FUTURE ELECTRONICS
A WT Microelectronics Company

Simulation of Switching Converters

An Introduction

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Agenda

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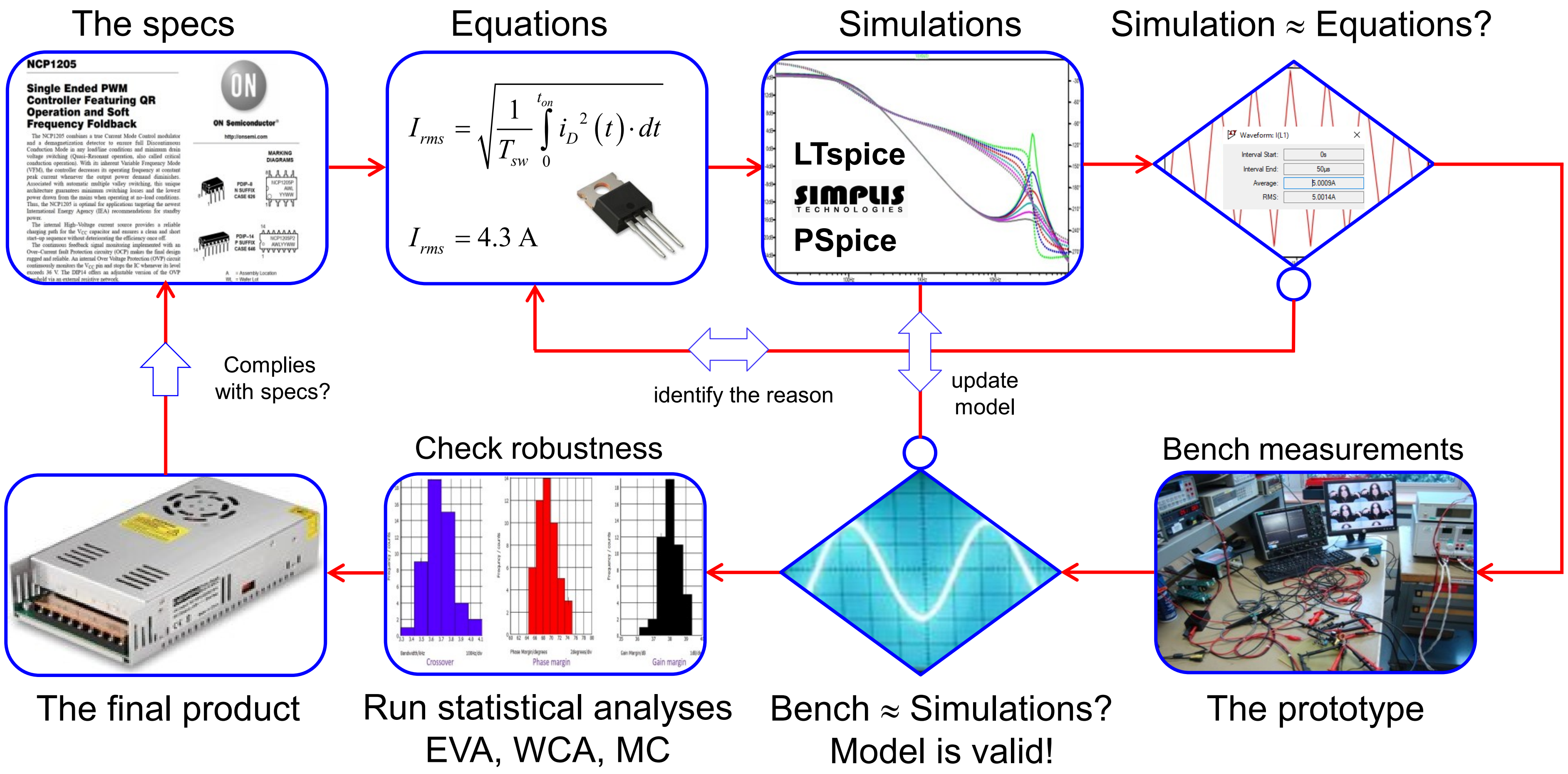
- Why Simulating?
- Different Simulation Engines
- Averaged Models
- Cycle-by-Cycle Models
- Simulation Examples of Converters

Different Approaches lead to Success

- The specs analysis is followed by an analytical equations-based approach

✓ Combining equations, simulations and hardware measurements: recipe for success!



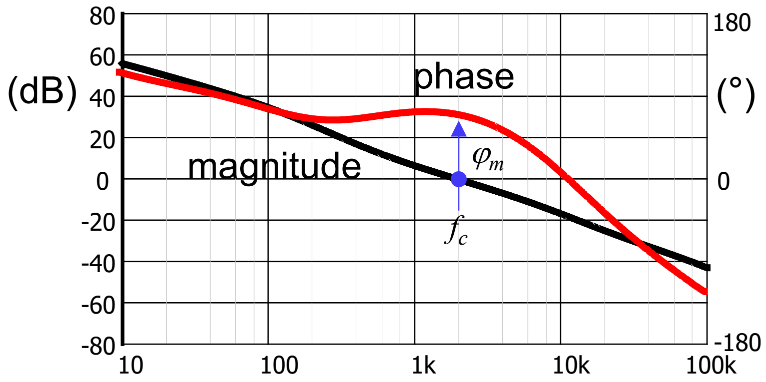
EVA: extreme value analysis – WCA: worst-case analysis – MC: Monte Carlo

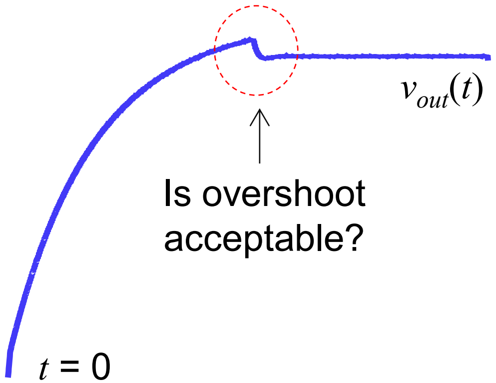
Why Simulating a Switching Converter?

- A badly-compensated loop can bring issues at the first power-on sequence

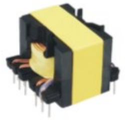
✓ Ac models deliver the power stage ac response to let you infer a compensation strategy

✓ Safely test the start-up sequence and confirm variables are within safe limits





- Is your transformer well dimensioned to deliver the required power?



- Do you have design margin on voltage and current limits for the semiconductors?

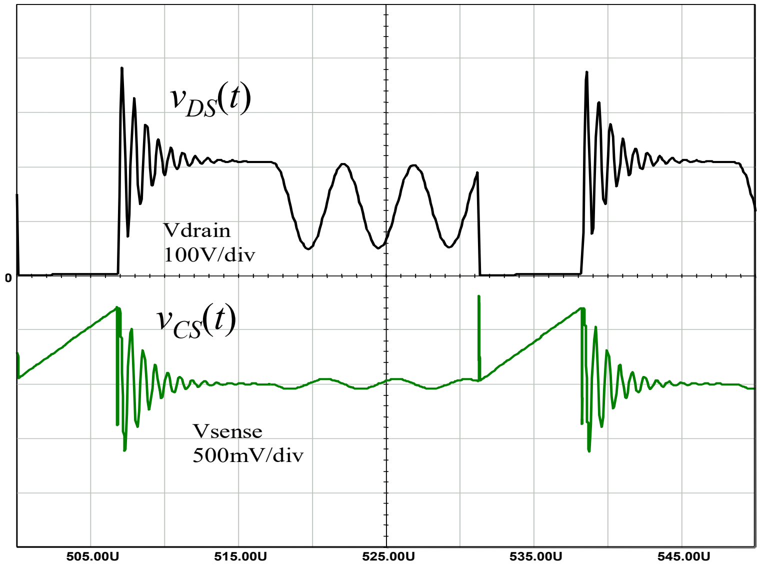
- What about the rms current in this capacitor at maximum output current?

Power libraries don’t burn – debug on the computer

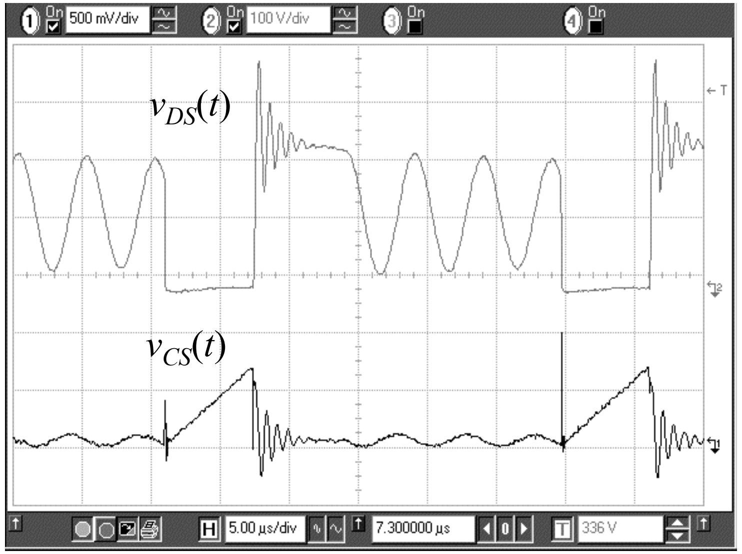
Simulations deliver reliable Results!

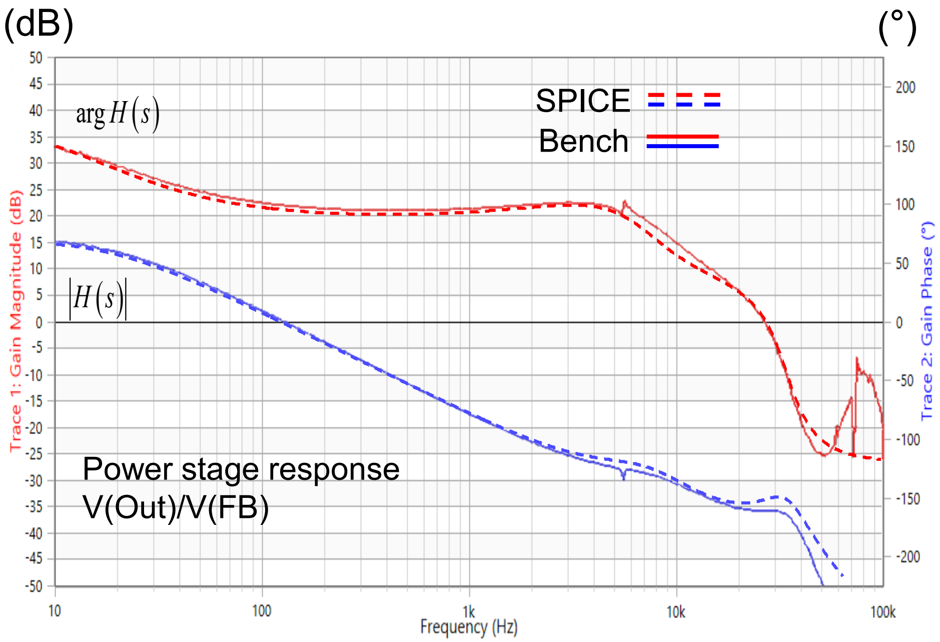
- If the subcircuits or models are fed with realistic parameters, simulation works
  - ➢ Carefully characterize the primary and leakage inductance of a transformer
  - ➢ Extract the ESR of the output capacitors for realistic losses and so on…

SPICE



bench





✓ You can predict oscillations, voltage and current stresses, overshoots…

✓ Comfortably close the loop with the computer and enjoy a perfect match on the bench

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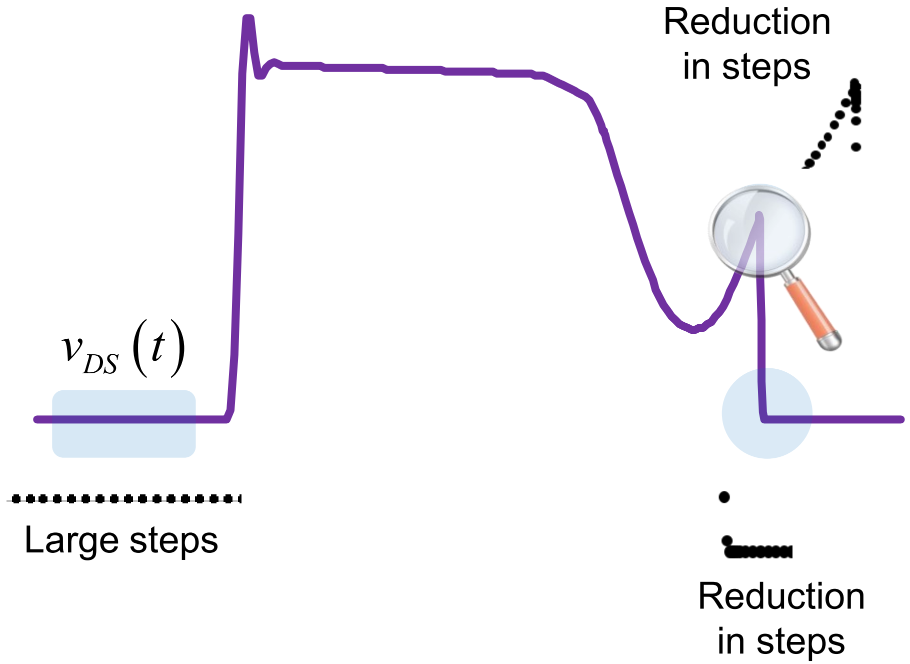
SPICE – a Reference since 1973

- SPICE is a linear solver in essence: any nonlinear behavior must be linearized
- SPICE samples at a variable timestep: it adjusts its course based on signals shapes
- ➢ Flat type of waveform: large timesteps are taken
- ➢ Change occurs: timestep reduction until enough precision is obtained

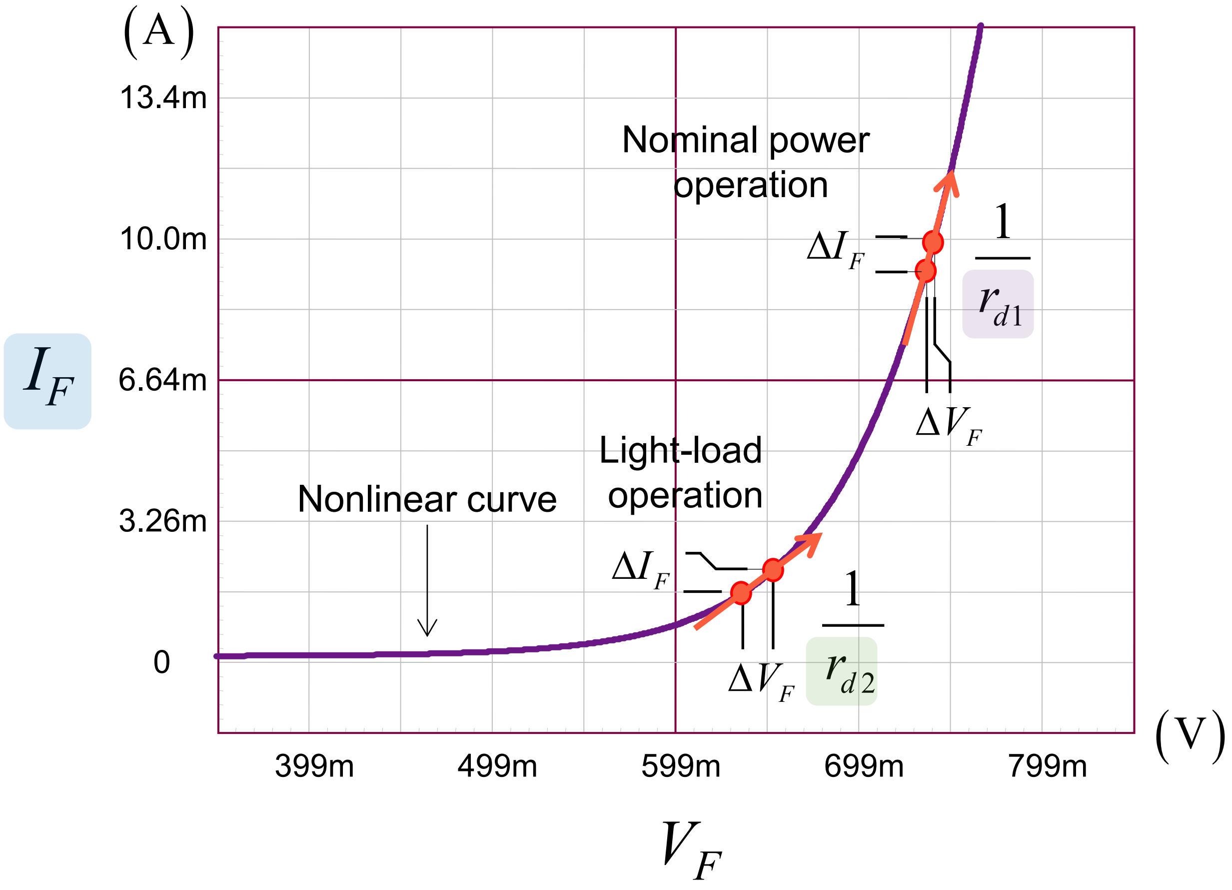


- ○ Timestep control algorithm is an essential part of the engine:
- ✓ It controls the number of iterations to find a solution
- ✓ It checks that timestep reduction brings a precise solution – jump to next point or fail!

Highly time-consuming process!

Linearizing the Shockley Equation

- A diode is a nonlinear device affected by a variable dynamic resistance r_d
- ✓ SPICE will have to linearize the component at every change in operating point



$$r_{d1} = \left.\frac{\Delta V_F}{\Delta I_F}\right|_{I_{F1}}$$

$$r_{d2} = \left.\frac{\Delta V_F}{\Delta I_F}\right|_{I_{F2}}$$

Operating points

Nonlinear expression

$$I_F = I_s\left(e^{\frac{v_F}{nV_T}} - 1\right)$$

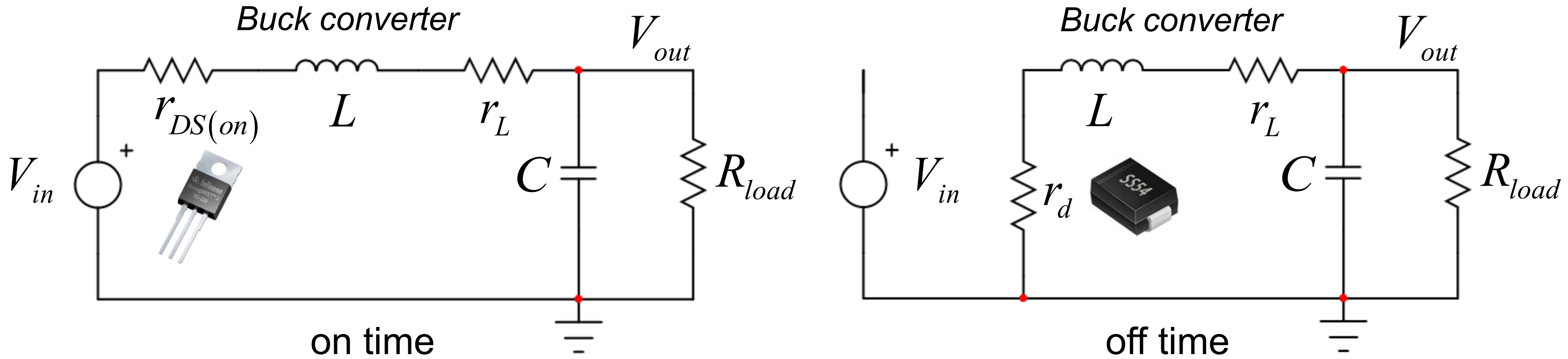
$$\hat{i}_F \approx I_F \frac{\hat{v}_F}{nV_T}$$

$$r_d \approx \frac{nV_T}{I_F}$$

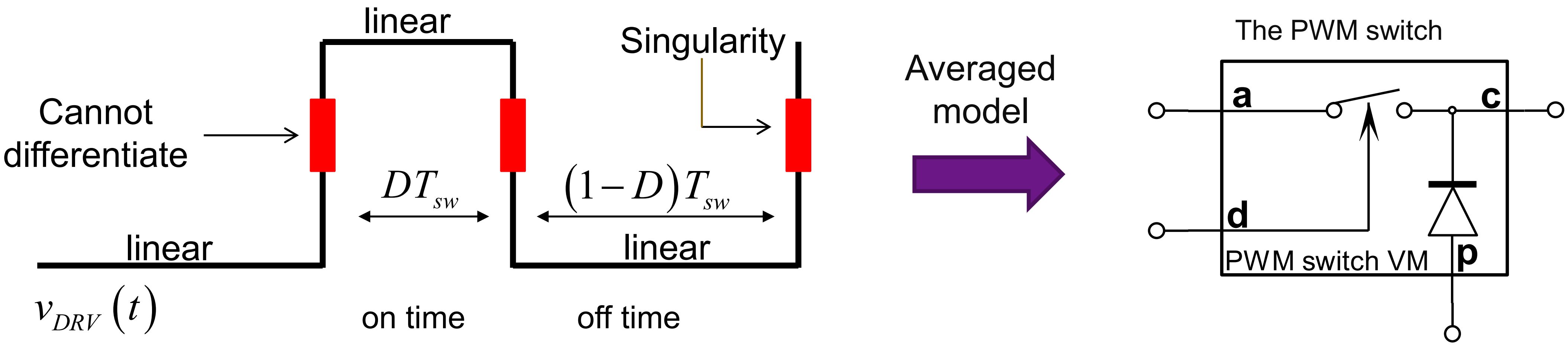
Resistance

A Switching Cell is a Nonlinear System

- A switching converter is exhibiting linear characteristics during t_{on} and t_{off}



- The toggling event between the two networks introduces a discontinuity



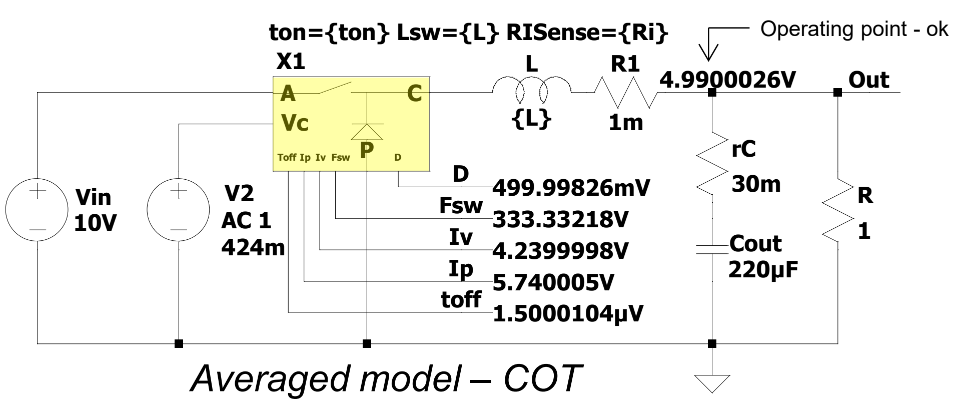
Averaged and Switched Models

- An *averaged model* is used for plotting a transfer function in an ac analysis

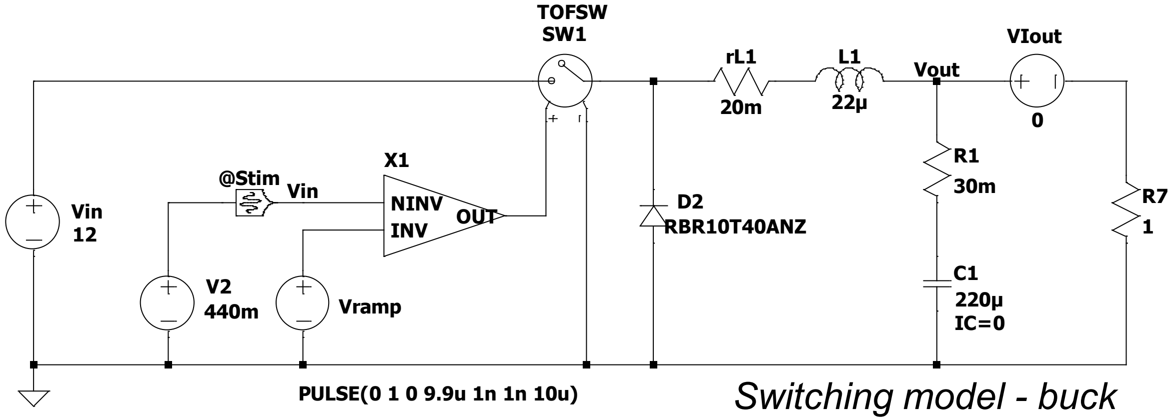
✓ There is no switching component – it simulates extremely fast

✓ You use it for extracting the control-to-output transfer function of a switching cell

✓ It can also work in transient simulations and lets you test compensation strategies



Averaged model – COT



Switching model - buck

- A *switched model* describes your converter as if you would breadboard it

✓ It is a cycle-by-cycle circuit and takes time to deliver results depending on the models

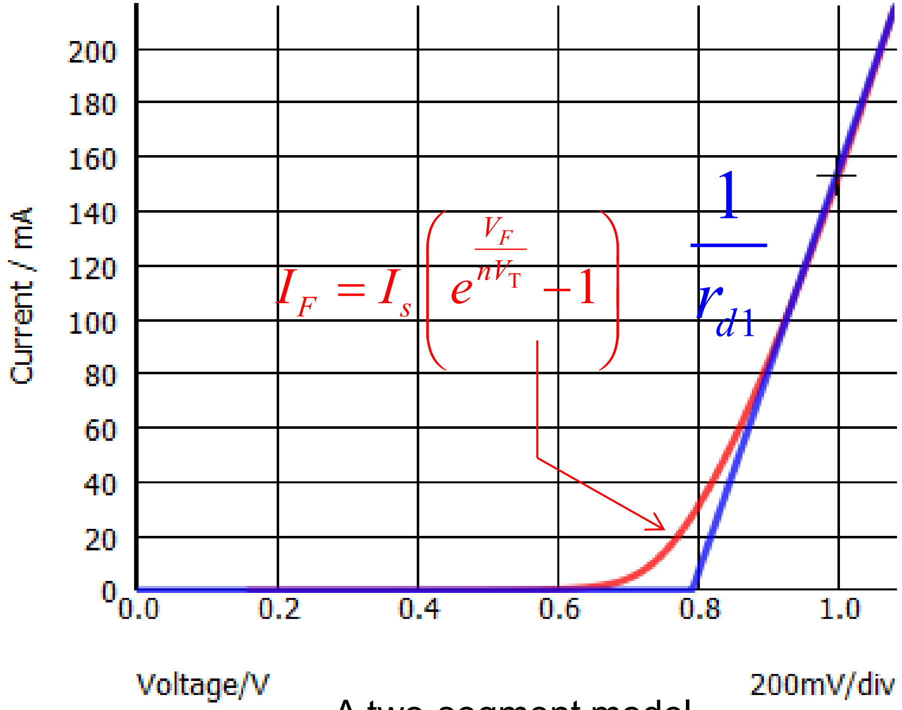
✓ You can include 2nd or 3rd-order effects – like leakage terms – and see their effects

✓ You cannot *easily* extract the ac response of a switching cell with a SPICE simulator

SIMPLIS – A Piece-Wise Linear Engine

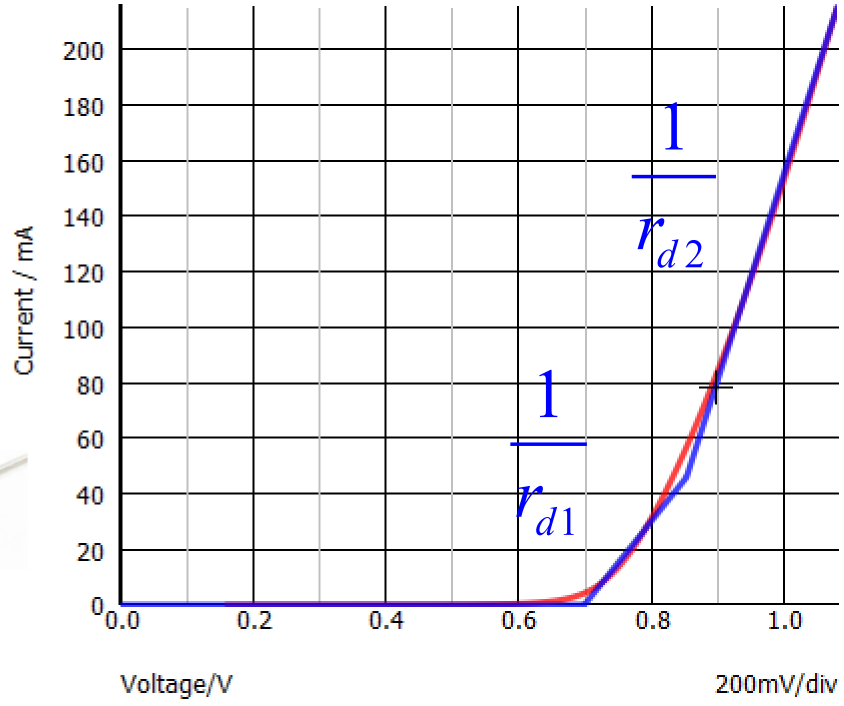
- SIMPLIS uses a PWL approach where a component is modeled through segments
  - Any change in operating point is modeled as a transition to another segment
  - ✓ At any instant in simulation time, the system is always linear!

