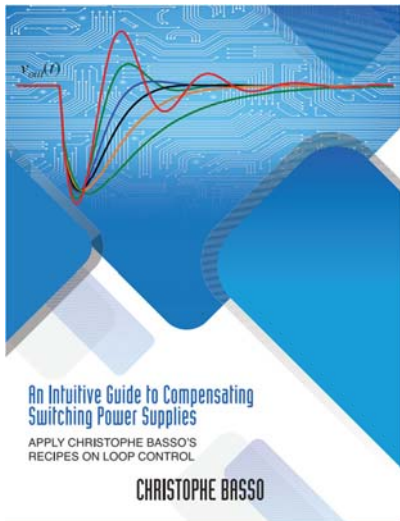


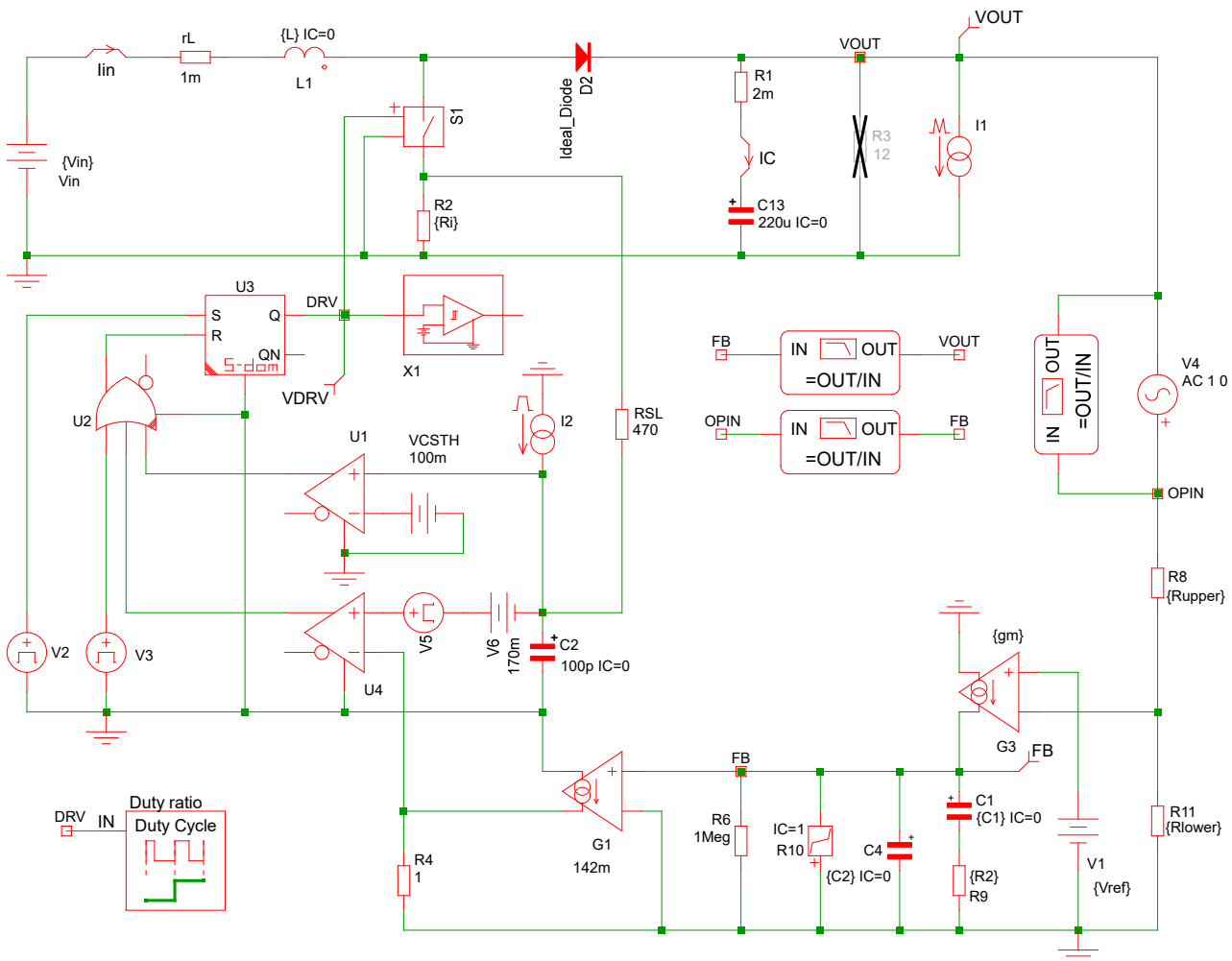
Released in June 2021



Released in September 2024

- | | | | | |
|---|--|--|--|---|
| <ul style="list-style-type: none"> Flyback CM non isolated - UC384x.sxsch Weinberg VM non isolated.sxsch Forward active clamp VM non-isolated.wxsch LLC CM Full Opto 500 W.sxsch Flyback CM QR Prim Reg 2 Outputs.sxsch Buck-Boost VM compensated TRAN.wxsch Boost CM PFC ac tran demo.wxsch CUK VM coupled.sxsch Boost TPPFC CCM 3-Level T-type Var toff.sxsch Boost PFC 1-Phase 3-Level Interleaved CCM M... Buck CM Synchro.sxsch Boost PFC 3-Phase 6-switch OCC - PoP.sxsch Boost CCM Var toff PFC tran 1.3 kW - interleav... Forward VM non iso PSRR OL.wxsch Flyback active clamp CM isolated and compen... Full Bridge 3-Level Ac Inverter.sxsch Flyback 25W CM isolated gate drive.wxsch Boost average CM PFC TRAN.sxsch Boost PFC NCP1654 TRAN Step.sxsch Full bridge phase shift CM isolated Zener.wxsch Boost CCM Var toff PFC ac analysis.sxsch LLC VM demo.wxsch Half bridge VM non iso.wxsch Flyback VM non-isolated compensated 12-24 ... Forward active clamp VM non-isolated with SR... Forward active clamp VM non-isolated - demo... Flyback VM QR single stage ac.wxsch Buck 2 Phase CM.wxsch Flyback CM single stage non iso MC33262 dc ... | <ul style="list-style-type: none"> Book Collection.zip Boost CM with OTA LM5155.sxsch Flyback CM QR isolated.wxsch LLC Bang Bang Charge Control demo.wxsch Flyback CM Isolated dc input - UC384x.sxsch Flyback CM isolated leakage.wxsch Buck VM Synchro.sxsch CUK CM coupled.sxsch Full bridge CM isolated - full version.wxsch Forward CM isolated.wxsch Buck CM.sxsch Forward CM isolated - UC384x.sxsch Boost PFC 1-Phase 3-Level CCM Mul.sxsch Buck Class D.sxsch Flyback CM QR open-loop.wxsch Half bridge VM isolated Zener.wxsch Full bridge phase shift VM isolated.wxsch Boost average CM PFC Step.sxsch Boost PFC NCP1654 AC.sxsch Full bridge phase shift CM isolated - full versio... Flyback CM isolated Zener diode.sxsch Tapped Buck VM.wxsch Half bridge VM isolated - full version.wxsch Buck 2 Phase VM.wxsch Buck BCM.wxsch Forward active clamp CM non-isolated - demo... Flyback CM single stage non iso MC33262 ac si... Boost CM PFC sine full version.wxsch OPSIMP.sxcmp | <ul style="list-style-type: none"> Buck VM Monte Carlo_mc.sxsch Buck VM PID analog.sxsch Flyback CM isolated.wxsch OPTOPARAM.sxcmp Boost VM PFC sine full version.wxsch Boost CCM Average Mode PFC 1854.sxsch CUK CM isolated.sxsch LLC Charge Control with Type 2.sxsch Boost TPPFC CCM Var toff tran.sxsch Buck VM Zin.sxsch Buck VM Monte Carlo.sxsch Flyback CM Isolated ac input - UC384x.sxsch Flyback VM non-isolated TRAN.wxsch Buck CM with OTA.sxsch Buck Ac-Ac Converter - full version.sxsch Boost CCM Var toff PFC tran 1.3 kW - demo Po... Full bridge phase shift VM isolated with DT and... Boost average CM PFC Ac V_loop.sxsch Boost CCM Var toff PFC tran 1.3 kW - demo.sx... Forward 25W CM non iso.wxsch Boost CCM Var toff PFC load step.sxsch Tapped Boost VM.wxsch Forward VM isolated.wxsch Boost VM compensated TRAN.wxsch LLC CM Demo.sxsch Flyback VM single stage non iso NCP1608 dc O... Flyback CM QR isolated ac sine input.wxsch Boost BCM CM.wxsch Buck FOT.wxsch | <ul style="list-style-type: none"> Buck VM digital PID.sxsch Full bridge CM isolated Zener.wxsch Buck-Boost CM.wxsch LLC VM type 2.sxsch Flyback VM non-isolated compensated AC.wx... Boost VM PFC ac tran demo.wxsch CUK VM isolated.sxsch Boost VM compensated AC.sxsch Boost TPPFC BCM.sxsch Forward VM non iso.wxsch Buck VM.sxsch Boost CM - UC3843.sxsch Boost CCM Var toff PFC tran CT.sxsch Buck VM Zout.sxsch Buck Ac-Ac Converter - demo.sxsch Pushpull CM isolated.wxsch LLC open loop demo.wxsch Boost average CM PFC Ac I_loop.sxsch Flyback active clamp CM non-isolated - demo ... Forward 25W CM isolated.wxsch Flyback active clamp CM non-isolated - demo... Tapped Buck VM.wxsch Forward 25W VM non iso.wxsch Boost 2 Phase VM compensated TRAN.wxsch Zeta Coupled CM.wxsch Flyback VM single stage non iso NCP1608 ac si... Flyback CM isolated ac sine input.wxsch Boost 2 Phase CM compensated.wxsch TL431_CB.sxcmp | <ul style="list-style-type: none"> Weinberg CM non isolated.sxsch Christophe Basso SIMPLIS Collection.pptx Boost CM.wxsch Flyback CM QR Weighted Reg 2 Outputs.sxsch Buck-Boost VM compensated AC.wxsch Buck Hysteretic.sxsch CUK VM uncoupled.sxsch Full bridge phase shift VM nonisolated with op... Boost PFC 1-Phase 3-Level Interleaved CCM Va... Buck COT.wxsch Boost PFC 3-Phase 6-switch MUL - PoP.sxsch Buck VM CCM - UC3843.sxsch Buck CM PoE.sxsch Buck VM with OTA.sxsch DAB converter closed loop.sxsch Boost CCM Var toff PFC tran 1.3 kW - demo Po... LLC open loop full bridge.sxsch Boost PFC NCP1654 TRAN.sxsch Forward CM non iso.wxsch Boost CCM Var toff PFC tran.sxsch Flyback VM non-isolated compensated AC Zin... Pushpull VM isolated.wxsch Forward 25W VM non iso.wxsch Boost 2 Phase VM compensated AC.wxsch Pushpull CM non iso.wxsch Flyback VM QR single stage sine.wxsch Flyback 25W CM isolated.wxsch SEPIC Coupled CM.wxsch SIMPLIS_Data |
|---|--|--|--|---|

There are 130+ free to download simulation templates
 ≈80% of these circuits work with the demonstration version Elements



```

*
.VAR Vin=6
.VAR Vout=24
.VAR Rload=12
.VAR L=6u
.VAR Ri=6m
.VAR Fs=440k
.VAR Ts={1/Fs}
*
.VAR D={1-(Vin/Vout)} * duty ratio calculation *
.VAR fRHPZ={(((1-D)^2*Rload/L)/(2*pi))}
.VAR fcMAX=0.2*fRHPZ
*
.VAR Gfc=6 * magnitude at crossover *
.VAR PS=-90 * phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.VAR fc=2k * targeted crossover *
.VAR PM=60 * choose phase margin at crossover *
*
* Enter the Values for Vout and Bridge Bias Current *
*
.VAR Ibias=1m
.VAR Vref=1
.VAR Rlower={Vref/Ibias}
.VAR Rupper={(Vout-Vref)/Ibias}
*
* Choose OTA characteristics *
*
.VAR gm=2m * transconductance in siemens *
*
.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))
*
.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)

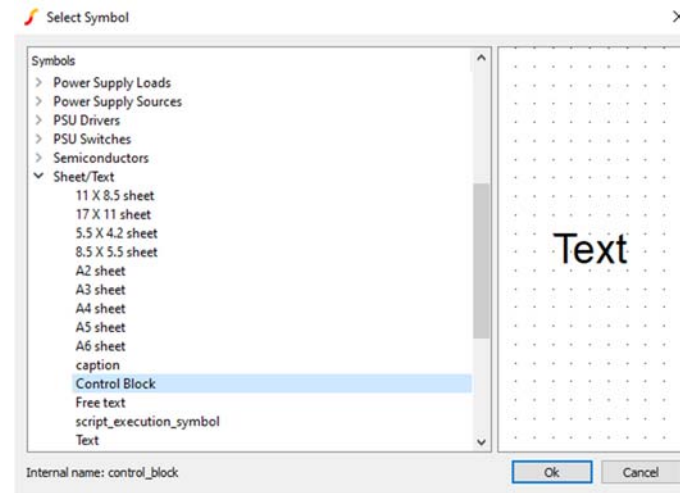
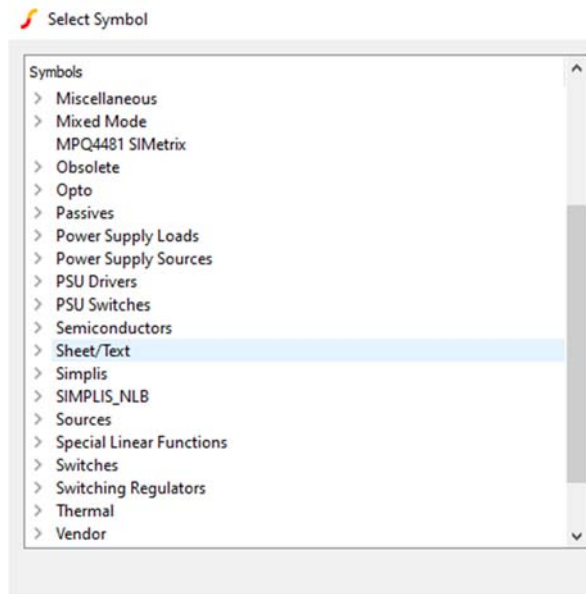
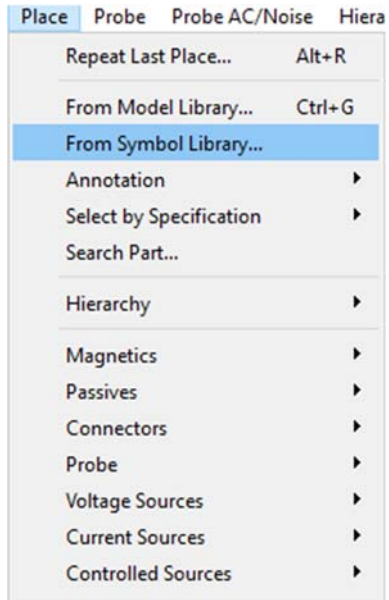
```



Change f_c to 1 kHz, $PM = 60^\circ$
 Change PM to 45° with step load

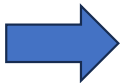
Boost CM with OTA LM5155

I use a Control Block to automate all my calculations:



It is NOT a free text window!

