ON Semiconductor®

Simulating Power Supplies with SPICE

Agenda

☐ Why simulating power supplies?
☐ Average modeling techniques
☐ The PWM switch concept, CCM
☐ The PWM switch concept, DCM
☐ The voltage-mode model at work
☐ Current-mode modeling
☐ The current-mode model at work
☐ Power factor correction
☐ Switching models
☐ EMI filtering
☐ Conclusion

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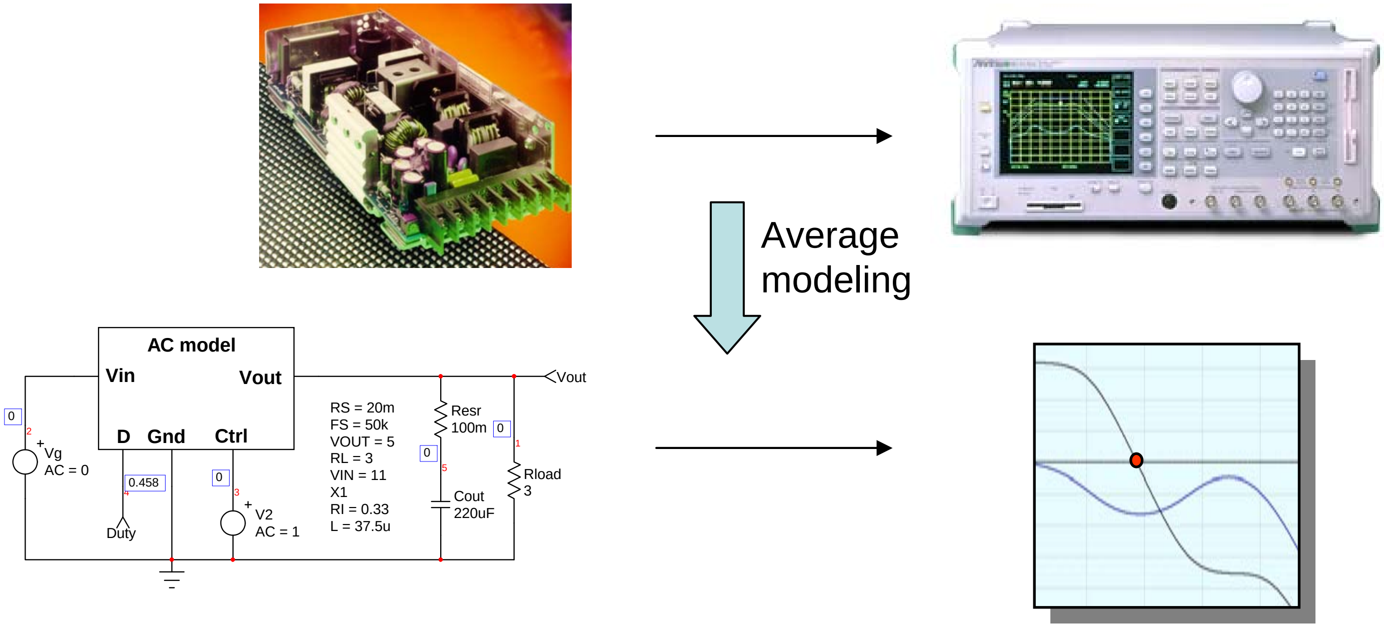
Why Simulate Switch Mode Power Supplies?

- Simulation helps feeling how the product behaves before breadboard
- Experiment What If? at any level. Power libraries do not blow!
- Easily shows impact of parameter variations: ESR, Load etc.
- Draw Bode plots without using costly equipments
- Avoid trials and errors: compensate the loop on the PC first!
- Use SPICE to assess current amplitudes, voltage stresses etc.
- Go to the lab. and check if the assumptions were valid.

SPICE does **NOT** replace the breadboard!

Why *Average* Simulations?

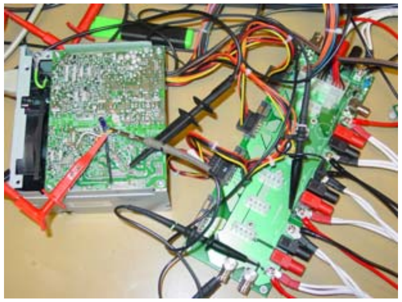
❑ An average model is made of equations that are continuous in time
❑ The switching component has disappeared, leading to:
❖ a simpler ac analysis of the power supply
❖ the study of the stability margins in various conditions
❖ the assessment of the ESRs contributions in the loop stability
❖ a flashing simulation time!

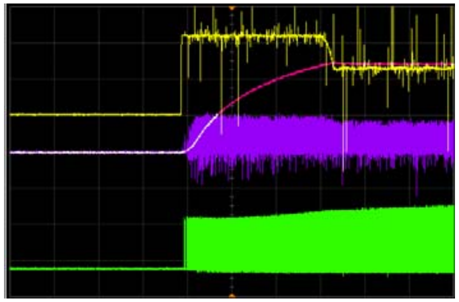


Average
modeling

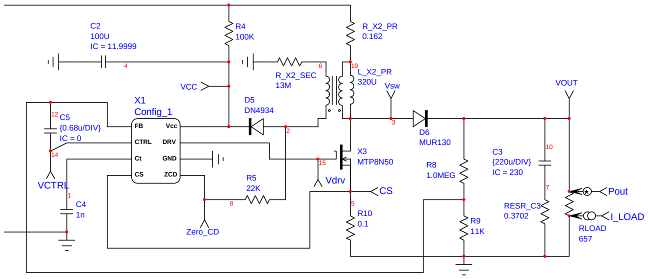
Why *Switching* Simulations?

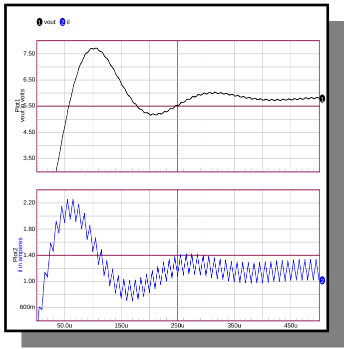
- ❑ An switching model is like breadboarding on the PC
- ❑ The switching component is back in place, leading to:
- ❖ the analysis of current and voltage stresses
- ❖ the study of leakage and stray elements impacts
- ❖ the analysis of the input current signature – EMI
- ❖ a longer simulation time…





Switching approach





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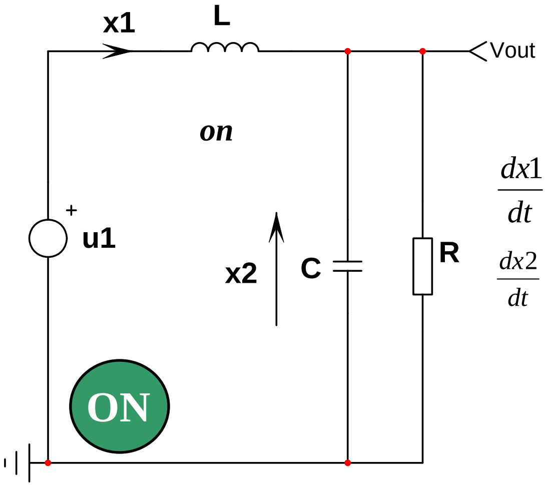
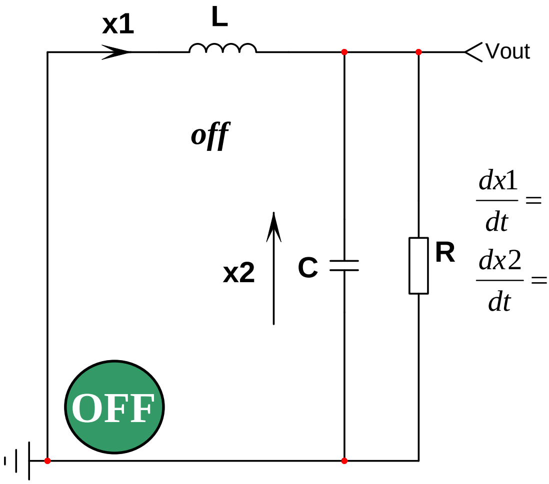
Average Modeling, the SSA

- State-Space Averaging (SSA)
- Introduced by Slobodan Ćuk in the 80’
- Long and painful process
- ***Fails*** to predict sub-harmonic oscillations



$$\frac{dx1}{dt} = -\frac{1}{L}x2 + \frac{1}{L}u$$

$$\frac{dx2}{dt} = \frac{1}{Cout}x1 - \frac{1}{Rload.Cout}x2$$



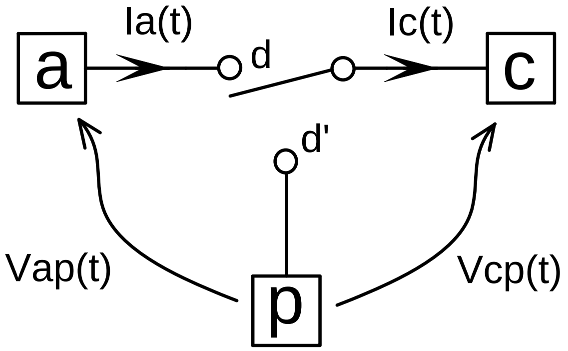
$$\frac{dx1}{dt} = -\frac{1}{L}x2$$

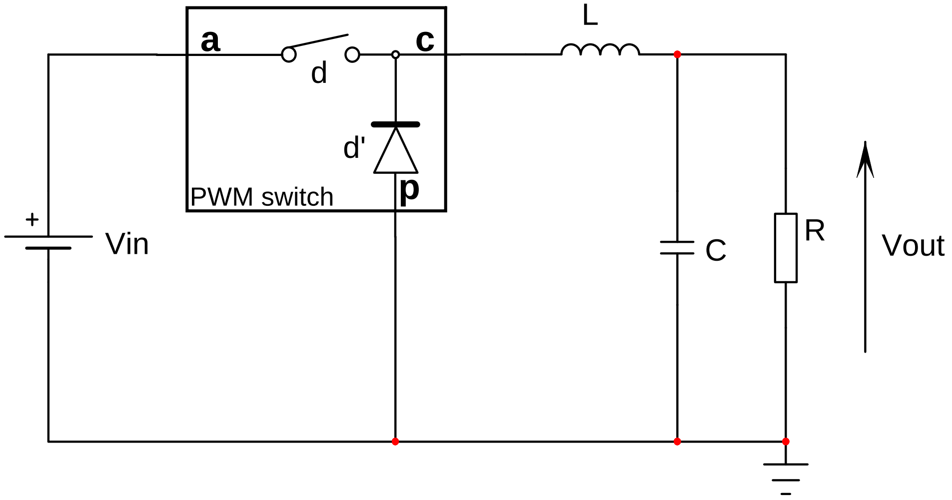
$$\frac{dx2}{dt} = \frac{1}{Cout}x1 - \frac{1}{Rload.Cout}x2$$

⇨ Apply smoothing process ⇨ Linearize ☹

Average Modeling, the PWM Switch

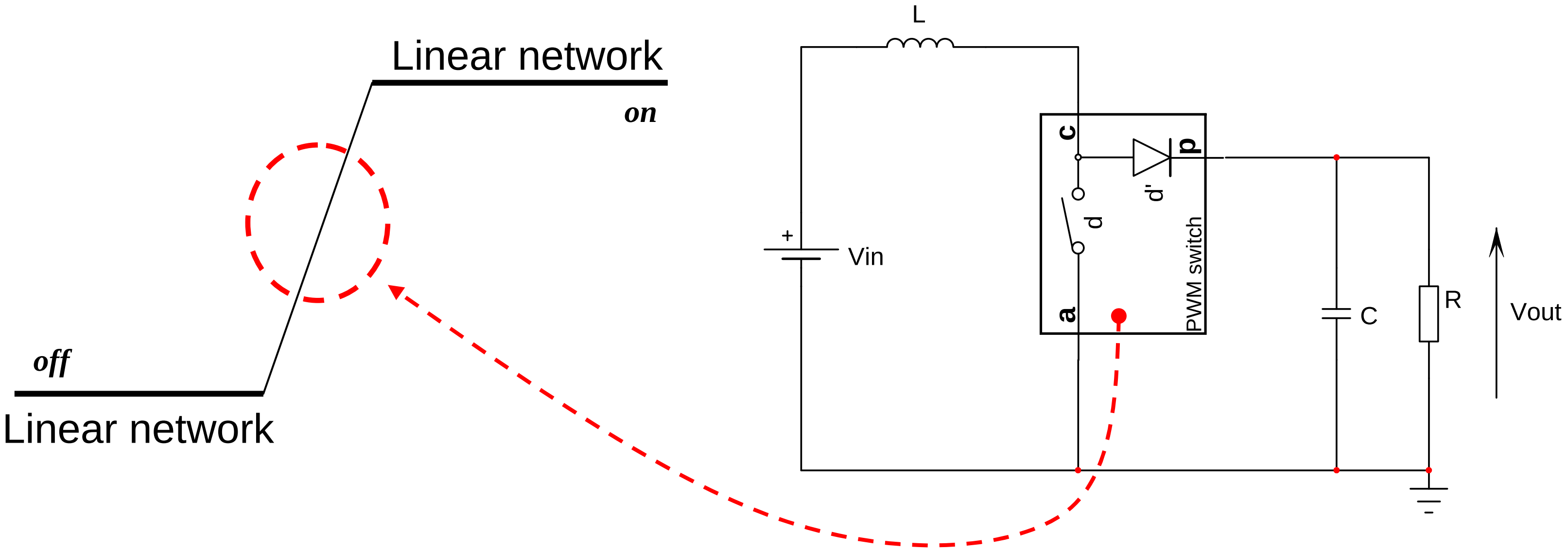
- The PWM Switch
- Introduced by Vatché Vorpérian in the mid-80’
- Easy to derive and fully invariant
- ***No*** auto-toggling mode models
- ***Can*** predict sub-harmonic oscillations in CCM
- DCM model in current-mode was never published!





The PWM Switch Concept

- ❑ Identify the guilty network: the transistor and the diode
- ❖ Average their voltage and current waveforms: large-signal model
- ❖ Linearize the equations around a dc point: small-signal model



diode + transistor = <u>guilty</u> for non-linearity!

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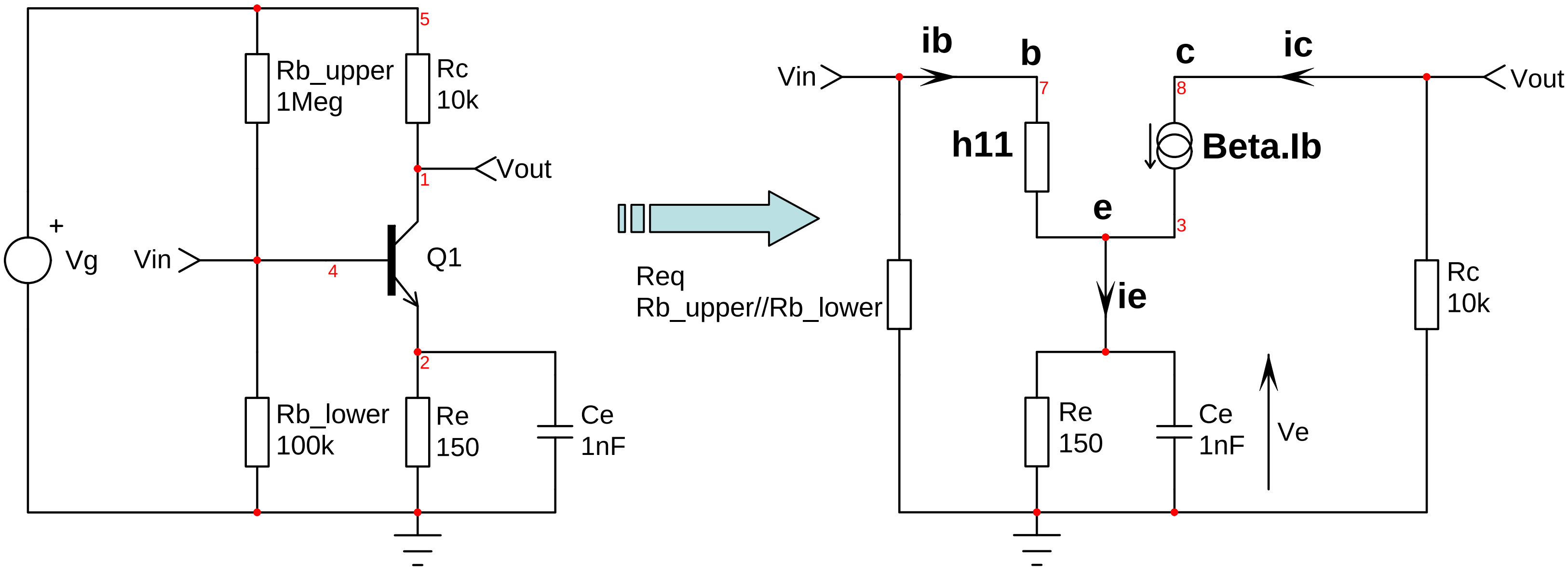
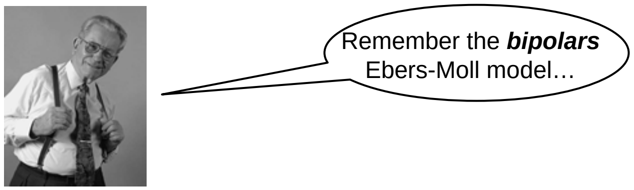
The PWM Switch Concept

- ❑ The transistor is a highly non-linear device:
  - ❖ Replace the transistor with its small-signal model
  - ❖ Solve a system of <u>linear</u> equations



Replace Q_1 by its small-signal model

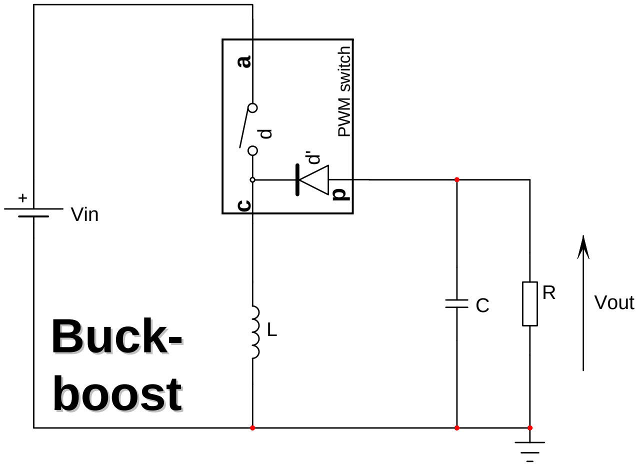


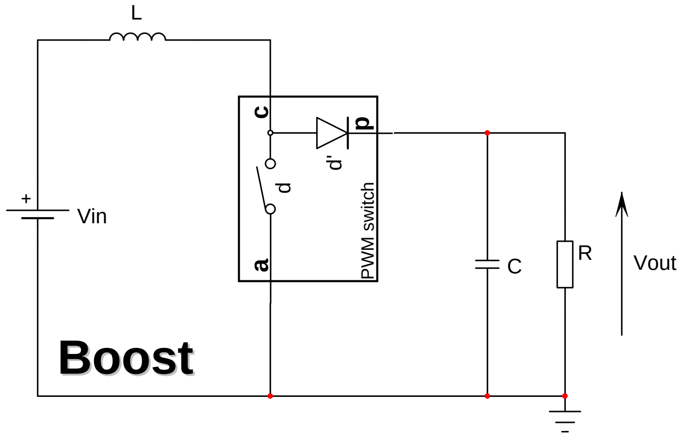
The PWM Switch Concept

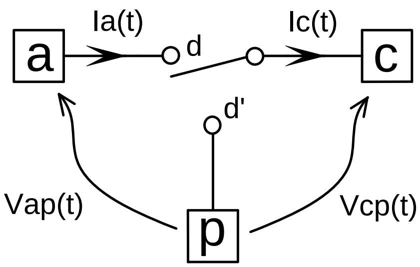
❑ The PWM switch model works in all two switch converters:

