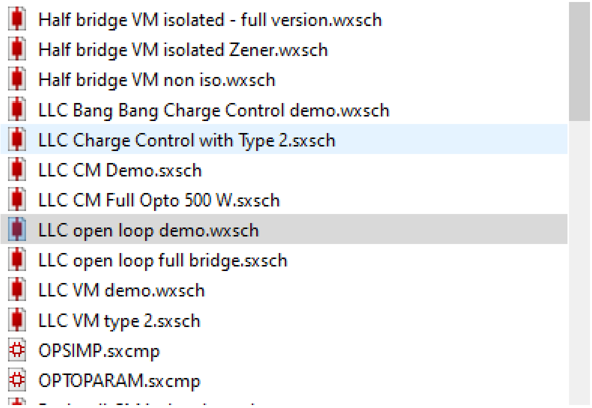
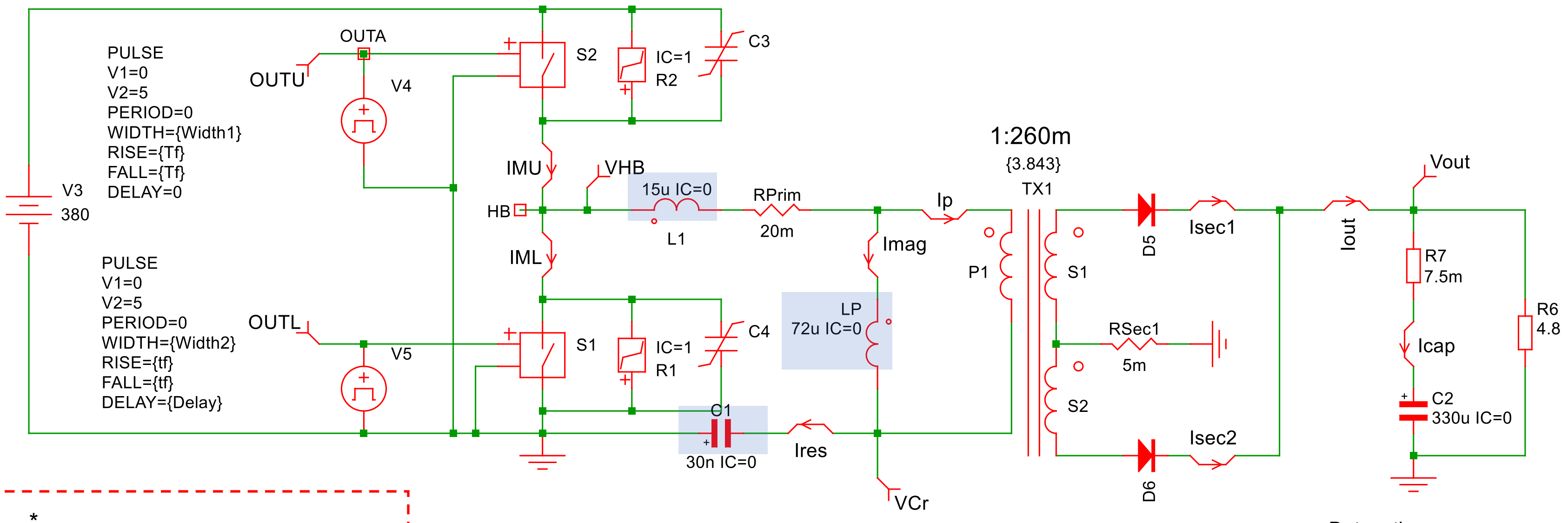
This presentation details how to combine the demonstration version of SIMPLIS called Elements to extract the ac response of a current-mode LLC converter operated with the NCP13992/94 from *onsemi*, stabilize the loop and reflect all values to a simplified LTspice template.

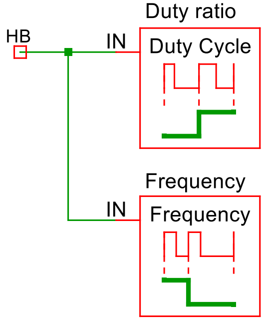
Once the demonstration version of Elements is installed, locate the file *LLC open loop demo.wxsch*






```
*
.VAR Fs=245k ; select frequency
.VAR DT=30n ; select deadtime
.VAR DC=0.5 ; select duty ratio
.VAR tf=1p
.VAR tr=1p
*
.VAR Ts={1/Fs}
.VAR Width1={DC*Ts-DT}
.VAR Width2={Ts*(1-DC)-DT}
.VAR Delay={Width1+DT}
*
```

Adjust F_s to what you've determined for this LLC



This is a simple open-loop-operated LLC converter using perfect switches and associated with nonlinar capacitance. This type of setup is perfectly suited to check LLC operating waveforms and verify the operating point is met with the selected components values. 48 V/10 A from a 385-V dc source, Fsw = 240 kHz

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You will have to modify the LLC values to reflect your design, as well as all surrounding components such as output capacitor, switching frequency, dead time, etc.

