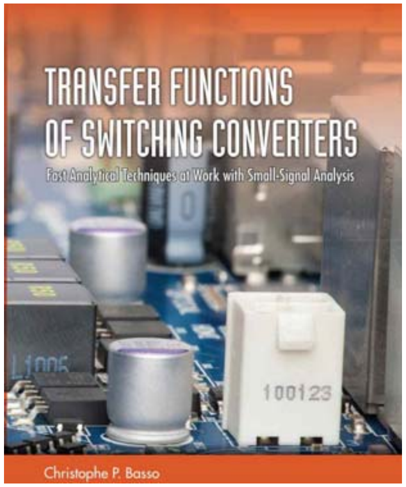
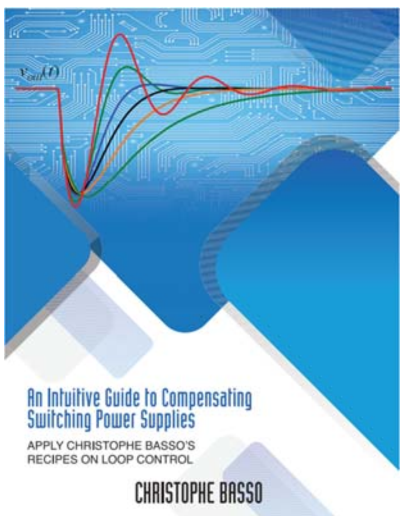
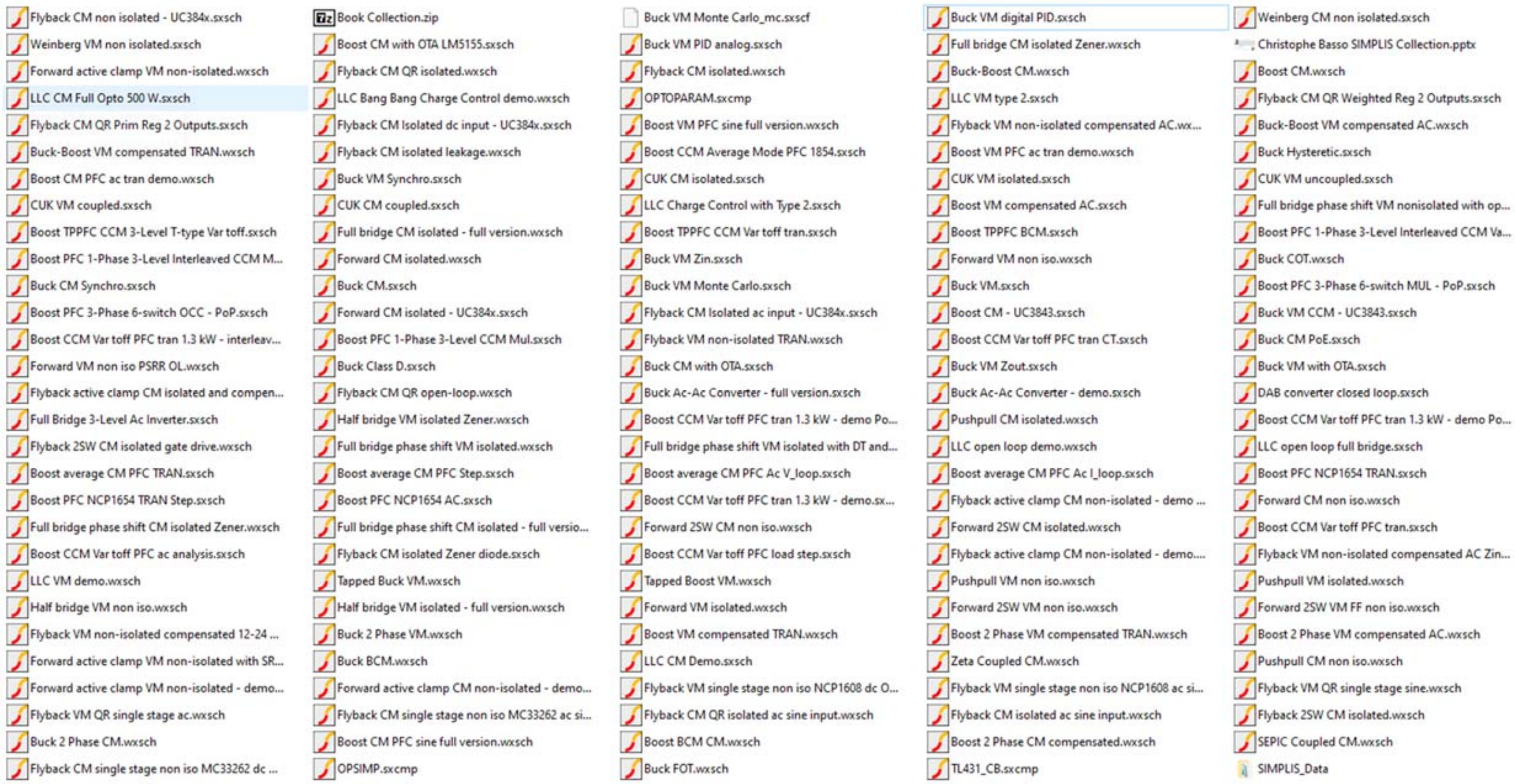


Released in June 2021

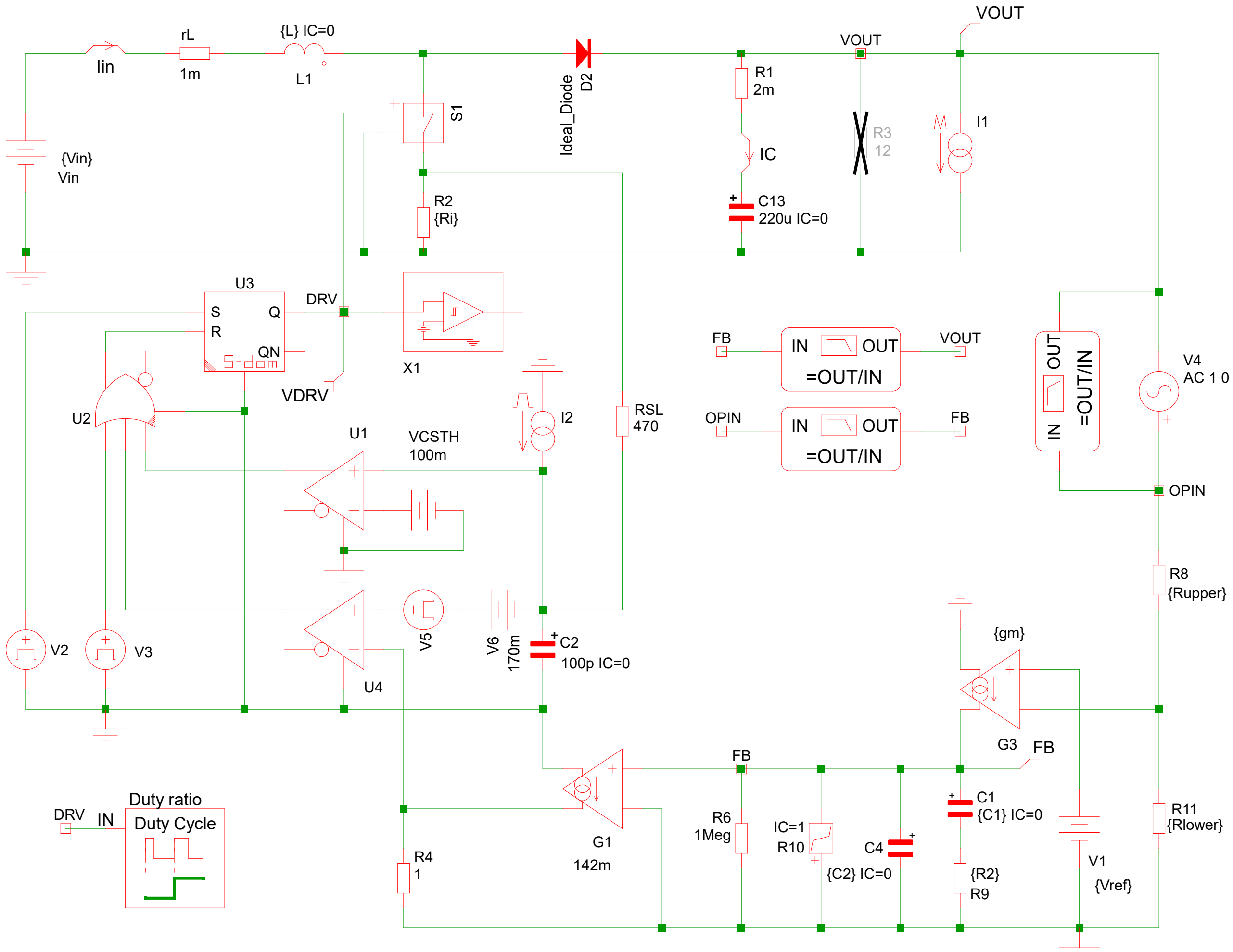


Released in September 2024



There are 130+ free to download simulation templates

≈80% of these circuits work with the demonstration version Elements



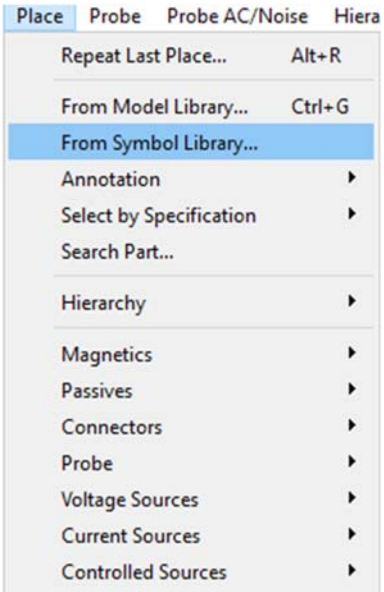
Boost CM with OTA LM5155

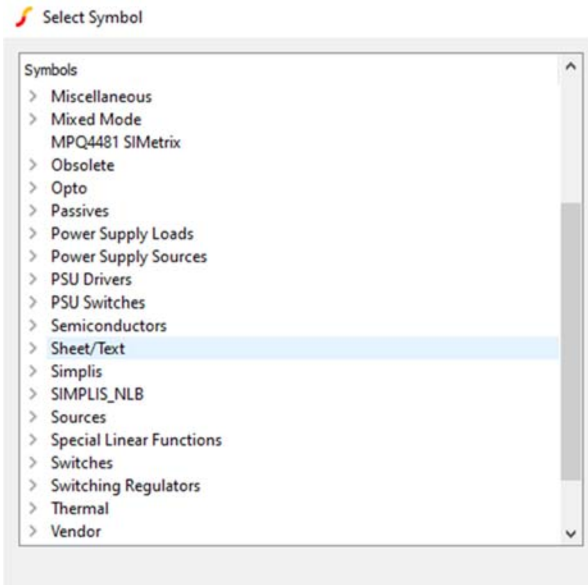
Change fc to 1 kHz, PM = 60°

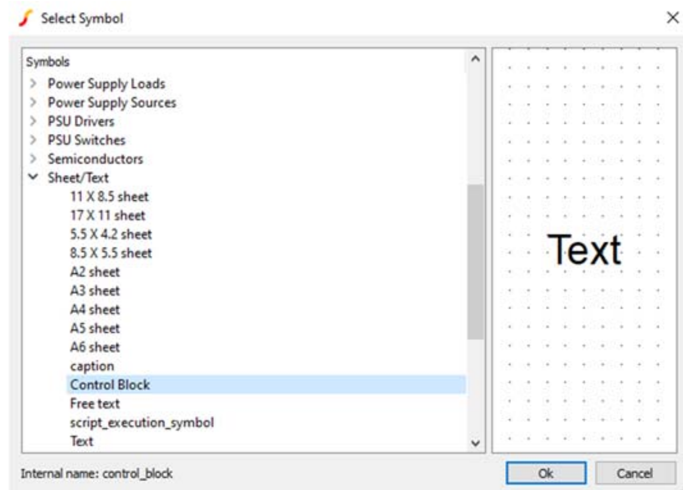
Change PM to 45° with step load

```
*
.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)
```

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.

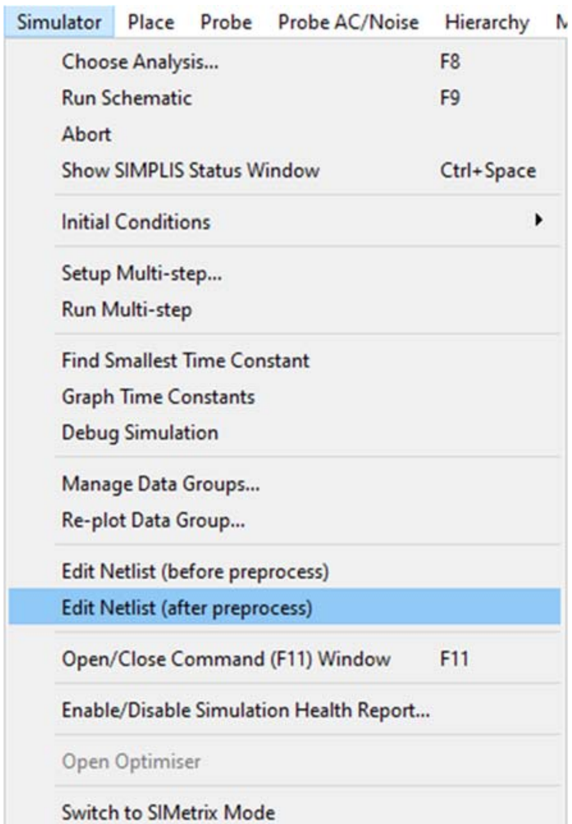
```
* Optocoupler specifications *
*
.VAR Rpullup=10k * check with the selected control chip *
.VAR Fopto=10k
.GLOBALVAR Copto=1/(2*pi*Fopto*Rpullup)
.GLOBALVAR CTR=0.8
*
```

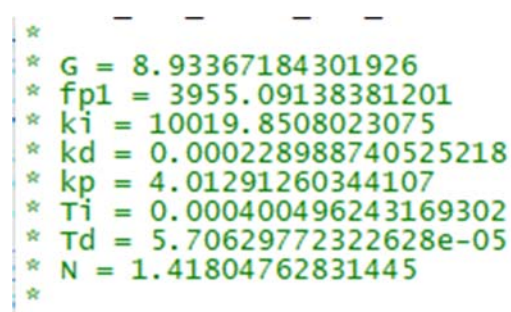
.VAR is a local variable
.GLOBALVAR is a global variable passed to a subcircuit