I prefer it over F11 control commands which are naturally hidden.



```
* Optocoupler specifications *  
*  
.VAR Rpullup=10k * check with the selected control chip *  
.VAR Fopto=10k  
.GLOBALVAR Copto=1/(2*pi*Fopto*Rpullup)  
.GLOBALVAR CTR=0.8  
*
```

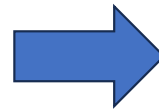
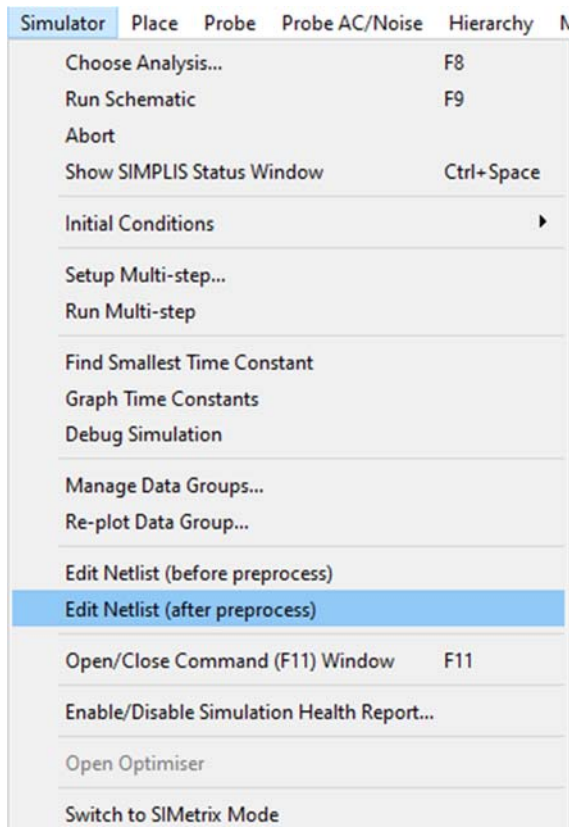
.VAR is a local variable

.GLOBALVAR is a global variable passed to a subcircuit

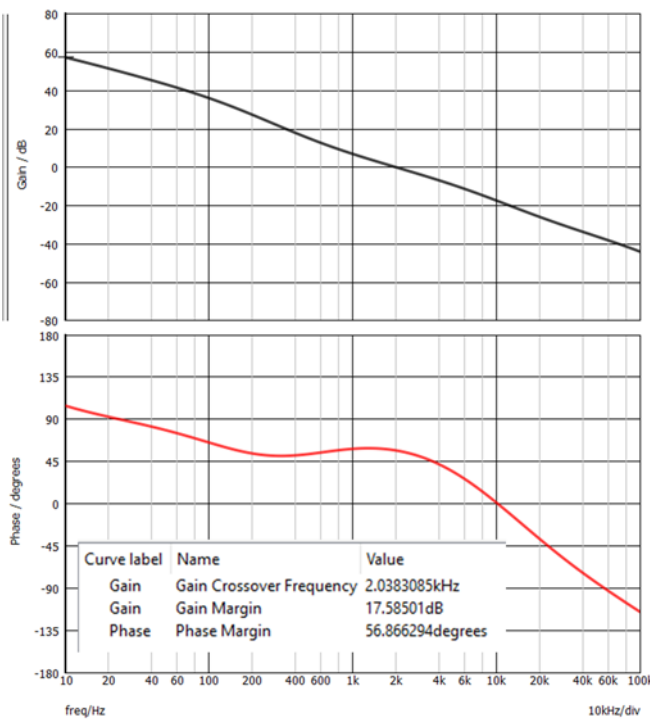
For debugging the automated macro, use the curly braces:

```
*  
{ '*' }  
{ '*' } G = {G}  
{ '*' } fp1 = {fp1}  
{ '*' } ki = {ki}  
{ '*' } kd = {kd}  
{ '*' } kp = {kp}  
{ '*' } Ti = {Ti}  
{ '*' } Td = {Td}  
{ '*' } N = {N}  
{ '*' }  
*
```

↑
Include these in
your control block



```
*  
*  
* G = 8.93367184301926  
* fp1 = 3955.09138381201  
* ki = 10019.8508023075  
* kd = 0.000228988740525218  
* kp = 4.01291260344107  
* Ti = 0.000400496243169302  
* Td = 5.70629772322628e-05  
* N = 1.41804762831445  
*
```



Design goal is 2 kHz f_c

$$C_{out} = 220 \mu\text{F}$$

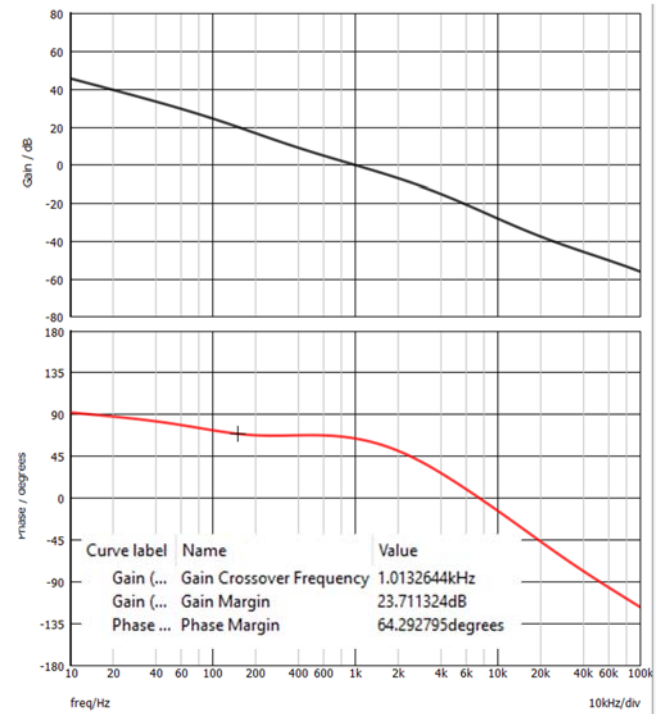
$$f_c = 1 \text{ kHz}$$

$$\Delta V_{out} \approx \frac{\Delta I_{out}}{2\pi f_c C_{out}} \approx 720 \text{ mV}$$

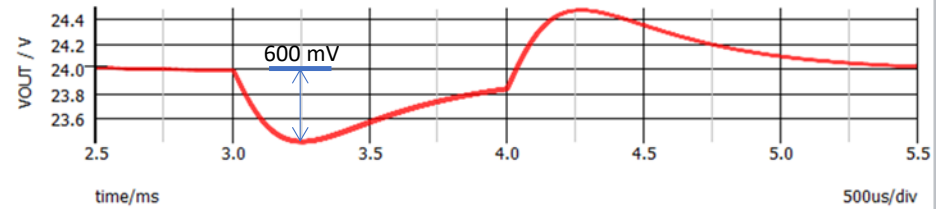
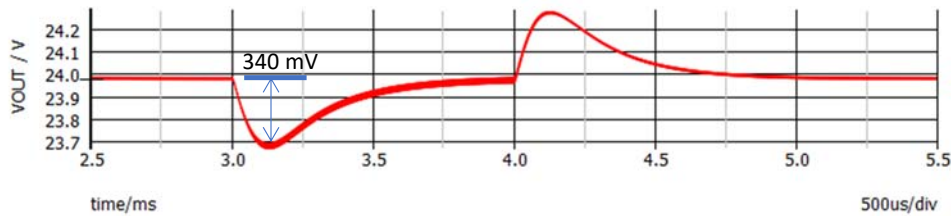
$$C_{out} = 220 \mu\text{F}$$

$$f_c = 2 \text{ kHz}$$

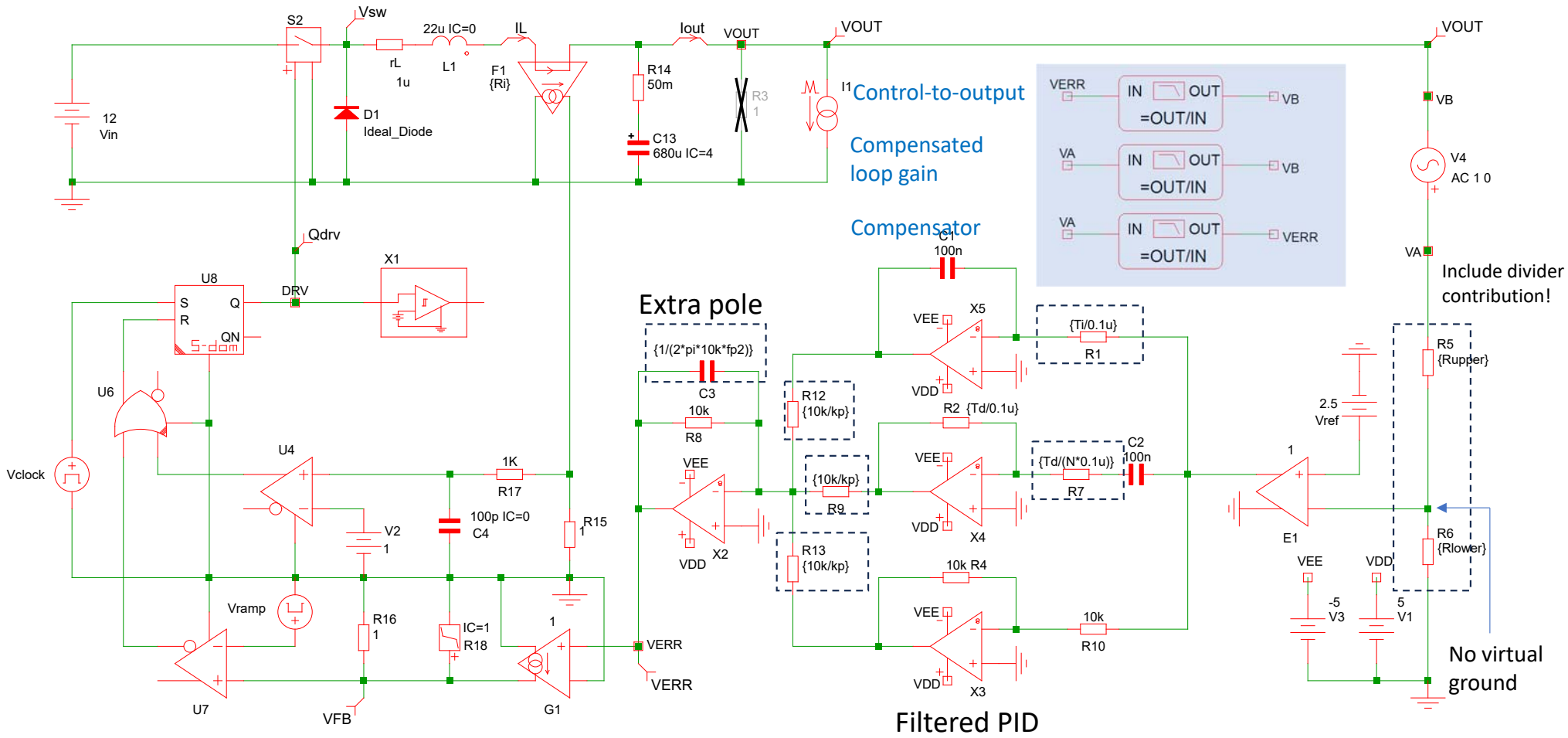
$$\Delta V_{out} \approx \frac{\Delta I_{out}}{2\pi f_c C_{out}} \approx 360 \text{ mV}$$



Design goal is 1 kHz f_c

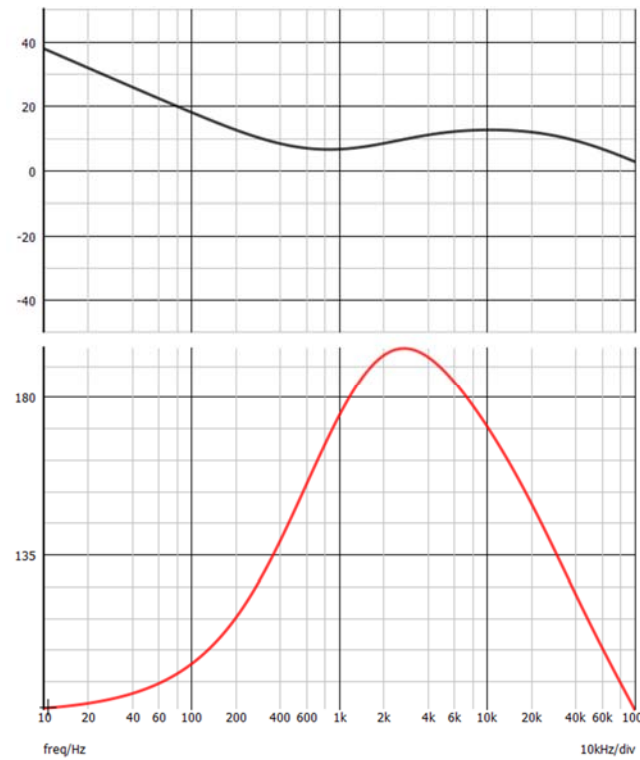
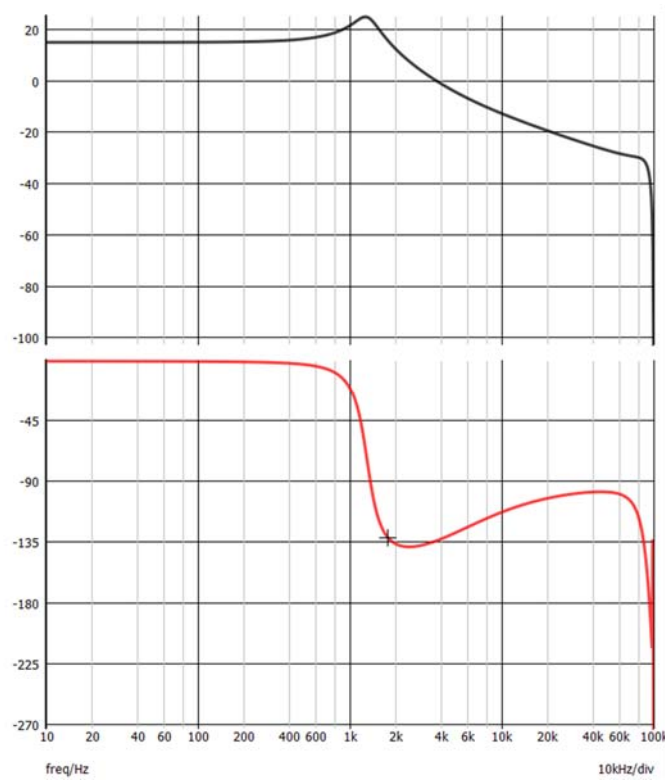


These Bode boxes let me plot three different transfer functions.

