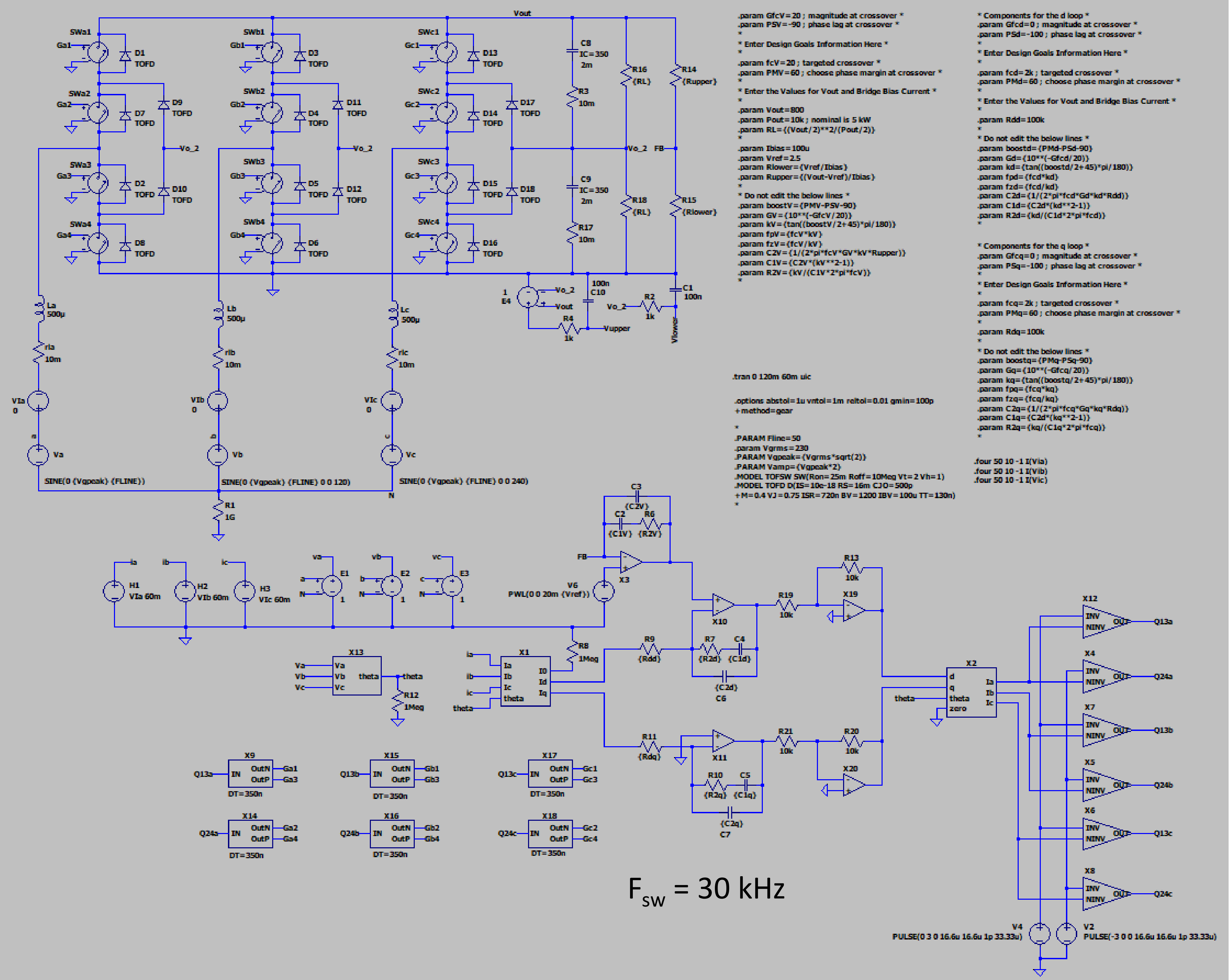


FUTURE ELECTRONICS

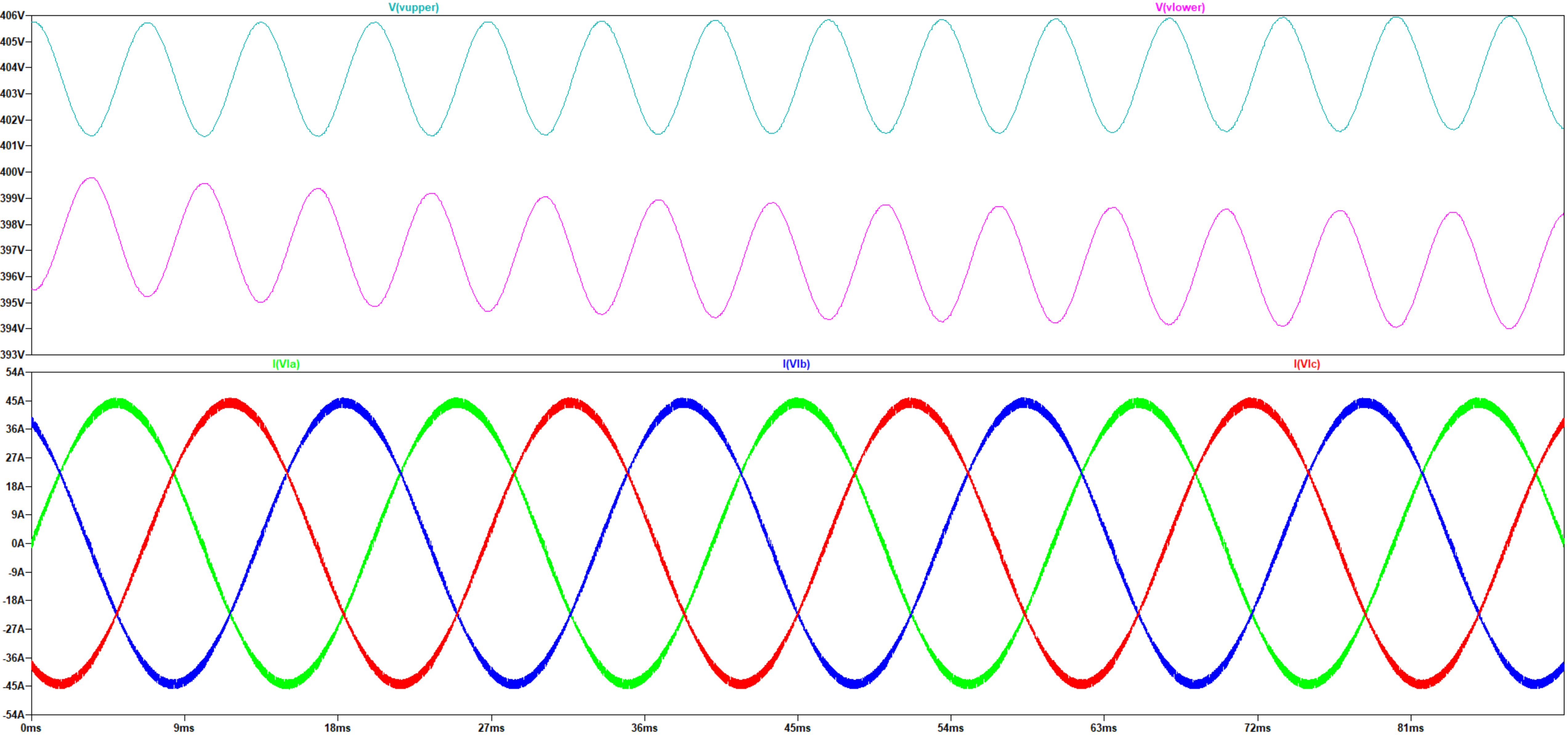
A WT Microelectronics Company

This is a 10-kW 3-phase neutral-point-clamped (NPC) power factor correction converter. The circuit uses dq0 loops to provide low distortion input currents. The two rails are regulated at 400 V but I did not add more loops for ensuring voltage balancing between rails. Please note that the computed d and q setpoints need to be reversed before entering the current setpoints reconstruction blocks. Deadtime are provided between the switching events of transistors 1/3 and 2/4.