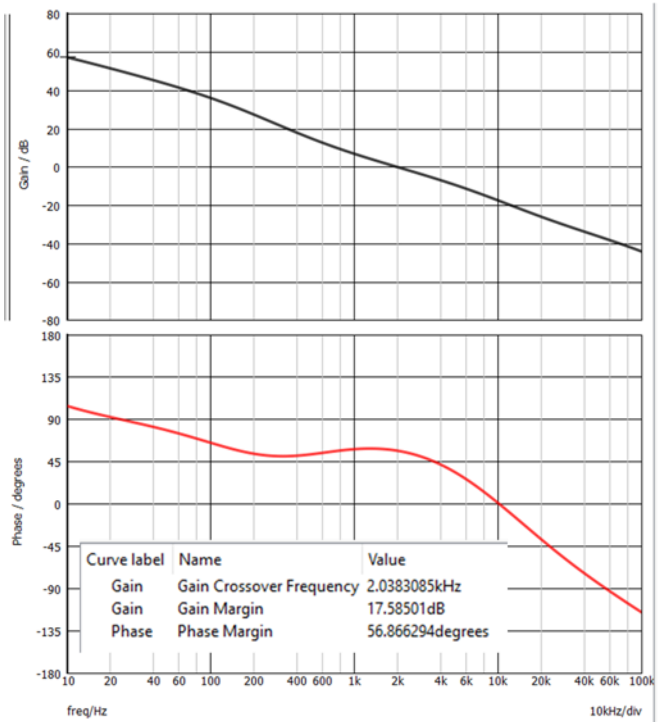
For debugging the automated macro, use the curly braces:

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

Include these in your control block

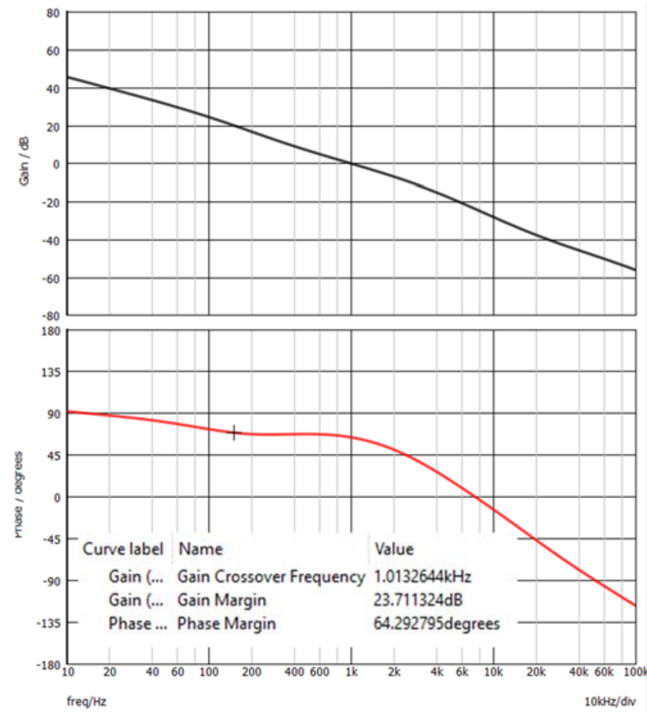






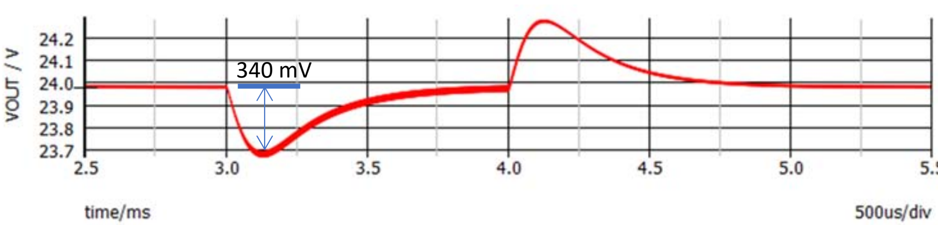
$$C_{out} = 220\ \mu F$$
$$f_c = 1\ kHz$$
$$\Delta V_{out} \approx \frac{\Delta I_{out}}{2\pi f_c C_{out}} \approx 720\ mV$$

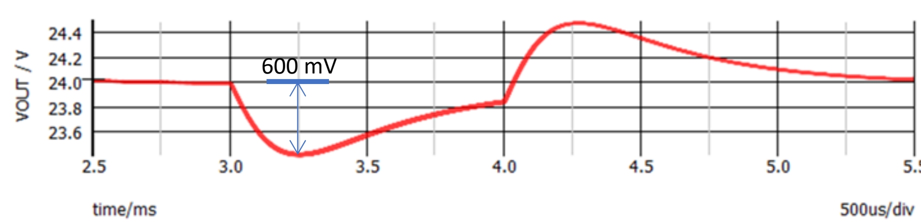
$$C_{out} = 220\ \mu F$$
$$f_c = 2\ kHz$$
$$\Delta V_{out} \approx \frac{\Delta I_{out}}{2\pi f_c C_{out}} \approx 360\ mV$$



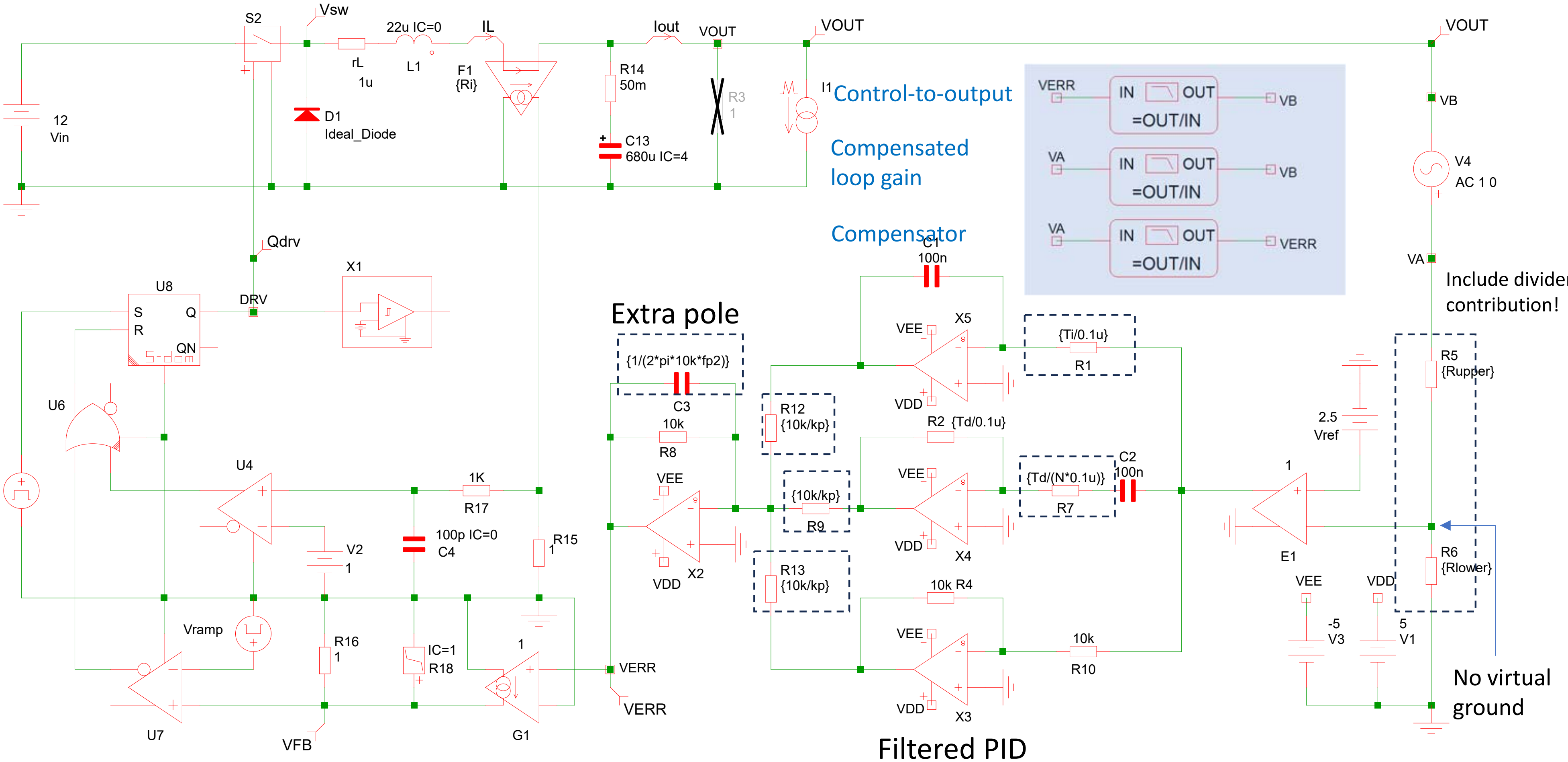
Design goal is 2 kHz f_c

Design goal is 1 kHz f_c



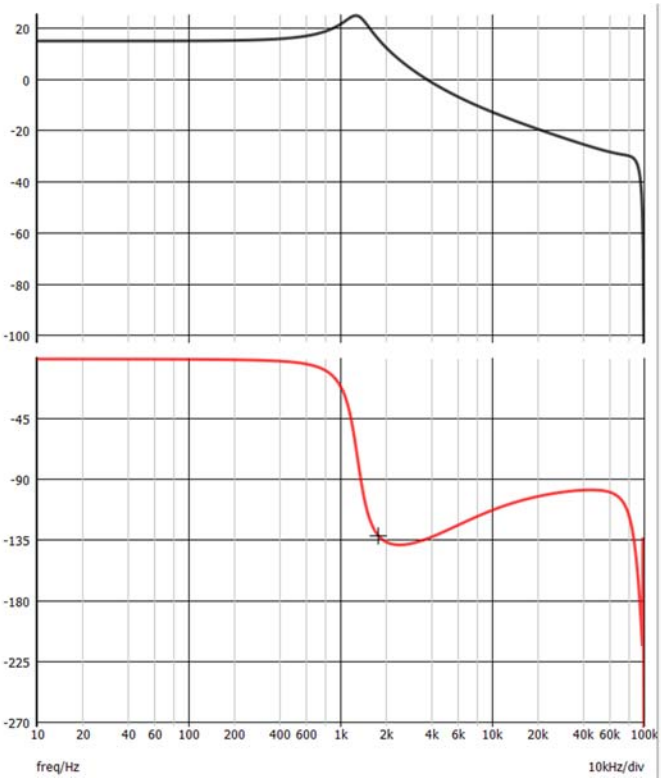


These Bode boxes let me plot three different transfer functions.

