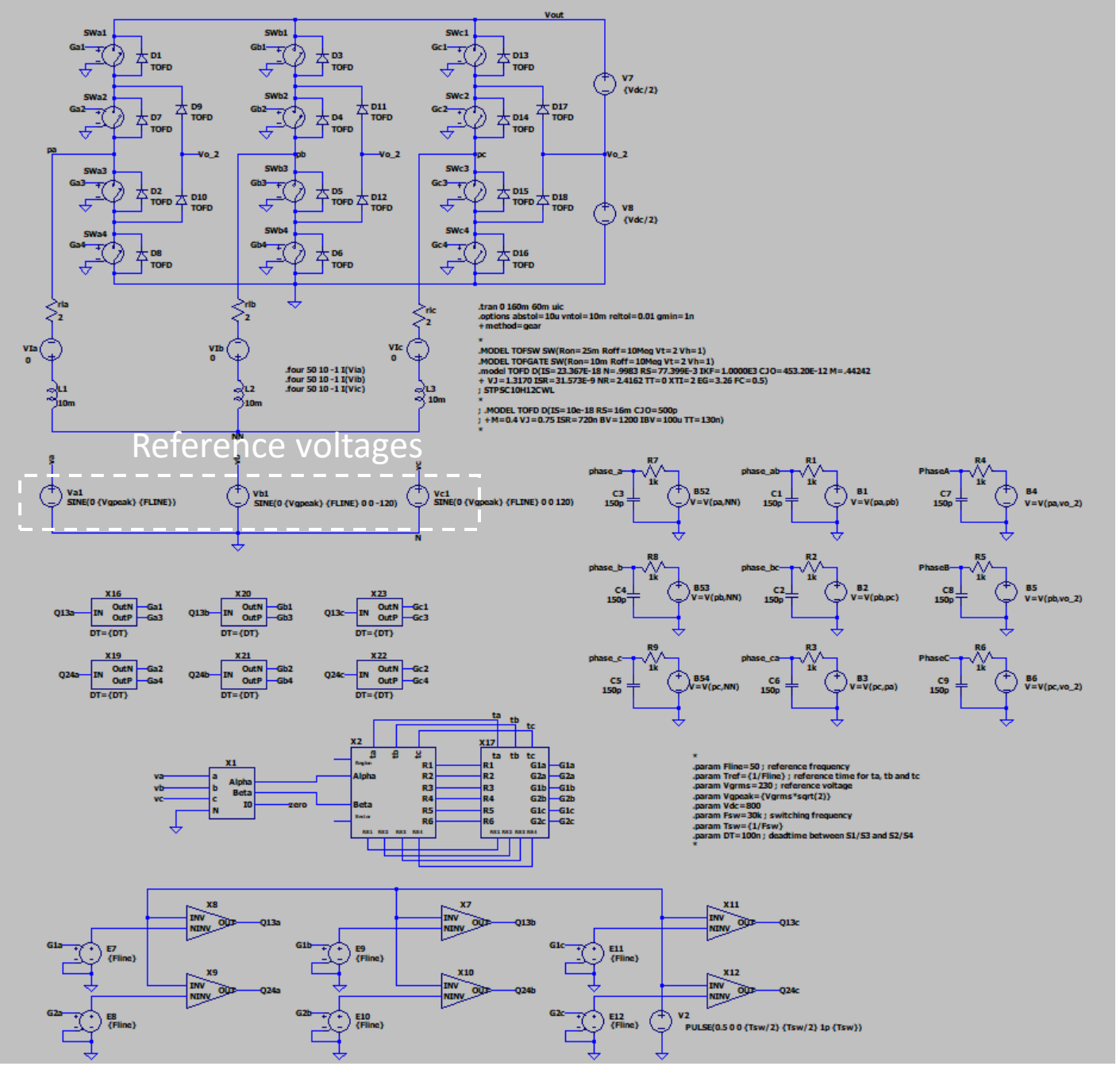
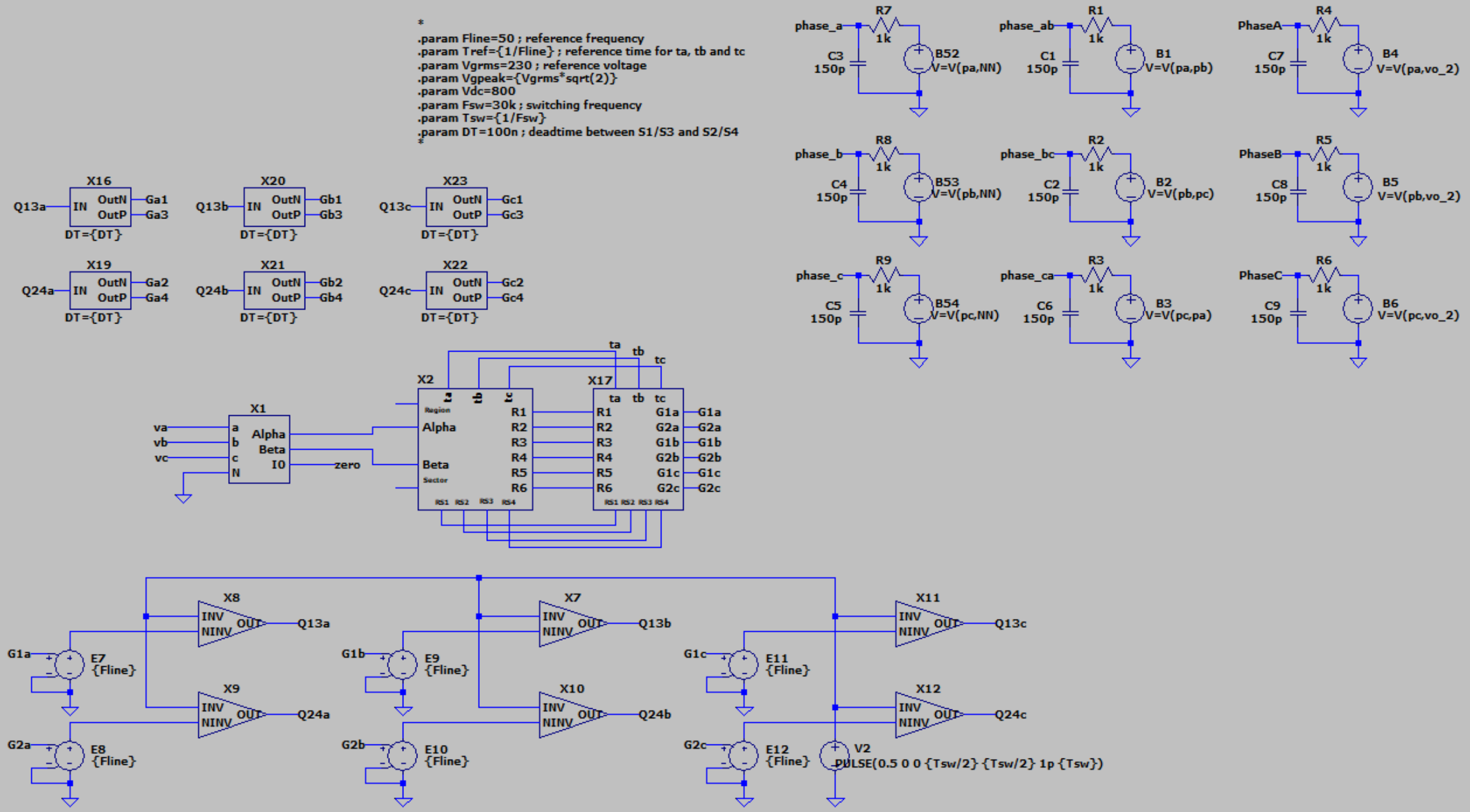


This is a typical 3-phase inverter as described by Ranit Sengupta in this video which is inspired from this IEEE paper, *Design and Implementation of Three-Level Space Vector PWM IP Core for FPGAs*. The reference voltages are set to 230 V rms at a 50-Hz frequency. The inverter's switching frequency is 30 kHz and the dc rail is 800 V. A 100-ns deadtime is inserted between the complimentary switches, S_1-S_3 and S_2-S_4.

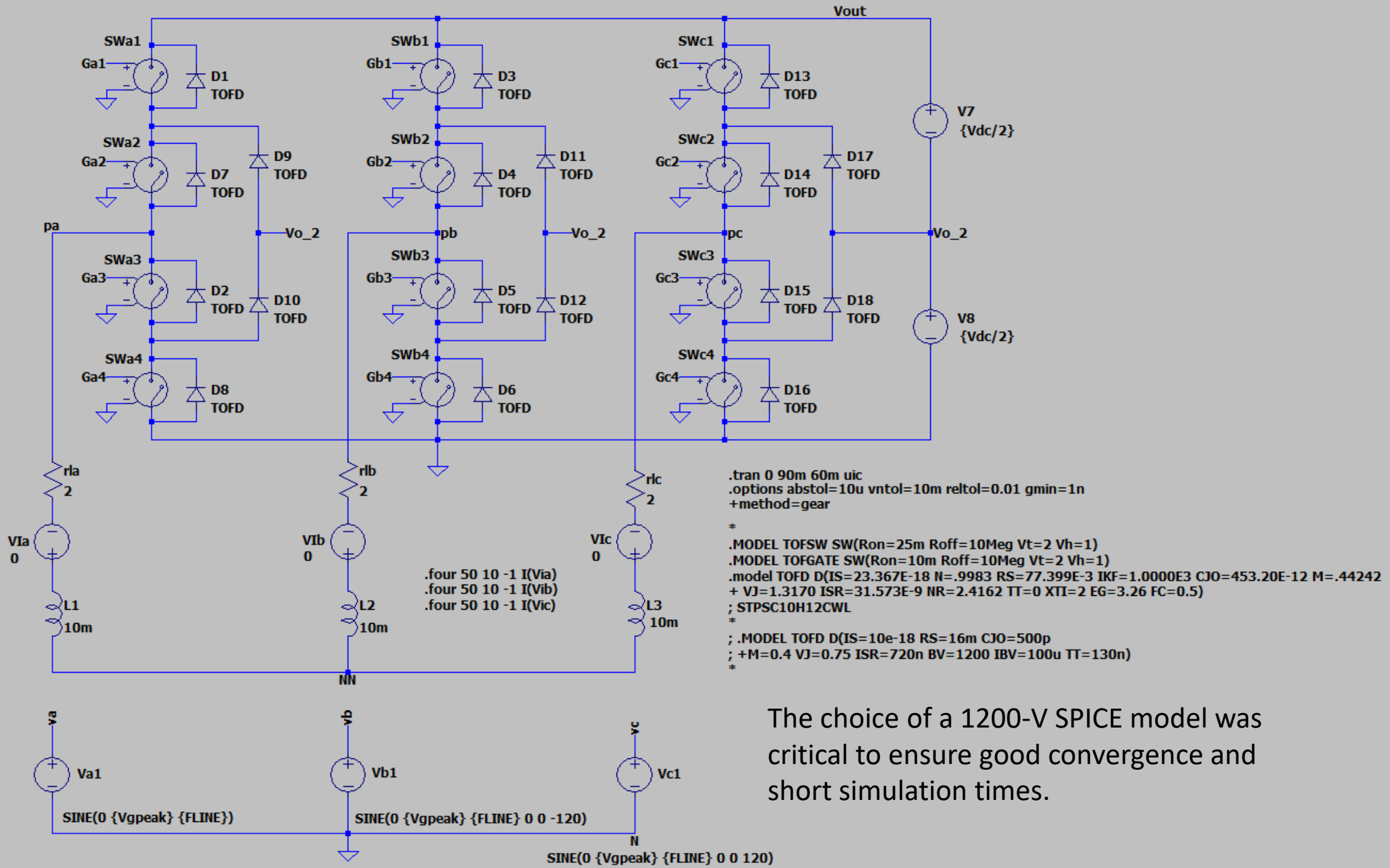
This left-side schematic is an open-loop version of an inverter (there is no control of power) where the phase currents are not monitored. Three ac sources impose the modulating waveforms to the circuit.

Christophe Basso – March 2025

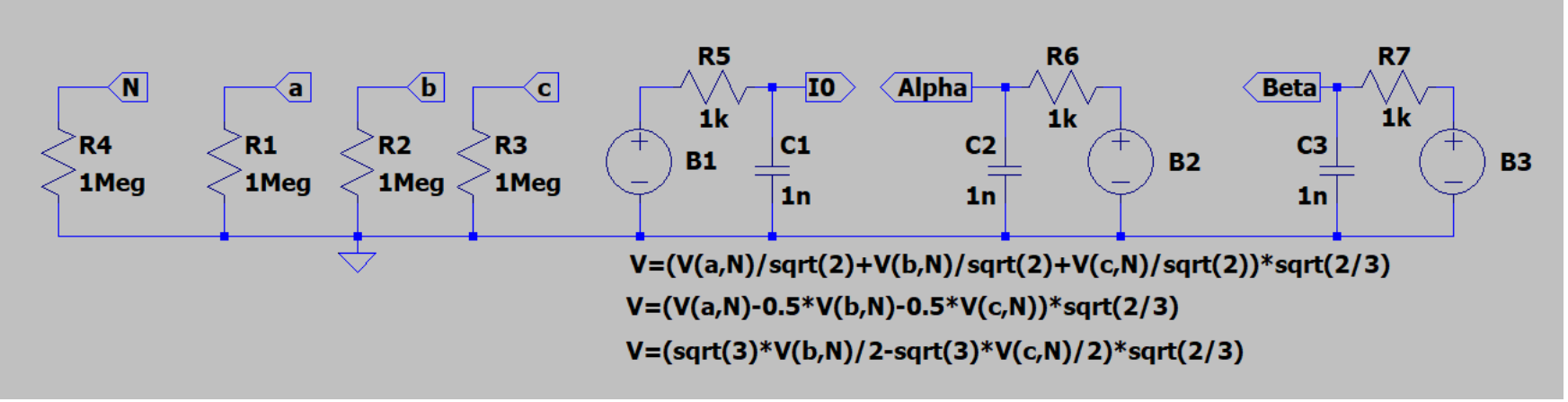
Haibing Hu, Wenxi Yao, Zhengyu Lu, *Design and Implementation of Three-Level Space Vector PWM IP Core for FPGAs*, in *IEEE Transactions on Power Electronics*, vol. 22, no. 6, pp. 2234-2244, Nov. 2007.

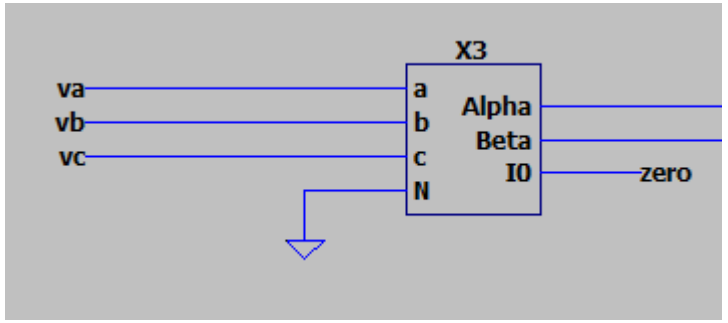


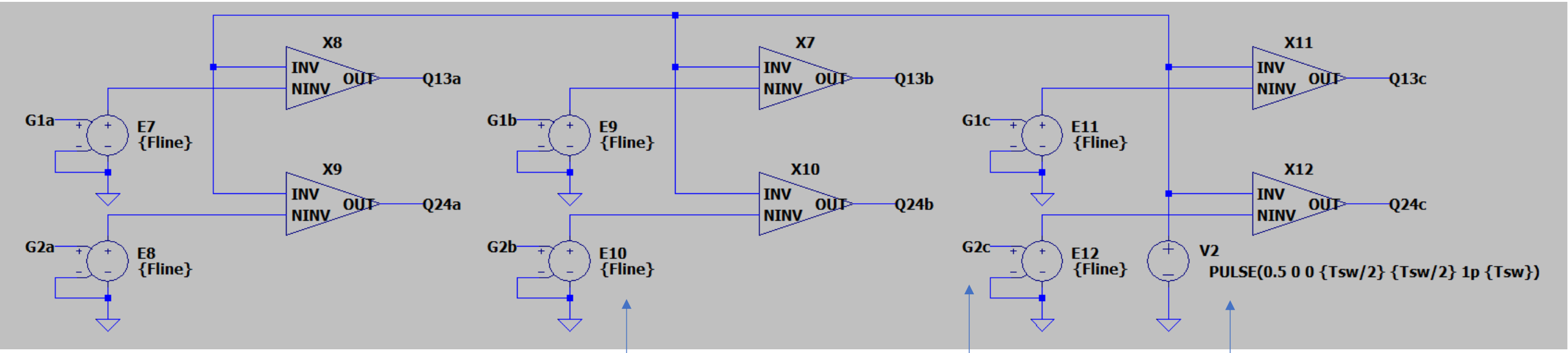
This is the modulation section with a 30-kHz 0.5-V triangular carrier authorizing 100% duty ratios.