Diode example



A two-segment model

More segments

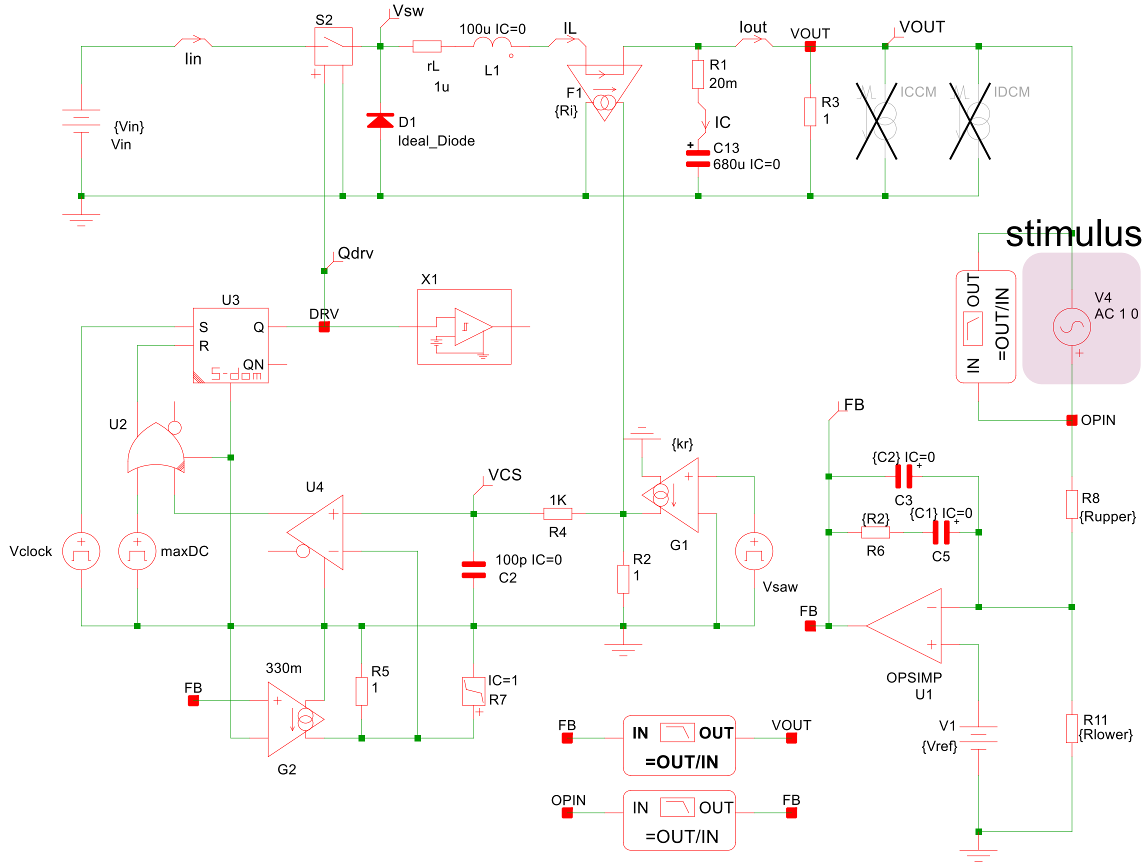


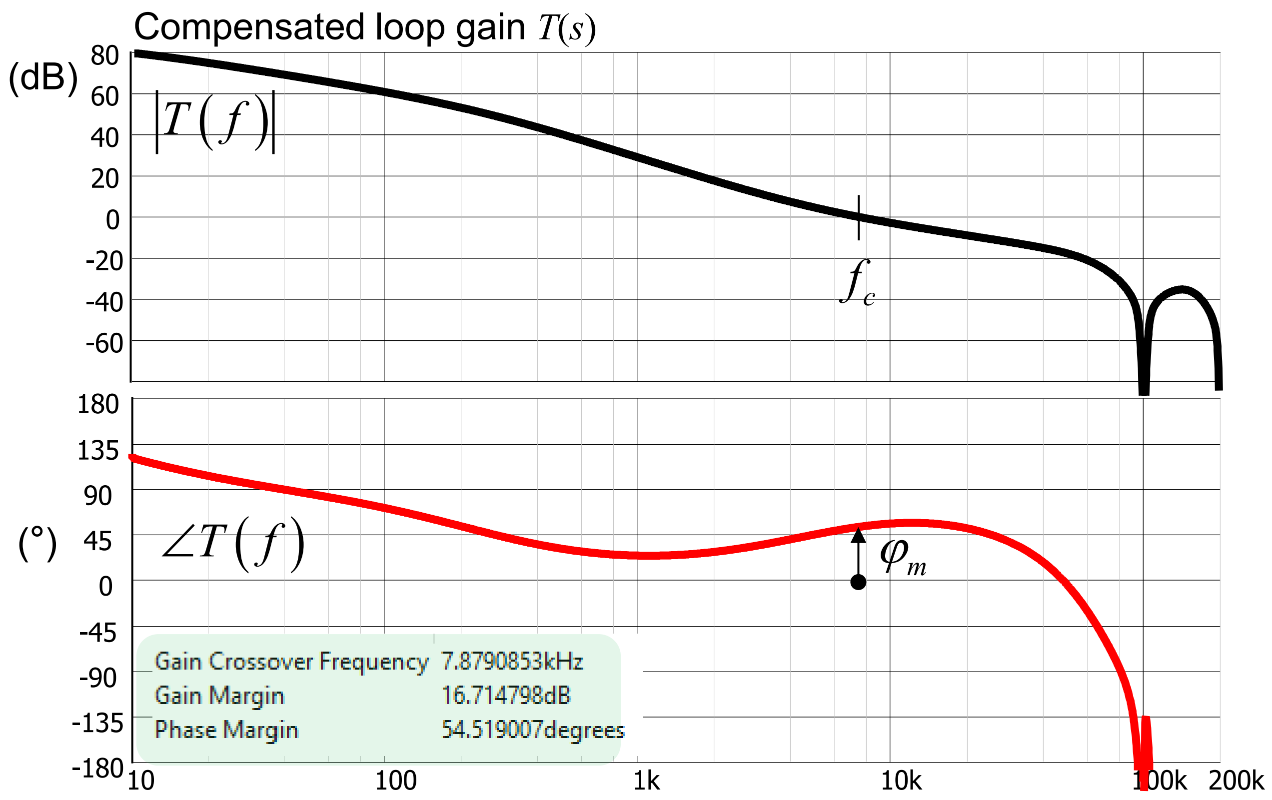
A three-segment model

AC Response from a Switching Circuit

- You can assemble your circuit to model your prototype and check the operating point
- From this simulation template, you can extract the ac response for closing the loop

✓ No need to involve an intermediate step with an averaged model





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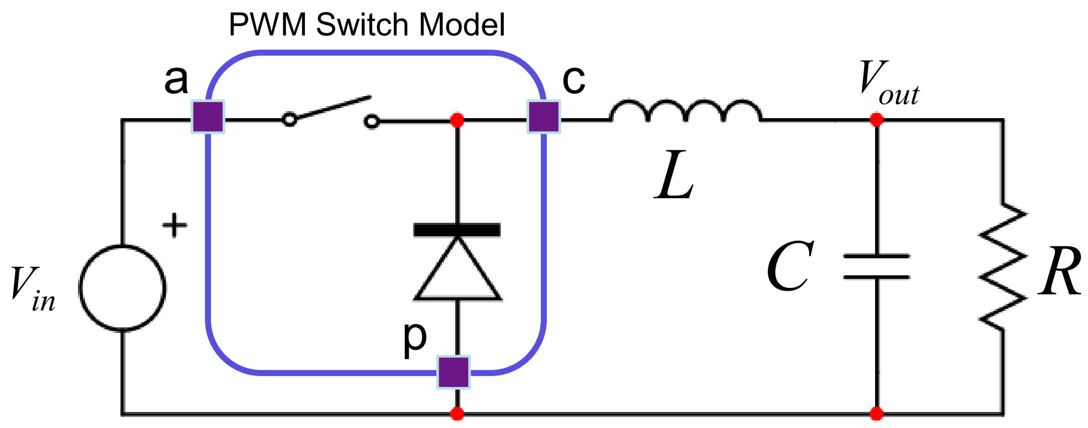
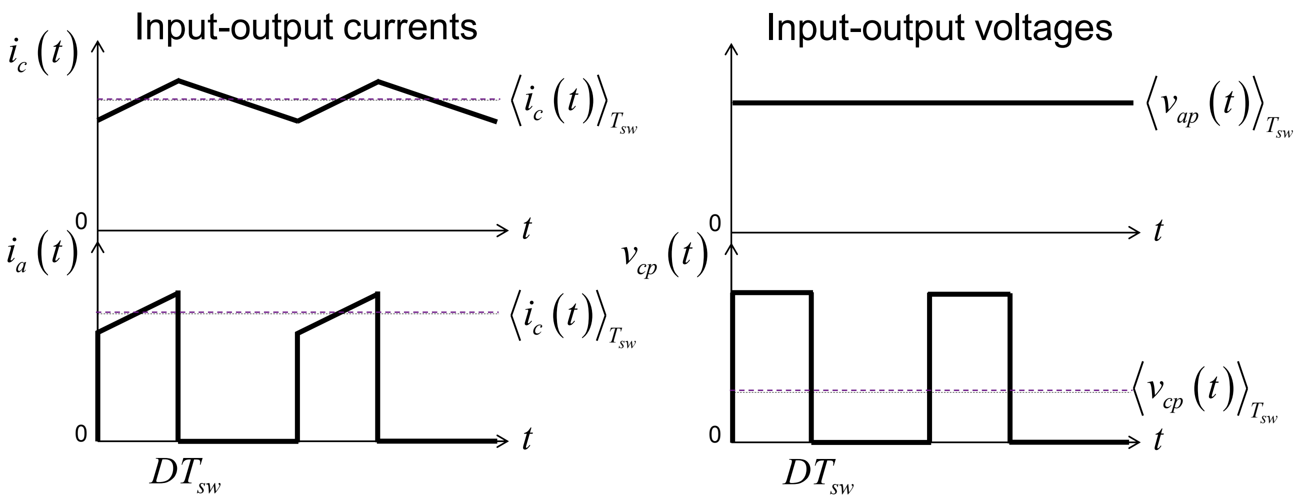
The PWM Switch Model in Voltage Mode

- We have seen that the discontinuity was brought by the switching cell
- ✓ Linearize the switching cell and leave the other elements untouched

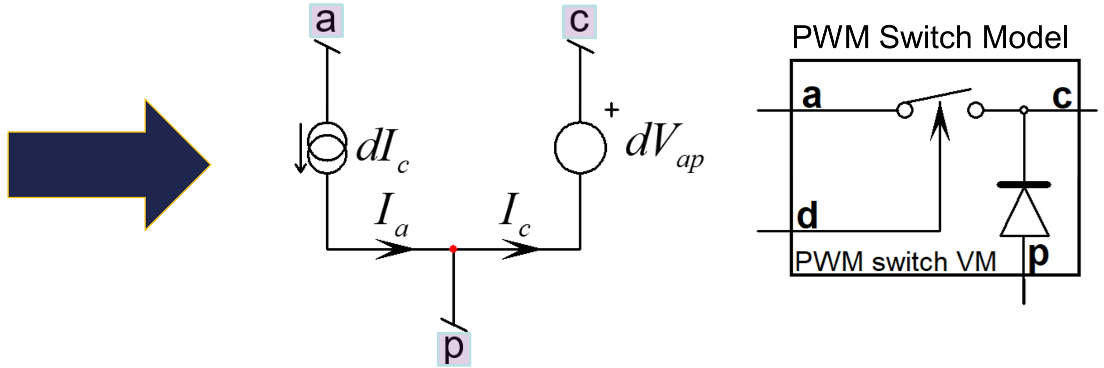




Time-continuous nonlinear expressions

$$\langle i_a(t)\rangle_{T_{sw}} = I_a = \frac{1}{T_{sw}}\int_0^{dT_{sw}} i_a(t)\,dt = D\langle i_c(t)\rangle_{T_{sw}} = DI_c$$

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

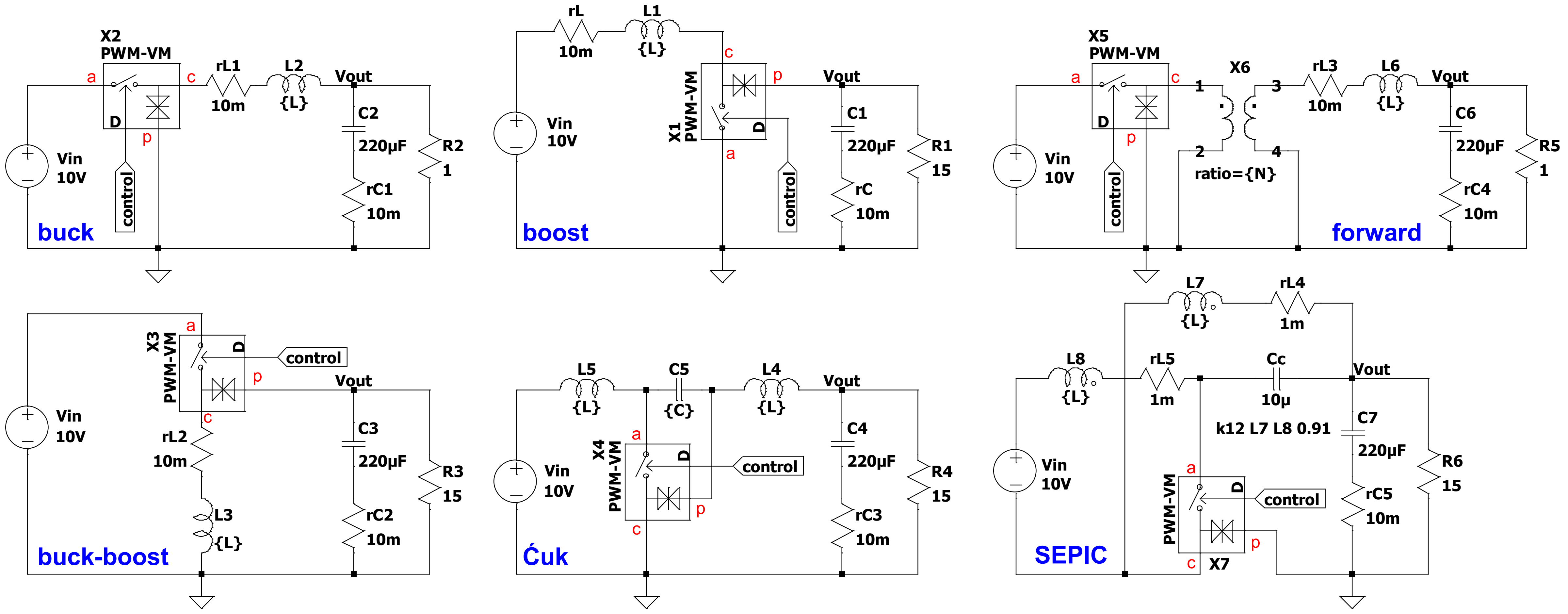


V. Vorpérian, *Simplified Analysis of PWM Converters using Model of PWM Switch, parts I and II*, IEEE Transactions on Aerospace and Electronic Systems, Vol. 26, NO. 3, 1990

A Model that fits many switching Cells

- Invariant equations are valid for most known switching converters

✓ Rotate the PWM switch model and have its terminals properly connected



Modeling a Buck Converter in VM Control

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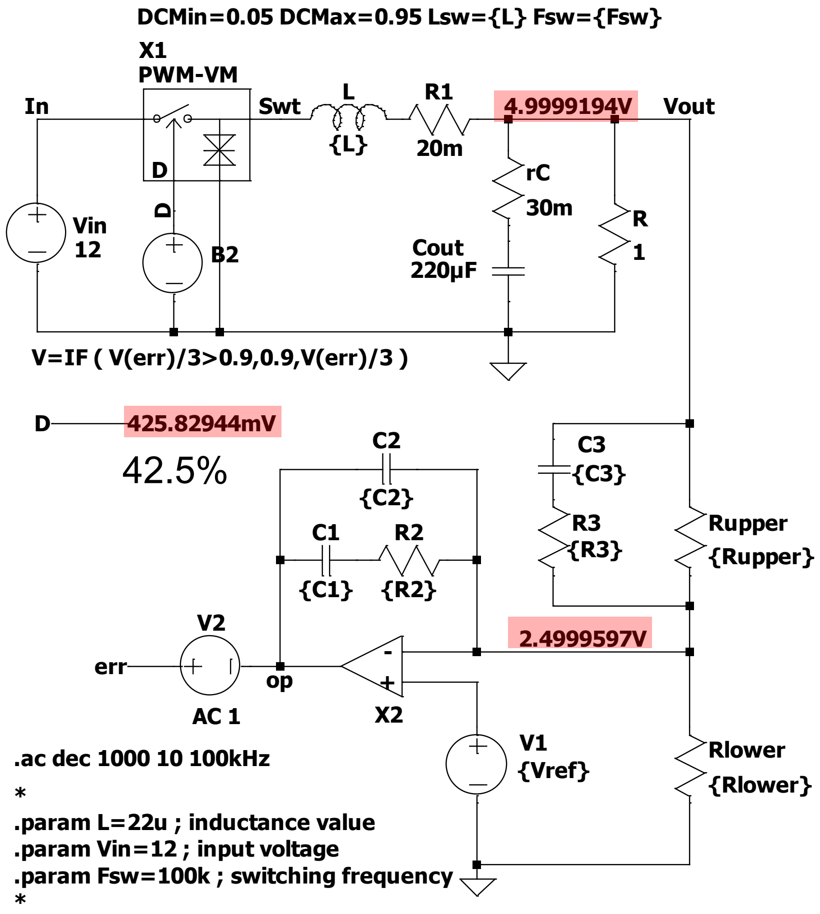
- Select the VM PWM switch model from the LTspice library and assemble the converter

✓ Check operating points are correct after the simulation has run



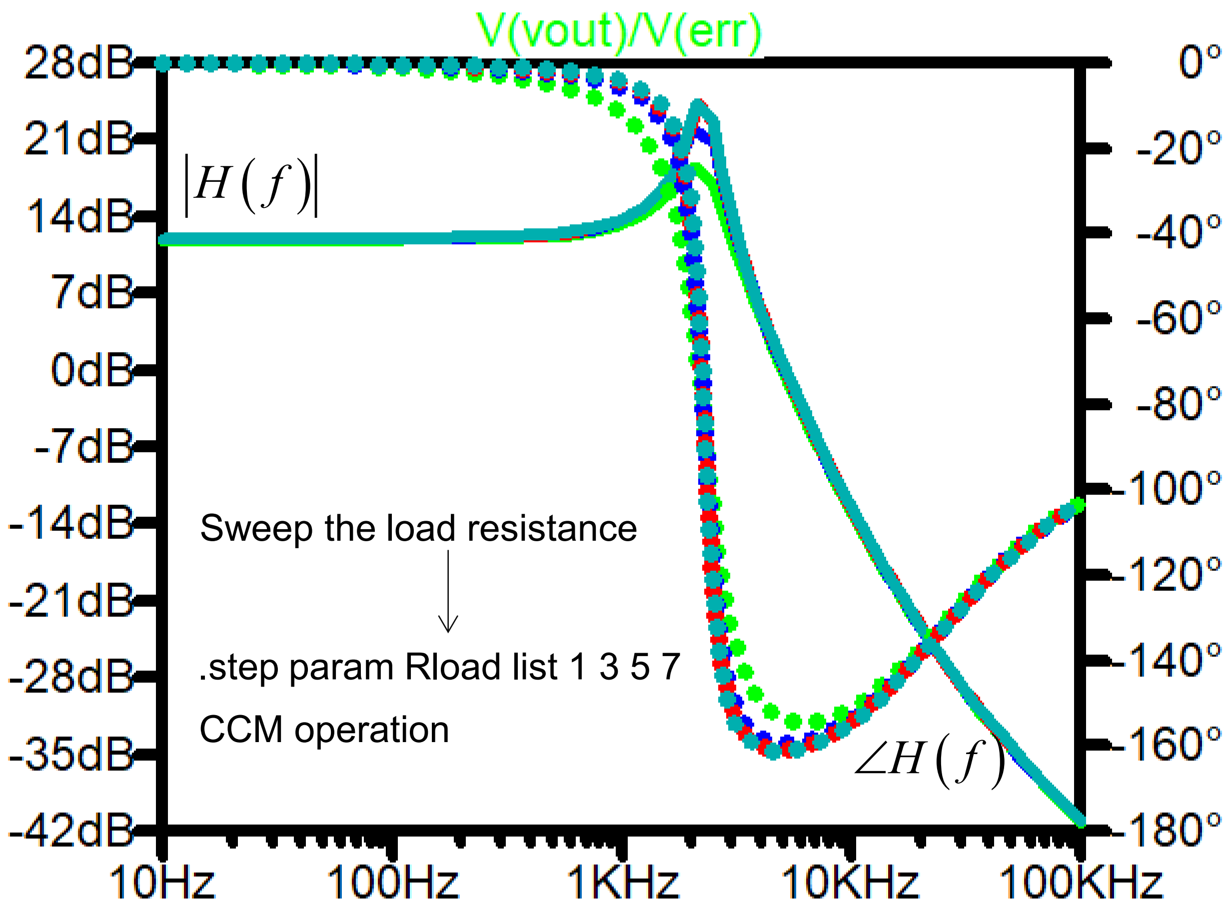

```
* Read from the power stage Bode plot
.param Gfc=-12 ; magnitude at crossover *
.param PS=-150 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fc=10k ; targeted crossover *
.param PM=70 ; choose phase margin at crossover *
*
* Capture the double zero position and
* one of the pole position
*
.param fz1=2k
.param fz2=2k
.param fp2=50k ; this pole is usually placed at Fsw/2
*
* Enter the Values for Vout and Bridge Bias Current *
*
.param Vout=5
.param Ibias=2m
.param Vref=2.5
*
```

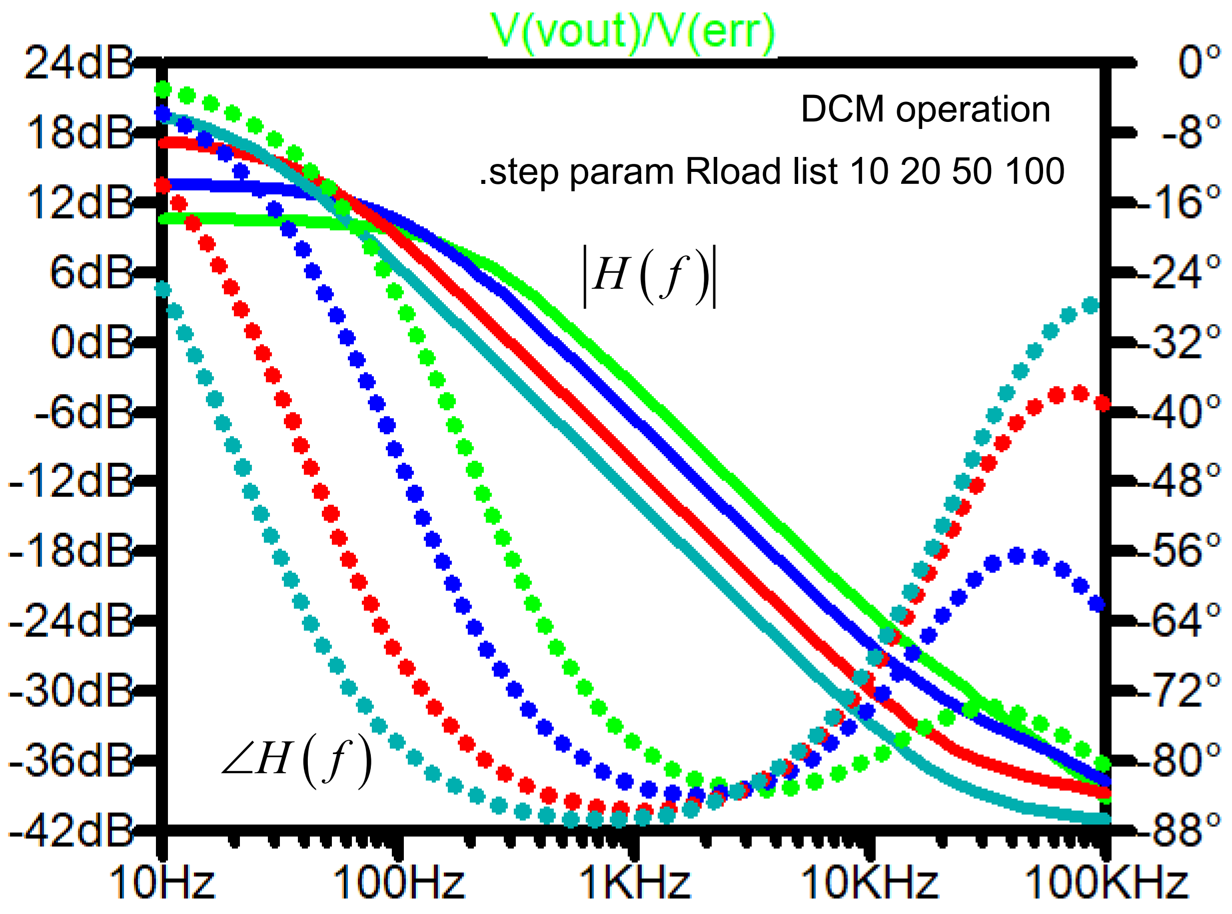
```
*
.param Rlower={Vref/Ibias}
.param Rupper={(Vout-Vref)/Ibias}
.param boost={PM-PS-90}
.param G={10**(-Gfc/20)}
.param fp1={fc/tan(atan(fc/fz1)+
+atan(fc/fz2)-atan(fc/fp2)-boost*pi/180)}
.param a={sqrt((fc**2/fp1**2)+1)}
.param b={sqrt((fc**2/fp2**2)+1)}
.param c={sqrt((fz1**2/fc**2)+1)}
.param d={sqrt((fc**2/fz2**2)+1)}
.param R2={((a*b/(c*d))/(fp1-fz1))*Rupper*G*fp1}
.param C1={1/(2*pi*fz1*R2)}
.param C2={C1/(C1*R2*2*pi*fp1-1)}
.param C3={(fp2-fz2)/(2*pi*Rupper*fp2*fz2)}
.param R3={Rupper*fz2/(fp2-fz2)}
.param G0={((R2*C1)/(Rupper*(C1+C2)))*c*d/(a*b)}
*
```

- The macro automates the compensation
- All components are calculated based on f_c and φ_m

Control-to-Output Transfer Function in VM

- The model automatically detects the operating mode and switches from CCM or DCM
- ✓ You don't need to determine the critical resistance to choose a DCM or CCM model

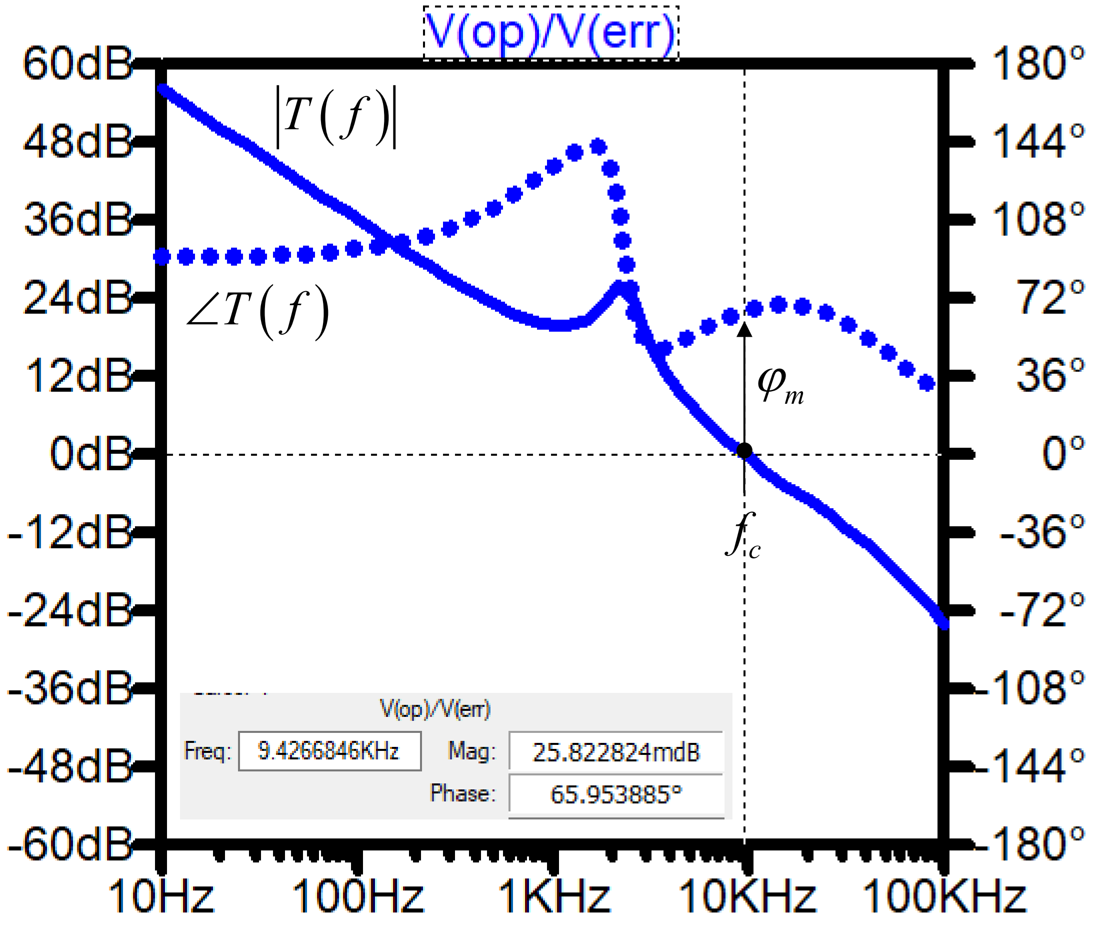


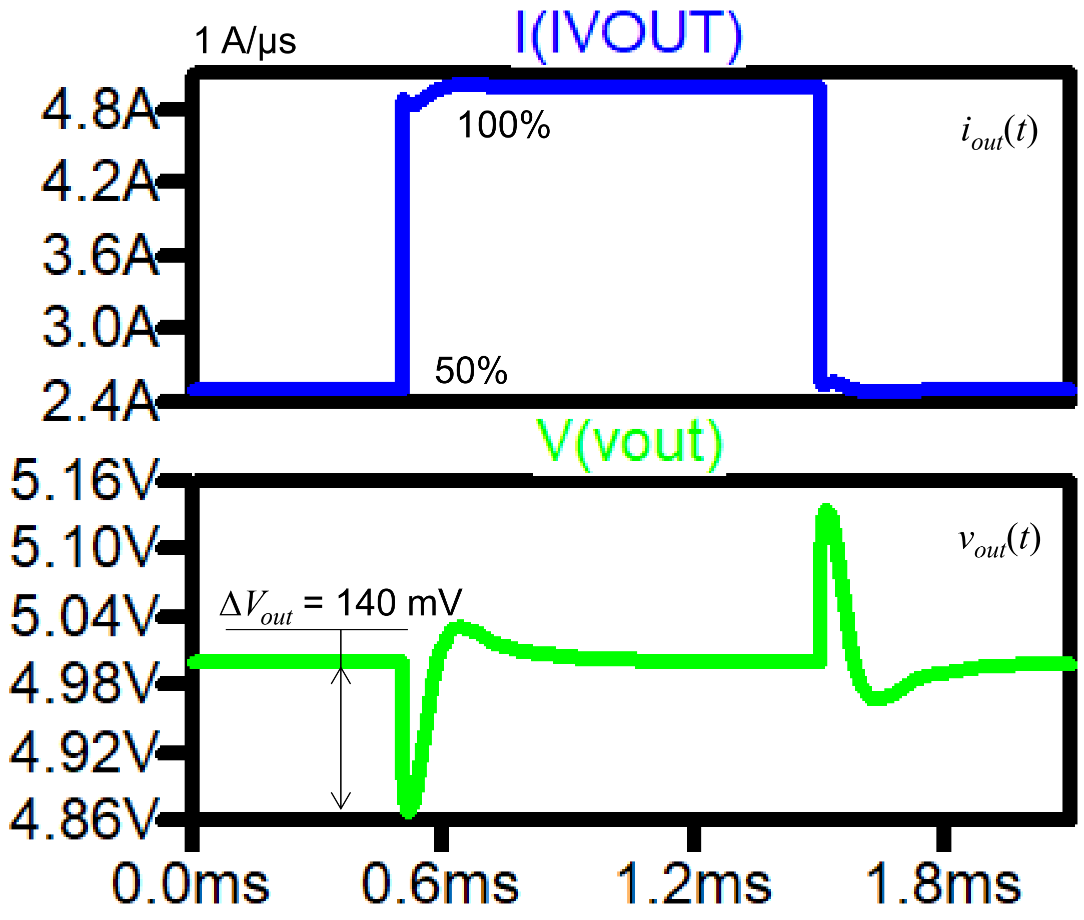


Transient Response of the Converter

- The compensated model lets you immediately check crossover and phase margin

✓ Owing to nonlinear equations, you can also test the corresponding transient response