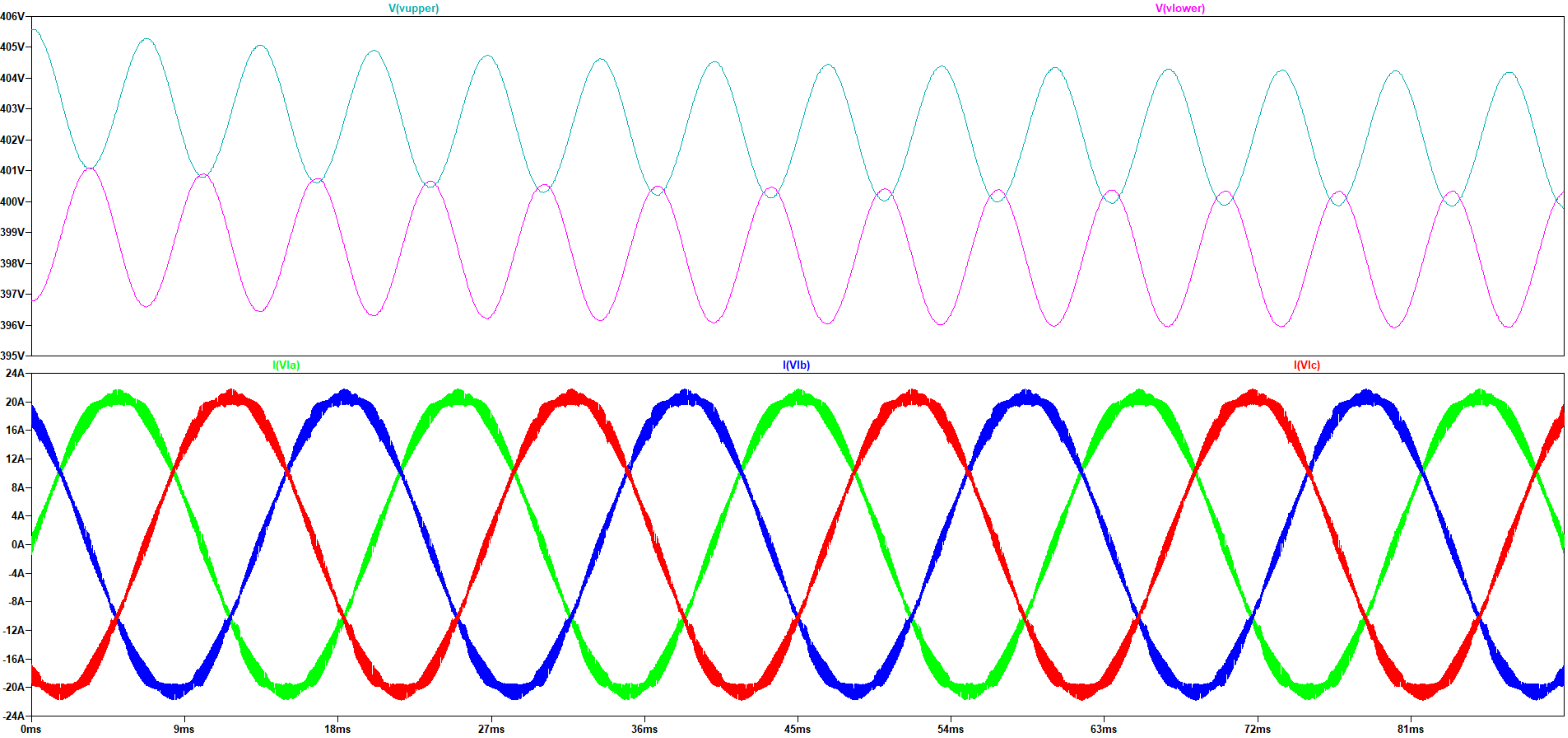
Christophe Basso

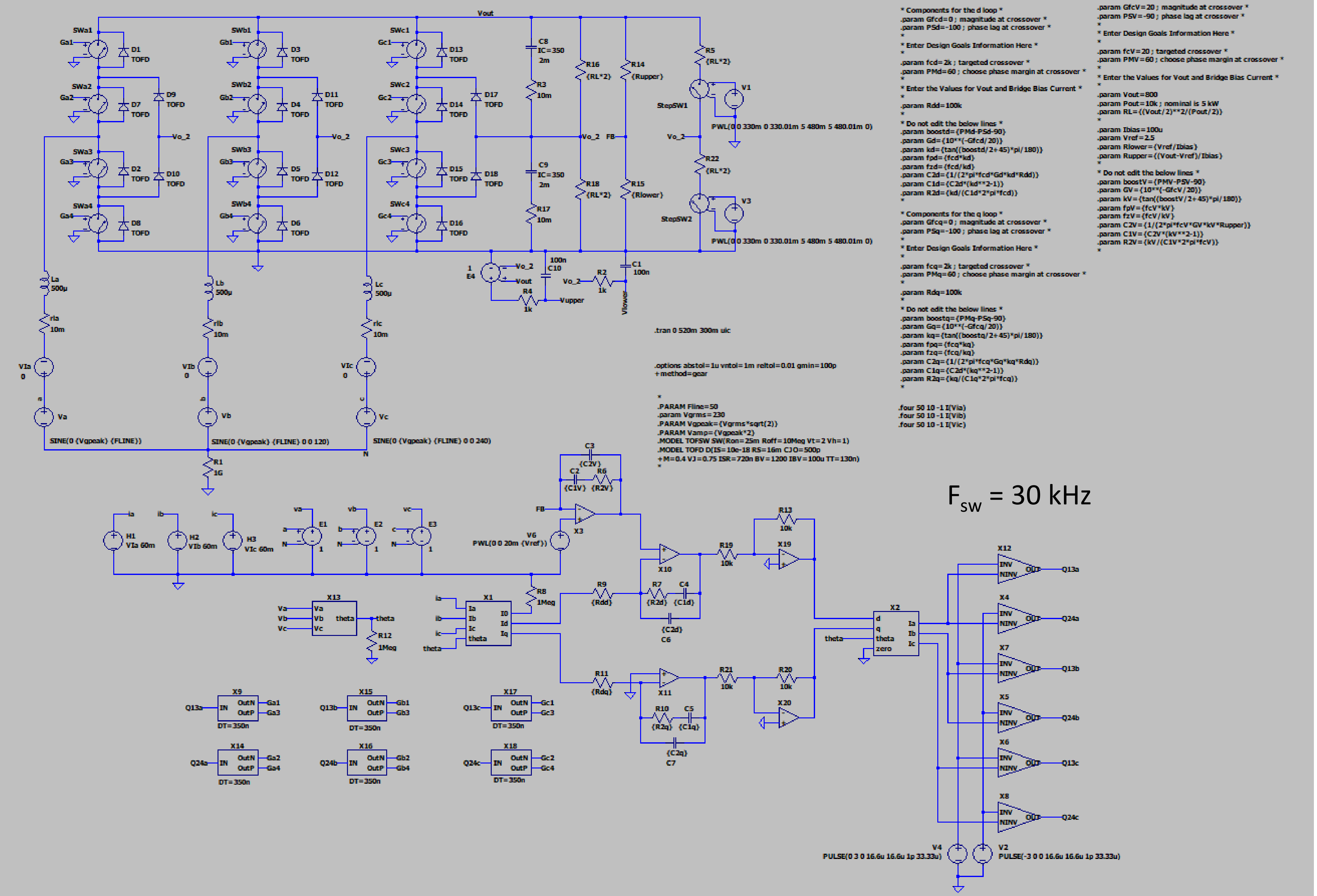
March 2025 – Rev. 0.36

V_{in} = 110 V rms, P_{out} = 10 kW – THD ≈5%



V_{in} = 230 V rms, P_{out} = 10 kW – THD ≈6%

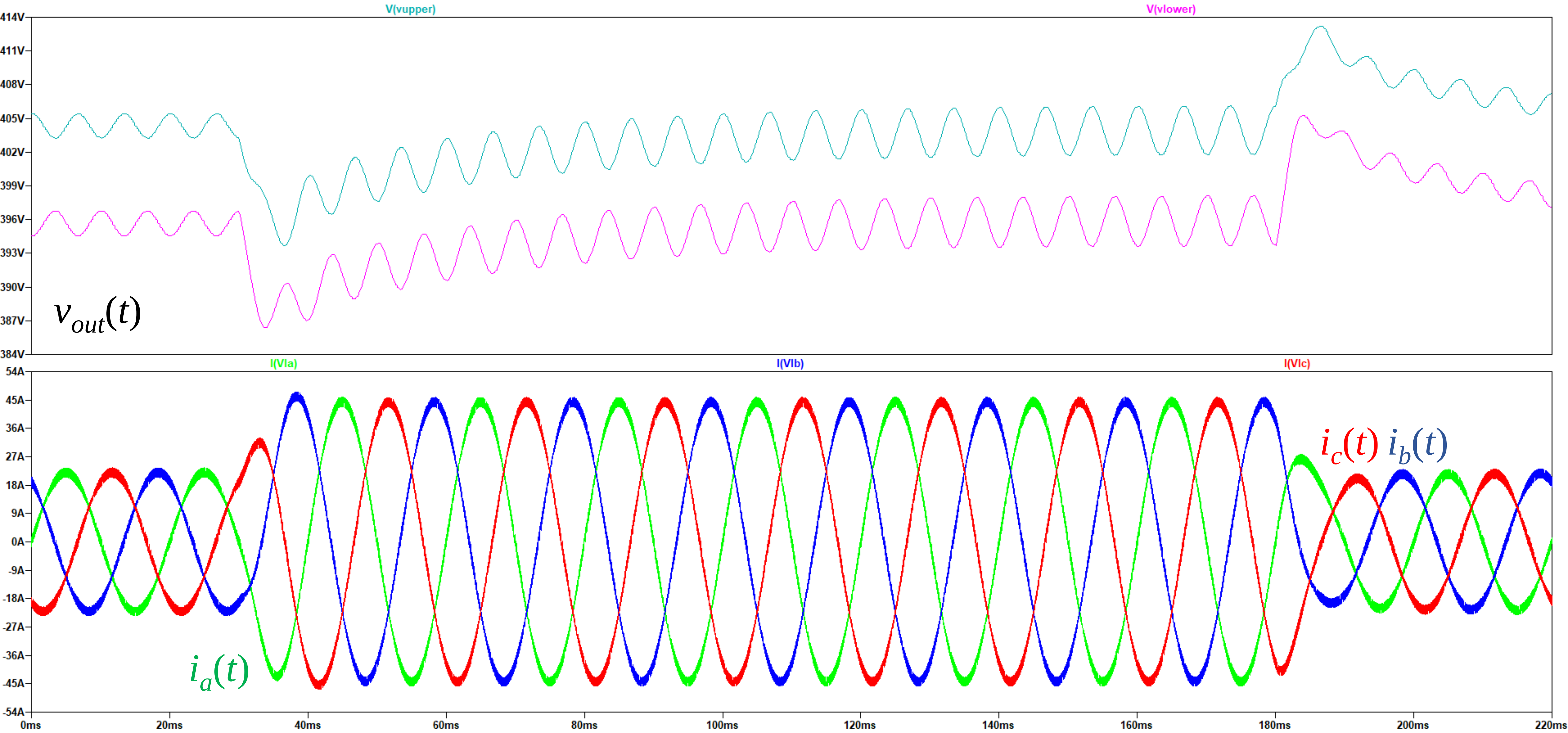




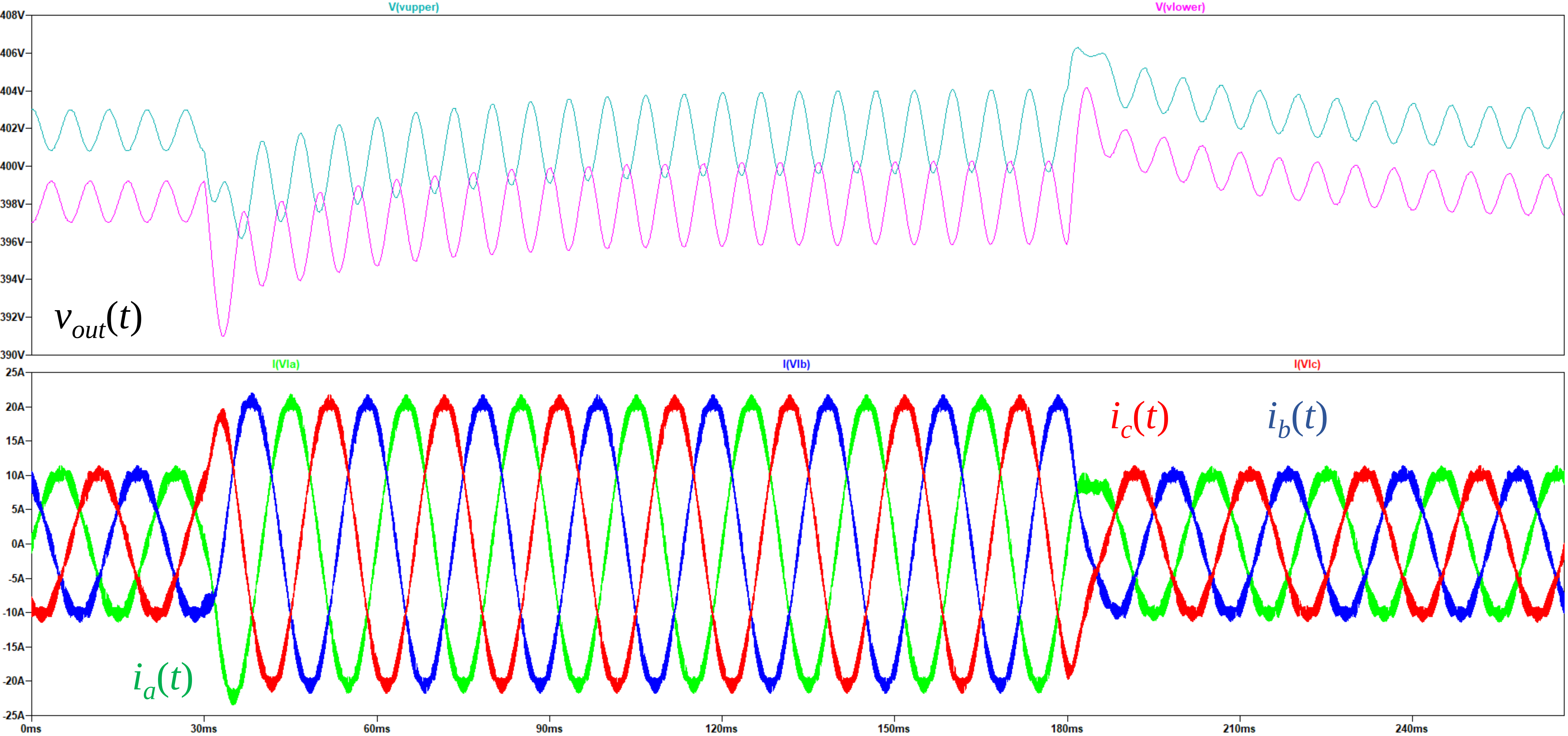
F_{sw} = 30 kHz

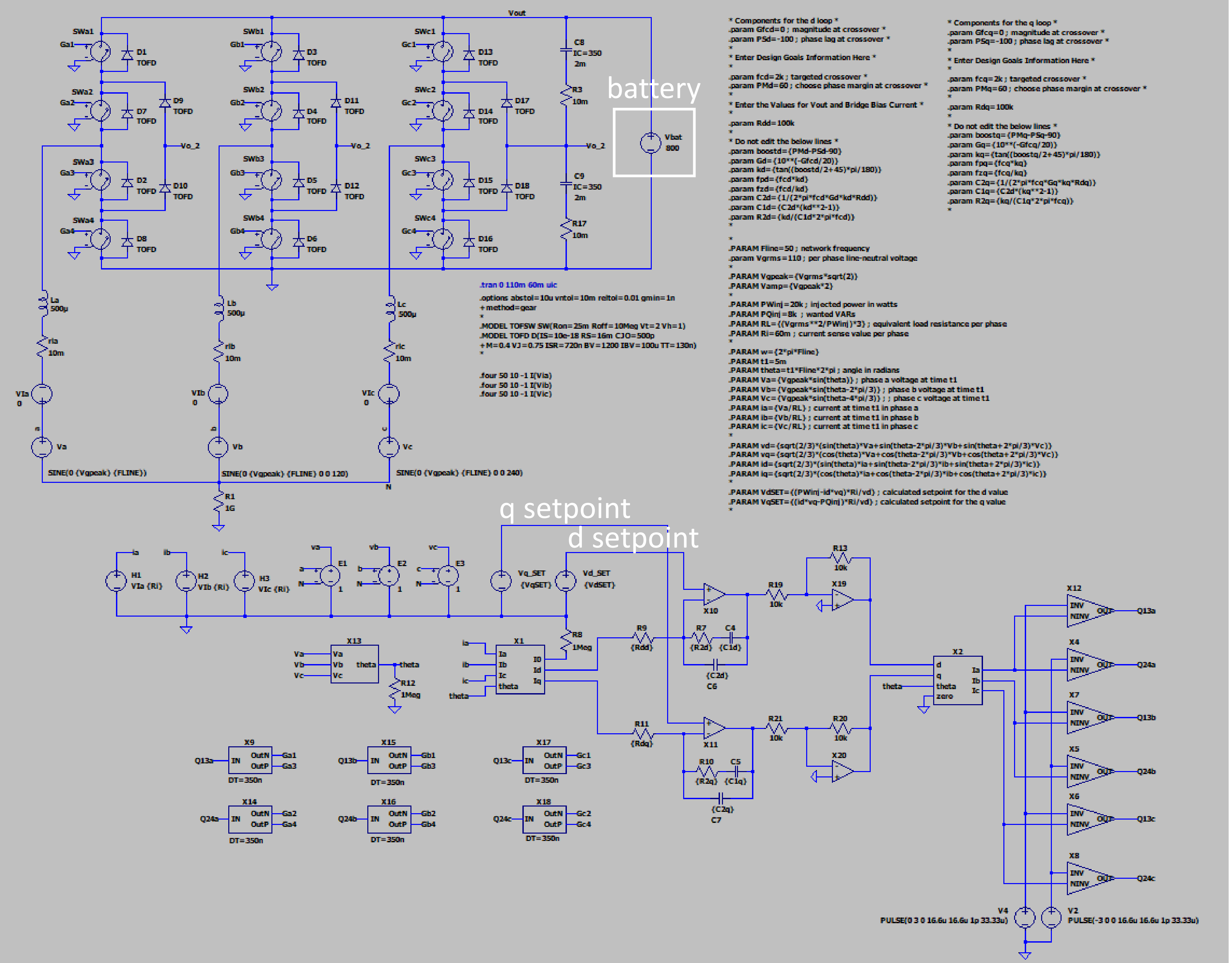
Transient load simulation from 50% to 100% loading.

In this example, the load is stepped from 5 to 10 kW, V_{in} = 110 V rms

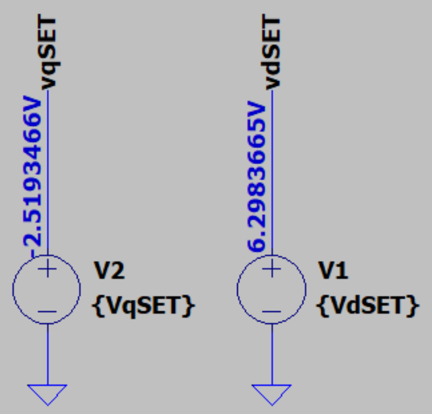


In this example, the load is stepped from 5 to 10 kW, V_{in} = 230 V rms





In inverter mode, the voltage-regulation loop has disappeared since the dc rail is now fixed by the 800-V battery in this example. The setpoint of the d and q inputs are now externally set by a microcontroller for instance. For instance, if my solar panels delivers an excess of 20 kW of power, I can reinject this level into the grid and d must be programmed accordingly. Similarly, I can set the reactive power in VARs to 0 via the q setpoint or, depending on the impedance I want to offer – inductive or capacitive – I can set the level of VARs by programming the q setpoint.

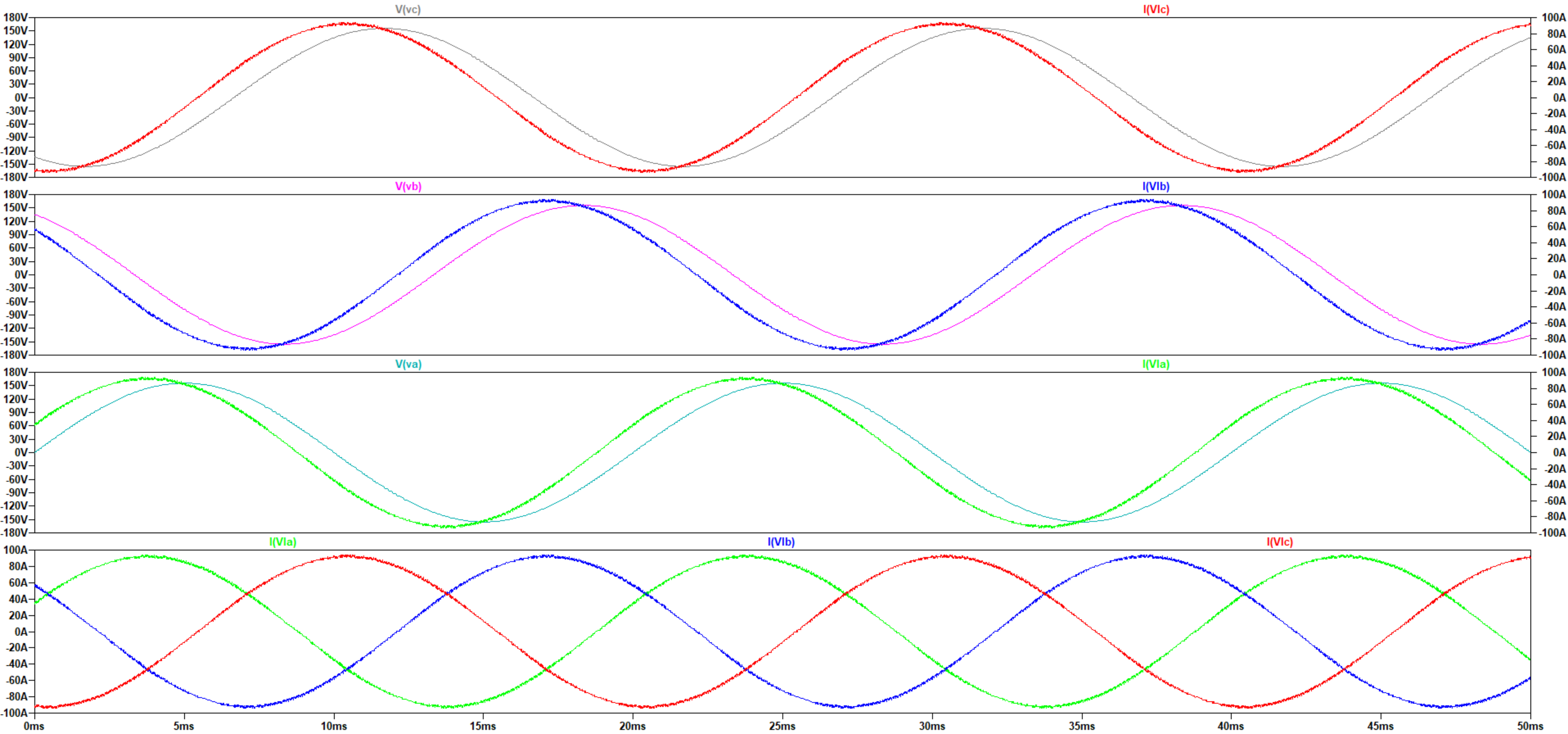



```
.op
```

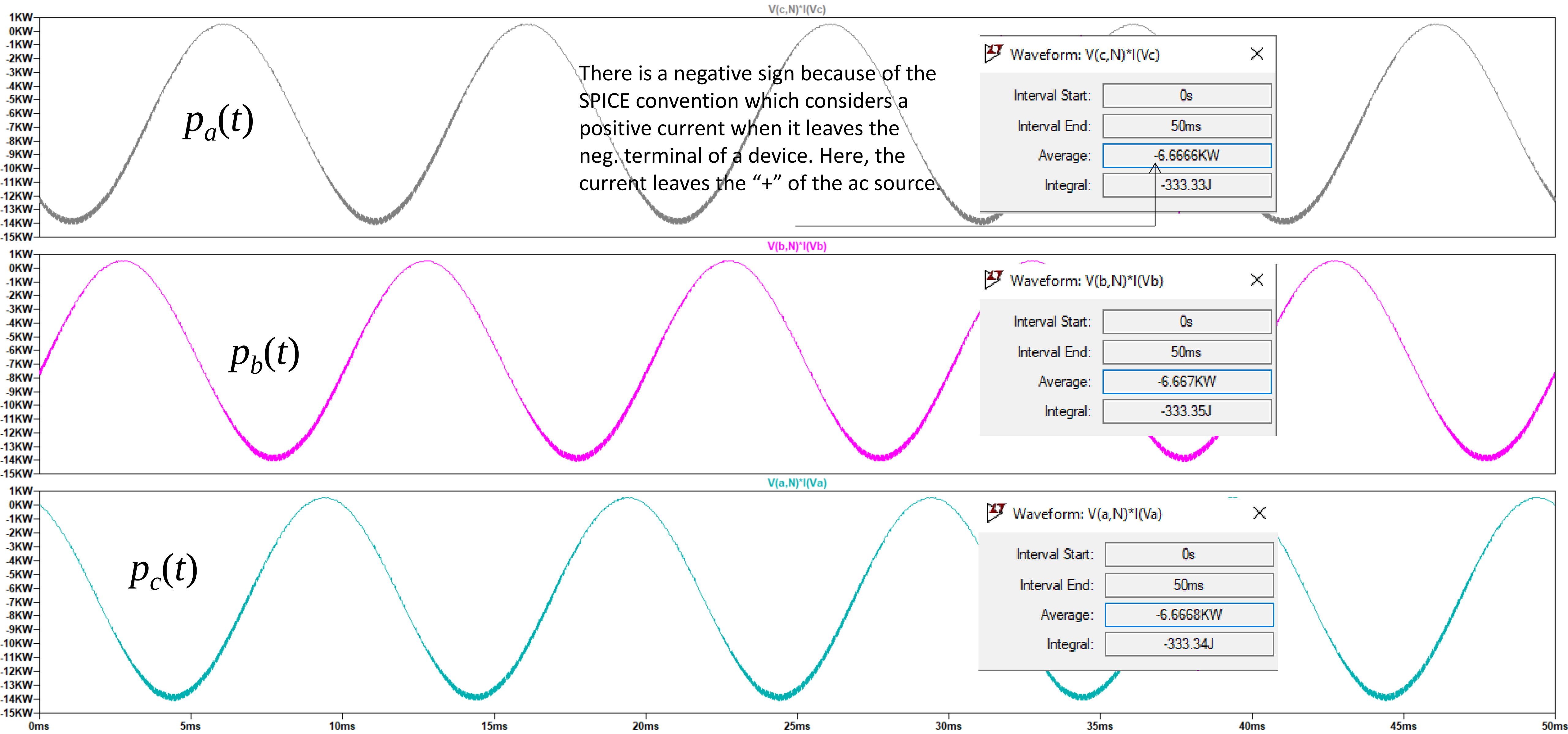
```
*
.PARAM Fline=50 ; network frequency
.param Vgrms=110 ; per phase line-neutral voltage
*
.PARAM Vgpeak={Vgrms*sqrt(2)}
.PARAM Vamp={Vgpeak*2}
*
.PARAM PWinj=20k ; injected power in watts
.PARAM PQinj=8k  ; wanted VARs
.PARAM RL={(Vgrms**2/PWinj)*3} ; equivalent load resistance per phase
.PARAM Ri=60m ; current sense value per phase
*
.PARAM w={2*pi*Fline}
.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 VdSET={(PWinj-id*vq)*Ri/vd}
.PARAM VqSET={(id*vq-PQinj)*Ri/vd}
```

The injected power in watts and the wanted VARs have to be transformed into d and q quantities for programming the currents. This is what is done through this macro, accounting for the sense resistance of 60 mΩ in this example. For a 20-kW absorbed power, the value for d is 6.3 V and is -2.52 V for a 8 kVARs or reactive power. The apparent power is estimated to be 21.54 kVAs.
Should you want to inject power instead, simple change 20 kW to -20 kW.

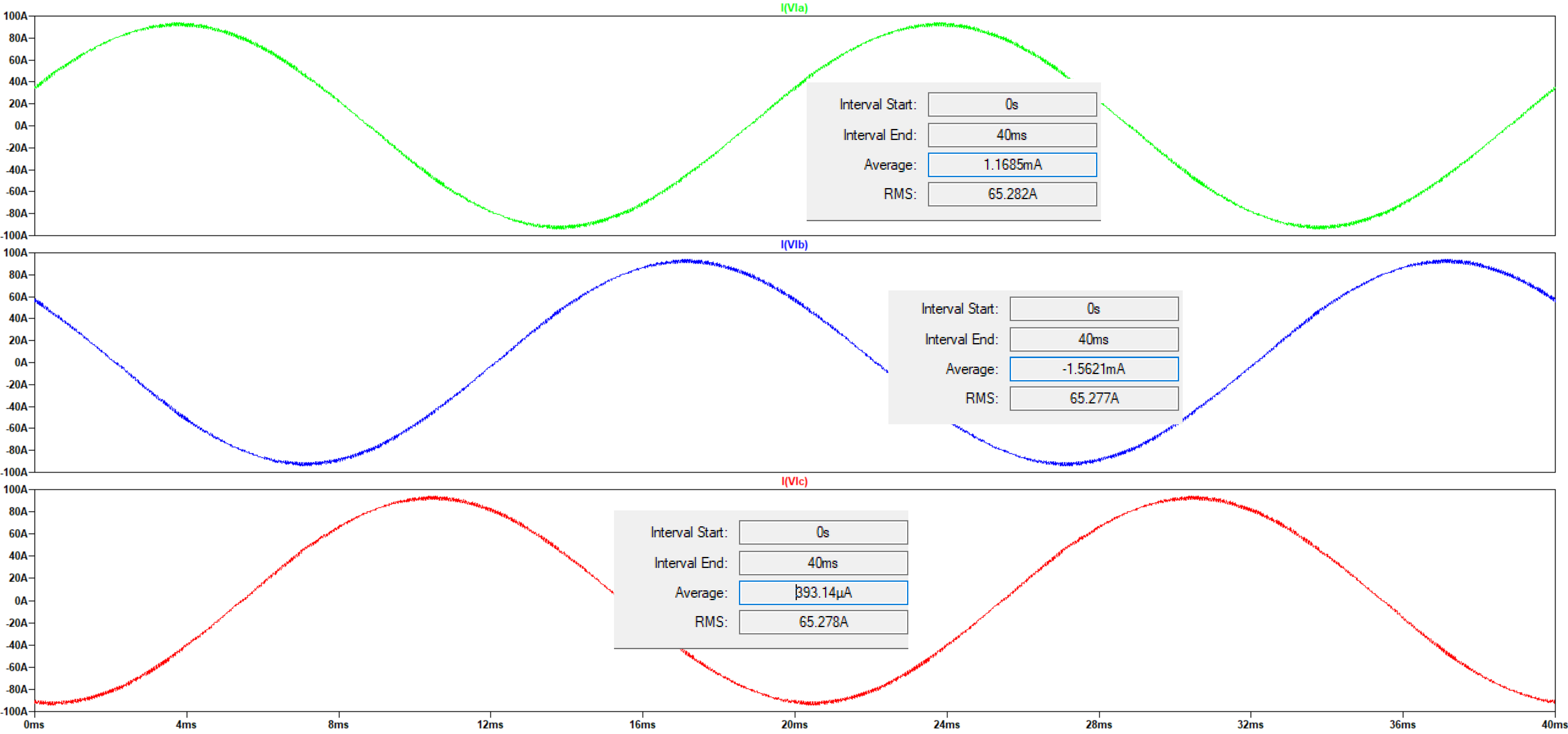
Simulated currents for the 20-kW absorbed power and 8 kVARs – the current leads the voltage, this is a capacitive impedance.



These are the three instantaneous powers per phase: 6.6666k + 6.667k + 6.6668k = 20 kW



Now isolate one or two line periods (40 ms here) and determine the rms currents in each phase



You can now determine the VAs per phase and sum for the total value:

Phase 1, P = 65.282 A x 110 V = 7.181 kVAs
Phase 2, P = 65.277 A x 110 V = 7.18 kVAs
Phase 3, P = 65.278 A x 110 V = 7.18 kVAs

The apparent power is thus the sum of these numbers or 21.54 kVAs
The VARs are thus:

$$Q = \sqrt{S^2 - P^2}\ [\mathrm{VAR}]$$

$$Q = \sqrt{21.54k^2 - 20k^2} = 7.9982\ \mathrm{kVARs}$$

$$\tan(\varphi) = \frac{[\mathrm{VAR}]}{[\mathrm{W}]} = \frac{8k}{20k} = 0.4$$

$$S = V_{rms} I_{rms}\ [\mathrm{VA}]$$

Always true regardless of waveforms

$$P = V_{rms} I_{rms} \cdot \cos(\varphi)\,[\mathrm{W}]$$

$$Q = V_{rms} I_{rms} \cdot \sin(\varphi)\,[\mathrm{VAR}]$$

Sinusoidal waveforms

$$S = P + jQ$$

$$P = \frac{1}{T}\int_0^T v(t)\cdot i(t)\cdot dt$$

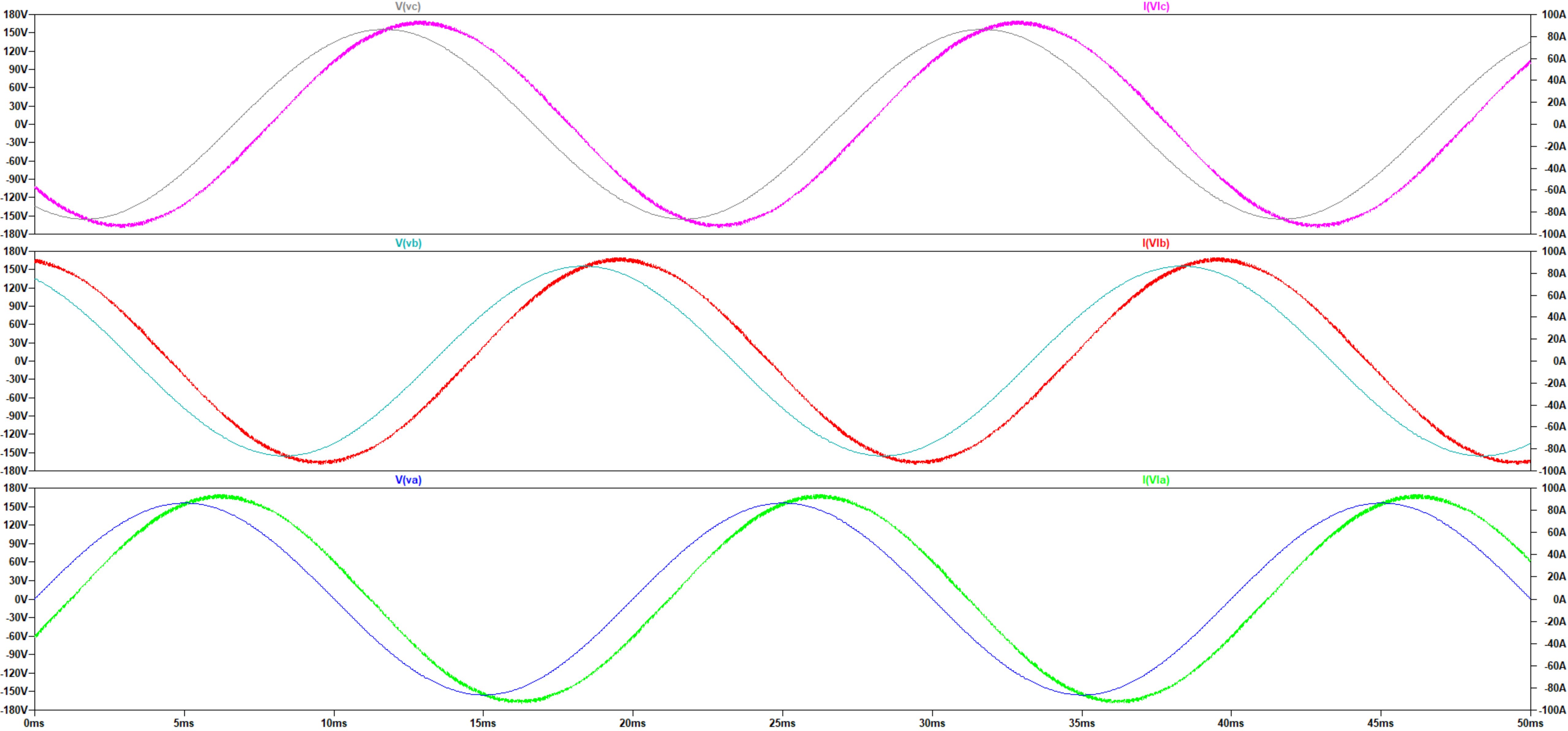
Always true regardless of waveforms

$$\mathrm{PF} = \frac{[\mathrm{W}]}{[\mathrm{VA}]} = \frac{V_{rms} I_{rms} \cos(\varphi)}{V_{rms} I_{rms}} = \cos(\varphi)$$

