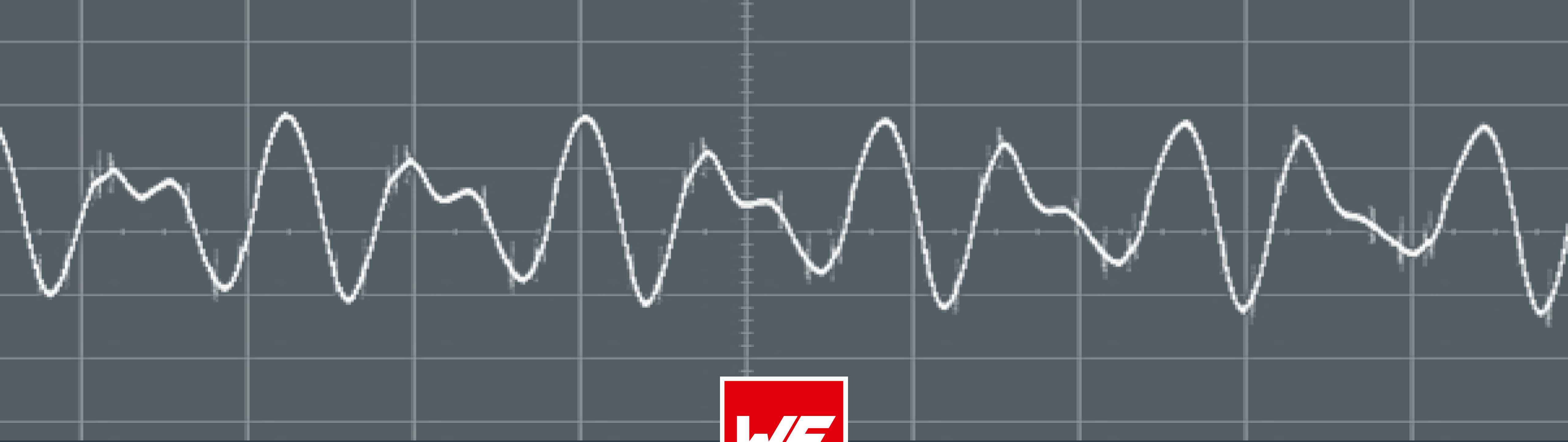


HOW THE OUTPUT CAPACITOR CAN CAUSE INSTABILITY OF A POWER SUPPLY

Eleazar Falco
Application Engineer

WÜRTH ELEKTRONIK MORE THAN YOU EXPECT

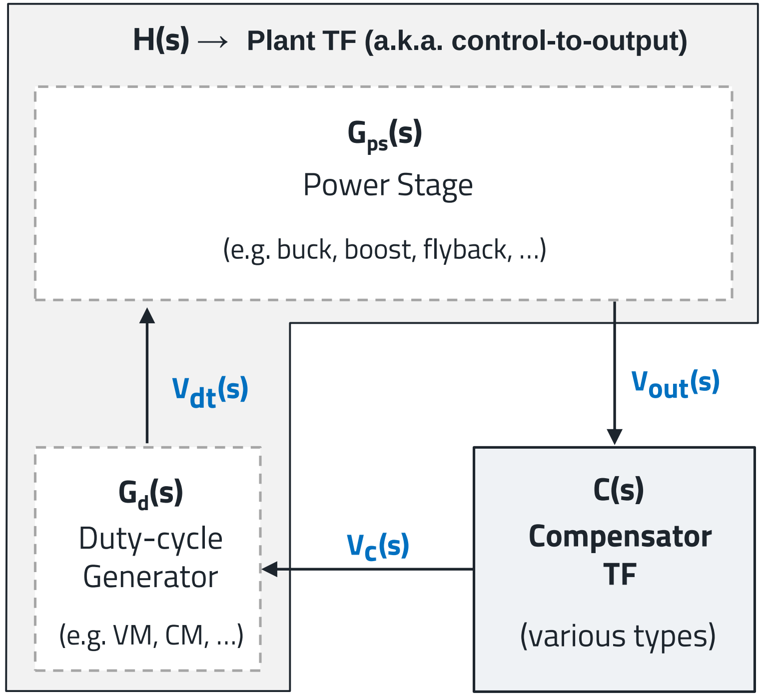
AGENDA

- Review of feedback loop stability basics
- The output capacitor in a VM-CCM buck converter
  - The output capacitor in the power stage transfer function
  - Impact of output capacitor parameter variations
- Design cases with real measurements:
