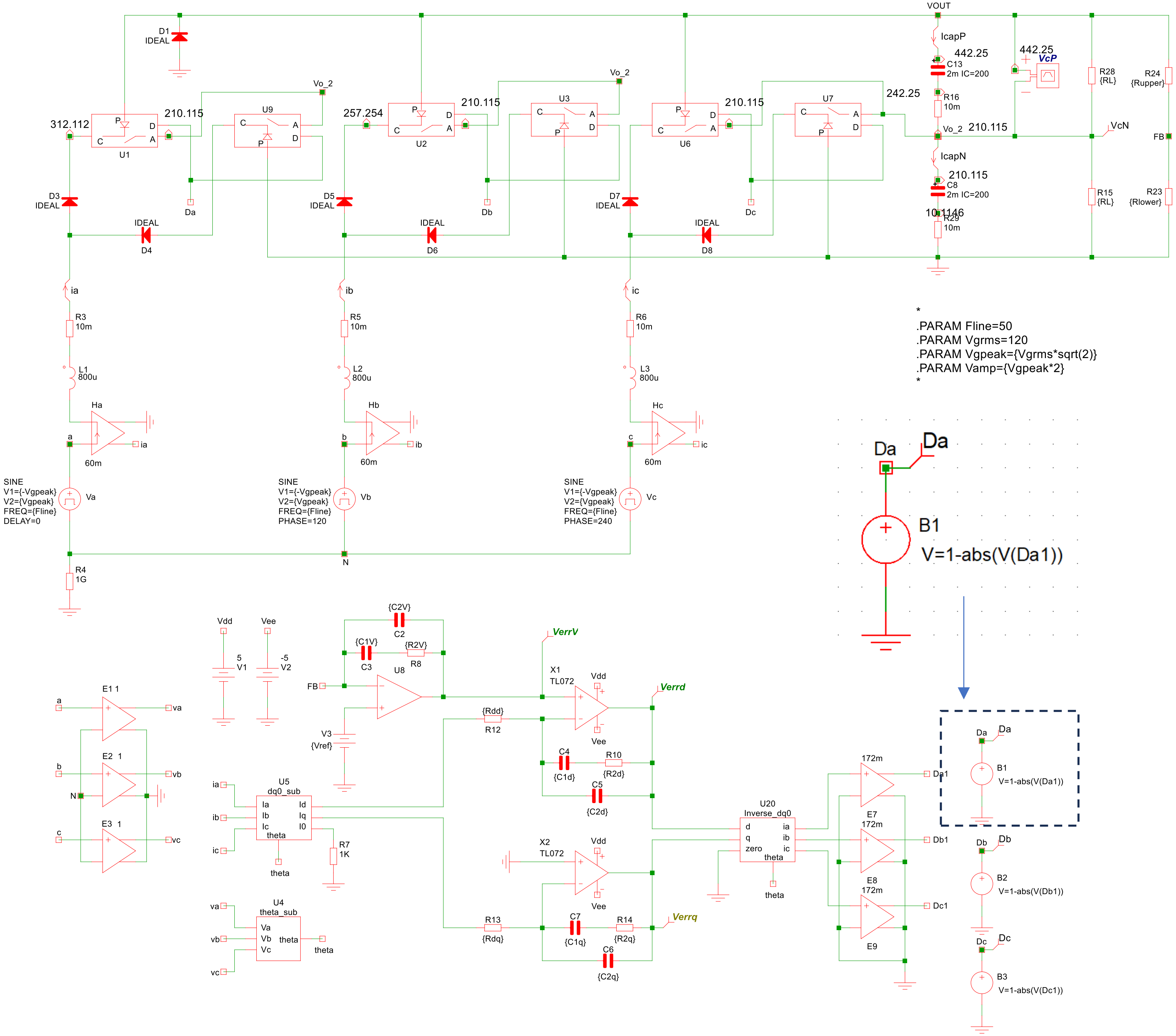


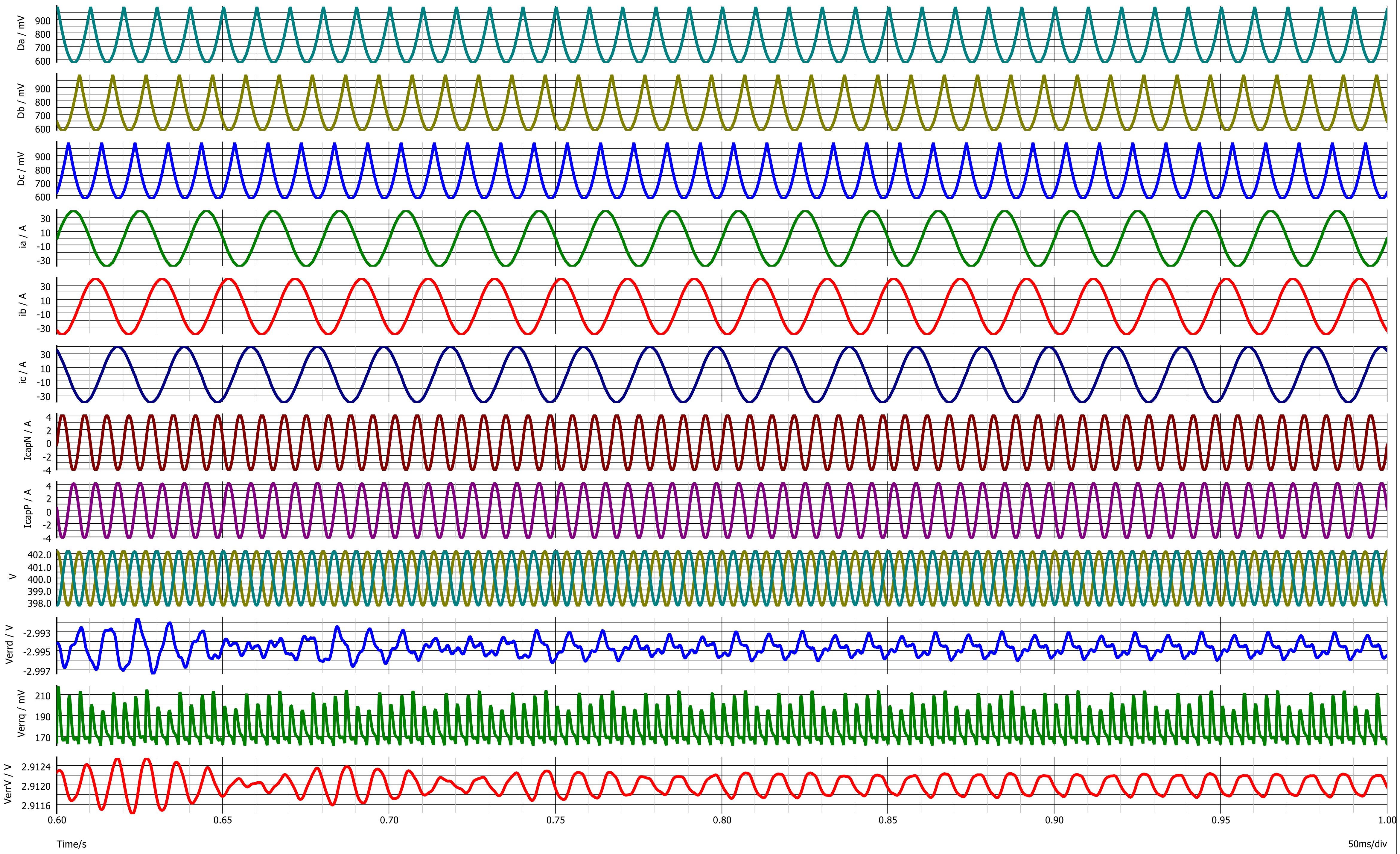
This is an averaged version of the Vienna rectifier using the model of the PWM switch. The PFC delivers 800 V for a 10-kW load. This is a low-line simulation (V_{in} = 120 V rms) to check the control section.

The dq0 modulator-demodulator is similar to the one used in the 6-pack example. An additional treatment is added in the output of the modulator to produce an off-time modulation (1-D) for this Vienna application.

This averaged model is used later to extract the ac response of the three loops and stabilize the converter.

I have appreciated interacting with Yang Fu from Shenzhen -多谢!

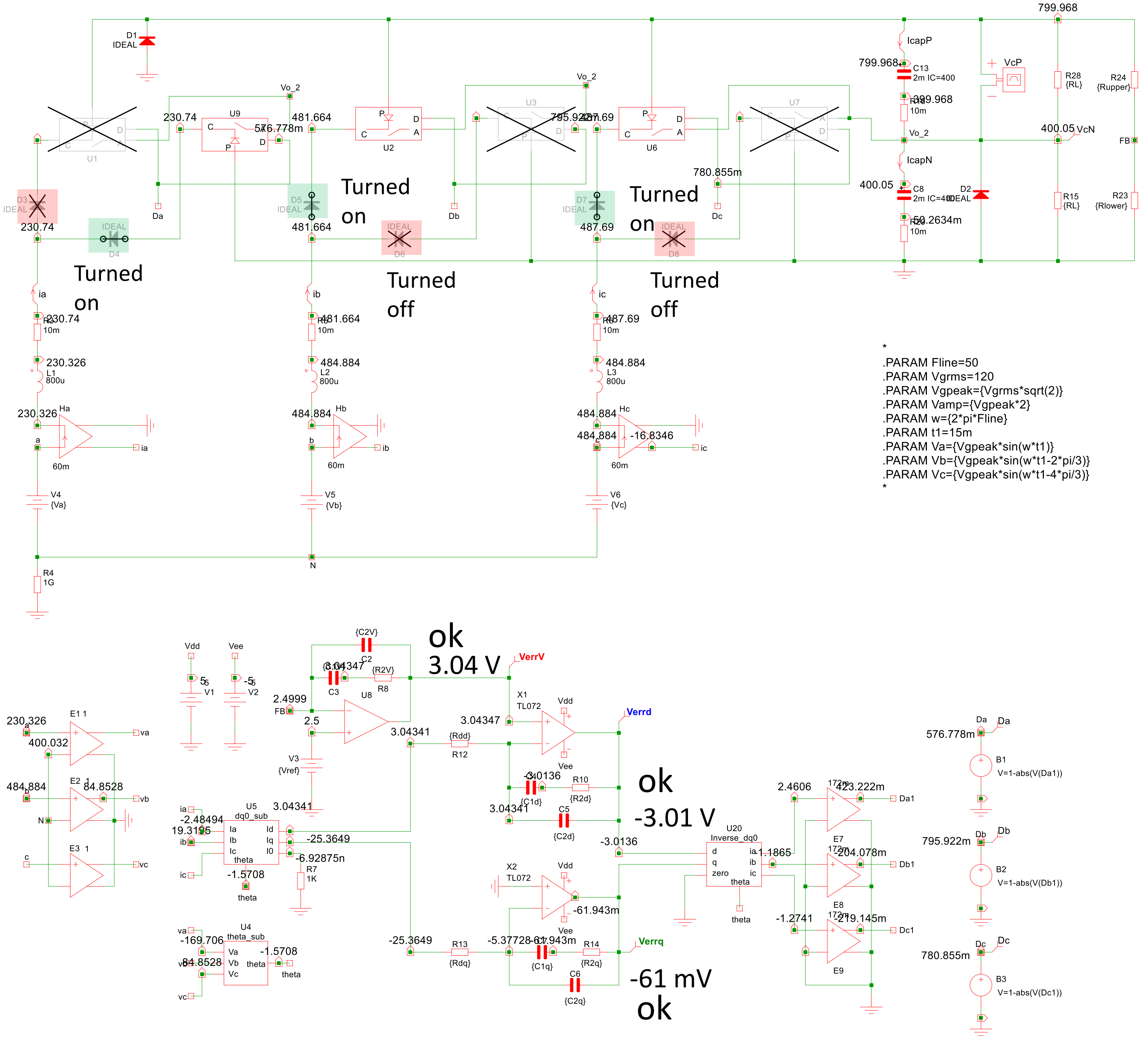
Christophe Basso – November 2024 Rev. 0.3


Da / mV
900
800
700
600
Db / mV
900
800
700
600
Dc / mV
900
800
700
600
ia / A
30
10
-10
-30
ib / A
30
10
-10
-30
ic / A
30
10
-10
-30
IcapN / A
4
2
0
-2
-4
IcapP / A
4
2
0
-2
-4
V
402.0
401.0
400.0
399.0
398.0
Verrd / V
-2.993
-2.995
-2.997
Verrq / mV
210
190
170
VerrV / V
2.9124
2.9120
2.9116
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
1.00
Time/s
50ms/div

-3 V

190 mV

3 V



```
*
.PARAM Fline=50
.PARAM Vgrms=120
.PARAM Vgpeak={Vgrms*sqrt(2)}
.PARAM Vamp={Vgpeak*2}
.PARAM w={2*pi*Fline}
.PARAM t1=15m
.PARAM Va={Vgpeak*sin(w*t1)}
.PARAM Vb={Vgpeak*sin(w*t1-2*pi/3)}
.PARAM Vc={Vgpeak*sin(w*t1-4*pi/3)}
*
```

For the dc operating point, I believe only some averaged models need to be active at a time considering the input line polarities at the selected time t_1. Here, I selected 15 ms implying:

$t_{10} := 15\text{ms}$

$v_a(t_{10}) = -169.706\ \text{V}$ neg

$v_b(t_{10}) = 84.853\ \text{V}$ pos

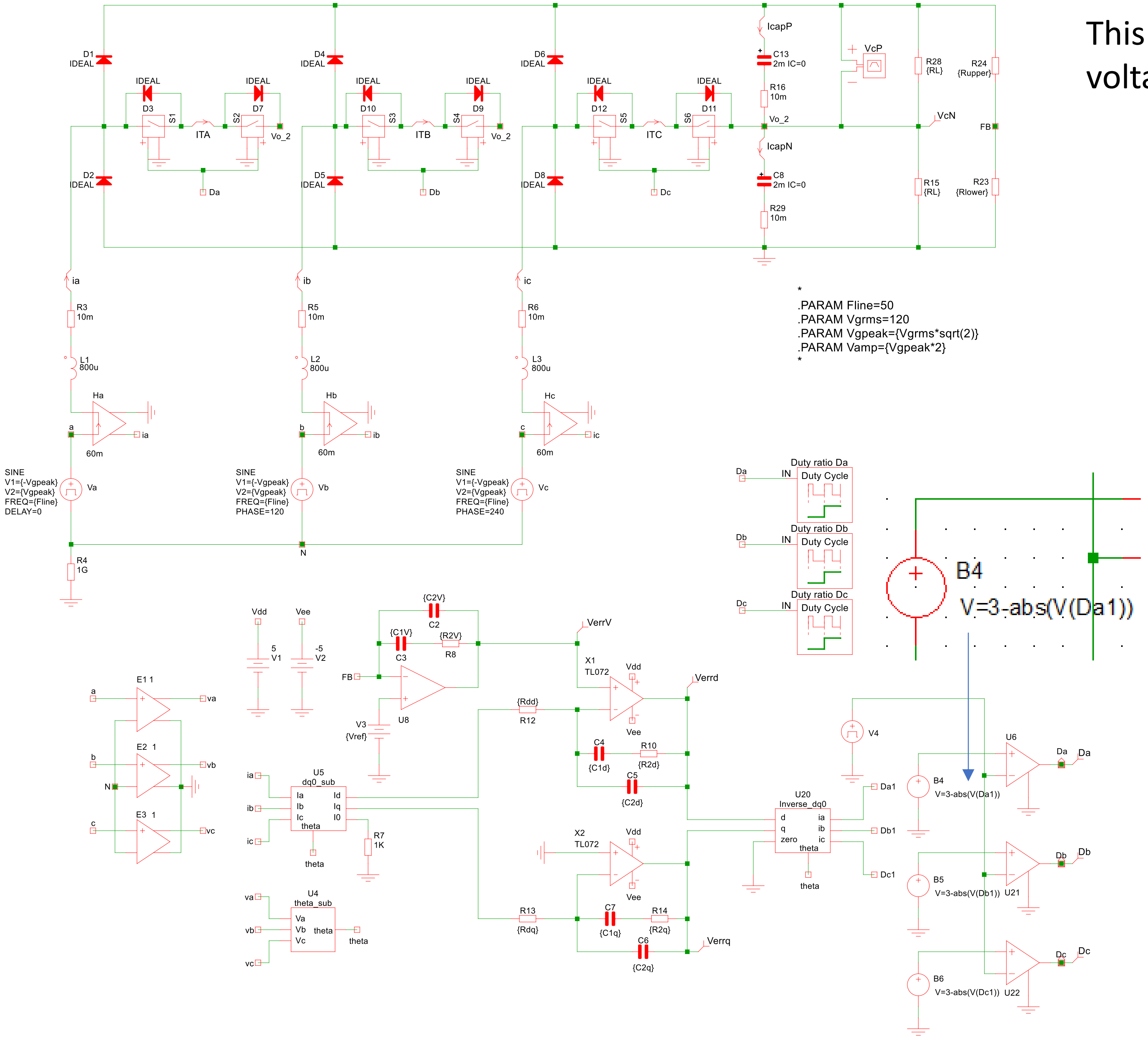
$v_c(t_{10}) = 84.853\ \text{V}$ pos

$\text{theta} := \text{atan2}(v_{cos}(t_{10}), v_{sin}(t_{10})) = -1.571$

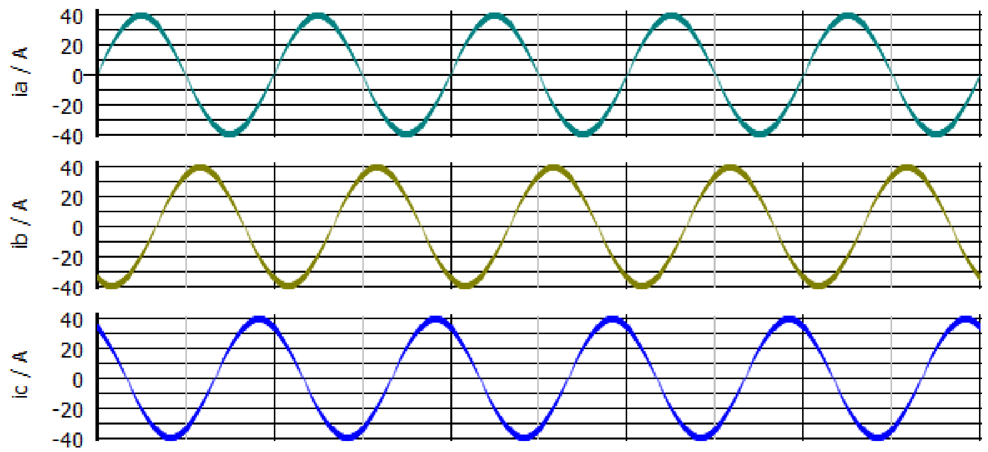
This selection implies that positive diodes on line b and c are turned on. The diode on the negative line a is active. Some of the models are turned off, easing the burden on the simulation engine.

The operating point seems correct and matches the transient simulation. Using three averaged models (or 6 in the transient simulation), makes the simulation sensitive to any parameter change: always check the dc point is ok.

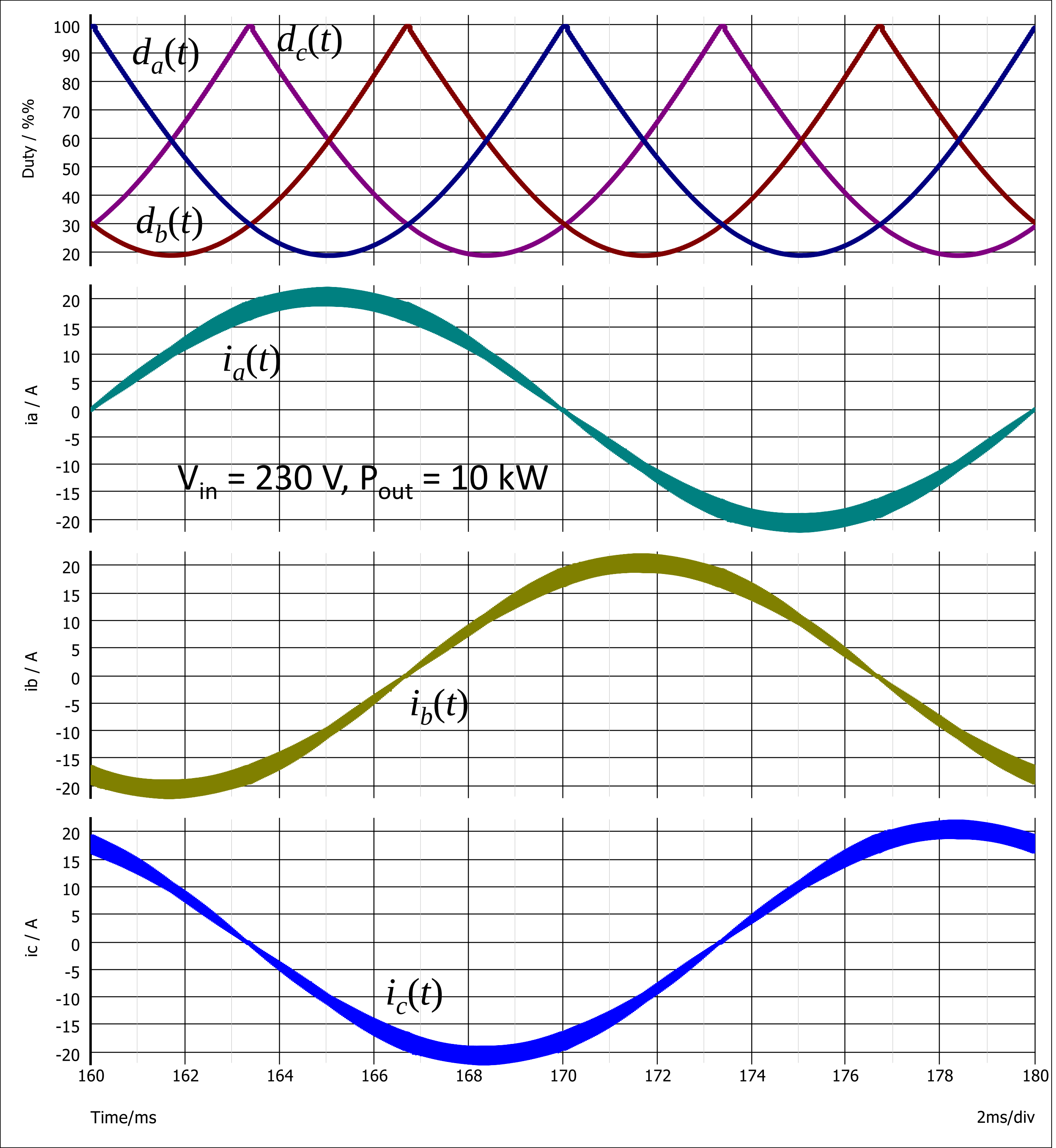
This is the cycle-by-cycle simulation. The output voltage is 800 V, P_{out} = 10 kW



```
*
.PARAM Fline=50
.PARAM Vgrms=120
.PARAM Vgpeak={Vgrms*sqrt(2)}
.PARAM Vamp={Vgpeak*2}
*
```



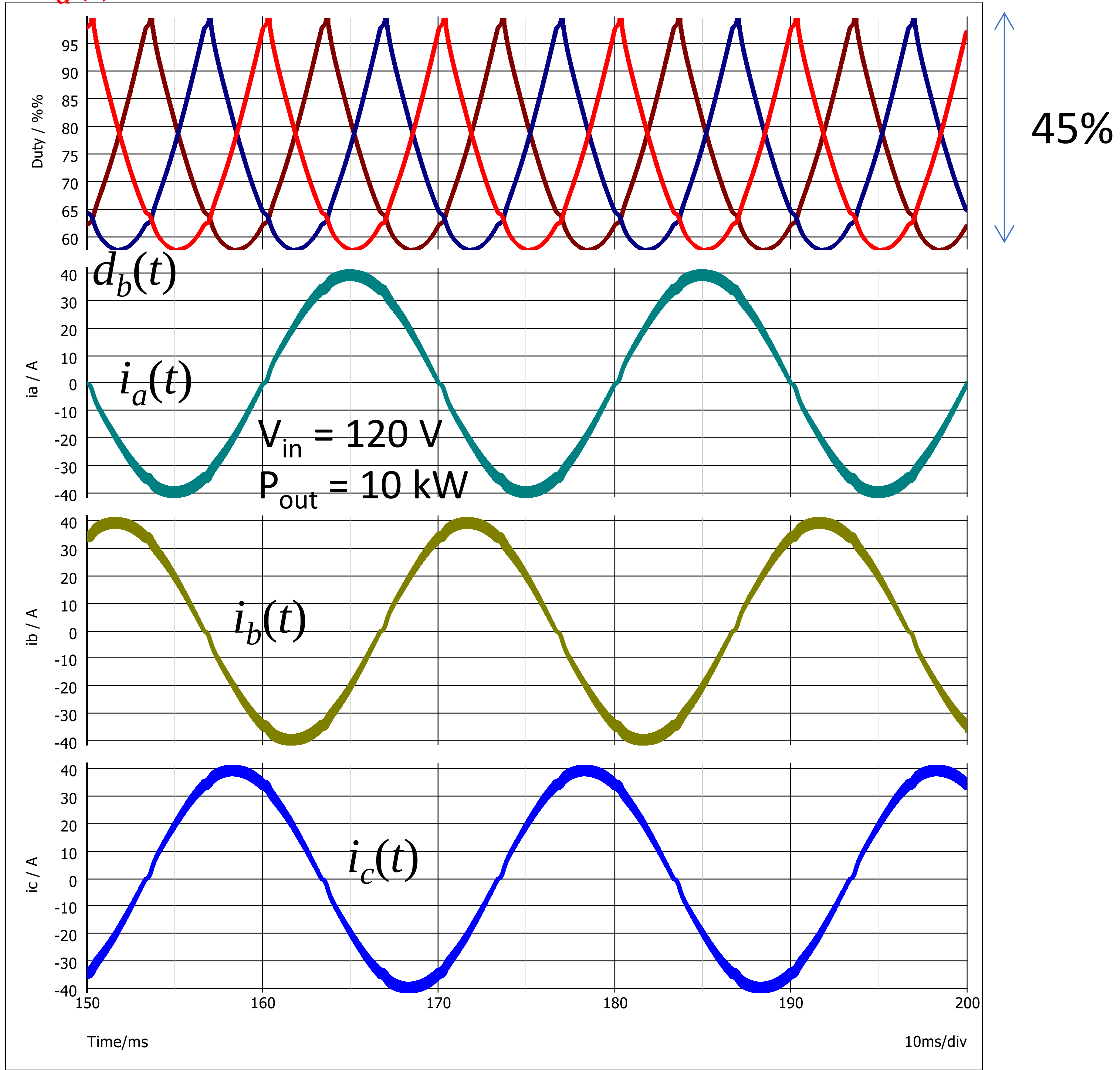
ia	Distortion/cycle	3.64304%
ib	Distortion/cycle	3.19371%
ic	Distortion/cycle	3.62285%