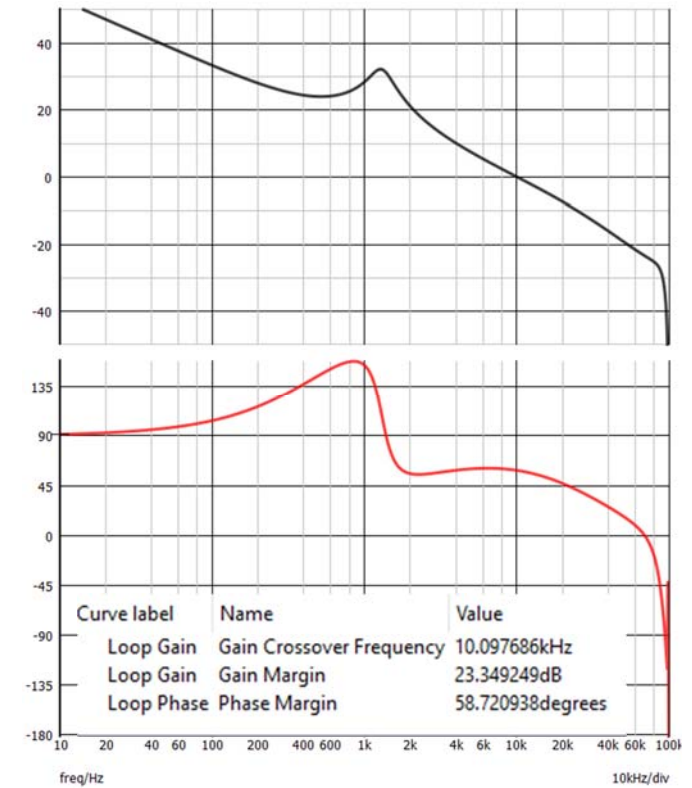


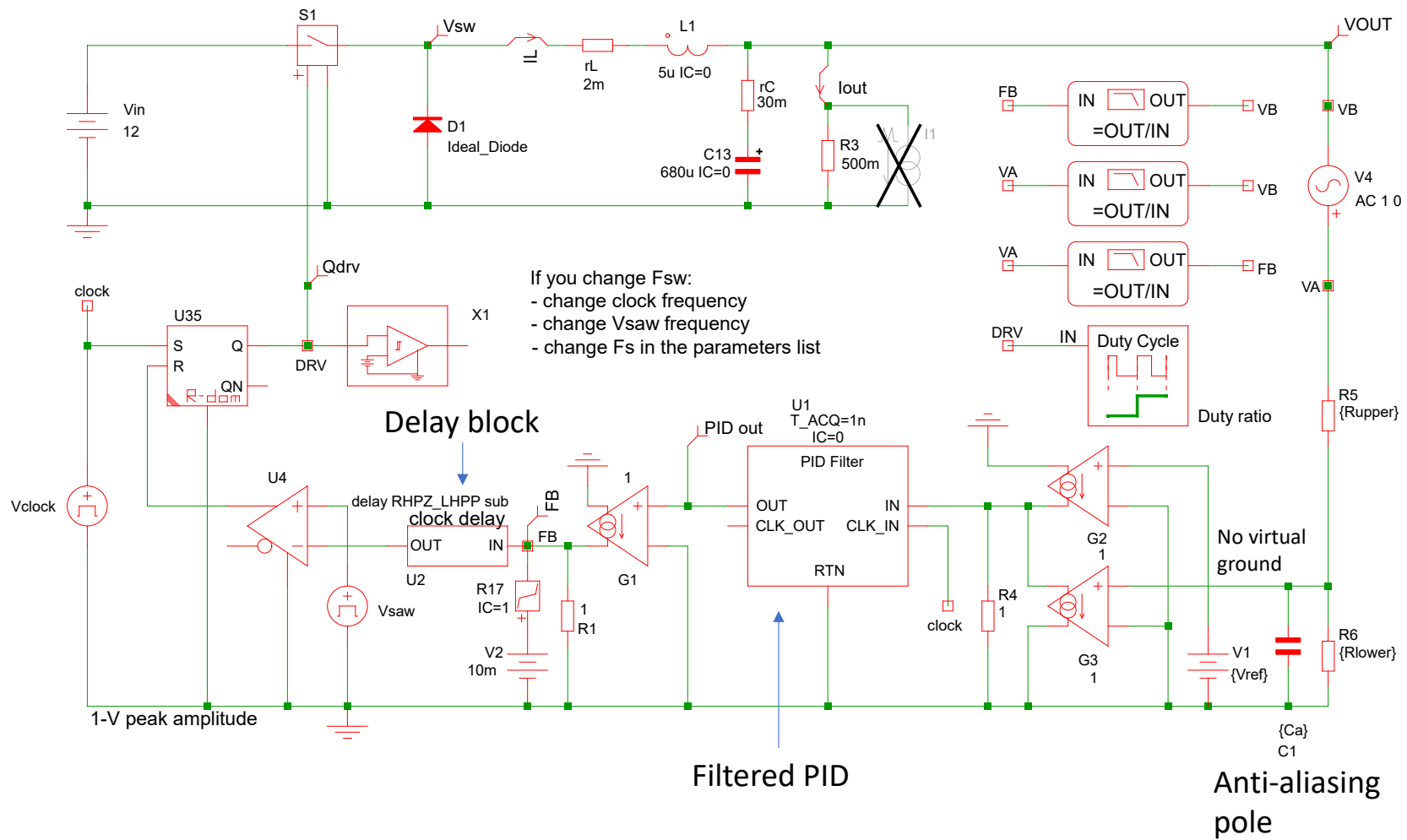
Filtered PID + extra pole → Type 3 compensator

Buck VM PID analog

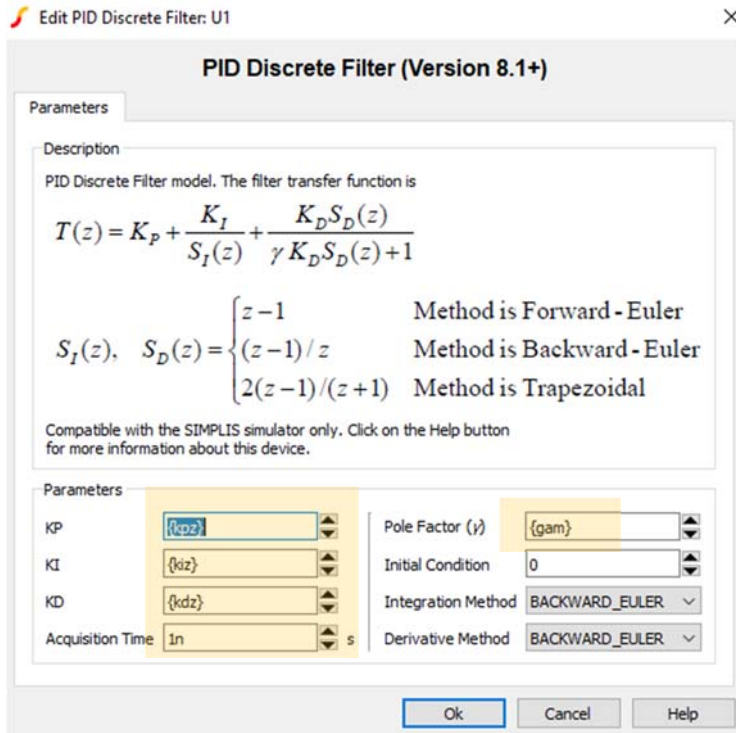


PID coefficients are automated from the macro





Buck VM with digital PID



```

* Capture the double zero position and one of the pole position *
.var fz1=2.5k
.var fz2=1k
.var fp2=125k ; pole is brought by the anti-aliasing filter at Fsw/2
*
* Do not edit the below lines *
.var boost=PM-PS-90
.var G=(10^(-Gfc/20))/kdiv
.var fp1=fc/tan((2*atan(fc/fz1)-atan(fc/fp2))-boost*pi/180) * adjust second pole for targeted boost *
.var Fs=250k
.var Ts={1/Fs}
*
.global var Wtau=1/Ts ; transport delay with zero PWM delay
.global var R={1/(10n*Wtau)}
*
.var Req={Rupper*Rlower/(Rupper+Rlower)} ; equivalent resistance driving Ca
.var Ca={1/(pi*Fs*Req)} ; anti-aliasing filter at Fsw/2
*
.var wz1={2*pi*fz1}
.var wz2={2*pi*fz2}
.var wp1={2*pi*fp1}
.var wp2={2*pi*fp2}
*
.var a=sqrt(1+(fc/fp1)^2)
.var b=sqrt(1+(fc/fp2)^2)
.var c=sqrt(1+(fz1/fc)^2)
.var d=sqrt(1+(fc/fz2)^2)
.var G0=(a*b/(c*d))*G
.var Cwp2={1/(wp2*1k)}
*
.var ki=G0*wz1
.var kd=((wz2-wp1)*(ki-G0*wp1))/(wp1^2*wz2)
.var kp=G0*((wz1+wz2)/wz2-wz1/wp1)
*
.var kpz=kp
.var kdz=kd/Ts
.var kiz=ki*Ts
.var gam=1/(wp1*kd)

```

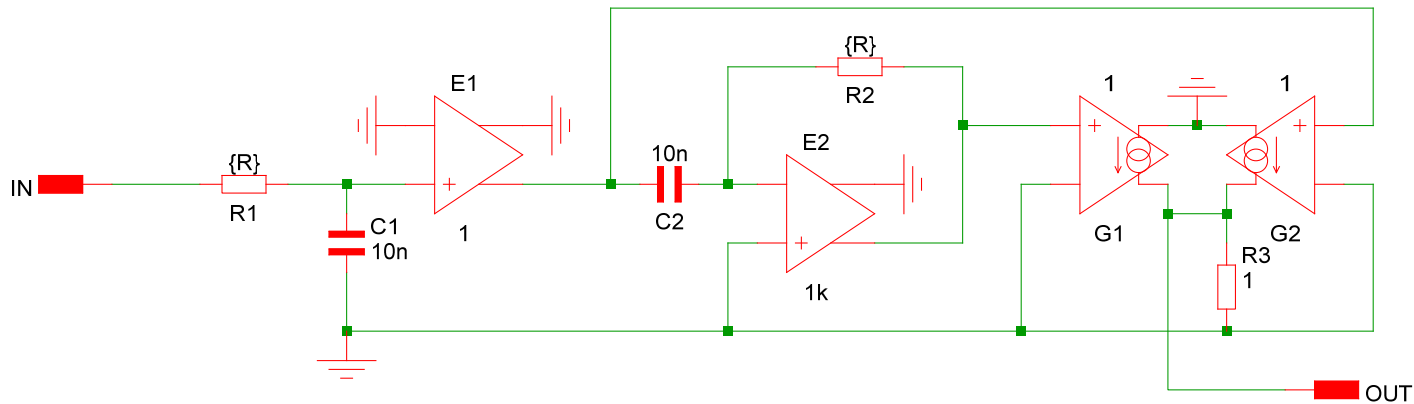
Calculation of the PID parameters based on poles-zeros placement

Discrete parameters passed to the digital PID model

A delay can be implemented based on the first-order Padé approximant:

$$e^{-sT_s} \approx \frac{1 - \frac{sT_s}{2}}{1 + \frac{sT_s}{2}}$$

← RHP zero located at $\omega_z = \frac{2}{T_s} \rightarrow f_z = \frac{1}{\pi T_s}$
 ← LHP pole located at $\omega_p = \frac{2}{T_s} \rightarrow f_p = \frac{1}{\pi T_s}$

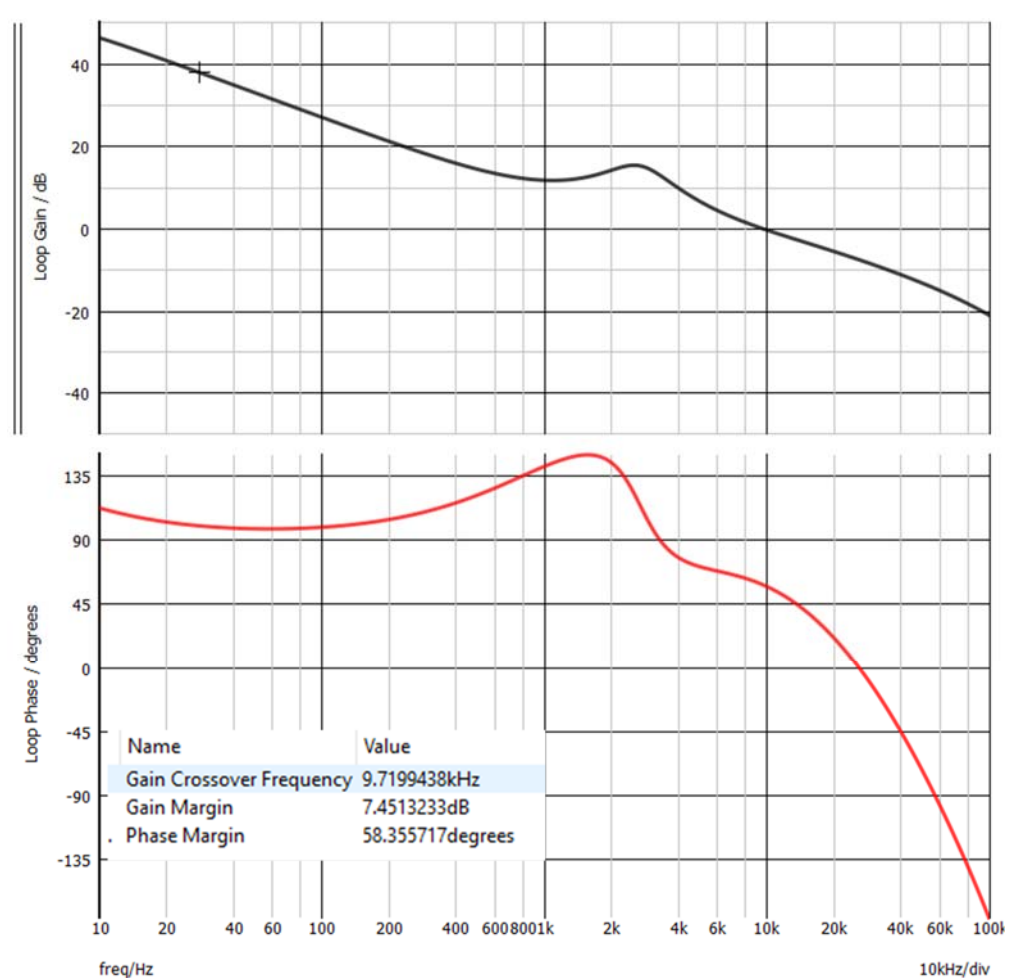
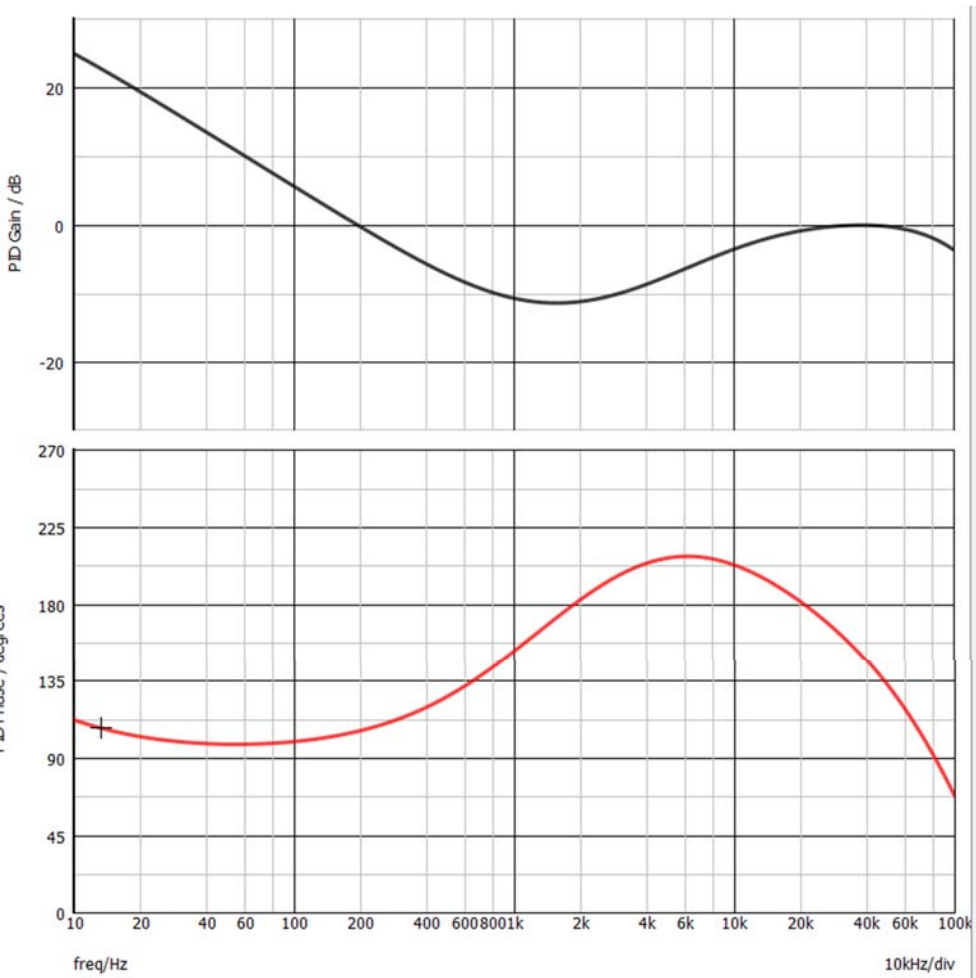


```
.globalvar Wtau=1/Ts ; transport delay
.globalvar R={1/(10n*Wtau)}
*
```

