# A Tutorial Introduction to Switching Converters


Christophe Basso

Business Development Manager

IEEE Senior Member

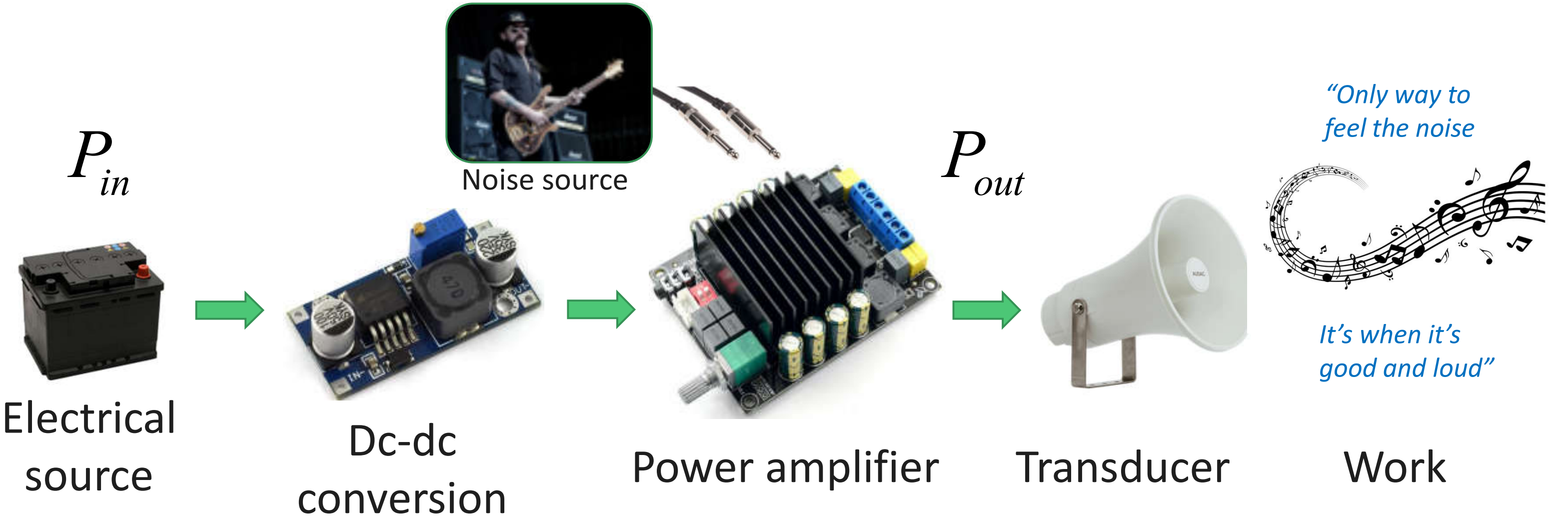

March 2023 – Rev 0.33

# Agenda

- Power Conversion Mechanisms
- Switching Cells and Control Schemes
- The Buck
- The Boost
- The Buck-Boost
- Introduction to Control Loop Design
- EMI Filter Interaction
- Introduction to Simulation

# The Goal of a Converter is to Deliver Power

- A converter transforms the energy from a source into a physical work
- The conversion mechanism generates losses and heat which must be evacuated




✓ Energy efficiency is about minimizing the losses in the conversion chain

✓ A highly-efficient converter implies lower-size heatsink and improved reliability

# No Loss in a Perfect World

- In an ideal system, all the energy coming from the source converts into work
- The ratio between the delivered power and the input power is efficiency

✓ The Greek letter “eta” designates a unitless number less than 1 or 100%

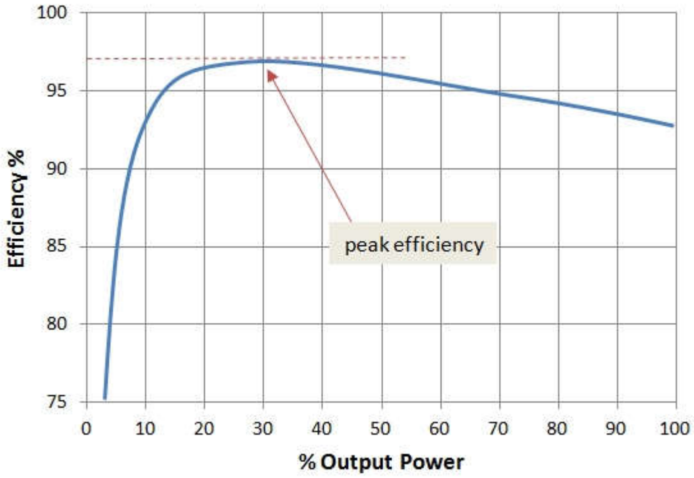
$$\eta = \frac{P_{out}}{P_{in}}$$

$$P_{loss} = P_{in} - P_{out} = \frac{P_{out}}{\eta} - P_{out} = P_{out}\left(\frac{1}{\eta} - 1\right)$$

A 50% efficiency means $P_{loss} = P_{out}$

e.g. $P_{out}$ = 100 W $\rightarrow$ $P_{loss}$ = 100 W

$P_{in}$ = 150 W, $P_{out}$ = 100 W $\rightarrow$ $\eta$ = 66%




✓ Efficiency is not constant and often peaks at a level different than nominal power

✓ Challenge is to keep losses low across a wide load range

FUTURE ELECTRONICS

# Efficiency Across the Load Range

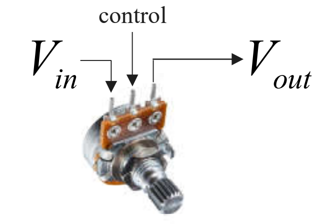
- Computers are rarely used at their full power capability
- Depending on the active program, computational burden affects consumption

✓ The 80+ standard established in 2004 defines efficiency at different load conditions

| 80 PLUS Test Type | 115 V Internal Non-Redundant | | | 230 V Internal Redundant | | | |
|---|---|---|---|---|---|---|---|
| Power supply usage | 20 % | 50 % | 100 % | 10 % | 20 % | 50 % | 100 % |
| 80 PLUS | 80 % | 80 % | 80 % | Not defined | | | |
| 80 PLUS Bronze | 82 % | 85 % | 82 % | --- | 81 % | 85 % | 81 % |
| 80 PLUS Silver | 85 % | 88 % | 85 % | --- | 85 % | 89 % | 85 % |
| 80 PLUS Gold | 87 % | 90 % | 87 % | --- | 88 % | 92 % | 88 % |
| 80 PLUS Platinum | 90 % | 92 % | 89 % | --- | 90 % | 94 % | 91 % |
| 80 PLUS Titanium | Inexistant | | | 90 % | 94 % | 96 % | 91 % |

# Performing Power Conversion

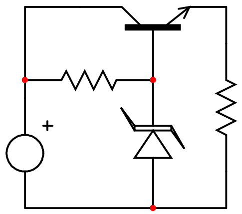
- Power conversion can be done in two ways, linear or switched
- The linear approach relies on a controlled resistance to regulate the flow
- The switching approach uses a power switch either open or closed




$R$ from 0 to ∞

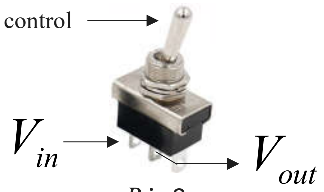
The **linear** approach:

- efficiency is poor
- good noise performance
- acceptable when ($V_{out}$-$V_{in}$) is small
- can only decrease the input level




Linear regulator

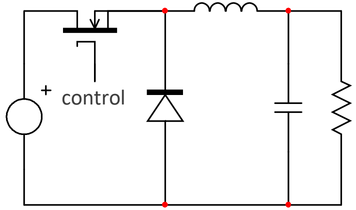
MC7805




$R$ is 0
or
$R$ is ∞

The **switching** approach:

- efficiency is high
- noise performance is poor
- works with large ($V_{out}$-$V_{in}$)
- increase/decrease/invert the input level
- requires energy-storing elements

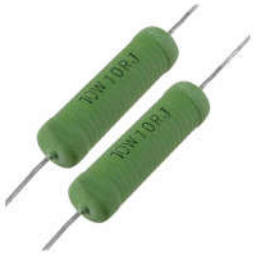


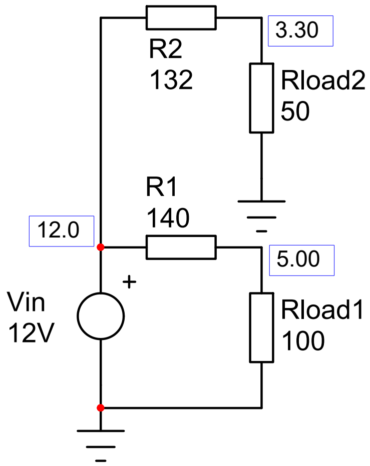

Switching regulator

MC34063

# Associating Resistors to Lower the Voltage

- Associating resistors together is a way to reduce the voltage
- It is however difficult to keep a stable value when operating conditions change




3.3 V DSP

5 V logic

$$P_{out} = \frac{5^2}{100} + \frac{3.3^2}{50} = 468\text{ mW}$$

$$P_{in} = \frac{12^2}{100+140} + \frac{12^2}{50+132} = 1.39\text{ W}$$

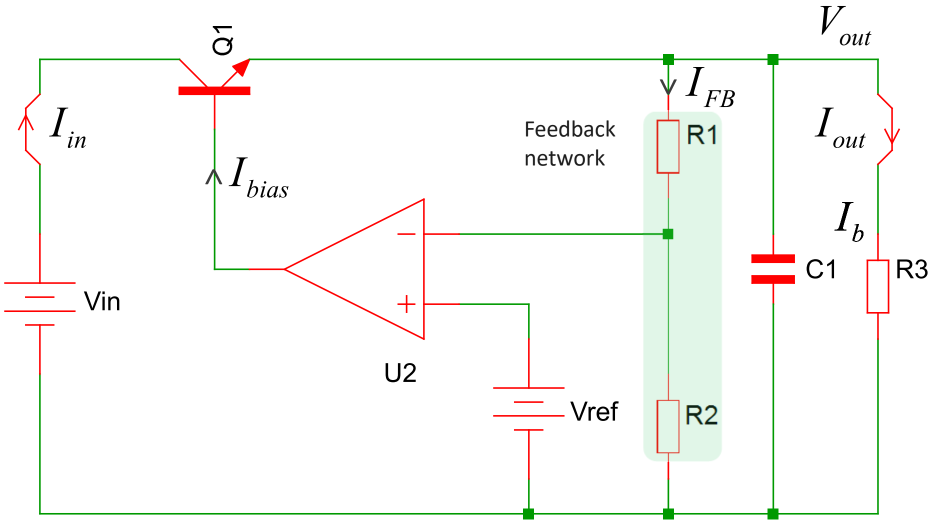
$$\eta = \frac{P_{out}}{P_{in}} = \frac{0.468}{1.39}100 = 33.6\%$$

✓ Efficiency is poor and power dissipation can be high

✓ Not suited for highly-variable output currents

# A Controlled Resistance

- The series resistance can be replaced by a controlled element  such as a transistor
- An error amplifier monitors the output voltage and adjusts the driving bias




❖ If the feedback current is neglected:

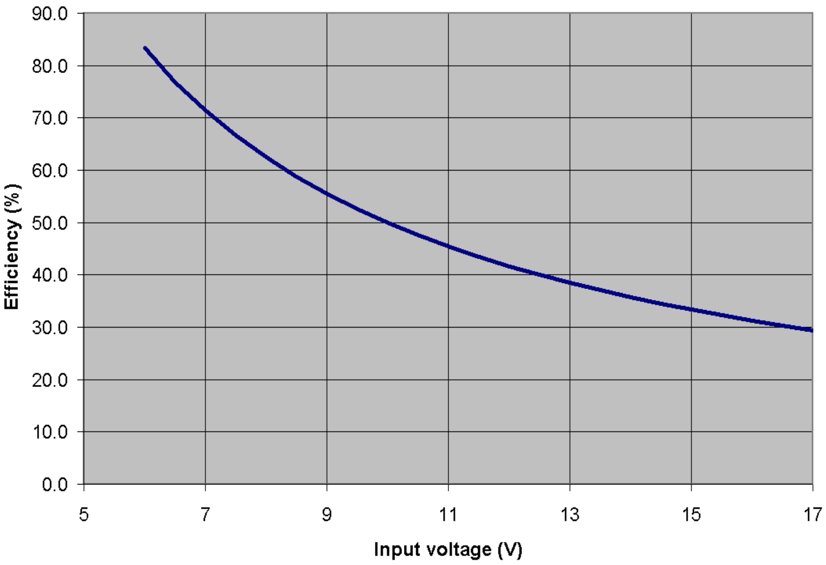
Conversion ratio

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{out} I_{out}}{V_{in} I_{in}} \approx \frac{V_{out}}{V_{in}} = \boxed{M}$$

✓ The efficiency depends on the difference between input and output voltages

# Linear Regulators can be Efficient

- A small difference $\Delta V$ between $V_{in}$ and $V_{out}$ brings good efficiency
- Efficiency betters if the $\Delta V$ drop is reduced compared to $V_{out}$




$V_{out}$ = 5 V

6 V → → 5 V/1 A

$$\eta \approx \frac{V_{out}}{V_{in}} = \frac{5}{6} = 83\%$$

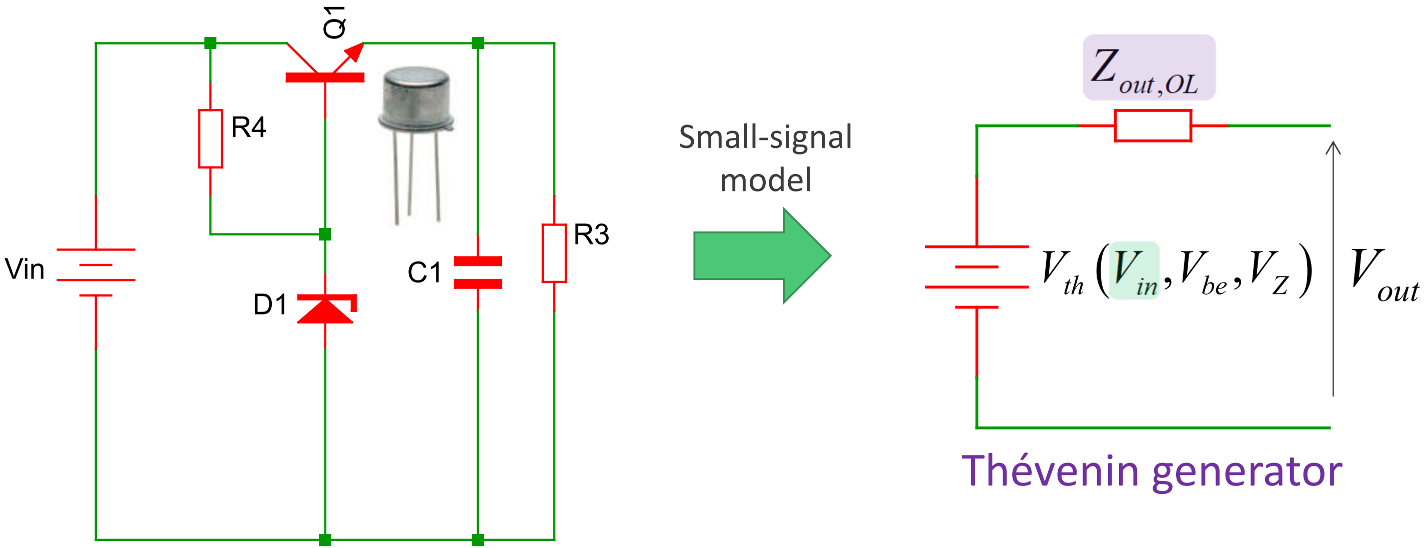
$$\Delta V << V_{out}$$

13 V → → 12 V/1 A

$$\eta \approx \frac{V_{out}}{V_{in}} = \frac{12}{13} = 92.3\%$$

# Modeling a Linear Regulator

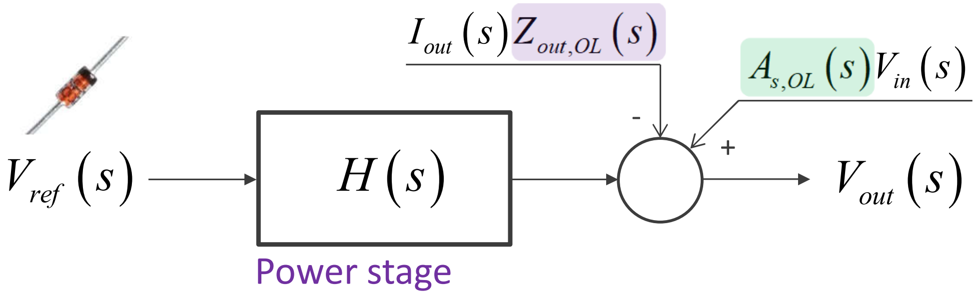
- Any linear system can be reduced to its equivalent Thévenin generator
  - A voltage source $V_{th}$ is affected by an output resistance $R_{th}$




- The output voltage is made of three contributors: $V_{in}$, $I_{out}$ , $V_{be}$ and $V_Z$

# Description by Block Diagrams

- It is possible to represent the linear regulator with blocks
- The $H$ stage describes the bipolar transistor power stage transfer function

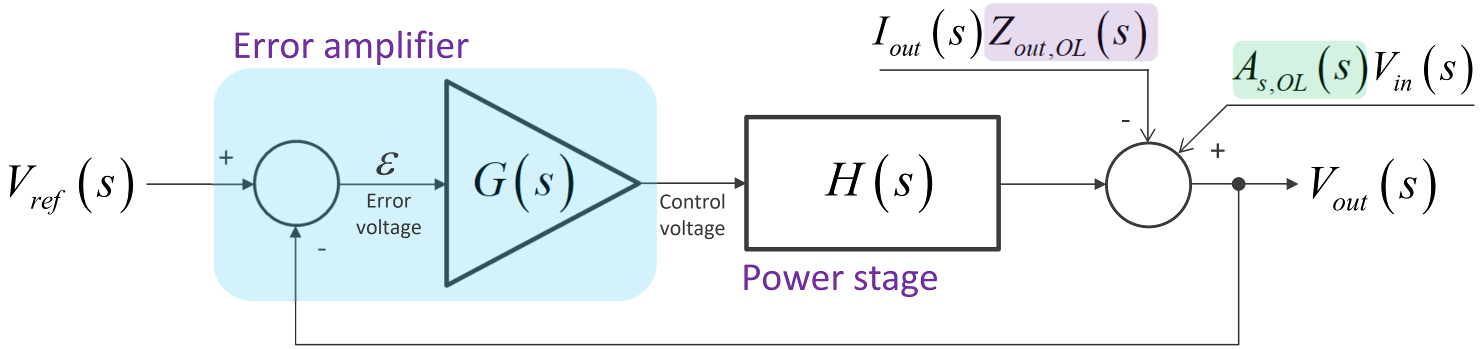



- We can easily write the equation describing the output voltage expression

$$V_{out}(s) = V_{ref}(s)\underbrace{H(s)}_{\text{Power stage}} - I_{out}(s)\underbrace{Z_{out,OL}(s)}_{\substack{\text{Open-loop output}\\\text{impedance}\\\text{contribution}}} + \underbrace{A_{s,OL}(s)}_{\substack{\text{Open-loop}\\\text{input voltage}\\\text{contribution}}}V_{in}(s)$$

# Benefits of closing the Loop

- The deviation between the reference and the output generates an error $\varepsilon$
- The error is then amplified and shaped by the compensator




$$V_{out}(s)=\left[V_{ref}(s)-V_{out}(s)\right]T(s)-I_{out}(s)Z_{out,OL}(s)+A_{s,OL}(s)V_{in}(s)$$

Loop gain

$$T(s)=G(s)H(s)$$

$$V_{out}(s)=\underbrace{V_{ref}(s)\frac{T(s)}{1+T(s)}}_{\text{Theoretical output}}-I_{out}(s)\underbrace{\frac{Z_{out,OL}(s)}{1+T(s)}}_{\text{Closed-loop output impedance}}+V_{in}(s)\underbrace{\frac{A_{s,OL}(s)}{1+T(s)}}_{\text{Closed-loop input rejection ratio}}$$

# Sensitivity Function

- A converter robustness qualifies its ability to reject perturbations
  - The input voltage, the output current or temperatures are perturbations
  - ✓ A high loop gain guarantees efficient perturbation rejection and improves robustness

$$V_{out}(s) = V_{ref}(s)\frac{T(s)}{1+T(s)} - I_{out}(s)Z_{out,CL}(s) + V_{in}(s)A_{s,CL}(s)$$

Static error

$$V_{out}(s) = V_{ref}(s)\frac{T(s)}{1+T(s)} \xrightarrow{T_0 \to \infty} V_{out}(s) \approx V_{ref}(s) \quad \varepsilon \to 0$$

No static error

Output impedance

$$Z_{out,CL}(s) = Z_{out,OL}\frac{1}{1+T(s)} \xrightarrow{T_0 \to \infty} R_{0,CL} \to 0\ \Omega$$

No output drop

PSRR

$$A_{sc,CL}(s) = A_{sc,OL}\frac{1}{1+T(s)} \xrightarrow{T_0 \to \infty} A_{sc,CL} \to 0$$

Infinite input rejection

Sensitivity function

# Small-Signal Parameters

- The output impedance and the rejection ratio are all small-signal parameters
- The static values can be measured in a two-step approach

$V_{in1}$, $V_{in2}$

$\rightarrow$ $V_{out1}\big|_{I_{out}}$, $V_{out2}\big|_{I_{out}}$

Dc PSRR $\Rightarrow$

$$A_{s,OL} = \frac{\Delta V_{out}}{\Delta V_{in}}$$

$V_{in}$

$\rightarrow$ $V_{out1}\big|_{I_{out1}}$, $V_{out2}\big|_{I_{out2}}$

$R_0$ $\Rightarrow$

$$R_{0,CL} = \frac{\Delta V_{out}}{\Delta I_{out}}$$

- Keep the input voltage or output current variations small for a linear behavior

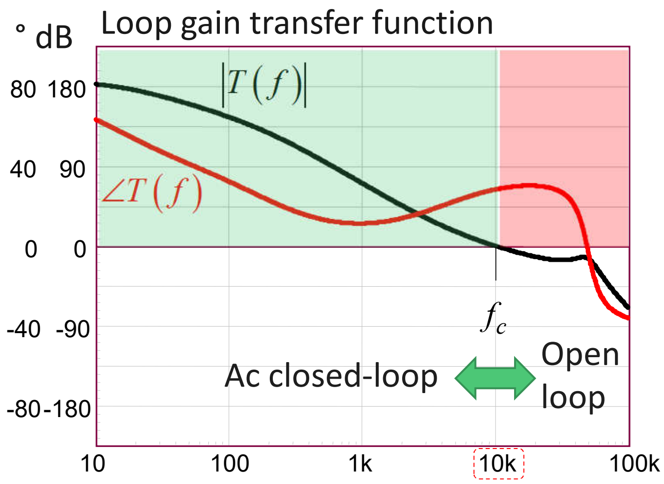
✓ A small variation means a differentiation:

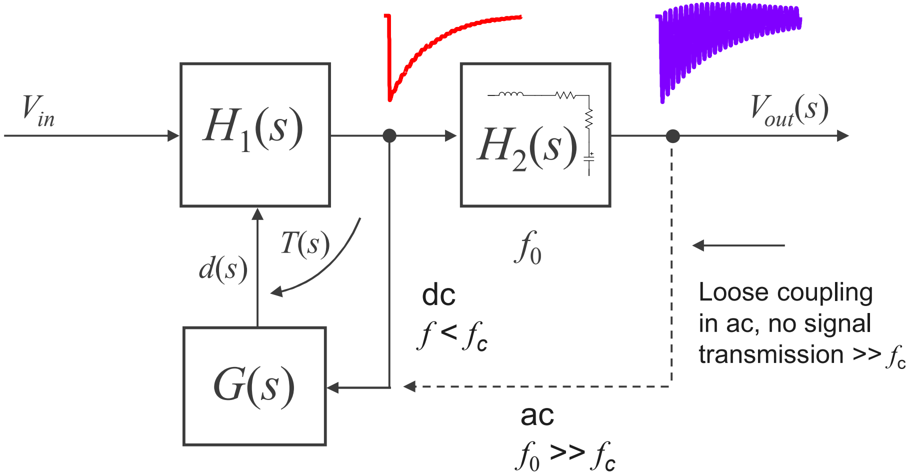
✓ Small-signal representation only

$$R_{0,CL} = \frac{V_{out2} - V_{out1}}{I_{out2} - I_{out1}} \quad \xLeftrightarrow[I_{out2} - I_{out1} \to 0]{} \quad R_{0,CL} = \frac{\mathrm{d}V_{out}}{\mathrm{d}I_{out}}\bigg|_{I_{out}}$$

# No Gain, no Feedback!

- We know the loop gain must drop to force crossover at a given frequency
- Crossover determines the dynamic behavior of the converter: speed, reaction time
- As long as the perturbation frequency is before crossover, correction occurs
- When perturbation frequency is beyond crossover, ac feedback is gone: open loop!