  - Adding/removing bulk capacitor
  - Same capacitance, different ESR
- A stable control-loop for any output capacitor?
- Q & A

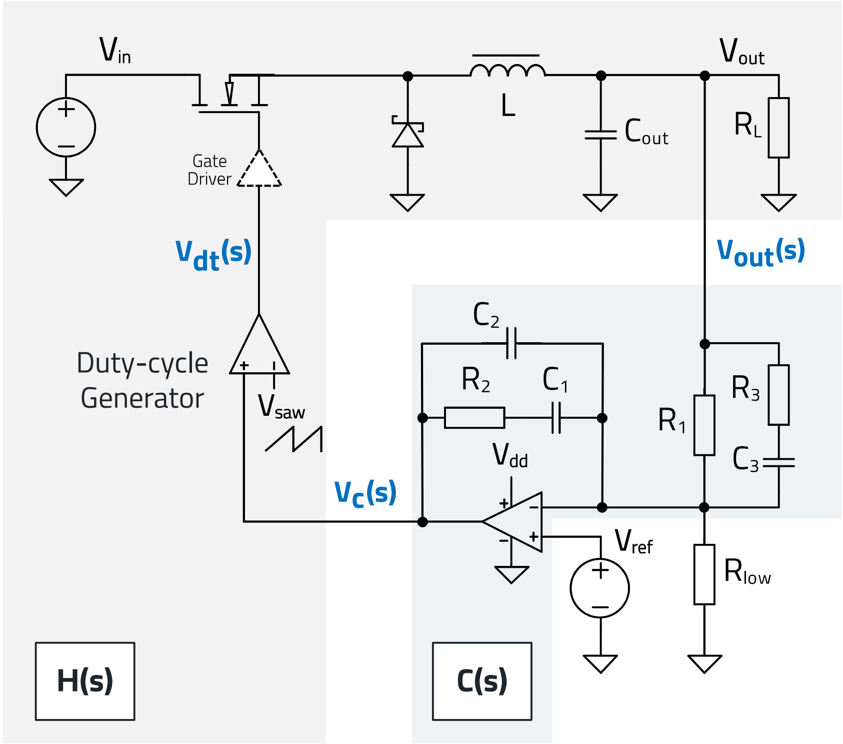
REVIEW OF FEEDBACK LOOP STABILITY CONCEPTS

REVIEW OF BASICS - FEEDBACK LOOP STABILITY OF DC-DC CONVERTERS

The blocks in the control loop of a DC-DC converter



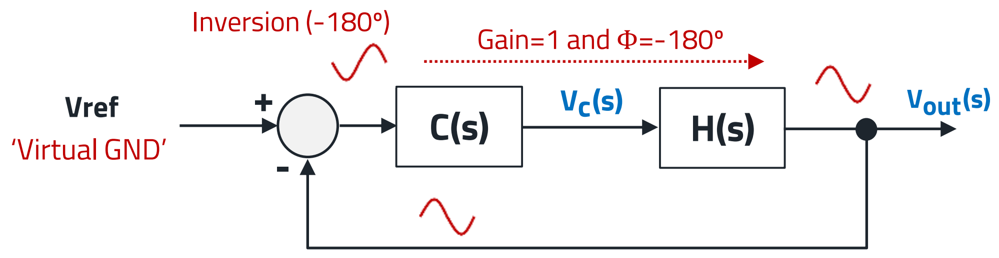
Voltage-mode buck converter with op-amp based type-3 compensator