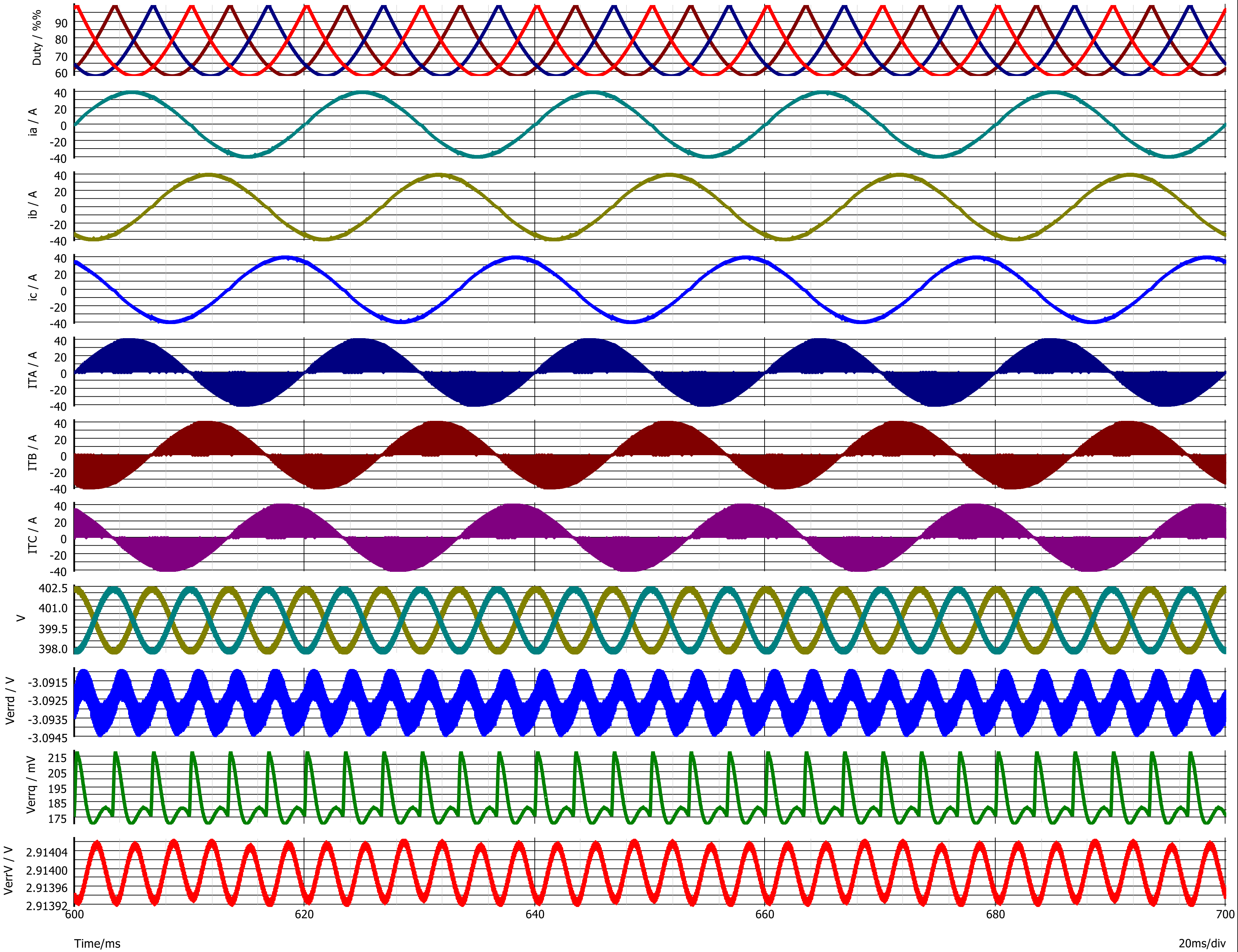


80%

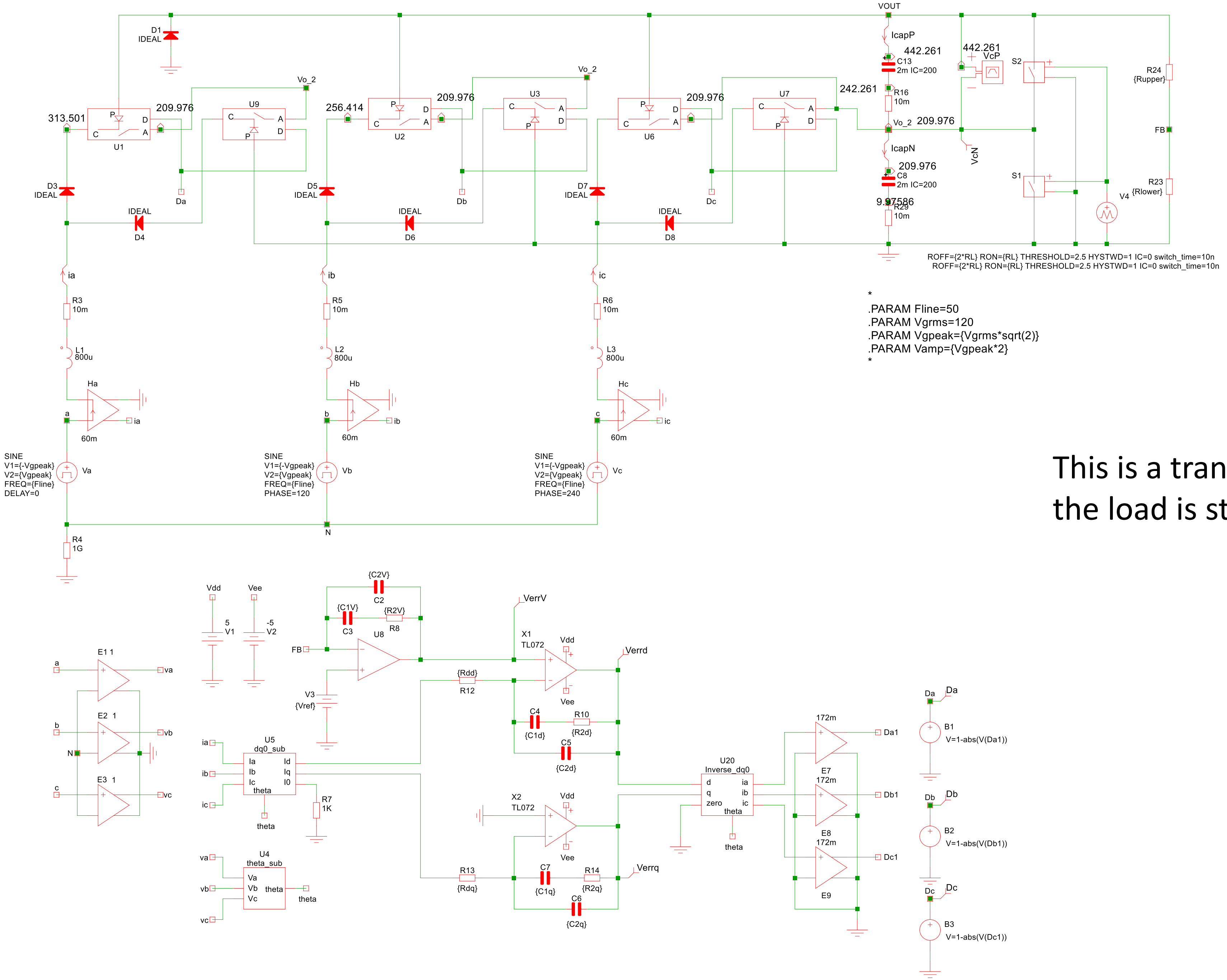
This is the way the duty ratio is elaborated to force sinusoidal input currents to the Vienna converter. The modulation depth is adjusted depending on operating conditions.

Low-line simulations





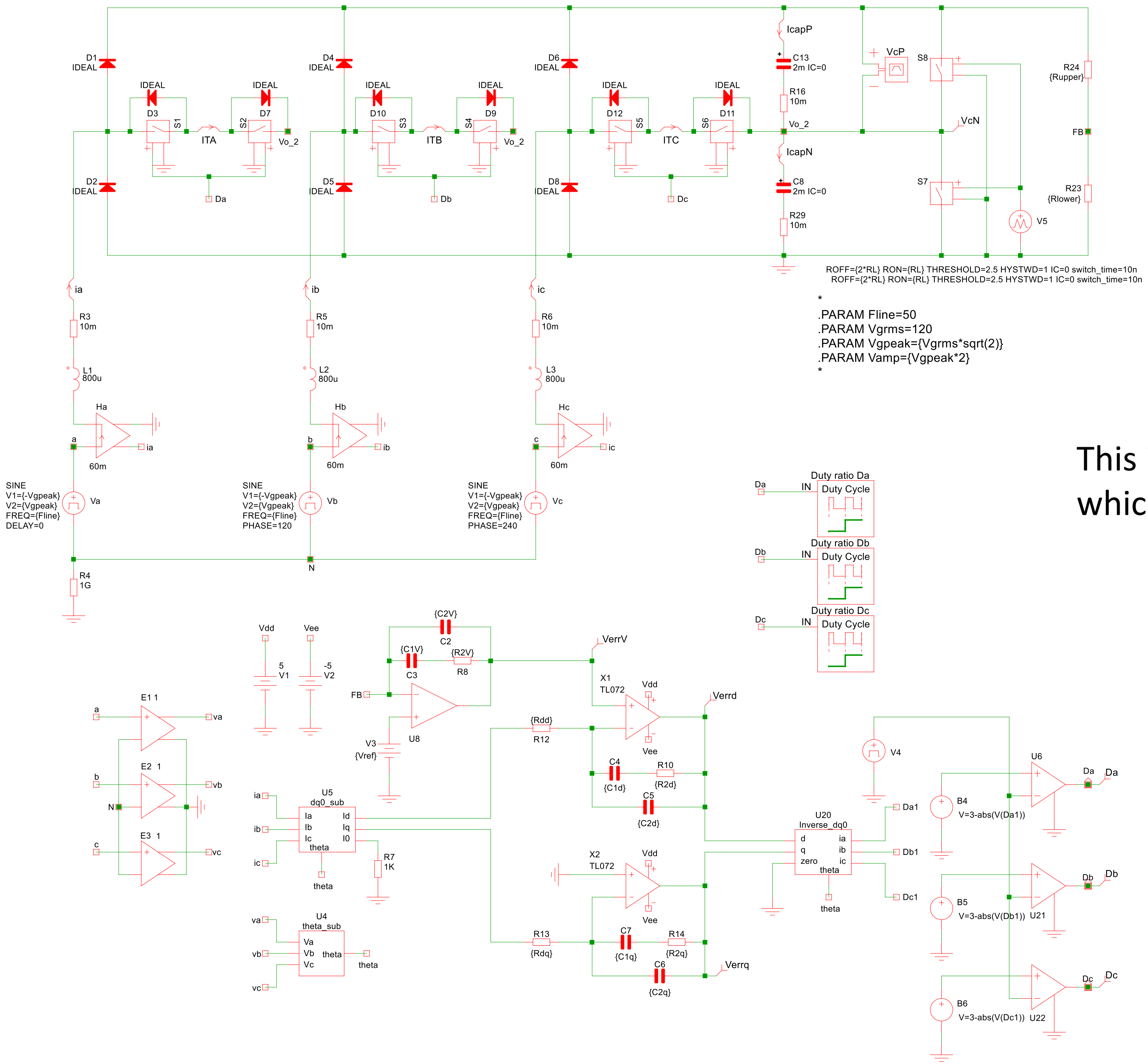
The cycle-by-cycle simulation confirms the operating points are good. The voltage is well spread between the two output capacitors for an 800-V rail. The values for the d, q and error voltage do match the averaged simulations.



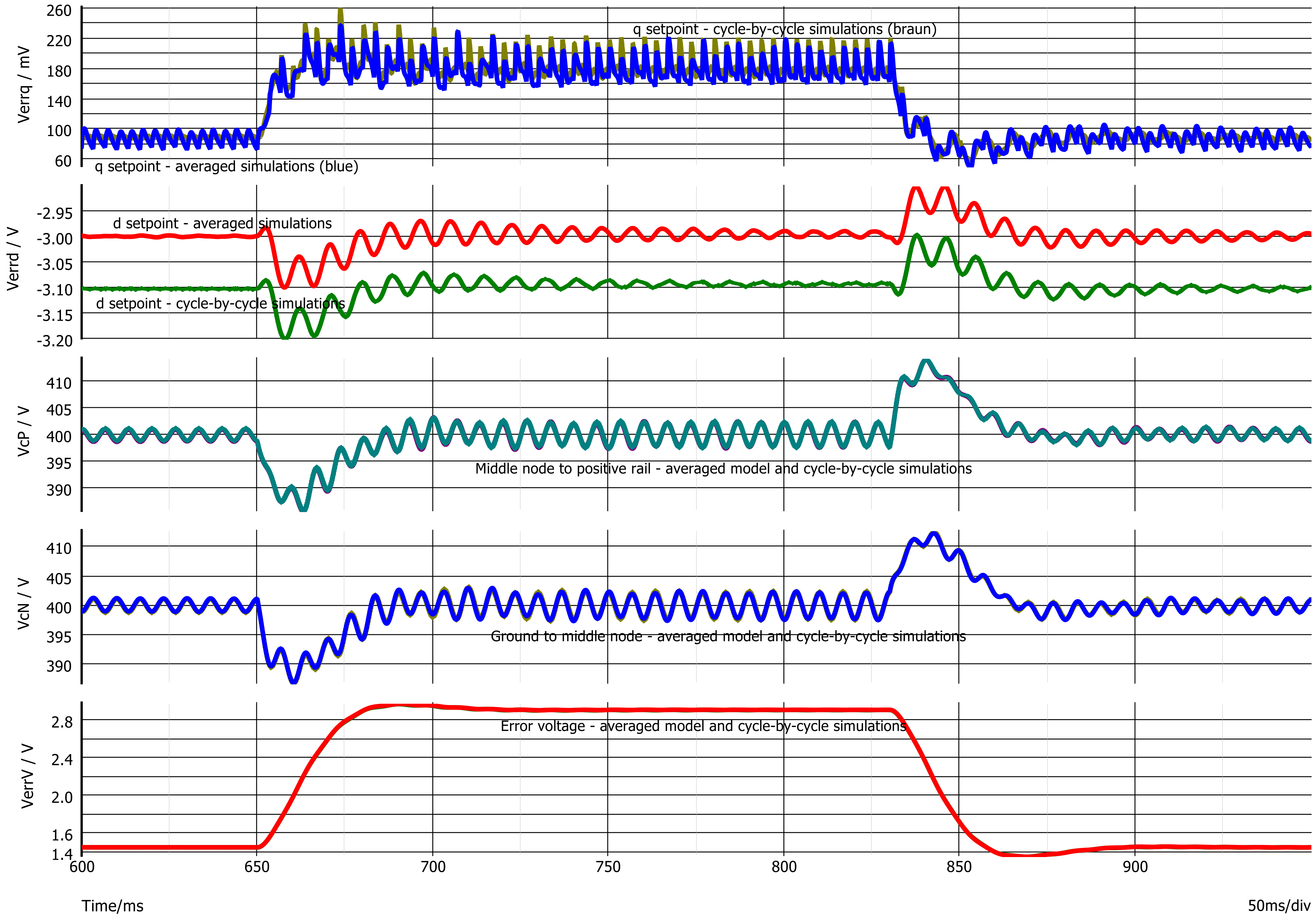
```
ROFF={2*RL} RON={RL} THRESHOLD=2.5 HYSTWD=1 IC=0 switch_time=10n
ROFF={2*RL} RON={RL} THRESHOLD=2.5 HYSTWD=1 IC=0 switch_time=10n
```

```
*
.PARAM Fline=50
.PARAM Vgrms=120
.PARAM Vgpeak={Vgrms*sqrt(2)}
.PARAM Vamp={Vgpeak*2}
*
```

This is a transient averaged simulation in which the load is stepped from $P_{out}/2$ to P_{out}.

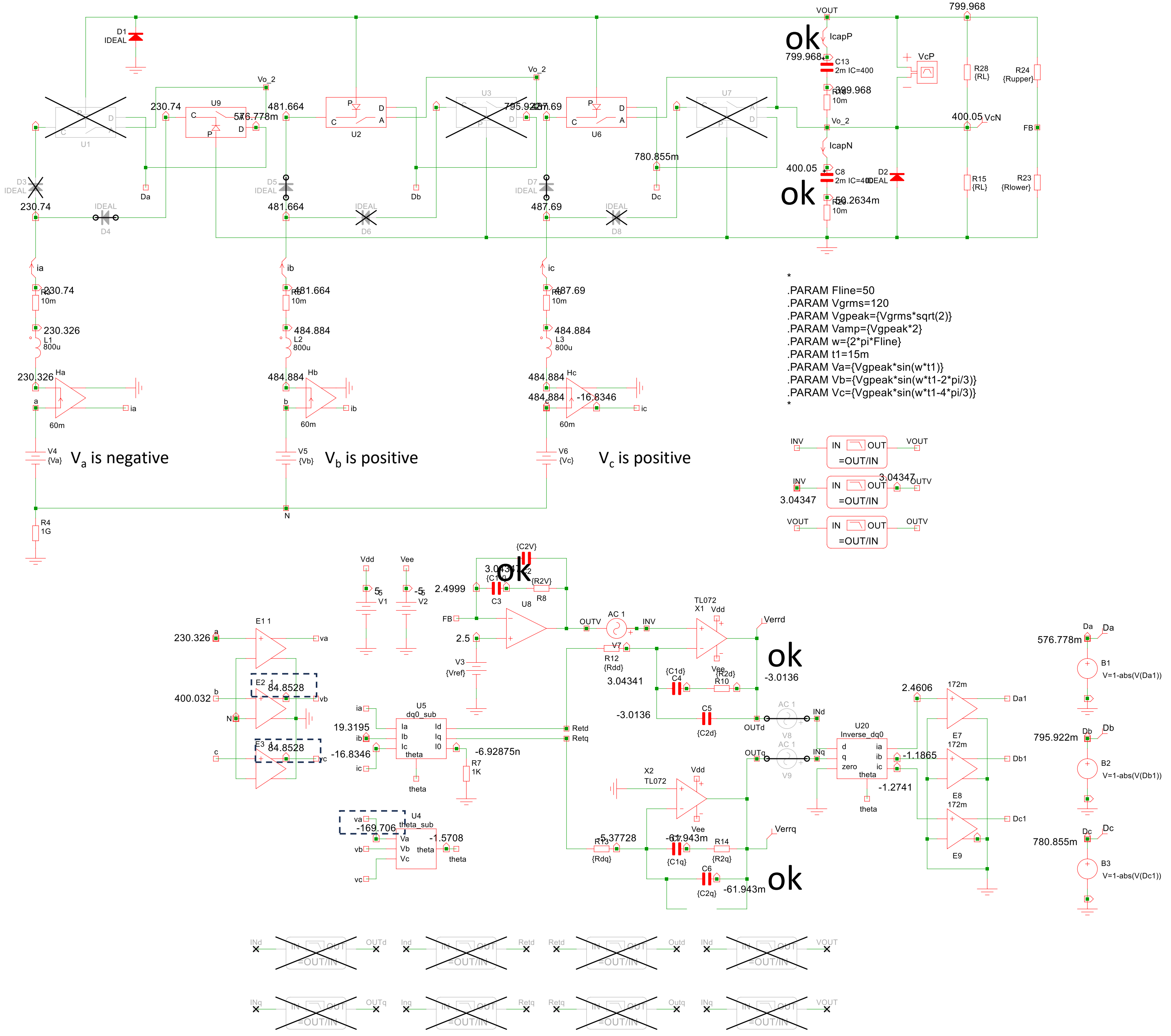


This is a transient cycle-by-cycle simulation in which the load is stepped from $P_{out}/2$ to P_{out}.



Excellent match between averaged and cycle-by-cycle simulations. There is a slight offset on the d levels but nothing serious.

Having averaged and cycle-by-cycle data well superimposed is a great reward and confirms the modeling approach.



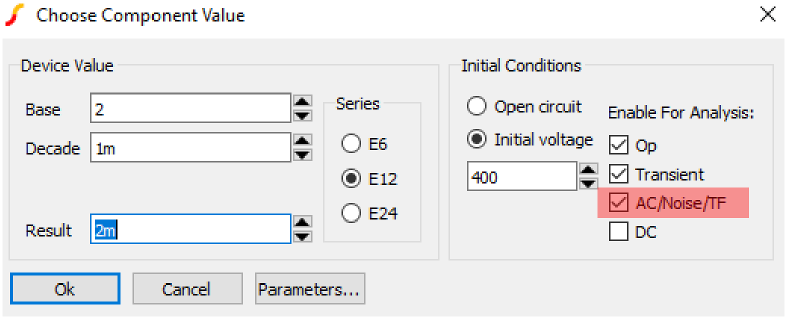
V_a is negative

V_b is positive

V_c is positive

```
*
.PARAM Fline=50
.PARAM Vgrms=120
.PARAM Vgpeak={Vgrms*sqrt(2)}
.PARAM Vamp={Vgpeak*2}
.PARAM w={2*pi*Fline}
.PARAM t1=15m
.PARAM Va={Vgpeak*sin(w*t1)}
.PARAM Vb={Vgpeak*sin(w*t1-2*pi/3)}
.PARAM Vc={Vgpeak*sin(w*t1-4*pi/3)}
*
```

The ac analysis is quite sensitive to the loop configurations, in particular the high open-loop gains of the TL072. Also, it is important to tick the correct box when using initial conditions for ac analyses: I was having good dc operating points in dc analysis but after an ac analysis, it was wrong and this is the reason:



Device Value

Base: 2

Decade: 1m

Result: 2m

Series: ○ E6 ● E12 ○ E24

Initial Conditions

○ Open circuit

● Initial voltage

400

Enable For Analysis:

☑ Op

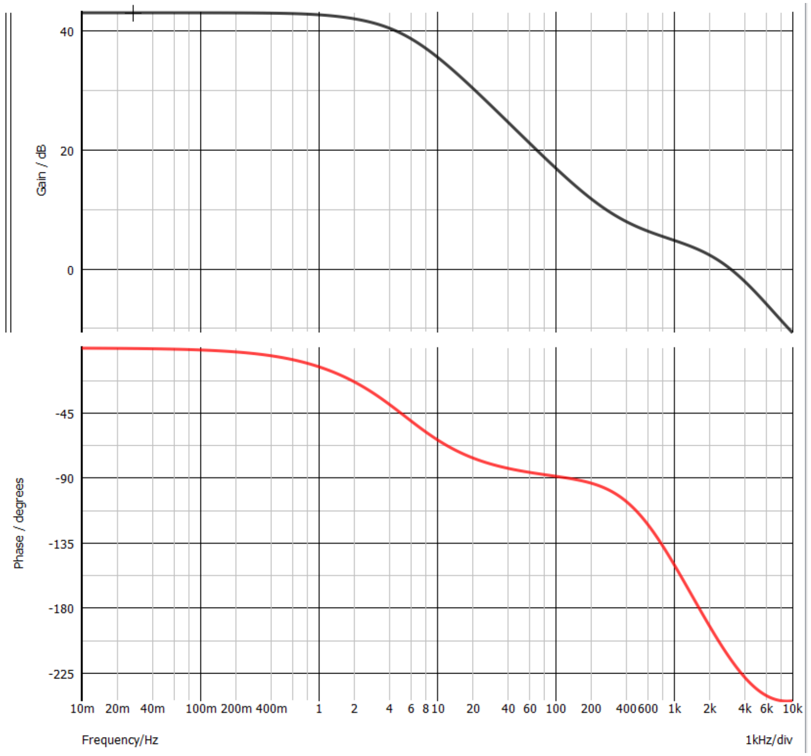
☑ Transient

☑ AC/Noise/TF

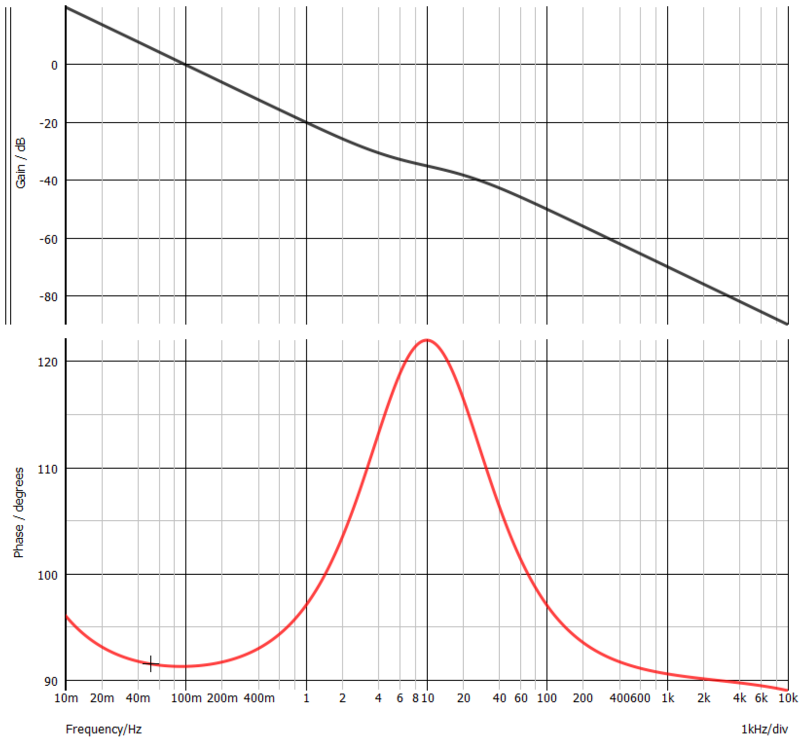
☐ DC

If it is not ticked, the bias point for this first ac analysis is wrong.

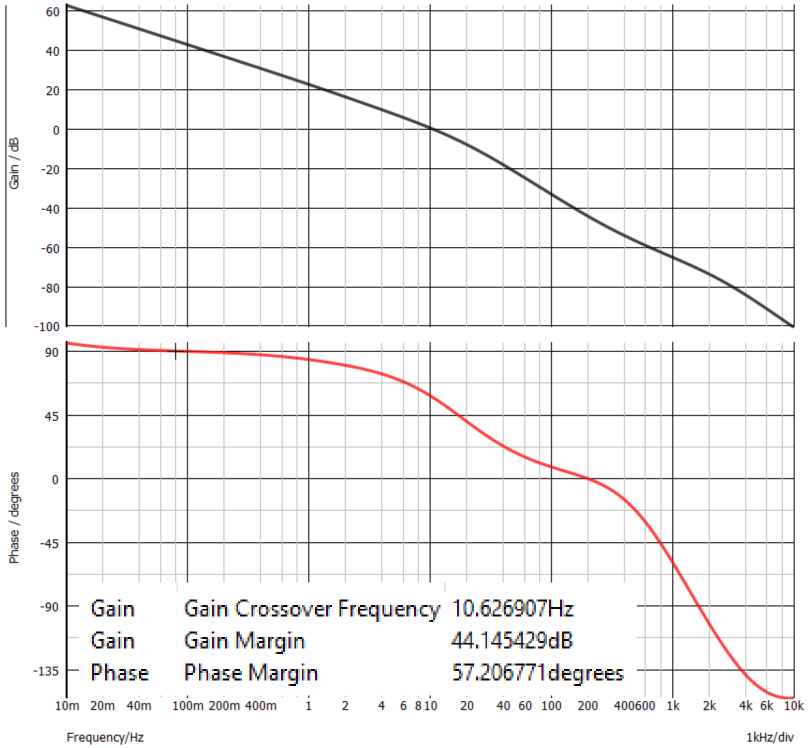
For the voltage loop, the bias is correct and we can sweep this first loop.



