Optimizer Based Loop Compensation Of Voltage Mode Buck Regulators

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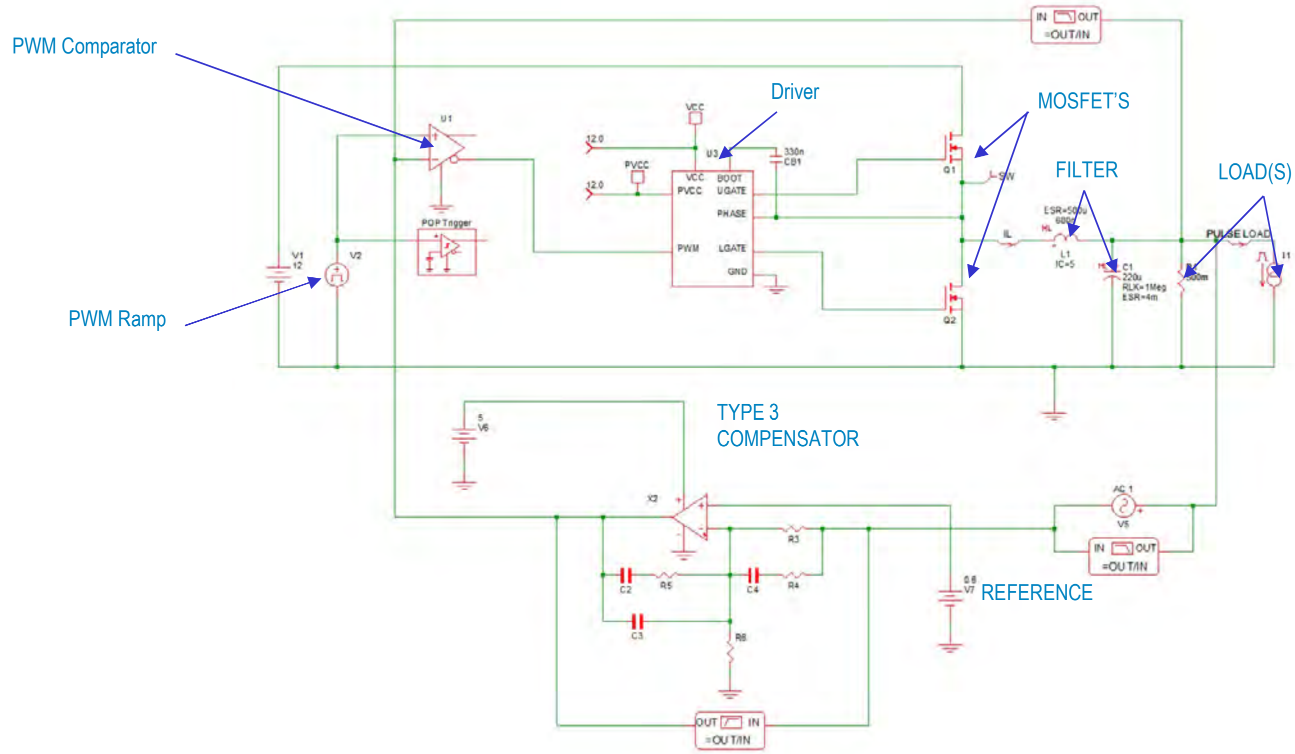
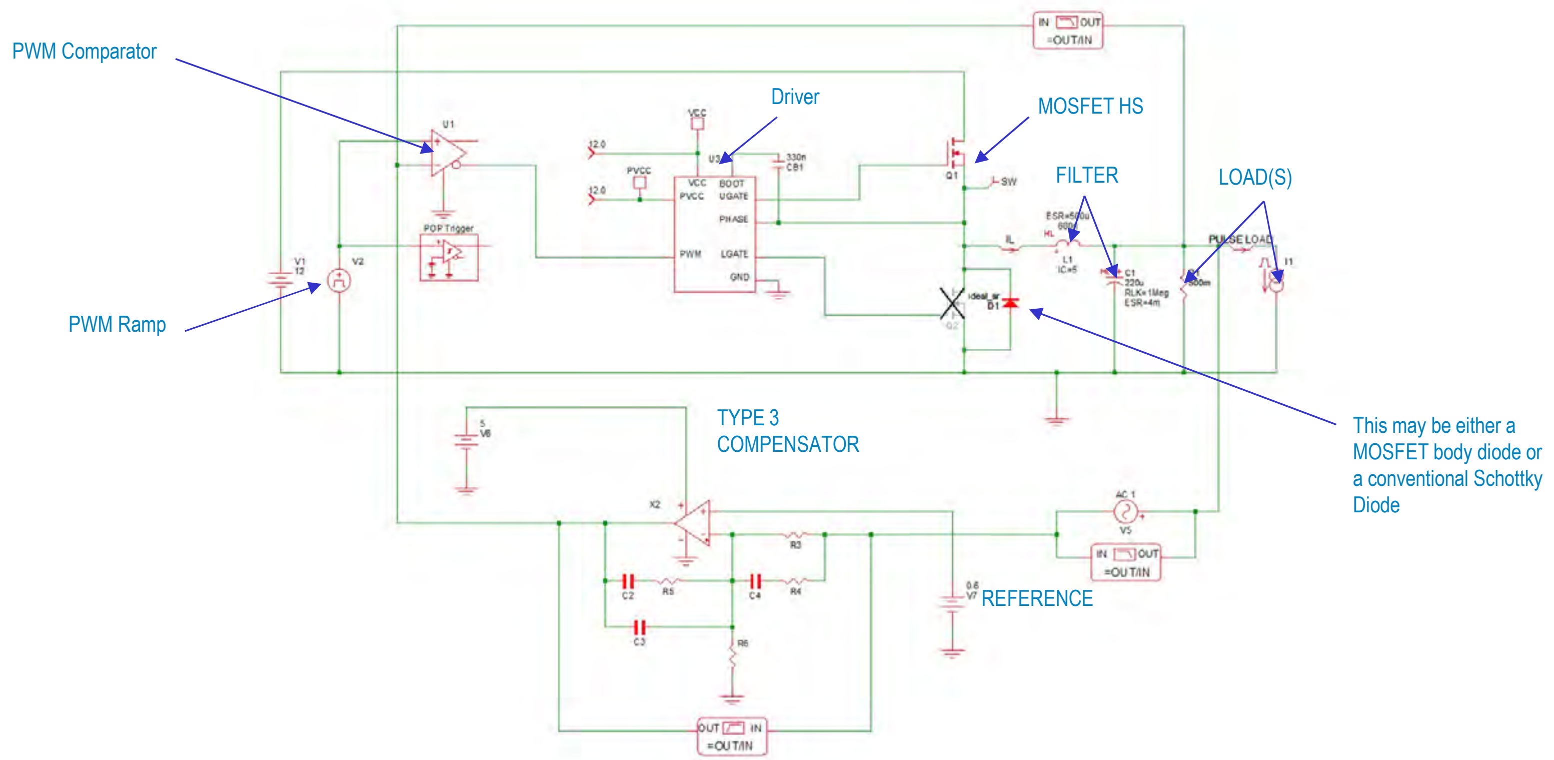
Seminar Roadmap

- The Synchronous Voltage Mode Control Buck Regulator
- The Voltage Mode Control Buck Regulator
- Relevant Waveforms
- Compensation Procedure – Classical Approach
- Is there another way? The Optimizer Approach
- Summary
- Questions/Answers

Synchronous VMC Buck Regulator



VMC Buck Regulator



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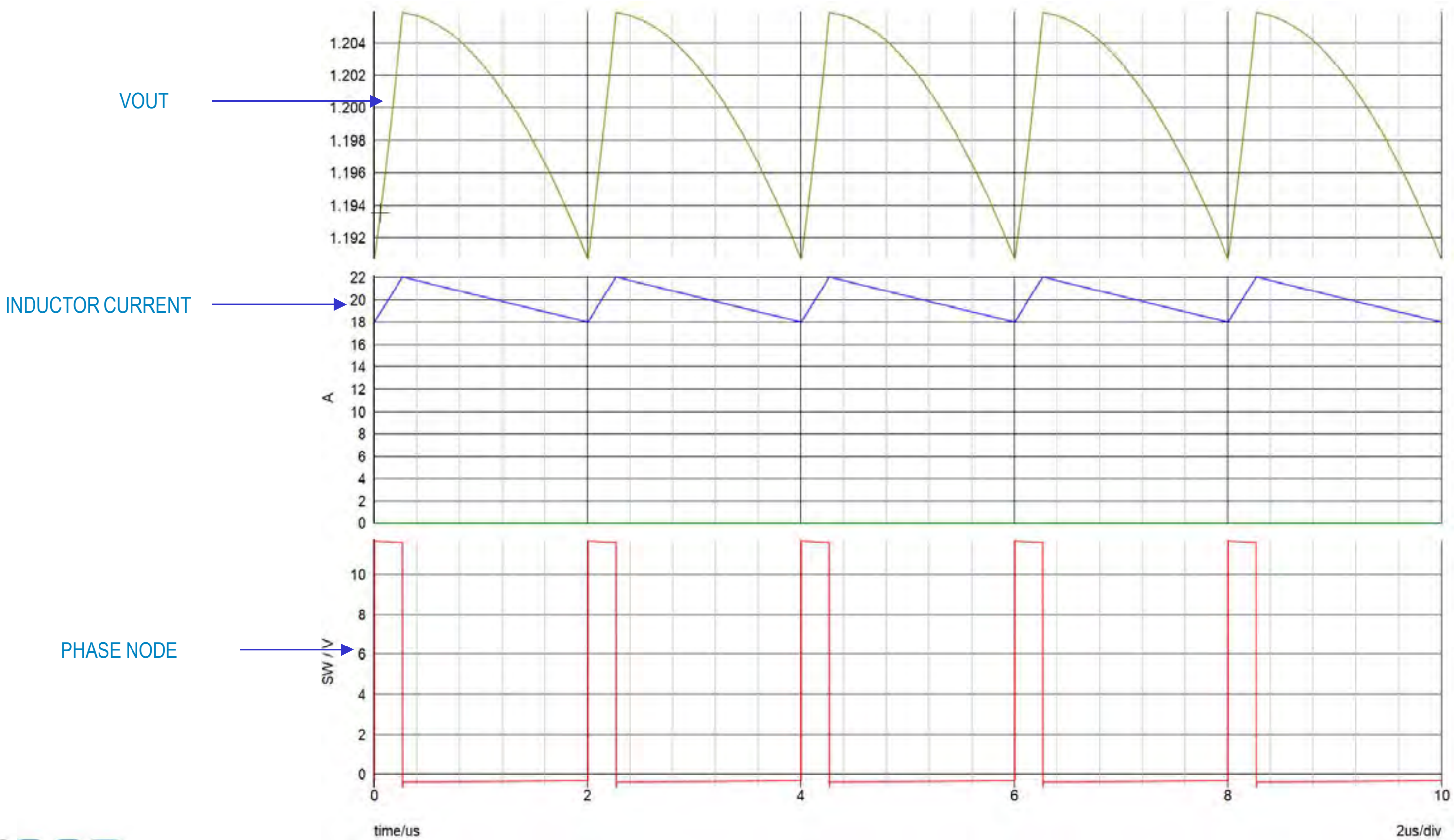
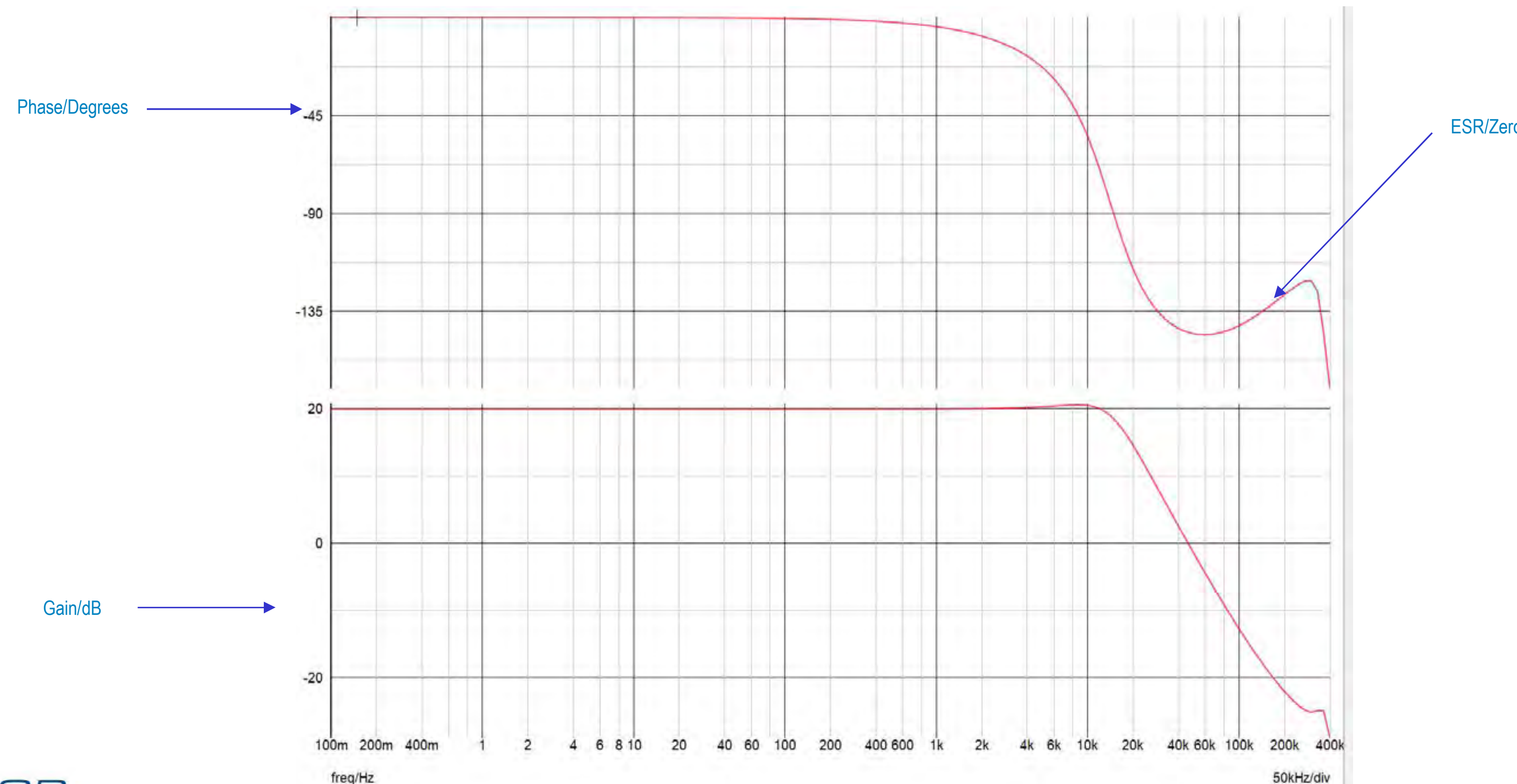
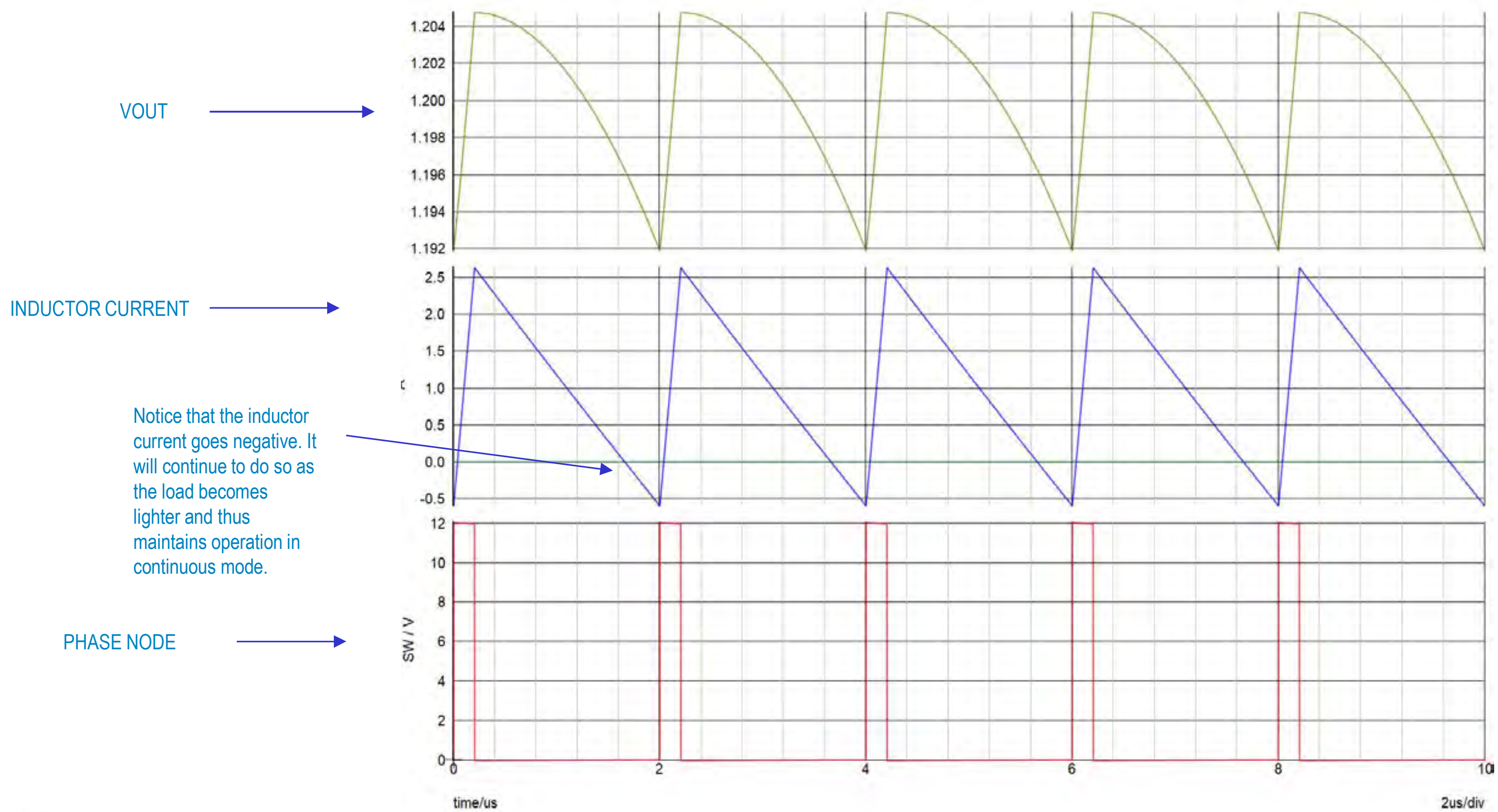
Relevant Waveforms –Sync Buck 20A Load



