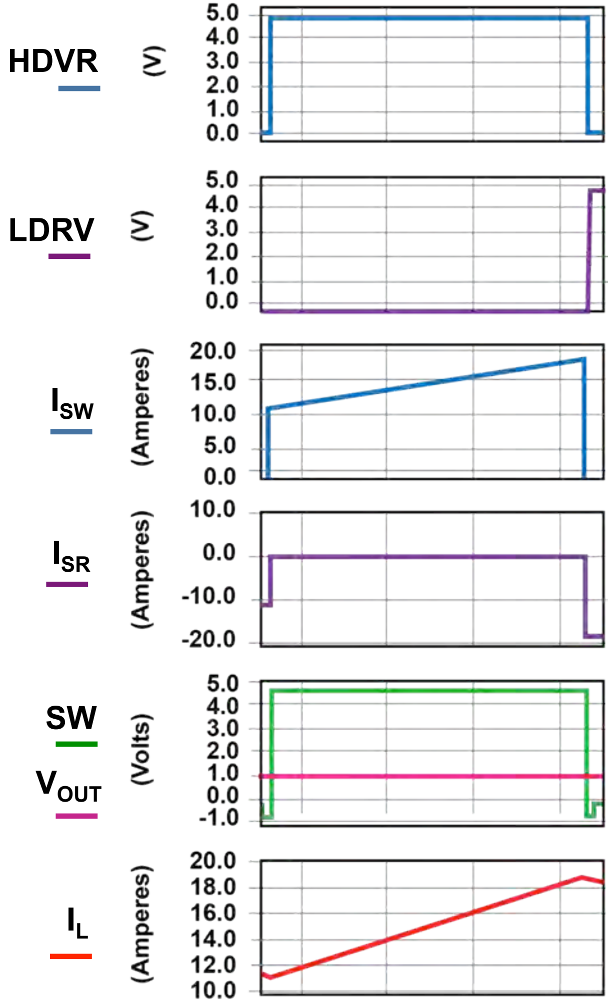



# Synchronous Buck Waveforms

**C**ontinuous
**C**onduction
**M**ode

Power transfer

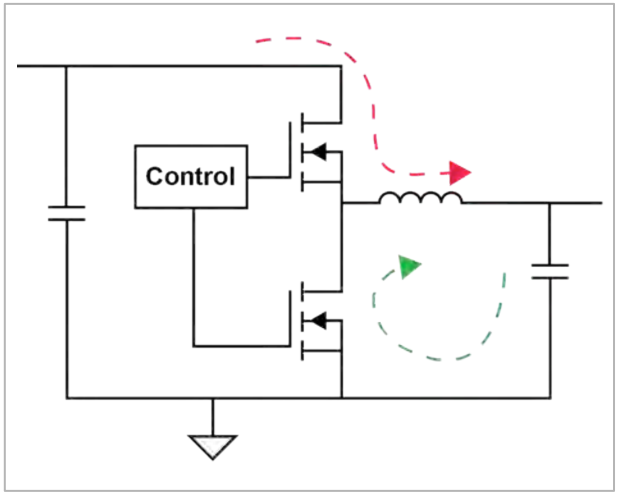


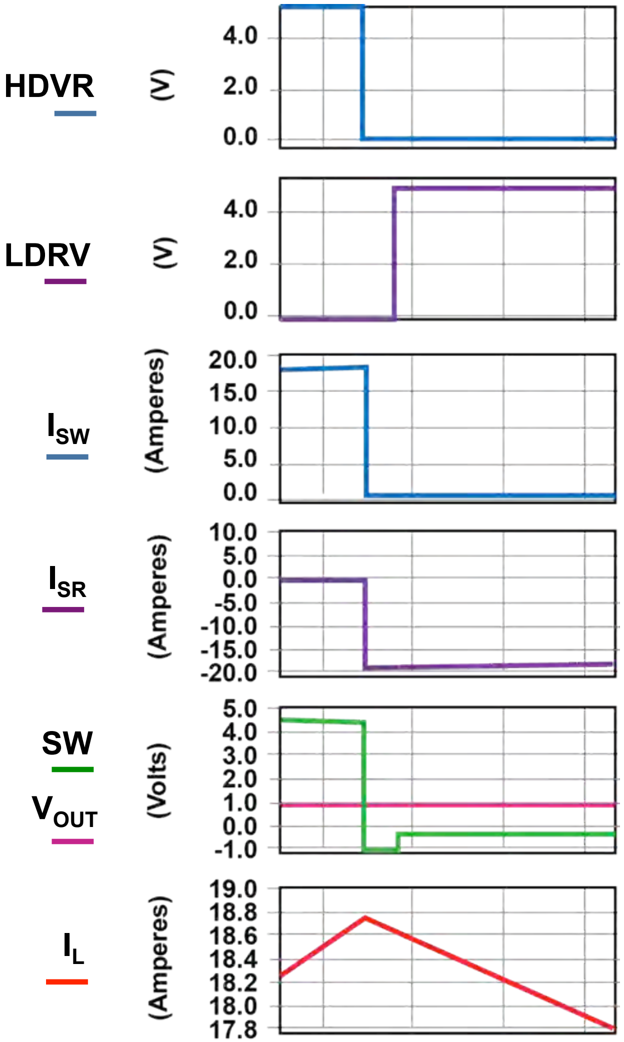



# Synchronous Buck Waveforms

**C**ontinuous
**C**onduction
**M**ode

Switch turn OFF transition to SR turn ON

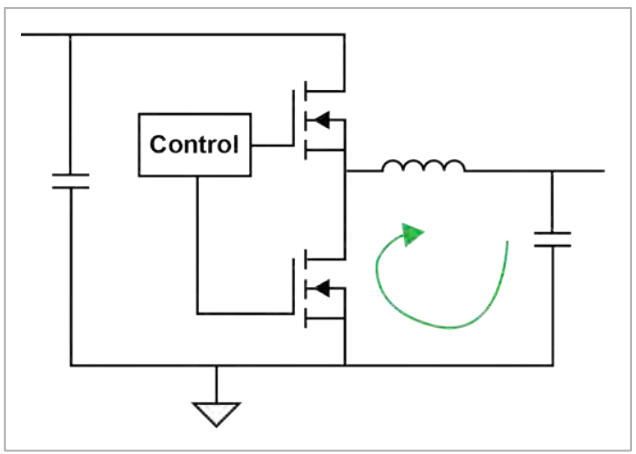


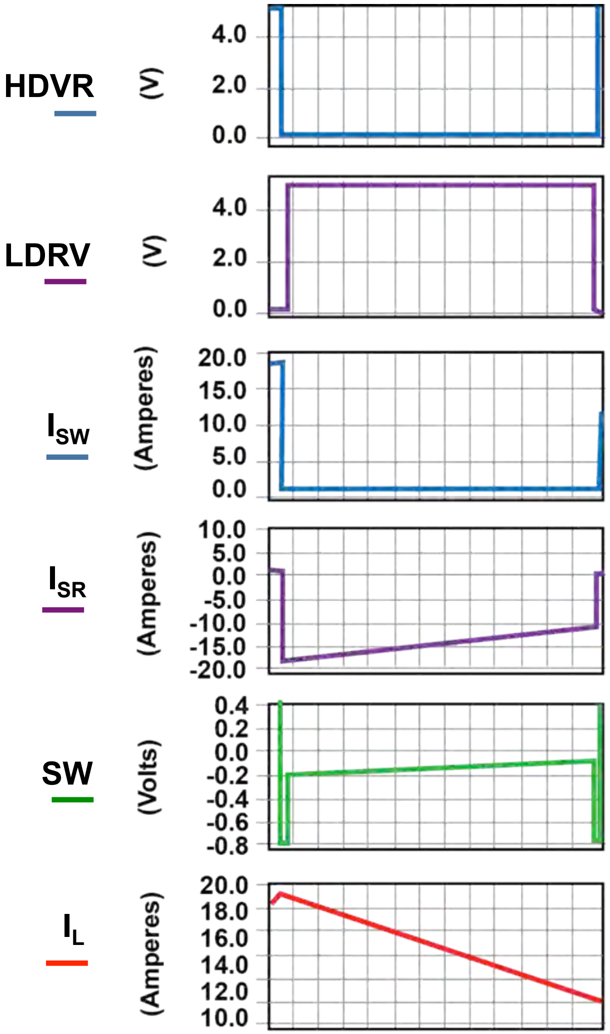



# Synchronous Buck Waveforms

**C**ontinuous
**C**onduction
**M**ode

Inductor reset

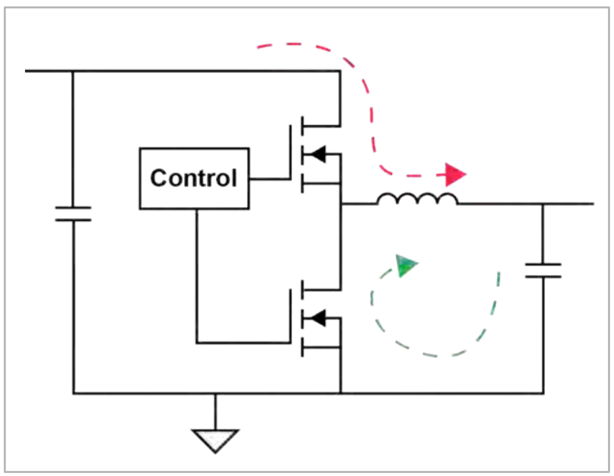


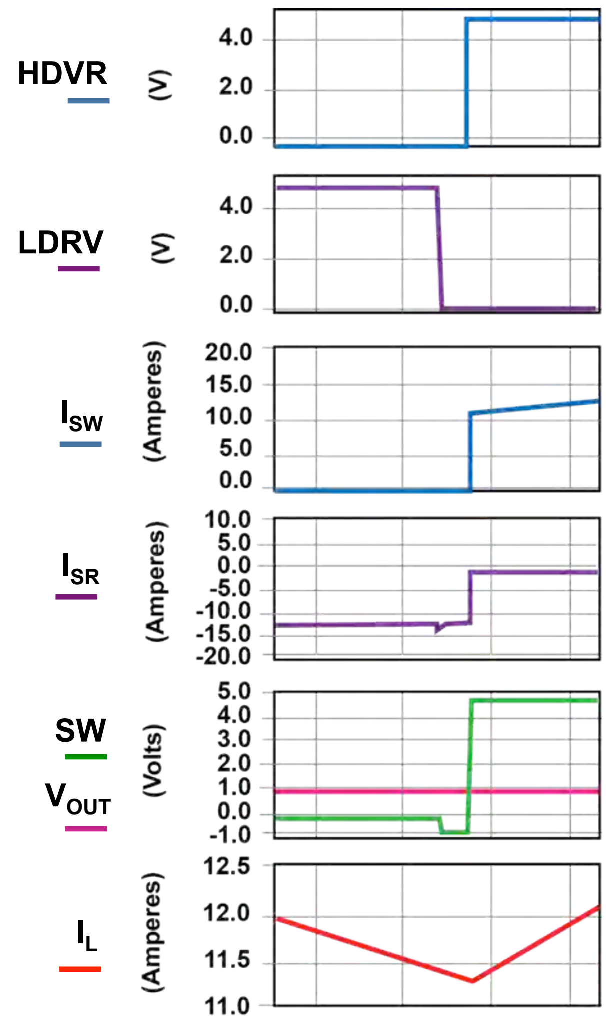



# Synchronous Buck Waveforms

**C**ontinuous
**C**onduction
**M**ode

Transition for next cycle



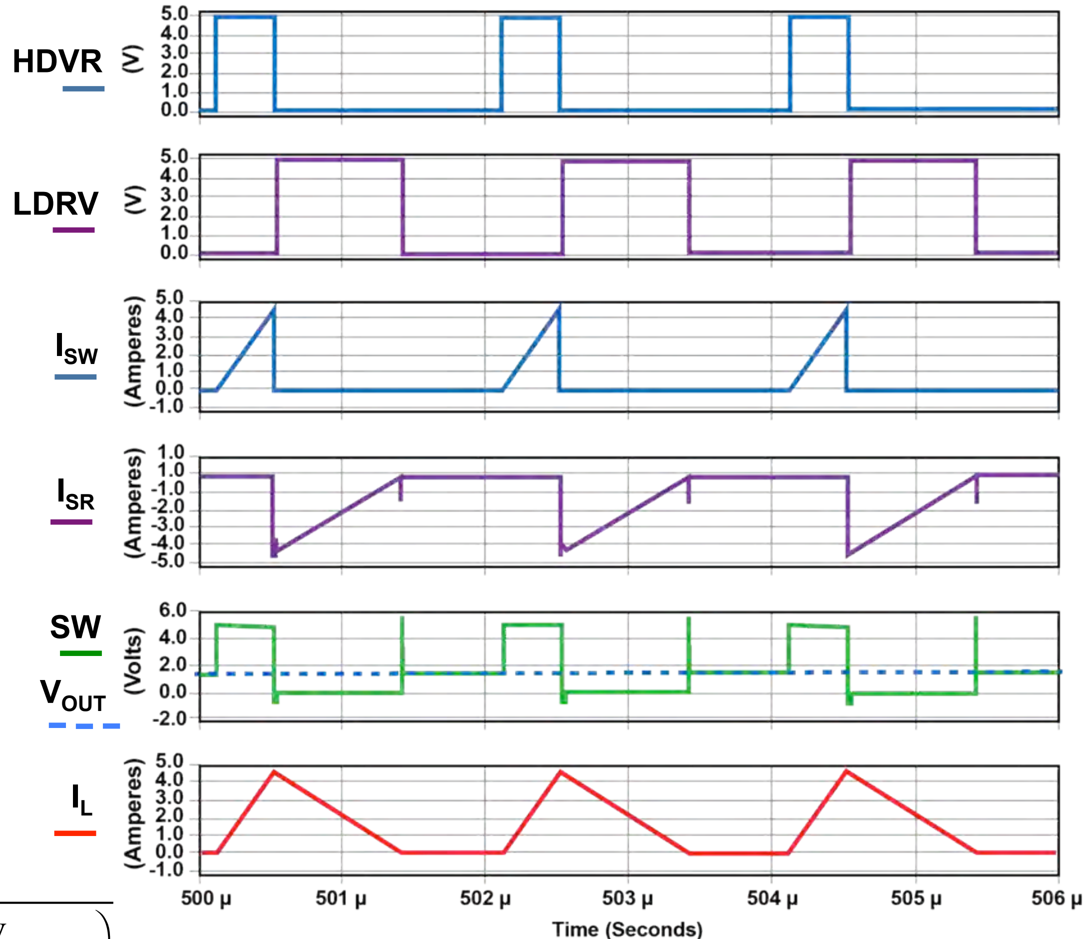
# Synchronous Buck Waveforms

**D**iscontinuous
**C**onduction
**M**ode

- Inductor current flow is discontinuous during the switching cycle

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

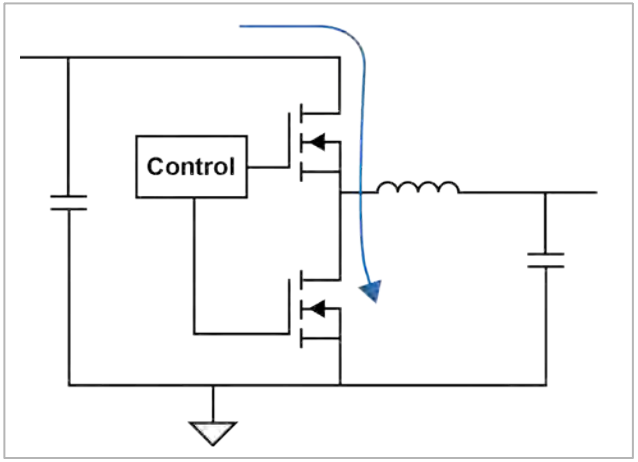
$$\text{Duty Cycle}_{DCM} = \sqrt{\frac{2 \times L \times I_{OUT}}{T_S \times V_{IN}} \times \left(\frac{V_{OUT}}{V_{IN} - V_{OUT}}\right)}$$