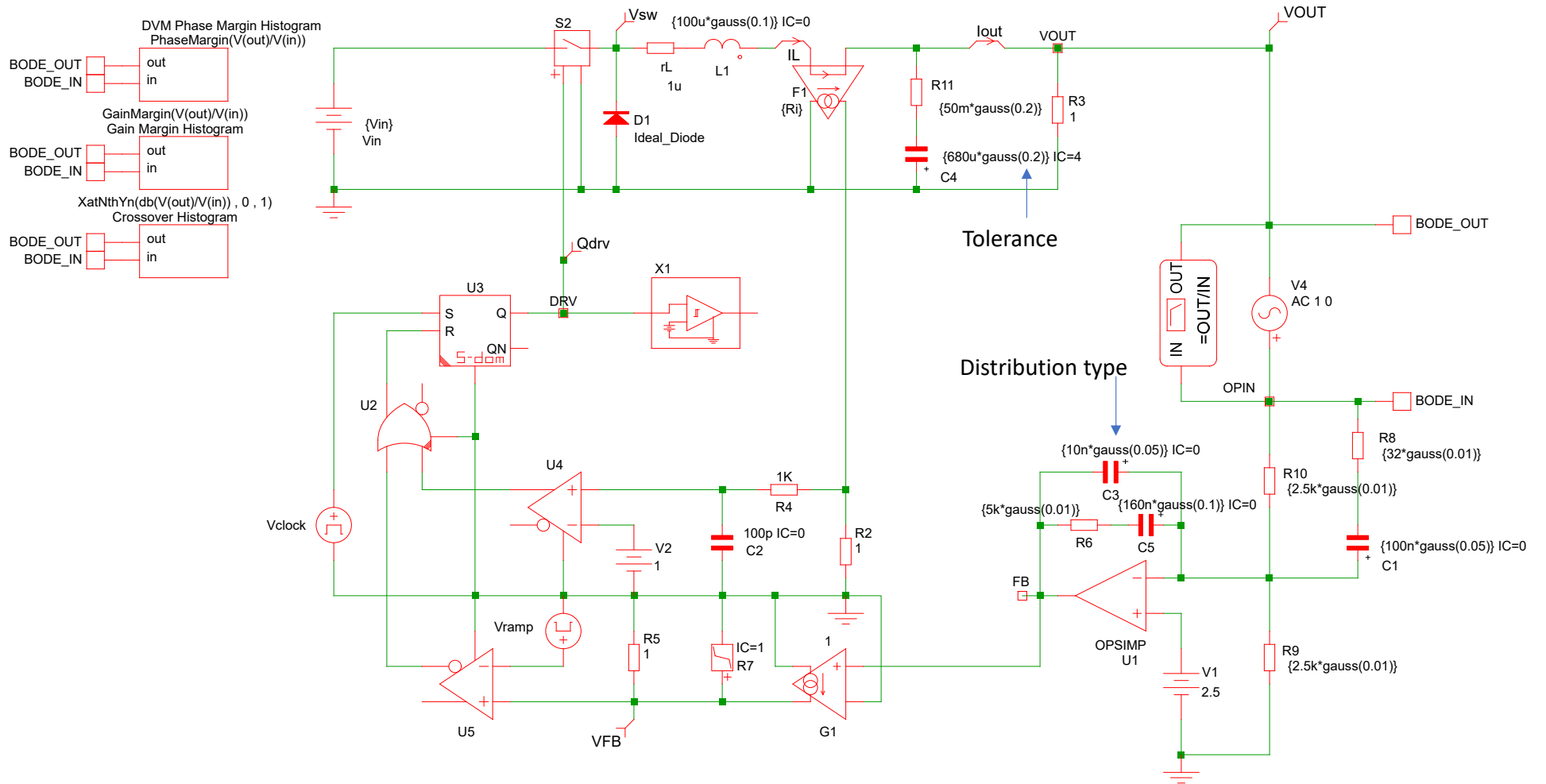
Total delay

$$e^{-s(T_s + DT_s)}$$

↑
 = 0
 Analog PWM



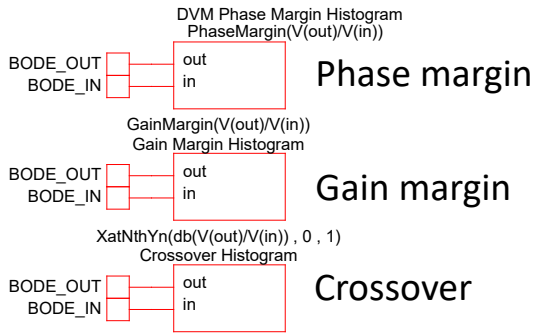
Transfer function of the filtered PID with an extra pole



[How2Power Monte Carlo](#) – Stéphanie Cannenterre
[Monte Carlo gone wrong](#) – Charles Hymowitz

Buck VM Monte Carlo

Goal functions to insert



Mean1(V(in)) Goal Functions...

GainMargin(V(out)/V(in)) ← Goal function

Curve label

Gain Margin Histogram

Use \$FREF\$ for hierarchical reference

Mean1(V(in)) Goal Functions...

PhaseMargin(V(out)/V(in))

Curve label

DVM Phase Margin Histogram

Mean1(V(in)) Goal Functions...

$\text{XatNthYn}(\text{db}(V(\text{out})/V(\text{in})), 0, 1)$

Curve label

Crossover Histogram

Use \$FREF\$ for hierarchical reference

Probe Probe AC/Noise Hierarchy Monte Carlo C-

Repeat last probe... Ctrl+R

Add Curve...

Voltage...

Voltage (New graph sheet)...

Voltage - Differential...

Voltage - Digital...

Voltage - AC coupled...

Voltage - Bus...

Current in Device Pin...

Current in Wire...

Current in Device Pin (New graph sheet)...

More Probe Functions...

Power In Device...

Fourier

New Graph Sheet

Enable/Disable Fixed Probes...

Place Fixed Voltage Probe... B

Place Fixed Current Probe... U

Place Fixed Power Probe...

Place Fixed Inline Current Probe

Place Fixed Diff. Voltage Probe...

Place Bus Probe

Place XY Probe

Place Fourier Voltage Probe

Create and Place Arbitrary Probe

Delete All Fixed Probes

Performance Analysis...

Plot histogram...

Edit Probe

Probe Options Axis Scales Axis Labels

Probe expression

Enter a goal function to define the probe. Use V(nr) for voltages and I(ss) for currents. /nr and /ss may be any string starting with a letter.

For example, the following will create a histogram of the mean of a single input voltage

Mean1(V(in)) Goal Functions...

Multi-step mode

Multiple curves

Performance analysis

Histogram

Histogram options

Number of bins: 1 default

Show advanced statistics

History

History depth: 1 default

Use separate curves. If enabled, a new curve is created for each new run and history depth is ignored.

On

Off

Global default may be set from menu File | Options | General...

Use default [OFF]

Graph

Use named graph

Graph name: _____

Set tab/caption to name

Keep different analysis types on same graph

Analyses

All analyses disabled

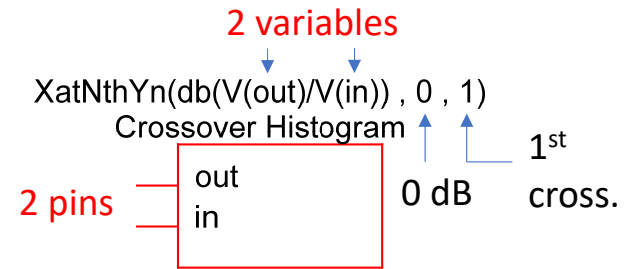
Transient

POP

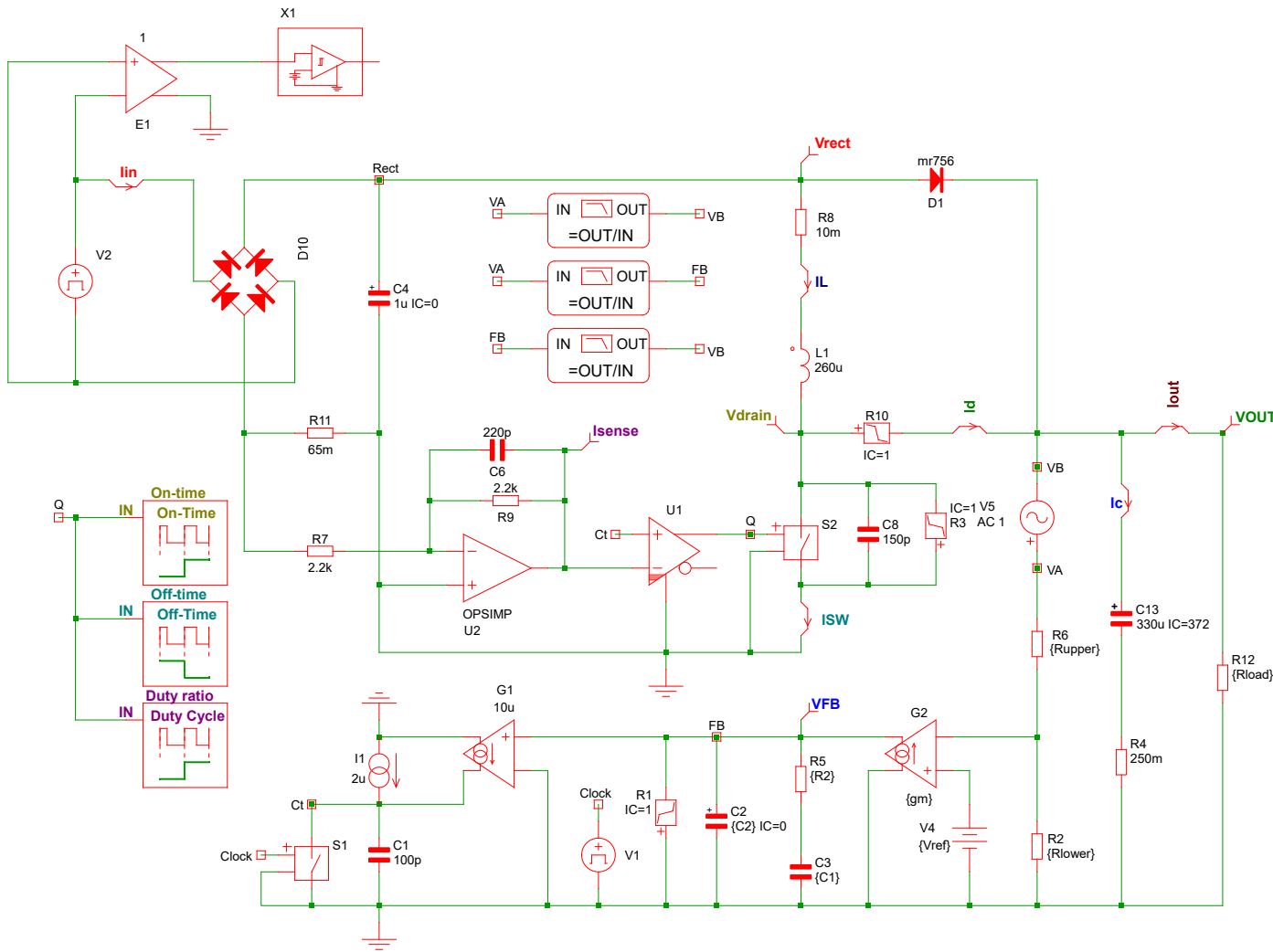
AC sweep

Plot on completion only

Ok Cancel Help



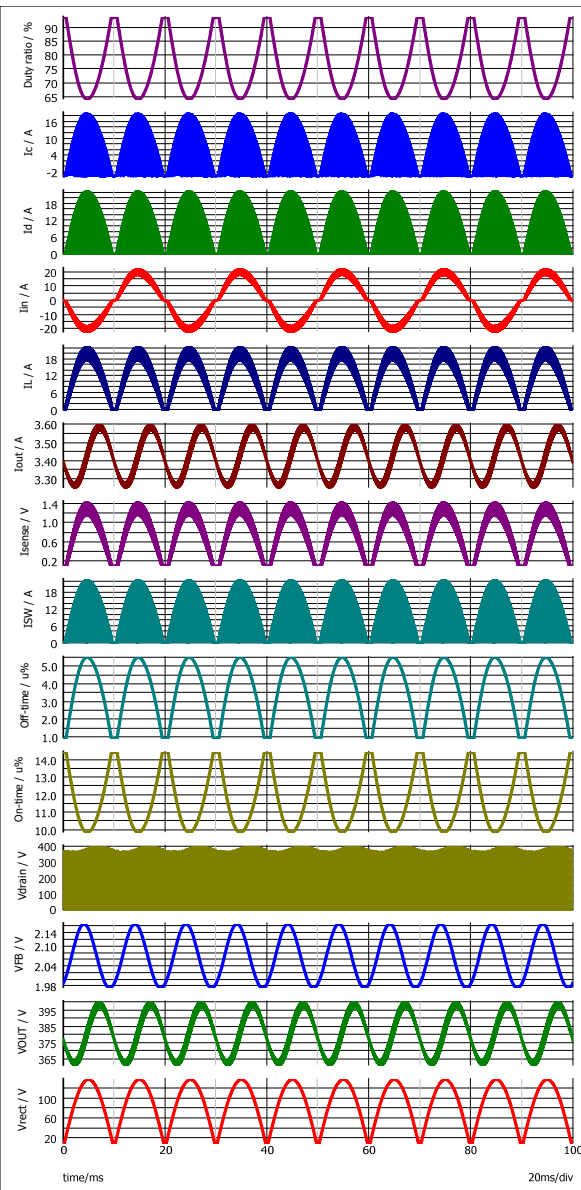
$\text{XatNthYn}(\text{data}, \text{yValue}, \text{n})$ X value at the Nth Y crossing with negative slope



In this example, the POP is found while the converter is supplied from an ac sinewave source. The ratio between the clock frequency and the input ac source must be an integer to have the POP converge.