The choice of a 1200-V SPICE model was critical to ensure good convergence and short simulation times.

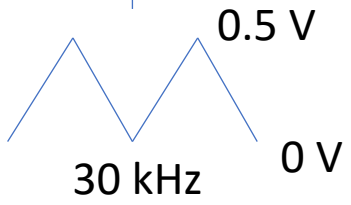


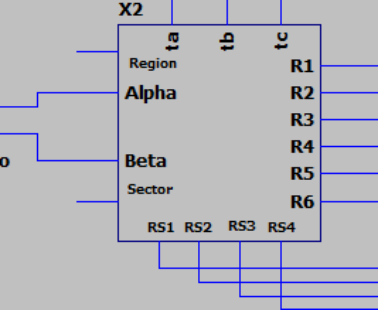


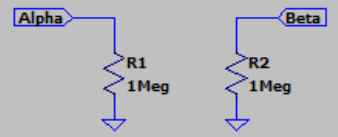


Gain to convert a time value of T_{sw} to 1 V (100% dc)

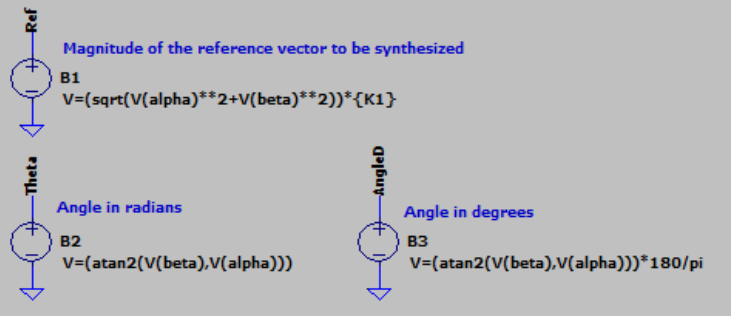
Voltage in mV

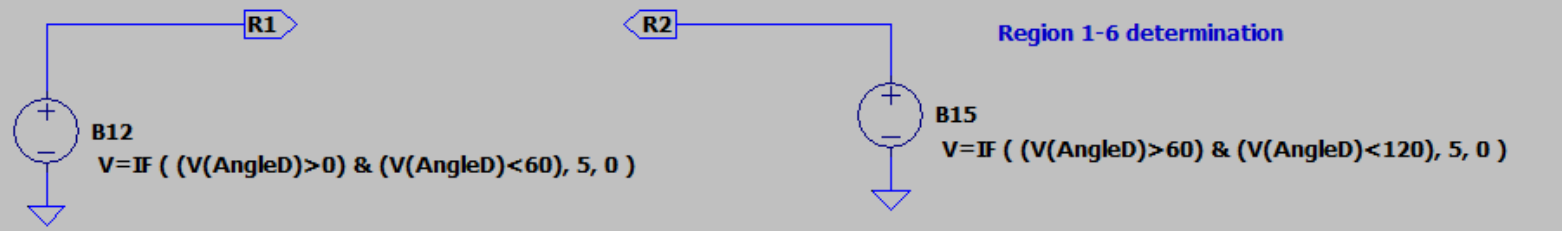




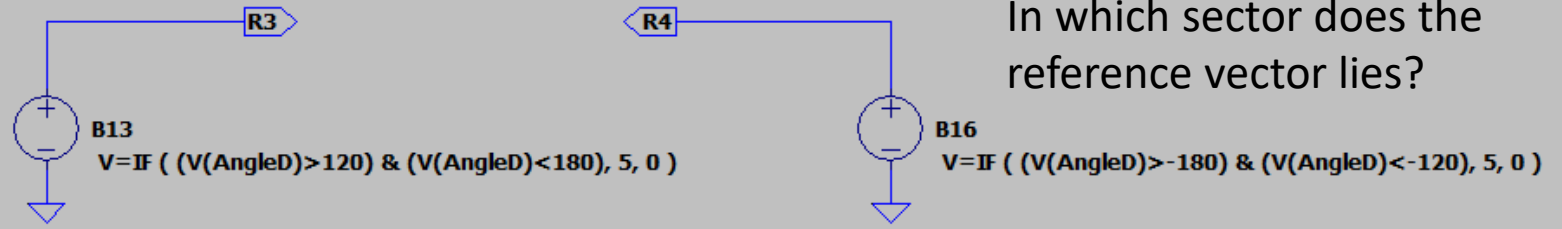


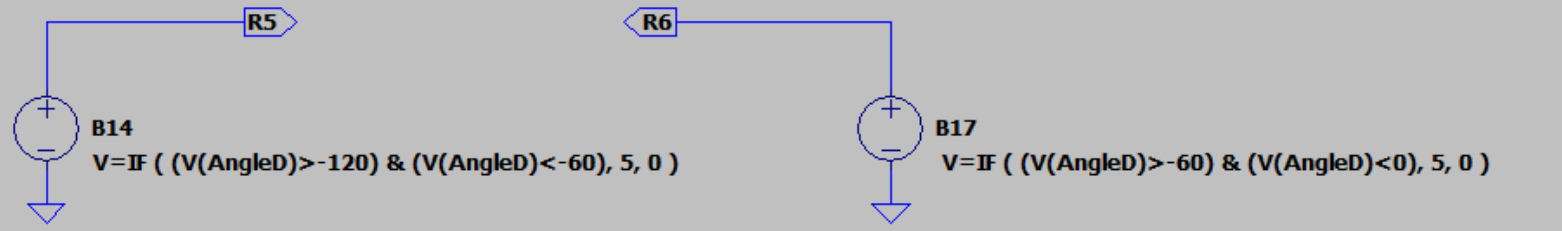
Magnitude and angle extraction

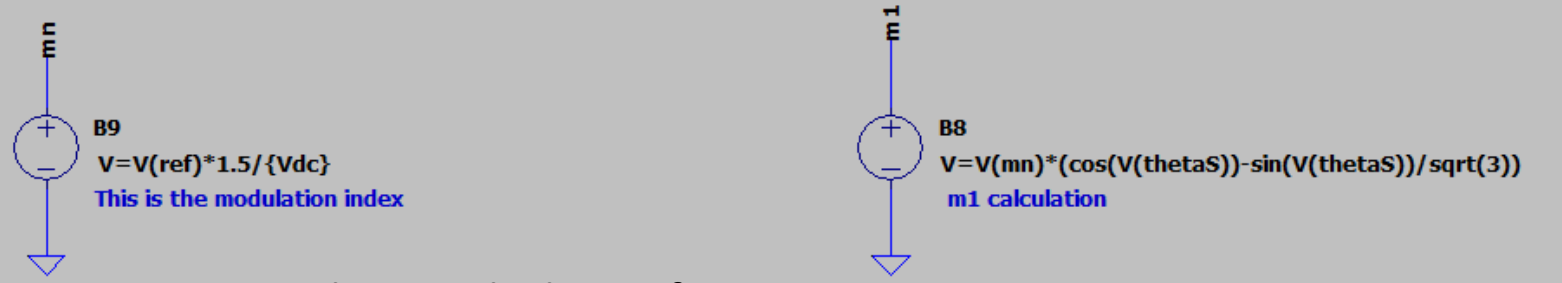




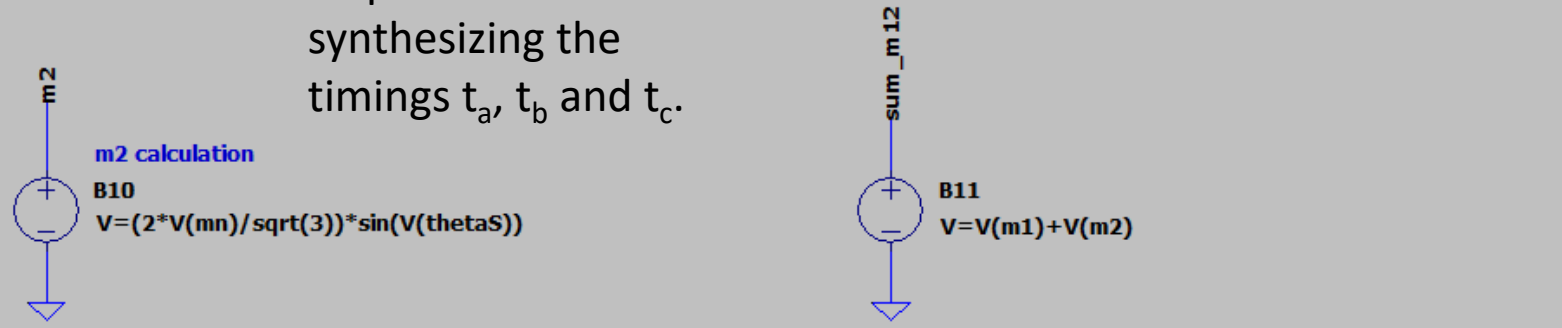
In which sector does the reference vector lies?



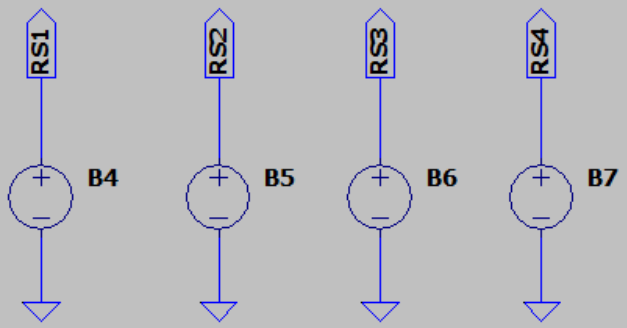




Slopes calculation for synthesizing the timings t_a, t_b and t_c.



Sub-region 1-4 determination



V=IF (V

V=If((V(m1)<0.5) & (V(m2)<0.5) & (V(sum_m12)<0.5), 5,0)

V=If((V(m1)<0.5) & (V(m2)<0.5) & (V(sum_m12)>0.5), 5,0)

V=If(V(m1)>0.5, 5,0)

V=If(V(m2)>0.5, 5,0)

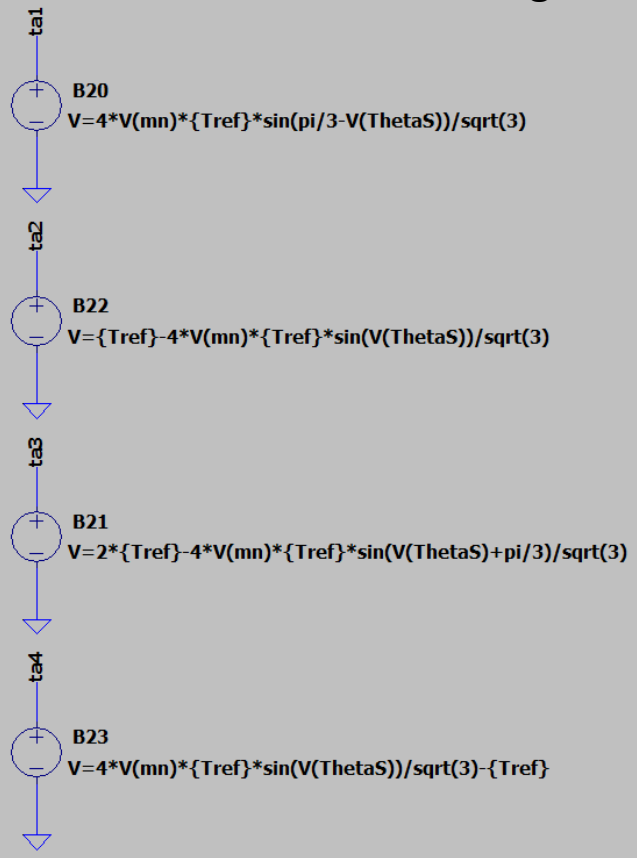
Angle relocation in sector I

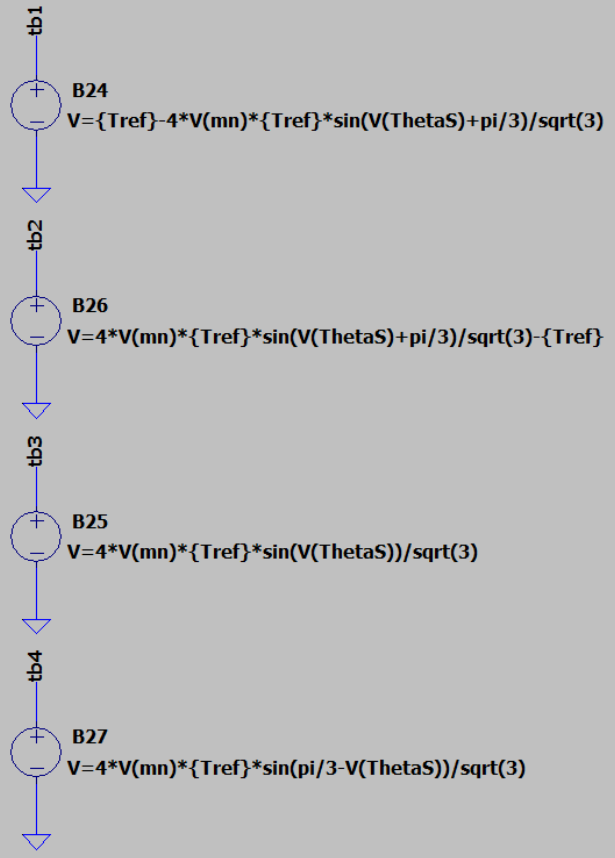
Brings any angle from the reference vector to an angle located in sector 1 - from 0 to 60° or 0 to pi/3

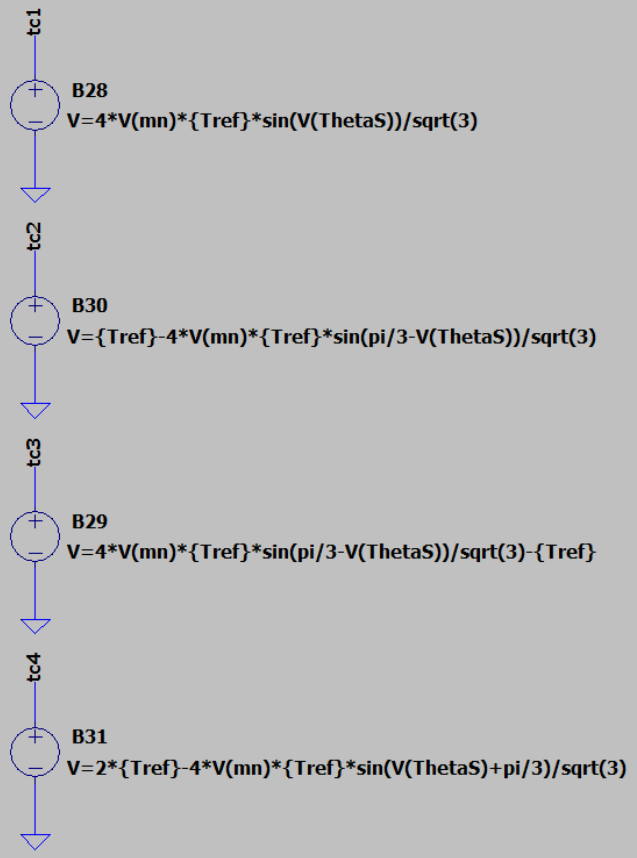
B18

V=If (V(R2)>2.5,V(theta)-pi/3, if (V(R3)>2.5,V(theta)-2*pi/3, If (V(R4)>2.5,V(theta)+pi, If (V(R5)>2.5,V(theta)+2*pi/3 , if (V(R6)>2.55,V(theta)+pi/3, V(theta))))))