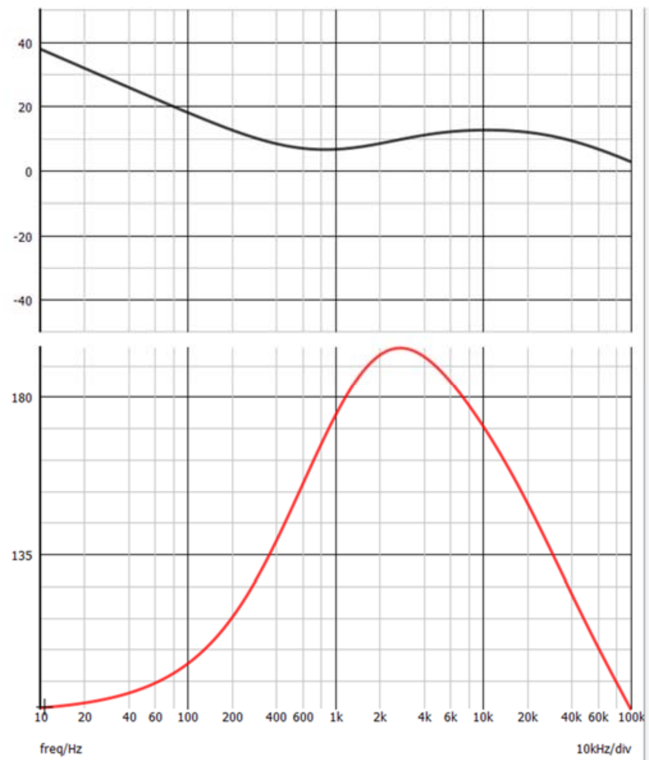


Filtered PID + extra pole ➡ Type 3 compensator

Buck VM PID analog

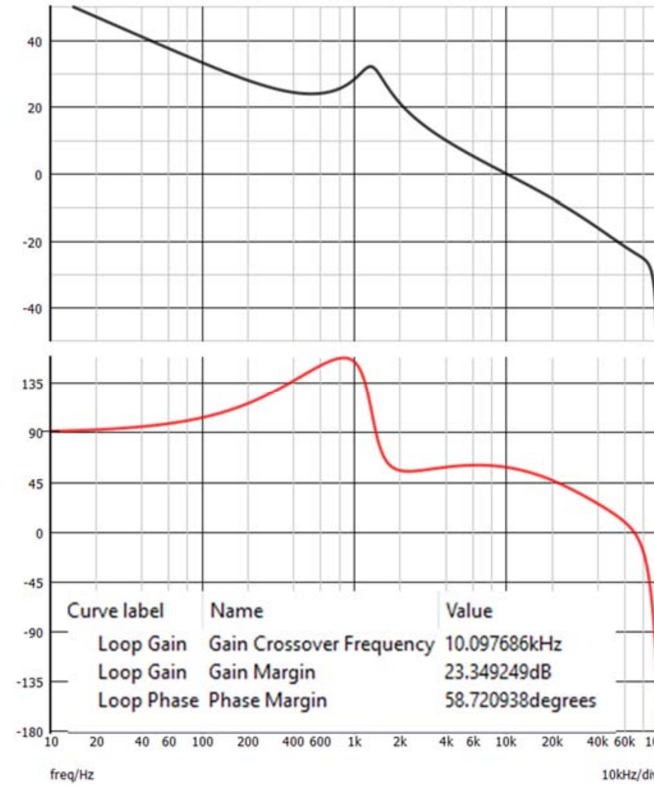


The starting point: the control-to-output transfer function

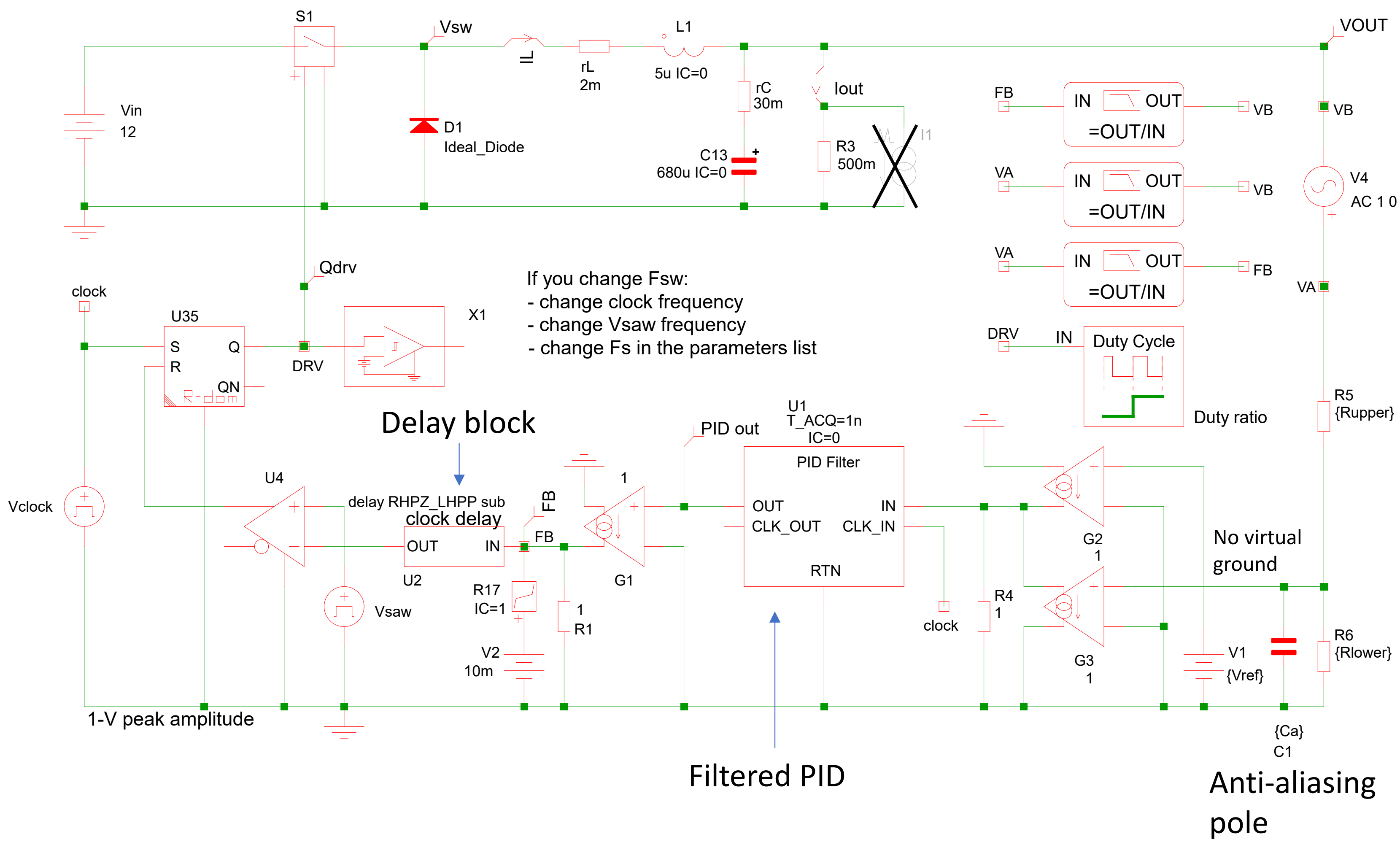


The PID response with poles and zeroes translated in k_p, k_i and k_d

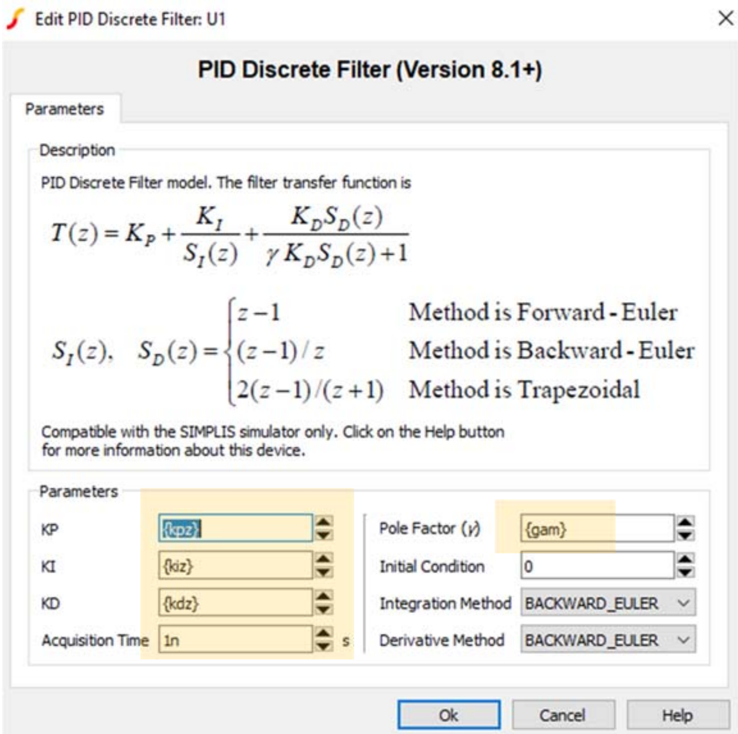
PID coefficients are automated from the macro



The compensated loop gain showing crossover, phase and gain margins



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}
*
.globalvar Wtau=1/Ts ; transport delay with zero PWM delay
.globalvar 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

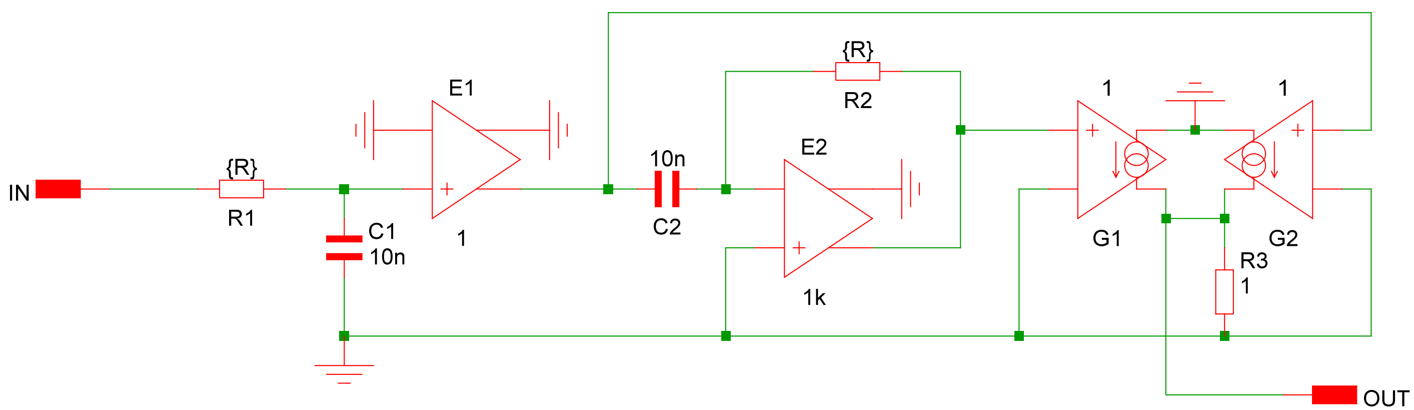
Discrete parameters passed to the digital PID model

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 $\omega_z = \frac{2}{T_s}$ → $f_z = \frac{1}{\pi T_s}$

LHP pole located at $\omega_p = \frac{2}{T_s}$ → $f_p = \frac{1}{\pi T_s}$



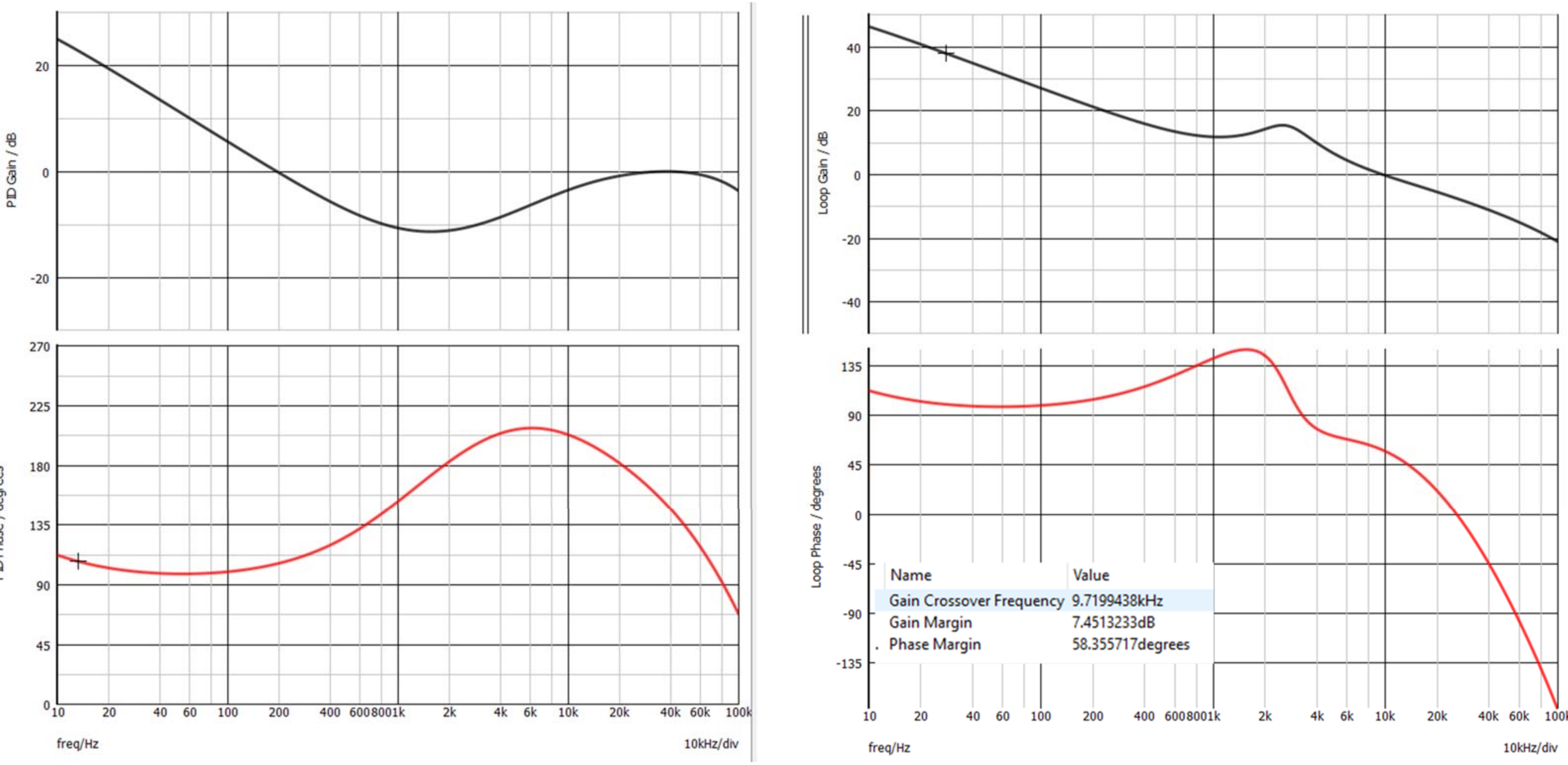

```
.globalvar Wtau=1/Ts ; transport delay
.globalvar R={1/(10n*Wtau)}
*
```

Total delay

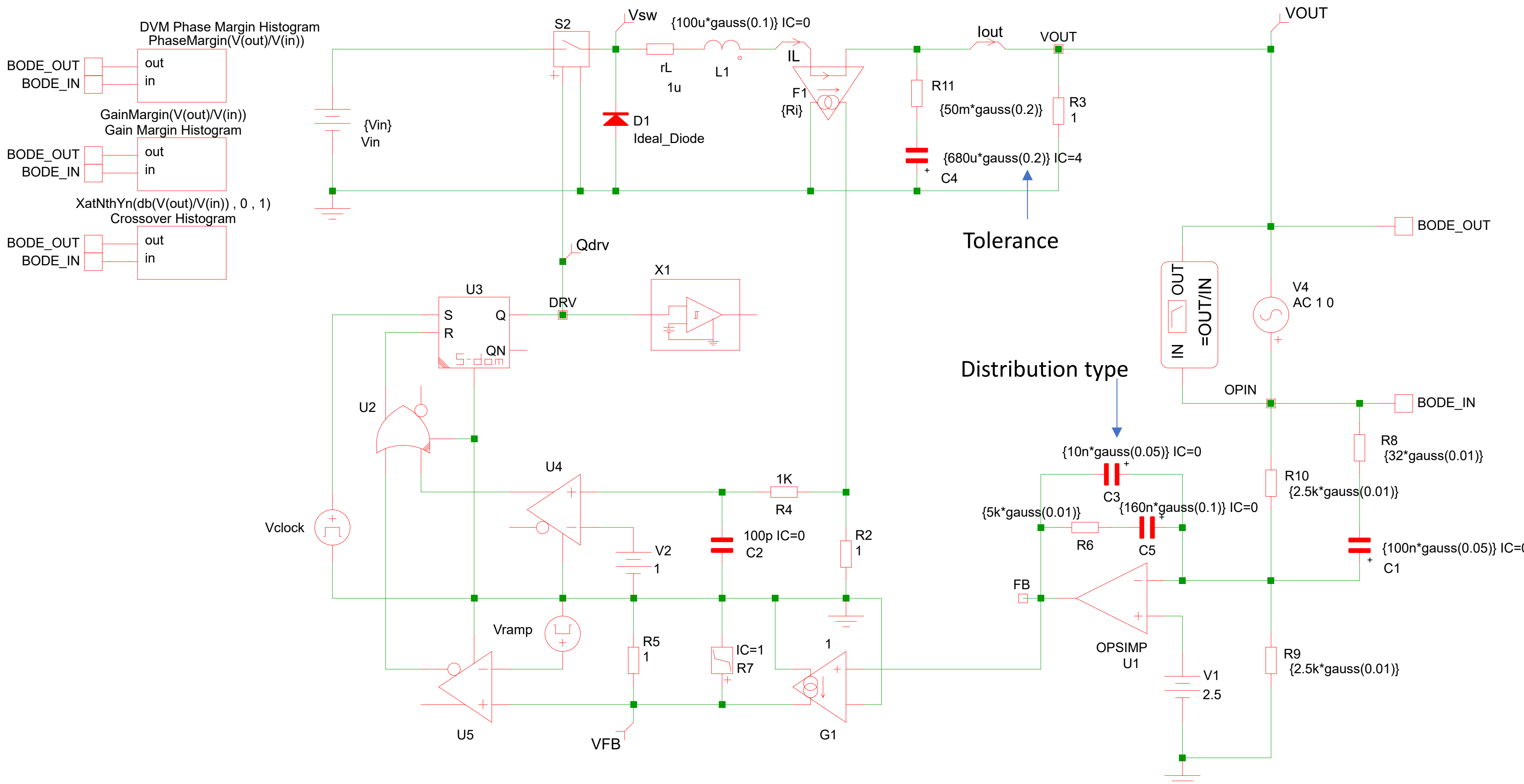
$$e^{-s(T_s+DT_s)}$$

= 0

Analog PWM



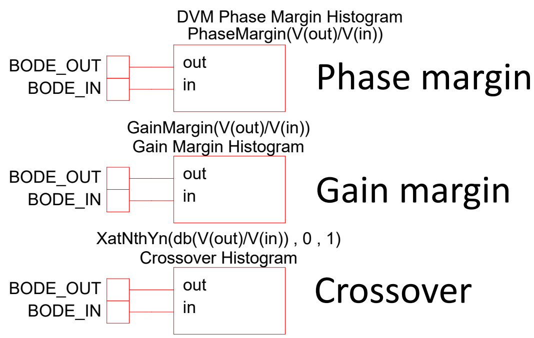
Transfer function of the filtered PID with an extra pole

