ON Semiconductor

The “PWM Switch” in mode transitioning SPICE models

PCIM Germany 2005

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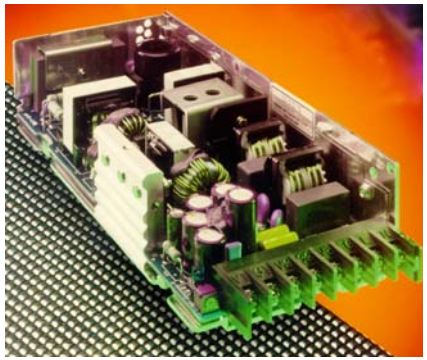
ON Semiconductor™

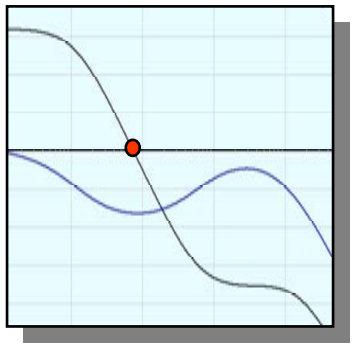
Agenda

- Why average simulations?
- What techniques already exist?
- The PWM Switch concept
- The voltage-mode case
- The current-mode case
- Checking *averaged* model’s validity
- Conclusion

Why average simulations?

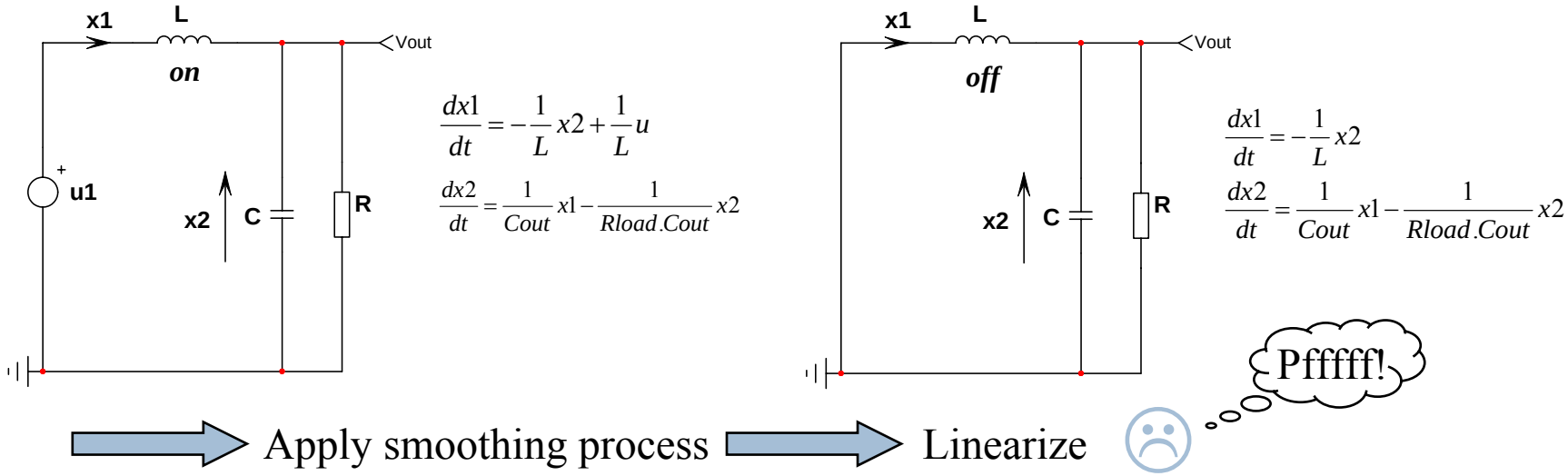
- Unveil open-loop ac response for stabilization purposes
- Helps to assess impact of stray elements variations on stability
- Can predict transient response with large-signal models
- Simulation time is quick as frequency component fades away





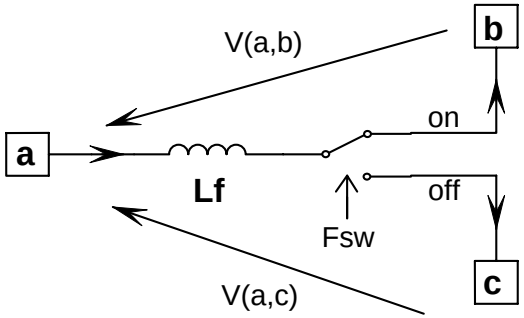
What techniques already exist?

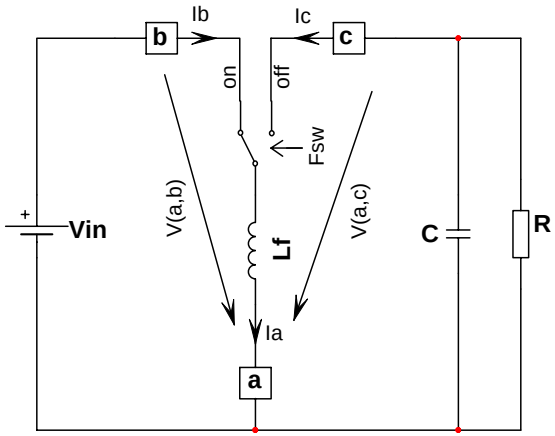
- **State-Space Averaging** (SSA)
- Introduced by Slobodan Ćuk in the 80’
- Long and painful process
- ***Fails*** to predict sub-harmonic oscillations



What techniques already exist?

- The **GSIM** concept
- Introduced by Sam Ben-Yaakov in the 90’
- Easy to derive but not fully invariant (dual inductors converters?)
- Fully ***auto-toggling*** mode models
- ***Fails*** to predict sub-harmonic oscillations

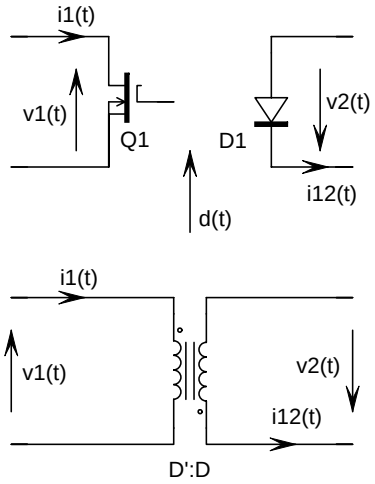




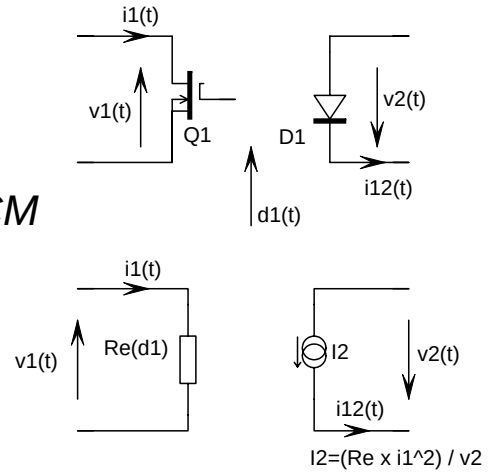
What techniques already exist?

- The **CoPEC** model
- Introduced by the Colorado Power Electronic Center in the 90’
- Easy to derive and fully invariant
- Fully ***auto-toggling*** mode models
- ***Fails*** to predict sub-harmonic oscillations

CCM

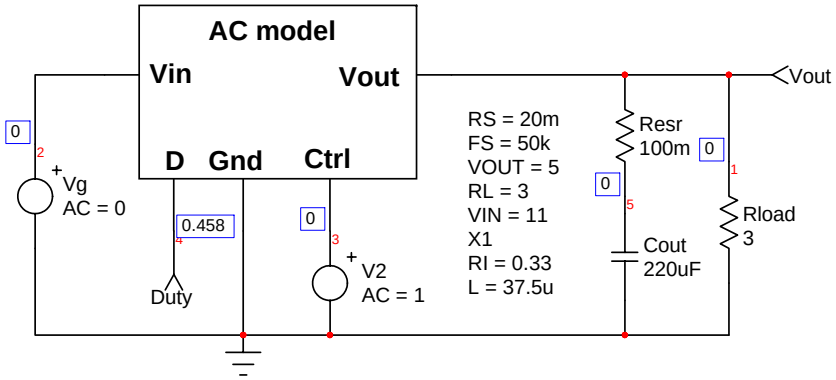


DCM



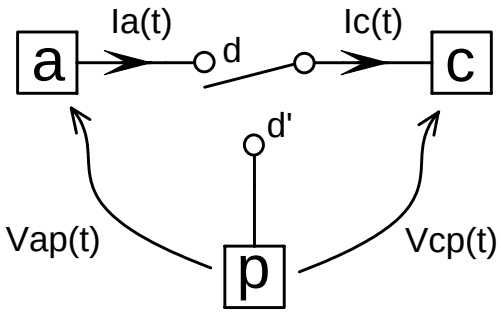
What techniques already exist?

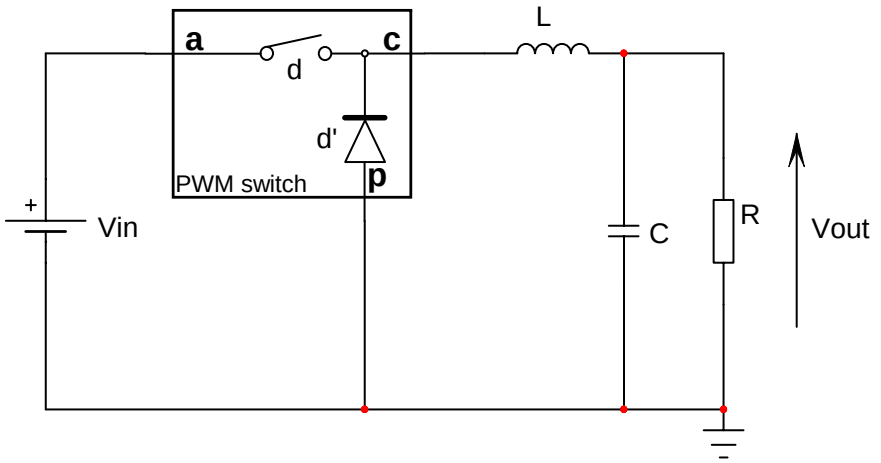
- The **Ridley** models
- Introduced by Raymond Ridley from VPEC in the 90’
- Use z-transform method
- **No** *auto-toggling* mode models
- Can only work in ac
- ***Can*** predict sub-harmonic oscillations in CCM