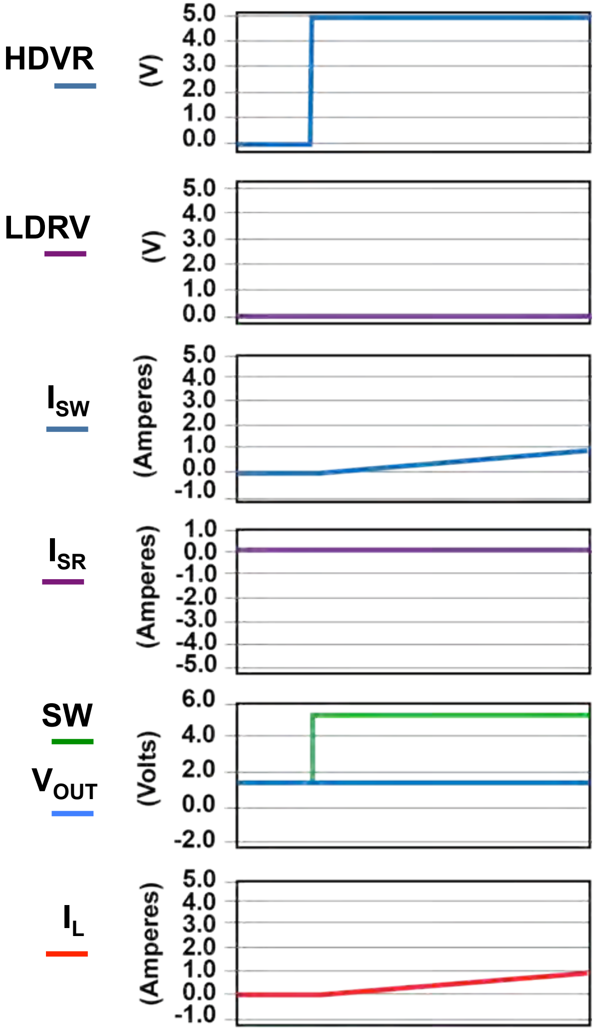


# Synchronous Buck Waveforms

**D**iscontinuous
**C**onduction
**M**ode

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

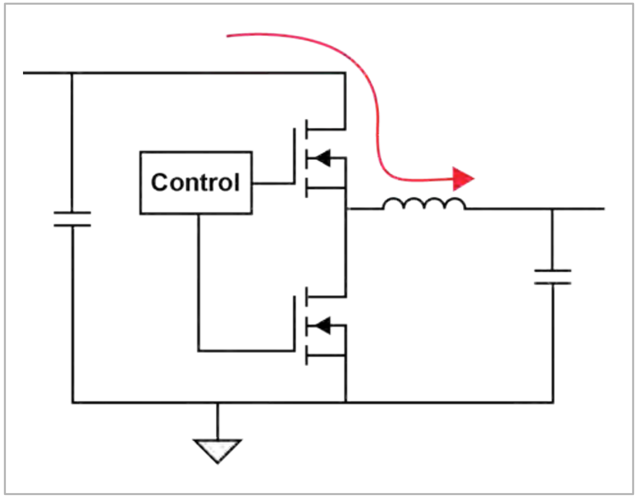


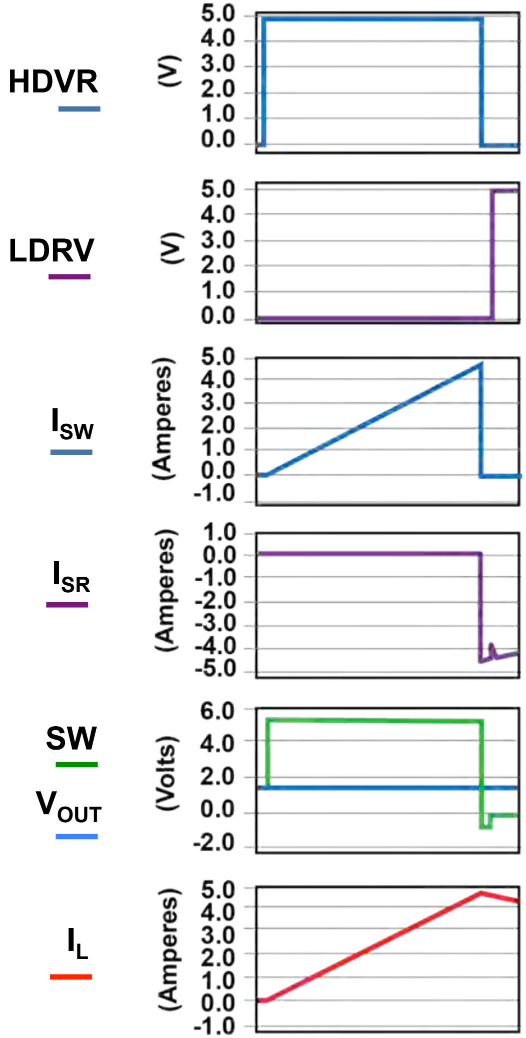



# Synchronous Buck Waveforms

**D**iscontinuous
**C**onduction
**M**ode

Switch ON

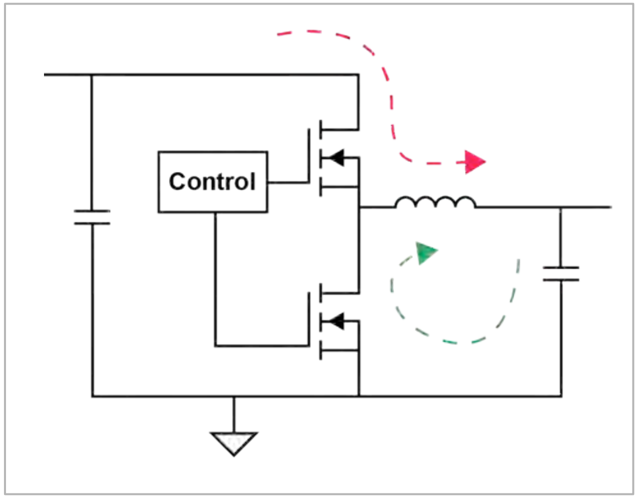


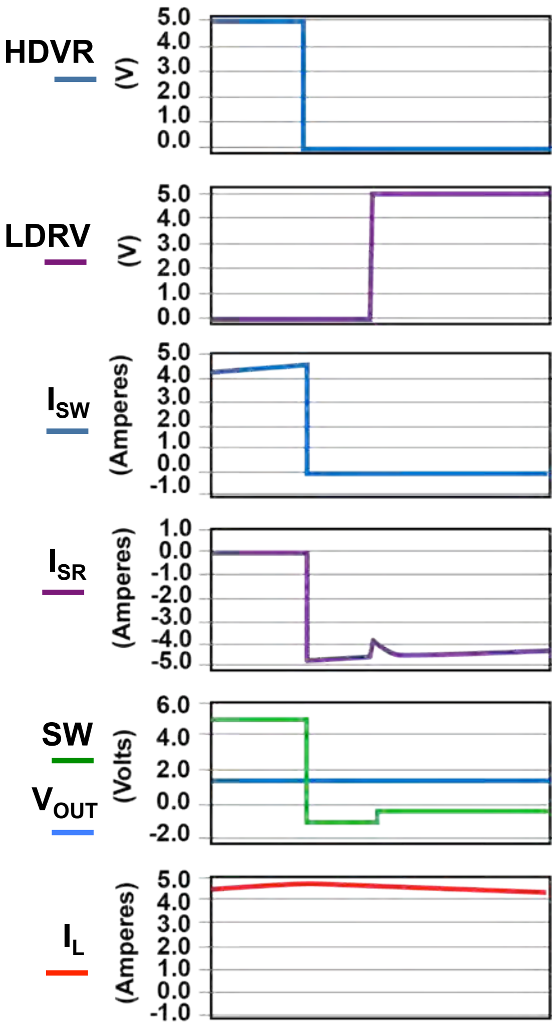



# Synchronous Buck Waveforms

**D**iscontinuous
**C**onduction
**M**ode

- Switch turn OFF
- SR turn ON

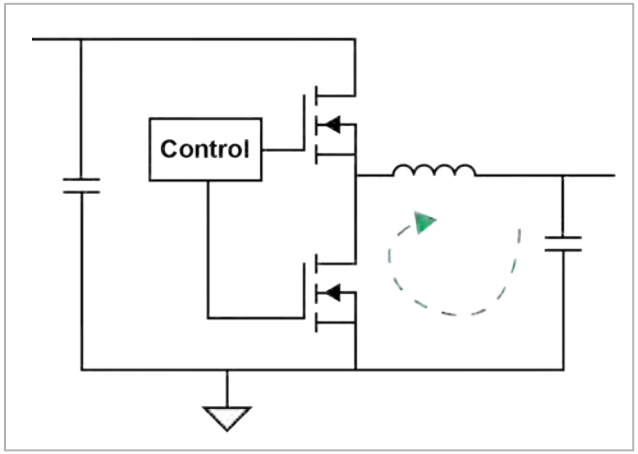


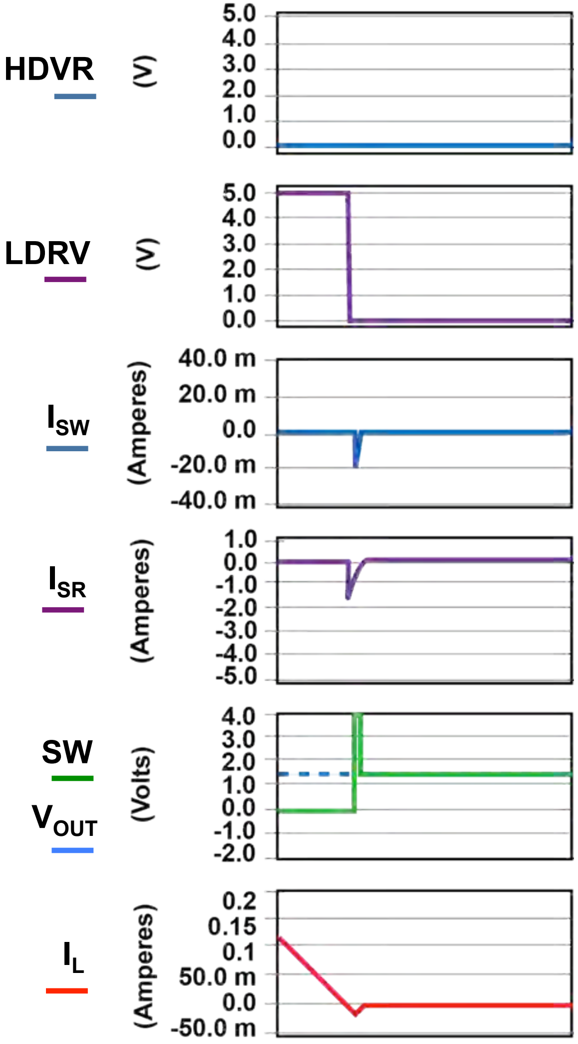



# Synchronous Buck Waveforms

**D**iscontinuous
**C**onduction
**M**ode

- SR turns OFF at zero current in inductor

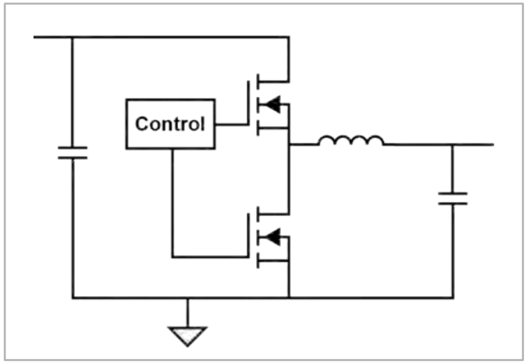


# Synchronous Buck Waveforms

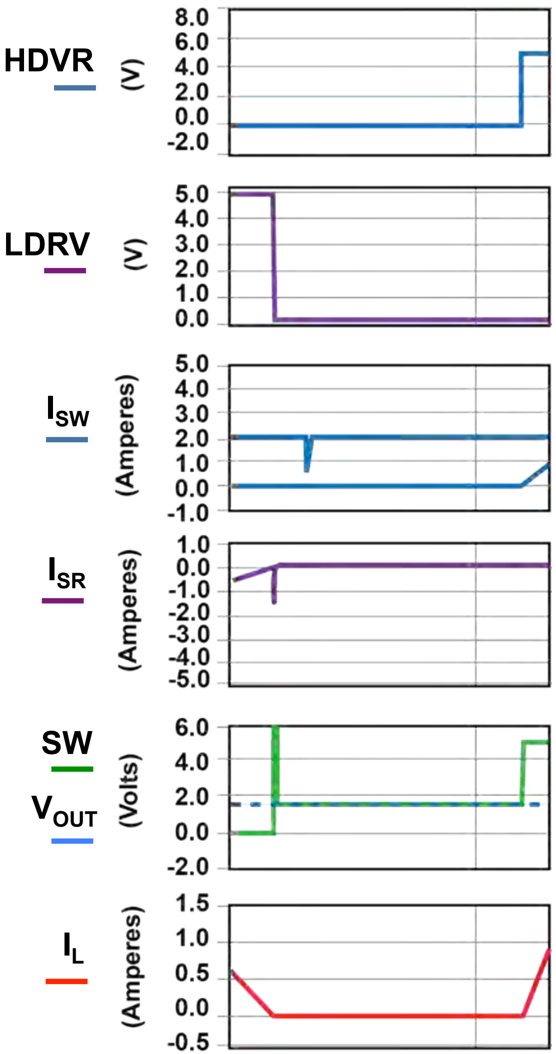
**D**iscontinuous
**C**onduction
**M**ode

- Freewheeling interval



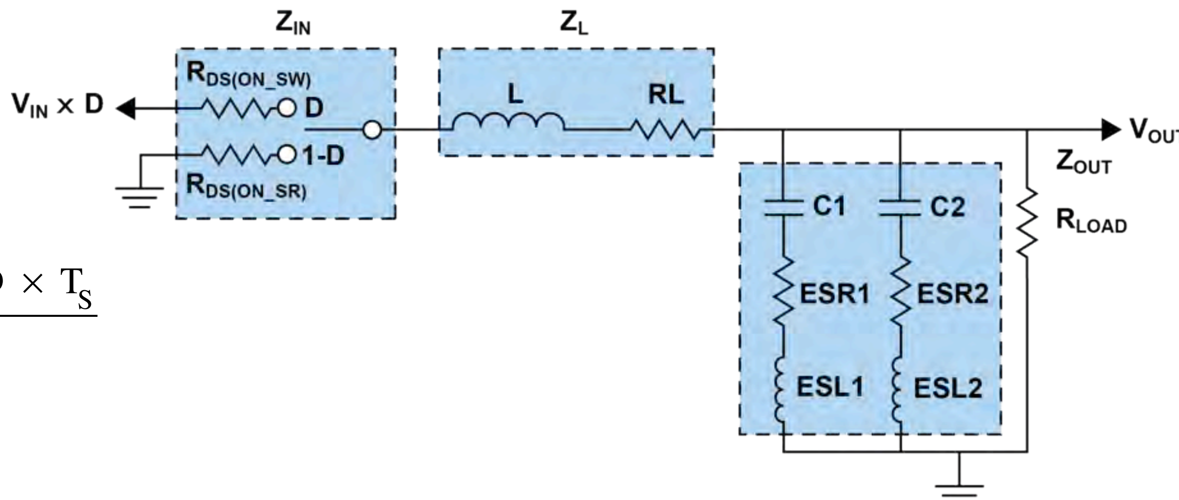

$$\text{Duty Cycle}_{DCM} = \frac{t_{ON}}{t_{ON} + t_{OFF} + t_{dead}}$$

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



# L-C Filter Design

- Inductor design for ripple current




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

- 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**

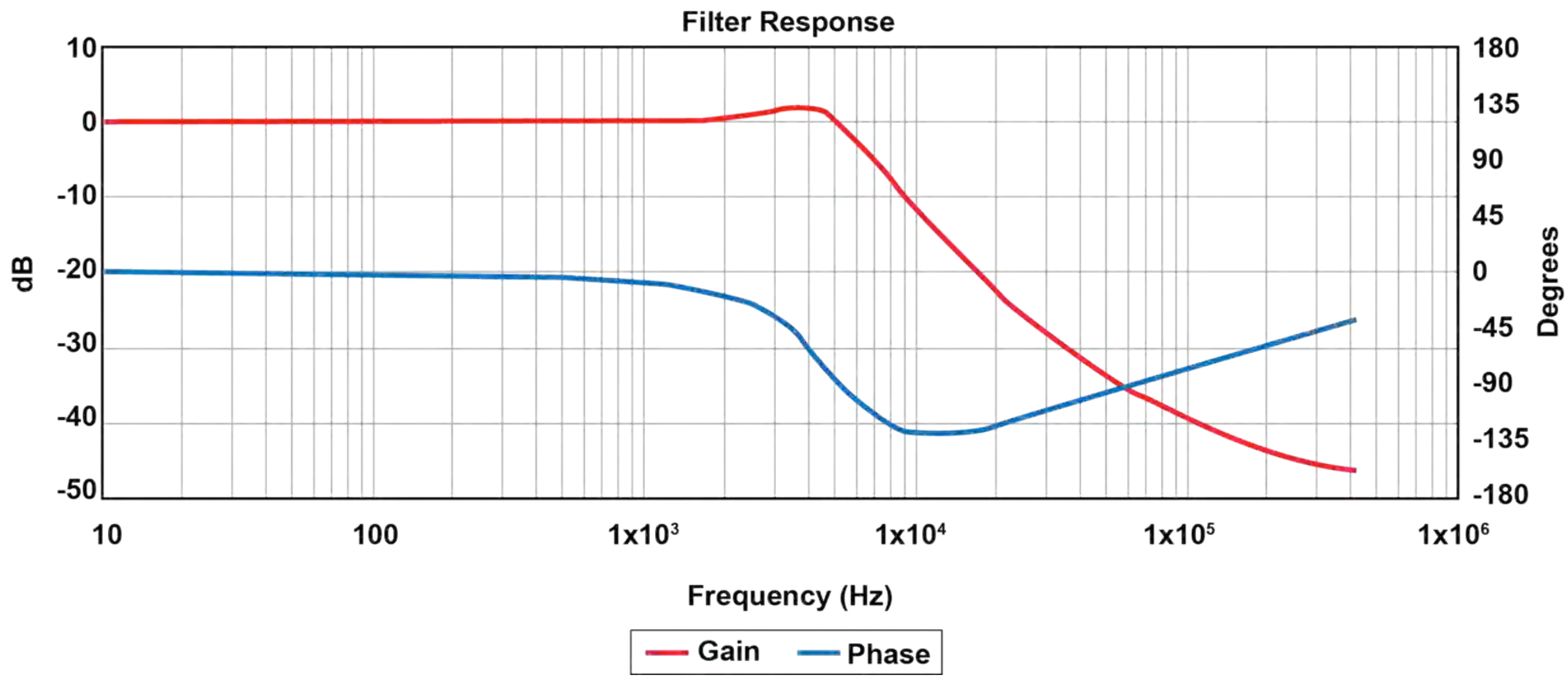
| Type of Cap | | Advantages | Disadvantages |
|---|---|---|---|
| **Ceramic** |  | Small size, low cost, low ESR, high ripple current rating | DC bias effects, low capacitance, cracking |
| **Aluminum Electrolytic** |  | High capacitance, low cost, good for high voltage | High ESR, low ripple current 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 |