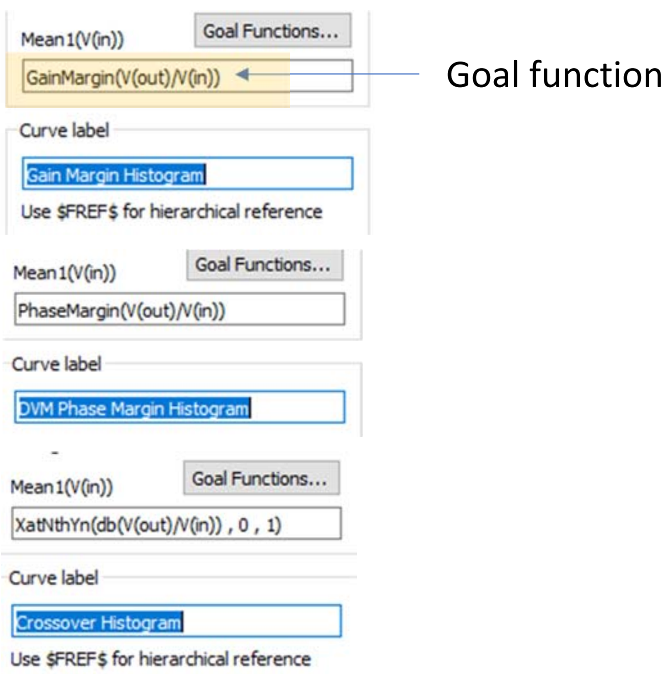


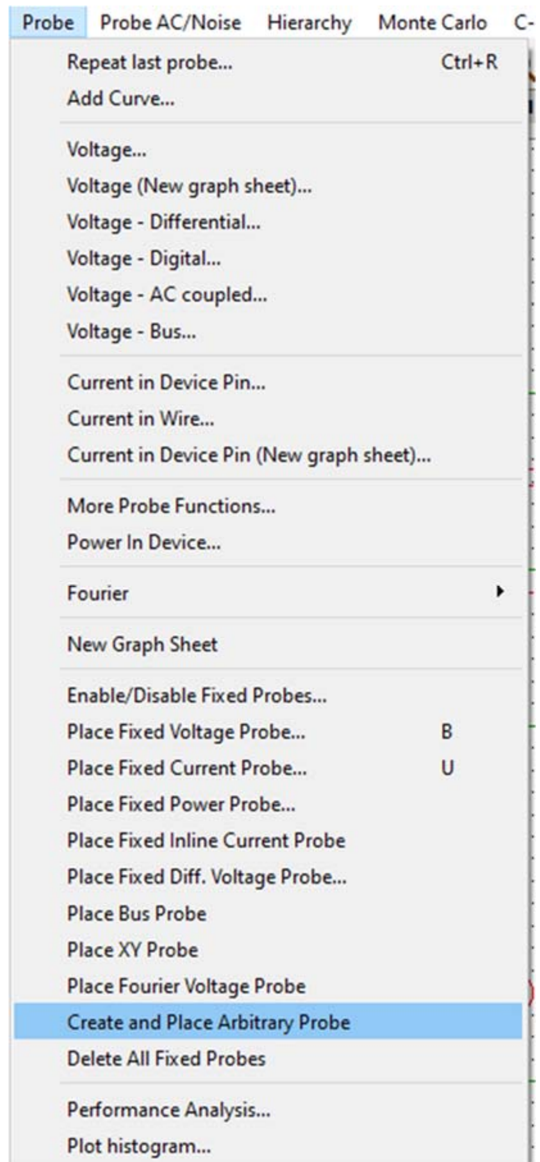
Buck VM Monte Carlo

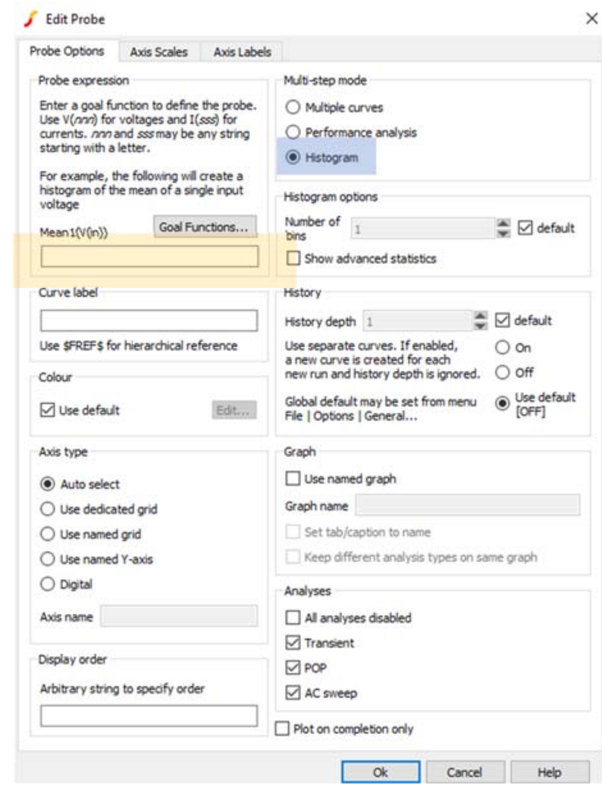
[How2Power Monte Carlo]– Stéphanie Cannenterre
[Monte Carlo gone wrong] – Charles Hymowitz

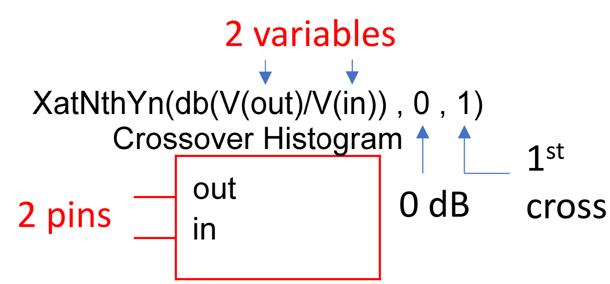
Goal functions to insert



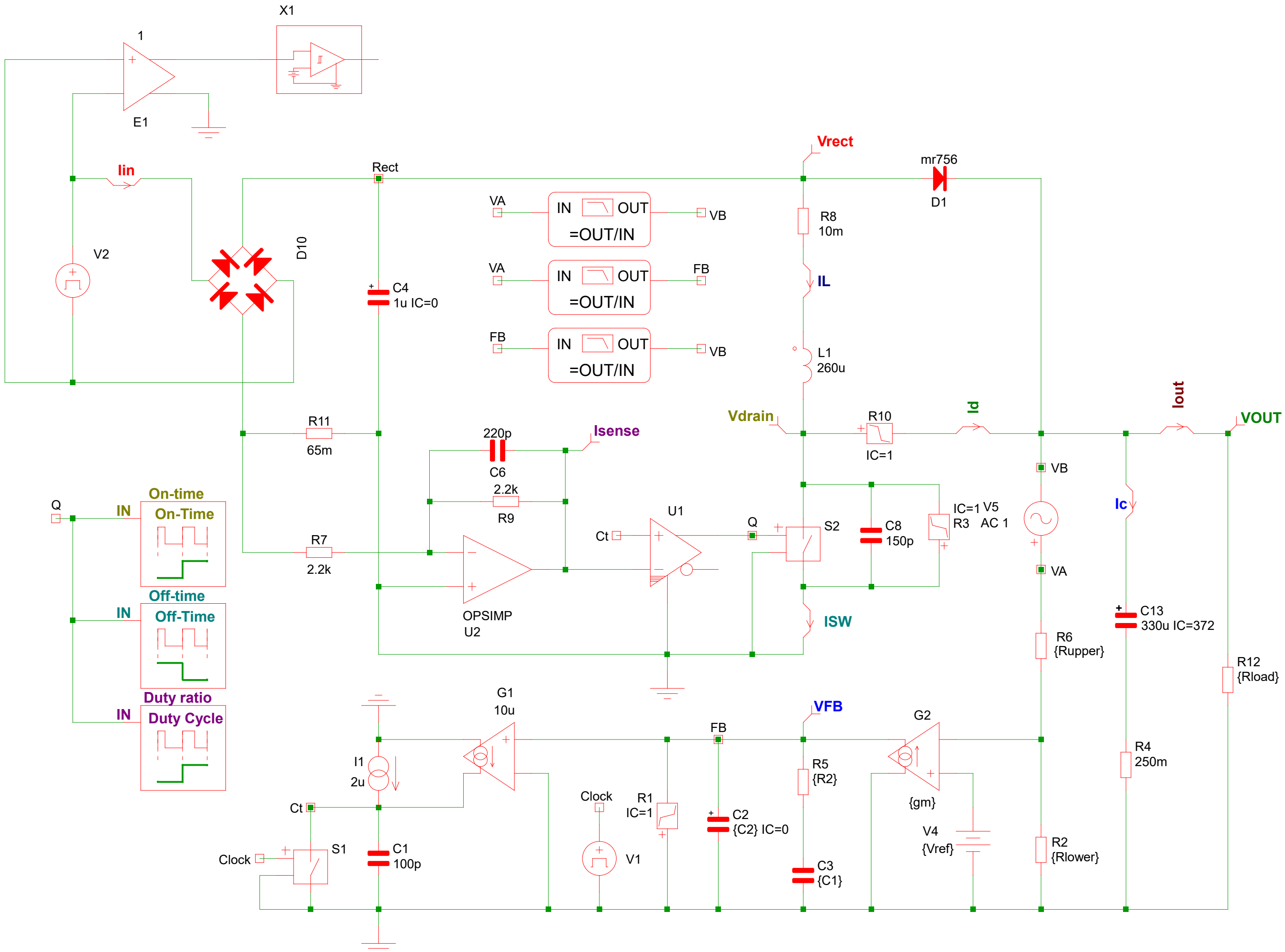








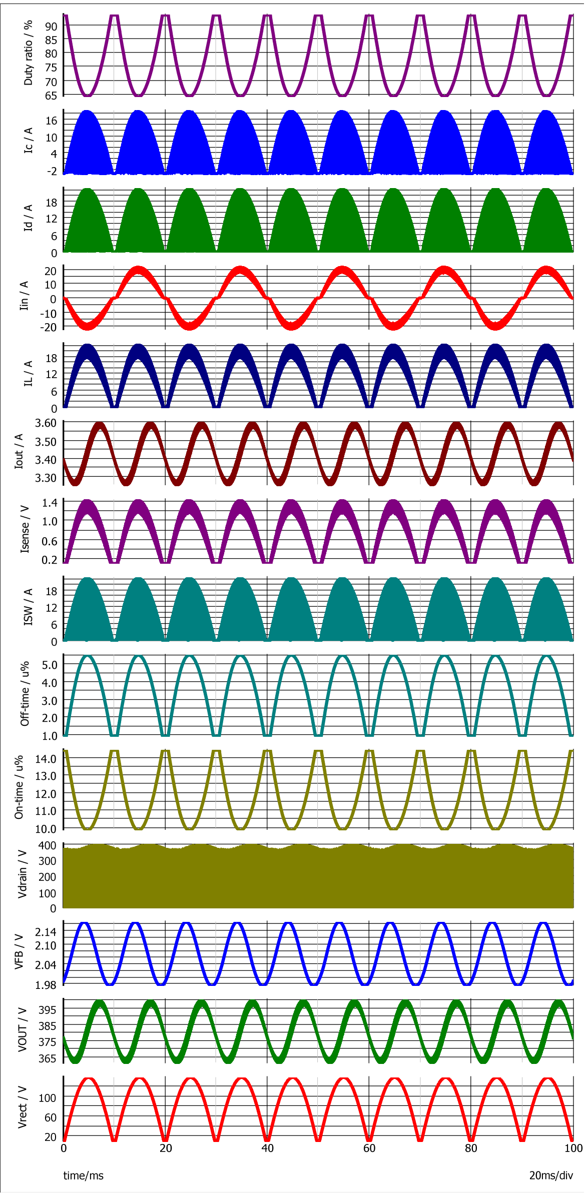
XatNthYn(data, yValue, n   X value at the Nth Y crossing with negative slope



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_{clock} = 65 kHz and f_{line} = 50 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.