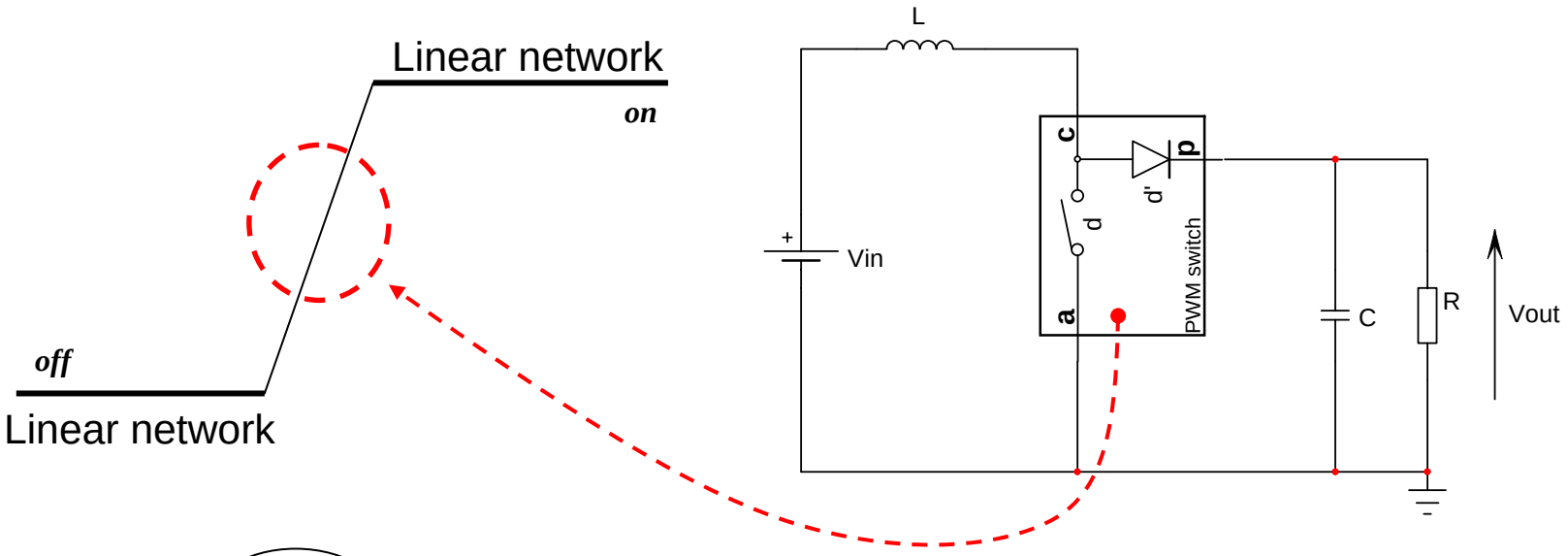
What techniques already exist?

- 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 was never published!



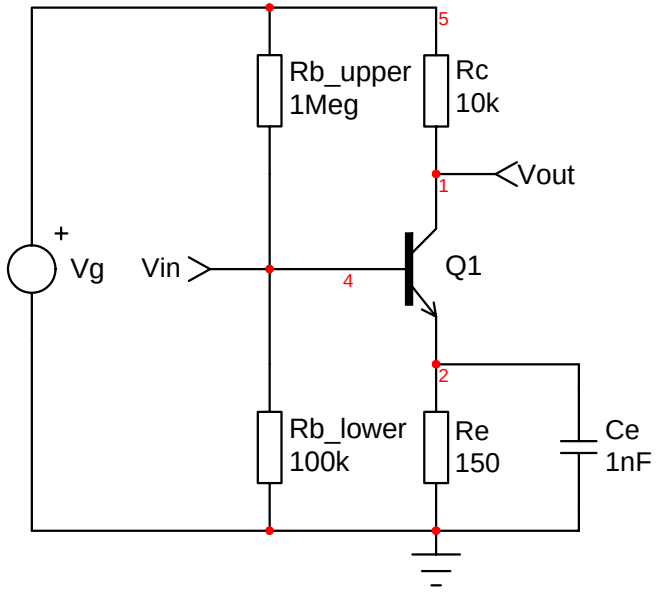


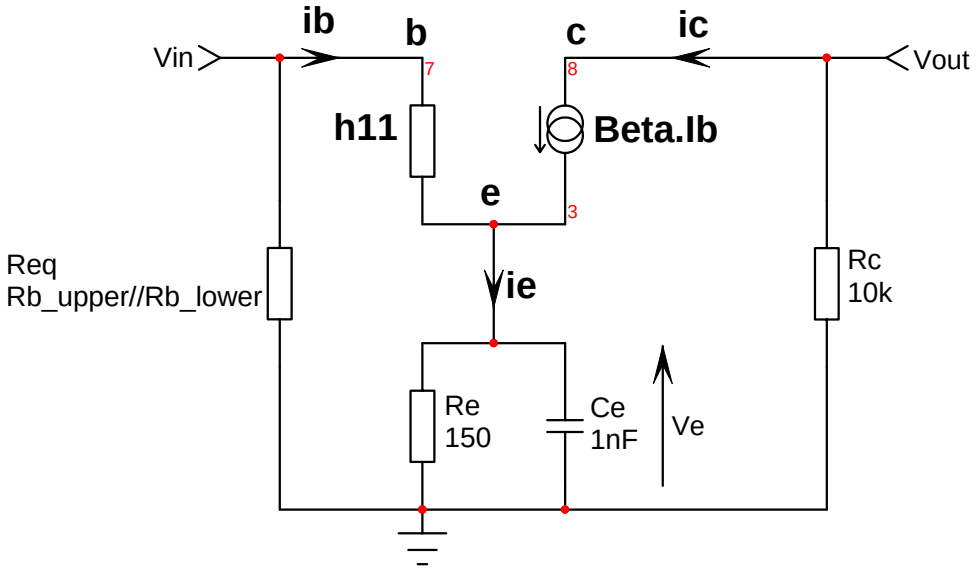
The PWM Switch concept



diode + transistor = guilty for non-linearity!

The PWM Switch concept

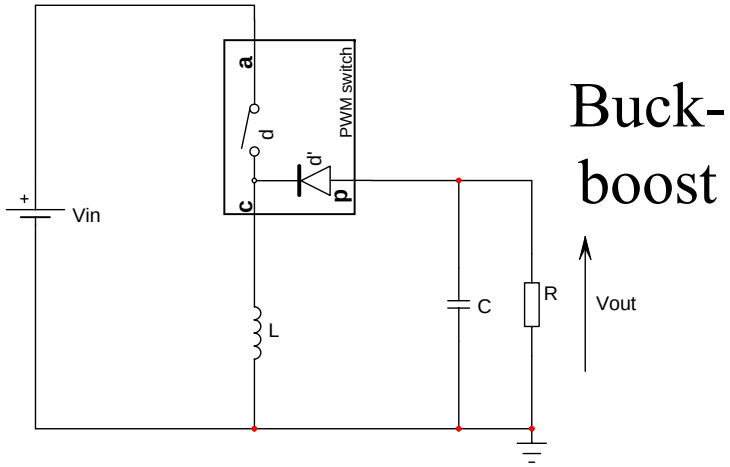




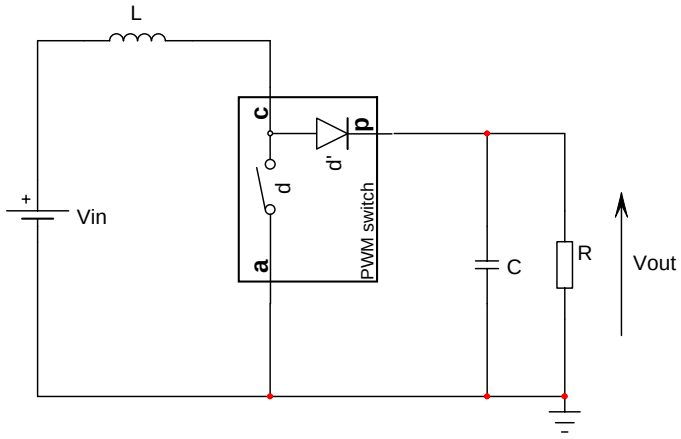
Remember the ***bipolars*** Ebers-Moll model…