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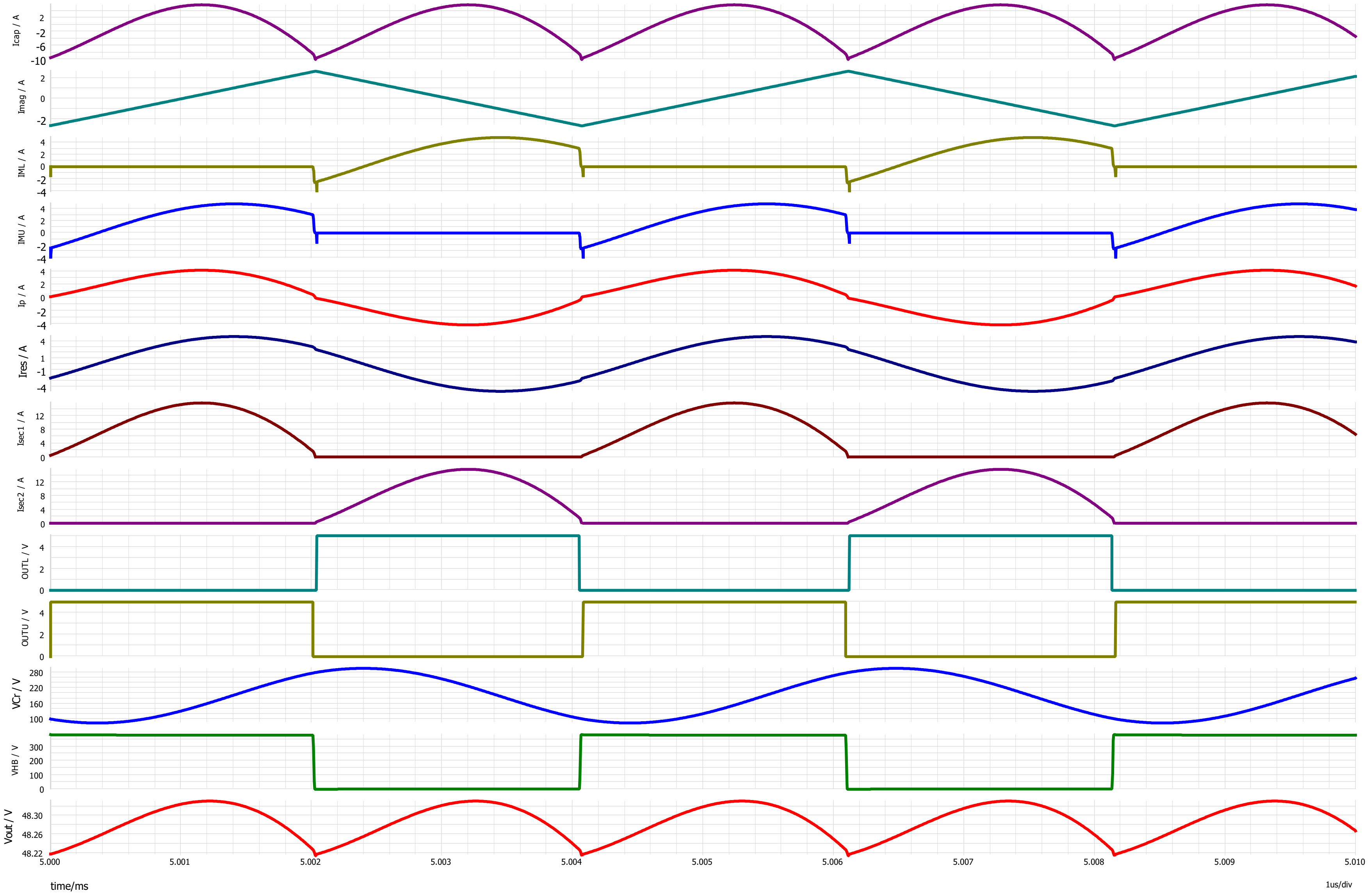
We have designed a 48-V/500-W LLC converter supplied from a 400-V input voltage. The switching frequency is set to 245 kHz and we verify that all operating waveforms correspond to what is expected: Vout is ok, currents look within expected values (you can determine rms currents in the output capacitor, in the simplified switches etc.):



This open-loop simulation is fast and helps you verify that the LLC network with its transformer turns ratio deliver the expected results. It is a simplified circuitry but once this step is validated, you can check the ac response.

You can also check if the dead-time is well adjusted to bring the expected ZVS operation.

V_{out} is 48 V, ok

The cycle-by-cycle simulations confirm the LLC network is correct, now we need the control-to-output transfer function: if a stimulus is applied at the control input, how does that stimulus propagate in the circuit to produce a response on the output? The mathematical relationship linking the response to the stimulus is the transfer function we need to think of our compensation strategy.

Now locate the file *LLC CM Demo.sxsch*

- Half bridge VM isolated - full version.wxsch
- Half bridge VM isolated Zener.wxsch
- Half bridge VM non iso.wxsch
- LLC Bang Bang Charge Control demo.wxsch
- LLC Charge Control with Type 2.sxsch
- LLC CM Demo.sxsch
- LLC CM Full Opto 500 W.sxsch
- LLC open loop demo.wxsch
- LLC open loop full bridge.sxsch
- LLC VM demo.wxsch
- LLC VM type 2.sxsch

It is an open-loop circuit (for the demo version to accept it) so you have to tweak the dc bias on the FB pin to obtain the right operating point.