Power stage



Type 2 centered at 10 Hz

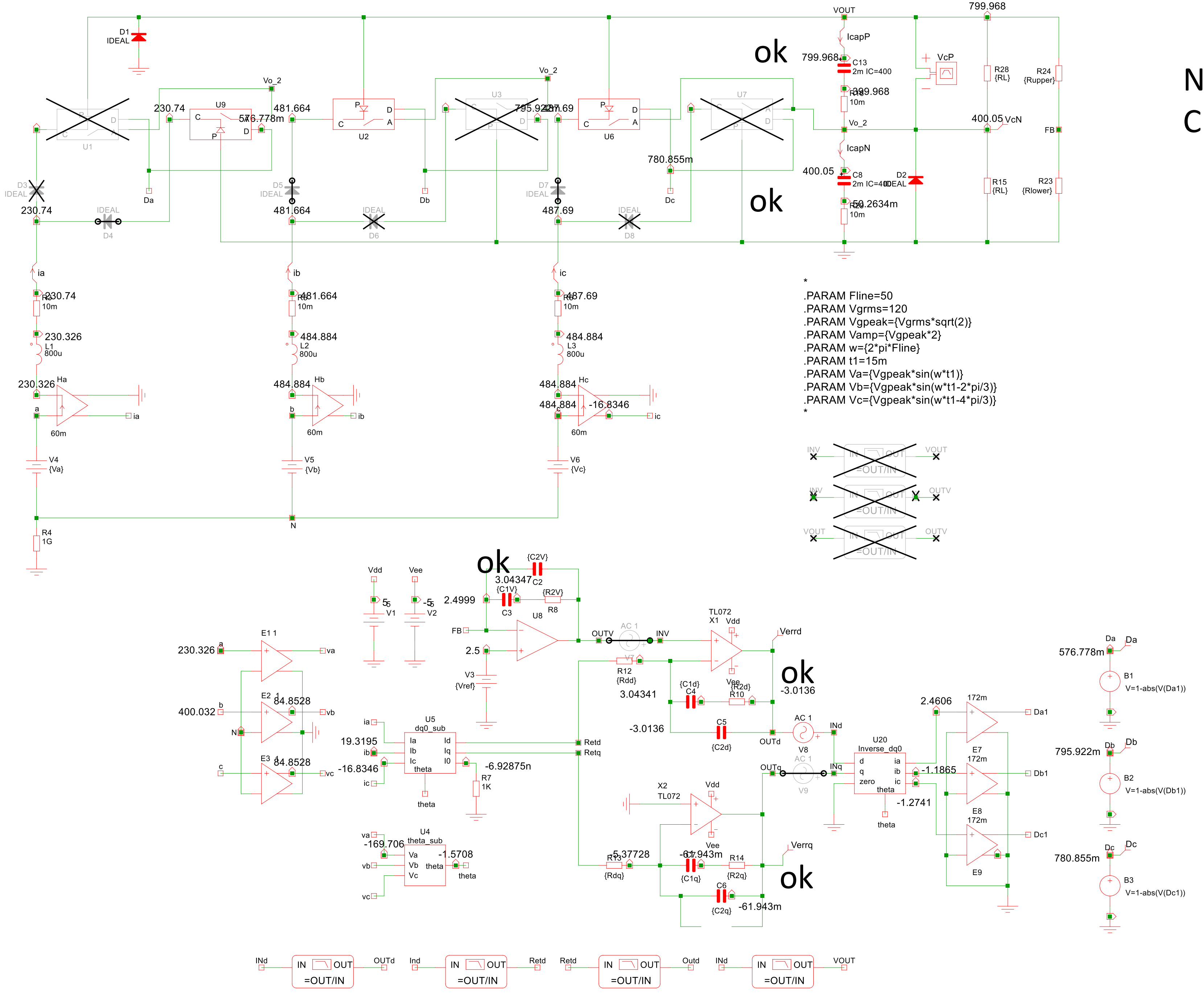


Gain	Gain Crossover Frequency	10.626907Hz
Gain	Gain Margin	44.145429dB
Phase	Phase Margin	57.206771degrees

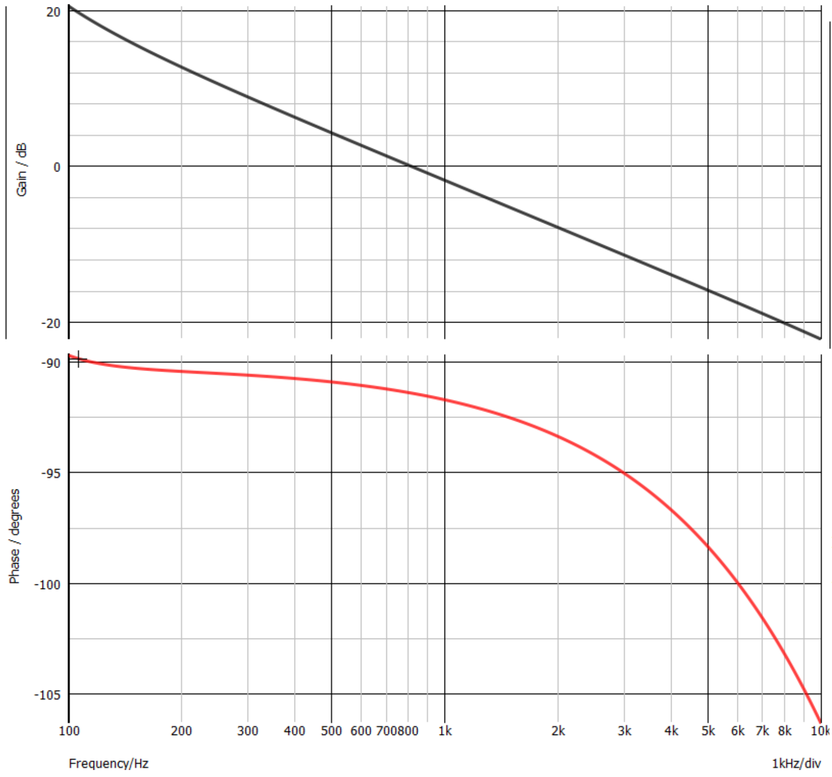
Compensated V loop

In the previous slide, you can see that some of the PWM switch models are grayed out. The reason is that I have selected a t_1 value (15 ms) for which V_a is negative (-169 V) while V_b and V_c are positive at 84 V. As such, the PWM switch model in V_a treating the positive polarity is made silent (grayed out) while only the one dealing with the negative value is active. Same with the models undergoing the negative polarities for V_b and V_c, they are also grayed out and only the ones treating the positive waves are active. The grayed-out models would normally be ignored by the engine considering the series diodes but the lighter the circuitry is, the easier it becomes for converging and finding a correct bias point.

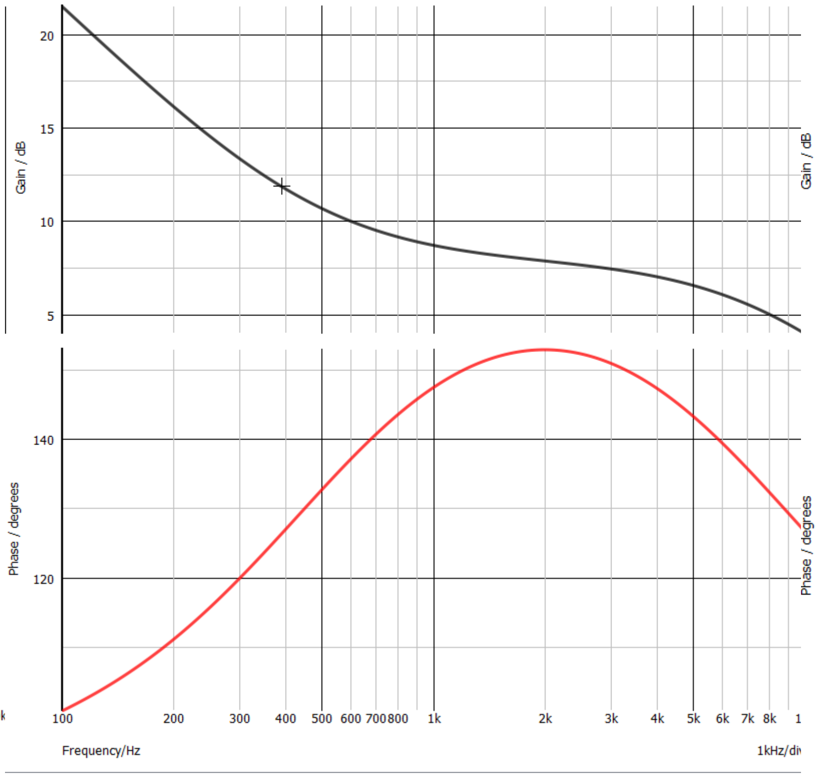
Now validate the d loop measurement.
Check operating point are ok still.



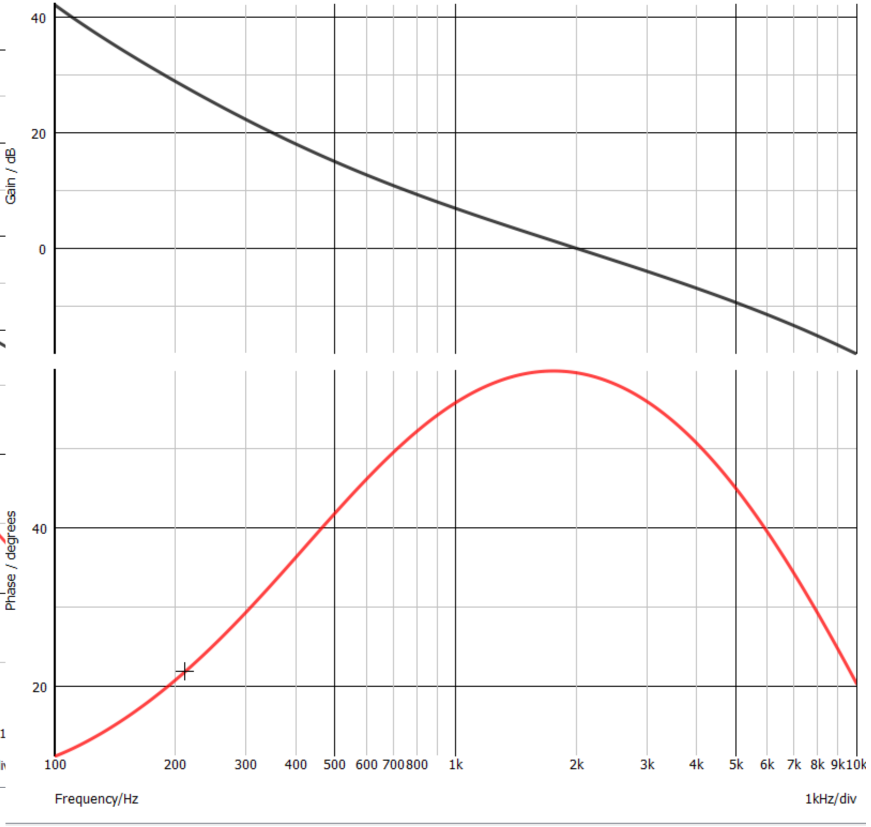
```
*
.PARAM Fline=50
.PARAM Vgrms=120
.PARAM Vgpeak={Vgrms*sqrt(2)}
.PARAM Vamp={Vgpeak*2}
.PARAM w={2*pi*Fline}
.PARAM t1=15m
.PARAM Va={Vgpeak*sin(w*t1)}
.PARAM Vb={Vgpeak*sin(w*t1-2*pi/3)}
.PARAM Vc={Vgpeak*sin(w*t1-4*pi/3)}
*
```



Power stage of d loop



Type 2 centered at 2 kHz

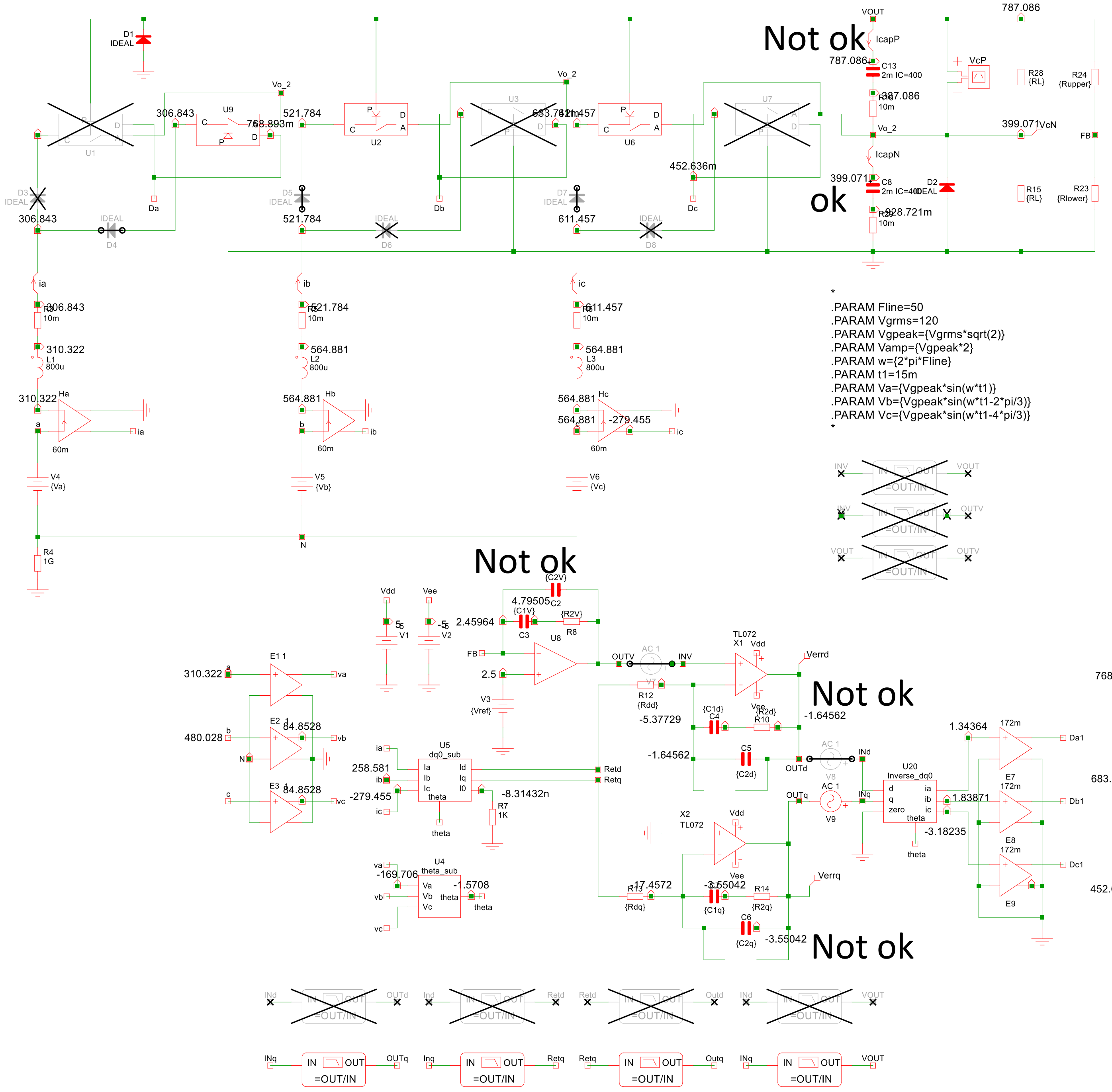


Gain	Gain Crossover Frequency	2.0142727kHz
Gain	Gain Margin	***ERROR***
Phase	Phase Margin	59.511622degrees

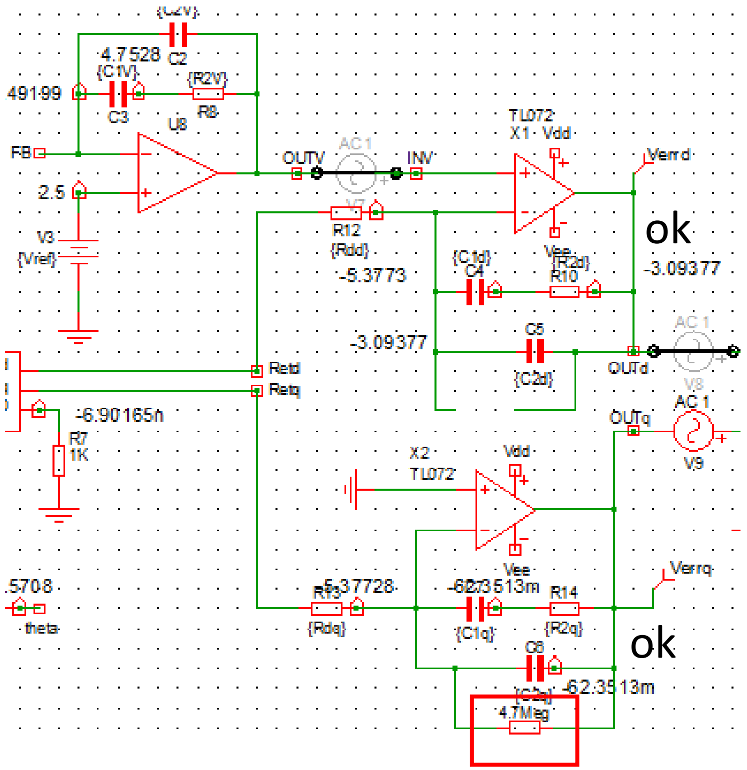
Compensated d loop

Now enable the q loop. In theory, both d and q loops have the same transfer function but it is always interesting to look at each individually. Here, by enabling the ac source with the q loop, the operating point is wrong.

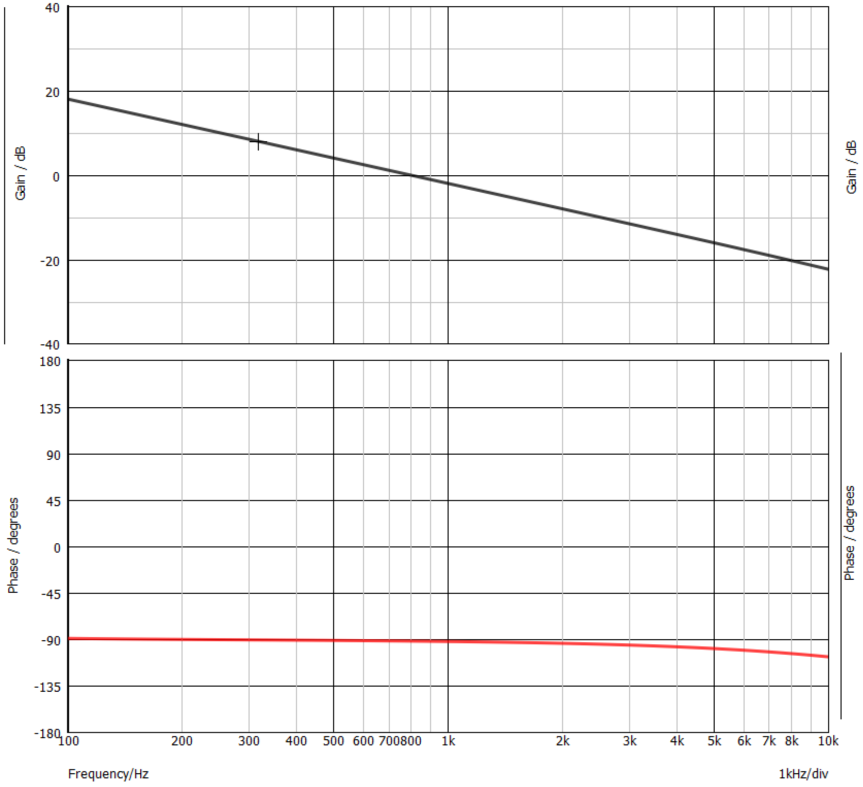
By locally reducing the open-loop gain of the q op-amp, the circuit converges:



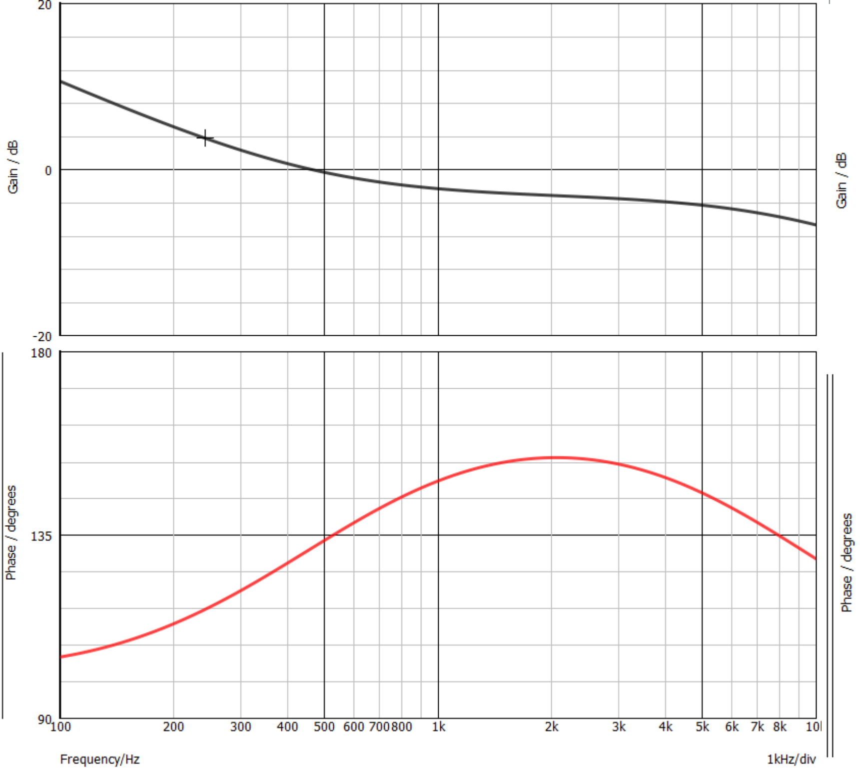
```
*
.PARAM Fline=50
.PARAM Vgrms=120
.PARAM Vgpeak={Vgrms*sqrt(2)}
.PARAM Vamp={Vgpeak*2}
.PARAM w={2*pi*Fline}
.PARAM t1=15m
.PARAM Va={Vgpeak*sin(w*t1)}
.PARAM Vb={Vgpeak*sin(w*t1-2*pi/3)}
.PARAM Vc={Vgpeak*sin(w*t1-4*pi/3)}
*
```



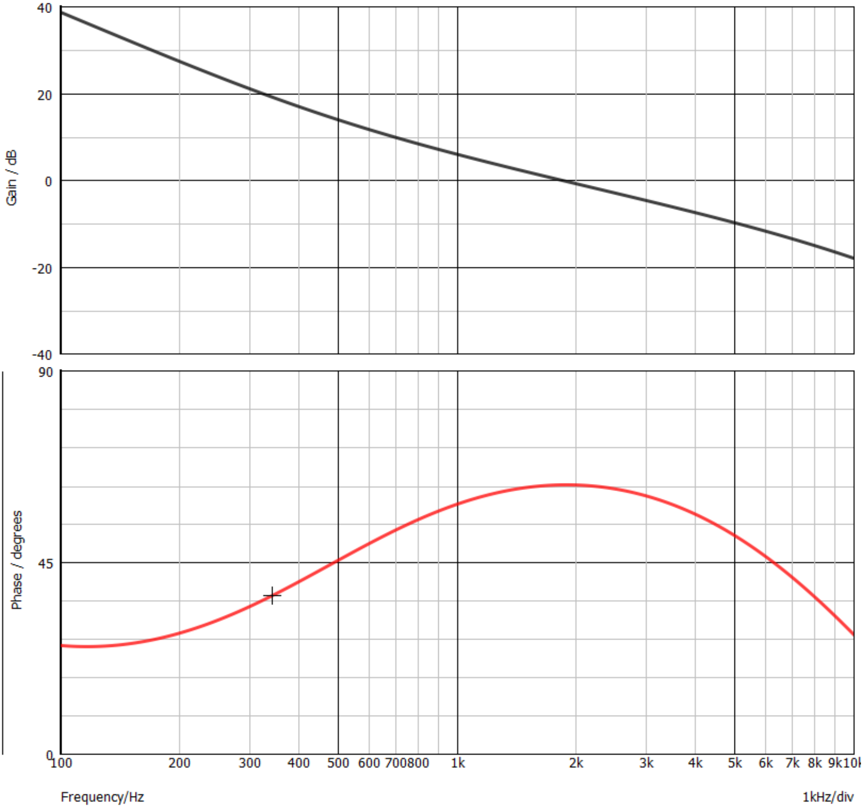
Added resistance
Remove it for other analyses



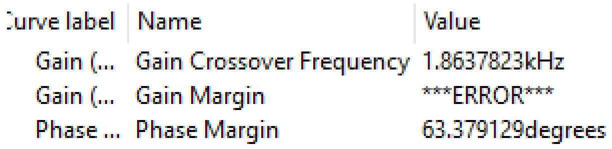
Power stage of q loop



Type 2 centered at 2 kHz



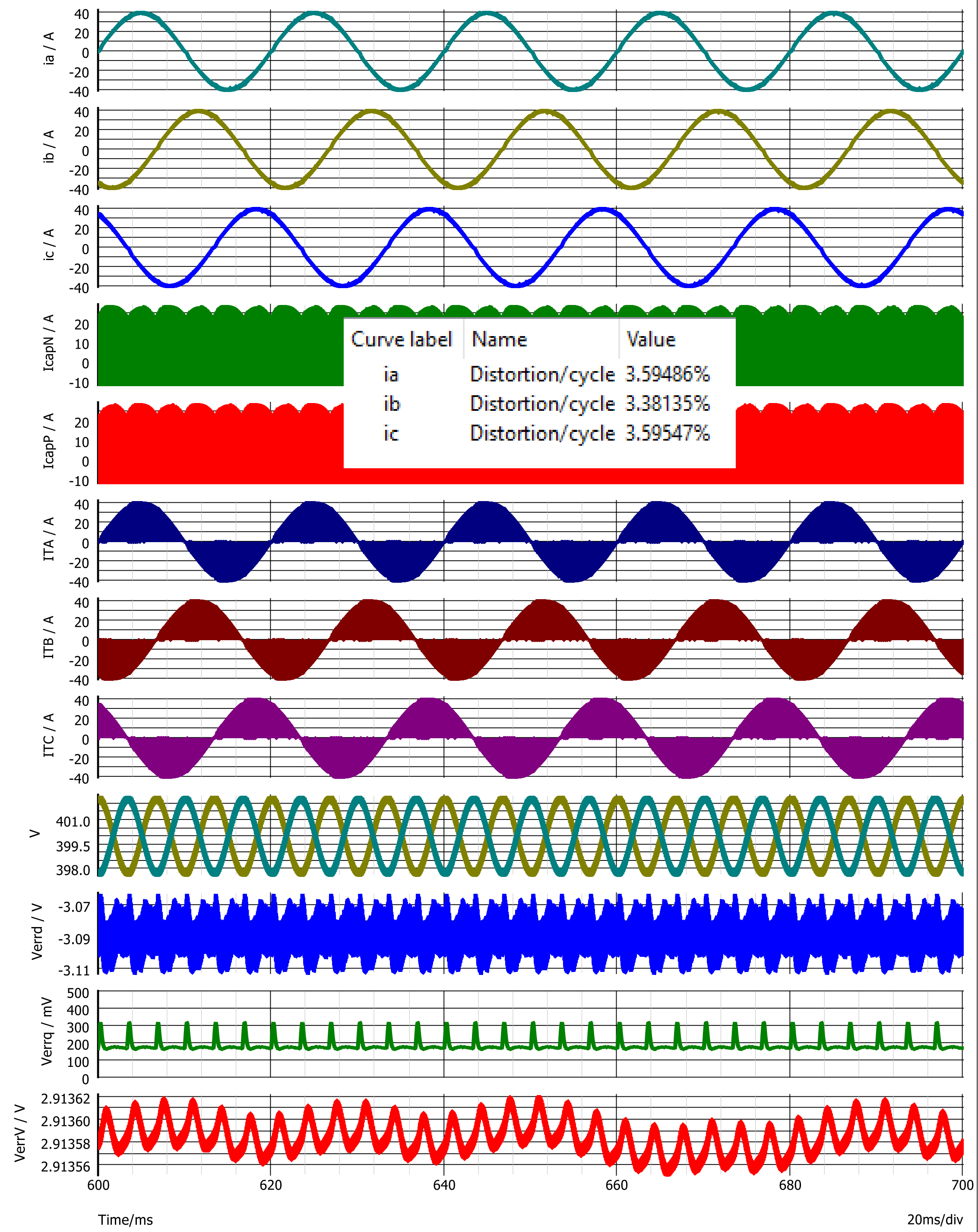
Compensated d loop



urve label	Name	Value
Gain (...	Gain Crossover Frequency	1.8637823kHz
Gain (...	Gain Margin	***ERROR***
Phase ...	Phase Margin	63.379129degrees

Finally, I have set the voltage loop at 10 Hz and the dq loops at 1 kHz.

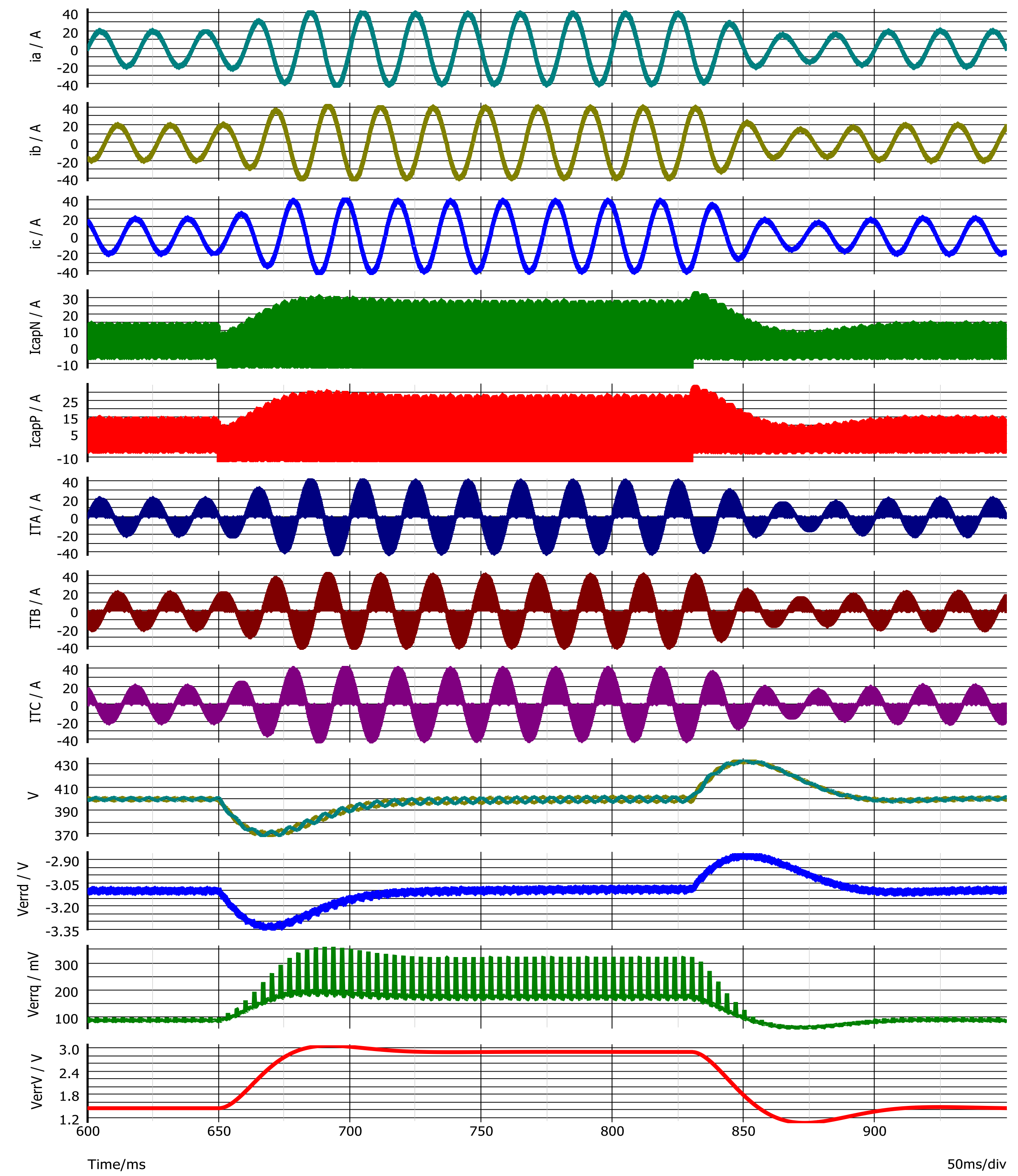
In theory, the d and q loops have the same ac response but changes can occur due to the dc loop kept closed during the ac sweep.