Replace Q_1 by its small-signal model

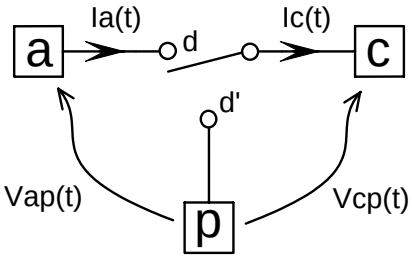
An **invariant** association

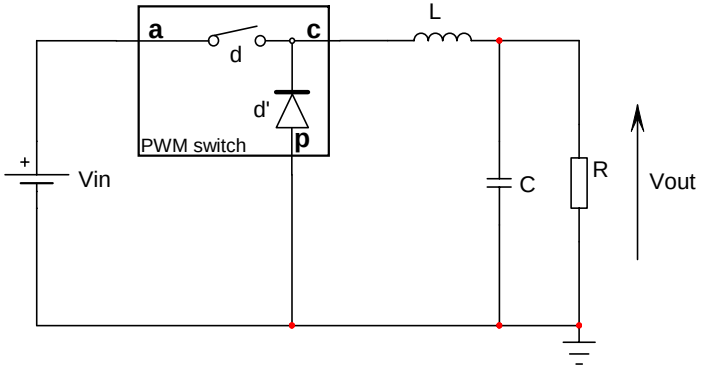


Buck-boost



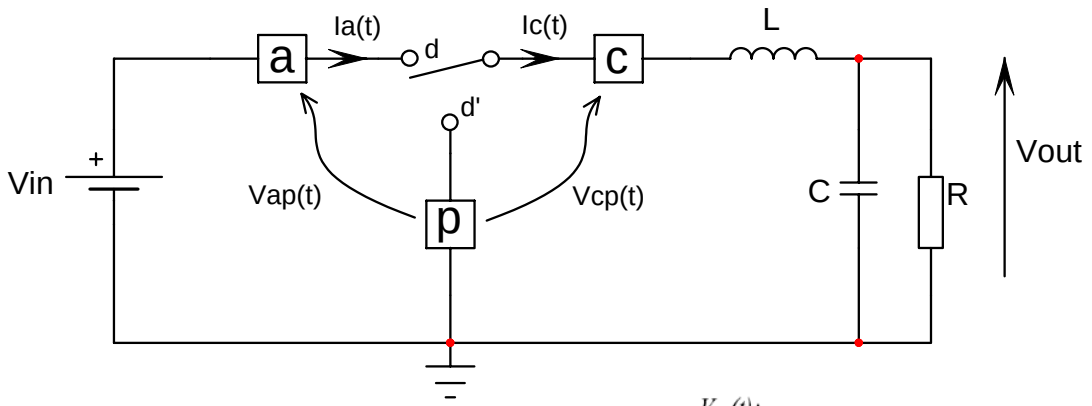
Boost

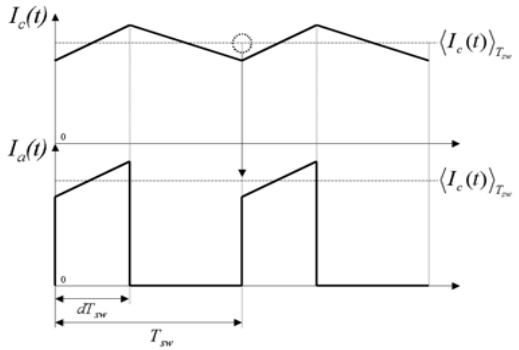




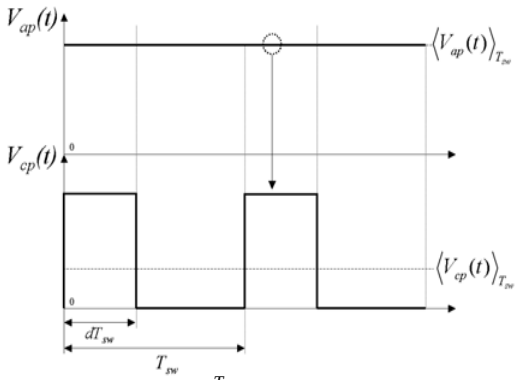
Buck

Observe waveforms and *average* them



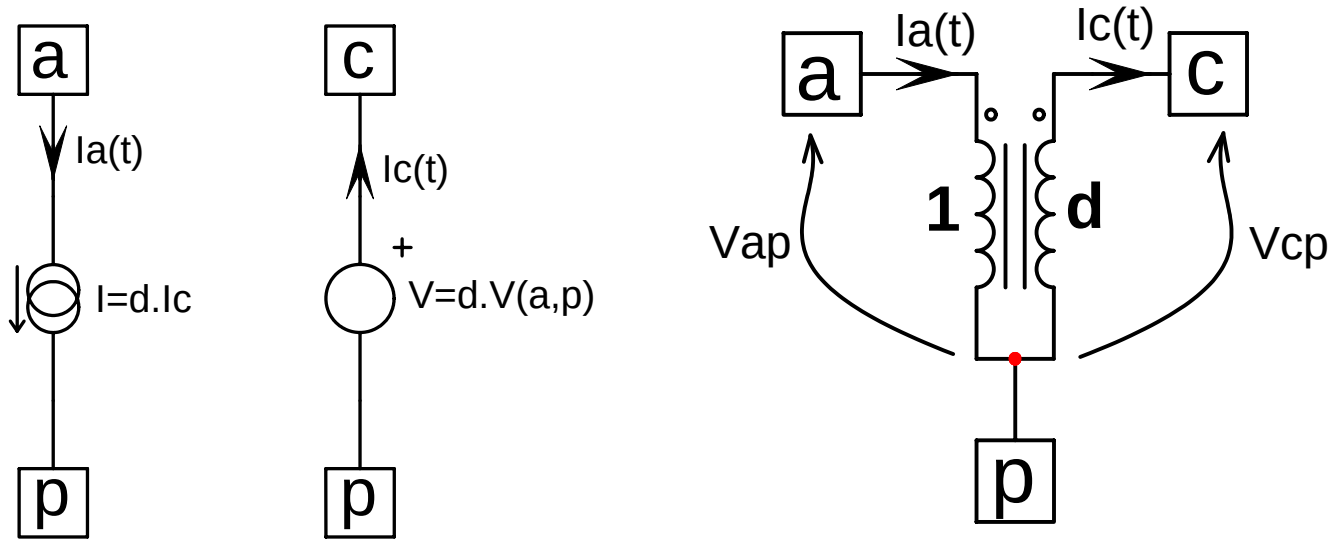


$$\langle I_a(t)\rangle_{T_{sw}} = I_a = \frac{1}{T_{sw}}\int_0^{T_{sw}} I_a(t)dt = d\langle I_c(t)\rangle_{T_{sw}} = dI_c$$



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

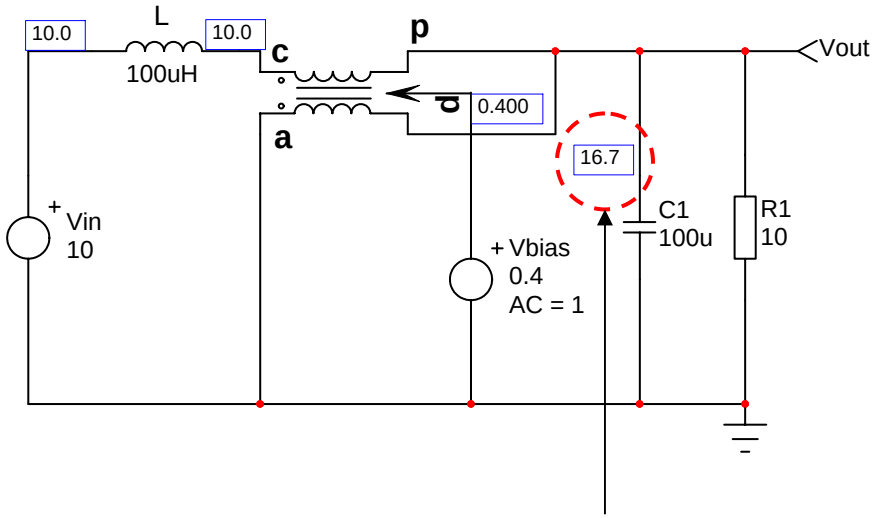
PWM Switch model in CCM: a 1:D transformer!

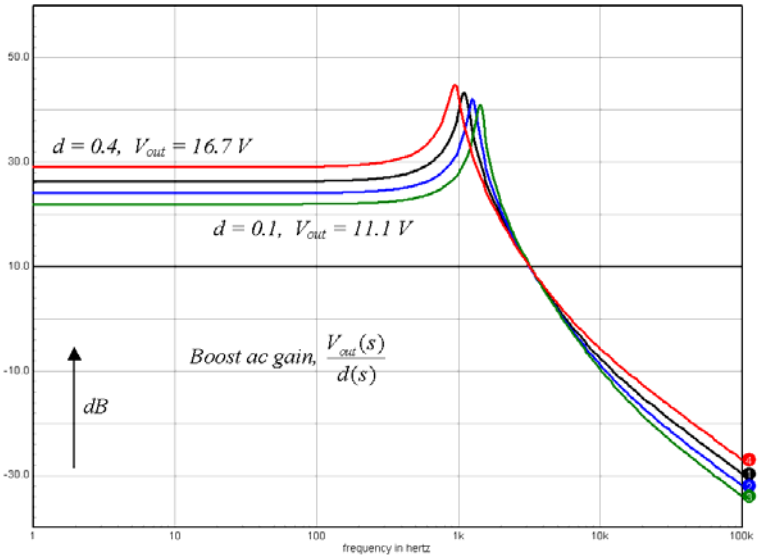


Large-signal (non-linear) model

The “PWM Switch” in mode transitioning SPICE models

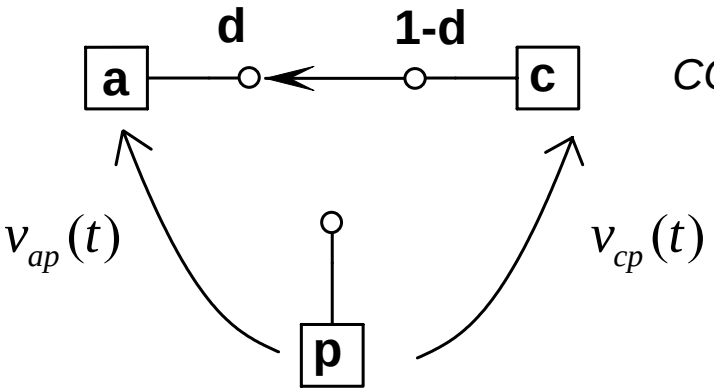
Use it immediately, ***SPICE*** linearizes it for you!



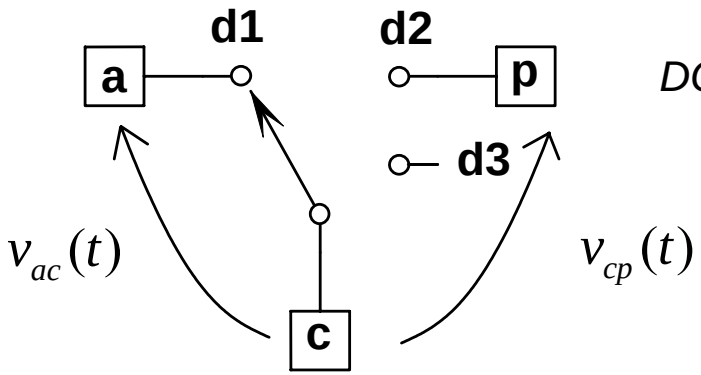


Always verify the dc operating point!

The original CCM/DCM PWM Switch models

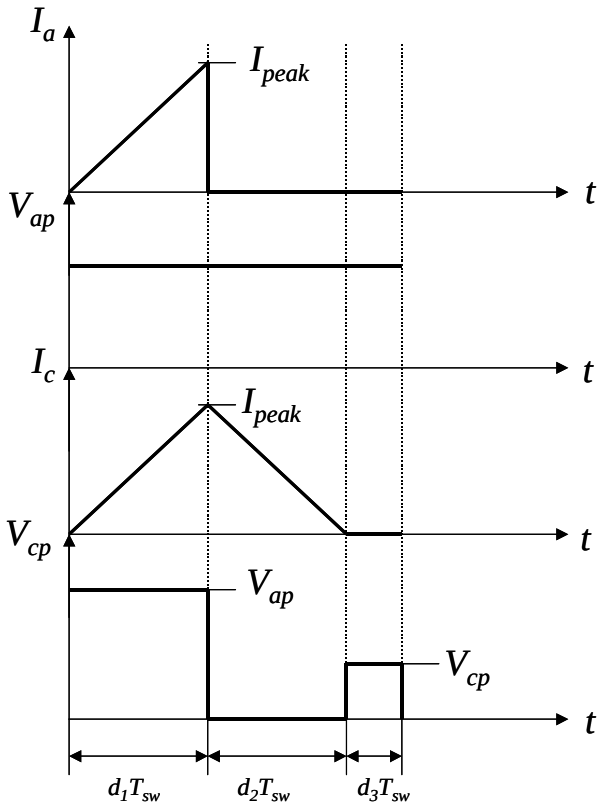


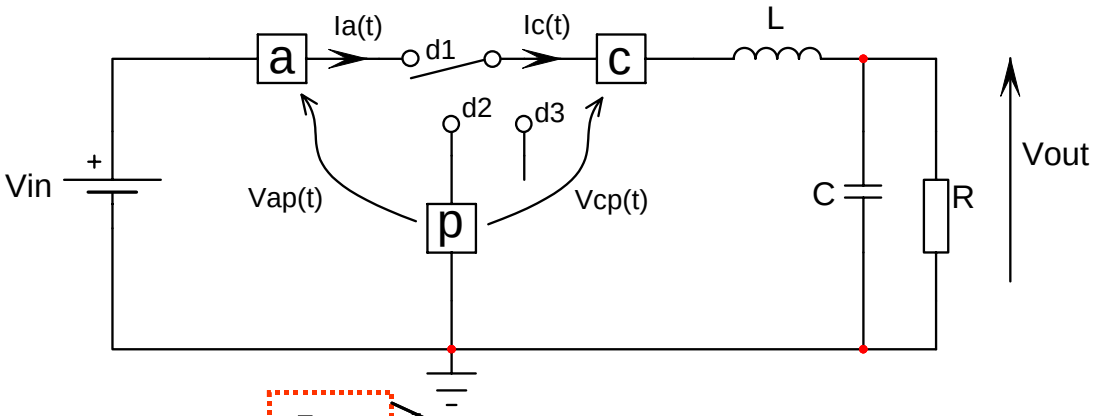
CCM: common « passive »