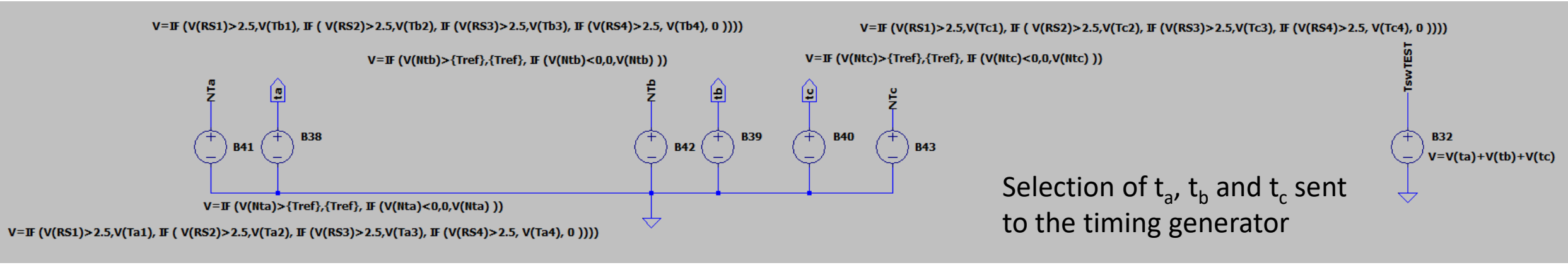
All calculations are done in sector 1, sub-triangles 1 to 4.
Depending where the reference vector lies, the angle is always brought back into sector 1 by adding or subtracting n x 60°



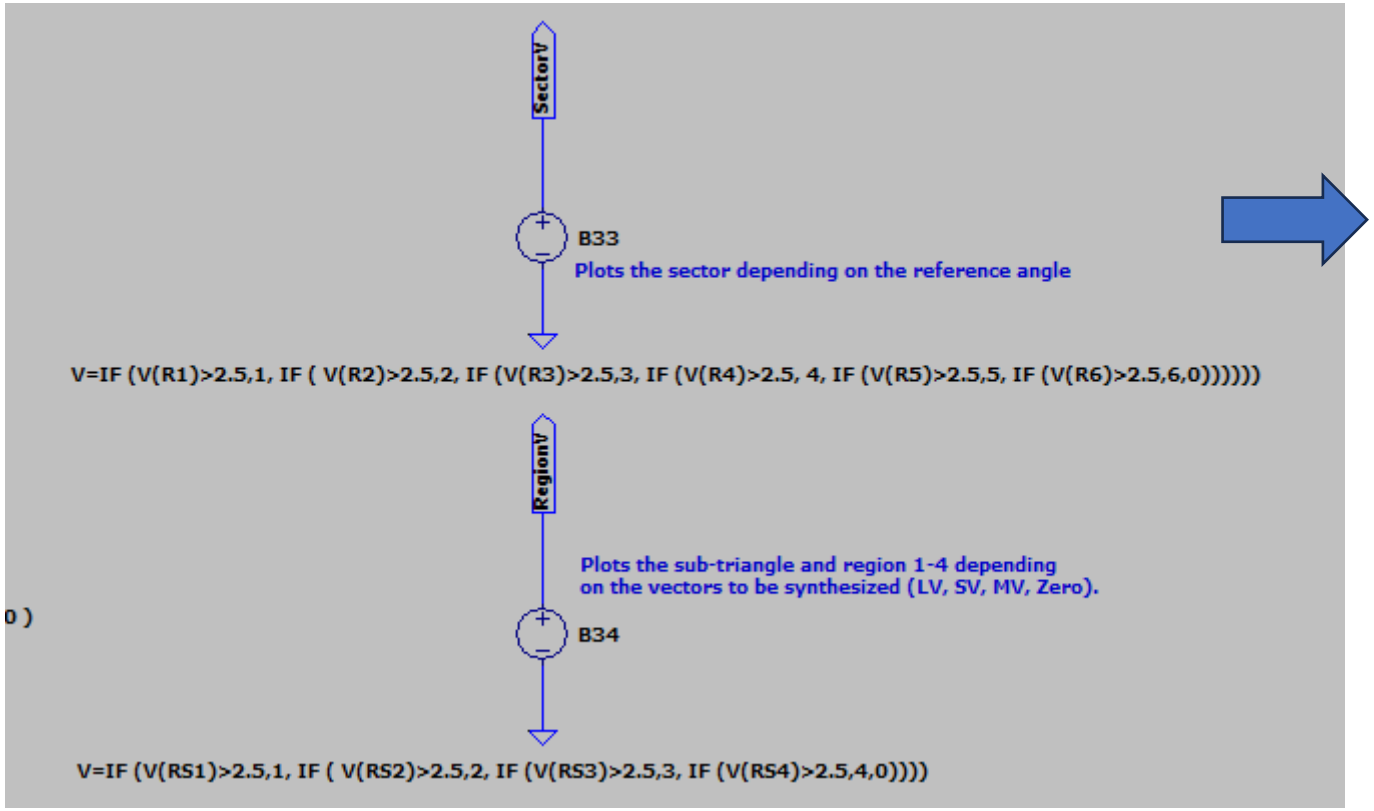


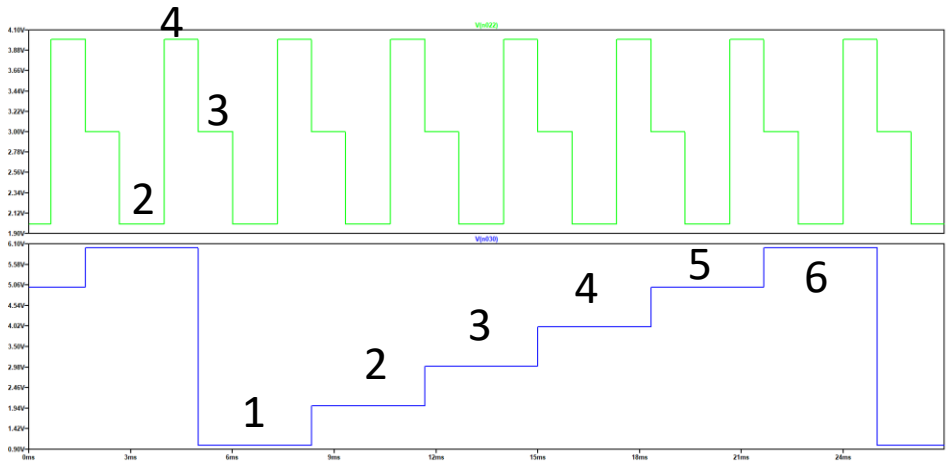


Time table calculation for t_a, t_b and t_c depending on the active sub-triangle 1-4 or region.
In this circuit, T_{ref} is the 20-ms of the input reference voltage (50 Hz).

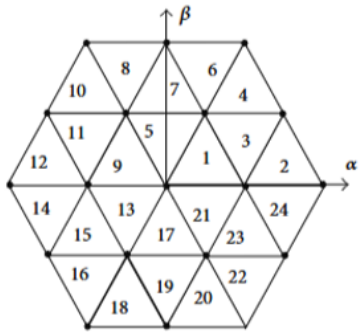


Selection of t_a, t_b and t_c sent to the timing generator



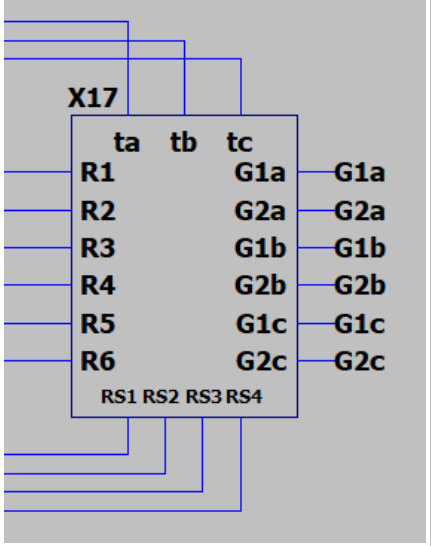


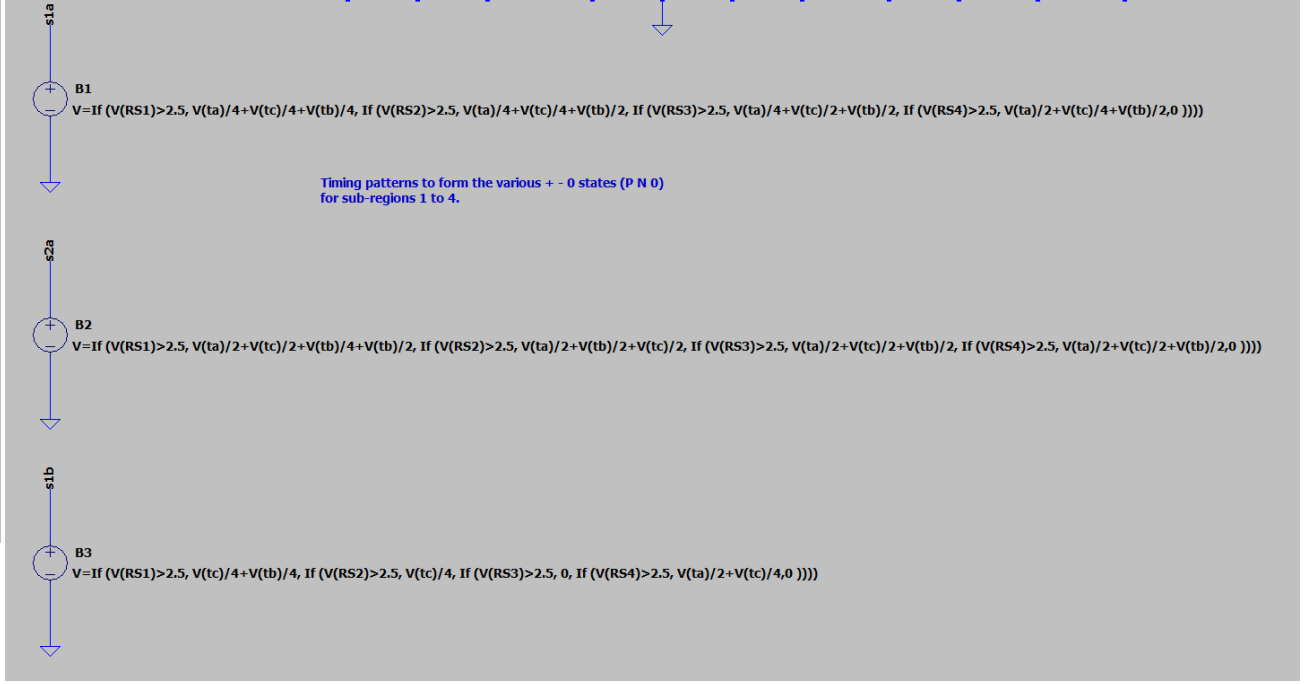
Sectors and region waveforms



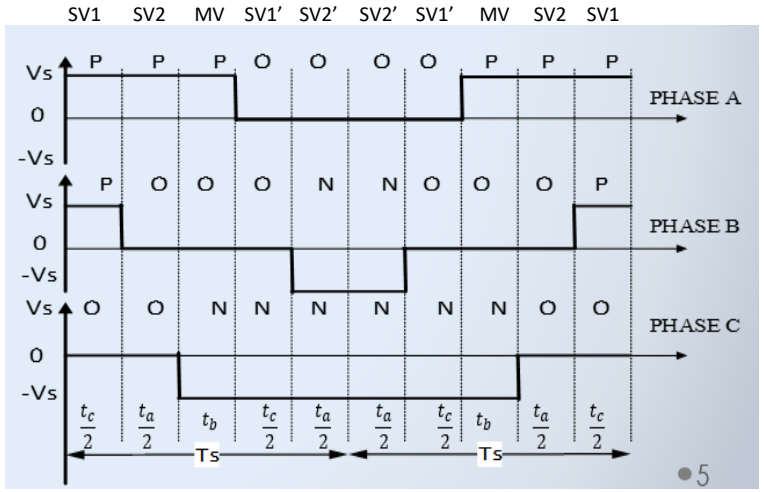
For a modulation index m < 0.75, the reference vector crosses sub-triangles 1, 5, 9, 13, 17 and 21.

If 0.75 < m < 1.15, the remaining triangles are crossed, 2, 3, 4, 6, 7, 8, 10, 11, 12, 14, 15, 16, 18, 19, 20, 22, 23 and 24.





I noticed that the switching pattern adopted by Ranit Sengupta is half of the duration described in the paper, keeping identical switching sequences though. I did not investigate the reason and effects further.



These are the generators providing the switching states for forming the above pattern in sub-triangle 2 for example.

SV1 SV2 MV SV1' SV2'

Region 2: PPO-POO-PON-OON-ONN

Symbol	Switching States				Terminal Voltage
	S1	S2	S3	S4	
P	ON	ON	OFF	OFF	Vs/2
O	OFF	ON	ON	OFF	0
N	OFF	OFF	ON	ON	-Vs/2

PPT from Ranit Sengupta

G1a

B7
V=If (V(R1)>2.5, V(S1a), IF (V(R2)>2.5, {Tsw}/2-V(s2b), IF (V(R3)>2.5, V(s1c), IF (V(R4)>2.5, {Tsw}/2-V(s2a), IF (V(R5)>2.5, V(S1b), IF (V(R6)>2.5, {Tsw}/2-V(s2c),0))))))

G2a

B8
V=If (V(R1)>2.5, V(S2a), IF (V(R2)>2.5, {Tsw}/2-V(s1b), IF (V(R3)>2.5, V(s2c), IF (V(R4)>2.5, {Tsw}/2-V(s1a), IF (V(R5)>2.5, V(S2b), IF (V(R6)>2.5, {Tsw}/2-V(s1c),0))))))

G1b

B9
V=If (V(R1)>2.5, V(S1b), IF (V(R2)>2.5, {Tsw}/2-V(s2c), IF (V(R3)>2.5, V(s1a), IF (V(R4)>2.5, {Tsw}/2-V(s2b), IF (V(R5)>2.5, V(S1c), IF (V(R6)>2.5, {Tsw}/2-V(s2a),0))))))

G2b

B10
V=If (V(R1)>2.5, V(S2b), IF (V(R2)>2.5, {Tsw}/2-V(s1c), IF (V(R3)>2.5, V(s2a), IF (V(R4)>2.5, {Tsw}/2-V(s1b), IF (V(R5)>2.5, V(S2c), IF (V(R6)>2.5, {Tsw}/2-V(s1a),0))))))

G1c

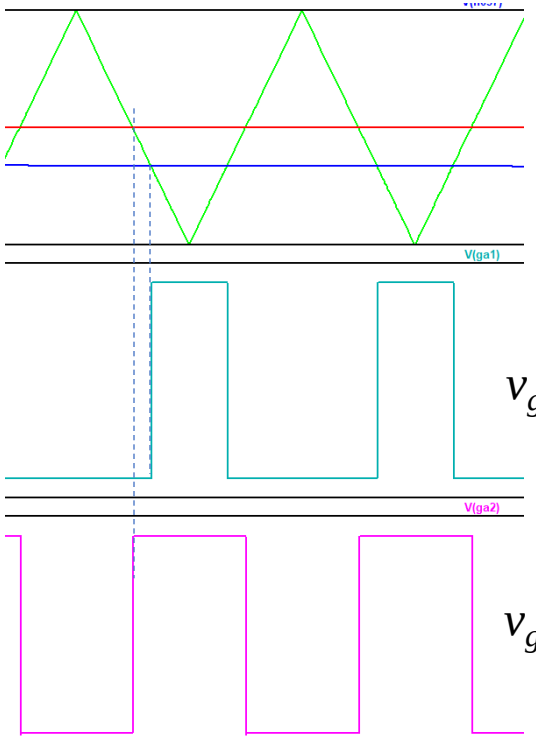
B11
V=If (V(R1)>2.5, V(S1c), IF (V(R2)>2.5, {Tsw}/2-V(s2a), IF (V(R3)>2.5, V(s1b), IF (V(R4)>2.5, {Tsw}/2-V(s2c), IF (V(R5)>2.5, V(S1a), IF (V(R6)>2.5, {Tsw}/2-V(s2b),0))))))

G2c

B12
V=If (V(R1)>2.5, V(S2c), IF (V(R2)>2.5, {Tsw}/2-V(s1a), IF (V(R3)>2.5, V(s2b), IF (V(R4)>2.5, {Tsw}/2-V(s1c), IF (V(R5)>2.5, V(S2a), IF (V(R6)>2.5, {Tsw}/2-V(s1b),0))))))

These sources generate the voltages sent to the pulse-width modulator to actually determine each power switch duration for phase a (G1/2-a), phase b (G1/2-b) and phase c (G1/2-c).