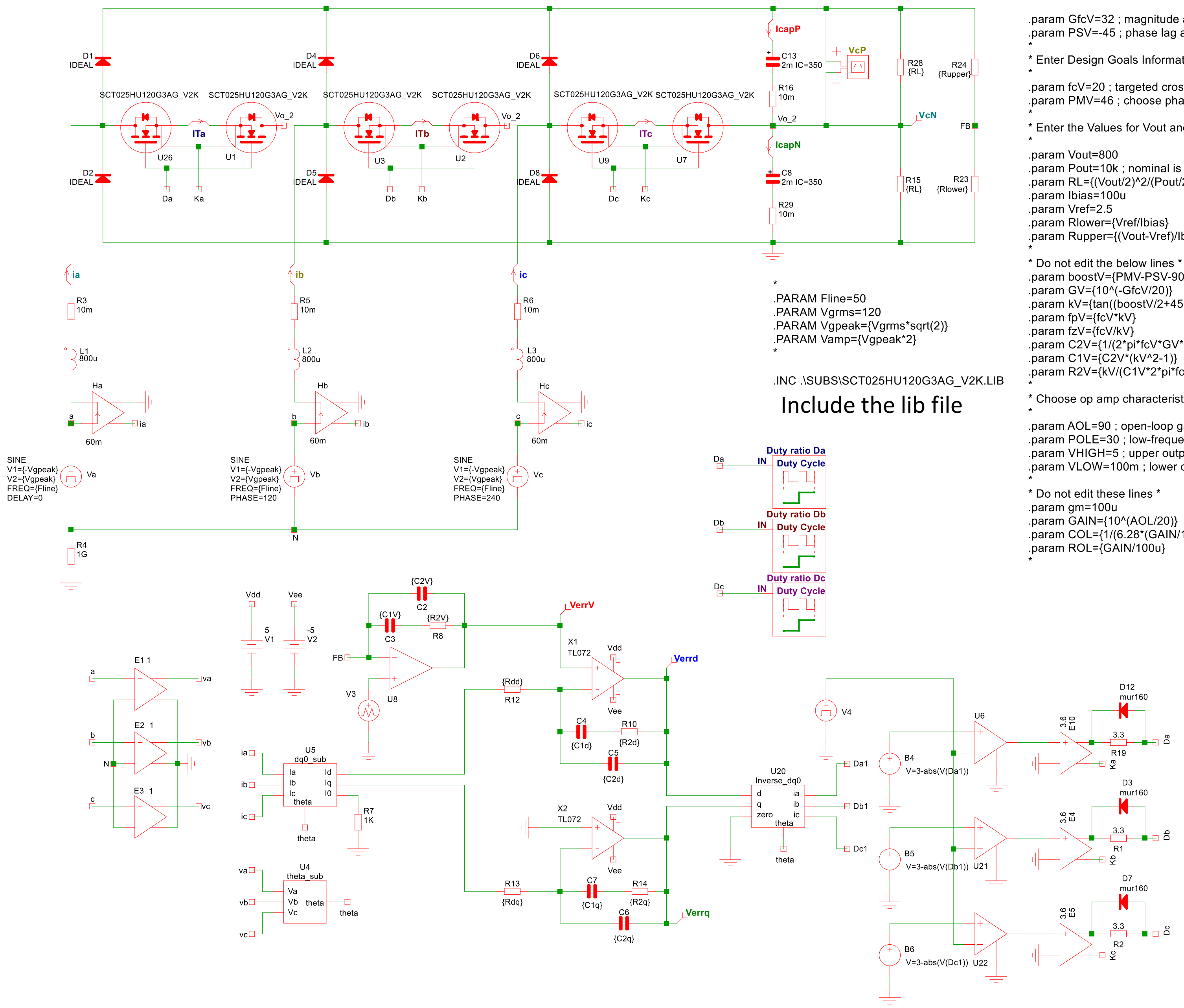
Curve label	Name	Value
ia	Distortion/cycle	3.59486%
ib	Distortion/cycle	3.38135%
ic	Distortion/cycle	3.59547%

New cycle-by-cycle test – all clear!

The step load response is good, with a nice recovery.



Finally, I have included SiC MOSFETs in the circuit:



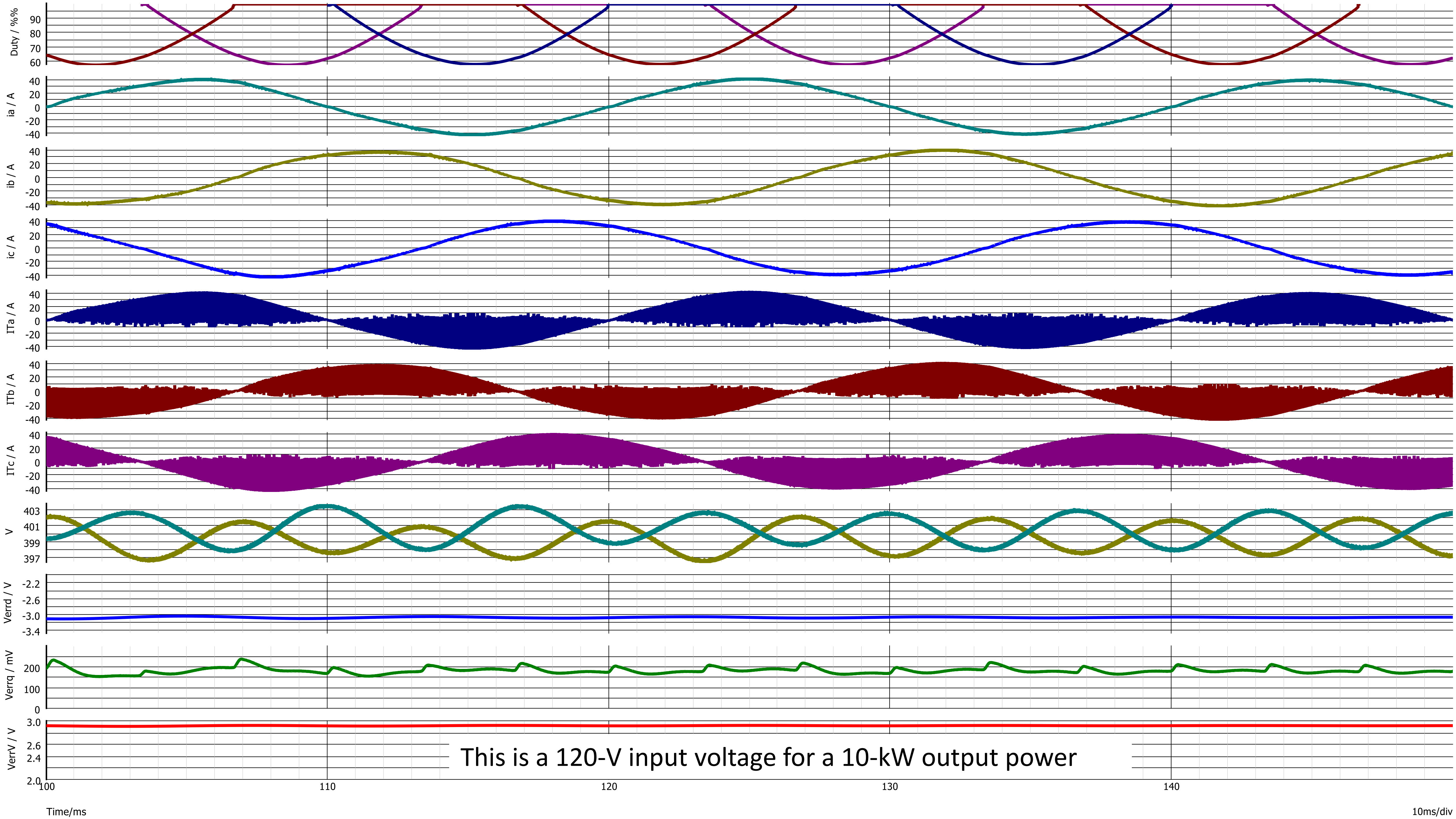
```
*
.PARAM Fline=50
.PARAM Vgrms=120
.PARAM Vgpeak={Vgrms*sqrt(2)}
.PARAM Vamp={Vgpeak*2}
*

.INC .\SUBS\SCT025HU120G3AG_V2K.LIB
```

Include the lib file

```
.param GfcV=32 ; magnitude at crossover *
.param PSV=-45 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcV=20 ; targeted crossover *
.param PMV=46 ; choose phase margin at crossover *
*
* Enter the Values for Vout and Bridge Bias Current *
*
.param Vout=800
.param Pout=10k ; nominal is 5 kW
.param RL={(Vout/2)^2/(Pout/2)}
.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)}
*
* Choose op amp characteristics *
*
.param AOL=90 ; open-loop gain in dB *
.param POLE=30 ; low-frequency pole *
.param VHIGH=5 ; upper output level *
.param VLOW=100m ; lower output level *
*
* Do not edit these lines *
.param gm=100u
.param GAIN={10^(AOL/20)}
.param COL={1/(6.28*(GAIN/100u)*POLE)}
.param ROL={GAIN/100u}
*
```

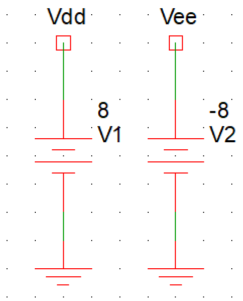
```
* Components for the d loop *
.param Gfcd=30 ; magnitude at crossover *
.param PSd=-93 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcd=2k ; targeted crossover *
.param PMd=60 ; choose phase margin at crossover *
*
* Enter the Values for Vout and Bridge Bias Current *
*
.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=10 ; 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={C2q*(kq^2-1)}
.param R2q={kq/(C1q*2*pi*fcq)}
*
```

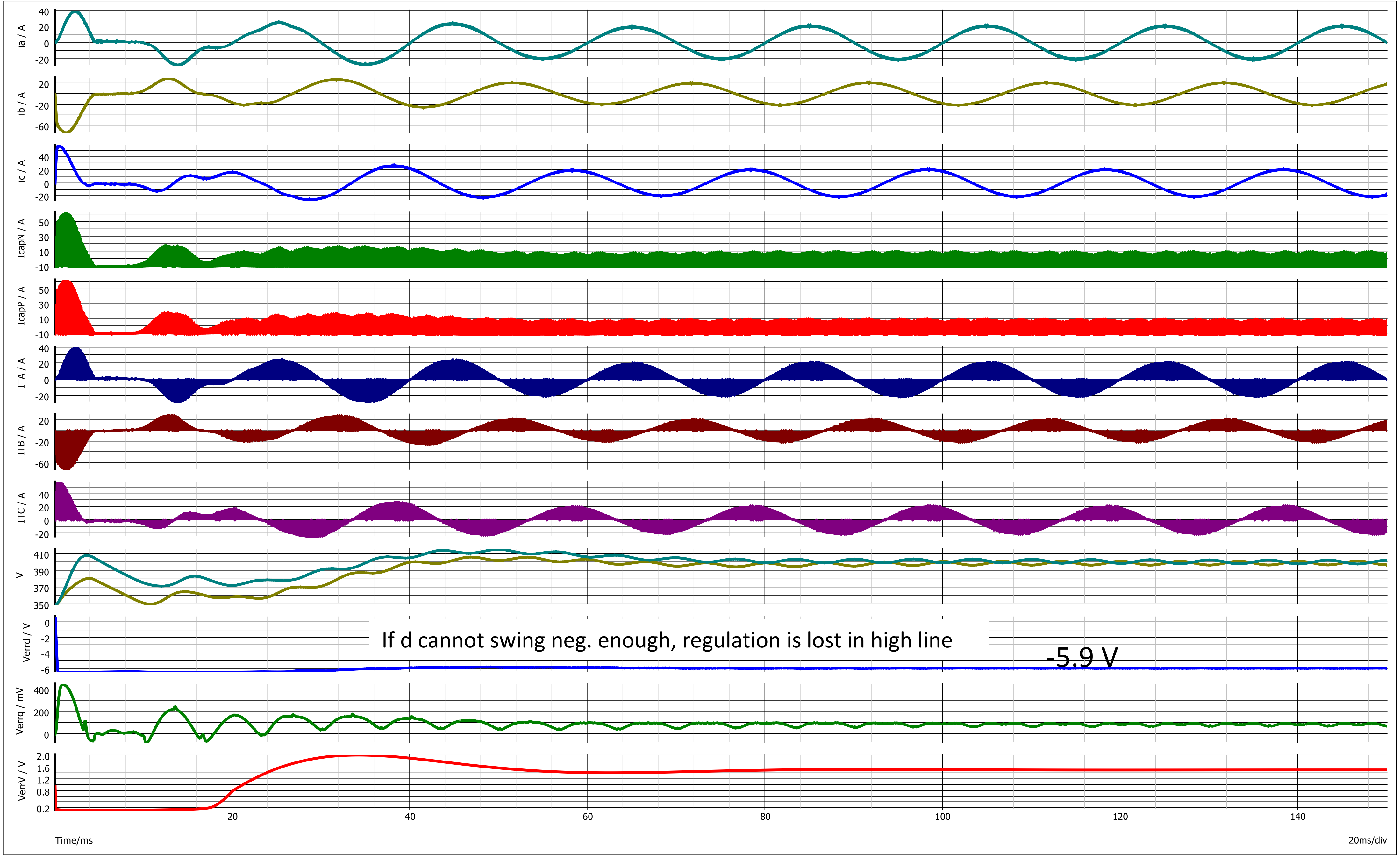
The simulation with SiC transistors is the final step. The driver side is simplified and delivers up to 18 V through a 3.3-Ω resistance. A more accurate simulation should include a comprehensive model of the driving path.



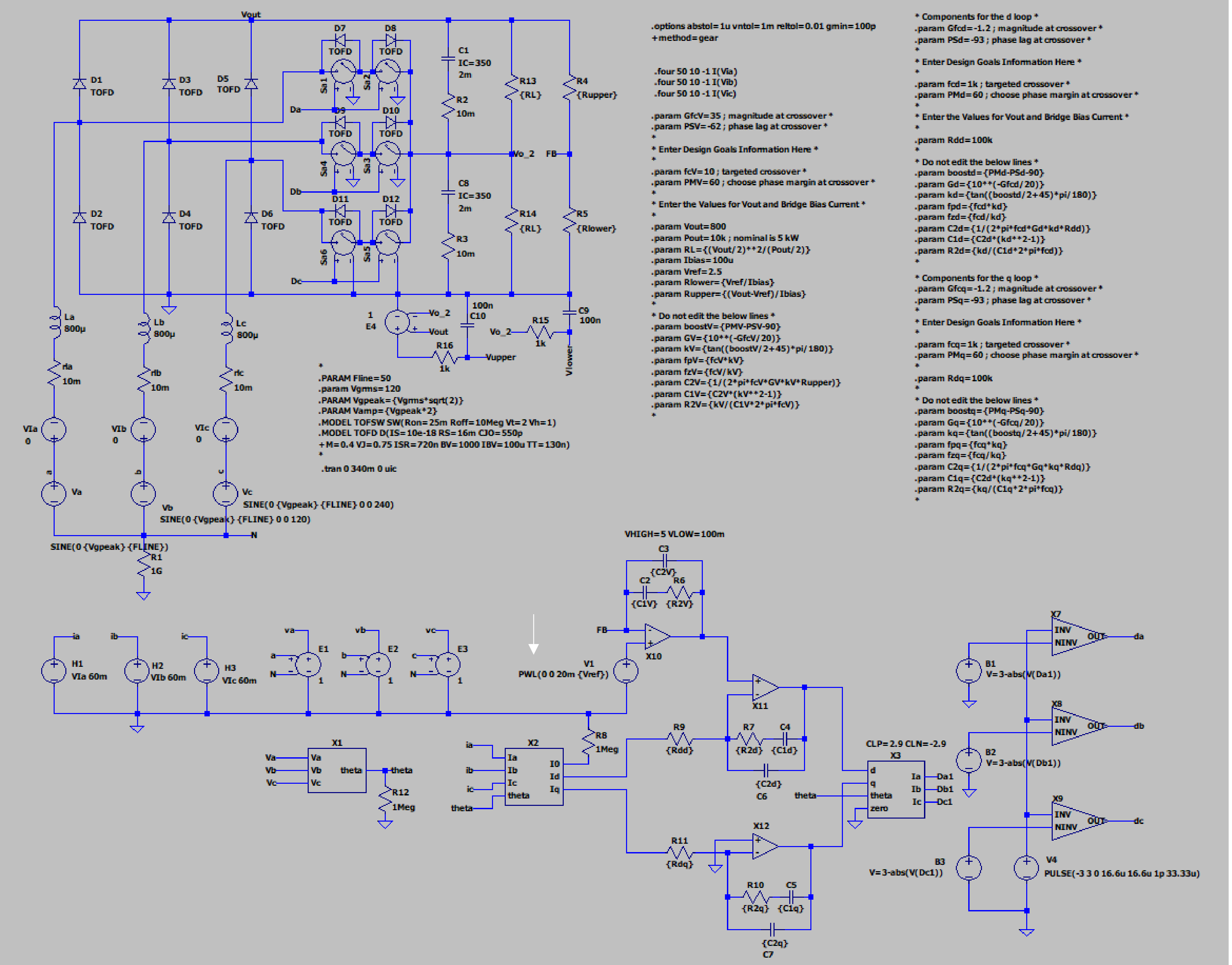
This is a 120-V input voltage for a 10-kW output power

This is the high-line simulation (230 V rms lie-neutral or 400 V line-to-line) and you can notice the d value swinging to almost -6 V. You need sufficient dc supplies on the op-amp, what I originally did not have with the +5/-5 V. I increased them to +8/-8 for this sim.




If d cannot swing neg. enough, regulation is lost in high line

-5.9 V



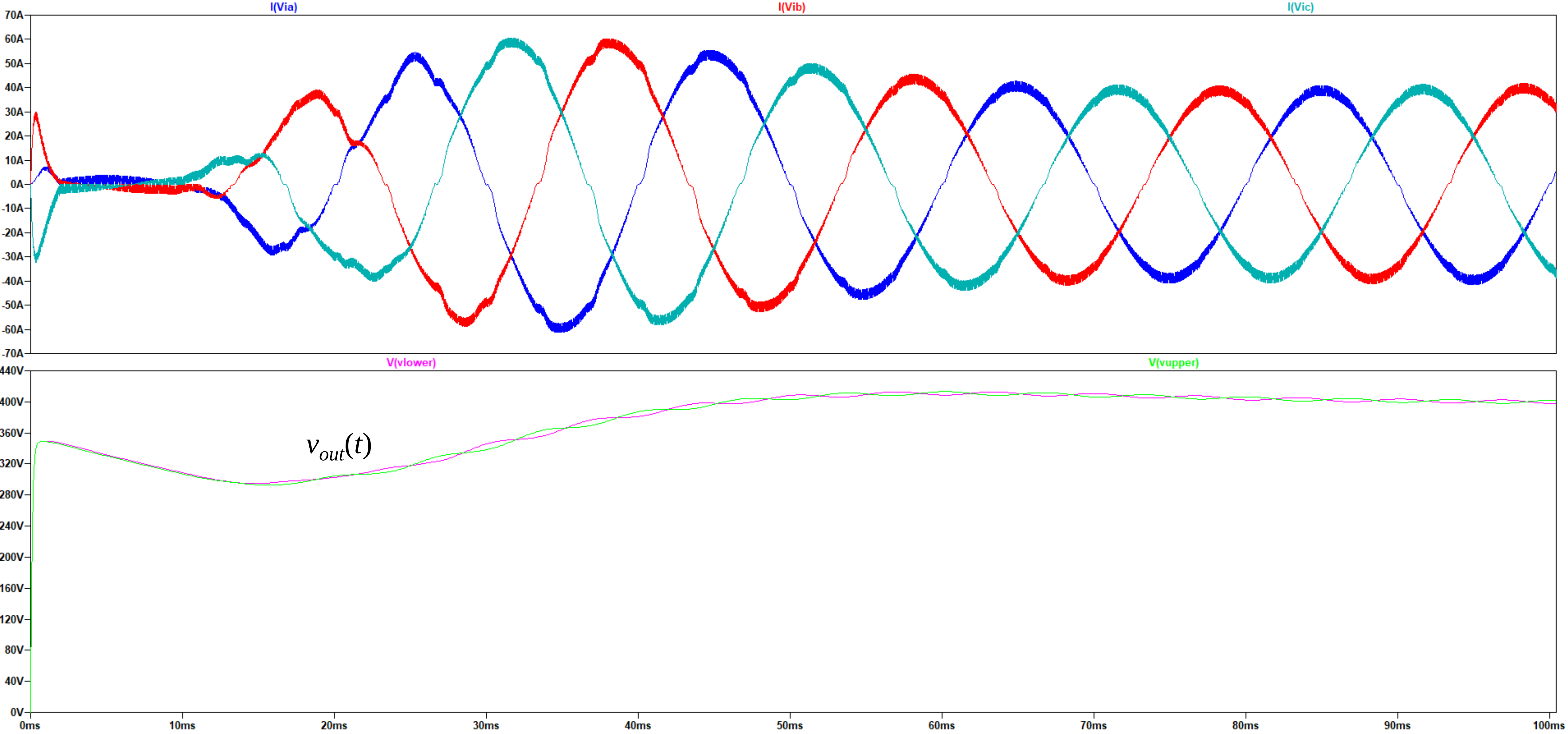
```
.options abstol=1u vntol=1m reltol=0.01 gmin=100p
+method=gear

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

.param GfcV=35 ; magnitude at crossover *
.param PSV=-62 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcV=10 ; targeted crossover *
.param PMV=60 ; choose phase margin at crossover *
*
* Enter the Values for Vout and Bridge Bias Current *
*
.param Vout=800
.param Pout=10k ; nominal is 5 kW
.param RL={(Vout/2)**2/(Pout/2)}
.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=-1.2 ; magnitude at crossover *
.param PSd=-93 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcd=1k ; 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=-1.2 ; magnitude at crossover *
.param PSq=-93 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcq=1k ; 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)}
*
```

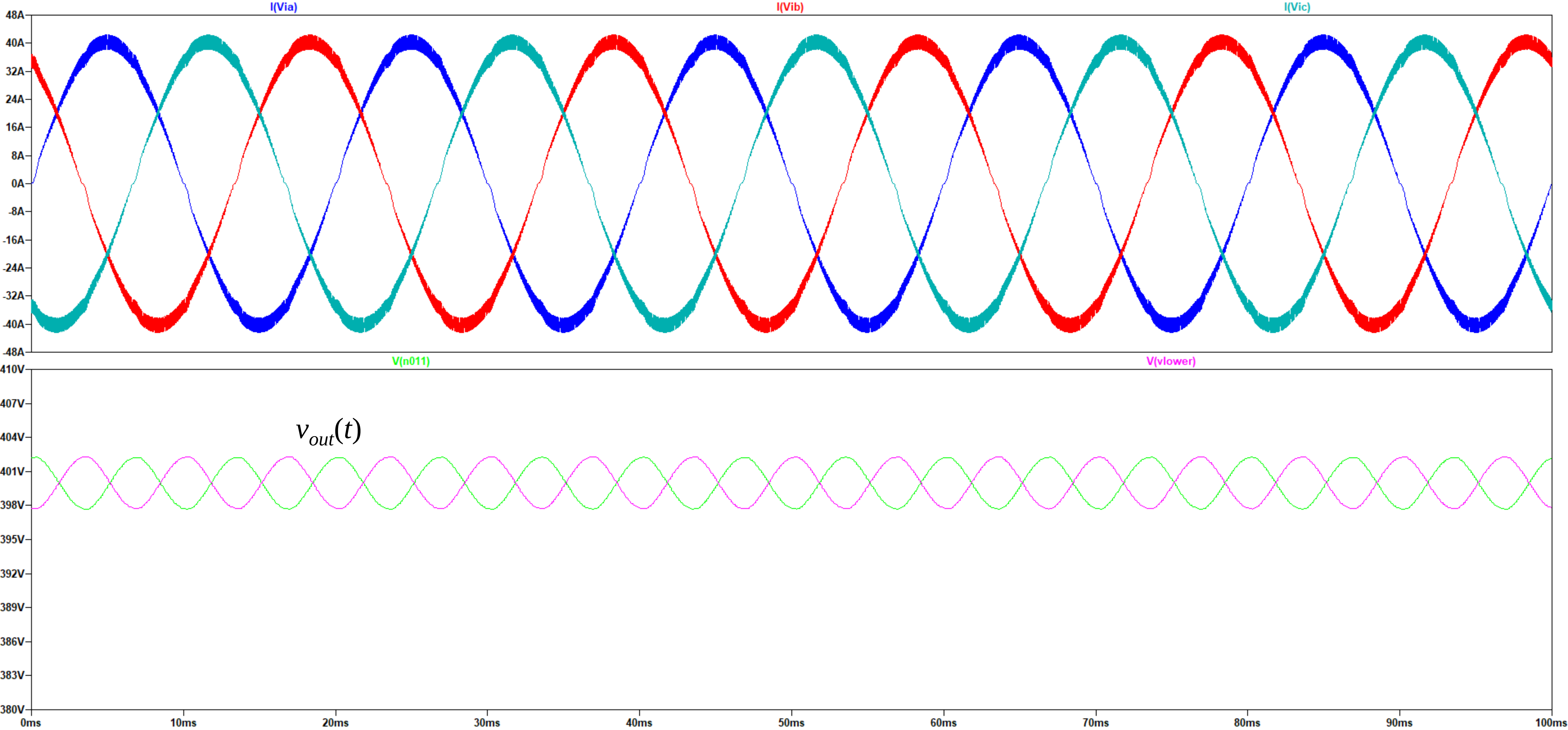
```
*
.PARAM Fline=50
.param Vgrms=120
.PARAM Vgpeak={Vgrms*sqrt(2)}
.PARAM Vamp={Vgpeak*2}
.MODEL TOFSW SW(Ron=25m Roff=10Meg Vt=2 Vh=1)
.MODEL TOFD D(IS=10e-18 RS=16m CJO=550p
+M=0.4 VJ=0.75 ISR=720n BV=1000 IBV=100u TT=130n)
*
 .tran 0 340m 0 uic
```

This is the cycle-by-cycle implementation in LTspice, reusing the dq blocks originally tested with the 6-pack PFC.