Relevant Waveforms –Sync Buck 20A Ctrl-Out



Relevant Waveforms –Sync Buck 1A Load

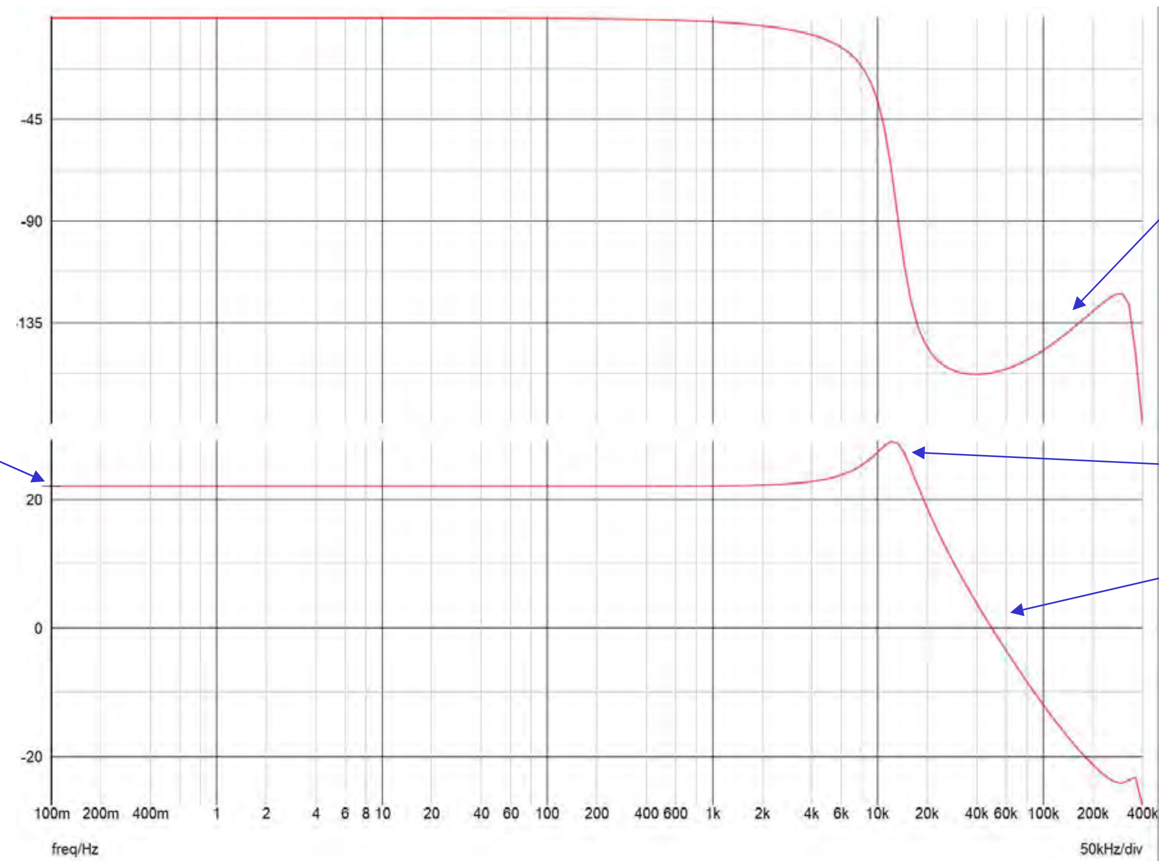


Relevant Waveforms –Sync Buck 1A Ctrl-Out

Phase/Degrees

DC gain is slightly higher at light load due to less loss in MOSFET's

Gain/dB

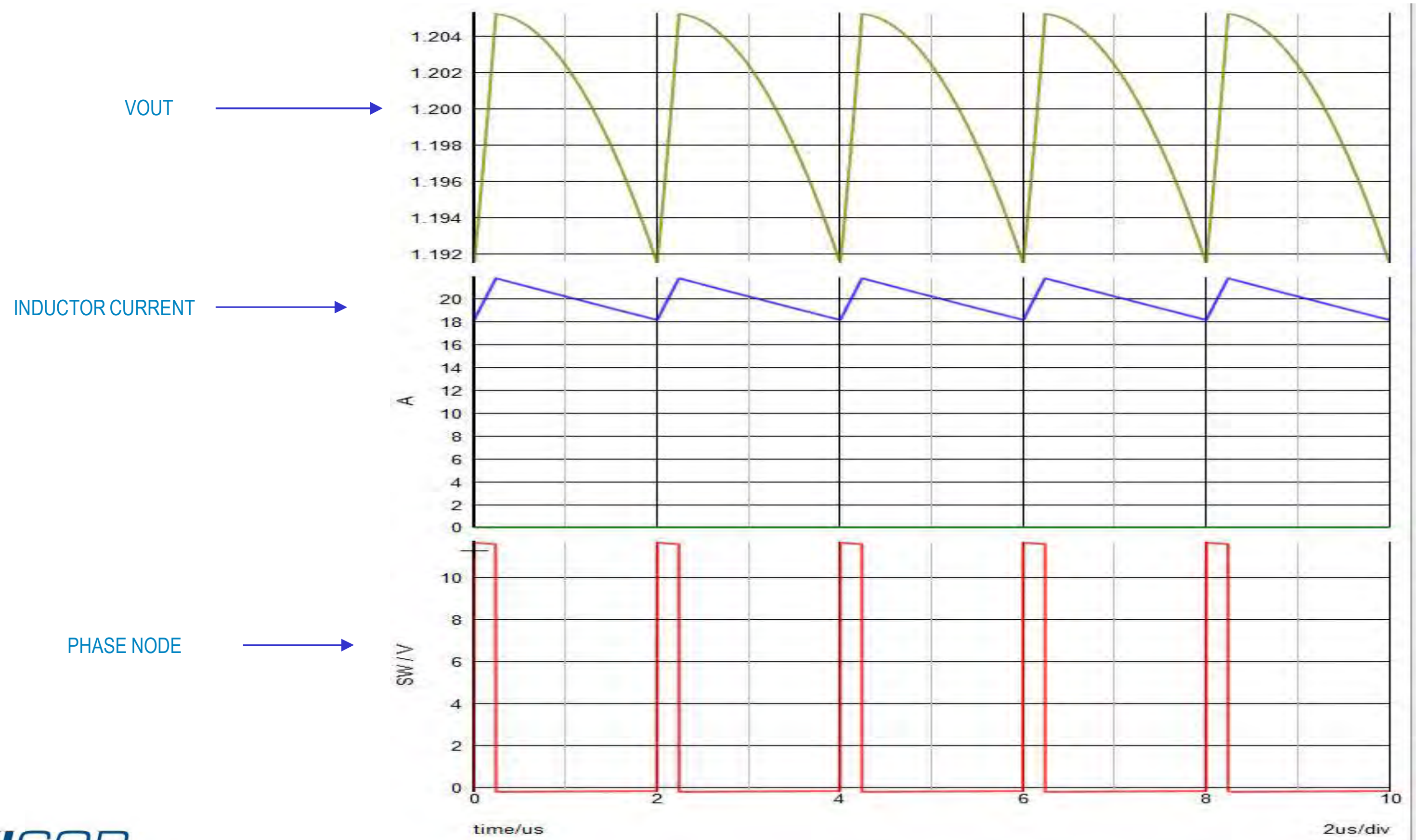


ESR/Zero

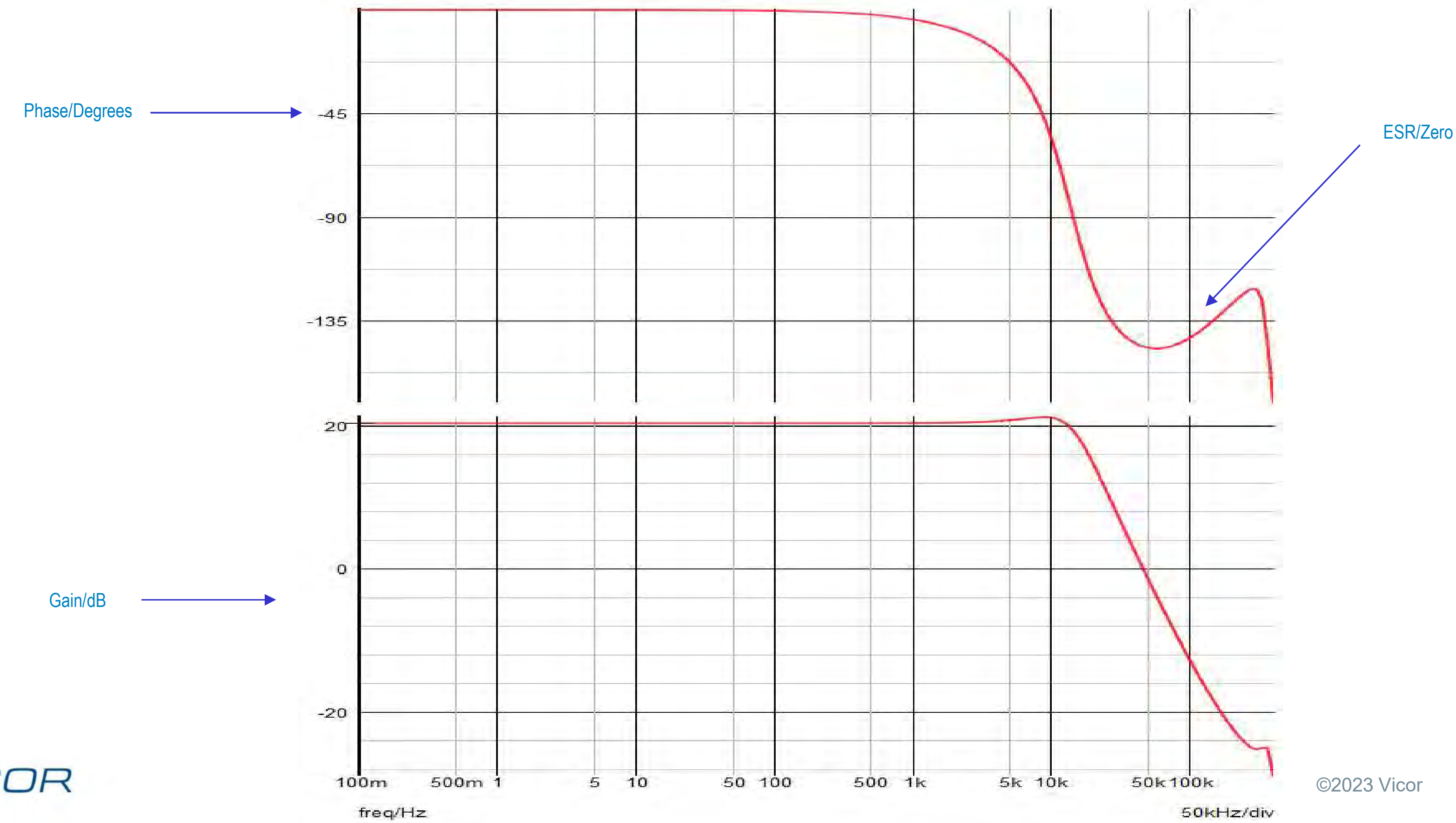
Filter damping changed due to higher load resistor

Open loop crossover frequency is slightly higher.