Simplified CM-LLC model for NCP1399 controllers.
This model packs the basic features necessary to predict the control-to-output transfer function.The operating duty ration is precisely 50%.
Works on SIMPLIS Elements, the free demo version.

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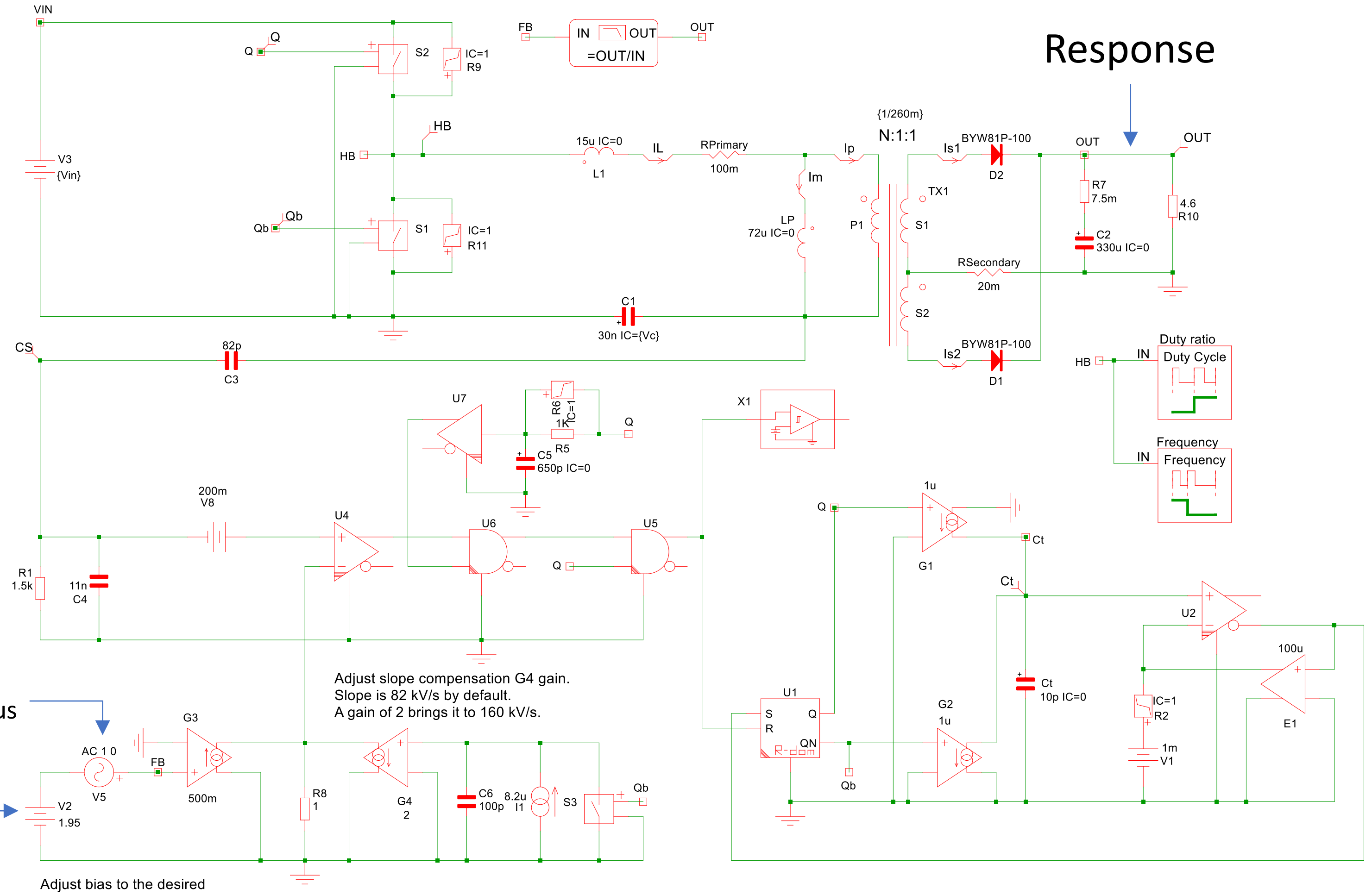
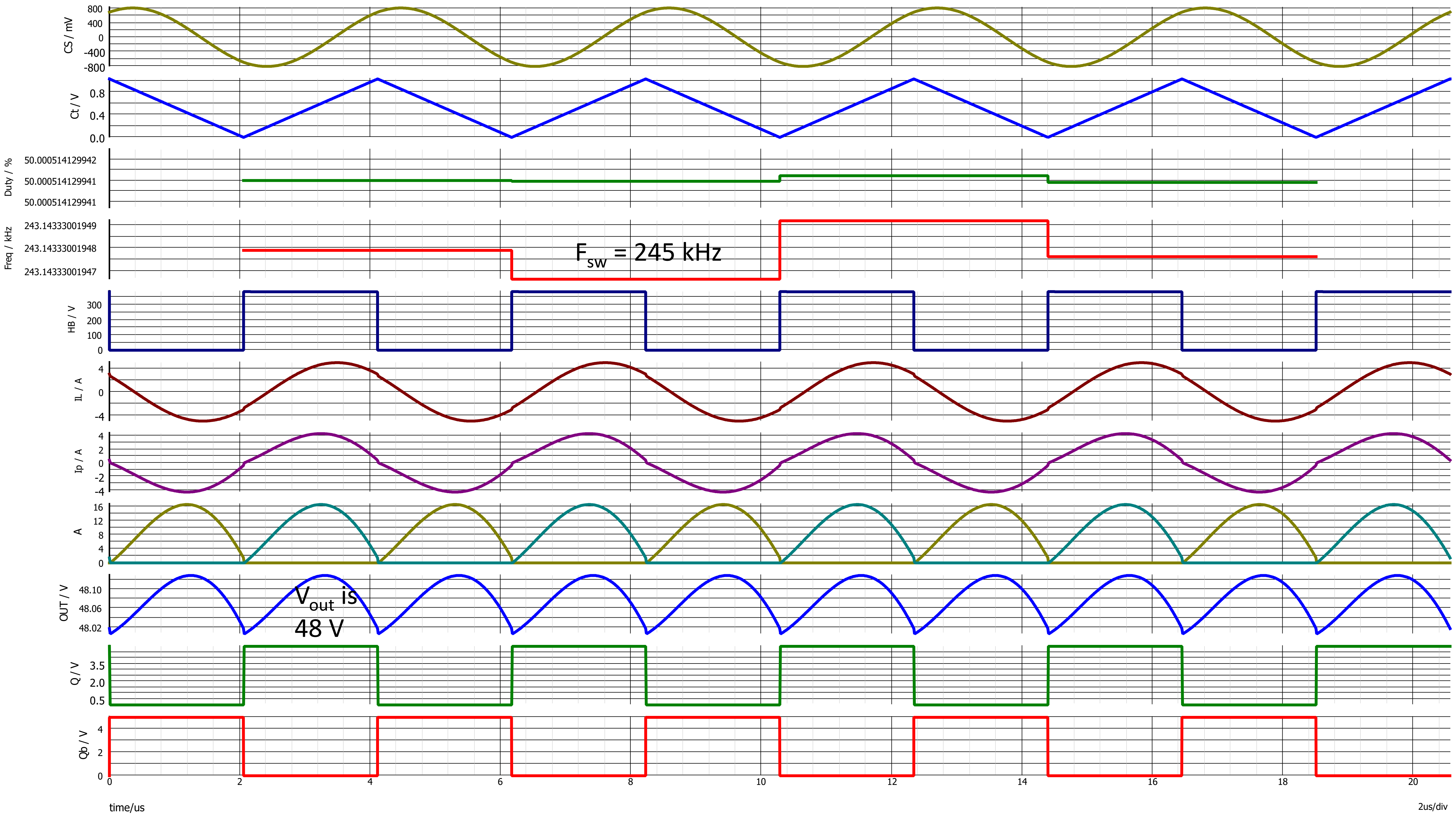
Response