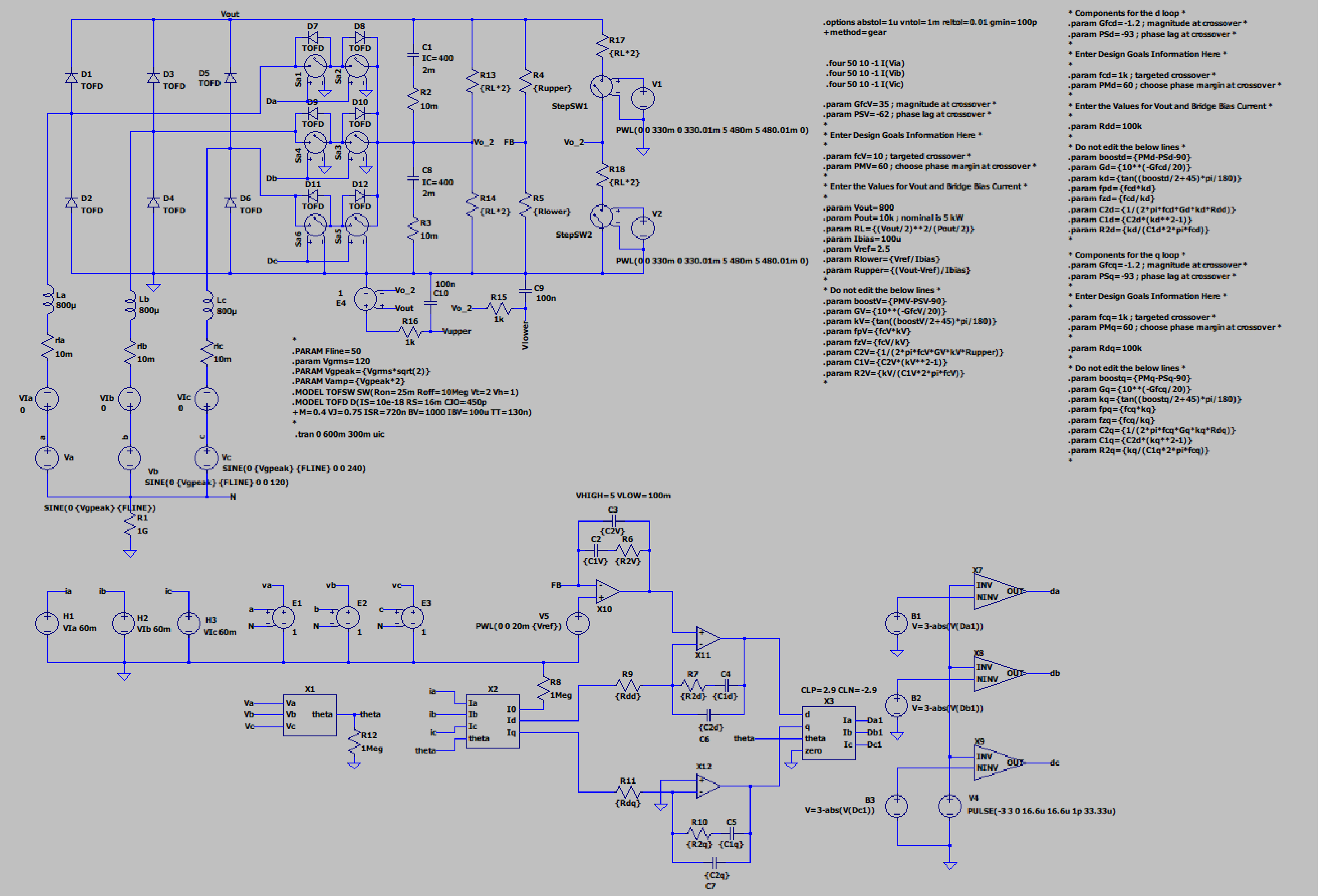
The reference voltage is soft-started for a smooth power-on sequence.



The input currents nicely grow to their nominal values after a few tens of milliseconds.



At steady-state, the input currents are well sinusoidal and the outputs are properly regulated.

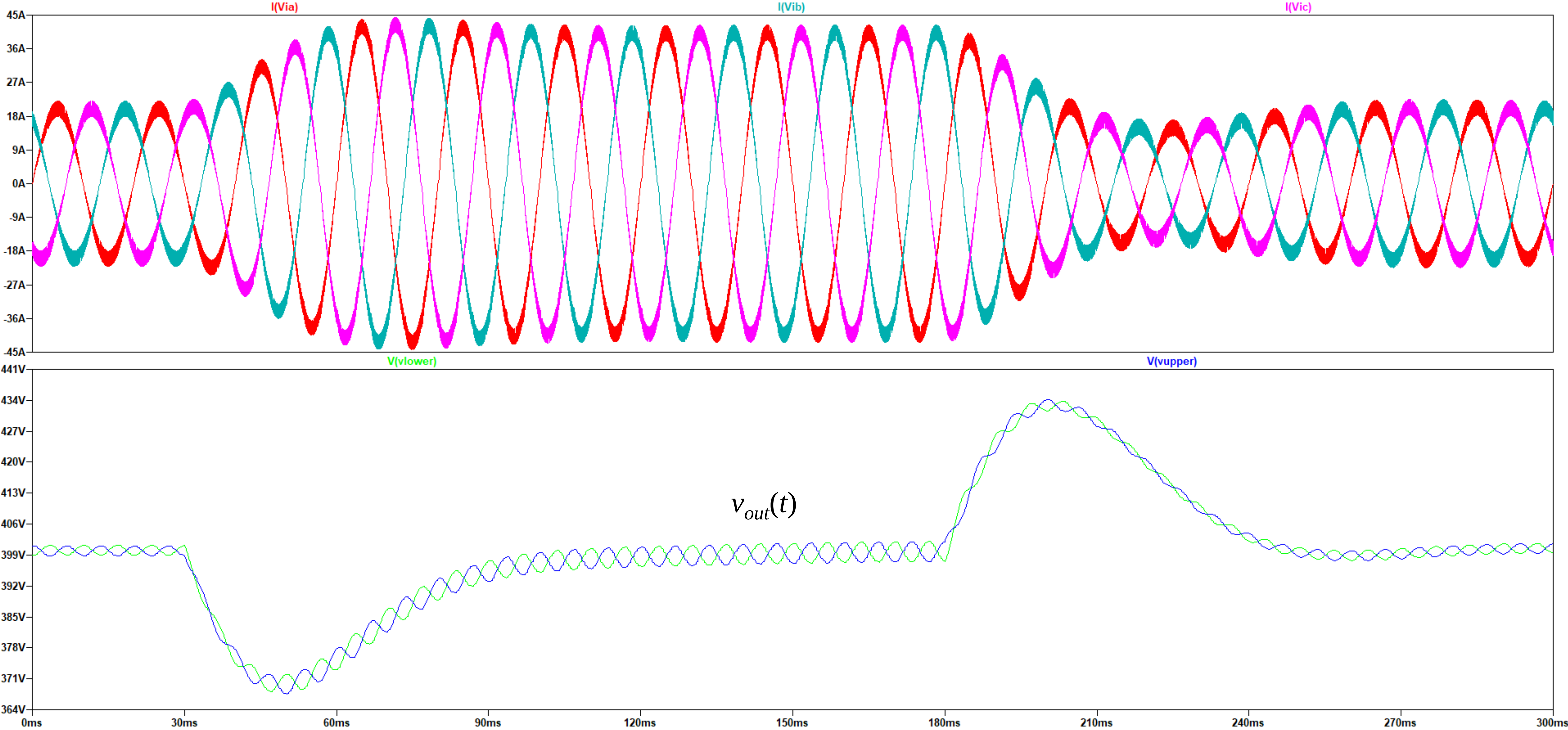


```
*
.PARAM Fline=50
.param Vgrms=120
.PARAM Vgpeak={Vgrms*sqrt(2)}
.PARAM Vamp={Vgpeak*2}
.MODEL TOFSW SW(Ron=25m Roff=10Meg Vt=2 Vh=1)
.MODEL TOFD D(IS=10e-18 RS=16m CJO=450p
+M=0.4 VJ=0.75 ISR=720n BV=1000 IBV=100u TT=130n)
*
 .tran 0 600m 300m uic
```

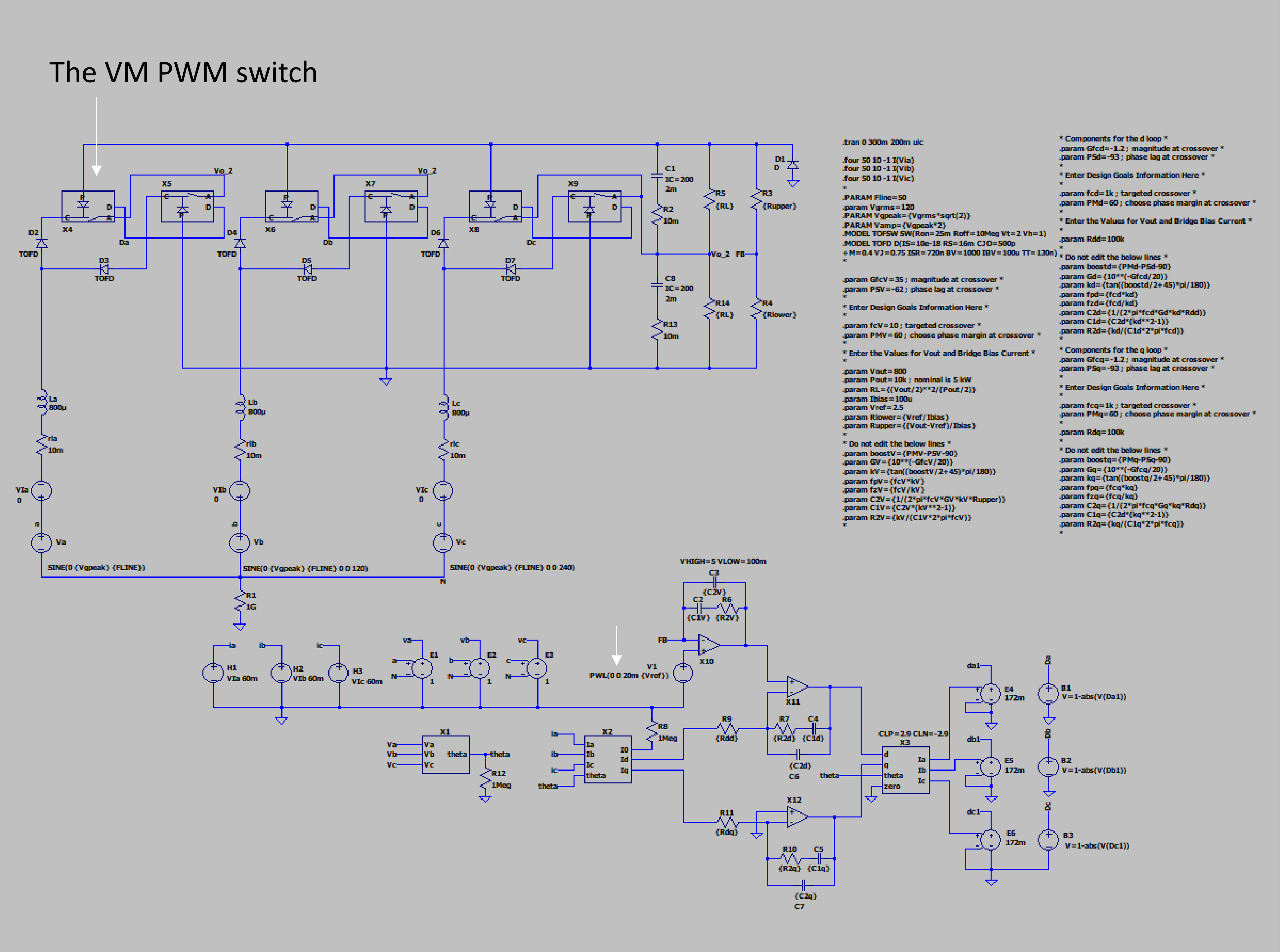
```
.options abstol=1u vntol=1m reltol=0.01 gmin=100p
+method=gear


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

.param GfcV=35 ; magnitude at crossover *
.param PSV=-62 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcV=10 ; targeted crossover *
.param PMV=60 ; choose phase margin at crossover *
*
* Enter the Values for Vout and Bridge Bias Current *
*
.param Vout=800
.param Pout=10k ; nominal is 5 kW
.param RL={(Vout/2)**2/(Pout/2)}
.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=-1.2 ; magnitude at crossover *
.param PSd=-93 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcd=1k ; 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=-1.2 ; magnitude at crossover *
.param PSq=-93 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcq=1k ; 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)}
*
```

In this simulation, the load is stepped from 50% to 100% on each of the output rails.



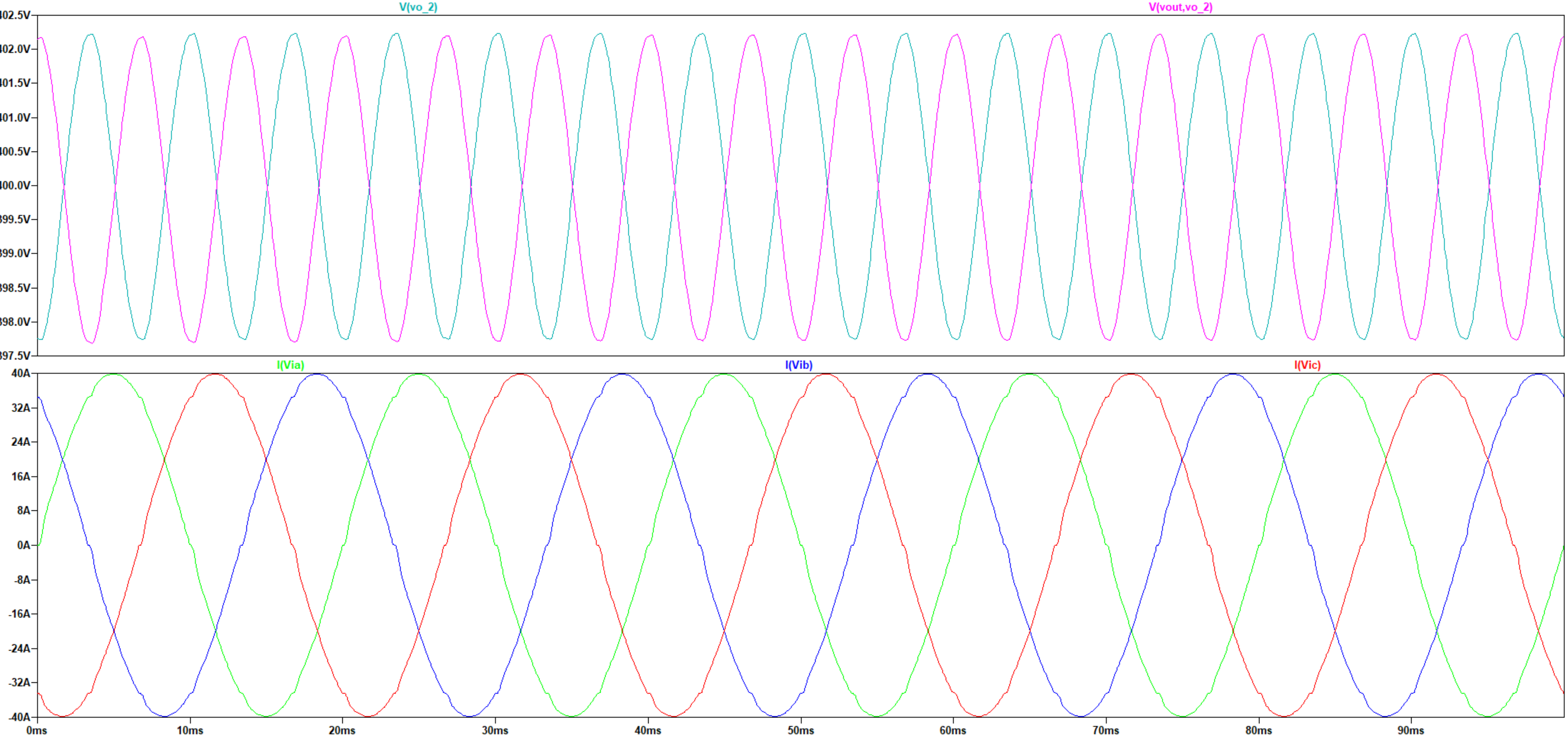
The output response is stable, with a good recovery.


The VM PWM switch

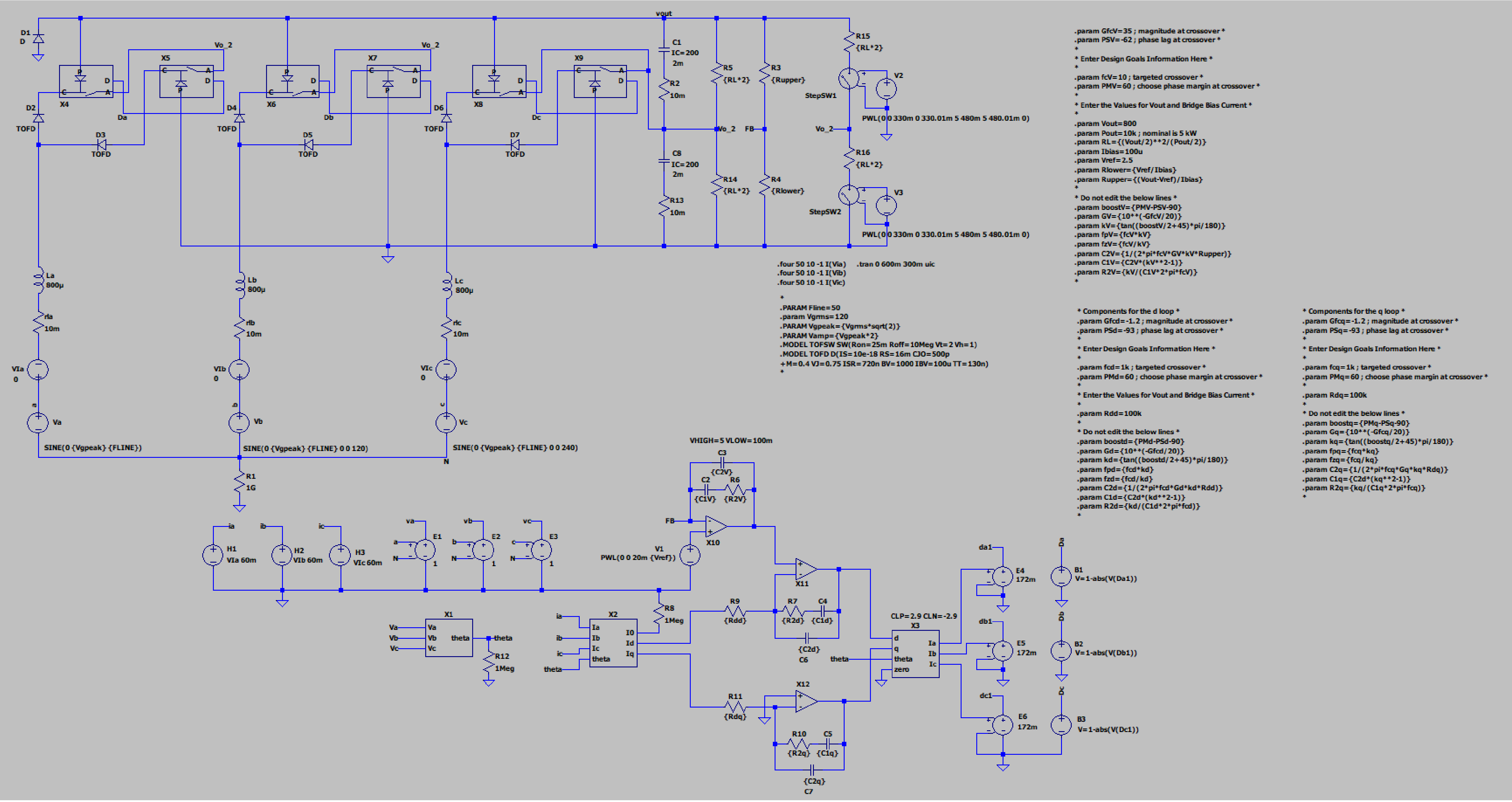
```
.tran 0 300m 200m uic

.four 50 10 -1 I(Via)
.four 50 10 -1 I(Vib)
.four 50 10 -1 I(Vic)
*
.PARAM Fline=50
.param Vgrms=120
.PARAM Vgpeak={Vgrms*sqrt(2)}
.PARAM Vamp={Vgpeak*2}
.MODEL TOFSW SW(Ron=25m Roff=10Meg Vt=2 Vh=1)
.MODEL TOFD D(IS=10e-18 RS=16m CJO=500p
+M=0.4 VJ=0.75 ISR=720n BV=1000 IBV=100u TT=130n)
*


.param GfcV=35 ; magnitude at crossover *
.param PSV=-62 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcV=10 ; targeted crossover *
.param PMV=60 ; choose phase margin at crossover *
*
* Enter the Values for Vout and Bridge Bias Current *
*
.param Vout=800
.param Pout=10k ; nominal is 5 kW
.param RL={(Vout/2)**2/(Pout/2)}
.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=-1.2 ; magnitude at crossover *
.param PSd=-93 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcd=1k ; 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=-1.2 ; magnitude at crossover *
.param PSq=-93 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcq=1k ; 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)}
*
```

This is the averaged model of the Vienna rectifier. The key here is, again, to soft-start the reference voltage.



The input currents are nicely sinusoidal and both output rails are regulated at 400 V
V_{in} = 120 V rms, P_{out} = 10 kW



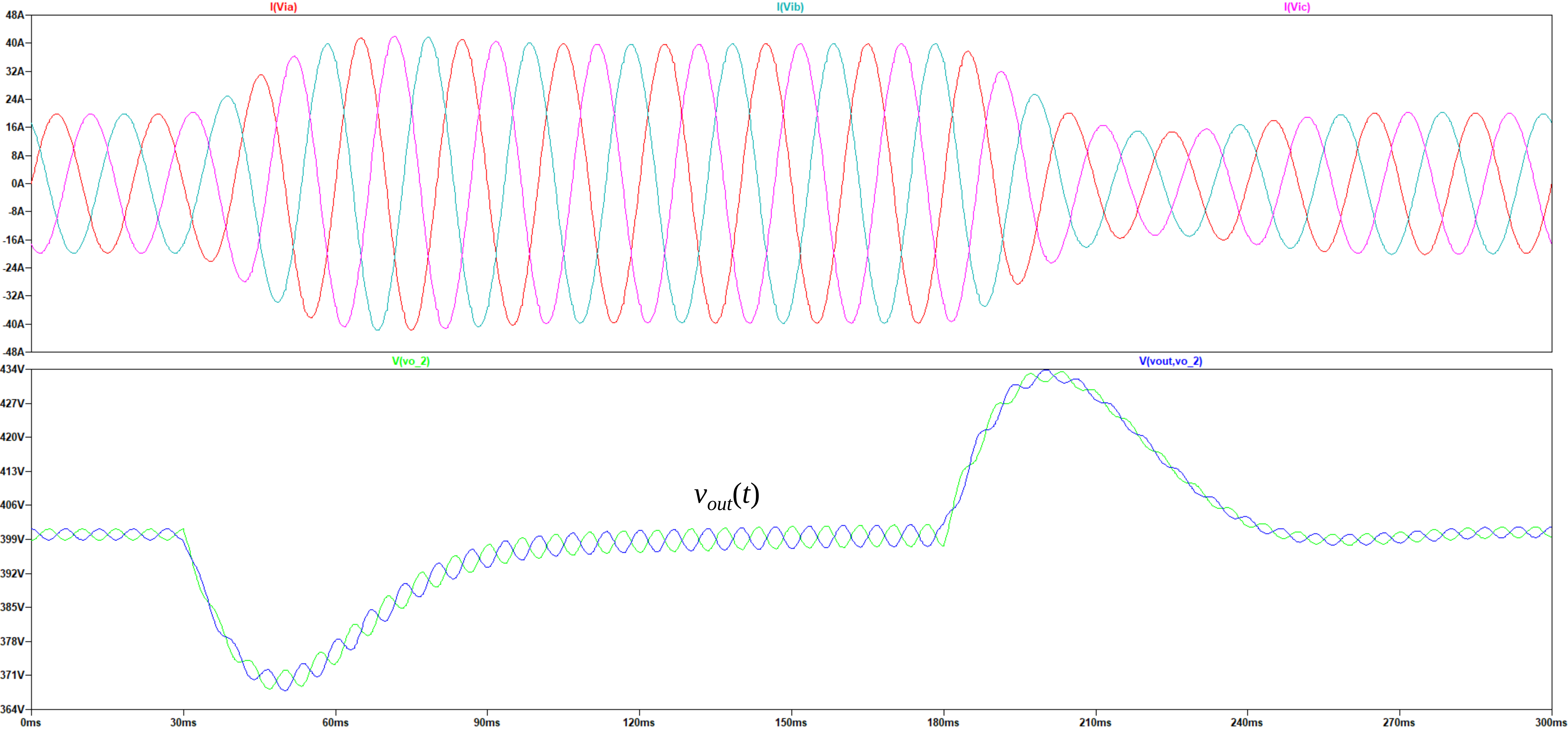
```
.param GfcV=35 ; magnitude at crossover *
.param PSV=-62 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcV=10 ; targeted crossover *
.param PMV=60 ; choose phase margin at crossover *
*
* Enter the Values for Vout and Bridge Bias Current *
*
.param Vout=800
.param Pout=10k ; nominal is 5 kW
.param RL={(Vout/2)**2/(Pout/2)}
.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)}
*
```

```
.four 50 10 -1 I(Via)     .tran 0 600m 300m uic
.four 50 10 -1 I(Vib)
.four 50 10 -1 I(Vic)

*
.PARAM Fline=50
.param Vgrms=120
.PARAM Vgpeak={Vgrms*sqrt(2)}
.PARAM Vamp={Vgpeak*2}
.MODEL TOFSW SW(Ron=25m Roff=10Meg Vt=2 Vh=1)
.MODEL TOFD D(IS=10e-18 RS=16m CJO=500p
+M=0.4 VJ=0.75 ISR=720n BV=1000 IBV=100u TT=130n)
*
```

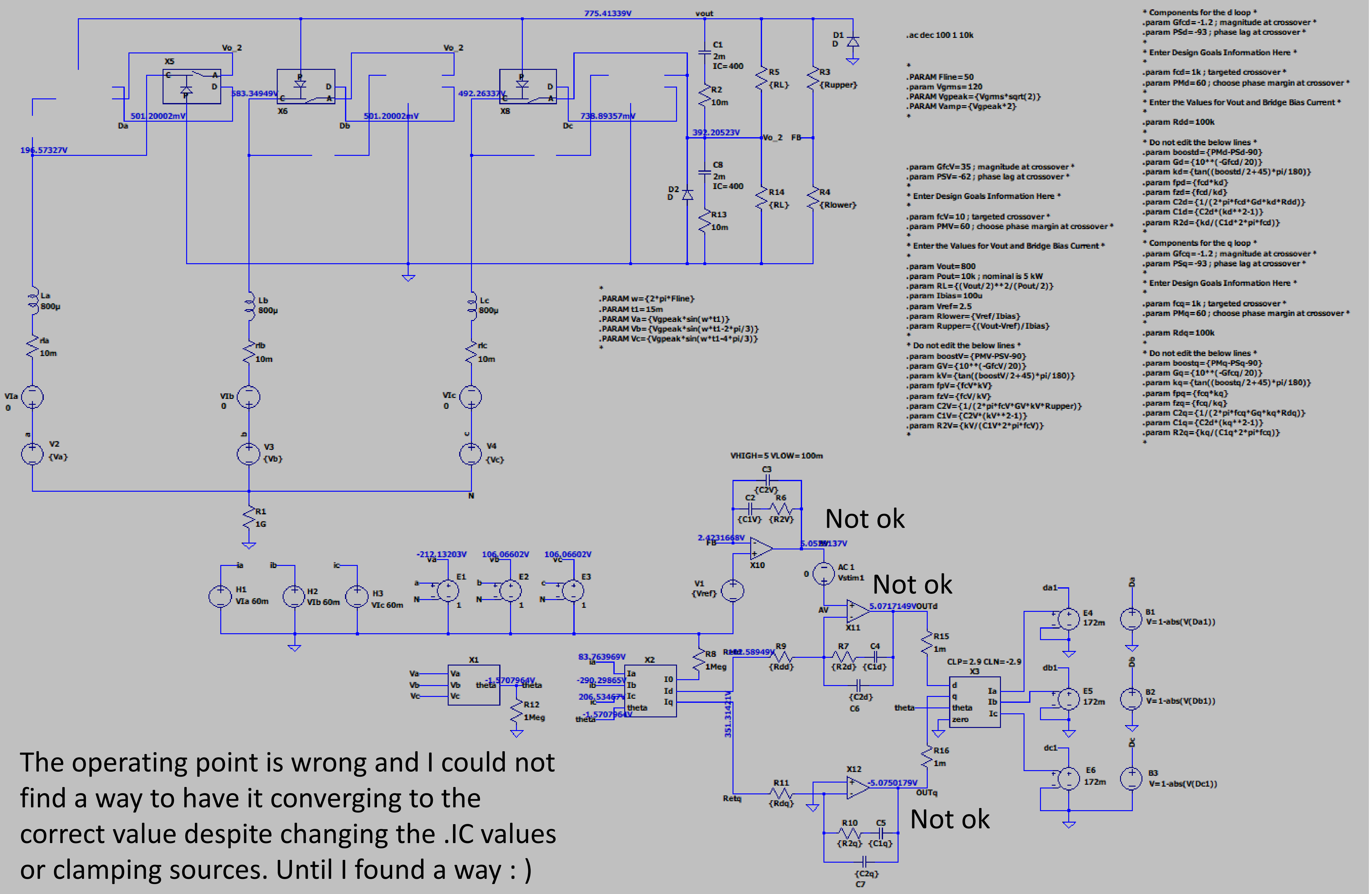
```
* Components for the d loop *
.param Gfcd=-1.2 ; magnitude at crossover *
.param PSd=-93 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcd=1k ; targeted crossover *
.param PMd=60 ; choose phase margin at crossover *
*
* Enter the Values for Vout and Bridge Bias Current *
*
.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=-1.2 ; magnitude at crossover *
.param PSq=-93 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcq=1k ; 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)}
*
```

This is template for the load transient response in averaged mode.