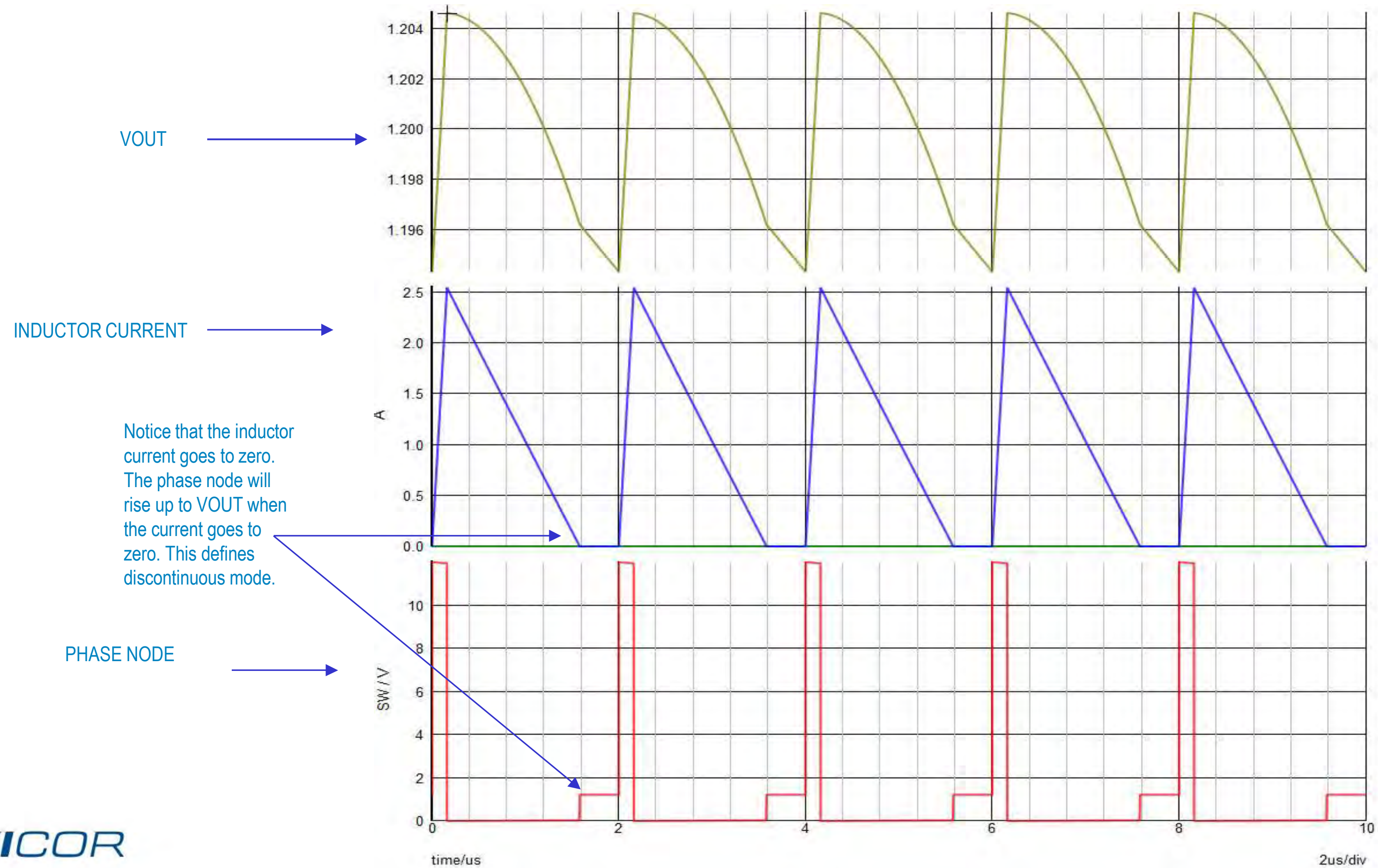
Relevant Waveforms – Buck 20A Load



Relevant Waveforms – Buck 20A Ctrl-Out



Relevant Waveforms – Buck 1A Load



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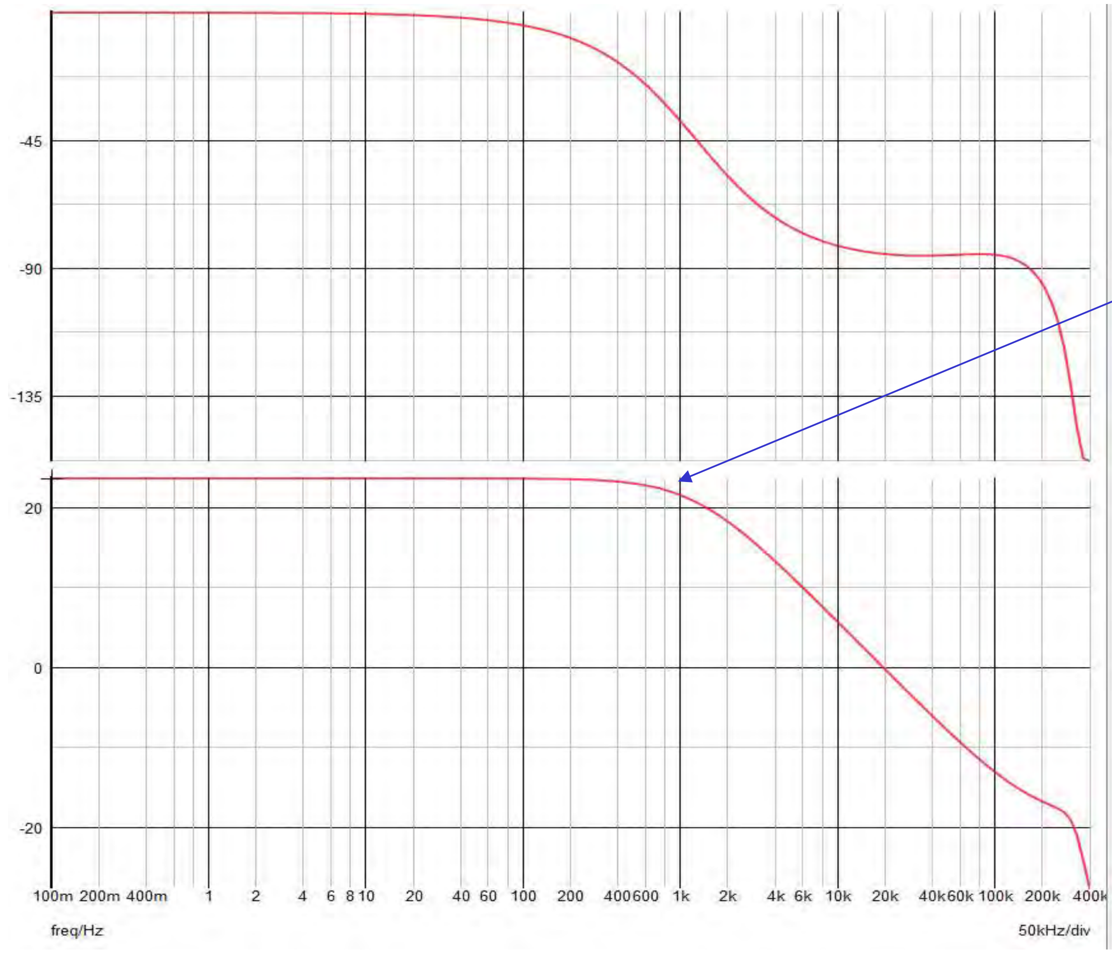
Relevant Waveforms – Buck 1A Ctrl-Out

Phase/Degrees

Gain/dB



Notice the corner frequency moves way in with a -1 slope. Phase is now -90 degrees. Modulator and filter look like a current source.

Compensation Procedure

We must compensate the feedback loop for the continuous conduction mode case as the converter operates there during most of the load range and since there is a double pole in the output filter, it is the more complex case…

Compensation Procedure – Classical Approach

Define the power train requirements :

$V_{in} := 12$ $F_{sw} := 500000$

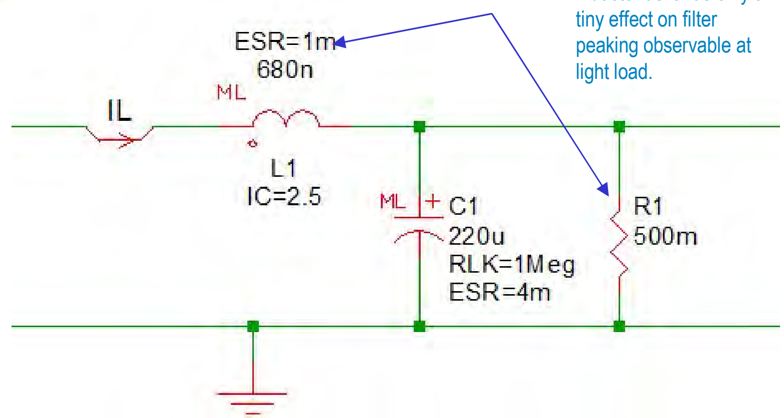
$V_{out} := 1.2$

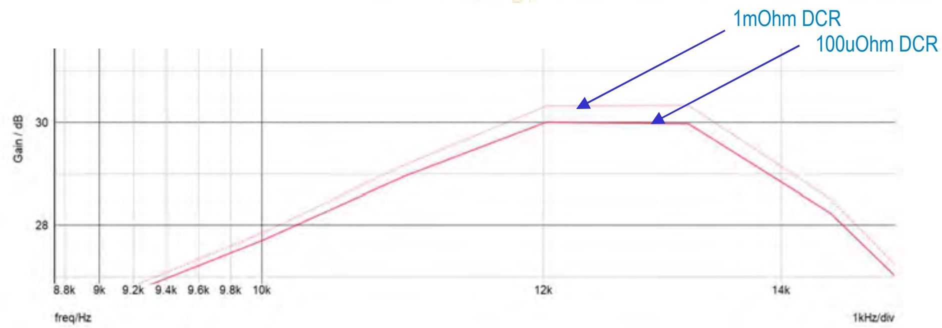
$L_{ind} := 680 \cdot 10^{-9}$ $R_{load} := 0.060$

$C_{out} := 220 \cdot 10^{-6}$

$R_{esr} := 4 \cdot 10^{-3}$

We can neglect the resistance of the inductor as it has only a tiny effect on filter peaking observable at light load.





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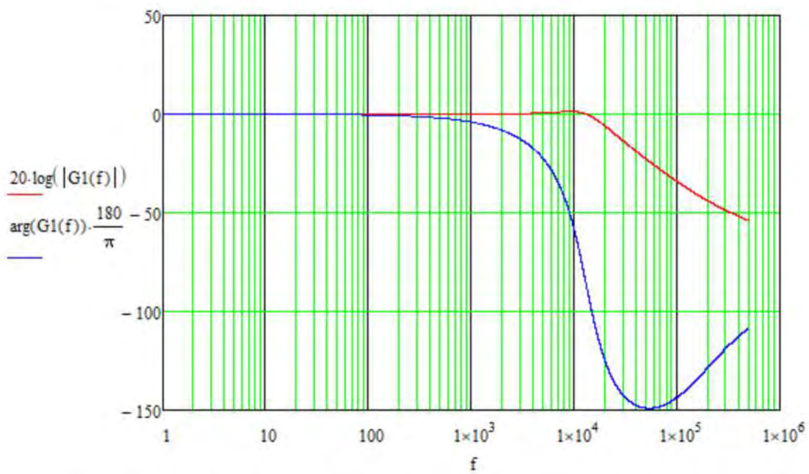
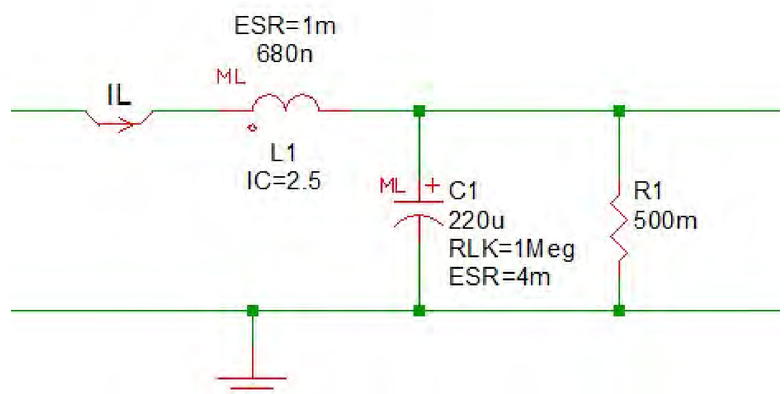
Compensation Procedure – Classical Approach