$$\tan(\varphi) = \frac{[\mathrm{VAR}]}{[\mathrm{W}]}$$

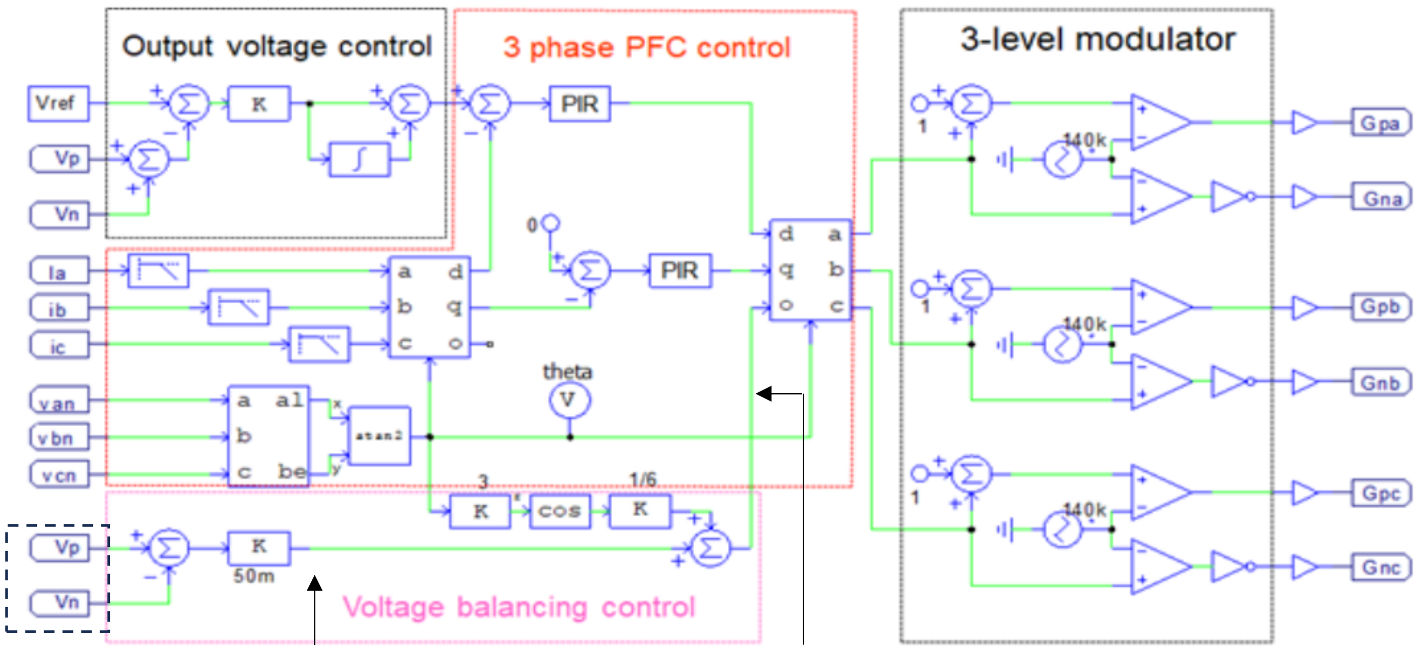
In the next simulation, I have changed the VARs to -8 kVARs and the inverter will now offer an inductive impedance. Changing the impedance of the inverter helps stabilizing the grid voltage when its value tends to be higher or lower than the specified value (+/- 10% on average over 10 mn, Enedis). By adjusting tan(phi) – which is Q [VAR]/P [W] – you have a means to compensate these voltage variations while you inject in the grid. This excellent video (in French) explains these phenomena in details.

Simulated currents for the 20-kW absorbed power and -8 kVARs – the current lags the voltage, this is an inductive impedance.



$$\tan(\varphi) = -0.4$$

Looking at the 30-kW Vienna demonstration board released by Microchip and described here, I thought I could try to add a compensation for imbalanced outputs in this NPC inverter:



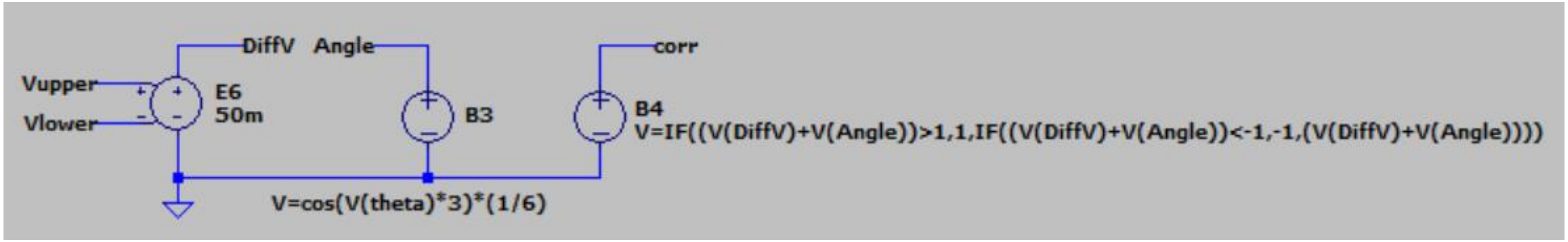
Output caps. voltages

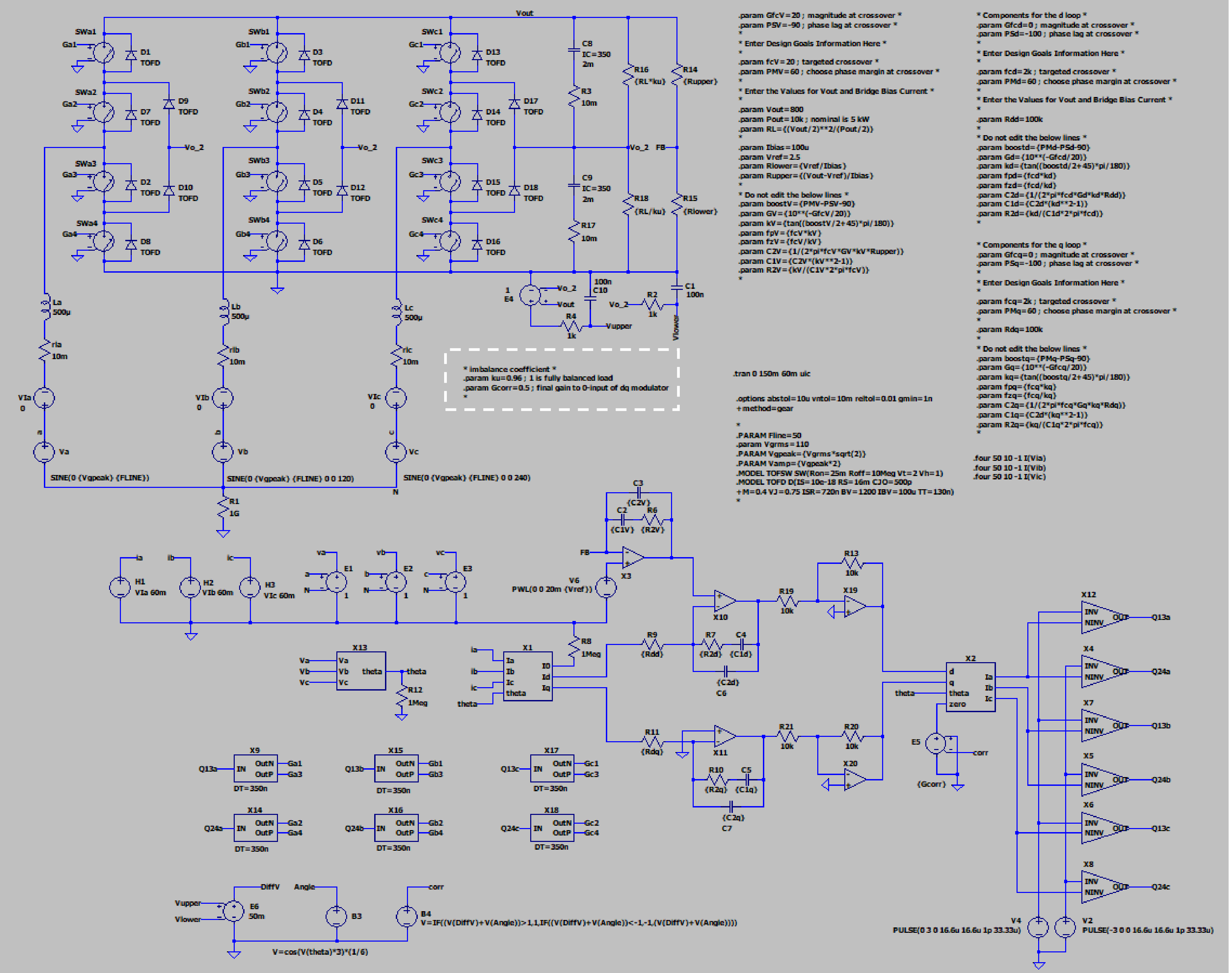
Error voltage

Correction voltage

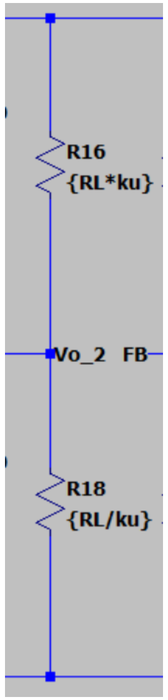
In this PSIM simulation circuit, the voltages across the low- and high-side capacitors are subtracted to generate an error voltage. The proportional coefficient is quite small, this is obviously a low-gain loop. The correction factor is made by taking the cosine of the angle, affected by some gain and added to the error voltage. The whole result is then biasing the 0-sequence input of the dq modulator. It is an interesting way for implementing the correction in this 3-level rectifier.

Loop implementation for compensating imbalance



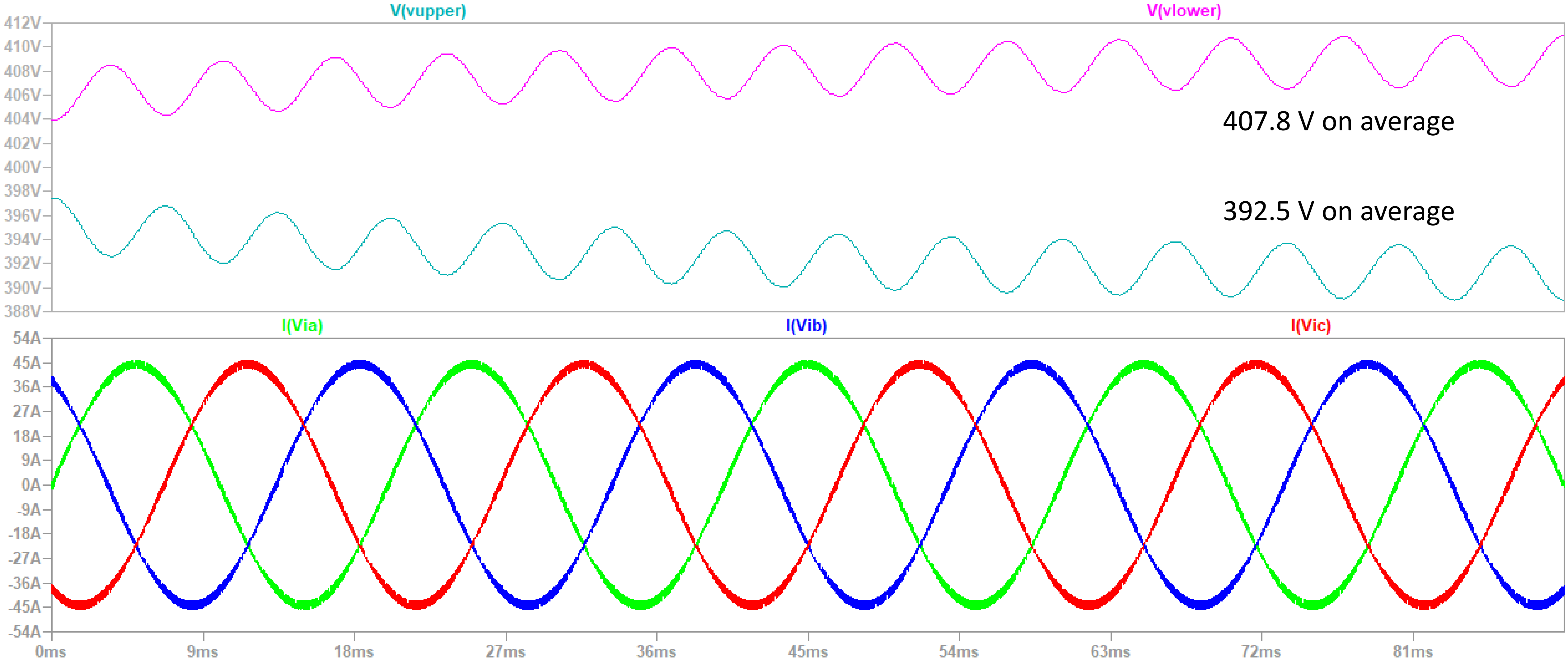


* imbalance coefficient *
.param ku=0.96 ; 1 is fully balanced load
.param Gcorr=0 ; final gain to 0-input of dq modulator
*



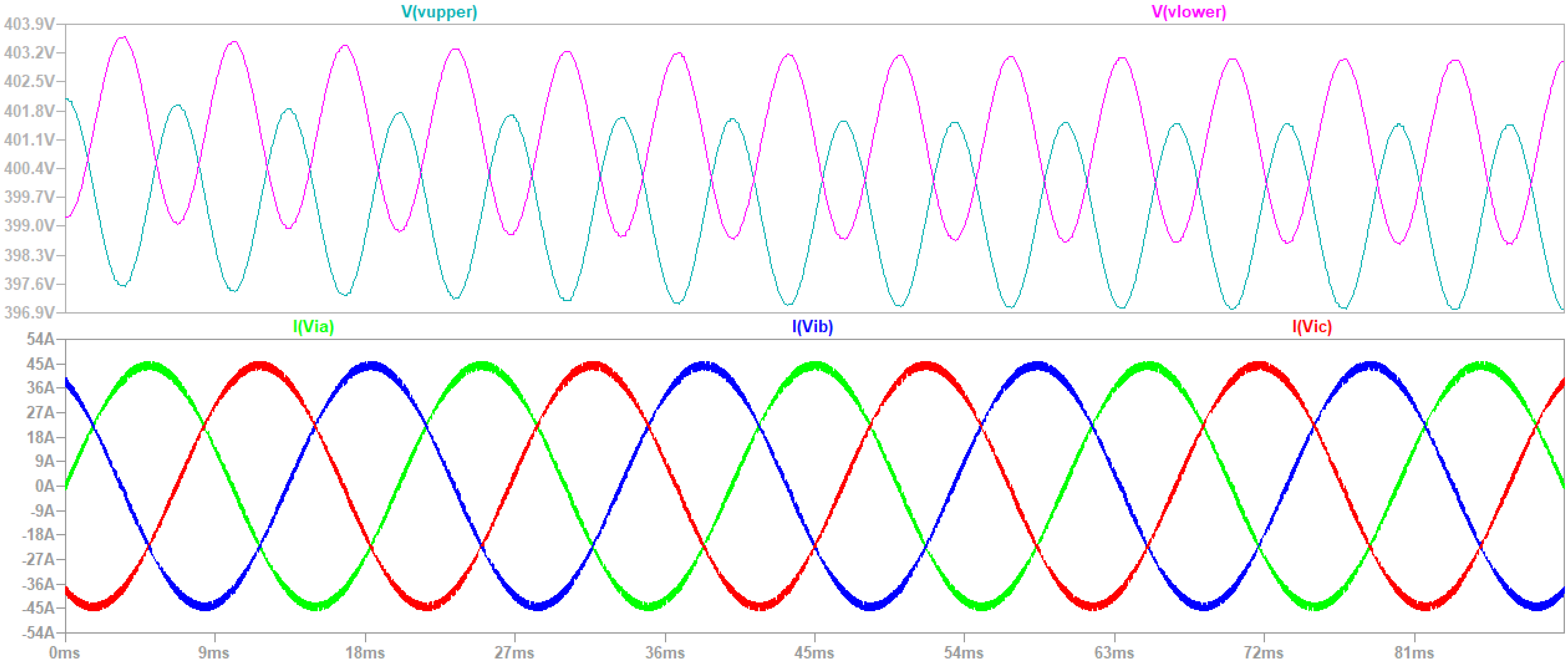
Coefficient ku helps purposely imbalance the loads. With G_{corr} = 0, the extra loop is turned off. When the loop is closed, it is set at 0.5.

In this mode, the voltage difference between the two capacitors is around 15.3 V, each load is imbalanced by 4% from their nominal value.



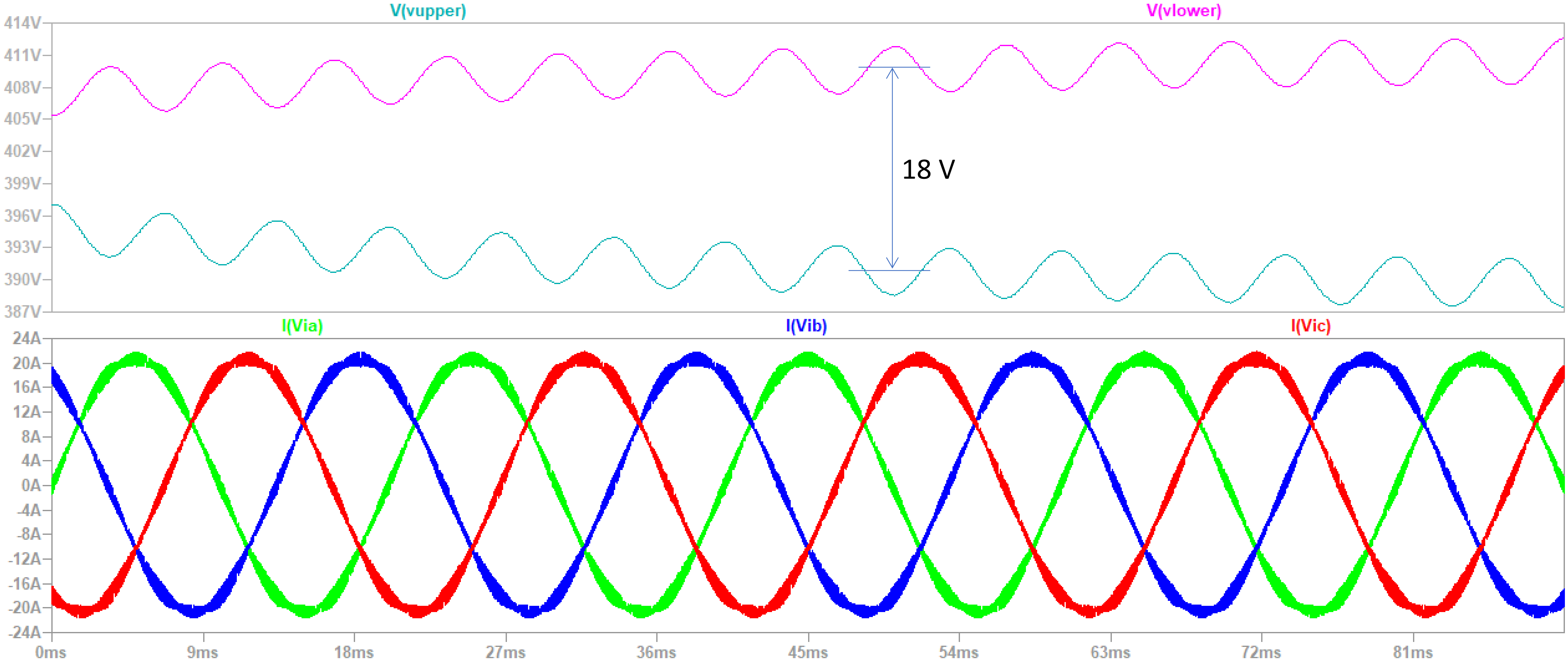
V_{in} = 110 V rms

In this mode, the imbalance loop is closed and the two voltages are almost identical at 400 V each. The coefficient is set to 0.5



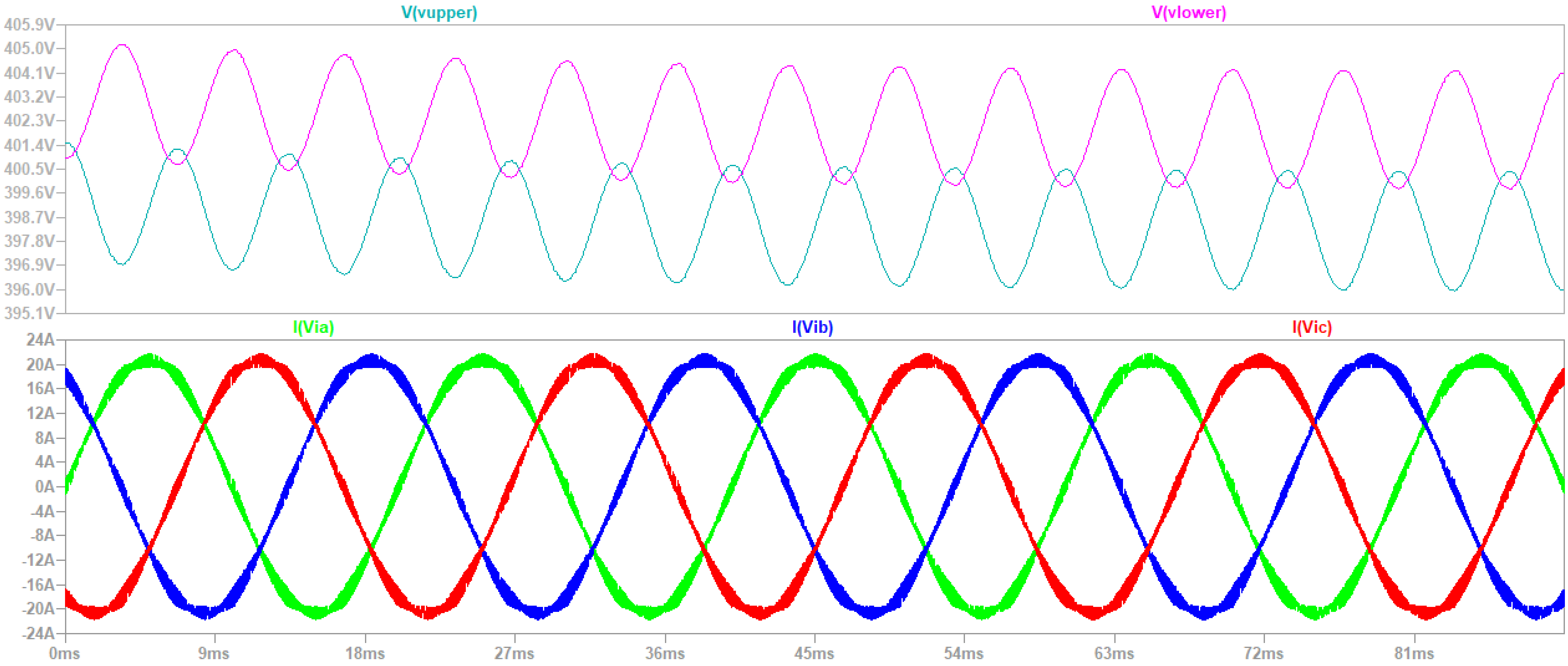
V_{in} = 110 V rms

In this mode, the voltage difference between the two capacitors is around 18 V, each load is imbalanced by 4% from its nominal value. The voltage is still diverging.