This is the response to a load step, from 5 to 10 kW. Excellent match with the cycle-by-cycle version.



```
.ac dec 100 1 10k

*
.PARAM Fline=50
.param Vgrms=120
.PARAM Vgpeak={Vgrms*sqrt(2)}
.PARAM Vamp={Vgpeak*2}
*
```

```
.param GfcV=35 ; magnitude at crossover *
.param PSV=-62 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcV=10 ; targeted crossover *
.param PMV=60 ; choose phase margin at crossover *
*
* Enter the Values for Vout and Bridge Bias Current *
*
.param Vout=800
.param Pout=10k ; nominal is 5 kW
.param RL={(Vout/2)**2/(Pout/2)}
.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=-1.2 ; magnitude at crossover *
.param PSd=-93 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcd=1k ; 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=-1.2 ; magnitude at crossover *
.param PSq=-93 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcq=1k ; 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)}
*
```

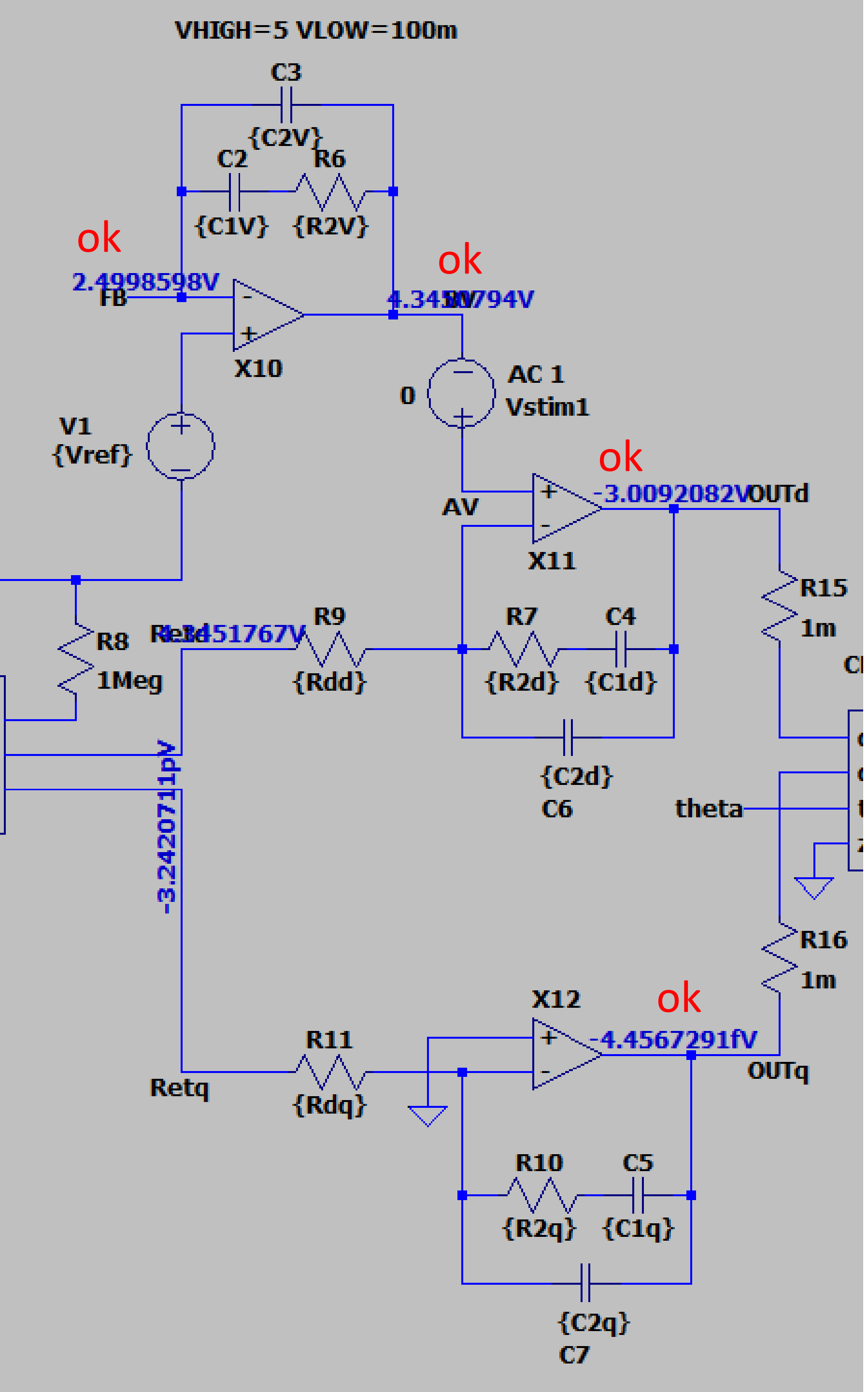
```
*
.PARAM w={2*pi*Fline}
.PARAM t1=15m
.PARAM Va={Vgpeak*sin(w*t1)}
.PARAM Vb={Vgpeak*sin(w*t1-2*pi/3)}
.PARAM Vc={Vgpeak*sin(w*t1-4*pi/3)}
*
```

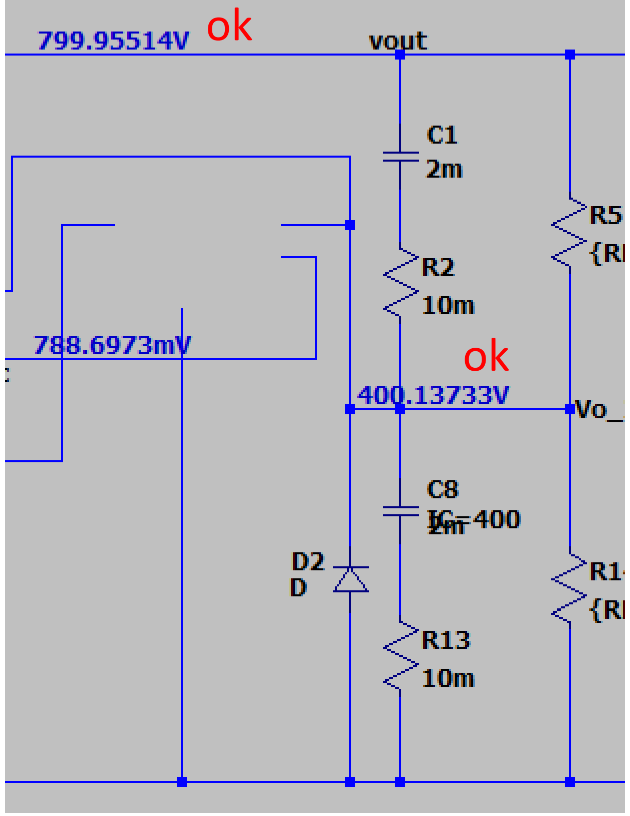
Not ok

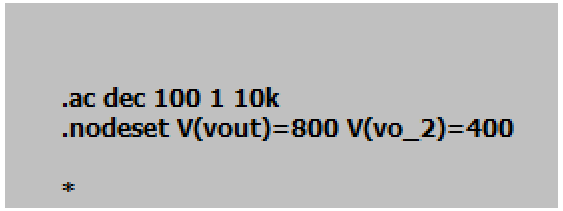
Not ok

Not ok

The operating point is wrong and I could not find a way to have it converging to the correct value despite changing the .IC values or clamping sources. Until I found a way :)

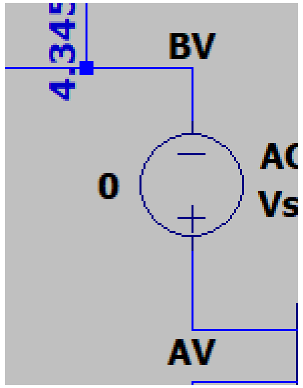




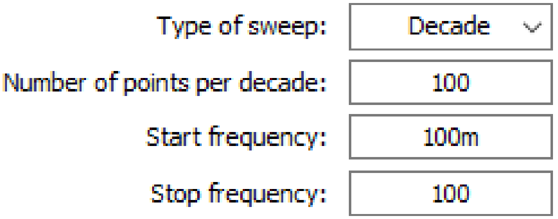


```
.ac dec 100 1 10k
.nodeset V(vout)=800 V(vo_2)=400
*
```

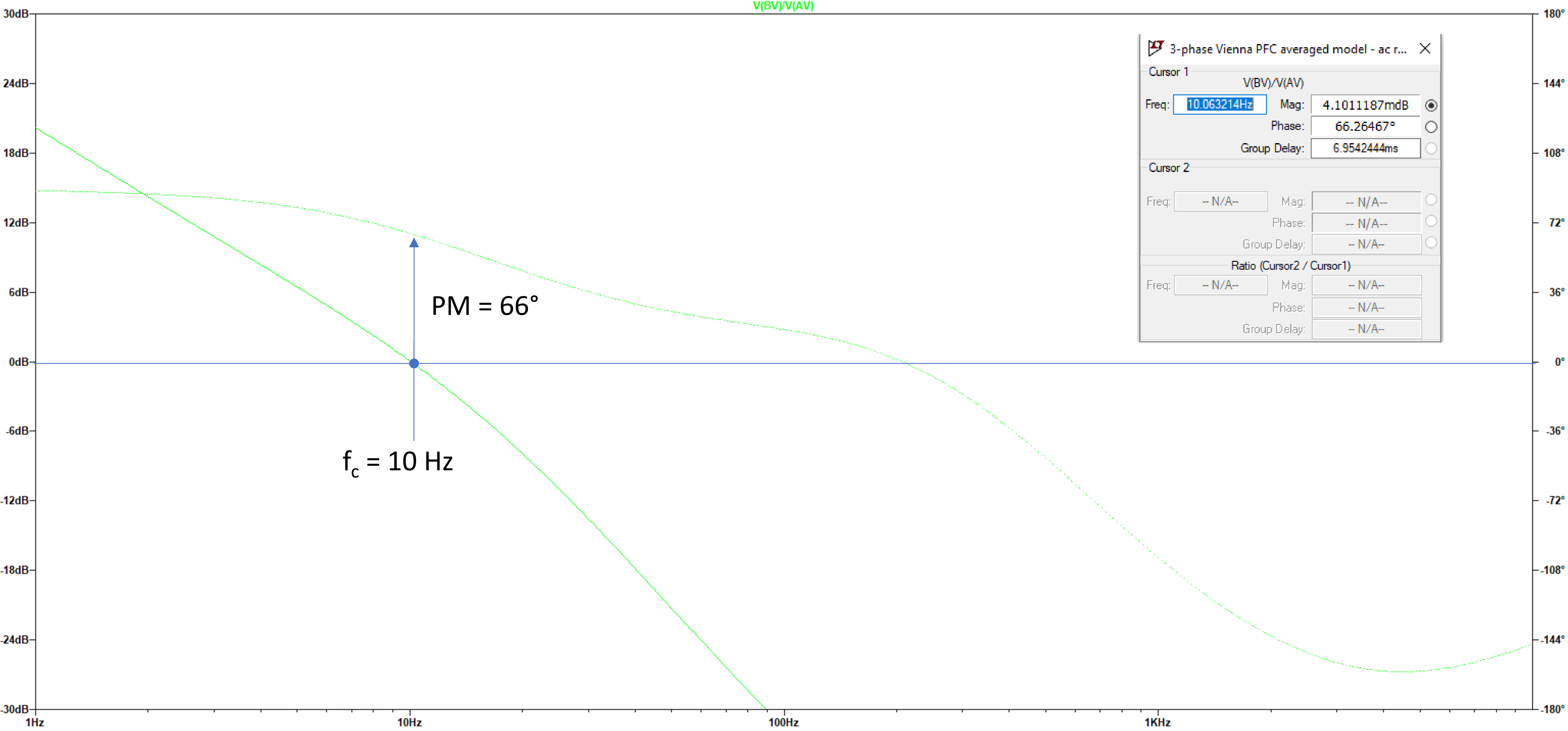
As I rarely give up, I've tried to keep one cap initialized (the low-side cap) to 400 V and added two .nodeset statements. It worked and the bias point is correct considering the given operating conditions. However, it is quite sensitive and might be an issue for a different setup. However, it validates the principle which is cool.



Plotting V(BV)/V(AV) gives the compensated loop gain. The control-to-output transfer function is obtained by plotting V(VOUT)/V(AV).



Type of sweep: Decade
Number of points per decade: 100
Start frequency: 100m
Stop frequency: 100



3-phase Vienna PFC averaged model - ac r...

Cursor 1

V(BV)/V(AV)

Freq: 10.063214Hz Mag: 4.1011187mdB ●

Phase: 66.26467° ○

Group Delay: 6.9542444ms ○

Cursor 2

Freq: -- N/A-- Mag: -- N/A-- ○

Phase: -- N/A-- ○

Group Delay: -- N/A-- ○

Ratio (Cursor2 / Cursor1)

Freq: -- N/A-- Mag: -- N/A--

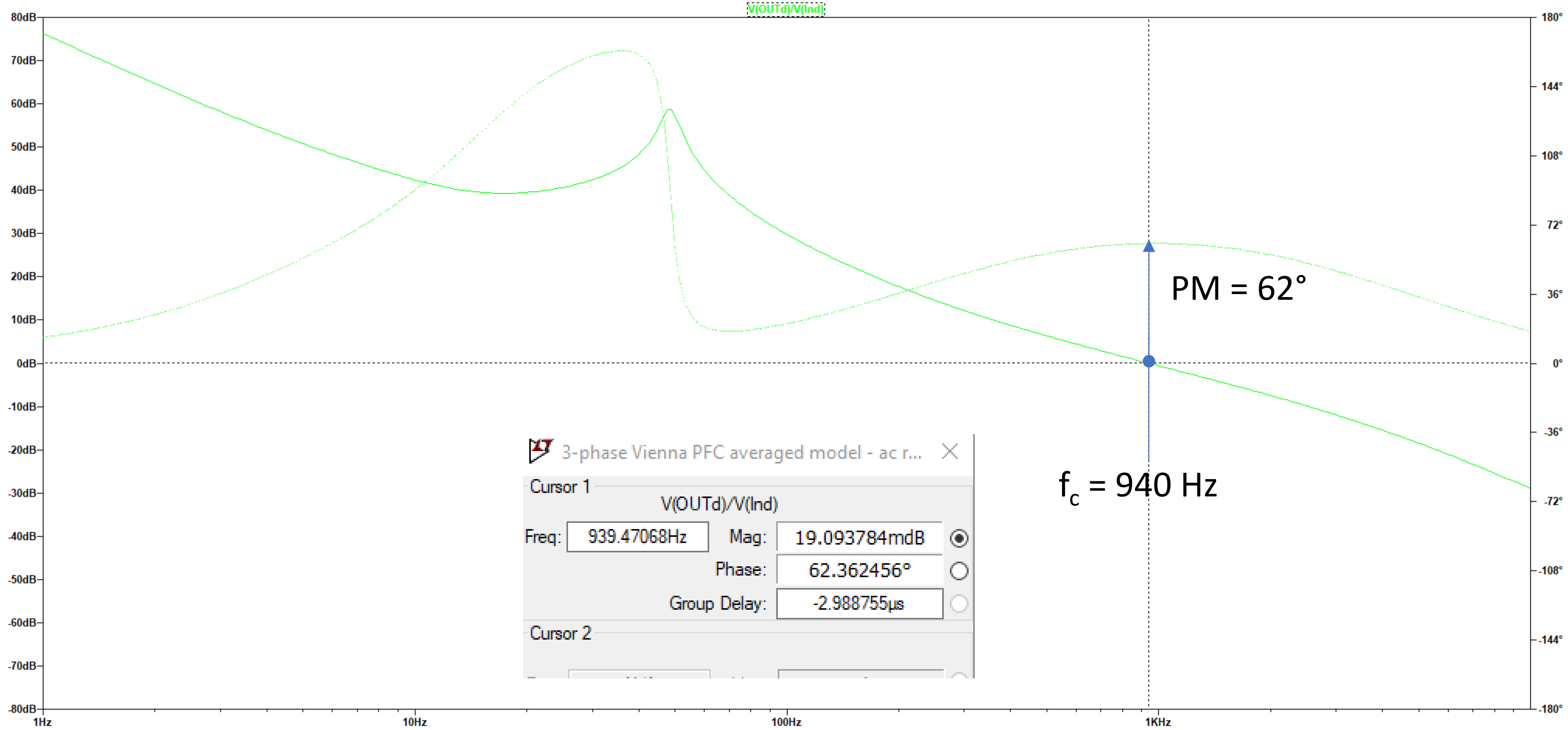
Phase: -- N/A--

Group Delay: -- N/A--

PM = 66°

f_c = 10 Hz

This is the compensated loop gain of the voltage loop.



3-phase Vienna PFC averaged model - ac r...

Cursor 1

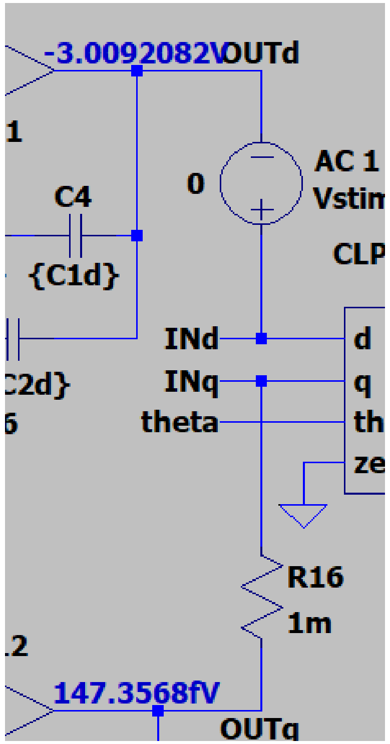
V(OUTd)/V(Ind)

Freq: 939.47068Hz Mag: 19.093784mdB ●

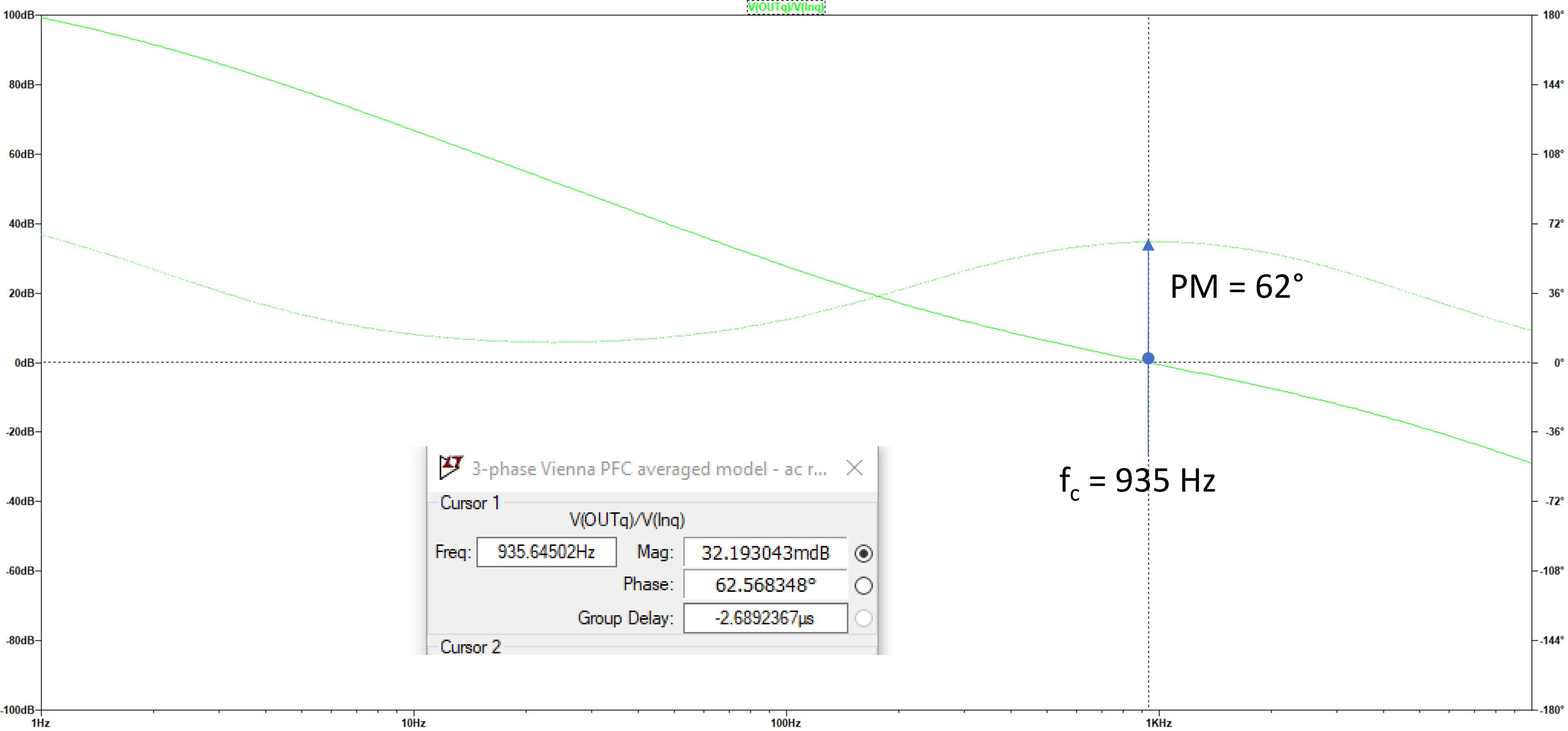
Phase: 62.362456° ○

Group Delay: -2.988755µs ○

Cursor 2



Now change the ac source to plot the d loop. Close the V-loop with R_{15} and plot V(OUTd)/V(Ind) for the compensated d-loop gain.



PM = 62°

f_c = 935 Hz

Cursor 1

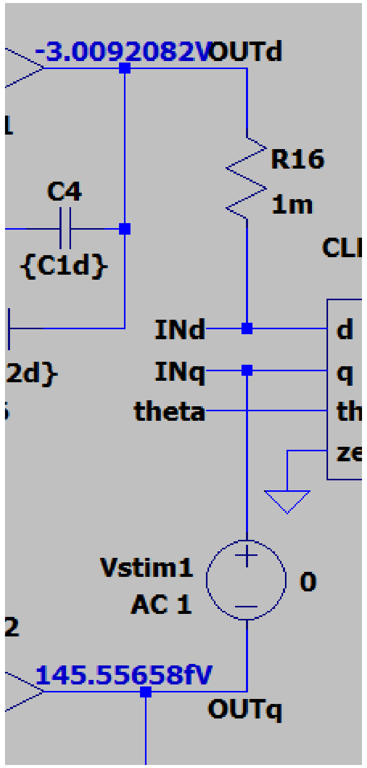
V(OUTq)/V(Inq)

Freq: 935.64502Hz Mag: 32.193043mdB ●

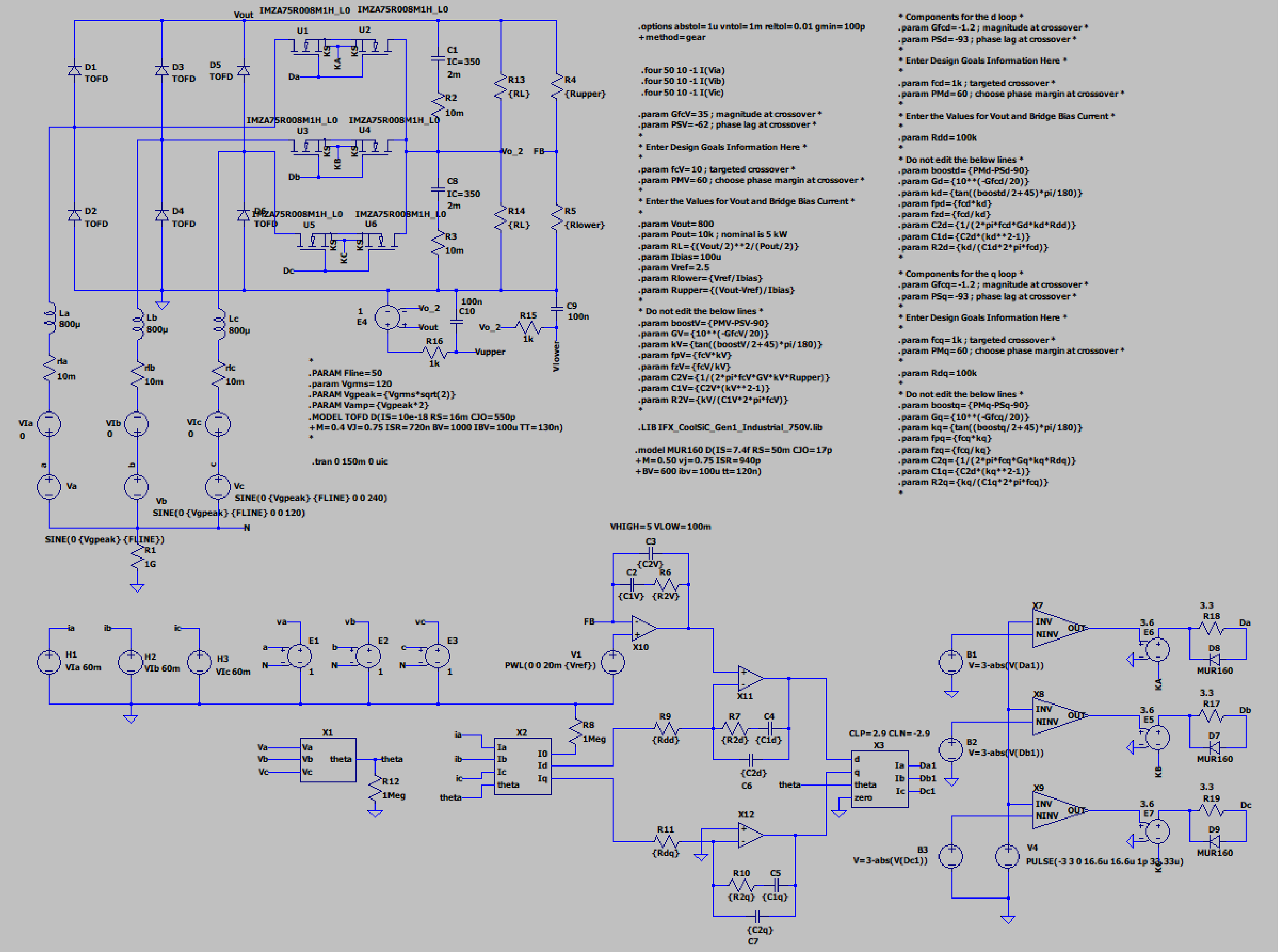
Phase: 62.568348° ○

Group Delay: -2.6892367µs ○

Cursor 2



Now change the ac source to plot the q loop. Close the d-loop with R_{16} and plot V(OUTq)/V(Inq) for the compensated q-loop gain.