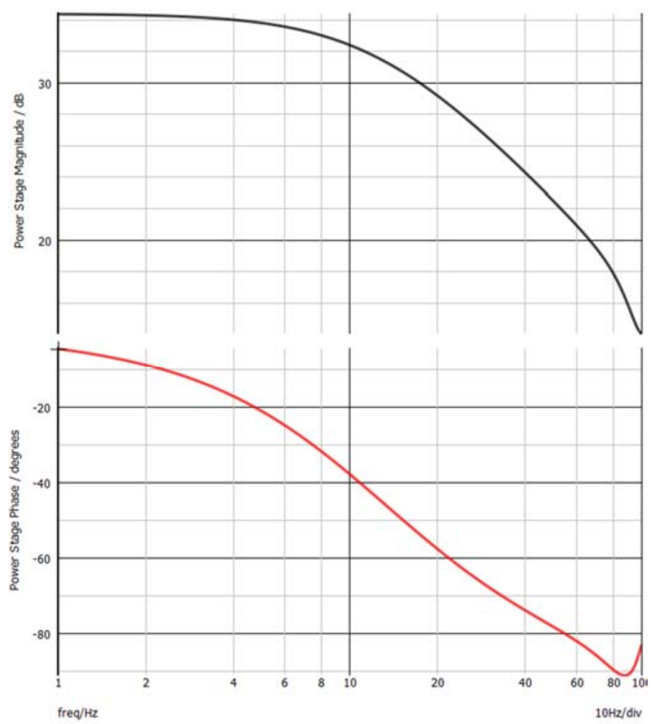
Boost CCM Var toff PFC tran 1.3 kW – demo POP



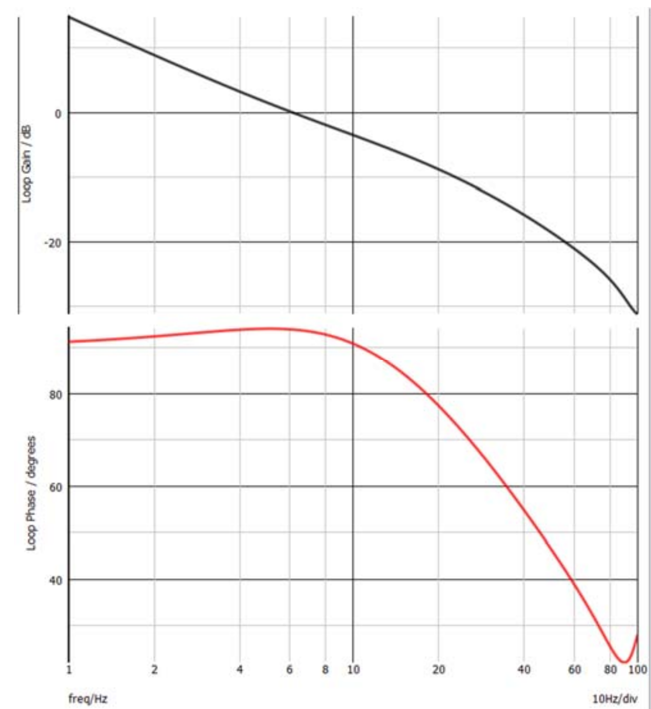
The simulation is done in less than 20 s for a 100-ms duration. For this CCM, you can extract information such as rms current in the output capacitor but also current distortion in different operating conditions.

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)

Power stage

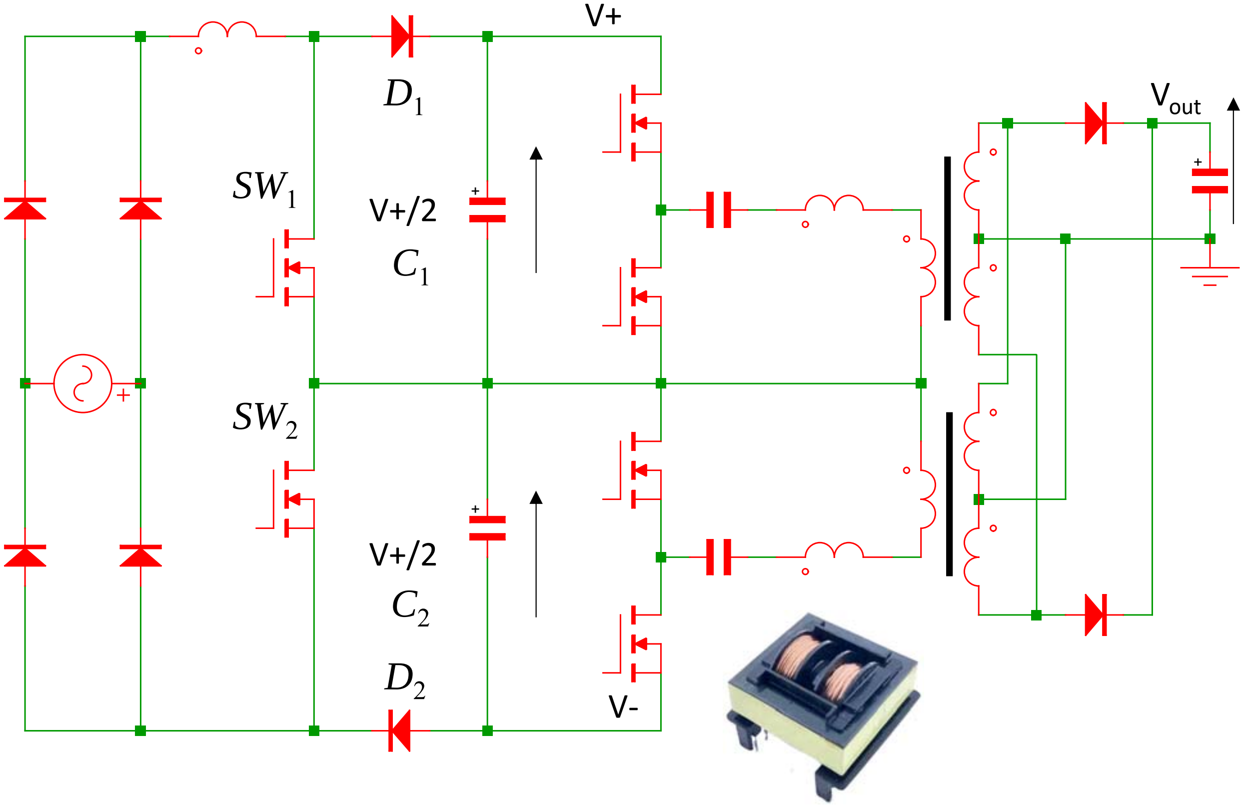


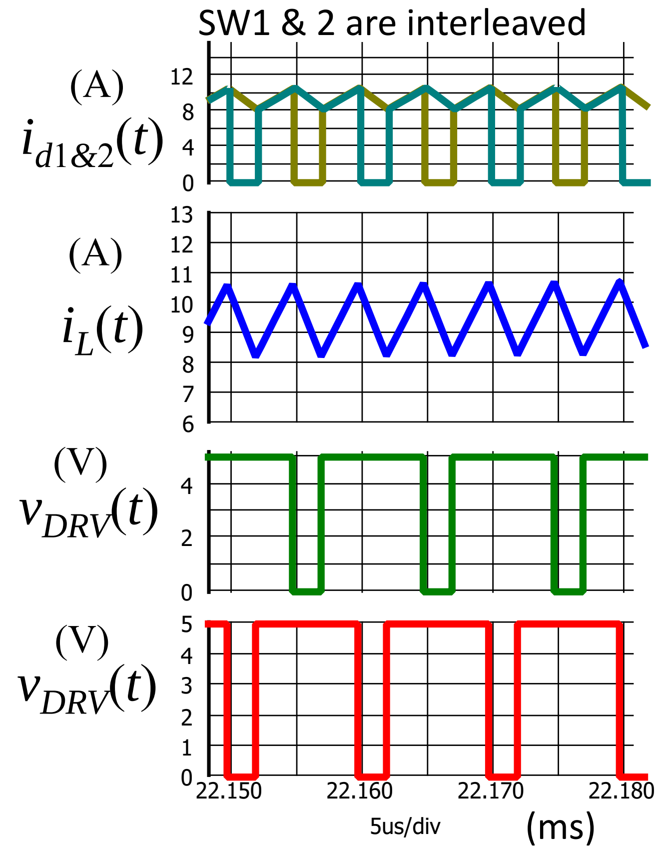
Compensated loop gain

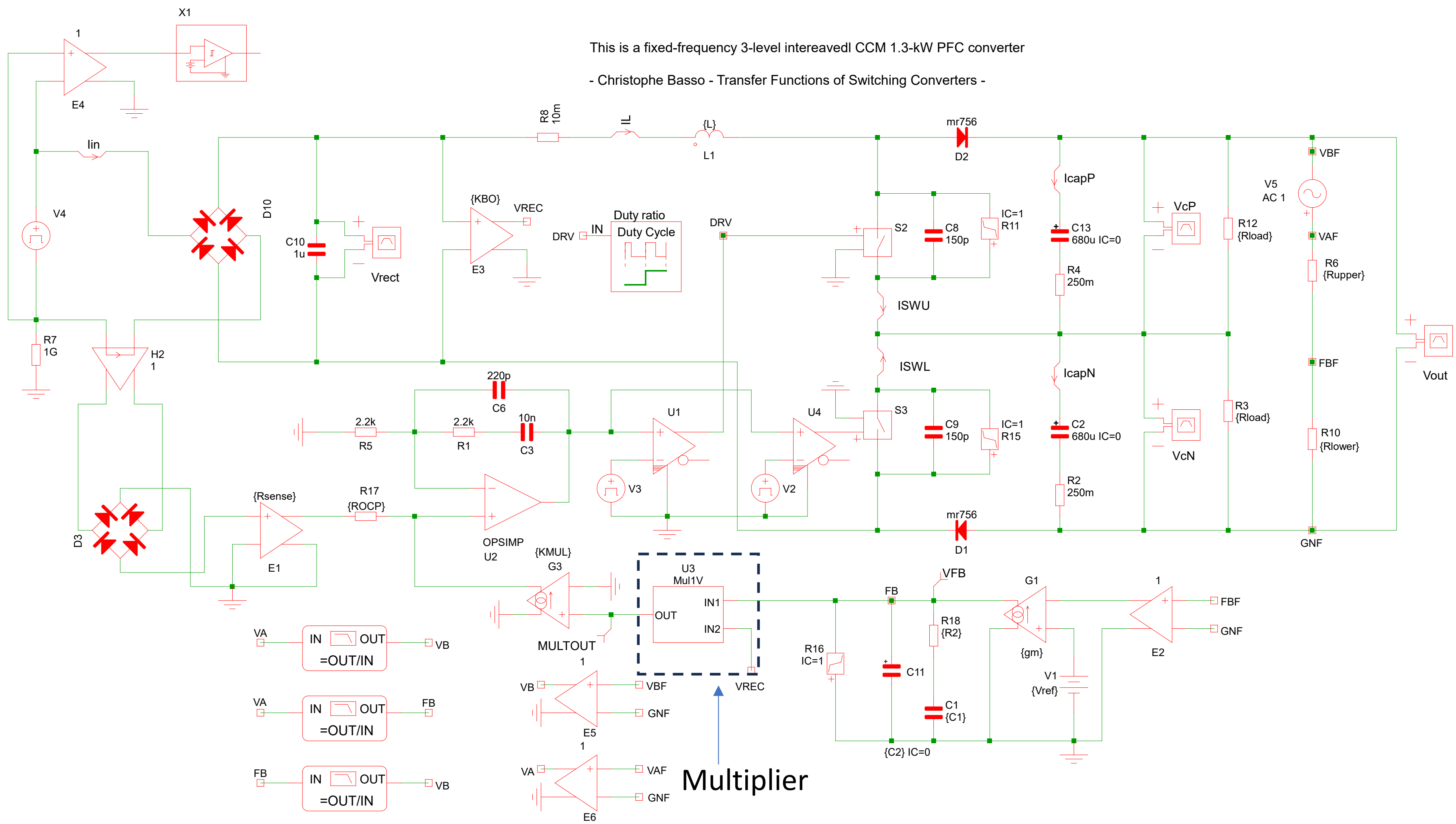


3-Level PFC Converters

- 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





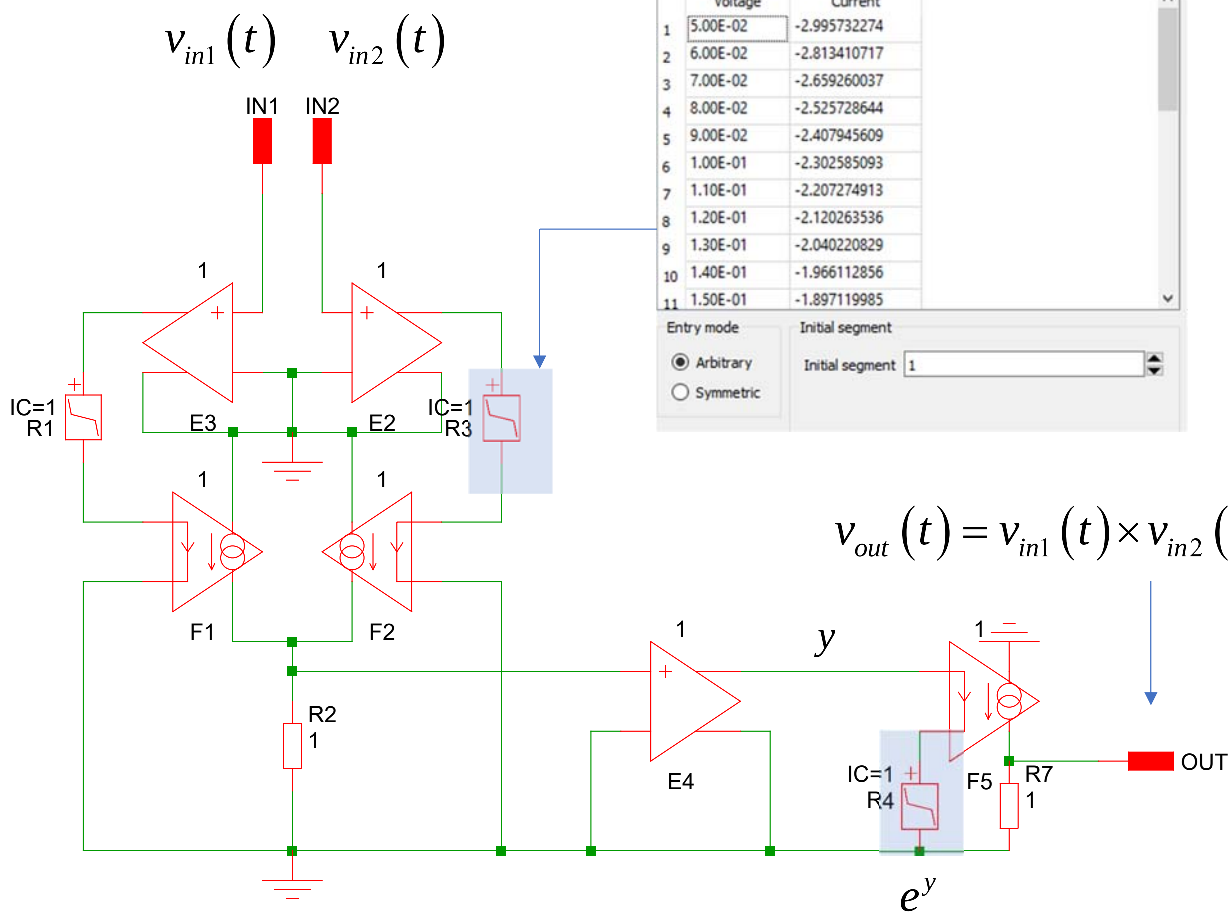


Boost PFC 1-phase 3-level Interleaved CCM Mul

Granularity will improve on precision
But more points slow down simulation

	Voltage	Current
1	5.00E-02	-2.995732274
2	6.00E-02	-2.813410717
3	7.00E-02	-2.659260037
4	8.00E-02	-2.525728644
5	9.00E-02	-2.407945609
6	1.00E-01	-2.302585093
7	1.10E-01	-2.207274913
8	1.20E-01	-2.120263536
9	1.30E-01	-2.040220829
10	1.40E-01	-1.966112856
11	1.50E-01	-1.897119985