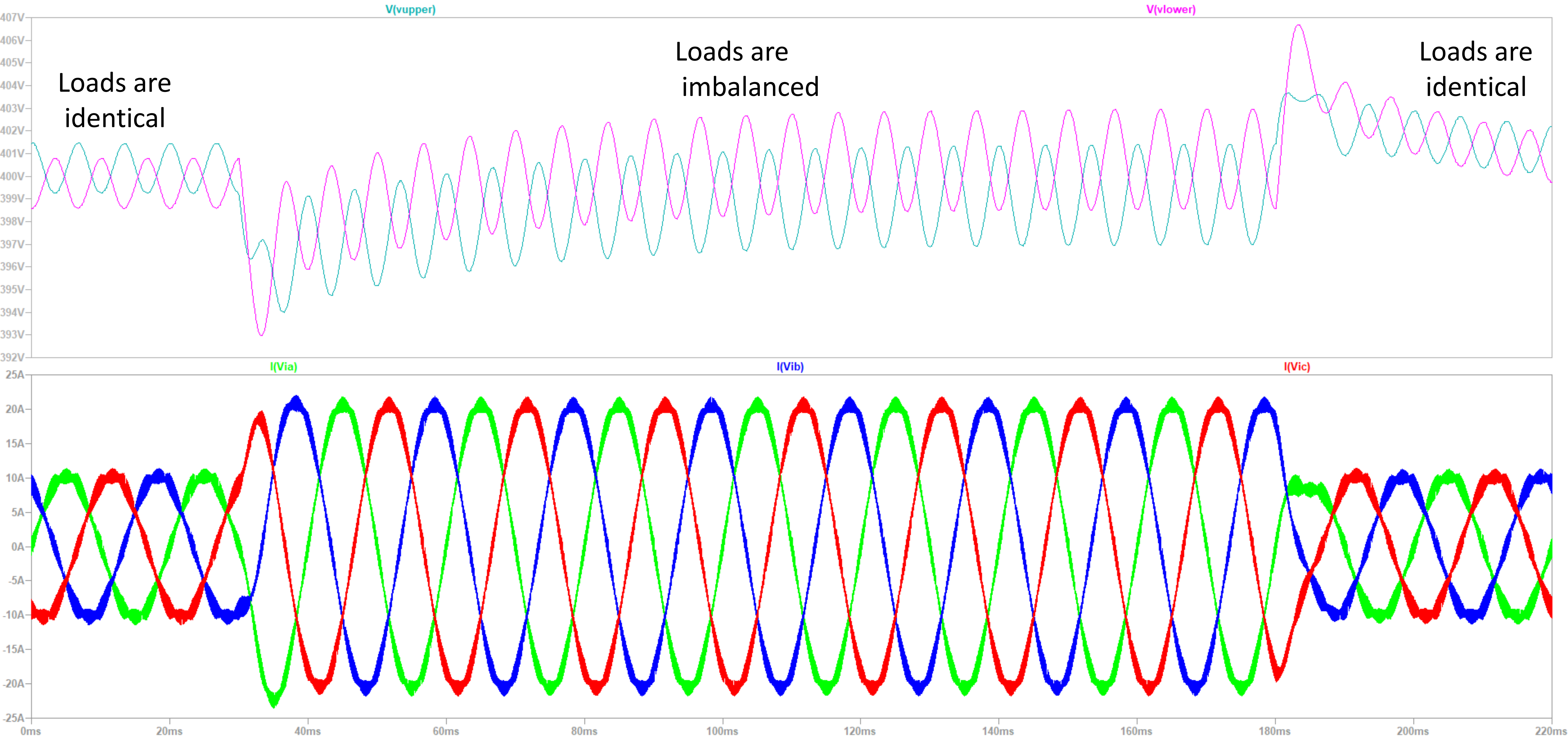
V_{in} = 230 V rms

When the loop is closed, the two capacitive voltages are well balanced.

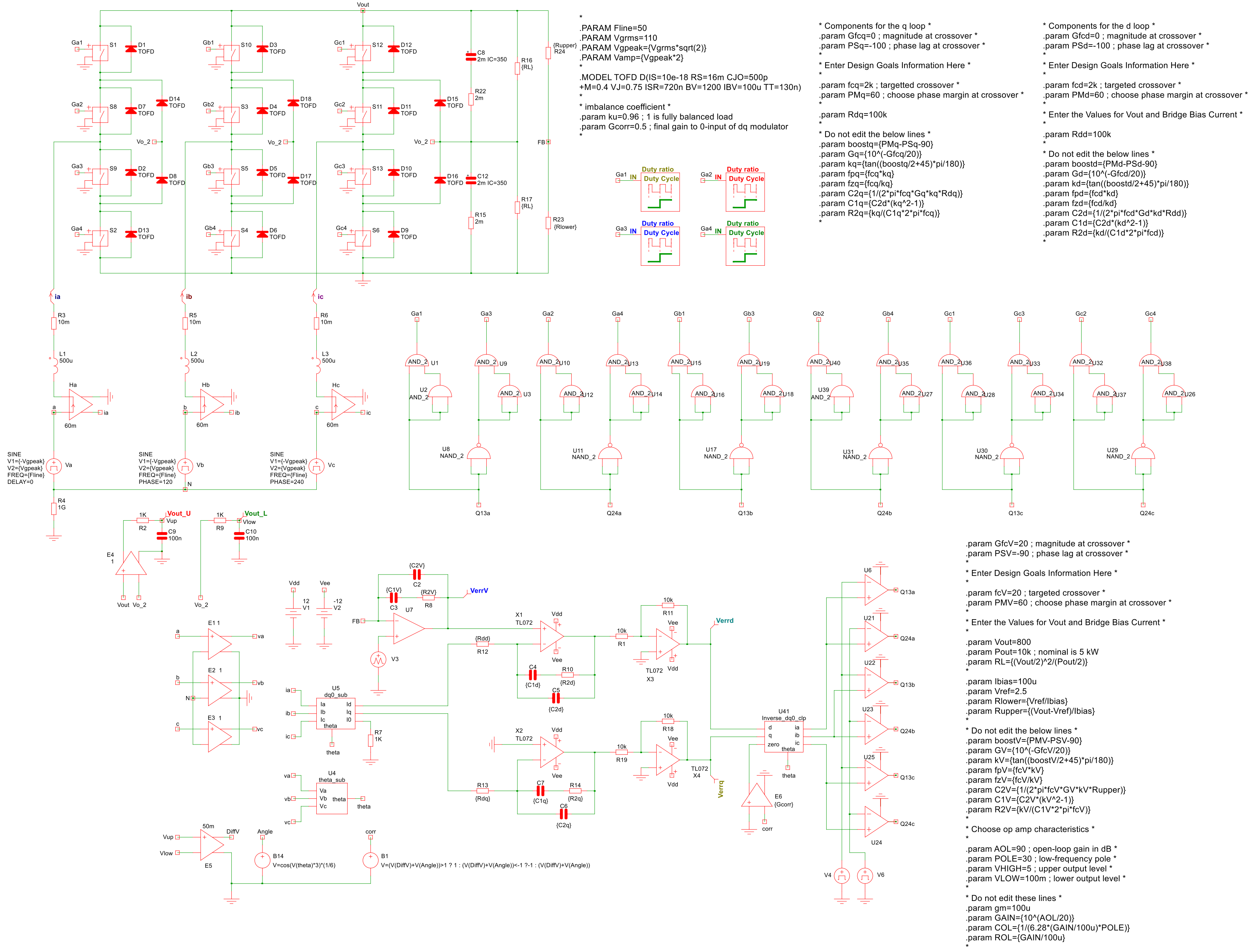


V_{in} = 230 V rms

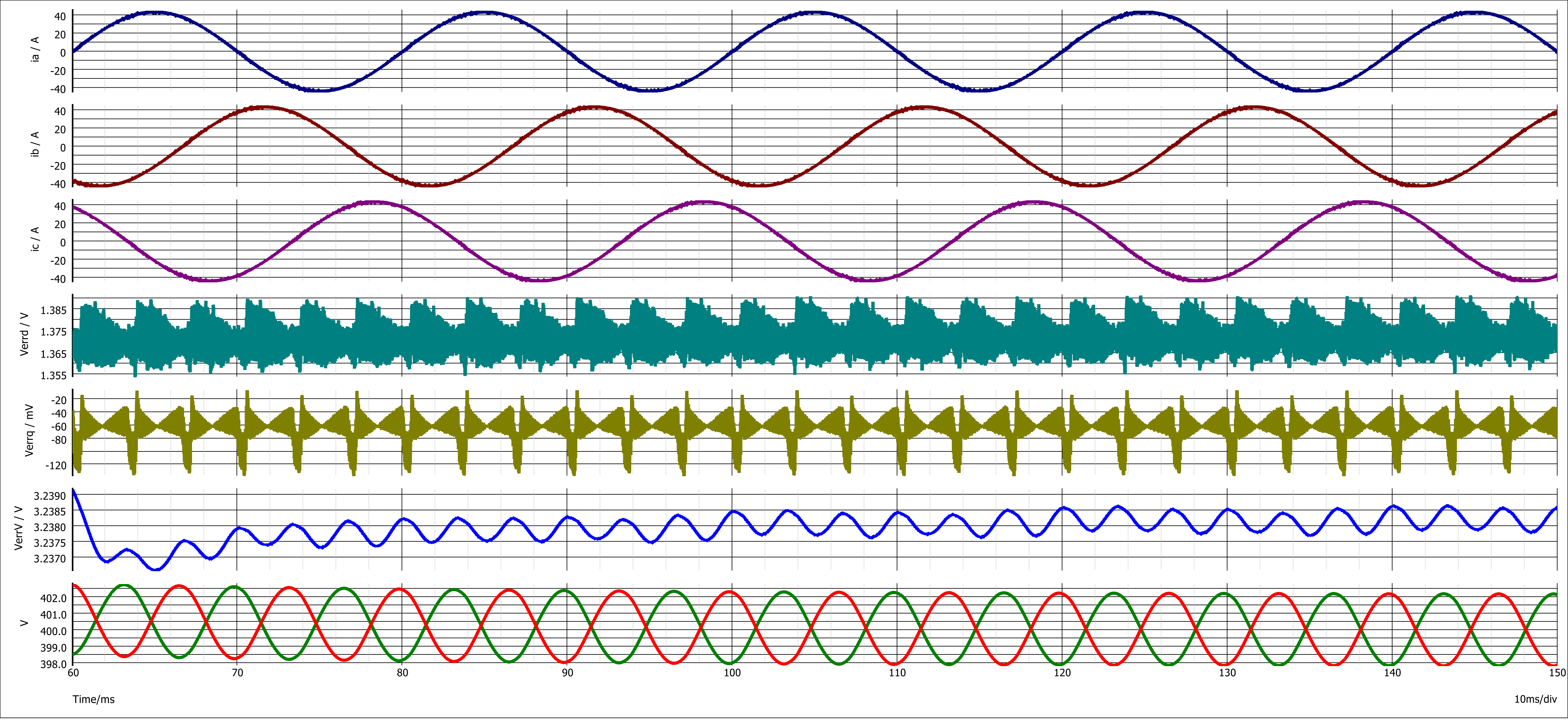
High-line transient step on both outputs, voltages remain well balanced.



V_{in} = 230 V rms

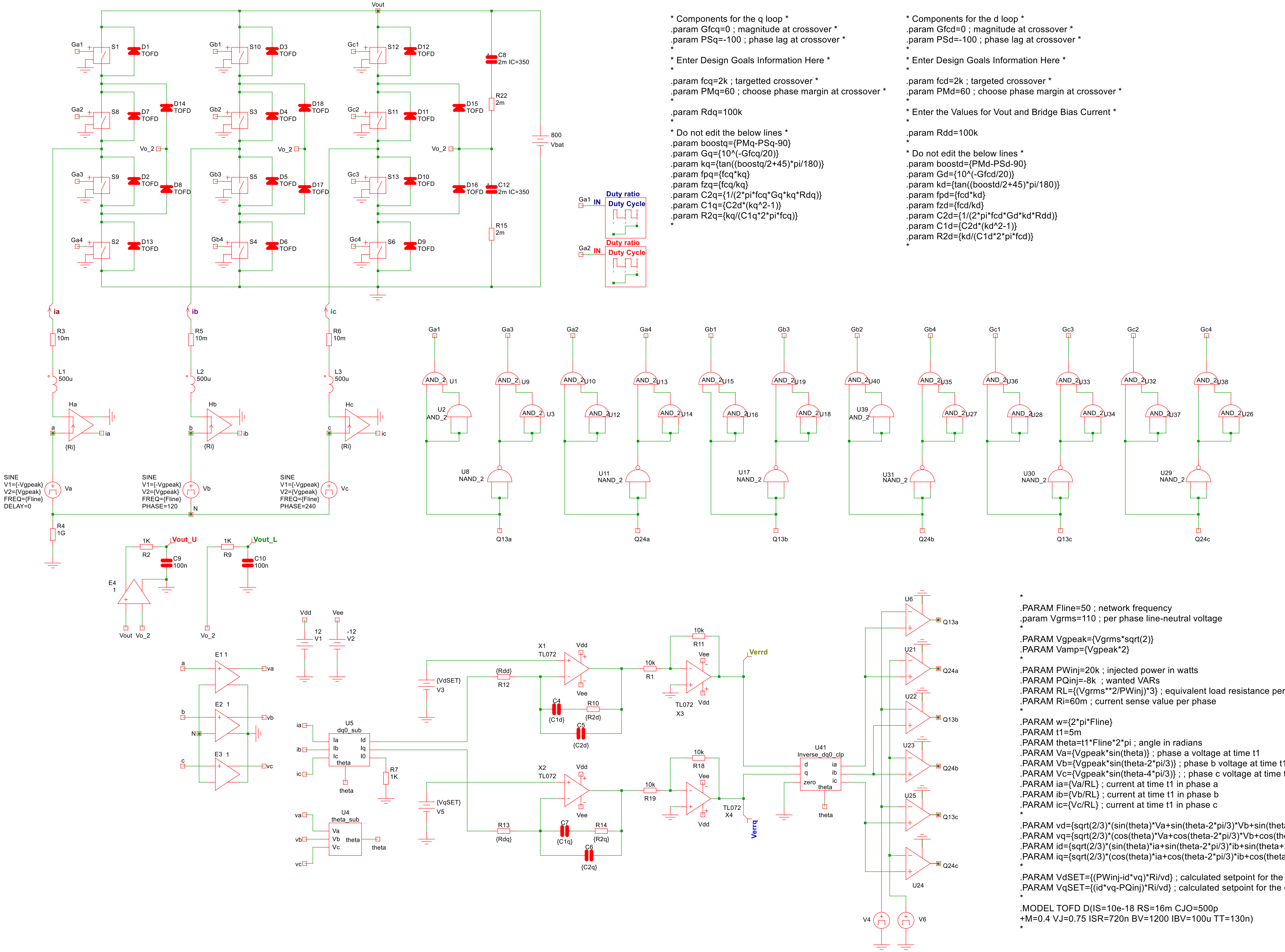


The NPC PFC is also available in SIMetrix and simulates well. The loop for balancing the capacitors is also implemented here.



The two loads are imbalanced by 4% and the loop does its job perfectly by keeping the same 400-V voltage across each output capacitor. The distortion is kept at a low level, V_{in} = 110 V rms and P_{out} = 10 kW.

Curve label	Name	Value
ia	Distortion/cycle	2.18957%
ib	Distortion/cycle	2.02856%
ic	Distortion/cycle	2.01560%



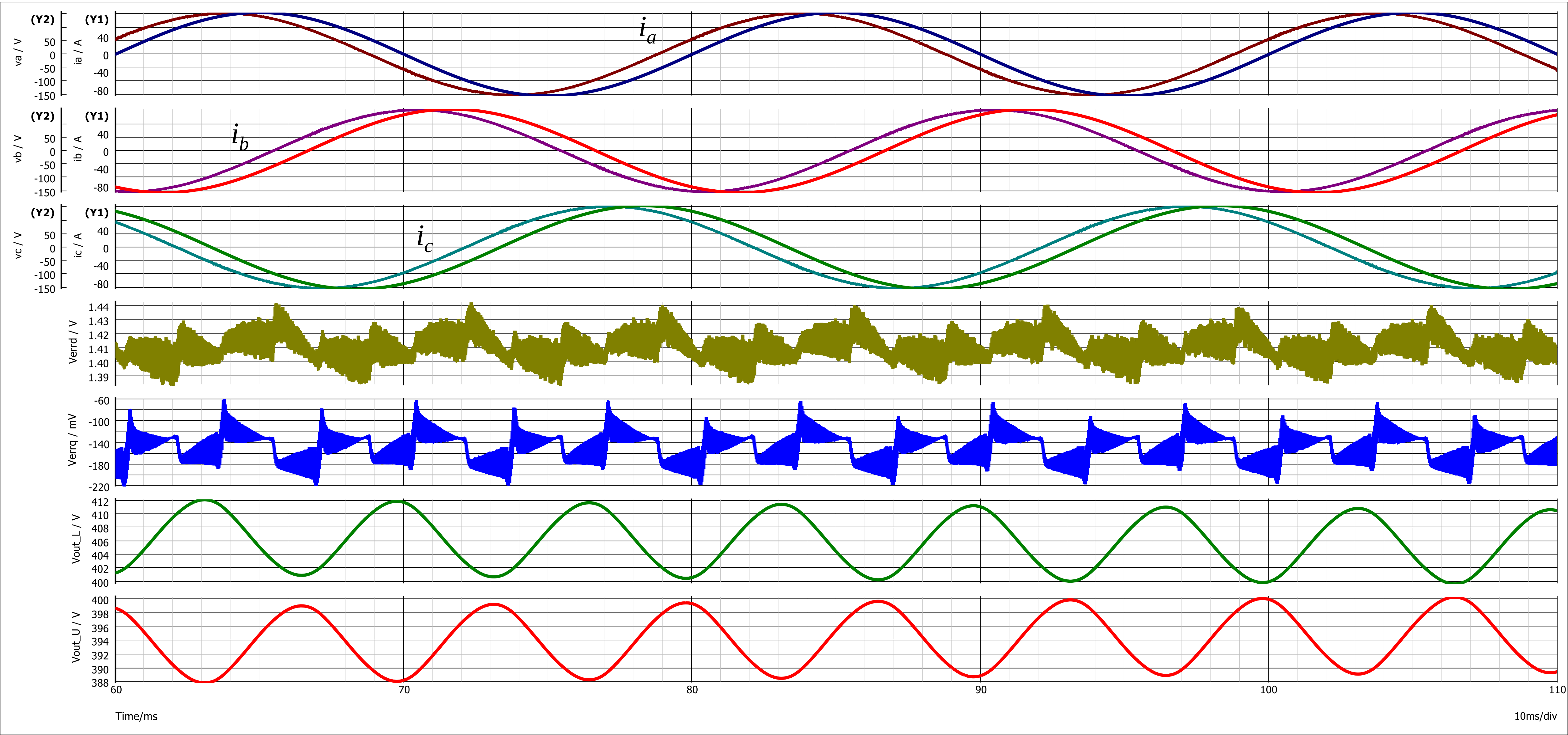
```
* Components for the q loop *
.param Gfcq=0 ; magnitude at crossover *
.param PSq=-100 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcq=2k ; targetted crossover *
.param PMq=60 ; choose phase margin at crossover *
*
.param Rdq=100k
*
* Do not edit the below lines *
.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)}
*
```

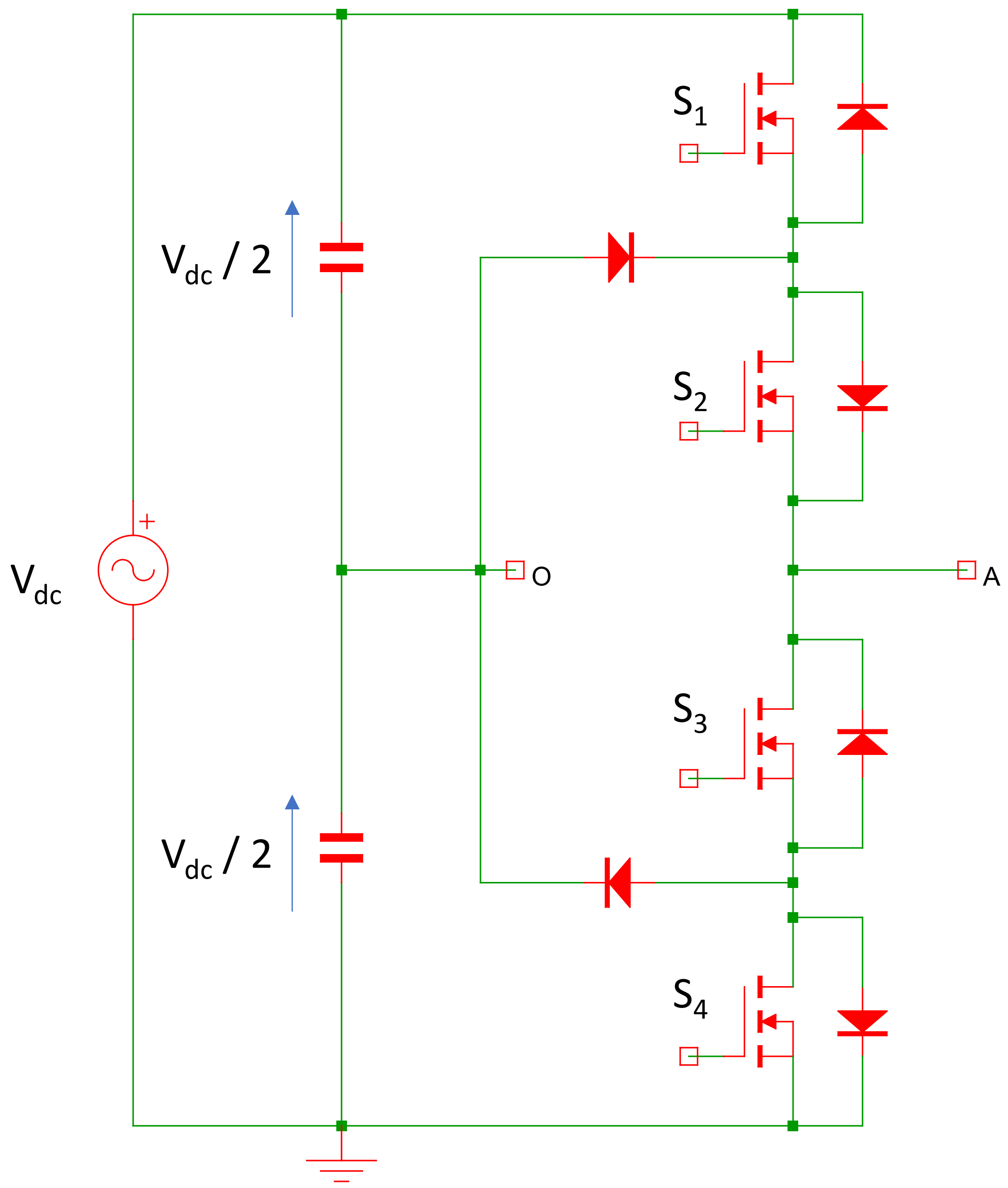
```
* Components for the d loop *
.param Gfcd=0 ; magnitude at crossover *
.param PSd=-100 ; phase lag at crossover *
*
* Enter Design Goals Information Here *
*
.param fcd=2k ; targetted crossover *
.param PMd=60 ; choose phase margin at crossover *
*
* Enter the Values for Vout and Bridge Bias Current *
*
.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)}
*
```

```
*
.PARAM Fline=50 ; network frequency
.param Vgrms=110 ; per phase line-neutral voltage
*
.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=60m ; current sense value per phase
*
.PARAM w={2*pi*Fline}
.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 VdSET={(PWinj-id*vq)*Ri/vd} ; calculated setpoint for the d value
.PARAM VqSET={(id*vq-PQinj)*Ri/vd} ; calculated setpoint for the q value
*
.MODEL TOFD D(IS=10e-18 RS=16m CJO=500p
+M=0.4 VJ=0.75 ISR=720n BV=1200 IBV=100u TT=130n)
*
```

The NPC being a bidirectional converter, I replaced the load by an 800-V battery and I now inject a certain active power (20 kW in this example) while specifying – or + 8 kVARs of reactive power. The choice is made in the macro and d and q are automatically calculated as a parameter passed to the dc setpoints.