The Output Filter Transfer Function :

$$G1(f) := \frac{1 + s(f)\cdot R_{esr}\cdot C_{out}}{1 + s(f)\cdot\left(\frac{L_{ind}}{R_{load}} + R_{esr}\cdot C_{out}\right) + s(f)^2\cdot L_{ind}\cdot(C_{out})}$$





$$L_{RF} := \frac{1}{2\cdot\pi\cdot\sqrt{L_{ind}\cdot(C_{out})}} \qquad L_{RF} = 1.301\times10^4$$ ← 13kHz LC filter

$$ESR_{zero} := \frac{1}{2\cdot\pi\cdot R_{esr}\cdot(C_{out})} \qquad ESR_{zero} = 1.809\times10^5$$ ← 181kHz ESR zero

Compensation Procedure – Classical Approach

Determine the modulator gain:

$D_{max} := 1$

$V_{ramp} := 1.0$

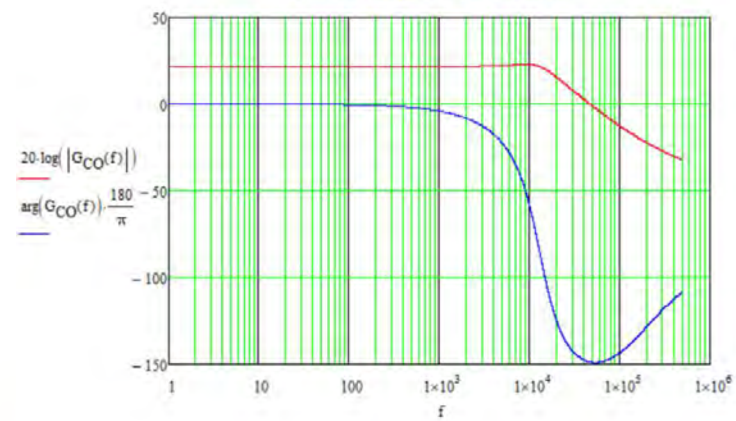
Where:

Dmax = converter upper MOSFET maximum duty cycle.
Vin = the input voltage under the condition tested.
Vramp = the peak to peak value of the oscillator ramp for the PWM.

$$G_{mod}(f) := \frac{D_{max} \cdot V_{in}}{V_{ramp}}$$

$$G_{CO}(f) := G_{mod}(f) \cdot G1(f)$$

Control To Output Transfer Function:



This is the transfer function we need to compensate for

Compensation Procedure – Classical Approach

Place the second zero to be equal to the resonant frequency of the LC filter:

$F_{Z2} := \frac{1}{2 \cdot \pi \cdot \sqrt{L_{ind} \cdot (C_{out})}}$ $\quad F_{Z2} = 1.301 \times 10^4$

Place the first zero to be 75% of the second zero:

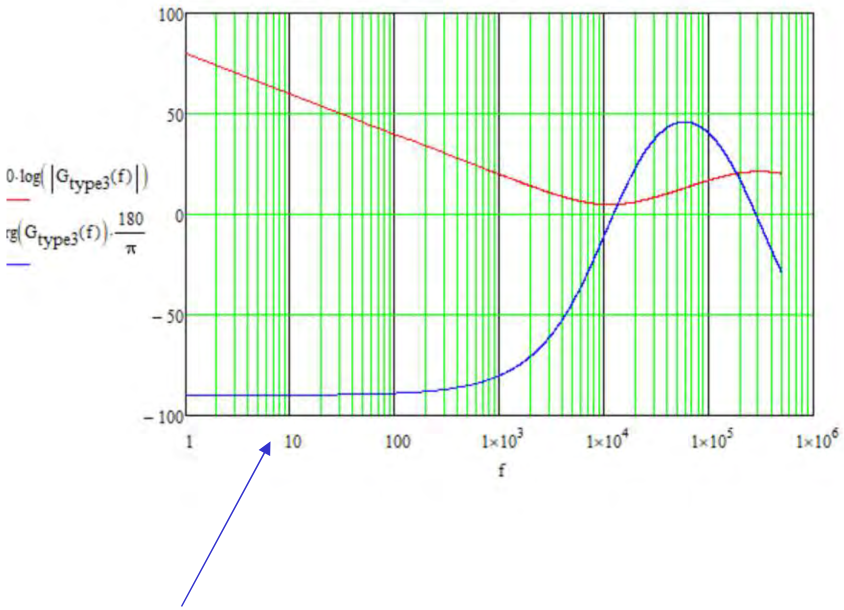
$F_{Z1} := F_{Z2} \cdot 0.75$ $\quad F_{Z1} = 9.759 \times 10^3$

Place the second pole to be 75% of the switching frequency:
The first pole is at the origin with a Type 3 amplifier

$F_{P2} := F_{sw} \cdot 0.75$ $\quad F_{P2} = 3.75 \times 10^5$

Place the third pole to be 50% of the switching frequency:

$F_{P3} := F_{sw} \cdot 0.5$ $\quad F_{P3} = 2.5 \times 10^5$

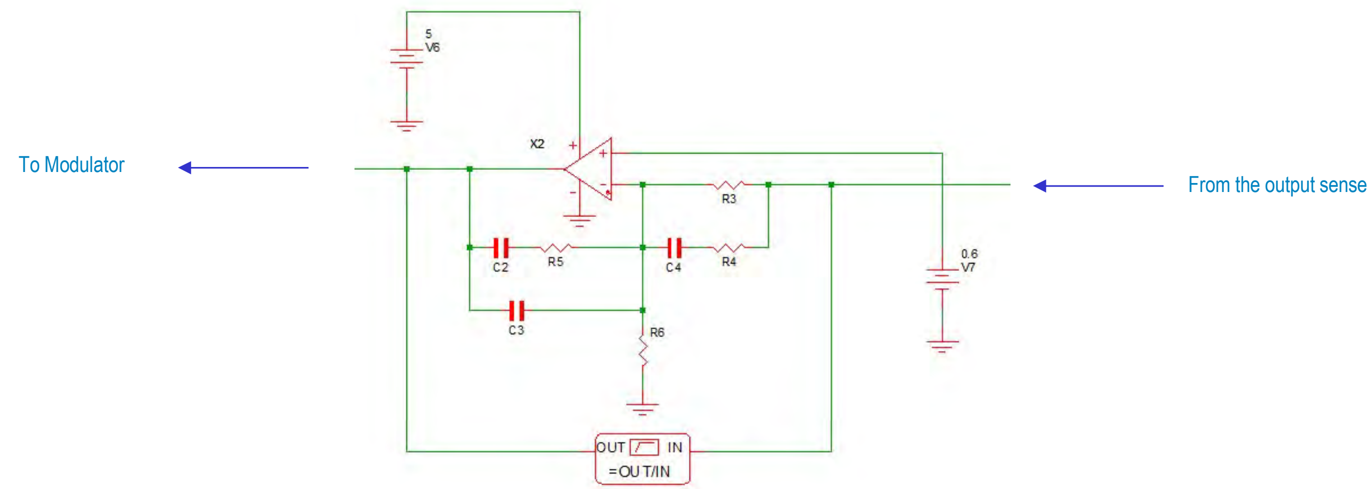


So here is our compensation pole/zero placement strategy as of now.

Compensation Procedure – Classical Approach

The Type 3 Error Amplifier:

Provides a 3 pole, 2 zero transfer function where one of the poles occurs at the origin. It should be used when there is small ESR in the output filter and the resulting zero is greater than the desired crossover frequency. It can be either an OPAMP or Transconductance Amplifier. We will use an OPAMP.



Compensation Procedure – Classical Approach

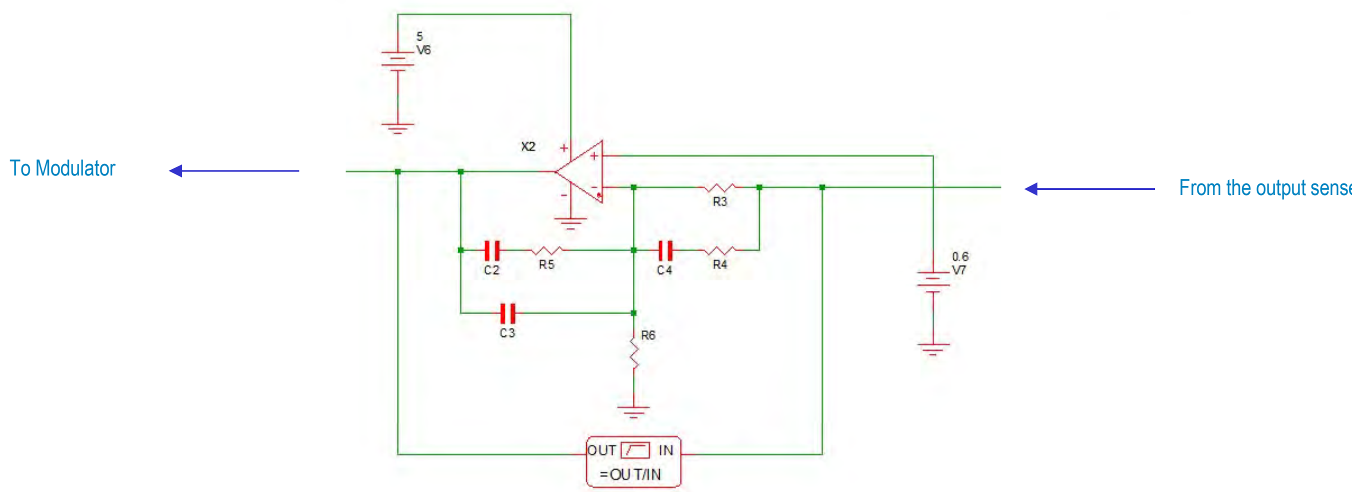
The transfer function for the type 3 error amplifier is..........

$$GEA(f) := \frac{(1 + s(f)\cdot R5\cdot C2)\cdot[1 + s(f)\cdot(R3 + R4)\cdot C4]}{s(f)\cdot R3\cdot(C2 + C3)\cdot(1 + s(f)\cdot R4\cdot C4)\cdot\left[1 + s(f)\cdot R5\cdot\left(\frac{C2\cdot C3}{C2 + C3}\right)\right]}$$

Zeros/Poles

The poles and zeros are symbolically:

$$Fz1 := \frac{1}{2\cdot\pi\cdot R5\cdot C2} \qquad Fz2 := \frac{1}{2\cdot\pi\cdot(R4 + R3)\cdot C4} \qquad Fp2 := \frac{1}{2\cdot\pi\cdot R4\cdot C4} \qquad Fp3 := \frac{1}{2\cdot\pi\cdot R5\cdot\left(\frac{C2\cdot C3}{C2 + C3}\right)}$$



Compensation Procedure – Classical Approach

Choose the desired crossover frequency:

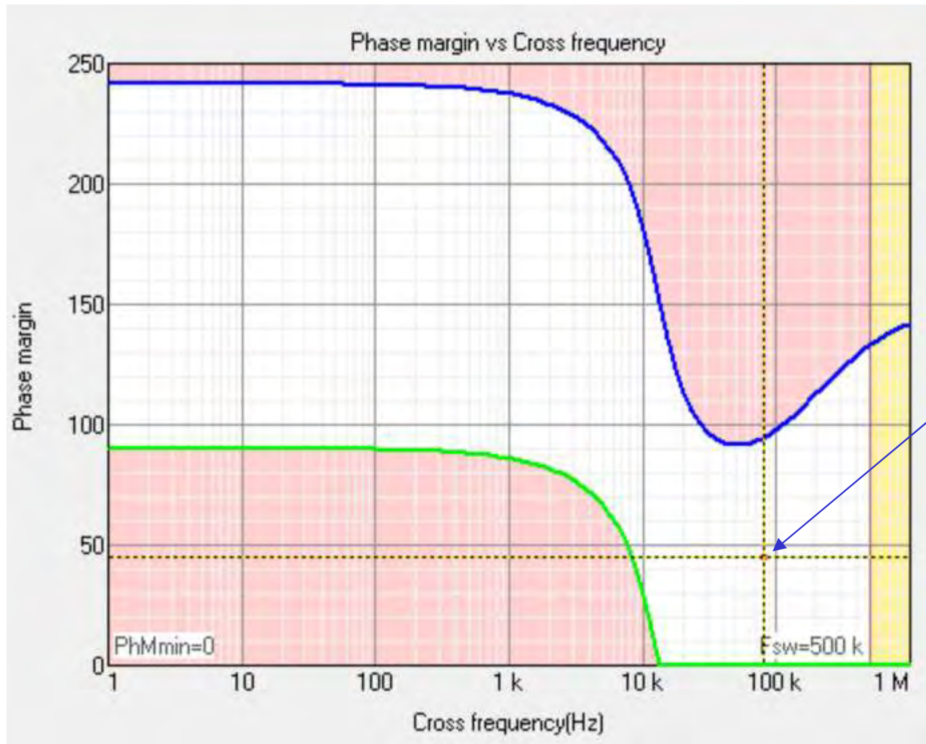
$V_{in} := 12$ $\quad F_{sw} := 500000$

$V_{out} := 1.2$

$L_{ind} := 680 \cdot 10^{-9}$ $\quad R_{load} := 0.060$

$C_{out} := 220 \cdot 10^{-6}$

$R_{esr} := 4 \cdot 10^{-3}$



We want to choose a value for crossover frequency that is less than 1/10 the switching frequency and have a minimum phase margin of 45 degrees. We also want to stay away from the shaded areas for our output filter and modulator

Compensation Procedure – Classical Approach

Calculate the component values:

Since C4 affects both a pole and a zero and affects the midband gain, choose it in an arbitrary manner:

$C4_{select} := 2.2 \cdot 10^{-9}$

Pick the crossover frequency:

$F_{crossover} := 80000$

Calculate R4 based on the frequency of the second pole:

$R4_{calc} := \frac{1}{(2 \cdot \pi \cdot F_{P2} \cdot C4_{select})}$ $R4_{calc} = 192.915$

Calculate R3 based on the frequency of the second zero:

$R3_{calc} := \frac{1}{(2 \cdot \pi \cdot F_{Z2} \cdot C4_{select})} - R4_{calc}$ $R3_{calc} = 5.367 \times 10^{3}$

Calculate R6 to obtain the correct output voltage:

$R6_{calc} := \frac{R3_{calc} \cdot V_{ref}}{V_{out} - V_{ref}}$ $R6_{calc} = 5.367 \times 10^{3}$

Calculate R5 to set the mid band gain for the crossover frequency:

$R5_{calc} := \frac{2 \cdot \pi \cdot F_{crossover} \cdot L_{ind} \cdot C_{out} \cdot V_{ramp}}{V_{in} \cdot C4_{select}}$ $R5_{calc} = 2.848 \times 10^{3}$

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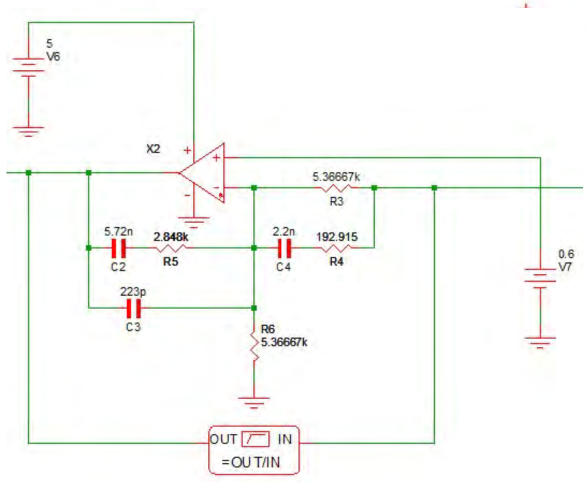
Compensation Procedure – Classical Approach

Calculate C2 based on the first zero and R5:

$$C2_{calc} := \frac{1}{2 \cdot \pi \cdot R5_{calc} \cdot F_{Z1}} \qquad C2_{calc} = 5.725 \times 10^{-9}$$

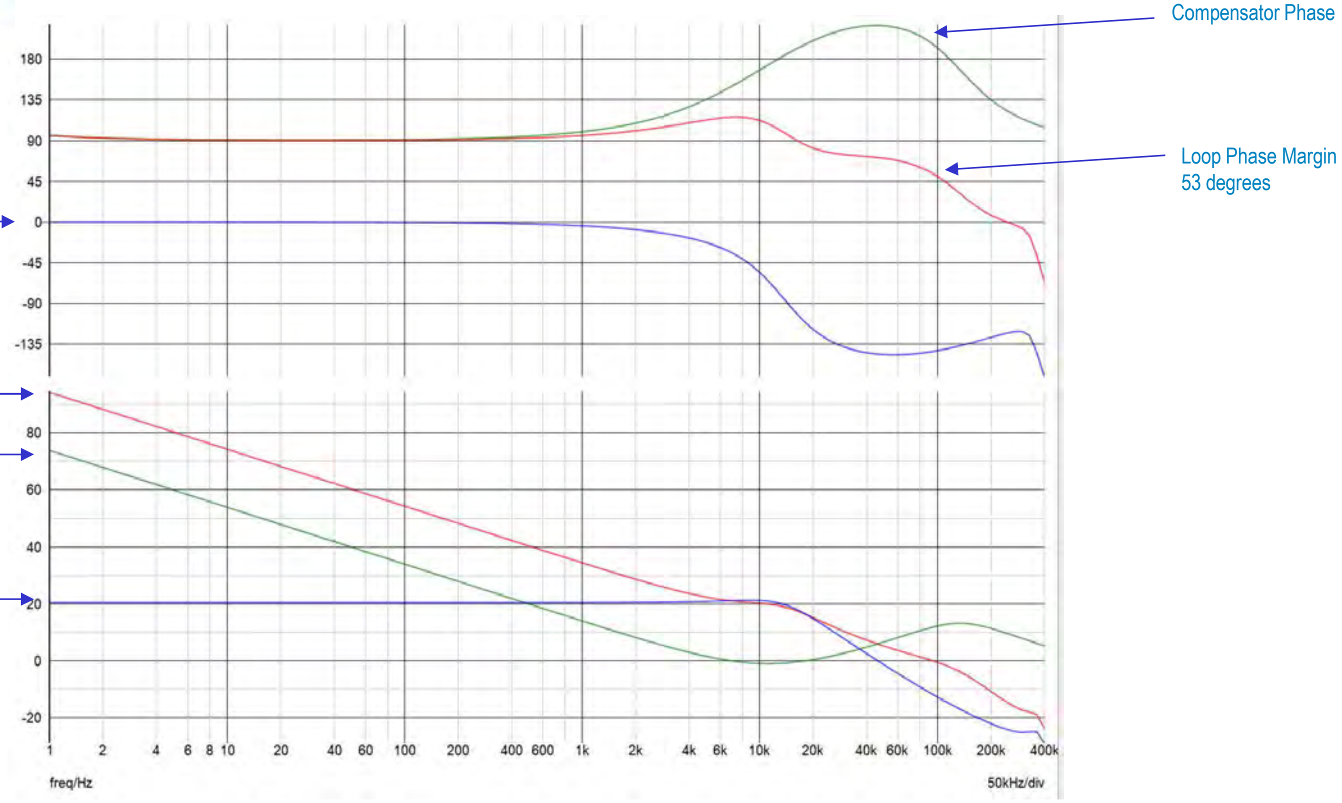
Finally, calculate C3 based on the third pole and R5:

$$C3_{calc} := \frac{1}{2 \cdot \pi \cdot R5_{calc} \cdot F_{P3}} \qquad C3_{calc} = 2.235 \times 10^{-10}$$



Compensation Procedure – Classical Approach

SIMPLIS SIMULATION RESULTS



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Is There Another Way?

One can see the classical approach is well established and works fairly well. However, it can be math intensive and still require some iteration as there are tradeoffs that must be applied due to available components. So you might ask, is there another way?

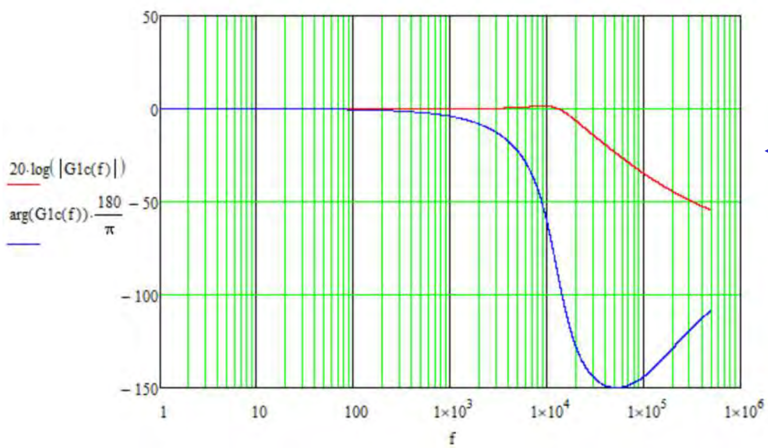
Let's ask the simulator!

Compensation Procedure – Optimization

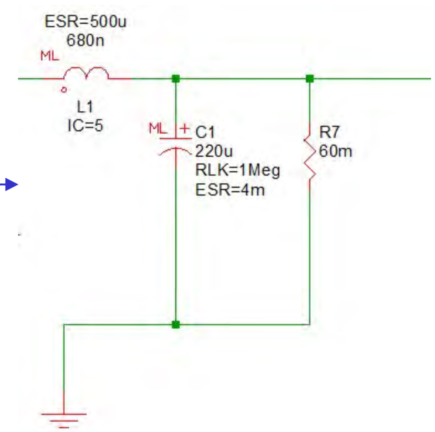
- Optimization
  - Is a type of goal seeking algorithm simulation where components are given initial values and the simulator is given a goal. The goal could be measured data or a curve. All components are parametric in nature.
  - Components are adjusted until the error between the result and the goal is reduced to a minimum.
  - Optimization can provide significant insight into a chosen design topology.
  - Can be done using AC, DC or transient analysis

Compensation Procedure – Optimization

$$G1c(f) := \frac{R_{load}\cdot\left(1 + s(f)\cdot R_{esr}\cdot C_{out}\right)}{L_{ind}\cdot C_{out}\cdot s(f)^2\cdot\left(R_{load} + R_{esr}\right) + s(f)\cdot\left(L_{ind} + R_{load}\cdot C_{out}\cdot R_{esr}\right) + R_{load}}$$



This complex function gets replaced by this



Compensation Procedure – Optimization

Determine the modulator gain:

$D_{max} := 1$

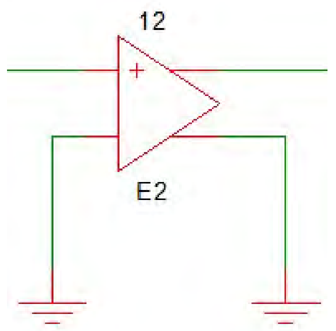
$V_{ramp} := 1.0$

Where:

Dmax = converter upper MOSFET maximum duty cycle.
Vin = the input voltage under the condition tested.
Vramp = the peak to peak value of the oscillator ramp for the PWM.

$$G_{mod}(f) := \frac{D_{max} \cdot V_{in}}{V_{ramp}}$$

← This function gets replaced by this →



Compensation Procedure – Optimization

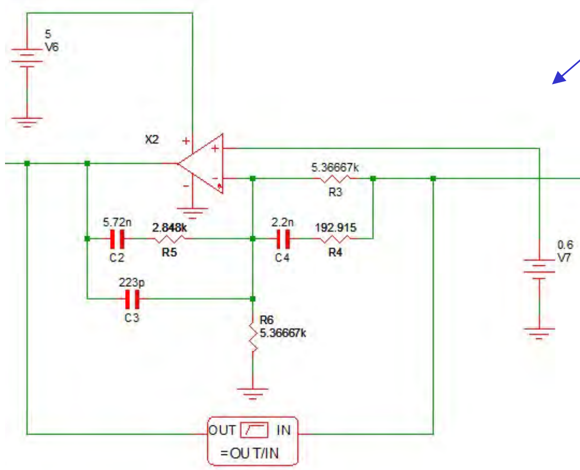
The transfer function for the type 3 error amplifier is..........

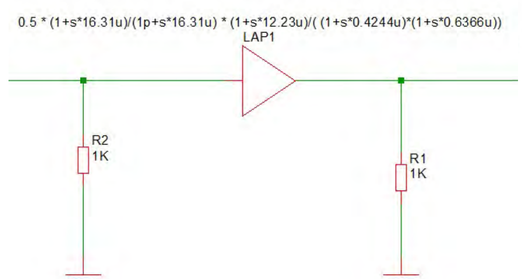
$$GEA(f) := \frac{(1 + s(f)\cdot R5\cdot C2)\cdot[1 + s(f)\cdot(R3 + R4)\cdot C4]}{s(f)\cdot R3\cdot(C2 + C3)\cdot(1 + s(f)\cdot R4\cdot C4)\cdot\left[1 + s(f)\cdot R5\cdot\left(\frac{C2\cdot C3}{C2 + C3}\right)\right]}$$

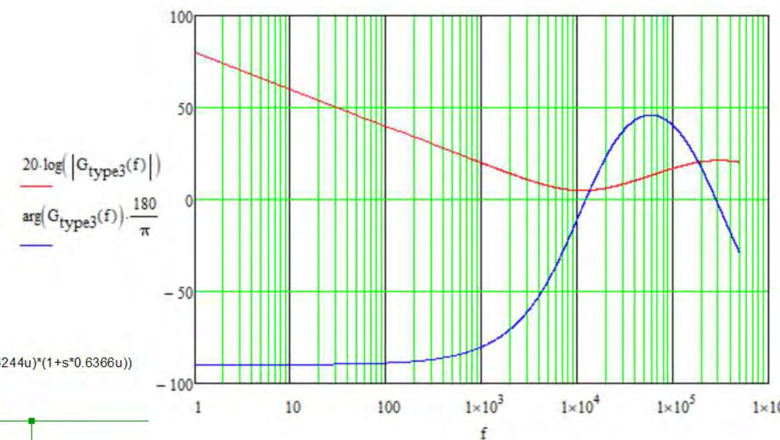
Zeros/Poles

$$G_{type3}(f) := \kappa\cdot\frac{1 + s(f)\cdot T_{Z1}}{s(f)\cdot T_{Z1}}\cdot\frac{1 + s(f)\cdot T_{Z2}}{(1 + s(f)\cdot T_{P2})\cdot(1 + s(f)\cdot T_{P3})}$$

This function gets replaced by this in the form of a Laplace Block







Compensation Procedure – Optimization

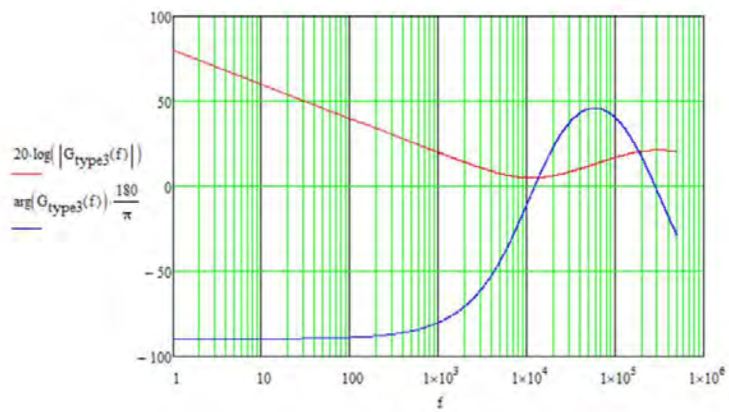
$\kappa := 1$

$T_{Z1} := \frac{1}{F_{Z1} \cdot 2 \cdot \pi}$ $T_{Z2} := \frac{1}{F_{Z2} \cdot 2 \cdot \pi}$ $T_{P2} := \frac{1}{F_{P2} \cdot 2 \cdot \pi}$ $T_{P3} := \frac{1}{F_{P3} \cdot 2 \cdot \pi}$

$T_{Z1} = 1.631 \times 10^{-5}$ $T_{Z2} = 1.223 \times 10^{-5}$ $T_{P2} = 4.244 \times 10^{-7}$ $T_{P3} = 6.366 \times 10^{-7}$

$$G_{type3}(f) := \kappa \cdot \frac{1 + s(f) \cdot T_{Z1}}{s(f) \cdot T_{Z1}} \cdot \frac{1 + s(f) \cdot T_{Z2}}{(1 + s(f) \cdot T_{P2}) \cdot (1 + s(f) \cdot T_{P3})}$$

Type 3



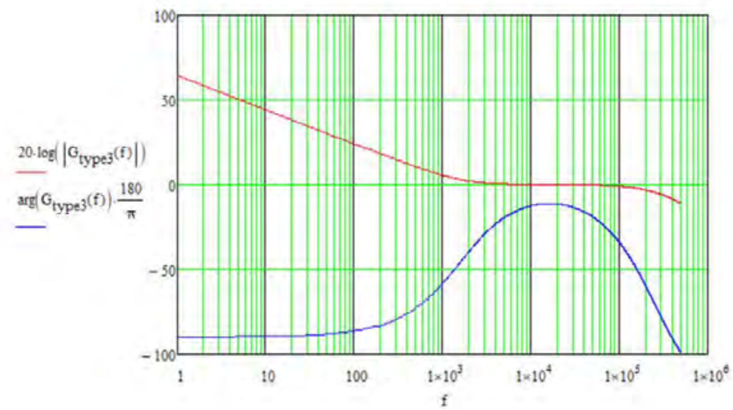
By changing the zero locations, we can actually produce a Type 2 response too.