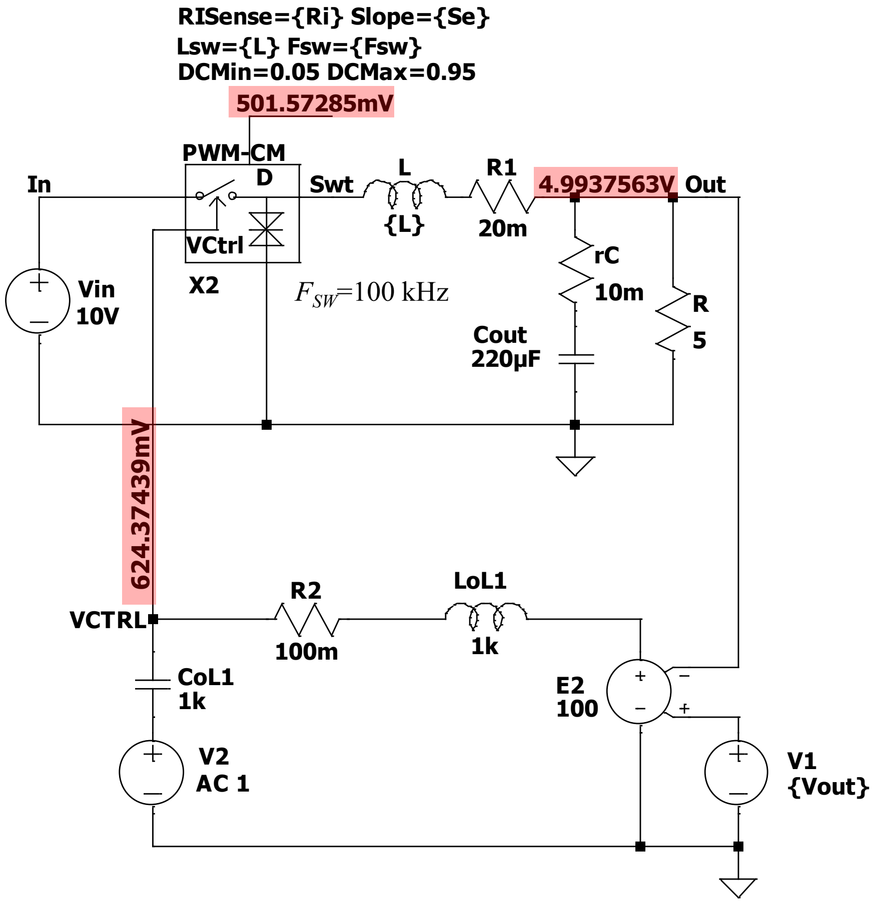


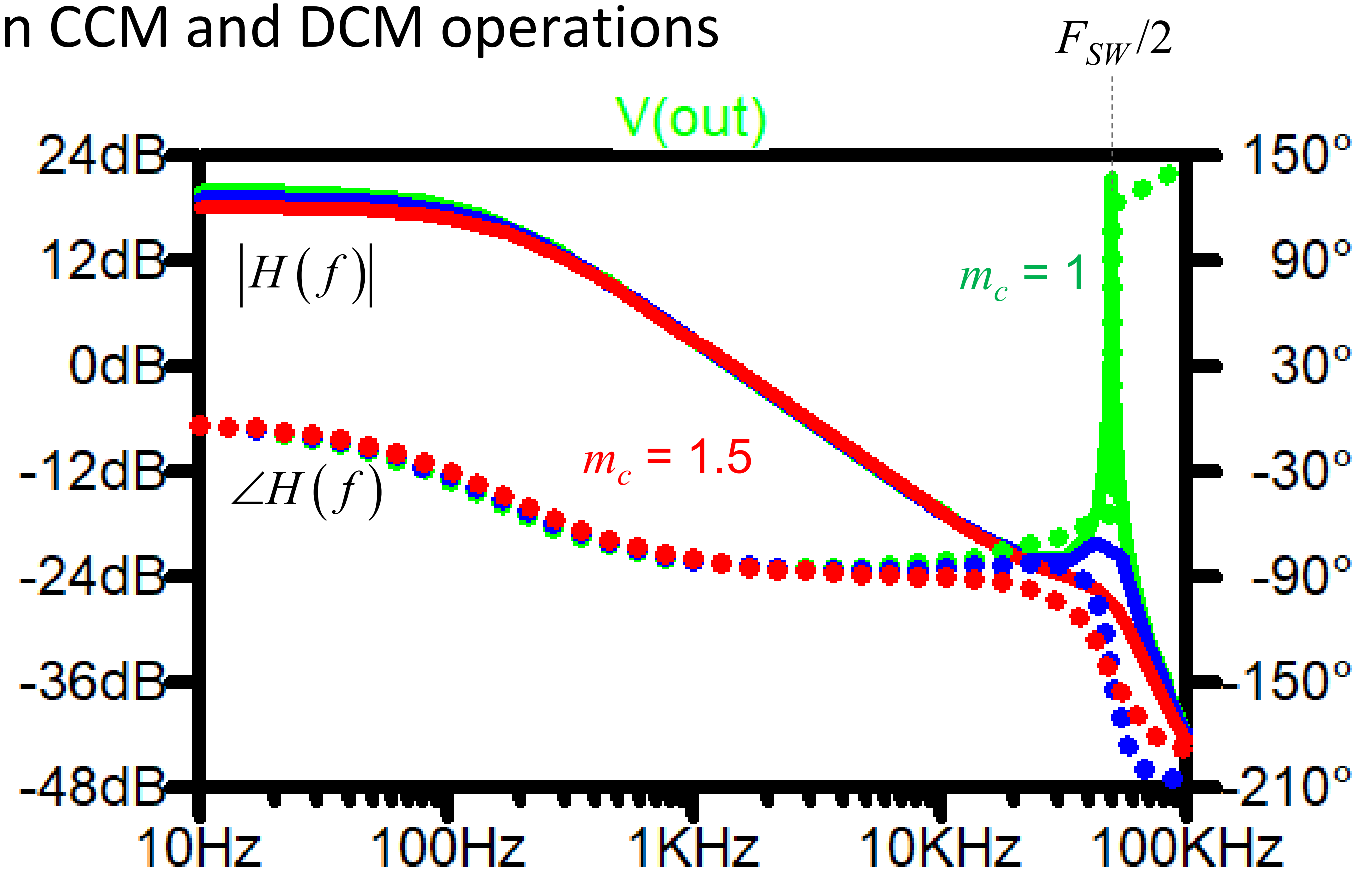


Modeling a Buck Converter in CM Control

- A current-model also exists – PWM CM – and it predicts subharmonic oscillations

✓ It is also capable to toggle between CCM and DCM operations





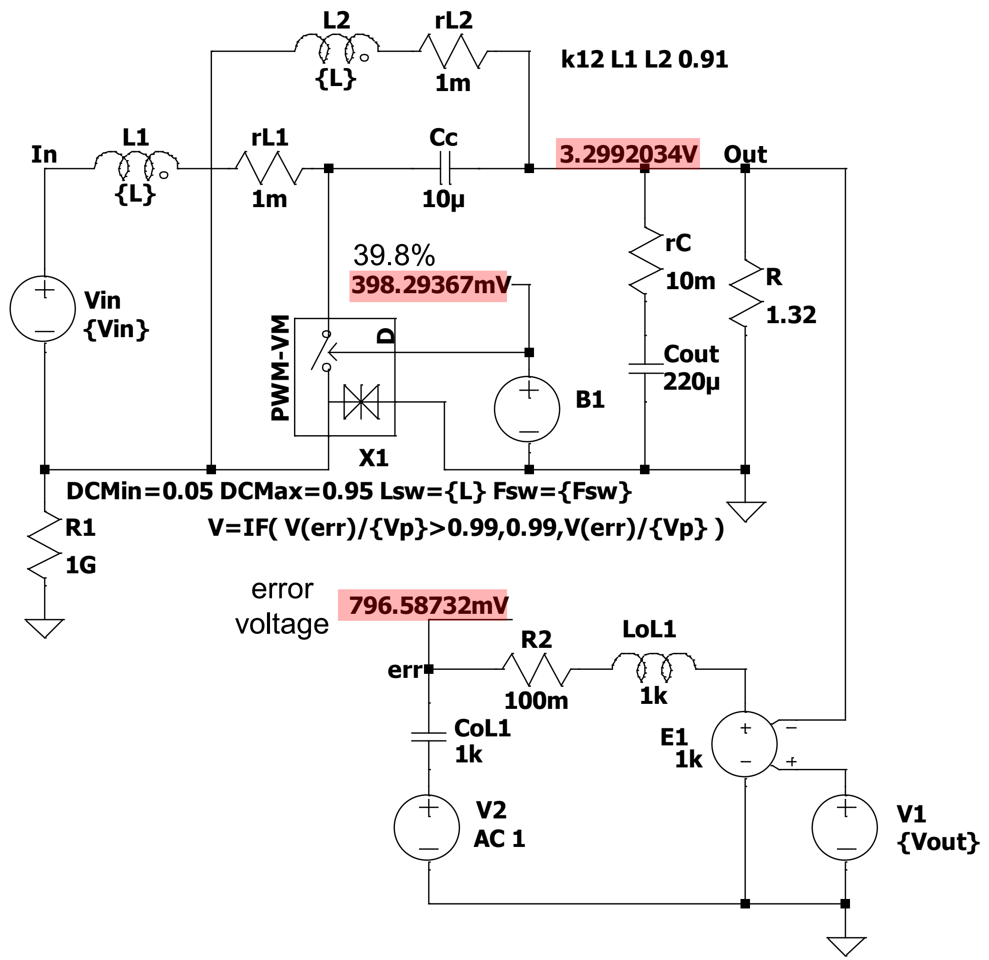
- Slope compensation is swept for m_c = 1, 1.2, 1.5
- $m_c = 1 + S_e / S_n$

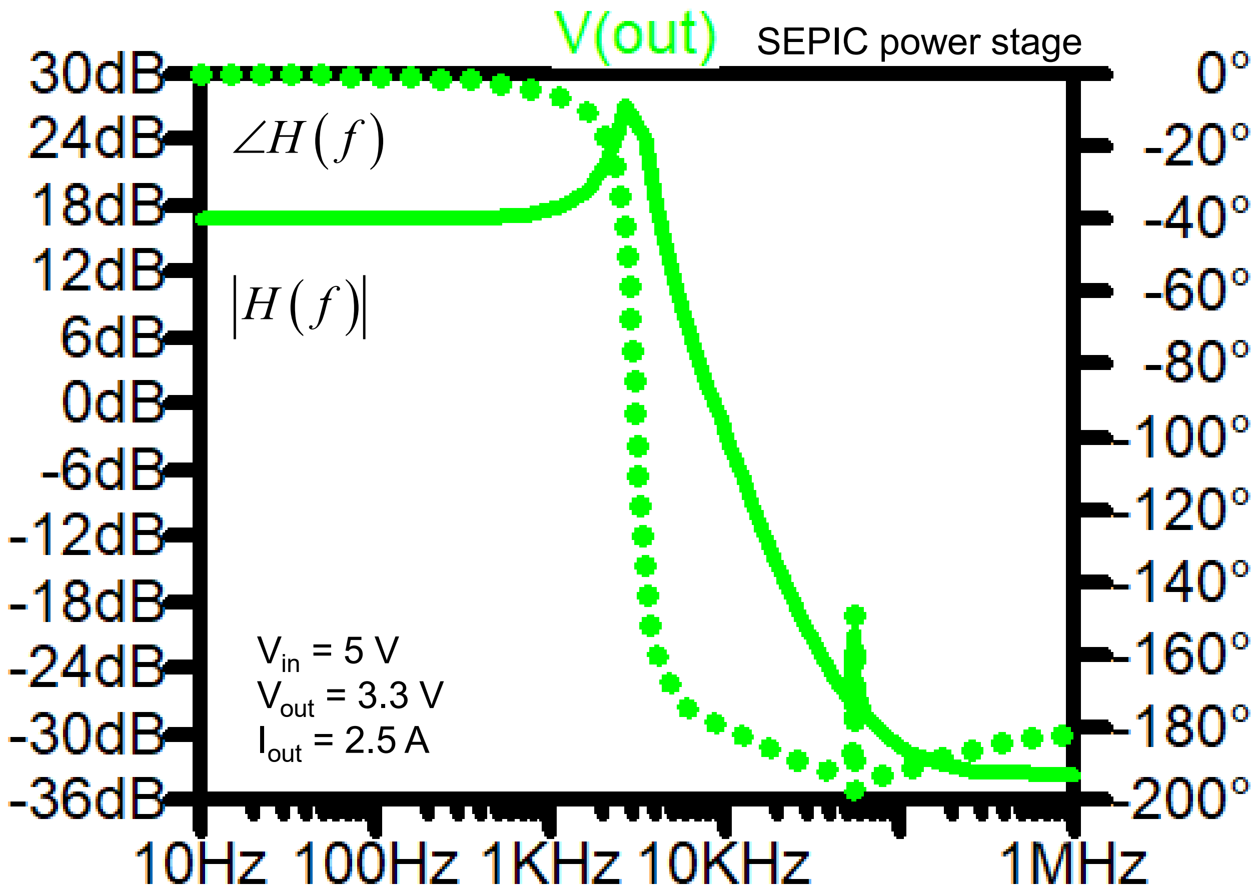
S_e is the external ramp, S_n is the inductor on-slope

The PWM Switch Model in a SEPIC

- By rotating the model and matching the port connections, a SEPIC can be studied

✓ This is a 4th-order converter with a complicated control-to-output transfer function

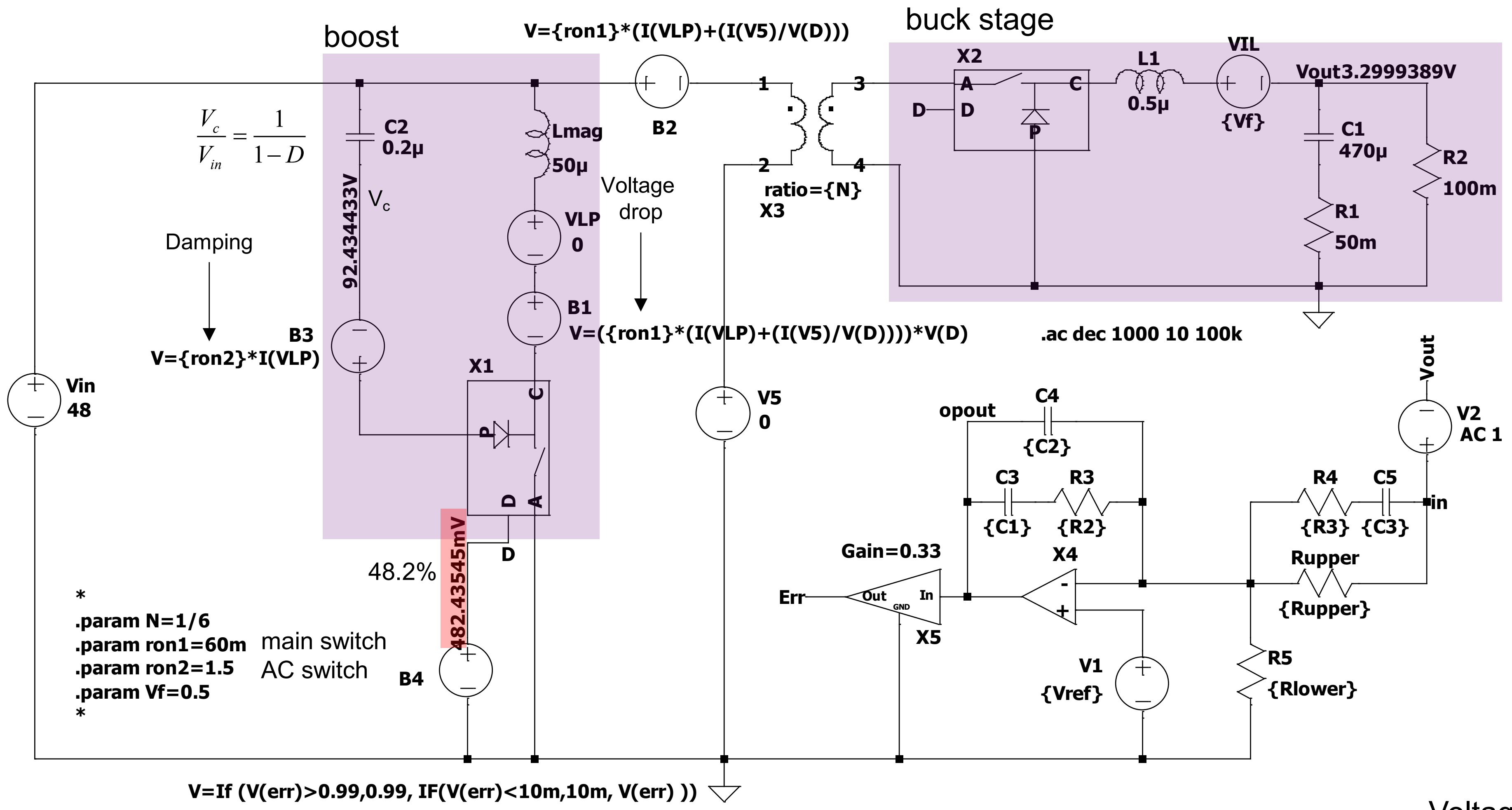




An Active-Clamp Forward Converter

- The AC forward lets you operate the converter with greater than 50% duty ratio

✓ Lends itself well to building large input voltage range dc-dc bricks, e.g. 36-75 V types



✓ You need two PWM switch models to unveil the resonant notch.

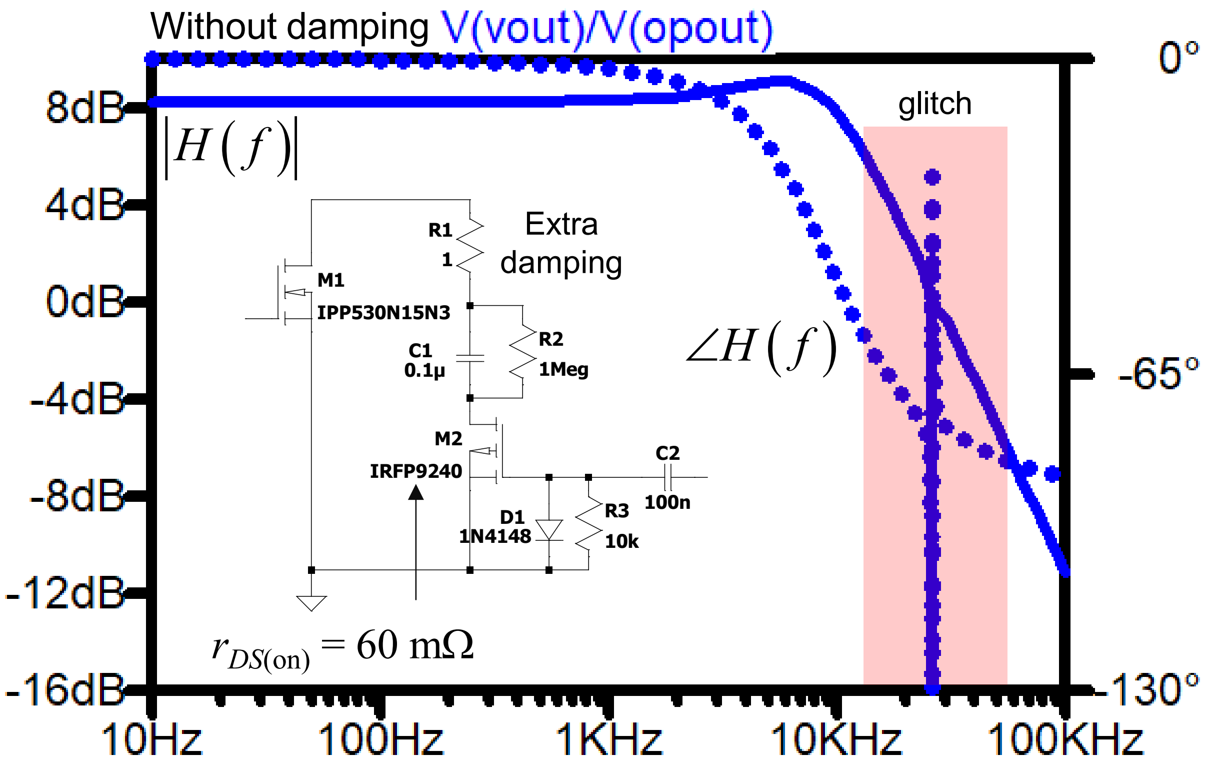
✓ Damping is provided by the P-channel $r_{DS(on)}$.

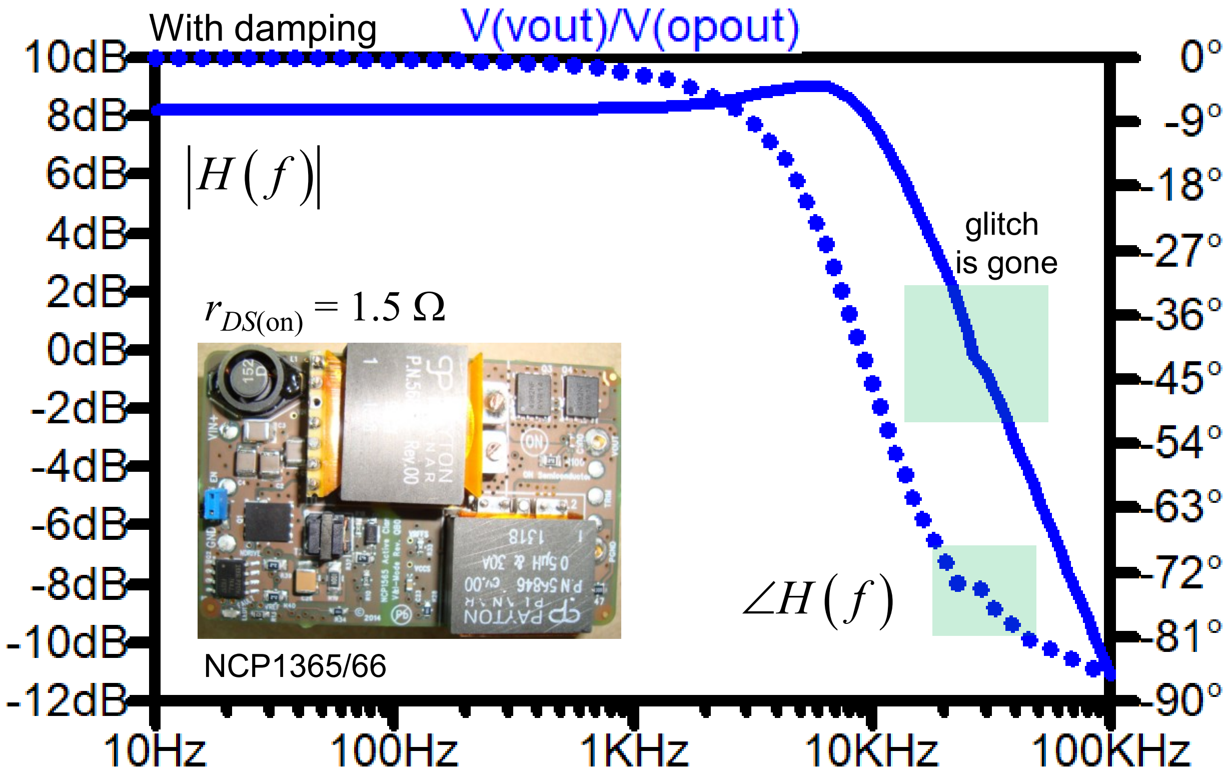
➢ You can push crossover frequency in voltage-mode control.

The Clamping Circuit Provides Damping

- The transistor $r_{DS(on)}$ in the active clamp circuit damps the notch

✓ You can extend crossover frequency beyond the notch and reduce output capacitance



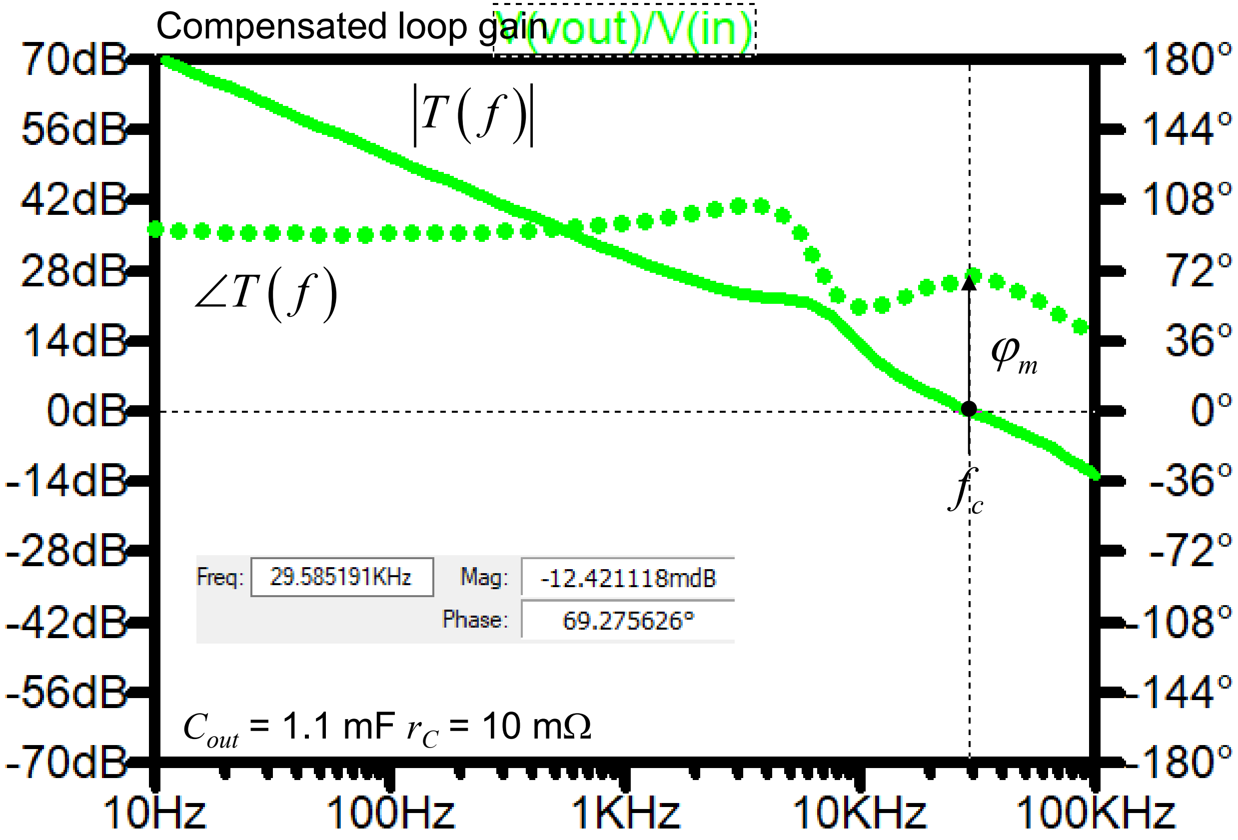


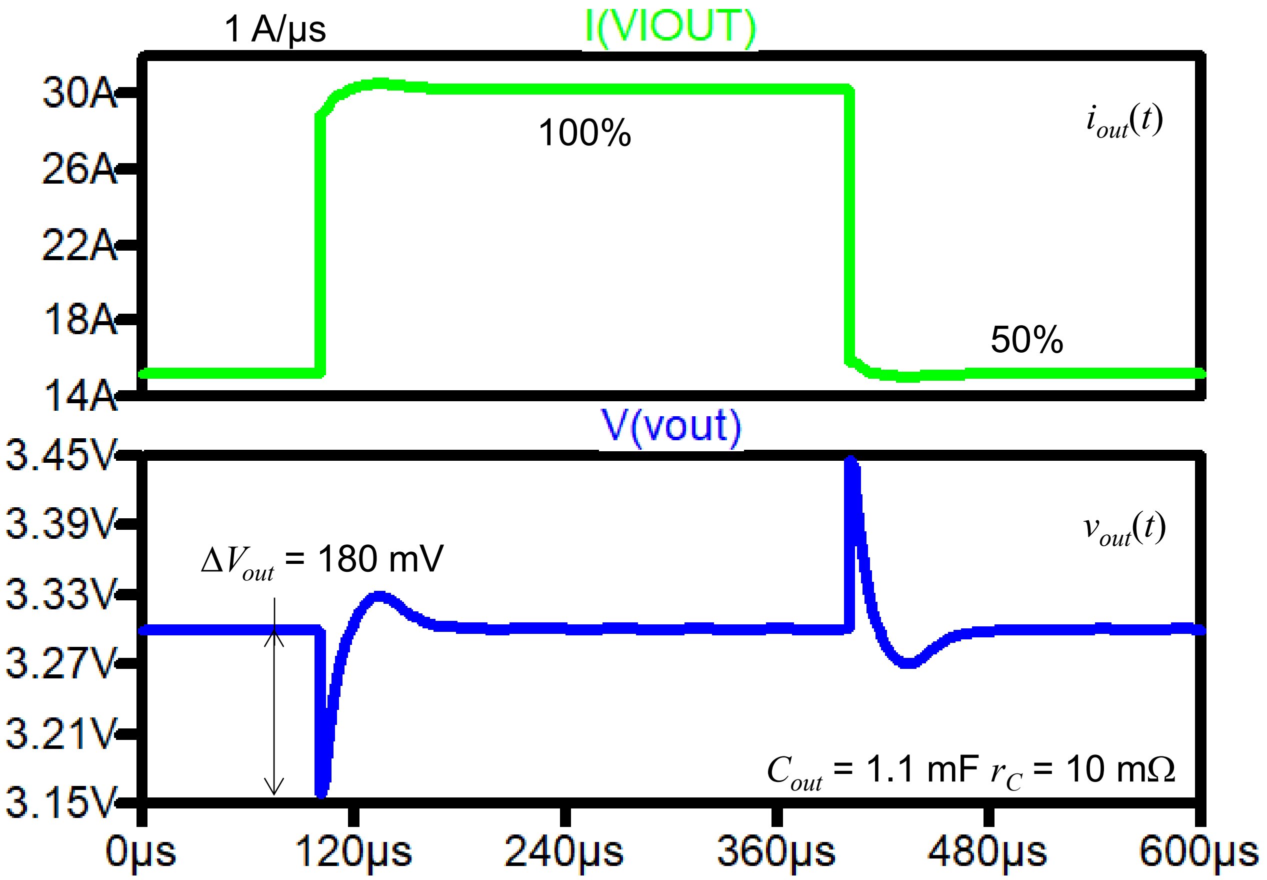
- Crossover frequencies can be as high at 30 kHz once the notch is damped

✓ The response becomes that of classical forward converter

Transient Response of the VM ACF

- The 30-kHz crossover frequency offers an excellent response to a 50-100% load step