Switch S_3 is complementary to S_1 with some deadtime, while S_4 is complementary to S_2, also with added deadtime.

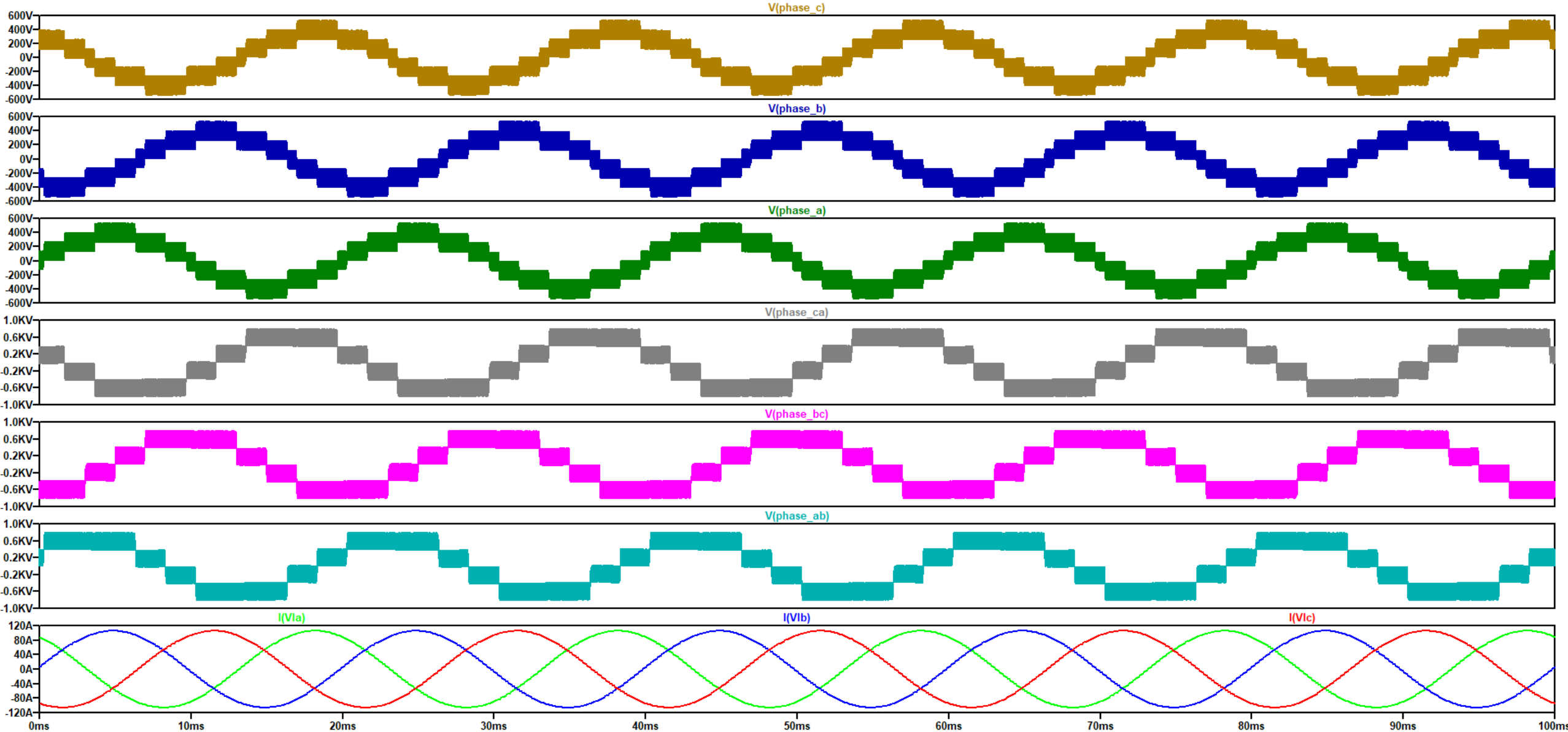


$v_{ga1}(t)$

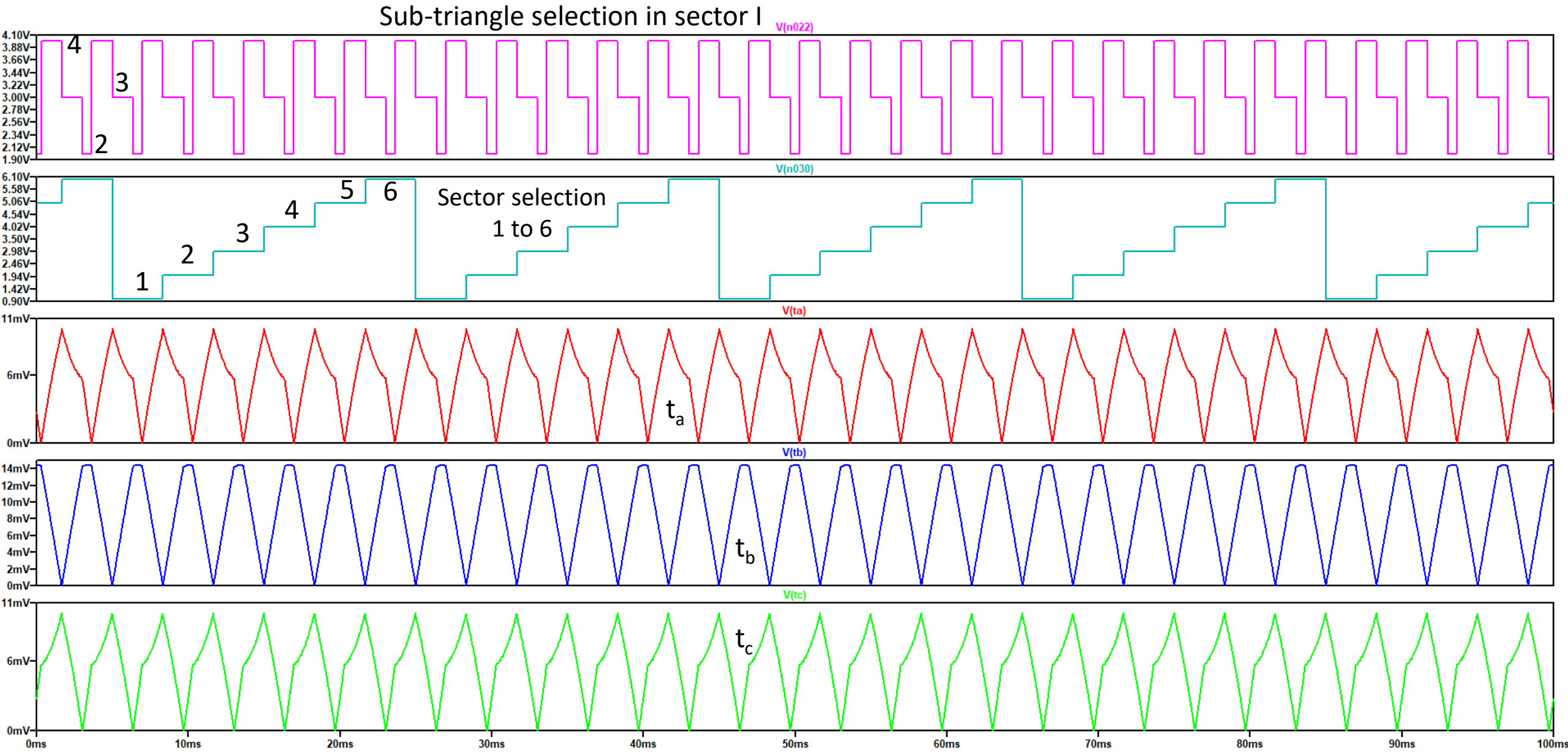
$v_{ga2}(t)$

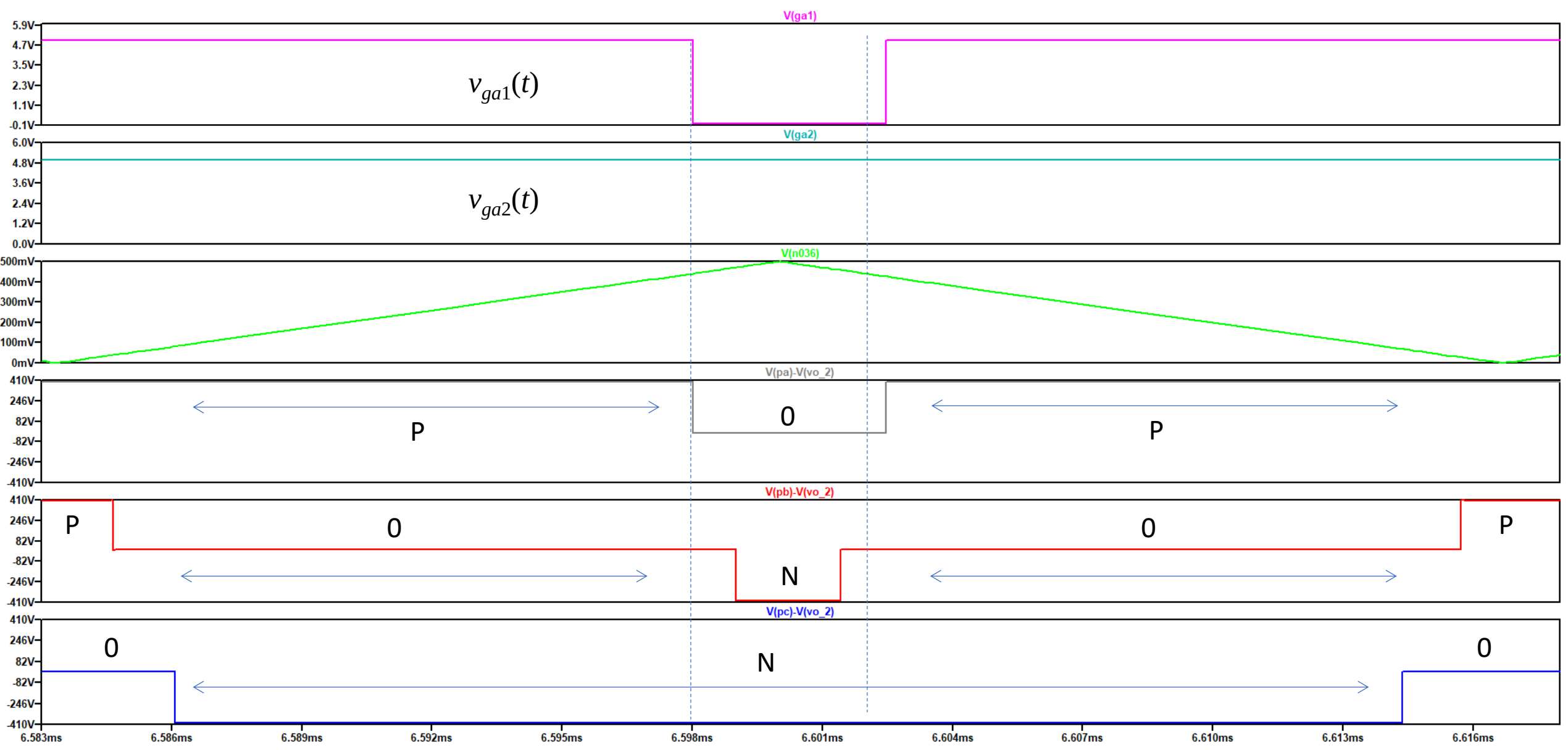
Typical switching signals

Simulation results for V_{dc} = 800 V, V_{ref} = 230 V rms, F_{sw} = 30 kHz

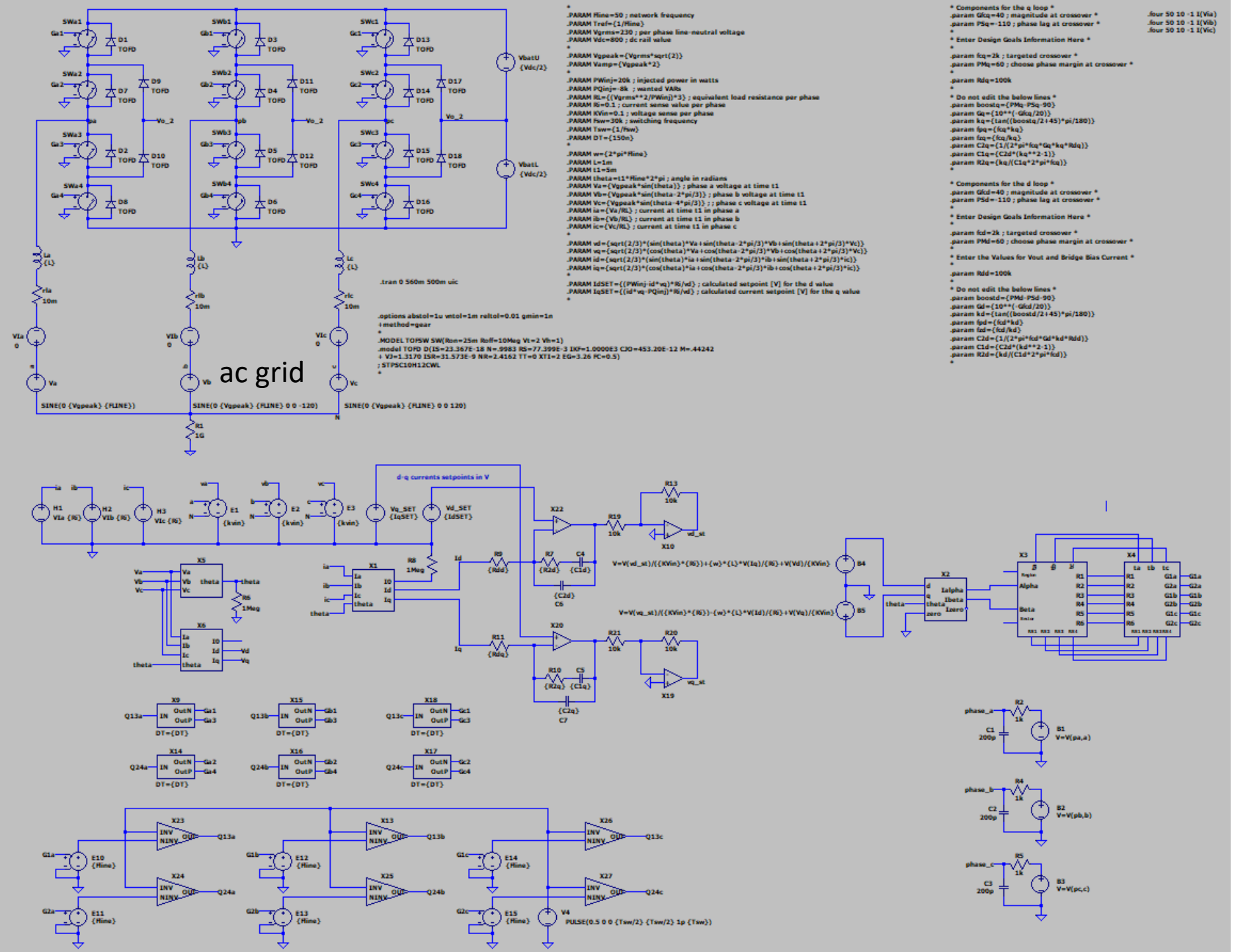


THD = 0.112%


Sub-triangle selection in sector I
V(n022)
4.10V
3.88V
3.66V
3.44V
3.22V
3.00V
2.78V
2.56V
2.34V
2.12V
1.90V
4
3
2
V(n030)
6.10V
5.58V
5.06V
4.54V
4.02V
3.50V
2.98V
2.46V
1.94V
1.42V
0.90V
1
2
3
4
5
6
Sector selection
1 to 6
V(ta)
11mV
6mV
0mV
t_a
V(tb)
14mV
12mV
10mV
8mV
6mV
4mV
2mV
0mV
t_b
V(tc)
11mV
6mV
0mV
t_c
0ms
10ms
20ms
30ms
40ms
50ms
60ms
70ms
80ms
90ms
100ms



These are the zoomed-in waveforms obtained for sector I and region/sub-triangle 2. They match what the diagram shows in the video and the paper.