$T_{Z1} := 0.0001$

$T_{Z2} := 0.0000001$

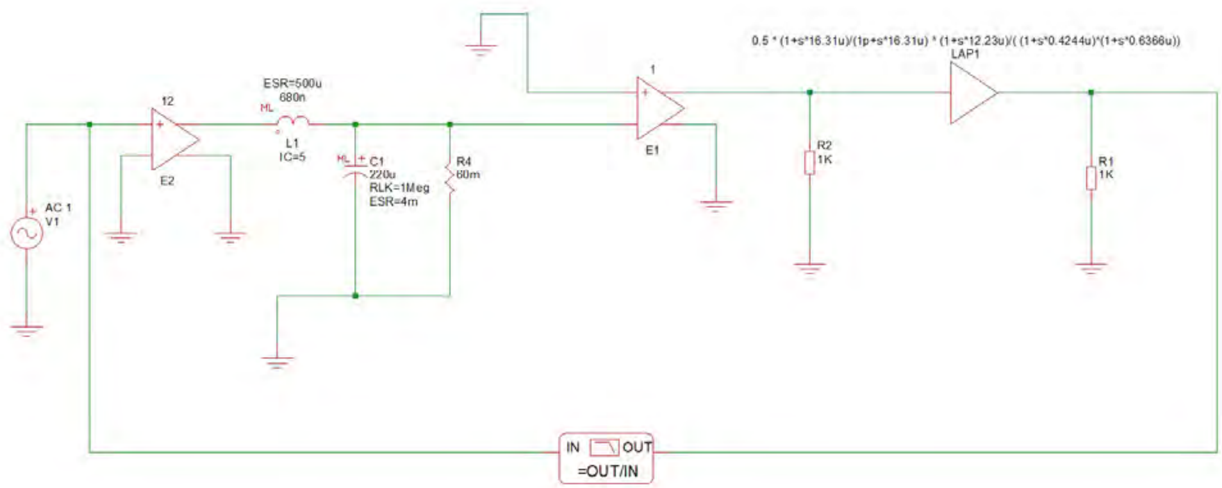
$$G_{type3}(f) := \kappa \cdot \frac{1 + s(f) \cdot T_{Z1}}{s(f) \cdot T_{Z1}} \cdot \frac{1 + s(f) \cdot T_{Z2}}{(1 + s(f) \cdot T_{P2}) \cdot (1 + s(f) \cdot T_{P3})}$$

Type 2



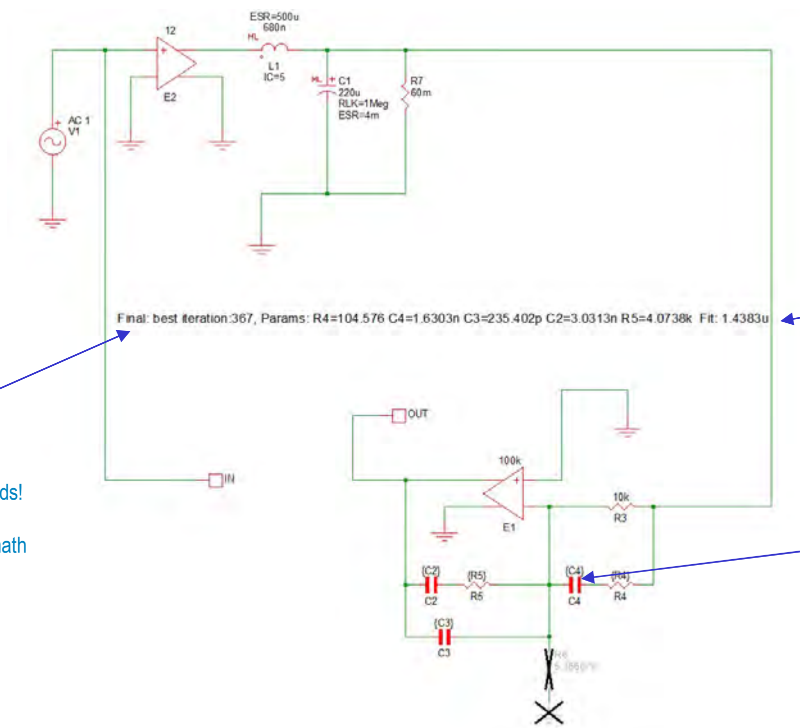
Compensation Procedure – Optimization

THIS CIRCUIT WILL GENERATE MY DESIRED REFERENCE FOR THE OPTIMIZER CIRCUIT.
I WILL FEED THE GAIN AND PHASE DATA VIA FILE INTO THE OPTIMIZER CIRCUIT.
THIS CIRCUIT EMULATES THE MODULATOR AND OUTPUT FILTER GAIN AND THEN INPUTS IT INTO THE LAPLACE BLOCK.
THE LAPLACE BLOCK IS SET UP AS A TYPE 3 AMPLIFIER WITH TWO POLES AND TWO ZEROS WITH A POLE AT THE ORIGIN.
IN THE OPTIMIZER SCHEMATIC, I WILL REPLACE THE LAPLACE BLOCK WITH AN AMPLIFIER MODELED BY A VCVS WITH AN OPEN LOOP GAIN OF 100K.
I WILL USE THE OPTIMIZER TO CALCULATE THE VALUES NEEDED TO MATCH THE AC RESPONSE OF THE REFERENCE CIRCUIT.



Frequency, gain and phase data is simulated based on only the pole and zero locations and adjustment of the gain to match my desired crossover frequency and phase margin. This data is saved to a text file directly from the bode plot.

Compensation Procedure – Optimization



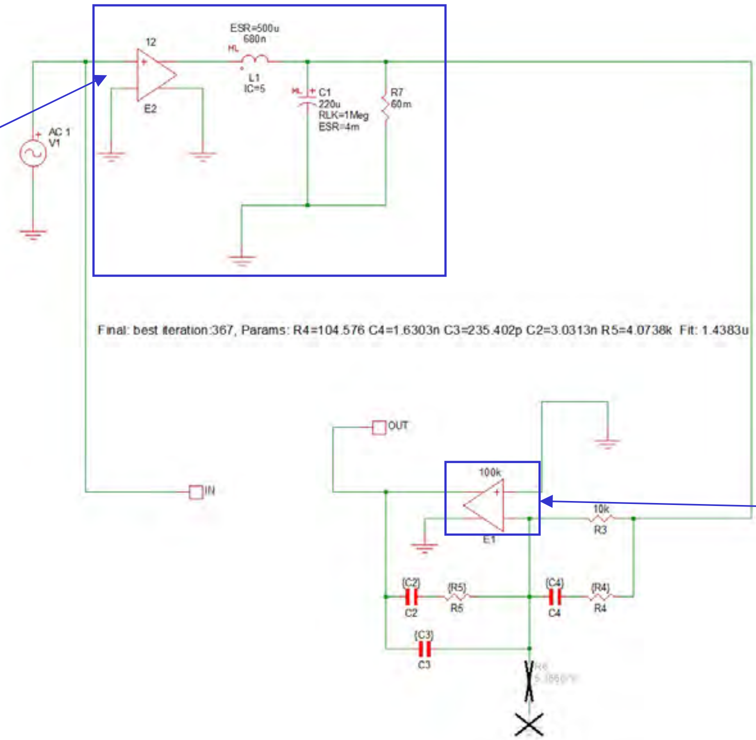
SIMetrix Optimizer chooses the values that make the response of the amplifier match that of the total Laplace block so that the total open loop gain is matched.

Total simulation time for 367 iterations was only 17 seconds! (shorter than the time my computer took to open the math software I used)

Notice I deliberately choose the value of R3 to be what I wanted for the set point viewing chain. C4 was left as an unknown as were the other parts with curly braces.

THIS CIRCUIT IS BEING OPTIMIZED SO THAT THE BODE PLOT FROM THIS CIRCUIT MATCHES THE REFERENCE PLOT.
THE IDEA IS TO LET SIMETRIX DETERMINE THE VALUES OF THE COMPENSATOR BASED ON THE LAPLACE BLOCK.
THE PARTS IN CURLY BRACES ARE THE ONES TO BE CALCULATED BY THE OPTIMIZER. THE FILE THAT IS USED TO MATCH THE CURVE COMES FROM THE OTHER CIRCUIT.

Compensation Procedure – Optimization



This block can be replaced with an averaged model of any topology!

An open loop DC bias point could be added to allow analysis with any number of OPAMP models

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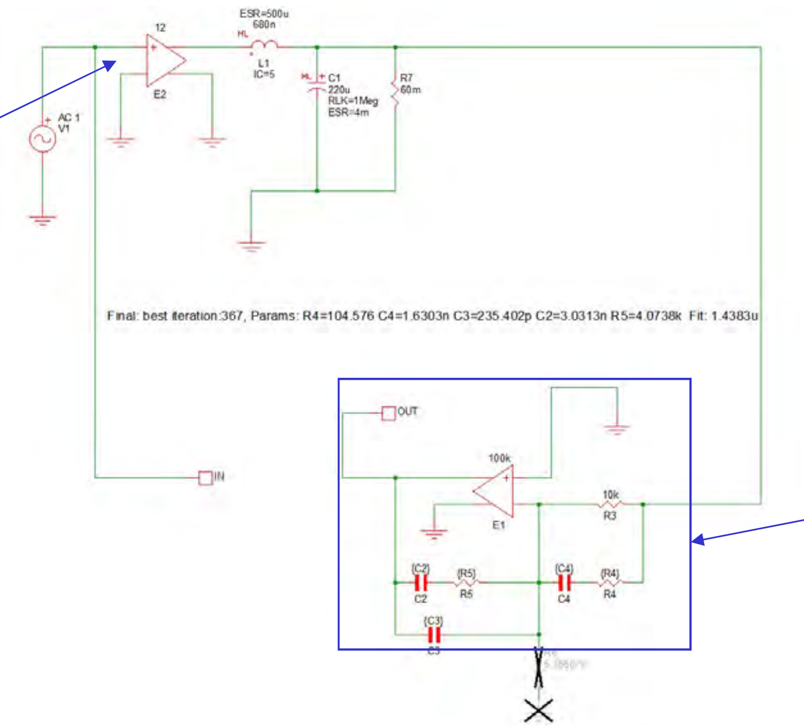
Compensation Procedure – Optimization

This block can be replaced with an averaged model of any topology!



A trans-conductance amplifier (OTA or gm) block could be added instead of the OPAMP approach.