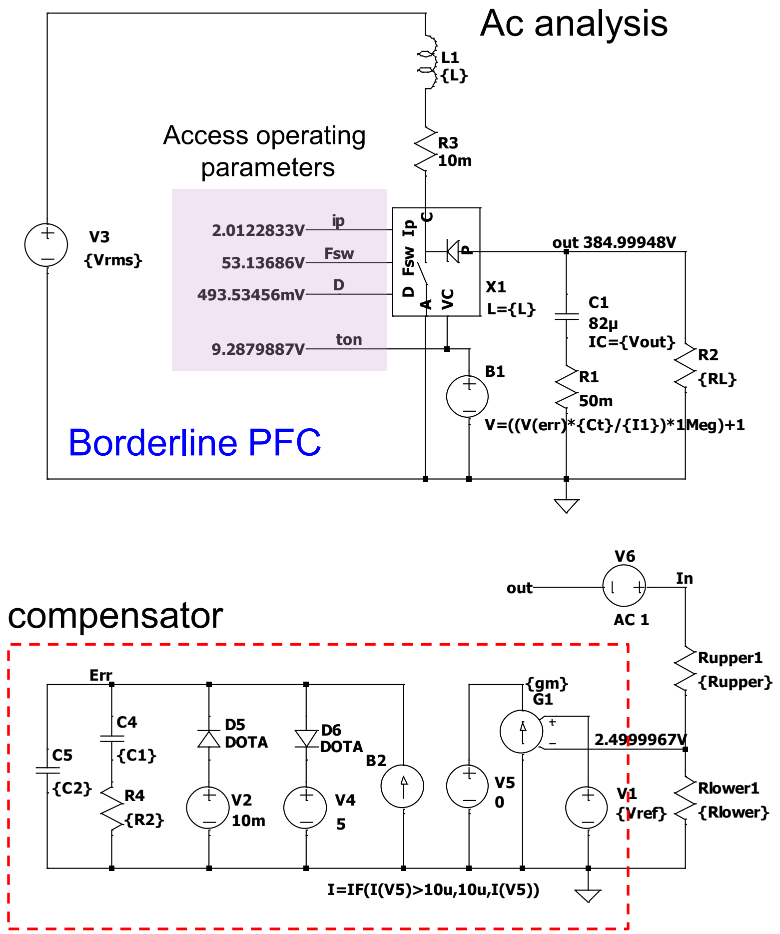


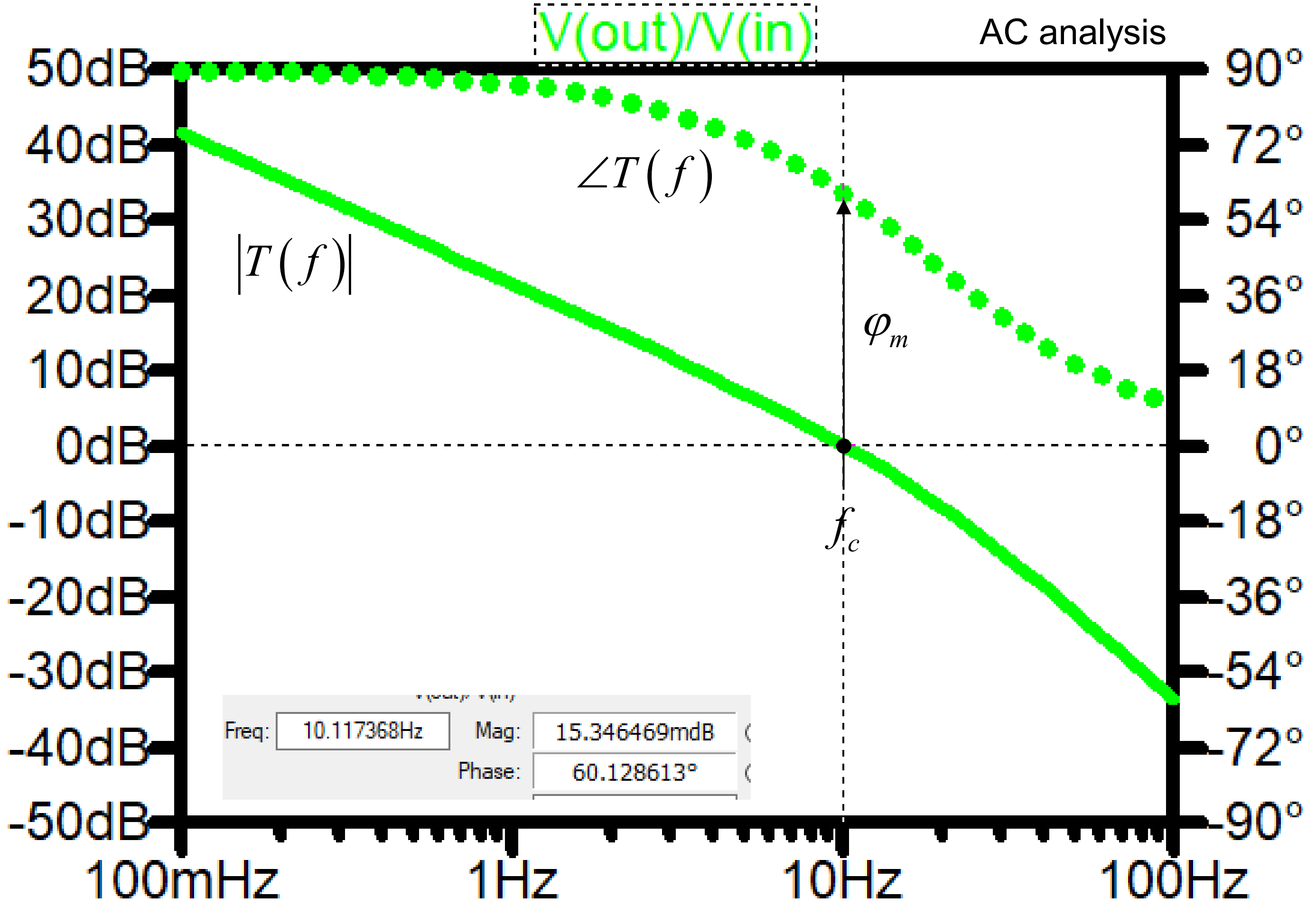


- The 70° phase margin will ensure a swift recovery with minimal overshoot
- The drops is mainly incurred to the 10-mΩ equivalent series resistance

Modeling Power Factor Correction in AC

- Averaged models lend themselves well to modeling and stabilizing PFCs
- You can extract the control-to-output transfer function and confirm operating points

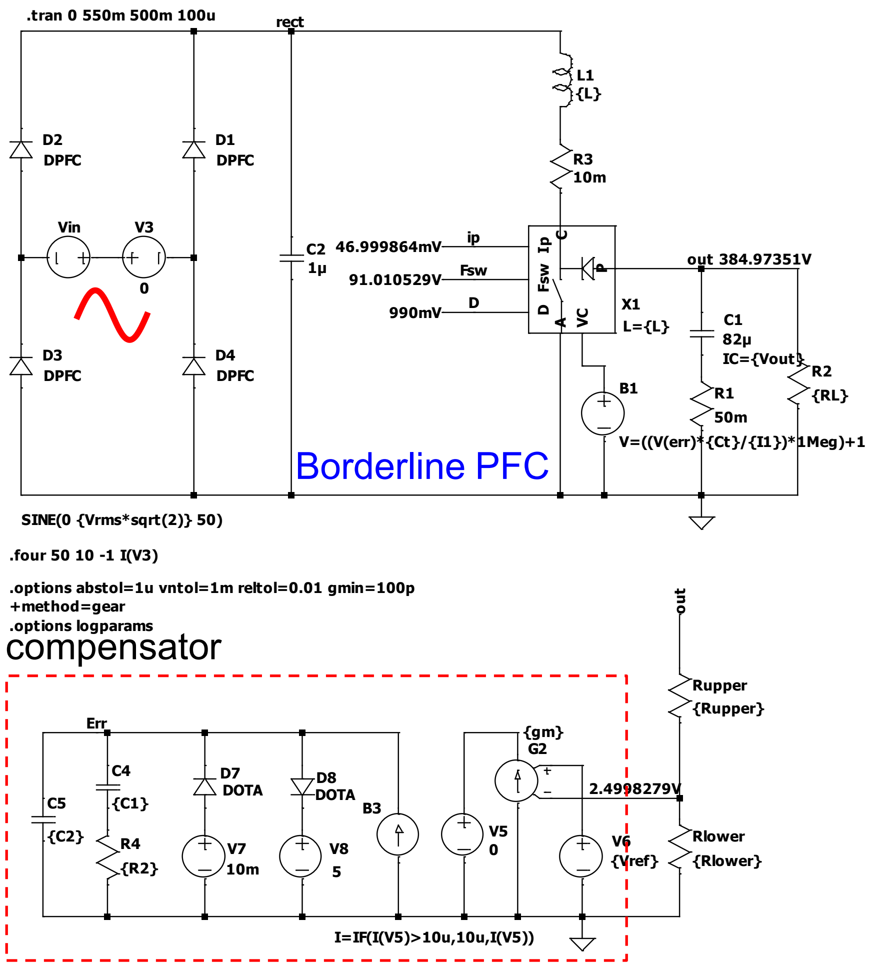


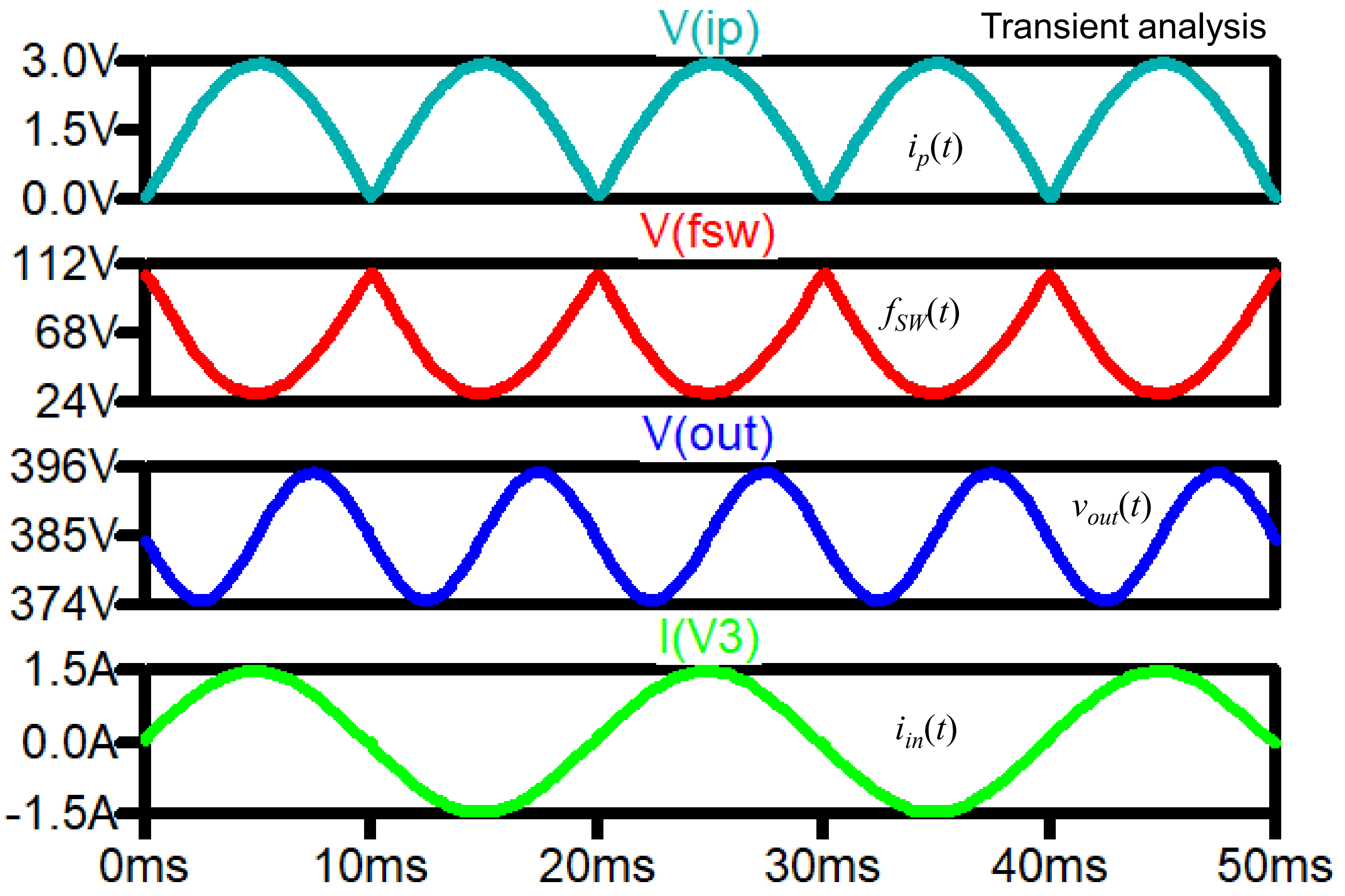


Power Factor Correction in Transient

- Bias the PFC with an ac source with a bridge rectifier and enjoy waveforms immediately

✓The lack of switching component makes simulation extremely fast

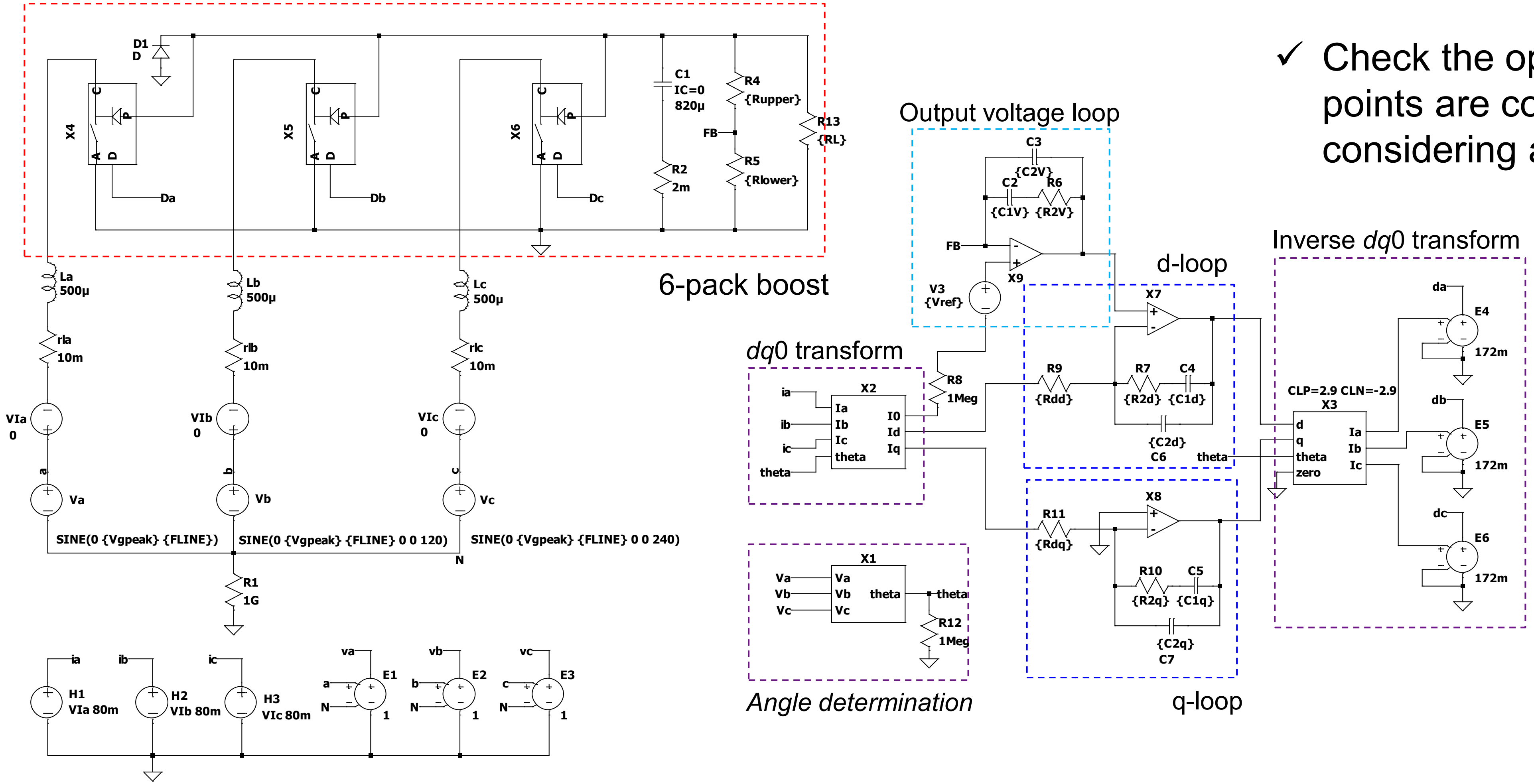




Modeling Three-Phase PFCs – AC Plots

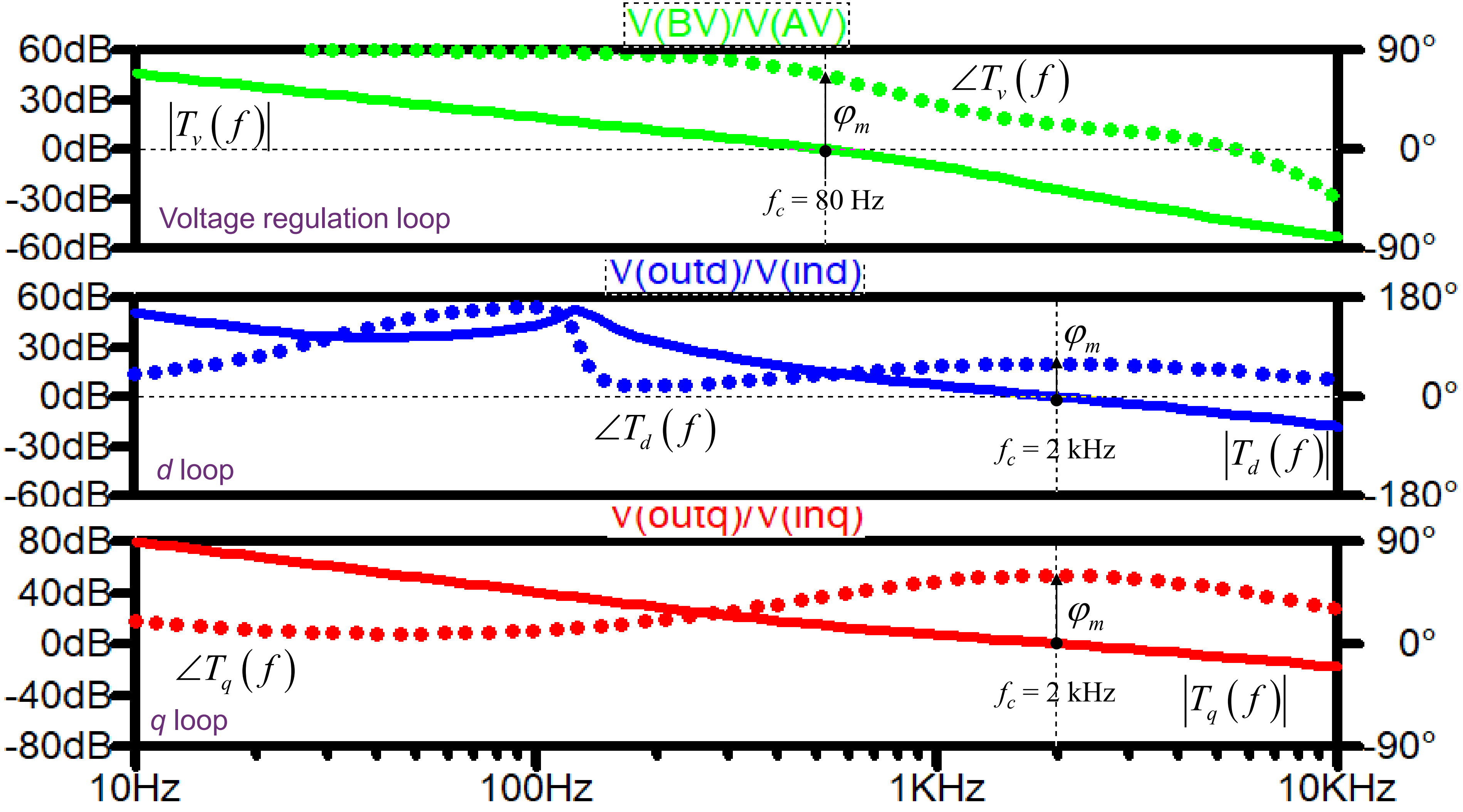
- Averaged models are very well suited to describe a 6-pack 3-phase PFC
- They can be used to extract the transfer functions in a *dq*0 type of control

✓ Check the operating points are correct before considering ac results!



Compensate the Three Loops Easily

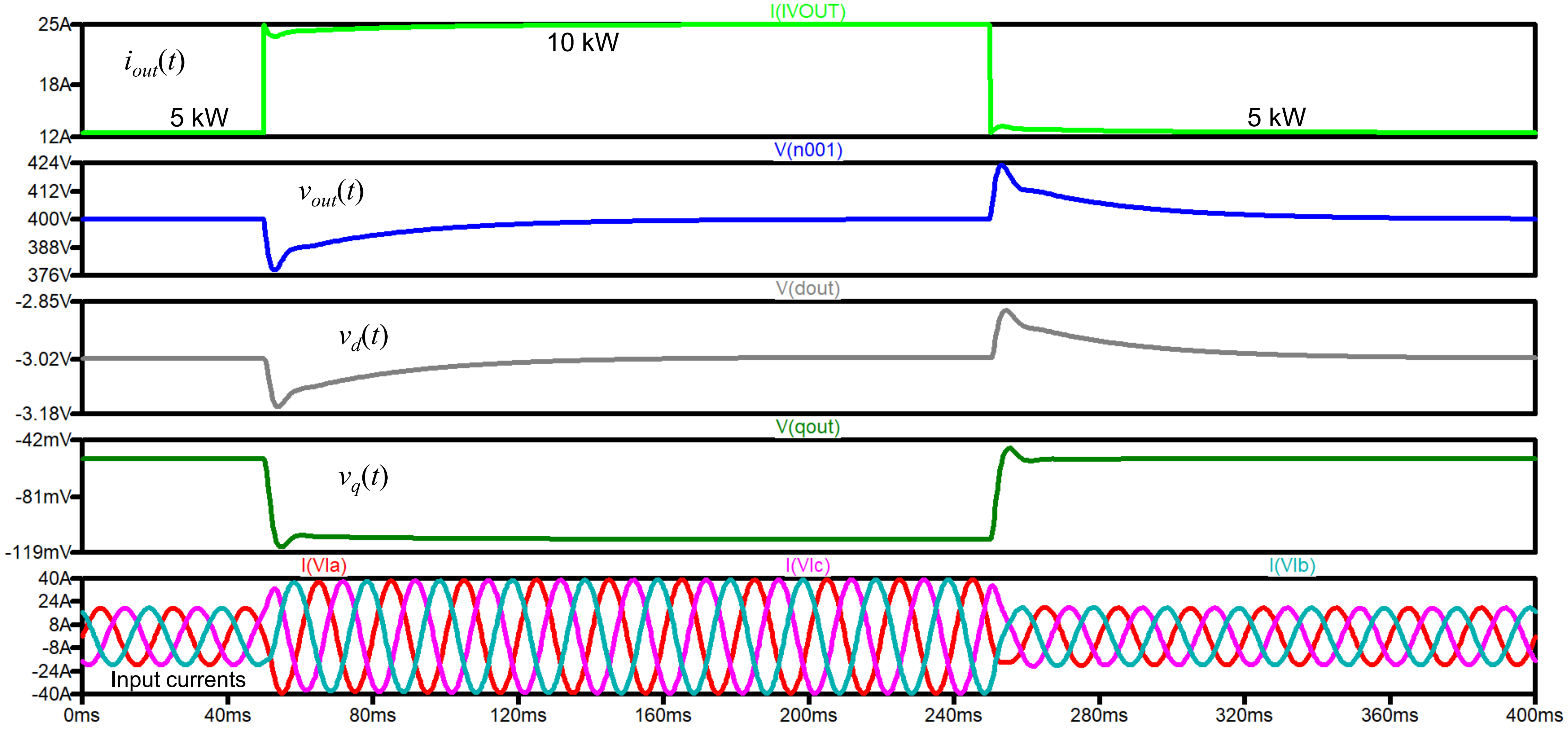
- The tree compensated ac responses are obtained in a few seconds of simulation time



- ✓ One loop is active for the ac sweep while the two other ones are silent.
- ✓ The voltage loop crossover can be as high as 100 Hz in a 3-phase PFC.
- ✓ The d and q loops are stabilized for a 2-kHz crossover frequency.

Sinusoidal Input Currents

- This is the power of averaged models, particularly for PFC studies: results in 5 s!



AC Model of a Vienna Rectifier

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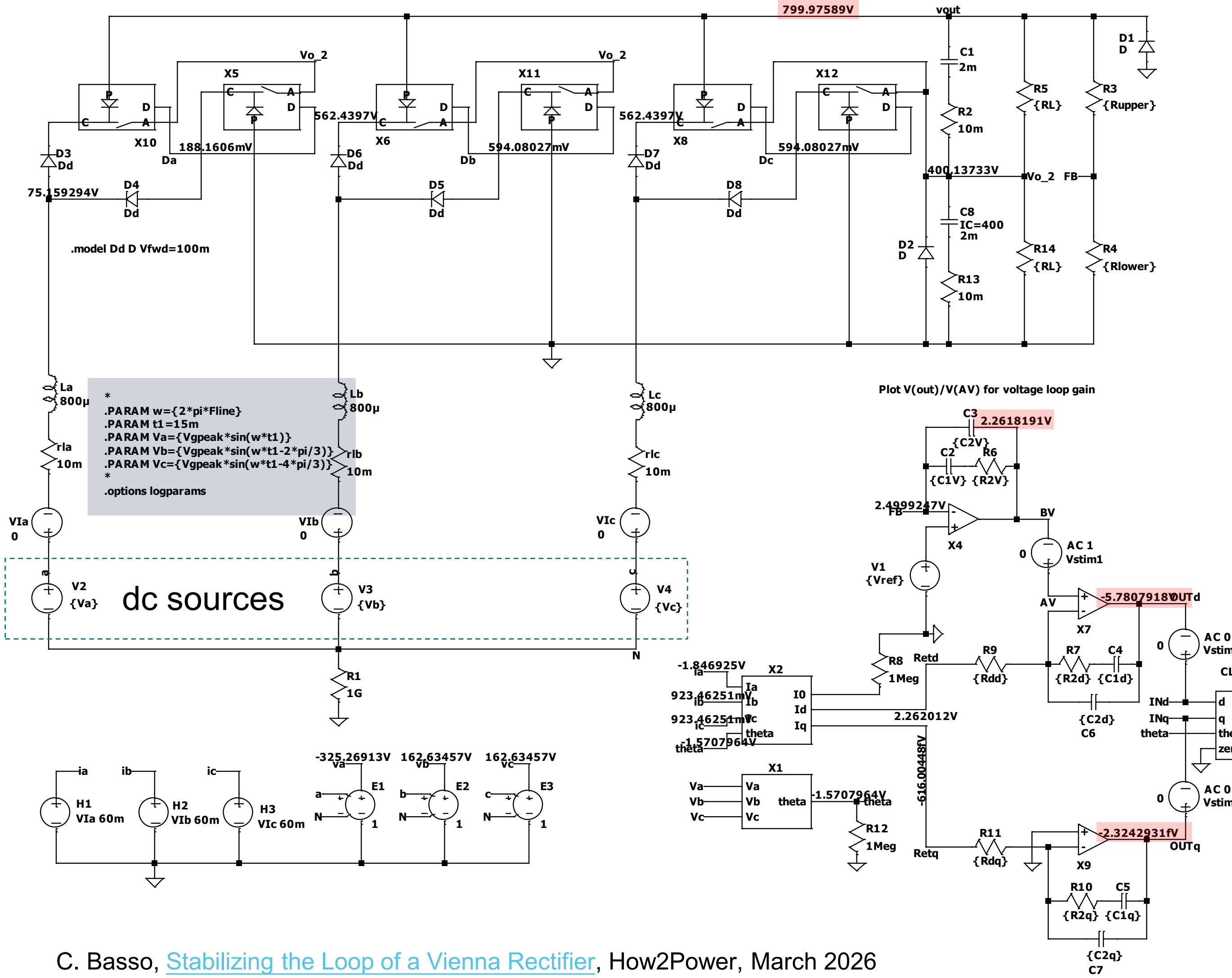
- It is possible to model a Vienna rectifier by resorting to six PWM switch models



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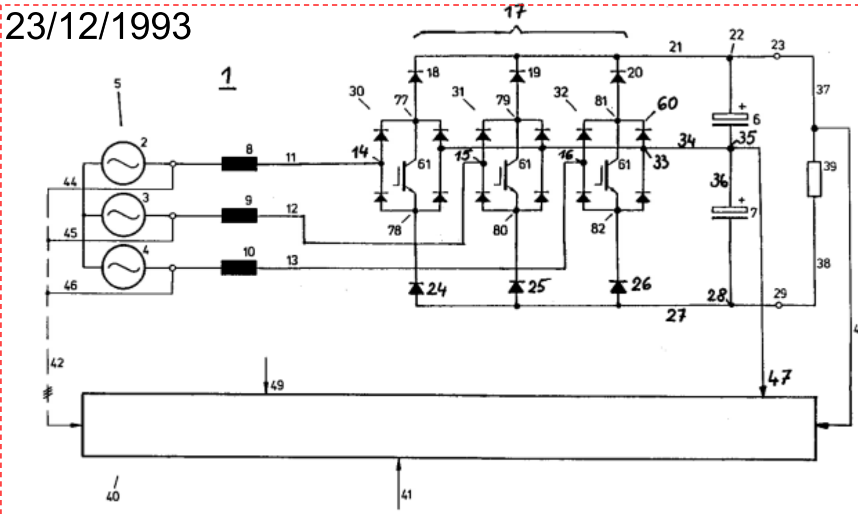
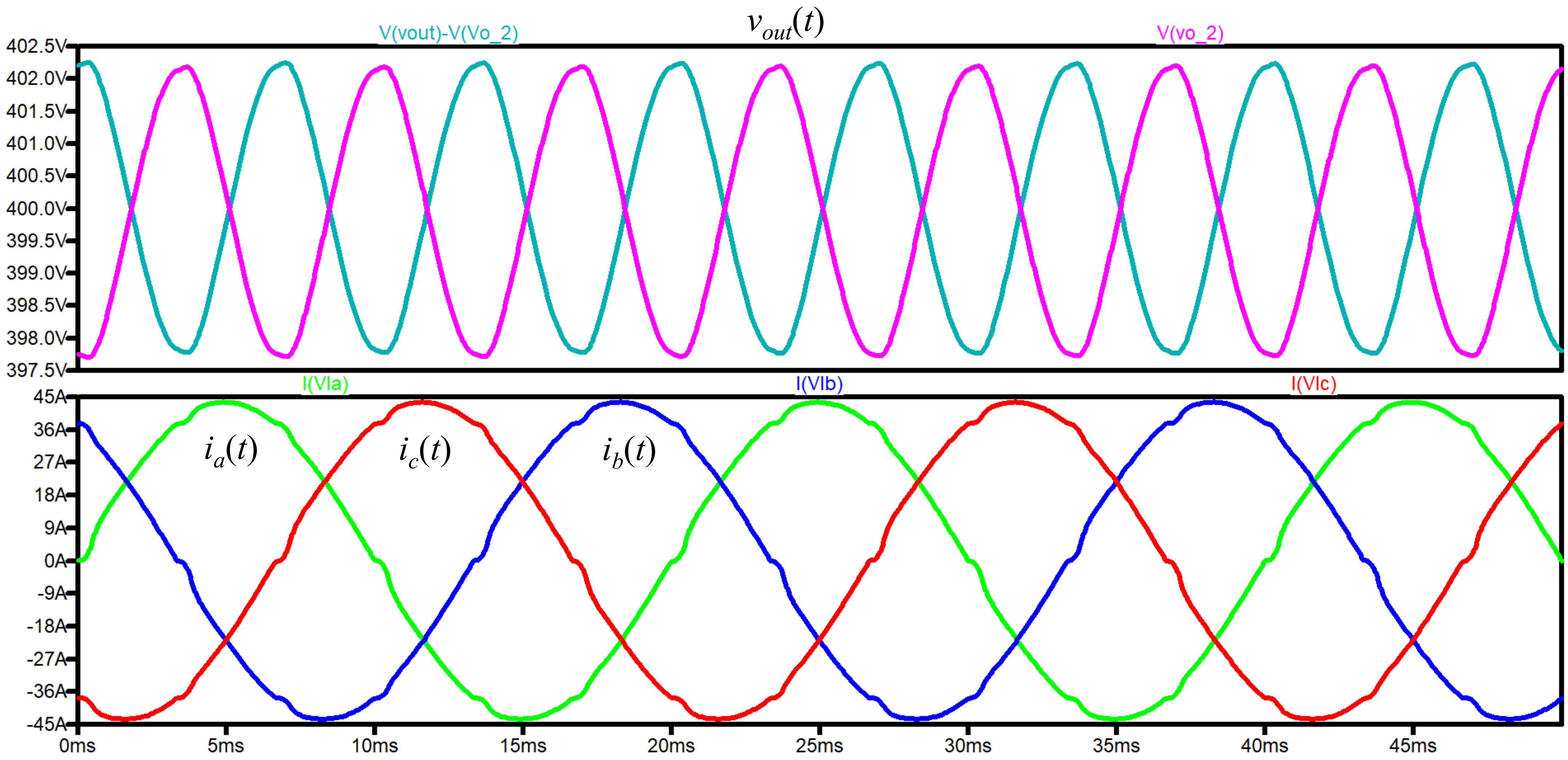


Fig. 1

✓ Six PWM switch models are necessary but only 3 are active at the same time, depending on the line polarities.