DCM: common « common »

Deriving the ***DCM*** PWM Switch in common « passive »



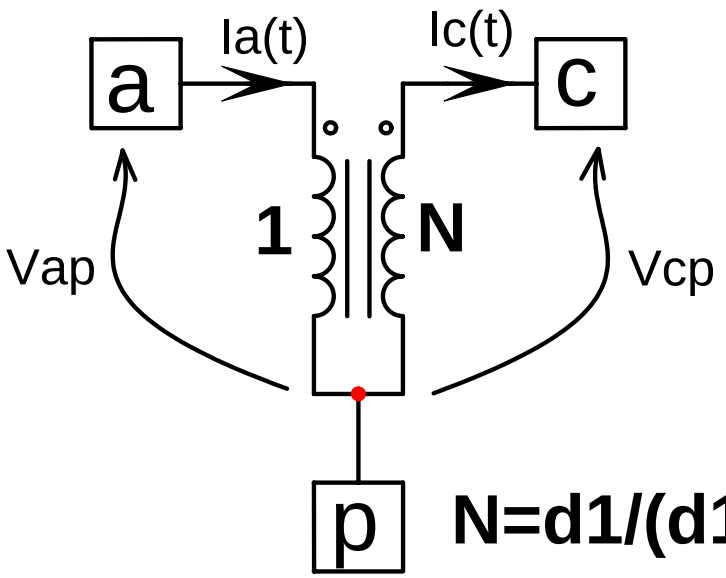


$$I_a = \frac{I_{peak} d_1}{2}$$

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

$$I_c = \frac{2 I_a}{d_1} \frac{(d_1 + d_2)}{2} = I_a \frac{(d_1 + d_2)}{d_1}$$

An auto-toggling version: ***clamp*** the equation!



Clamp d_2:

d_2 CCM = 1- d_1

d_2 DCM = 1- d_1- d_3

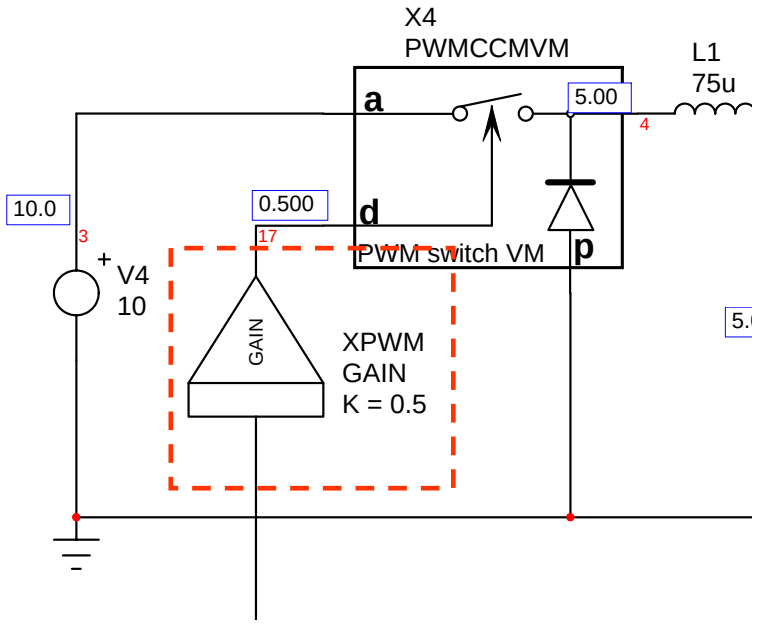
$d_2 < d_2$ CCM

model is in DCM!