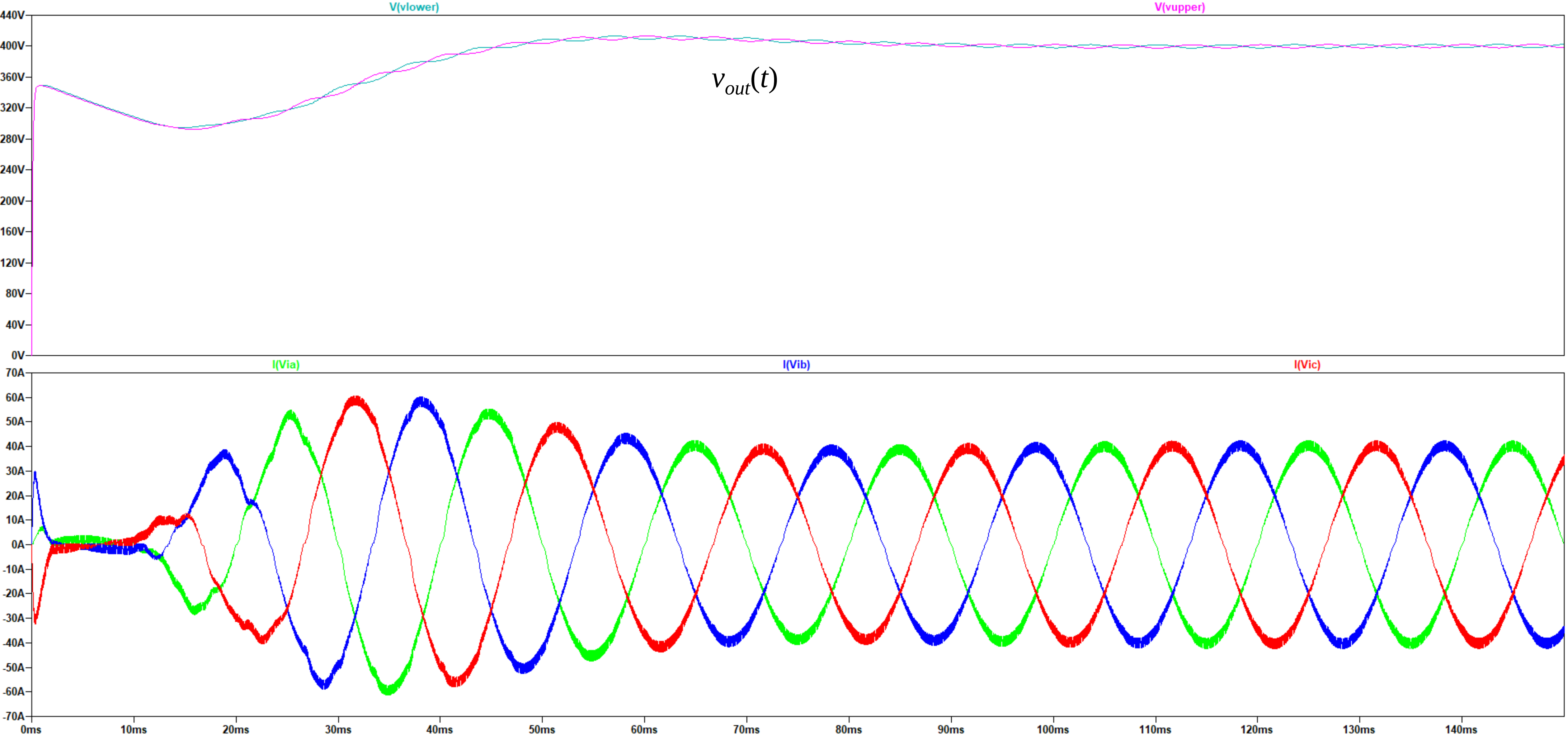


```
.options abstol=1u vntol=1m reltol=0.01 gmin=100p
+method=gear

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

.param GfcV=35 ; magnitude at crossover *
.param PSV=-62 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcV=10 ; targeted crossover *
.param PMV=60 ; choose phase margin at crossover *
*
* Enter the Values for Vout and Bridge Bias Current *
*
.param Vout=800
.param Pout=10k ; nominal is 5 kW
.param RL={(Vout/2)**2/(Pout/2)}
.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)}
*

.LIB IFX_CoolSiC_Gen1_Industrial_750V.lib

.model MUR160 D(IS=7.4f RS=50m CJO=17p
+M=0.50 vj=0.75 ISR=940p
+BV=600 ibv=100u tt=120n)
```

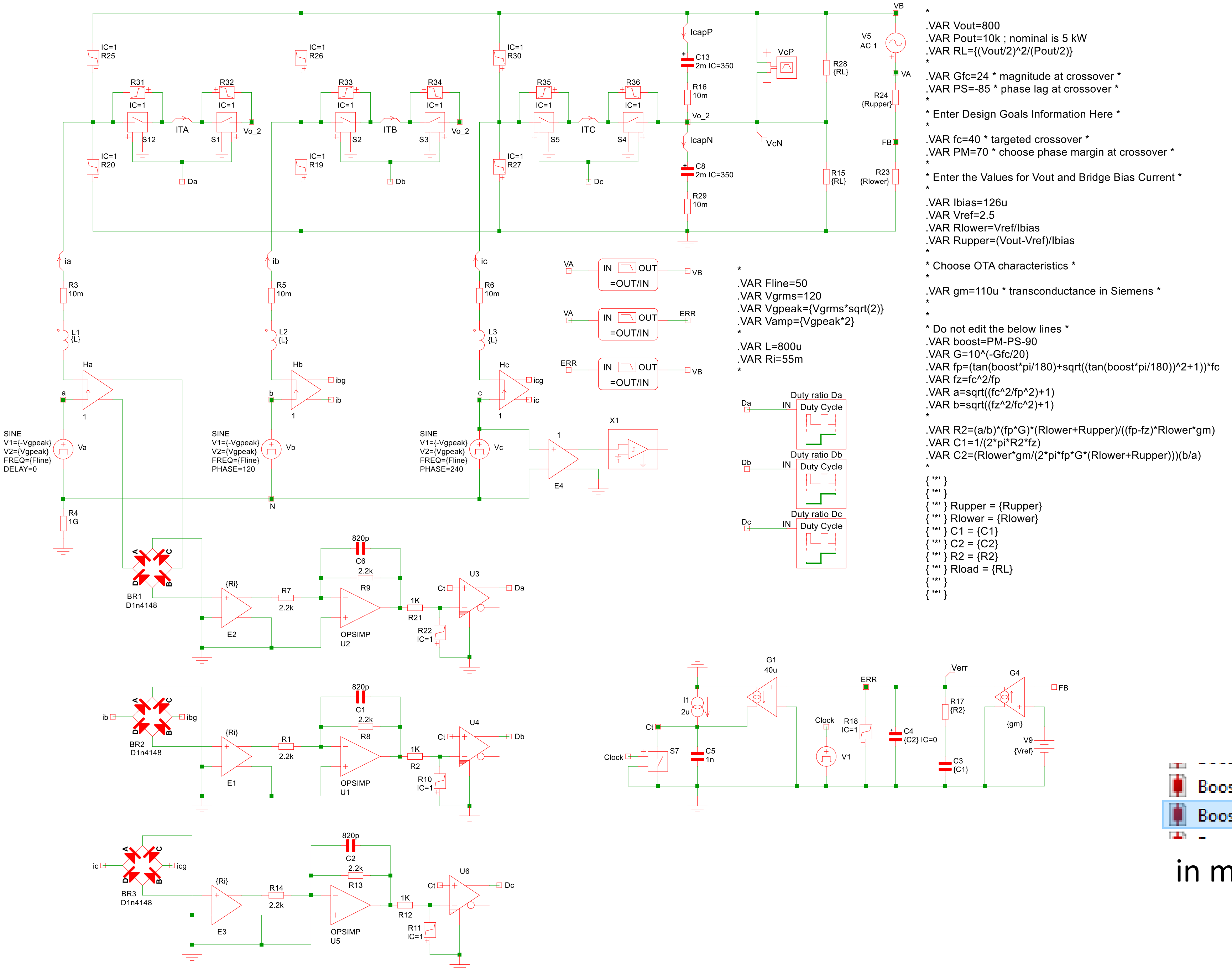
```
* Components for the d loop *
.param Gfcd=-1.2 ; magnitude at crossover *
.param PSd=-93 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcd=1k ; targeted crossover *
.param PMd=60 ; choose phase margin at crossover *
*
* Enter the Values for Vout and Bridge Bias Current *
*
.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=-1.2 ; magnitude at crossover *
.param PSq=-93 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcq=1k ; 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)}
*
```

```
*
.PARAM Fline=50
.param Vgrms=120
.PARAM Vgpeak={Vgrms*sqrt(2)}
.PARAM Vamp={Vgpeak*2}
.MODEL TOFD D(IS=10e-18 RS=16m CJO=550p
+M=0.4 VJ=0.75 ISR=720n BV=1000 IBV=100u TT=130n)
*

.tran 0 150m 0 uic
```

The perfect switches have been replaced by SiC transistors models to check if the rectifier still works well in this mode.



V_{in} = 120 V rms, P_{out} = 10 kW

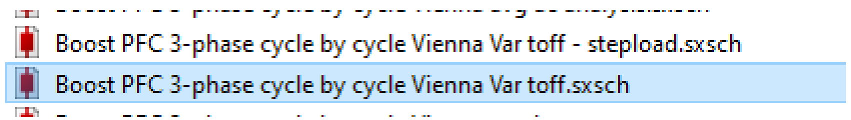


```
*
.VAR Fline=50
.VAR Vgrms=120
.VAR Vgpeak={Vgrms*sqrt(2)}
.VAR Vamp={Vgpeak*2}
*
.VAR L=800u
.VAR Ri=55m
*
```

```
*
.VAR Vout=800
.VAR Pout=10k ; nominal is 5 kW
.VAR RL={(Vout/2)^2/(Pout/2)}
*
.VAR Gfc=24 * magnitude at crossover *
.VAR PS=-85 * phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.VAR fc=40 * targeted crossover *
.VAR PM=70 * choose phase margin at crossover *
*
* Enter the Values for Vout and Bridge Bias Current *
*
.VAR Ibias=126u
.VAR Vref=2.5
.VAR Rlower=Vref/Ibias
.VAR Rupper=(Vout-Vref)/Ibias
*
* Choose OTA characteristics *
*
.VAR gm=110u * transconductance in Siemens *
*
*
* Do not edit the below lines *
.VAR boost=PM-PS-90
.VAR G=10^(-Gfc/20)
.VAR fp=(tan(boost*pi/180)+sqrt((tan(boost*pi/180))^2+1))*fc
.VAR fz=fc^2/fp
.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)
*
{ '*' }
{ '*' }
{ '*' } Rupper = {Rupper}
{ '*' } Rlower = {Rlower}
{ '*' } C1 = {C1}
{ '*' } C2 = {C2}
{ '*' } R2 = {R2}
{ '*' } Rload = {RL}
{ '*' }
{ '*' }
```

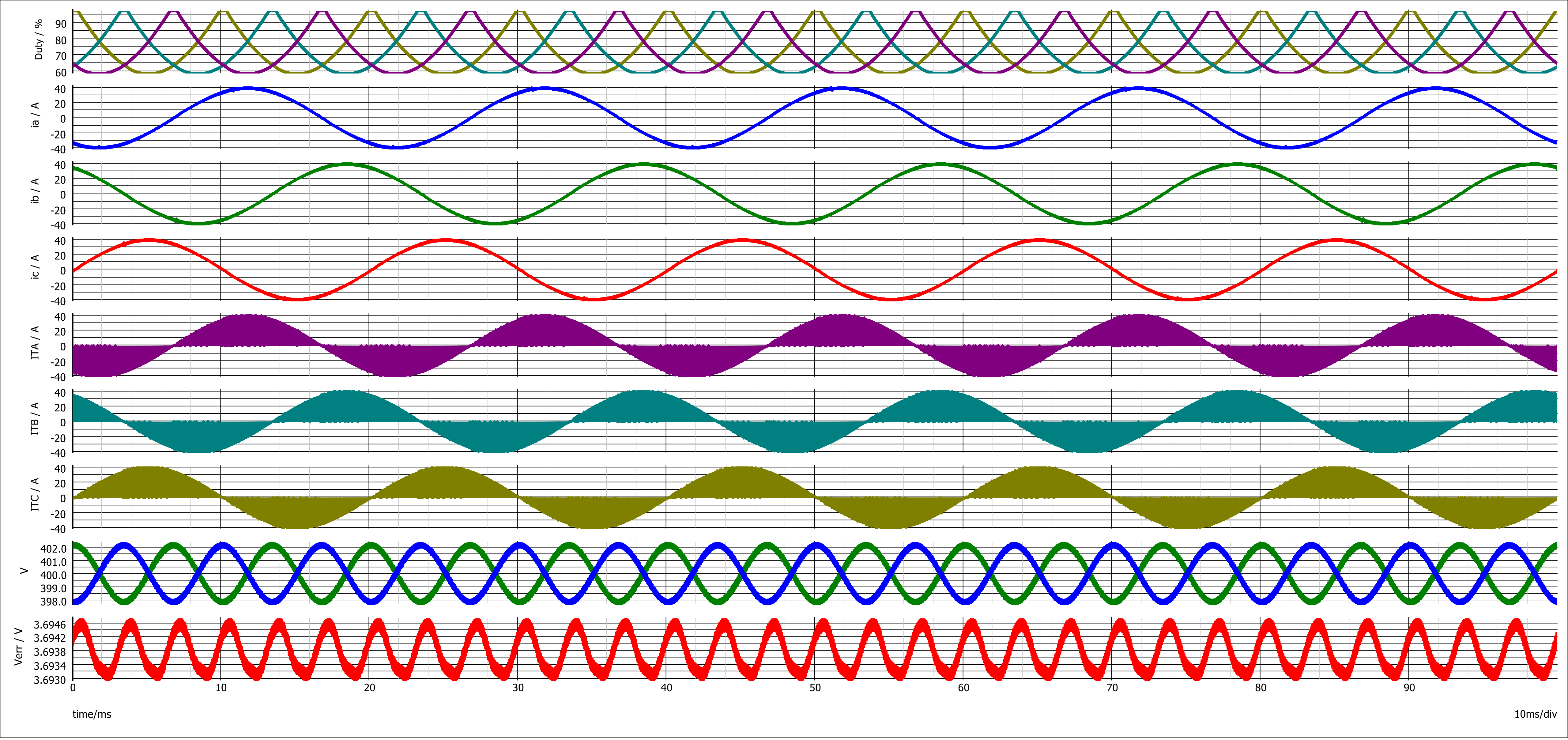
This is another simplified way to control the 3-phase Vienna rectifier. I am using the method documented by Sam Ben-Yaakov in the paper referenced below. I have adapted it to this 3-phase rectifier and it brings excellent results without sensing the high-voltage rail.

The good thing is that it runs on SIMPLIS and I can extract the small-signal response of the voltage loop via a POP and set a crossover frequency of 40 Hz with a good phase margin.


Boost PFC 3-phase cycle by cycle Vienna Var toff - stepload.sxsch
Boost PFC 3-phase cycle by cycle Vienna Var toff.sxsch

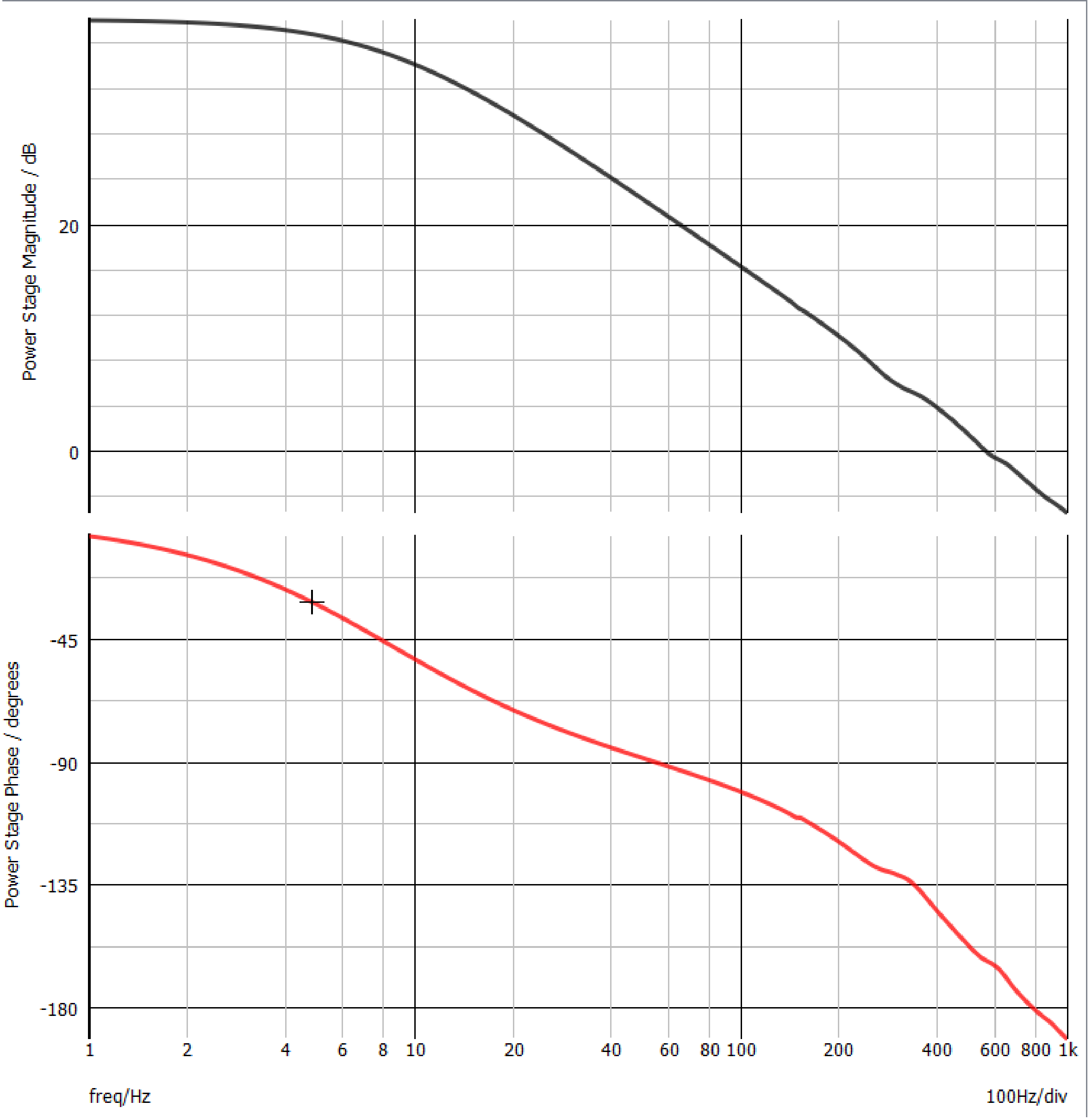
in my ZIP file.

S. Ben-Yaakov, I. Zehser, *PWM Converters with Resistive Input*, IEEE Transactions on Industrial Electronics, vol. 45, no. 3, pp. 519-520, June 1998

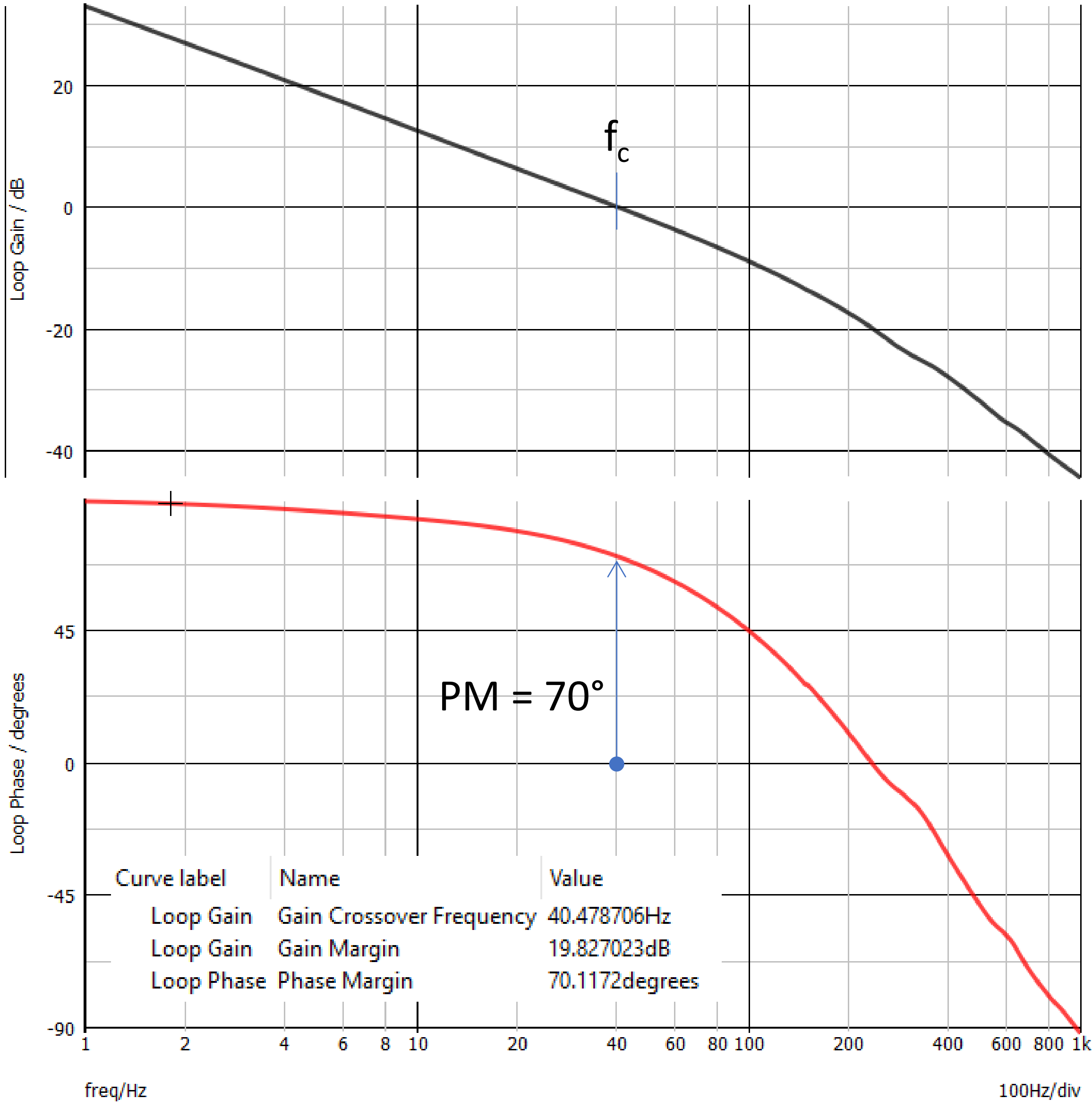


Curve label	Name	Value
ia	Distortion/cycle	3.23318%
ib	Distortion/cycle	3.23793%
ic	Distortion/cycle	3.23321%

V_{in} = 120 V rms, P_{out} = 10 kW



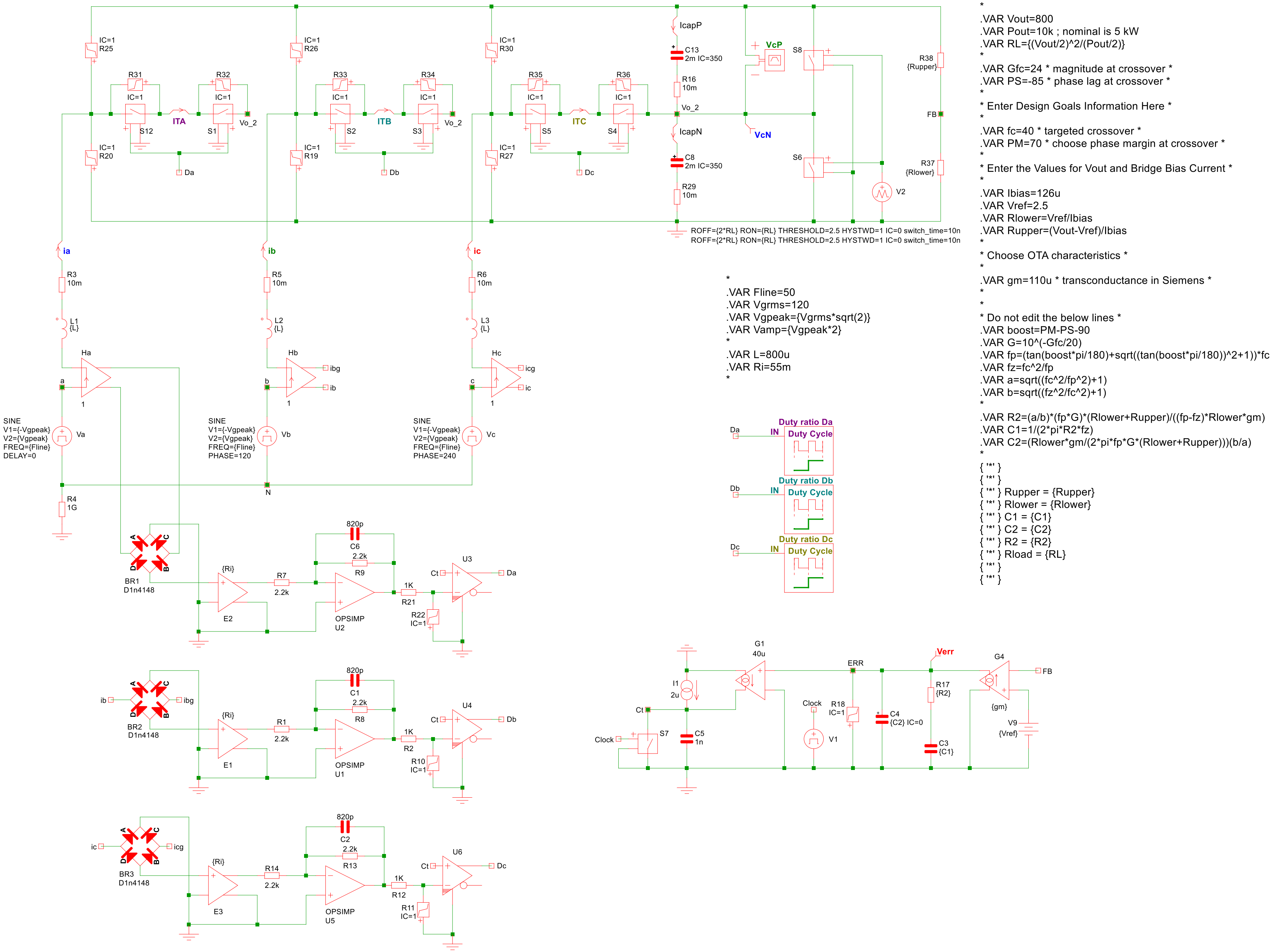
Power stage response



Curve label	Name	Value
Loop Gain	Gain Crossover Frequency	40.478706Hz
Loop Gain	Gain Margin	19.827023dB
Loop Phase	Phase Margin	70.1172degrees

Compensated loop gain

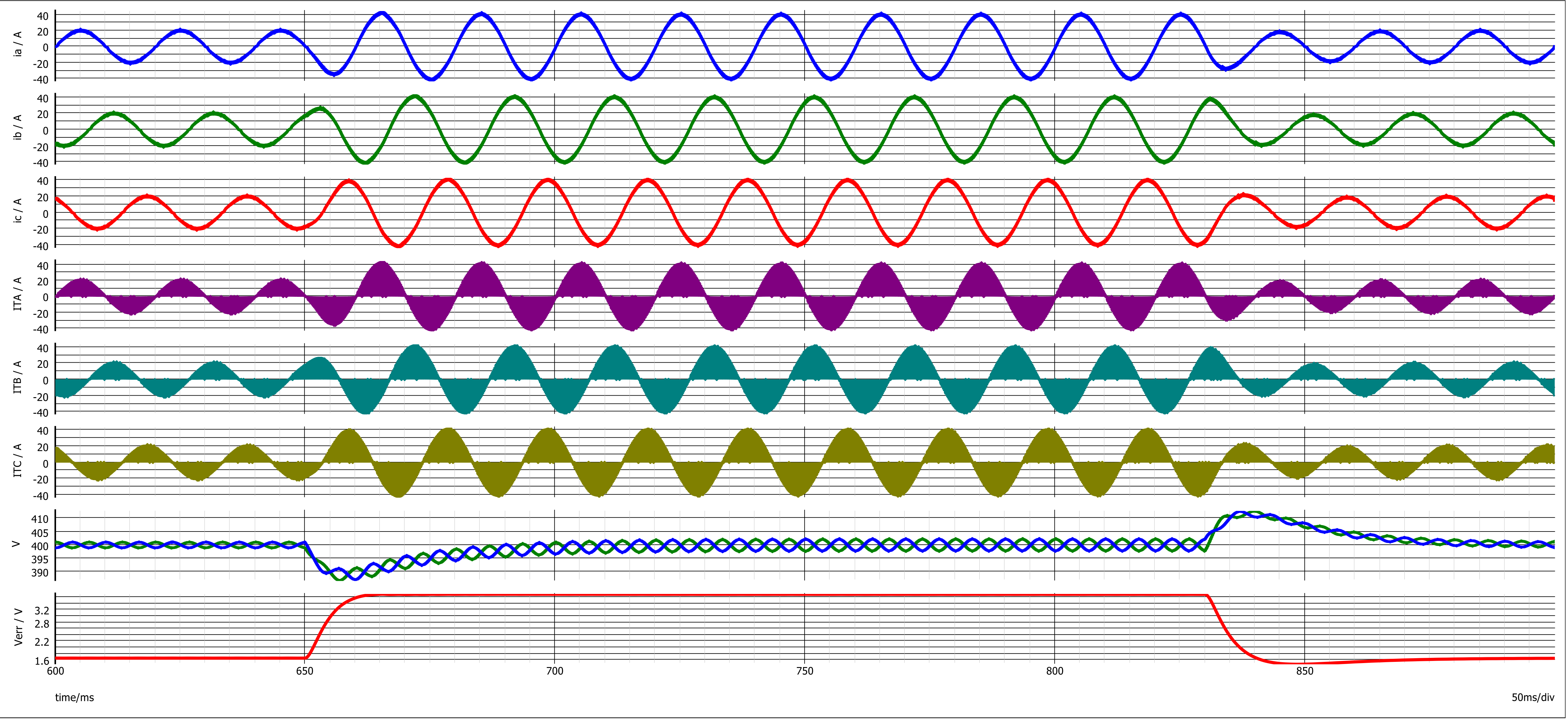
The final test includes the transient load step.