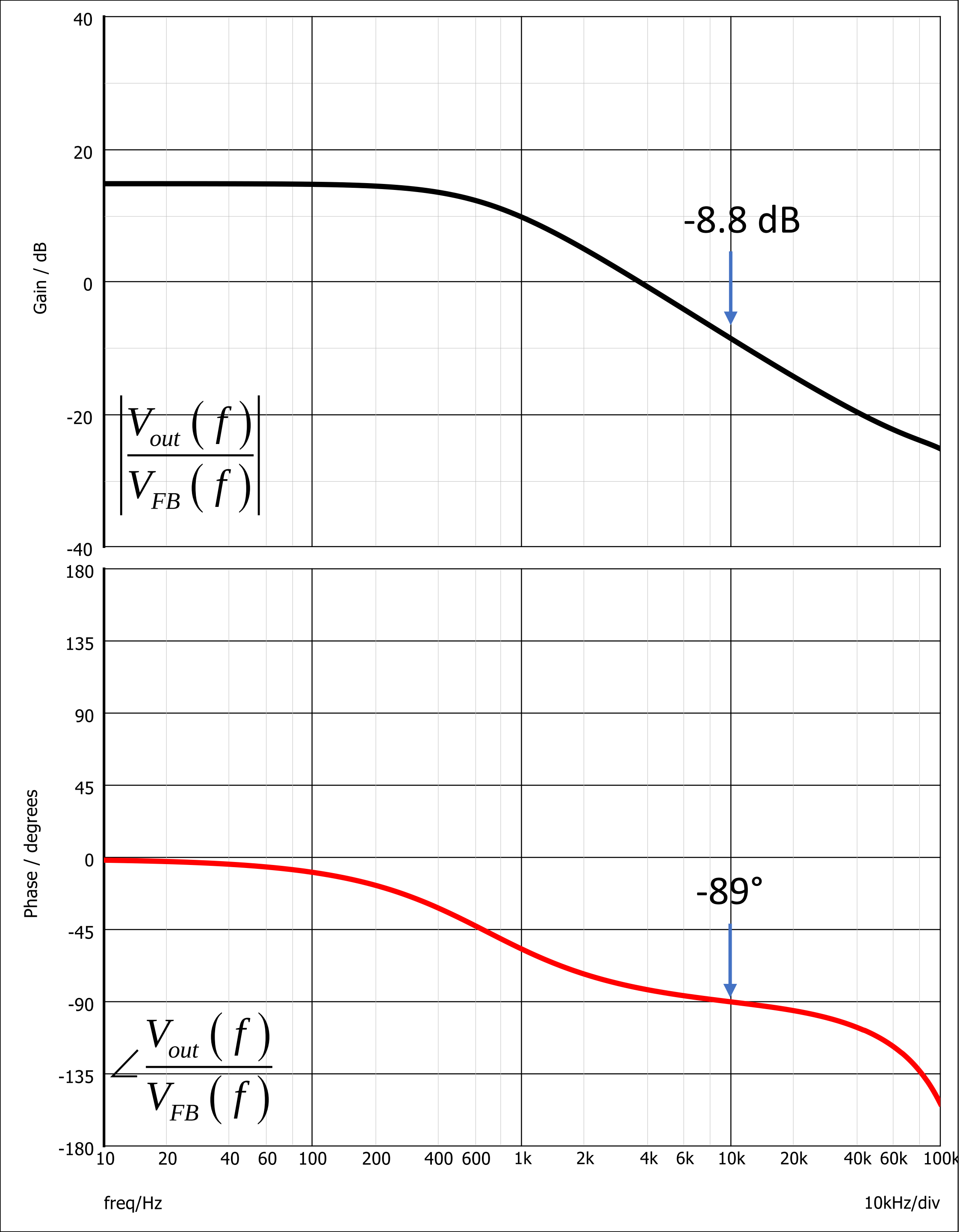
Ac stimulus

Adjust slope compensation G4 gain.
Slope is 82 kV/s by default.
A gain of 2 brings it to 160 kV/s.

Adjust bias to the desired Vout level. Here, a 1.95-V bias gives 48 V/10 A.



CS / mV
800
400
0
-400
-800
Ct / V
0.8
0.4
0.0
Duty / %
50.000514129942
50.000514129941
50.000514129941
Freq / kHz
243.14333001949
243.14333001948
243.14333001947
F_sw = 245 kHz
HB / V