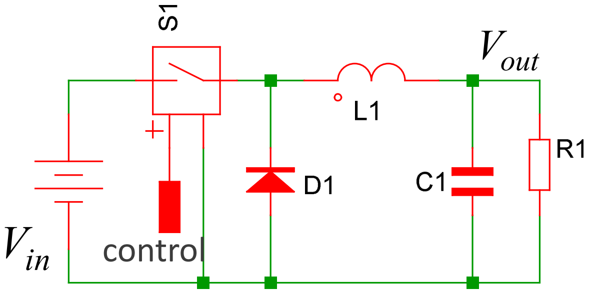



# Agenda

- Power Conversion Mechanisms
- Switching Cells and Control Schemes
- The Buck
- The Boost
- The Buck-Boost
- Introduction to Control Loop Design
- EMI Filter Interaction
- Introduction to Simulation

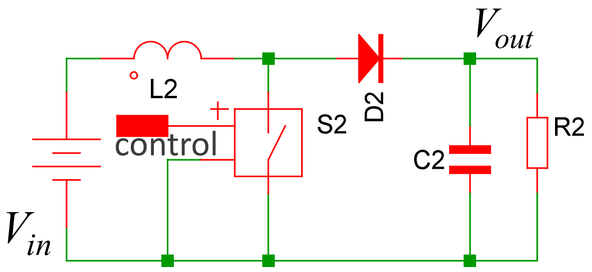
# Core Switching Cells

- The basic switching cells consist of three different converters
- ✓ The buck converter – it reduces the input voltage
- ✓ The boost converter – it increases the input voltage
- ✓ The buck-boost converter – it can increase or decrease the input voltage



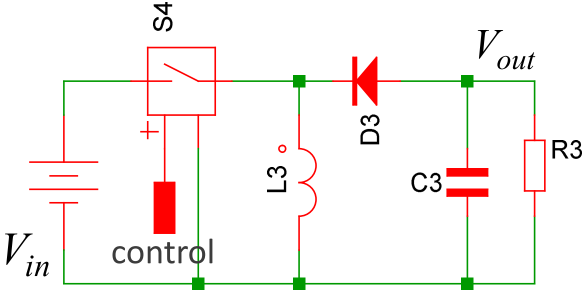

$$V_{out} < V_{in}$$

Buck




$$V_{out} > V_{in}$$

Boost

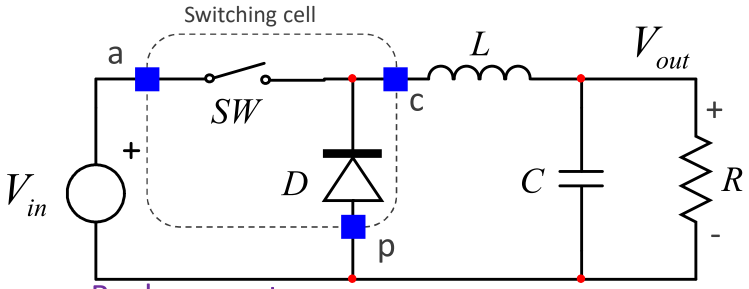



$$|V_{out}| < \text{or} > V_{in}$$

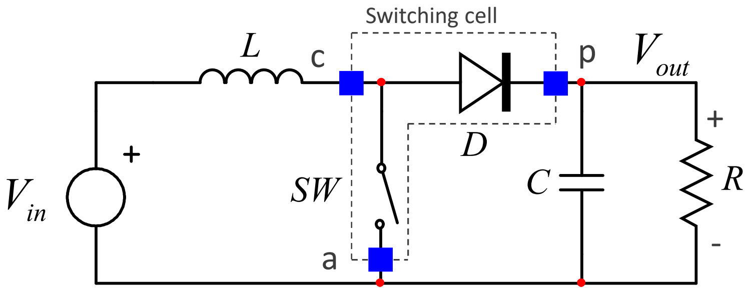
Buck-boost

# A Two-Switch Model

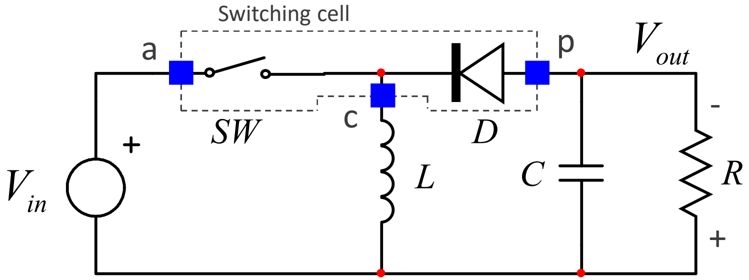
- Each basic structure shares a common switch + diode arrangement
- The switching cell is actually a single-pole double-throw power switch




Buck converter

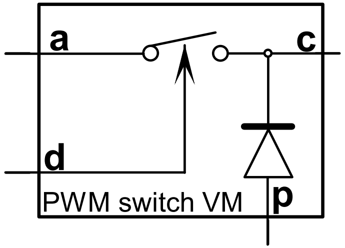



Boost converter




Buck-boost converter

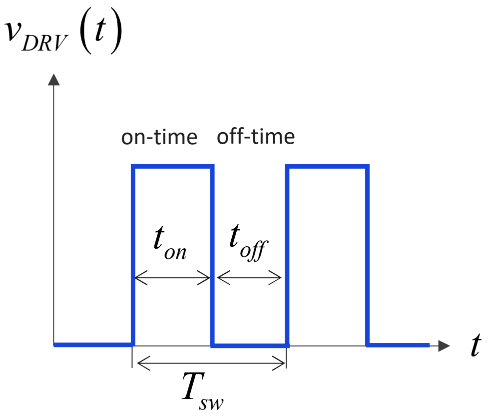
PWM switch model




a: active
c: common
p: passive

# Frequency and Duty Ratio

- The duty ratio $D$ defines the on-time duration divided by the switching period $T_{sw}$




$$D = \frac{t_{on}}{T_{sw}} \rightarrow t_{on} = DT_{sw}$$

On-time

$$D' = \frac{t_{off}}{T_{sw}} \rightarrow t_{off} = D'T_{sw}$$

Off-time

$$t_{on} + t_{off} = T_{sw}$$

$$T_{sw} = DT_{sw} + D'T_{sw}$$

$$D' = 1 - D$$

- There are two events in the switch activation: one switch is off while the other is off

✓ This is typical of a converter operated in continuous conduction mode or CCM

✓ A third event with all switches off occur in discontinuous conduction mode or DCM

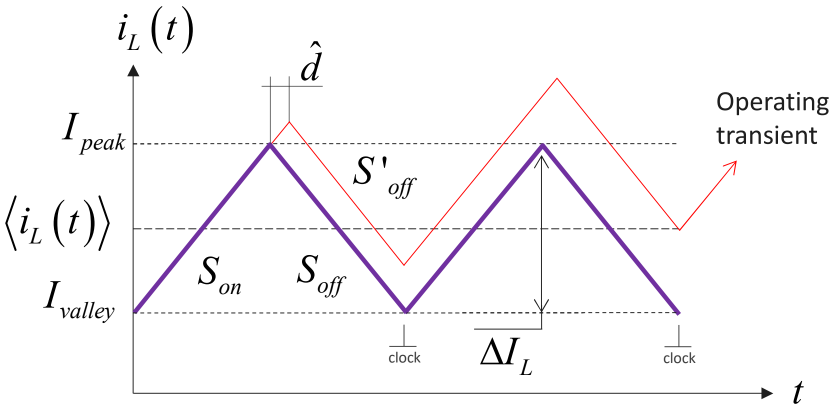
For all basic cells, the duty ratio $D$ controls the output voltage

# Inductive Current

- The current in an inductor ramps up and down during the switching period
- The current slope $S$ in A/s depends on the voltage applied across the inductor: $S = \frac{V}{L} \frac{[\mathrm{A}]}{[\mathrm{s}]}$

➢ The inductor energizes (stores energy) during the on-time

➢ The inductor de-energizes (releases energy) during the off-time




✓ The distance between $I_{peak}$ and $I_{valley}$ defines the ripple current $\Delta I_L$

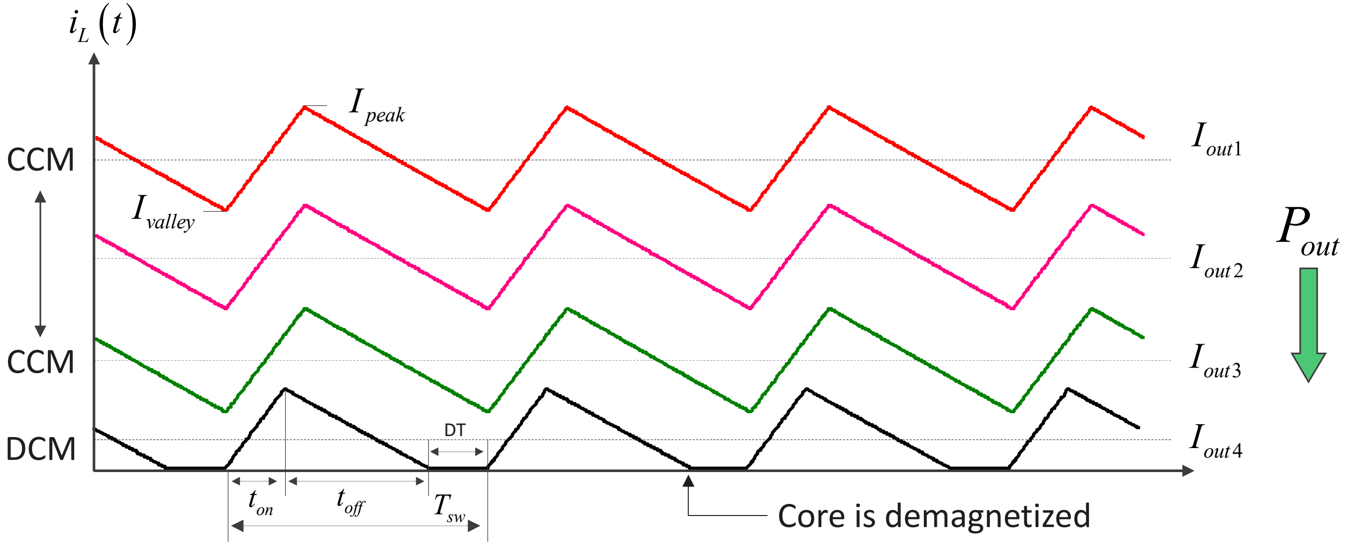
✓ Current starts from $I_{valley}$ and returns to the same level within the switching cycle

❖ If current keeps increasing: saturation

➨ If valley current is the same within one cycle: steady-state operation

# Conduction Mode

- The peak and valley currents determine the amount of processed energy
- Their levels depend on operating conditions set by input and output values




CCM: continuous conduction mode

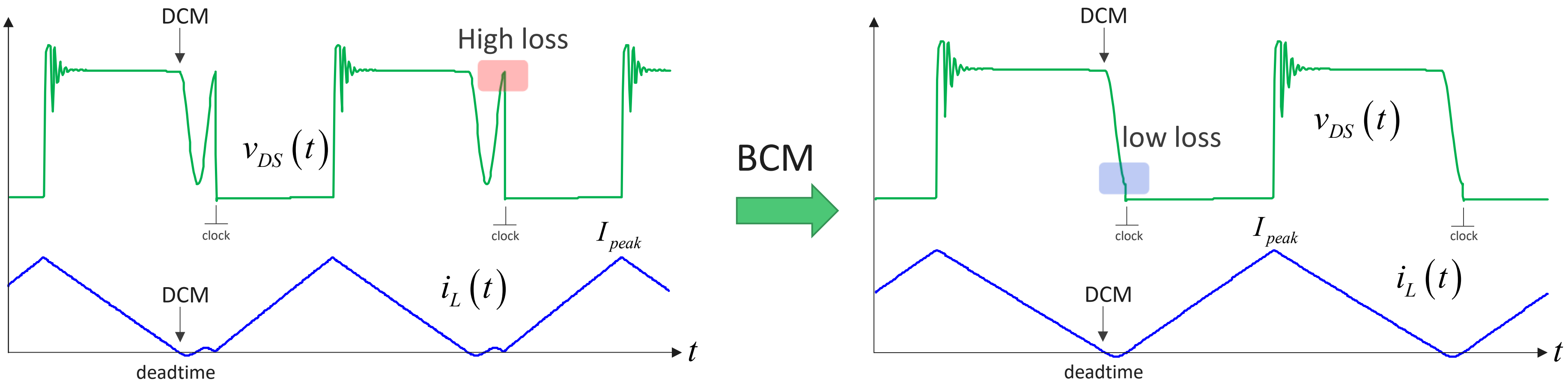
DCM: discontinuous conduction mode

✓ The converter operates in heavy CCM then goes into lighter CCM as $P_{out}$ decreases

✓ In light-load conditions, the valley current disappears and DCM is entered

# Borderline Conduction Mode

- A deadtime appears in DCM where both switches are blocked
- A specific control scheme restarts the main switch when the valley is 0 A




✓ Inserting a smaller deadtime in BCM leads to reducing the turn-on losses

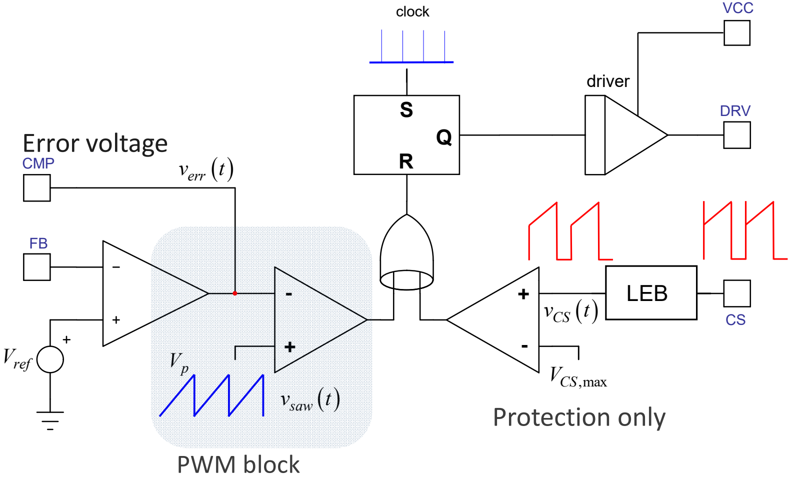
❖ A BCM-operated converter offers a highly variable switching frequency

BCM: borderline conduction mode

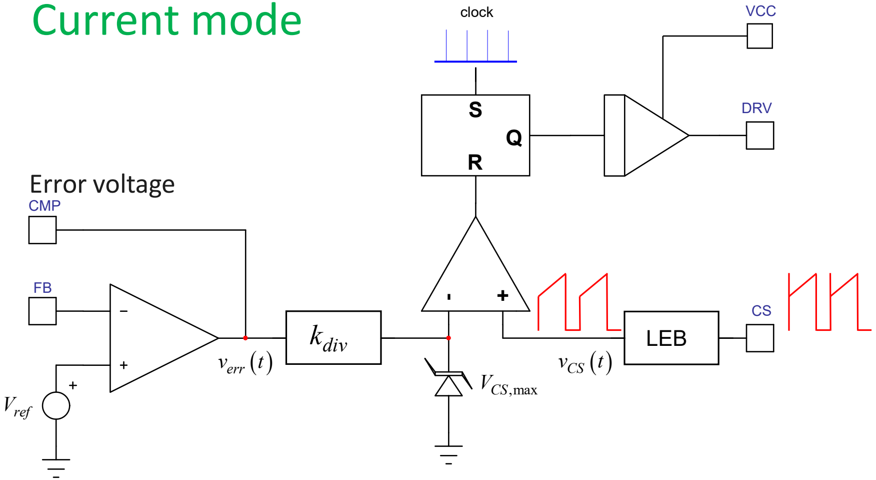
# Control Techniques

- A switching converter can be controlled in different ways
- The most classical solutions are fixed-frequency voltage- and current-mode control

## Voltage mode




## Current mode




✓ In VM control, the error voltage *directly* determines the duty ratio

✓ In CM control, the error voltage controls the peak current and *indirectly* the duty ratio

# Voltage- and Current-Mode Control

- Each control technique presents advantages and drawbacks

## Voltage-mode control:

- Ease of implementation: no need to sense inductor current
- Can operate down to very low duty ratio
- Large-amplitude artificial voltage brings good noise immunity
- Inherently-low output impedance
- ❖ Poor input rejection: any perturbation must first propagate before correction
- ❖ Second-order response complicates compensation

many controllers operate in voltage-mode control

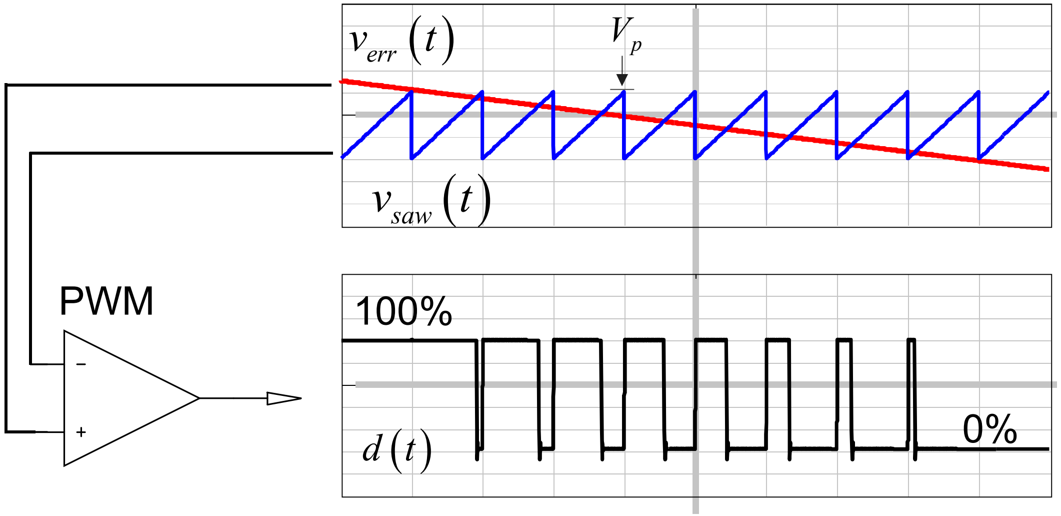
## Current-mode control:

- Natural input feedforward brings excellent input voltage rejection
- Inherent cycle-by-cycle overcurrent protection
- First-order response eases feedback loop design
- ❖ Inherently-high output impedance requires high loop gain
- ❖ Sub-harmonic instability in CCM needs slope compensation
- ❖ Difficult to operate at very low duty ratio

Mostly current-mode control

# Voltage-Mode Control – Duty Ratio Generator

- The duty ratio is obtained by comparing a sawtooth and the error voltage
- When the two signals intersect, the comparator toggles




$$v_{saw}(t) = V_p \frac{t}{T_{sw}}$$

$$v_{err}(t) = V_p d(t)$$

$$d(t) = \frac{v_{err}(t)}{V_p}$$

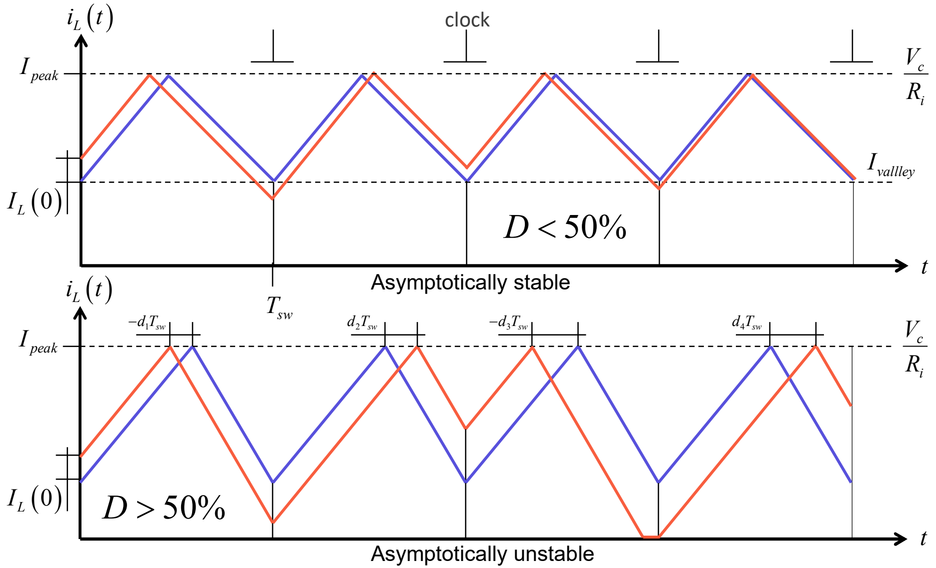
Discrete value!

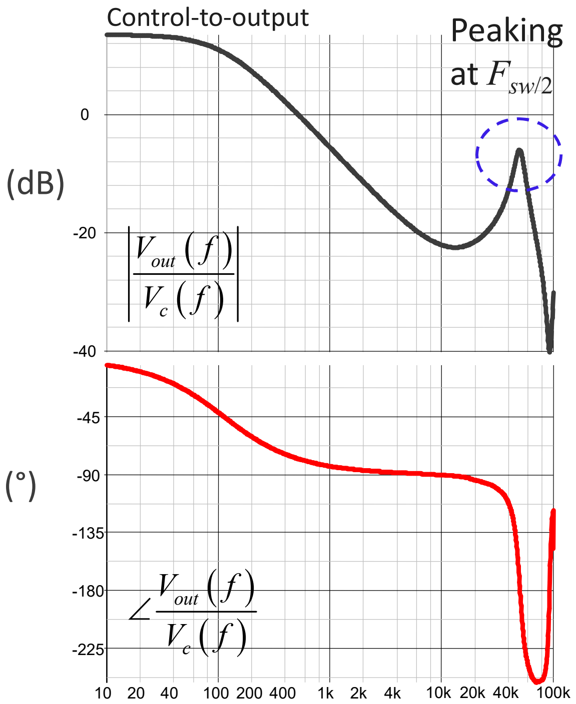
✓ This is a *naturally sampled* modulator

✓ The small-signal gain of this PWM block is $G_{PWM} = \frac{1}{V_p}$

# Current-Mode Control – Subharmonic Oscillations

- Current-mode-controlled converters can be become instable in CCM
- When the duty ratio approaches 50% subharmonic oscillations can appear

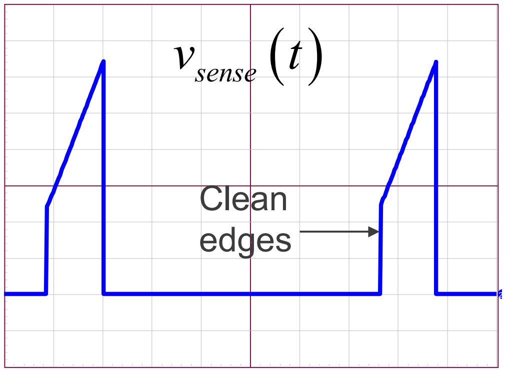


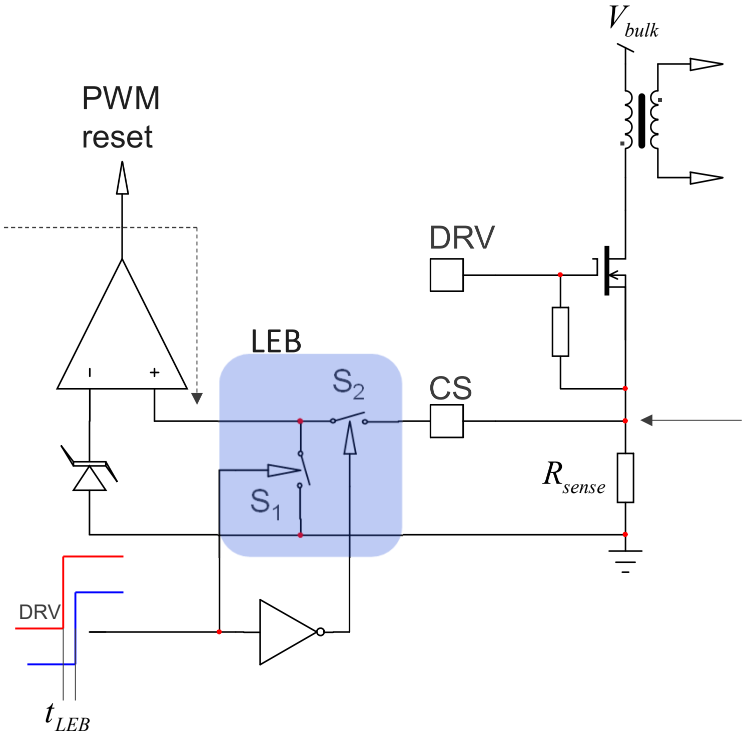



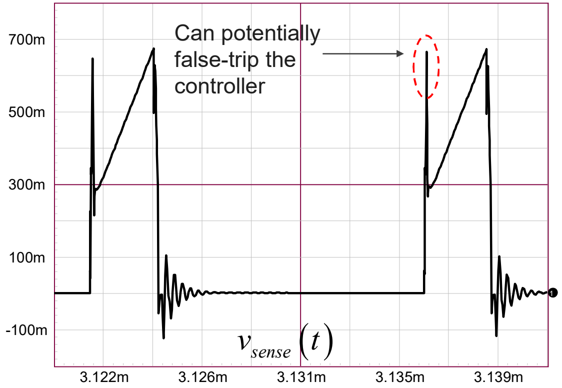

- ✓ The inner current loop can bring instability
- ✓ Slope compensation helps stabilizing the loop

# Leading-Edge Blanking

- For reliable operations it is important to sense the switch current cycle by cycle
- Regardless of the control mode, the inductor current needs to be cleaned up



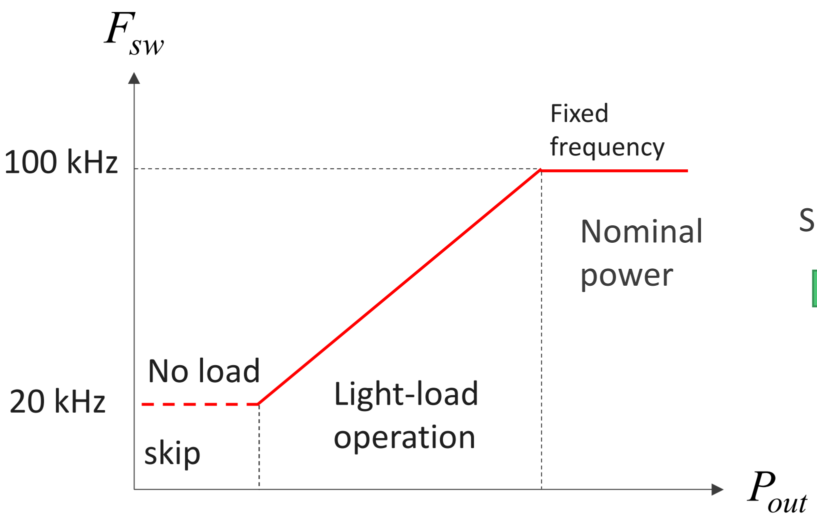




✓ The LEB cleans the signal up and ensures reliable operation

✓ The voltage image of the current is polluted by spikes

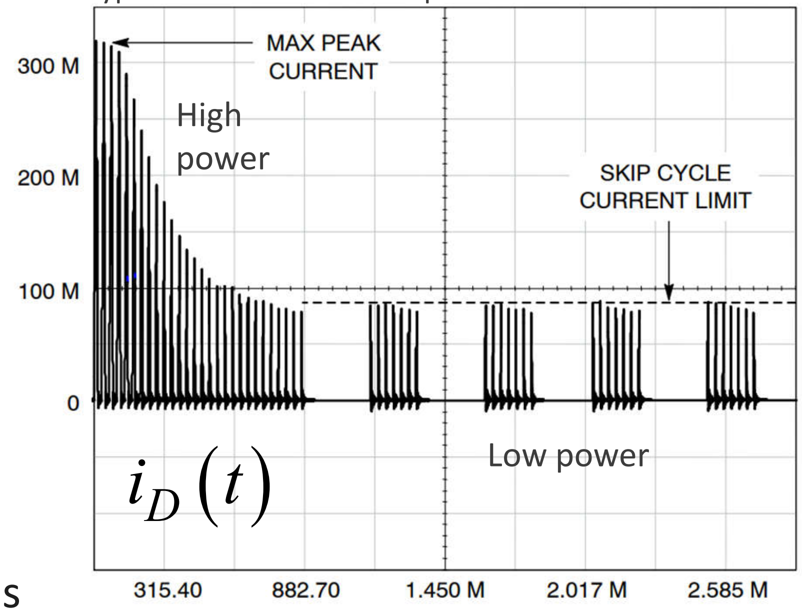
# Skip Cycle and Frequency Reduction

- For efficient light-load operations, frequency foldback can be implemented
- In no-load conditions the part can enter skip cycle to further improve standby




Skip cycle

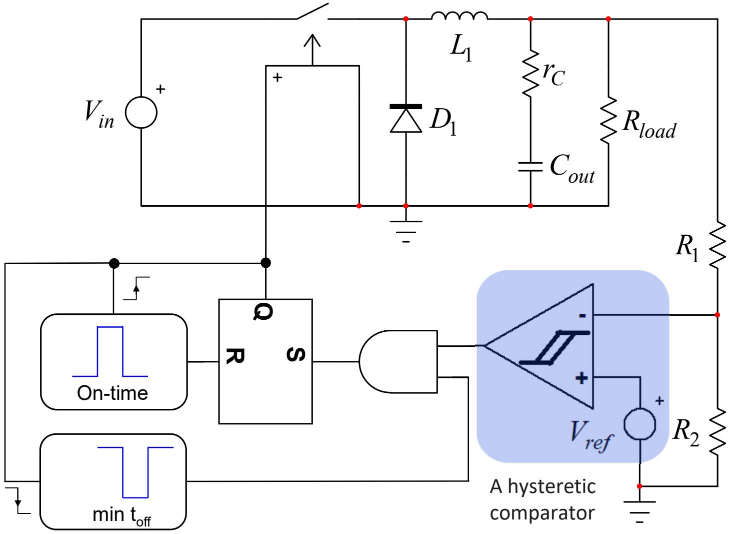
Typical drain current in skip mode

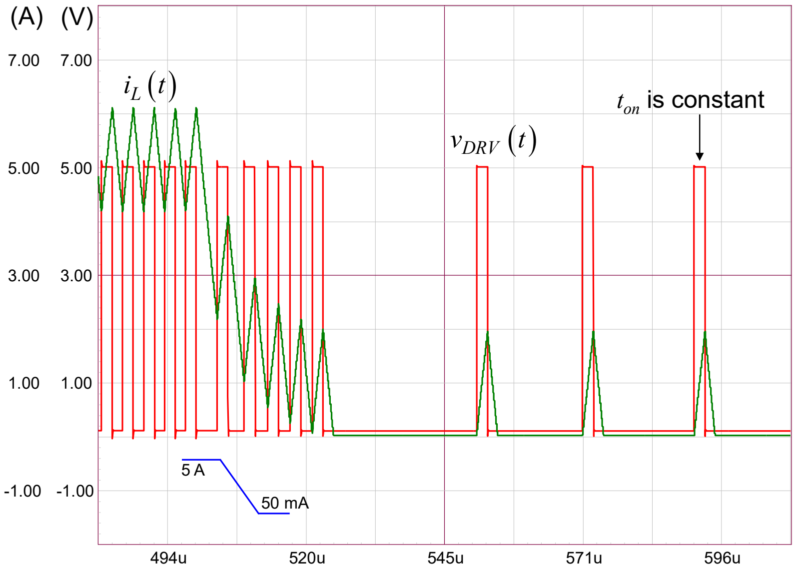



✓ Frequency linearly reduces as power decreases

# Hysteretic Converters

- A comparator affected by a hysteresis band trips a constant-on-time circuit
- The circuit is intrinsically instable and does not require compensation

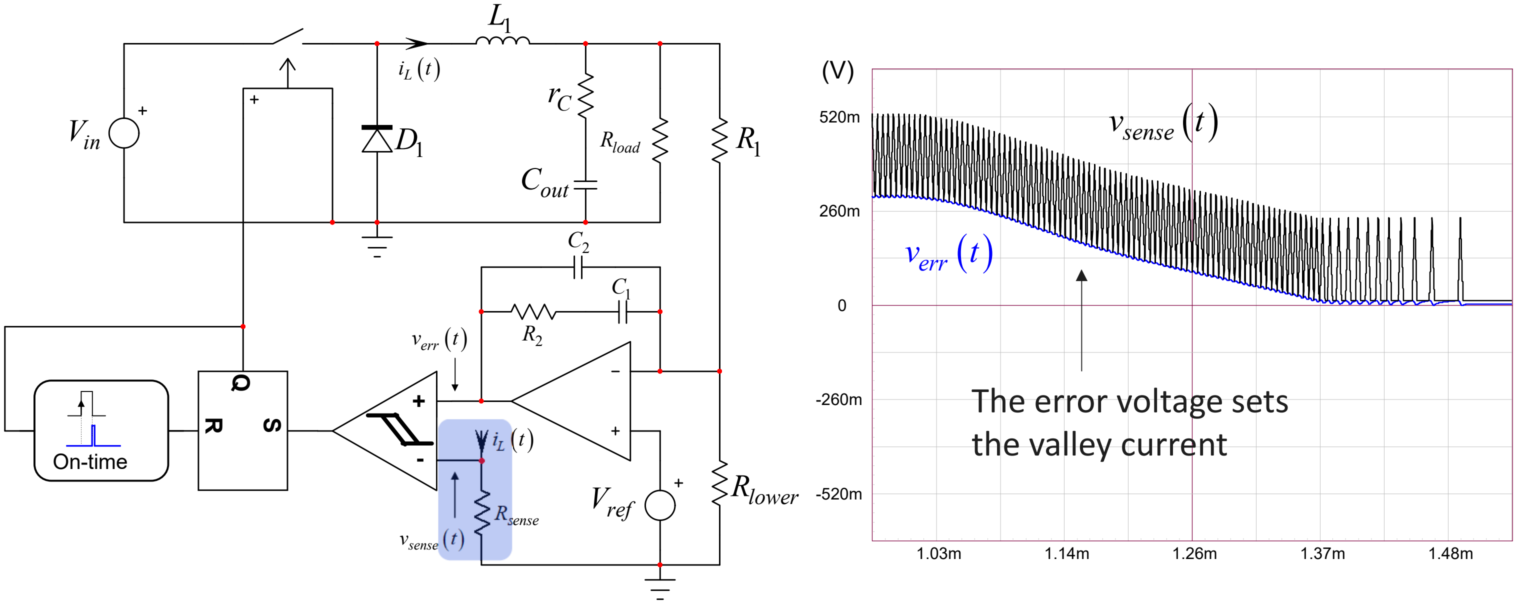



- ✓ The frequency adapts to the input and output conditions
- ✓ The circuit naturally enters a low-frequency mode in light-load conditions