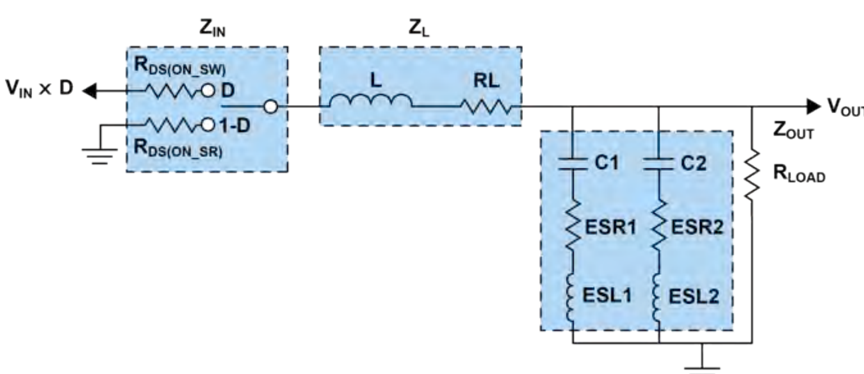
# Output Inductors

**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



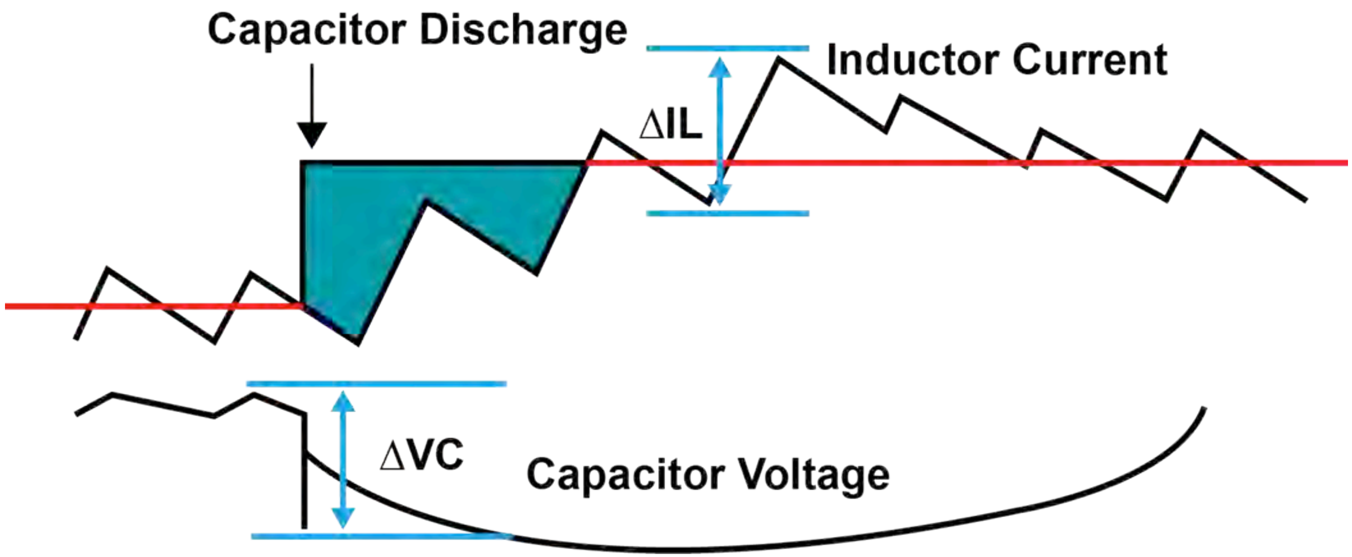




Corner frequency ~ 5 kHz

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
- $\mathrm{Ton}_{\mathrm{MIN}} \leq \dfrac{V_{\mathrm{OUT}}}{V_{\mathrm{IN\_max}} \times f_{\mathrm{max}}}$
- 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)

$$\mathrm{Ton}_{\mathrm{MIN}} \leq \frac{5\ \mathrm{V}}{60\ \mathrm{V} \times 600\ \mathrm{kHz} \times 1.1} = 140\ \mathrm{ns}$$

$$\mathrm{Ton}_{\mathrm{MIN}} \leq \frac{3.3\ \mathrm{V}}{60\ \mathrm{V} \times 600\ \mathrm{kHz} \times 1.1} = 91\ \mathrm{ns}$$

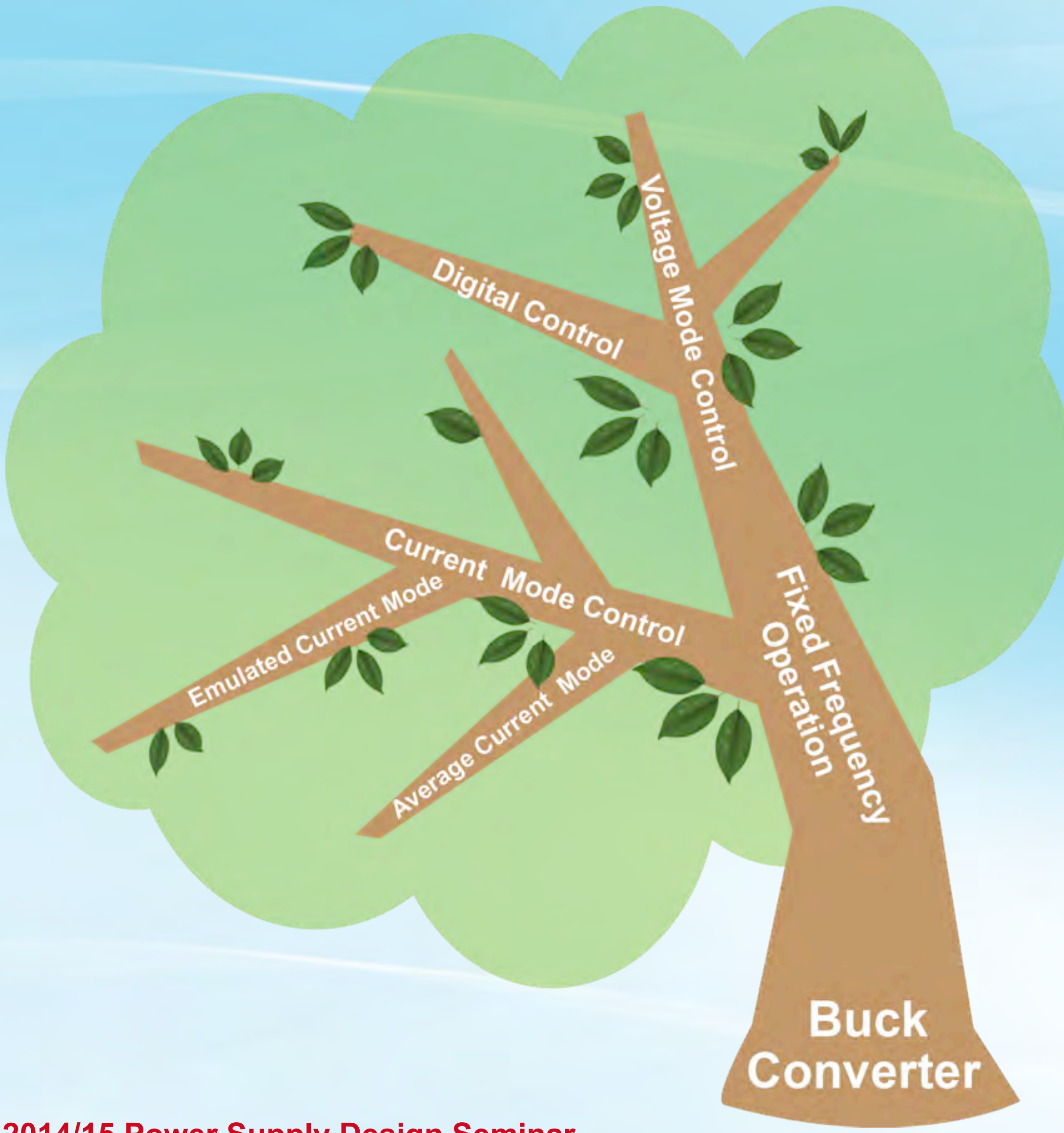
- For a 3.3 V output, the frequency would need to be lowered to ensure no pulse skipping

# Fixed Frequency vs. Variable Frequency

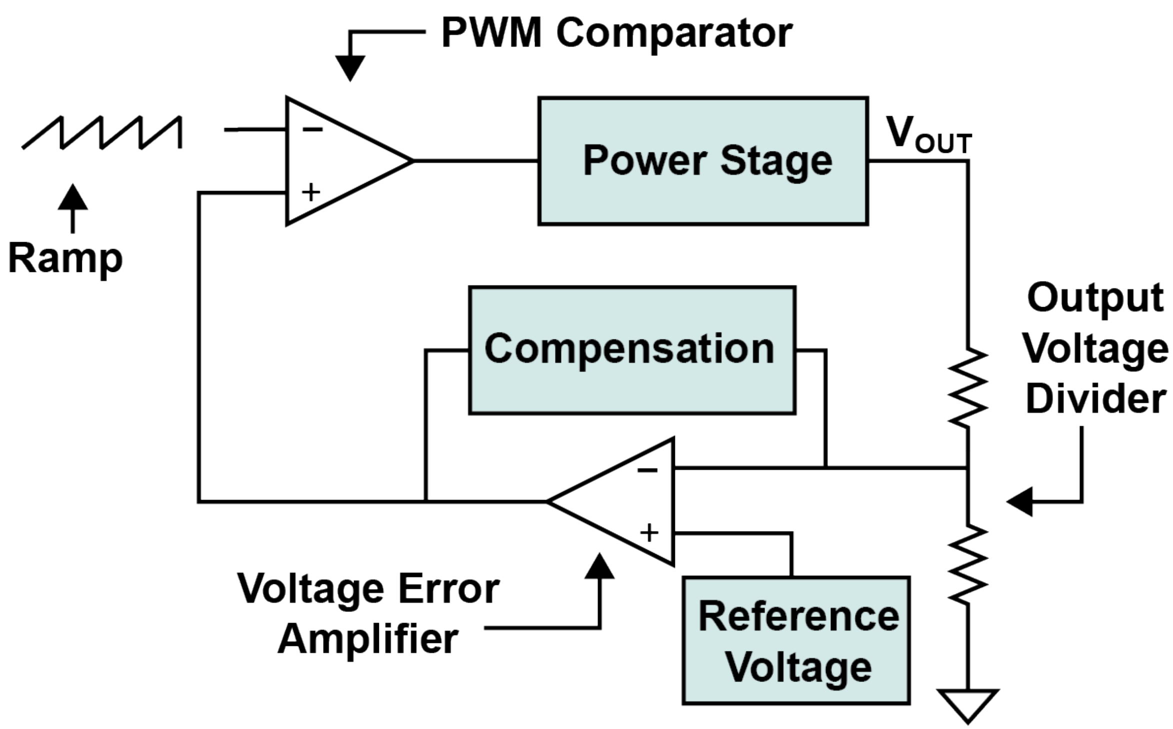
- Fixed frequency operation (Part A)
  - Synchronize multiple devices
    - Eliminate beat frequencies between multiple converters
    - Ripple cancellation to reduce losses in capacitors and PCB traces
  - EMI peaks consistent at any operating mode
  - Minimum controllable pulse width