300
200
100
0
IL / A
4
0
-4
Ip / A
4
2
0
-2
-4
A
16
12
8
4
0
OUT / V
48.10
48.06
48.02
V_out is
48 V
Q / V
3.5
2.0
0.5
Qb / V
4
2
0
0
2
4
6
8
10
12
14
16
18
20
time/us
2us/div



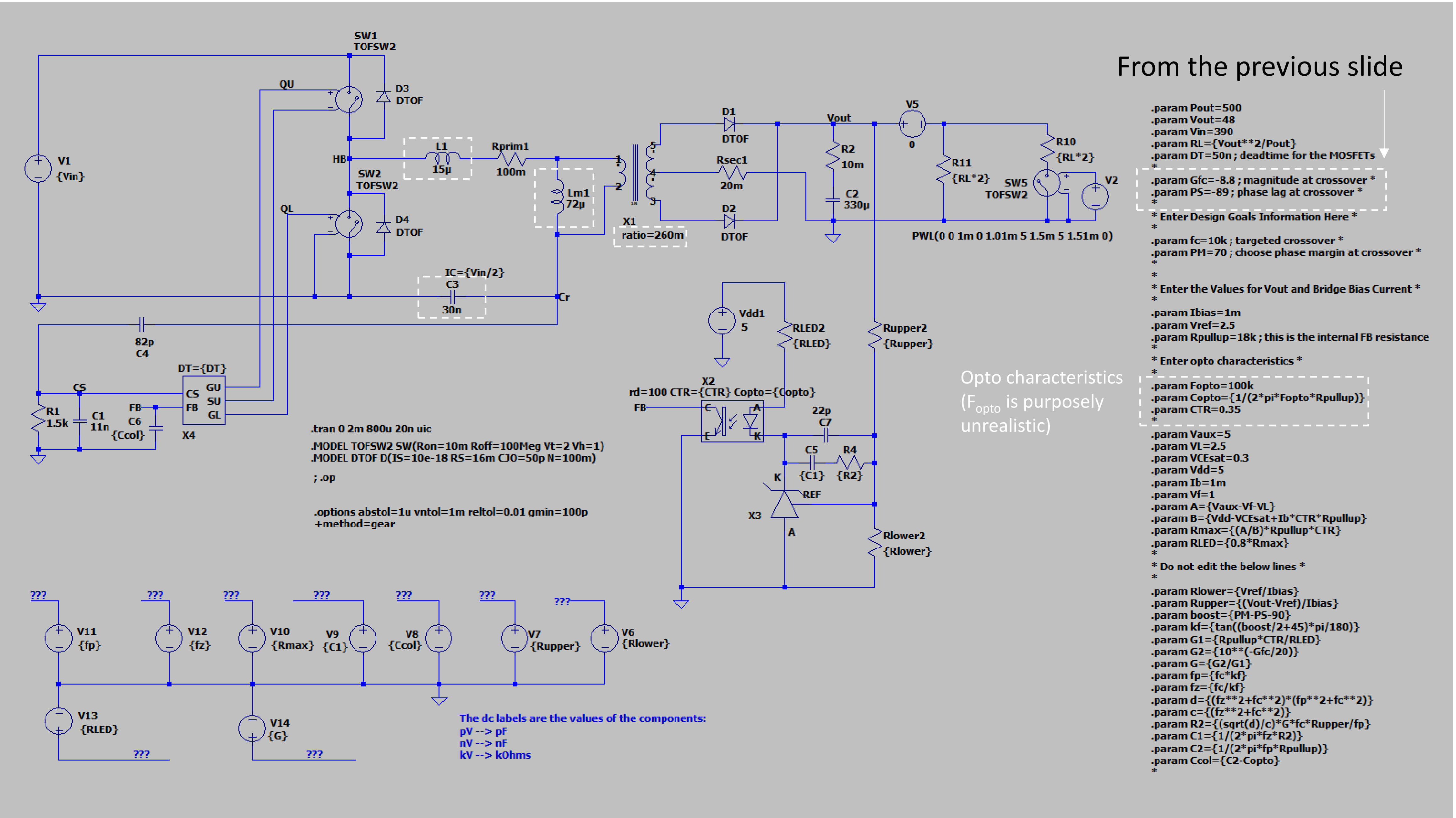
We now have the control-to-output transfer function of this LLC converter operated in current-mode control. I recommend you explore different operating conditions like min and max input voltages.