This is the closed-loop version of the inverter where the input voltages and currents are monitored for regulation purposes. You choose the level of injected power in watts and the amount of reactive power you want, with polarity management (capacitive or inductive impedance). In this example, the circuit injects 20 kW with -8 kVARs of reactive power from a 400-V dc rail.

$V_{in} := 230V$ rms value $\quad F_{line} := 50Hz \quad R_i := 0.06\Omega \quad k_V := 0.1$

$t := 10\mu s, 20\mu s .. 40ms \quad T_{line} := \frac{1}{F_{line}}$

$P_W := 20kW$ total power $\quad P_Q := -8kW$ (in VARs) $\quad L_1 := 500\mu H$

$\omega := 2 \cdot \pi \cdot F_{line}$ Load resistance per phase for a total of Pout

$tan\_phi := \frac{P_Q}{P_W} = -0.4$ tangent phi is positive, inductive absorption: current lags V
tangent phi is negative, capacitive absorption: current leads V

$v_a(t) := V_{in} \cdot \sqrt{2} \cdot \sin(\omega \cdot t)$

$v_b(t) := V_{in} \cdot \sqrt{2} \cdot \sin(\omega \cdot t - 120°)$

$v_c(t) := V_{in} \cdot \sqrt{2} \cdot \sin(\omega \cdot t + 120°)$

$S = V_{rms} \cdot I_{rms} = \sqrt{P_W^2 + P_Q^2}$ total apparent power per phase

$I_{rms} := \frac{\sqrt{P_W^2 + P_Q^2}}{3 \cdot V_{in}} = 31.218\,A$ rms current per phase

$R_L := \frac{V_{in}}{I_{rms}} = 7.367\,\Omega$ Equivalent ohmic value for rms current, inclusive of VARs. This value is either purely resistive (VAR = 0) or a combination of inductive or capacitive components added to a resistance.

$I_{peak} := I_{rms} \cdot \sqrt{2} = 44.149\,A$ Peak inductor current per phase

$P_W = V_{rms} \cdot I_{rms} \cdot \cos(\varphi)$ Power in W related to cos phi

$P_Q = V_{rms} \cdot I_{rms} \cdot \sin(\varphi)$ Power in VARs related to sin phi

Sinusoidal signals

$Phi = acos\left(\frac{\frac{P_W}{3}}{I_{rms} \cdot V_{in}}\right) \quad \varphi_1 := acos\left(\frac{P_W}{\sqrt{P_Q^2 + P_W^2}}\right) = 21.801 \cdot °$

$Phi = asin\left(\frac{\frac{P_Q}{3}}{I_{rms} \cdot V_{in}}\right) \quad \varphi_2 := asin\left(\frac{P_Q}{\sqrt{P_Q^2 + P_W^2}}\right) = -21.801 \cdot °$

$t_1 := 5ms$ sampling event

$v_a(t_1) = 325.269\,V$ instantaneous values at t1:

$v_b(t_1) = -162.635\,V$

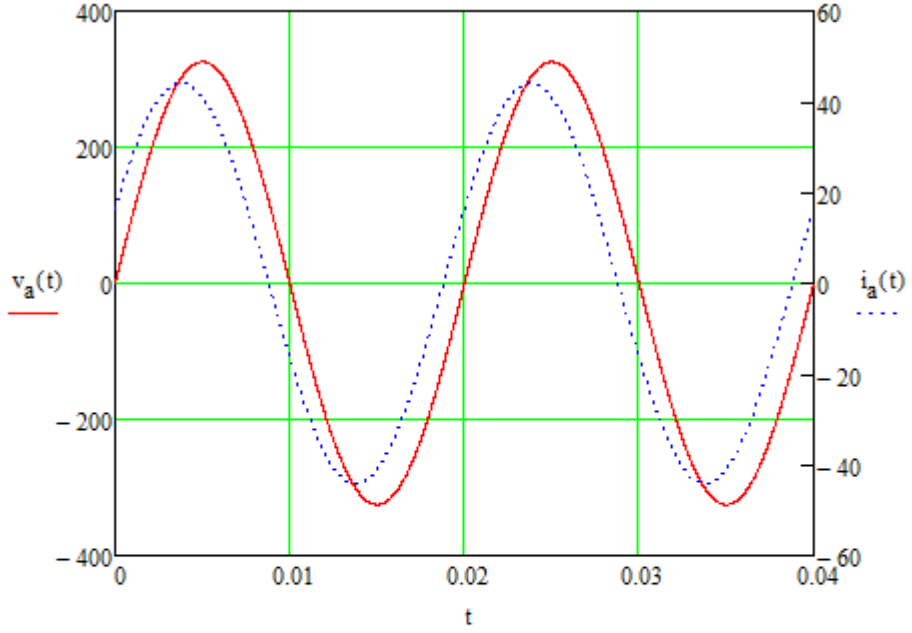
$v_c(t_1) = -162.635\,V$

$\phi_v := \frac{t_1}{T_{line}} \cdot 2 \cdot \pi = 90 \cdot °$ corresponding angle for time t1

$atan2(P_W, P_Q) = -21.801 \cdot °$ sanity check

$i_a(t) := \frac{V_{in} \cdot \sqrt{2} \cdot \sin(\omega \cdot t - \varphi_2)}{R_L} \quad i_b(t) := \frac{V_{in} \cdot \sqrt{2} \cdot \sin(\omega \cdot t - 120° - \varphi_2)}{R_L} \quad i_c(t) := \frac{V_{in} \cdot \sqrt{2} \cdot \sin(\omega \cdot t + 120° - \varphi_2)}{R_L}$

These calculations are necessary to verify that the programmed power levels in W or VARs with LTspice, match what is expected.



$$P_a := \frac{1}{T_{line}} \cdot \int_0^{T_{line}} v_a(t) \cdot i_a(t)\, dt = 6.667 \cdot kW$$ Watted pow

$$I_{aRMS} := \sqrt{\frac{1}{T_{line}} \cdot \int_0^{T_{line}} \left(i_a(t)\right)^2 dt} = 31.218\,A$$

$P_{Wtot} := P_a + P_b + P_c = 20 \cdot kW$ $S_{tot} := V_{in} \cdot I_{aRMS} + V_{in} \cdot I_{bRMS} + V_{in} \cdot I_{cRMS} = 21.541 \cdot kW$ (VAs)

$$x := \frac{V_{in} \cdot \sqrt{2} \cdot \sin(\omega \cdot 5ms)}{V_{in} \cdot \sqrt{2} \cdot \sin(\omega \cdot 5ms - \varphi_2)} = 1.077$$

$$k_Q := \begin{cases} -1 & \text{if } v_a(1\mu s) > 0 \wedge i_a(1\mu s) > 0 \\ 1 & \text{if } v_a(1\mu s) > 0 \wedge i_a(1\mu s) < 0 \end{cases}$$

$$5 \cdot \omega \cdot ms - \operatorname{asin}\left(\frac{1}{x} \cdot \sin(5 \cdot \omega \cdot ms)\right) = 21.801 \cdot °$$

$k_Q = -1$

$PQtot := k_Q \cdot \sqrt{S_{tot}^{\,2} - P_{Wtot}^{\,2}} = -8 \cdot kW$ (VARs)

with q-axis alignment with alpha axis:

$$v_d := \sqrt{\frac{2}{3}} \cdot \left(\sin(\phi_v) \cdot v_a(t_1) + \sin\left(\phi_v - \frac{2 \cdot \pi}{3}\right) \cdot v_b(t_1) + \sin\left(\phi_v + \frac{2 \cdot \pi}{3}\right) \cdot v_c(t_1)\right) = 398.372\,V$$

$$v_q := \sqrt{\frac{2}{3}} \cdot \left(\cos(\phi_v) \cdot v_a(t_1) + \cos\left(\phi_v - \frac{2 \cdot \pi}{3}\right) \cdot v_b(t_1) + \cos\left(\phi_v + \frac{2 \cdot \pi}{3}\right) \cdot v_c(t_1)\right) = 0\,V$$

$$i_d := \sqrt{\frac{2}{3}} \cdot \left(\sin(\phi_v) \cdot i_a(t_1) + \sin\left(\phi_v - \frac{2 \cdot \pi}{3}\right) \cdot i_b(t_1) + \sin\left(\phi_v + \frac{2 \cdot \pi}{3}\right) \cdot i_c(t_1)\right) = 50.204\,A$$

$$i_q := \sqrt{\frac{2}{3}} \cdot \left(\cos(\phi_v) \cdot i_a(t_1) + \cos\left(\phi_v - \frac{2 \cdot \pi}{3}\right) \cdot i_b(t_1) + \cos\left(\phi_v + \frac{2 \cdot \pi}{3}\right) \cdot i_c(t_1)\right) = 20.082\,A$$

$v_d \cdot i_d + v_q \cdot i_q = 20 \cdot kW$ active power

$v_q \cdot i_d - v_d \cdot i_q = -8 \cdot kW$ VARs

$v_d \cdot i_d + v_q \cdot i_q = PW_{inj}$

$v_q \cdot i_d - v_d \cdot i_q = PQinj$

$$i_{dSET} := \frac{P_W - i_q \cdot v_q}{v_d} = 50.204\,A$$

$$i_{qSET} := \frac{i_d \cdot v_q - P_Q}{v_d} = 20.082\,A$$

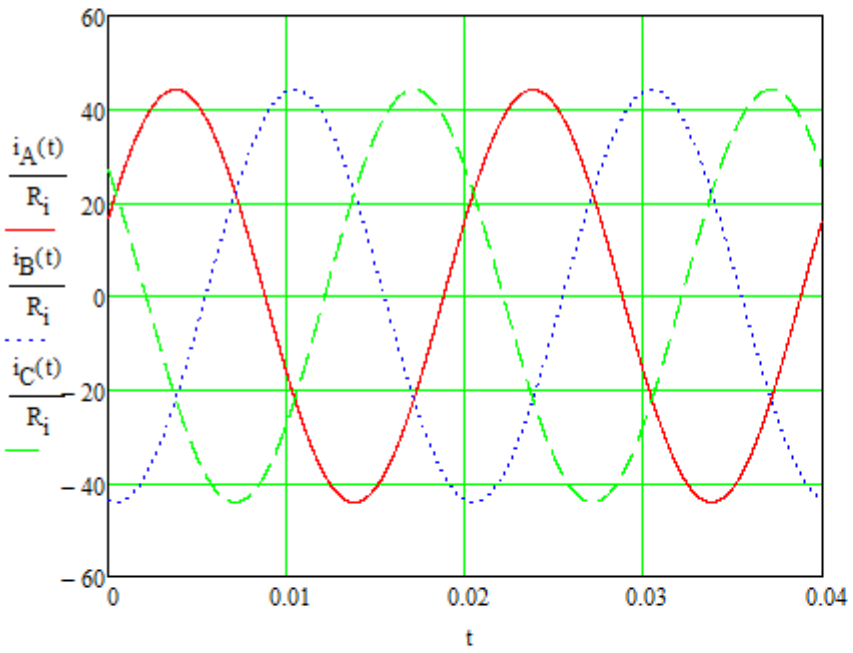
$i_0 := 0A$

$$i_A(t) := \sqrt{\frac{2}{3}} \cdot \left(\sin(\theta(t)) \cdot i_{dSET\_V} + \cos(\theta(t)) \cdot i_{qSET\_V} + \frac{1}{\sqrt{2}} \cdot i_0 \right)$$

$$i_B(t) := \sqrt{\frac{2}{3}} \cdot \left(\sin\left(\theta(t) - \frac{2 \cdot \pi}{3}\right) \cdot i_{dSET\_V} + \cos\left(\theta(t) - \frac{2 \cdot \pi}{3}\right) \cdot i_{qSET\_V} + \frac{1}{\sqrt{2}} \cdot i_0 \right)$$

$$i_C(t) := \sqrt{\frac{2}{3}} \cdot \left(\sin\left(\theta(t) + \frac{2 \cdot \pi}{3}\right) \cdot i_{dSET\_V} + \cos\left(\theta(t) + \frac{2 \cdot \pi}{3}\right) \cdot i_{qSET\_V} + \frac{1}{\sqrt{2}} \cdot i_0 \right)$$

Reconstructed input currents:



$$I_{A\_RMS} := \frac{\sqrt{\frac{1}{T_{line}} \cdot \int_0^{T_{line}} (i_A(t))^2 \, dt}}{R_i} = 31.218\,A$$