- 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

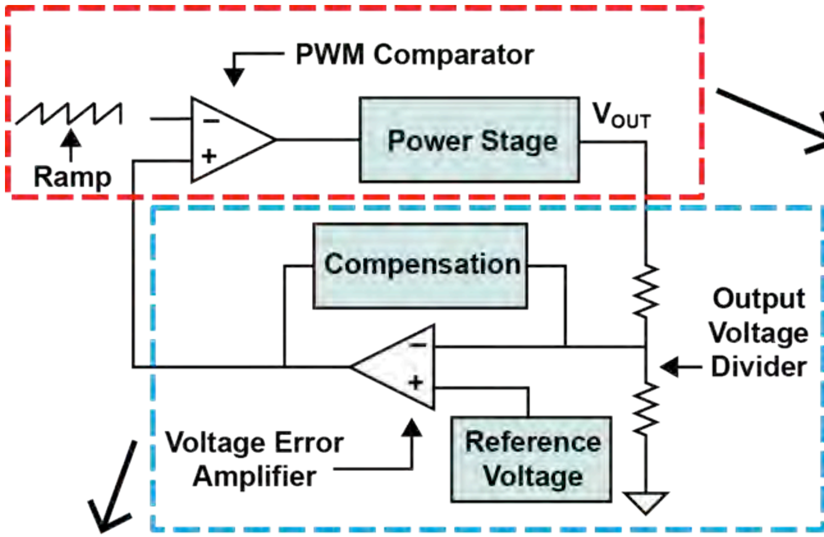
# Fixed Frequency Control

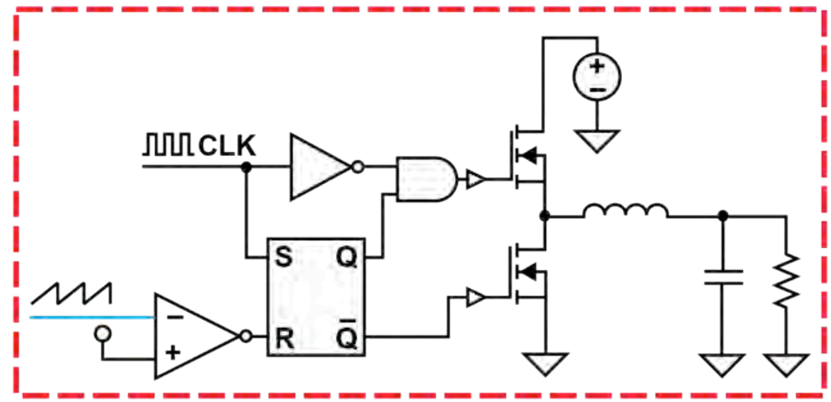


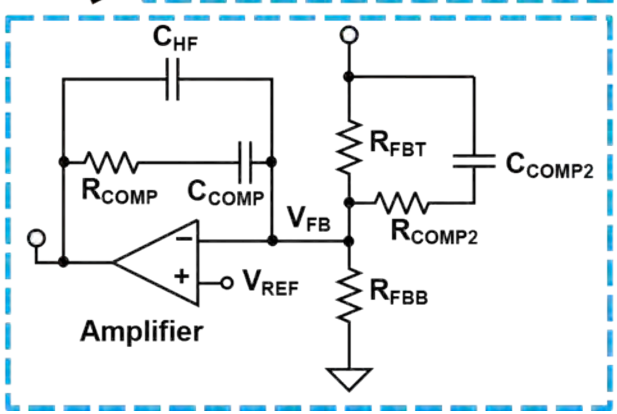
# Voltage Mode Control Introduction



# Voltage Mode Control – Basic Operation

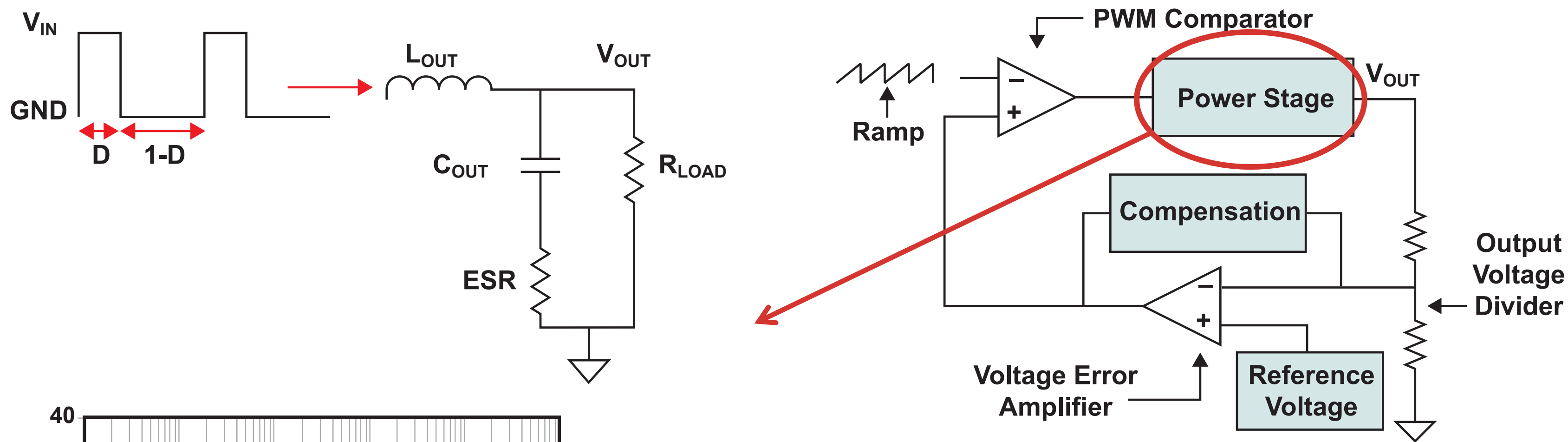


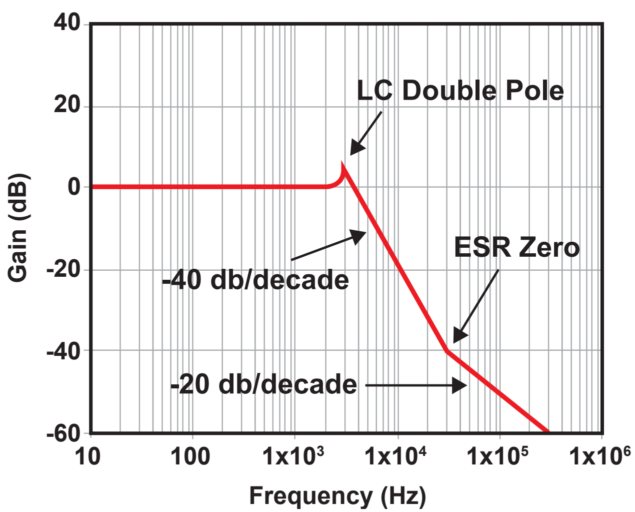




- Power switches generate a square wave
- Output inductor and output capacitor form a low pass filter
- $V_{OUT} = D \times V_{IN}$ (CCM)
- Type 3 compensator generally required

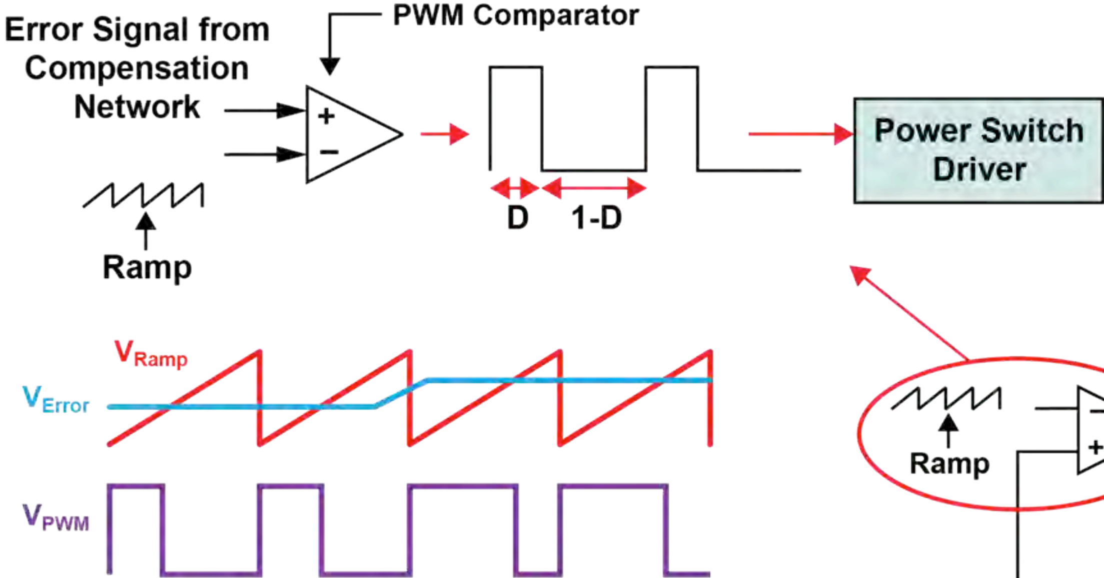
# Voltage Mode Control – Power Stage

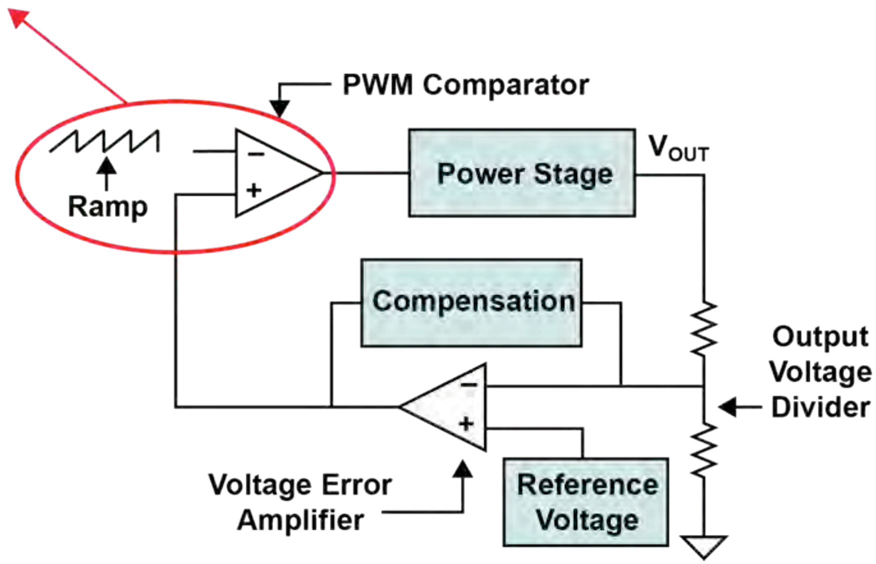



$$H_{PS}(s) = \frac{1 + (C_{OUT} \times R_{ESR})s}{1 + \left(\frac{L_{OUT}}{R_{OUT}} + R_{ESR} \times C_{OUT}\right)s + \left(\frac{R_{OUT} + R_{ESR}}{R_{OUT}}\right)L_{OUT} \times C_{OUT} \times s^2}$$

# Voltage Mode Control – Pulse Width Modulator

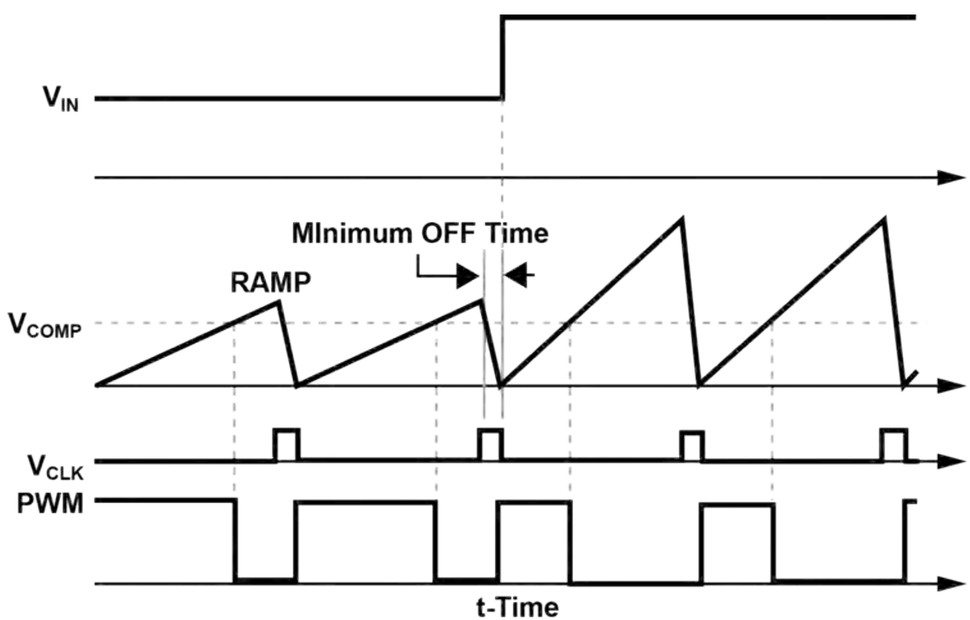


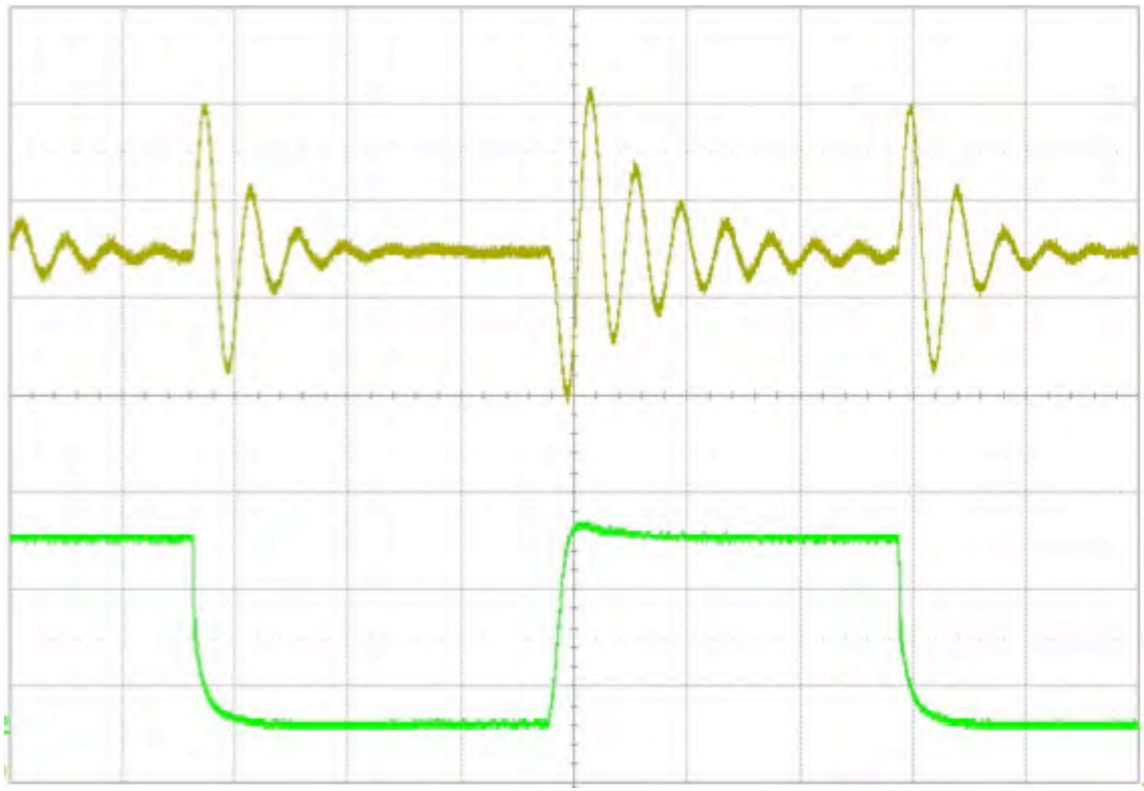

- If the output voltage is too low, the duty cycle is increased
- If the output voltage is too high, the duty cycle is reduced
- Gain of the modulator: $H_{Mod} = \frac{V_{IN}}{V_{Ramp}}$

# 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: $H_{Mod} = \dfrac{V_{IN}}{V_{Ramp}} = \dfrac{V_{IN}}{K \times V_{IN}}$
- Feed Forward increases the ramp amplitude proportional to the input voltage



# Why Do We Compensate?



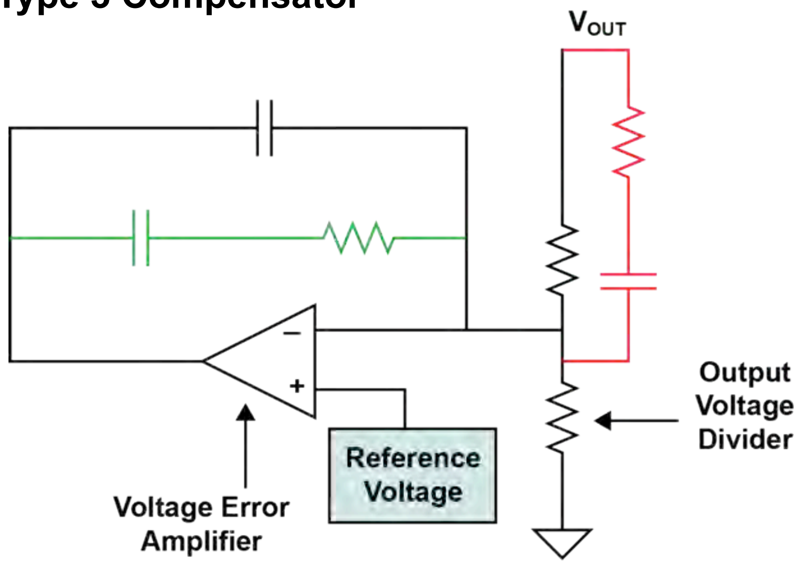
Output Voltage
(AC coupled)
50 mV/Division