# Hysteretic Converters with an Op-Amp

- The hysteretic constant-on-time converter can be supplemented with an op-amp
- The converter operates in current-mode control with a valley setpoint adjustment




✓ Immune to sub-harmonic oscillations

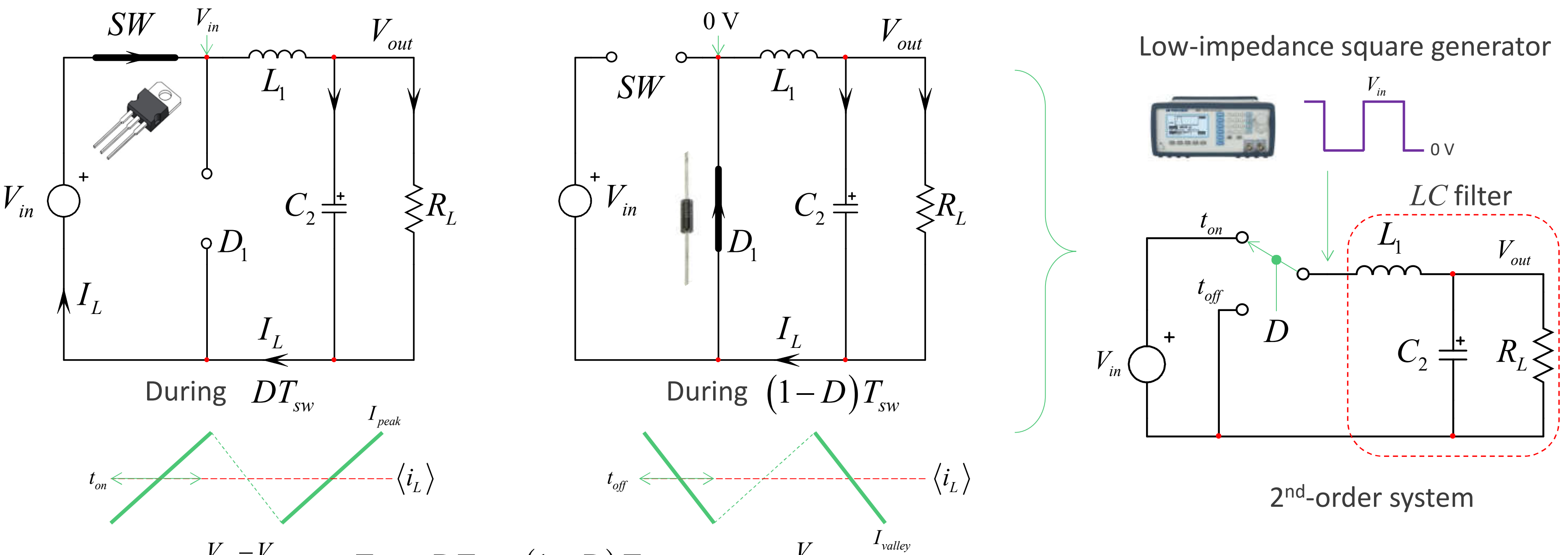
✓ Naturally goes in standby mode in light-load

# Agenda

- Power Conversion Mechanisms
- Switching Cells and Control Schemes
- The Buck
- The Boost
- The Buck-Boost
- Introduction to Control Loop Design
- EMI Filter Interaction
- Introduction to Simulation

# The Buck Converter

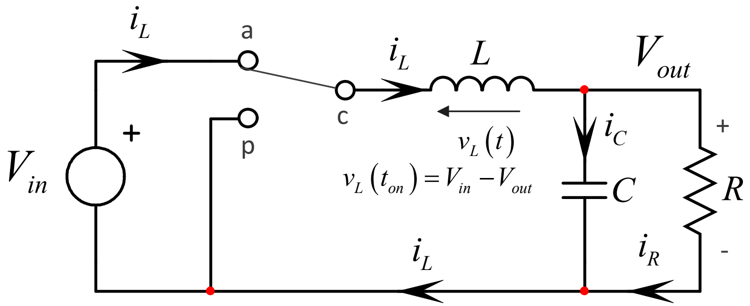
- The buck converter reduces the input voltage and operates up to 100% duty ratio
- The common SW-D node swings between $V_{in}$ and 0 V



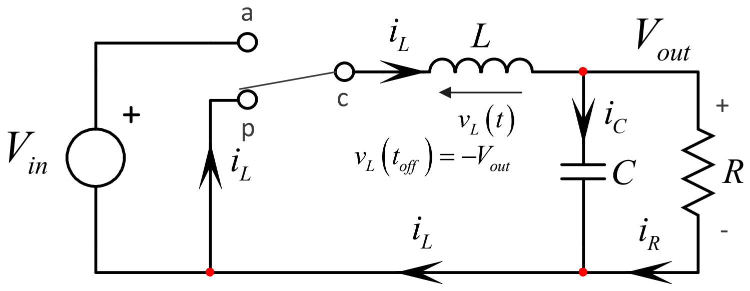

$$S_{on} = \frac{V_{in} - V_{out}}{L_1} \qquad T_{sw} = DT_{sw} + (1-D)T_{sw} \qquad S_{off} = -\frac{V_{out}}{L_1}$$

# Transfer Characteristic of the CCM Buck

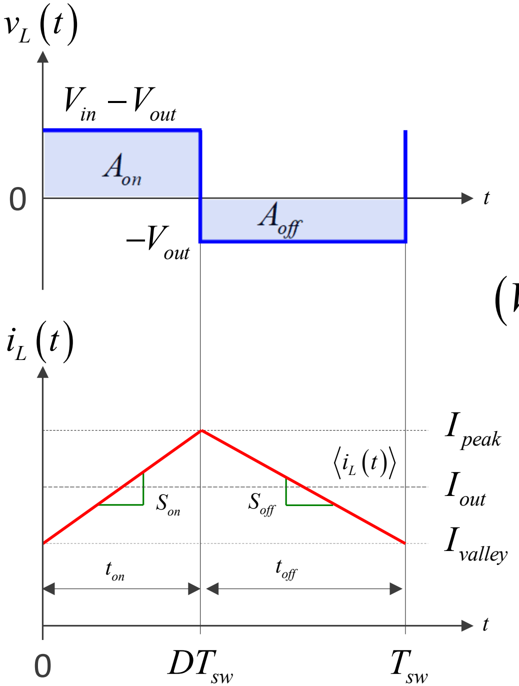
- Consider the average inductor voltage to determine the dc transfer characteristic
- Express the volt-seconds of the inductor during the on- and off-times




During $t_{on}$ or $DT_{sw}$




During $t_{off}$ or $(1-D)T_{sw}$




V-s balance

$$\langle v_L(t) \rangle_{T_{sw}} = 0 \text{ V}$$

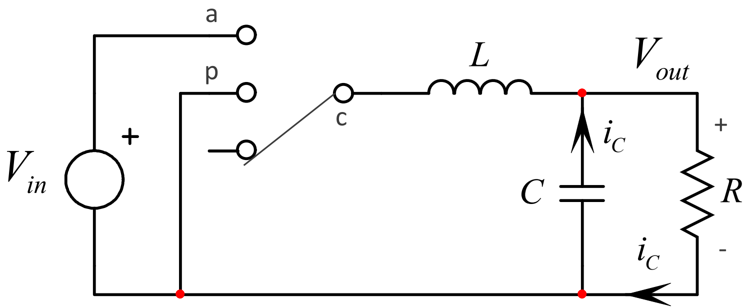
$$(V_{in} - V_{out}) DT_{sw} = V_{out}(1-D)T_{sw}$$

$$V_{out} = DV_{in}$$

$$M = \frac{V_{out}}{V_{in}} = D$$

# Transfer Characteristic of the DCM Buck

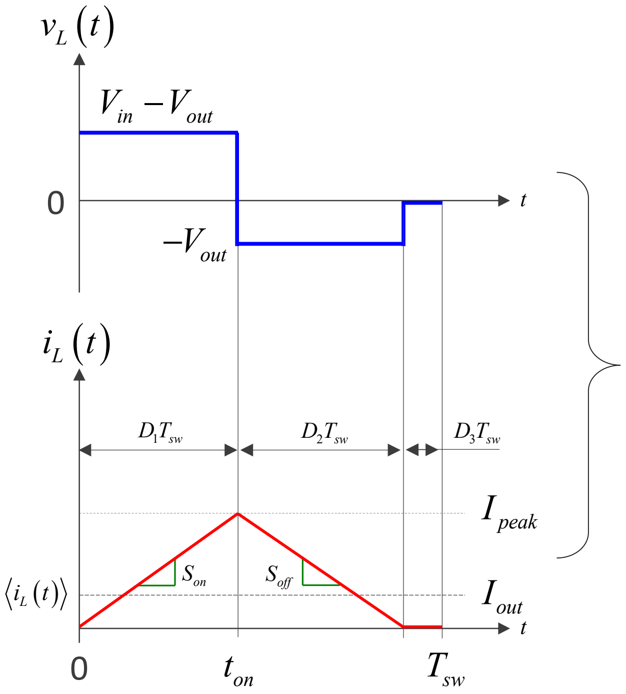
- When the load current decreases, the valley current goes to 0 A and deadtime appears
- The condition at which DCM occurs is determined by the *critical* input or load value




During $D_3T_{sw}$

$$R_{critical} = \frac{2LF_{sw}}{1-D}$$

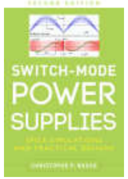
$$R < R_{critical} \rightarrow \mathrm{CCM}$$
$$R = R_{critical} \rightarrow \mathrm{BCM}$$
$$R > R_{critical} \rightarrow \mathrm{DCM}$$




$$M = \frac{2}{1+\sqrt{1+\dfrac{8LF_{sw}}{RD_1^{2}}}}$$

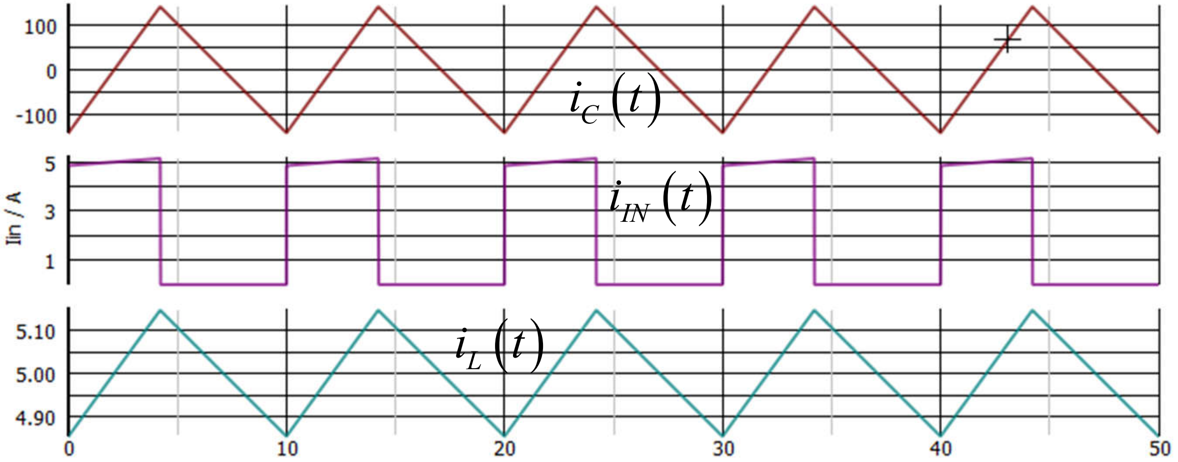
- ✓ Depends on $F_{sw}$
- ✓ Depends on $R$

C. Basso, *SMPS SPICE Simulations*, McGraw-Hill, 2014



# Input and Output Currents

- It is important to know the nature of the circulating input and output currents
- The inductance located in the output naturally smooths current which is *non-pulsating*
- The input current is *pulsating* and highly discontinuous: high ac component




✓ The output capacitor is non-pulsating and is of low rms value

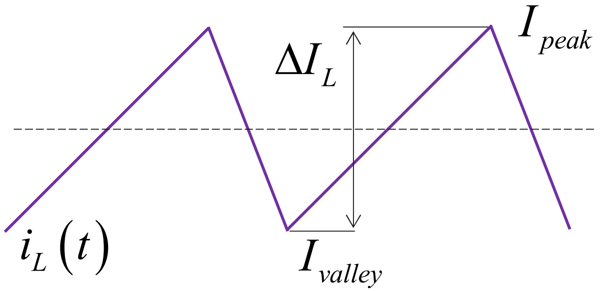
✓ The input current is highly discontinuous and contributes a high rms value

✓ The inductor current is a smooth triangular waveform

- The buck converter is quiet on the output and noisy on the input: difficult EMI

# Peak Current and Inductor Value

- From the output current and the acceptable ripple you can pick the right switcher
- The sweet spot of the inductor ripple current is around 40% with modern core
- How to select the switcher maximum peak current?




$$\langle i_L(t) \rangle = I_{out}$$

$$\Delta I_L = 40\% I_{out} = \frac{V_{out}}{L}(1-D)T_{sw}$$

$$L = \frac{V_{out}(1-D)}{I_{out}F_{sw} \times 0.4} \Rightarrow L \approx 73\ \mu\text{H}$$

$F_{sw}$: 100 kHz

- ✓ Assume $V_{in}$ = 12 V, $V_{out}$ = 5 V, $I_{out}$ = 1 A
- ✓ Select a ripple of 40%

$$I_{peak} = I_{out} + \frac{\Delta I_L}{2}$$

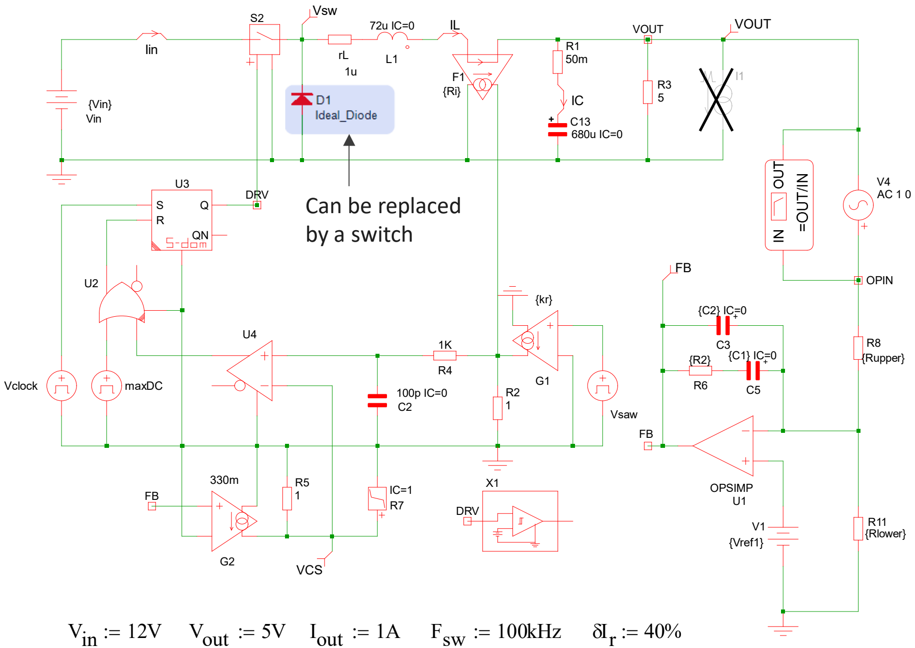
$$I_{peak} = I_{out} + \frac{40\% I_{out}}{2} = I_{out}\left(1 + \frac{0.4 \times 1}{2}\right)$$

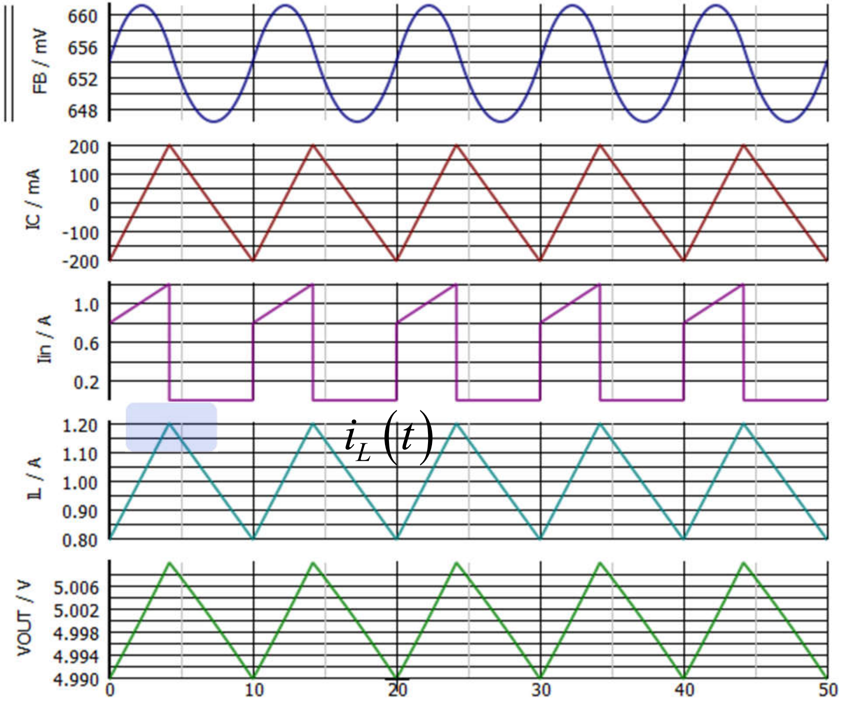
$$I_{peak} = 1 \times \left(1 + \frac{0.4 \times 1}{2}\right) = 1.2 \times I_{out} = 1.2\ \text{A}$$

Choose a switcher with at least this peak

# Simulation Gives Immediate Results

- It is interesting to run a quick SIMPLIS simulation to verify the calculated values
- The buck can be operated at its nominal conditions 5 V/1 A from the 12-V input



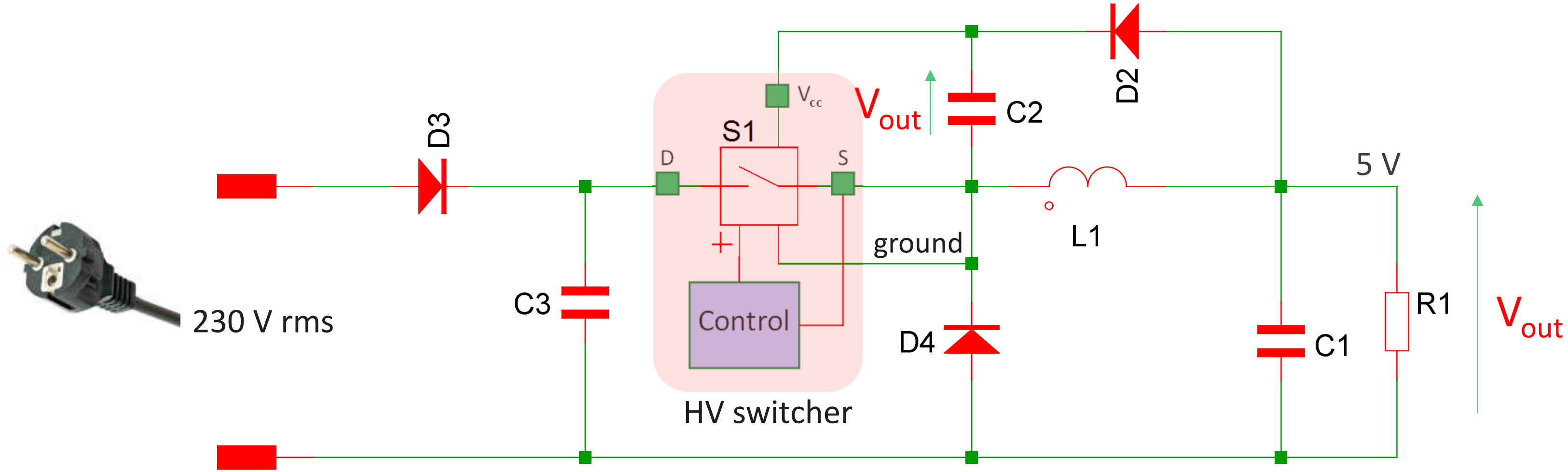

$V_{in} := 12V \quad V_{out} := 5V \quad I_{out} := 1A \quad F_{sw} := 100kHz \quad \delta I_r := 40\%$

$D := \frac{V_{out}}{V_{in}} = 41.667\% \qquad L_1 := \frac{V_{out} \cdot (1 - D)}{F_{sw} \cdot I_{out} \cdot \delta I_r} = 72.917 \mu H$

# High-Side Buck



- The control section can be ground-referenced or floating for high-voltage switchers
- The output voltage is rectified and referenced to the source of the switcher

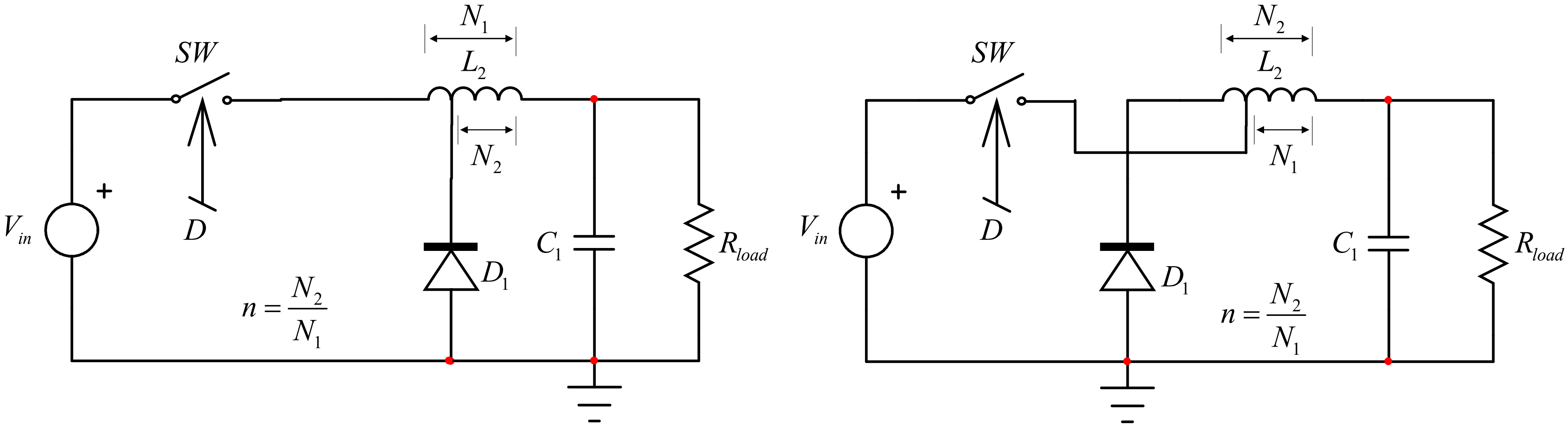



✓ Any low- or high-voltage switcher can be used in a floating configuration

➢ Watch for feedback polarity which should allow duty ratio reduction with bias increase

# Buck-Derived Topologies

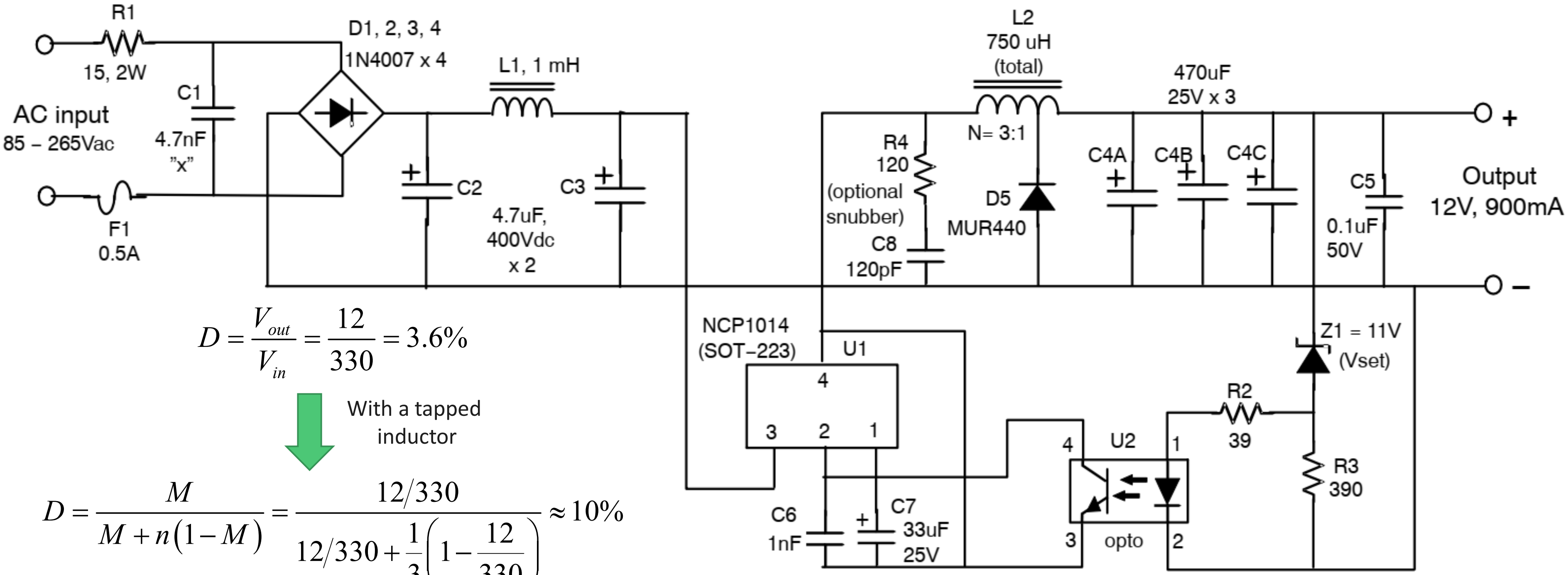
- The tapped-buck converter can be used for large differences between $V_{out}$ and $V_{in}$
- It brings a higher duty ratio despite a low output voltage




✓ The transfer characteristic of the tapped buck is $M = \dfrac{D}{D + \dfrac{1-D}{n}}$

# Typical Tapped Buck Application

- A tapped buck lends itself well to high-voltage non-isolated converters
- The duty ratio is increased owing to the tap in the inductor




$$D = \frac{V_{out}}{V_{in}} = \frac{12}{330} = 3.6\%$$

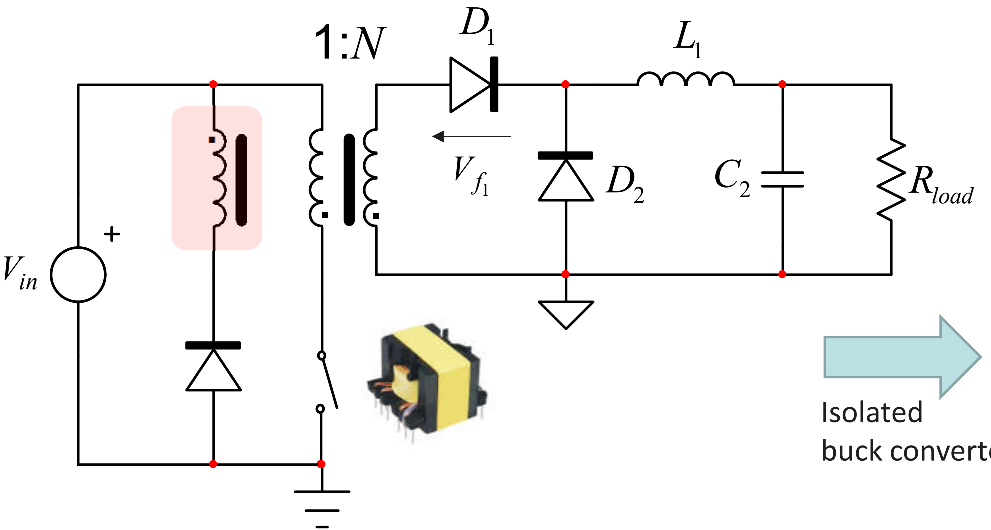
With a tapped inductor

$$D = \frac{M}{M + n(1 - M)} = \frac{12/330}{12/330 + \frac{1}{3}\left(1 - \frac{12}{330}\right)} \approx 10\%$$