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

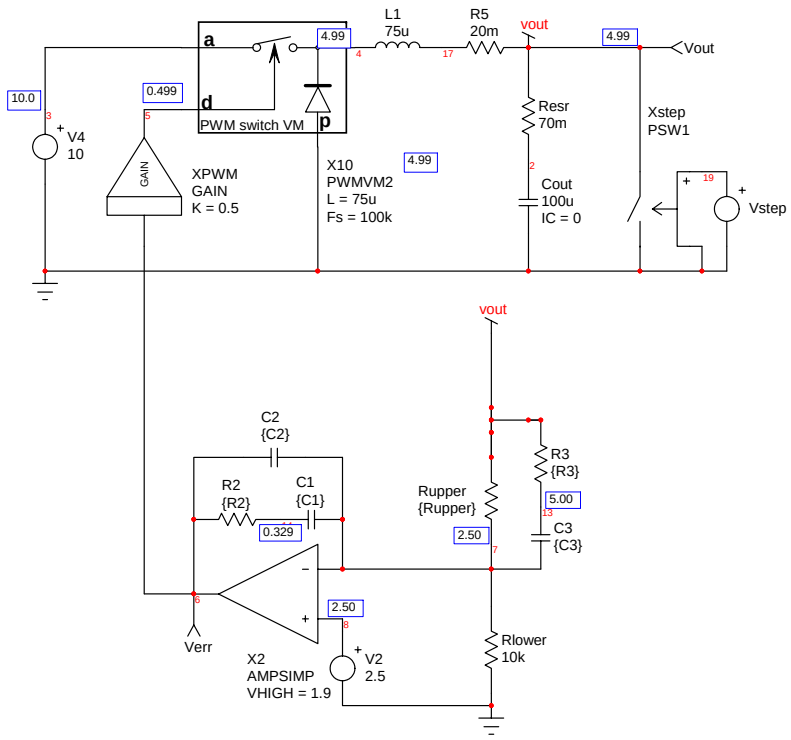
Model input

In voltage mode, add the PWM ***modulator*** gain

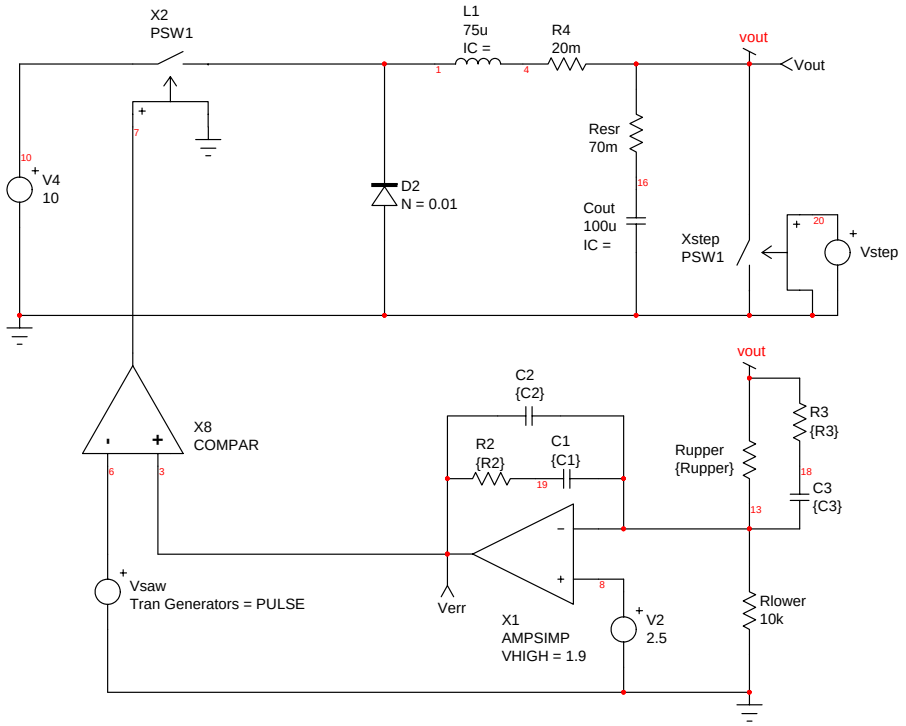


$$K_{PWM} = \frac{1}{V_{peak}}$$

Testing the ***auto-toggling*** model

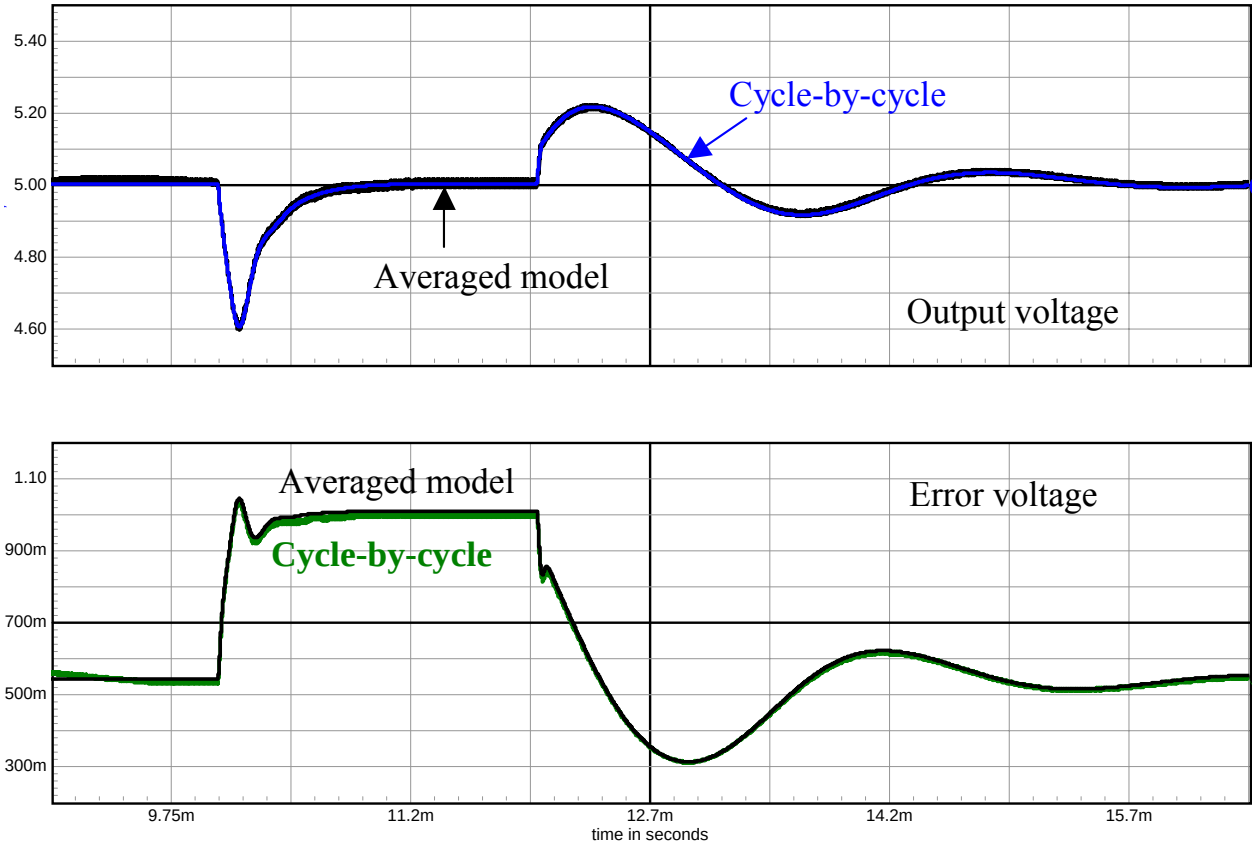


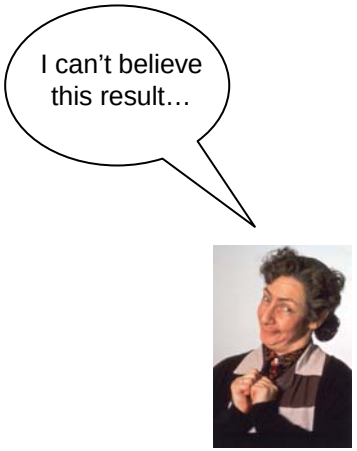
Averaged model



Cycle-by-cycle

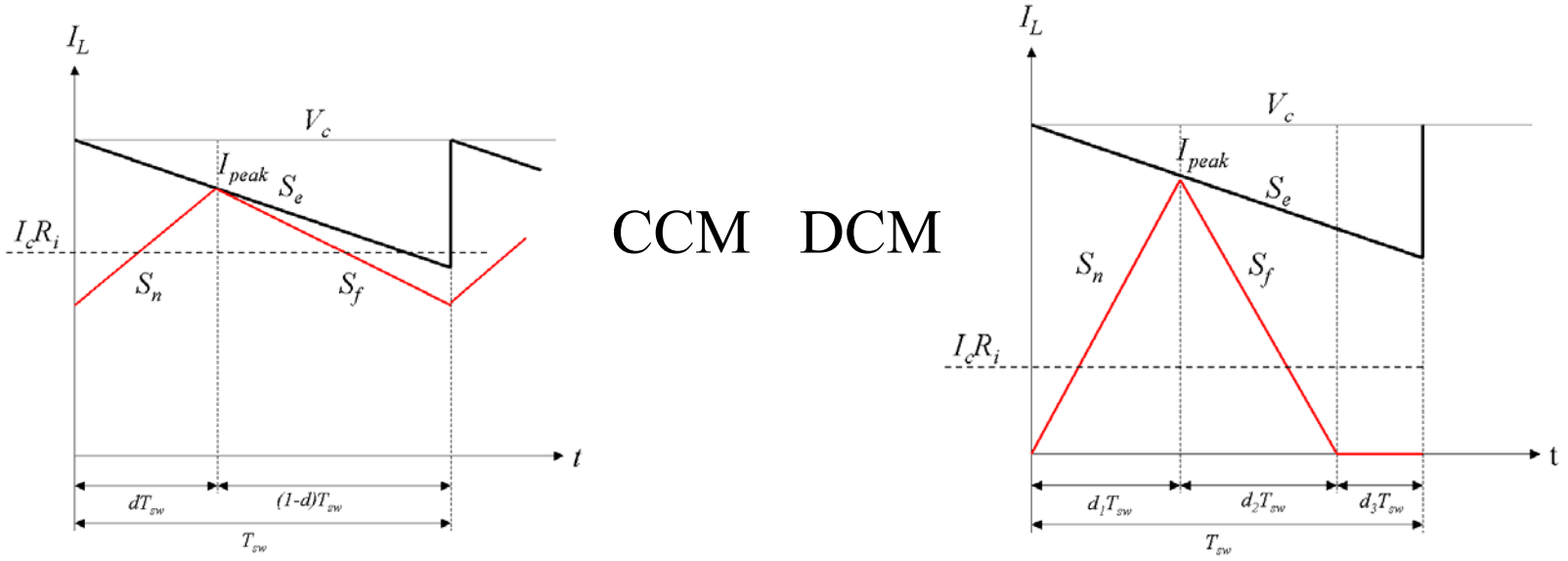
Comparing ***results*** with a stepload…



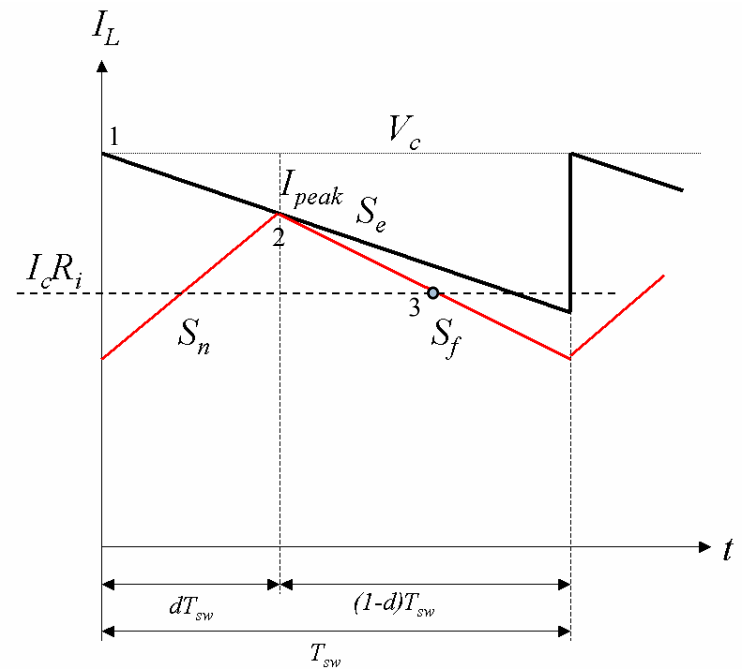


Current-mode PWM switch

- ❑ Same approach as before:
- ✓ observe and average waveforms
- ✓ get the equivalent representation
- ✓ perturb for small-signal analysis

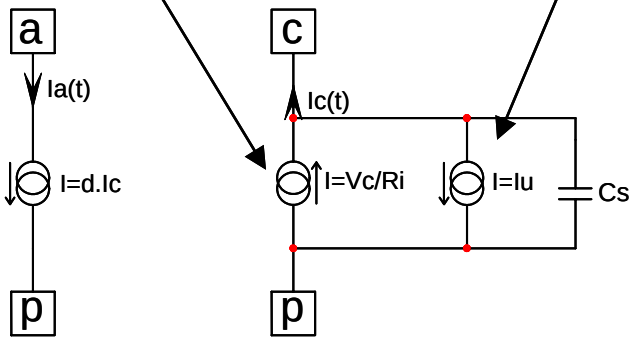


CCM operation, current expression

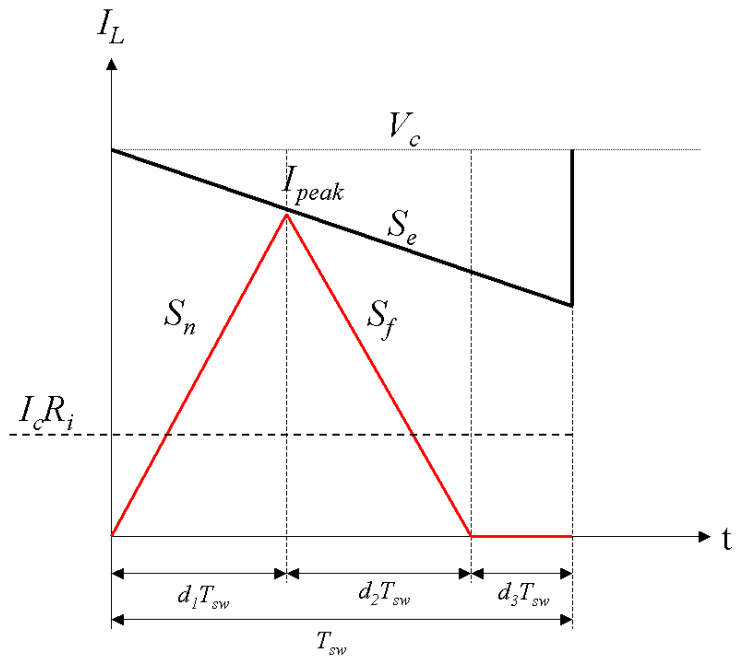


$$I_c(t)R_i = \overset{1}{V_c}(t) - \overset{2}{d(t)}T_{sw}S_e - \frac{S_f \overset{3}{d'(t)}T_{sw}}{2}$$

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



DCM operation, current expression

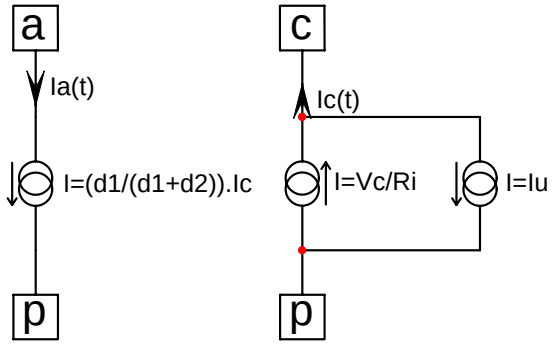


$$I_{peak} = \frac{V_c - d_1 T_{sw} \times S_e}{R_i}$$

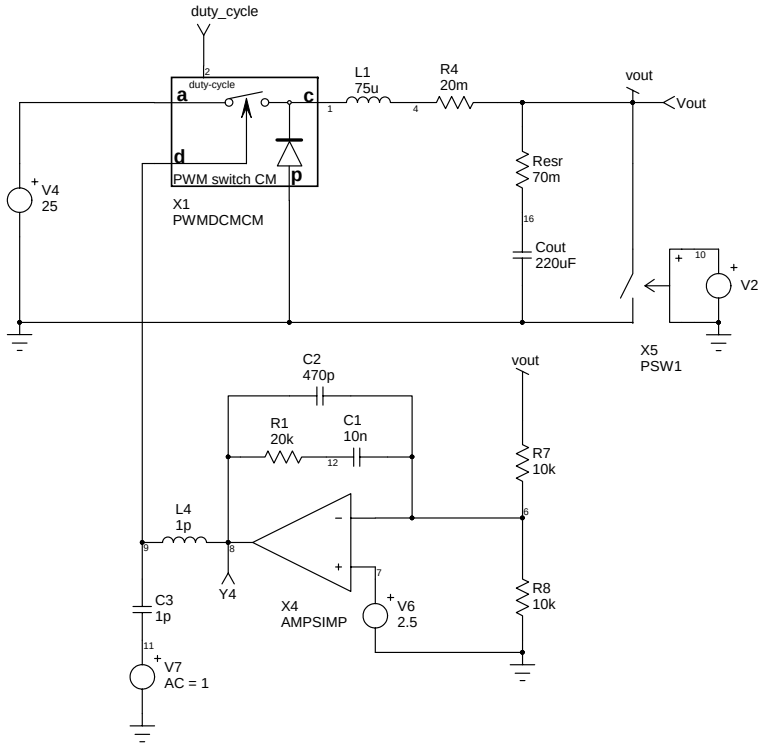
$$I_c = \frac{V_c - d_1 T_{sw} S_e}{R_i} - \alpha d_2 T_{sw} S_f$$