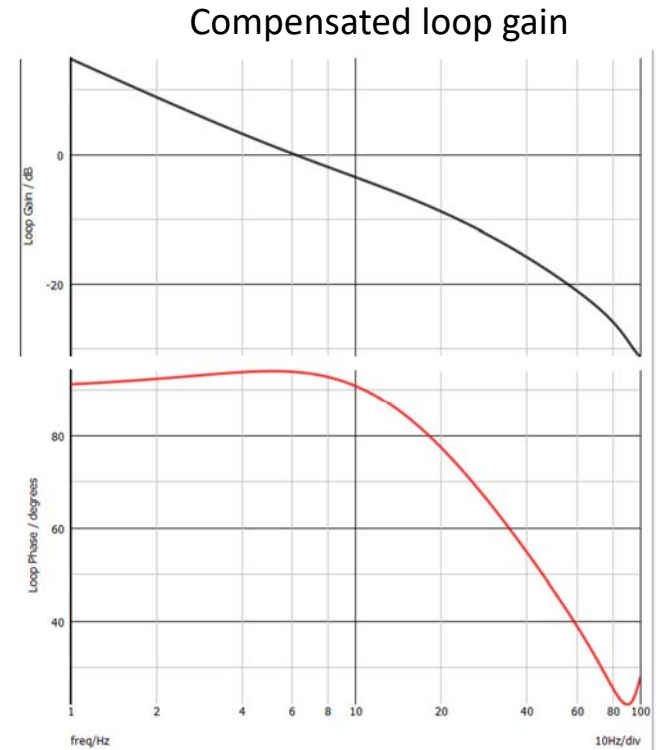
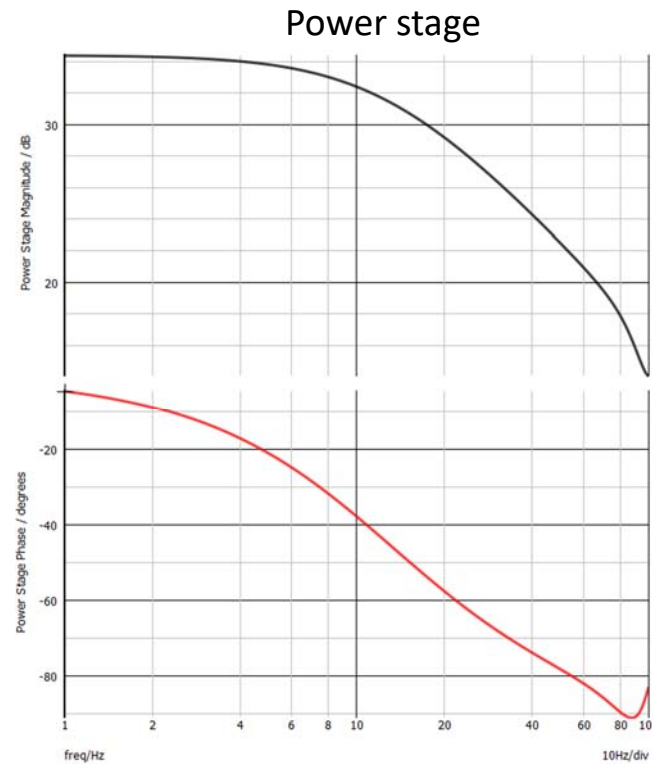
Here, $f_{\text{clock}} = 65 \text{ kHz}$ and $f_{\text{line}} = 50 \text{ Hz}$ giving an exact ratio of 1300. If you want to test a 60-Hz source, adjust the clock to 64.98 kHz for a ratio of 1083.

Boost CCM Var toff PFC tran 1.3 kW – demo POP



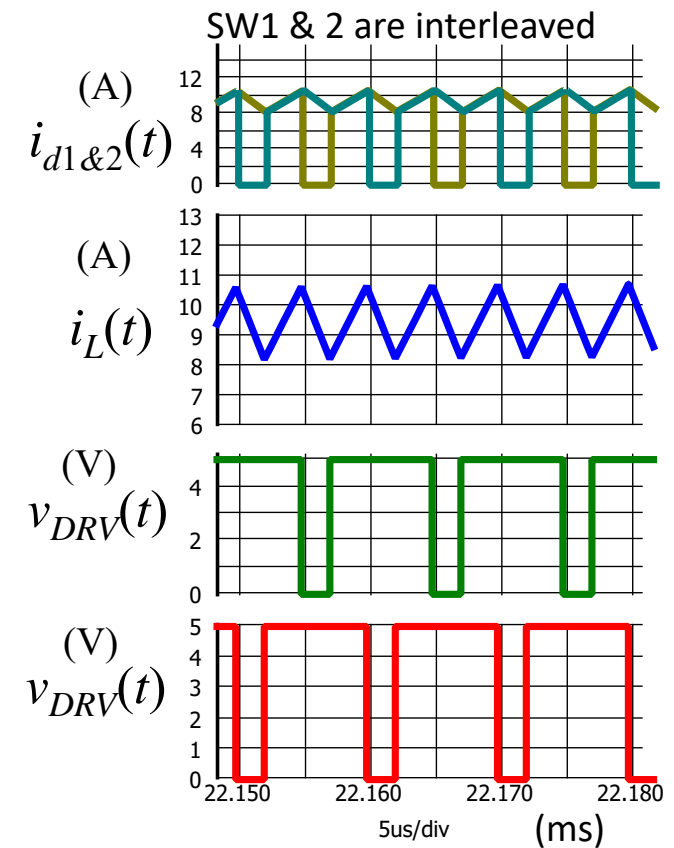
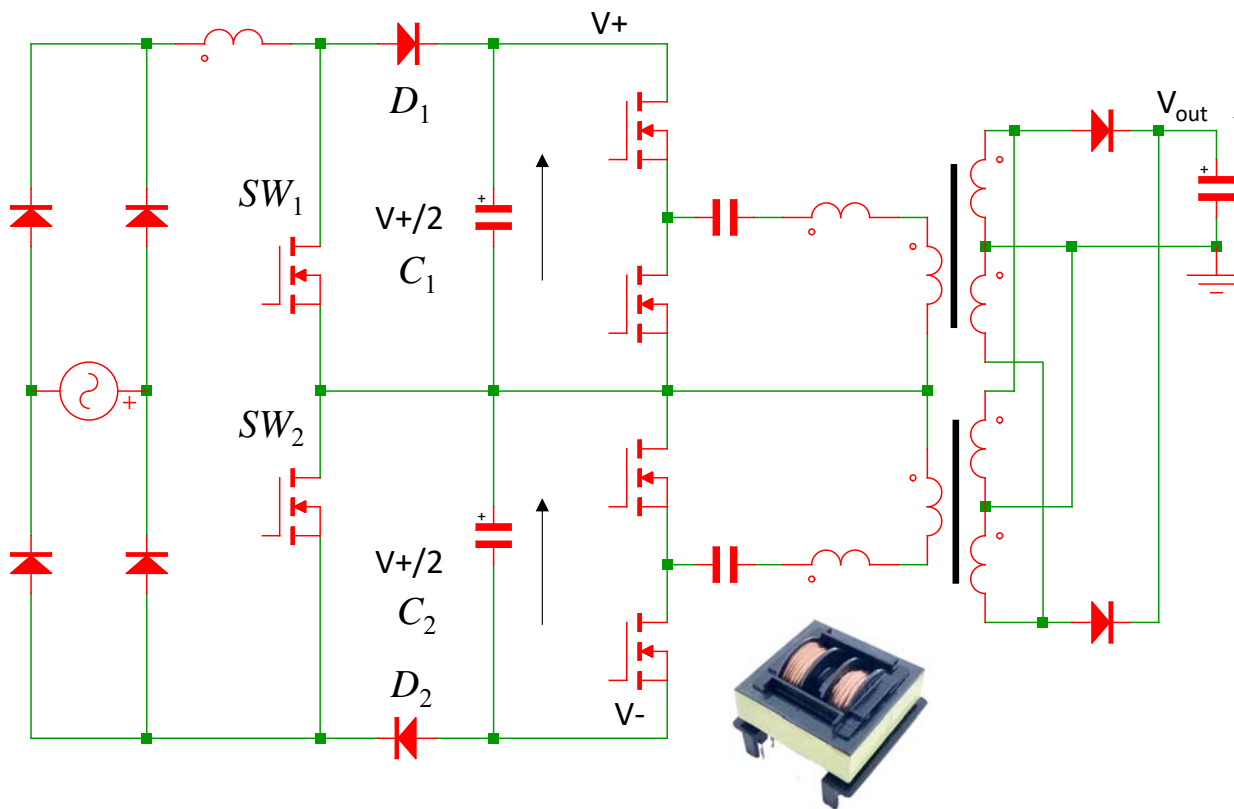
The simulation is done in less than 20 s for a 100-ms duration. For this CCM, you can extract information such as rms current in the output capacitor but also current distortion in different operating conditions.

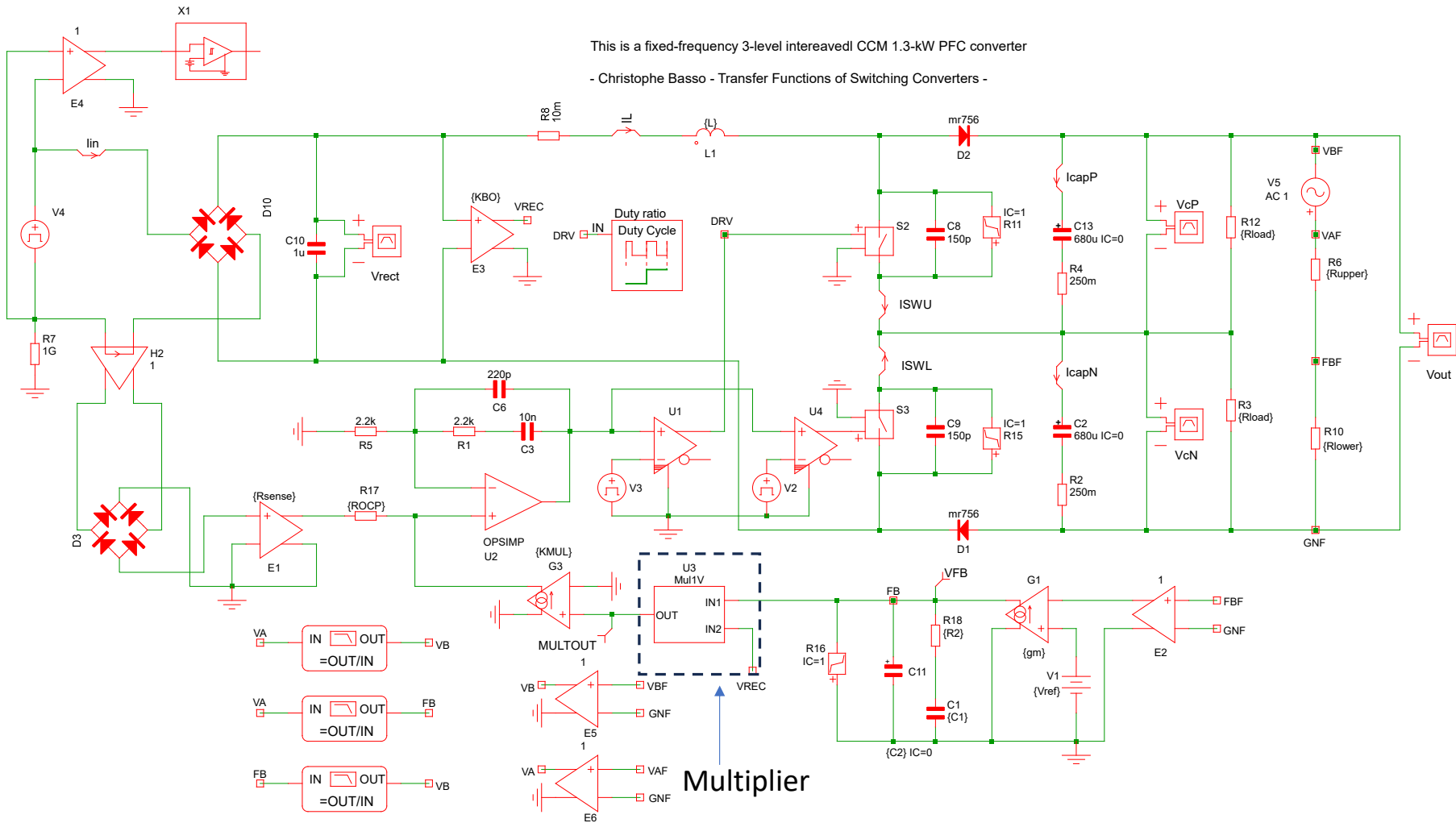
Ac analysis is fully operational with the ac source but takes a little longer than with a classical dc bias (4 mn, 1-100 Hz)