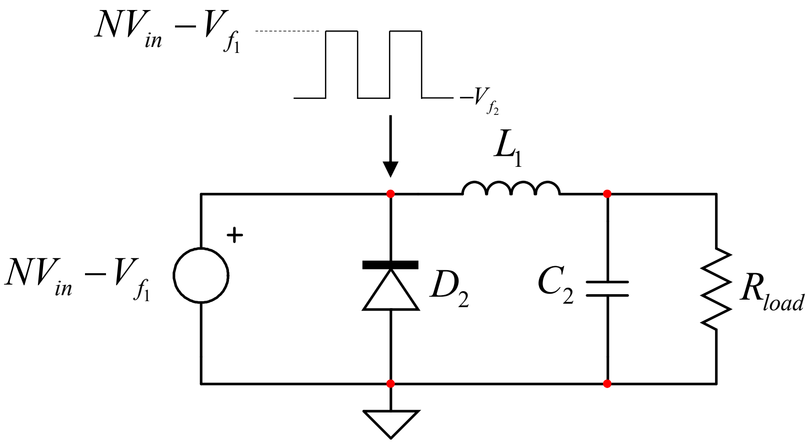
https://www.onsemi.com/pub/Collateral/AND8318-D.PDF

# The Forward Converter

- A transformer provides the necessary galvanic isolation for safe operations
- The transformer features 3 windings and one of them performs core reset




Isolated
buck converter




✓ Well suited for low output voltage with strong output currents

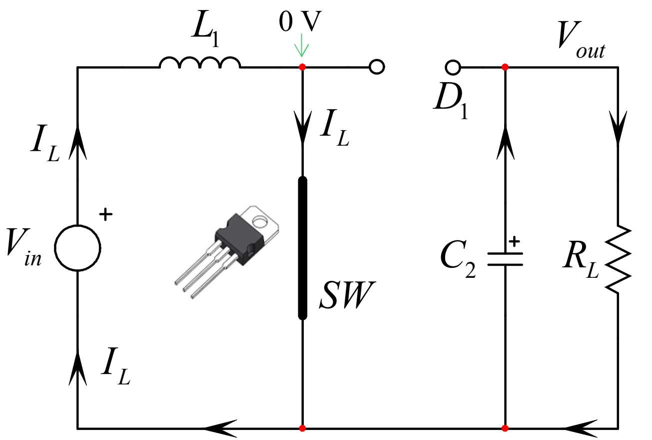
✓ Very popular in multi-output coupled-inductors silver boxes for computers

# Agenda

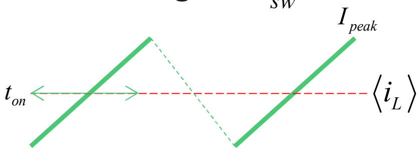
- Power Conversion Mechanisms
- Switching Cells and Control Schemes
- The Buck
- The Boost
- The Buck-Boost
- Introduction to Control Loop Design
- EMI Filter Interaction
- Introduction to Simulation

# The Boost Converter

- The boost converter increases the input voltage up to a certain limit
- The common SW-D node swings between 0 V and $V_{out}$

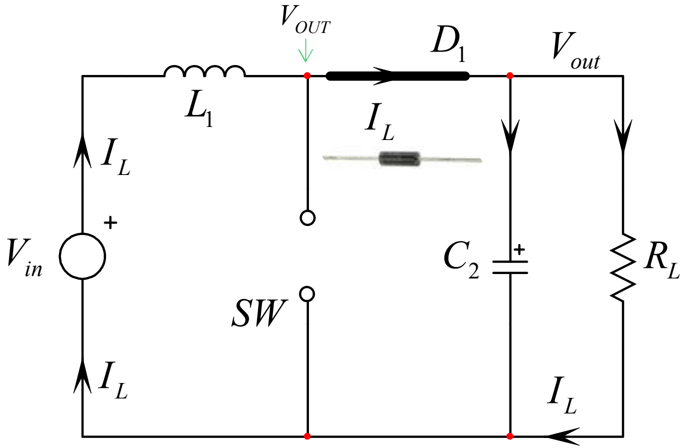



During $DT_{sw}$

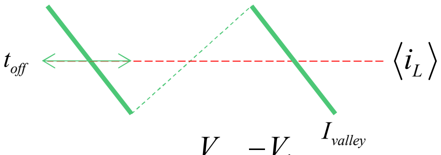



$$S_{on} = \frac{V_{in}}{L_1}$$

$$T_{sw} = DT_{sw} + (1-D)T_{sw}$$



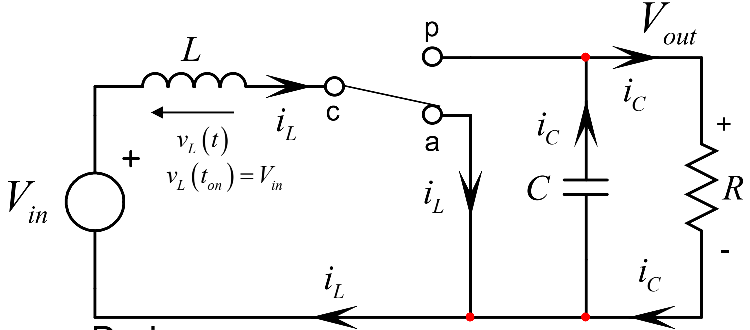

During $(1-D)T_{sw}$



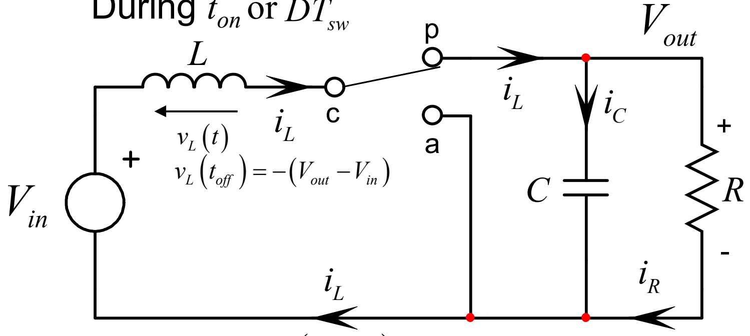

$$S_{off} = -\frac{V_{out} - V_{in}}{L_1}$$

# Transfer Characteristic of the CCM Boost

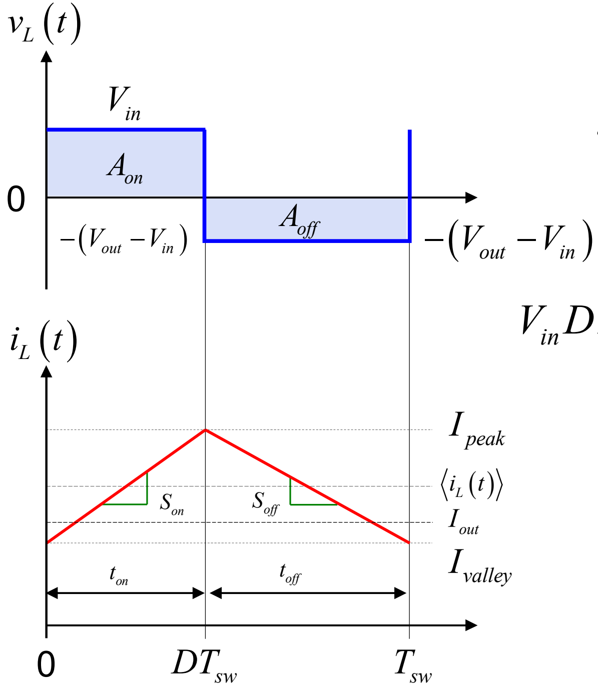
- Consider the average inductor voltage to determine the dc transfer characteristic
- Express the volt-seconds of the inductor during the on- and off-times




During $t_{on}$ or $DT_{sw}$




During $t_{off}$ or $(1-D)T_{sw}$




$$\langle i_L(t) \rangle_{T_{sw}} = I_{out}/(1-D)$$

V-s balance

$$\langle v_L(t) \rangle_{T_{sw}} = 0\ \mathrm{V}$$

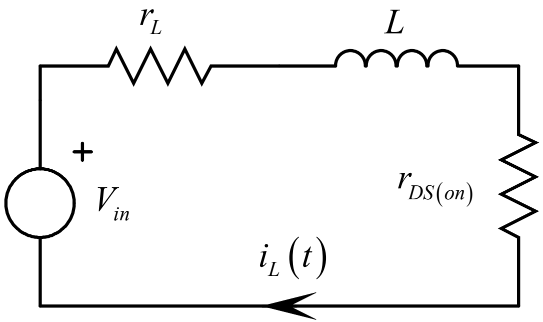
$$V_{in} DT_{sw} = (V_{out} - V_{in})(1-D)T_{sw}$$

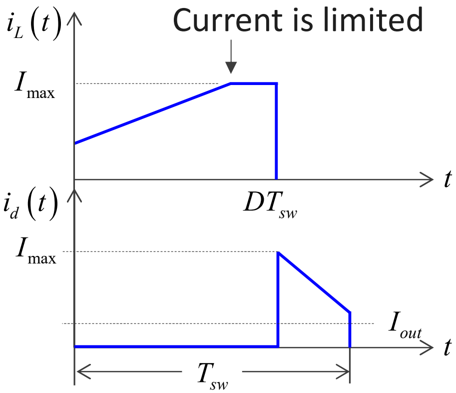
$$V_{out} = \frac{V_{in}}{1-D}$$

$$M = \frac{1}{1-D}$$

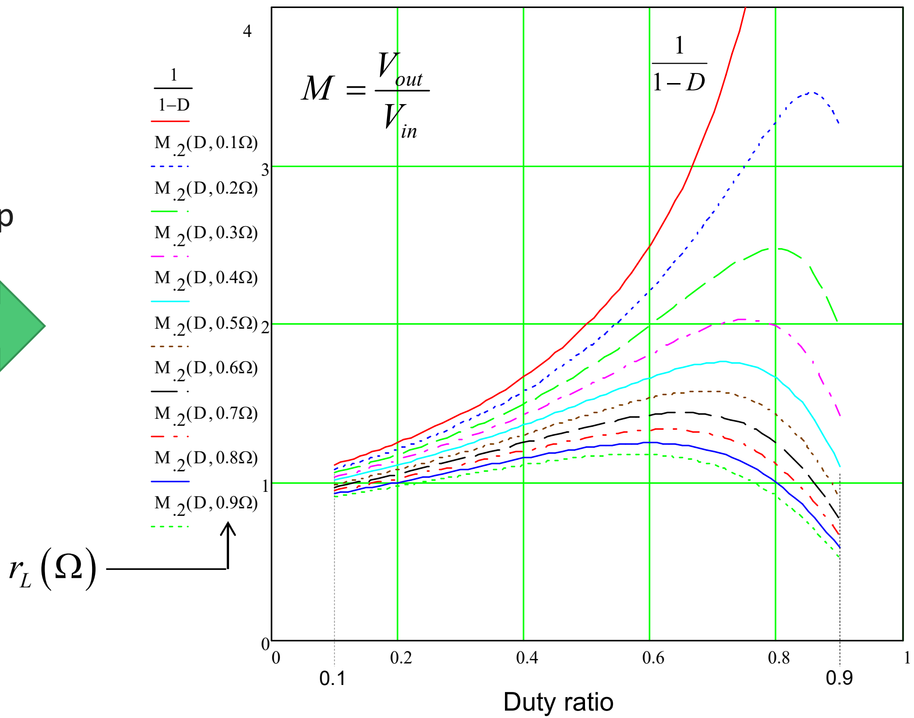
# A Finite Conversion Ratio

- The conversion ratio is limited by ohmic losses in the circuit
- The output can fall if duty ratio keeps increasing past a limit: this is the latch-up effect



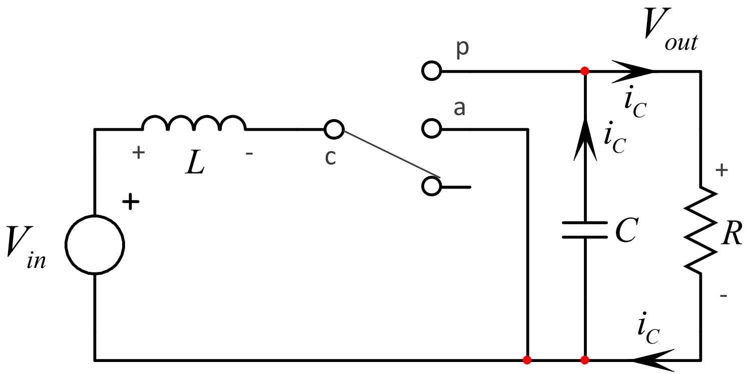




Latch-up effect



# Transfer Characteristic of the DCM Boost

- As the load current decreases, the converter enters discontinuous conduction mode
- The catch diode spontaneously blocks when the inductor current reaches 0 A



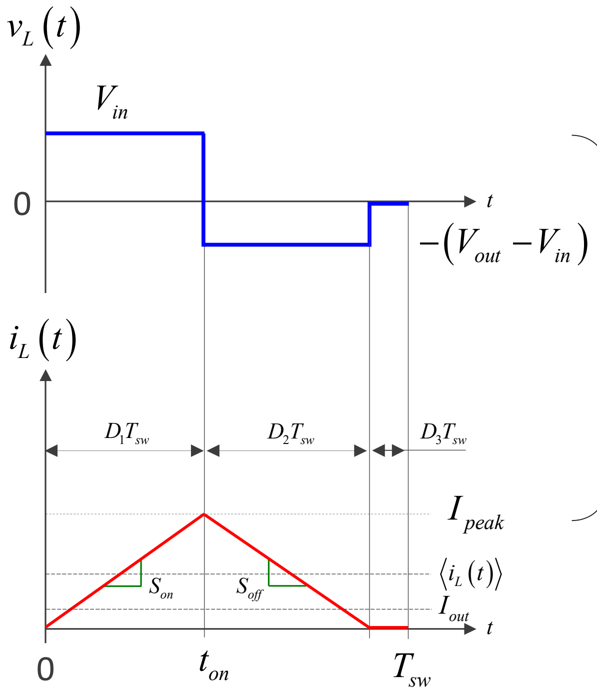

During DT or $D_3T_{sw}$

$$R_{critical} = \frac{2LF_{sw}}{D(1-D)^2}$$

$R < R_{critical} \rightarrow$ CCM

$R = R_{critical} \rightarrow$ BCM

$R > R_{critical} \rightarrow$ DCM




$$M = \frac{1 + \sqrt{1 + \frac{2D_1^2}{\tau_L}}}{2}$$

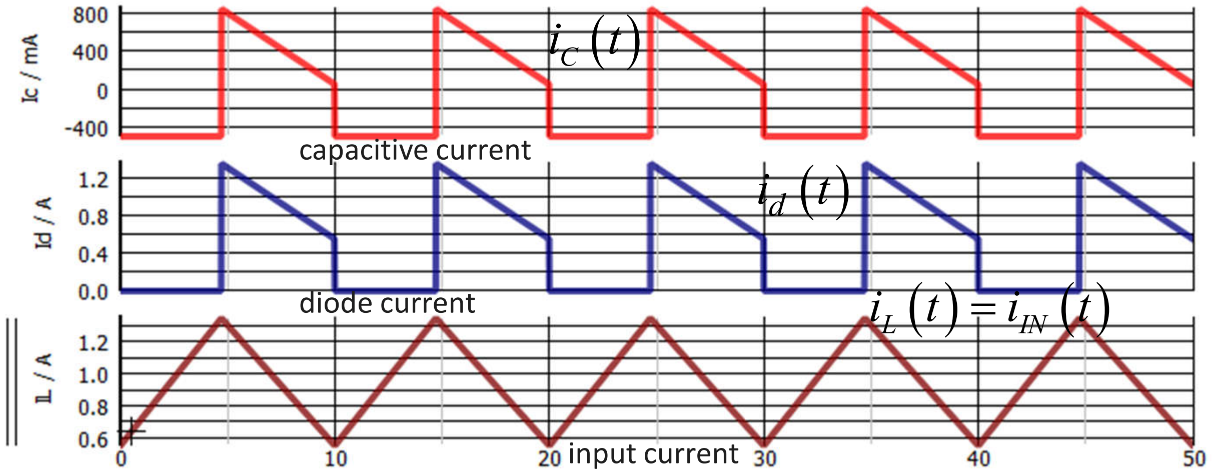
✓ Depends on $F_{sw}$

✓ Depends on $R$

$$\tau_L = \frac{L}{RT_{sw}}$$

# Input and Output Currents

- It is important to know the nature of the circulating input and output currents
- The inductance located in the input naturally smooths current which is *non-pulsating*
- The output current is *pulsating* and highly discontinuous: high rms component




✓ The output capacitor is highly pulsating and is of strong rms value

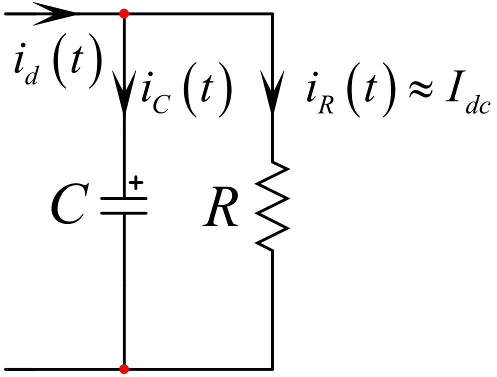
✓ The input current is very smooth and presents a good EMI signature

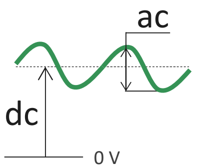
✓ The inductor current is a smooth triangular waveform

- The boost converter is quiet on the input and noisy on the output

# Rms Current in the Output Capacitor

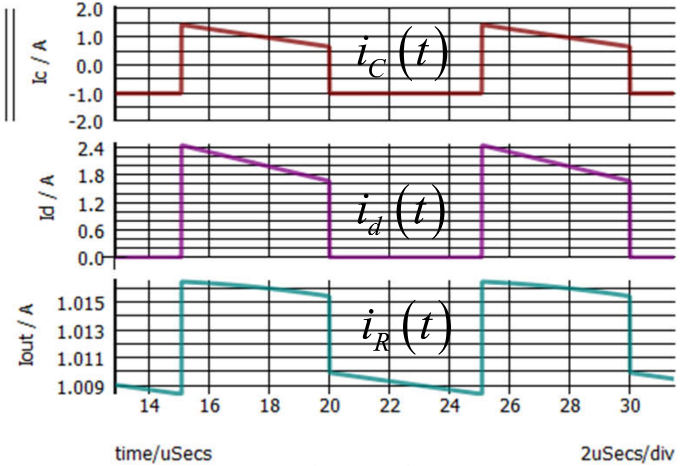
- The output current is highly discontinuous and stresses the output capacitor
- It is important to determine the worst-case rms current in this capacitor
- ✓ Make sure the selected type accepts this stress at the highest operating temperature




$$I_{rms} = \sqrt{I_{ac}^2 + I_{dc}^2}$$

$$I_{C,rms} = \sqrt{I_d^2 - I_{dc}^2}$$

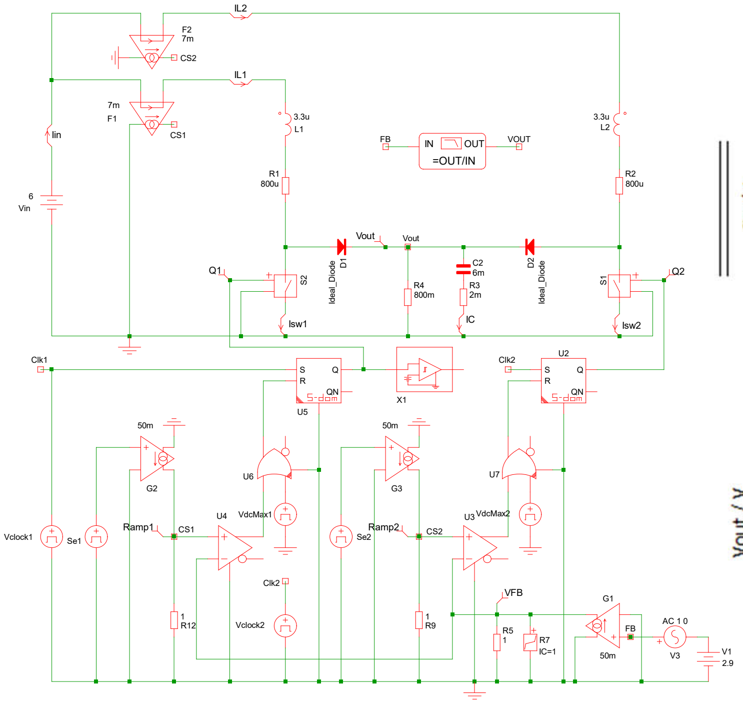


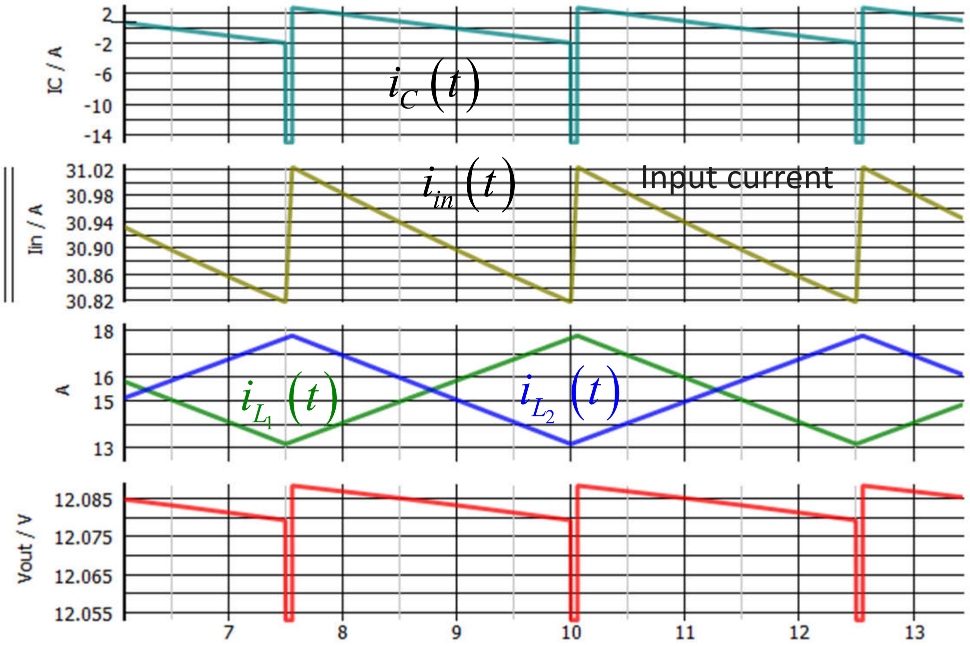

| | | |
|---|---|---|
| Ic | RMS/cycle | 1.0356366A |
| Id | RMS/cycle | 1.4508399A |
| Iout | RMS/cycle | 1.0125429A |

$$i_{C,rms} = \sqrt{1.45^2 - 1.021^2} = 1.03\text{ A}$$

# Multiphase to Reduce Ripple Currents

- High-power types of boost converters impose a heavy rms burden to the capacitor
- Adding extra switching phases reduces the input and output ripple currents




$$I_{C,rms} = 15\text{ A}$$

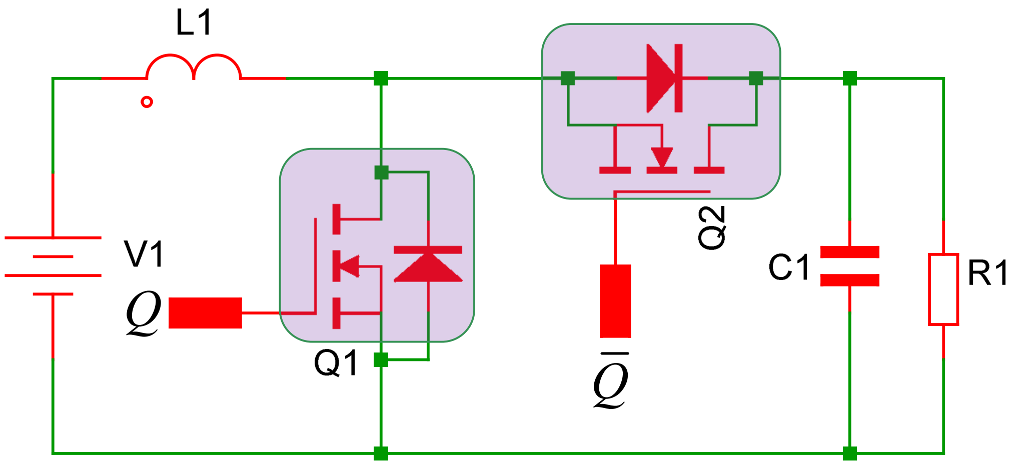
1 phase

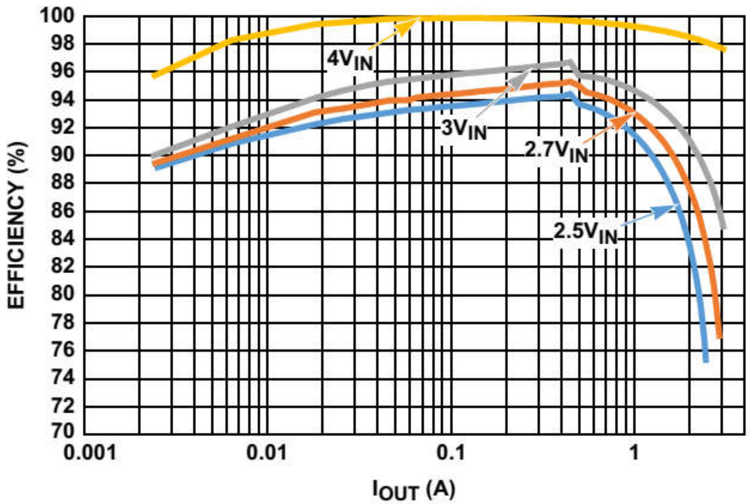
$$I_{C,rms} = 2.65\text{ A}$$

2 phases

# Synchronous Rectification

- Efficiency depends on the difference between output and input voltages
- Synchronous rectification further helps improving performance at low $V_{out}$




Typical curve for the ISL91133

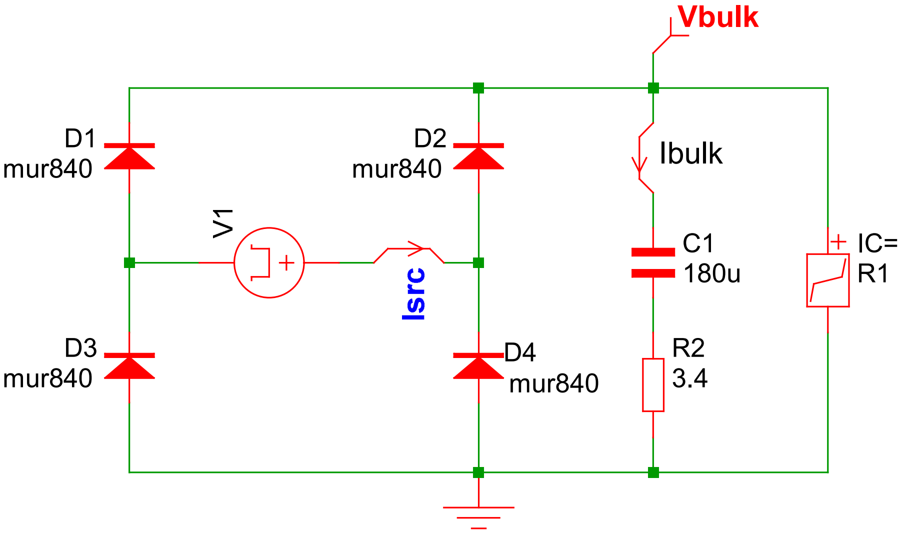
✓ A second switch is added to short the catch diode

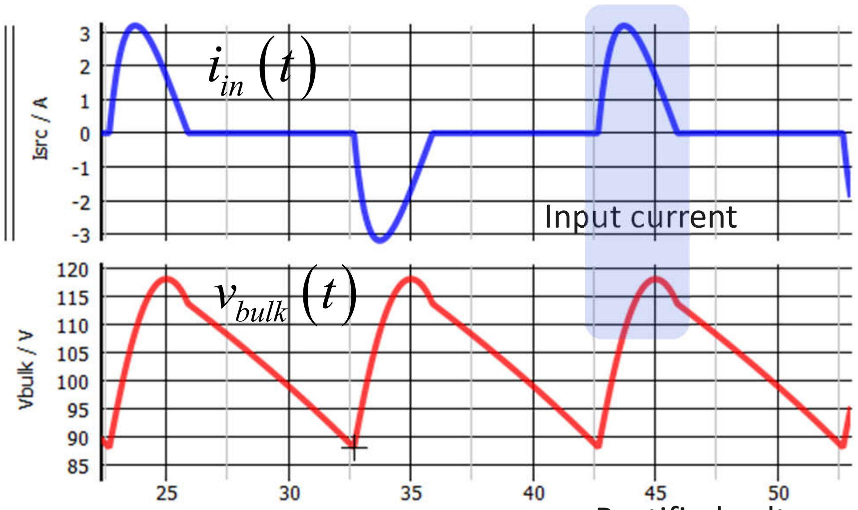
✓ Some dead-time is inserted between transitions to avoid shoot-through