Entry mode
Arbitrary
Symmetric
Initial segment
Initial segment 1

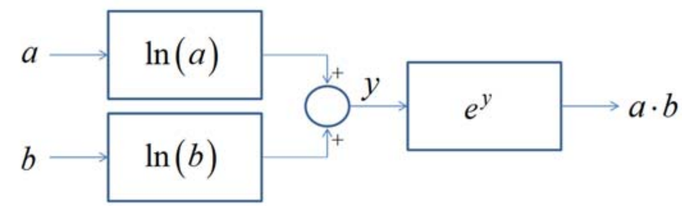


$$v_{in1}(t) \quad v_{in2}(t)$$

$$e^y$$

$$v_{out}(t) = v_{in1}(t) \times v_{in2}(t)$$

Napierian logarithm



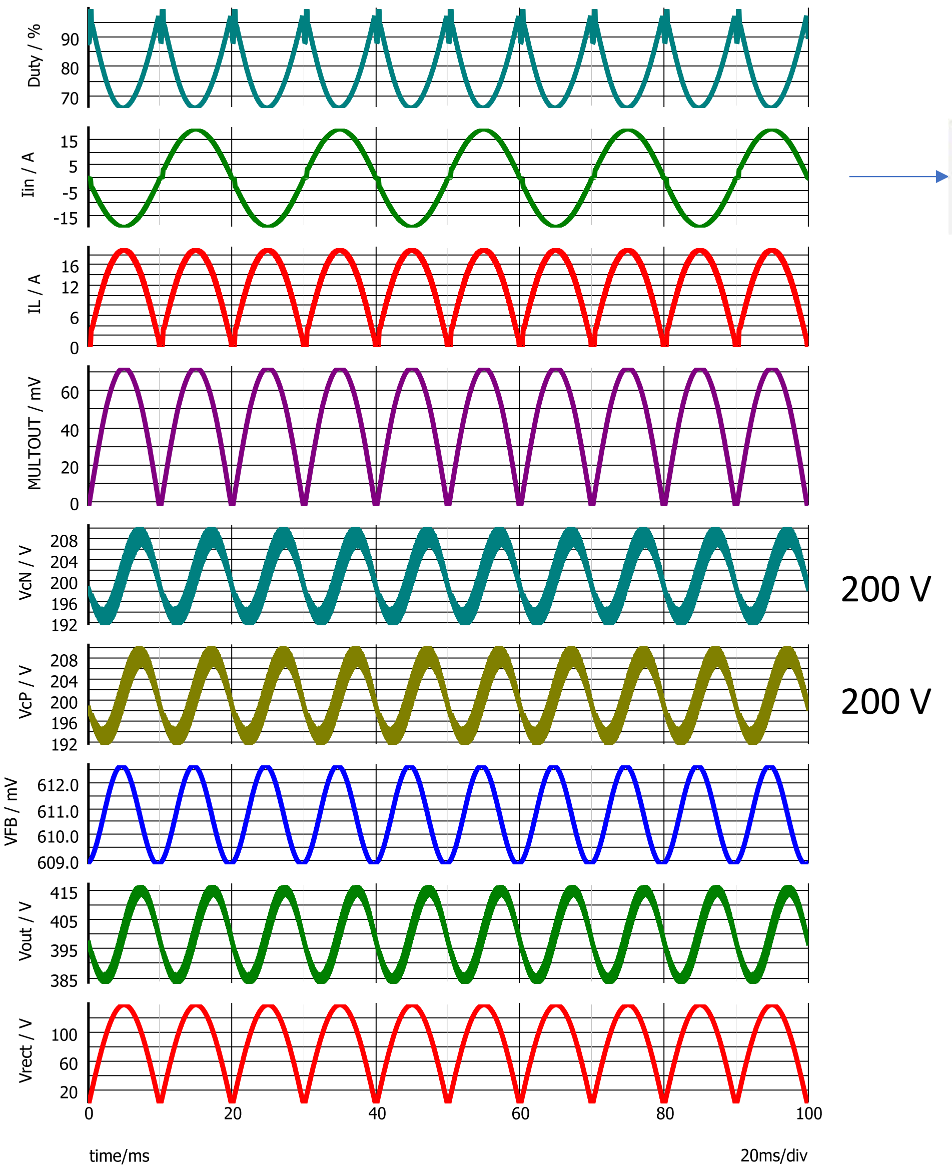
e base

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

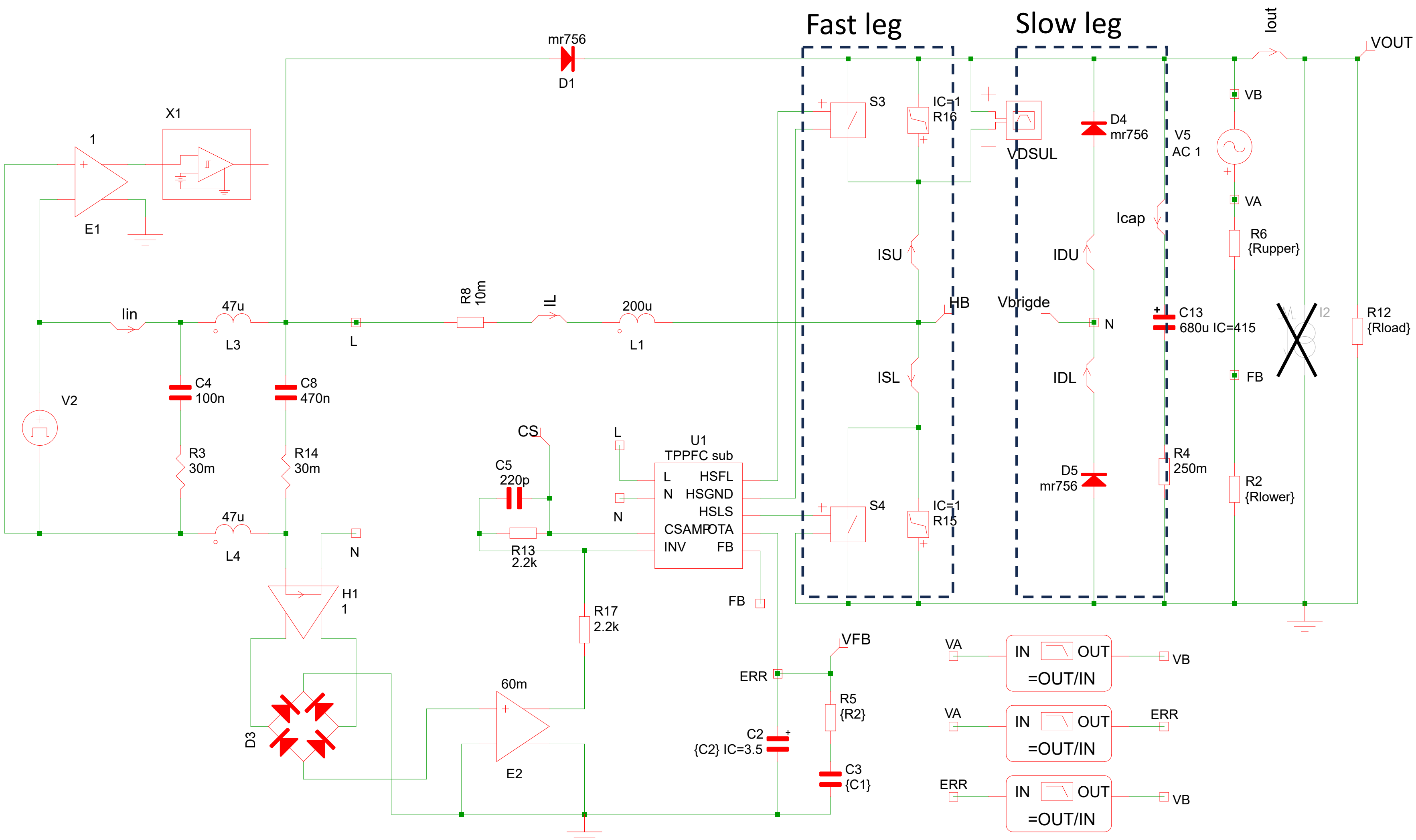
$$e^{(\ln a + \ln b)} = a \cdot b$$

Check this link for detailed explanation

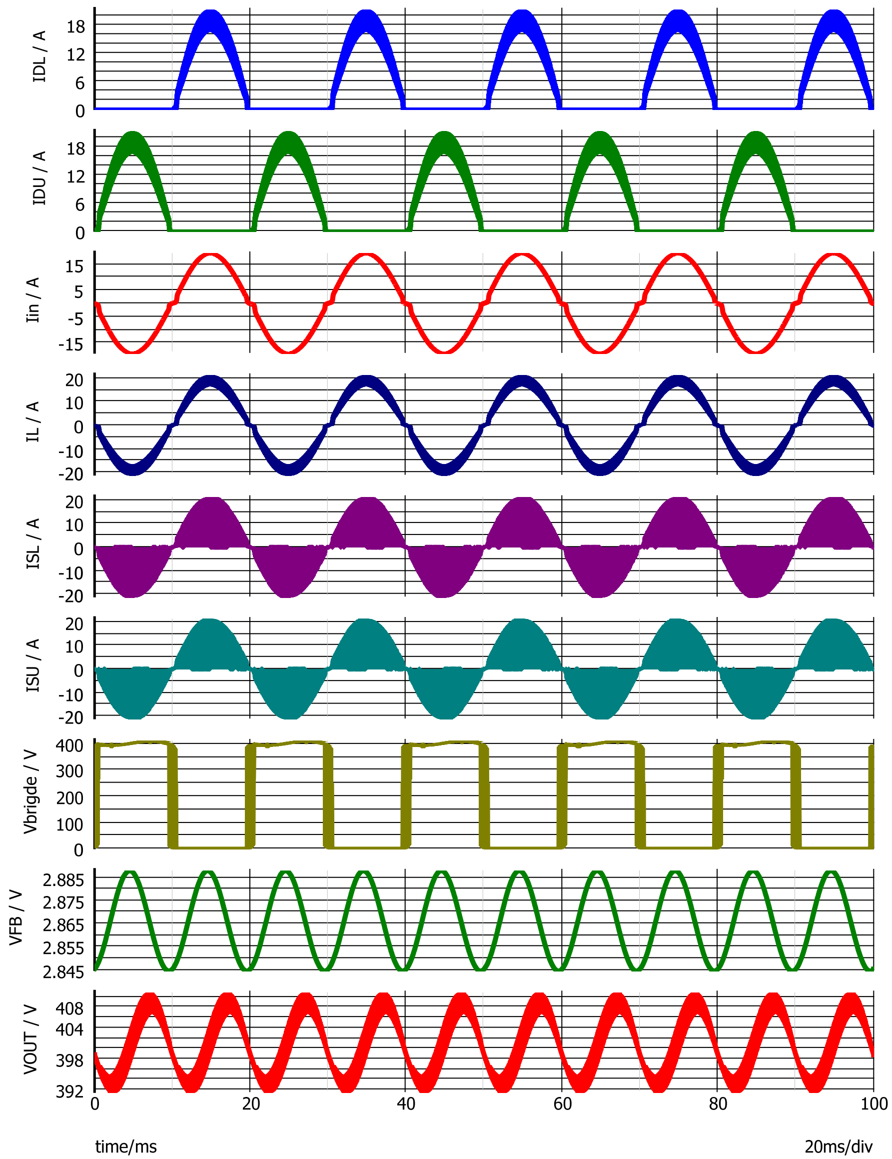
Building a simple multipliers



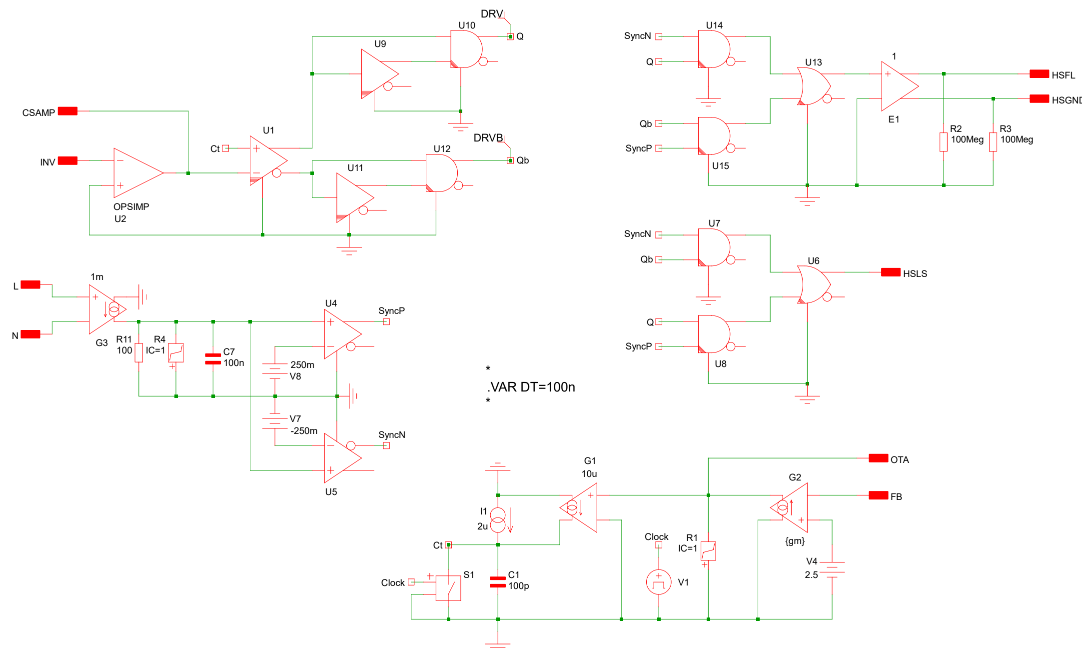
Curve label	Name	Value
Iin	Distortion	2.53601%