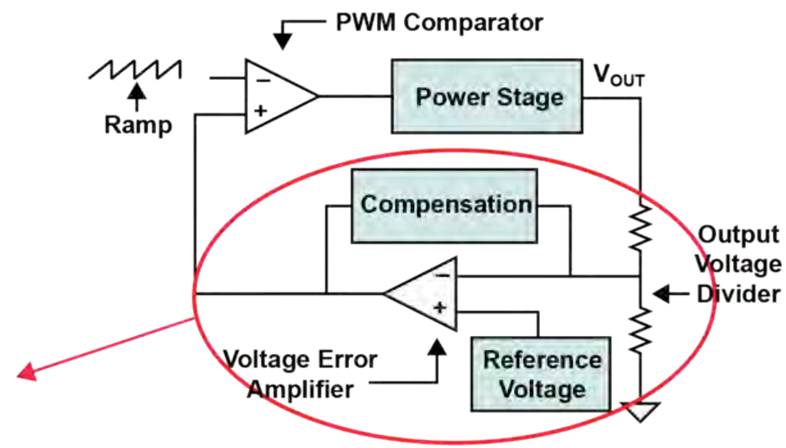
Output Current
500 mA/Division

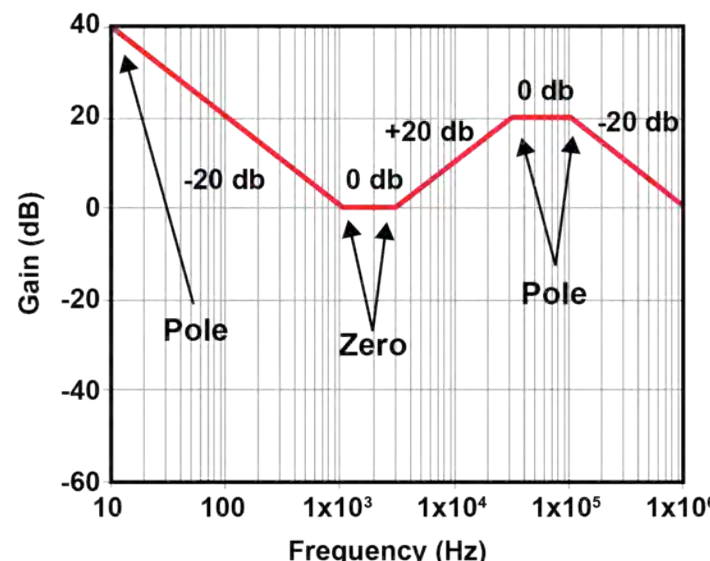
**100 µs/Division**

# Voltage Mode Control – Compensation

**Type 3 Compensator**



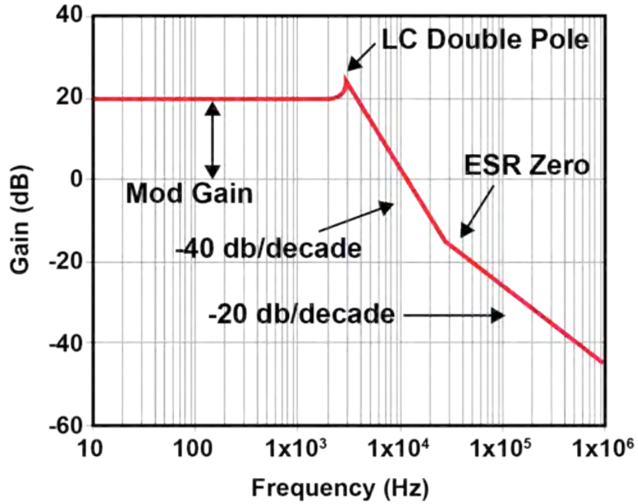



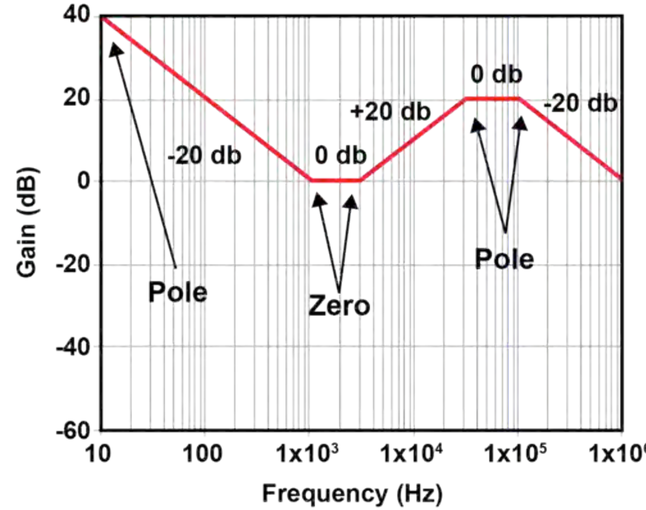

- Type 1 compensator – single dominant pole
- Type 2 compensator – two poles, one zero
- Type 3 compensator – three poles, two zeros

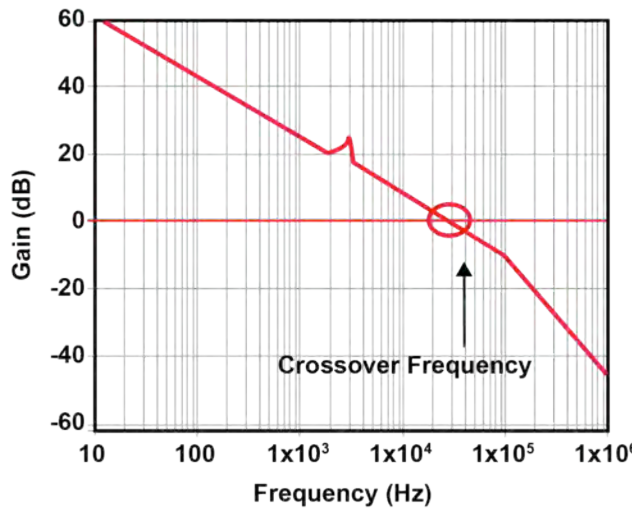
# Voltage Mode Control Loop Compensation

**Power Stage + Modulation**




**Type 3 Compensator**

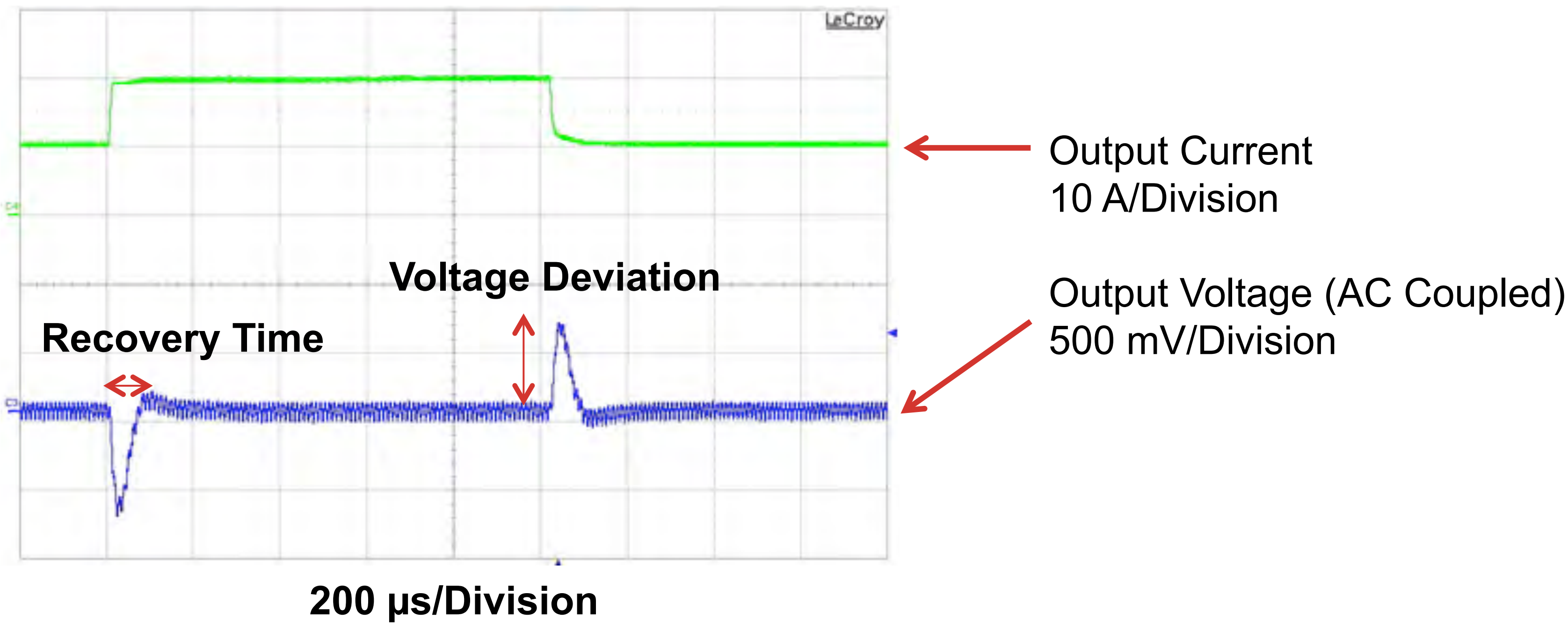



- Use double zero to cancel double pole
- Cross 0 dB with -20 dB/ decade response
- Cross 1/10$^{th}$ to 1/4$^{th}$ below the switching frequency

# 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



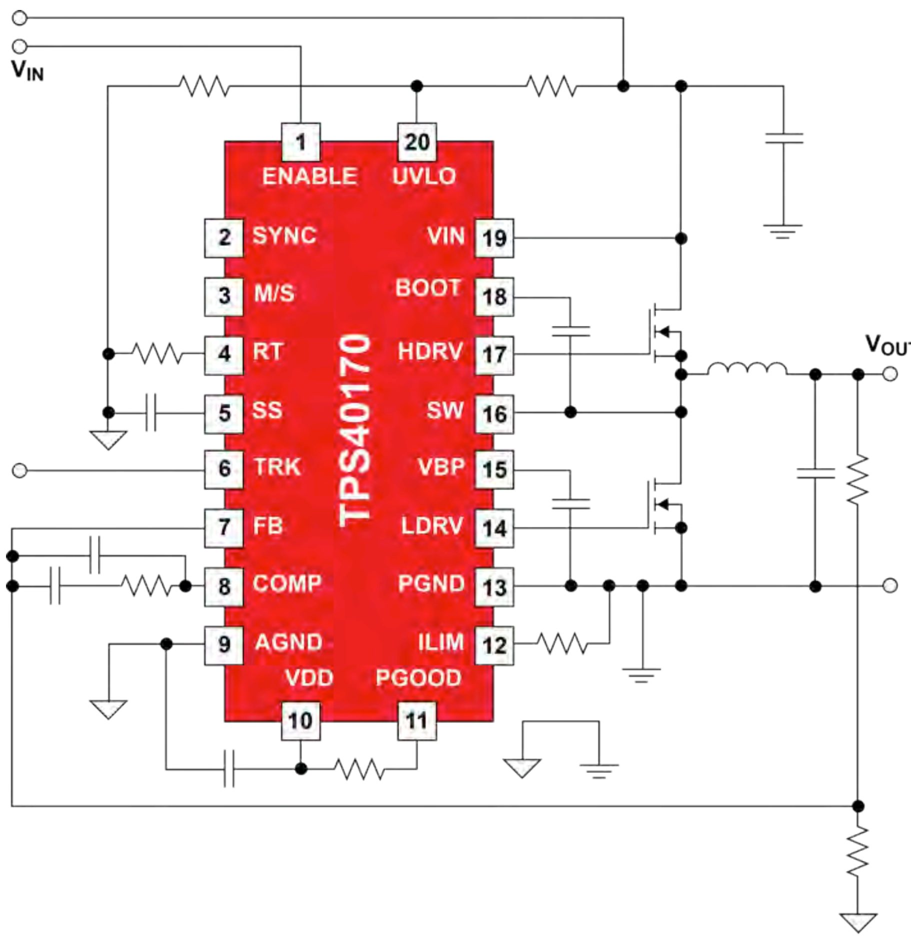
# Voltage Mode Control

| 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

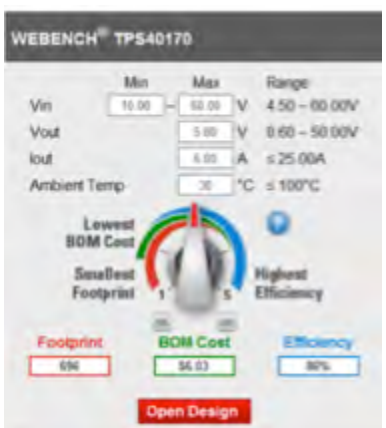
| Design Specifications | |
|---|---|
| Input voltage range | 10 V to 60 V |
| Target output voltage | 5 V |
| Output current range | 0 A to 6 A |
| Switching frequency | 300 kHz |
| Controller | TPS40170 |

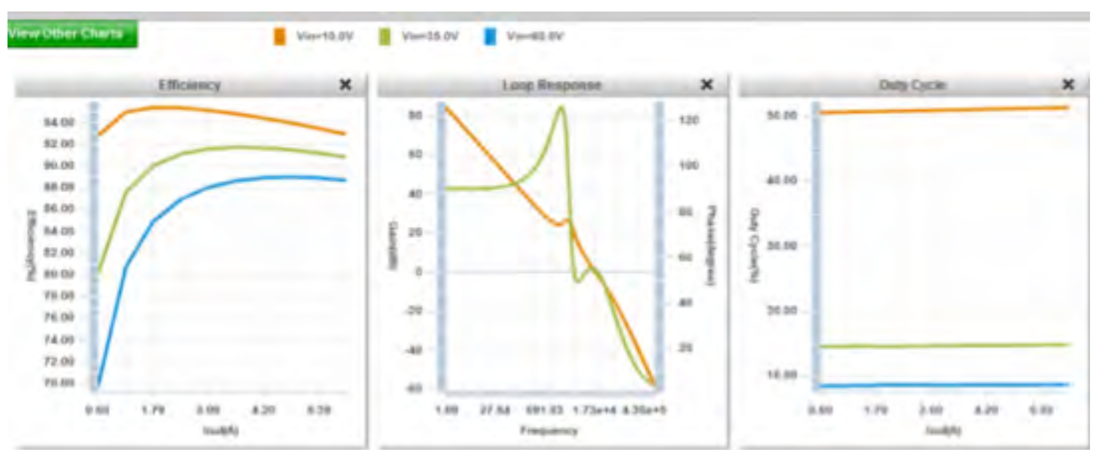
| Operating Values (Theoretical) | |
|---|---|
| Minimum duty cycle | 0.083 |
| Minimum on-time | 0.277 µs |
| Maximum duty cycle | 0.500 |
| Maximum on-time | 1.667 µs |



# 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

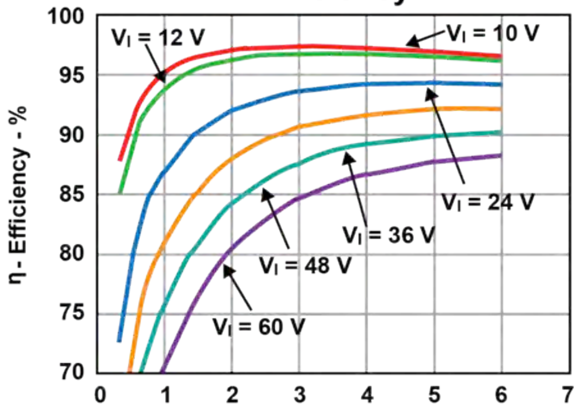


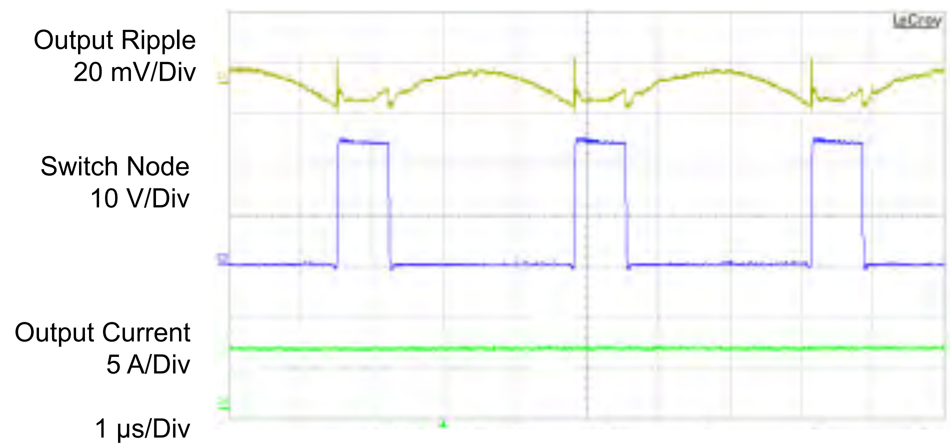
# Design Example #1
# Voltage Mode – Performance Graphs