# Full-Wave Rectification

- A resistor supplied by the mains absorbs a sinusoidal current in phase with the voltage
- A full-wave rectifier connected to the mains absorbs a non-sinusoidal current

✓ International standards impose regulatory limits for a power greater than 75 W



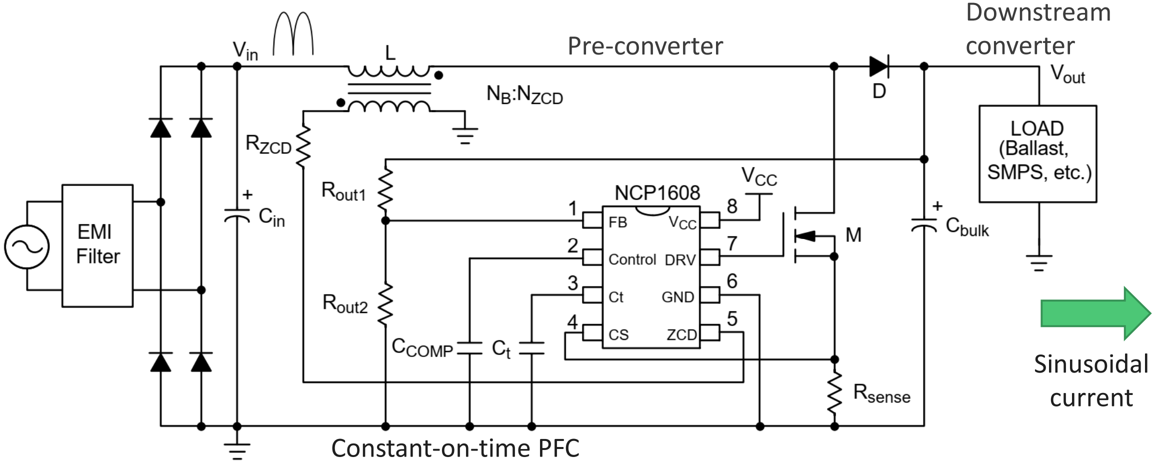

Rectified voltage

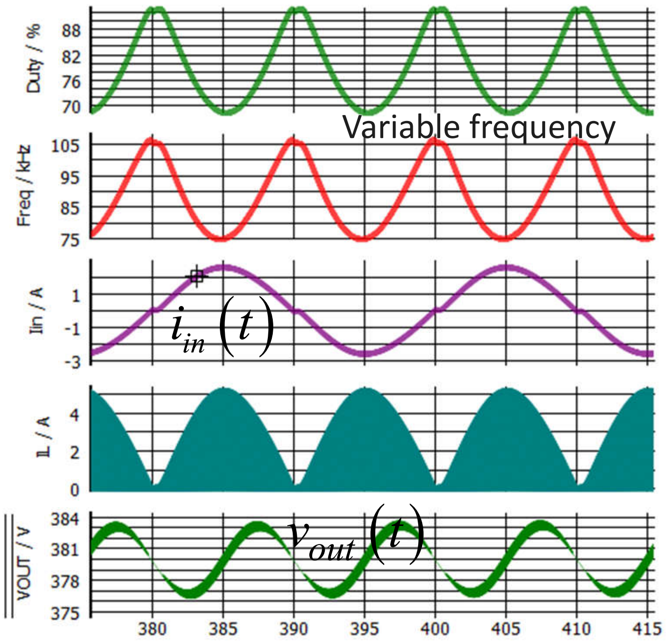
❖ The capacitor refueling occurs only at the voltage peak → $PF = \frac{\mathrm{W}}{\mathrm{V} \cdot \mathrm{A}} < 1$

PF: power factor

# Power Factor Correction

- A power factor corrector forces the absorption of a sinusoidal current
- The boost structure is the most popular converter for this application
- Low-power PFCs operate in BCM while high-power pre-converters run in CCM



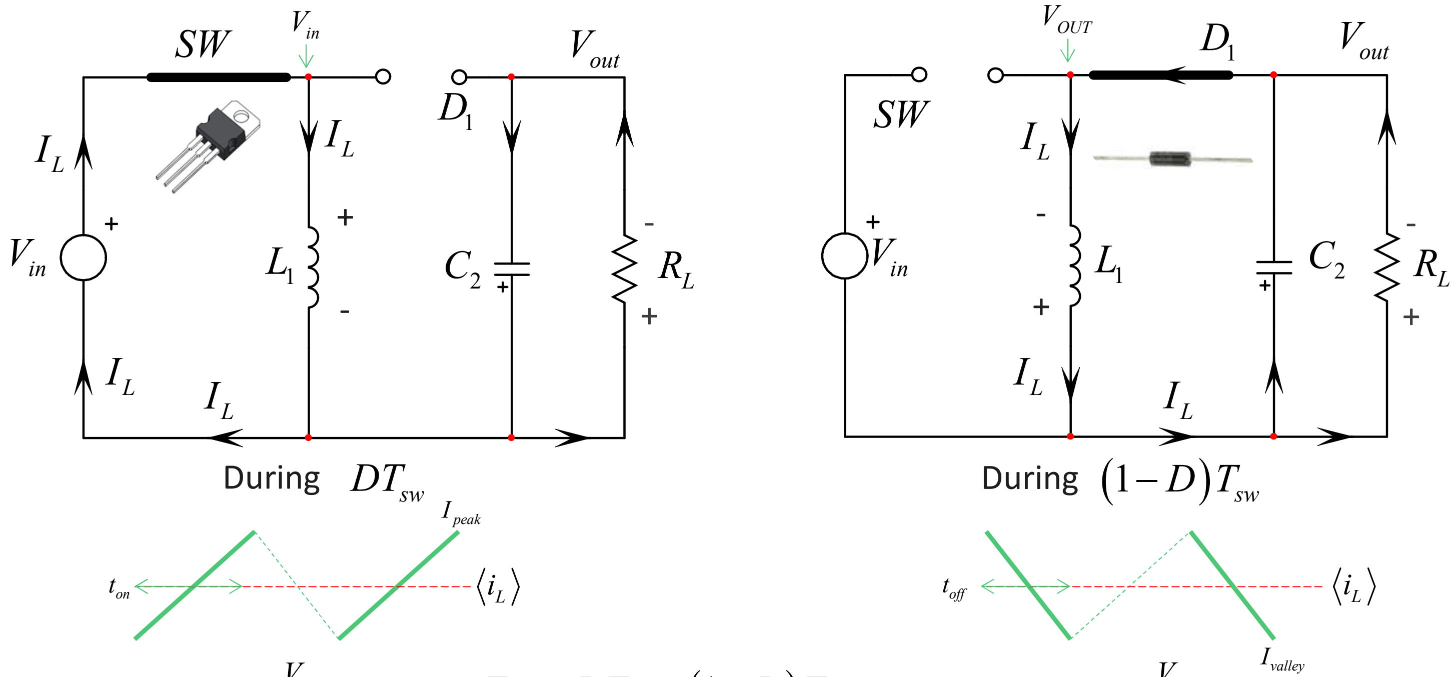

- Output ripple limits crossover frequency

# Agenda

- Power Conversion Mechanisms
- Switching Cells and Control Schemes
- The Buck
- The Boost
- The Buck-Boost
- Introduction to Control Loop Design
- EMI Filter Interaction
- Introduction to Simulation

# The Buck-Boost Converter

- The buck-boost converter increases or decreases the output voltage
- The converter inverts the input and the delivered voltage is negative

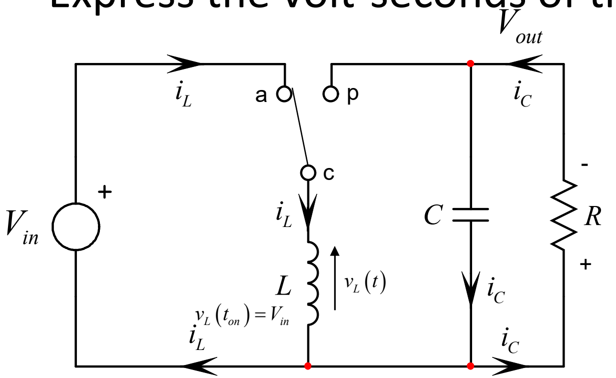



$$S_{on} = \frac{V_{in}}{L_1} \qquad T_{sw} = DT_{sw} + (1-D)T_{sw} \qquad S_{off} = \frac{V_{out}}{L_1}$$

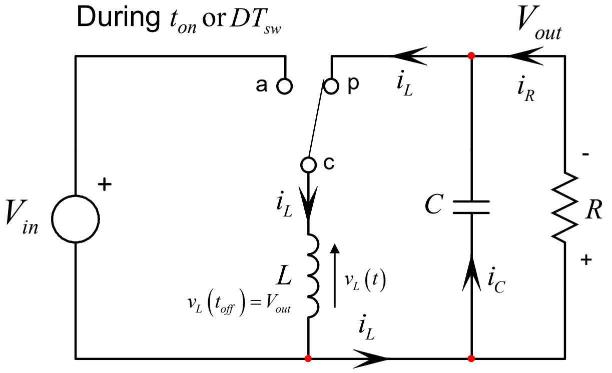
$V_{out}$ is negative

# Transfer Characteristic of the CCM Buck-Boost

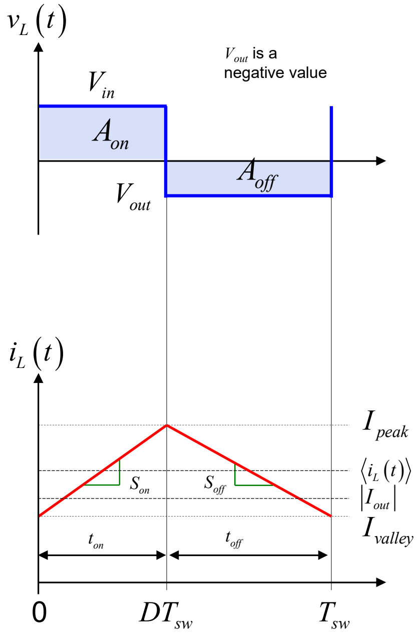
- Consider the average inductor voltage to determine the dc transfer characteristic
- Express the volt-seconds of the inductor during the on- and off-times




During $t_{on}$ or $DT_{sw}$




During $t_{off}$ or $(1-D)T_{sw}$




$\langle i_L(t)\rangle_{T_{sw}} = I_{out}/(1-D)$

V-s balance

$$\langle v_L(t)\rangle_{T_{sw}} = 0\ \mathrm{V}$$

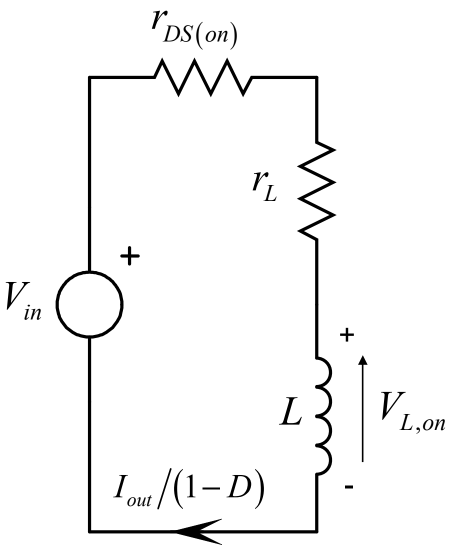
$$V_{in} D T_{sw} = -V_{out}(1-D)T_{sw}$$

$$V_{out} = -V_{in}\frac{D}{1-D}$$

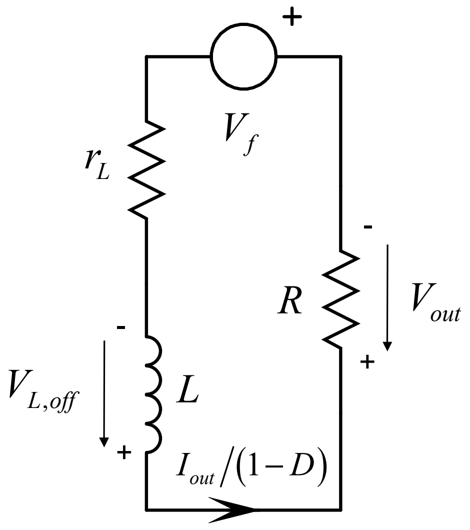
$$M = -\frac{D}{1-D}$$

# A Finite Conversion Ratio

- Resistances in series limit the maximum peak current in the inductor
- The conversion ratio is thus limited as in the boost converter case

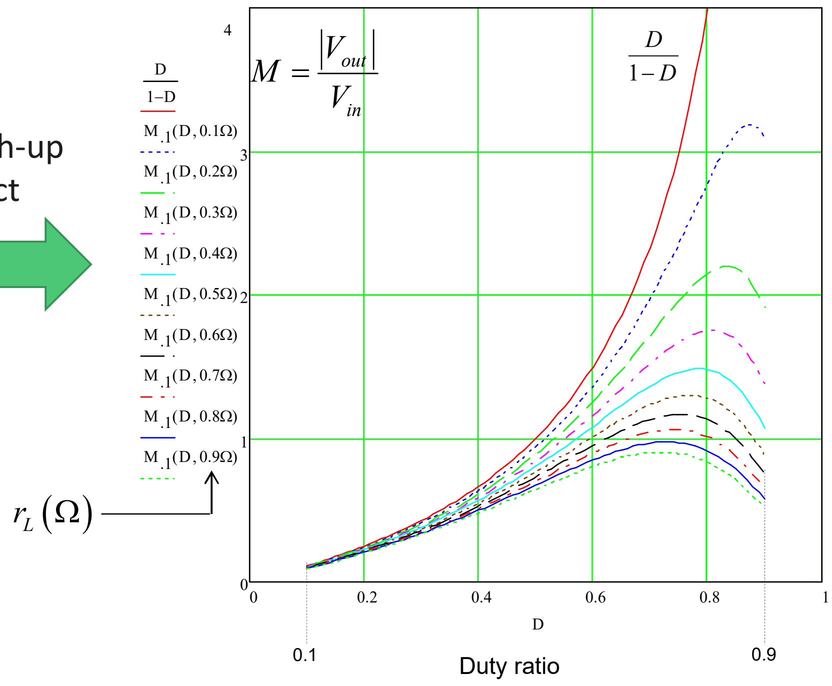



During $DT_{sw}$



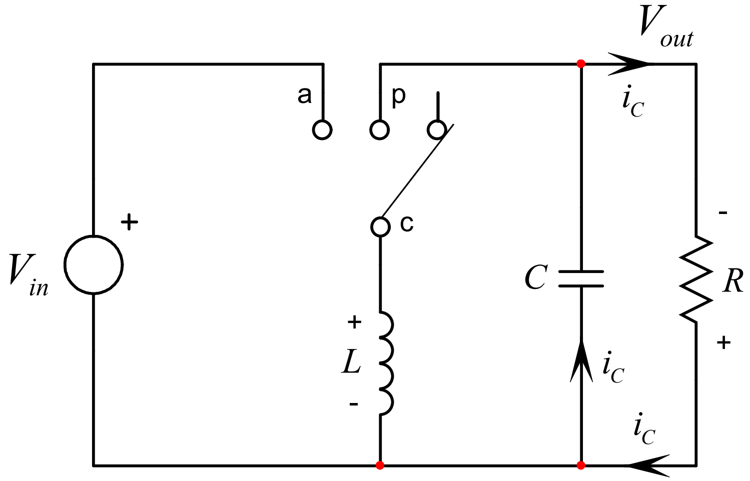

During $(1-D)T_{sw}$

Latch-up effect



# Transfer Characteristic of the DCM Buck-Boost

- The converter enters the discontinuous conduction mode in light-load conditions
- Both switches are blocked and the capacitor alone feeds the load



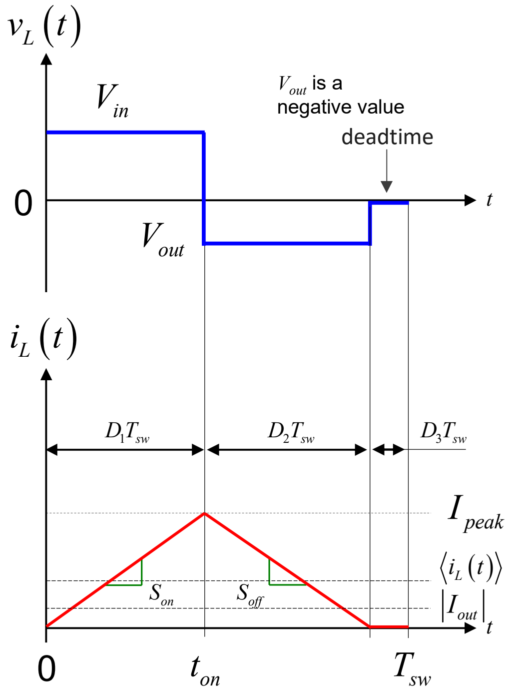

During DT or $D_3T_{sw}$

$$R_{critical} = \frac{2LF_{sw}}{(1-D)^2}$$

$R < R_{critical} \rightarrow \mathrm{CCM}$

$R = R_{critical} \rightarrow \mathrm{BCM}$

$R > R_{critical} \rightarrow \mathrm{DCM}$




$$M = -D_1\sqrt{\frac{1}{2\tau_L}}$$

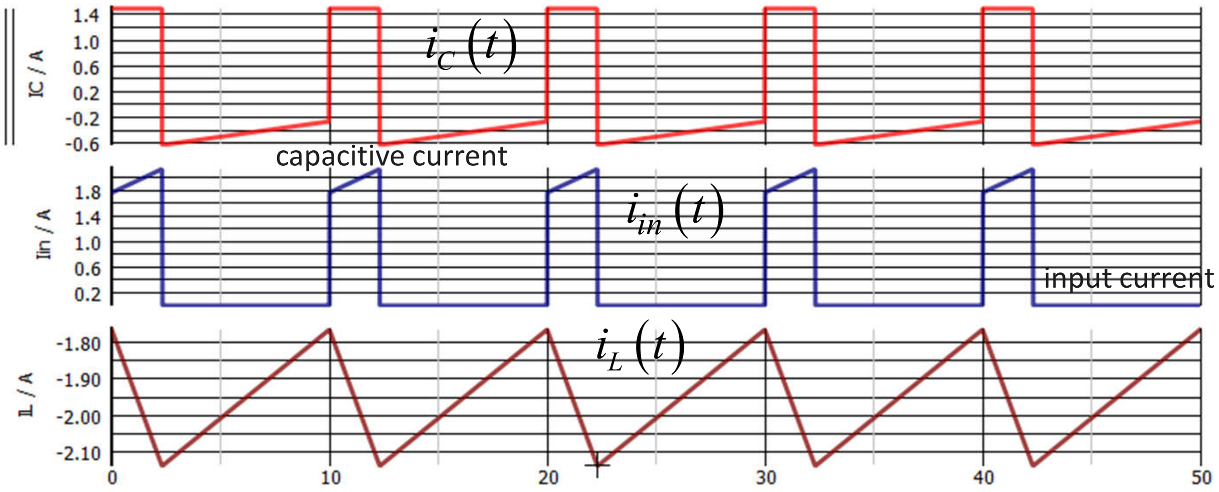
✓ Depends on $F_{sw}$

✓ Depends on $R$

# Input and Output Currents

- The buck-boost is the worst of all basic switching cells
- The inductor is ground referenced and connects alternatively to the input or the output

✓ Input and output current are *pulsating* and highly discontinuous: high rms component




✓ The output capacitor is highly pulsating and is of strong rms value

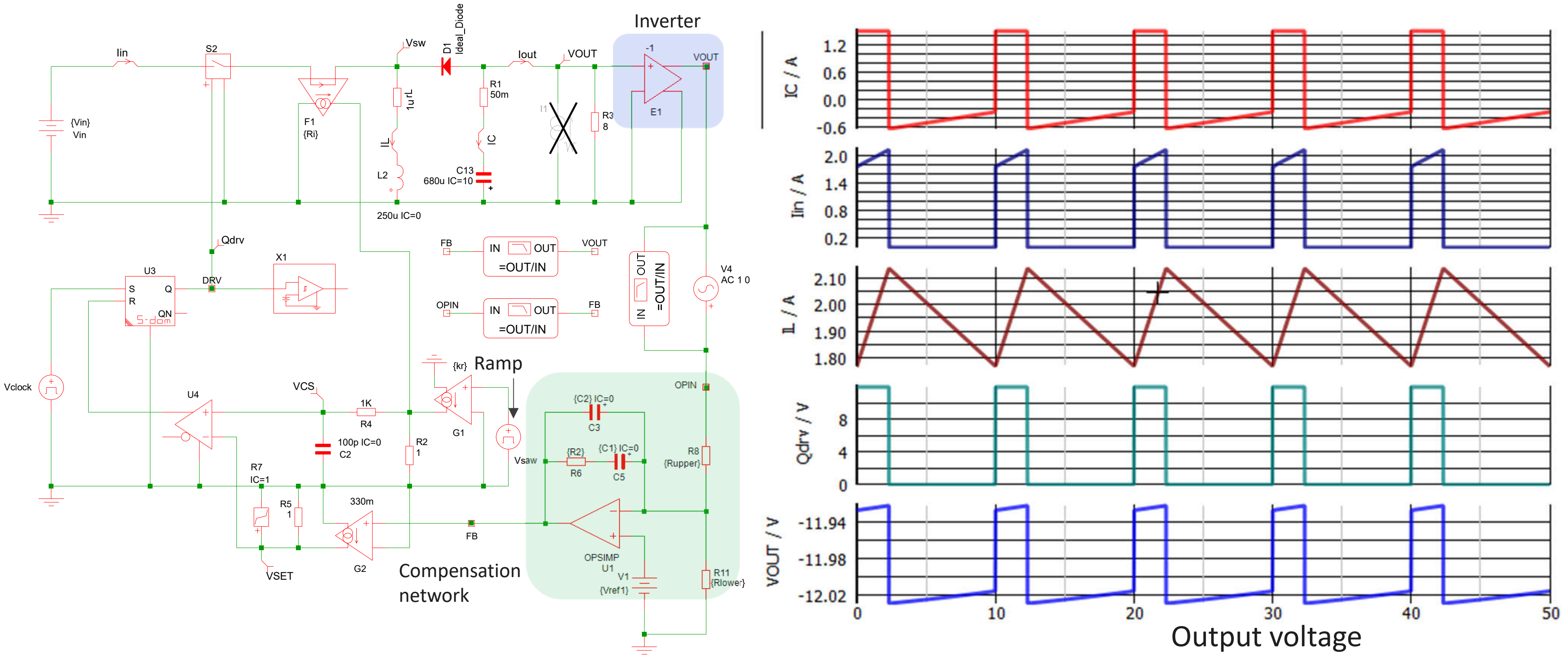
✓ The input current is also pulsating implying a poor EMI signature

✓ The inductor current is a smooth triangular waveform

- The buck-boost converter is noisy on the input and noisy on the output

# Simulation of a Buck-Boost Converter

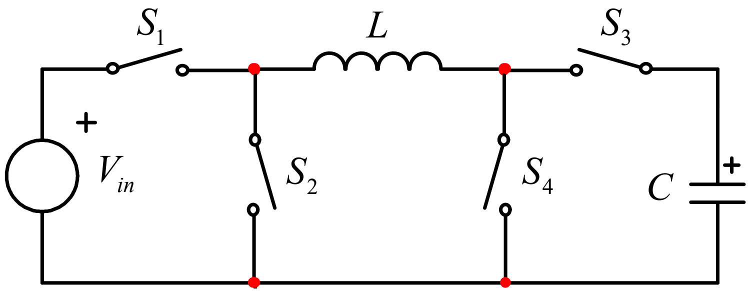
- The negative output requires an inversion for proper regulation
- This is a current-mode-controlled application featuring slope compensation

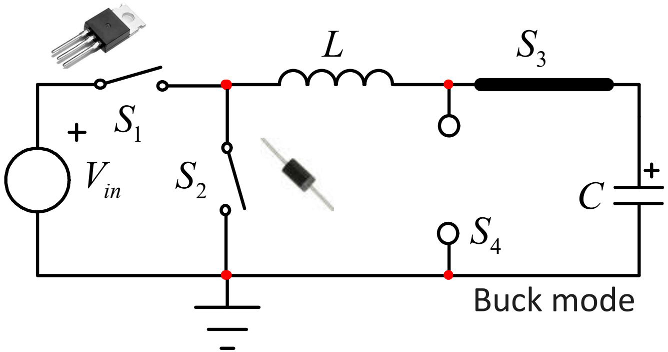


Output voltage

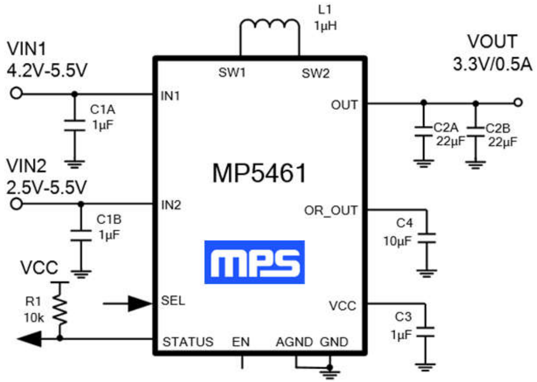
# Four-Switch Buck-Boost Version

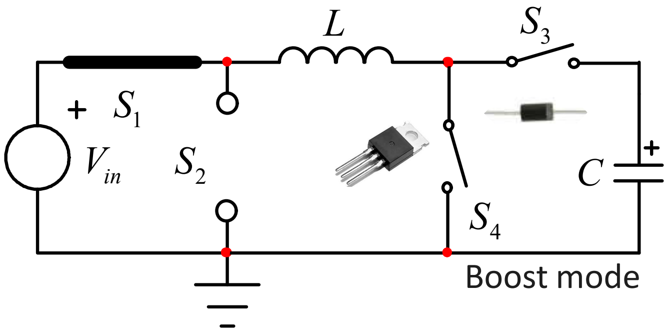
- A 4-switch version operates in buck or boost and no longer inverts the output
- The control requires a more complicated control logic




- ✓ $S_1$ and $S_2$ are acting in buck mode
- ✓ $S_3$ and $S_4$ are respectively on and off.

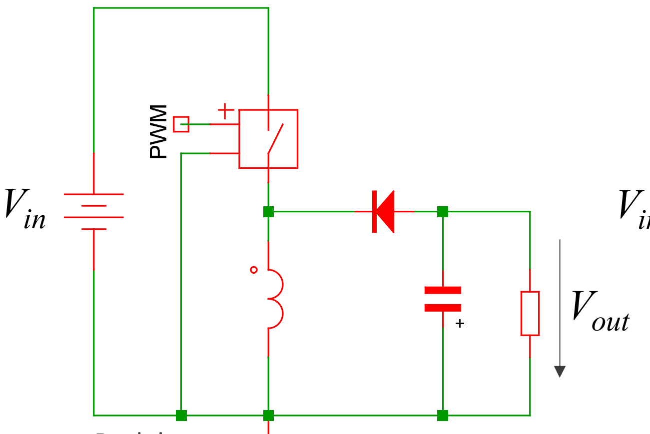


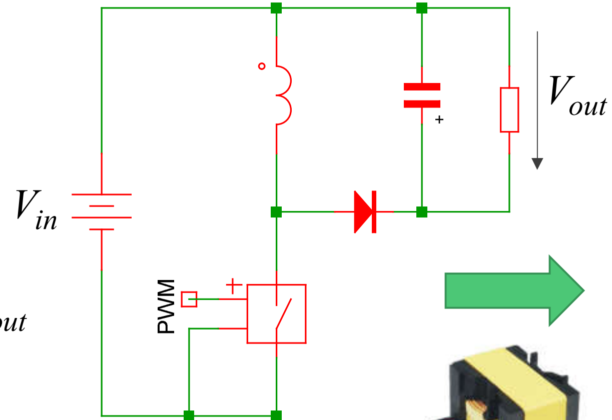

- ✓ $S_1$ and $S_2$ are respectively on and off.
- ✓ $S_3$ and $S_4$ are actuated in boost mode.