Once there, you have to pick a crossover frequency f_c based on the reaction speed you want. Assume we want a fast converter and a 10-kHz crossover would seem feasible. Be aware that the more you push f_c, the more sensitive the converter becomes.

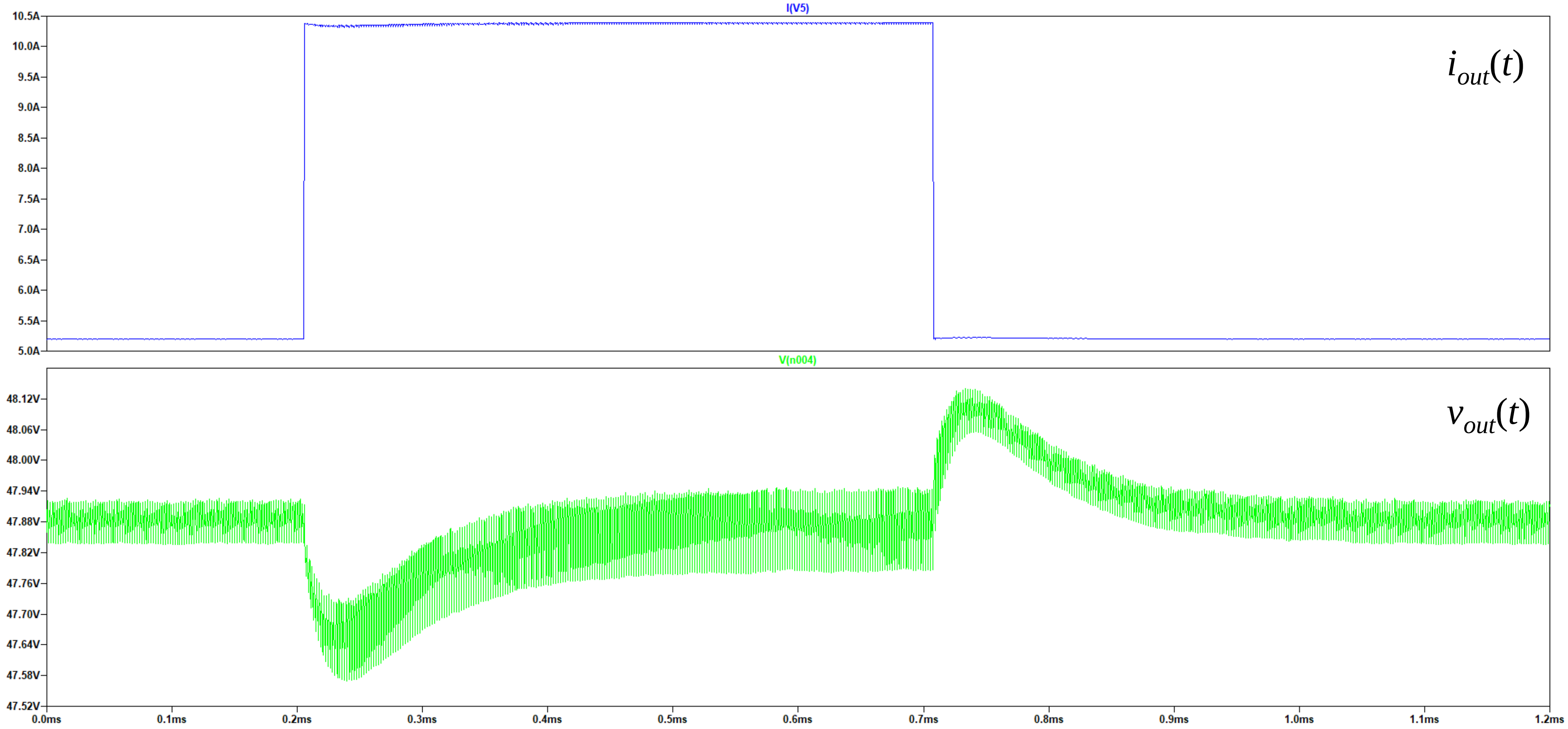
For such a high crossover, make sure the optocoupler is well characterized in ac and you know what its parasitic capacitance is. It is a step you cannot skip for a reliable design.