THIS CIRCUIT IS BEING OPTIMIZED SO THAT THE BODE PLOT FROM THIS CIRCUIT MATCHES THE REFERENCE PLOT.
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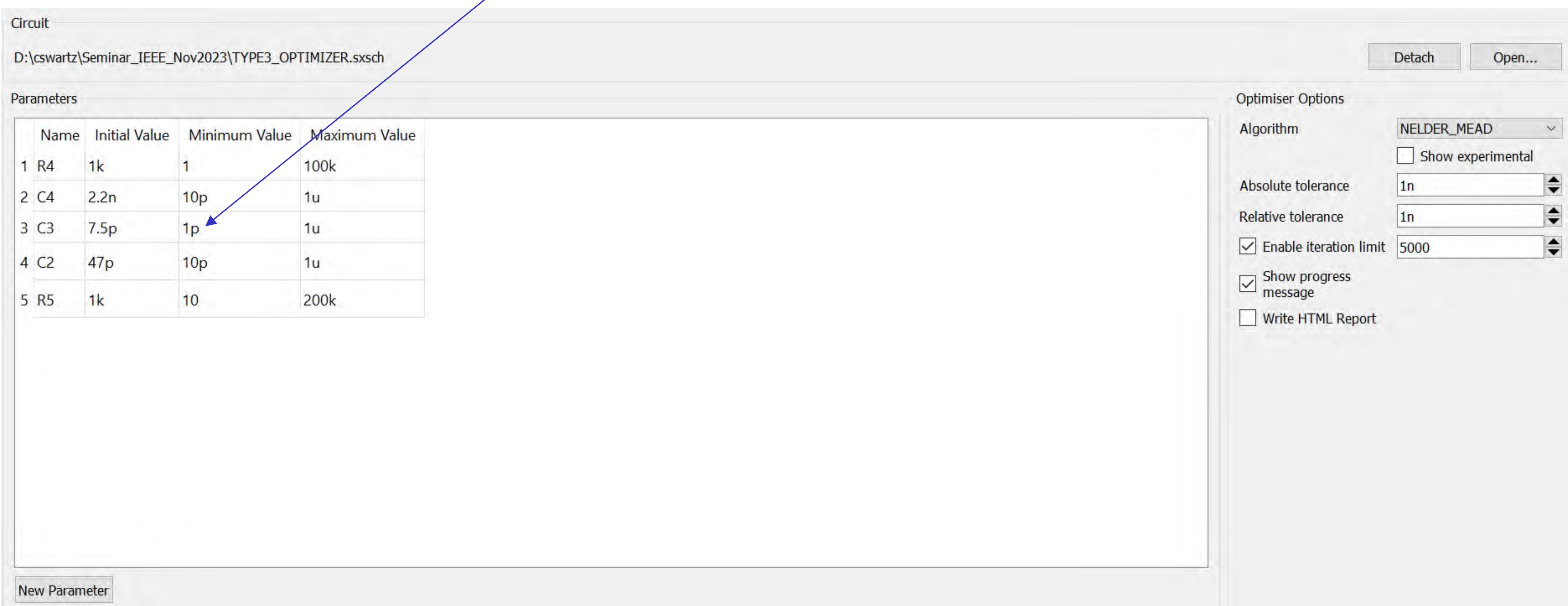
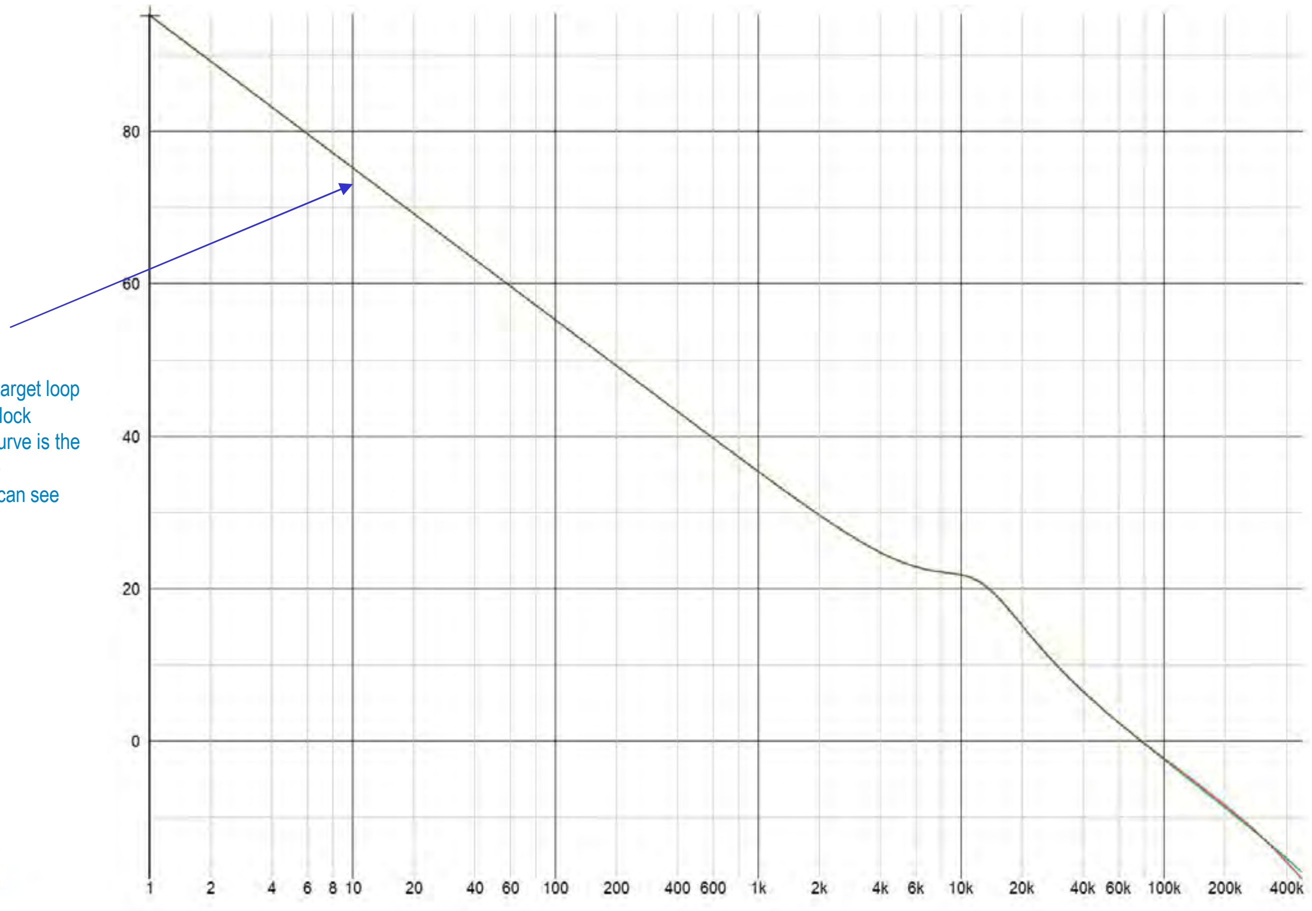
Compensation Procedure – Optimization

Here I applied some initial conditions and some reasonable limits on component values.



	Name	Initial Value	Minimum Value	Maximum Value
1	R4	1k	1	100k
2	C4	2.2n	10p	1u
3	C3	7.5p	1p	1u
4	C2	47p	10p	1u
5	R5	1k	10	200k

Compensation Procedure – Optimization



The green curve is the target loop gain from the Laplace block reference and the red curve is the type 3 amplifier with the calculated values. You can see they match perfectly.

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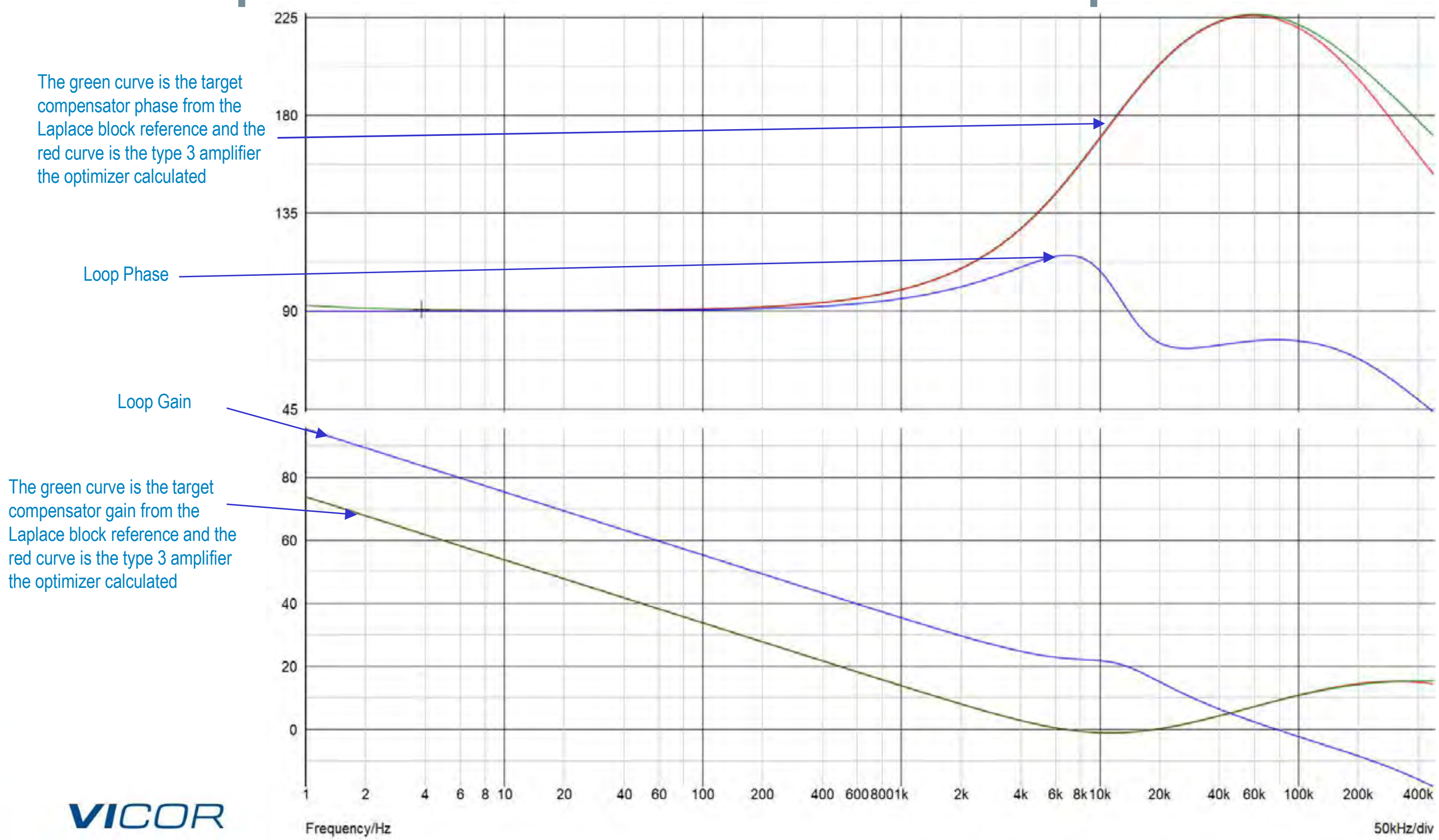
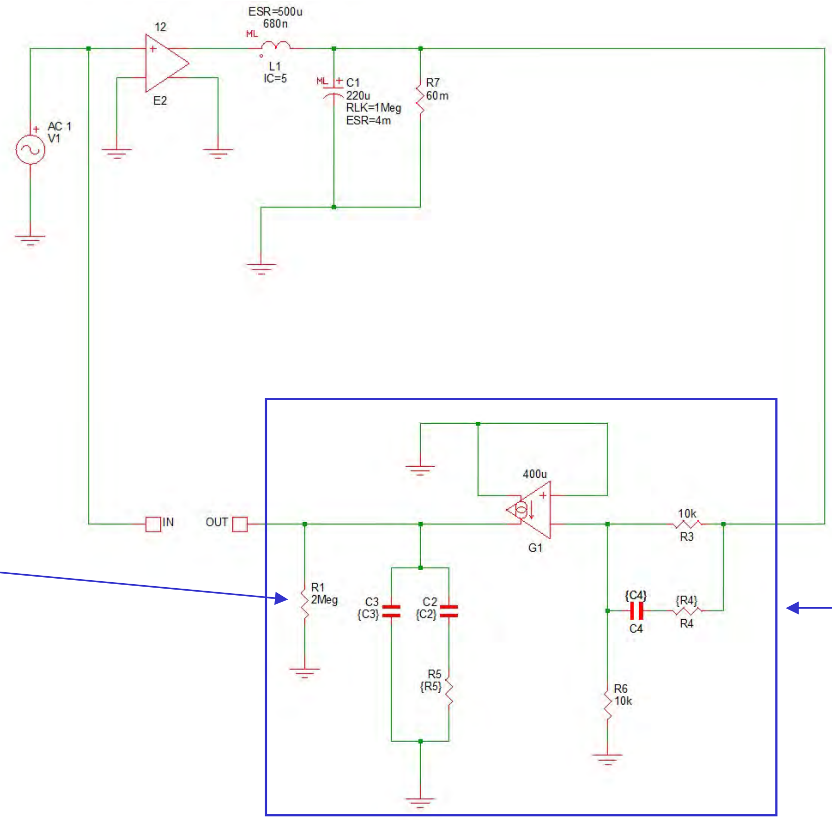
Compensation Procedure – Optimization



Compensation Procedure – Optimization

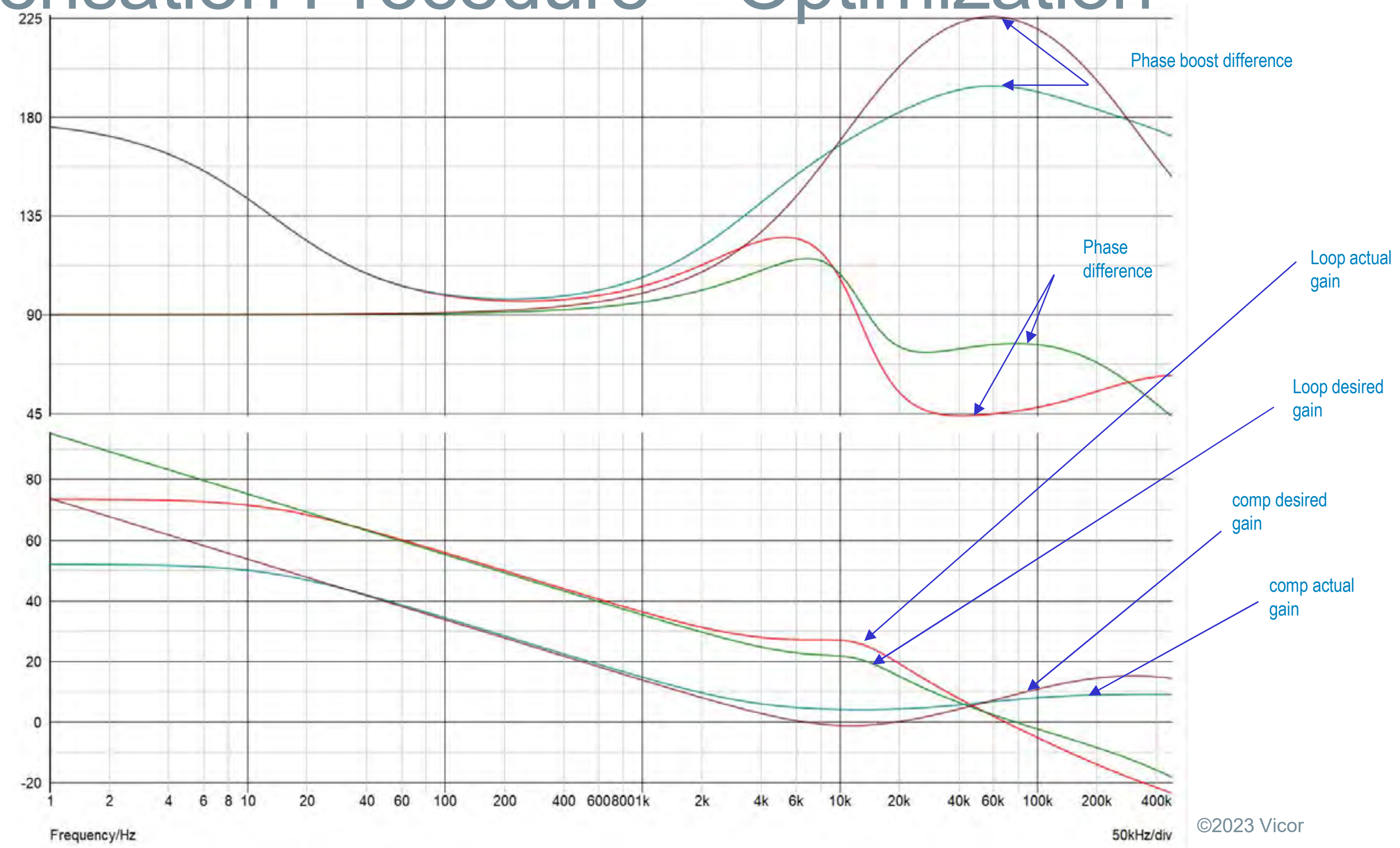


Note that all gm amplifiers (OTA) have some output resistance which determines the maximum output gain. We need to include that here

This is now a type 3 trans-conductance amplifier (OTA). We need to specify what the gm is.