# The Flyback Converter

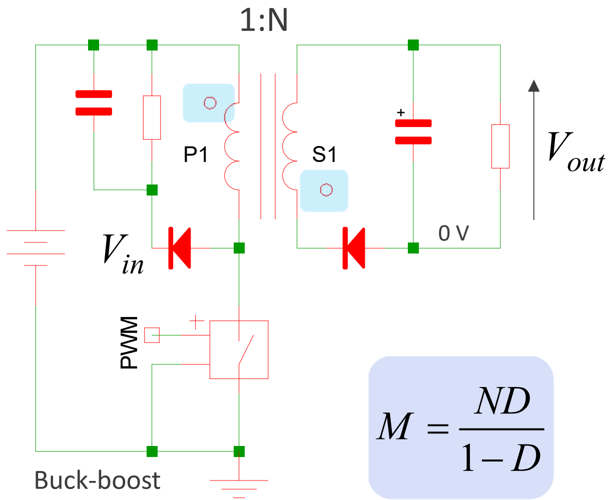
- Adding a transformer brings galvanic isolation: flyback converter
- The converter can now deliver positive or negative levels, increase or decrease $V_{in}$




Buck-boost
ground-referenced




Buck-boost
input-referenced




Buck-boost
isolated

$$M = \frac{ND}{1-D}$$

- The flyback converter can be identified with its winding dots located in opposite ends

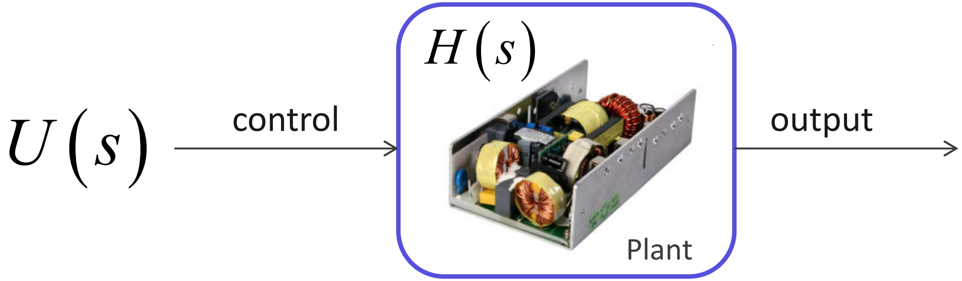
✓ A clamping network is necessary to protect the power switch

# Agenda

- Power Conversion Mechanisms
- Switching Cells and Control Schemes
- The Buck
- The Boost
- The Buck-Boost
- Introduction to Control Loop Design
- EMI Filter Interaction
- Introduction to Simulation

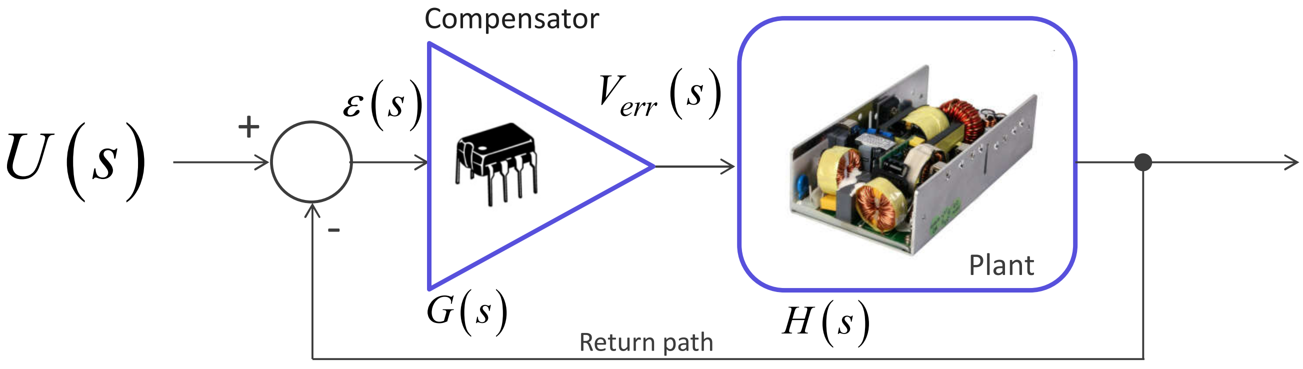
# What is a Control System?

- An open-loop system links an output with a control variable




$$Y(s) = U(s)H(s)$$

- A control system observes the output and minimizes the error by closing the loop

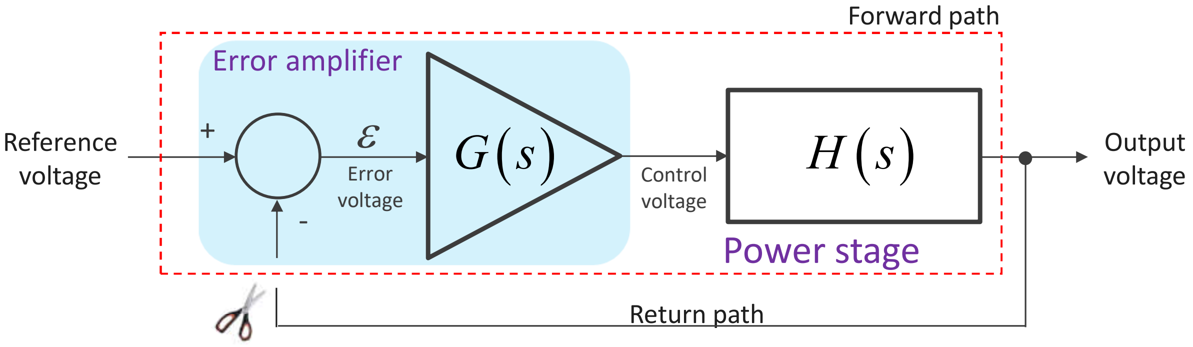



$$Y(s) = V_{err}(s)H(s)$$

$$V_{err}(s) = \underbrace{\left[U(s)\right.}_{\text{input}} - \underbrace{\left.Y(s)\right]}_{\text{output}} G(s)$$

# What is Loop Gain?

- The error amplifier and the power stage define the system *loop gain*
- Its value affects the stability and robustness or susceptibility of the circuit




- The loop gain designated as $T$ is defined as $T(s) = G(s)H(s)$

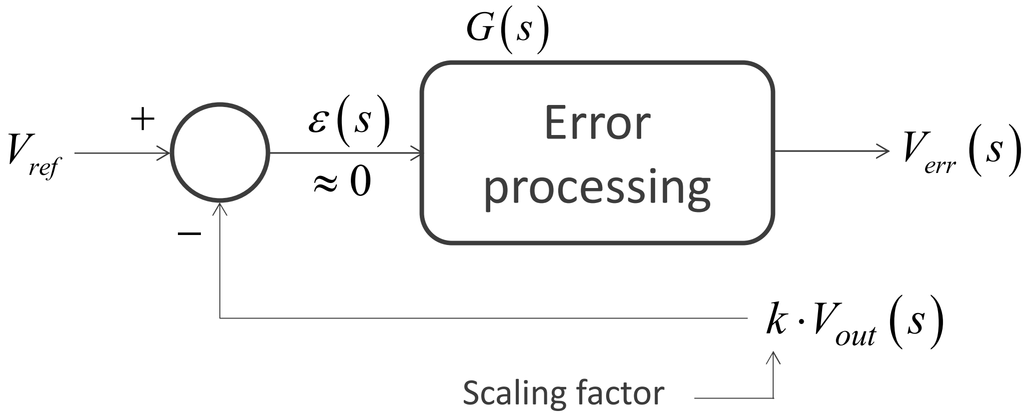
$$\frac{V_{out}(s)}{V_{ref}(s)} = \frac{H(s)G(s)}{1+H(s)G(s)} = \frac{T(s)}{1+T(s)}$$ If $T >> 1$ $V_{out}(s) = V_{ref}(s)$

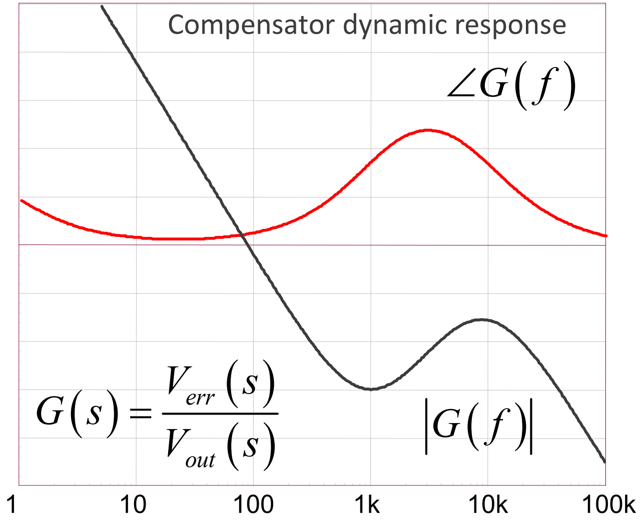
$$1+T(s)=0 \Rightarrow \begin{array}{l} |T(s)| = 1 \text{ or } 0 \text{ dB} \\ \angle T(s) = -180° \end{array}$$

✓ Nyquist stability criterion

# Shaping the Loop with the Compensator

- The compensator  builds the error variable and ensures stability
  - ➢ Insert poles and zeros to create the compensation strategy
  - ➢ Choose how to cross over at $f_c$ with phase and gain margins

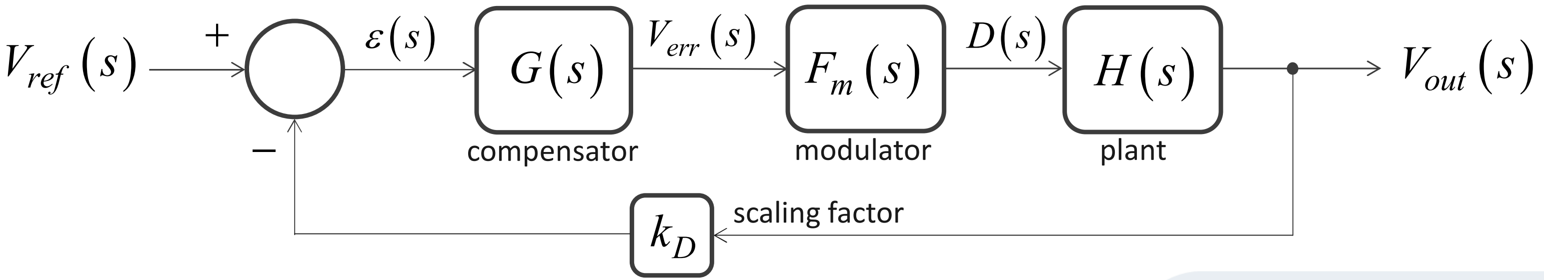


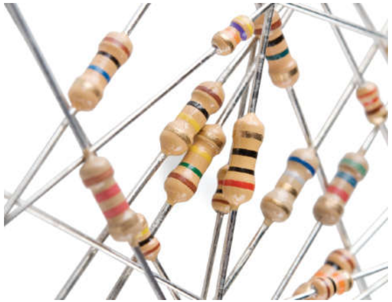

- The block amplifies and shapes the error $\varepsilon$ between $V_{ref}$ and $V_{out}$
  - ✓ Minimize the error between the setpoint and the output

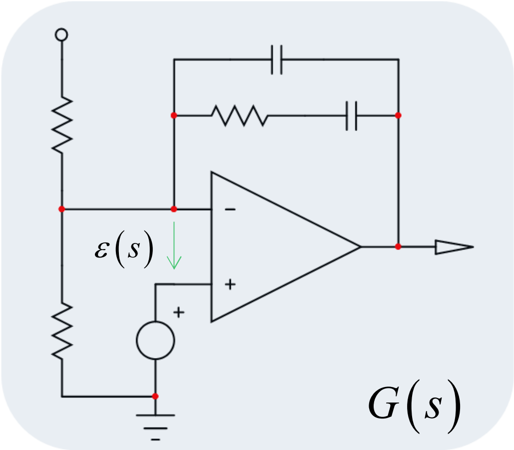
# Building the Compensator – the Analogue Way

- Associate active and passive components to form the compensation chain




1. Select poles/zeroes placement
2. Calculate components values
3. Solder resistors and capacitors

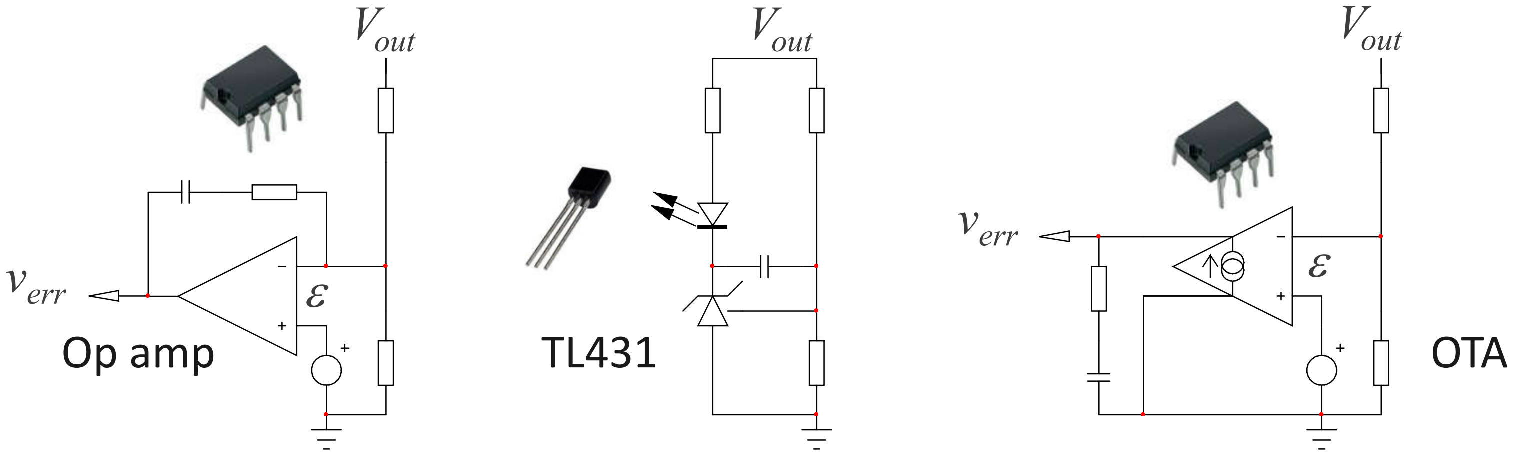





→ Change in strategy requires new components values

# How do you Build an Analogue Compensator?

- A compensator can be a passive or active filter shaped for a specific response

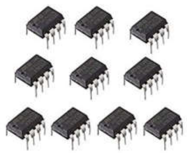



✓ Passive components suffer drawbacks:

1. Tolerance, aging
2. Sensitivity to temperature, humidity

✓ Active components are not perfect!

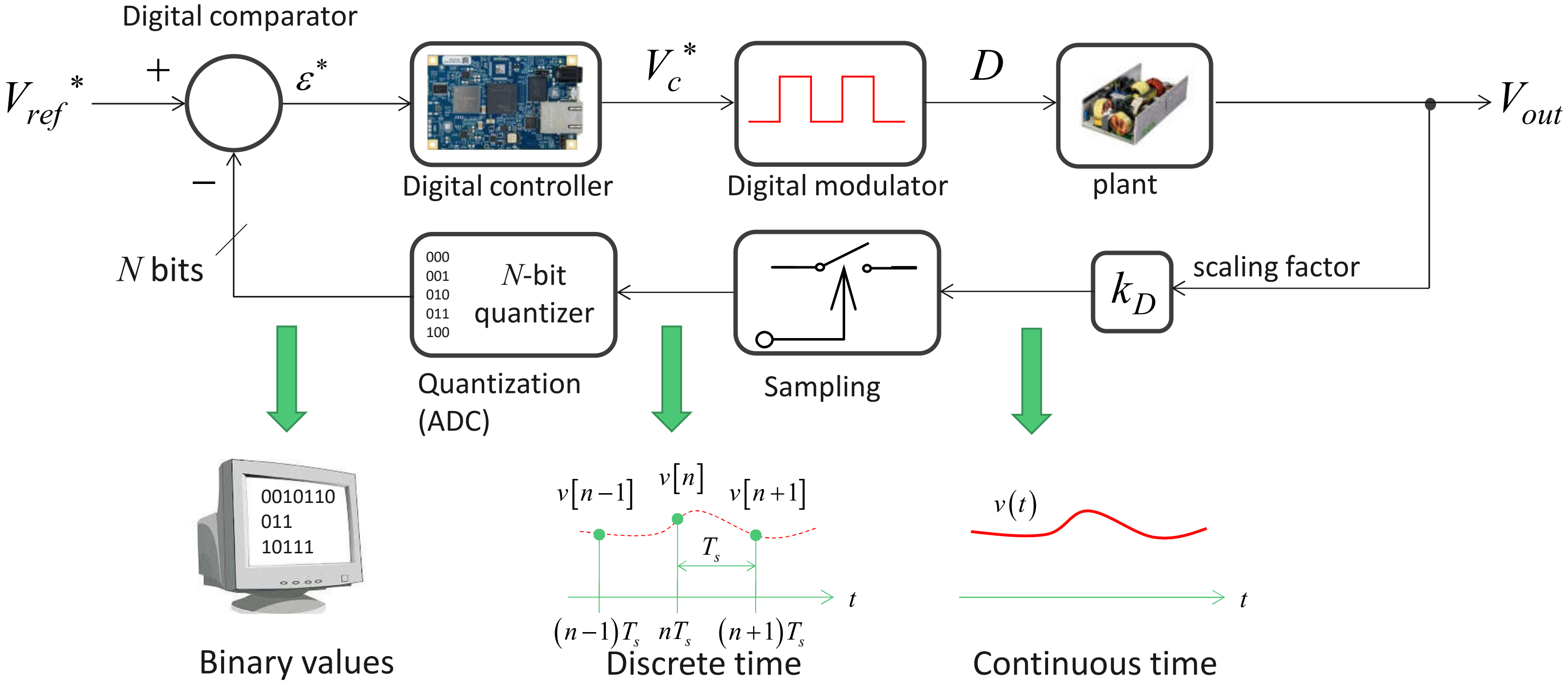
1. Open-loop gain, bias requirements
2. Limited in bandwidth, slew-rate
3. Temperature drift



OTA: operational transconductance amplifier

# Building the Compensator – the Digital Way

- A digitally-controlled system mixes sampled and continuous-time data

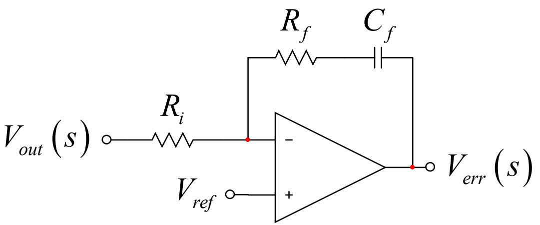



* designates a discrete variable

M. Jovanović, *Introduction to Digital Control of Switch-Mode Converters*, in-house course, PHX 2014

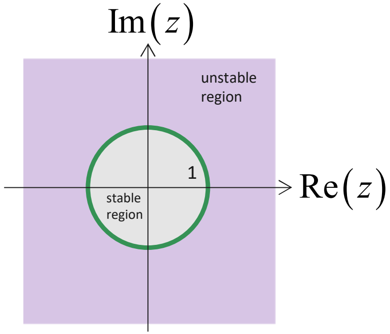
# How do you Build a Digital Compensator?

- You can start from a continuous-time transfer function expressed in $s$




$$sV_{err}(s) = -s\frac{R_f}{R_i}V_{out}(s) - \frac{1}{R_iC_f}V_{out}(s)$$

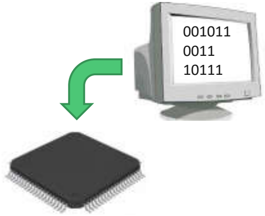
Map into the z-domain




Difference equation

$$b_0V_{err}(z) + b_1z^{-1}V_{err}(z) = a_0V_{out}(z) + a_1z^{-1}V_{err}(z)$$

- Code the filter equation with a micro-controller or hard-wire it in a FPGA




Digital control

```
import PID
import time
import os.path

from OmegaExpansion import AdcExp
from OmegaExpansion import pwmExp

pwmExp.setVerbosity(-1)
pwmExp.driverInit()
adc = AdcExp.AdcExp()

targetT = 35
P = 10
I = 1
D = 1
```

- ✓ No tolerance or age issues
- ✓ Flexibility and optimization
- ✓ On-the-fly poles-zeroes changes
- ❖ More complex to analyze
- ❖ Warping occurs during mapping
- ❖ Lower crossover systems

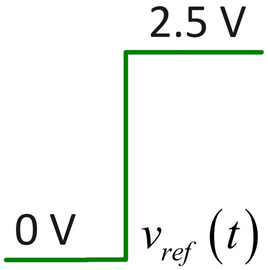
Learning curve

FUTURE ELECTRONICS

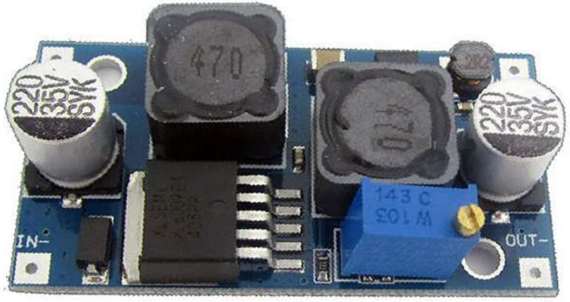
# Why do we need to Close the Loop?

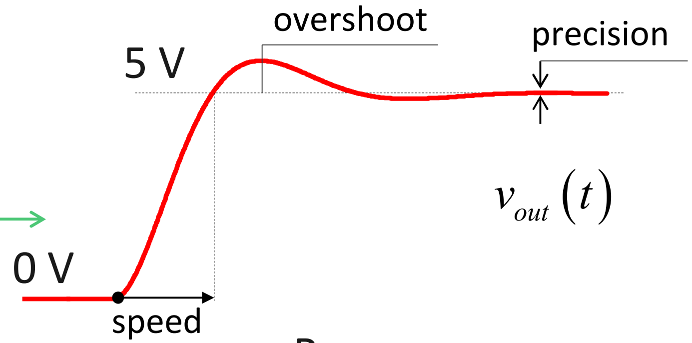
- You need to compensate the power stage deficiencies to obtain:

| | | |
|---|---|---|
| ➢ Speed | → | ✓ High bandwidth |
| ➢ Precision | | ✓ Large dc gain |
| ➢ Robustness | | ✓ High gain below $f_c$ |




Stimulus




Response

What compensation strategy?

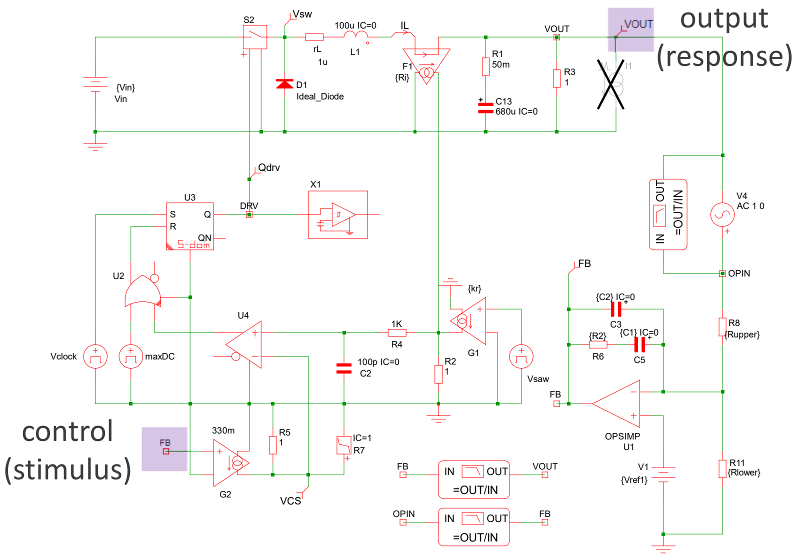
# Power Stage Transfer Function

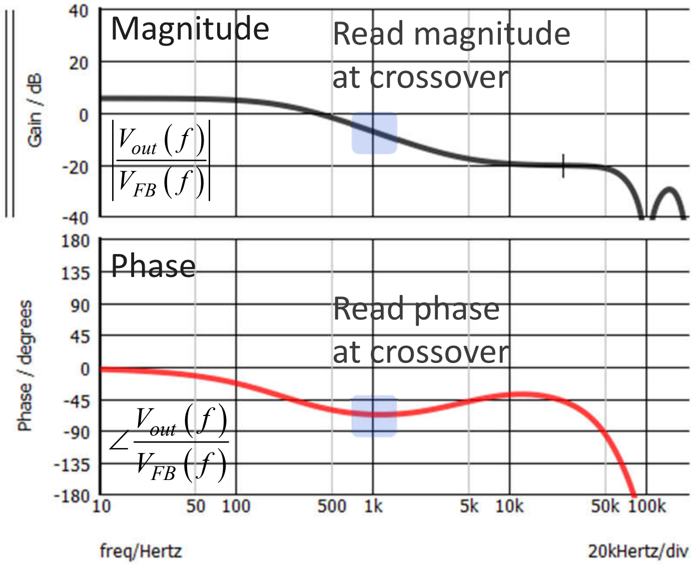
- The control-to-output transfer function is the starting point:

✓ Use a frequency-response analyzer (FRA) to extract it

✓ Run a simulation with an averaged model to obtain a Bode plot

✓ Determine the transfer function analytically with small-signal analysis

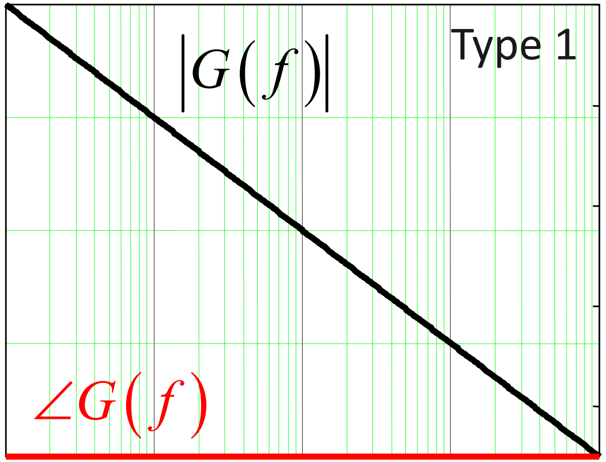


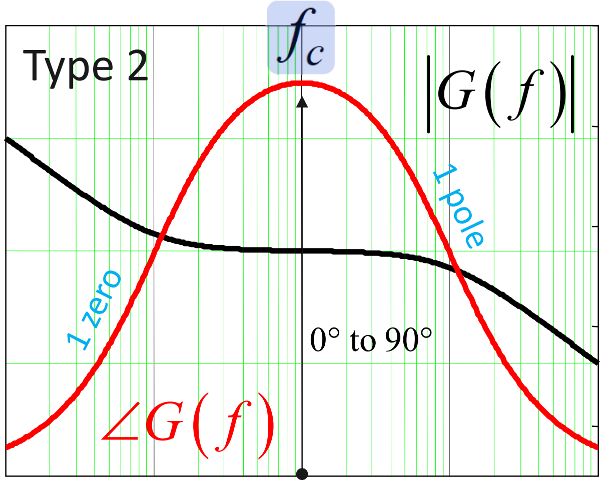

C. Basso, *Transfer Functions of Switching Converters*, Faraday Press, 2021

# Compensator Types

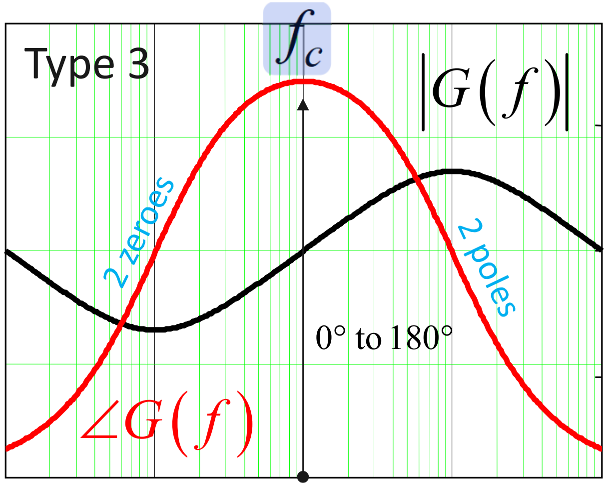
- Poles, zeroes and gain are your tools to shape the compensator response
- ✓ Phase margin depends on the wanted transient response
- ✓ Crossover depends on the expected reaction speed