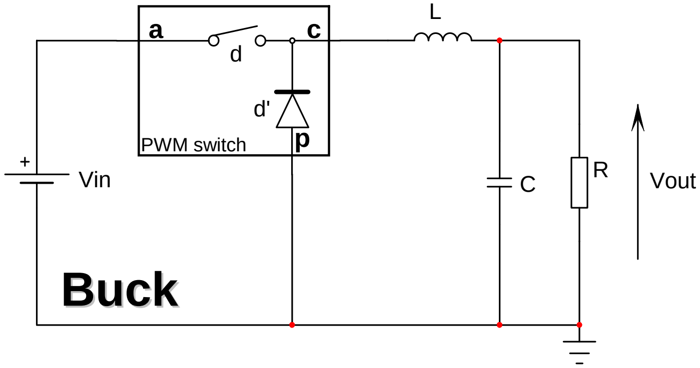
❖ Rotate the model to match the switch and diode connections

❖ Solve a system of linear equations



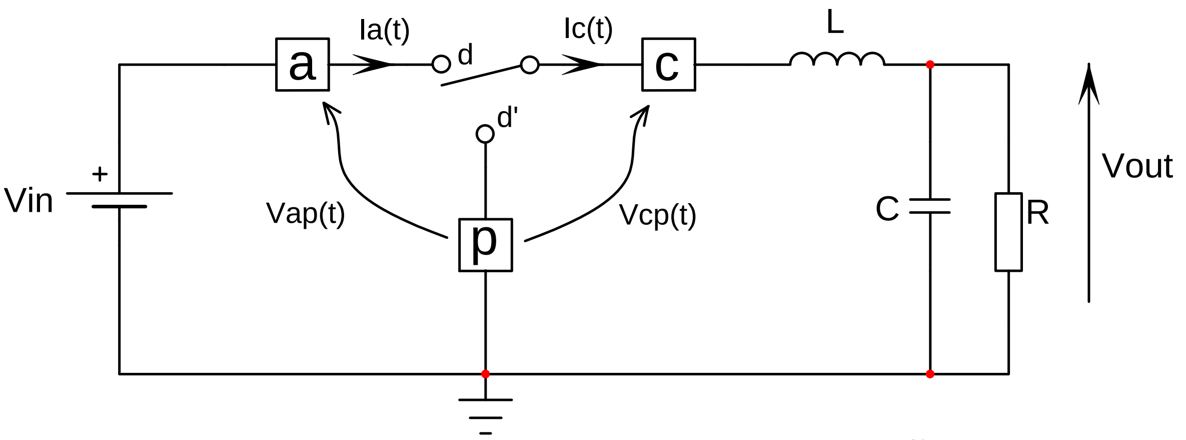


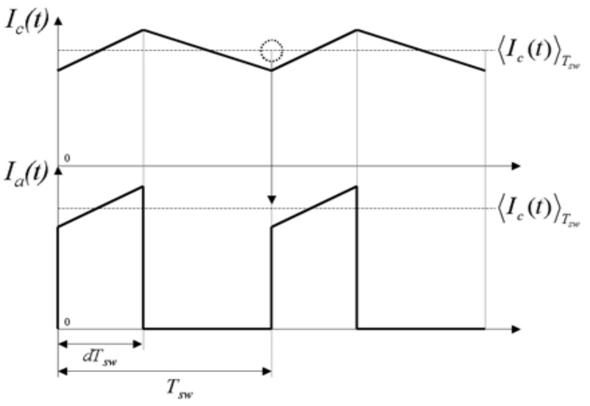


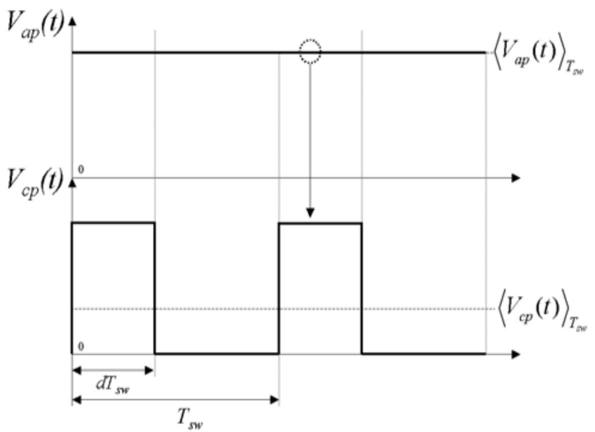


The PWM Switch Concept

- ☐ The keyword with average modeling: waveforms averaging





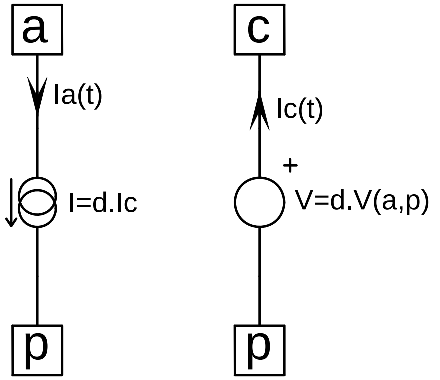


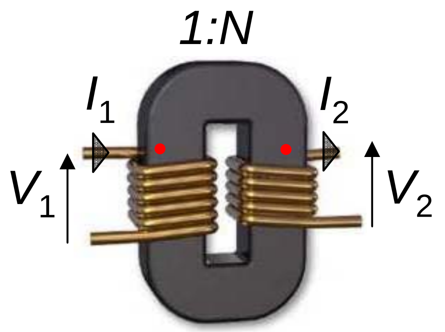
$$\langle I_a(t)\rangle_{T_{sw}} = I_a = \frac{1}{T_{sw}}\int_0^{T_{sw}} I_a(t)dt = d\langle I_c(t)\rangle_{T_{sw}} = \boxed{dI_c}$$

$$\langle V_{cp}(t)\rangle_{T_{sw}} = V_{cp} = \frac{1}{T_{sw}}\int_0^{T_{sw}} V_{cp}(t)dt = d\langle V_{ap}(t)\rangle_{T_{sw}} = \boxed{dV_{ap}}$$

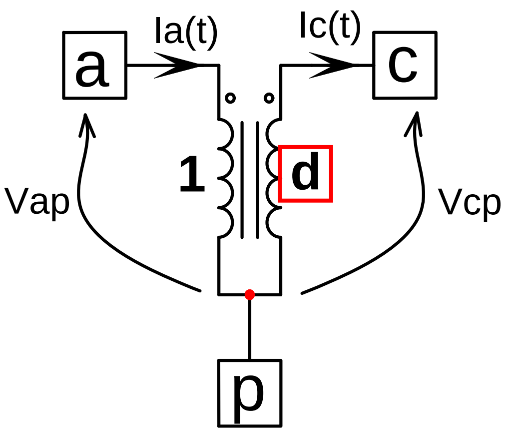
The PWM Switch Concept

- ❑ The obtained set of equations is that of a transformer
- ➢ A CCM two-switch DC-DC can be modeled like a *1*:*D* transformer!





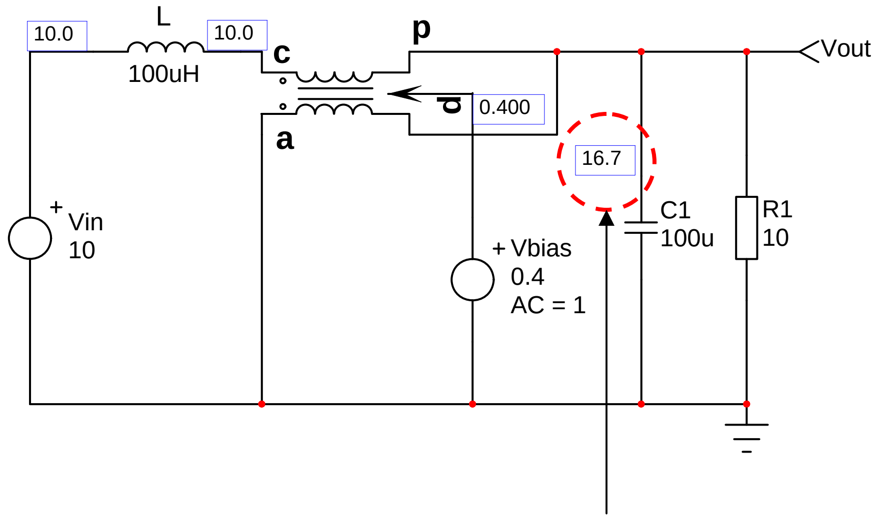
$$V_2 = NV_1$$
$$I_1 = NI_2$$



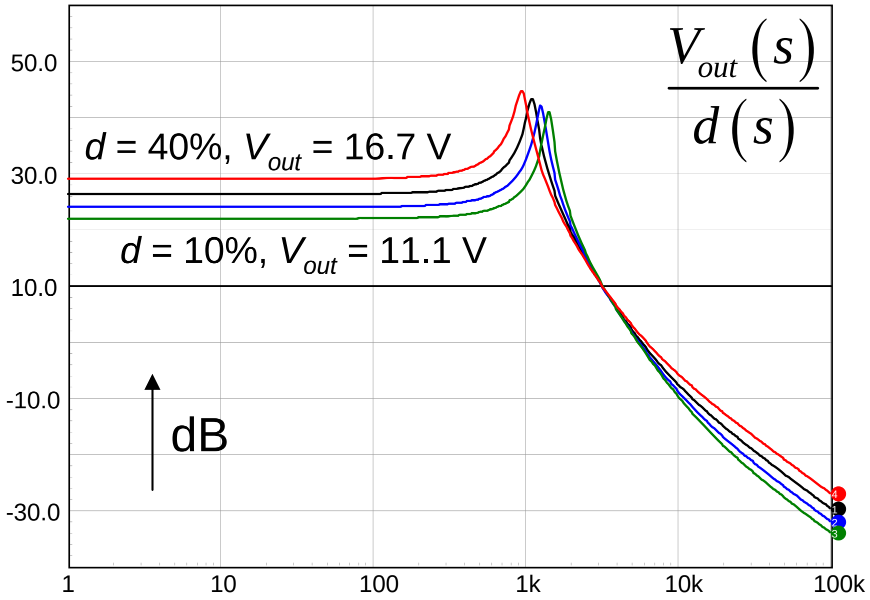
Large-signal (non-linear) model

The PWM Switch Concept

- SPICE only deals with linear equations
- It first computes a bias point then it linearizes the network



Always verify the dc operating point!



- No equations, result appears in a second!
- Make sure the bias point is correct…

The PWM Switch Concept

❑ We have a set of non-linear equations: can't derive transfer functions!
❑ We need a small-signal model: linearize the equations by hand
❖ two options: perturbation or partial derivatives…

Pertubation

$$I_a = dI_c \qquad V_{cp} = dV_{ap}$$

$$I_a = I_{a0} + \hat{i}_a \qquad V_{cp} = V_{cp0} + \hat{v}_{cp}$$

$$I_c = I_{c0} + \hat{i}_c \qquad d = d_0 + \hat{d}$$

$$d = d_0 + \hat{d}$$

same

$$I_{a0} + \hat{i}_a = \left(d_0 + \hat{d}\right)\left(I_{c0} + \hat{i}_c\right)$$

$$\boxed{I_{a0} = d_0 I_{c0} \qquad V_{cp0} = d_0 V_{ap0}}$$

$$\boxed{\hat{i}_a = d_0 \hat{i}_c + \hat{d} I_{c0} \qquad \hat{v}_{cp} = d_0 \hat{v}_{ap} + \hat{d} V_{ap0}}$$

ac and dc equations

Partial derivatives

$$I_a = dI_c \qquad V_{cp} = dV_{ap}$$

$$\hat{i}_a = \frac{\partial I_a}{\partial I_c}\hat{i}_c + \frac{\partial I_a}{\partial d}\hat{d} \qquad \hat{v}_{cp} = \frac{\partial V_{cp}}{\partial V_{ap}}\hat{v}_{ap} + \frac{\partial V_{cp}}{\partial d}\hat{d}$$

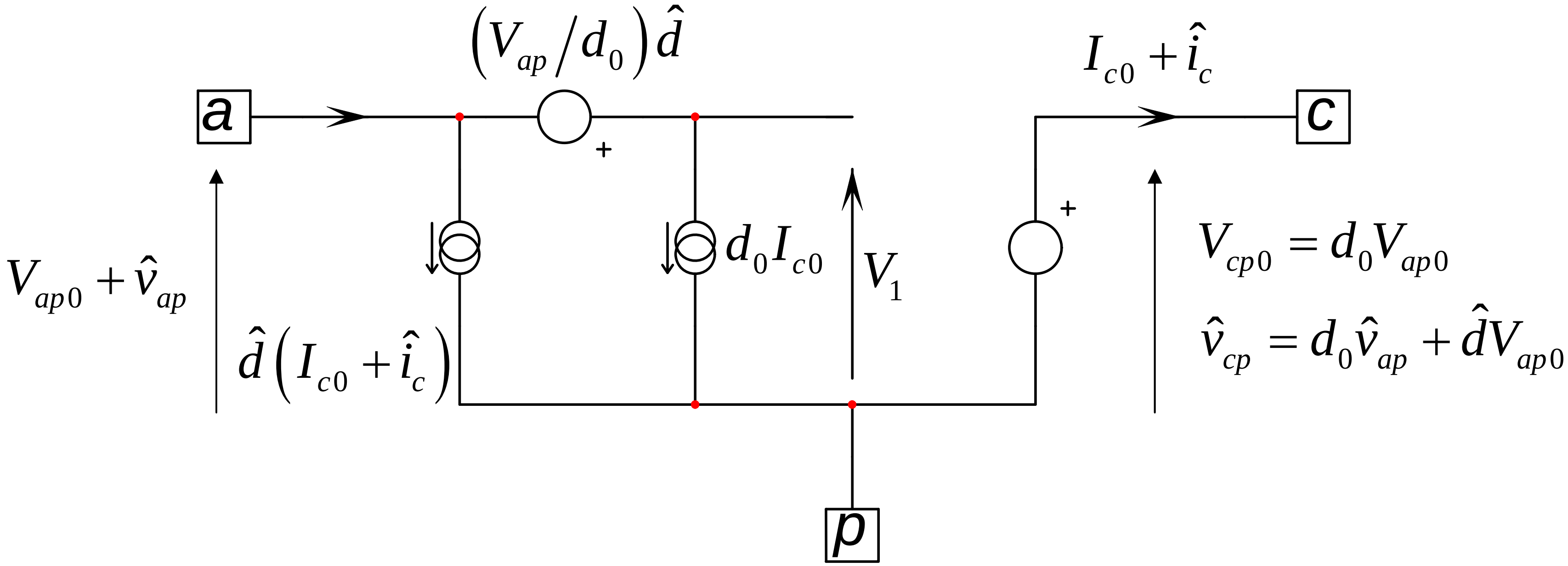
$$\downarrow \qquad \downarrow$$

$$\underbrace{\hat{i}_a = d_0 \hat{i}_c + \hat{d} I_{c0} \qquad \hat{v}_{cp} = d_0 \hat{v}_{ap} + \hat{d} V_{ap0}}$$

ac equations
No dc point

The PWM Switch Concept

- ☐ Put the small-signal sources in the large-signal model
  - ❖ You obtain the small-signal model of the CCM PWM switch



$$V_{cp0}=d_0 V_{ap0}$$

$$\hat{v}_{cp}=d_0\hat{v}_{ap}+\hat{d}V_{ap0}$$

- ☐ You can now analytically find the dc bias and the ac response!

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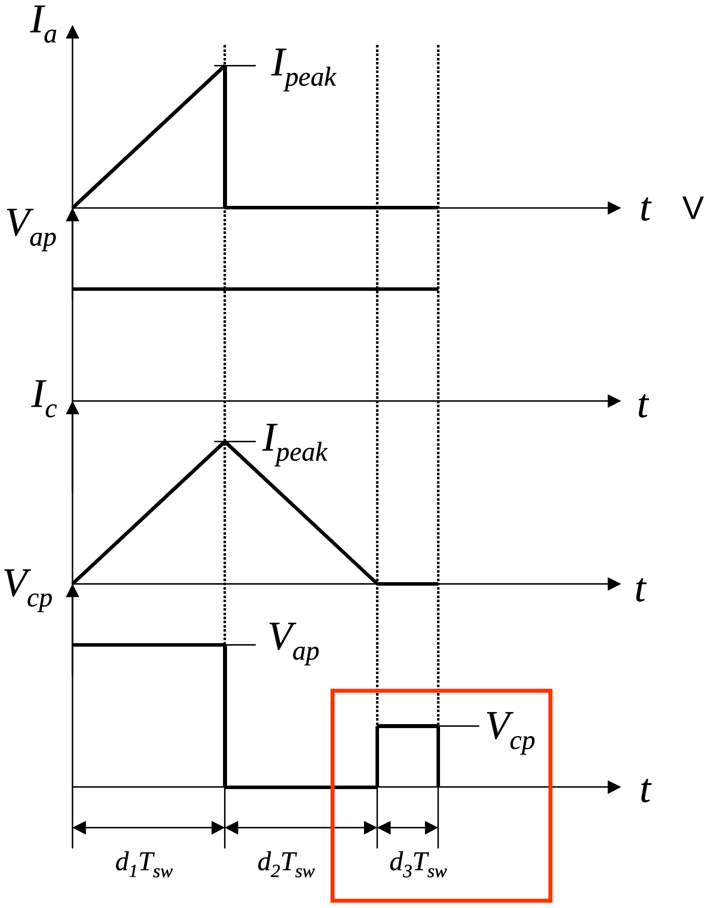
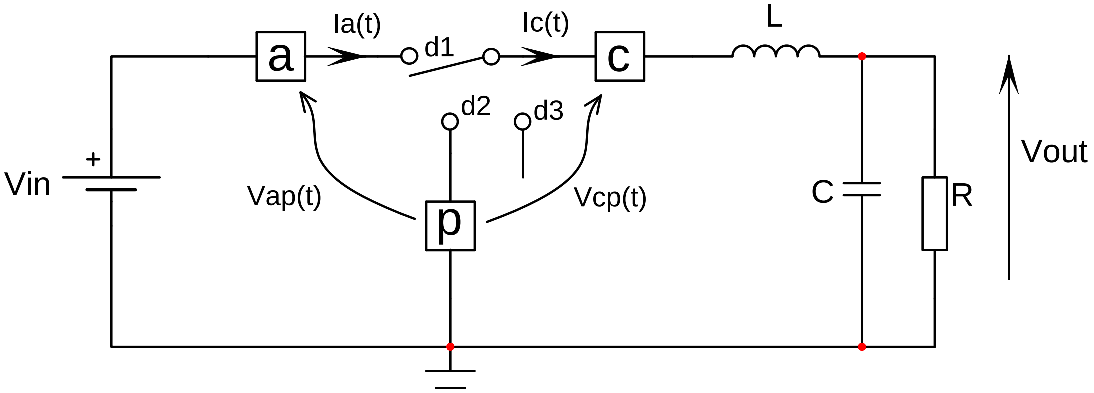
The PWM Switch in DCM

- The original model could not be auto-toggling
- A new DCM-CCM model has been derived