The current leads the voltage, the inverter offers a capacitive impedance. Changing the sign of the PQinj parameter would force an inductive impedance, the current then lagging the voltage.





3-level conversion

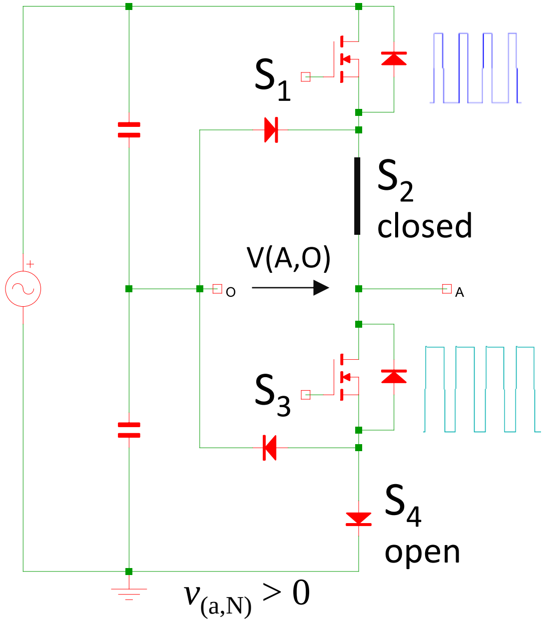
S_1	S_2	$S_3=\overline{S_1}$	$S_4=\overline{S_2}$	V(A,O)
1	1	0	0	V_{dc} / 2
0	1	1	0	0
0	0	1	1	-V_{dc} / 2

Switching states

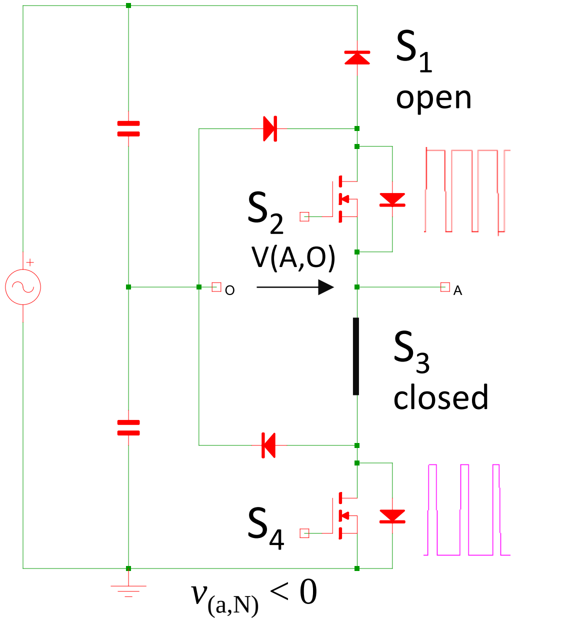
3 switching states for leg A
3 switching states for leg B
3 switching states for leg C

Total are 3 x 3 x 3 =27 states

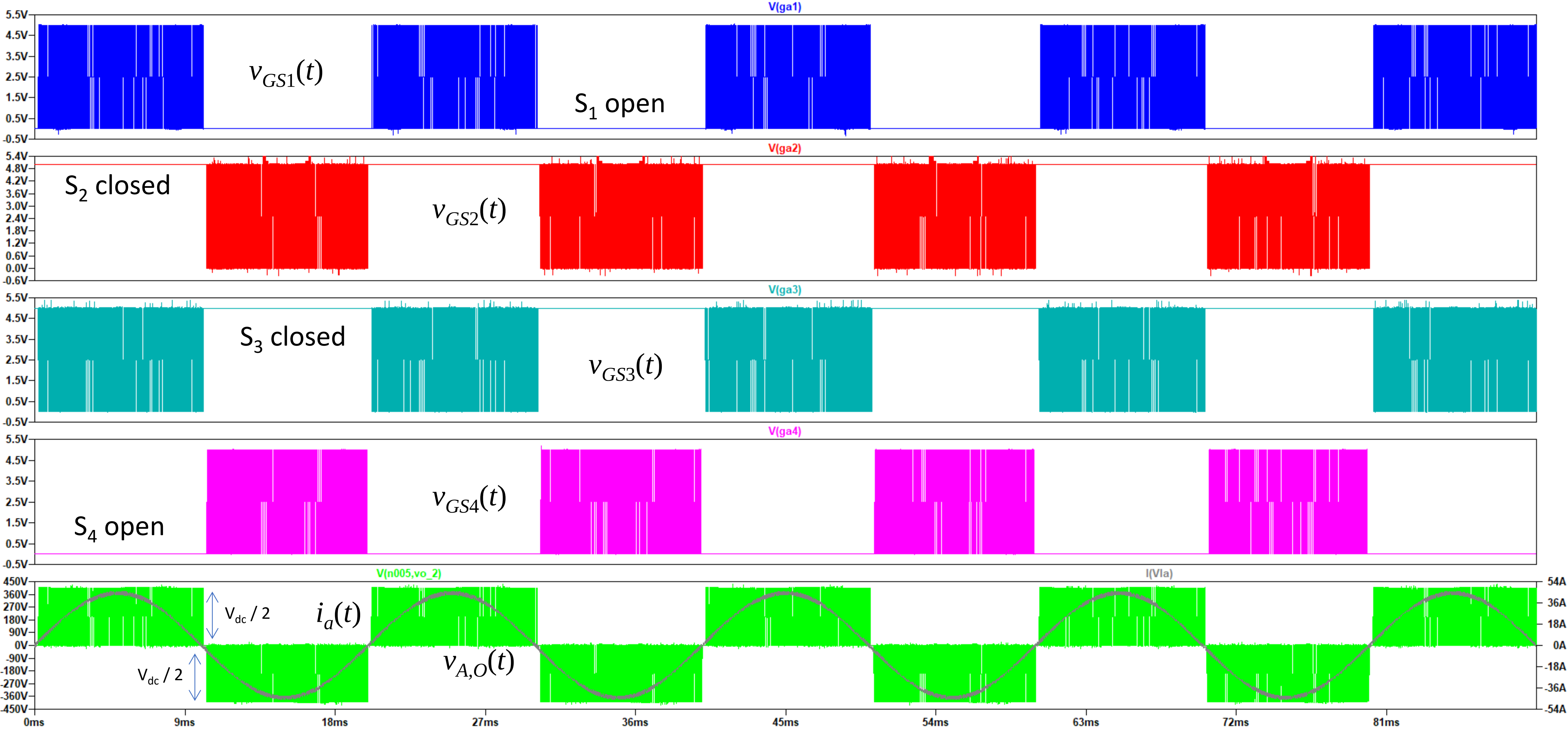
S_1 closed, S_3 open
V(A,O) = $V_{dc}/2$
S_1 open, S_3 closed
V(A,O) = 0



S_2 closed, S_4 open
V(A,O) = 0
S_2 open, S_4 closed
V(A,O) =-$V_{dc}/2$

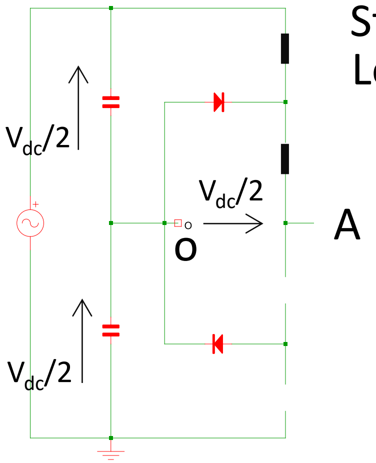


Leg A switching pattern

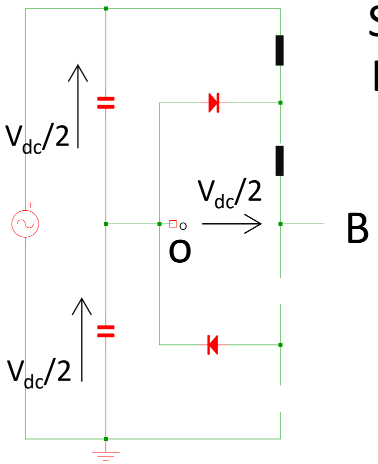


There are 27 vectors when the voltage imposed by any of the three legs is either $V_{dc}/2$, 0 or $-V_{dc}/2$. Consider 6 *large vectors* in which the voltage at node A/B/C and o can only take on $V_{dc}/2$ or $-V_{dc}/2$. Check the video from Mrs. Tabish Mir for more details.

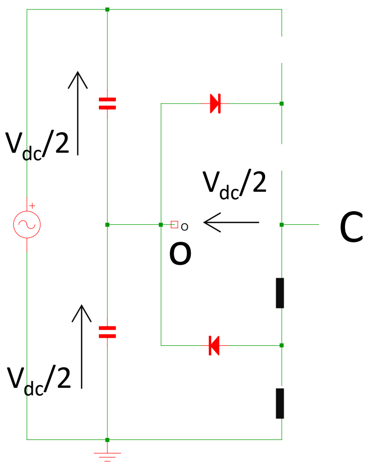
State "+"
Leg A



State "+"
Leg B



State "-"
Leg C



A	B	C
+	+	-
+	-	+
-	+	+
-	-	+
-	+	-
+	-	-

6 large vectors

The reference vector is synthesized by summing the legs voltages:

$$V_{ref} = \frac{2}{3}\left(V_{a,o} + V_{b,o}\angle 120° + V_{c,o}\angle -120°\right) \rightarrow \frac{2}{3}\left(\frac{V_{dc}}{2} + \frac{V_{dc}}{2}\angle 120° - \frac{V_{dc}}{2}\angle -120°\right) \quad \text{for + + -}$$

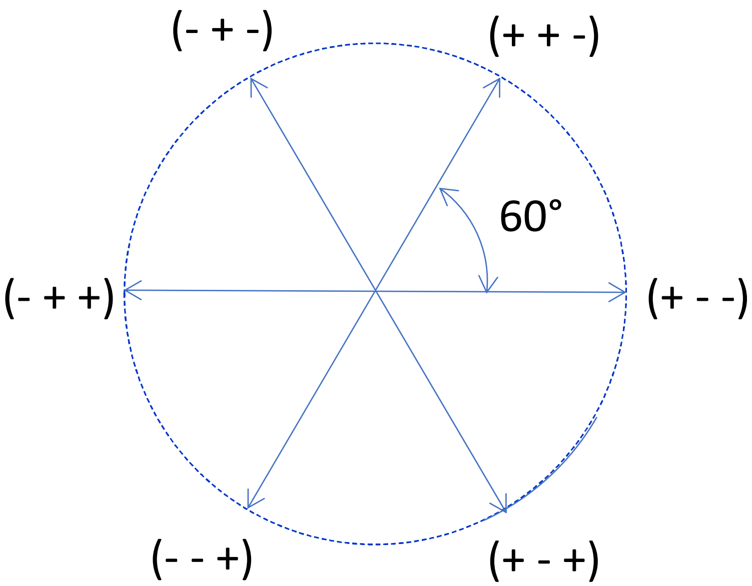
You can synthesize the vectors with Mathcad and it's cool :)

A	B	C
+	+	-
+	-	+
-	+	+
-	-	+
-	+	-
+	-	-

2/3

leg A, leg B, leg C	Complex equivalent	Argument	Magnitude	Polar coordinates
$\frac{2}{3}\cdot\left[\frac{V_{dc}}{2}+\left(\frac{V_{dc}}{2}\right)\angle(120°)-\left(\frac{V_{dc}}{2}\right)\angle(-120°)\right]$	$\rightarrow \frac{V_{dc}}{3}+\frac{2i\cdot V_{dc}\cdot\sin(120\cdot°)}{3}$	$\arg\left(\frac{1}{3}+\frac{2i\cdot 1\cdot\sin(120\cdot°)}{3}\right)=60°$	$\left\lvert\frac{1}{3}+\frac{2i\cdot 1\cdot\sin(120\cdot°)}{3}\right\rvert=0.667$	$\vec{V}_{ref}=\frac{2}{3}V_{dc}\angle 60°$
$\frac{2}{3}\cdot\left[\frac{V_{dc}}{2}-\left(\frac{V_{dc}}{2}\right)\angle(120°)+\left(\frac{V_{dc}}{2}\right)\angle(-120°)\right]$	$\rightarrow \frac{V_{dc}}{3}-\frac{2i\cdot V_{dc}\cdot\sin(120\cdot°)}{3}$	$\arg\left(\frac{1}{3}-\frac{2i\cdot 1\cdot\sin(120\cdot°)}{3}\right)=-60°$	$\left\lvert\frac{1}{3}-\frac{2i\cdot 1\cdot\sin(120\cdot°)}{3}\right\rvert=0.667$	$\vec{V}_{ref}=\frac{2}{3}V_{dc}\angle -60°$
$\frac{2}{3}\cdot\left[-\frac{V_{dc}}{2}+\left(\frac{V_{dc}}{2}\right)\angle(120°)+\left(\frac{V_{dc}}{2}\right)\angle(-120°)\right]$	$\rightarrow \frac{2\cdot V_{dc}\cdot\cos(120\cdot°)}{3}-\frac{V_{dc}}{3}$	$\arg\left(\frac{2\cdot 1\cdot\cos(120\cdot°)}{3}-\frac{1}{3}\right)=180°$	$\left\lvert\frac{2\cdot 1\cdot\cos(120\cdot°)}{3}-\frac{1}{3}\right\rvert=0.667$	$\vec{V}_{ref}=\frac{2}{3}V_{dc}\angle 180°$
$\frac{2}{3}\cdot\left[-\frac{V_{dc}}{2}-\left(\frac{V_{dc}}{2}\right)\angle(120°)+\left(\frac{V_{dc}}{2}\right)\angle(-120°)\right]$	$\rightarrow -\frac{V_{dc}}{3}-\frac{2i\cdot V_{dc}\cdot\sin(120\cdot°)}{3}$	$\arg\left(-\frac{1}{3}-\frac{2i\cdot 1\cdot\sin(120\cdot°)}{3}\right)=-120°$	$\left\lvert-\frac{1}{3}-\frac{2i\cdot 1\cdot\sin(120\cdot°)}{3}\right\rvert=0.667$	$\vec{V}_{ref}=\frac{2}{3}V_{dc}\angle -120°$
$\frac{2}{3}\cdot\left[-\frac{V_{dc}}{2}+\left(\frac{V_{dc}}{2}\right)\angle(120°)-\left(\frac{V_{dc}}{2}\right)\angle(-120°)\right]$	$\rightarrow -\frac{V_{dc}}{3}+\frac{2i\cdot V_{dc}\cdot\sin(120\cdot°)}{3}$	$\arg\left(-\frac{1}{3}+\frac{2i\cdot 1\cdot\sin(120\cdot°)}{3}\right)=120°$	$\left\lvert-\frac{1}{3}+\frac{2i\cdot 1\cdot\sin(120\cdot°)}{3}\right\rvert=0.667$	$\vec{V}_{ref}=\frac{2}{3}V_{dc}\angle 120°$
$\frac{2}{3}\cdot\left[\frac{V_{dc}}{2}-\left(\frac{V_{dc}}{2}\right)\angle(120°)-\left(\frac{V_{dc}}{2}\right)\angle(-120°)\right]$	$\rightarrow \frac{V_{dc}}{3}-\frac{2\cdot V_{dc}\cdot\cos(120\cdot°)}{3}$	$\arg\left(\frac{1}{3}-\frac{2\cdot 1\cdot\cos(120\cdot°)}{3}\right)=0°$	$\left\lvert\frac{1}{3}-\frac{2\cdot 1\cdot\cos(120\cdot°)}{3}\right\rvert=0.667$	$\vec{V}_{ref}=\frac{2}{3}V_{dc}\angle 0°$

Large vectors: largest possible magnitude is $2V_{dc}/3$

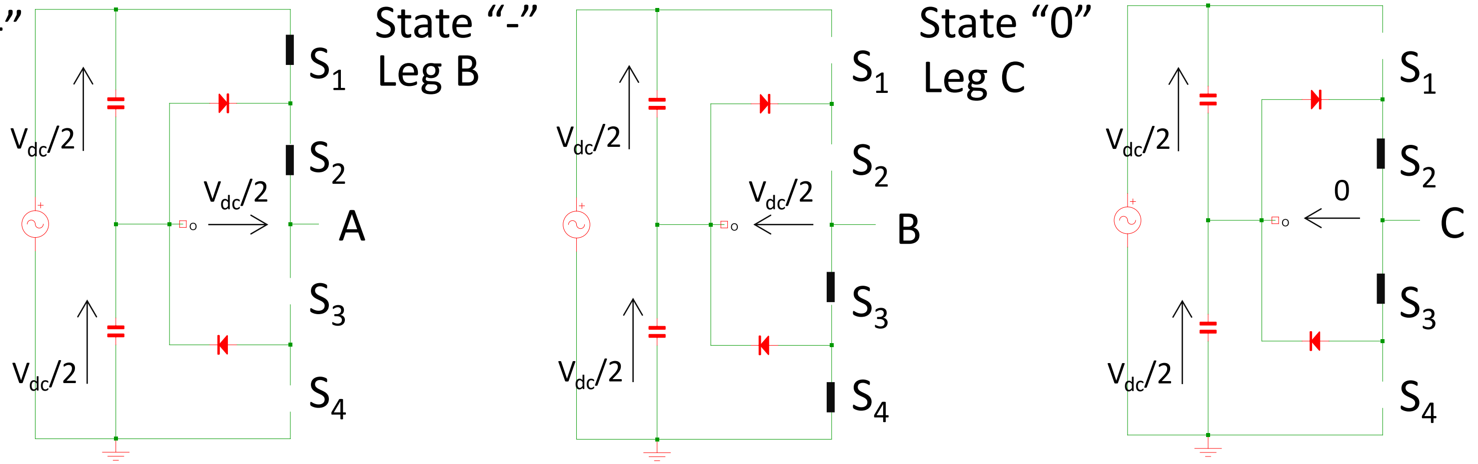


Now consider 6 *medium vectors* in which the voltage at node A/B/C and o now includes 0 V, $V_{dc}/2$ and $–V_{dc}/2$.