The Vienna is a Three-Level Converter

- The two output voltages are well balanced and the input currents THD is below 2%



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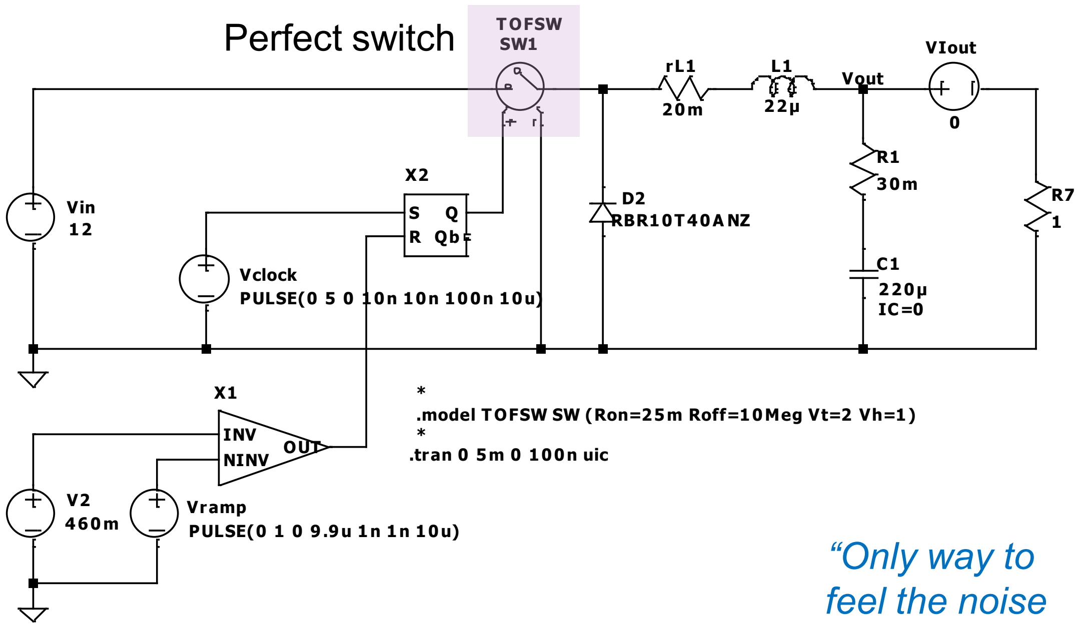
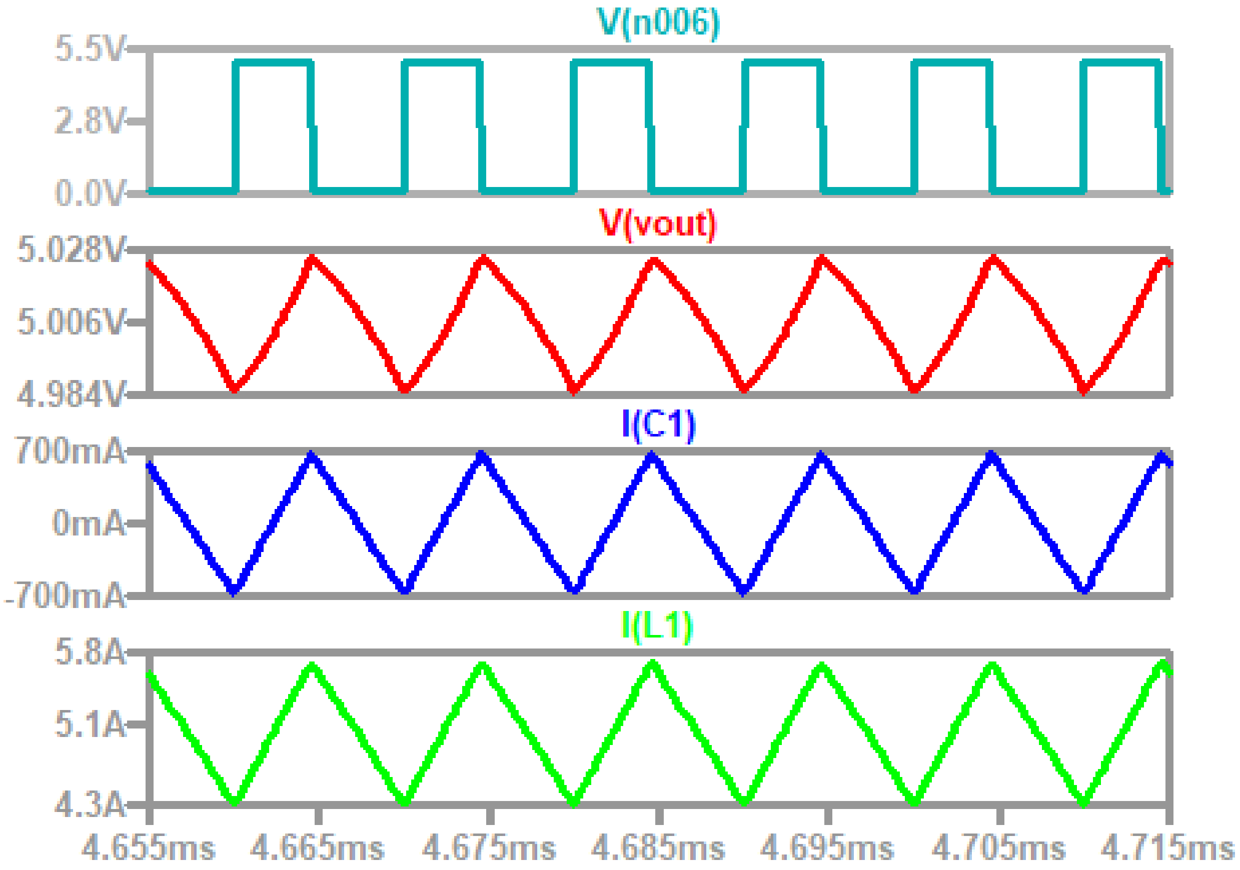
Assembling simple Circuits First

- The goal is to first test the component values you have determined

✓ Is my inductance well sized, what is the ripple current, is the capacitor stress ok?





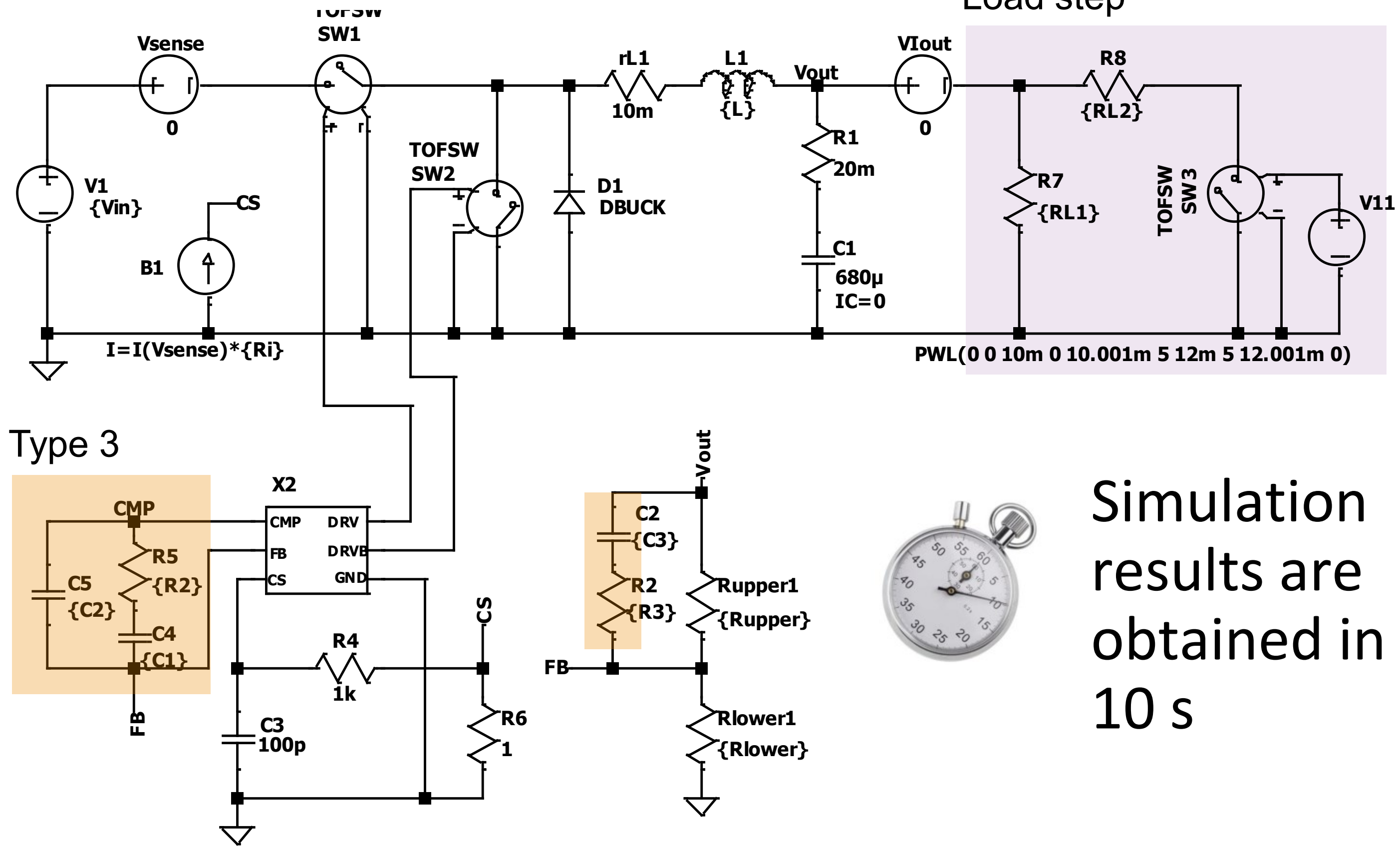
"Only way to feel the noise

It's when it's good and loud"

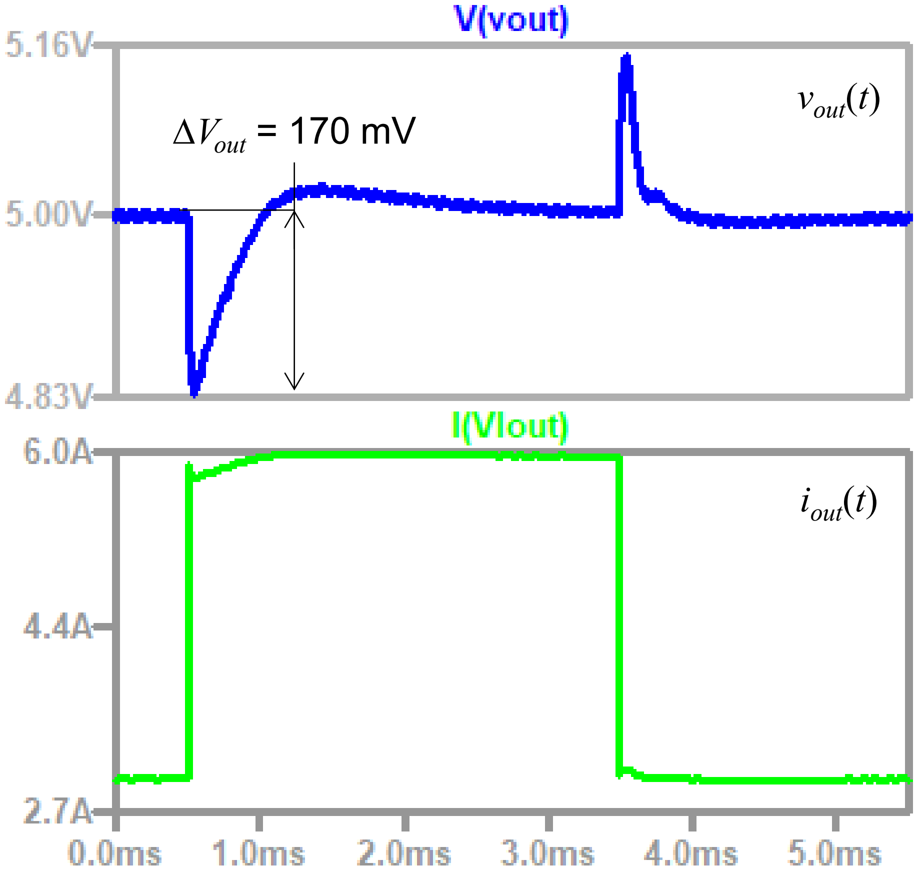
- You don't need the *bells and whistles* of a complex controller model at first!

Using a Generic Model for fast Simulations

- Once the circuit is operational in its most basic concept, increase complexity
- A generic model simulates fast and lets you test if your compensation strategy works

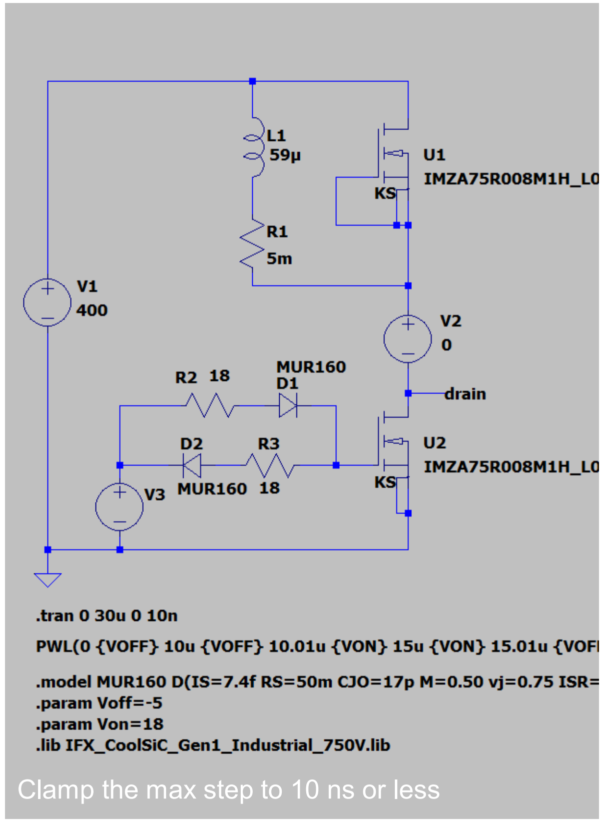


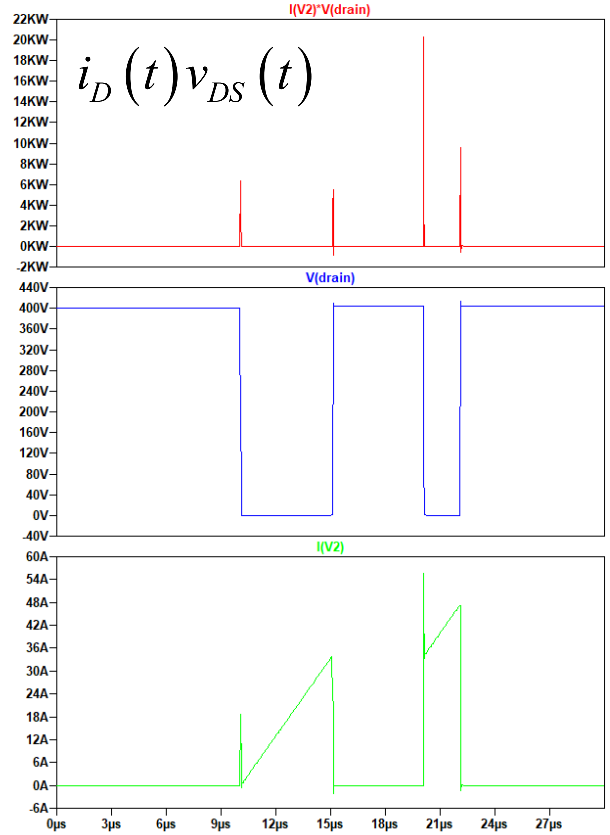
Simulation results are obtained in 10 s



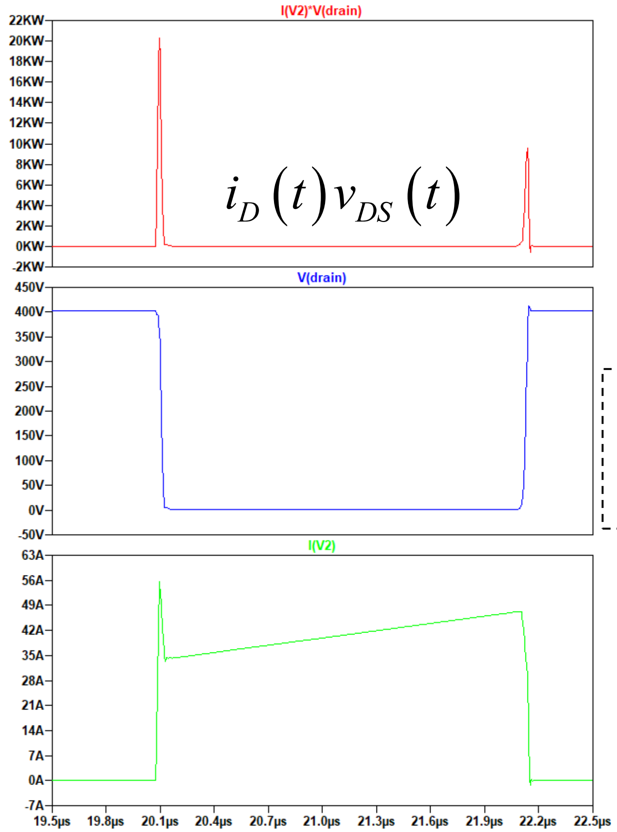
Make sure your Models are Reliable

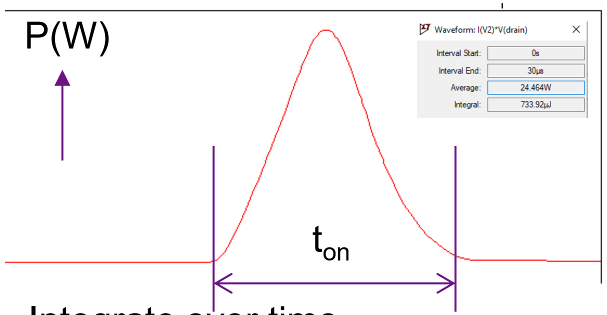
- An accurate model is necessary otherwise: garbage-in garbage out (GIGO)
- ✓ Implement a double-pulse test with the data-sheet conditions and check losses





CTRL + left click on trace name



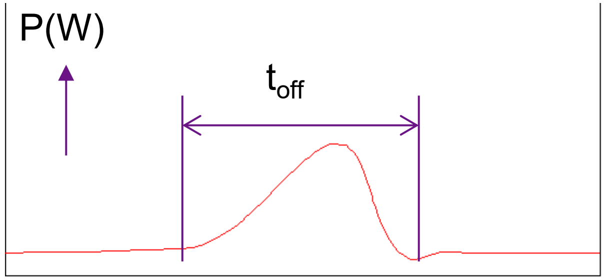


Integrate over time

$$E_{on} = P_{avg}\Big|_{\Delta t = t_{on}} t_{on}\ [\mathrm{J}]$$

$$E_{off} = P_{avg}\Big|_{\Delta t = t_{off}} t_{off}\ [\mathrm{J}]$$

Check these losses!



PWL(0 {VOFF} 10u {VOFF} 10.01u {VON} 15u {VON} 15.01u {VOFF} 20u {VOFF} 20.01u {VON} 22u {VON} 22.01u {VOFF})

The Complete Cycle-by-Cycle Circuit

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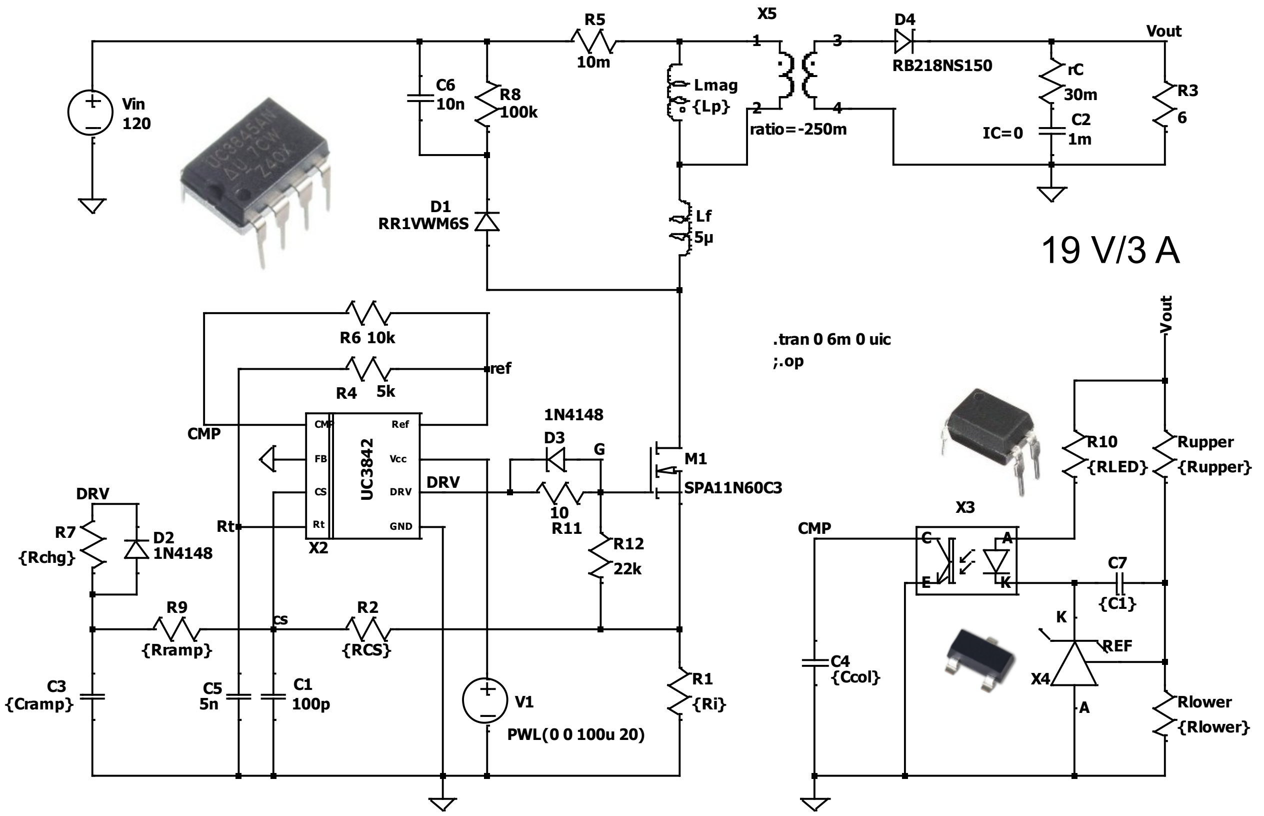
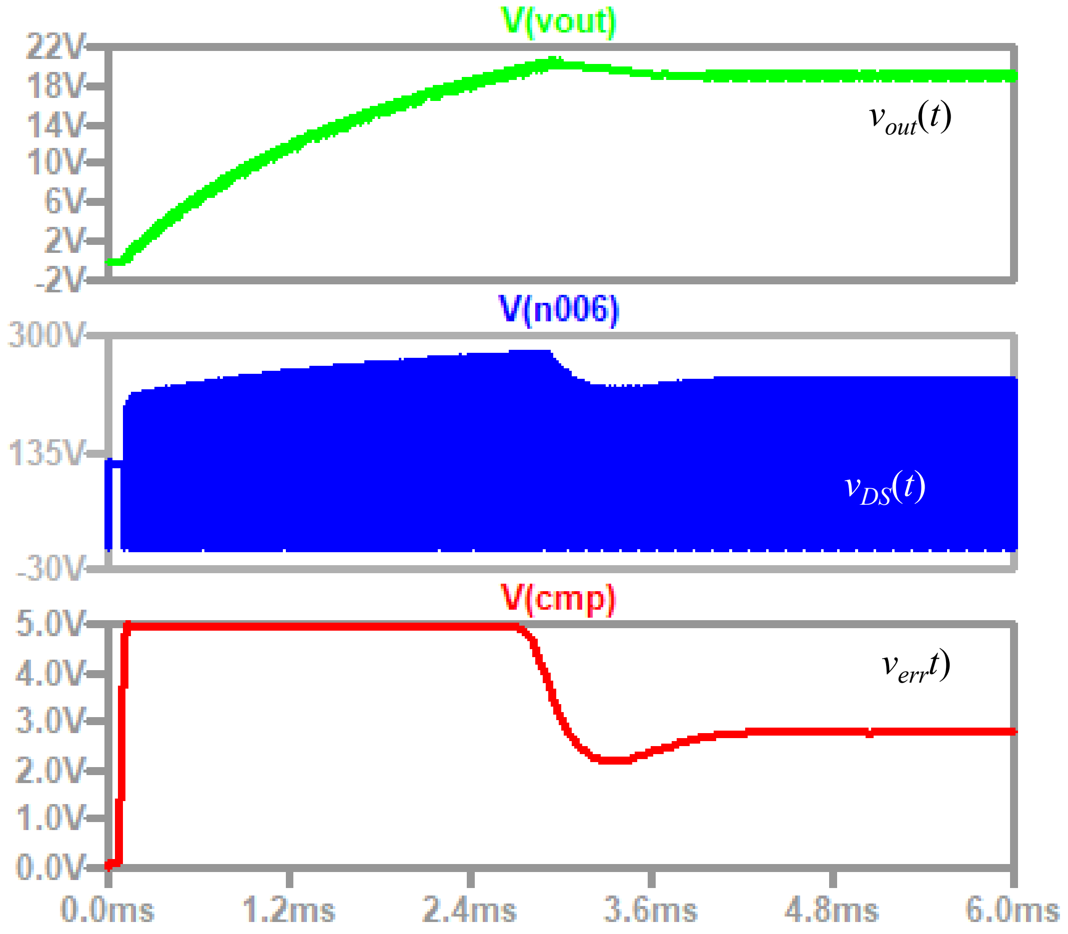
- Your component values are now validated and deliver the right results
- ✓ It's time to run the complete circuit with semiconductor models



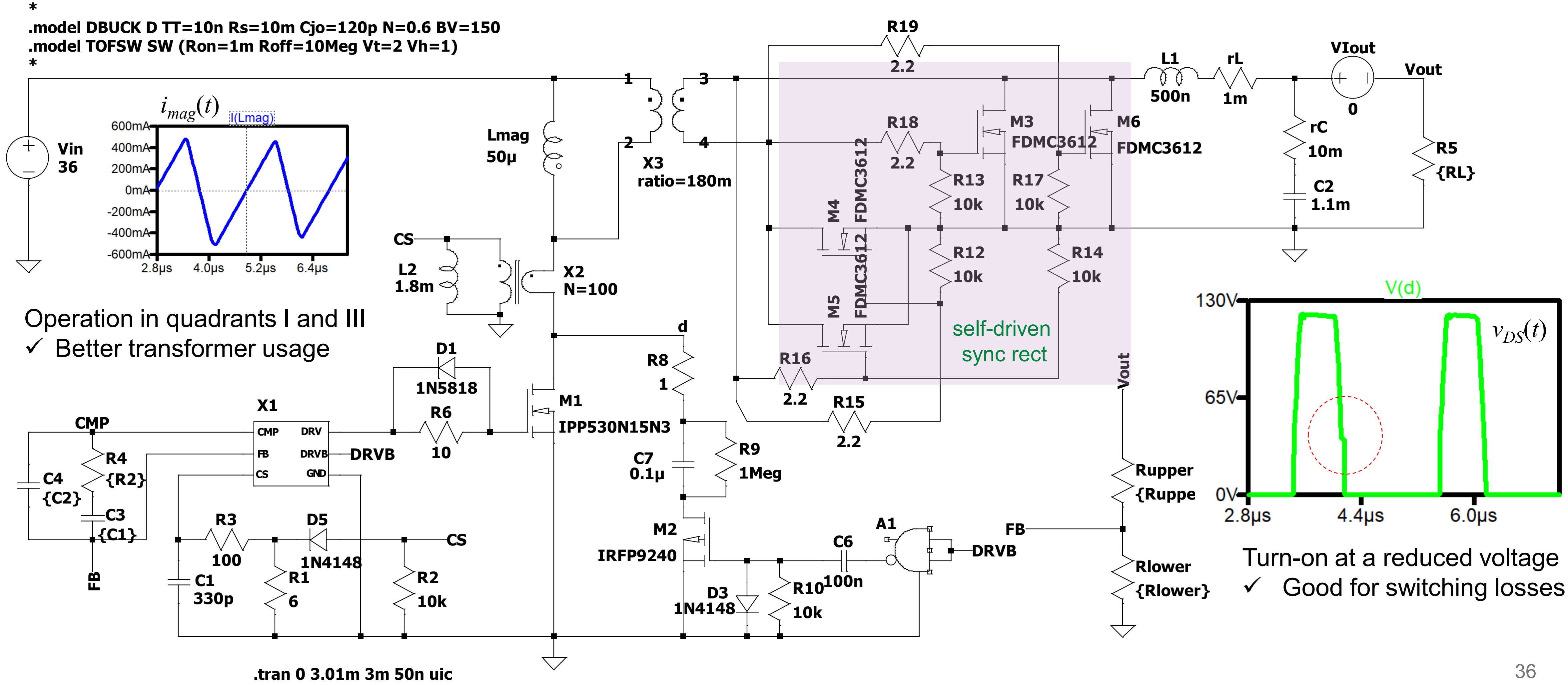


- Always carefully draw your circuit
- ✓ A well-drawn schematic is easier to read!