0° phase boost
1 pole at the origin only



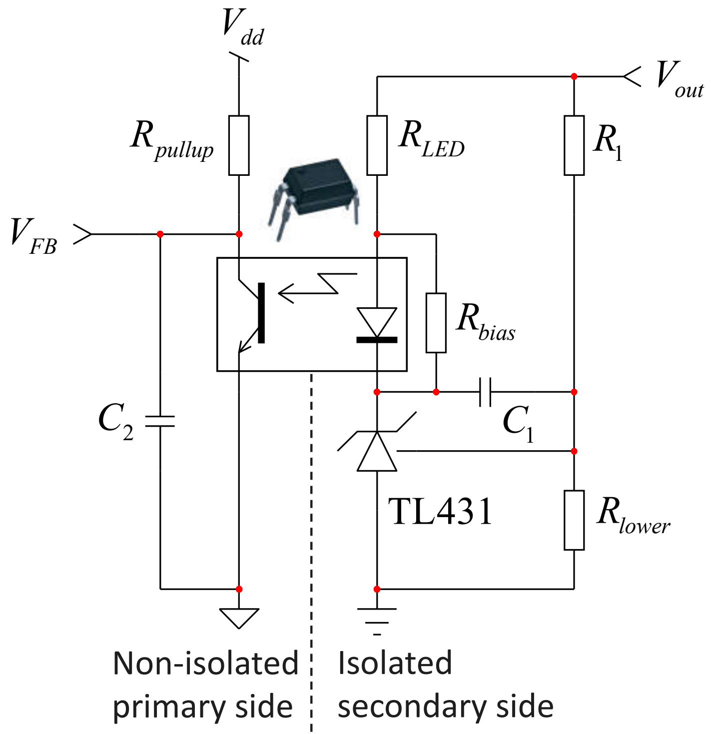

Up to 90° phase boost
1 pole at the origin
1 zero and 1 pole

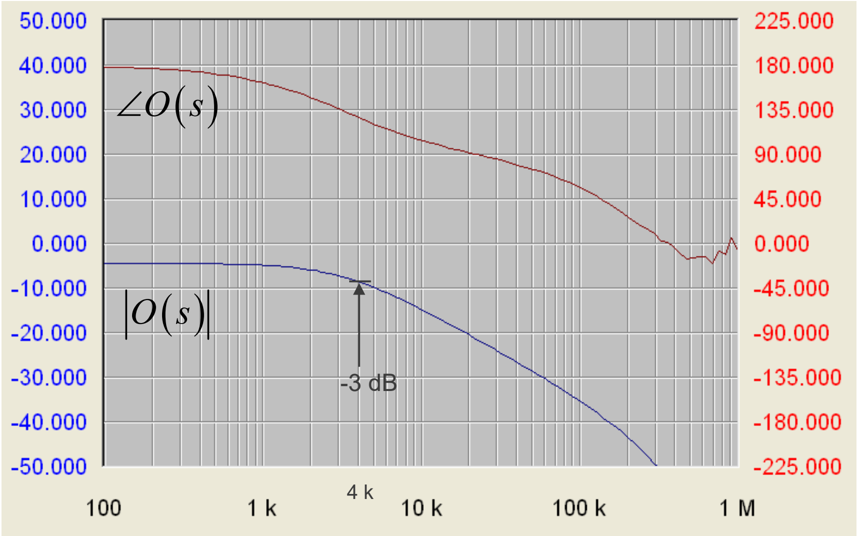



Up to 180° phase boost
1 pole at the origin
2 zeroes and 2 poles

# Isolated Feedback

- An optocoupler brings the isolated output voltage image to the primary side
- This component degrades the compensator response and must be characterized



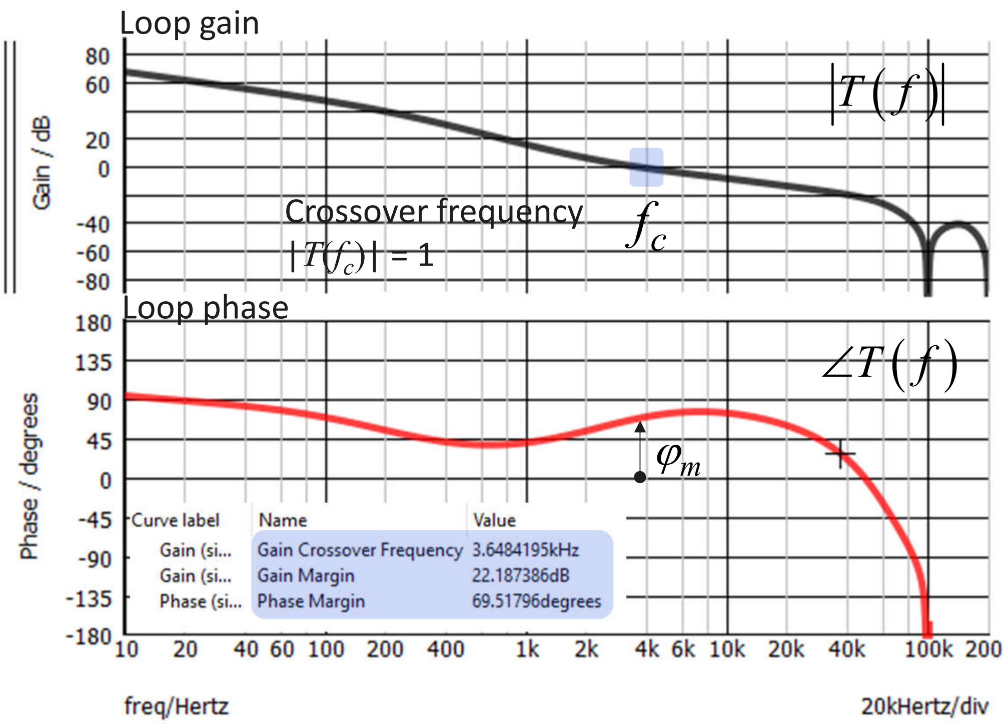



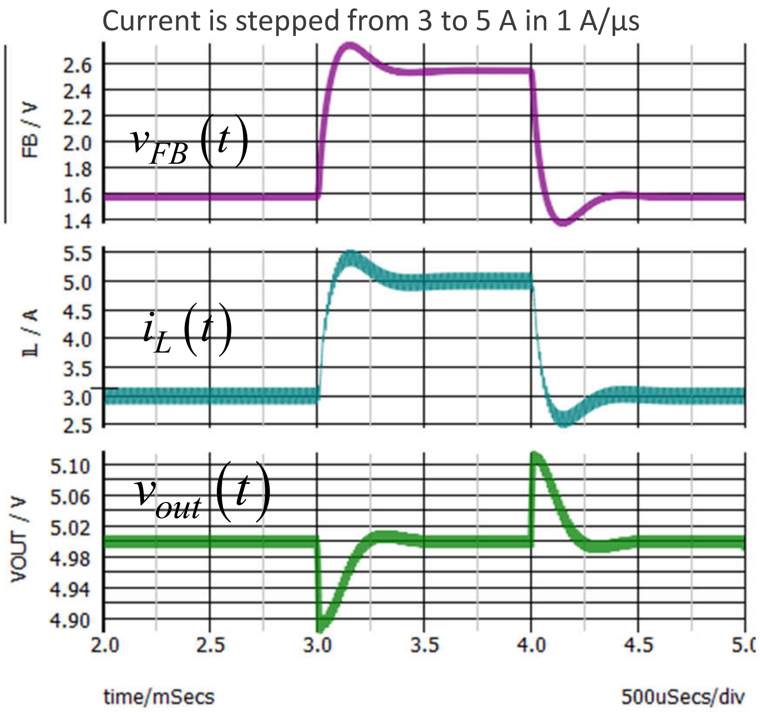

- The optocoupler features a low-frequency pole

✓ Characterize it carefully

# Compensated Converter

- Check the loop gain and make sure phase and gain margins are within safe limits
- A transient step will tell you if the undershoot meets the specs



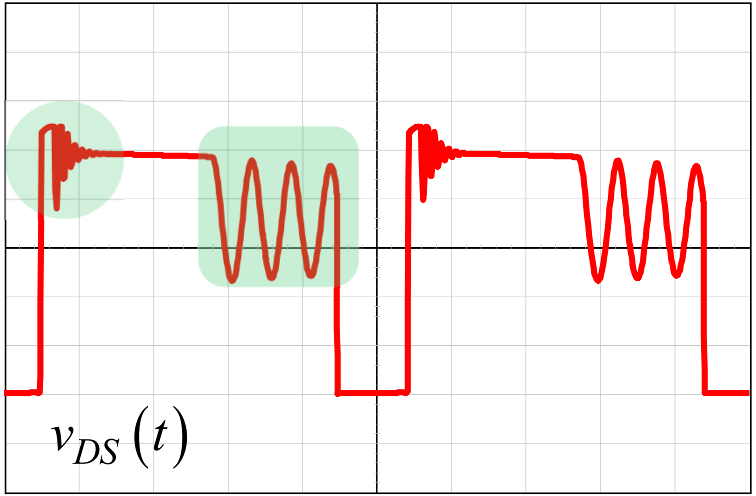



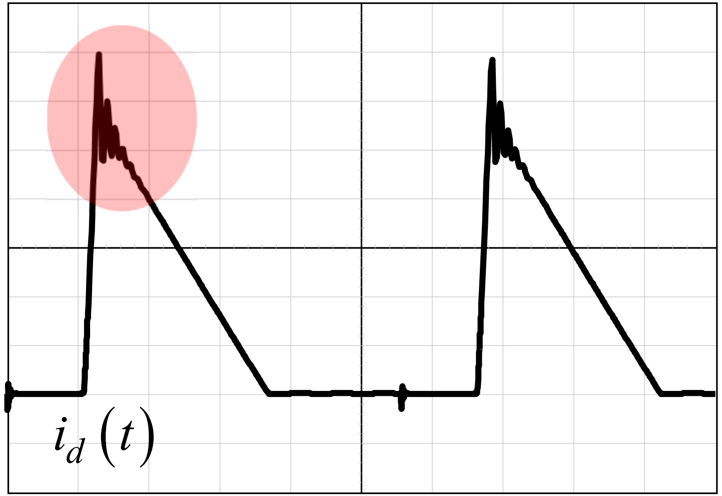
# Agenda

- Power Conversion Mechanisms
- Switching Cells and Control Schemes
- The Buck
- The Boost
- The Buck-Boost
- Introduction to Control Loop Design
- EMI Filter Interaction
- Introduction to Simulation

# A Noise Source

- A switching converter is a noise generator in essence
  - ✓ Abrupt voltage changes impose circulating currents in parasitic capacitors
  - ✓ Rapid current changes excite parasitic networks and generate ringing

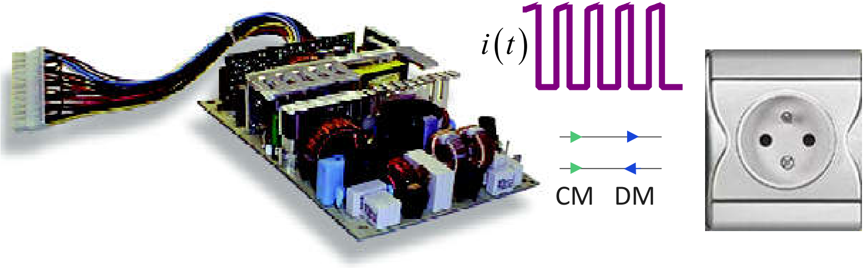


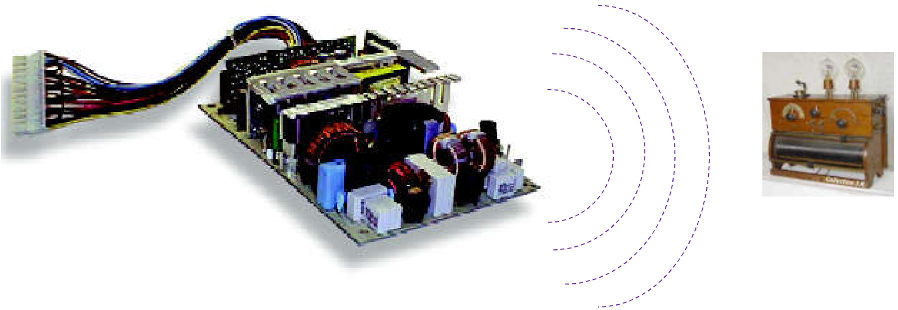

High-current loops are naturally radiating noise and must be treated

# Radiated or Conducted?

- Noise can be injected in the supply cables and return to the source
- ✓ This is so-called *conducted* parasitic noise
- Noise is coupled in the air through various mechanisms and disturb equipment
- ✓ In this case, we talk about *radiated* noise

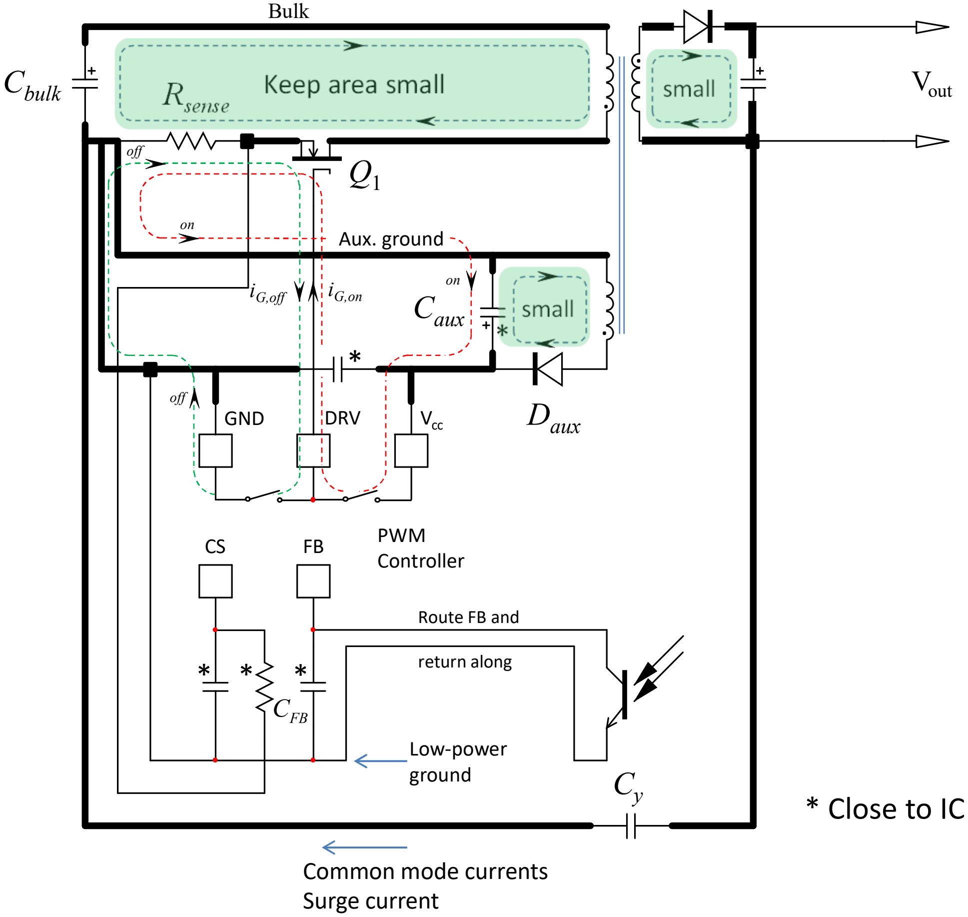



Conducted noise
150 kHz – 30 MHz



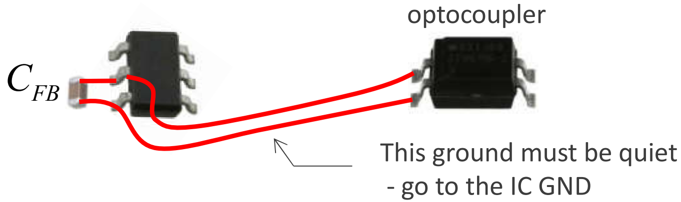

Radiated noise
30 MHz – 1 GHz

# The Importance of the Loops



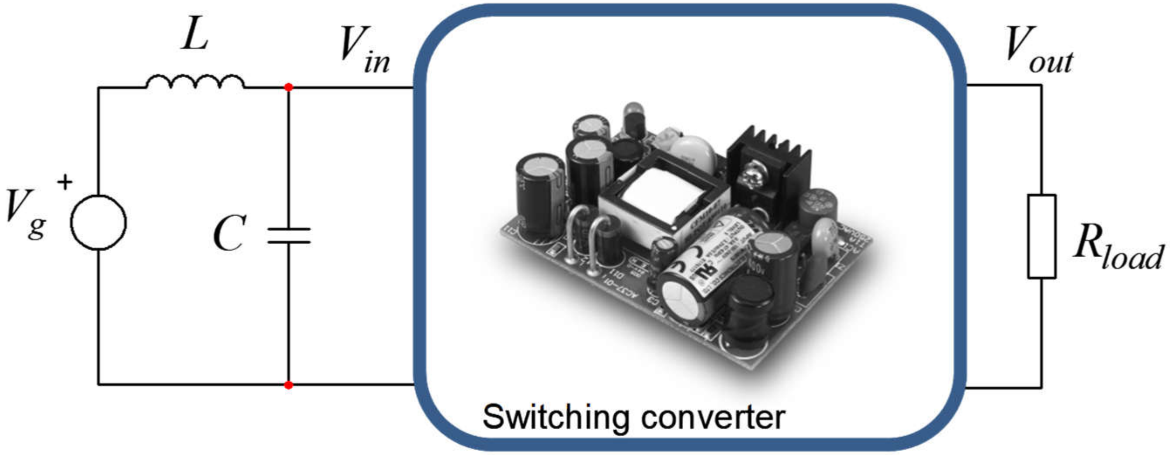

* Close to IC

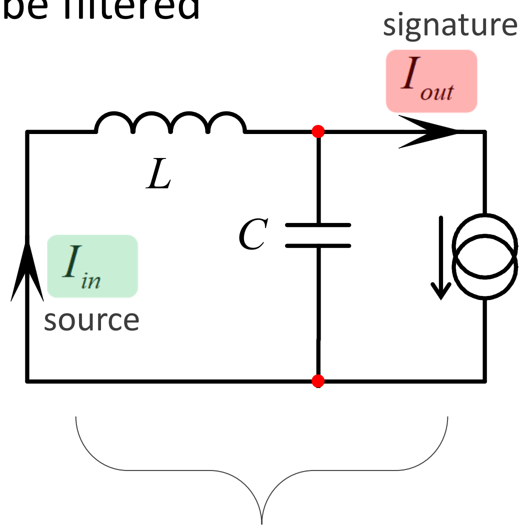
- ✓Identify the high-current switching paths and keep connections short
- ✓Reduce the area enclosed by the circulating currents to minimize radiated noise
- ✓Pay attention to the routing and how you select your return grounds
- ✓Decoupling components must be located closely to the controller
- ✓ Star-cabling around the bulk capacitor is recommended for surge performance



# Filtering the Conducted Noise

- A $LC$ filter is selected to block high-frequency emissions back to the source
- The attenuation is calculated depending on the current to be filtered




$$\frac{I_{in}}{I_{out}} \approx \left(\frac{\omega_0}{\omega}\right)^2$$

Assume a 50-dB attenuation at 100 kHz

$$f_0 = \sqrt{A_{filter}} \cdot f_{SW} = \sqrt{3m} \times 100k \approx 17 \text{ kHz}$$

# Watch for the Interaction with the Filter

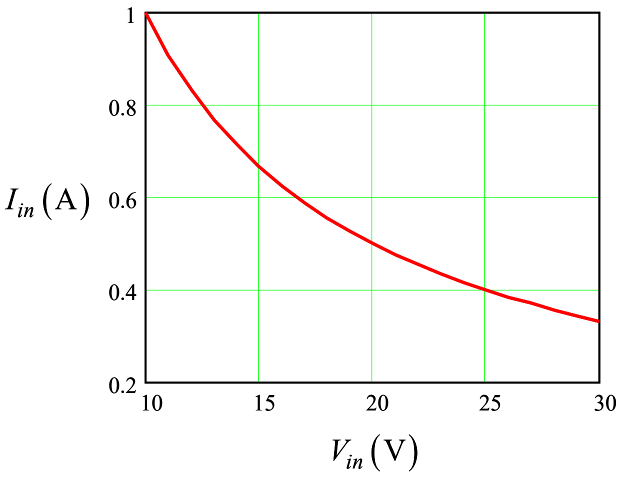
- The incremental input resistance of a switching converter is negative
- When loading an $LC$ filter, deleterious interaction is likely to occur

✓ Filter damping is an absolute necessity to stay away from troubles

$$P_{out} = P_{in}$$

$$I_{in}V_{in} = I_{out}V_{out}$$

$$I_{in}\left(V_{in}\right) = \frac{P_{out}}{V_{in}}$$




$$\frac{dI_{in}\left(V_{in}\right)}{dV_{in}} = \frac{d\left(\frac{P_{out}}{V_{in}}\right)}{dV_{in}} = -\frac{P_{out}}{V_{in}^{\;2}}$$

The incremental input resistance is negative

$$\boxed{R_{in} = -\frac{V_{in}^{\;2}}{P_{out}}}$$

Negative incremental resistance occurs because of closed-loop operation

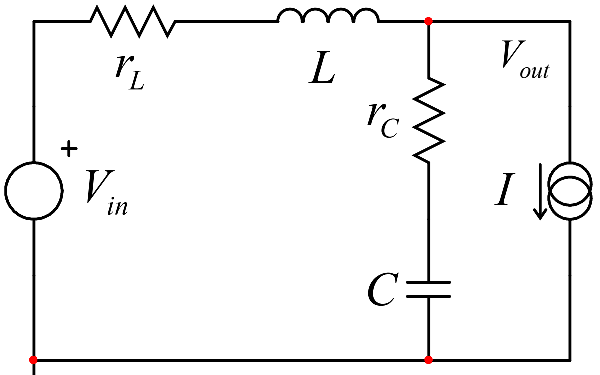
# A Negative Resistance Oscillator

- A negative load for the $LC$ filter can compensate insertion losses
- Damped or sustained oscillations occur depending on resulting damping

$$H(s) = H_0 \frac{1 + s/\omega_z}{\frac{s^2}{\omega_0^2} + \frac{s}{\omega_0 Q} + 1} \qquad Q = \frac{1}{2\boxed{\zeta}}$$

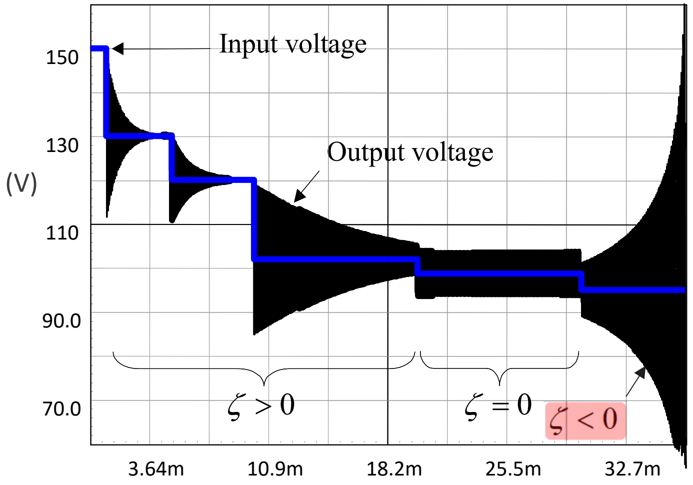
→ If ohmic losses are gone, the damping ratio is zero, $Q$ is infinite.

✓ The poles can jump in the right half-plane and instability occurs!




$I = \frac{P_{out}}{V_{out}}$ (constant) → Negative resistance

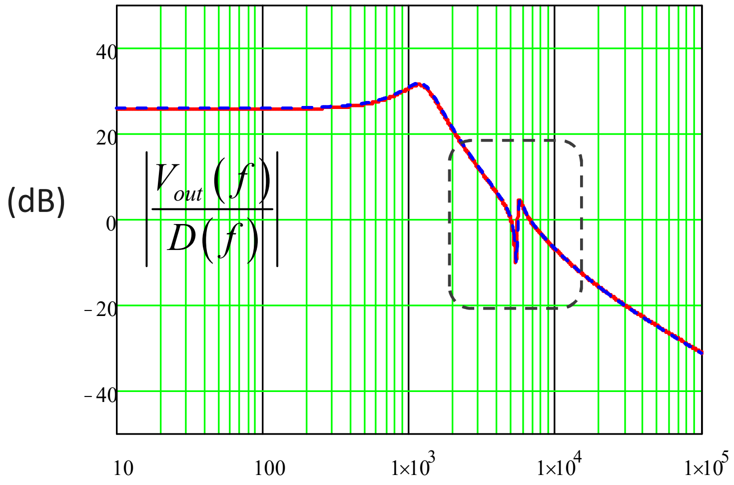
Infinite bandwidth



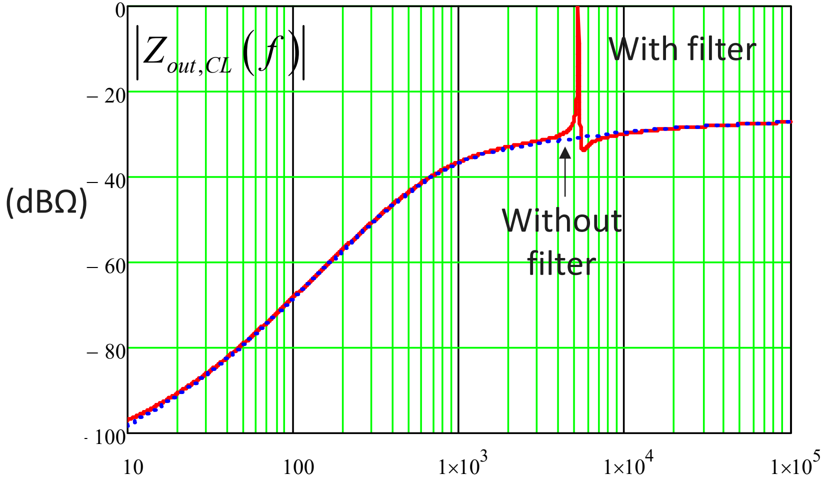
# The Filter Affects the Transfer Function

- Inserting a front-end filter can potentially bring instability to the converter

✓ Power stage response and output impedance can be altered by the $LC$ network




Control-to-output transfer function



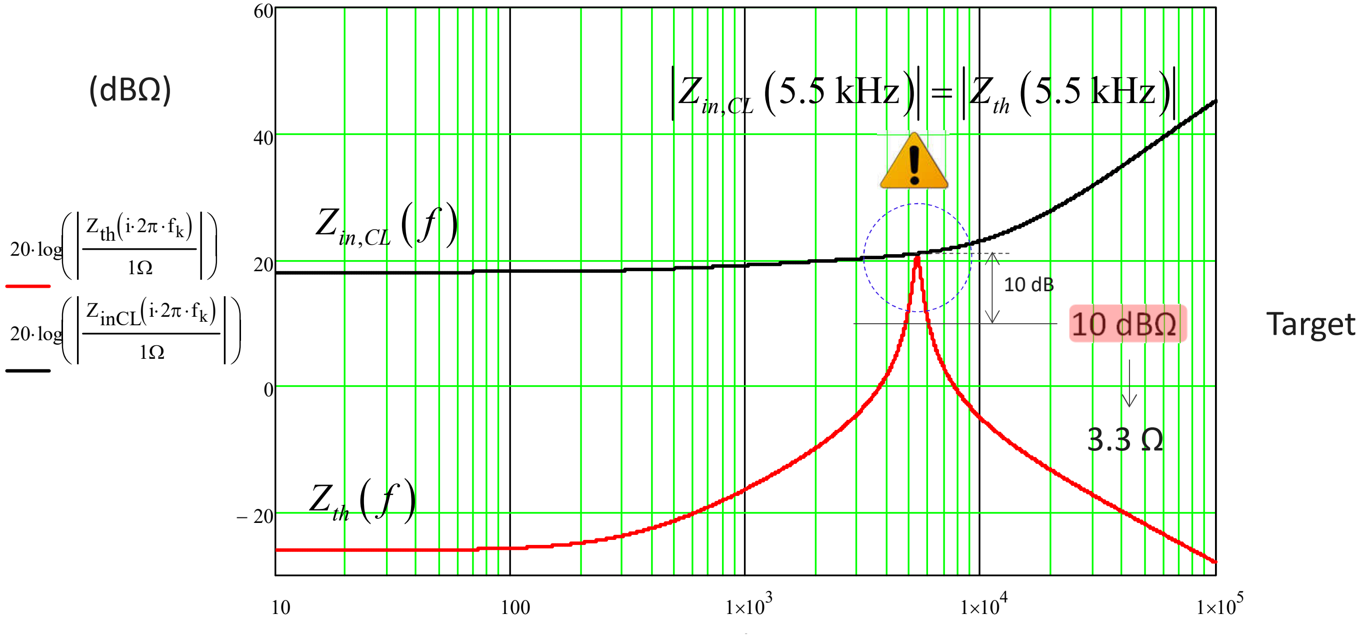

Closed-loop output impedance

✓ Magnitude distortion and severe output impedance peaking are observed

# Keep the Filter Output Impedance Low

1. Plot the input impedance of the compensated converter
2. Add the output impedance of the EMI filter

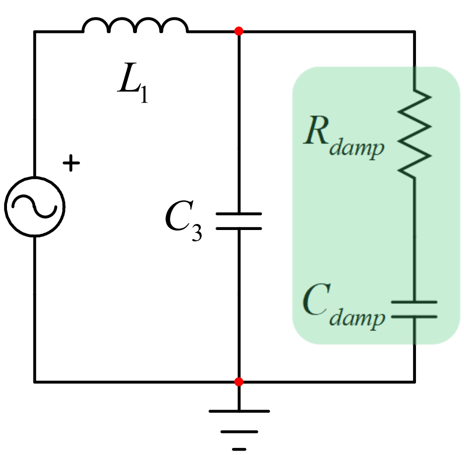
✓ Any overlap represents a possible condition for instabilities



# Losses in the Filter Participate to Damping

- Damping consists of adding extra losses to dissipate power
- The series connection of a capacitor and a resistor offers a simple solution