3rd event linked to DCM



Extract and replace

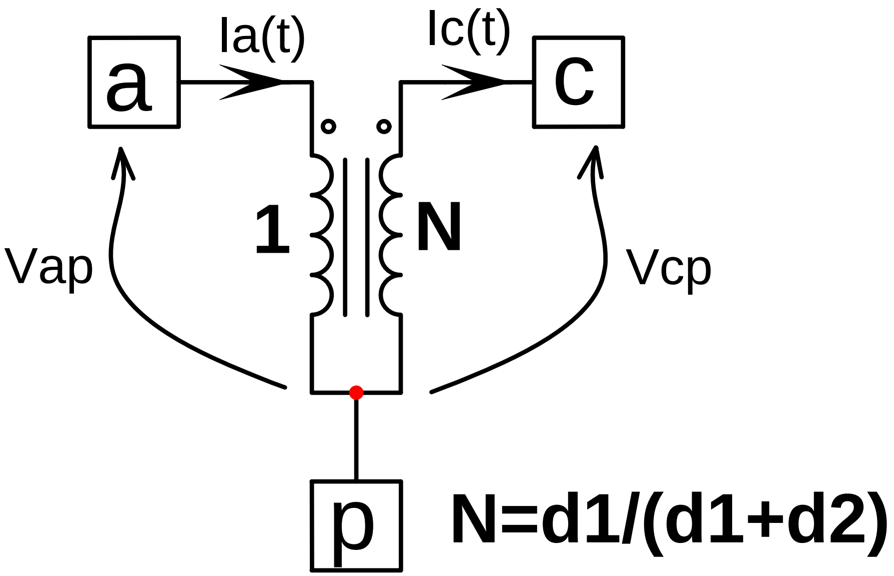
$$I_a = \frac{\boxed{I_{peak}}\, d_1}{2}$$

$$I_c = \frac{\boxed{I_{peak}}\,(d_1 + d_2)}{2}$$

$$I_c = I_a \frac{(d_1 + d_2)}{d_1}$$

The PWM Switch in DCM

❑ By clamping the d_2 equation, the circuit toggles between the modes



Clamp d_2:

d_2 CCM = 1- d_1

d_2 DCM = 1- d_1- d_3

⇩

$d_2 < 1 - d_1$

model is in DCM!

$$d_2 = \frac{2I_c L - V_{ac} d_1{}^2 T_{sw}}{V_{ac} d_1 T_{sw}} = \frac{2LF_{sw}}{d_1} \frac{I_c}{V_{ac}} - \boxed{d_1}$$

Model input

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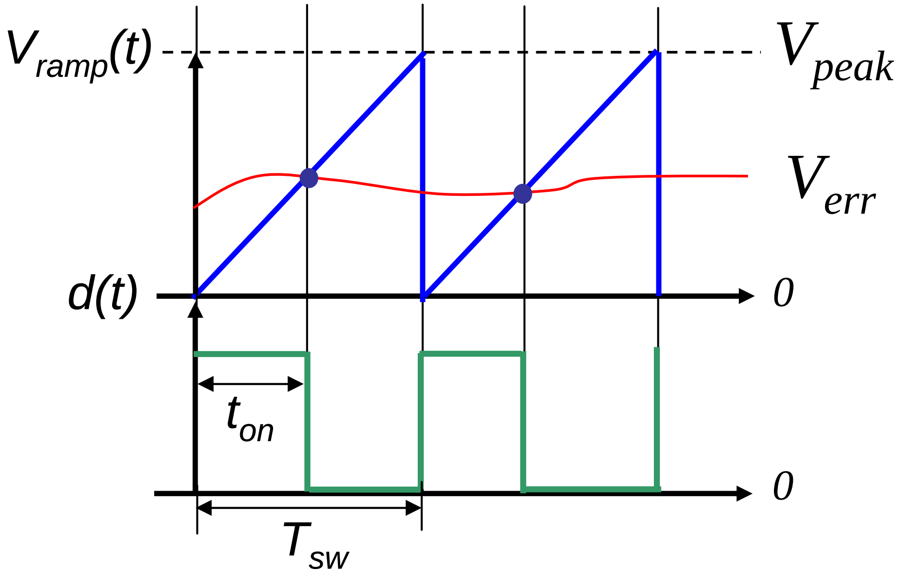
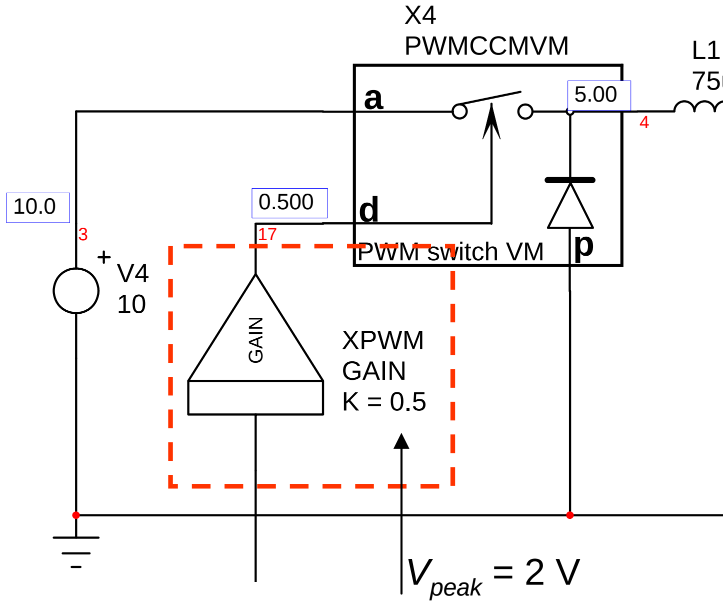
The PWM Switch in DCM

- In voltage-mode, the duty-cycle is built with a ramp generator
- The transition occurs when the error voltage crosses the ramp



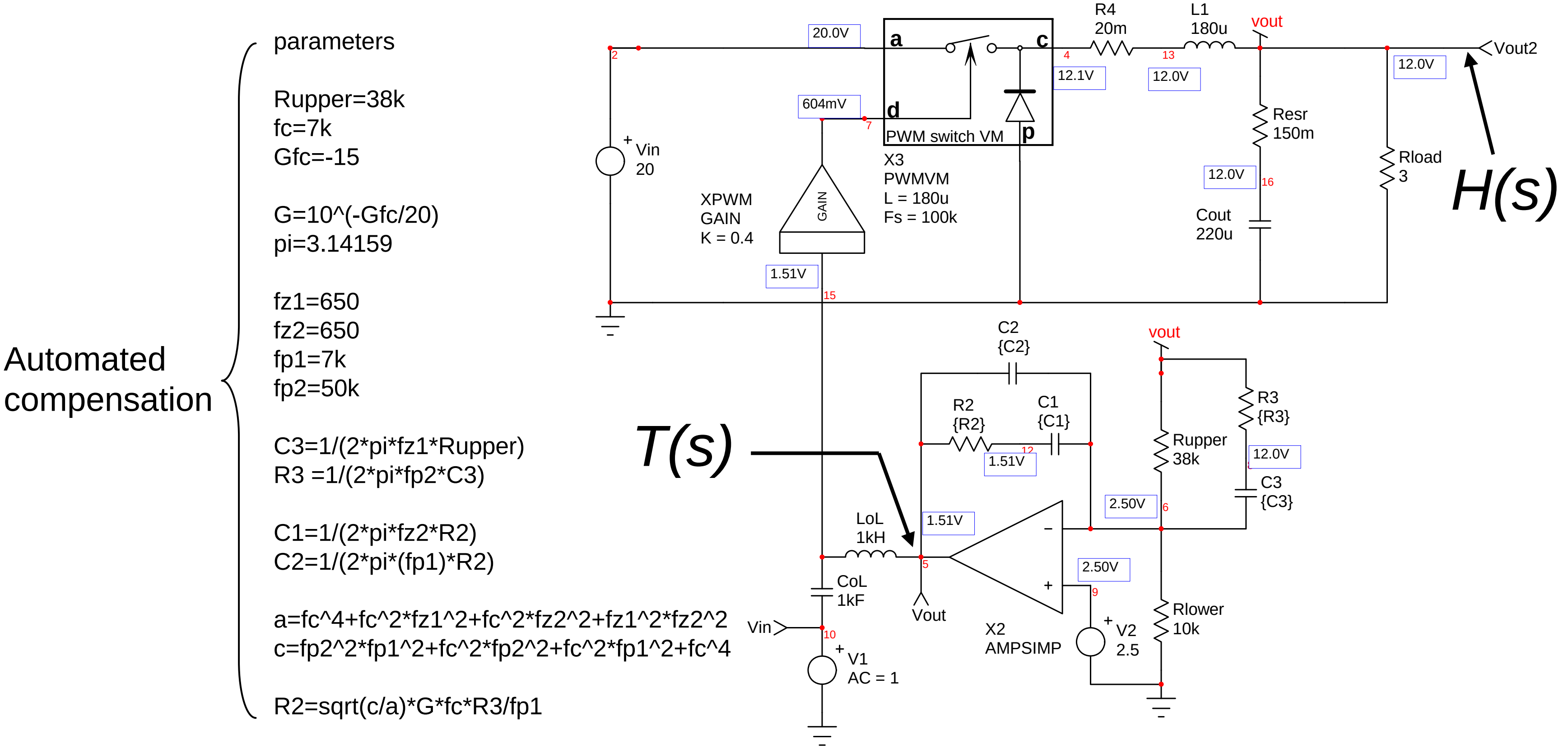


$$\left.\begin{aligned} V_{err}(t) &= V_{peak}\frac{t_{on}(t)}{T_{sw}} = V_{peak}\,d(t) \\ d(t) &= \frac{V_{err}(t)}{V_{peak}} \end{aligned}\right\} \quad \frac{d}{d}\left(\frac{d(t)}{V_{err}(t)}\right) = \frac{1}{V_{peak}} = K_{PWM}$$

The Voltage-Mode Model at Work

- ❑ Let us compensate a buck converter operated in CCM and DCM

1. Run an open-loop Bode plot at full load, lowest input
2. Identify the excess/deficiency of gain at the selected cross over
3. Place a double zero at f_0, a pole at the ESR zero and a pole at $F_{sw}/2$
4. Check final loop gain and run a transient load test



Automated compensation

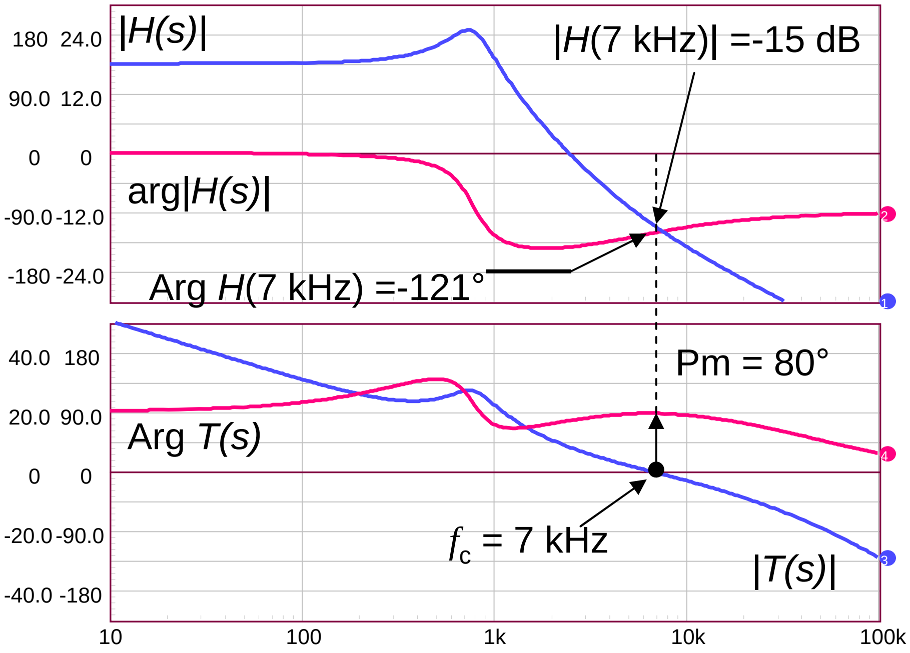
```
parameters

Rupper=38k
fc=7k
Gfc=-15

G=10^(-Gfc/20)
pi=3.14159

fz1=650
fz2=650
fp1=7k
fp2=50k

C3=1/(2*pi*fz1*Rupper)
R3 =1/(2*pi*fp2*C3)

C1=1/(2*pi*fz2*R2)
C2=1/(2*pi*(fp1)*R2)

a=fc^4+fc^2*fz1^2+fc^2*fz2^2+fz1^2*fz2^2
c=fp2^2*fp1^2+fc^2*fp2^2+fc^2*fp1^2+fc^4

R2=sqrt(c/a)*G*fc*R3/fp1
```

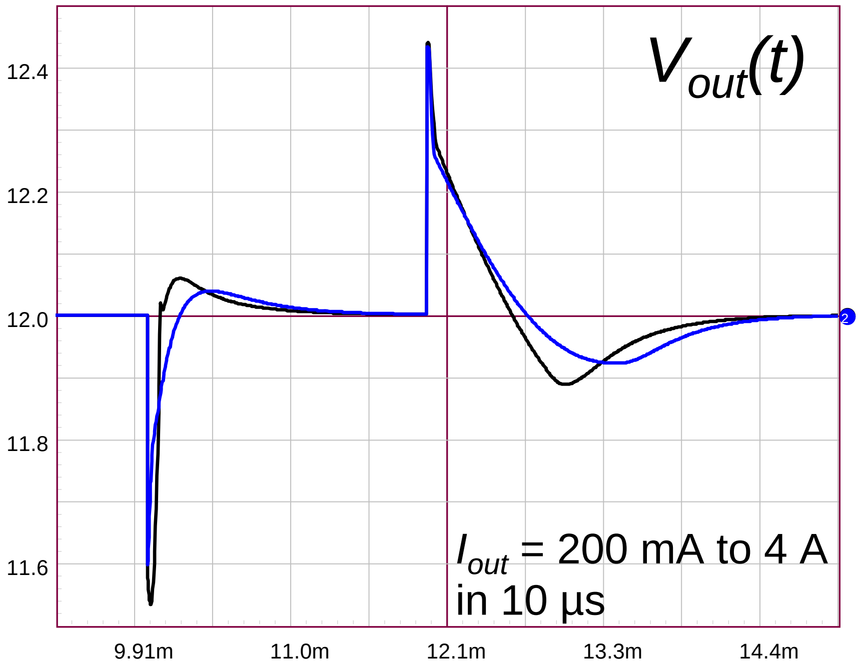
T(s)

H(s)

The Voltage-Mode Model at Work

- ❑ The Bode plot reveals a gain loss of -15 dB at 7 kHz
- ❑ The compensator provides a +15 dB gain increase plus phase boost





- ❑ The final loop gain shows a comfortable phase margin
- ❑ The transient response at both input levels shows a stable signal

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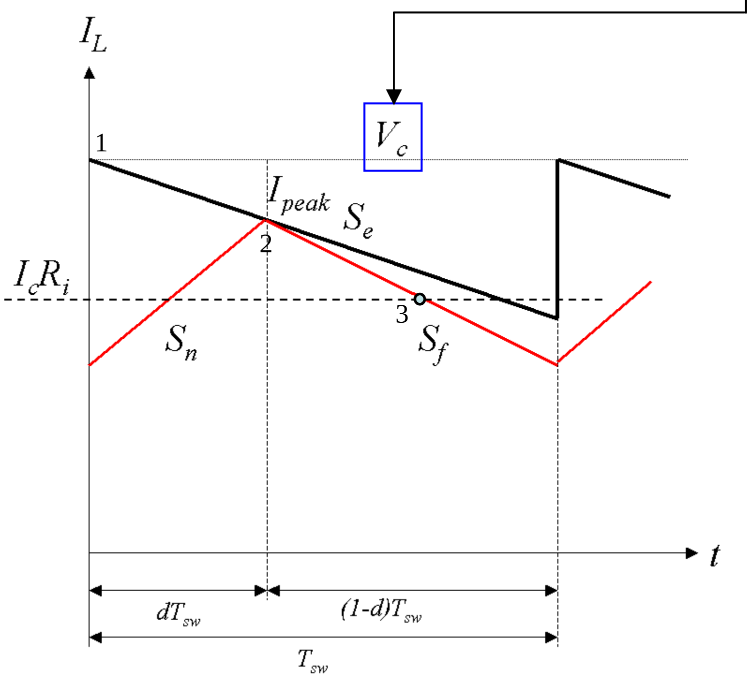
Current-Mode Operation

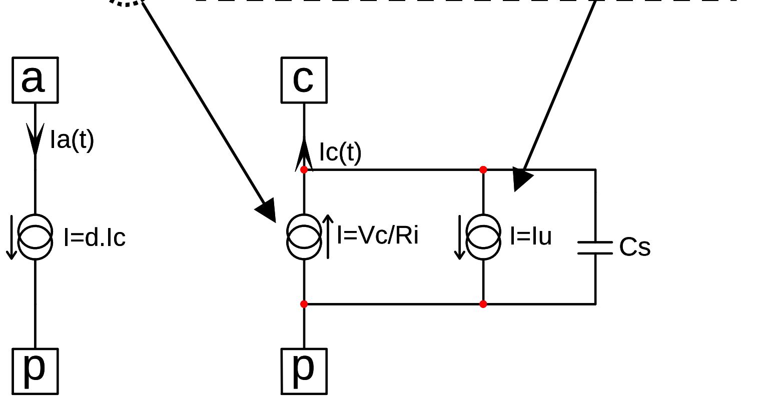
- ☐ In voltage-mode, the error signal directly controls the duty cycle
- ☐ In current mode, the error voltage sets the inductor peak current
- ☐ To derive a model, observe the current signals and average them!



CCM

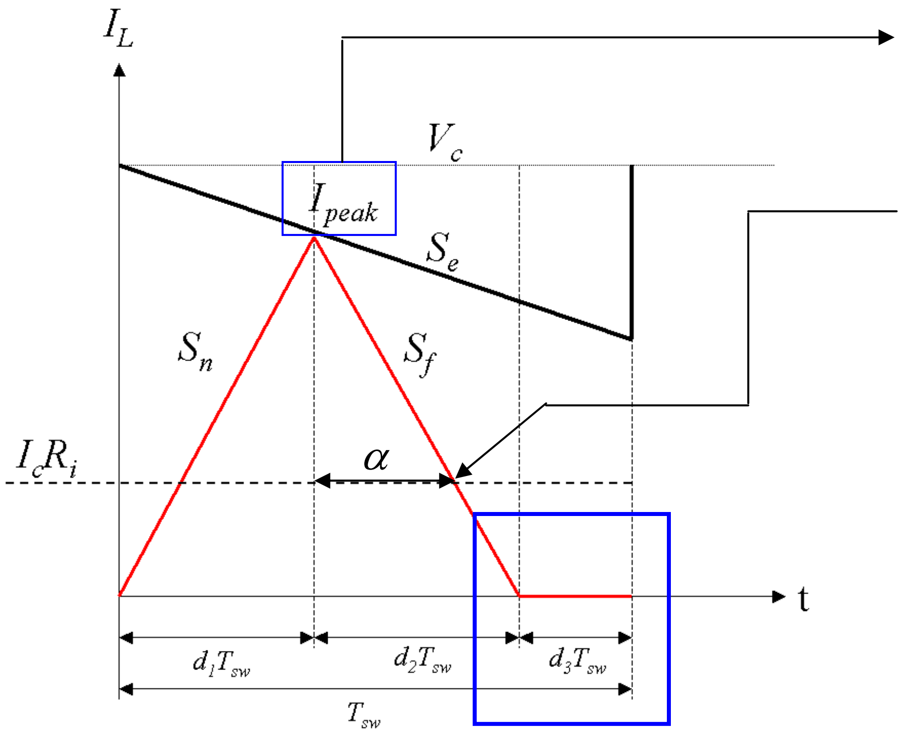
$$I_c(t)R_i = \overset{1}{V_c(t)} - \overset{2}{d(t)T_{sw}S_e} - \overset{3}{\frac{S_f d'(t)T_{sw}}{2}}$$

$$I_c = \boxed{\frac{V_c}{R_i}} - \boxed{d\frac{T_{sw}S_e}{R_i} - V_{cp}(1-d)\frac{T_{sw}}{2L}}$$



Current-Mode Operation

- ☐ Do the same for DCM signals
- ☐ Match the previous structure to build a CCM/DCM model