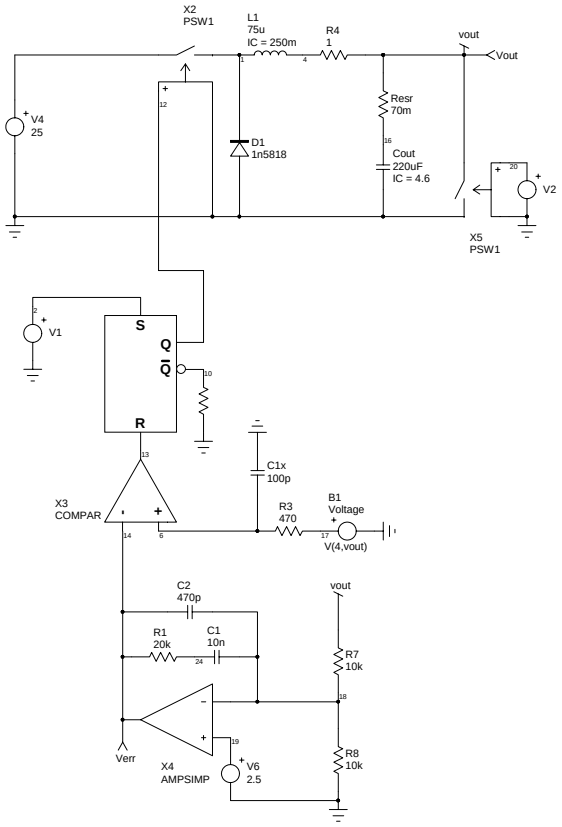
$$I_c = \frac{I_{peak} d_1}{2} + \frac{I_{peak} d_2}{2} = \frac{I_{peak}\left(d_1 + d_2\right)}{2}$$

$$I\mu = \frac{d_1 \times Tsw \times Se}{Ri} + d_2 \times Tsw \times \frac{V(c,p)}{L} \times \left(1 - \frac{d_1 + d_2}{2}\right)$$



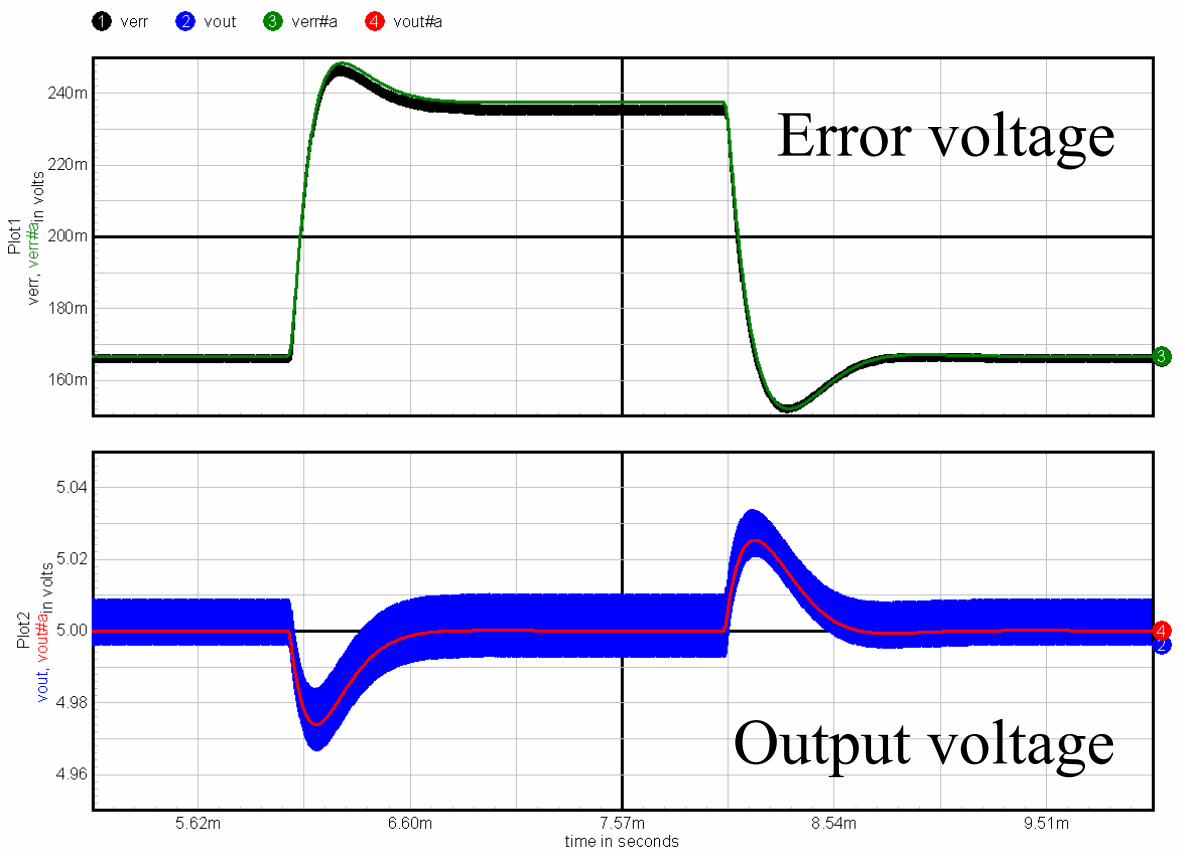
The **PWM Switch**, the final encapsulation

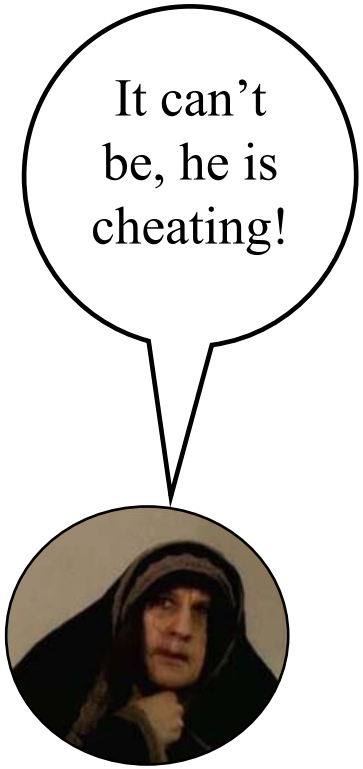




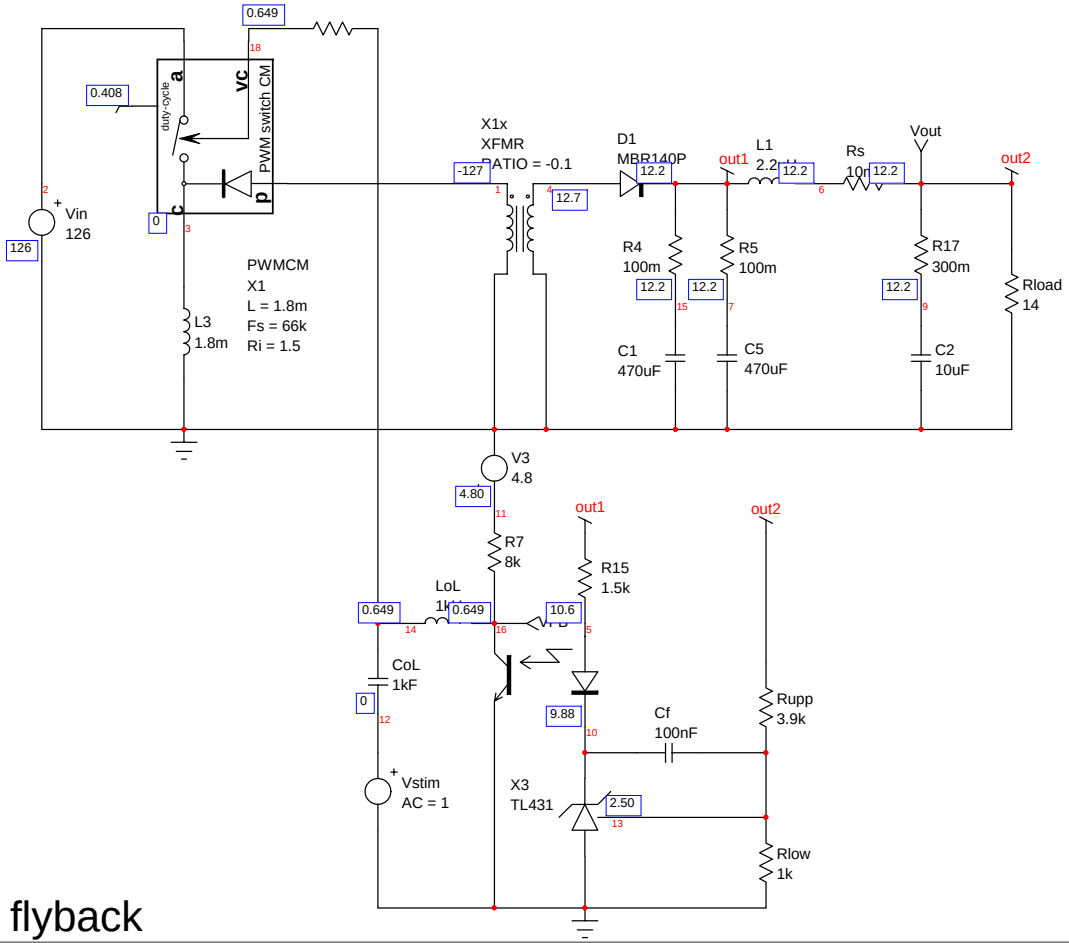
A buck: averaged model vs cycle-by-cycle