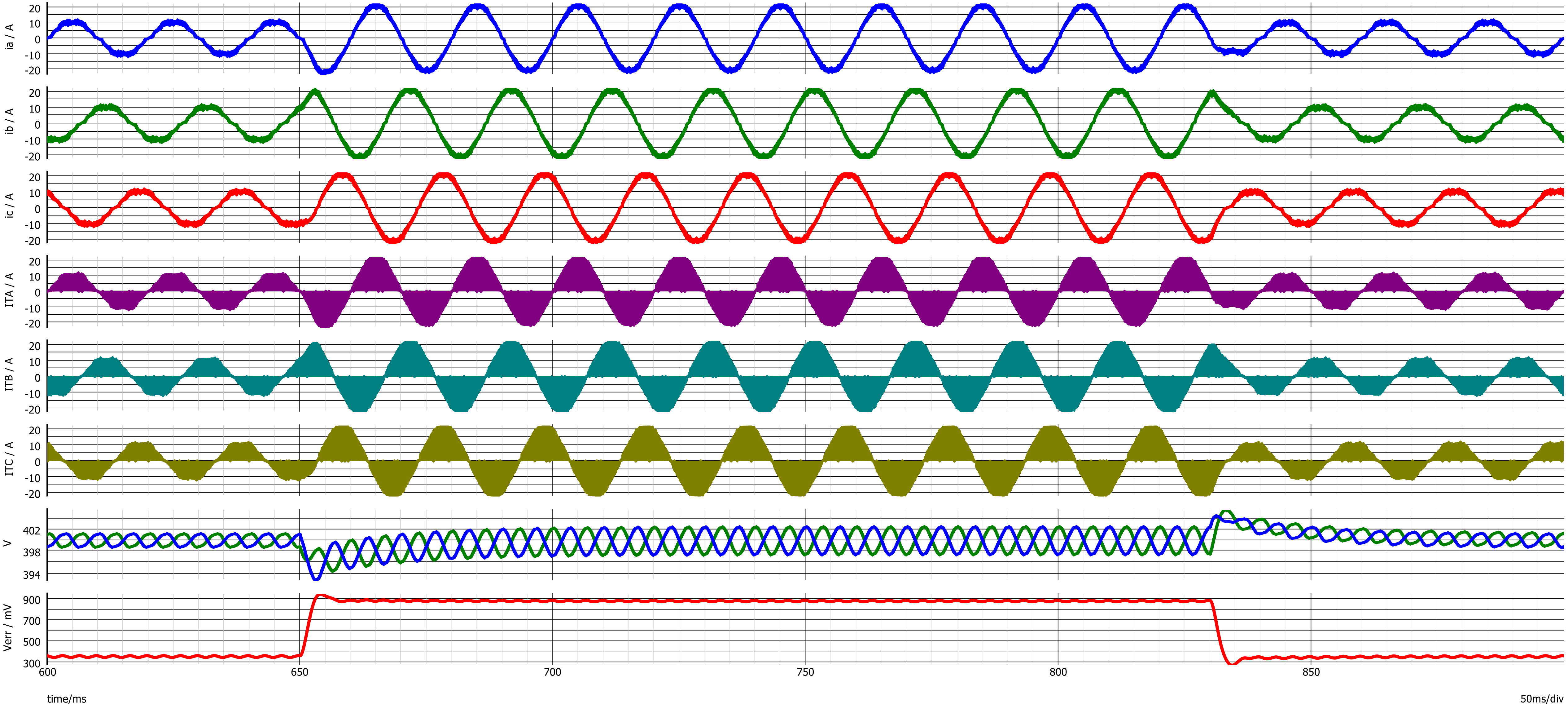
```
ROFF={2*RL} RON={RL} THRESHOLD=2.5 HYSTWD=1 IC=0 switch_time=10n
ROFF={2*RL} RON={RL} THRESHOLD=2.5 HYSTWD=1 IC=0 switch_time=10n
```

```
*
.VAR Fline=50
.VAR Vgrms=120
.VAR Vgpeak={Vgrms*sqrt(2)}
.VAR Vamp={Vgpeak*2}
*
.VAR L=800u
.VAR Ri=55m
*
```

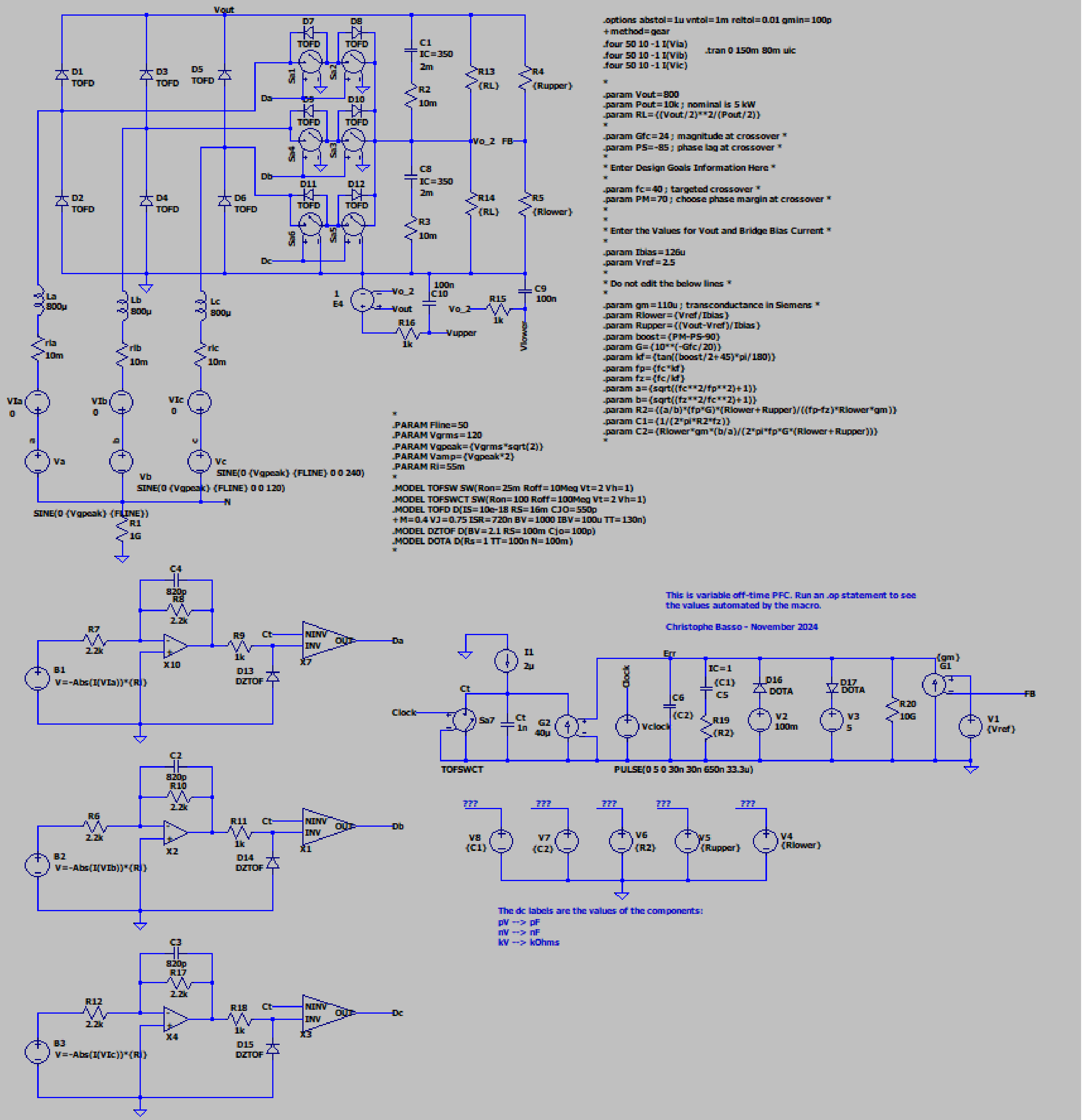
```
*
.VAR Vout=800
.VAR Pout=10k ; nominal is 5 kW
.VAR RL={(Vout/2)^2/(Pout/2)}
*
.VAR Gfc=24 * magnitude at crossover *
.VAR PS=-85 * phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.VAR fc=40 * targeted crossover *
.VAR PM=70 * choose phase margin at crossover *
*
* Enter the Values for Vout and Bridge Bias Current *
*
.VAR Ibias=126u
.VAR Vref=2.5
.VAR Rlower=Vref/Ibias
.VAR Rupper=(Vout-Vref)/Ibias
*
* Choose OTA characteristics *
*
.VAR gm=110u * transconductance in Siemens *
*
*
* Do not edit the below lines *
.VAR boost=PM-PS-90
.VAR G=10^(-Gfc/20)
.VAR fp=(tan(boost*pi/180)+sqrt((tan(boost*pi/180))^2+1))*fc
.VAR fz=fc^2/fp
.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)
*
{ '*' }
{ '*' }
{ '*' } Rupper = {Rupper}
{ '*' } Rlower = {Rlower}
{ '*' } C1 = {C1}
{ '*' } C2 = {C2}
{ '*' } R2 = {R2}
{ '*' } Rload = {RL}
{ '*' }
{ '*' }
```



V_{in} = 120 V rms, P_{out} stepped from 5 to 10 kW



V_{in} = 230 V rms, P_{out} stepped from 5 to 10 kW



```
.options abstol=1u vntol=1m reltol=0.01 gmin=100p
+method=gear
.four 50 10 -1 I(Via)
.four 50 10 -1 I(Vib)
.four 50 10 -1 I(Vic)
*
.param Vout=800
.param Pout=10k ; nominal is 5 kW
.param RL=((Vout/2)**2/(Pout/2))
*
.param Gfc=24 ; magnitude at crossover *
.param PS=-85 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fc=40 ; targeted crossover *
.param PM=70 ; choose phase margin at crossover *
*
*
* Enter the Values for Vout and Bridge Bias Current *
*
.param Ibias=126u
.param Vref=2.5
*
* Do not edit the below lines *
*
.param gm=110u ; transconductance in Siemens *
.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 a={sqrt((fc**2/fp**2)+1)}
.param b={sqrt((fz**2/fc**2)+1)}
.param R2={(a/b)*(fp*G)*(Rlower+Rupper)/((fp-fz)*Rlower*gm)}
.param C1={1/(2*pi*R2*fz)}
.param C2={Rlower*gm*(b/a)/(2*pi*fp*G*(Rlower+Rupper))}
*
```

```
.tran 0 150m 80m uic
```

```
*
.PARAM Fline=50
.PARAM Vgrms=120
.PARAM Vgpeak={Vgrms*sqrt(2)}
.PARAM Vamp={Vgpeak*2}
.PARAM Ri=55m
*
.MODEL TOFSW SW(Ron=25m Roff=10Meg Vt=2 Vh=1)
.MODEL TOFSWCT SW(Ron=100 Roff=100Meg Vt=2 Vh=1)
.MODEL TOFD D(IS=10e-18 RS=16m CJO=550p
+M=0.4 VJ=0.75 ISR=720n BV=1000 IBV=100u TT=130n)
.MODEL DZTOF D(BV=2.1 RS=100m Cjo=100p)
.MODEL DOTA D(Rs=1 TT=100n N=100m)
*
```

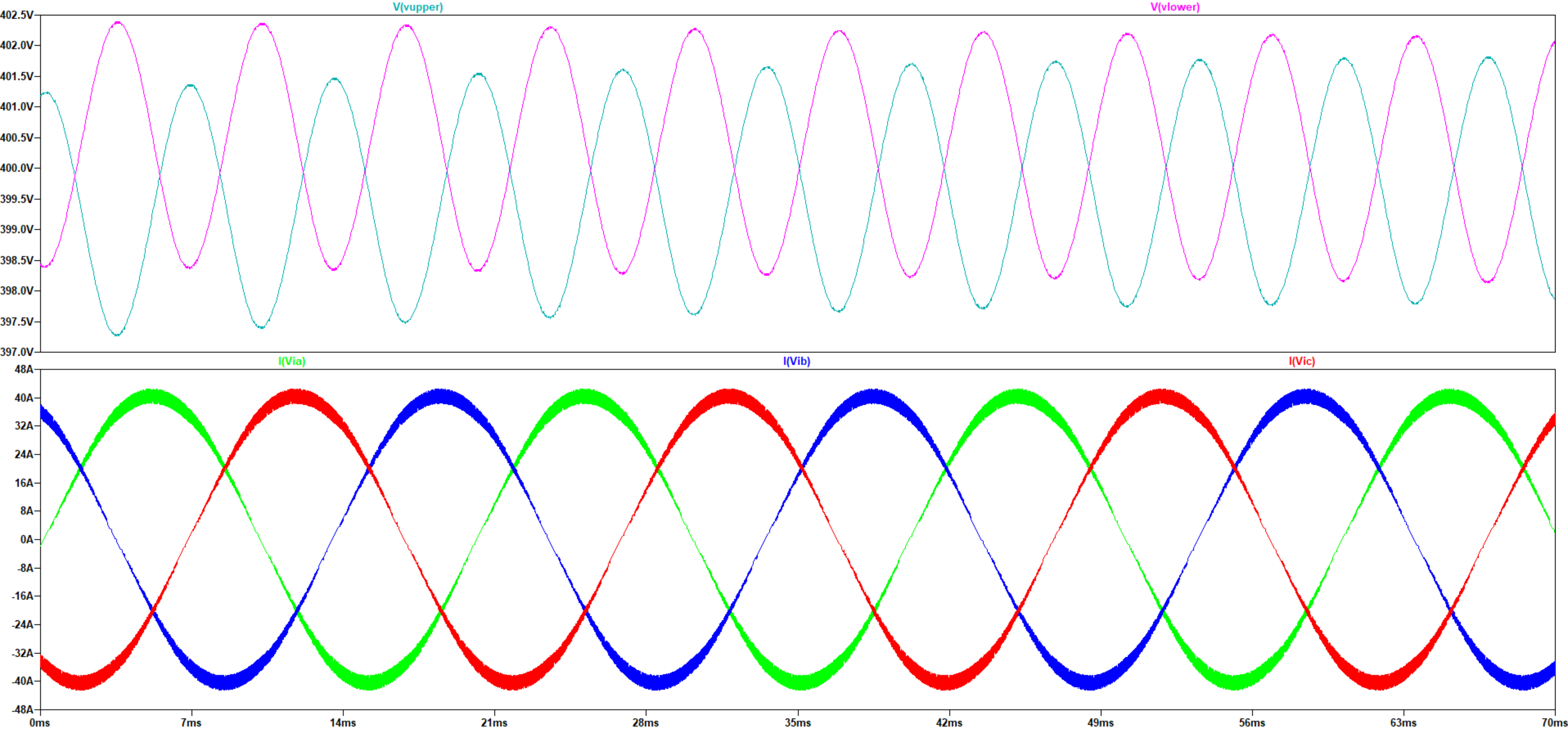
This is variable off-time PFC. Run an .op statement to see the values automated by the macro.

Christophe Basso - November 2024

The dc labels are the values of the components:
pV --> pF
nV --> nF
kV --> kOhms

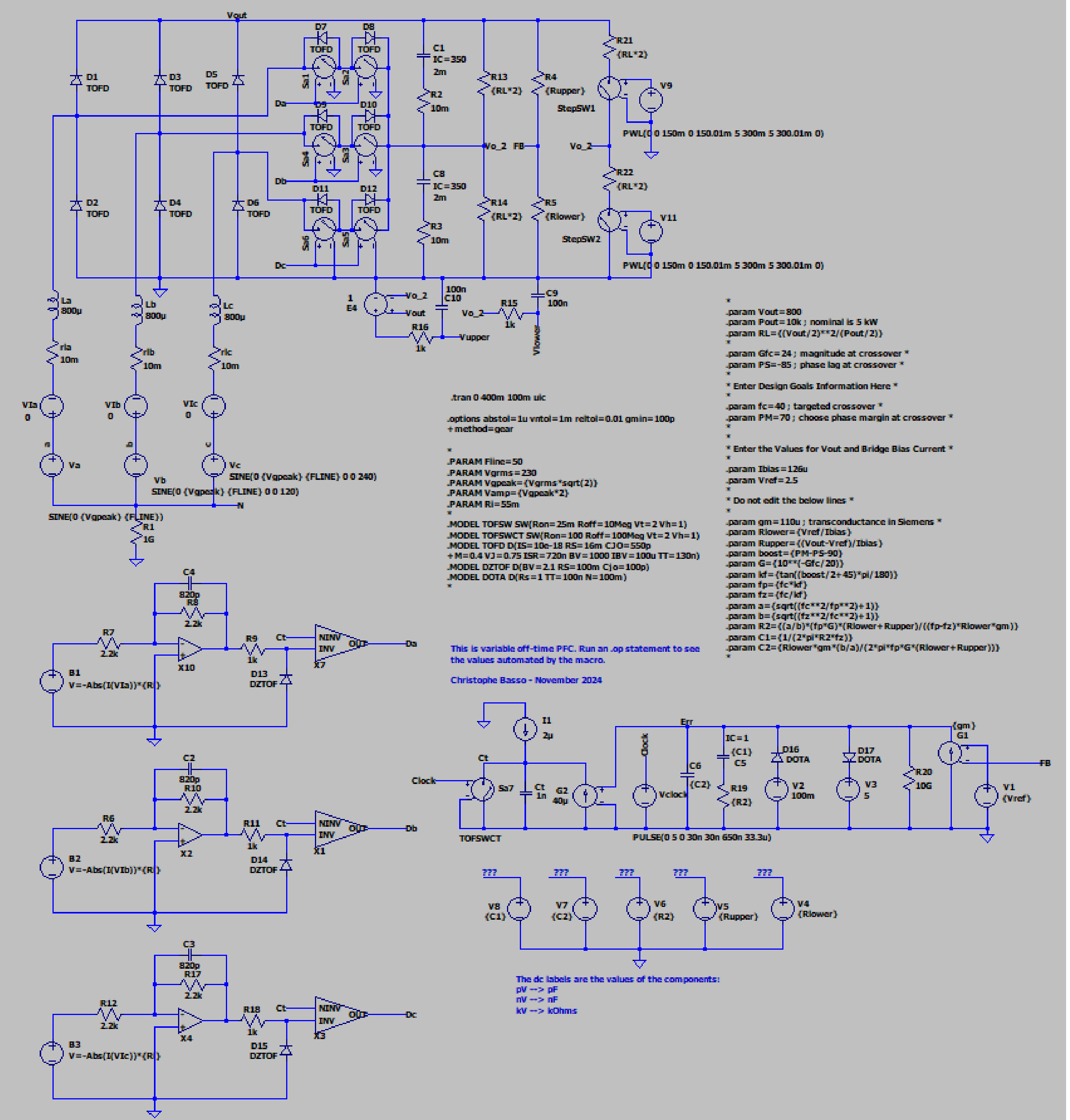
This is the LTspice version of the variable off-time 3-phase VIENNA rectifier and it simulates fast. The rectifier used in SIMPLIS is no longer necessary and I used an ABS in-line equation to rectify the input currents for phases a, b and c.

The right-side macro automates the type 2 OTA compensator for a 10-Hz crossover frequency as obtained in SIMPLIS. Running an .op analysis will display the components values as bias points in the schematic diagram.



V_{in} = 120 V rms, P_{out} = 10 kW

```
Total Harmonic Distortion:   3.232831%
```



```
.tran 0 400m 100m uic

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

*
.PARAM Fline=50
.PARAM Vgrms=230
.PARAM Vgpeak={Vgrms*sqrt(2)}
.PARAM Vamp={Vgpeak*2}
.PARAM Ri=55m
*
.MODEL TOFSW SW(Ron=25m Roff=10Meg Vt=2 Vh=1)
.MODEL TOFSWCT SW(Ron=100 Roff=100Meg Vt=2 Vh=1)
.MODEL TOFD D(IS=10e-18 RS=16m CJO=550p
+ M=0.4 VJ=0.75 ISR=720n BV=1000 IBV=100u TT=130n)
.MODEL DZTOF D(BV=2.1 RS=100m Cjo=100p)
.MODEL DOTA D(Rs=1 TT=100n N=100m)
*
```

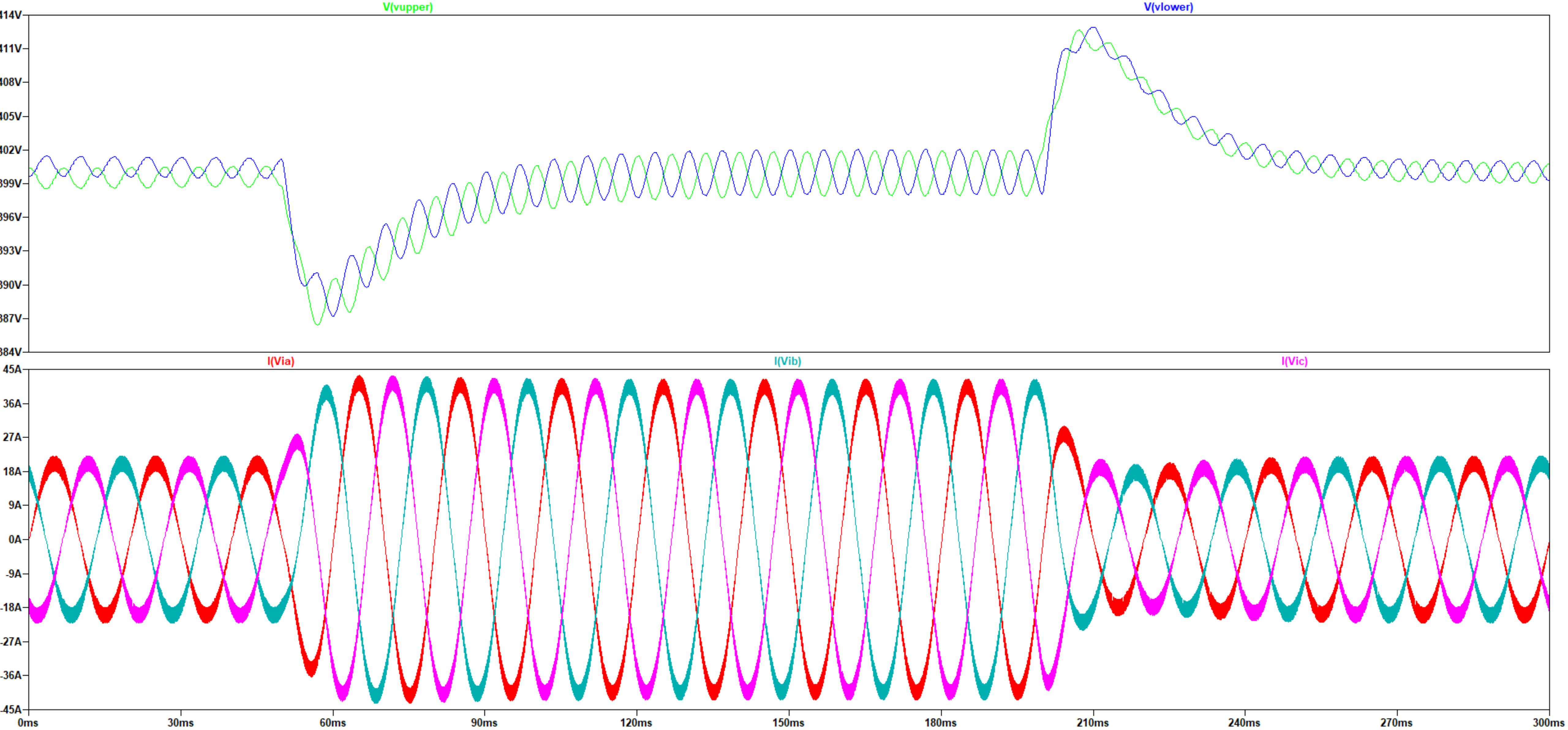
```
*
.param Vout=800
.param Pout=10k ; nominal is 5 kW
.param RL={(Vout/2)**2/(Pout/2)}
*
.param Gfc=24 ; magnitude at crossover *
.param PS=-85 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fc=40 ; targeted crossover *
.param PM=70 ; choose phase margin at crossover *
*
*
* Enter the Values for Vout and Bridge Bias Current *
*
.param Ibias=126u
.param Vref=2.5
*
* Do not edit the below lines *
*
.param gm=110u ; transconductance in Siemens *
.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 a={sqrt((fc**2/fp**2)+1)}
.param b={sqrt((fz**2/fc**2)+1)}
.param R2={(a/b)*(fp*G)*(Rlower+Rupper)/((fp-fz)*Rlower*gm)}
.param C1={1/(2*pi*R2*fz)}
.param C2={Rlower*gm*(b/a)/(2*pi*fp*G*(Rlower+Rupper))}
*
```

This is variable off-time PFC. Run an .op statement to see the values automated by the macro.

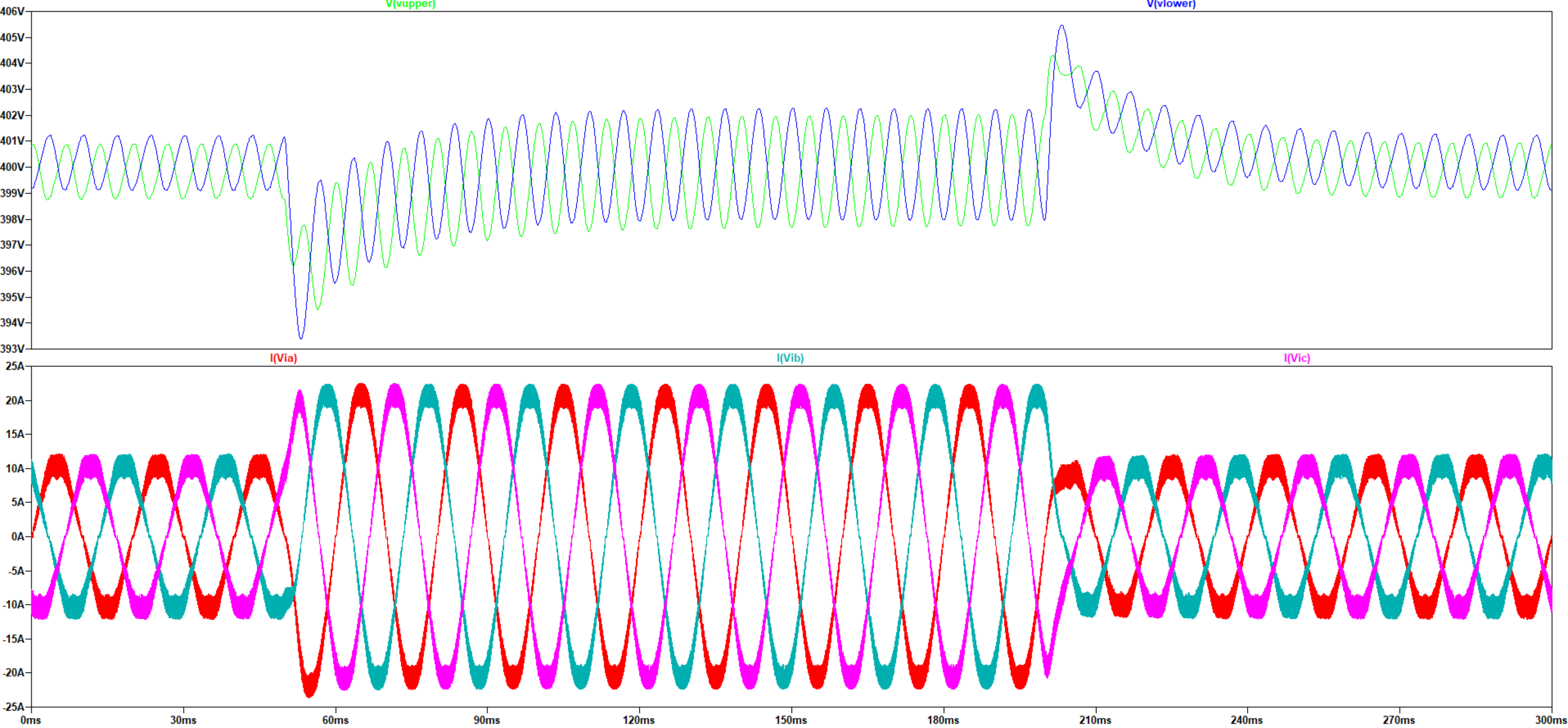
Christophe Basso - November 2024

The dc labels are the values of the components:
pV --> pF
nV --> nF
kV --> kOhms

This is the same circuit now equipped with two controlled switches on the output, toggling the load from 50 to 100% of its nominal value (5 kW to 10 kW).



V_{in} = 120 V rms, P_{out} stepped from 5 to 10 kW



V_{in} = 230 V rms, P_{out} stepped from 5 to 10 kW