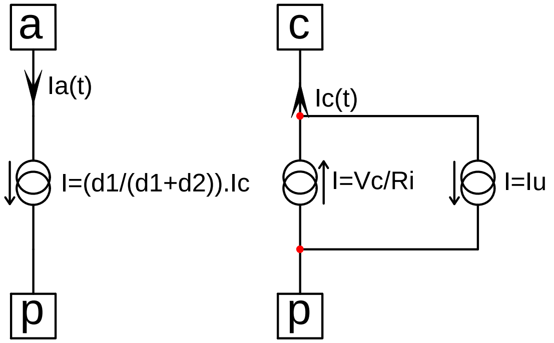
3rd event linked to DCM

DCM

$$I_{peak} = \frac{V_c - d_1 T_{sw} S_e}{R_i}$$

$$I_c = \frac{V_c - d_1 T_{sw} S_e}{R_i} - \alpha d_2 T_{sw} S_f$$

$$I_\mu = \frac{d_1 T_{sw} S_e}{R_i} + d_2 T_{sw} \frac{V_{cp}}{L}\left(1 - \frac{d_1 + d_2}{2}\right)$$



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The Current-Mode Model at Work

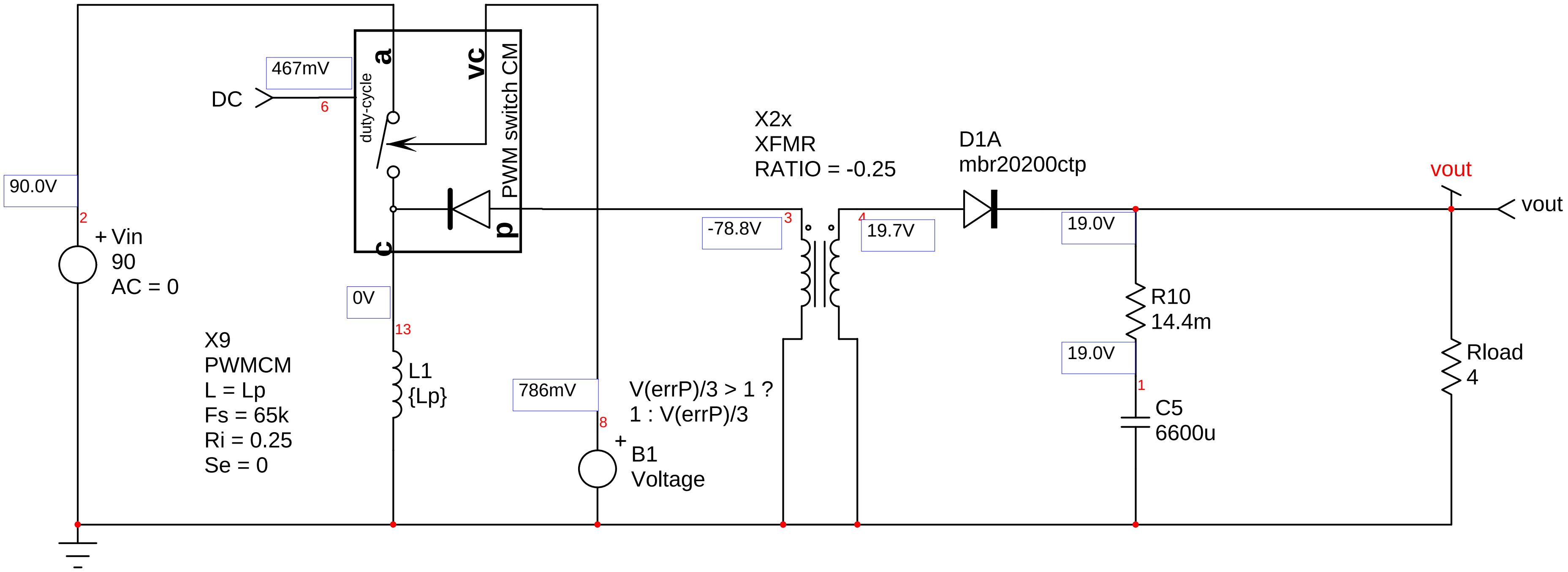
- ☐ To study a converter, we can write down the equations
- ☐ Or use a SPICE simulation to get the Bode plot in a second
- ☐ Take the example of a current-mode flyback converter

$$\left|H(f)\right| = 20\log_{10}\left[G_0 \frac{\sqrt{1+\left(\frac{f}{f_{z1}}\right)^2}\sqrt{1+\left(\frac{f}{f_{z_2}}\right)^2}\sqrt{1+\left(\frac{f}{f_{z3}}\right)^2}}{\sqrt{1+\left(\frac{f}{f_{p_1}}\right)^2}} \frac{1}{\sqrt{\left(1-\left(\frac{f}{f_n}\right)^2\right)^2+\left(\frac{f}{f_nQ_p}\right)^2}}\right]$$

$$\arg H(f) = \tan^{-1}\left(\frac{f}{f_{z_1}}\right) - \tan^{-1}\left(\frac{f}{f_{z_2}}\right) + \tan^{-1}\left(\frac{f}{f_{z_3}}\right) - \tan^{-1}\left(\frac{f}{f_{p_1}}\right) - \tan^{-1}\left(\frac{f}{f_nQ_p}\frac{1}{1-\left(\frac{f}{f_n}\right)^2}\right)$$

Stabilizing a CCM Flyback Converter

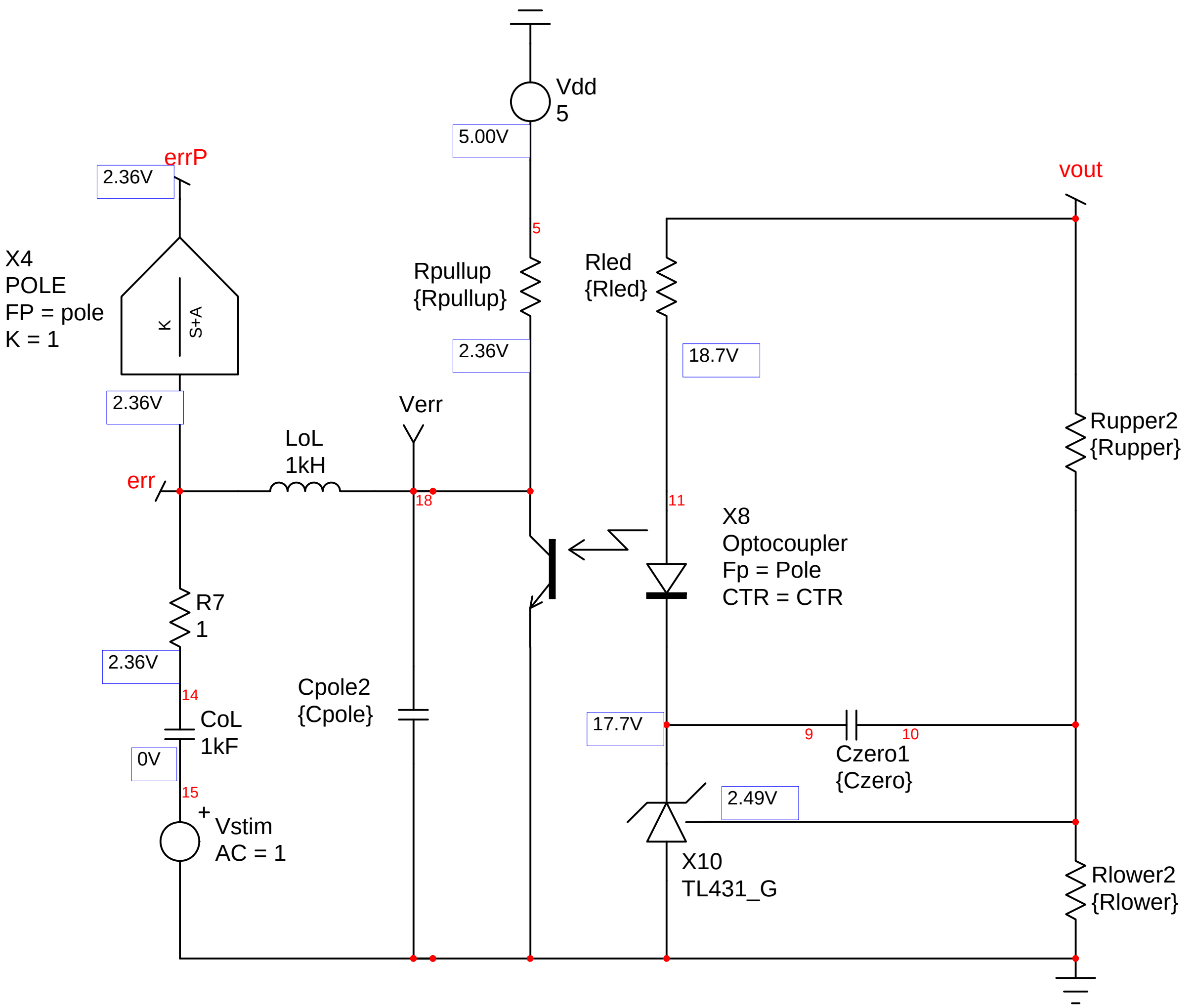
- Capture a SPICE schematic with an averaged model



- Look for the bias points values: V_{out} = 19 V, ok
- $V_{setpoint}$ < 1 V, enough margin on current sense

Stabilizing a CCM Flyback Converter

- Capture a SPICE schematic with an averaged model



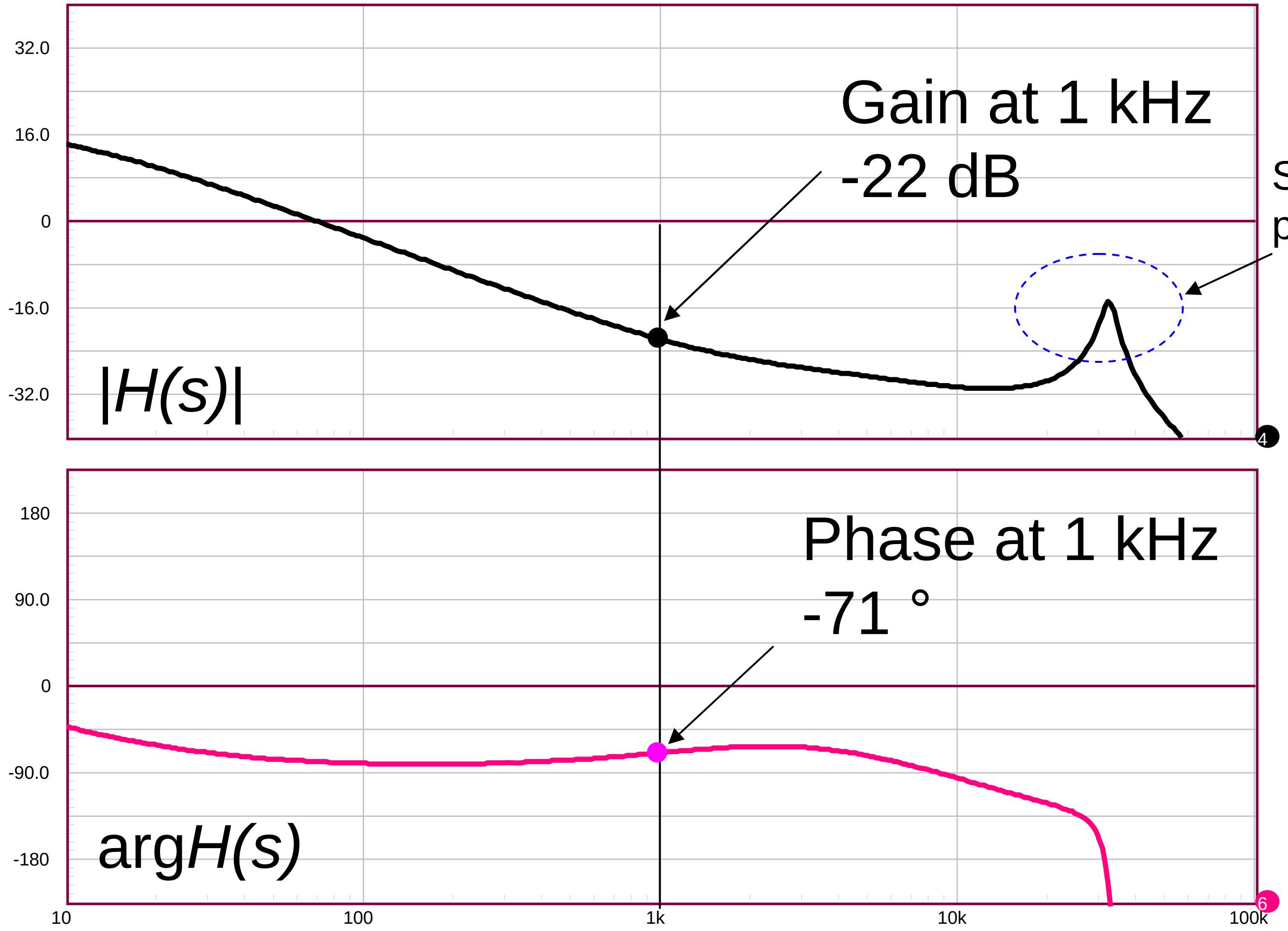
parameters

Vout=19
Ibridge=250u
Rlower=2.5/Ibridge
Rupper=(Vout-2.5)/Ibridge
Lp=350u
Se=20k
fc=1k
pm=60
Gfc=-22
pfc=-71
G=10^(-Gfc/20)
boost=pm-(pfc)-90
pi=3.14159
K=tan((boost/2+45)*pi/180)
Fzero=fc/k
Fpole=k*fc
Rpullup=20k
RLED=CTR*Rpullup/G
Czero=1/(2*pi*Fzero*Rupper)
Cpole=1/(2*pi*Fpole*Rpullup)
CTR=1.5
Pole=6k

from Bode

Stabilizing a CCM Flyback Converter

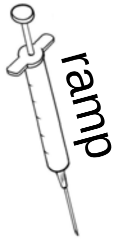
❑ Capture a SPICE schematic with an averaged model



Gain at 1 kHz
-22 dB

Phase at 1 kHz
-71 °

Sub harmonic poles



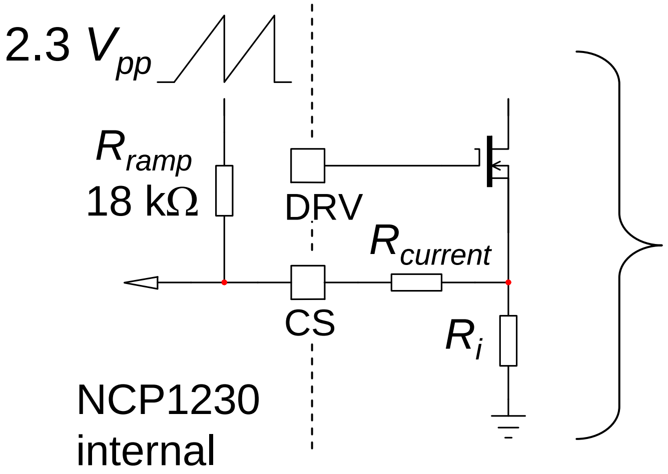
Inject ramp compensation

Stabilizing a CCM Flyback Converter

- ☐ The easiest way to damp the poles:
- ➢ Calculate the equivalent quality coefficient at $F_{sw}/2$
- ➢ Calculate the external ramp to make Q less than 1

$$Q=\frac{1}{\pi\left(D'\frac{S_e}{S_n}+\frac{1}{2}-D\right)}=\frac{1}{3.14\times\left(0.5-0.46\right)}=8$$

$$S_e=\frac{S_n}{D'}\left(\frac{1}{\pi}-0.5+D\right)=\frac{V_{in}R_i}{L_pD'}\left(\frac{1}{\pi}-0.5+D\right)=\frac{90\times0.25}{320u\times\left(1-0.46\right)}\left(\frac{1}{3.14}-0.5+0.46\right)=36\,kV/s$$



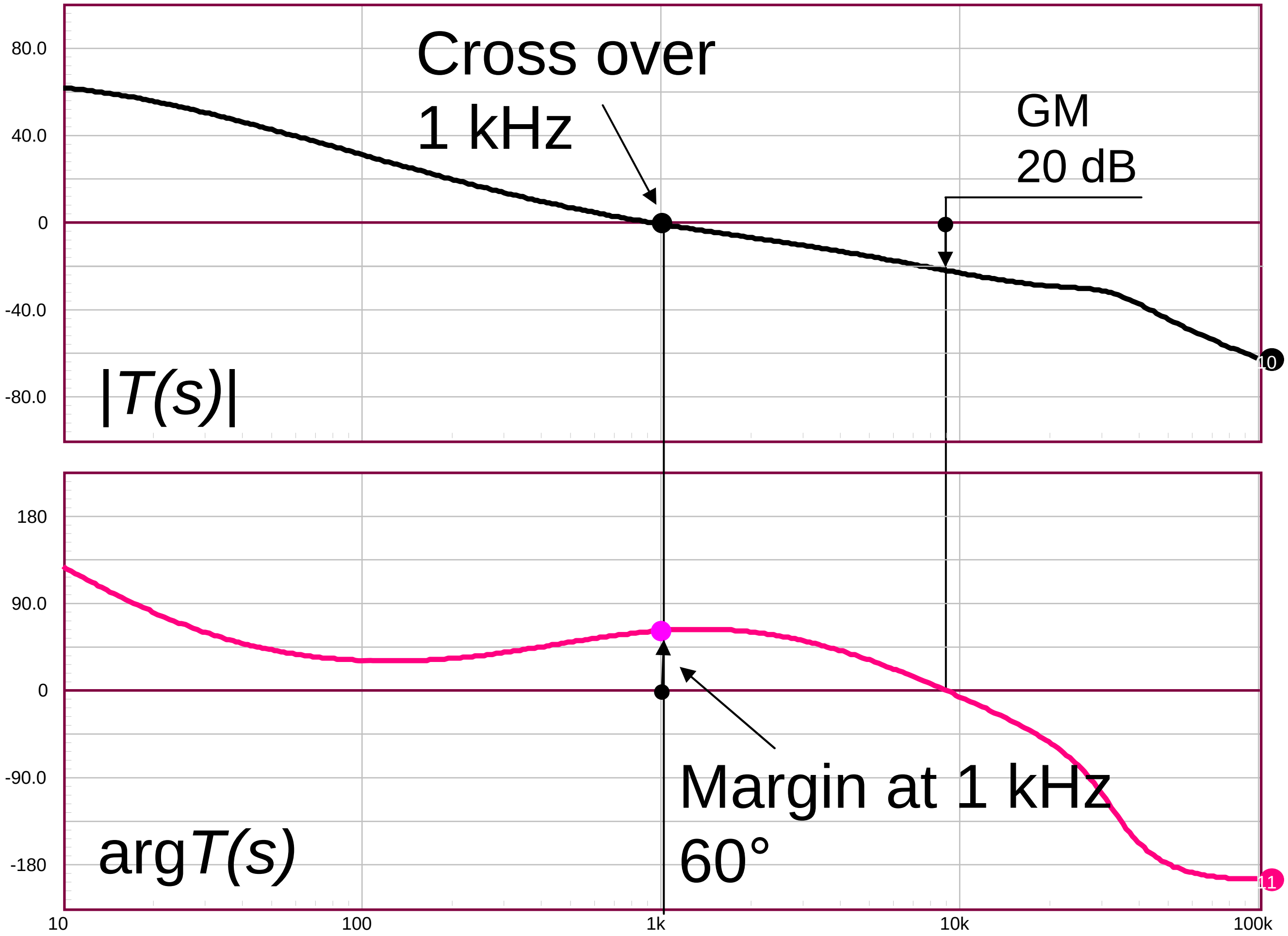
$$M_r=\frac{S_e}{S_n}=\frac{36k}{\underset{\longleftarrow \text{ On-time slope } \frac{V_{in}R_i}{L_p}}{70k}}=51\%$$

$$S_{ramp}=\frac{2.3}{15u}=153\,kV/s$$

$$R_{current}=\frac{M_rS_nR_{ramp}}{S_{ramp}}=\frac{0.51\times70k\times18k}{153k}=4.1\,k\Omega$$