Good matching between both models



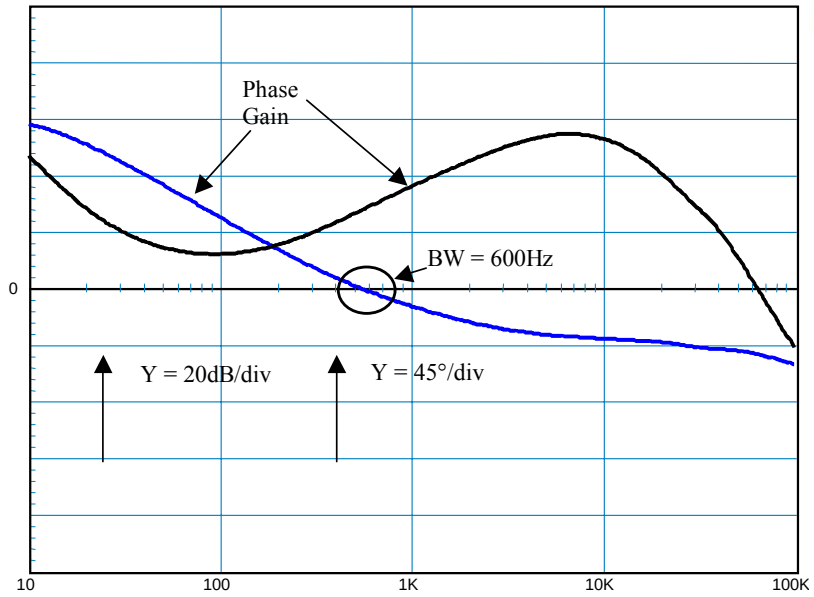


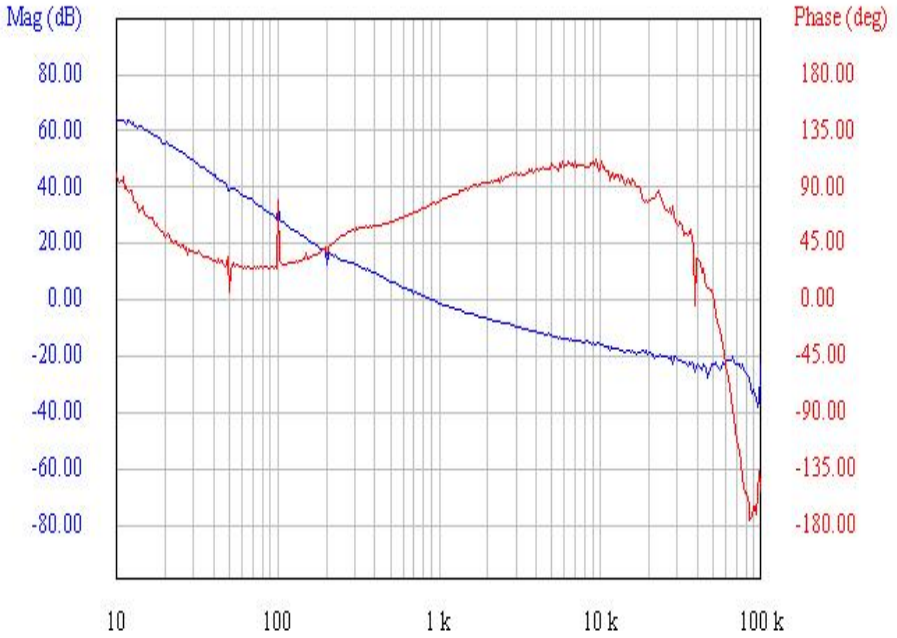
Testing the *ac* response



A dcm current-mode flyback

Ac simulation results of the flyback converter

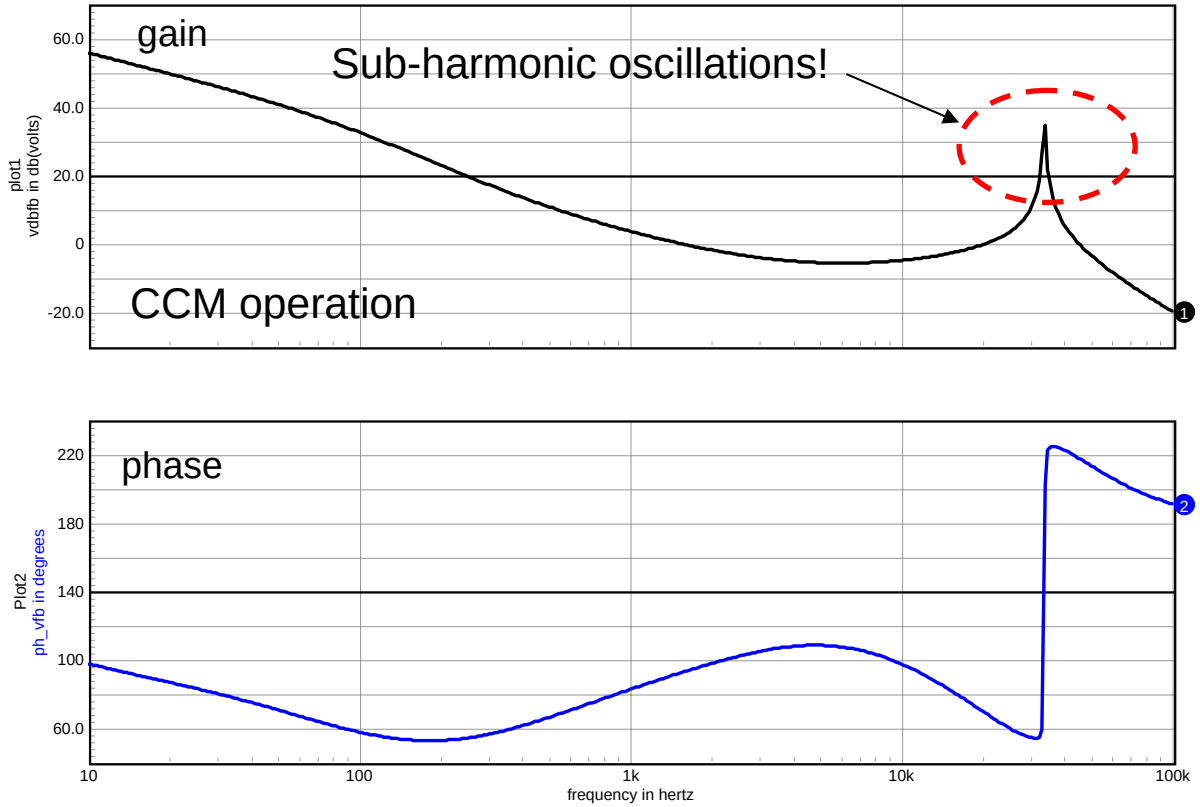




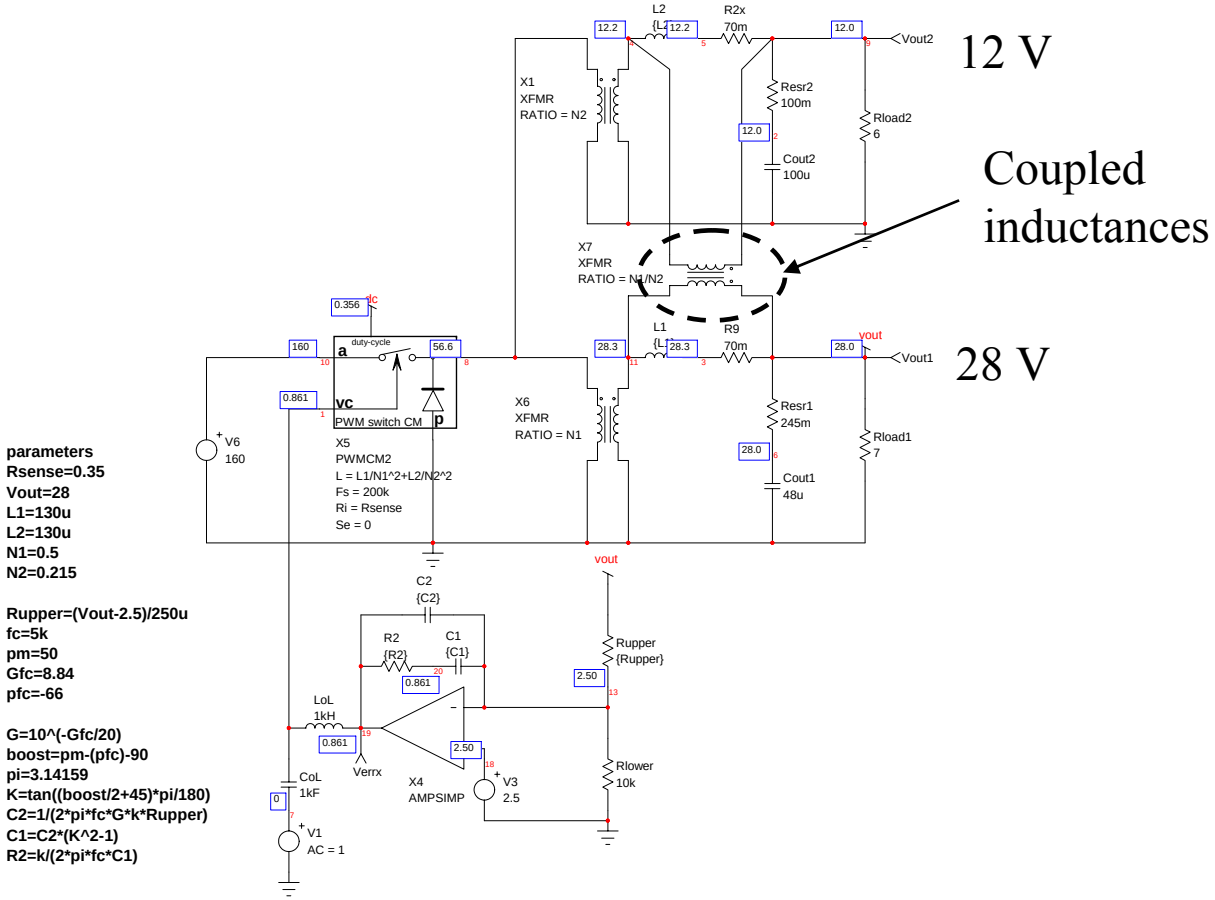
Simulation

Measurement

If the load increases…

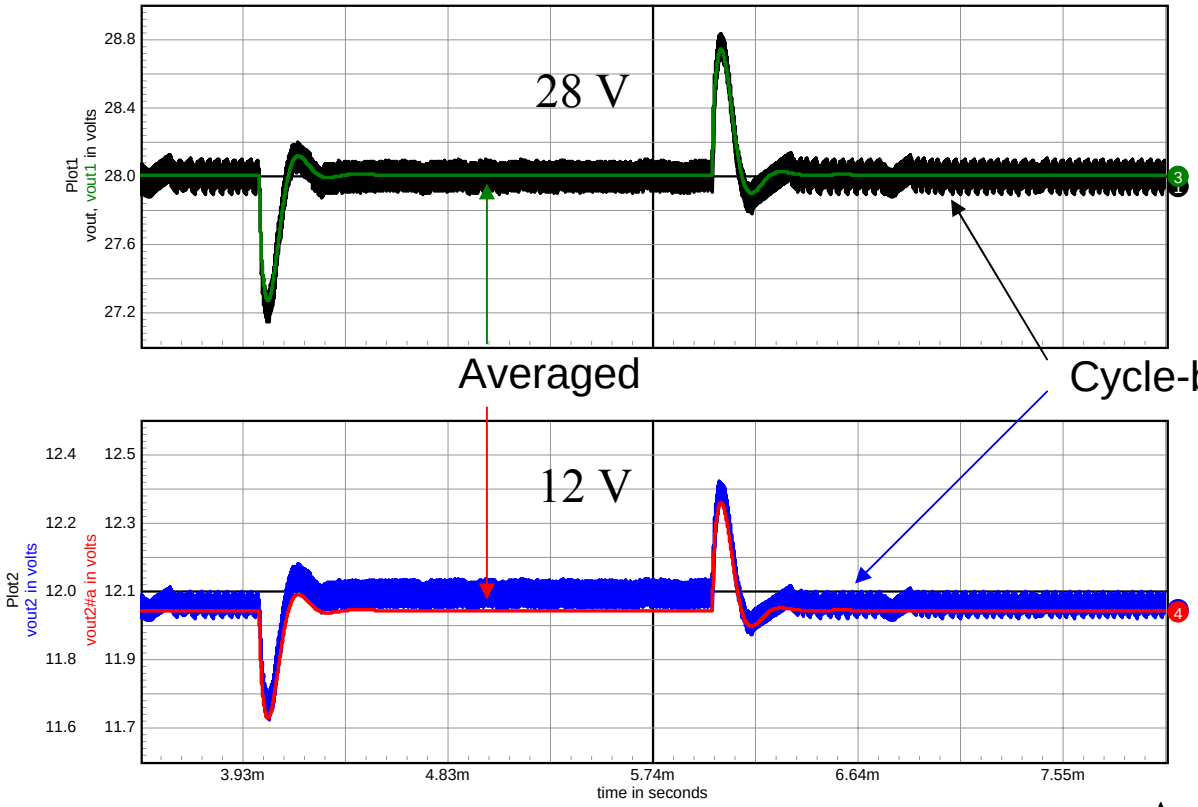


Testing on a multi-output forward



A multi-output forward

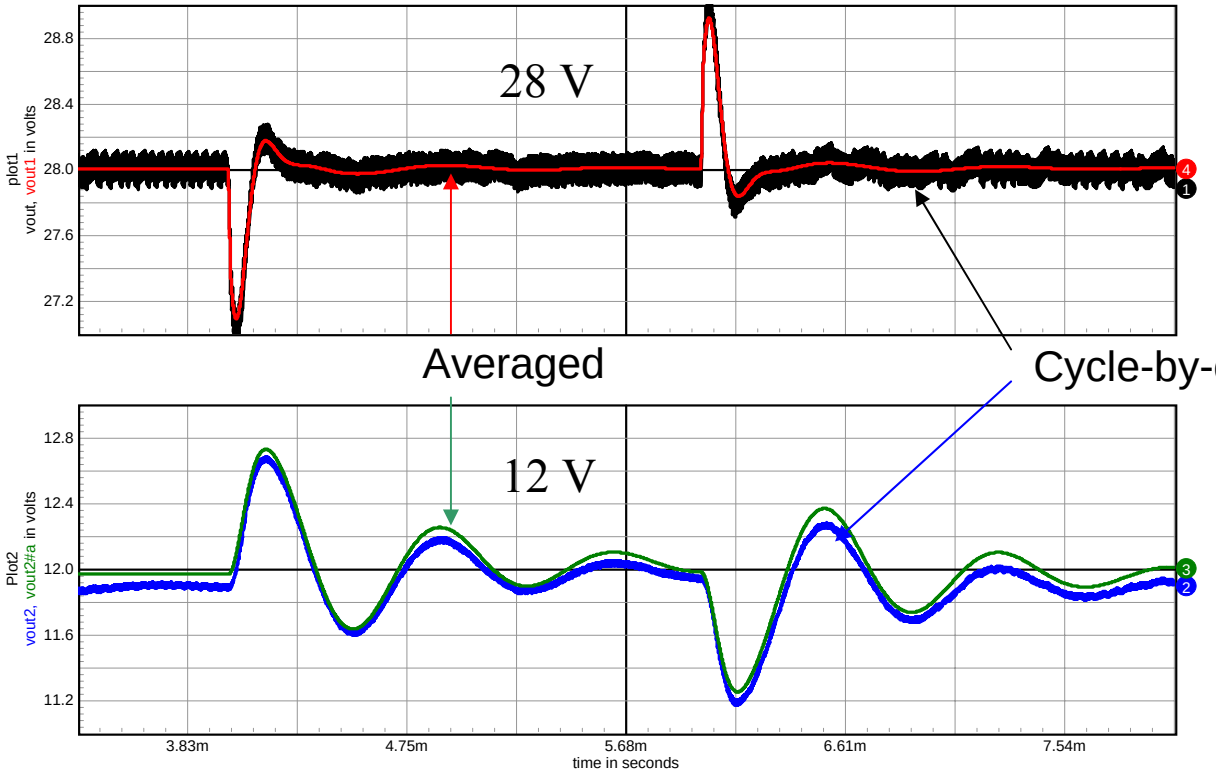
Output voltage bang on the 28 V output…



Inductances are coupled…