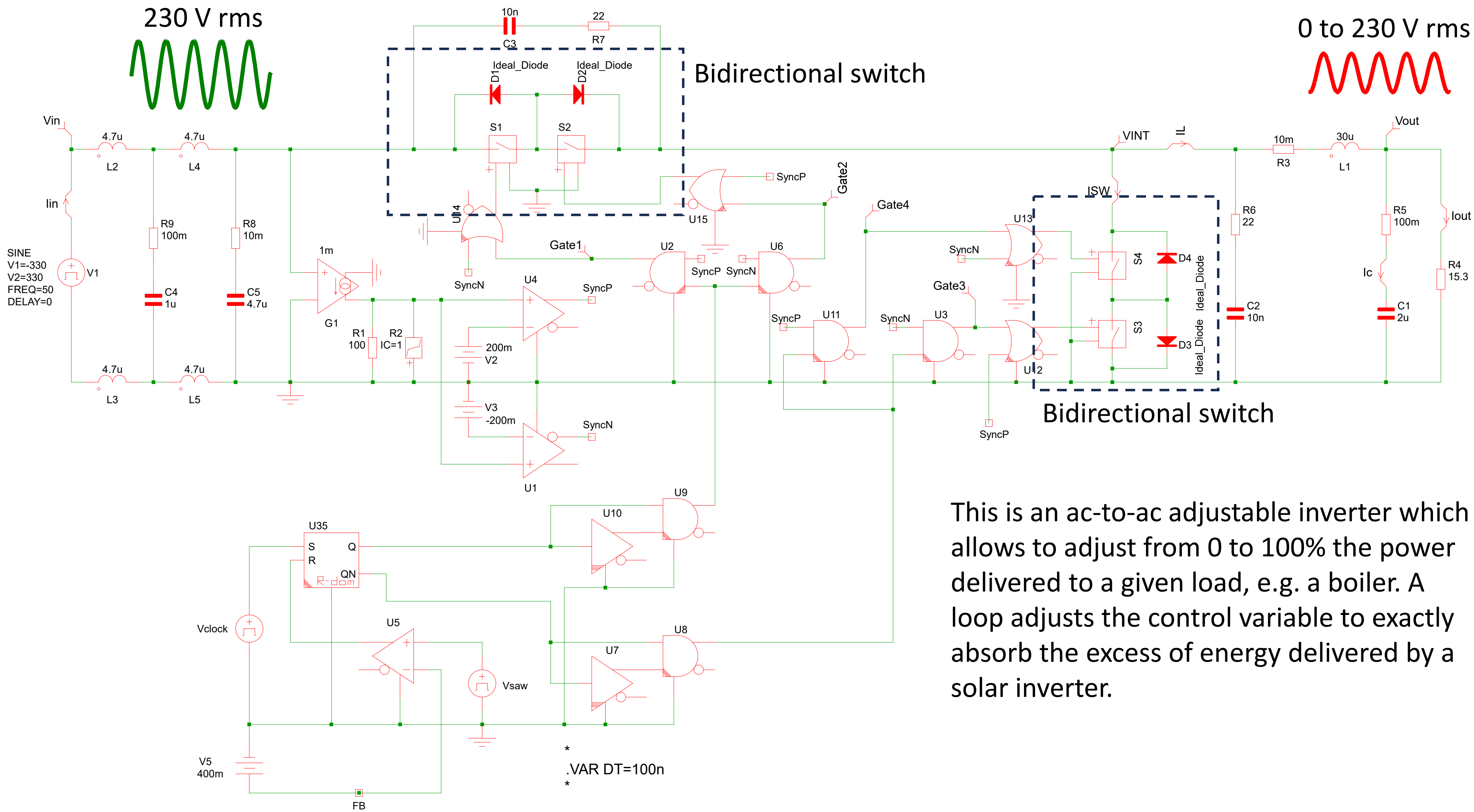


Boost TPPFC CCM Var toff tran



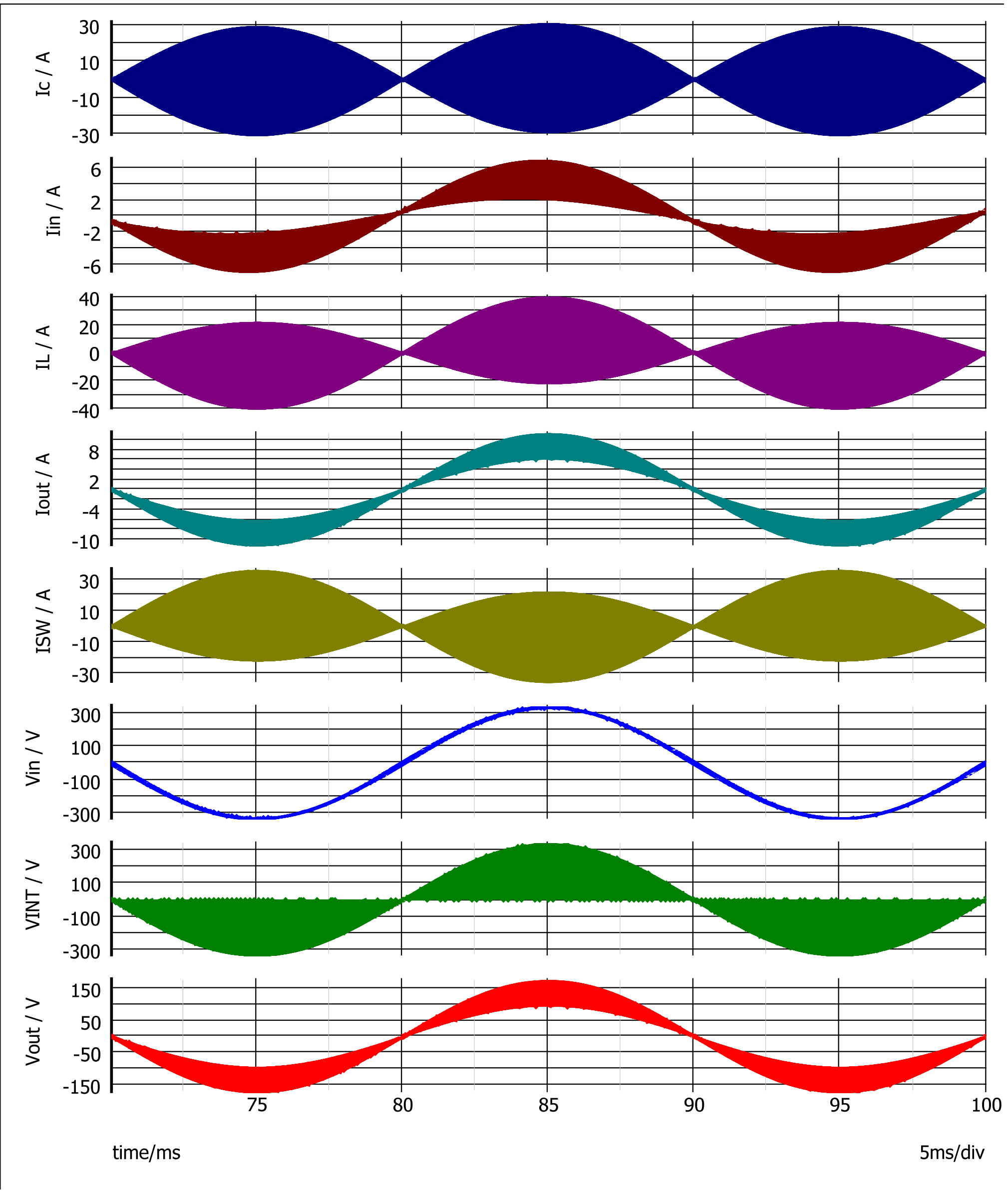
In this TPPFC topology, a decoder is needed to route the driving signal to the lower- or upper-side switch depending on the input current polarity





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

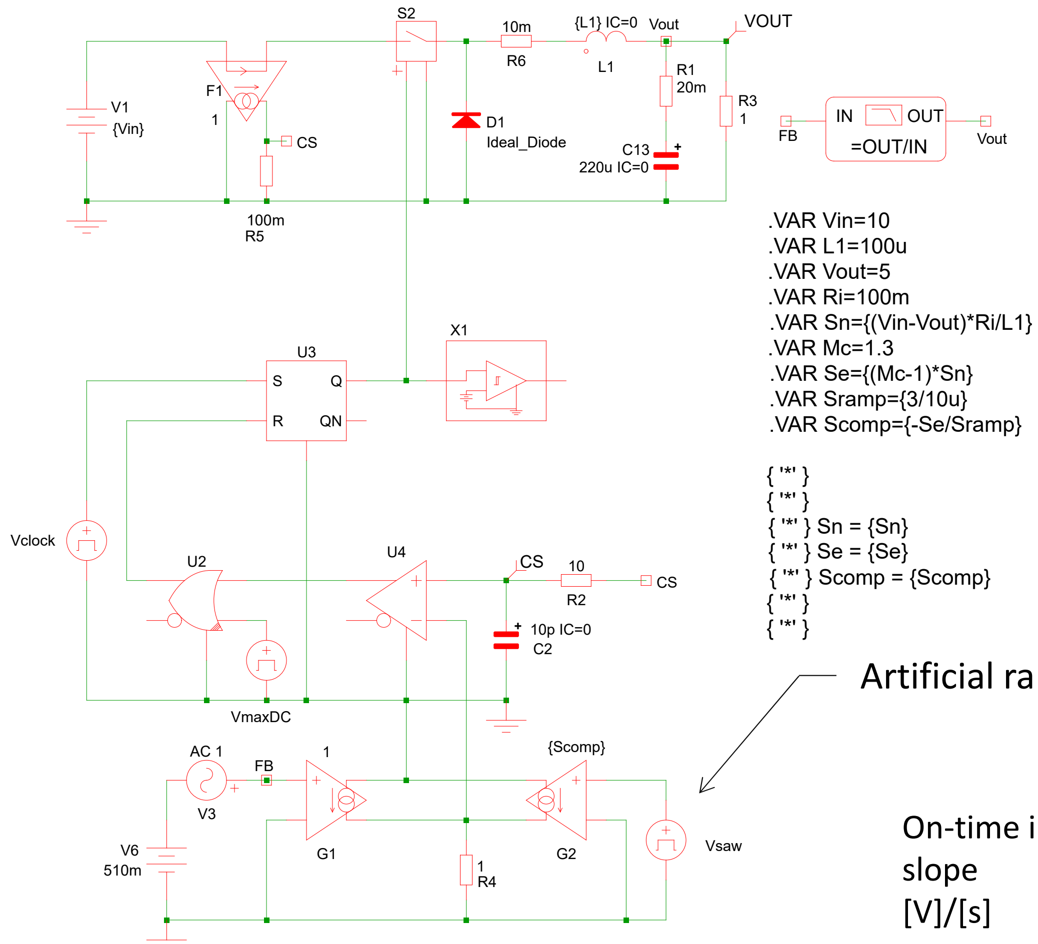


Fixed ac input voltage, 230 V rms

Adjustable ac output voltage, 100 V rms

Current-mode power converter

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



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

The duty ratio is 50%

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

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

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

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

Artificial ramp

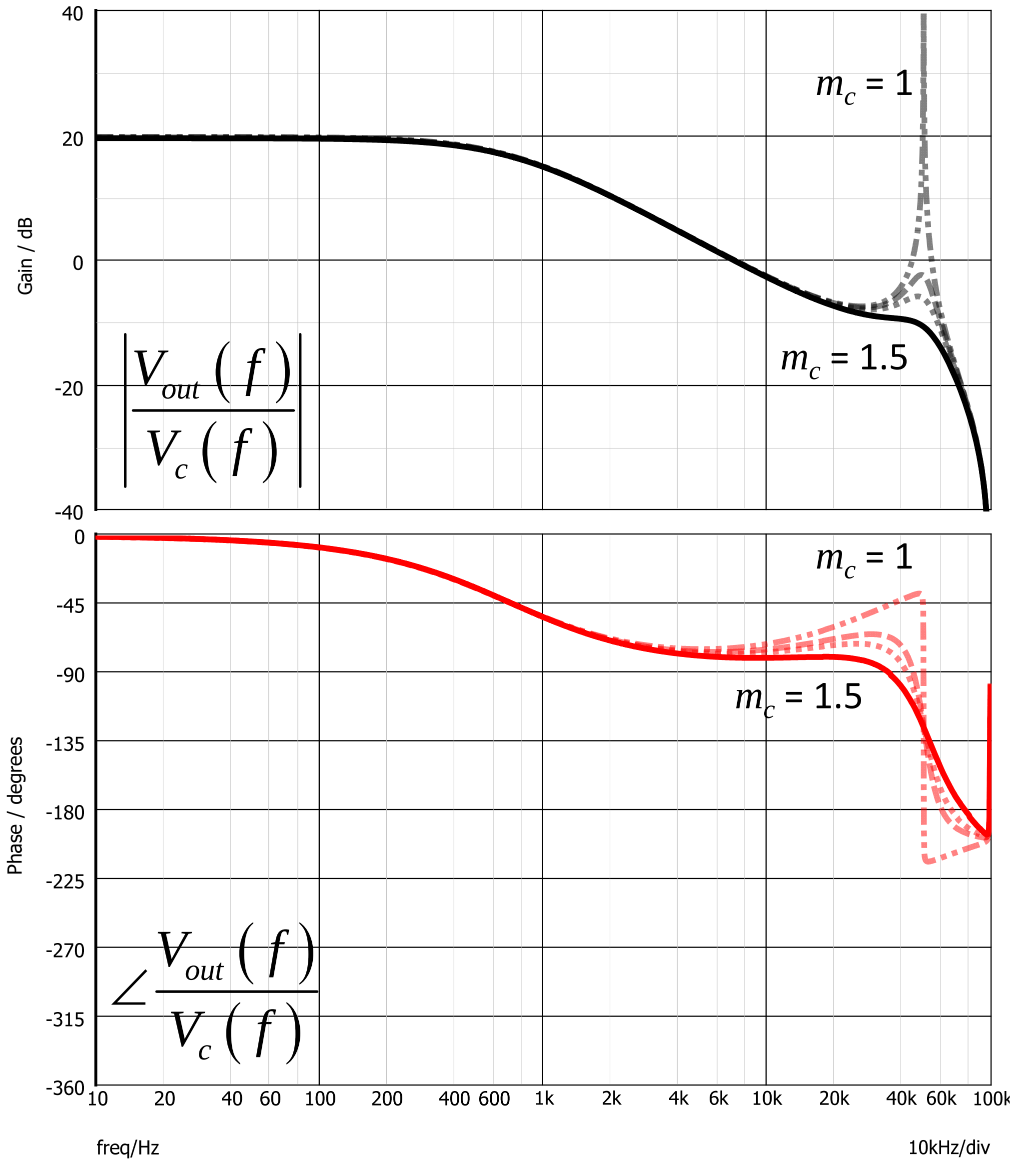
$$m_c = \frac{S_e}{S_n} + 1$$

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

m_c = 1 → no ramp

m_c = 1.5 → 50% compensation

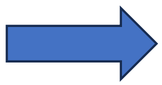
[1] R. Ridley, *A New Small-Signal Model for Current Mode Control*, Ph. D. dissertation, Virginia Polytechnic Institute and State University, 1990