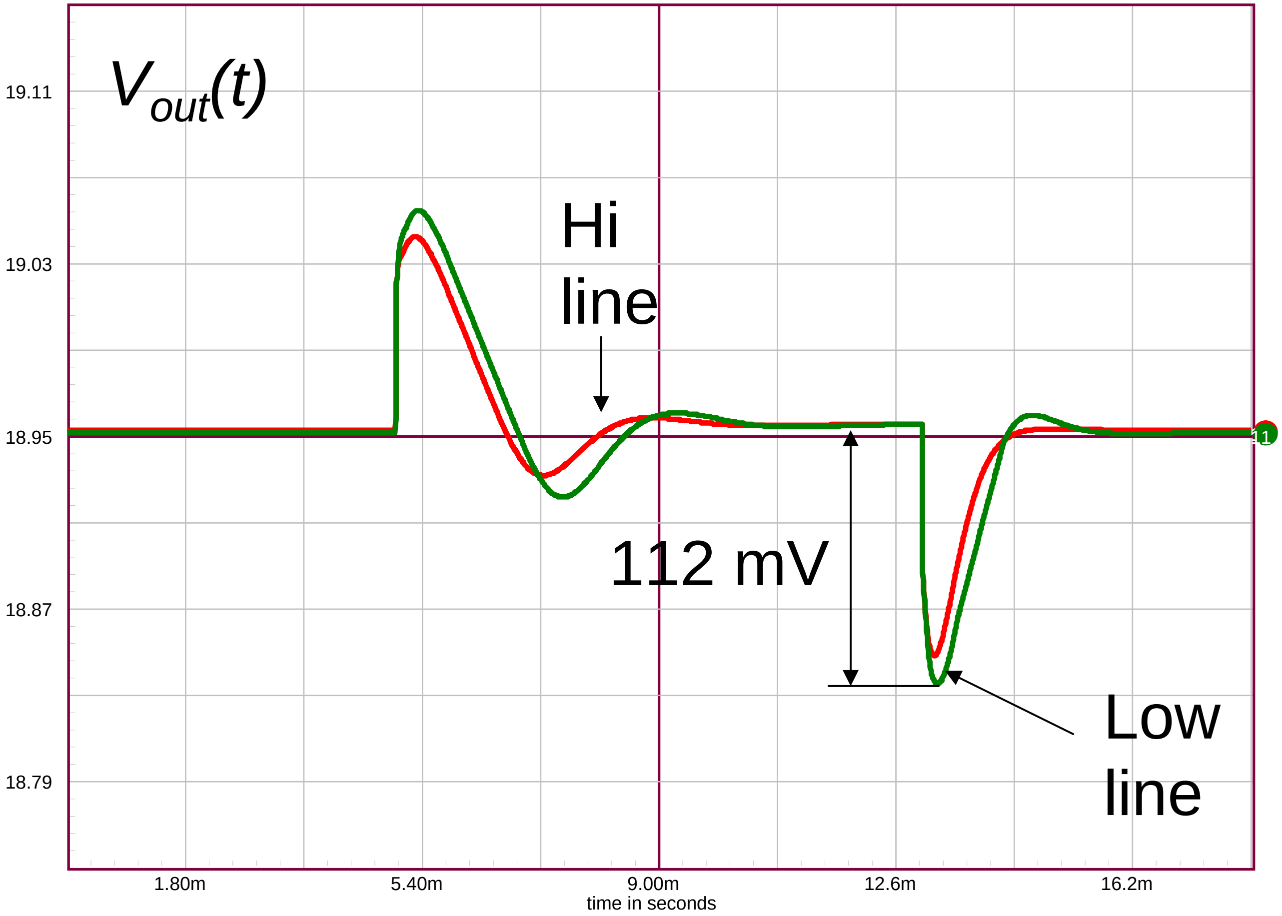
Stabilizing a CCM Flyback Converter

- ☐ Boost the gain by +22 dB, boost the phase at f_c



Stabilizing a CCM Flyback Converter

- ☐ Test the response at both input levels, 90 and 265 Vrms
- ☐ Sweep ESR values and check margins again

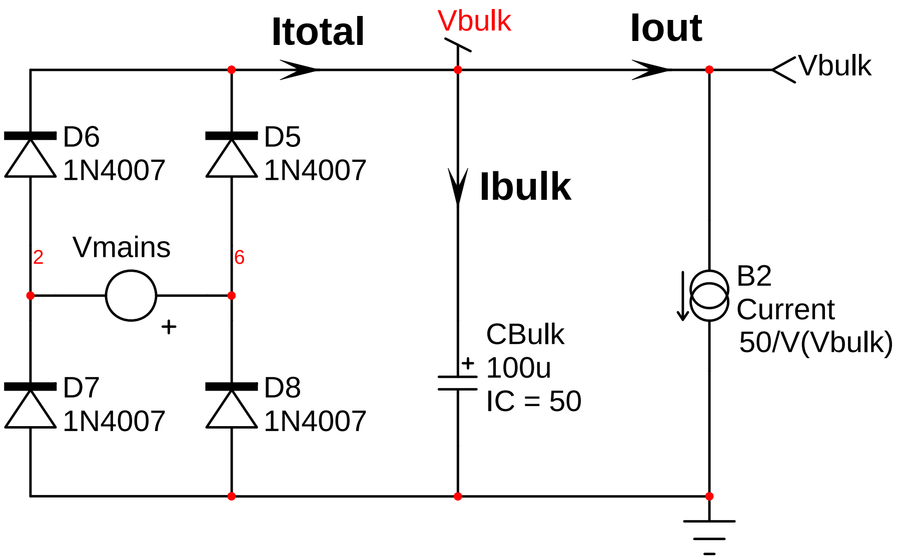


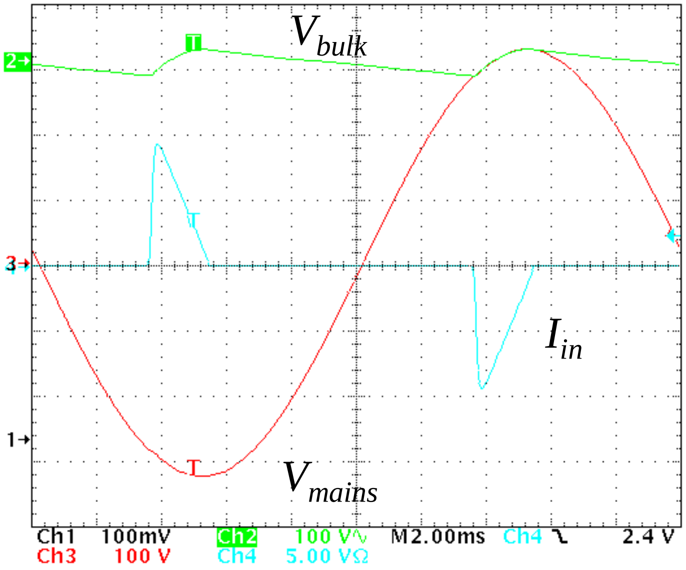
Agenda

- ☐ Why simulating power supplies?
- ☐ Average modeling techniques
- ☐ The PWM switch concept, CCM
- ☐ The PWM switch concept, DCM
- ☐ The voltage-mode model at work
- ☐ Current-mode modeling
- ☐ The current-mode model at work
- ☐ **Power factor correction**
- ☐ Switching models
- ☐ EMI filtering
- ☐ Conclusion

Power Factor Correction

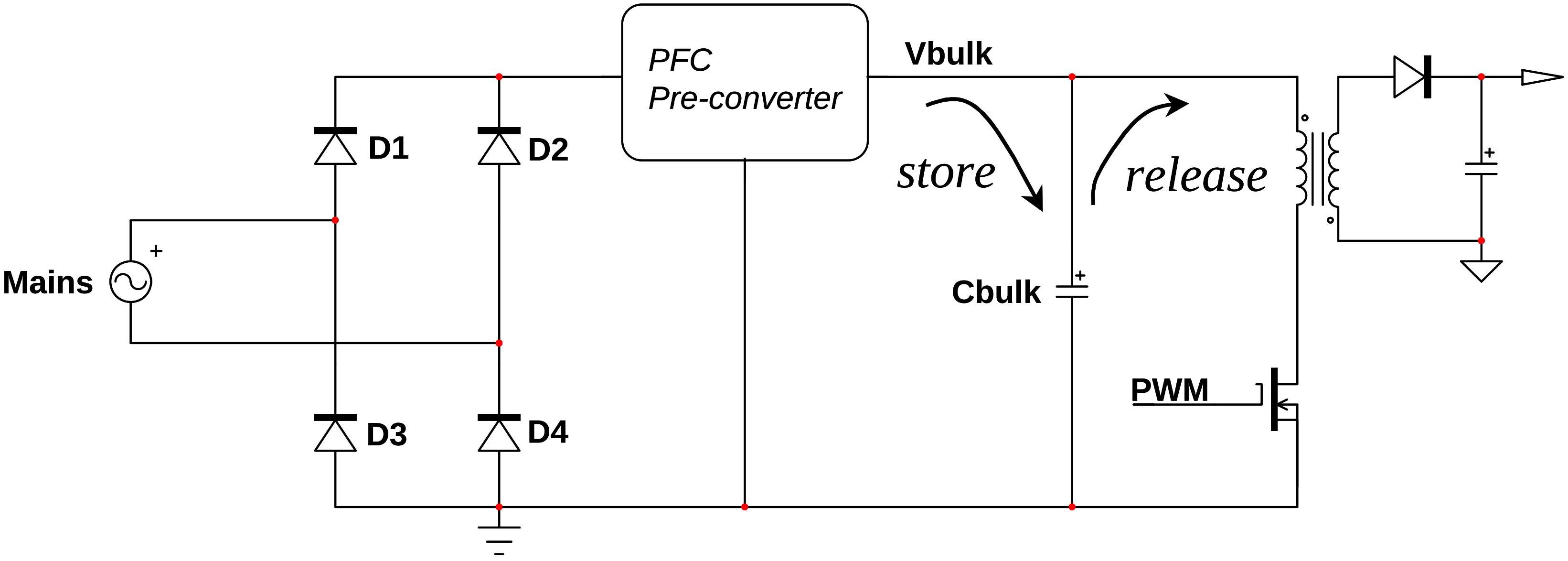
- The bulk capacitor connects to a low-impedance source
- At the bulk capacitor refueling, a narrow peak current flows
- This peak conveys a large harmonic content





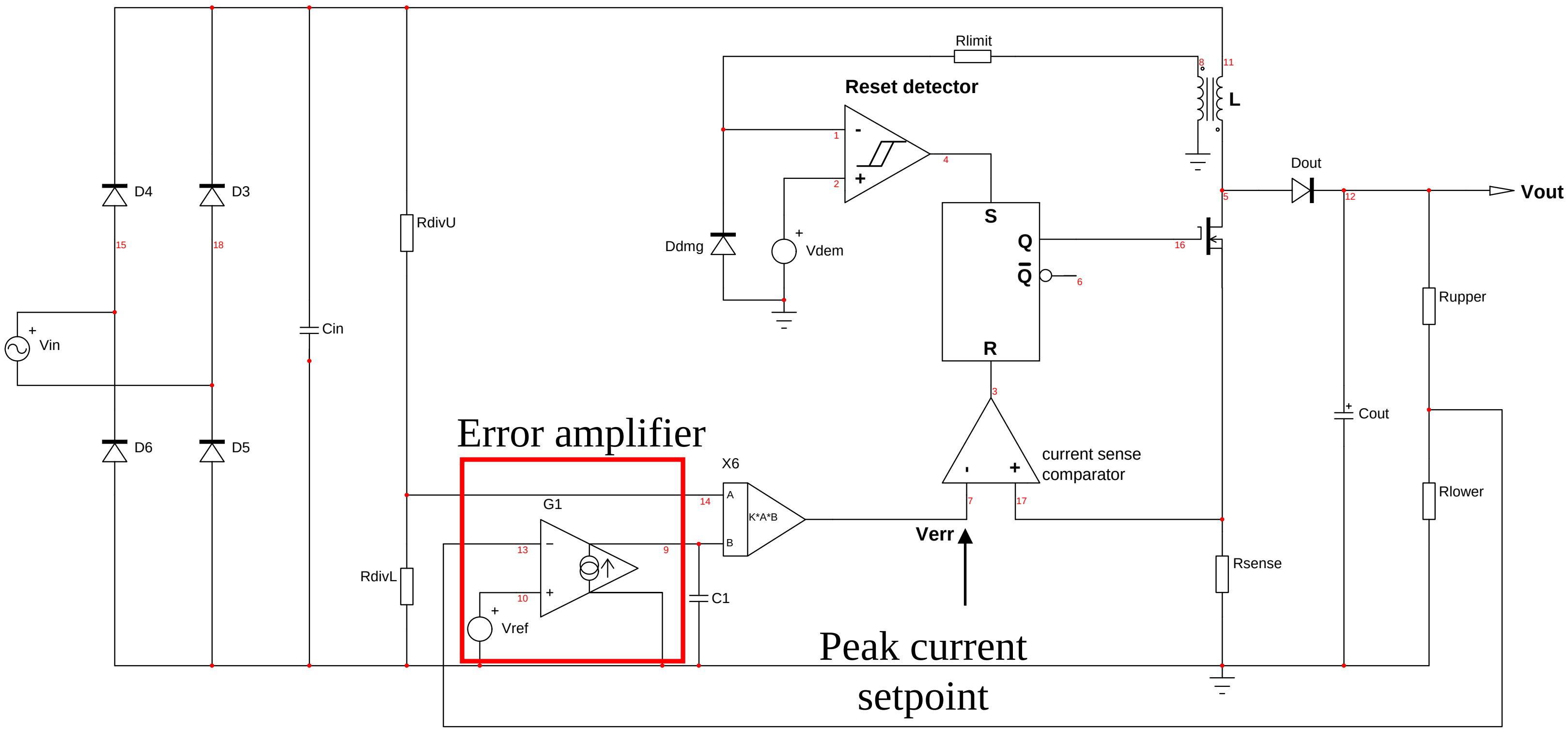
Power Factor Correction

- A pre-converter is installed as a front-end section
- The pre-converter draws a sinusoidal current
- The energy is stored and released in/by the bulk capacitor



Power Factor Correction

- One of the most popular techinique uses Borderline mode
- The MC33262 operates in peak current mode control

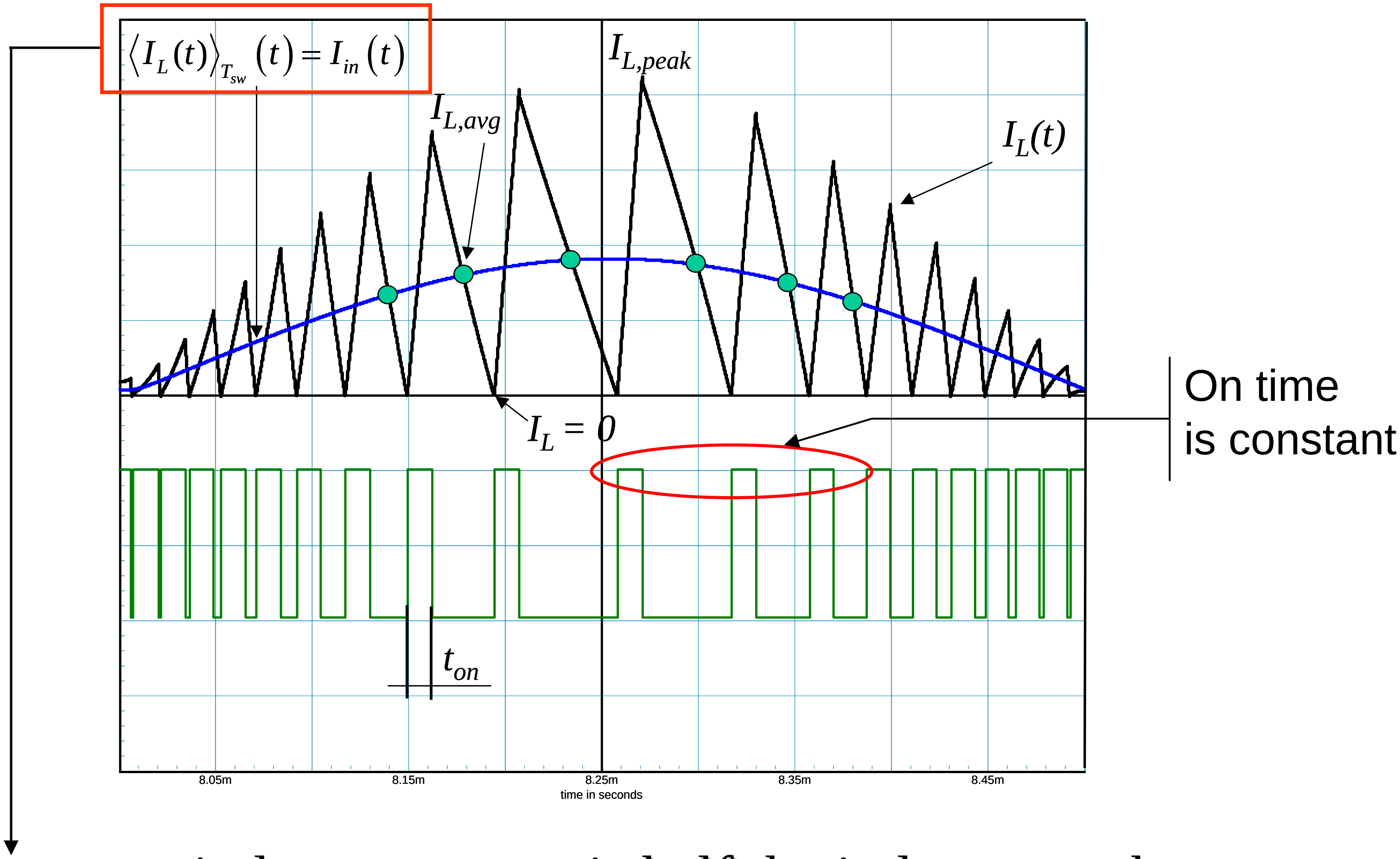

Error amplifier

Peak current setpoint

- The NCP1606 also operates in constant-on time

Power Factor Correction

- ❑ The core is always reset from cycle to the other



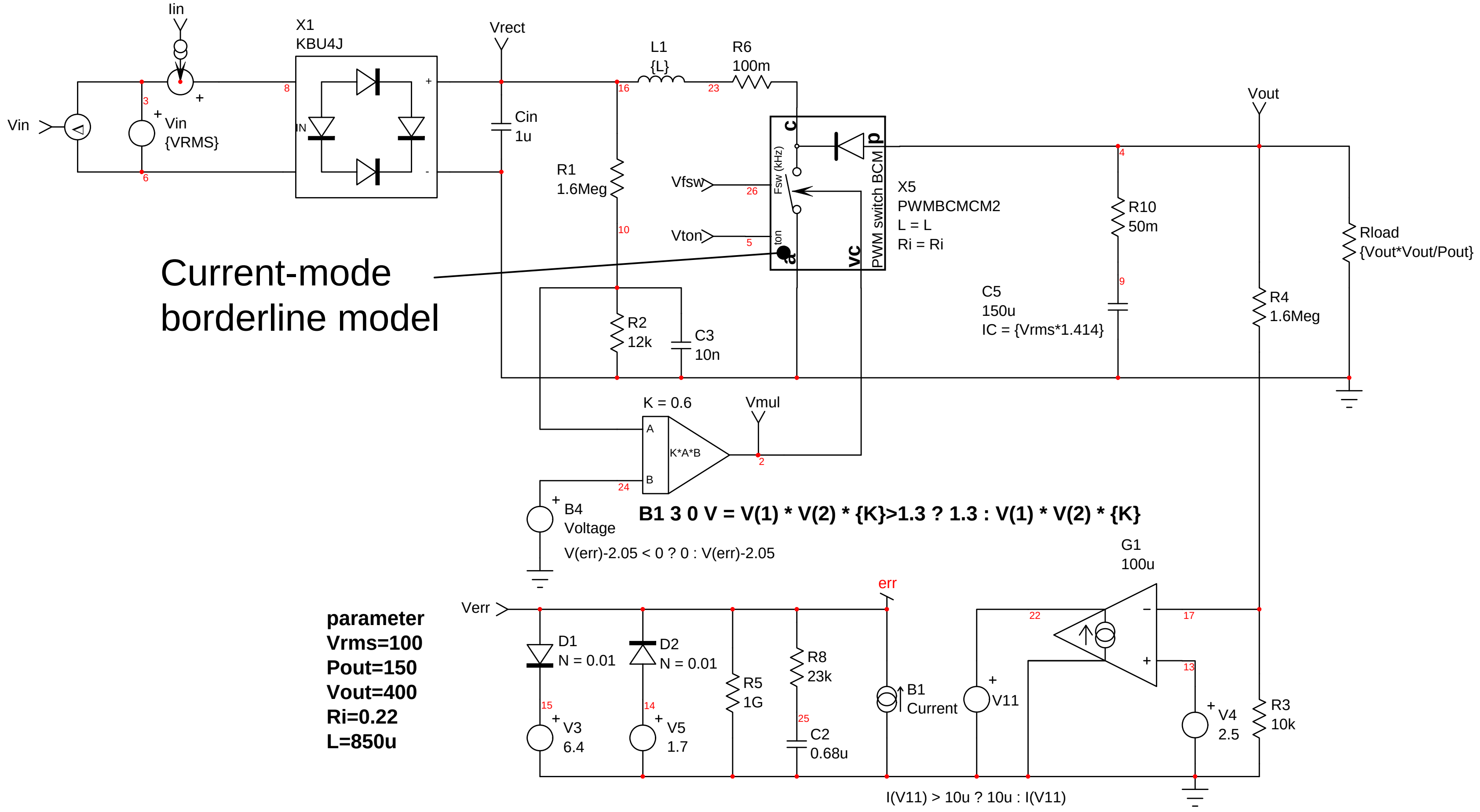
$\langle I_L(t)\rangle_{T_{sw}}(t) = I_{in}(t)$