State "+" Leg A

State "-" Leg B

State "0" Leg C



A	B	C
+	-	0
-	+	0
0	+	-
0	-	+
+	0	-
-	0	+

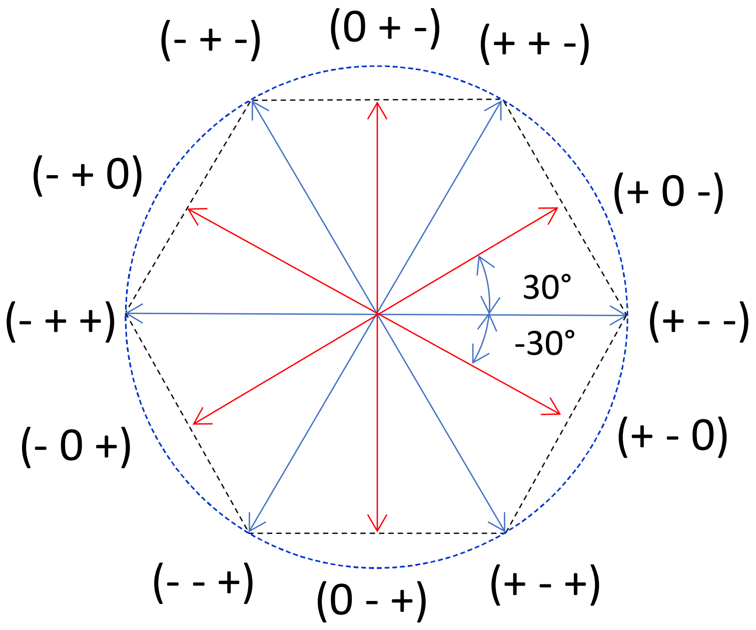
6 medium vectors

The reference vector is synthesized by summing the legs voltages:

$$V_{ref} = \frac{2}{3}\left(V_{a,o} + V_{b,o}\angle 120° + V_{c,o}\angle -120°\right) \to \frac{2}{3}\left(\frac{V_{dc}}{2} - \frac{V_{dc}}{2}\angle 120° + 0\right) \quad \text{for + - 0}$$

A	B	C	leg A, leg B, leg C → Complex equivalent	Magnitude	Argument	Polar coordinates
+	-	0	$\frac{2}{3}\cdot\left[\frac{V_{dc}}{2} - \left(\frac{V_{dc}}{2}\right)\angle(120°) - 0\right] \to \frac{1}{3} - \frac{\cos(120\cdot°)}{3} - \frac{\sin(120\cdot°)\cdot i}{3}$	$\left\lvert\frac{1}{3} - \frac{\cos(120\cdot°)}{3} - \frac{\sin(120\cdot°)\cdot i}{3}\right\rvert = 0.577$	$\arg\left(\frac{1}{3} - \frac{\cos(120\cdot°)}{3} - \frac{\sin(120\cdot°)\cdot i}{3}\right) = -30°$	$\vec{V}_{ref} = \frac{1}{\sqrt{3}}V_{dc}\angle -30°$
-	+	0	$\frac{2}{3}\cdot\left[-\frac{V_{dc}}{2} + \left(\frac{V_{dc}}{2}\right)\angle(120°) - 0\right] \to \frac{\cos(120\cdot°)}{3} - \frac{1}{3} + \frac{\sin(120\cdot°)\cdot i}{3}$	$\left\lvert\frac{\cos(120\cdot°)}{3} - \frac{1}{3} + \frac{\sin(120\cdot°)\cdot i}{3}\right\rvert = 0.577$	$\arg\left(\frac{\cos(120\cdot°)}{3} - \frac{1}{3} + \frac{\sin(120\cdot°)\cdot i}{3}\right) = 150°$	$\vec{V}_{ref} = \frac{1}{\sqrt{3}}V_{dc}\angle 150°$
0	+	-	$\frac{2}{3}\cdot\left[0 + \left(\frac{V_{dc}}{2}\right)\angle(120°) - \left(\frac{V_{dc}}{2}\right)\angle(-120°)\right] \to \frac{2i\cdot\sin(120\cdot°)}{3}$	$\left\lvert\frac{2i\cdot\sin(120\cdot°)}{3}\right\rvert = 0.577$	$\arg\left(\frac{2i\cdot\sin(120\cdot°)}{3}\right) = 90°$	$\vec{V}_{ref} = \frac{1}{\sqrt{3}}V_{dc}\angle 90°$
0	-	+	$\frac{2}{3}\cdot\left[0 - \left(\frac{V_{dc}}{2}\right)\angle(120°) + \left(\frac{V_{dc}}{2}\right)\angle(-120°)\right] \to -\frac{2i\cdot\sin(120\cdot°)}{3}$	$\left\lvert-\frac{2i\cdot\sin(120\cdot°)}{3}\right\rvert = 0.577$	$\arg\left(-\frac{2i\cdot\sin(120\cdot°)}{3}\right) = -90°$	$\vec{V}_{ref} = \frac{1}{\sqrt{3}}V_{dc}\angle -90°$
+	0	-	$\frac{2}{3}\cdot\left[\left[\frac{V_{dc}}{2} - (0)\angle(120°)\right] - \left(\frac{V_{dc}}{2}\right)\angle(-120°)\right] \to \frac{1}{3} - \frac{\cos(120\cdot°)}{3} + \frac{\sin(120\cdot°)\cdot i}{3}$	$\left\lvert\frac{1}{3} - \frac{\cos(120\cdot°)}{3} + \frac{\sin(120\cdot°)\cdot i}{3}\right\rvert = 0.577$	$\arg\left(\frac{1}{3} - \frac{\cos(120\cdot°)}{3} + \frac{\sin(120\cdot°)\cdot i}{3}\right) = 30°$	$\vec{V}_{ref} = \frac{1}{\sqrt{3}}V_{dc}\angle 30°$
-	0	+	$\frac{2}{3}\cdot\left[\left[-\frac{V_{dc}}{2} - (0)\angle(120°)\right] + \left(\frac{V_{dc}}{2}\right)\angle(-120°)\right] \to \frac{\cos(120\cdot°)}{3} - \frac{1}{3} - \frac{\sin(120\cdot°)\cdot i}{3}$	$\left\lvert\frac{\cos(120\cdot°)}{3} - \frac{1}{3} - \frac{\sin(120\cdot°)\cdot i}{3}\right\rvert = 0.577$	$\arg\left(\frac{\cos(120\cdot°)}{3} - \frac{1}{3} - \frac{\sin(120\cdot°)\cdot i}{3}\right) = -150°$	$\vec{V}_{ref} = \frac{1}{\sqrt{3}}V_{dc}\angle -150°$

6 medium vectors



Medium vectors: largest possible magnitude is $V_{dc}/\sqrt{3}$

Compared to the 2-level hexagon which has 6 quadrants, there are now 12 points for sampling the circle: granularity is improved.

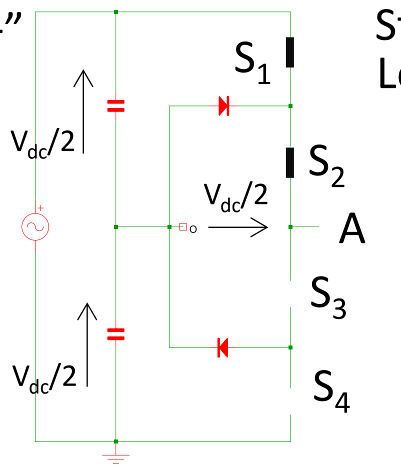
Now consider 12 *small vectors* in which the voltage at node A/B/C and o now includes 0 V and $V_{dc}/2$ but also 0 and $-V_{dc}/2$.

Length of long vector is $2V_{dc}/3$

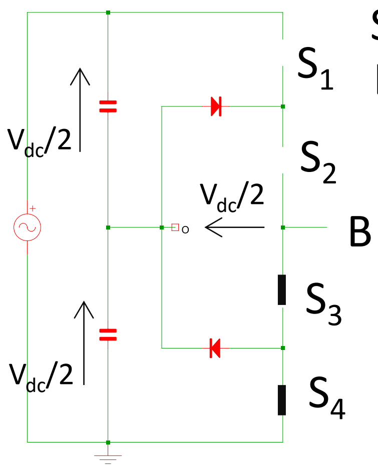
Length of medium vector is $V_{dc}/\sqrt{3}$

Length of small vector is $V_{dc}/3$ (they are along the large vectors but if half length)

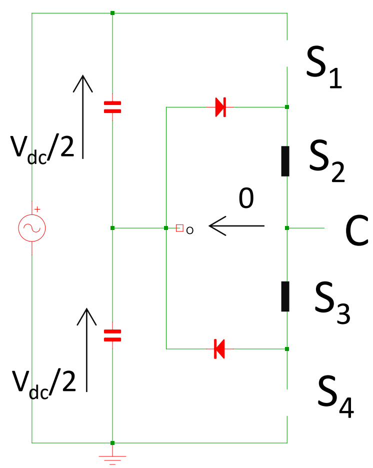
State "+" Leg A



State "-" Leg B



State "0" Leg C



A	B	C
+	0	0
0	+	0
0	0	+
+	+	0
+	0	+
0	0	+

SV2

SV1

6 short vectors

$$\frac{2}{3}\cdot\left[\left[\frac{V_{dc}}{2} - (0)\angle(120°)\right] + (0)\angle(-120°)\right] \rightarrow \frac{1}{3}$$

Redundancy in vectors: 12 switching states but 6 vectors produced

SV2'

SV1'

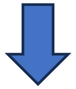
A	B	C
0	-	-
-	0	-
-	-	0
0	0	-
0	-	0
-	-	0

6 short vectors

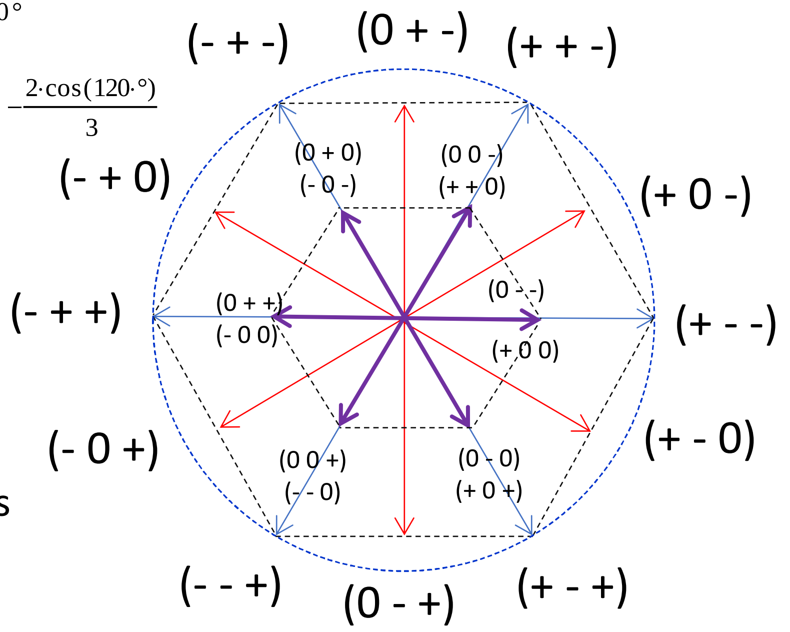
$$\left|-\frac{2\cdot\cos(120\cdot°)}{3}\right| = 0.333 \qquad \arg\left(-\frac{2\cdot\cos(120\cdot°)}{3}\right) = 0°$$

$$\frac{2}{3}\cdot\left[\left[0 - \left(\frac{V_{dc}}{2}\right)\angle(120°)\right] - \left(\frac{V_{dc}}{2}\right)\angle(-120°)\right] \rightarrow -\frac{2\cdot\cos(120\cdot°)}{3}$$

Here, the + 0 0 and 0 - - combinations lead to the same vector, 0.33 ∠0°

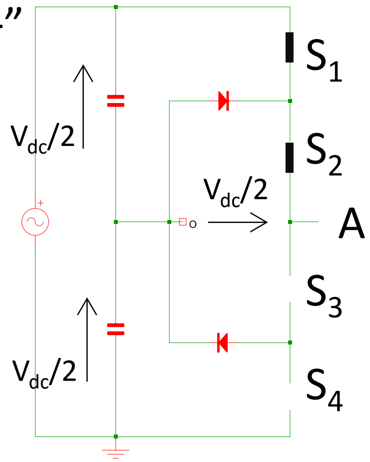


Choice in switching states helps to meet a certain strategy, like voltage balancing for instance.

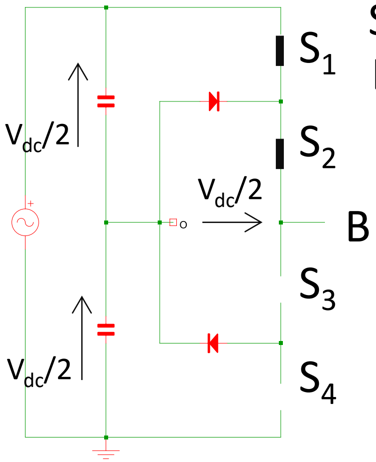


Now consider 3 *zero vectors* in which the voltage at nodes A/B/C and o is equal three times to either 0 V, $V_{dc}/2$ or $-V_{dc}/2$

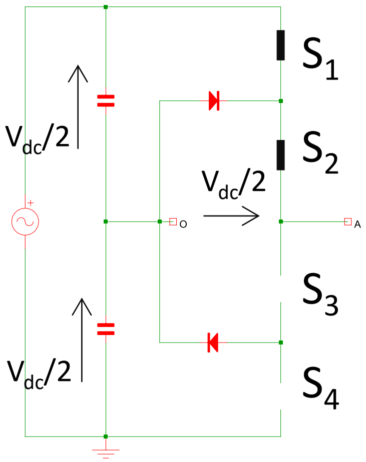
State "+" Leg A



State "+" Leg B



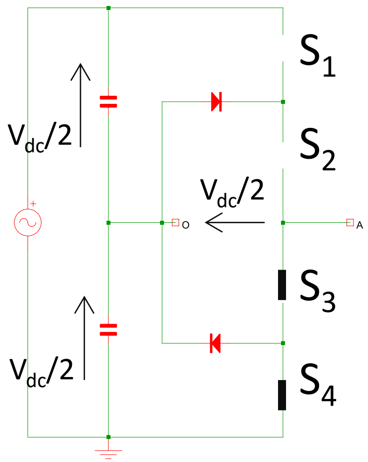
State "+" Leg C



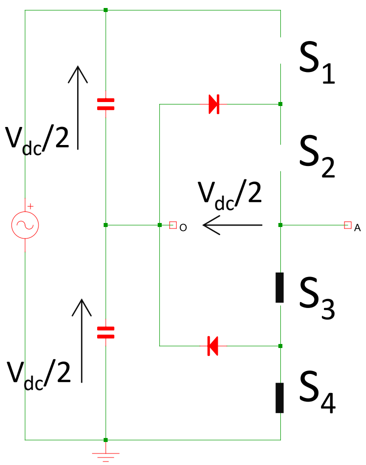
A	B	C
+	+	+
-	-	-
0	0	0

3 zero vectors ●

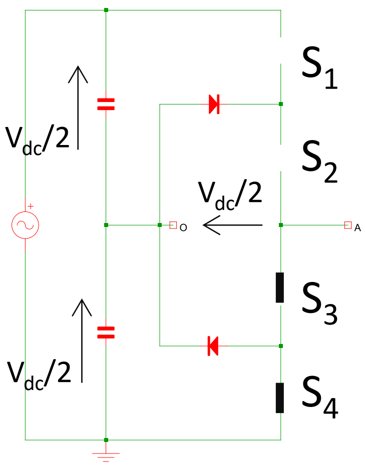
State "-" Leg A

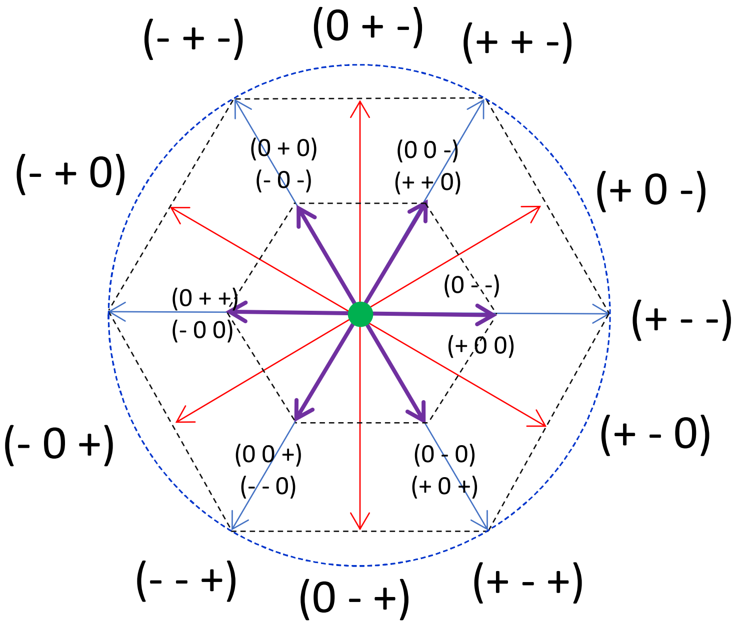


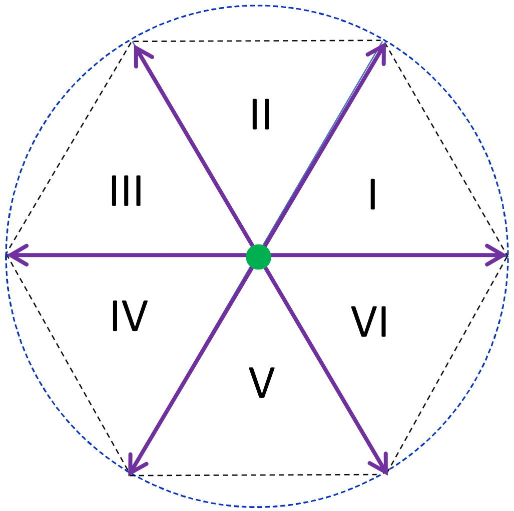
State "-" Leg B



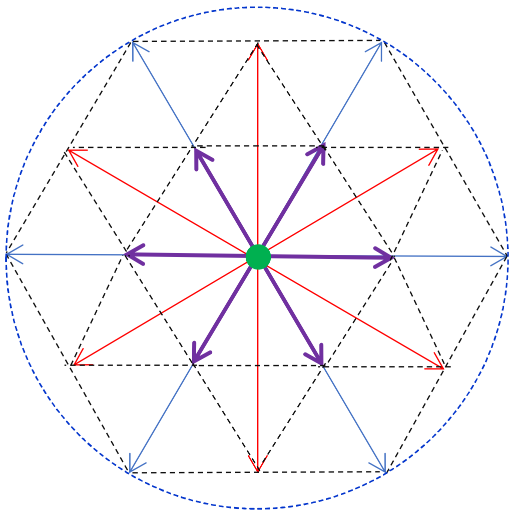
State "-" Leg C





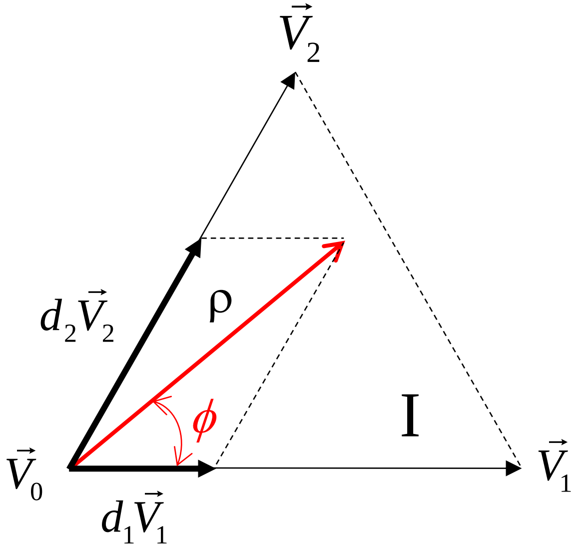


More choices in a 3-level type (27 states)



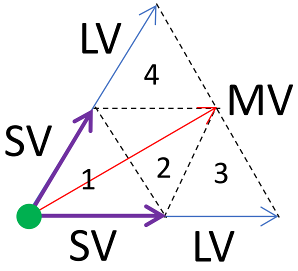
In a three-level converter, 19 positions are available to synthetize the reference vector (18 plus the 0). Redundancy also exists for different strategies.

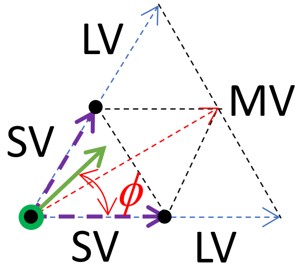
In a two-level converter, only 7 positions are available to synthetize the reference vector (6 large vectors plus the 0).



To synthesize the same vector in the 3-level inverter, you now have access to two small vectors (2 switching states for each), two large vectors (1 switching state for each) and then 2 medium vectors (1 switching state for each). You obtain a better resolution.

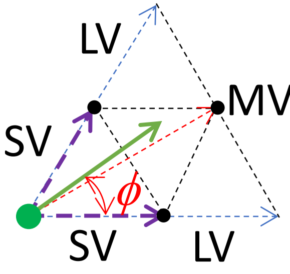
You have to identify the region where the reference vector appears.





Combine 0, SV, SV

Example 1



Combine SV, MV, SV

Example 2

Determine the triangle region where the reference vector appears and choose the closest switching states to synthesize its magnitude and angle. You will average the vector by combining the switching states durations:

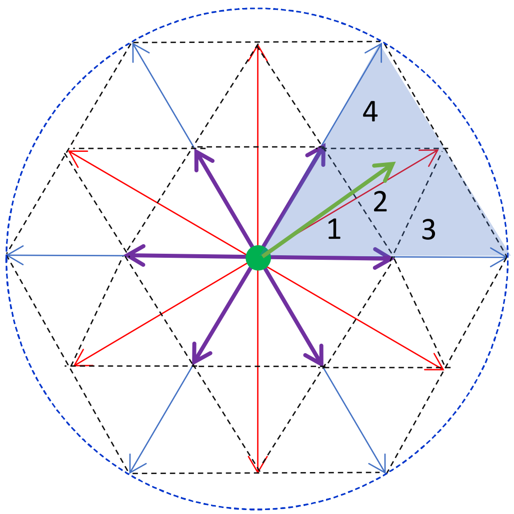
SV MV SV

$$\left[V_{ref}\angle\phi\right]\cdot T_{sw}=\frac{V_{dc}}{3}t_a+\left[\frac{V_{dc}}{\sqrt{3}}\angle 30°\right]\cdot t_b+\left[\frac{V_{dc}}{3}\angle 60°\right]\cdot t_c$$

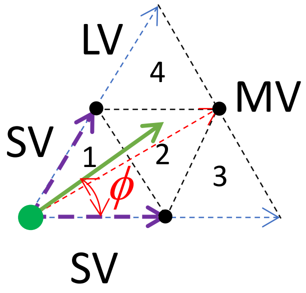
$$t_a+t_b+t_c=T_{sw}$$

This is the wanted vector

The hexagon is made of 6 sectors (long vectors every 60°), it self made of smaller hexagons. To calculate the dwell times, one has to know in which triangle the reference vector lies.