**Data is taken with TPS40170 EVM (HPA578)**

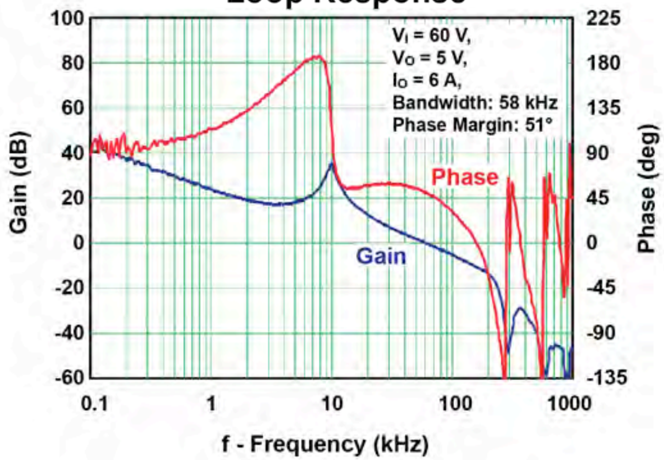
### Efficiency



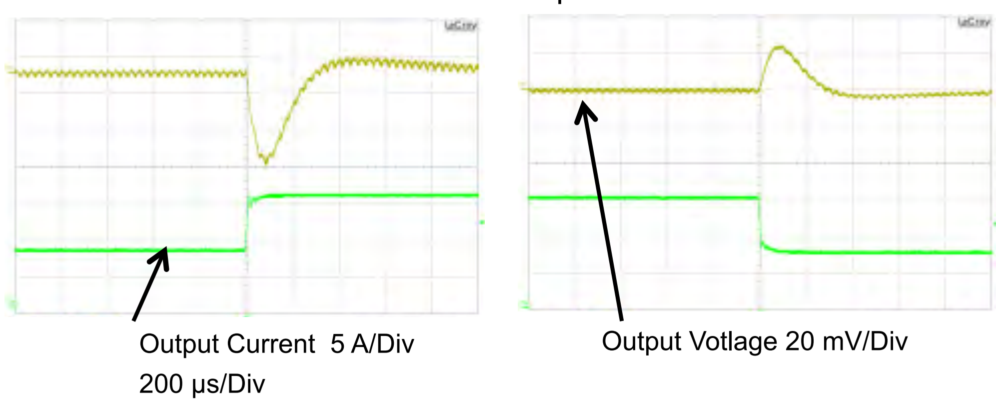

### Switching Operation



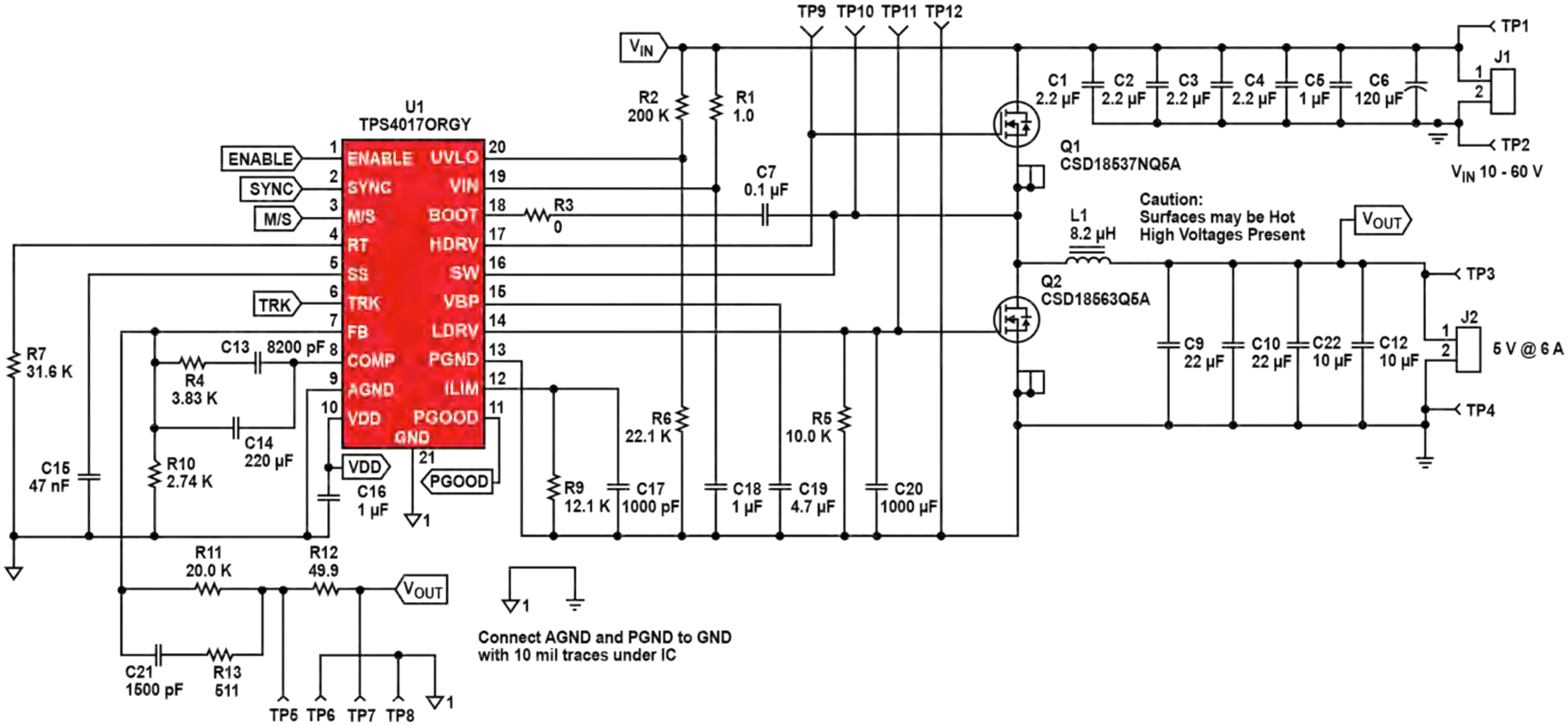

### Loop Response



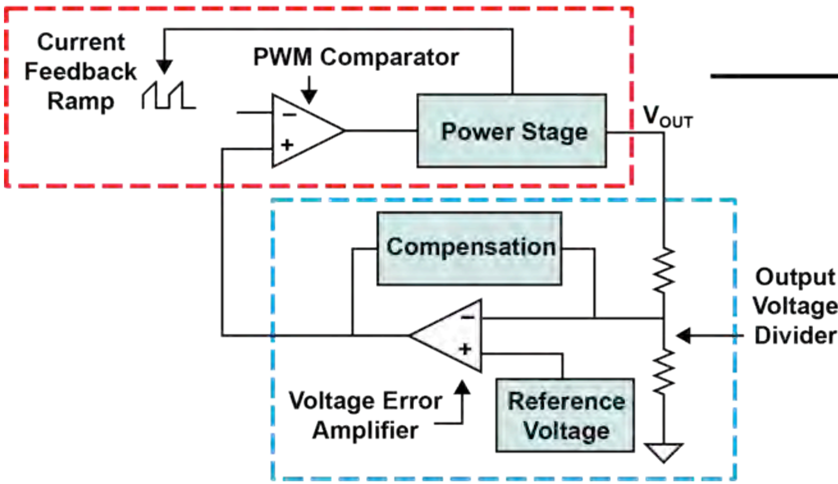

### Transient Response

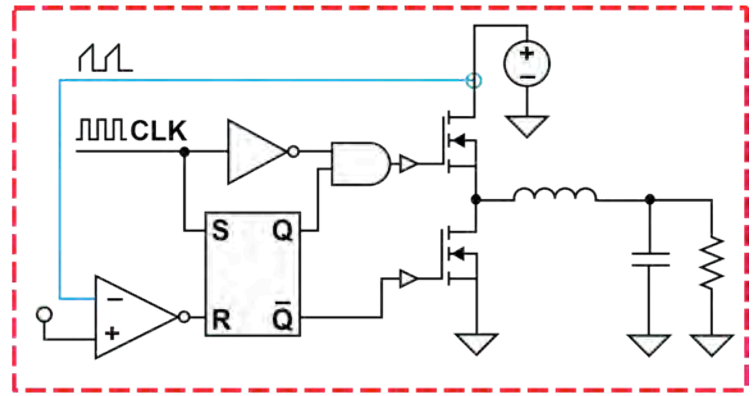


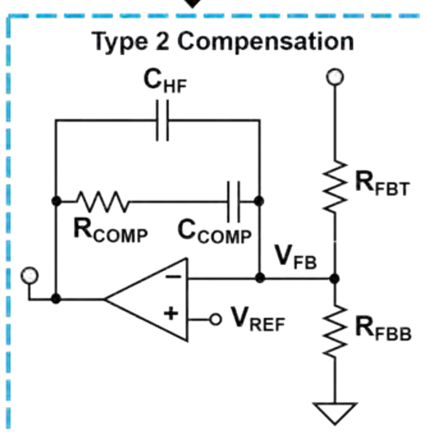
# Design Example #1
# Voltage Mode – Schematic (HPA578)



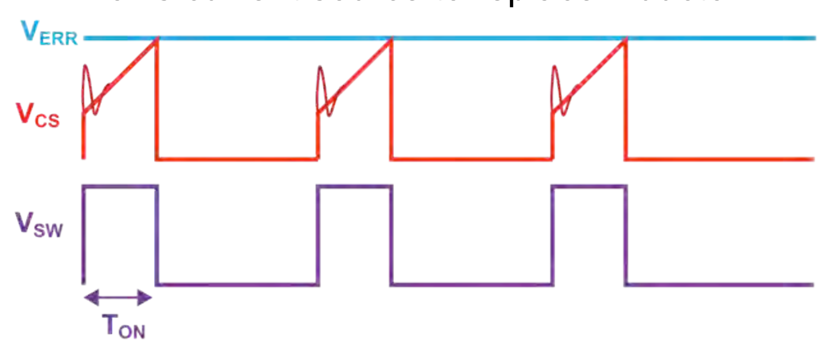
# Current Mode Control
# Basic Operation



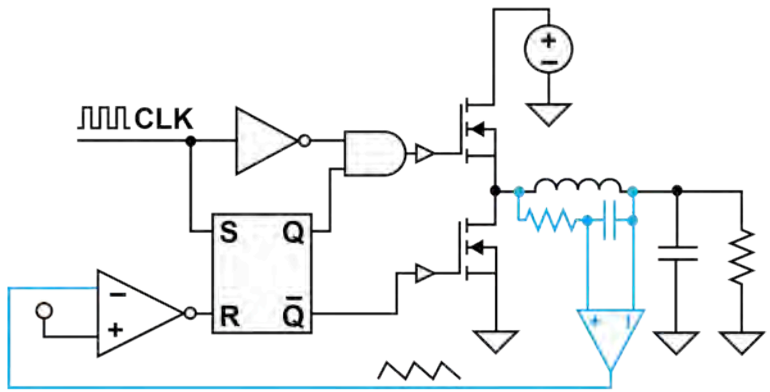




- Peak current mode is more popular than valley
- Outer voltage loop + inner current loop
- High-side / DCR current sensing
- Error amp output controls peak inductor current
- Allows current source to replace inductor

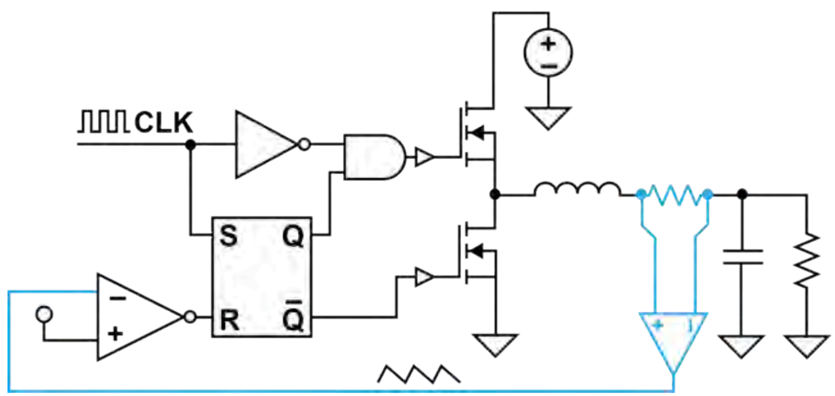


# Current Mode Control
# Other Considerations

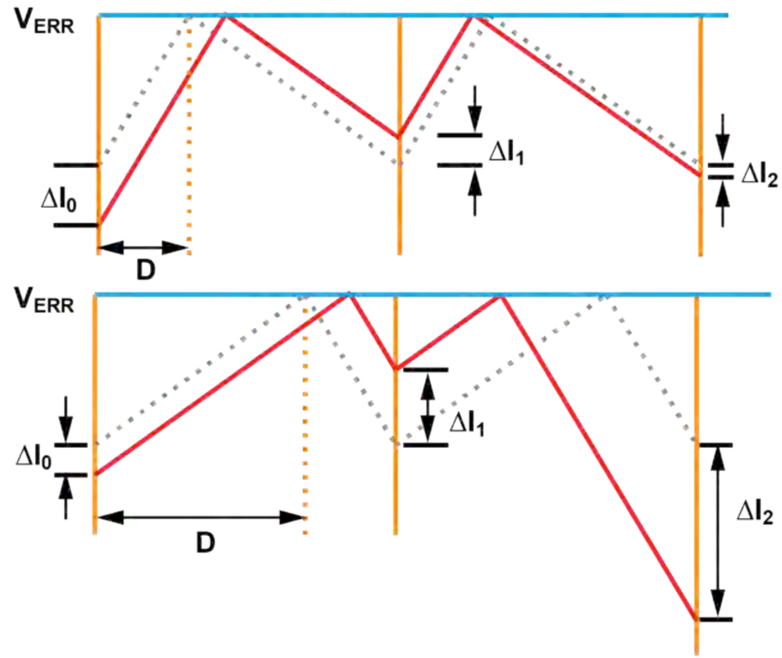
DCR Sensing




Resistor Sensing

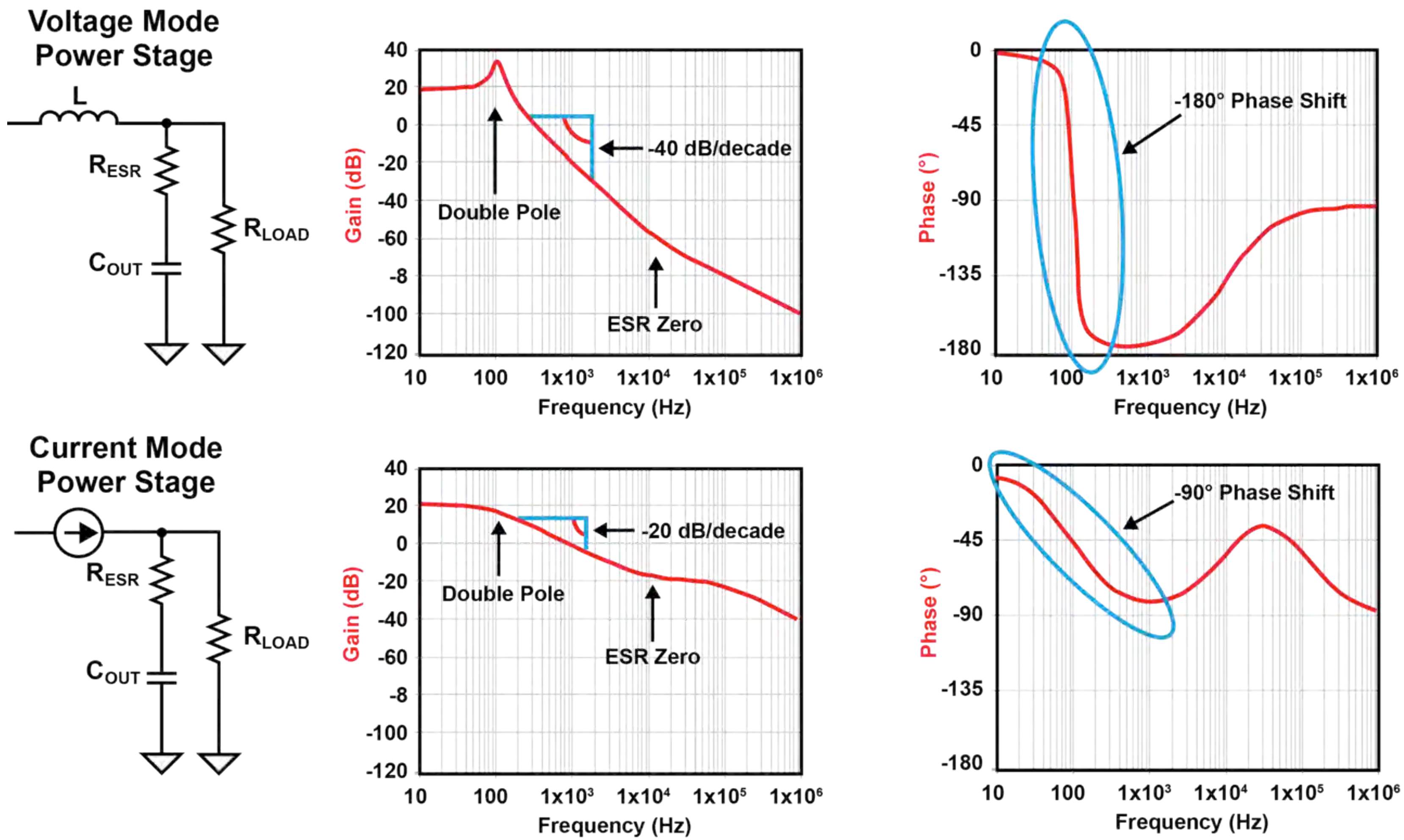



Sub-Harmonic Oscillation

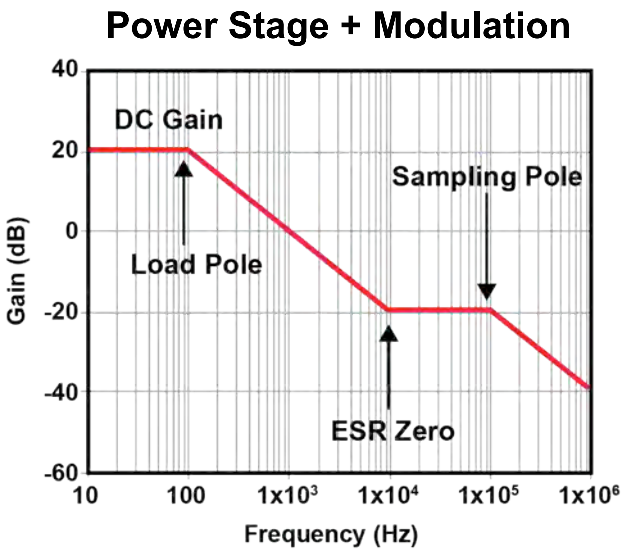


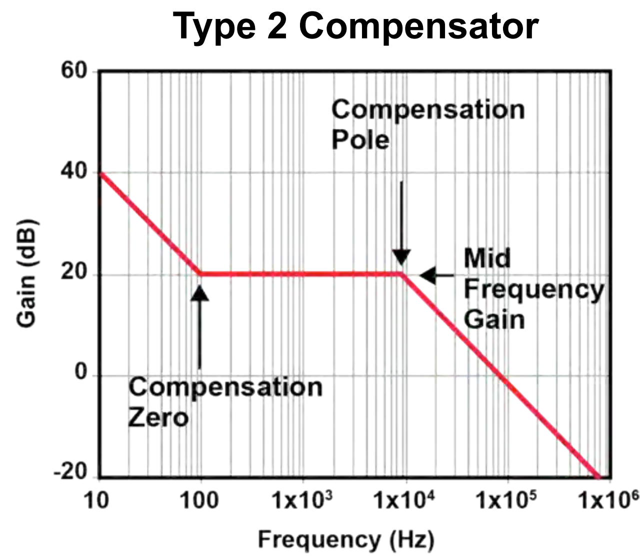

- $\Delta I_0 > \Delta I_1 > \Delta I_2$ when $D < 0.5$
- $\Delta I_0 < \Delta I_1 < \Delta I_2$ when $D > 0.5$ (sub-harmonic Oscillation)
- Requires slope compensation to be stable