On time
is constant

- ❑ the <u>average</u> inductor current is <u>half</u> the inductor peak current value

Power Factor Correction

- ❑ A 150 W BCM PFC average example with the MC33262



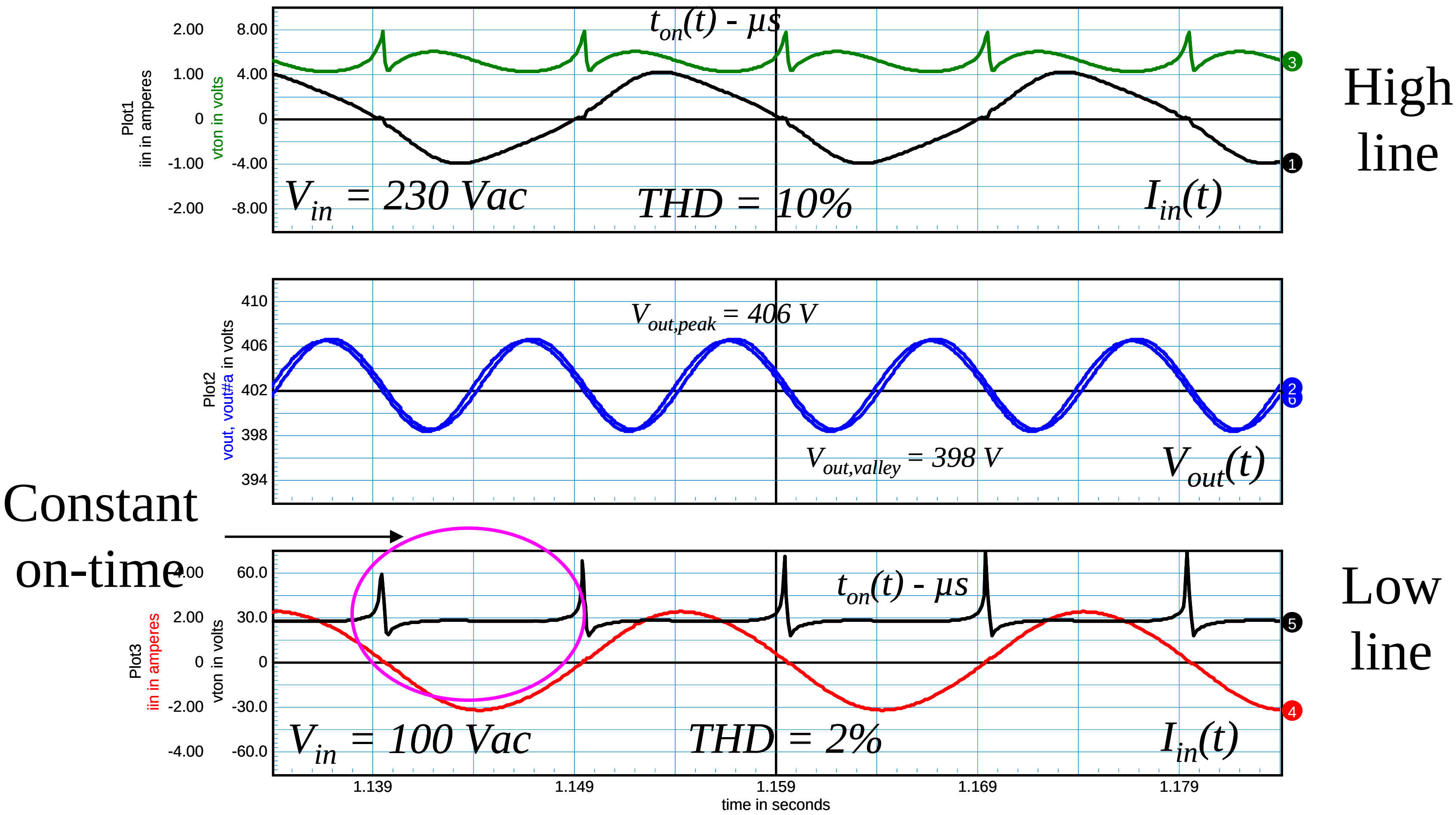
Current-mode borderline model

B1 3 0 V = V(1) * V(2) * {K}>1.3 ? 1.3 : V(1) * V(2) * {K}

parameter
Vrms=100
Pout=150
Vout=400
Ri=0.22
L=850u

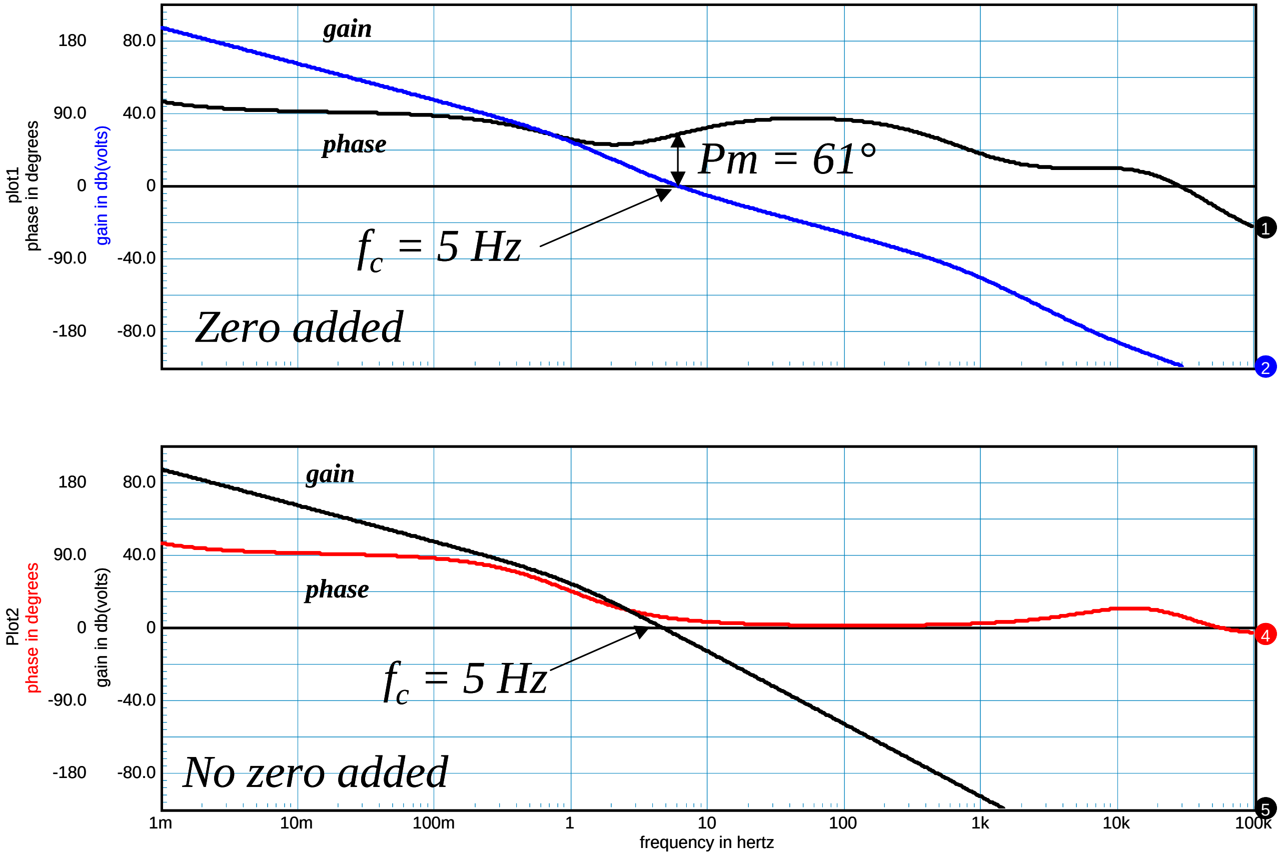
Power Factor Correction

- ☐ Average models can also work in transient conditions



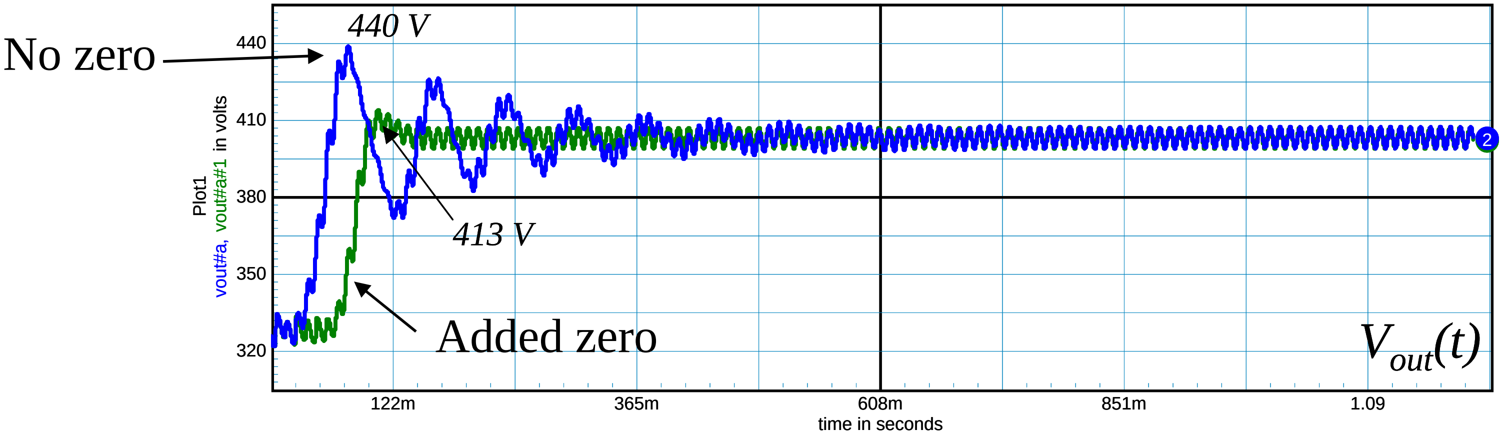
Power Factor Correction

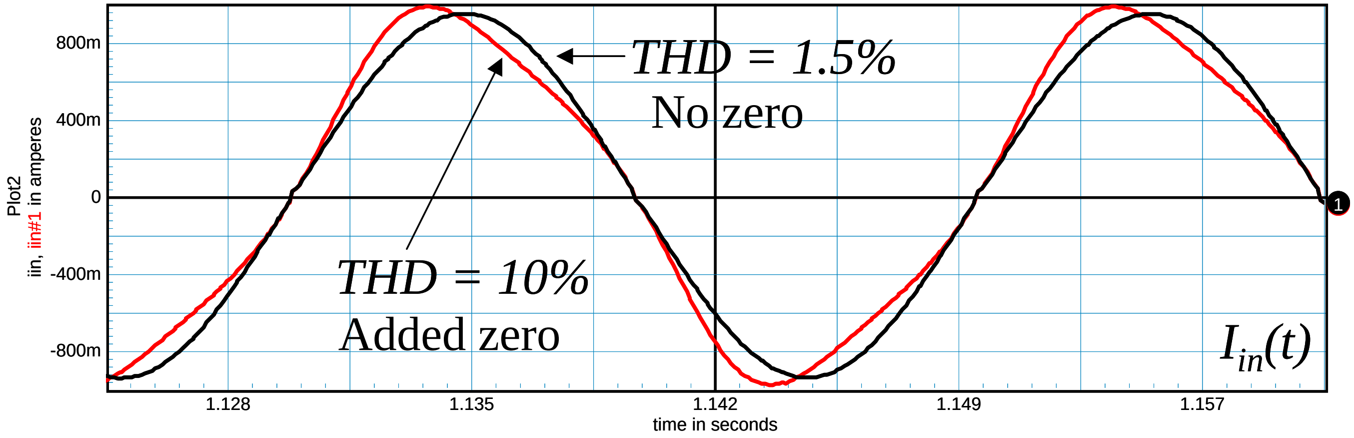
- ❑ Use the model to boost the phase at the cross over point



Power Factor Correction

- ❑ The zero improves the overshoot but degrades the THD…





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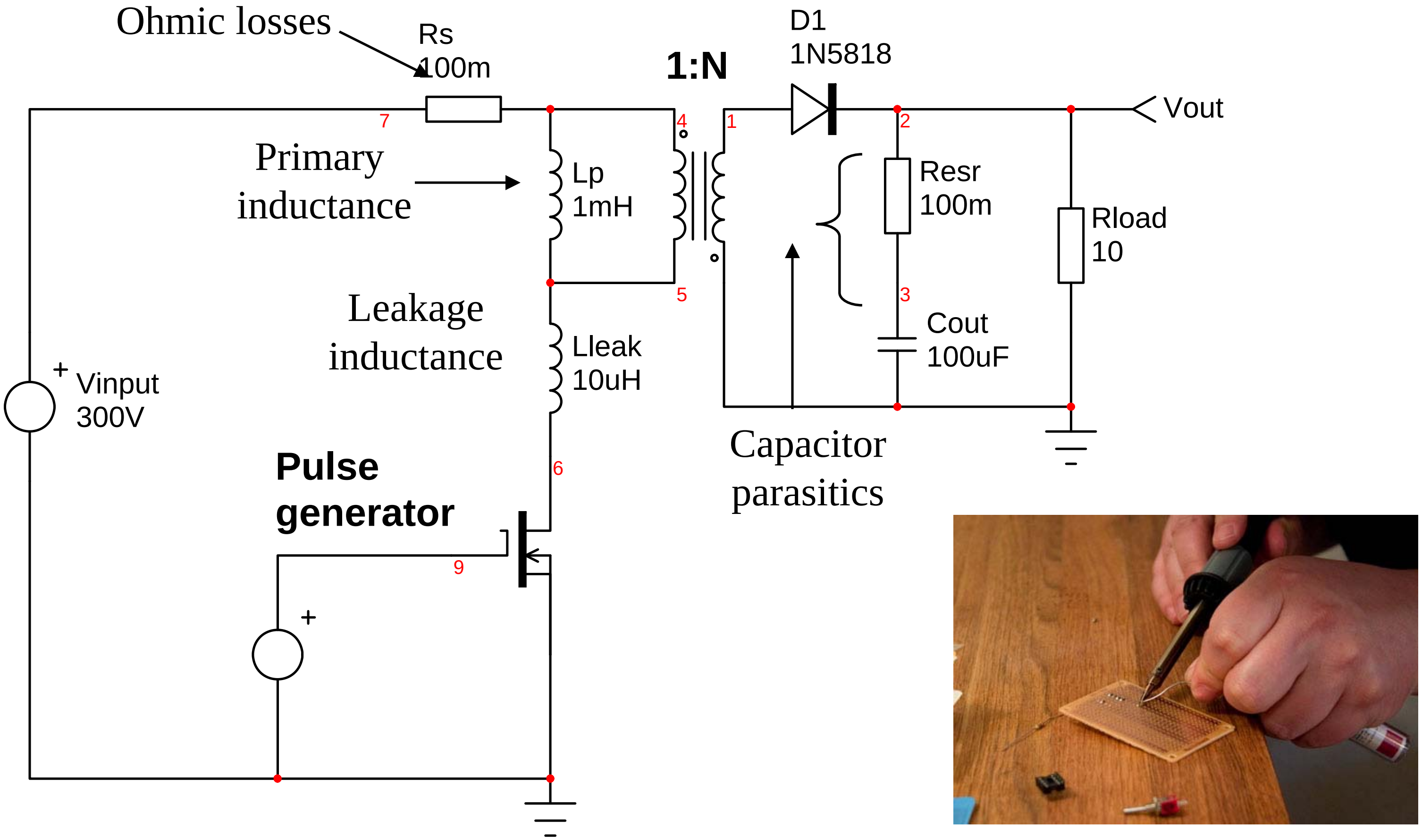
- ☐ EMI filtering
- ☐ Conclusion