Assume V_{ref} is in sector I

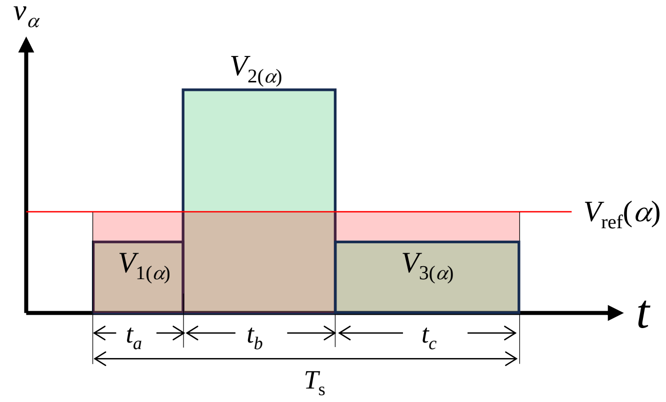


You will combine the three vectors available at the triangle junctions. In this example, the reference vector lies in sub-triangle 2 and can be described by weighting SV and MV vectors. If it lied in sub-triangle 1, then synthesizing it would require time on the zero and short/small vectors. The total duration equals the switching period T_{sw}. We have these two equations and three unknowns:

$$\left[V_{ref}\angle\phi\right]\cdot T_{sw} = \frac{V_{dc}}{3}t_a + \left[\frac{V_{dc}}{\sqrt{3}}\angle 30°\right]\cdot t_b + \left[\frac{V_{dc}}{3}\angle 60°\right]\cdot t_c$$

Extract real and imaginary parts then equate them (3 equations)

$$T_{sw} = t_a + t_b + t_c \rightarrow 1 = d_1 + d_2 + d_3$$



$$\int_0^{T_{sw}} \vec{V}_{ref}\,dt = \int_0^{t_a} \vec{V}_{\mathrm{LV}}\,dt + \int_{t_a}^{t_b} \vec{V}_{\mathrm{MV}}\,dt + \int_{t_a+t_b}^{T_{sw}} \vec{V}_{\mathrm{LV}}\,dt$$

$$\left\|\vec{V}_{ref}\right\| T_{sw} = \left\|\vec{V}_{\mathrm{LV}}\right\| t_a + \left\|\vec{V}_{\mathrm{MV}}\right\| t_b + \left\|\vec{V}_{\mathrm{MV}}\right\| t_c$$

$$T_{sw}\cdot\left(V_{ref}\cdot\cos(\phi) + V_{ref}\cdot i\cdot\sin(\phi)\right) = \frac{V_{dc}}{3}\cdot t_a + \left(\frac{V_{dc}}{\sqrt{3}}\cdot\cos(30°) + \frac{V_{dc}}{\sqrt{3}}\cdot i\cdot\sin(30°)\right)\cdot t_b + \left(\frac{V_{dc}}{3}\cdot\cos(60°) + \frac{V_{dc}}{3}\cdot i\cdot\sin(60°)\right)\cdot t_c$$

$$T_{sw}\cdot\left(V_{ref}\cdot\cos(\phi) + V_{ref}\cdot i\cdot\sin(\phi)\right) = \frac{V_{dc}}{3}\cdot t_a + \left(\frac{V_{dc}}{\sqrt{3}}\cdot\cos\left(\frac{\pi}{6}\right) + \frac{V_{dc}}{\sqrt{3}}\cdot i\cdot\sin\left(\frac{\pi}{6}\right)\right)\cdot t_b + \left(\frac{V_{dc}}{3}\cdot\cos\left(\frac{\pi}{3}\right) + \frac{V_{dc}}{3}\cdot i\cdot\sin\left(\frac{\pi}{3}\right)\right)\cdot t_c$$ in radians

$$T_{sw}\cdot\left(V_{ref}\cdot\cos(\phi) + V_{ref}\cdot\sin(\phi)\cdot i\right) = \frac{V_{dc}\cdot t_a}{3} + t_b\cdot\left(\frac{V_{dc}}{2} + \frac{\sqrt{3}\cdot V_{dc}\cdot i}{6}\right) + t_c\cdot\left(\frac{V_{dc}}{6} + \frac{\sqrt{3}\cdot V_{dc}\cdot i}{6}\right)$$ group real and imaginary

$$T_{sw}\cdot\left(V_{ref}\cdot\cos(\phi)\right) = \frac{V_{dc}}{3}\cdot t_a + \frac{V_{dc}}{\sqrt{3}}\cdot\cos(30°)\cdot t_b + \frac{V_{dc}}{3}\cdot\cos(60°)\cdot t_c$$ real part

$$T_{sw}\cdot\left(V_{ref}\cdot i\cdot\sin(\phi)\right) = \frac{V_{dc}}{\sqrt{3}}\cdot i\cdot\sin(30°)\cdot t_b + \frac{V_{dc}}{3}\cdot i\cdot\sin(60°)\cdot t_c$$ imaginary part

$$t_a + t_b + t_c = T_{sw}$$

3 equations

Given

$$T_{sw}\cdot(V_{ref}\cdot\cos(\theta)) = \frac{V_{dc}}{3}\cdot t_a + \frac{V_{dc}}{\sqrt{3}}\cdot\frac{\sqrt{3}}{2}\cdot t_b + \frac{V_{dc}}{3}\cdot\frac{1}{2}\cdot t_c$$

$$T_{sw}\cdot(V_{ref}\cdot i\cdot\sin(\theta)) = \frac{V_{dc}}{\sqrt{3}}\cdot i\cdot\frac{1}{2}\cdot t_b + \frac{V_{dc}}{3}\cdot i\cdot\frac{\sqrt{3}}{2}\cdot t_c$$

$$t_a + t_b + t_c = T_{sw}$$

$$t_a := \frac{T_{sw}\cdot\left(V_{dc} - 2\cdot\sqrt{3}\cdot V_{ref}\cdot\sin(\theta)\right)}{V_{dc}}$$

$$t_b := \frac{T_{sw}\cdot\left(3\cdot V_{ref}\cdot\cos(\theta) - V_{dc} + \sqrt{3}\cdot V_{ref}\cdot\sin(\theta)\right)}{V_{dc}}$$

$$t_c := \frac{T_{sw}\cdot\left(V_{dc} - 3\cdot V_{ref}\cdot\cos(\theta) + \sqrt{3}\cdot V_{ref}\cdot\sin(\theta)\right)}{V_{dc}}$$

Assume the following instantaneous values

$V_{in} := 230V$ rms value $\quad F_{line} := 50Hz$

$\omega := 2\cdot\pi\cdot F_{line} \quad t_1 := 6ms$

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

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

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

This is the 3-phase input voltage

$v_a(t_1) = 309.349\,V \quad v_b(t_1) = -67.627\,V \quad v_c(t_1) = -241.722\,V$

These are the values of v_a, v_b and v_c at 6 ms. How to synthesize the corresponding vector in $\alpha\beta$ coordinates?

$$V_\alpha(t) := \frac{2}{3}\cdot\left(v_a(t) - \frac{1}{2}\cdot v_b(t) - \frac{1}{2}\cdot v_c(t)\right) \qquad V_\beta(t) := \frac{2}{3}\cdot\left(0\cdot v_a(t) + \frac{\sqrt{3}}{2}\cdot v_b(t) - \frac{\sqrt{3}}{2}\cdot v_c(t)\right)$$

$V_\alpha(t_1) = 309.349\,V \quad V_\beta(t_1) = 100.514\,V$

$V_{ref} := \left|V_\alpha(t_1) + i\cdot V_\beta(t_1)\right| = 325.269\,V$

It is the vector to be synthetized by SVM in the alpha-beta reference frame.

$\theta := \arg\left(V_\alpha(t_1) + i\cdot V_\beta(t_1)\right) = 18\cdot°$

$$t_a := \frac{T_{sw}\cdot\left(V_{dc} - 2\cdot\sqrt{3}\cdot V_{ref}\cdot\sin(\theta)\right)}{V_{dc}} = 18.825\cdot\mu s$$

$$t_b := \frac{T_{sw}\cdot\left(3\cdot V_{ref}\cdot\cos(\theta) - V_{dc} + \sqrt{3}\cdot V_{ref}\cdot\sin(\theta)\right)}{V_{dc}} = 12.589\cdot\mu s$$

$$t_c := \frac{T_{sw}\cdot\left(V_{dc} - 3\cdot V_{ref}\cdot\cos(\theta) + \sqrt{3}\cdot V_{ref}\cdot\sin(\theta)\right)}{V_{dc}} = 1.919\cdot\mu s$$

$F_{sw} := 30kHz$

$T_{sw} := \frac{1}{F_{sw}} = 33.333\cdot\mu s$

$V_{dc} := 800V$

$t_a + t_b + t_c = 33.333\cdot\mu s$

The Ranit Sengupta in this video came up with different definitions for the three timings but ended up in identical results:

$$m_n := \frac{V_{ref}}{V_{dc} \cdot \frac{2}{3}} = 0.61$$ Modulation index

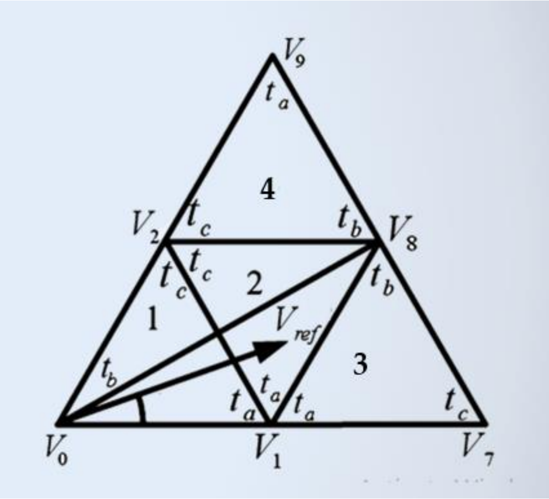
$$t_{aaa} := T_{sw} - \frac{4}{\sqrt{3}} \cdot m_n \cdot T_{sw} \cdot \sin(\theta) = 18.825 \cdot \mu s$$

$$t_{bbb} := \frac{4}{\sqrt{3}} \cdot m_n \cdot T_{sw} \cdot \sin(60° + \theta) - T_{sw} = 12.589 \cdot \mu s$$

$$t_{ccc} := T_{sw} - \frac{4}{\sqrt{3}} \cdot m_n \cdot T_{sw} \cdot \sin(60° - \theta) = 1.919 \cdot \mu s$$

Same results

$$t_{aaa} + t_{bbb} + t_{ccc} = 33.333 \cdot \mu s$$



The complicated part is to determine in which sub-triangle does the reference vector fall? Plenty of IEEE papers which offer various approaches, each of them being optimized for the smallest computational time.

$$m_1 := m_n \cdot \left(\cos(\theta) - \frac{\sin(\theta)}{\sqrt{3}} \right) = 0.471$$

$$m_2 := \frac{2}{\sqrt{3}} \cdot m_n \cdot \sin(\theta) = 0.218$$

$$m_1 + m_2 = 0.689$$

if m1, m2 and (m1+m2) < 0.5 --> Region 1

if m1 and m2 < 0.5 AND (m1+m2) > 0.5 --> Region 2

if m1 > 0.5 --> Region 3

if m2 > 0.5 --> region 4

REGION	t_a	t_b	t_c
1	$\frac{4}{\sqrt{3}} m_n T_s \sin\left(\frac{\pi}{3} - \alpha\right)$	$T_s - \frac{4}{\sqrt{3}} m_n T_s \sin\left(\frac{\pi}{3} + \alpha\right)$	$\frac{4}{\sqrt{3}} m_n T_s \sin \alpha$
2	$T_s - \frac{4}{\sqrt{3}} m_n T_s \sin \alpha$	$\frac{4}{\sqrt{3}} m_n T_s \sin\left(\frac{\pi}{3} + \alpha\right) - T_s$	$T_s - \frac{4}{\sqrt{3}} m_n T_s \sin\left(\frac{\pi}{3} - \alpha\right)$
3	$2T_s - \frac{4}{\sqrt{3}} m_n T_s \sin\left(\frac{\pi}{3} + \alpha\right)$	$\frac{4}{\sqrt{3}} m_n T_s \sin \alpha$	$\frac{4}{\sqrt{3}} m_n T_s \sin\left(\frac{\pi}{3} - \alpha\right) - T_s$
4	$\frac{4}{\sqrt{3}} m_n T_s \sin \alpha - T_s$	$\frac{4}{\sqrt{3}} m_n T_s \sin\left(\frac{\pi}{3} - \alpha\right)$	$2T_s - \frac{4}{\sqrt{3}} m_n T_s \sin\left(\frac{\pi}{3} + \alpha\right)$

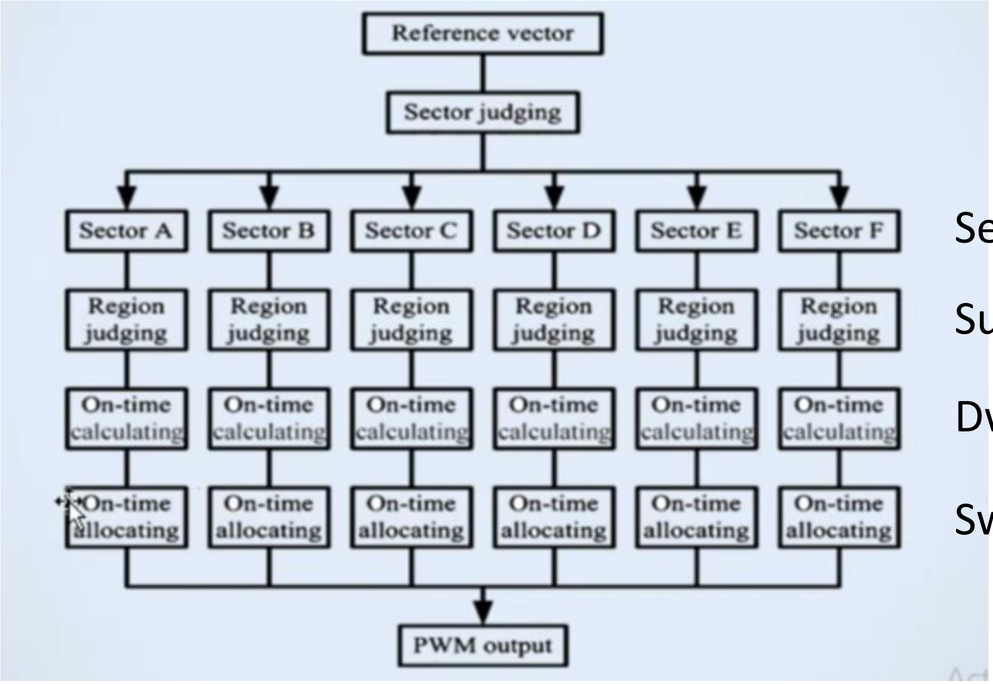
The calculation is then updated depending on the identified triangle.

t_a, t_b and t_c values are the time during which you generate the corresponding vectors. This not the switching pattern applied to the power switches.

a + jb

$$\frac{V_{dc}}{3} \cdot \frac{t_a}{T_{sw}} + \left(\frac{V_{dc}}{\sqrt{3}} \cdot \cos(30°) + \frac{V_{dc}}{\sqrt{3}} \cdot i \cdot \sin(30°) \right) \cdot \frac{t_b}{T_{sw}} + \left(\frac{V_{dc}}{3} \cdot \cos(60°) + \frac{V_{dc}}{3} \cdot i \cdot \sin(60°) \right) \cdot \frac{t_c}{T_{sw}} = (309.349 + 100.514i)\ V$$

To ease calculations, any reference vector outside sector 1 – meaning an angle outside the 0-60° region, is brought back into sector 1 by adding or subtracting an offset. This is how it is coded in the Matlab routine:



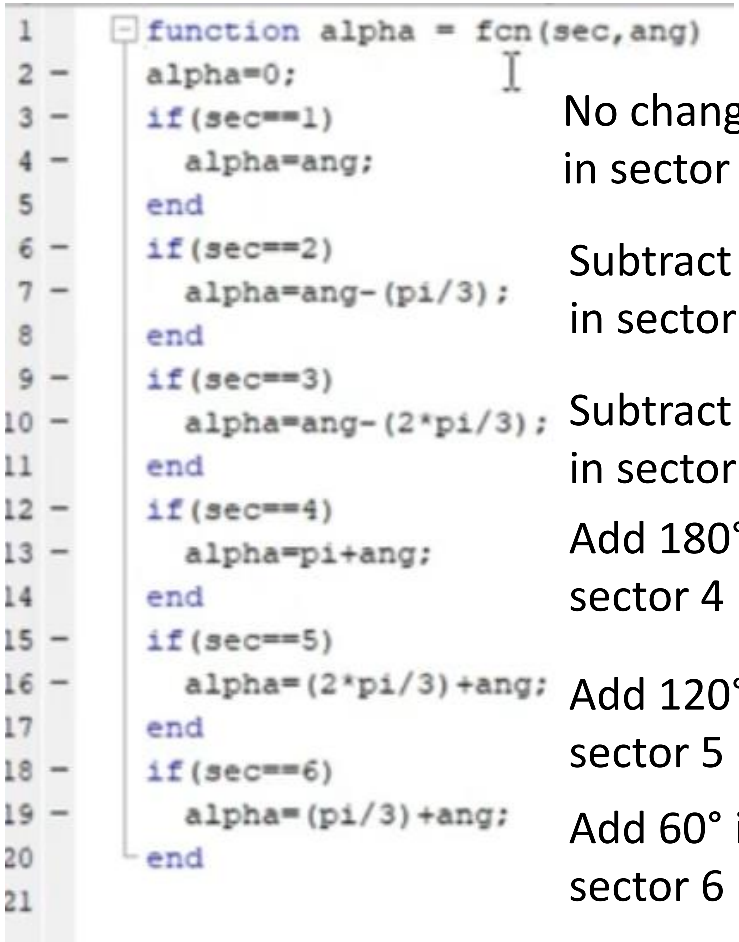
Sector 1-6?

Sub-triangle 1-4?

Dwell time calculation

Switches identification

Update angle



```
function alpha = fcn(sec,ang)
alpha=0;
if(sec==1)
  alpha=ang;
end
if(sec==2)
  alpha=ang-(pi/3);
end
if(sec==3)
  alpha=ang-(2*pi/3);
end
if(sec==4)
  alpha=pi+ang;
end
if(sec==5)
  alpha=(2*pi/3)+ang;
end
if(sec==6)
  alpha=(pi/3)+ang;
end
```

No change in sector 1

Subtract 60° in sector 2

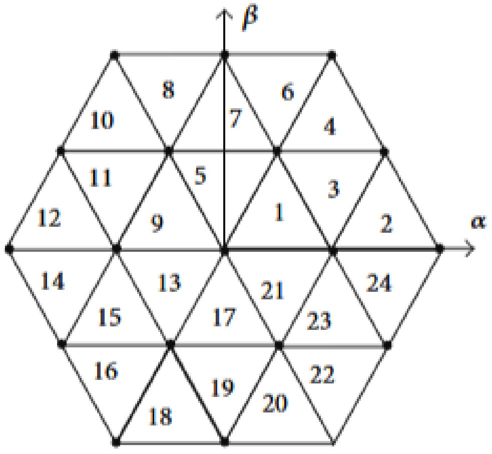
Subtract 120° in sector 3

Add 180° in sector 4

Add 120° in sector 5

Add 60° in sector 6

Screenshot from the Ranit's video



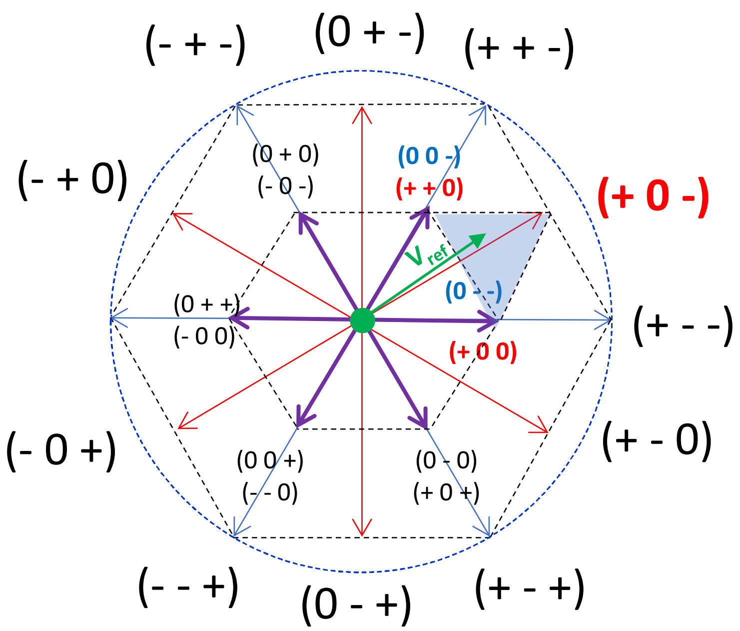
(c)

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.

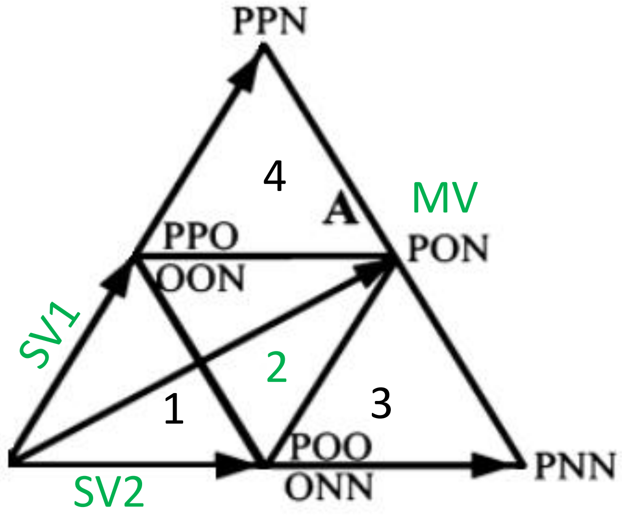
I. Ouerdani et al., Space Vector Modulation Technique for 3-level NPC Converter with Constant Switching Frequency, Hindawi Publishing Corp, Wiley Online Library.

The switching sequences now depend on the type of vectors you want to weight, LV, SV or medium vectors.