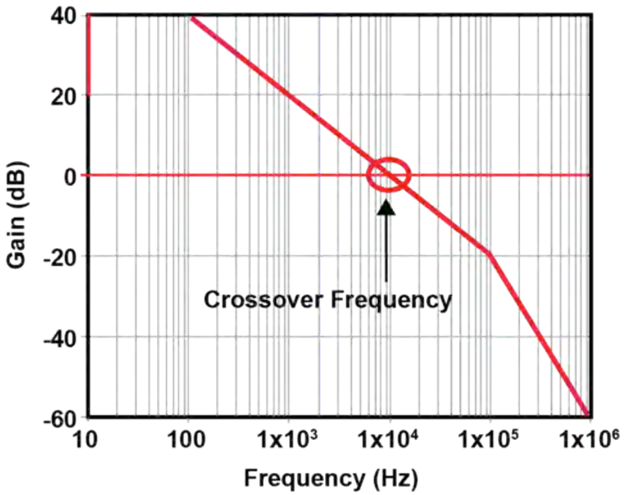
# Current Mode Control
# Power Stage + Modulation



# Current Mode Control Loop Compensation



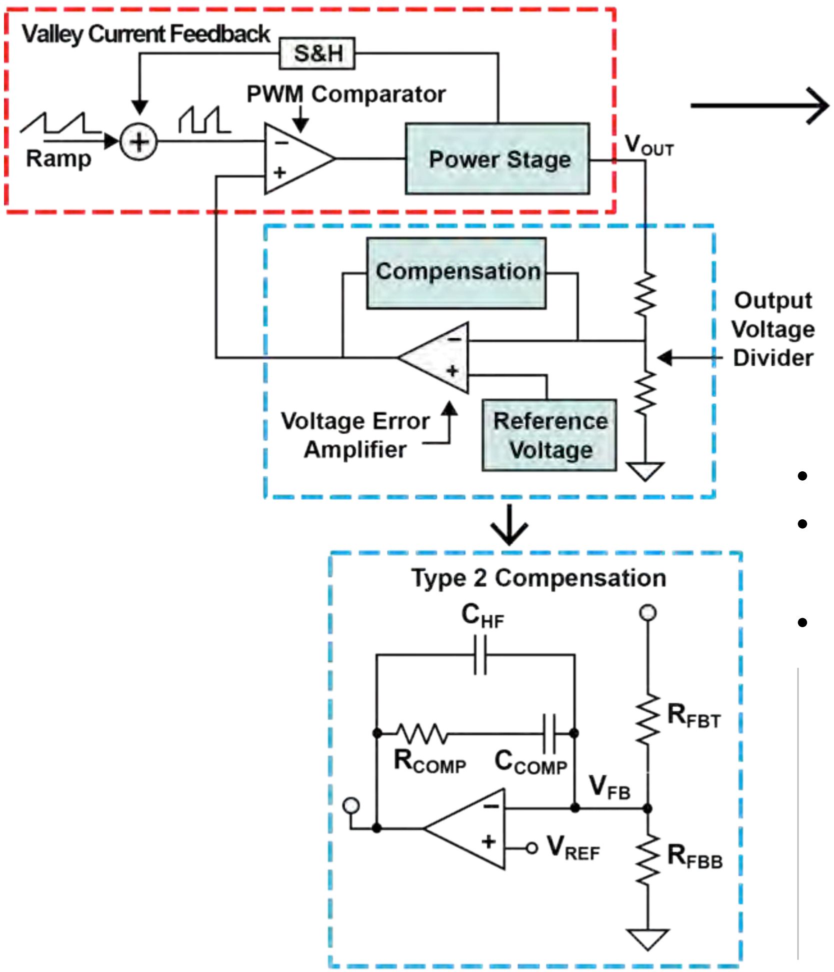



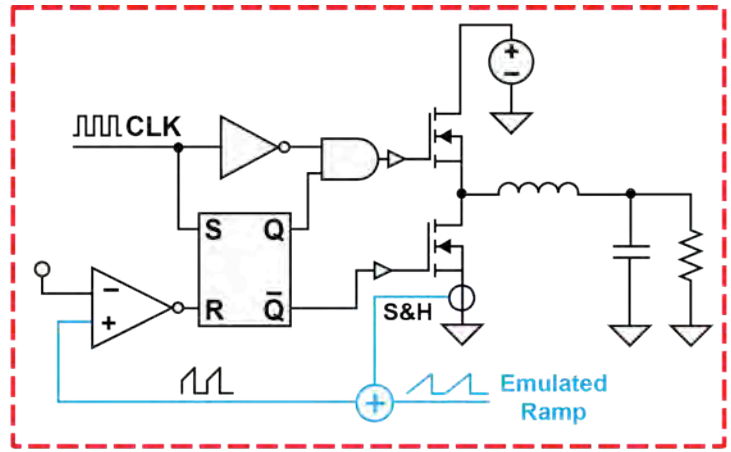

- Cancel load pole and ESR zero by placing error amplifier zero and pole
- Cross 0 dB with -20 dB/decade response

# Current Mode Control

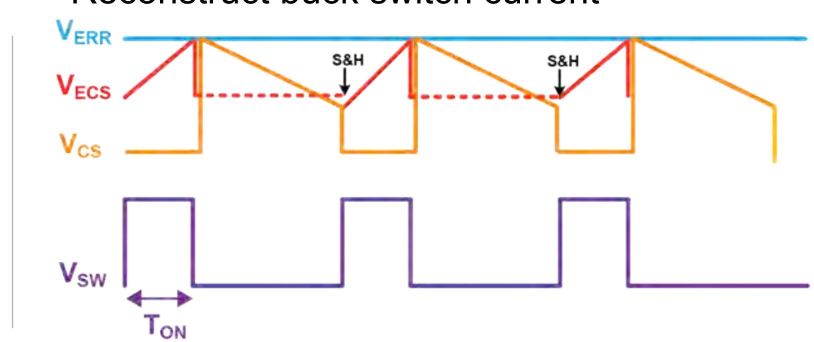
| Advantages | Disadvantages |
|---|---|
| Single pole system allows simple Type 2 compensation | Need for slope compensation to eliminate sub-harmonic oscillation |
| Inherent feed forward improves line transient performance | Noise sensitivity at leading edge spike |
| Easy implementation of cycle-by-cycle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

# Emulated Current Mode Control
# Basic Operation



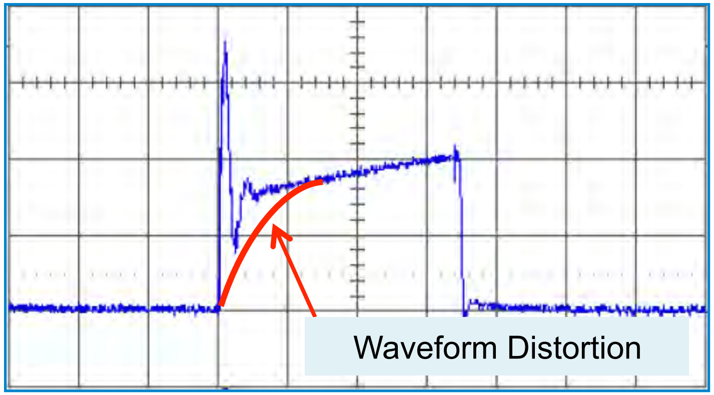

- Low-side current sensing during free-wheeling
- Sample & hold valley current before high-side switch turns on
- Reconstruct buck switch current



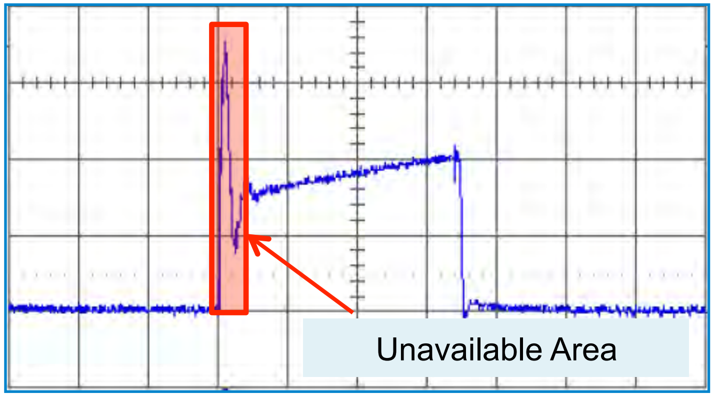
# Emulated Current Mode Control
# Leading Edge Spike

- 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

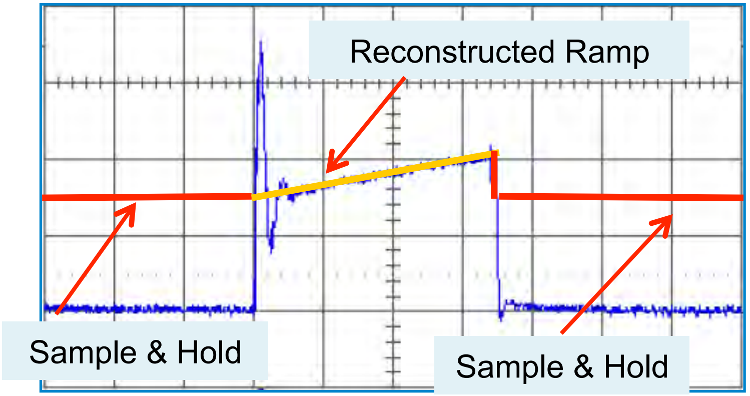
**R-C Filter**



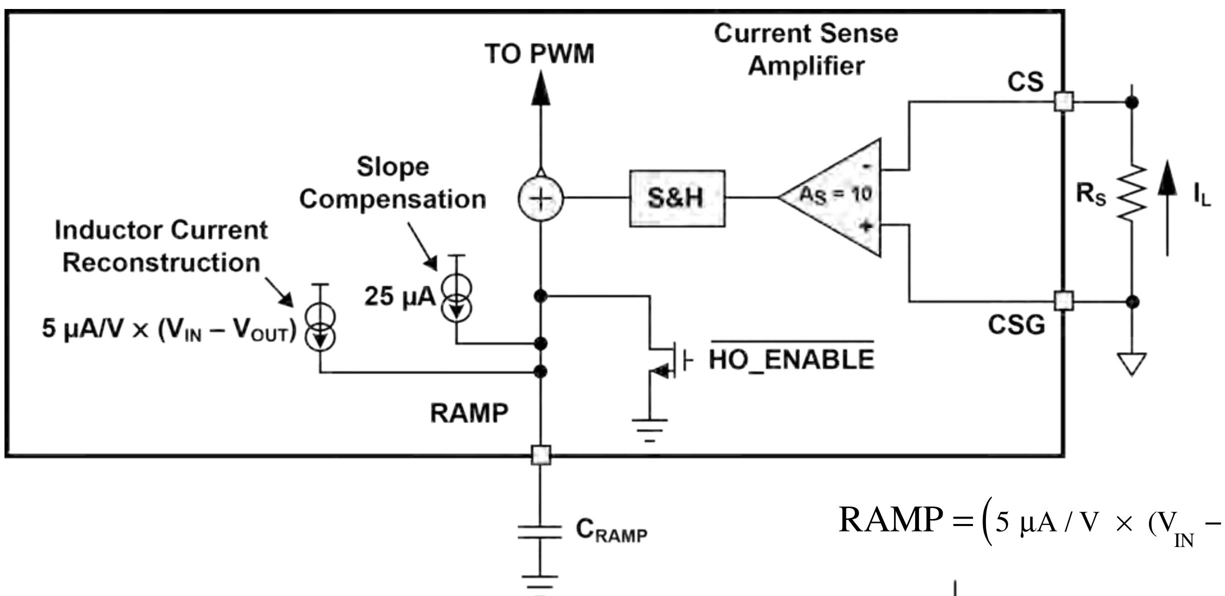

**Leading Edge Blanking**



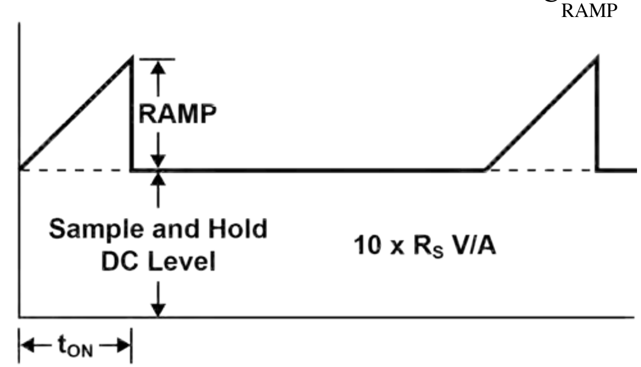

**Emulated Current Mode**



# 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

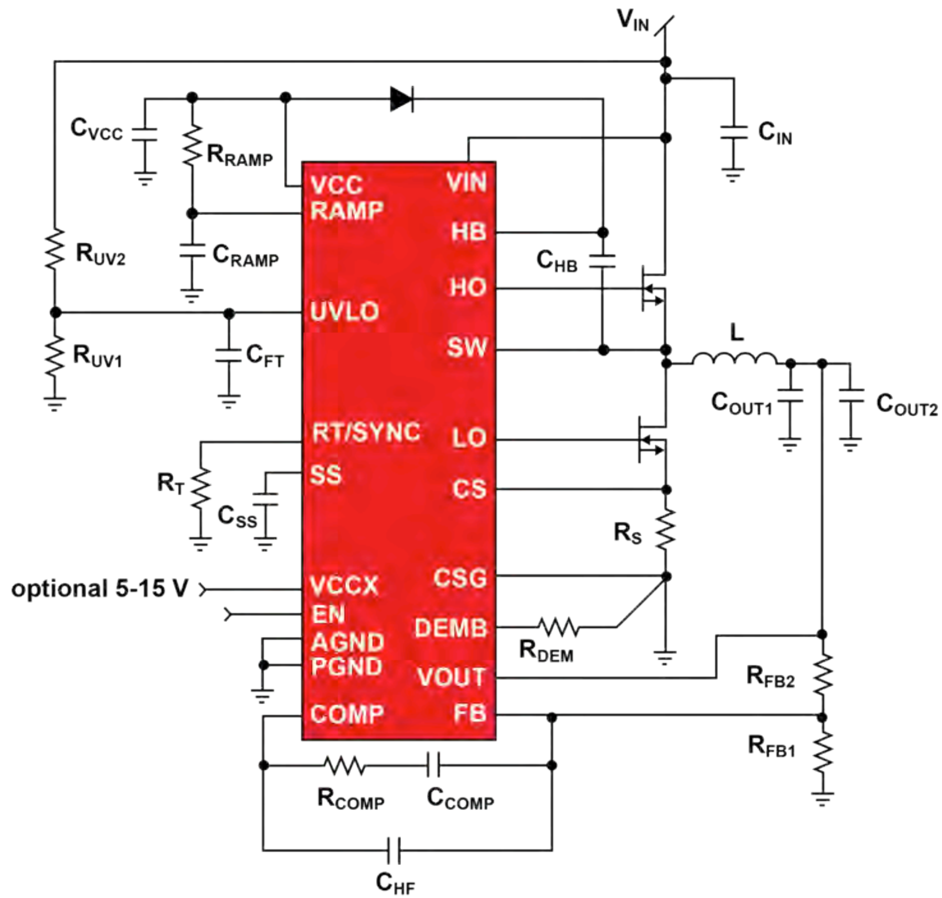
| Advantages | Disadvantages |
|---|---|
| Single-pole system allows simple Type 2 compensation | Need for slope compensation to eliminate sub-harmonic oscillation |
| Inherent feed forward improves line transient performance | Need for relatively long minimum off-time than peak current mode |
| Easy 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 |