An Active-Clamp Forward in Current-Mode

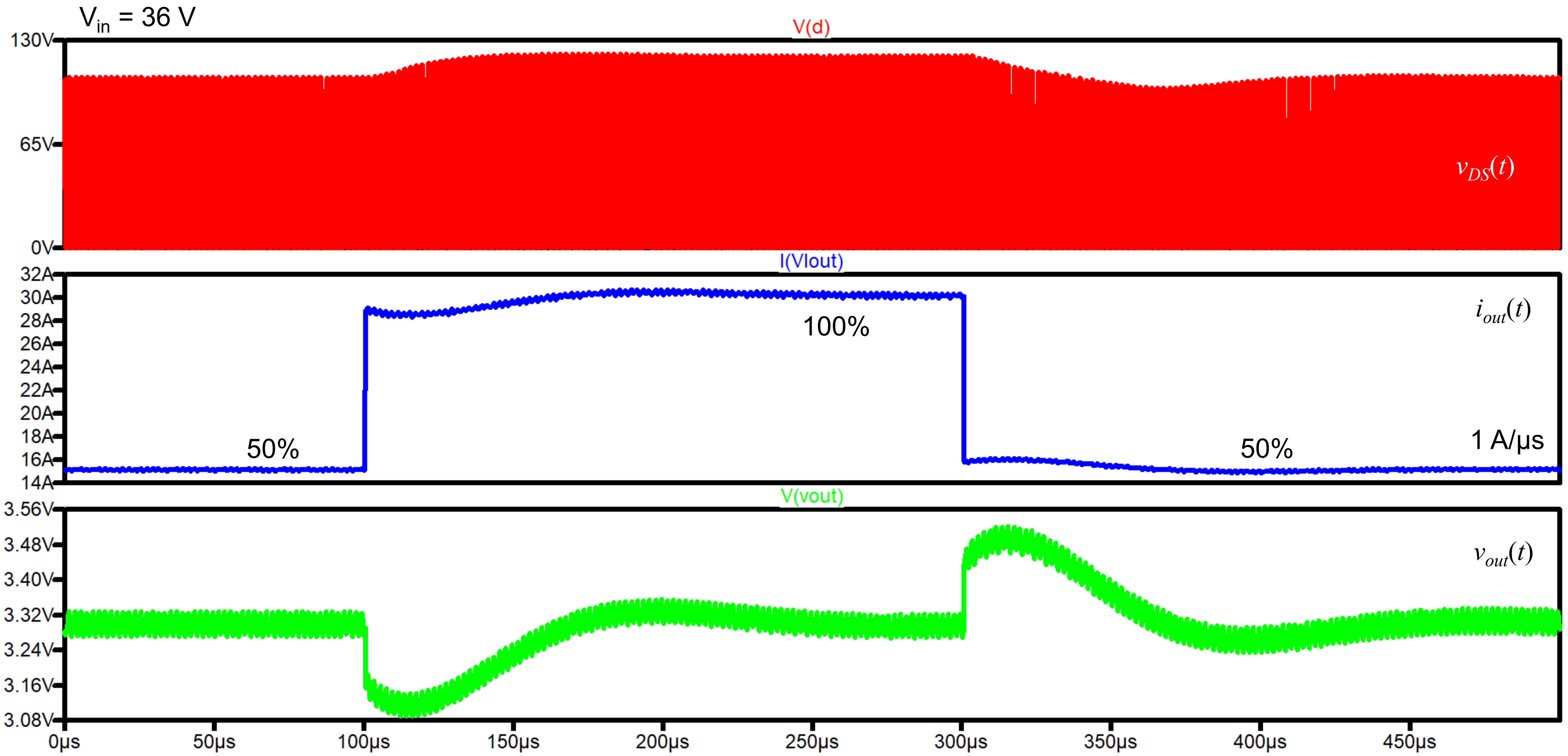
- The dedicated CM averaged model is used to stabilize the loop

✓ The extra high-frequency pole severely limits crossover in this case



Transient Response of the CM ACF

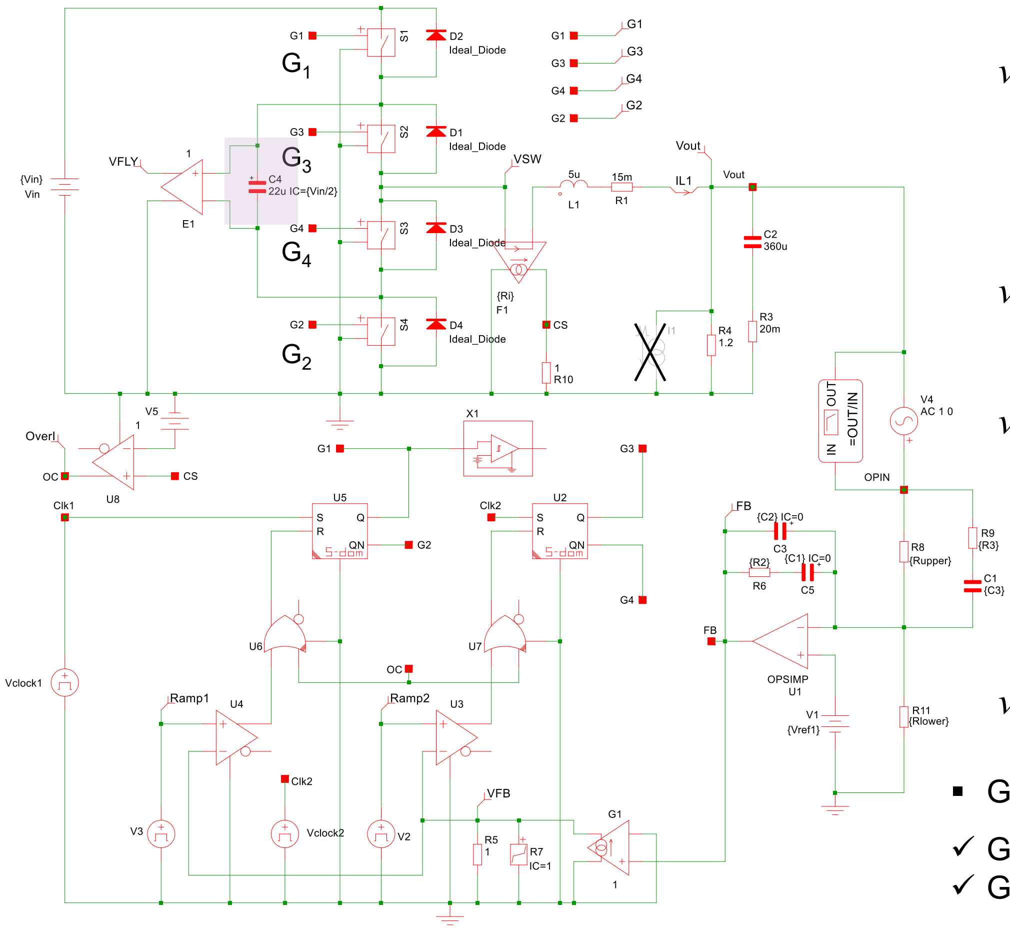
- A high crossover frequency ensures an excellent response to a 15-A step

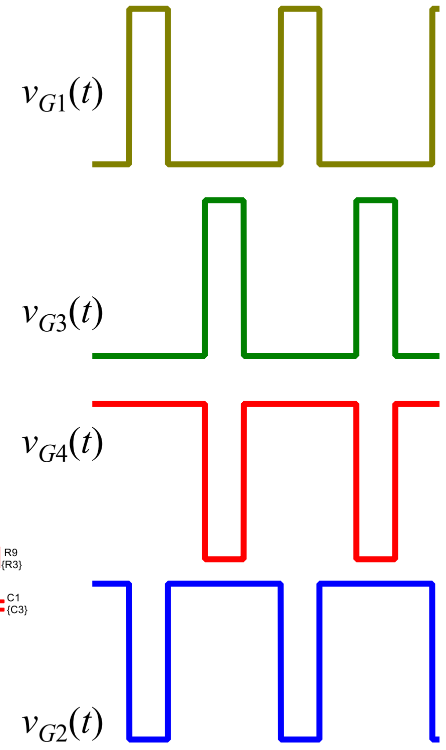


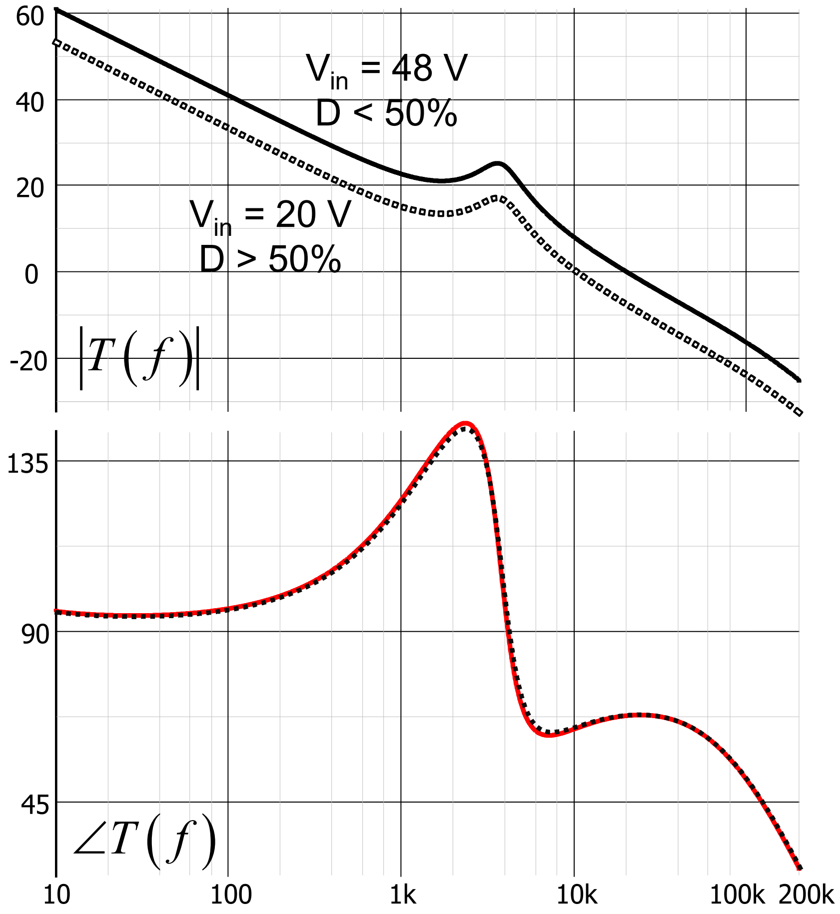
Three-Level Buck Converter – AC Response

- A three-level structure helps reducing the voltage stress across power switches

✓ SIMPLIS can deliver the control-to-output transfer function in a few seconds







- G_1 and G_3 are driven in multiphase

✓ $G_2 = \overline{G_1}$

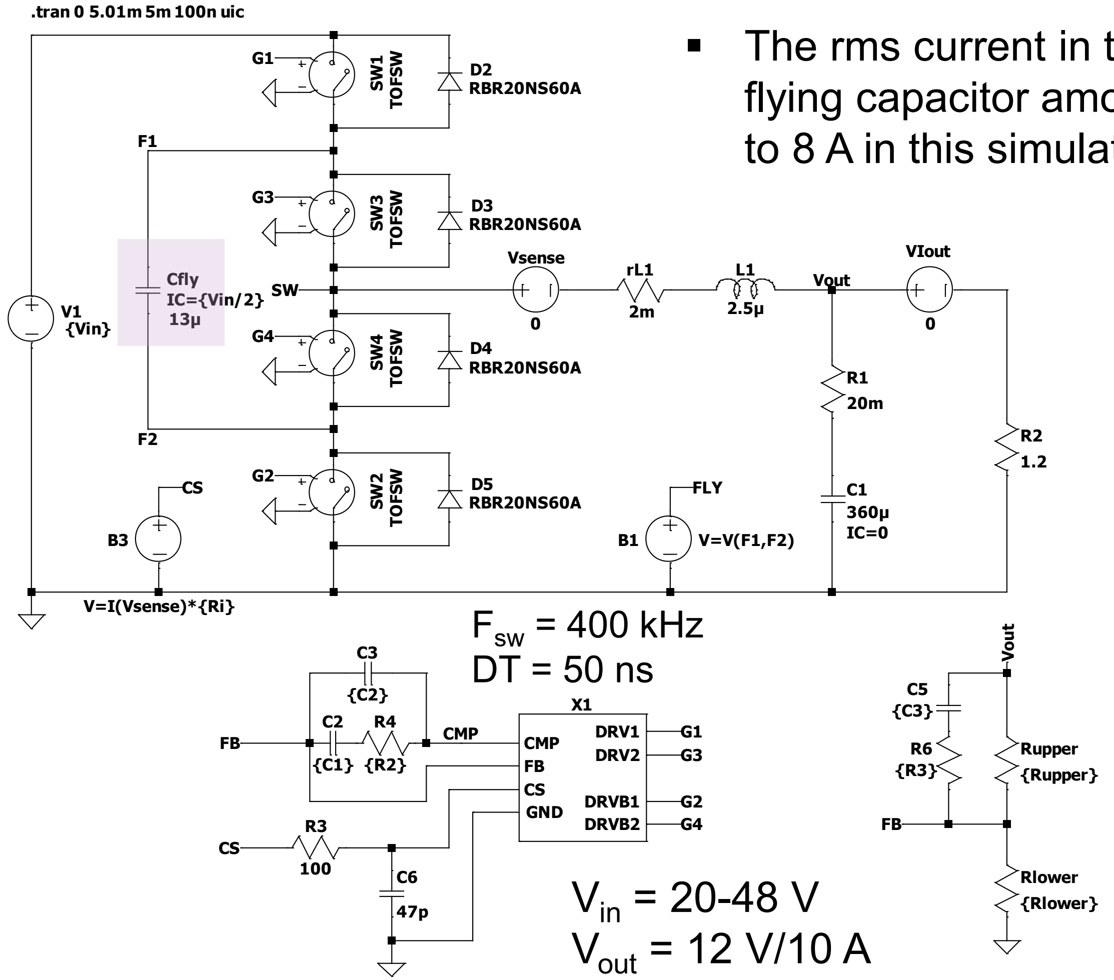
✓ $G_4 = \overline{G_3}$

T. Meynard, H. Foch, Multi-level conversion: high voltage choppers and voltage-source inverters, *IEEE Power Electronics Specialists Conference*, 1992

Simulating a Buck with a Flying Capacitor

- A modified multiphase buck controller can be used to control the converter

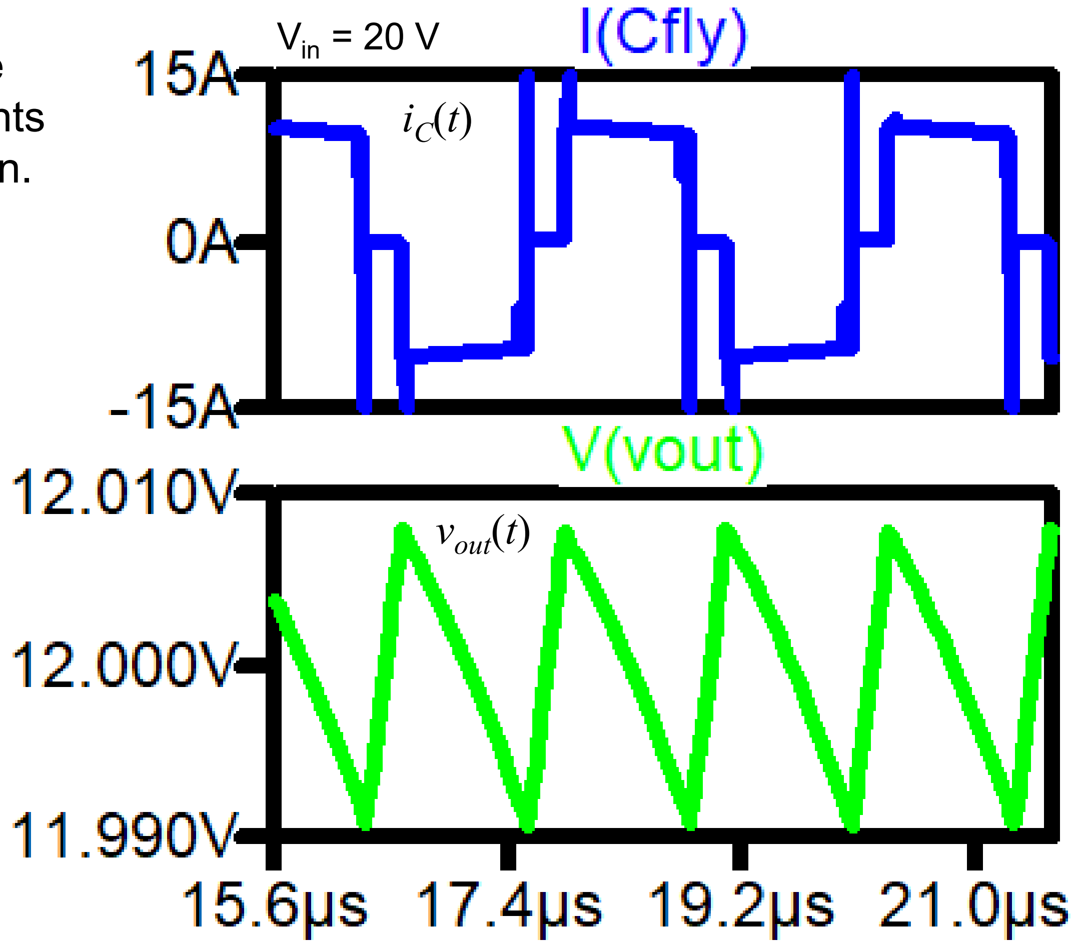
✓ LTspice shows the voltage at the main switching node for the two duty ratios



- The rms current in the flying capacitor amounts to 8 A in this simulation.

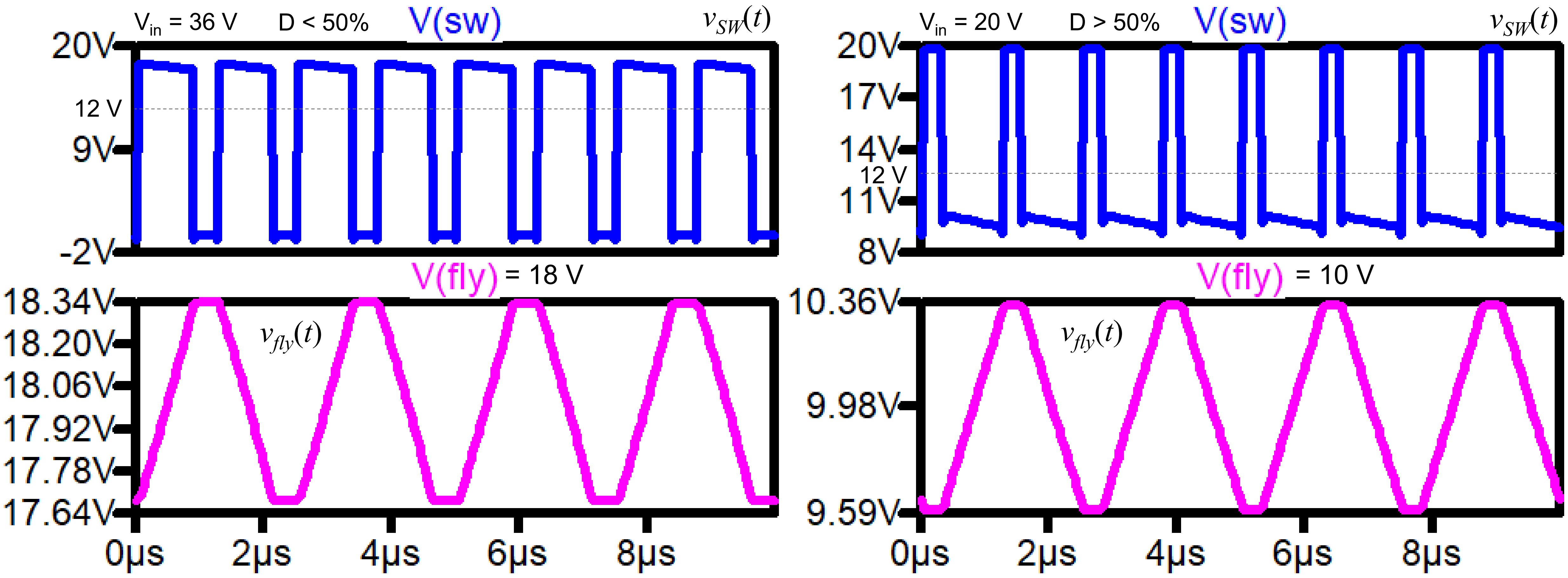
F_{SW} = 400 kHz
DT = 50 ns

V_{in} = 20-48 V
V_{out} = 12 V/10 A



Reduced Voltages across Switches

- The voltage at the power switching node depends on the duty ratio
  - ✓ It swings between 0 and ½V_{in} for D < 50% or ½V_{in} and V_{in} D > 50%



6-Pack 3-Phase PFC with SiC MOSFETs

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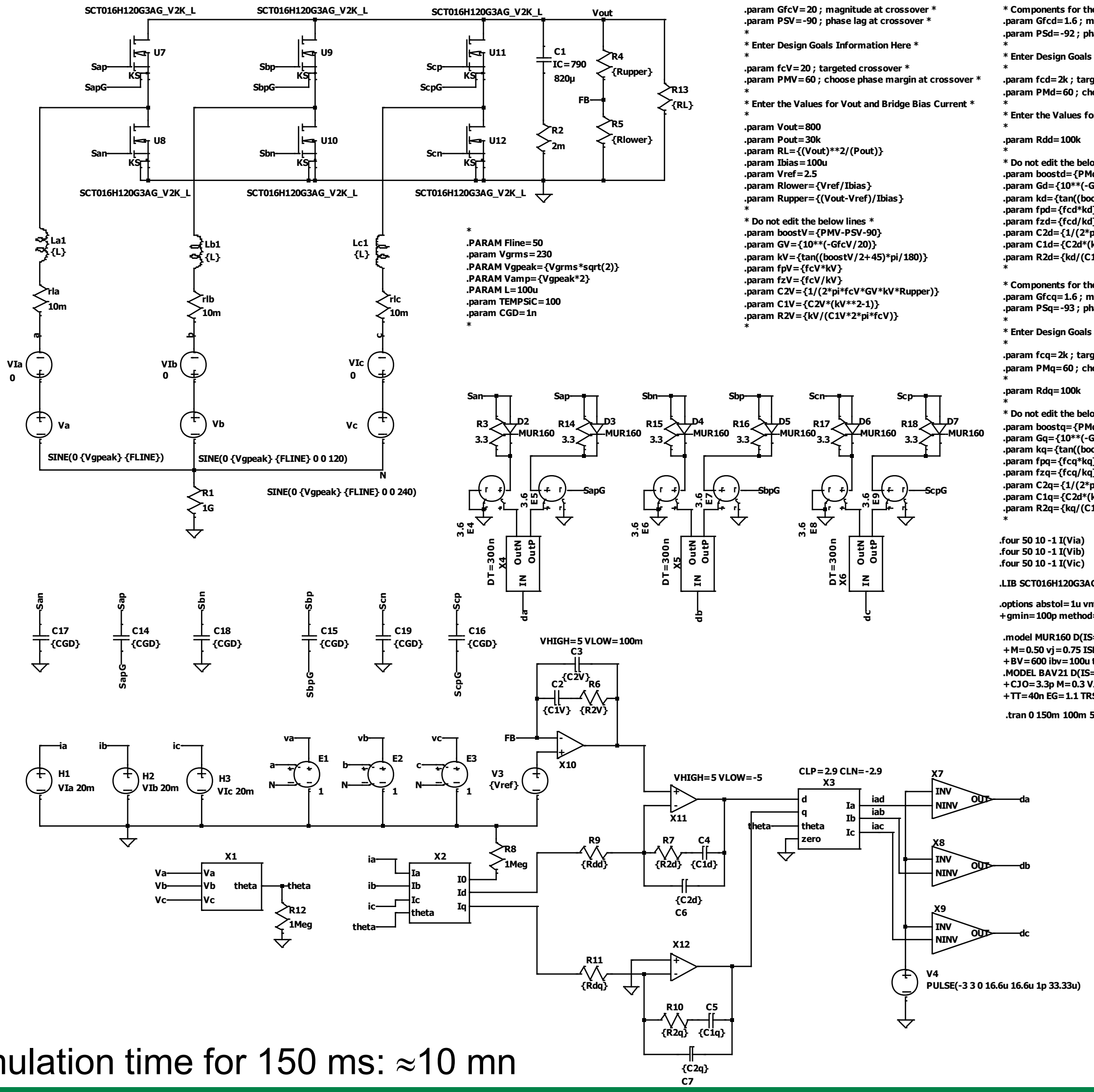
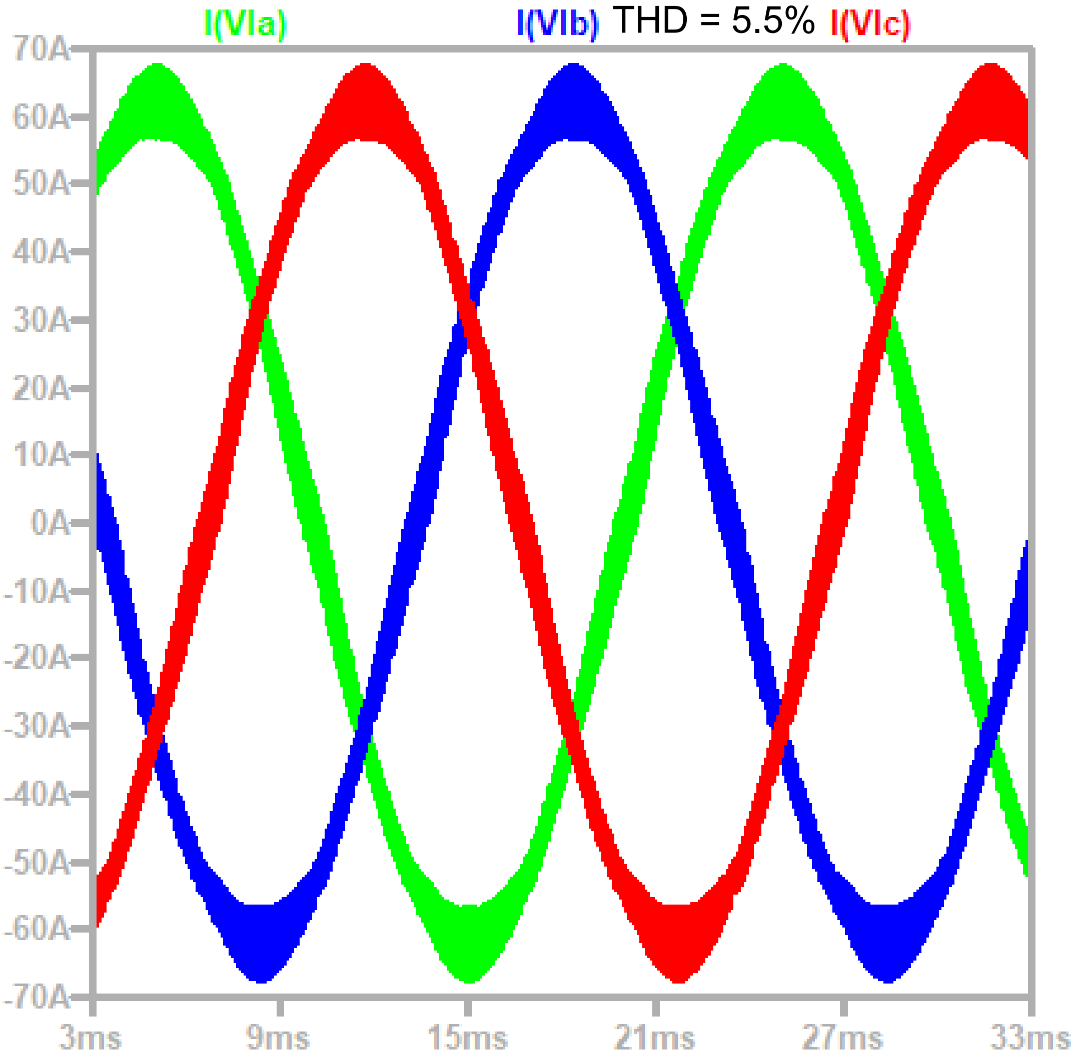
- You can run a simulation with dq0 control and SiC transistors



```
*
.PARAM Fline=50
.param Vgrms=230
.PARAM Vgpeak={Vgrms*sqrt(2)}
.PARAM Vamp={Vgpeak*2}
.PARAM L=100u
.param TEMPSiC=100
.param CGD=1n
*
```

```
.param GfcV=20 ; magnitude at crossover *
.param PSV=-90 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcV=20 ; targeted crossover *
.param PMV=60 ; choose phase margin at crossover *
*
* Enter the Values for Vout and Bridge Bias Current *
*
.param Vout=800
.param Pout=30k
.param RL={(Vout)**2/(Pout)}
.param Ibias=100u
.param Vref=2.5
.param Rlower={Vref/Ibias}
.param Rupper={(Vout-Vref)/Ibias}
*
* Do not edit the below lines *
.param boostV={PMV-PSV-90}
.param GV={10**(-GfcV/20)}
.param kV={tan((boostV/2+45)*pi/180)}
.param fpV={fcV*kV}
.param fzV={fcV/kV}
.param C2V={1/(2*pi*fcV*GV*kV*Rupper)}
.param C1V={C2V*(kV**2-1)}
.param R2V={kV/(C1V*2*pi*fcV)}
*
```

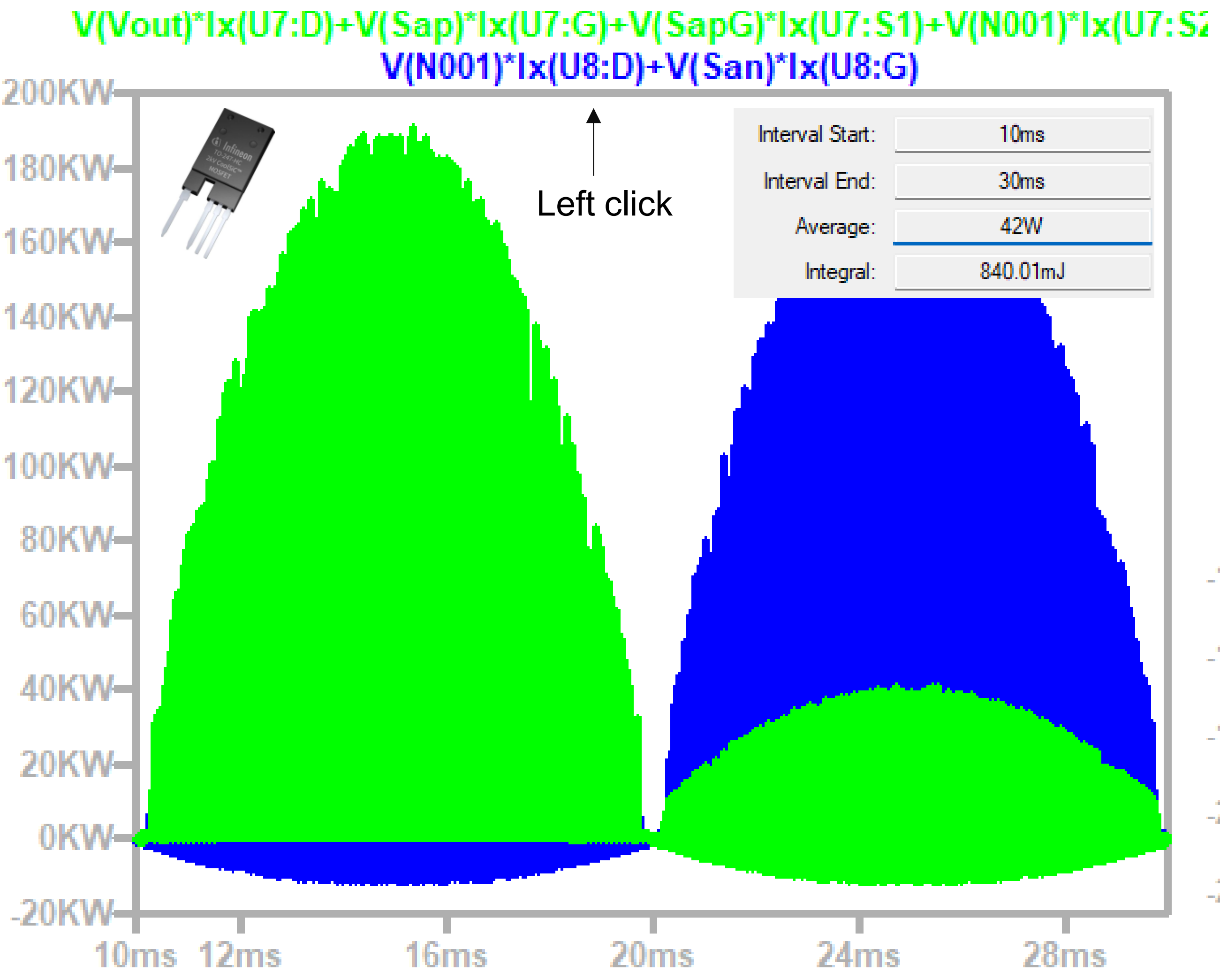
```
* Components for the d loop *
.param Gfcd=1.6 ; magnitude at crossover *
.param PSd=-92 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcd=2k ; targeted crossover *
.param PMd=60 ; choose phase margin at crossover *
*
* Enter the Values for Vout and Bridge Bias Current *
*
.param Rdd=100k
*
* Do not edit the below lines *
.param boostd={PMd-PSd-90}
.param Gd={10**(-Gfcd/20)}
.param kd={tan((boostd/2+45)*pi/180)}
.param fpd={fcd*kd}
.param fzd={fcd/kd}
.param C2d={1/(2*pi*fcd*Gd*kd*Rdd)}
.param C1d={C2d*(kd**2-1)}
.param R2d={kd/(C1d*2*pi*fcd)}
*

* Components for the q loop *
.param Gfcq=1.6 ; magnitude at crossover *
.param PSq=-93 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcq=2k ; targeted crossover *
.param PMq=60 ; choose phase margin at crossover *
*
.param Rdq=100k
*
* Do not edit the below lines *
.param boostq={PMq-PSq-90}
.param Gq={10**(-Gfcq/20)}
.param kq={tan((boostq/2+45)*pi/180)}
.param fpq={fcq*kq}
.param fzq={fcq/kq}
.param C2q={1/(2*pi*fcq*Gq*kq*Rdq)}
.param C1q={C2d*(kq**2-1)}
.param R2q={kq/(C1q*2*pi*fcq)}
*

.four 50 10 -1 I(Via)
.four 50 10 -1 I(Vib)
.four 50 10 -1 I(Vic)

.LIB SCT016H120G3AG_V2K_L.LIB

.options abstol=1u vntol=1m reltol=0.01
+gmin=100p method=gear

.model MUR160 D(IS=7.4f RS=50m CJO=17p
+M=0.50 vj=0.75 ISR=940p
+BV=600 ibv=100u tt=120n)
.MODEL BAV21 D(IS=15p RS=0.5 IKF=1.3m
+CJO=3.3p M=0.3 VJ=0.7 BV=200 IBV=.03u
+TT=40n EG=1.1 TRS1=1u N=1.2 XTI=5)

.tran 0 150m 100m 50n uic
```