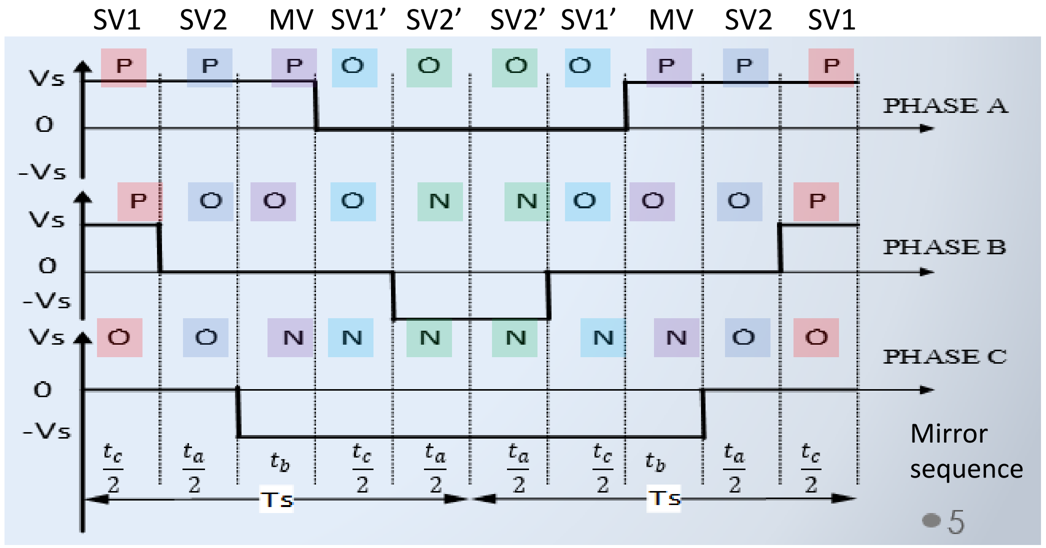
- Sub-1:NNN-ONN-OON-OOO-POO-PPO-PPP & return
- Sub-2:PPO-POO-PON-OON-ONN & return We are here
- Sub-3:ONN-PNN-PON-POO & return
- Sub-4:OON-PON-PPN-PPO & return

PPO-POO first set of short vectors (SV1-SV2)
OON-ONN second set of short vectors (SV1'-SV2')



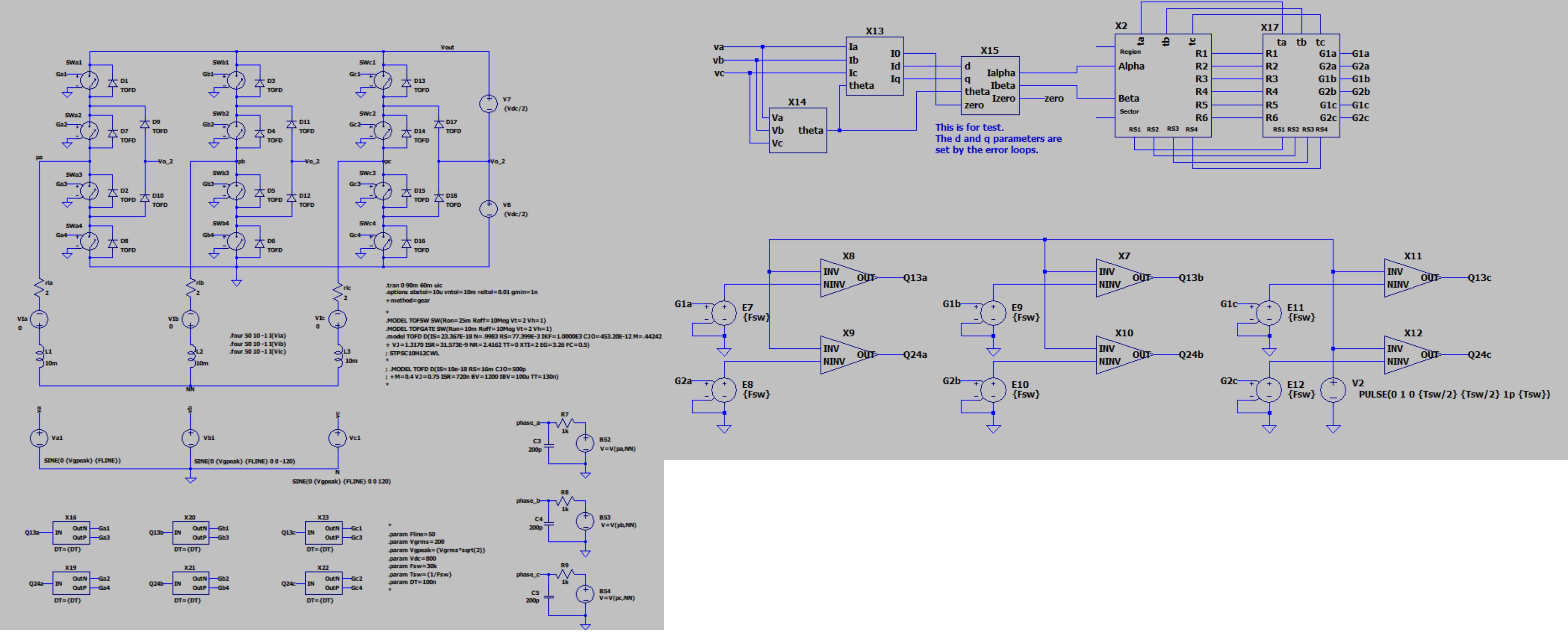
$$\left\|\vec{V}_{ref}\right\|T_{sw} = \left\|\vec{V}_{LV}\right\|t_a + \left\|\vec{V}_{MV}\right\|t_b + \left\|\vec{V}_{MV}\right\|t_c$$

Switching pattern for sub-triangle 2:



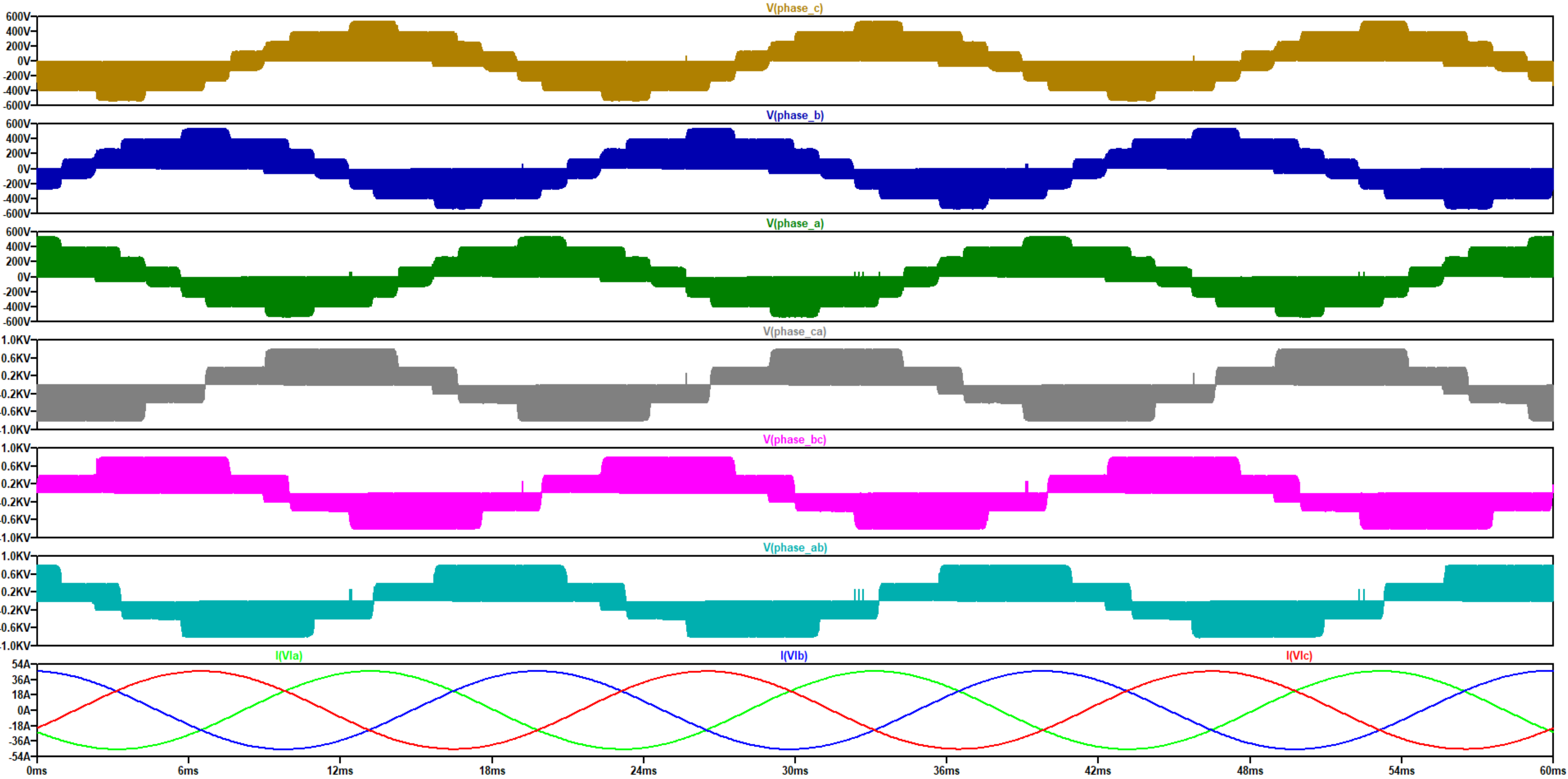

```
if(reg==2)
    s1a=Tc/4+Ta/4+Tb/2;
    s2a=(Ta+Tb+Tc)/2;
    s1b=Tc/4;
    s2b=Tc/2+Tb/2+Ta/4;
    s1c=0;
    s2c=Ta/4+Tc/4;
```

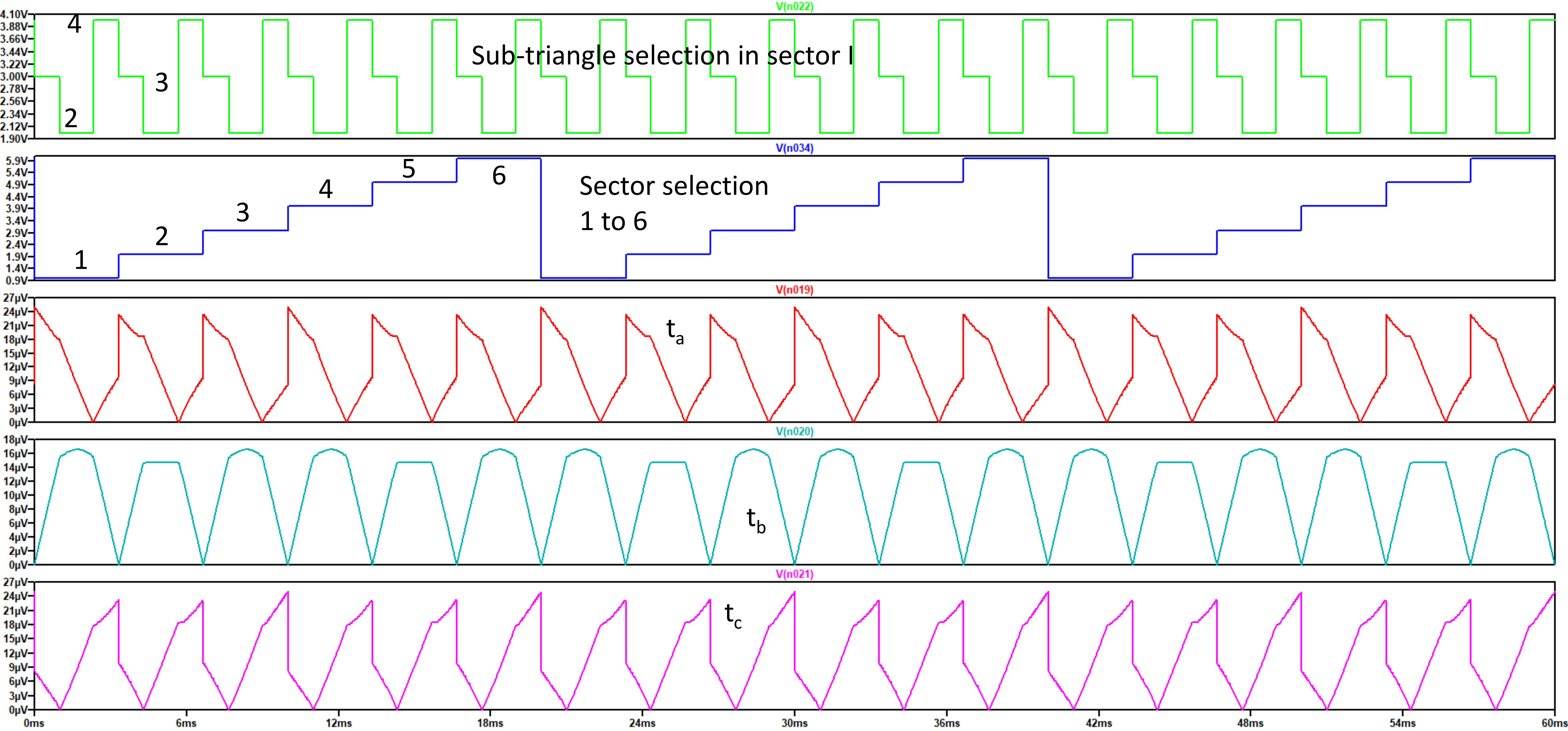
Ranit Sengupta – PPT from this link



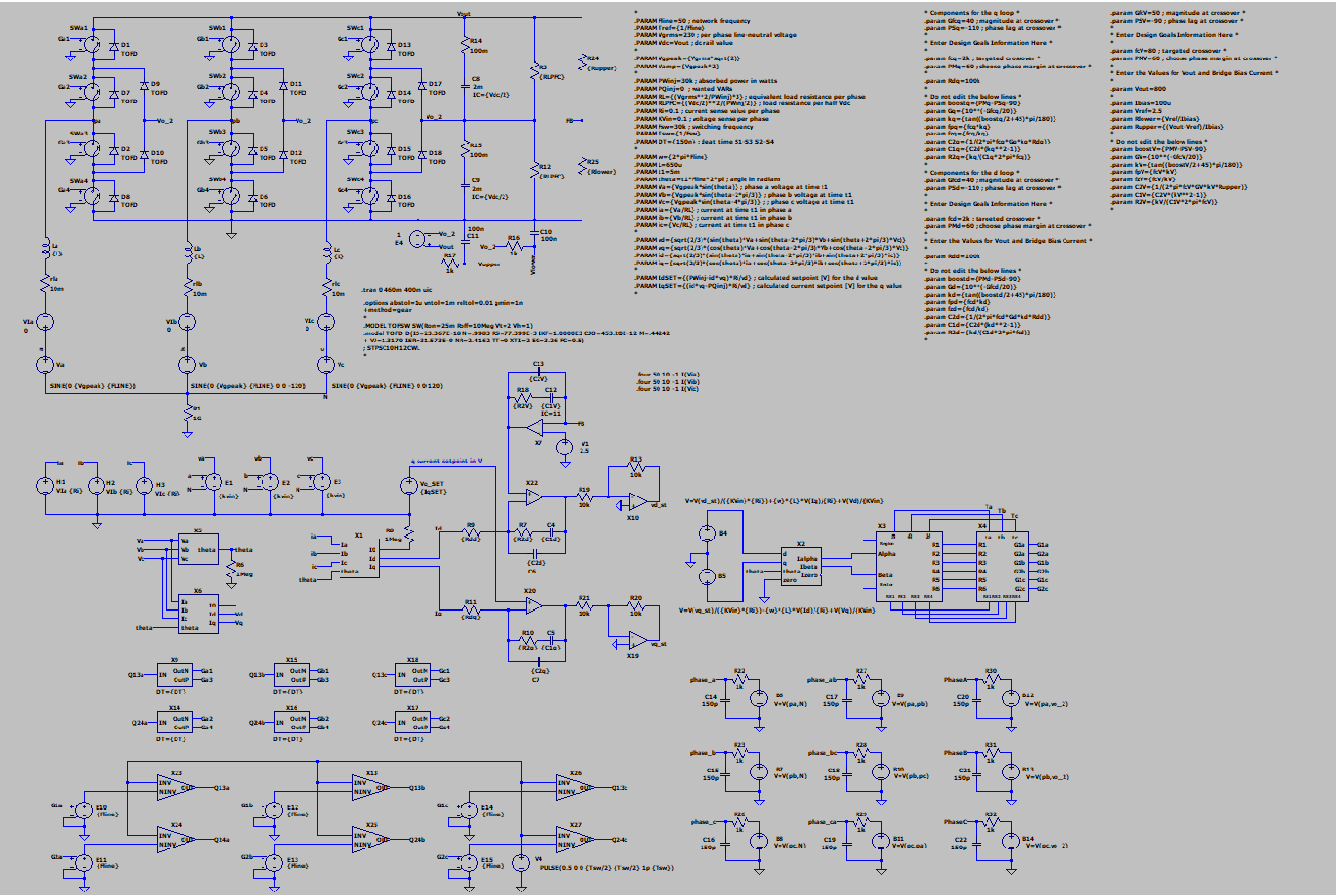
In this example, the 3-phase NPC converter feeds a motor from a 800-V rail (2 x 400 V) and inject currents into the windings. The observed phase voltage is filtered to lower the noise. The references are coming from the 3 ac sources and the rms value is arbitrarily set to 200 V phase to neutral.

Simulation results for V_{dc} = 800 V, V_{ref} = 300 V rms, F_{sw} = 30 kHz




V(n022)
Sub-triangle selection in sector I
4
3
2
V(n034)
Sector selection
1 to 6
1
2
3
4
5
6
V(n019)
t_a
V(n020)
t_b
V(n021)
t_c
0ms
6ms
12ms
18ms
24ms
30ms
36ms
42ms
48ms
54ms
60ms

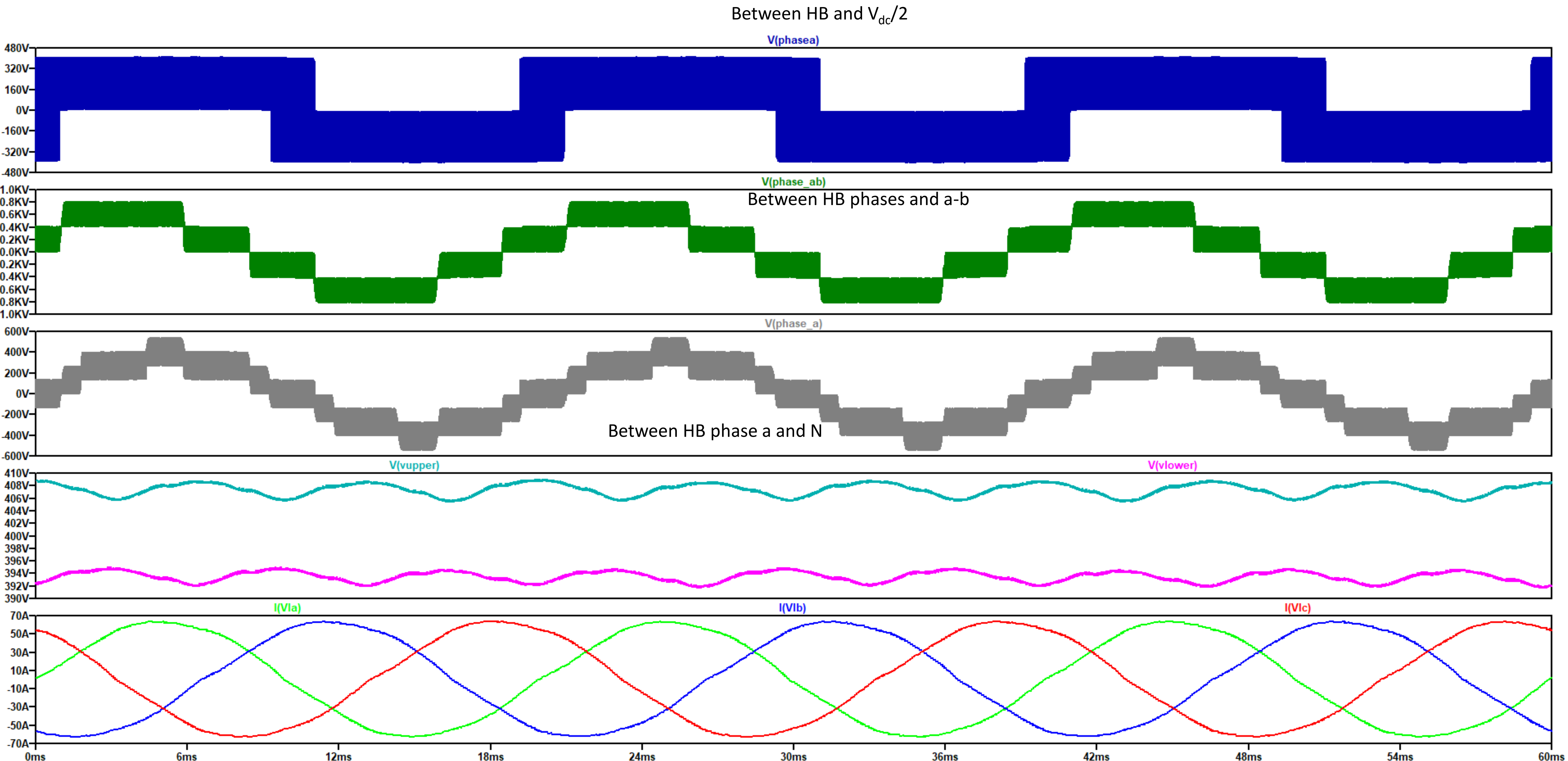
This is the 3-phase PFC version of this inverter, with added control loops



This simulation model is available from the TOFPACK ZIP file and can be freely used.

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%
```



Interesting documents and application notes to read on NPC PFCs:

3L-ANPC vs. 3L-NPC Inverters – UnitedSiC

Gate Drive and Protection of Three-Level Inverters – UnitedSiC

Inverter/PFC Converter Topology – Overview – Texas Instruments

Video commenting on the above slides from Texas Instruments

3L NPC, TNPC & ANPC Topology – Semikron Danfoss

Nabae, I. Takahashi and H. Akagi, A New Neutral-Point-Clamped PWM Inverter, in *IEEE Transactions on Industry Applications*, vol. IA-17, no. 5, pp. 518-523, Sept. 1981

K.-P Kang, Y. Cho, M.-H Ryu, J.-W Baek, A Harmonic Voltage Injection Based DC-Link Imbalance Comp Tech for 1-Phase 3-level NPC Converters, MDPI 2018

N. Celanovic and D. Boroyevich, A fast space-vector modulation algorithm for multilevel three-phase converters, in *IEEE Transactions on Industry Applications*, vol. 37, no. 2, pp. 637-641, March-April 2001

J. Pou, J. Zaragoza, S. Ceballos, M. Saeedifard and D. Boroyevich, A Carrier-Based PWM Strategy With Zero-Sequence Voltage Injection for a Three-Level Neutral-Point-Clamped Converter, in *IEEE Transactions on Power Electronics*, vol. 27, no. 2, pp. 642-651, Feb. 2012

Space Vector Modulation of a 3 level Neutral Point Clamped Converter – Dr. Tabish Mir video on YouTube

3-Level Space Vector PWM based three phase Multilevel Inverter | SVPWM | DCMLI | MATLAB Simulation – Ranit Sengupta YouTube video

H. Hu, W. Yao and Z. 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