Compensation Procedure – Optimization

Here is the result and it does not match as expected. It seems that one of the programmed zeros is not producing the desired phase boost! WHAT HAPPENED???



Compensation Procedure – Optimization

$$R6_{select} := 10000$$

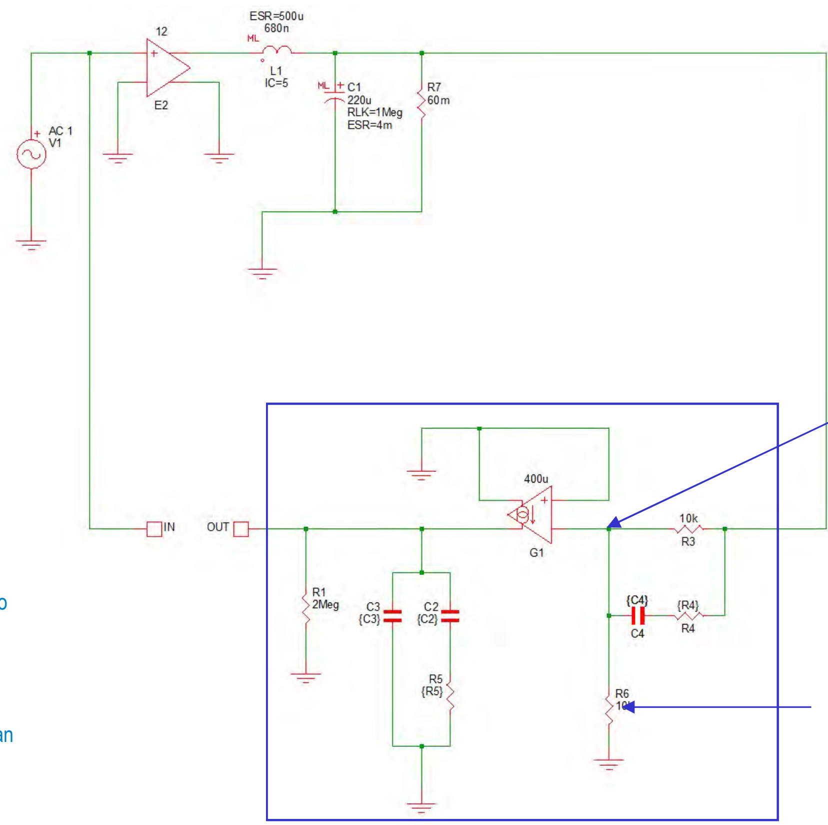
$$R3_{select} := 10000$$

$$F_{Z1gmcalc} := \frac{1}{2 \cdot \pi \cdot R5_{calc} \cdot C2_{calc}} \qquad F_{Z1gmcalc} = 9.759 \times 10^{3}$$

$$F_{Z2gmcalc} := \frac{1}{2 \cdot \pi \cdot \left(R3_{select} + R4_{calc}\right) \cdot C4_{select}} \qquad F_{Z2gmcalc} = 7.097 \times 10^{3}$$

$$F_{P1gmcalc} := \frac{\left(C2_{calc} + C3_{calc}\right)}{2 \cdot \pi \cdot R5_{calc} \cdot C3_{calc} \cdot C2_{calc}} \qquad F_{P1gmcalc} = 2.598 \times 10^{5}$$

$$F_{P2gmcalc} := \frac{1}{2 \cdot \pi \cdot \left(\frac{R3_{select} \cdot R6_{select}}{R3_{select} + R6_{select}} + R4_{calc}\right) \cdot C4_{select}} \qquad F_{P2gmcalc} = 1.393 \times 10^{4}$$

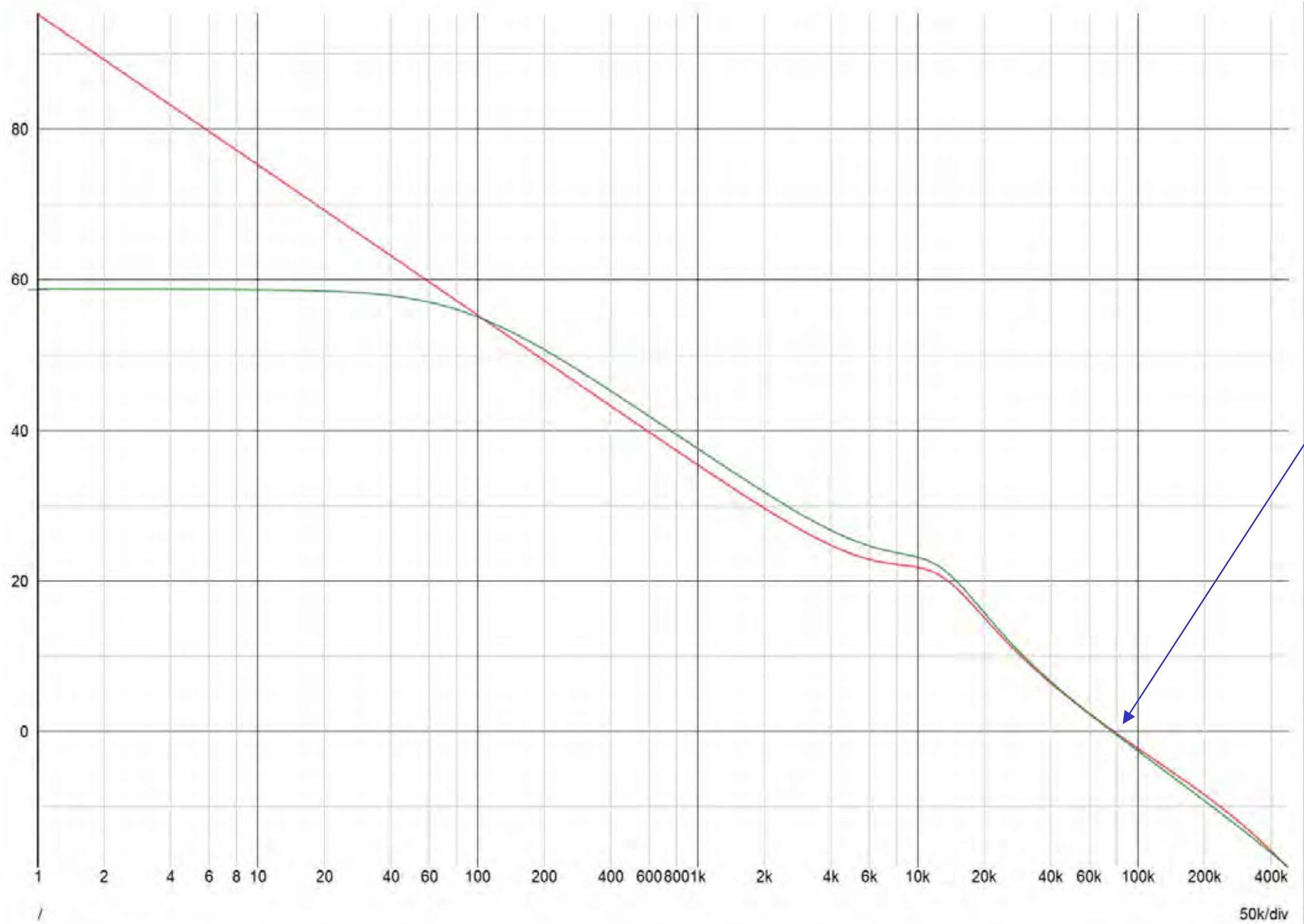


There is no virtual ground like that found in an operational amplifier type 3.

So R6 determines the second pole and that pole is tied to the zero that is determined by R3. So if the ratio of R3 to R6 is small, you can't have the zero and pole separated far enough to achieve the desired response. The Optimizer does the best that it can based on this constraint. So without doing anything else, the Optimizer has found a circuit limitation based on the reference and divider used to operate at 1.2V!!

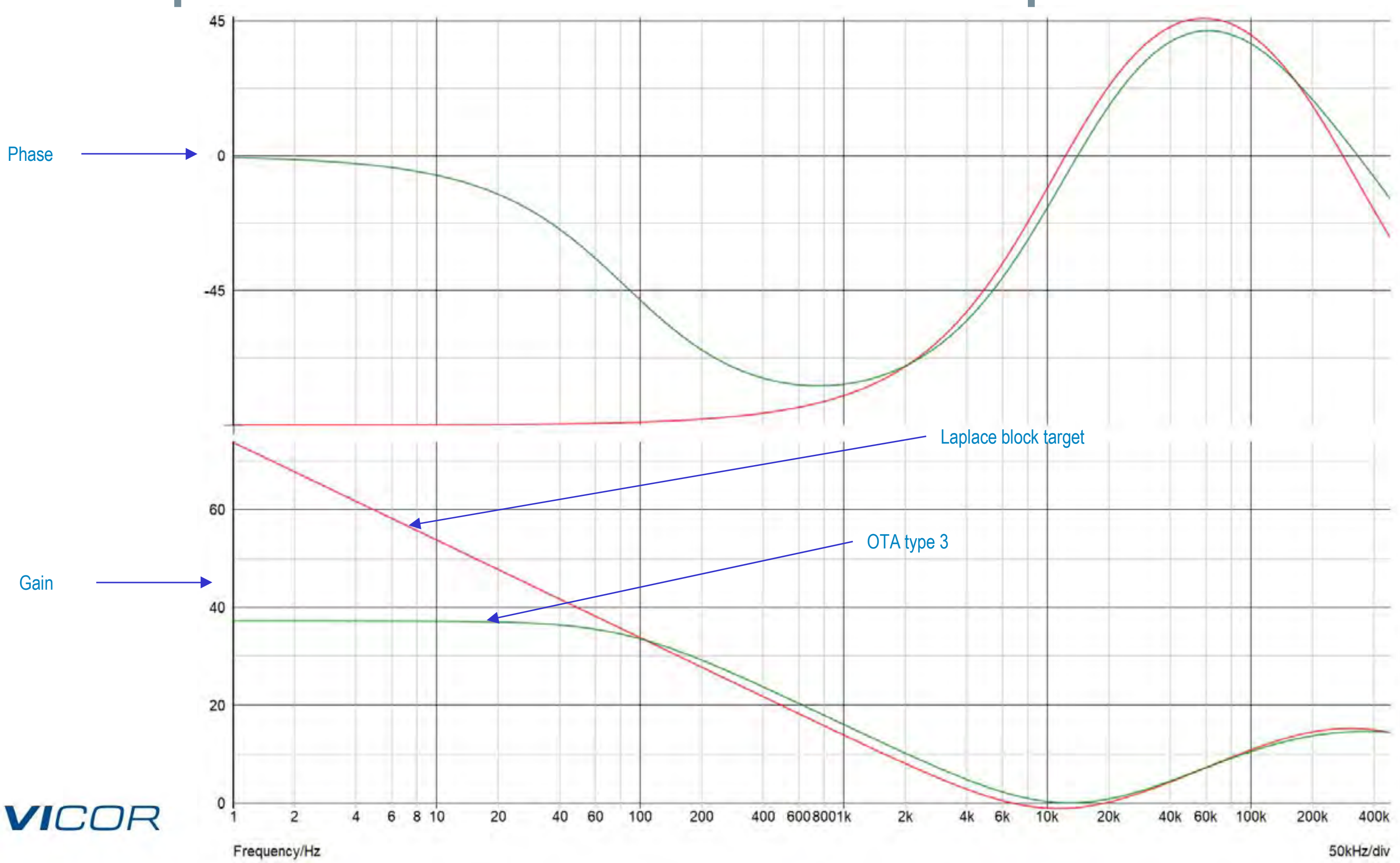
I selected R3 and R6 to match the OPAMP type 3 configuration as shown. Unlike the OPAMP, the gm amplifier response is affected by R6 as shown to the left.

Compensation Procedure – Optimization



Here I selected R3 to be 10k and R6 to be 1k. With proper separation of the zero and pole I can get a very good match as to my desired response. So the Optimizer method shows that an OTA does not have the same flexibility as an OPAMP when used as a type 3 amplifier configuration with low output voltage. This would work well for a higher voltage output like 10V or 12V. The Optimizer provides good insight into design limitations and quickly.

Compensation Procedure – Optimization



Here is the target response (red) vs the type 3 gm amplifier designed by the Optimizer with R3 = 10k and R6 = 1k to show what can be achieved.

Summary

- Today we have discussed:
  - Basic waveforms and transfer functions of the buck regulator using equations and SIMPLIS
  - Basic loop compensation of a buck regulator using a classical approach to calculate component values.
  - Use of a simulation based optimizer (SIMetrix Optimizer) to calculate all of the component values for both OPAMP based and OTA based type 3 amplifiers with data generated by knowing pole and zero locations and a gain term.
  - The optimizer approach has flexibility to work with other topologies and amplifier configurations.
  - That the optimizer approach can add significant insight to the chosen design topology and can aid in the selection of the proper choice of compensator.

References

SIMetrix/SIMPLIS (www.simplistechnologies.com)
Powersim/Altair (www.altair.com)
Infineon Application Note AN-1162 (www.infineon.com)

Thank you

Questions?

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