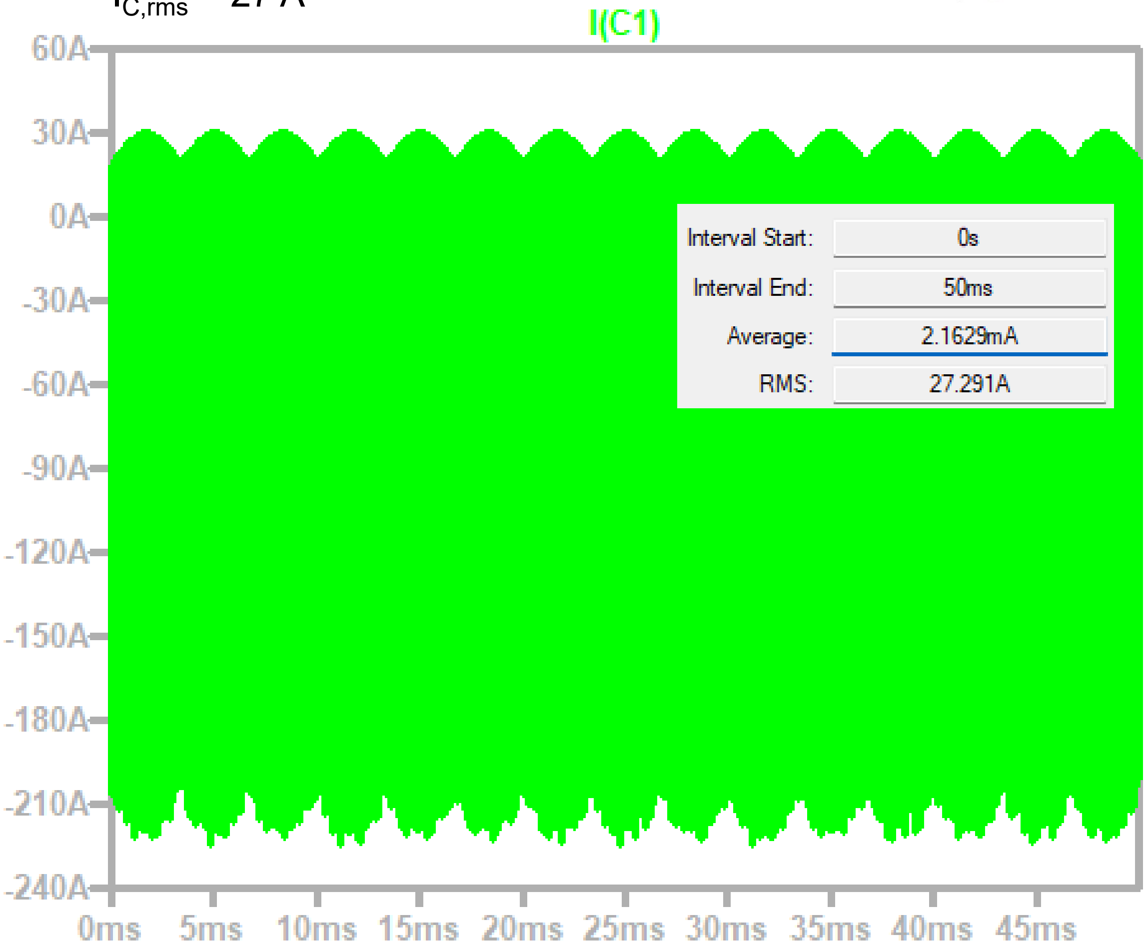
Simulation time for 150 ms: ≈10 mn

Assess Conduction and Switching Losses

- After stabilization, you can assess the power dissipated by each transistor

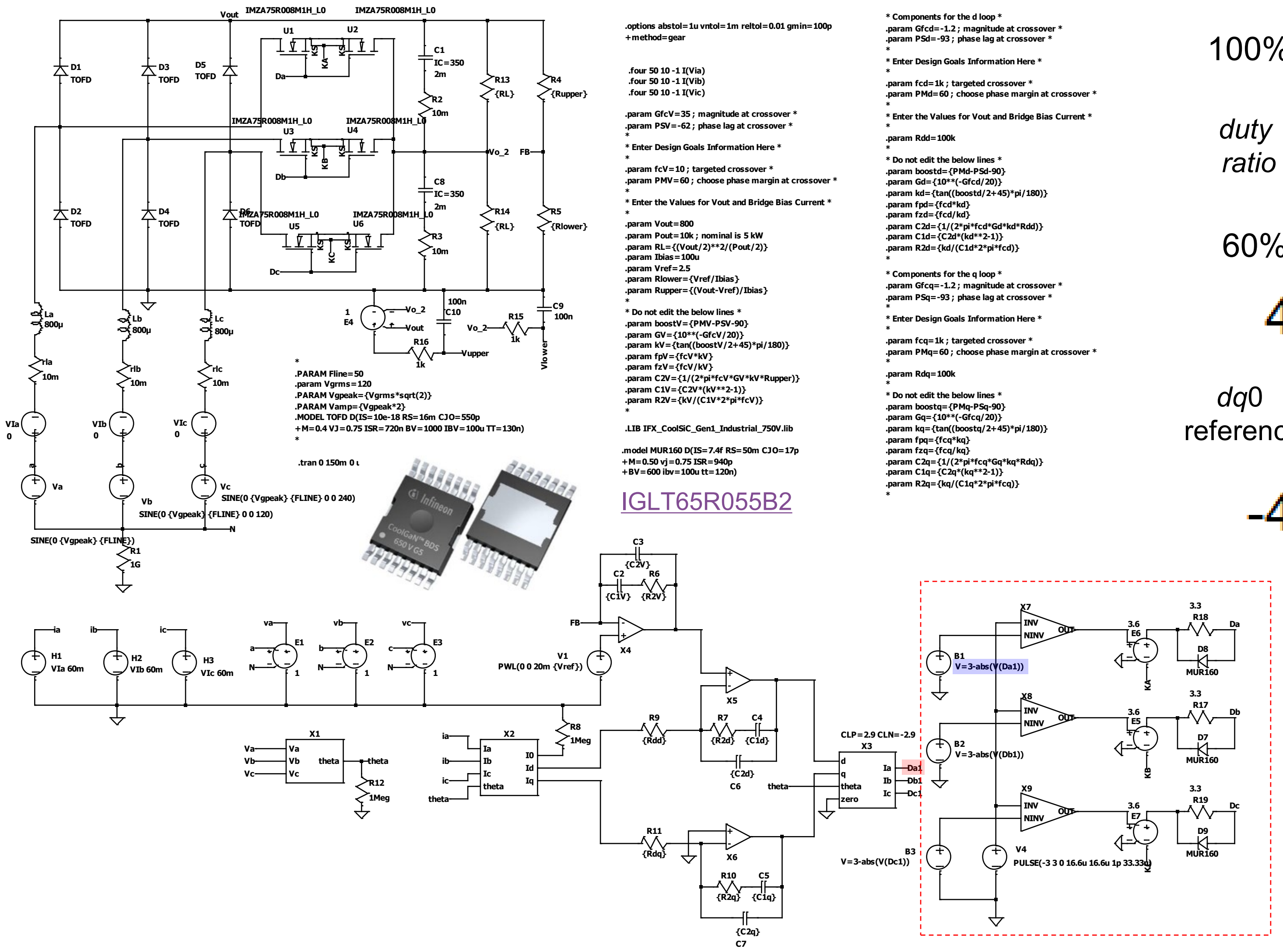


$I_{C,rms}$ = 27 A

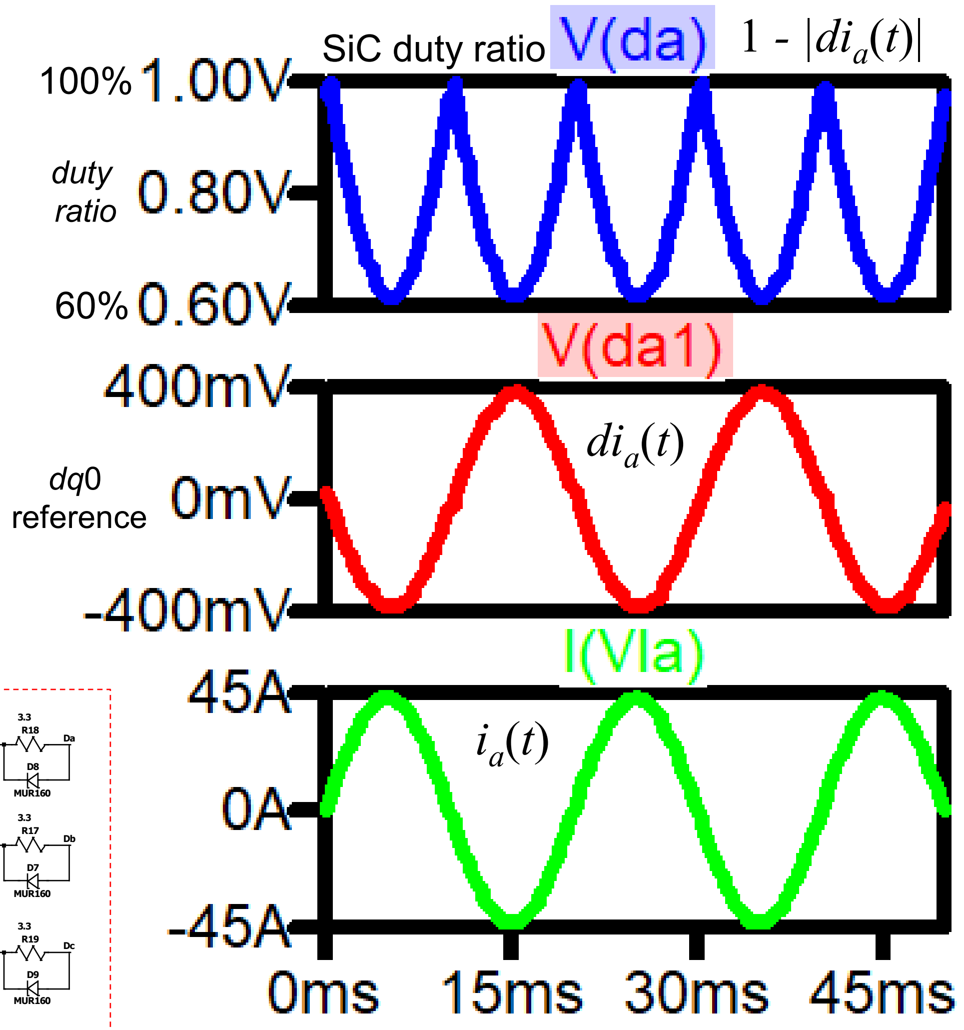


Simulating a Vienna Rectifier with SiC

- Two back-to-back MOSFETs are used for creating bidirectional switches

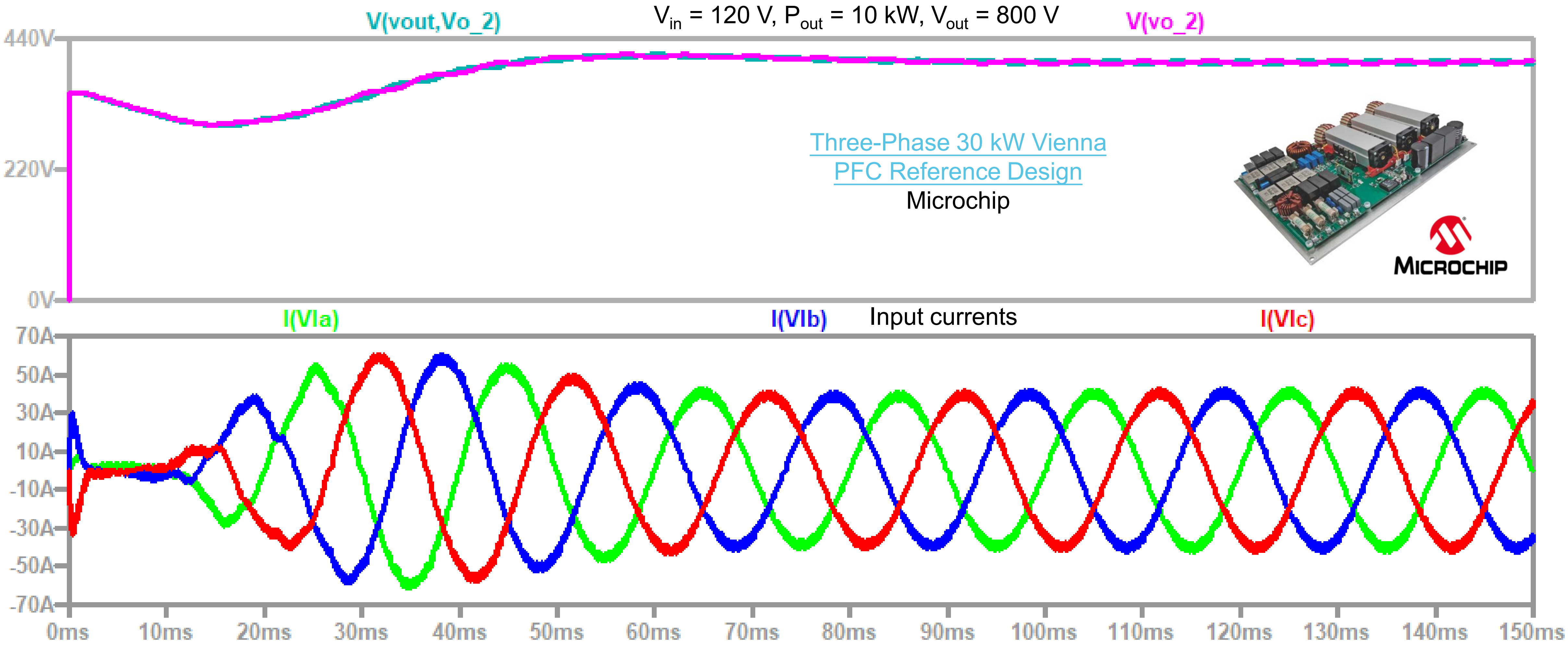


IGLT65R055B2



Steady-State Simulation of the Vienna

- The start-up sequence is very smooth without significant overshoot



Agenda

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- Why Simulating?
- Different Simulation Engines
- Averaged Models
- Cycle-by-Cycle Models
- Simulation Examples of Converters

Stabilizing the Loop of a Boost Converter

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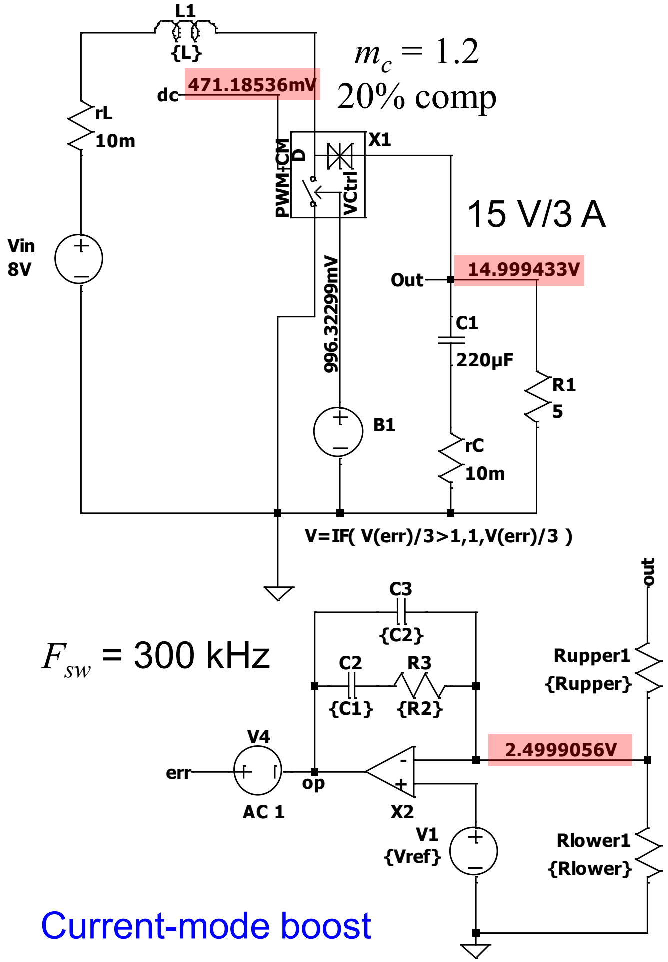
- This is a current-mode boost converter delivering 15 V/3 A from a 10-V source

✓ You start by determining the RHP zero at the minimum input of 8 V



- The RHP zero is located at:

$$f_z = \frac{5\,\Omega(1-0.47)^2}{22\,\mu\text{H}\cdot 2\pi} \approx 10.2\text{ kHz}$$

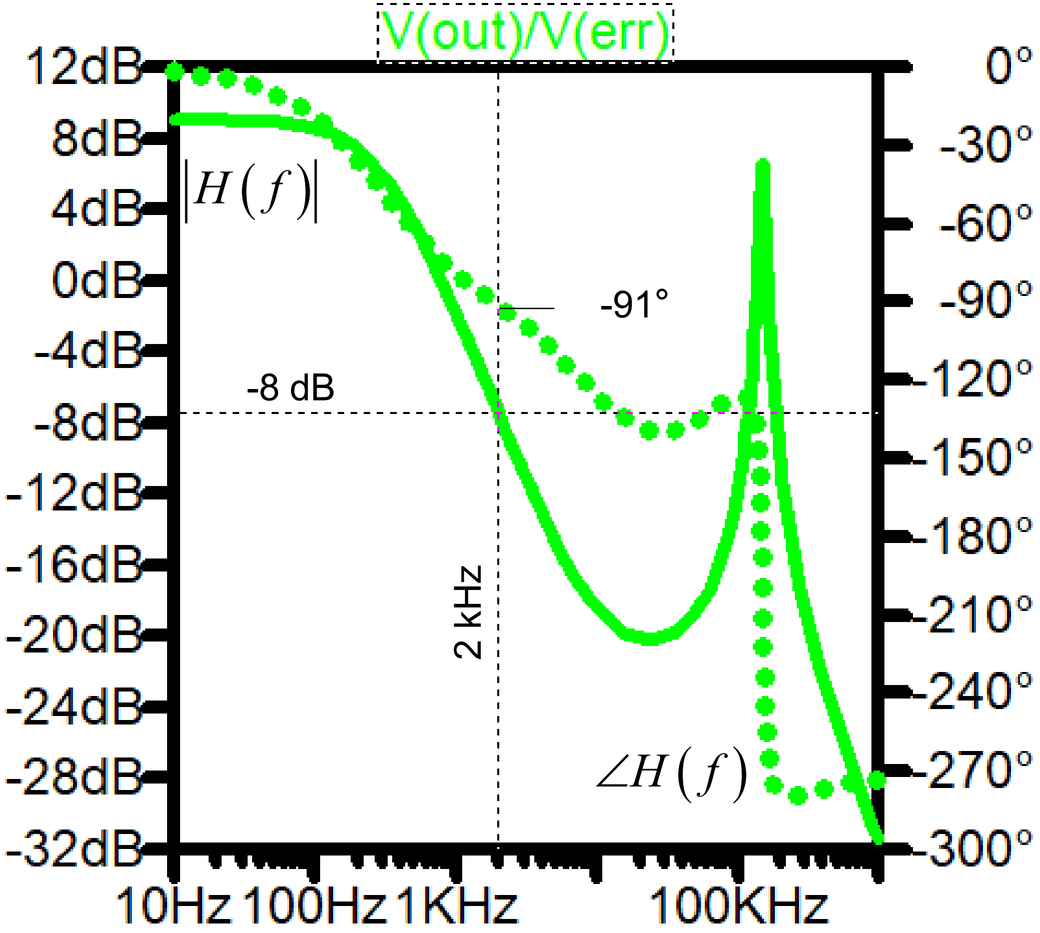
- Choose f_c 20% max of the RHPZ $\longrightarrow f_c$ = 2 kHz
- Read the mag and phase from the control-to-output plot: Gfc = -8 dB and PS = -91°
- The compensator will exhibit 8 dB of gain at 2 kHz and a phase lag of -209° for a 60° phase margin:

✓ - 91° - 270° + 61° = -300°

Power stage *-180° op-amp pole at origin* *Phase boost*

φ_m

-360°

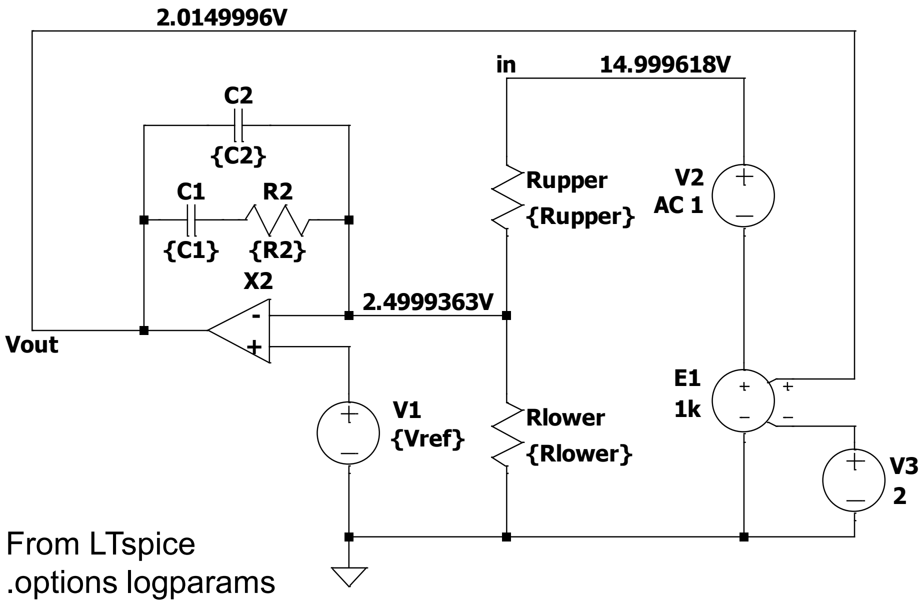


control-to-output transfer function

The type 2 Compensator with an op-amp

- The compensator is an active filter tuned to provide phase boost at fc

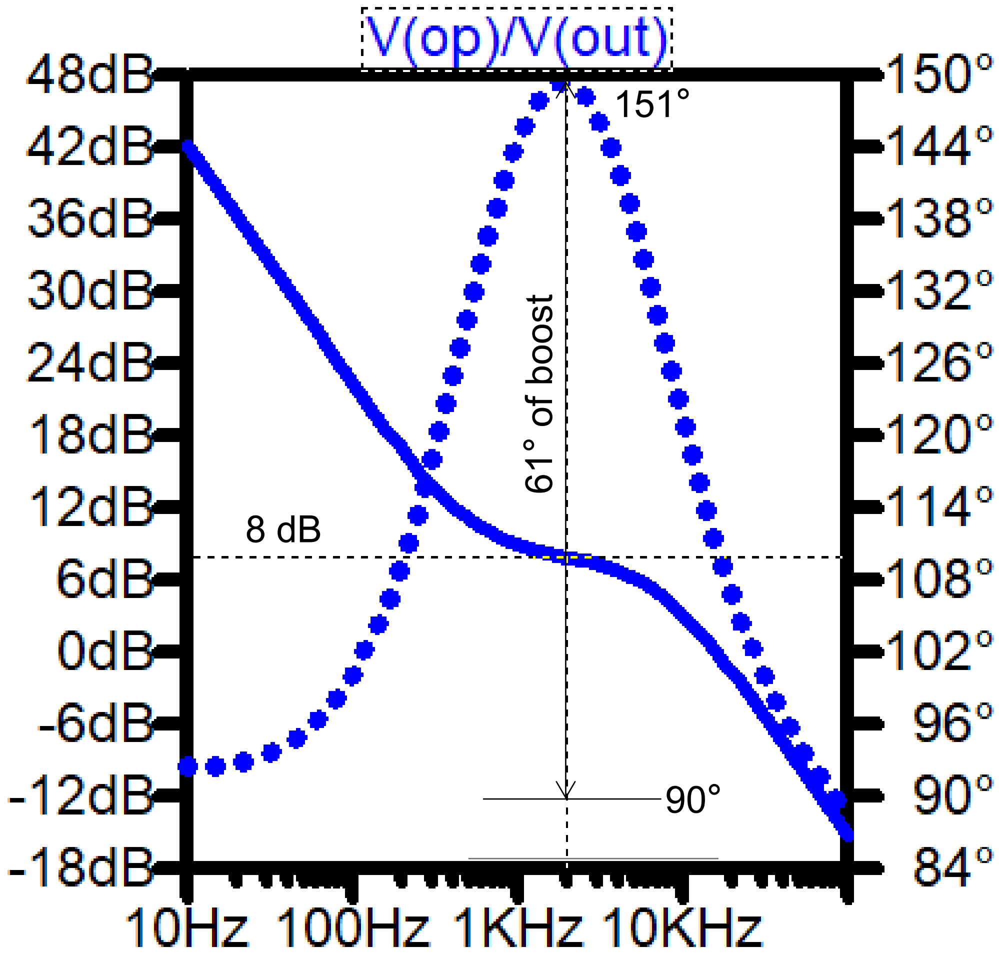
✓ All component values are automated with the macro



From LTspice
.options logparams

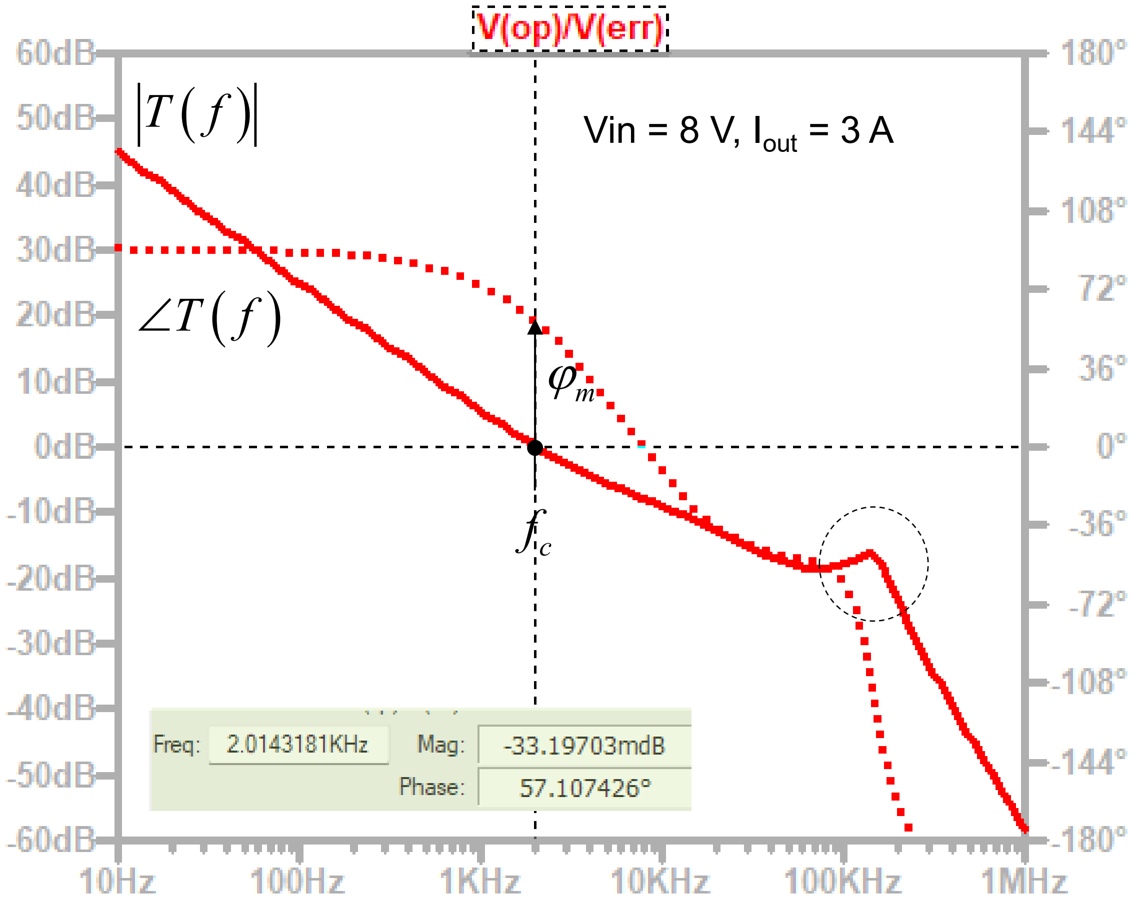
boost = 6.10000e+01 -> boost = 61°
r2 = 1.34596550e+05 -> R_2 = 133 kΩ
c1 = 2.28611544e-09 -> C_1 = 2.2 nF
c2 = 1.63861974e-10 -> C_2 = 164 pF
fc = 2.00000000e+03 -> f_c = 2 kHz
fp = 7.73342618e+04 -> f_p = 7.7 kHz
fz = 5.17235168e+02 -> f_z = 517 Hz

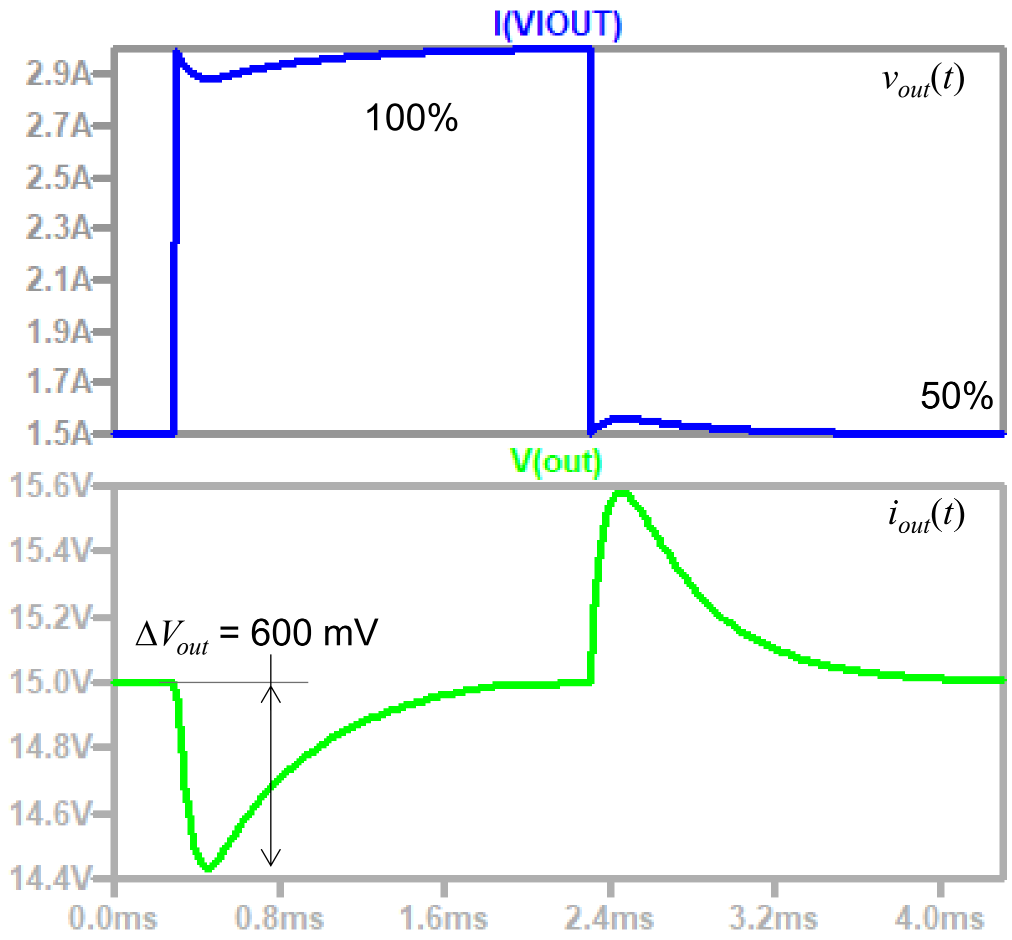
```
*                From power stage
.param Gfc=-8 ; magnitude at crossover *
.param PS=-91 ; phase lag at crossover *
*
* Enter Design Goals Information
*
.param fc=2k ; targeted crossover *
.param PM=60 ; choose phase margin
*
.param Vout=15
.param Ibias=250u
.param Vref=2.5
*
.param Rlower={Vref/Ibias}
.param Rupper={(Vout-Vref)/Ibias}
.param boost={PM-PS-90}
.param G={10**(-Gfc/20)}
.param kf={tan((boost/2+45)*pi/180)}
.param fp={fc*kf}
.param fz={fc/kf}
.param C2=1/{(2*pi*fc*G*kf*Rupper)}
.param C1={C2*(kf**2-1)}
.param R2={kf/(C1*2*pi*fc)}
*
```