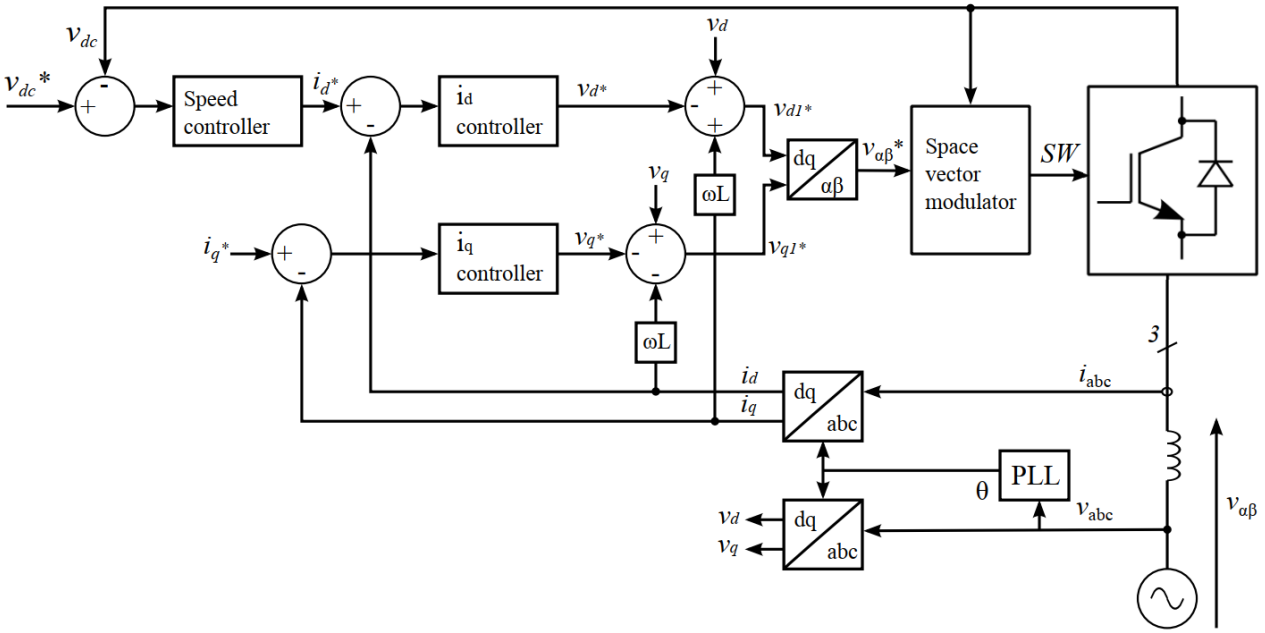
$$I_{B\_RMS} := \frac{\sqrt{\frac{1}{T_{line}} \cdot \int_0^{T_{line}} (i_B(t))^2 \, dt}}{R_i} = 31.218\,A$$

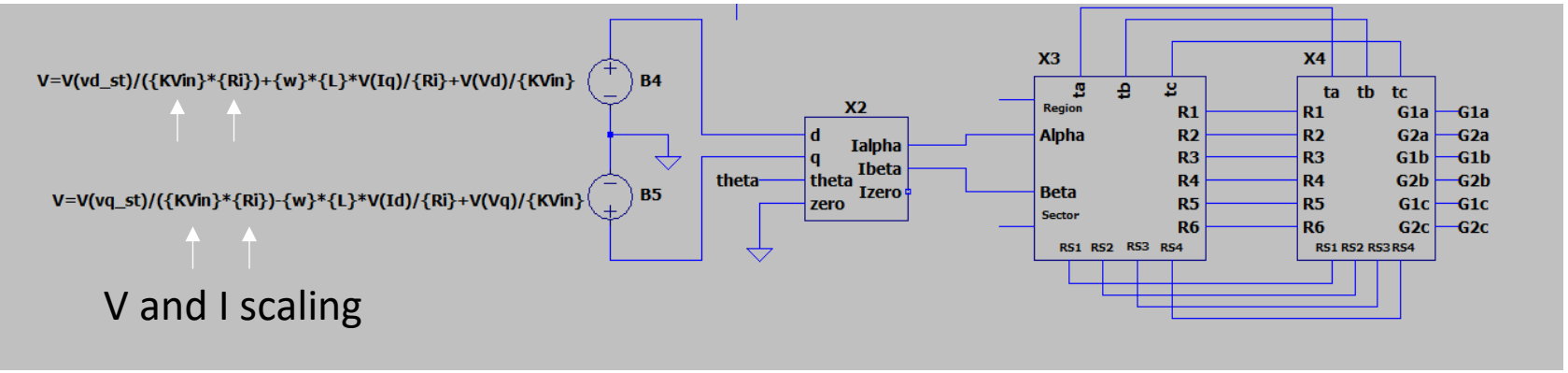
$$I_{C\_RMS} := \frac{\sqrt{\frac{1}{T_{line}} \cdot \int_0^{T_{line}} (i_C(t))^2 \, dt}}{R_i} = 31.218\,A$$

$$v_d \cdot \frac{i_{dSET\_V}}{R_i} + v_q \cdot \frac{i_{qSET\_V}}{R_i} = 20 \cdot kW \quad \text{active power}$$

$$v_q \cdot \frac{i_{dSET\_V}}{R_i} - v_d \cdot \frac{i_{qSET\_V}}{R_i} = -8 \cdot kW \quad \text{VARs}$$

Currents and power reconstruction after the dq transform.





Scaling

```
*
.PARAM Fline=50 ; network frequency
.PARAM Tref={1/Fline}
.PARAM Vgrms=110 ; per phase line-neutral voltage
.PARAM Vdc=400 ; dc rail value
*
.PARAM Vgpeak={Vgrms*sqrt(2)}
.PARAM Vamp={Vgpeak*2}
*
.PARAM PWinj=20k ; injected power in watts
.PARAM PQinj=-8k  ; wanted VARs
.PARAM RL={(Vgrms**2/PWinj)*3} ; equivalent load resistance per phase
.PARAM Ri=0.1 ; current sense value per phase
.PARAM KVin=0.1 ; voltage sense per phase
.PARAM Fsw=30k ; switching frequency
.PARAM Tsw={1/Fsw}
.PARAM DT={150n}
*
.PARAM w={2*pi*Fline}
.PARAM L=500u
.PARAM t1=5m
.PARAM theta=t1*Fline*2*pi ; angle in radians
.PARAM Va={Vgpeak*sin(theta)} ; phase a voltage at time t1
.PARAM Vb={Vgpeak*sin(theta-2*pi/3)} ; phase b voltage at time t1
.PARAM Vc={Vgpeak*sin(theta-4*pi/3)} ; ; phase c voltage at time t1
.PARAM ia={Va/RL} ; current at time t1 in phase a
.PARAM ib={Vb/RL} ; current at time t1 in phase b
.PARAM ic={Vc/RL} ; current at time t1 in phase c
*
.PARAM vd={sqrt(2/3)*(sin(theta)*Va+sin(theta-2*pi/3)*Vb+sin(theta+2*pi/3)*Vc)}
.PARAM vq={sqrt(2/3)*(cos(theta)*Va+cos(theta-2*pi/3)*Vb+cos(theta+2*pi/3)*Vc)}
.PARAM id={sqrt(2/3)*(sin(theta)*ia+sin(theta-2*pi/3)*ib+sin(theta+2*pi/3)*ic)}
.PARAM iq={sqrt(2/3)*(cos(theta)*ia+cos(theta-2*pi/3)*ib+cos(theta+2*pi/3)*ic)}
*
.PARAM IdSET={(PWinj-id*vq)*Ri/vd} ; calculated setpoint [V] for the d value
.PARAM IqSET={(id*vq-PQinj)*Ri/vd} ; calculated current setpoint [V] for the q value
*
```

Scaling

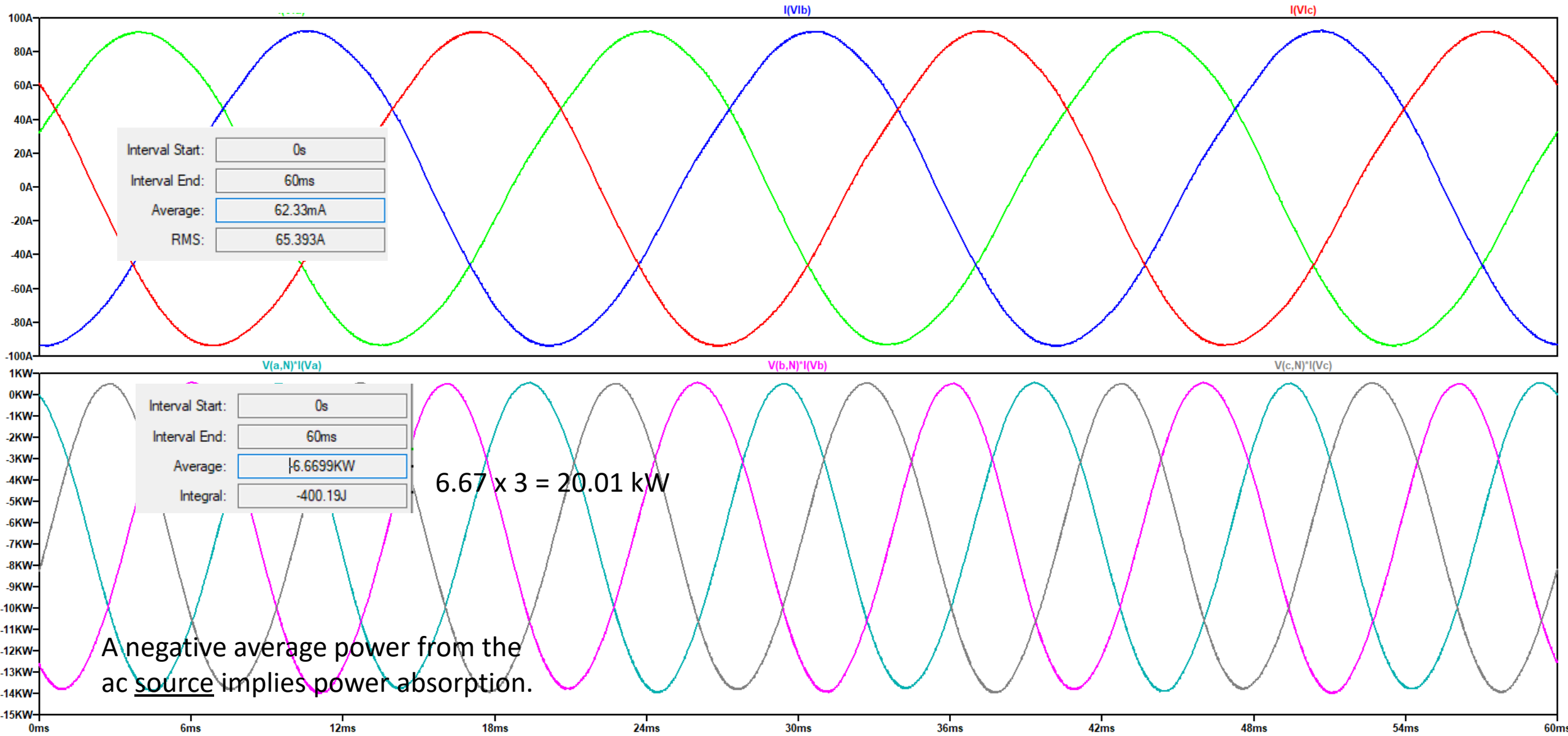
This is the control section for the closed-loop operation of this inverter as a PFC. Both d and q are decoupled with the ωL term. Scaling is important to limit the sensed signals on the current and voltage sides.

John Schönberger, *Space Vector Control of a Three-Phase Rectifier using PLECS®*, PLEXIM 2013

V_{in} = 110 V, P = 20 kW, Q = -8 kVARs, V_{dc} = 400 V, L = 500 µH, F_{sw} = 30 kHz

$$I_{rms} := \frac{\sqrt{P_W^{\,2} + P_Q^{\,2}}}{3 \cdot V_{in}} = 65.275\,A$$ rms current per phase

Partial Harmonic Distortion: 4.049236%
Total Harmonic Distortion: 4.068471%

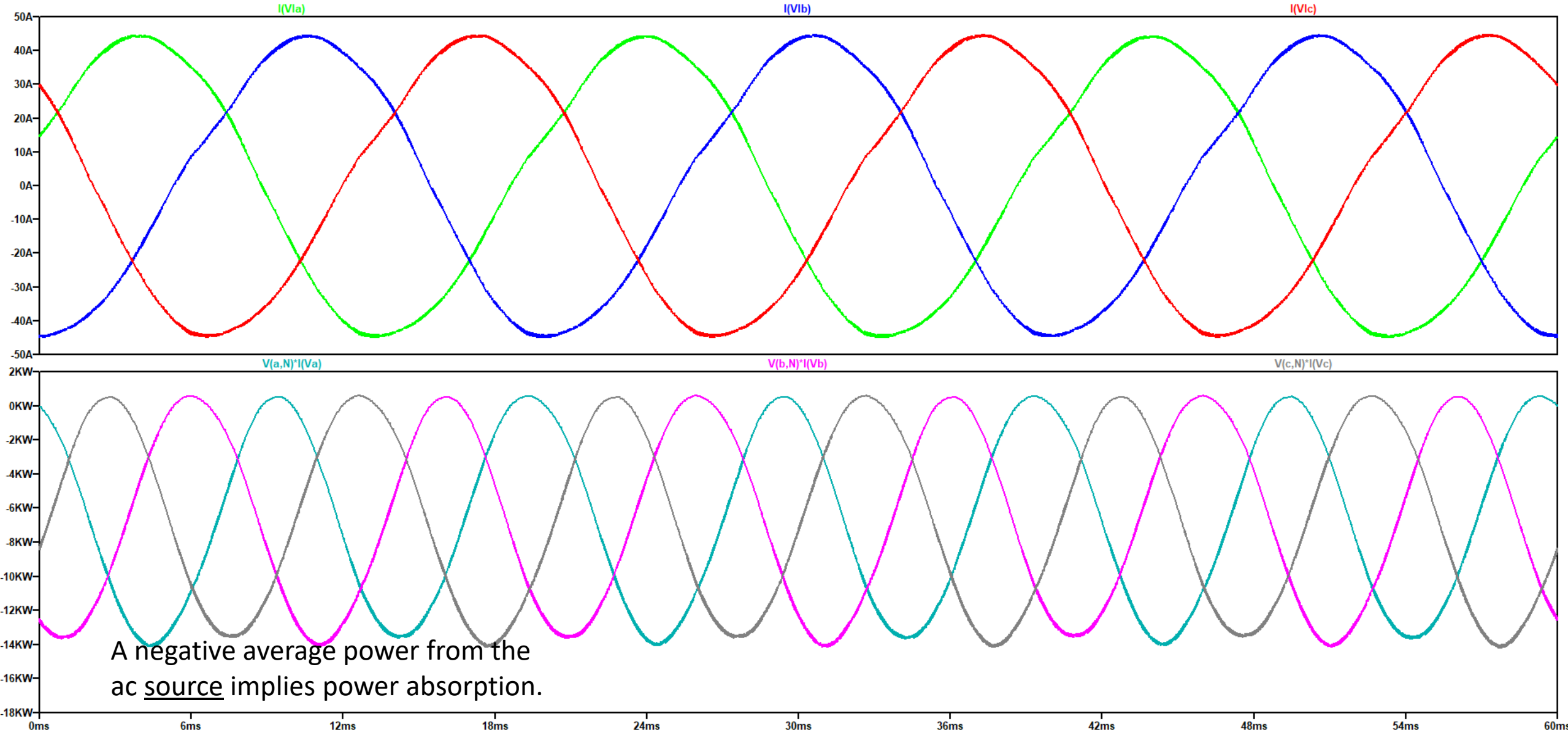


6.67 x 3 = 20.01 kW

A negative average power from the ac source implies power absorption.