3-Level PFC Converters

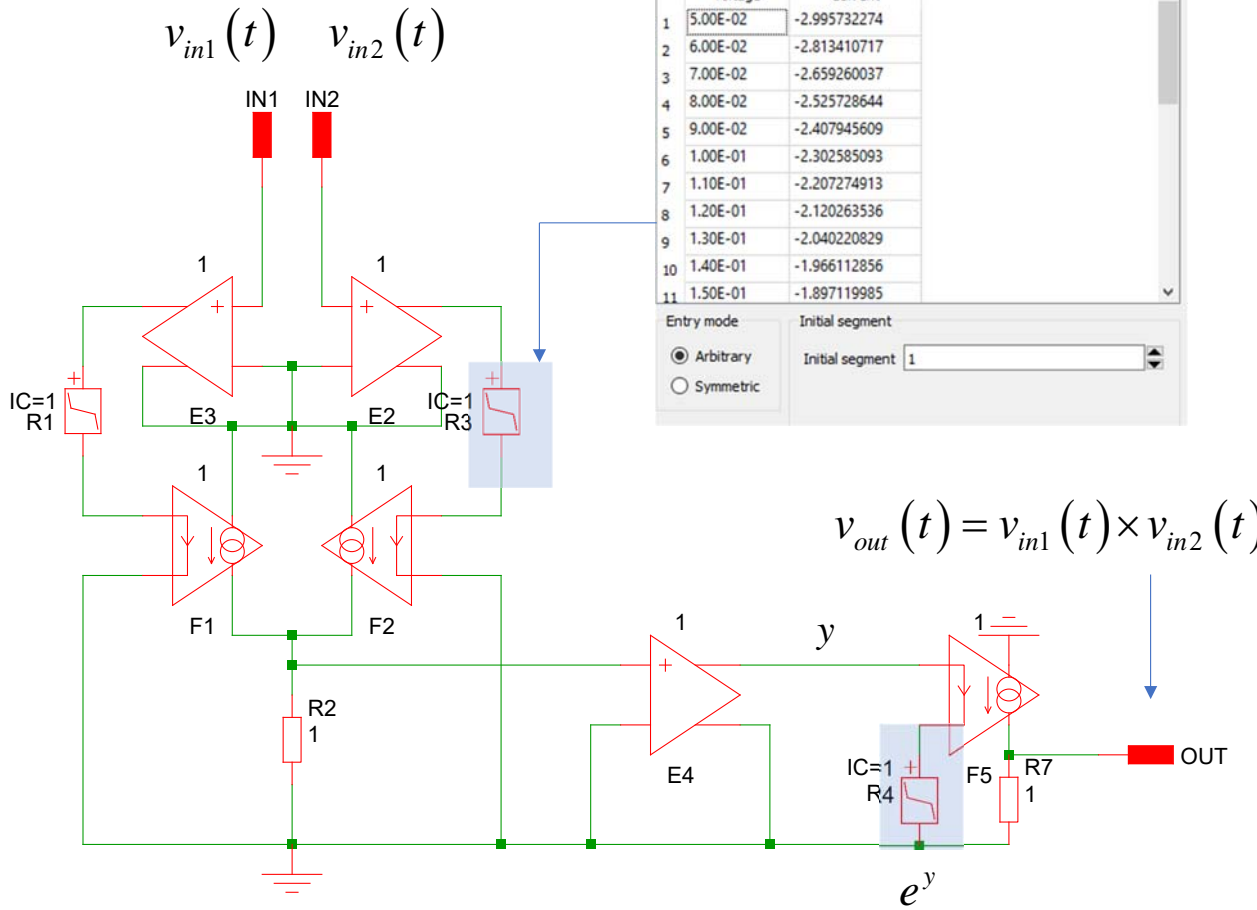
- The two dc rails of equal values let you use semiconductors of lower voltage
- The output transformers can then be serialized or paralleled for more power





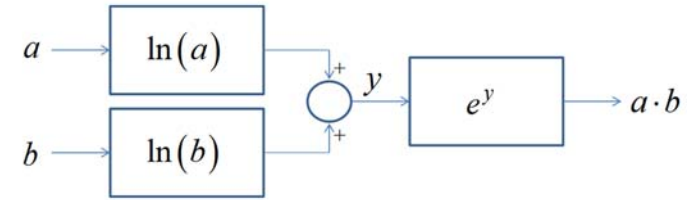
Boost PFC 1-phase 3-level Interleaved CCM Mul

Granularity will improve on precision
But more points slow down simulation



Building a simple multipliers

Napierian logarithm

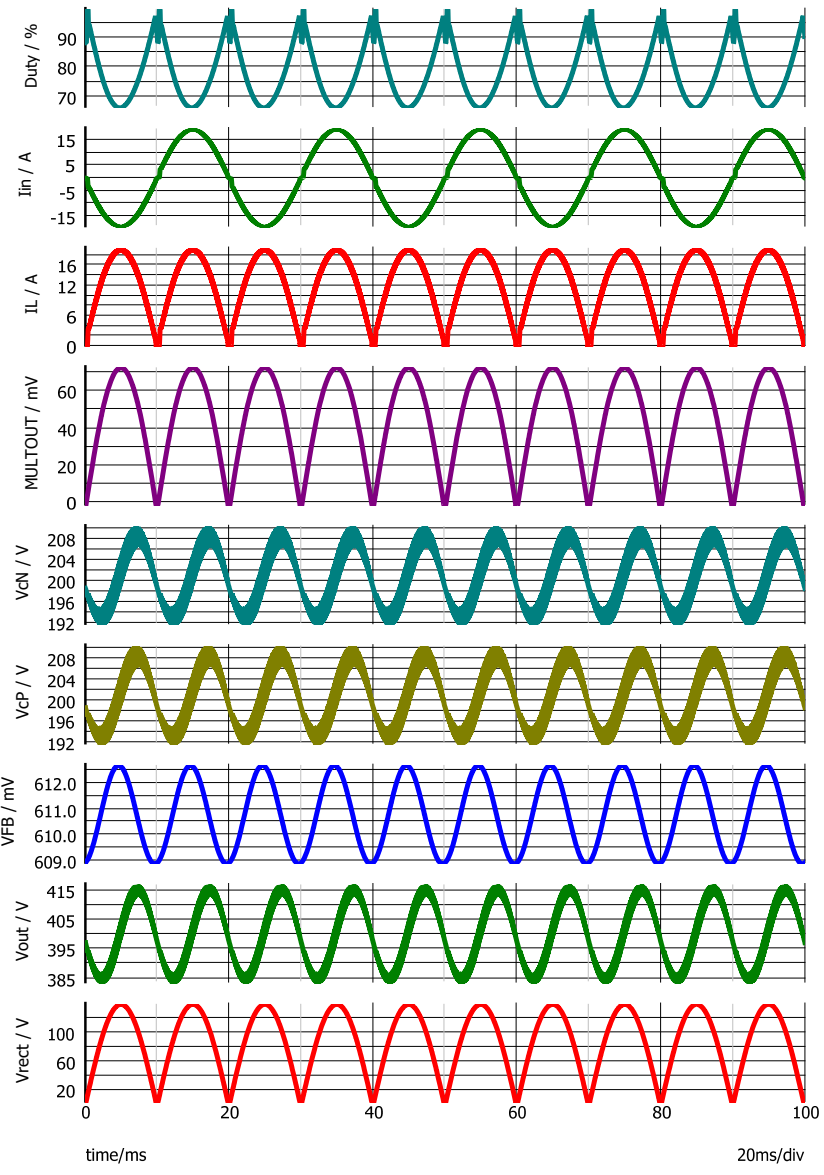


e base

$$\ln(a \cdot b) = \ln a + \ln b$$

$$e^{(\ln a + \ln b)} = a \cdot b$$

Check this [link](#) for detailed explanation

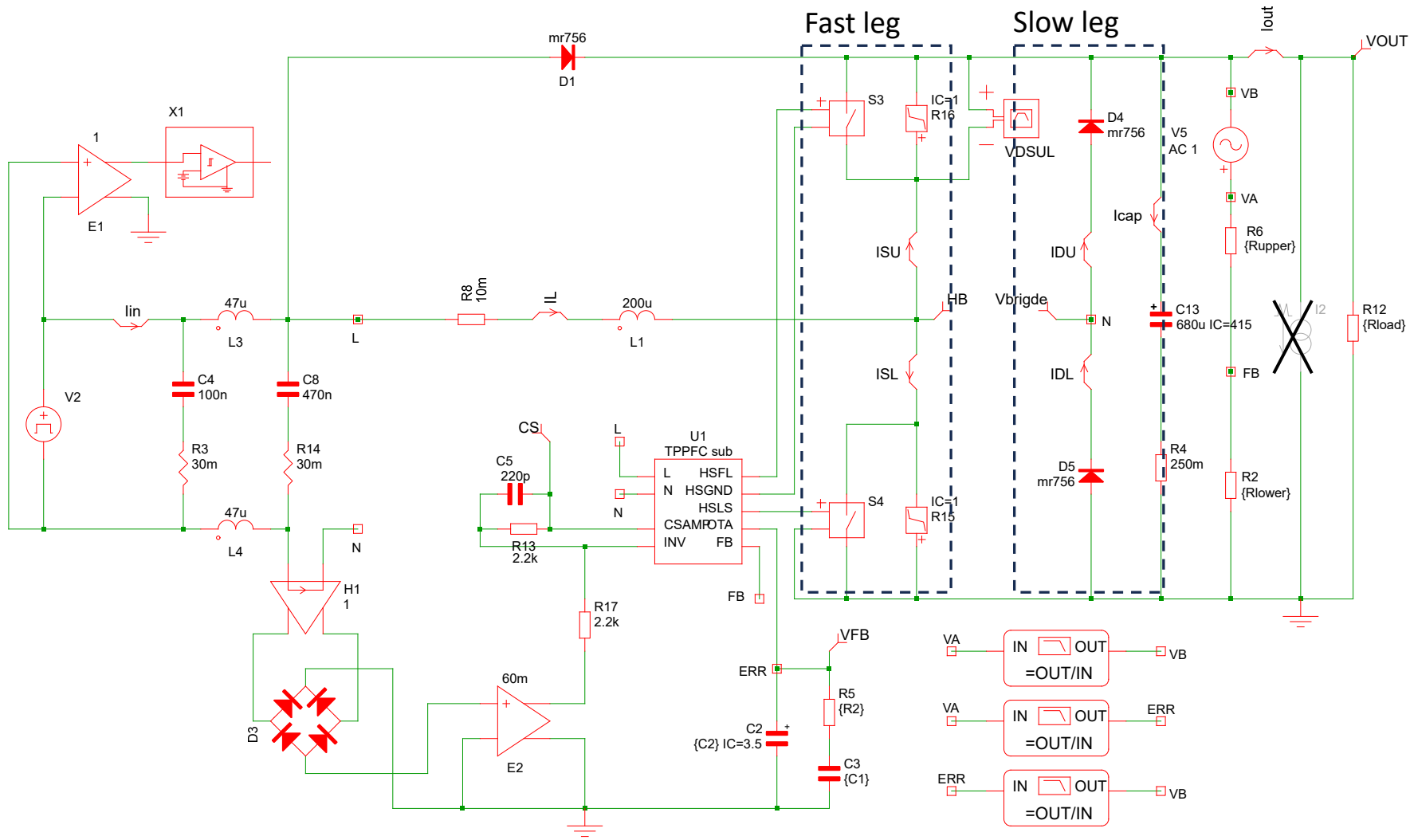


→

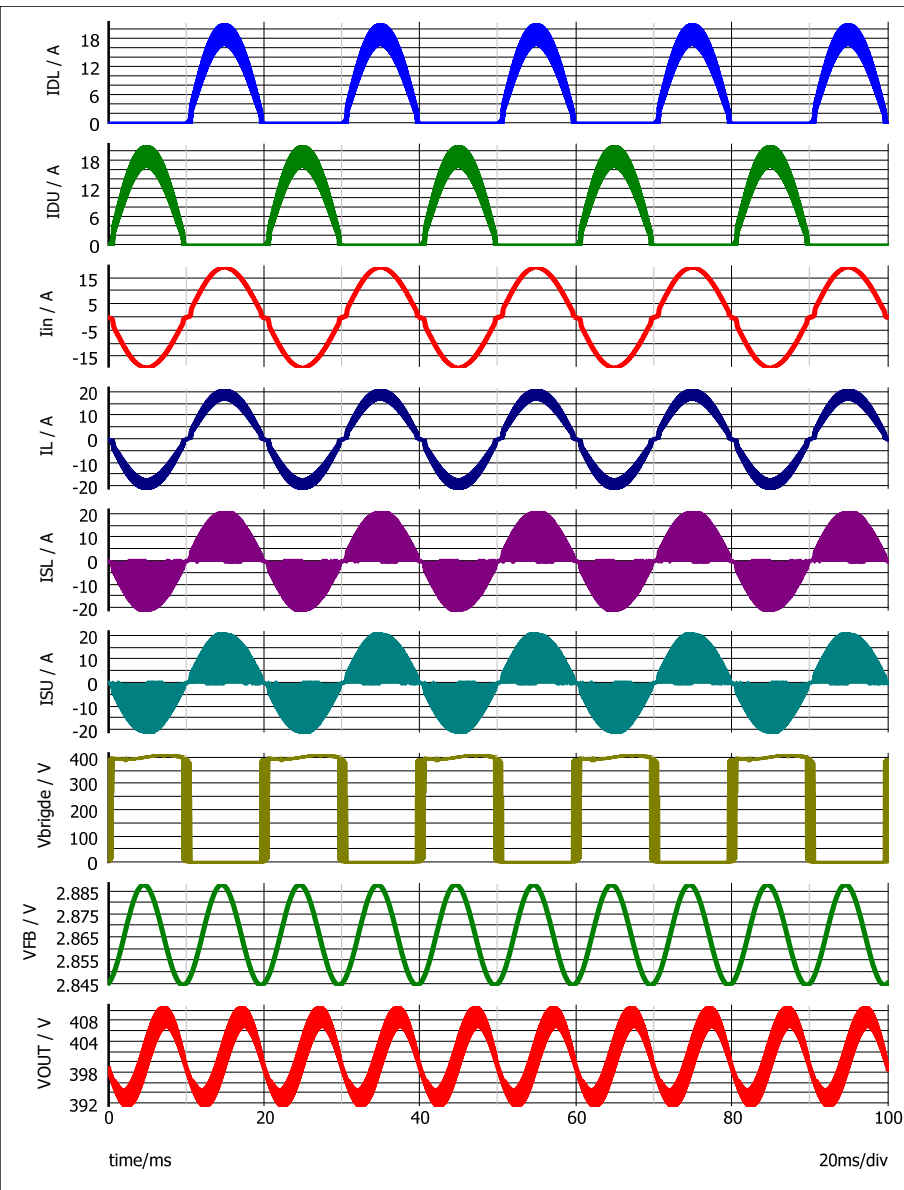
Curve label	Name	Value
lin	Distortion	2.53601%