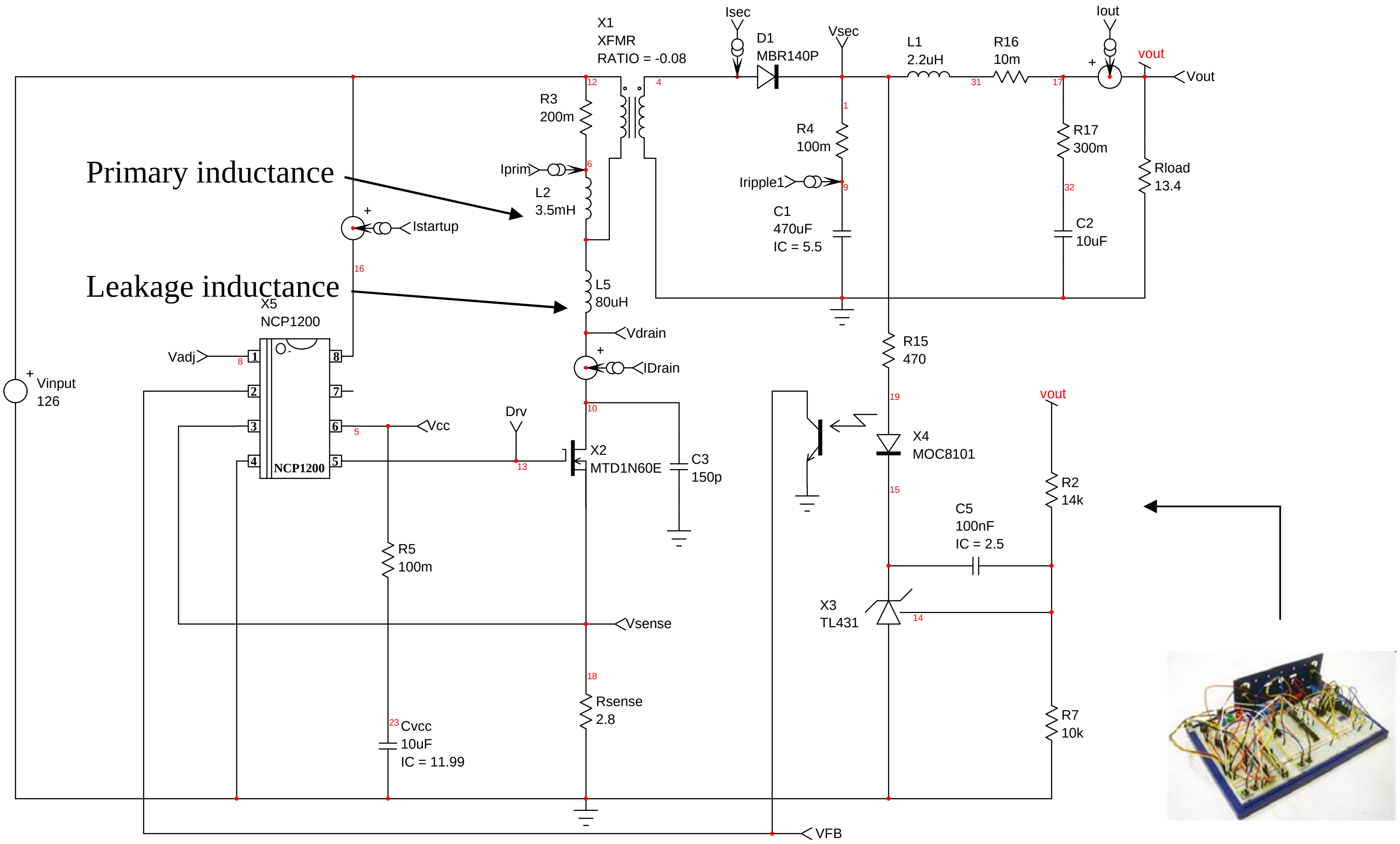
Switching Models, the Breadboard on PC

- ❑ Turn your PC into a virtual breadboard



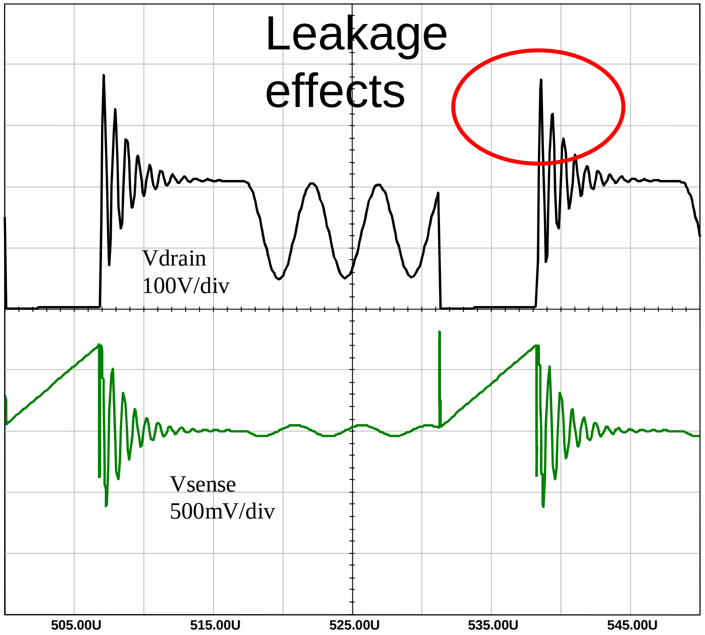
Switching Models, the Breadboard on PC

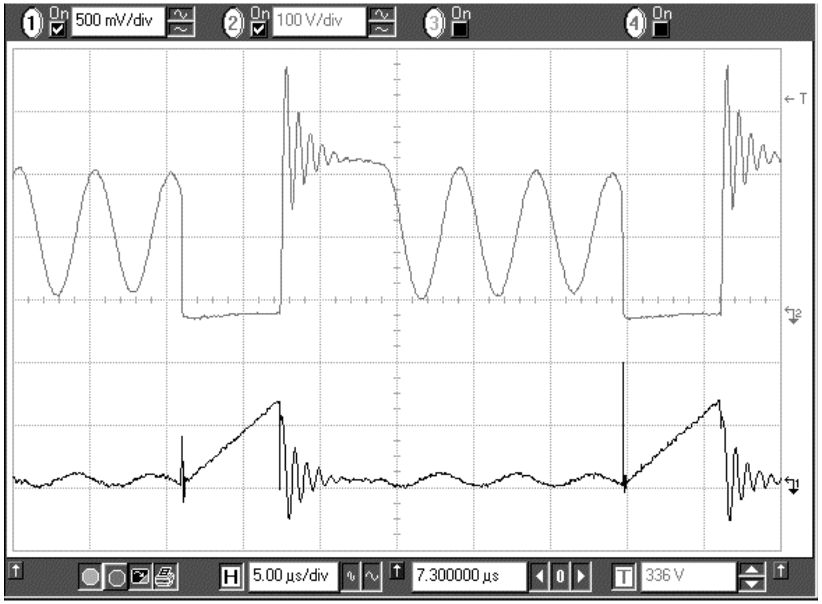
- ☐ Wire your device as you would do in the lab.



Simulations (Really) Work!!

- ☐ Assess the average, rms currents in your circuit
- ☐ Check if enough margins exist on your semiconductors





500 mV/div

100 V/div

5.00 µs/div

7.300000 µs

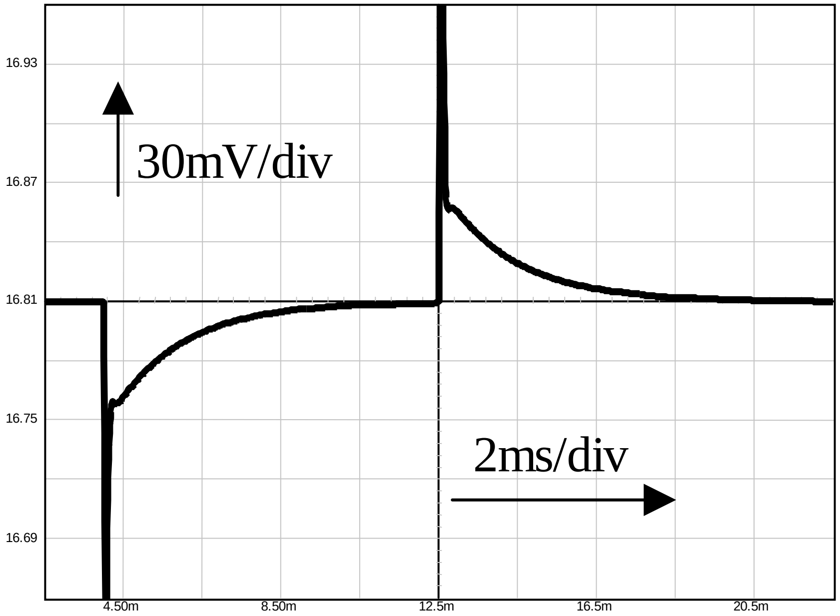
336 V

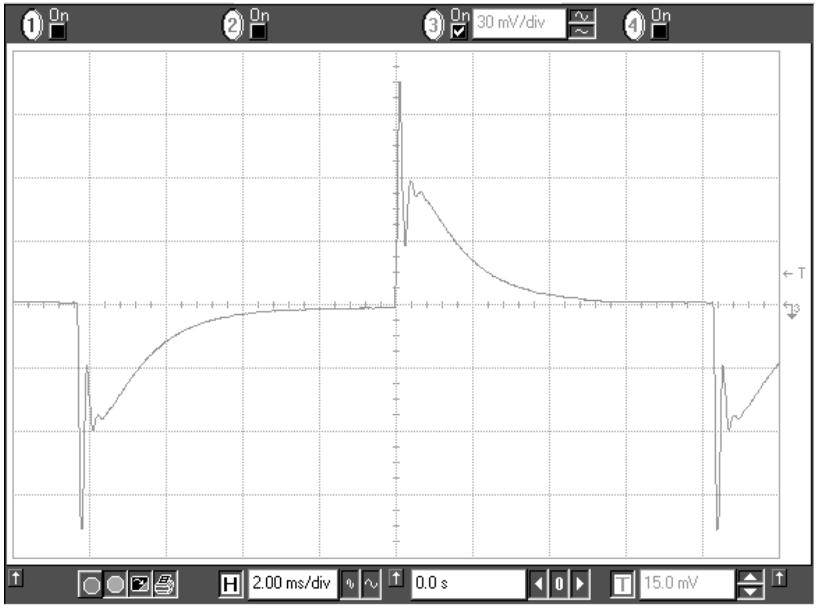
simulated

measured

Simulations (Really) Work!!

- ☐ With accurate models, the simulation results are excellent
- ☐ You can then vary the parasitic terms and see their impact





simulated

measured

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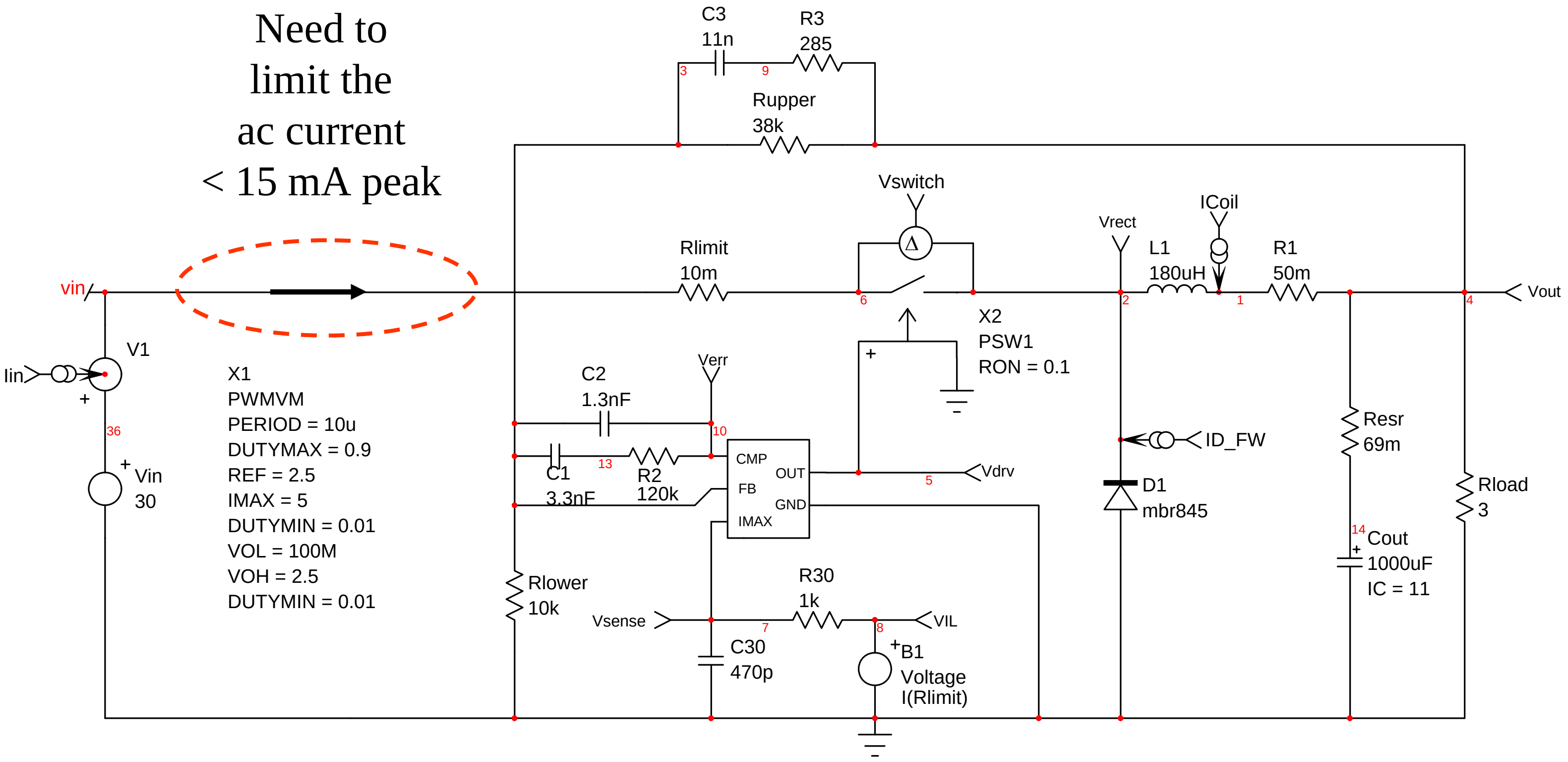
- ☐ Conclusion

EMI Filtering on a DC-DC

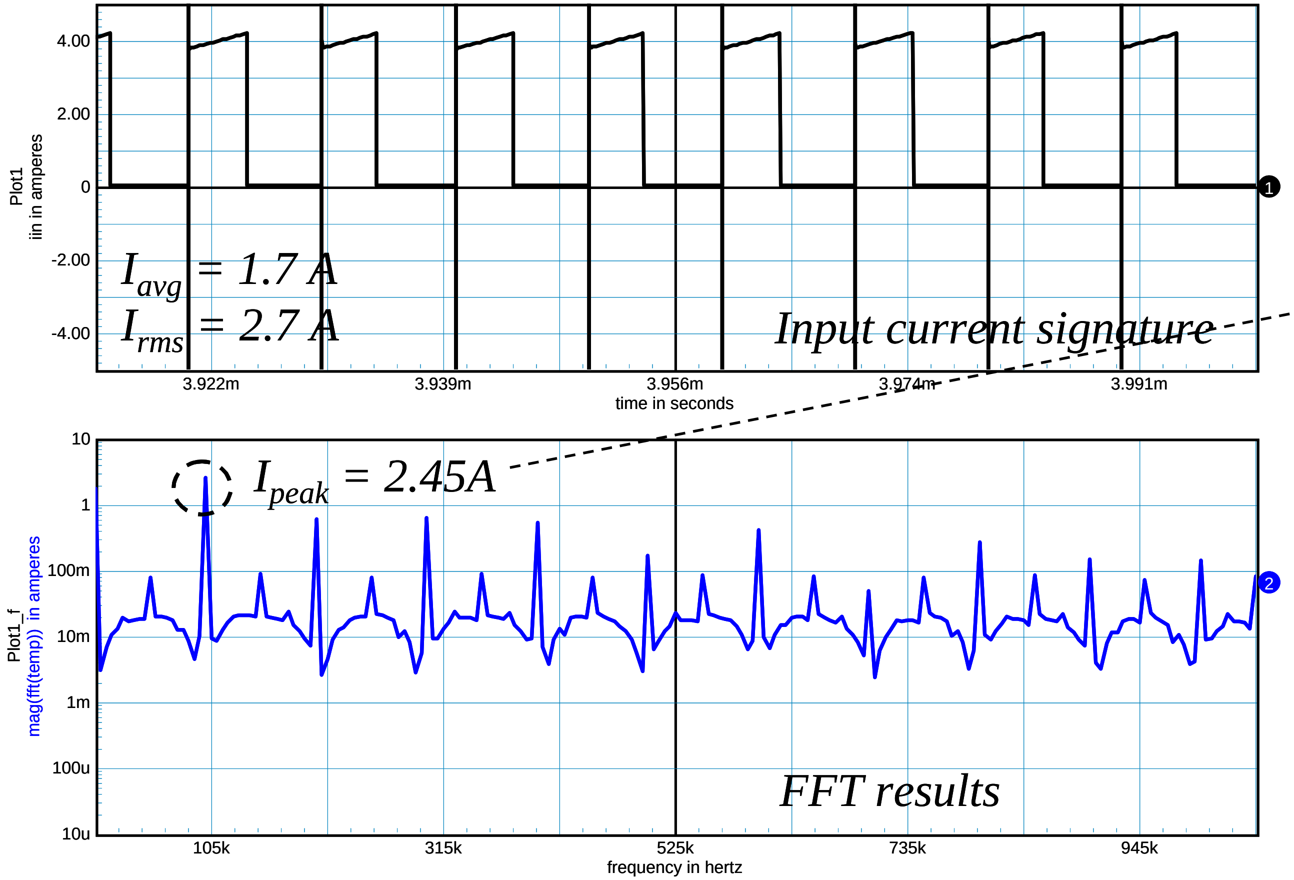
- ☐ DC-DC are highly EMI polluting systems
- ☐ A filter has to be installed to avoid noise in the source



Need to limit the ac current < 15 mA peak

EMI Filtering on a DC-DC

- ☐ Use SPICE to extract the current signature
- ☐ Run Fourier analysis to look at the spectrum



$I_{avg} = 1.7\ A$

$I_{rms} = 2.7\ A$

Input current signature

$I_{peak} = 2.45A$

FFT results

$$I_{ripple} < 15\text{ mA}$$

attenuation

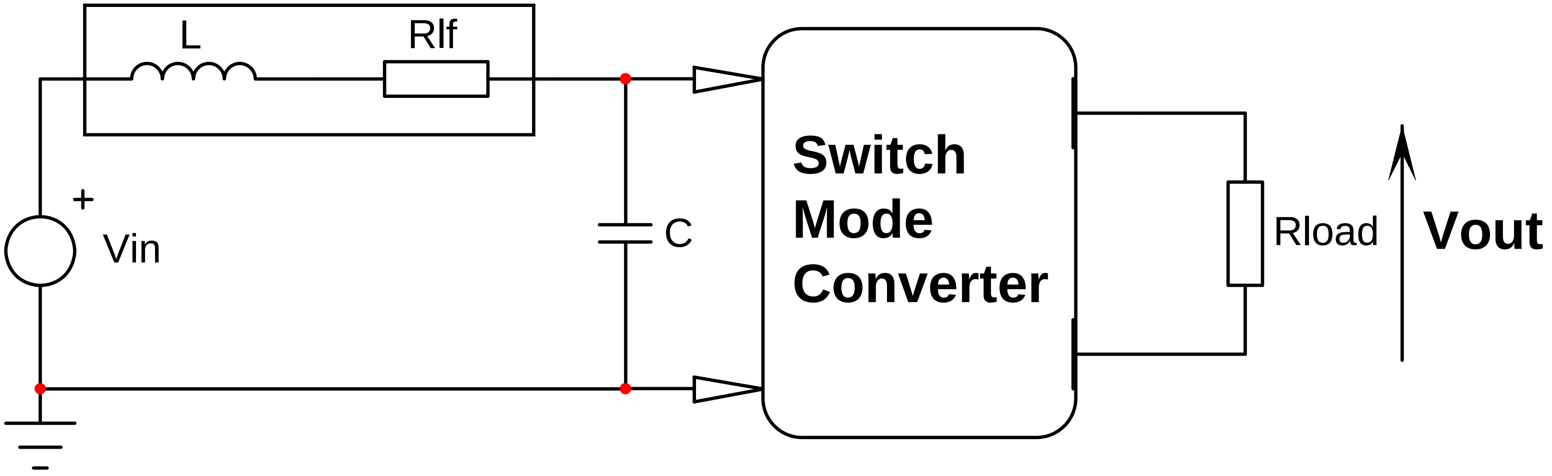
$$A_{filter} < \frac{15m}{\boxed{2.45}} < 6m$$

$$f_0 < \sqrt{0.006 \times F_{sw}} < 7.7\ kHz$$

Position the cutoff frequency of the *LC* filter

EMI Filtering on a DC-DC

- A *LC* configuration offers the best efficiency
- As any *LC* network, it is subject to resonances