Read the Bode plot at 10 kHz and extract the magnitude and phase information. Now go to the LTspice application circuit.

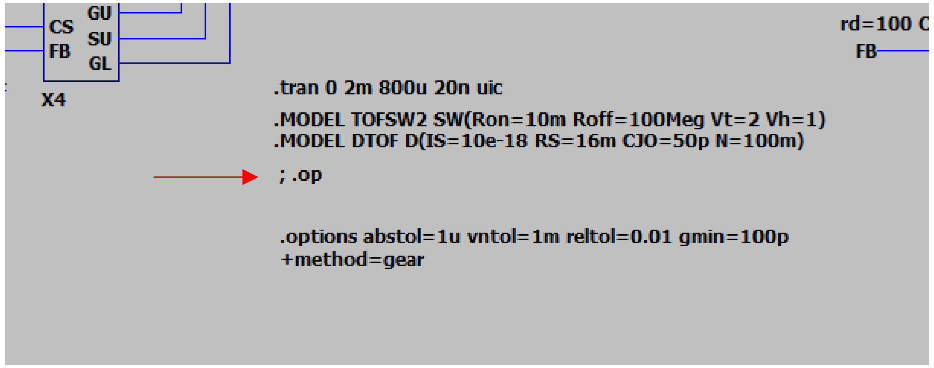
Now open the LTspice file *CM LLC example with sub – step load.asc*. This is the CM converter operated in closed-loop control. Reflect all your LLC elements in the circuit and run the simulation.

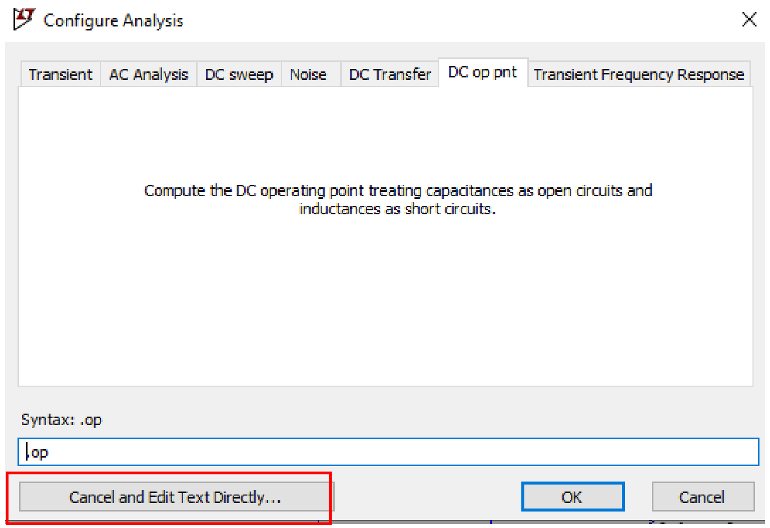


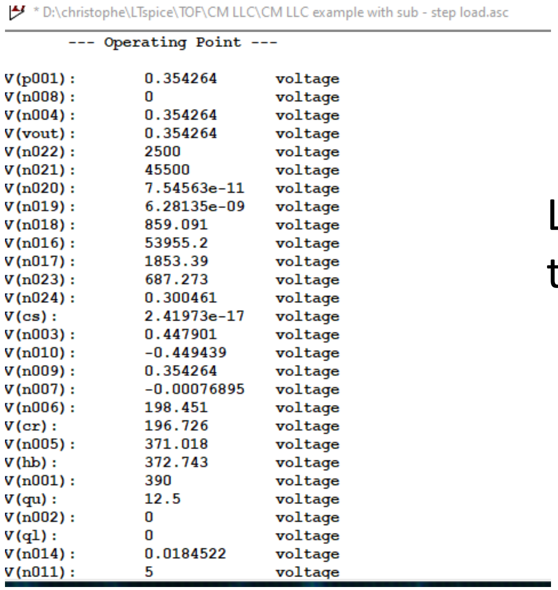
If everything runs fine, you should see the following transient response when the current stepped from 50 to 100% of its nominal value. Once there, you can change the input voltage and load to see the impact in stability. However, keep in mind that this is a simplified model and there are more whistles and bells in the real circuit like skip cycle, auto-adaptive deadtime and so on.