A forward converter

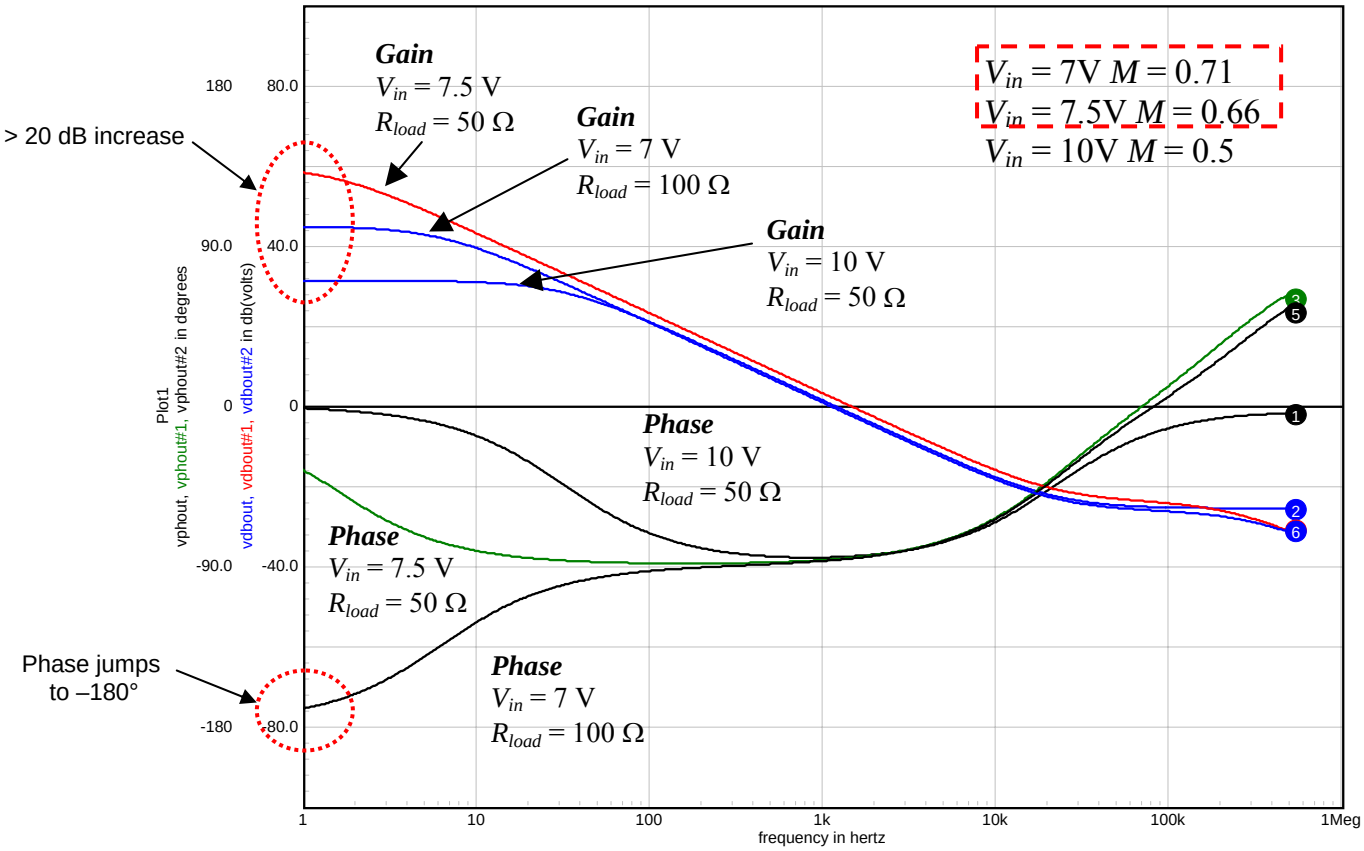
Output voltage bang on the 28 V output…



Inductances are un-coupled…

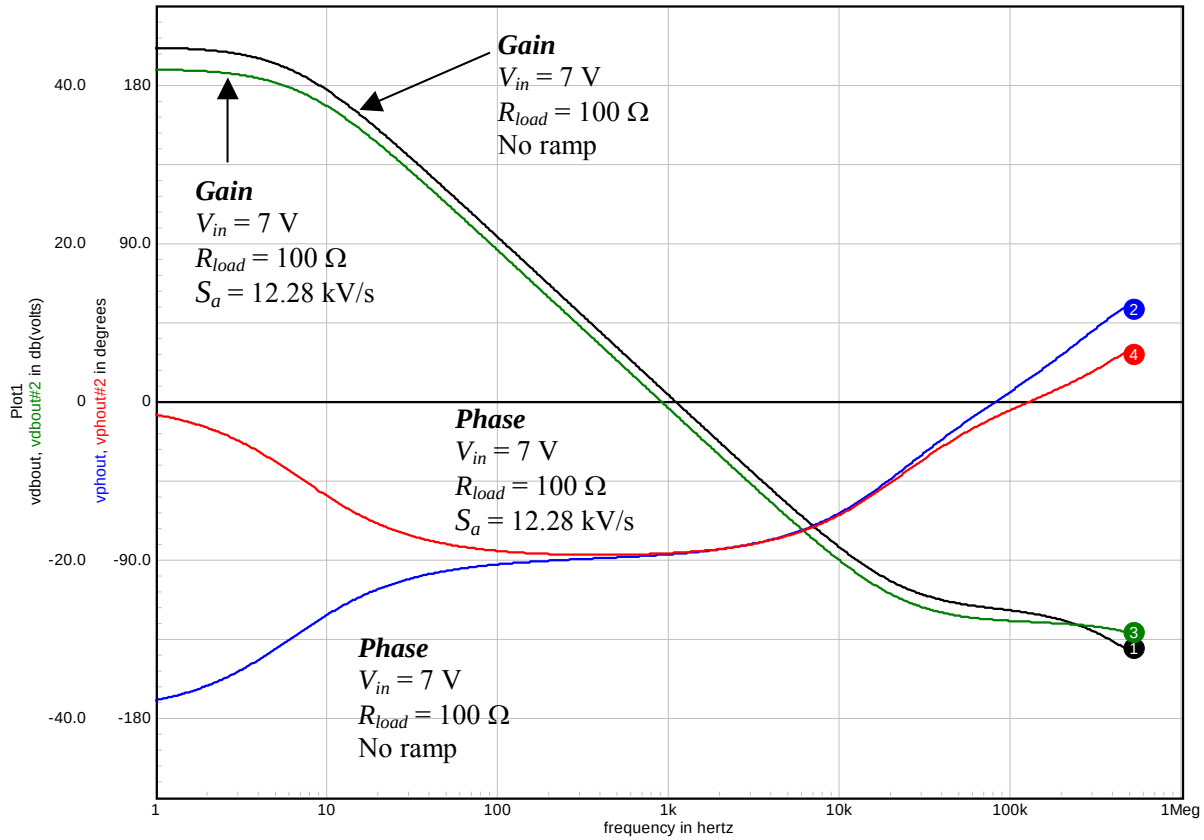
A forward converter

Instability in the buck DCM current-mode



The DCM buck shows instability as M > 0.66 without ramp

Instability in the buck DCM current-mode



Adding 0.086 x S_{off} cures the problem

The conclusion

- The CM PWM Switch DCM was derived
- Two auto-toggling models developed
- Good matching of average vs reality
- Models also exist in BCM (PFC simulations)
- Exist in both IsSpice and PSpice