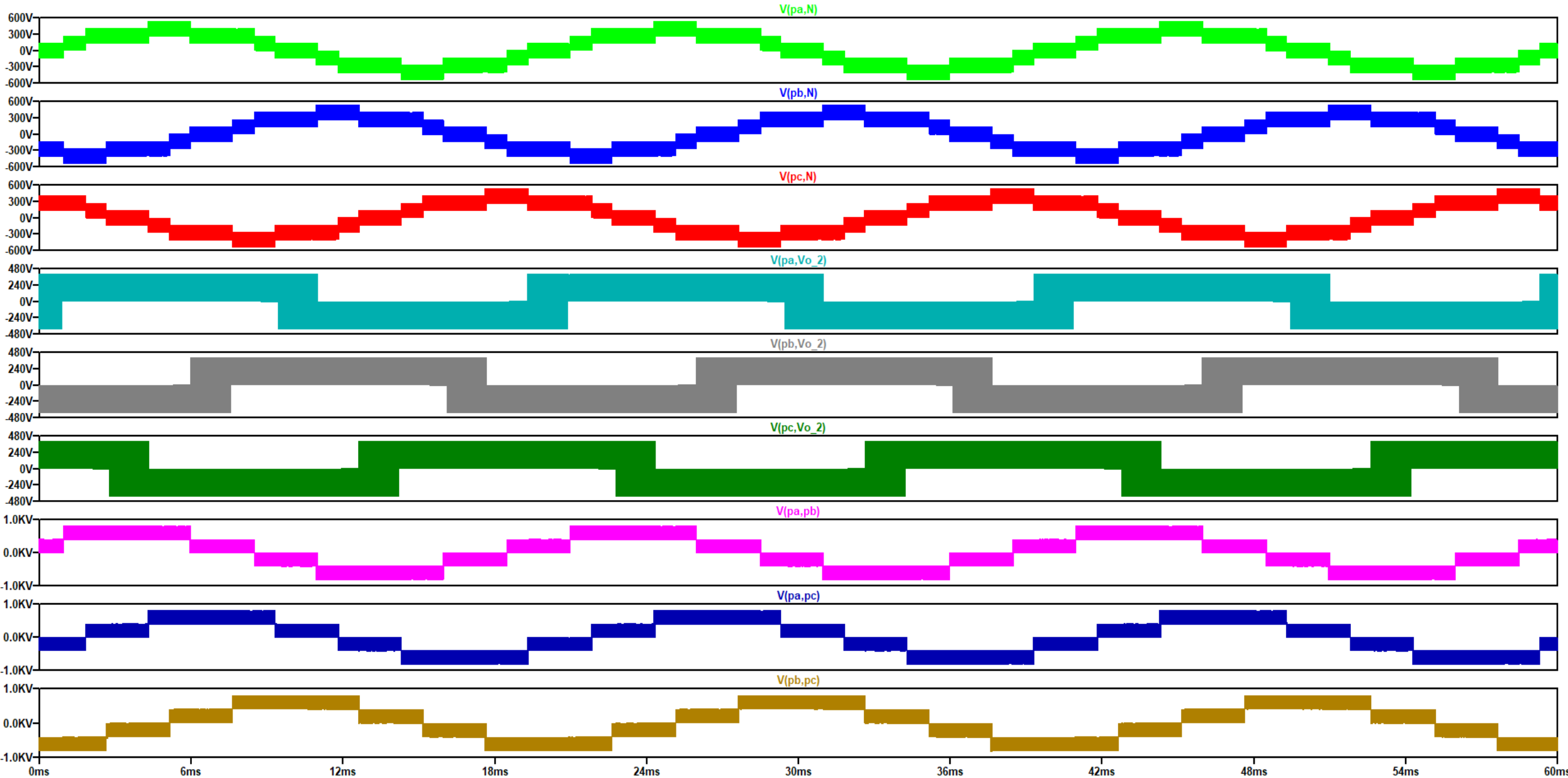
V_{in} = 230 V, P = 20 kW, Q = -8 kVARs, V_{dc} = 800 V, L = 1 mH, F_{sw} = 30 kHz

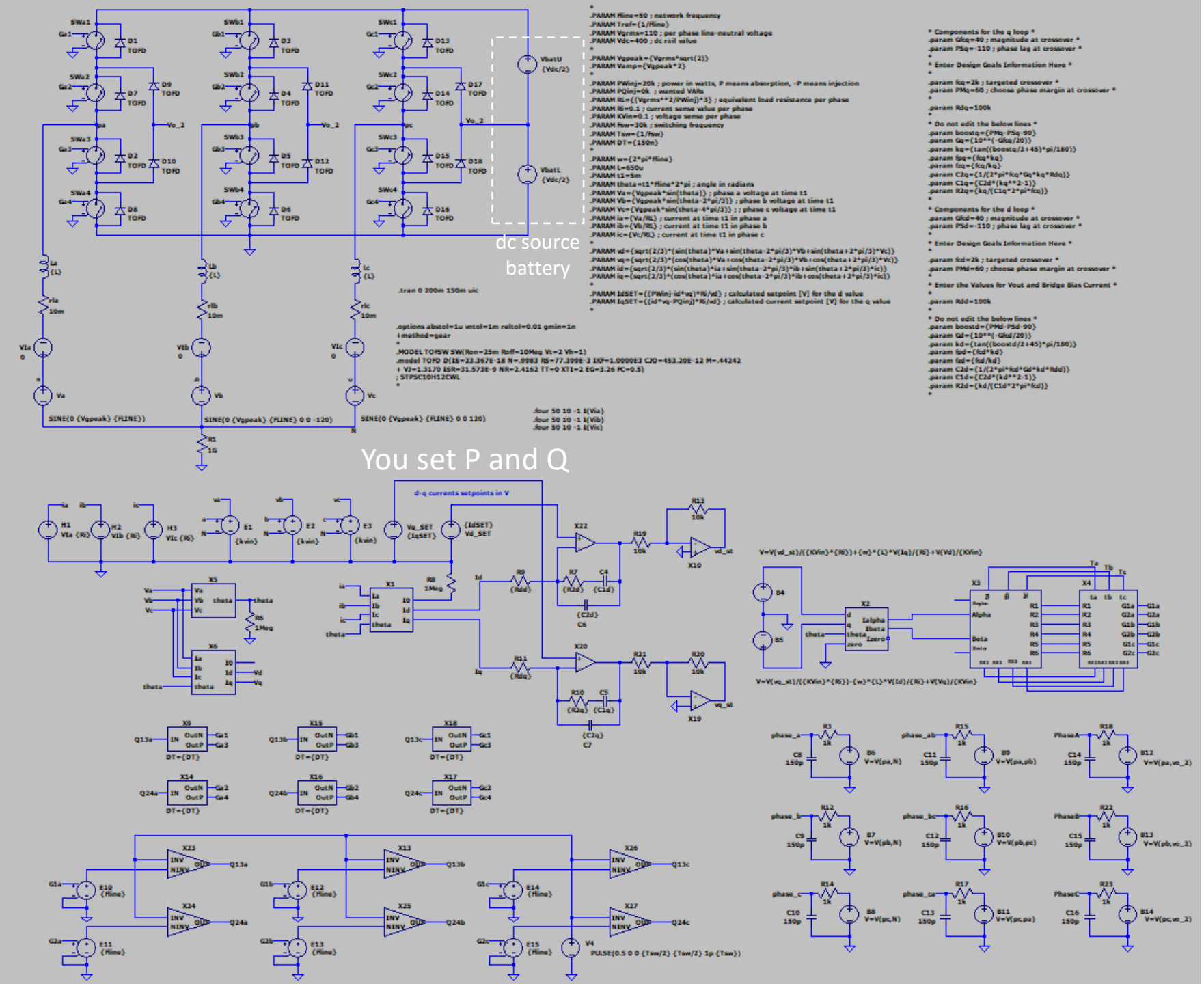
```
Partial Harmonic Distortion: 5.560944%
Total Harmonic Distortion:   5.606957%
```



A negative average power from the ac source implies power absorption.

V_{in} = 230 V, P = 20 kW, Q = -8 kVARs, V_{dc} = 800 V, L = 1 mH, F_{sw} = 30 kHz



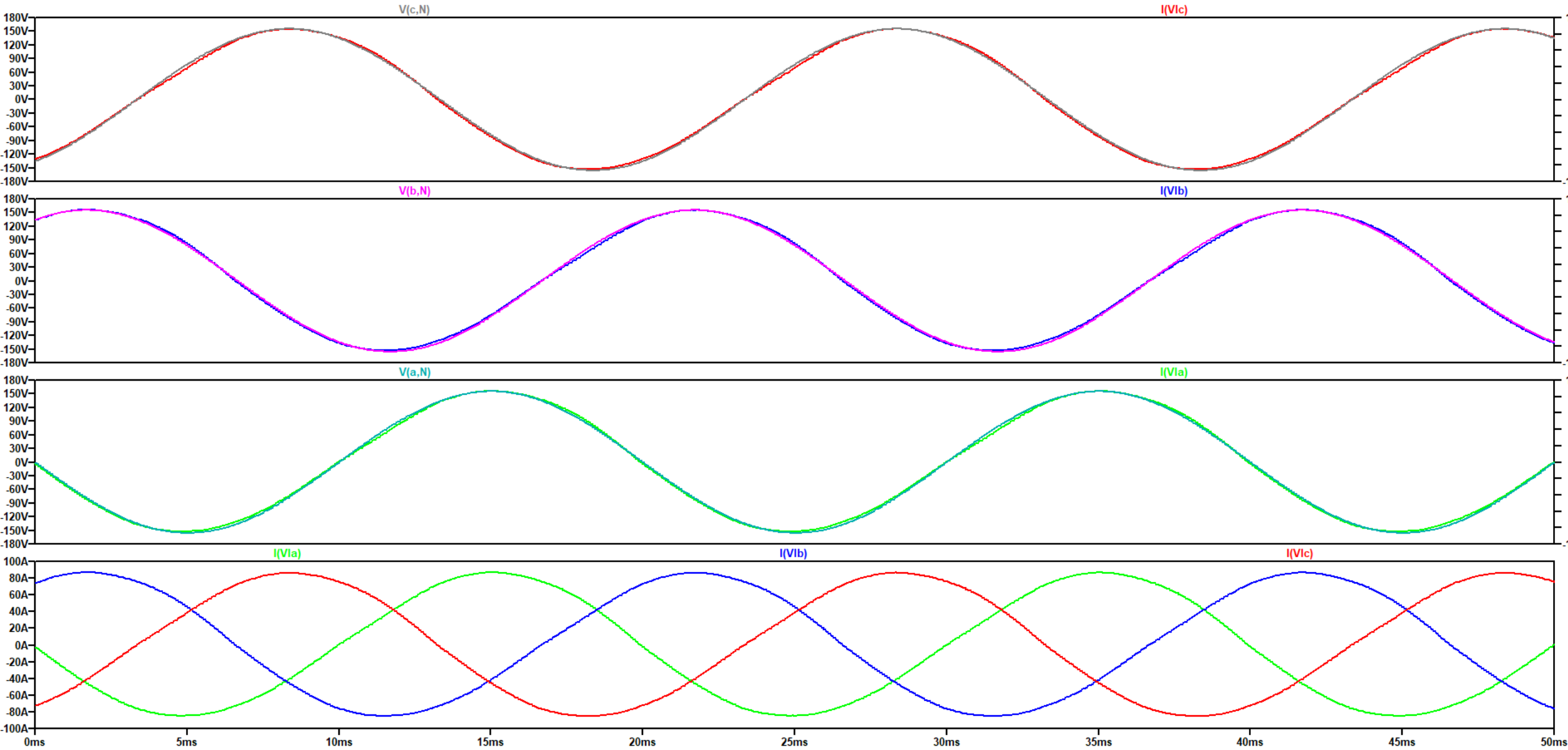


This is an inverter in which you program the power in watts, positive (absorption) or negative (injection). You can also decide what impedance you offer, inductive or capacitive, by programming positive or negative VARs.