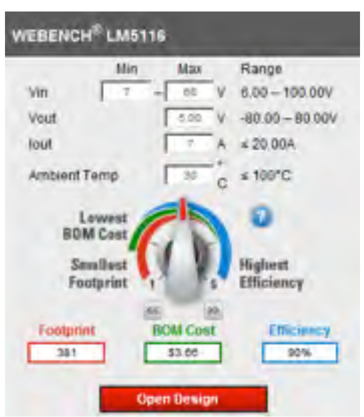
| Operating Values (Theoretical) | |
|---|---|
| Minimum duty cycle | 0.083 |
| Minimum on-time | 0.333 µs |
| Maximum duty cycle | 0.714 |
| Maximum on-time | 2.857 µs |

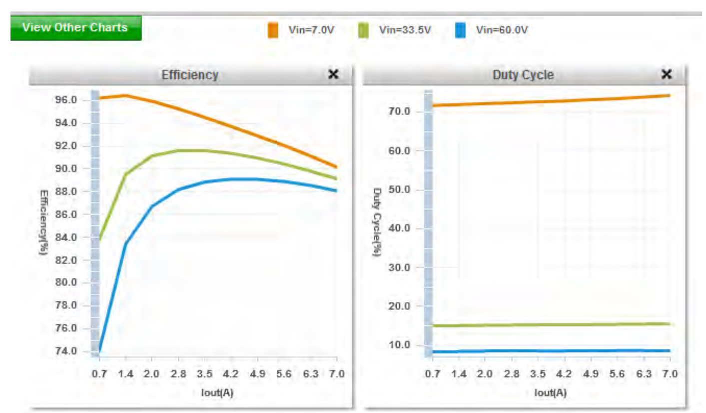


# Design Example #2 – Calculation

- 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

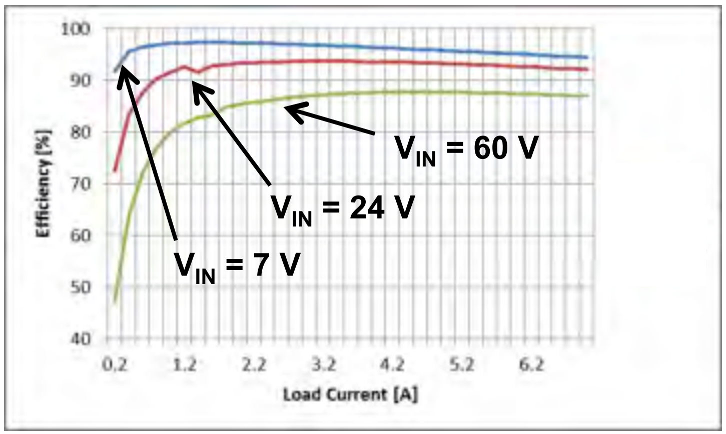


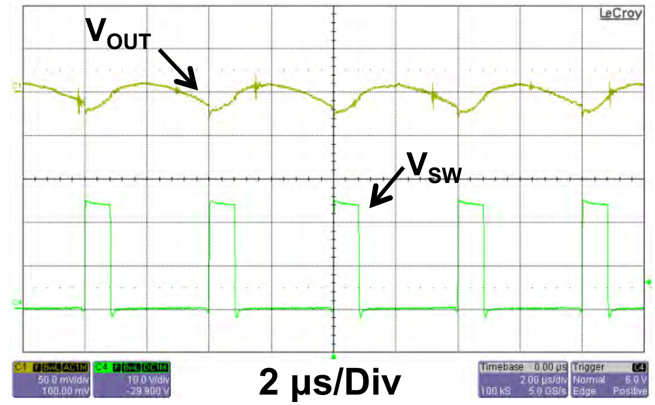
# Design Example #2 – Performance Graphs

**Data is taken with LM5116EVM**

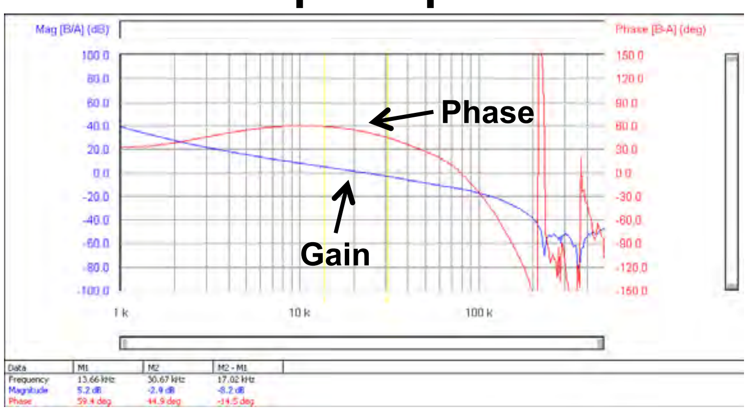
## Efficiency



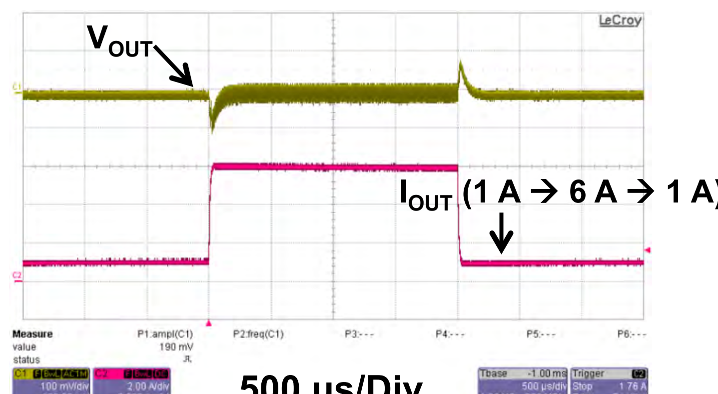

## Switching Operation



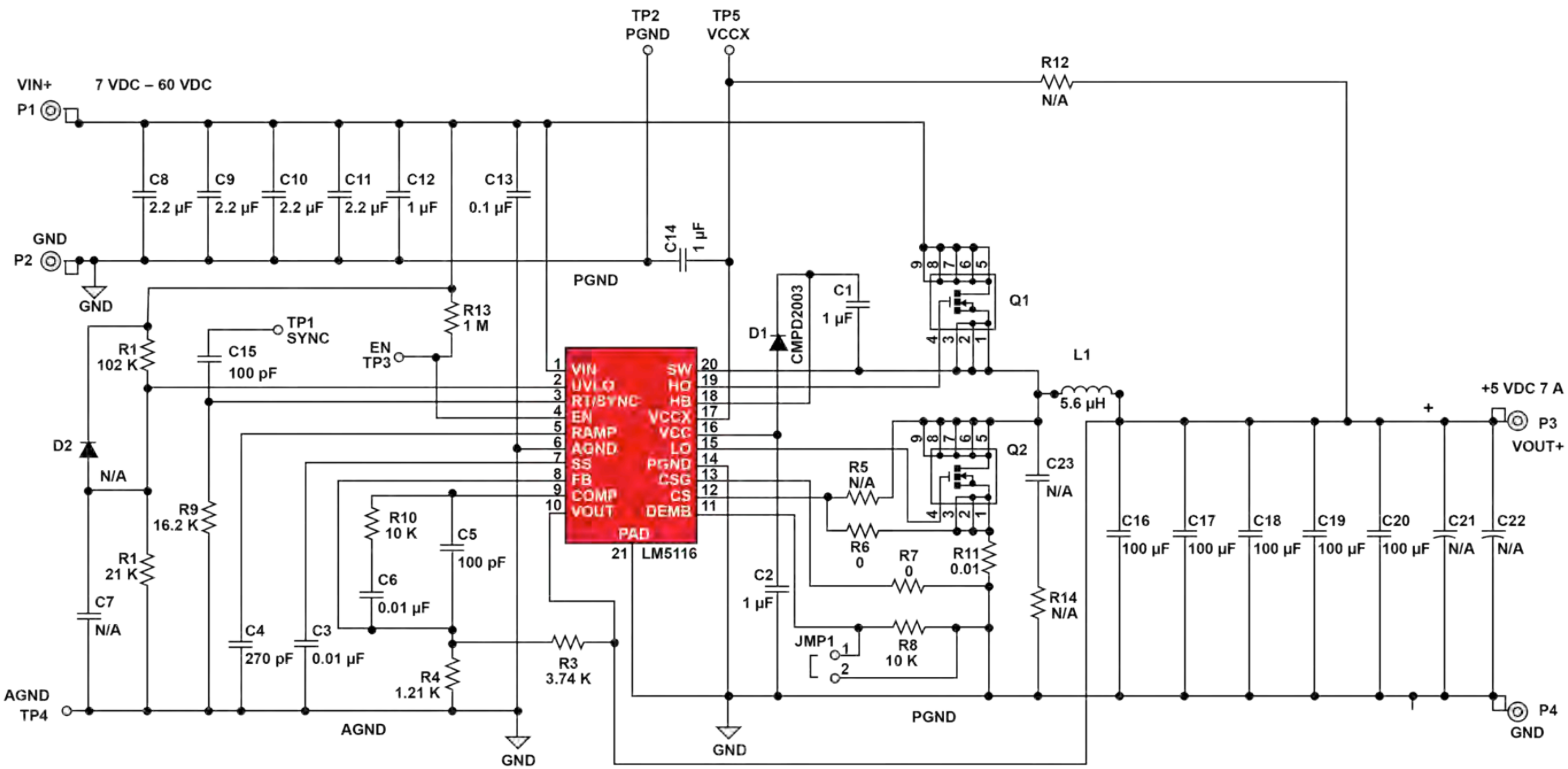

## Loop Response




## Transient Response

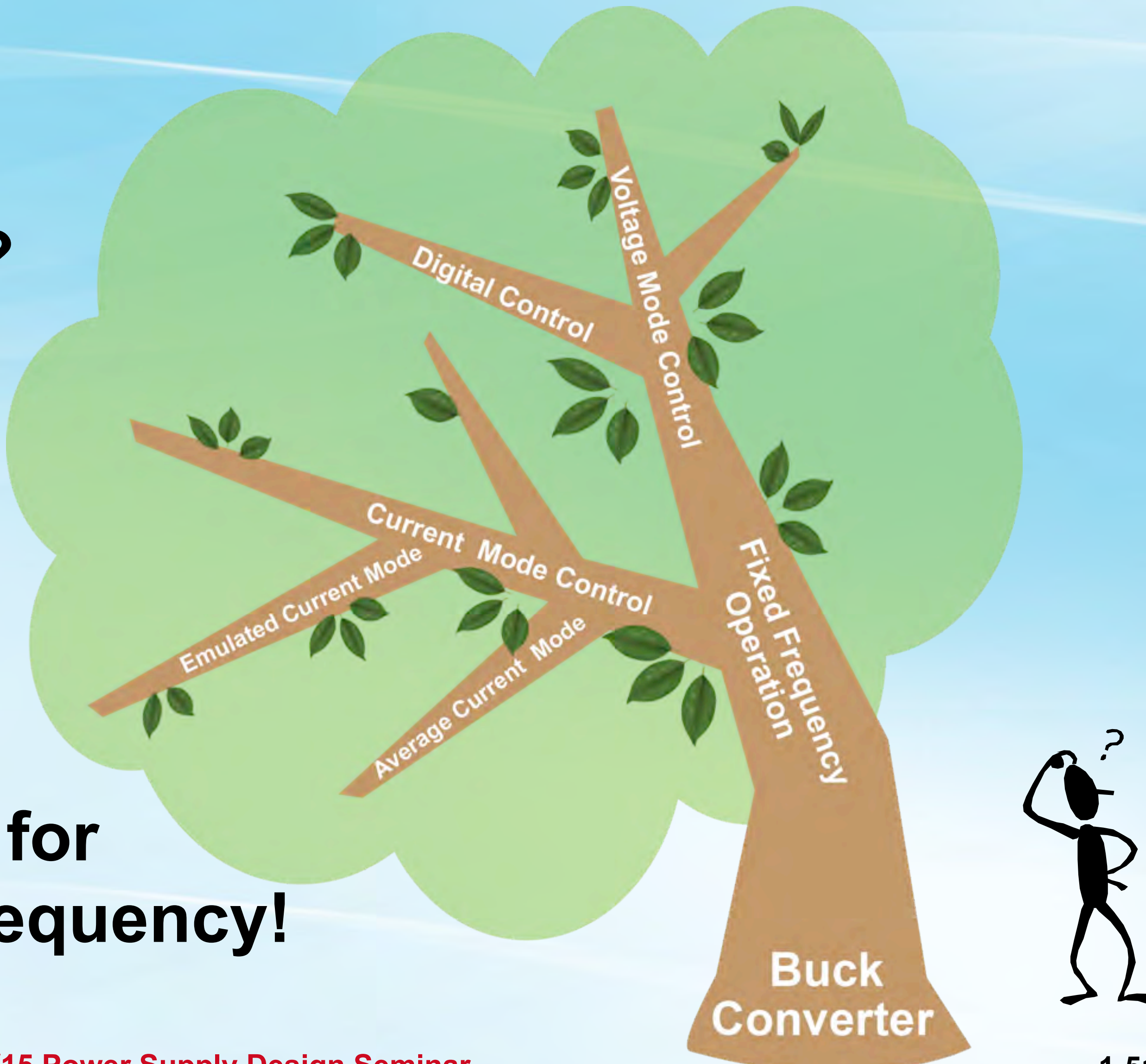


# Design Example #2 - Schematic



# Fixed Frequency Control

**Questions?**




**Stay tuned for Variable Frequency!**

# TI Worldwide Technical Support

## Internet

**TI Semiconductor Product Information Center Home Page**

support.ti.com

**TI E2E™ Community Home Page**

e2e.ti.com

## Product Information Centers

| | | |
|---|---|---|
| **Americas** | Phone | +1(512) 434-1560 |
| **Brazil** | Phone | 0800-891-2616 |
| **Mexico** | Phone | 0800-670-7544 |
| | Fax | +1(972) 927-6377 |
| | Internet/Email | support.ti.com/sc/pic/americas.htm |

### Europe, Middle East, and Africa

Phone

| | |
|---|---|
| European Free Call | 00800-ASK-TEXAS (00800 275 83927) |
| International | +49 (0) 8161 80 2121 |
| Russian Support | +7 (4) 95 98 10 701 |

**Note:** The European Free Call (Toll Free) number is not active in all countries. If you have technical difficulty calling the free call number, please use the international number above.

| | |
|---|---|
| Fax | +(49) (0) 8161 80 2045 |
| Internet | www.ti.com/asktexas |
| Direct Email | asktexas@ti.com |

### Japan

| | | |
|---|---|---|
| Phone | Domestic | 0120-92-3326 |
| Fax | International | +81-3-3344-5317 |
| | Domestic | 0120-81-0036 |
| Internet/Email | International | support.ti.com/sc/pic/japan.htm |
| | Domestic | www.tij.co.jp/pic |

### Asia

Phone

| | |
|---|---|
| International | +91-80-41381665 |
| Domestic | Toll-Free Number |

**Note:** Toll-free numbers do not support mobile and IP phones.

| | |
|---|---|
| Australia | 1-800-999-084 |
| China | 800-820-8682 |
| Hong Kong | 800-96-5941 |
| India | 000-800-100-8888 |
| Indonesia | 001-803-8861-1006 |
| Korea | 080-551-2804 |
| Malaysia | 1-800-80-3973 |
| New Zealand | 0800-446-934 |
| Philippines | 1-800-765-7404 |
| Singapore | 800-886-1028 |
| Taiwan | 0800-006800 |
| Thailand | 001-800-886-0010 |

| | |
|---|---|
| International | +86-21-23073444 |
| Fax | +8621-23073686 |
| Email | tiasia@ti.com or ti-china@ti.com |
| Internet | support.ti.com/sc/pic/asia.htm |



**B090714**



TEXAS INSTRUMENTS