200 V

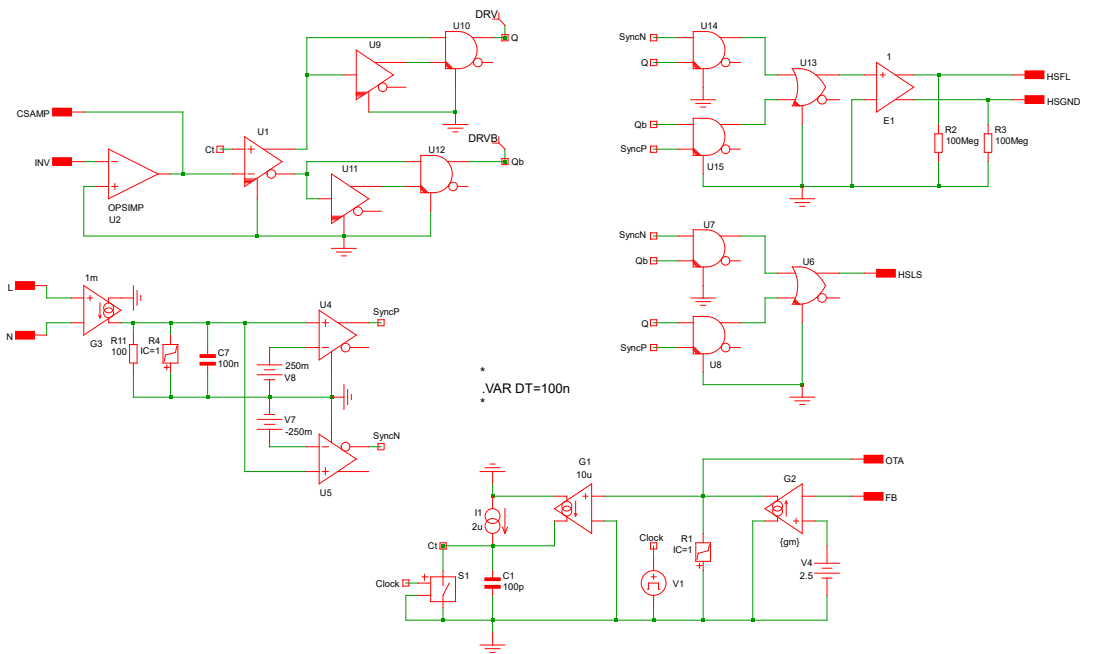
200 V

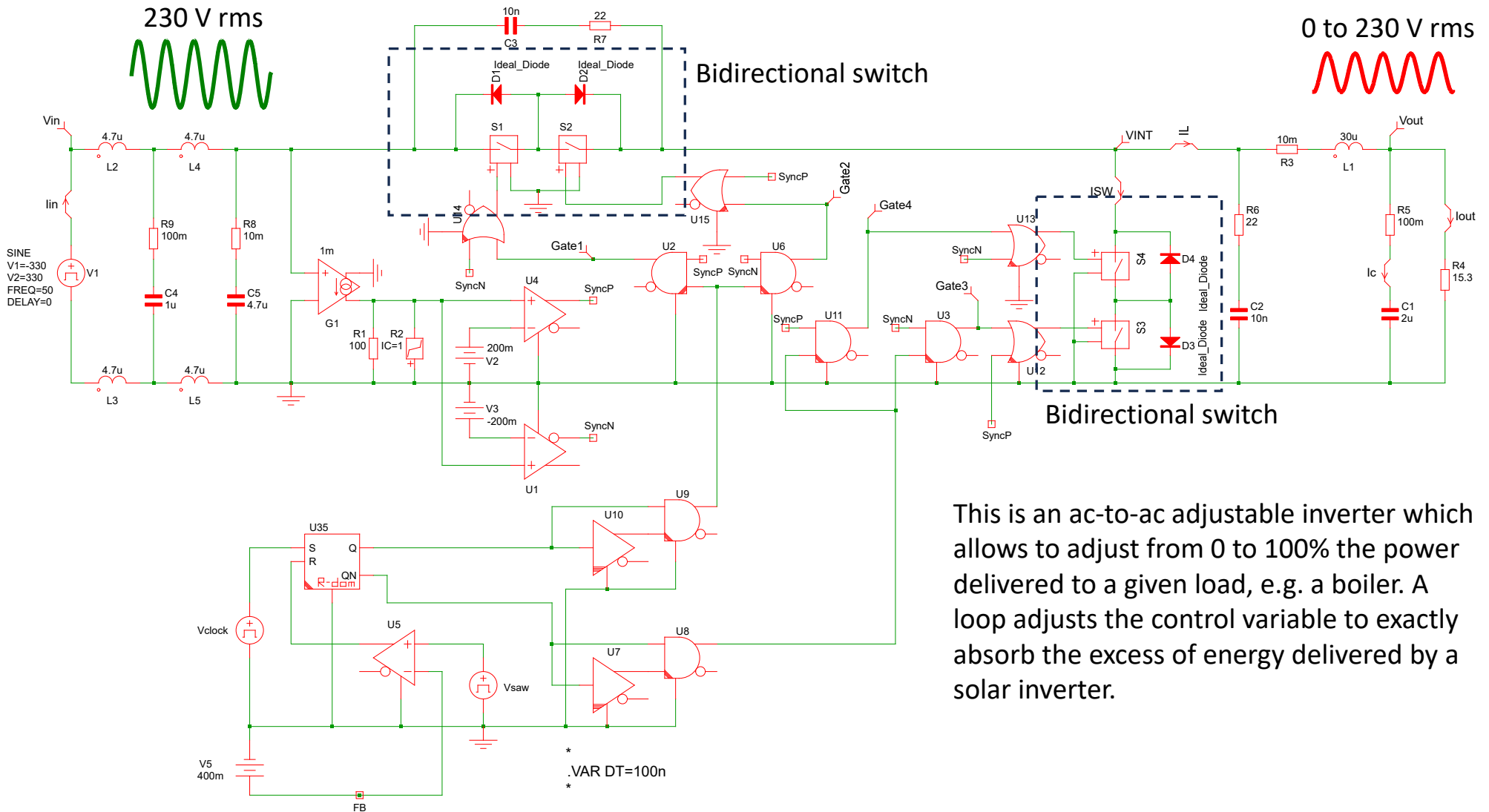


Boost TPPFC CCM Var toff tran



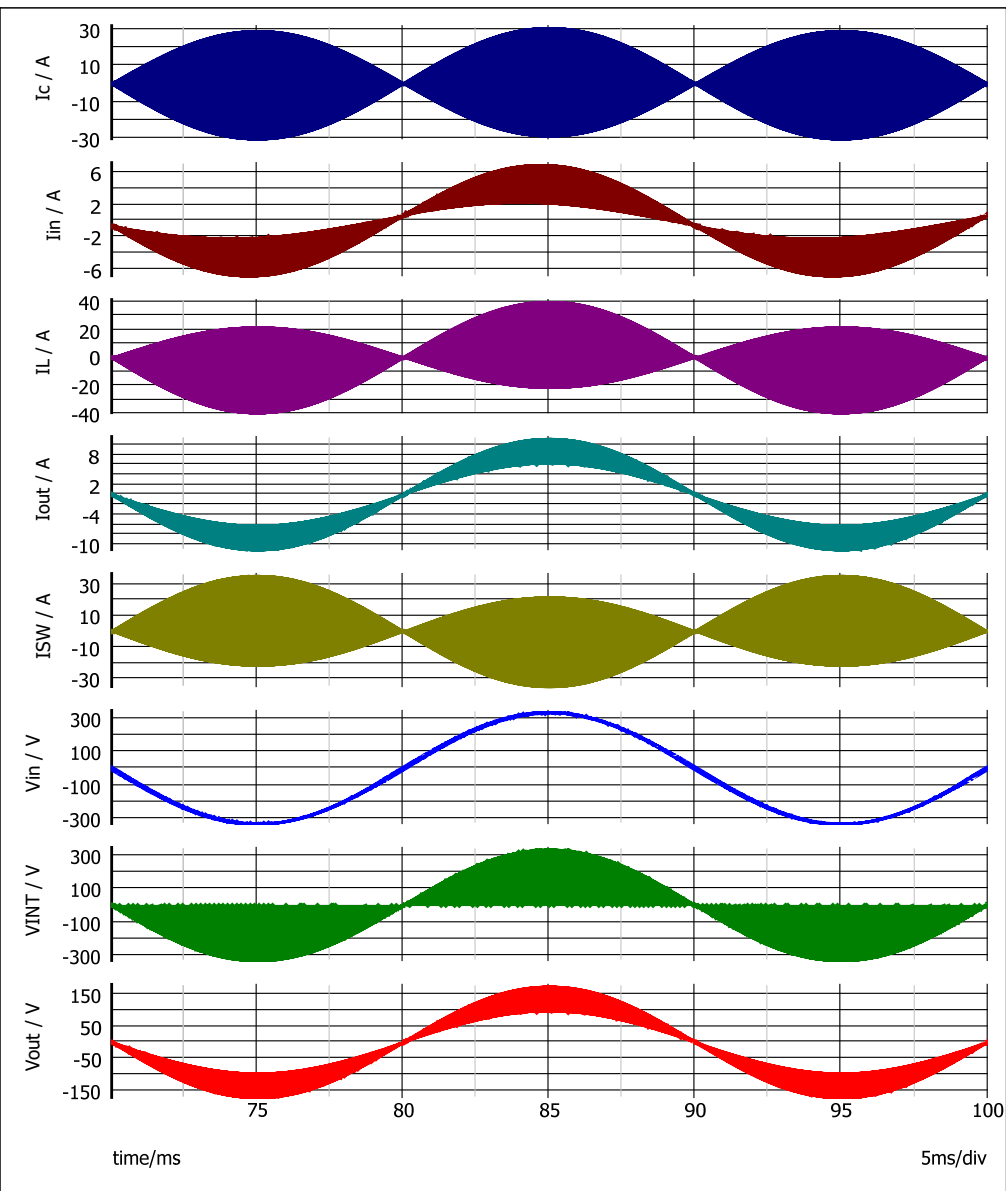
In this TPPFC topology, a decoder is needed to route the driving signal to the lower- or upper-side switch depending on the input current polarity





This is an ac-to-ac adjustable inverter which allows to adjust from 0 to 100% the power delivered to a given load, e.g. a boiler. A loop adjusts the control variable to exactly absorb the excess of energy delivered by a solar inverter.

Buck Ac-Ac Converter – full version

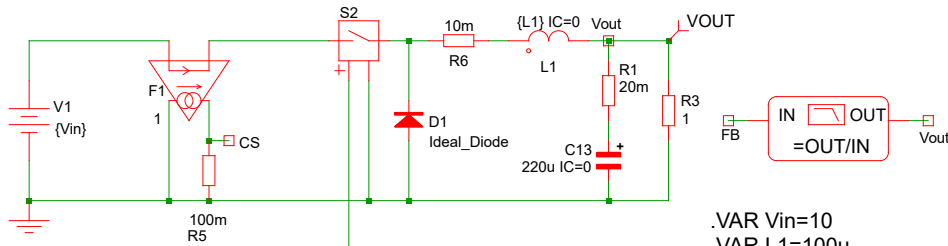


Fixed ac input voltage, 230 V rms

Adjustable ac output voltage, 100 V rms

Current-mode power converter

\buck\Buck CM\sampled analysis\buck CM digital modulator – current loop



```
.VAR Vin=10
.VAR L1=100u
.VAR Vout=5
.VAR Ri=100m
.VAR Sn={{(Vin-Vout)*Ri/L1}}
.VAR Mc=1.3
.VAR Se={{(Mc-1)*Sn}}
.VAR Sramp={3/10u}
.VAR Scomp=-{Se/Sramp}
```

```
{**}
{**}
{**} Sn = {Sn}
{**} Se = {Se}
{**} Scomp = {Scomp}
{**}
```

This is an open-loop current-mode buck converter operated at a 100-kHz switching frequency.

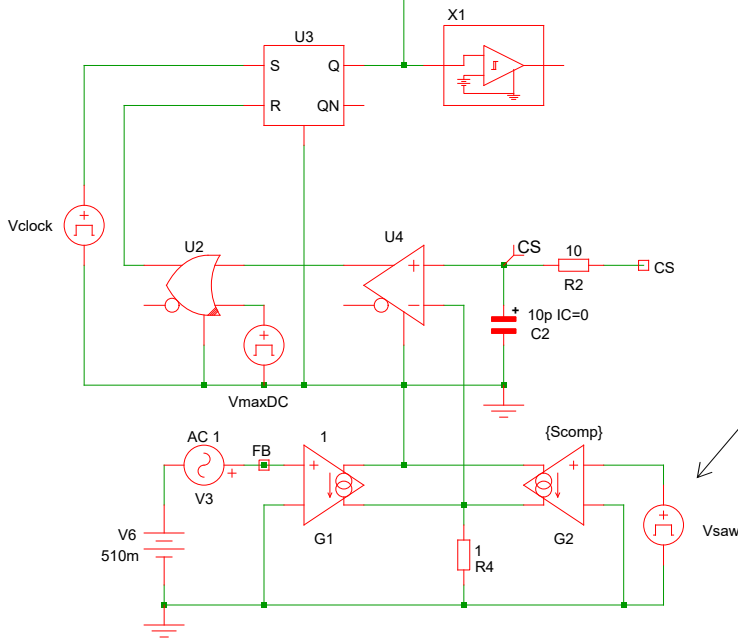
The duty ratio is 50%

$$V_{in} = 10 \text{ V}, V_{out} = 5 \text{ V}, I_{out} = 5 \text{ A}$$

From [1], we know that the double poles located at $F_{sw}/2$ are affected by a quality factor Q_p :

$$Q_p = \frac{1}{\pi [m_c (1 - D) - 0.5]}$$

The poles are damped by adding an artificial ramp to the current sense signal:



Artificial ramp

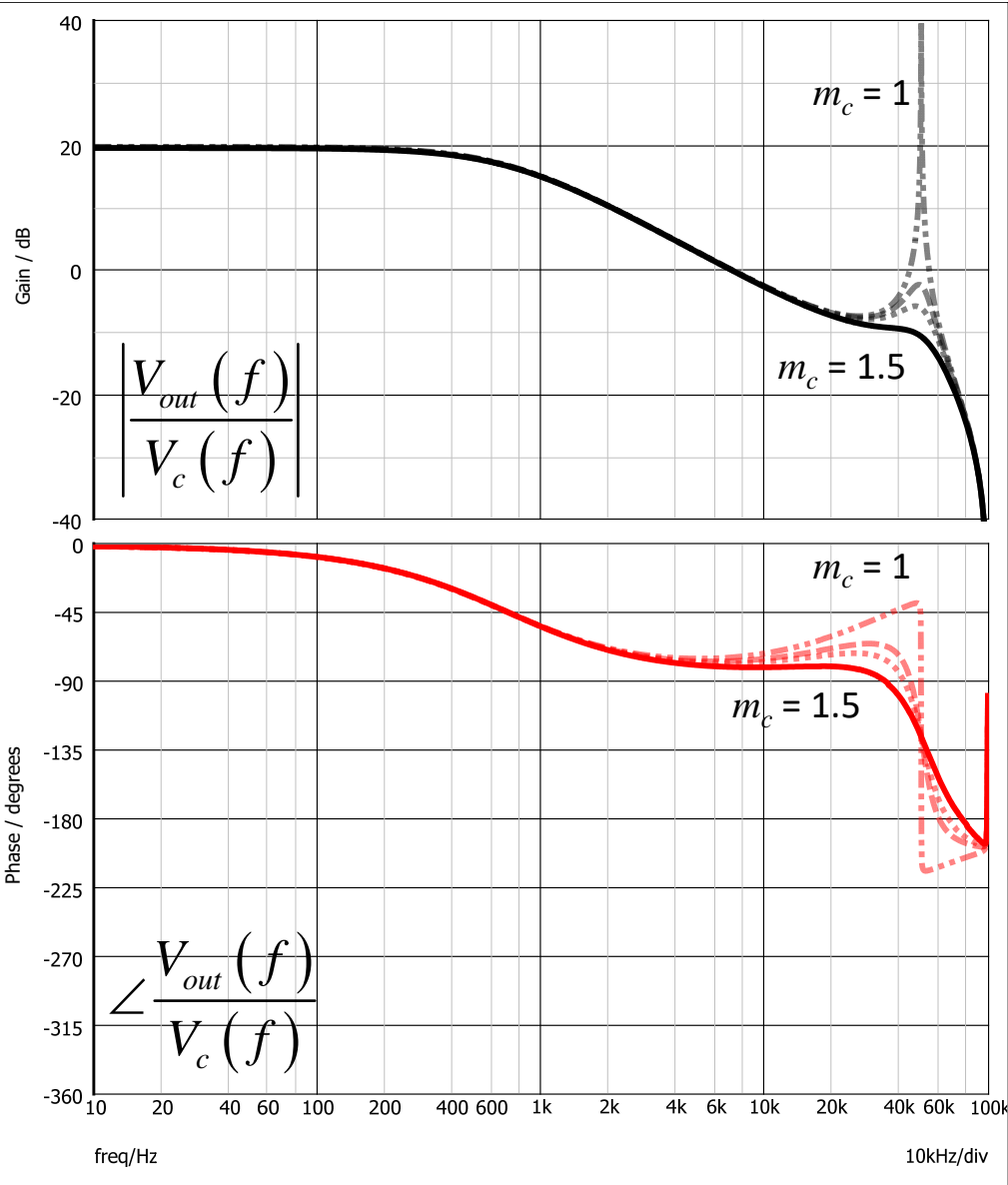
$$m_c = \frac{S_e}{S_n} + 1$$

$m_c = 1 \rightarrow$ no ramp

$m_c = 1.5 \rightarrow$ 50% compensation

On-time inductor slope [V]/[s]