V_{dc} = 400 V, V_{ac} = 110 V rms, P = 20 kW, Q = 0

Voltage and current are in phase, this is a resistive power absorption

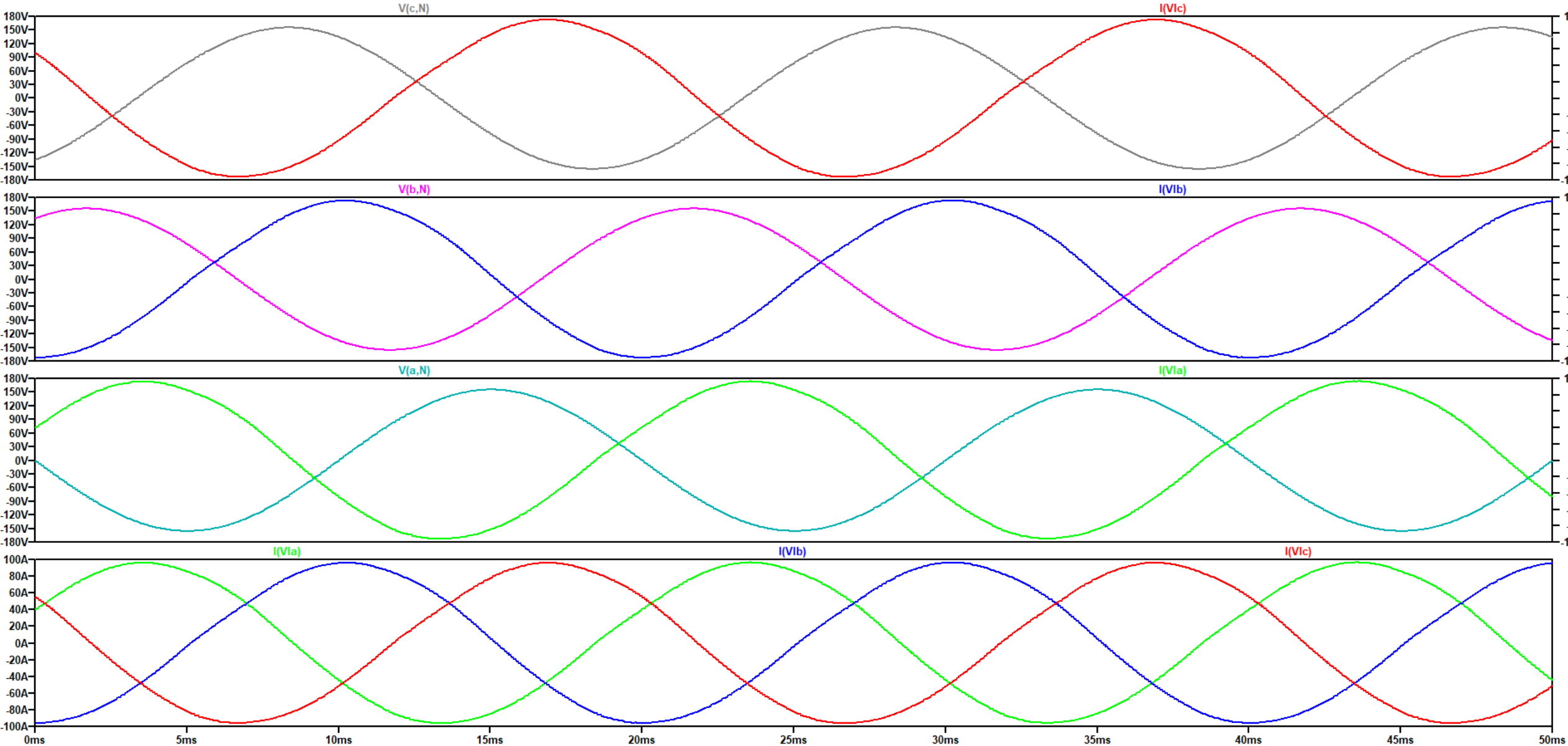
Phase current

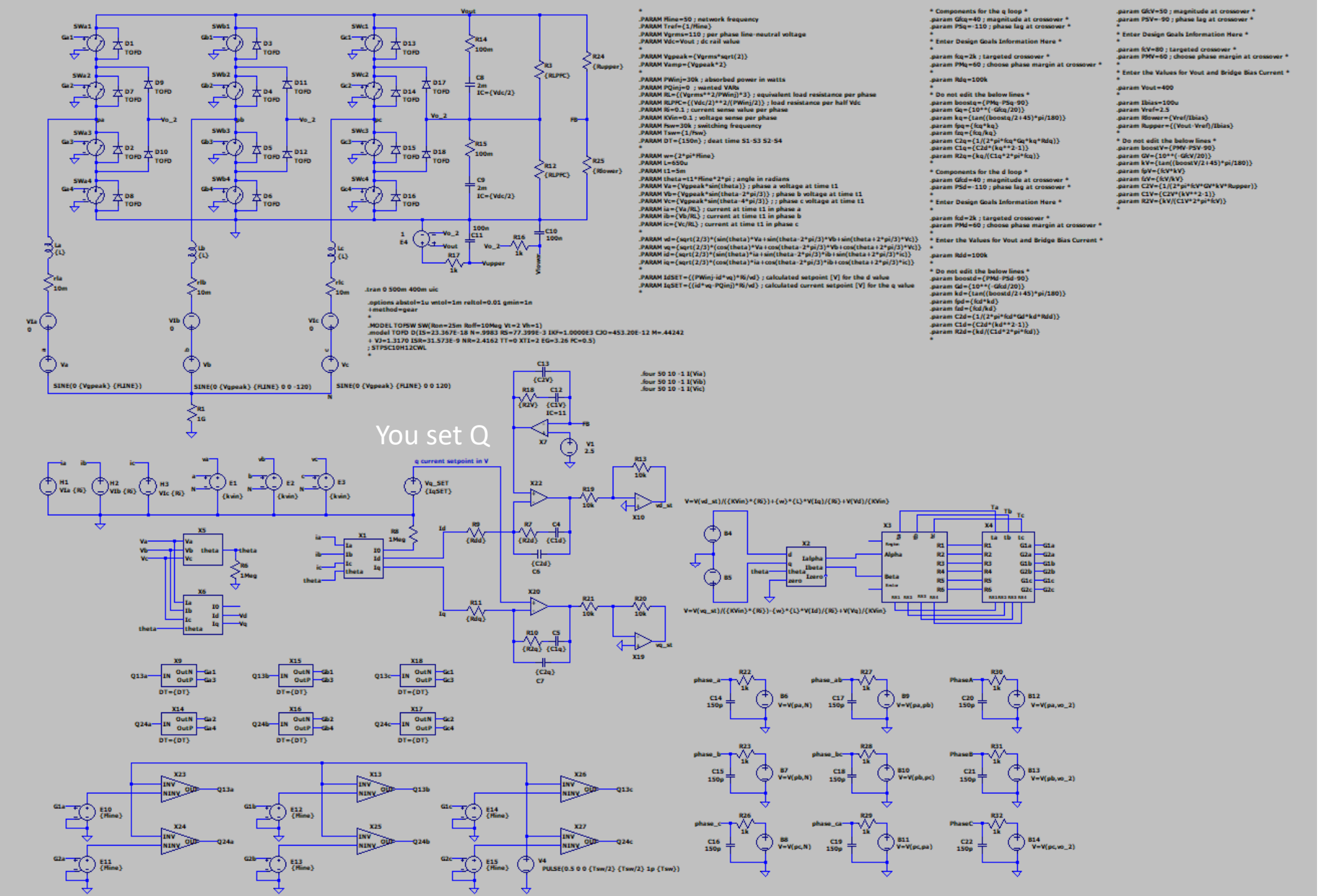


V_{dc} = 400 V, V_{ac} = 110 V rms, P = -20 kW, Q = -10 kVARs

Voltage and current are in phase reversal with some shift, this is power injection. P_{avg} = 6.68k x 3 =20 kW, I_{rms} = 67.81 A

S = 110 x 67.81 x 3 = 22.38 kVAs → Q = sqrt(22.38k²-20k²) =10.03 kVARs

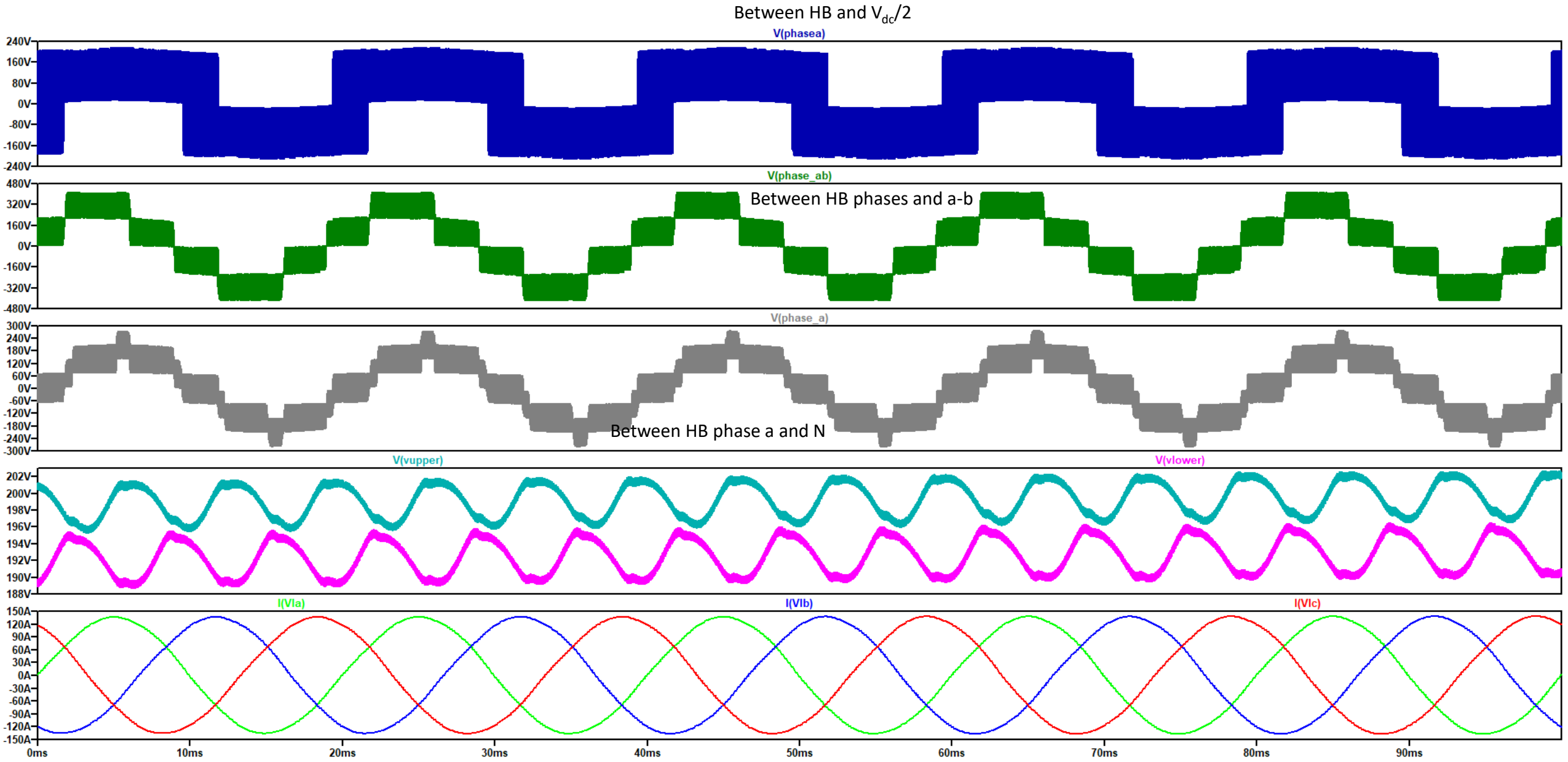




This is a 400-V 110-V rms PFC delivering 30 kW of of power and the Q in VARs can be adjusted via the macro to offer an inductive or capacitive impedance.

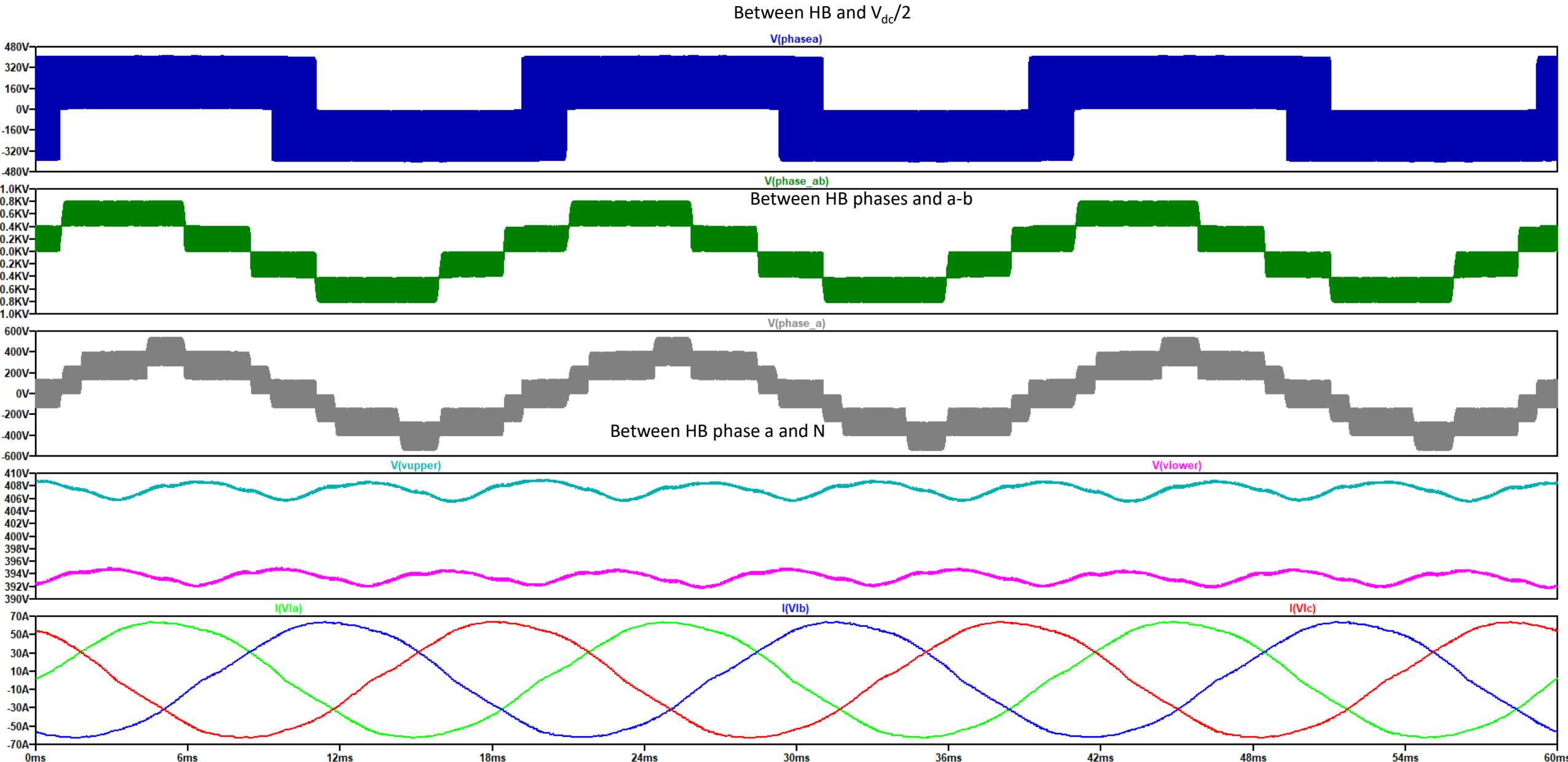
The output power is 30 kW, Q = 0, V_{in} = 110 V rms. The THD is below 2%.

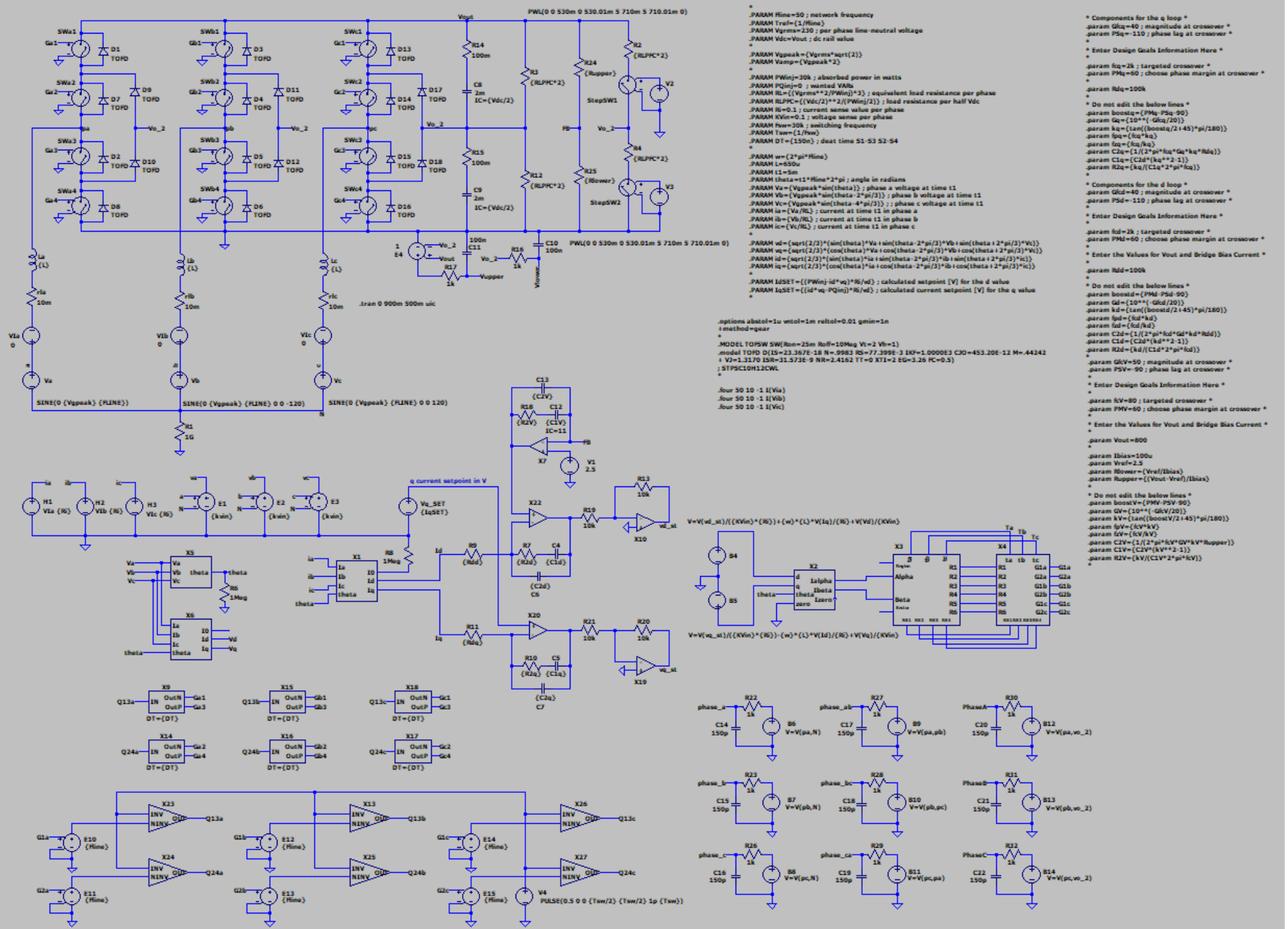
```
Partial Harmonic Distortion: 1.836485%
Total Harmonic Distortion:   1.896696%
```



The output power is 30 kW, Q = 0, V_{in} = 230 V rms. The THD is 3%.

```
Partial Harmonic Distortion: 2.864874%
Total Harmonic Distortion:   3.018450%
```





This is a closed-loop PFC with an 800-V dc link voltage. The power is stepped from 15 to 30 kW. The simulation time is long and the raw data file did amount to 20 Go :)

Transient response, V_{in} = 230 V rms, V_{dc} = 800 V, P from 15 to 30 kW in 10 µs.