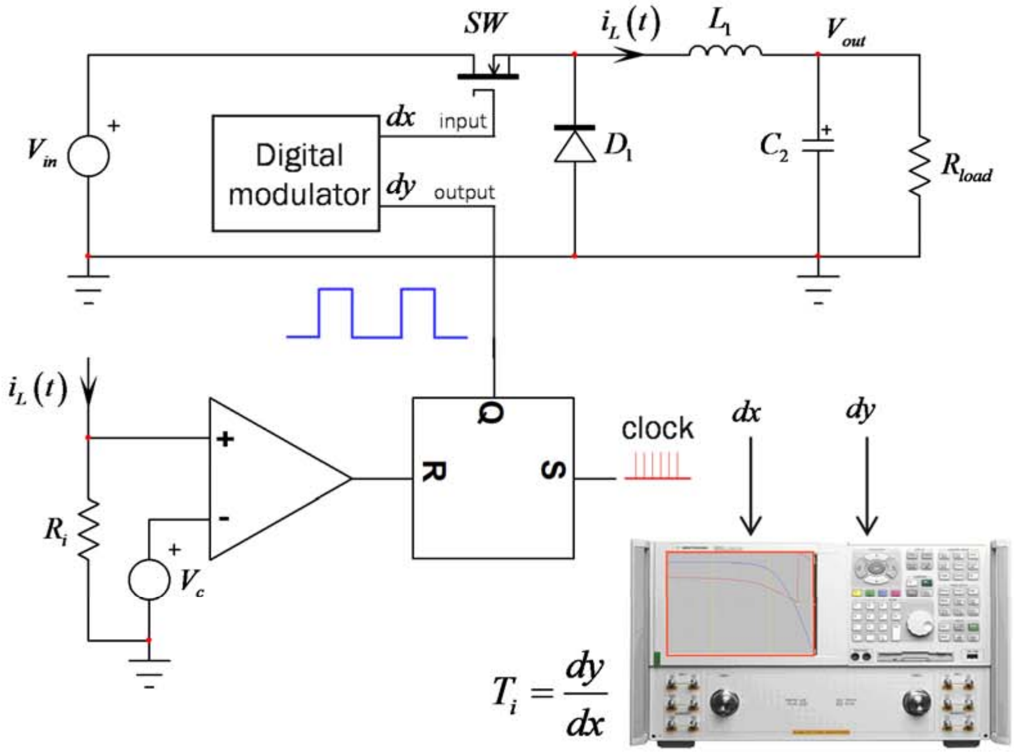
By adding slope compensation, we are damping the subharmonic poles and the converter gains in overall stability.

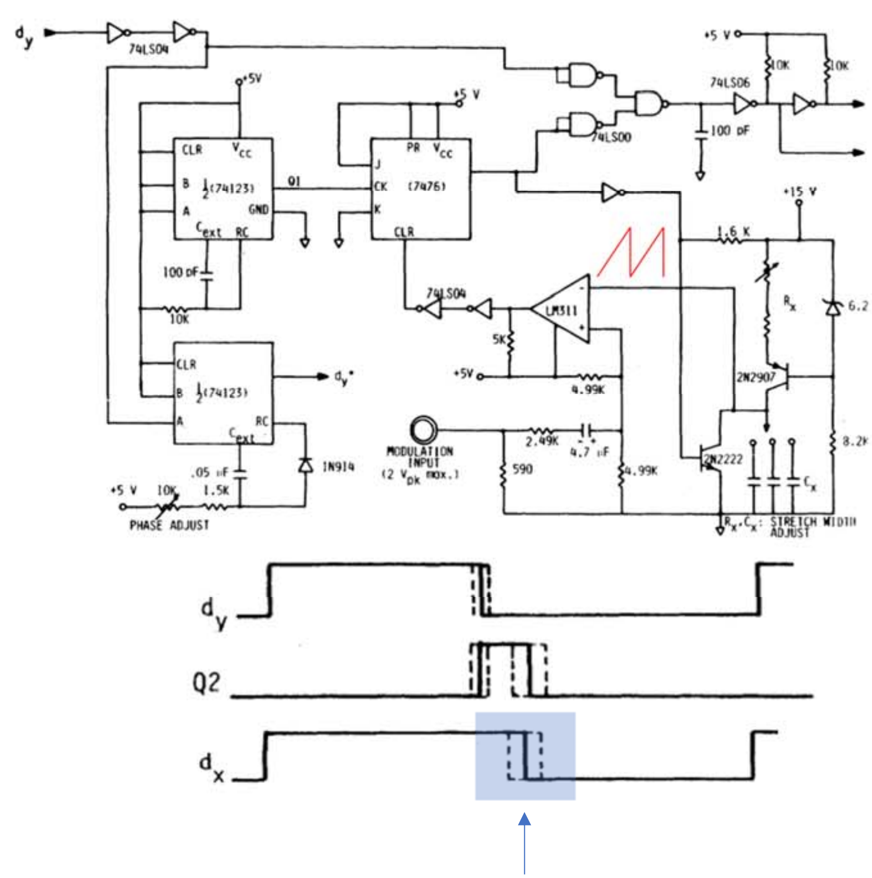
Where does this instability come from?

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?



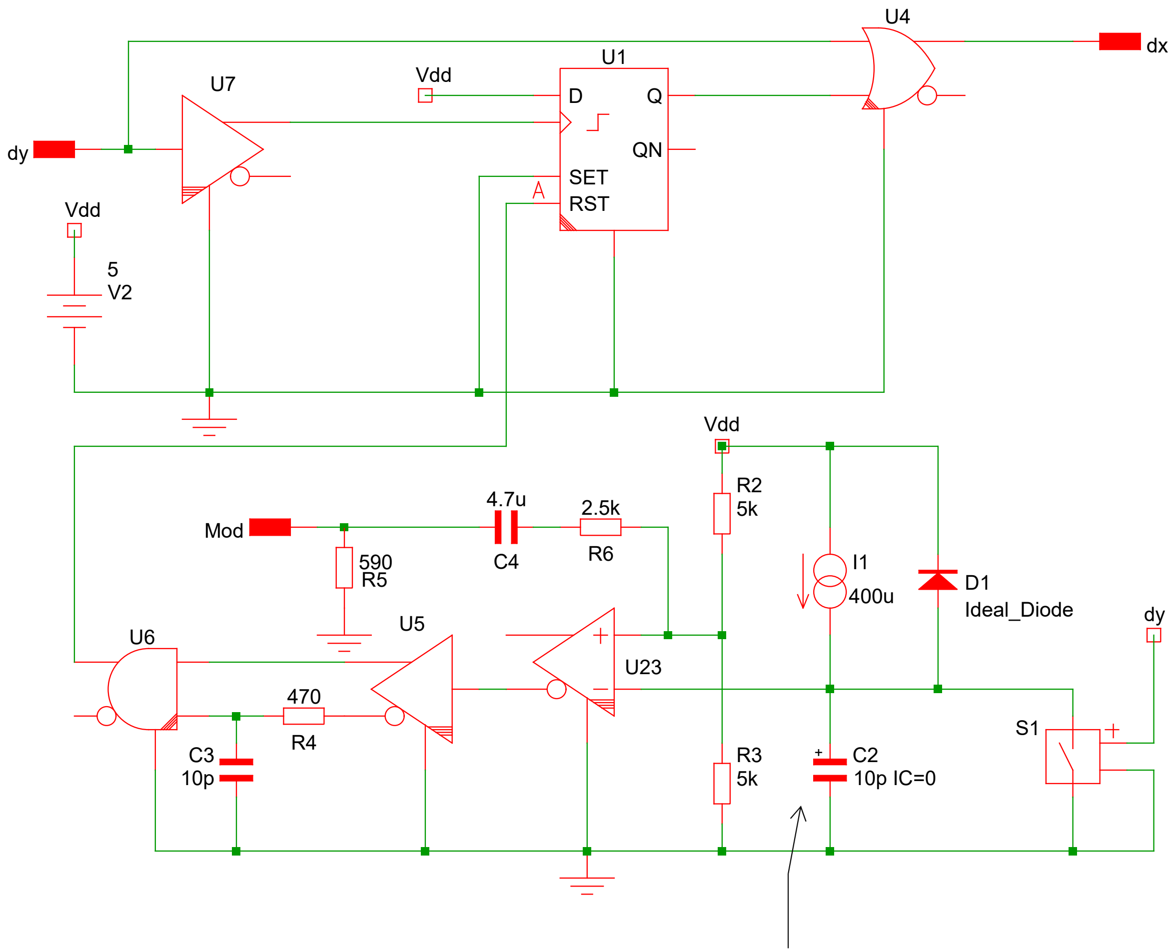
Implement a digital modulator





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

B. Cho, F. Lee, *Measurement of Loop Gain with the Digital Modulator*, IEEE Transactions on Power Electronics, January 1986



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

This is the digital modulator that I described in this paper published on How2Power:

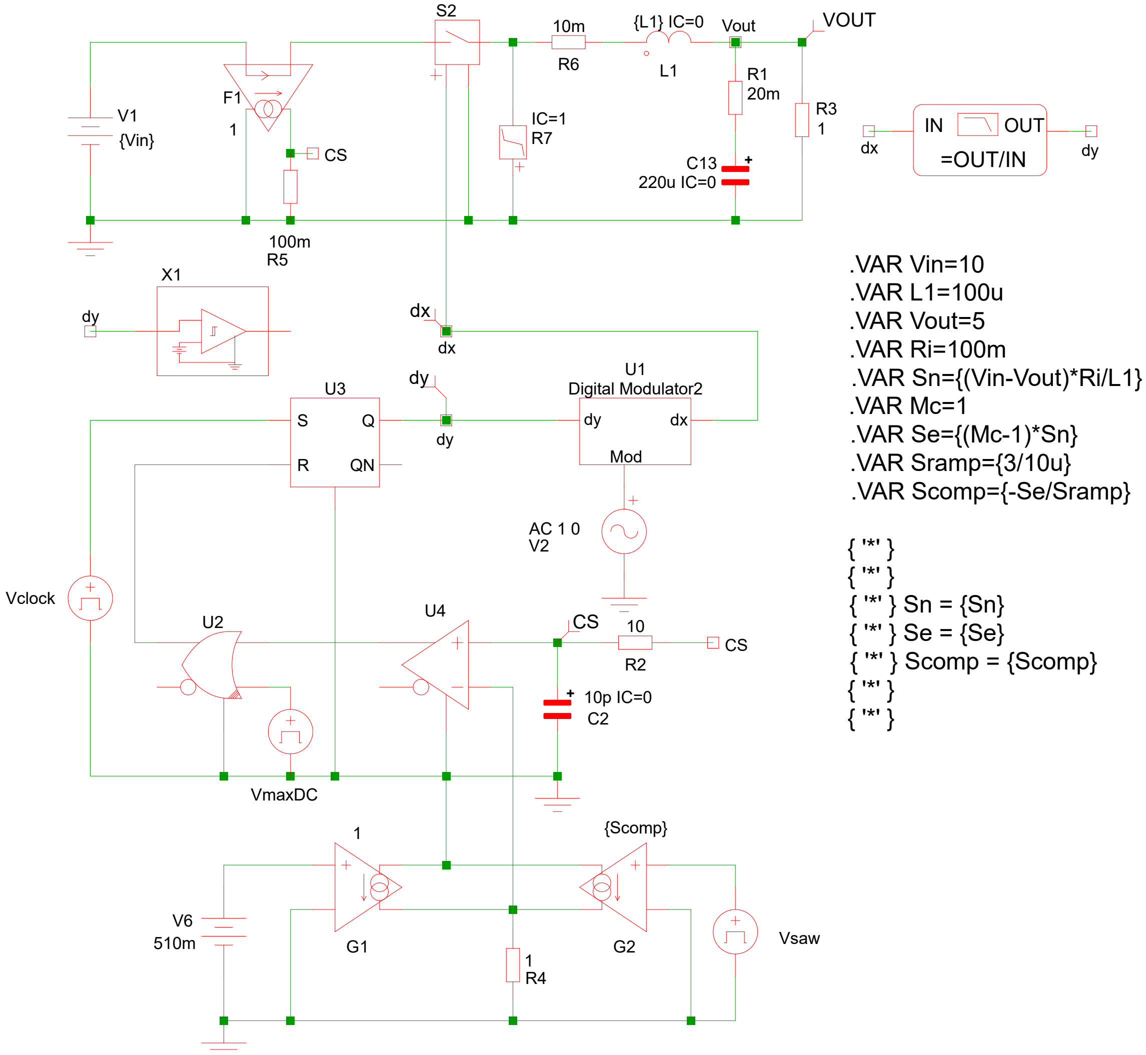
HOW2POWER TODAY
Your Power Design Newsletter

Exclusive Technology Feature

ISSUE: January 2021

Simulation Demonstrates Impact Of Current-Loop Crossover Frequency On Stability

by Christophe Basso, ON Semiconductor, Toulouse, France



\buck\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