[1] R. Ridley, *A New Small-Signal Model for Current Mode Control*, Ph. D. dissertation, Virginia Polytechnic Institute and State University, 1990



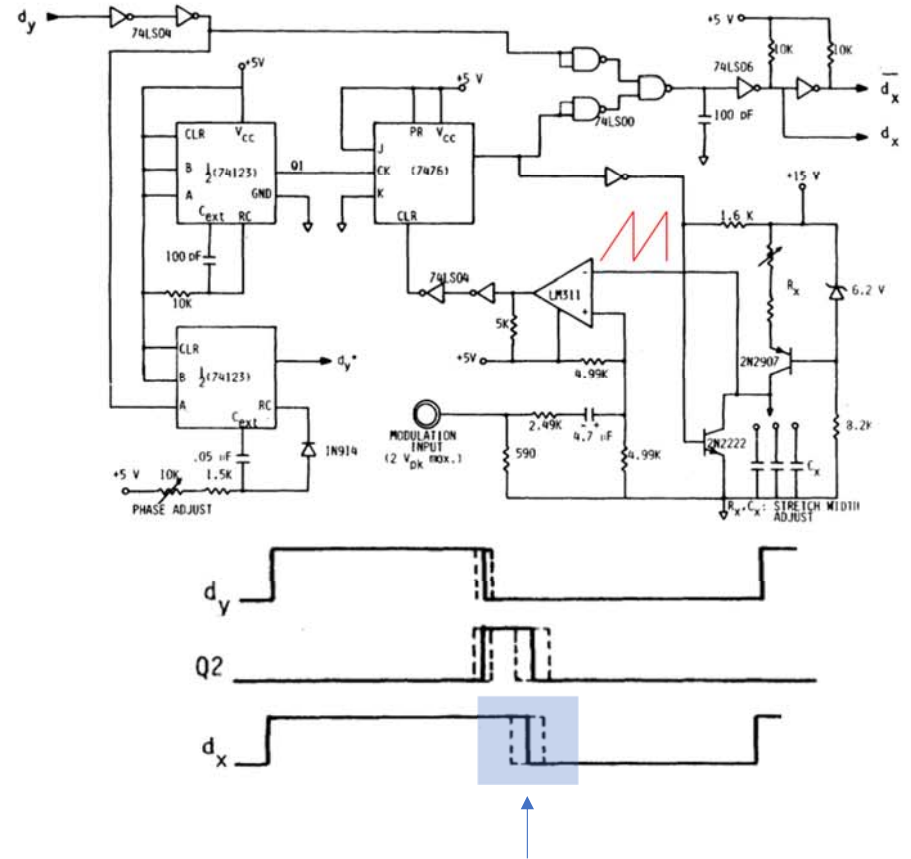
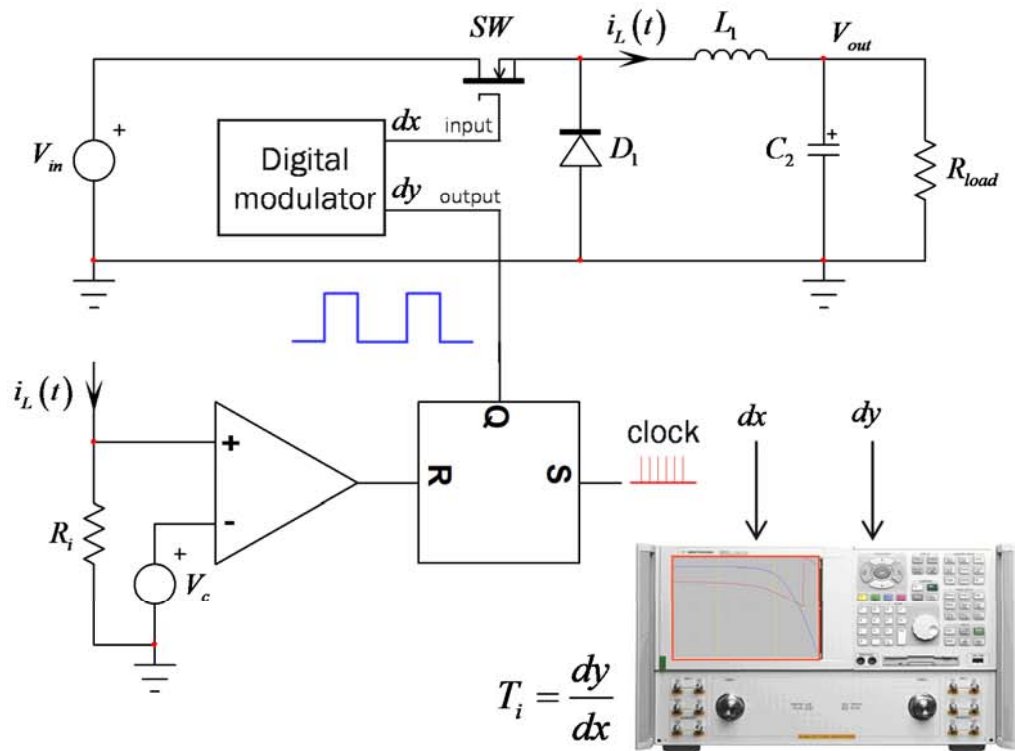
By adding slope compensation, we are damping the subharmonic poles and the converter gains in overall stability.

Where does this instability come from?

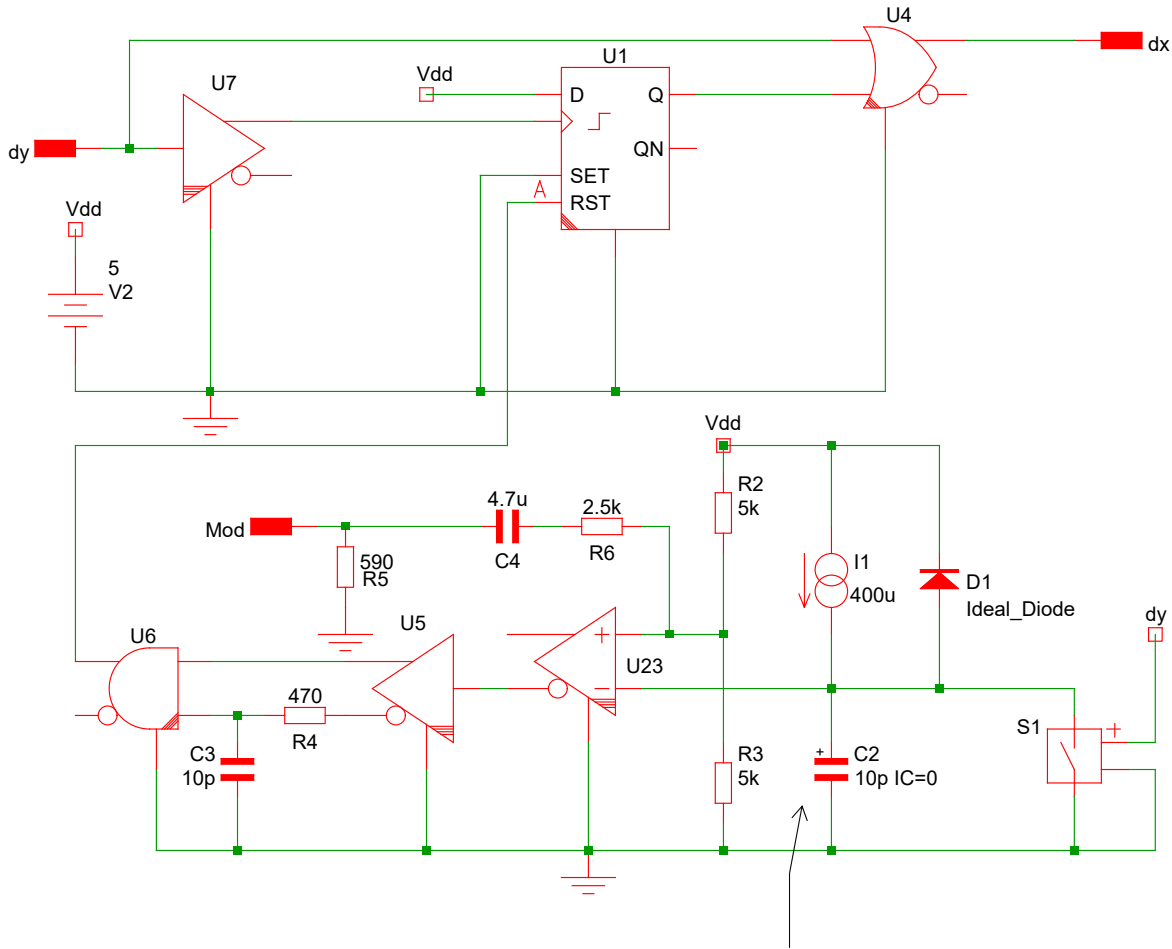
We can have a look at the inner current loop gain which links the duty ratio to the inductor peak current. However, both variables are discrete points, how do we do?



Implement a digital modulator



The digital modulator introduces an ac perturbation in $d(t)$



This is the digital modulator that I described in this paper published on [How2Power](#):



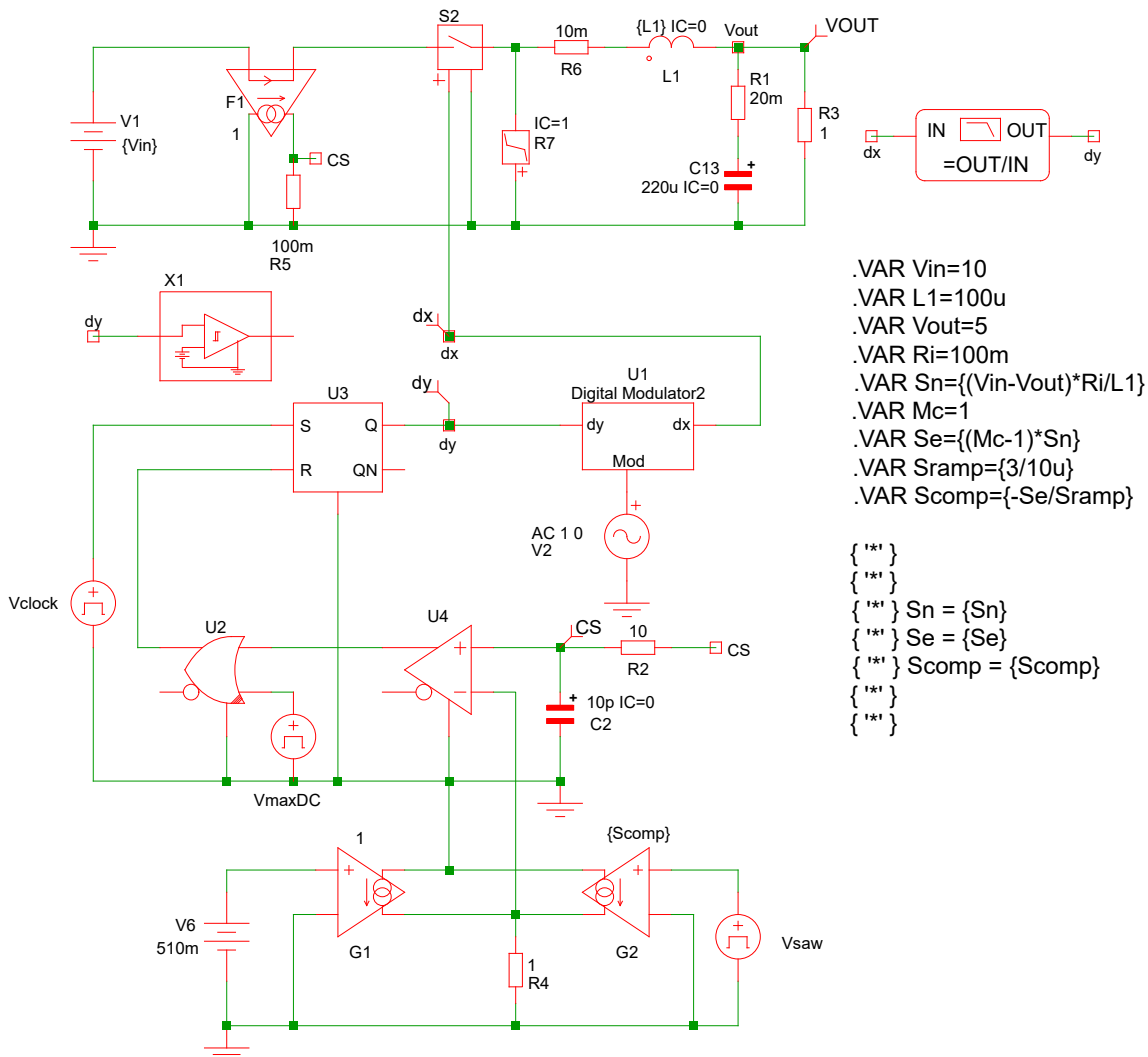
Exclusive Technology Feature

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Simulation Demonstrates Impact Of Current-Loop Crossover Frequency On Stability

by Christophe Basso, ON Semiconductor, Toulouse, France

When d_y goes high, d_x immediately follows, C_2 is discharged and stays low
 When d_y goes low, d_x goes low after C_2 charges to the ac-modulated threshold



\back Buck CM digital modulator – current loop gain

The digital modulator is inserted and I can extract the *duty-ratio-to-inductor-peak-current* transfer function