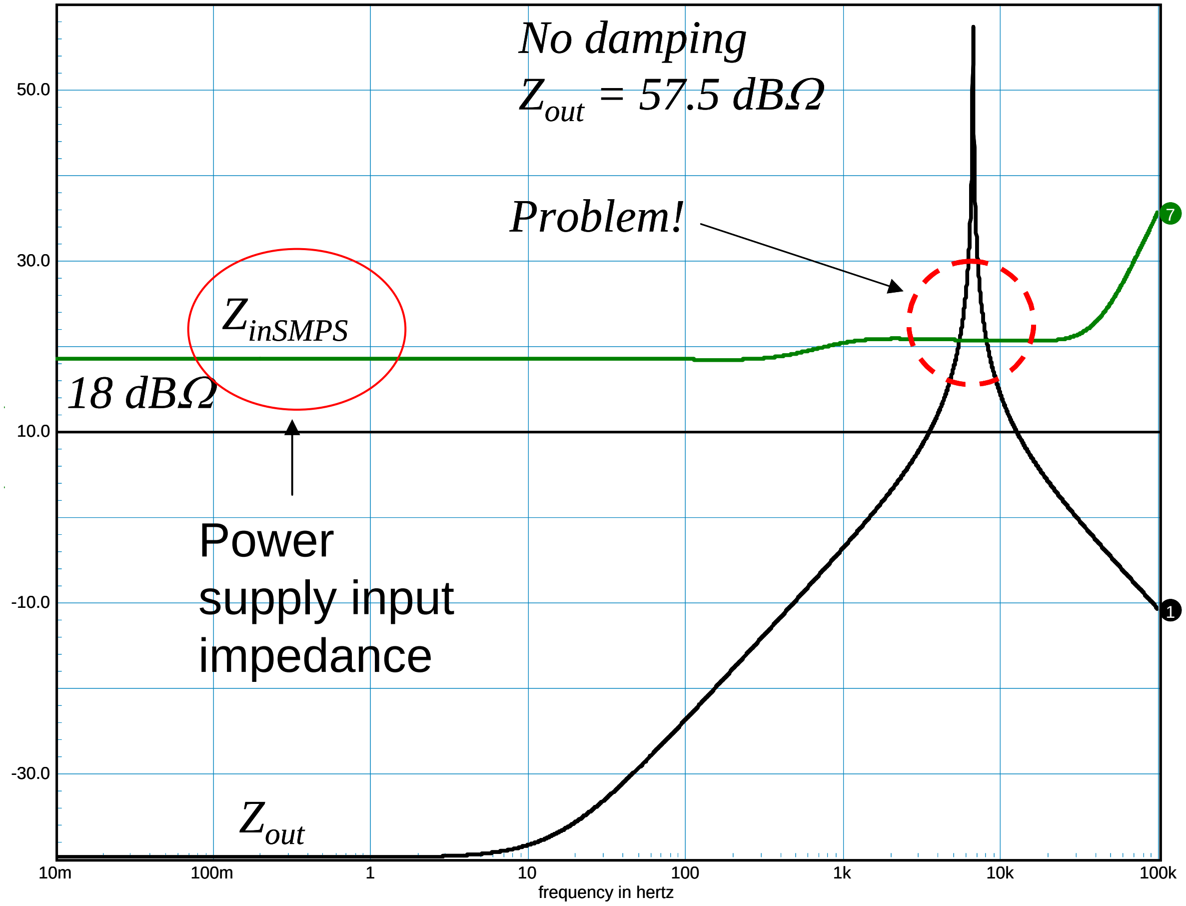
$$L = 100\ \mu H$$

$$C = \frac{1}{4\pi^2 f_0{}^2 L} = 5.2\ \mu F \xrightarrow[\text{Check impedance peaking}]{} \left\|Z_{outFILTER}\right\|_{max} = \frac{Z_0{}^2}{R_1}\sqrt{1+\left(\frac{R_1}{Z_0}\right)^2}$$

7.7 kHz

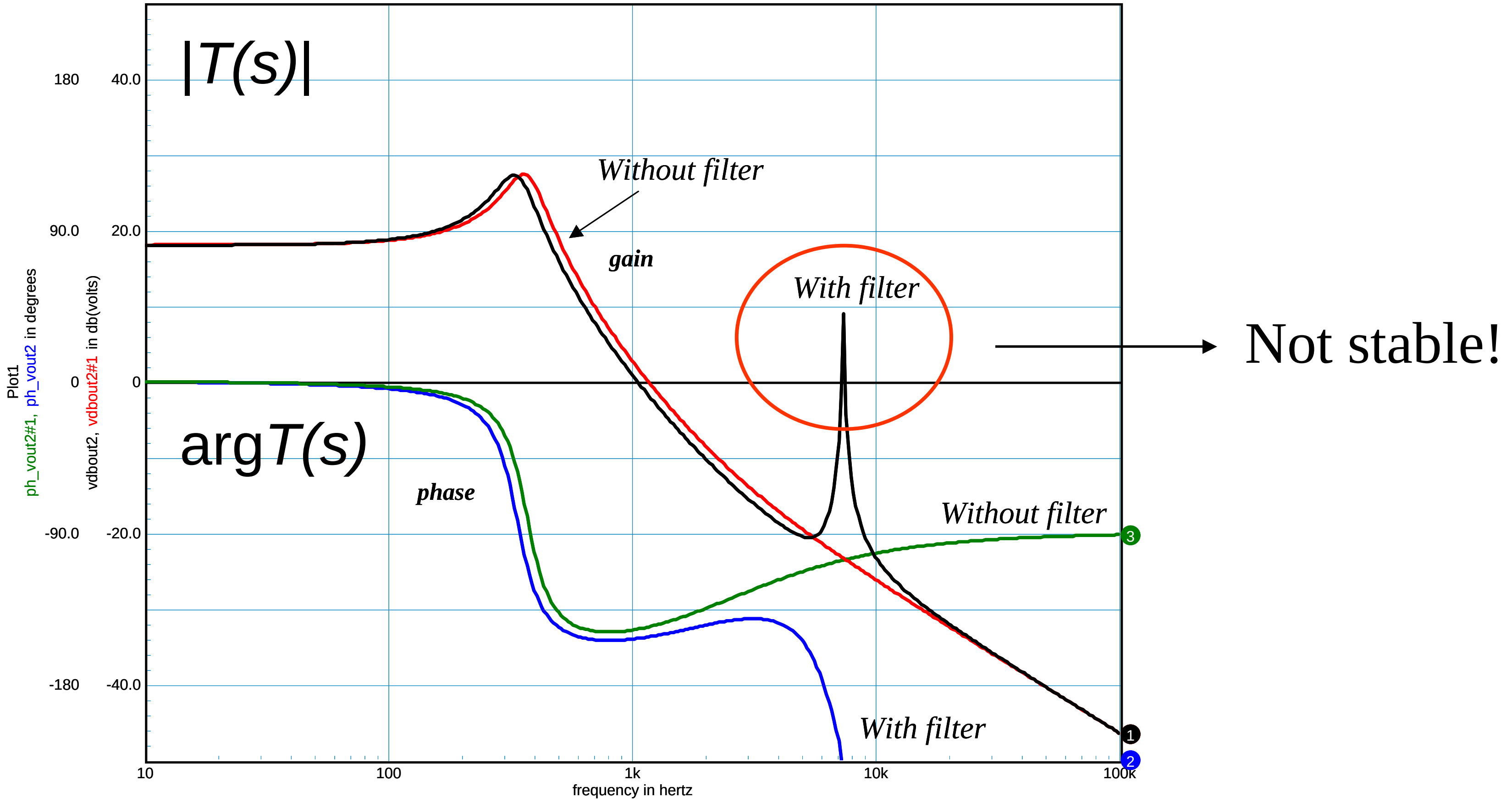
EMI Filtering on a DC-DC

- The incremental input resistance of a DC-DC in negative
- A *LC* filter loaded by a negative resistance can oscillate!



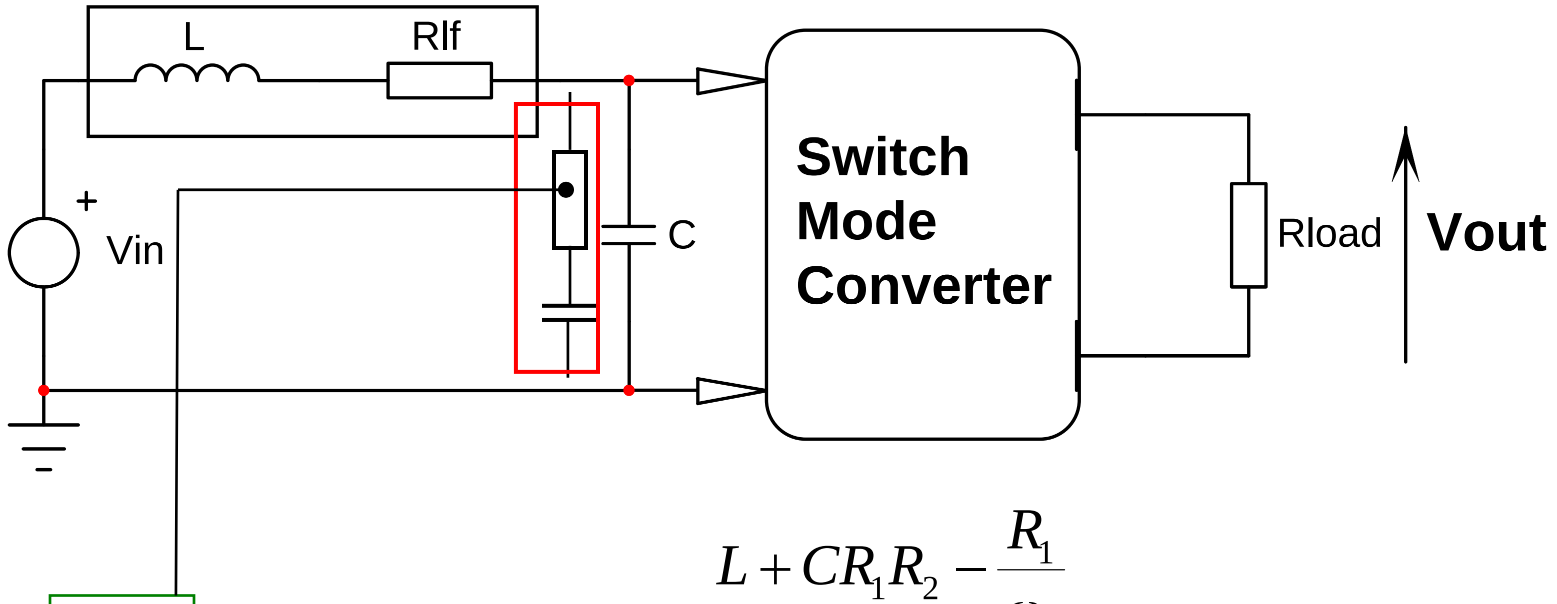
EMI Filtering on a DC-DC

- ❑ If the resonance is too peaky, problems can arise



EMI Filtering on a DC-DC

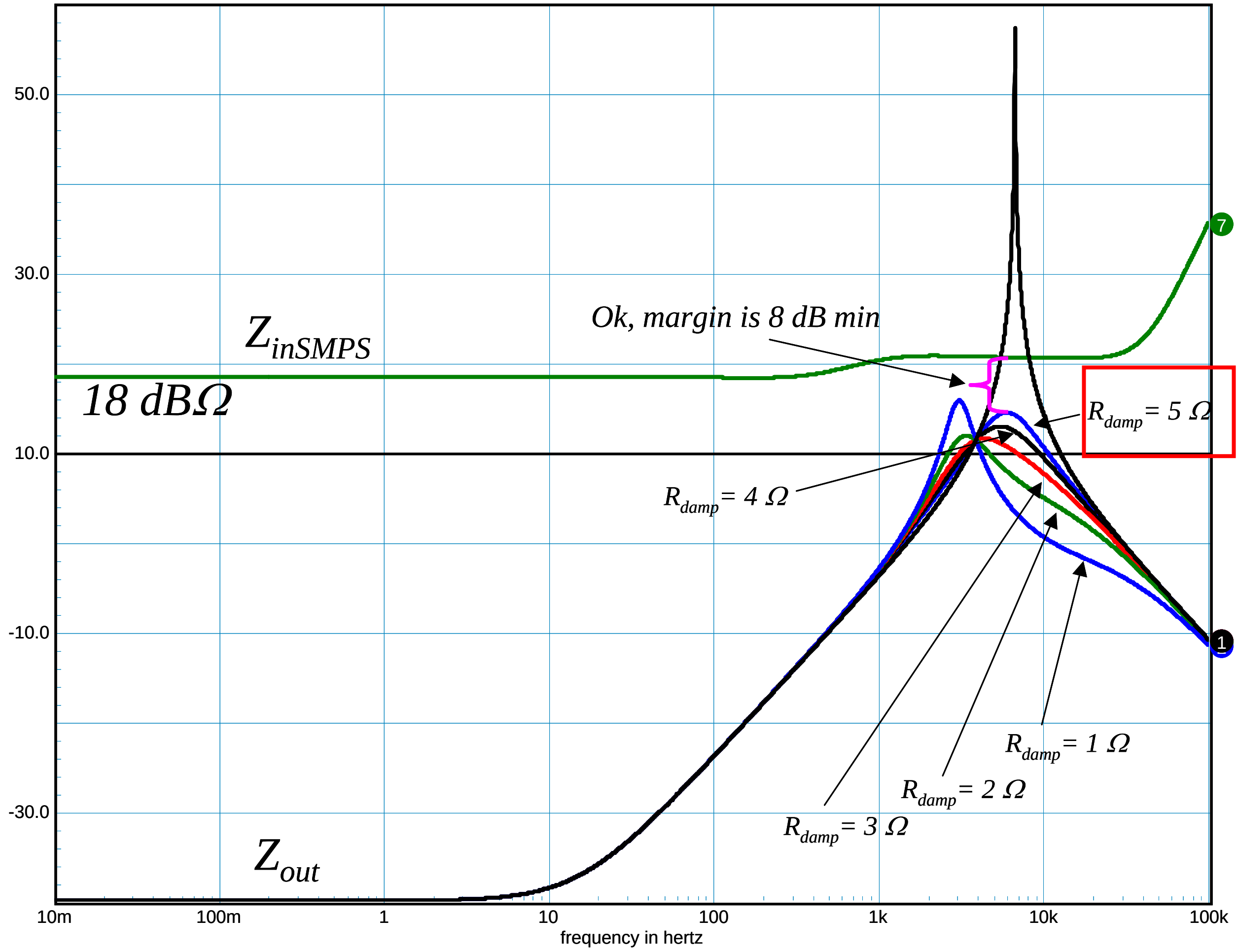
- A resistor is damping the LC filter by creating losses
- A dc-block capacitor is installed to limit dissipation



$$\boxed{R_{damp}} = -Z_{inSMPS} \frac{L + CR_1R_2 - \dfrac{R_1}{\omega_0}}{2Z_{inSMPS}CR_1 - \dfrac{Z_{inSMPS}}{\omega_0} + L + CR_2R_1 - \dfrac{R_1}{\omega_0}}$$

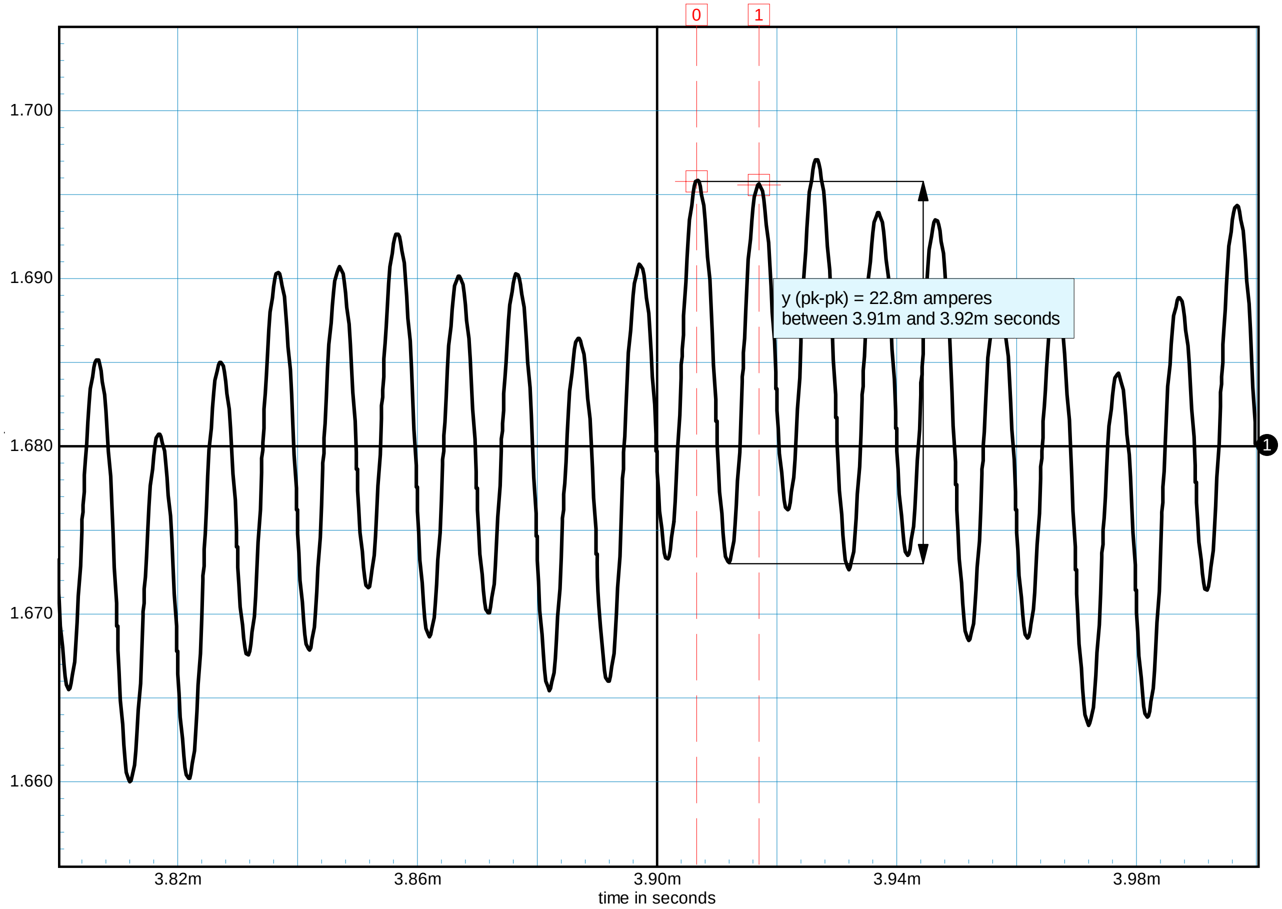
EMI Filtering on a DC-DC

- ☐ The right resistor prevents the overlaps between curves



EMI Filtering on a DC-DC

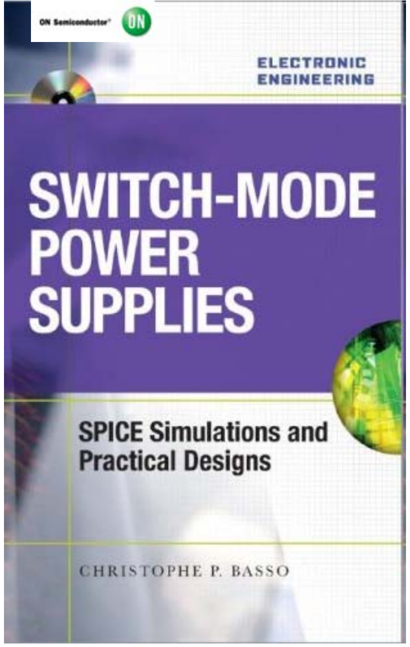
- ☐ A final check shows a noise amplitude under control



A Book on Power Supply Design

- To learn more about power supplies and simulations…

886 pages, 8 chapters



ON Semiconductor

ELECTRONIC ENGINEERING

SWITCH-MODE
POWER
SUPPLIES

SPICE Simulations and
Practical Designs

CHRISTOPHE P. BASSO

- Learn DC-DC converters theory
- Understand average modeling
- Feedback and loop control
- Design examples of DC-DC and AC-DC
- Power Factor Correction
- Chapters on flyback and forward converters
- Supplied CDROM with working examples

Conclusion

- SPICE can be seen as a design companion
- It shields us from going through complex equations
- Simulation time is short and PC helps to run tests
- Use SPICE before going to the bench: NO trial and error!
- Once the simulation is stable, build the prototype
- Simulations and laboratory debug: the success recipe!

For More Information

- View the extensive portfolio of power management products from ON Semiconductor at www.onsemi.com
- View reference designs, design notes, and other material supporting the design of highly efficient power supplies at www.onsemi.com/powersupplies