To check the components values calculated by LTspice, it is not that practical. You can see dc sources in the bottom of the schematic and they should deliver a dc value corresponding to the parameter that is passed. I thought LTspice would update the nets after the transient simulation is done (after the dc bias point is calculated actually) but it doesn't. Therefore, locate the below state and right-click on the .op statement then remove the ";". → Run the sim







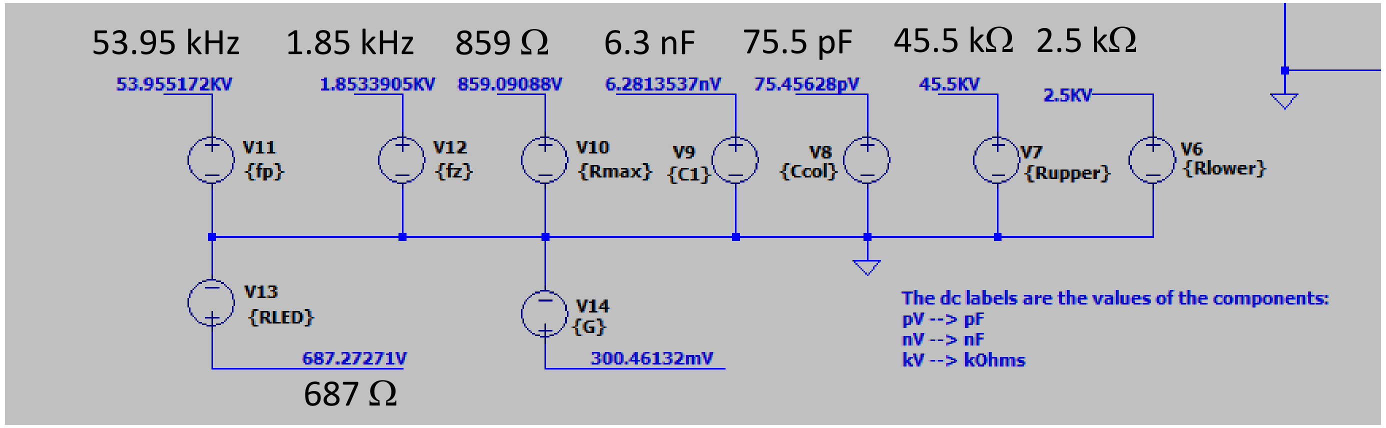
* D:\christophe\LTspice\TOF\CM LLC\CM LLC example with sub - step load.asc

--- Operating Point ---

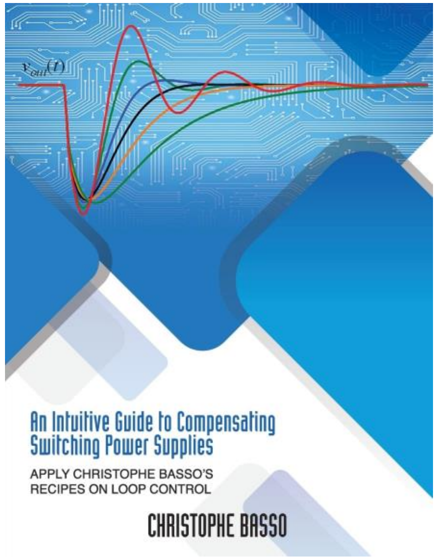
V(p001):	0.354264	voltage
V(n008):	0	voltage
V(n004):	0.354264	voltage
V(vout):	0.354264	voltage
V(n022):	2500	voltage
V(n021):	45500	voltage
V(n020):	7.54563e-11	voltage
V(n019):	6.28135e-09	voltage
V(n018):	859.091	voltage
V(n016):	53955.2	voltage
V(n017):	1853.39	voltage
V(n023):	687.273	voltage
V(n024):	0.300461	voltage
V(cs):	2.41973e-17	voltage
V(n003):	0.447901	voltage
V(n010):	-0.449439	voltage
V(n009):	0.354264	voltage
V(n007):	-0.00076895	voltage
V(n006):	198.451	voltage
V(cr):	196.726	voltage
V(n005):	371.018	voltage
V(hb):	372.743	voltage
V(n001):	390	voltage
V(qu):	12.5	voltage
V(n002):	0	voltage
V(ql):	0	voltage
V(n014):	0.0184522	voltage
V(n011):	5	voltage

Close the window

LTspice updates the nets →



The whole process of stabilizing the loop requires knowledge on how to place poles and zeroes based on wanted characteristics like crossover, phase and gain margins. My last book covers the topic in depth, without too much theory. It will let you build the foundations you need to understand the terminology and stabilize your own converter.



Available in PDF or soft cover at the publisher's site

If you are new to SIMPLIS and what to learn more about this piece-wise linear program, check this introductory seminar.

After you have installed Elements, check this tutorial which will teach you the basic ropes on how to operate the program. You will learn how to download my free 130+ ready-made templates and run basic simulations.