✓ The resistor and the capacitor can be optimally determined




$$R_0 = \sqrt{\frac{L_f}{C_f}}$$

$$\frac{\left|Z_{out}\right|_{mm}}{R_0} = \sqrt{\frac{2(2+n)}{n^2}}$$

$$Q_{opt} = \sqrt{\frac{(4+3n)(2+n)}{2n^2(4+n)}}$$

$$n = \frac{R_0\left(R_0 + \sqrt{R_0^{\,2} + 4\left(\left|Z_{out}\right|_{mm}\right)^2}\right)}{\left(\left|Z_{out}\right|_{mm}\right)^2} = 3.5$$

target

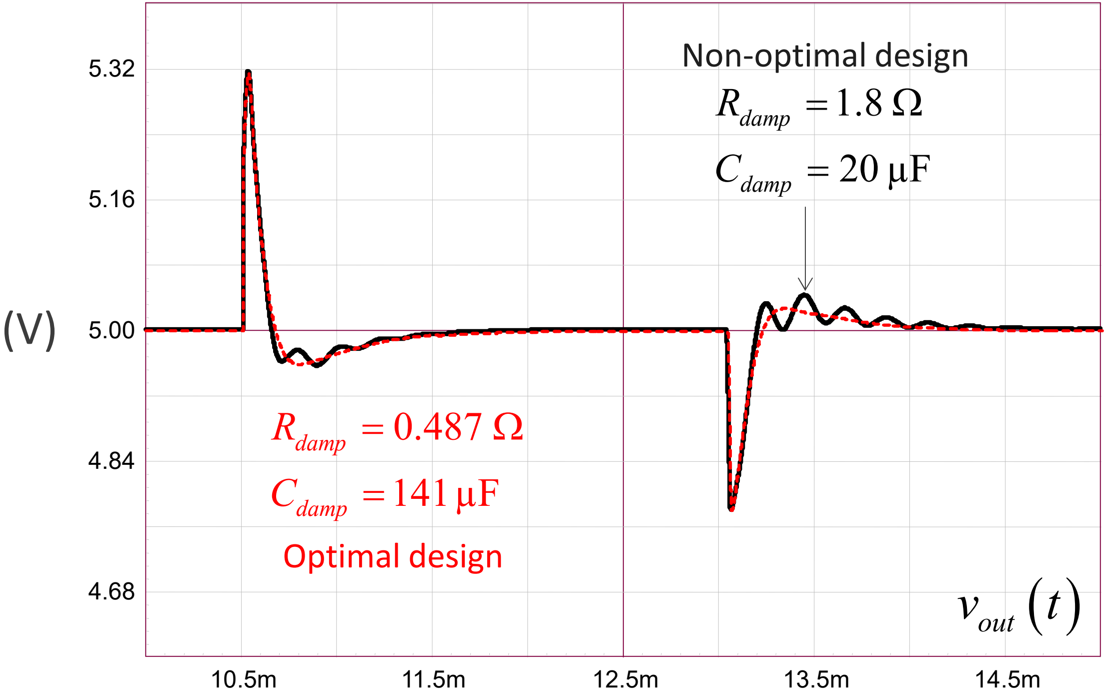
$$R_{damp} = R_0 Q_{opt}$$

$$C_{damp} = nC_f$$

✓ An electrolytic capacitor with its ESR can do the job

# Testing the Transient Response

- It is important to check the response to a load step once damping is done
- Two different damping combinations bring different responses in this case




✓ In one case, the filter has been studied together with the converter for an optimal combination

✓ In the second case, filter was damped after compensation strategy was designed

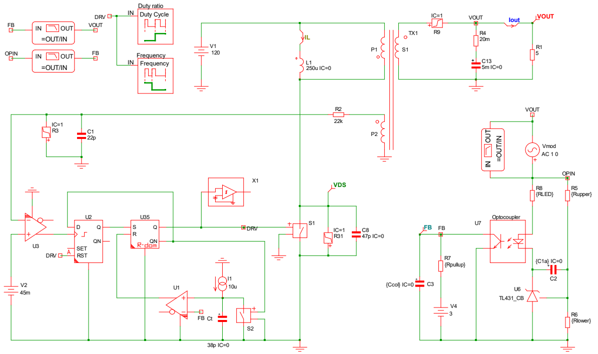
# Agenda

- Power Conversion Mechanisms
- Switching Cells and Control Schemes
- The Buck
- The Boost
- The Buck-Boost
- Introduction to Control Loop Design
- EMI Filter Interaction
- Introduction to Simulation

# Why Simulating Switching Power Converters?

- Check if the converter works on the computer before a prototype is built
- ✓ Are operating voltages and currents within expected safe limits before power on?
- ➢ Power libraries do not blow and let you explore many *What If?* scenarios
- Easily check impacts of parameters variations such as load, input voltage, ESRs etc.
- Work a compensation strategy easily with the ability to draw Bode plots
- ✓ Stabilize the converter with the simulator and confirms margins on the bench

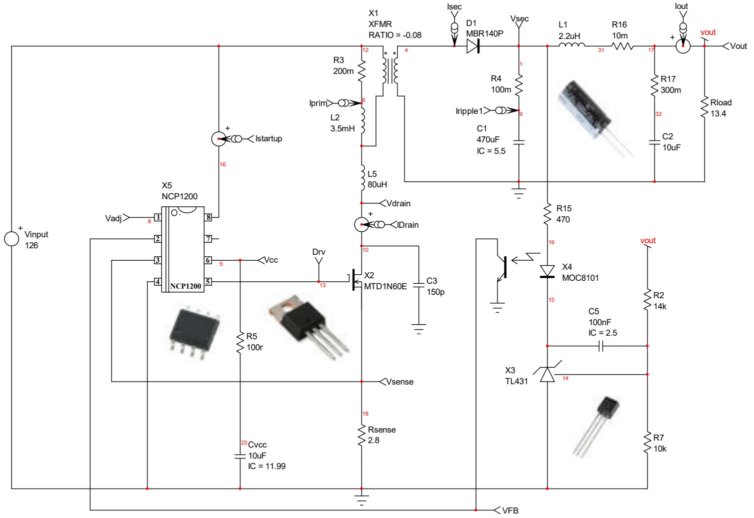
Simulations do **NOT** replace experiments: always build a hardware prototype



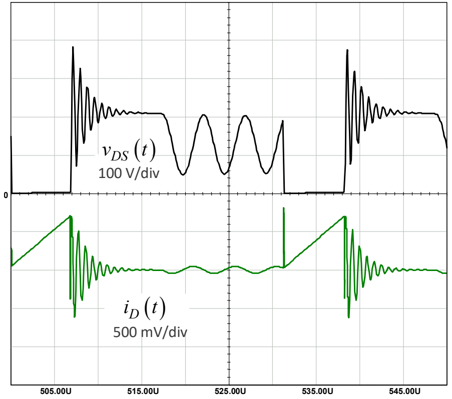
Jim Williams - LT

# Switching Models

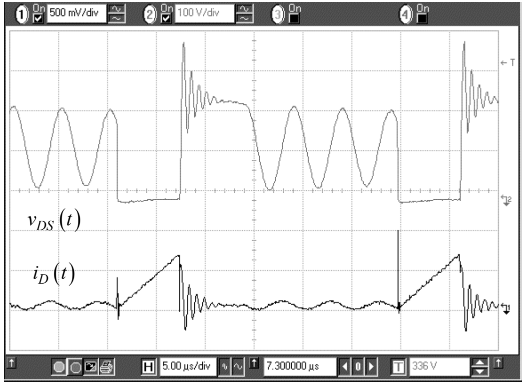
- A cycle-by-cycle model represents the entire switching power converter
- ✓ Include parasitic terms and obtain excellent correlation with bench results
- Simulation time can be long and prone to convergence issues
- No access to ac response for loop stabilization




Simulated waveforms



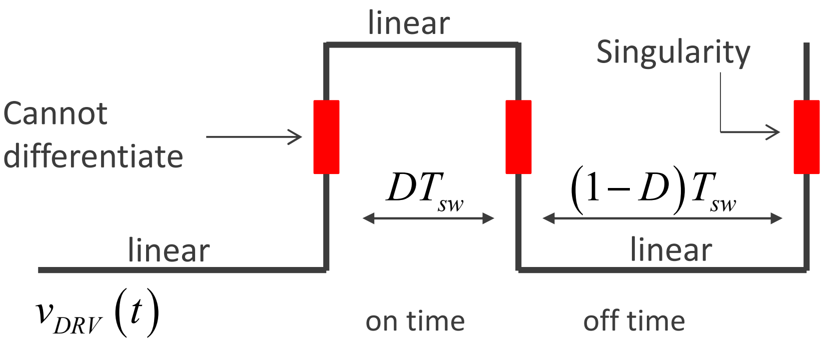

Measured waveforms



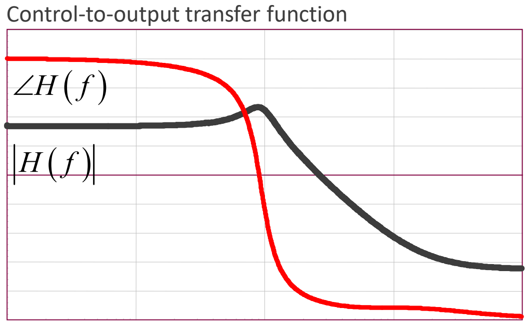

Simulation really works!

# Averaged Models

- Modeling the small-signal response of a switching converter is a difficult exercise
- The problem comes from time-discontinuous waveforms

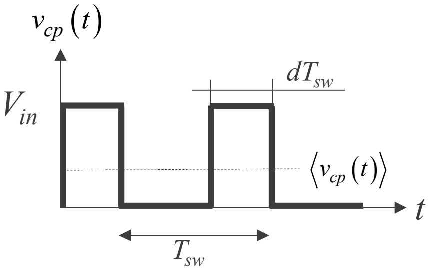



How do we get this?




- The PWM switch introduced in the 90's by Dr. Vorpérian offers an elegant solution

✓ Switching waveforms are *averaged* and described by a time-continuous expression




$$\langle v_{cp}(t)\rangle_{T_{sw}} = V_{cp} = \frac{1}{T_{sw}}\int_0^{dT_{sw}} v_{cp}(t)\,dt = D\langle v_{ap}(t)\rangle_{T_{sw}} = DV_{ap}$$

Small-signal

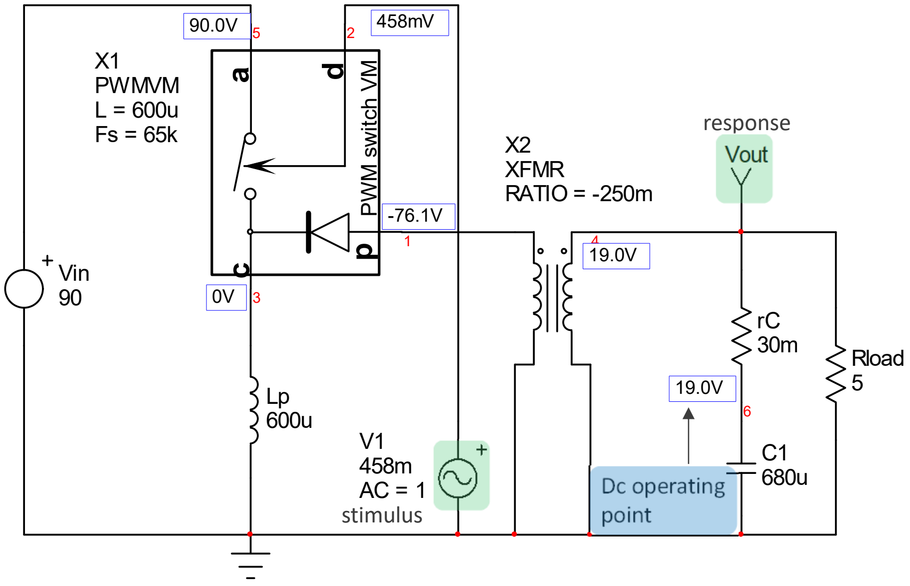
$$\hat{v}_{cp} = D\hat{v}_{ap} + V_{ap}\hat{d}$$

$$V_{cp} = DV_{ap}$$

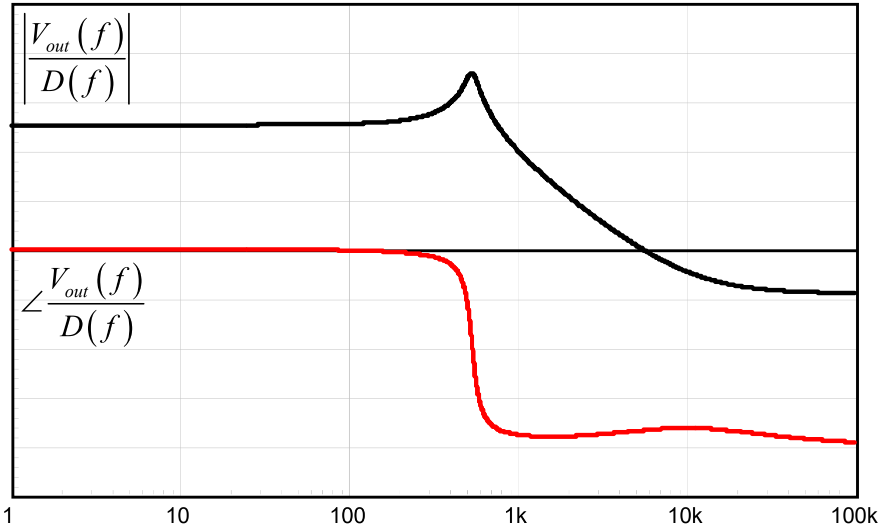
Dc equation

# Ac Analyses with Averaged Models

- Averaged models are free of switching component and simulate fast
- They work in transient and ac analyses: small-signal response is immediate
- There is no averaged model for the LLC converter



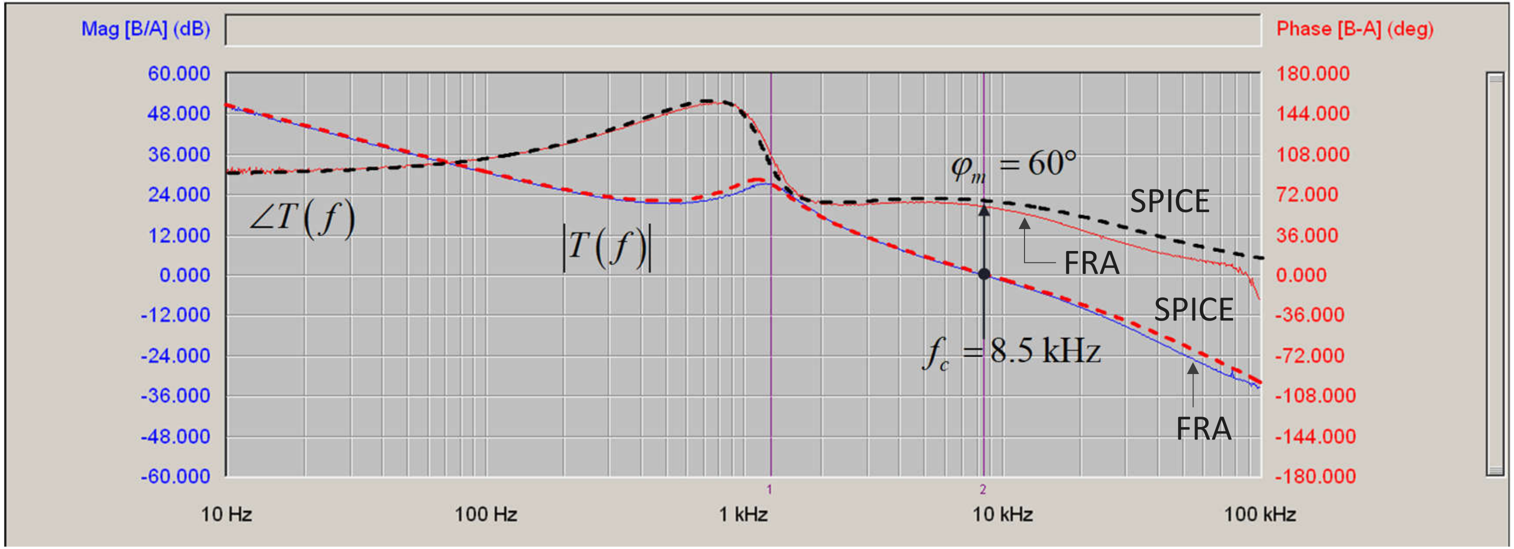

Power stage response of a CCM flyback



# Simulation Results you can Trust

- Simulation matches with hardware when parasitics are well extracted from components

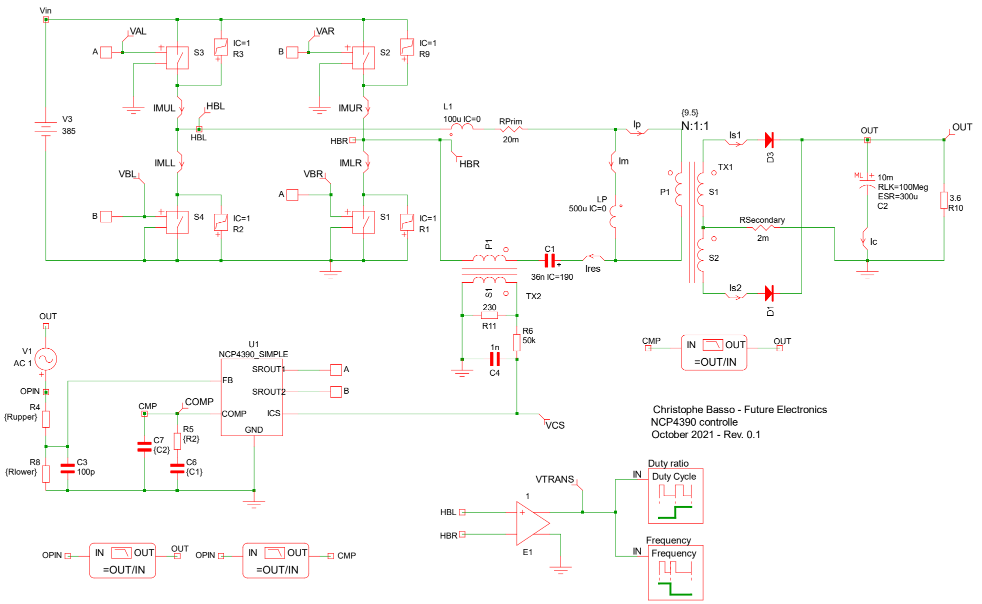
✓ Run and test the compensation strategy and confirm bench measurements are ok



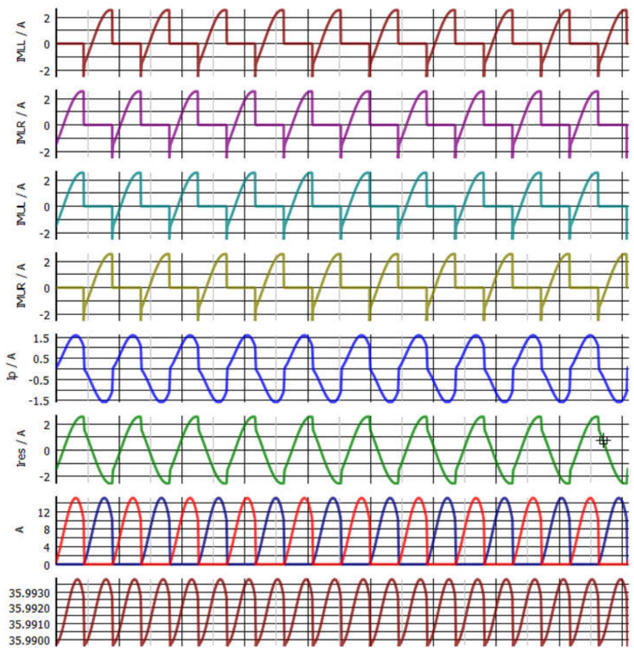

- When the computed model is validated you can run in-depth analyses with Monte Carlo

# Piece-Wise Linear Simulation Engine

- Piece-wise linear simulators can extract the ac response from a switching converter
- ✓ Build the circuit using classical switching components and run an ac analysis
- ✓ It works with any converter structure and there is no need for average model



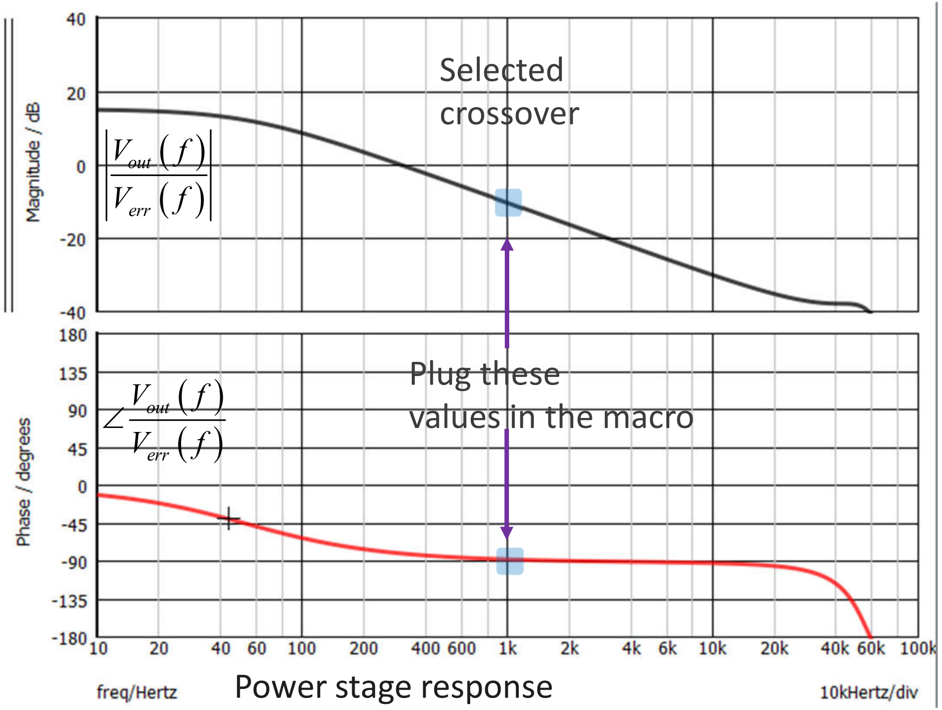

A full-bridge LLC with NCP4390




Operating point

# Ac Analyses from a Switching Circuit

- The engine ac-sweeps the converter and delivers the control-to-output transfer function
- Determine the compensation strategy and automate components calculations




Power stage response

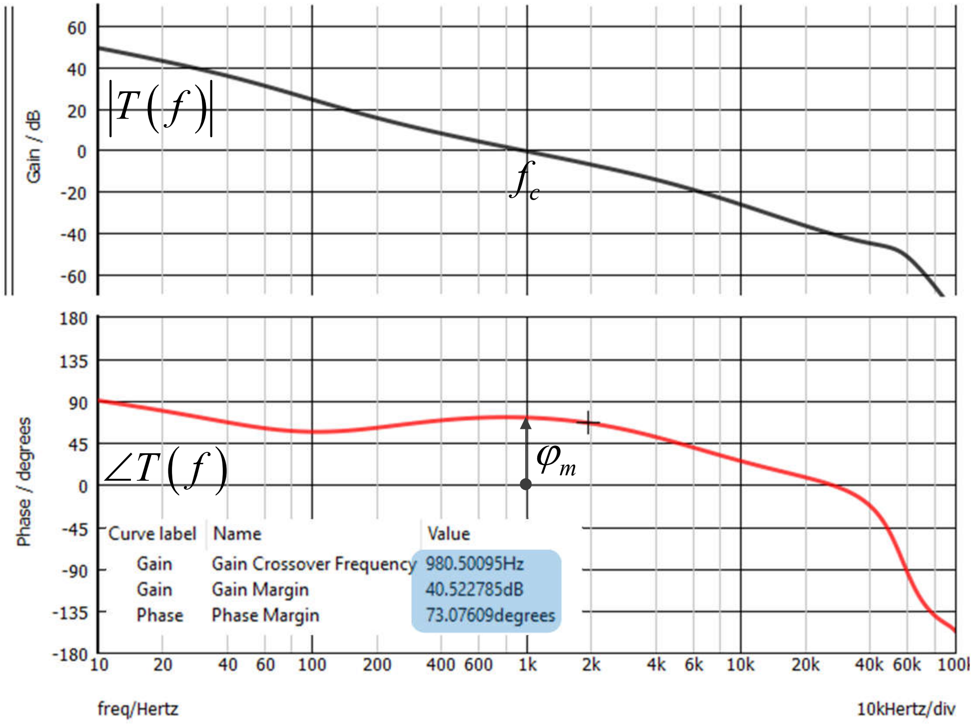
```
.VAR Gfc=-10 * magnitude at crossover *
.VAR PS=-90 * phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.VAR fc=1k * targetted crossover *
.VAR PM=70 * choose phase margin at crossover *
*
* Enter the Values for Vout and Bridge Bias Current *
*
.VAR Vout=36
.VAR Ibias=1m
.VAR Vref=2.4
.VAR Rlower={Vref/Ibias}
.VAR Rupper={(Vout-Vref)/Ibias}
*
* Choose OTA characteristics *
*
.VAR gm=300u * transconductance in Siemens *
*
*
.VAR R2=(a/b)*(fp*G)*(Rlower+Rupper)/((fp-fz)*Rlower*gm)
.VAR C1=1/(2*pi*R2*fz)
.VAR C2=(Rlower*gm/(2*pi*fp*G*(Rlower+Rupper)))(b/a)
*
```

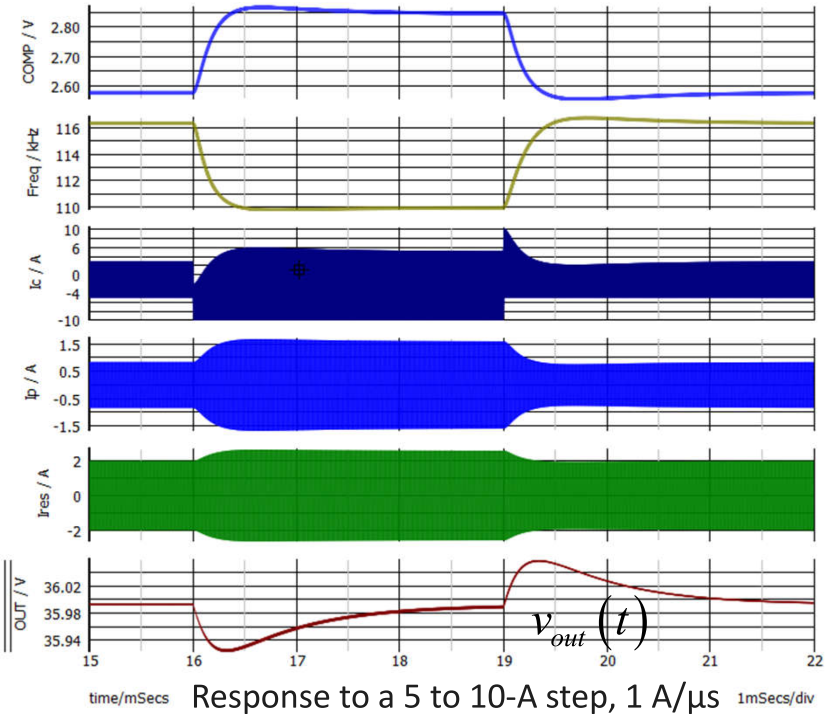
```
*
* Do not edit the below lines *
.VAR boost=PM-PS-90
.VAR G=10^(-Gfc/20)
.VAR k=tan((boost/2+45)*pi/180)
.VAR fp=fc*k
.VAR fz=fc/k
.VAR a=sqrt((fc^2/fp^2)+1)
.VAR b=sqrt((fz^2/fc^2)+1)
*
* Simpler approach if C2 << C1 *
*
* .VAR R2=G*(Rlower+Rupper)/(Rlower*gm)
* .VAR C1=1/(2*pi*R2*fz)
* .VAR C2=1/(2*pi*R2*fp)
*
```

Components calculations are automated

# Check Compensated Response

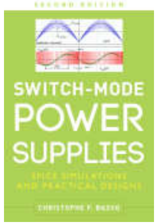
- The compensated loop gain is immediate and you can check the transient response
- Run various analyses for robustness verifications once model is validated by hardware



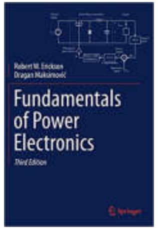




Response to a 5 to 10-A step, 1 A/µs

# Books on Power Electronics




Switch-Mode Power Supplies: SPICE Simulations and Practical Designs, 2nd edition
Christophe Basso – Mcgraw-Hill 2014




Fundamentals of Power Electronics, 3rd edition
Robert Erickson, Dragan Maksimovic – Springer 2020


Designing Control Loops for Linear and Switching Power Supplies
Christophe Basso – Artech House 2012


Transfer Functions of Switching Converters
Christophe Basso – Faraday Press 2021


How2Power, a free power electronics newsletter

My personal webpage with all my APEC seminars and lot of power electronics documents to download
https://cbasso.pagesperso-orange.fr/Spice.htm

All the former Unitrode (now TI) seminars are available from this landing page

# Conclusion

- ❑ Compared to linear regulators, switching converters excel in efficiency
  - ❖ Switching converters are noisy in essence
- ❑ There are 3 basic switching cells made of a controlled switch and a diode
  - ✓ Some of these cells can be extended to versions featuring isolation
  - ✓ Different input/output characteristics are observed and must be understood
  - ❖ Input/output currents can be smooth or pulsating and impact capacitors
- ❑ Loop control is an essential part of the design and cannot be neglected
- ❑ EMI filter are necessary to keep noise within accepted limits
  - ❖ Their insertion can severely affect the converter performance
- ❑ Simulation offers a great way to test the converter on the computer
  - ❖ Use it extensively while always using engineering judgment on the results