Close the Loop and check Step Response

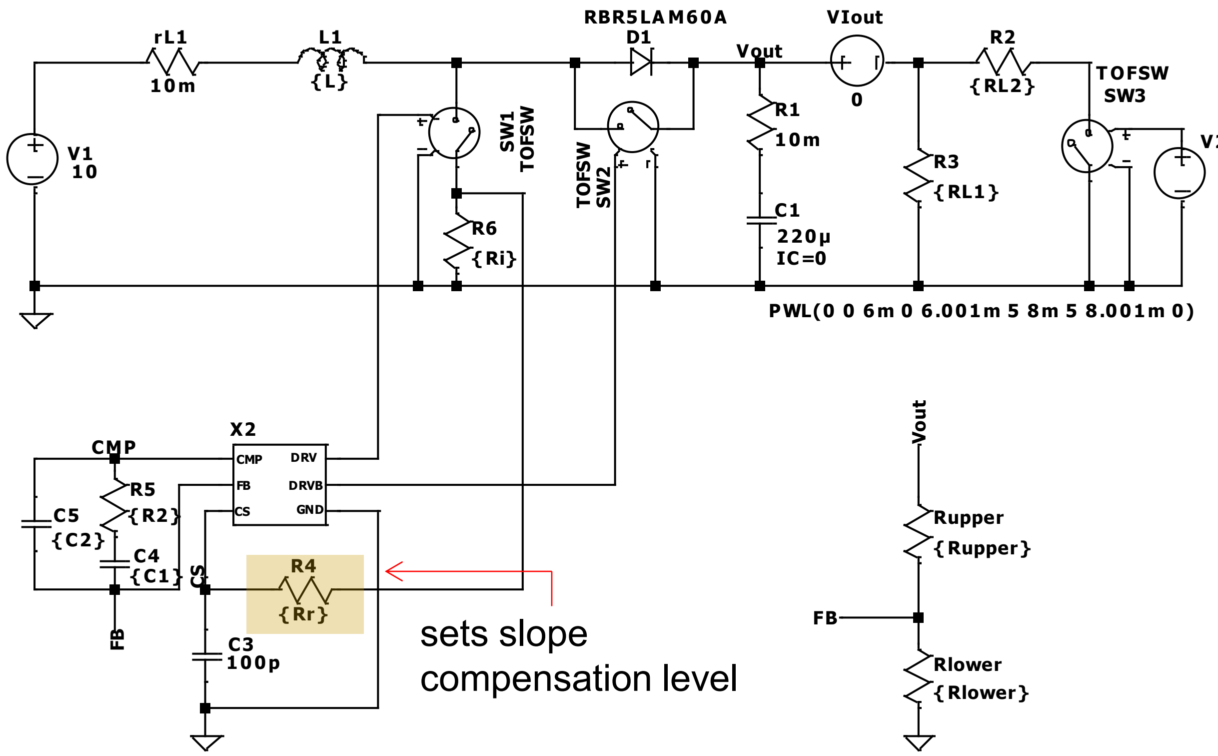
- Plot the compensated gain and explore different operating conditions
- Run a load and input step to check if the output voltage deviation is acceptable

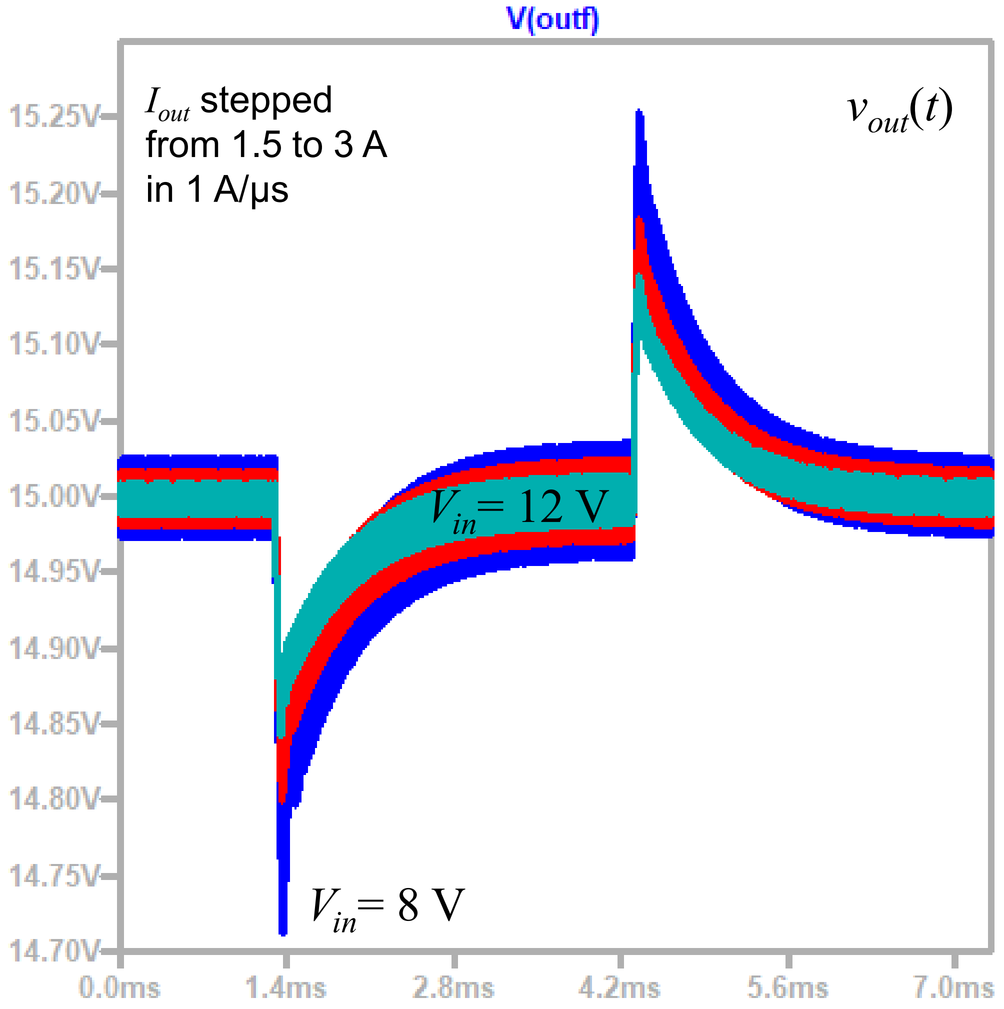




Verify the Design with a Switched Model

- Use averaged model results to close the loop around a switched model
- Run a transient load step to confirm the design is stable

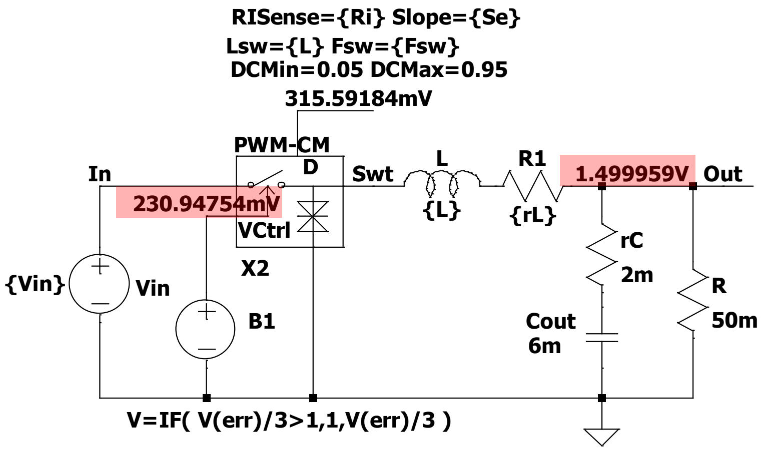




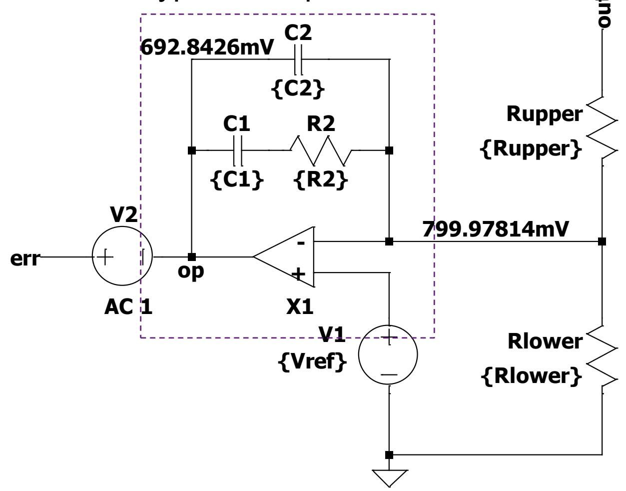
- The transient response is stable at the three input voltages: 8, 10 and 12 V

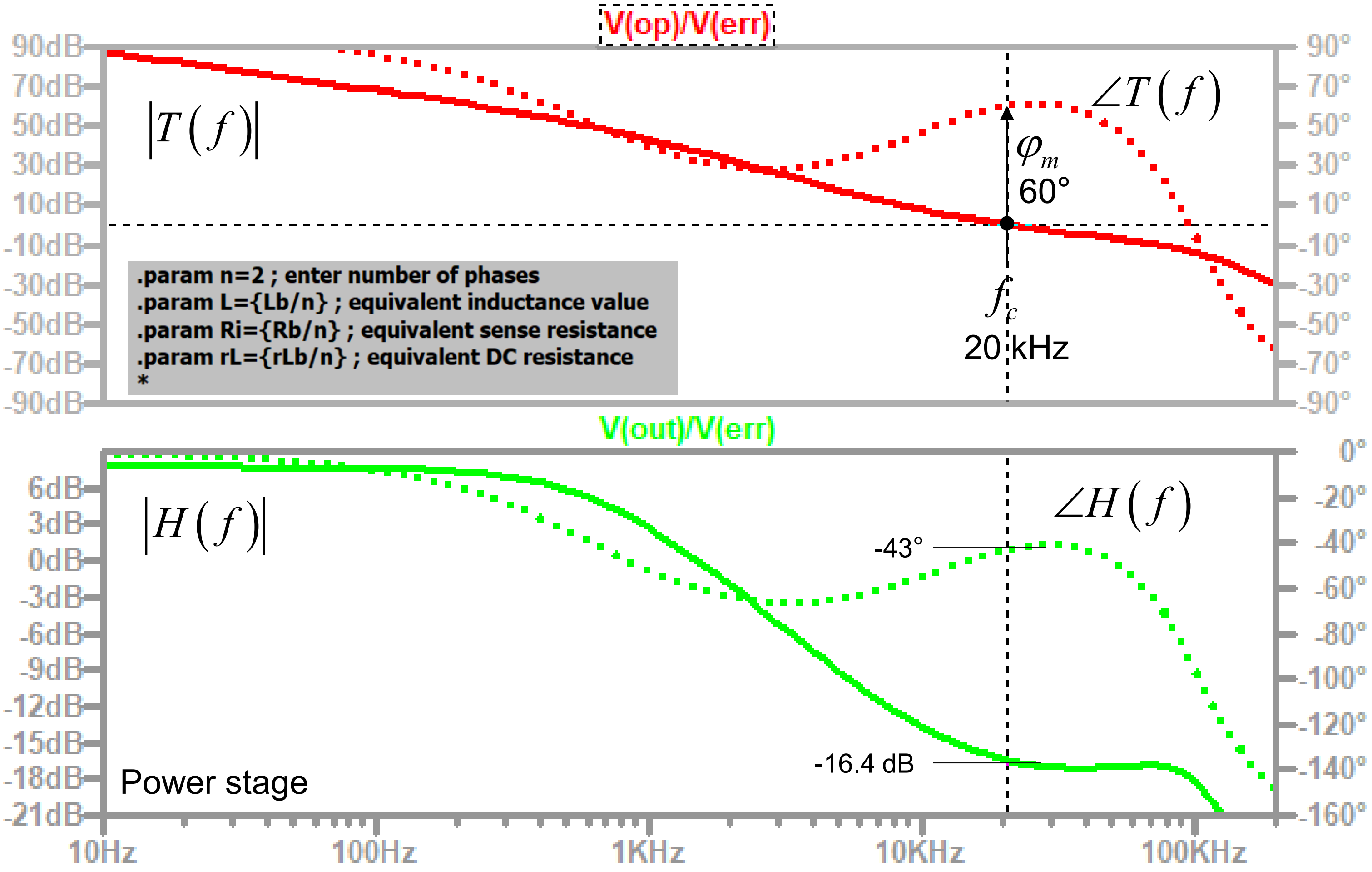
A Two-Phase CM Buck Converter

- Multiphase converters are helpful to reduce semiconductor stresses and output ripple
- A two-phase buck operated in current-mode control requires adaptation of the model



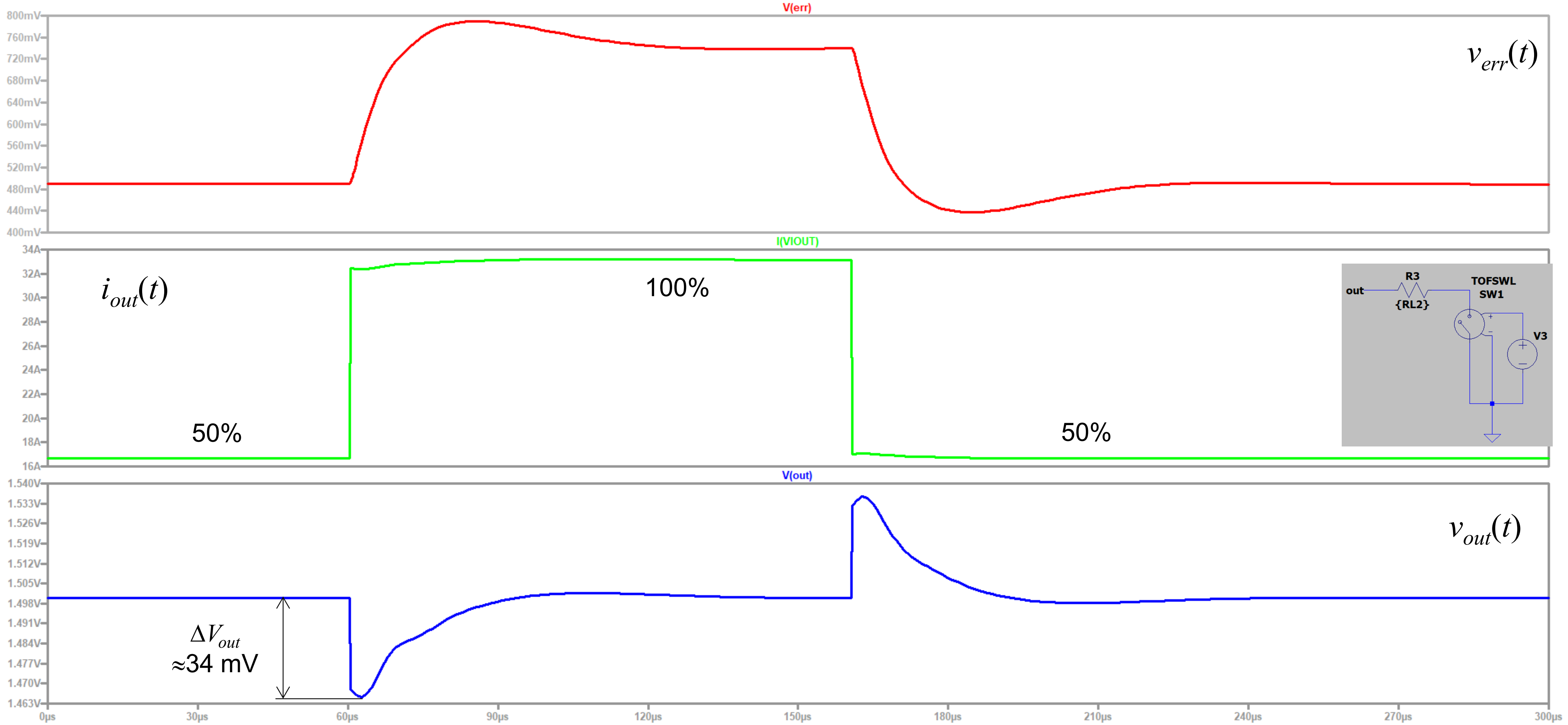
Type 2 compensator





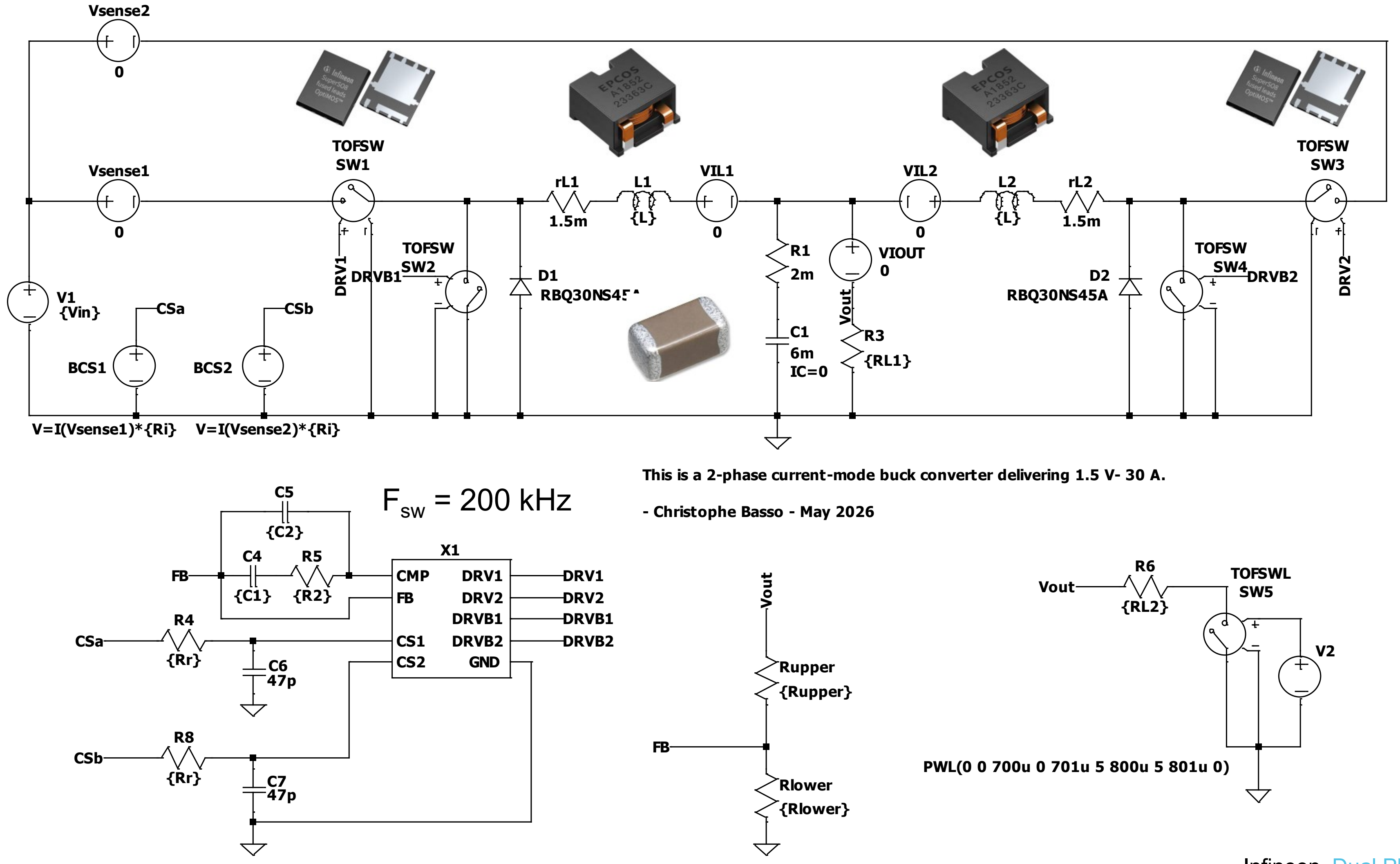
Step Load Response of the Multiphase Buck

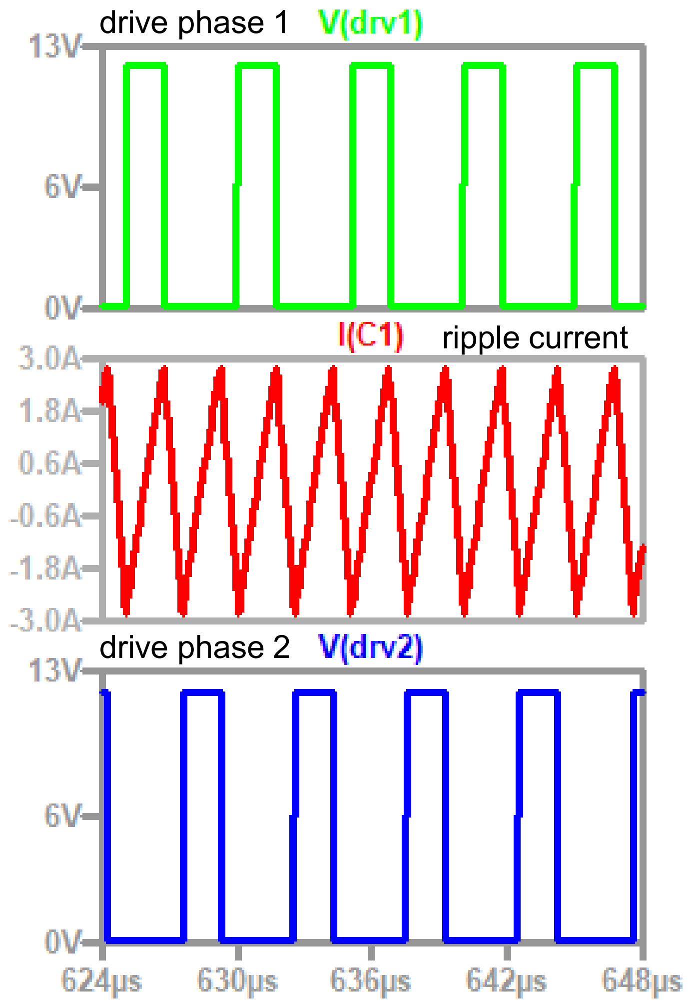
- The output voltage deviation is extremely small despite a 15-A load step



Cycle-by-Cycle Simulation of the CM Buck

- The cycle-by-cycle circuit implements a dedicated 2-phase generic controller

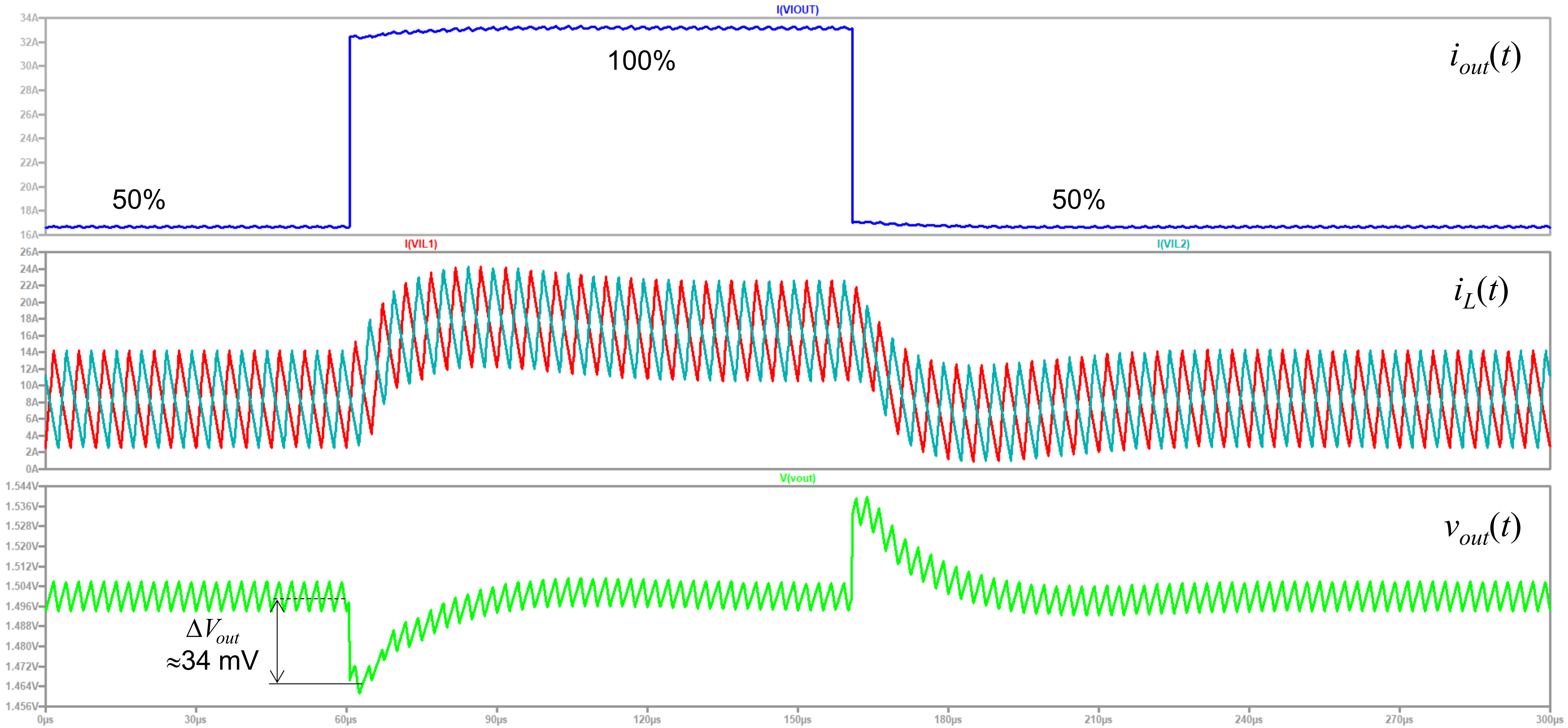




Infineon, Dual Phase Operation in Multiphase Buck Applications

Transient Response of the Switching Model

- The cycle-by-cycle circuit implements a dedicated generic controller



Conclusion

- Designing a converter combines equations, simulation and bench measurements
- A simulator is a design companion which confirms or not your calculations
- There are two types of models: averaged and switched models

✓ An averaged model simulates fast and lets you stabilize the control loop

✓ A switched model is slower and you “breadboard” the circuit on the computer

✓ A piece-wise linear simulator like SIMPLIS extracts the ac response from a switching circuit

➢ Combine ac modeling with transient simulation for a safe first power-on experiment

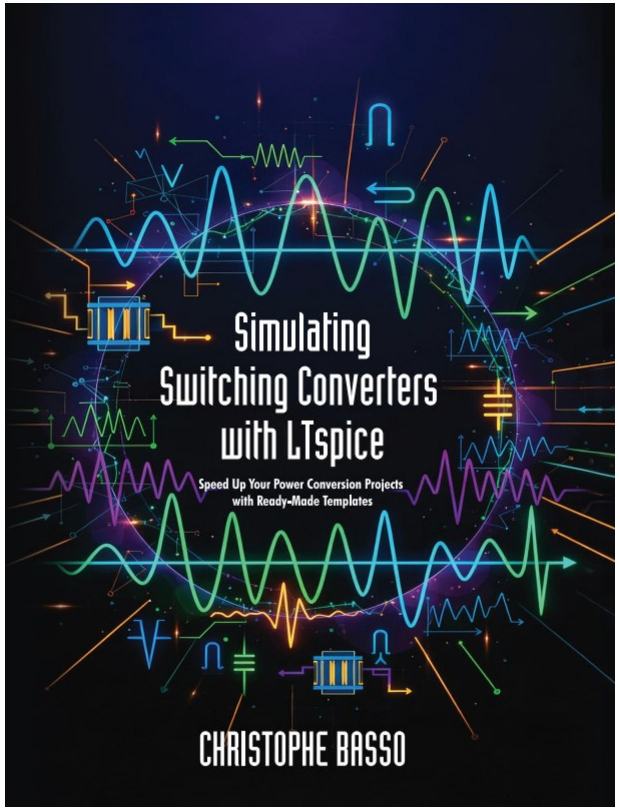
Combine analytical analysis,
simulation, prototype:
It is the recipe for success!

Snowshoeing is way cooler than simulating power supplies!

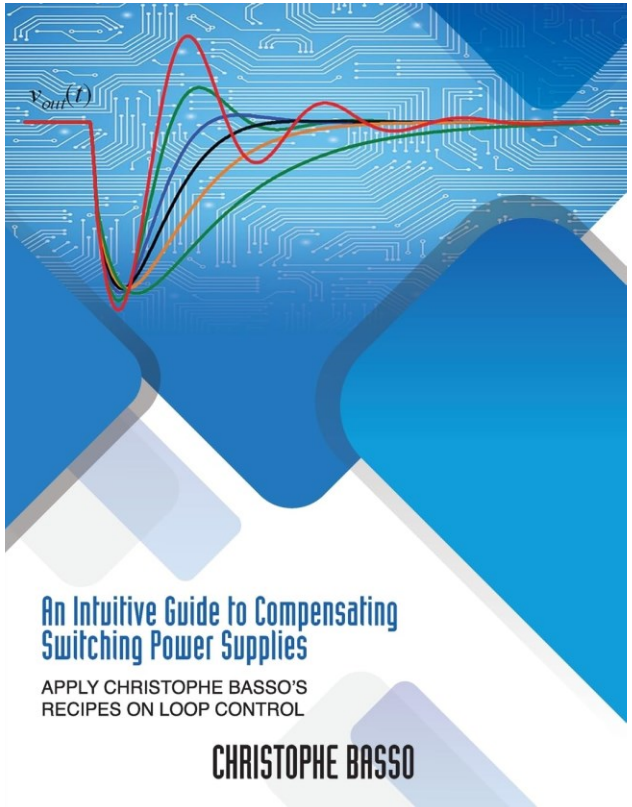
https://powersimtof.com/Spice.htm

Models and Additional Reading

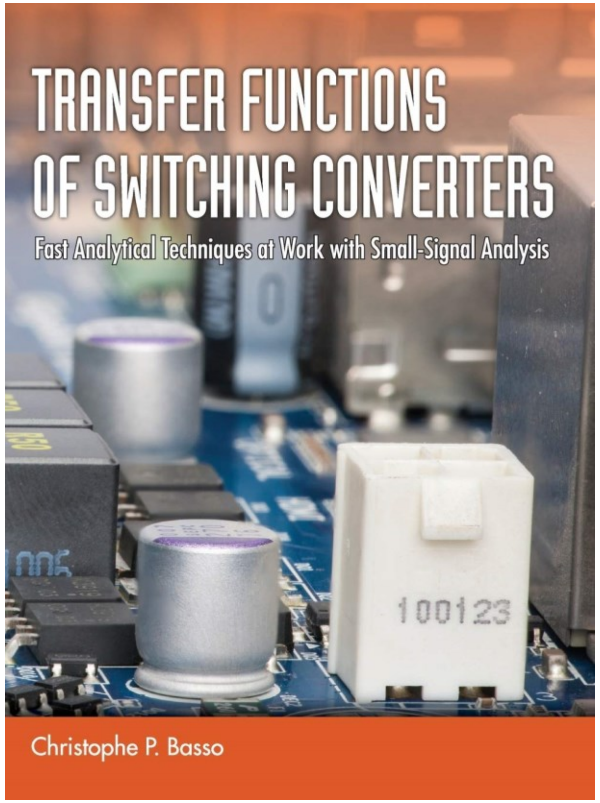
- The LTspice/SIMPLIS models can be downloaded from my webpage: https://powersimtof.com/Spice.htm



How to use my 250+ ready-made switching templates



If you want a crash course on loop control, this book is for you!



If the weather is rainy for 1 month or so, why not try small-signal analysis?