REVIEW OF BASICS - FEEDBACK LOOP STABILITY OF DC-DC CONVERTERS

Open-loop transfer function and basic stability criteria

Control-loop block diagram for AC (s-domain)



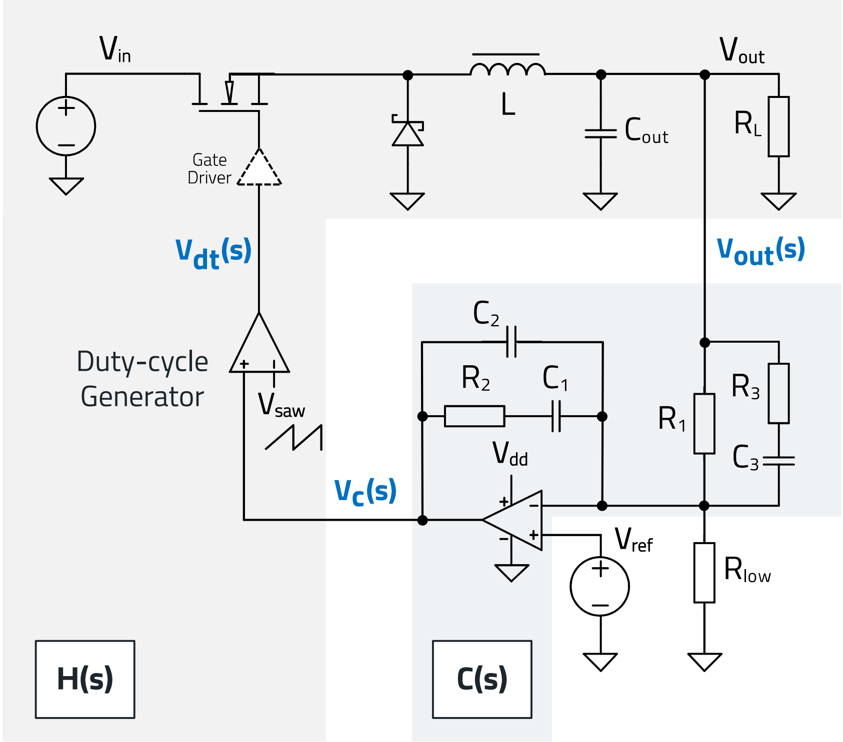
Open–loop TF → $G_{OL}(s)=C(s)\cdot H(s)$

Stability criteria (only one crossover):

- For $|G_{OL}(f_c)|=0$ dB (Gain=1) then:

$\Phi(GOL(fc))>-180°$

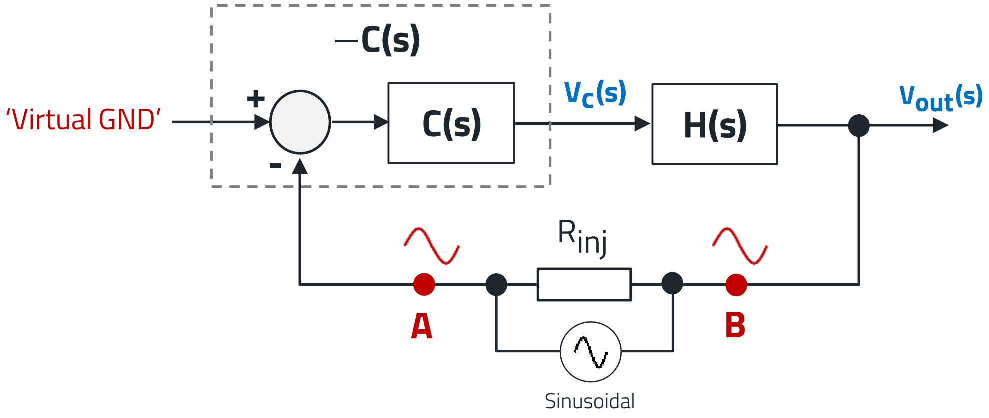
Voltage-mode buck converter with op-amp based type-3 compensator



REVIEW OF BASICS - FEEDBACK LOOP STABILITY OF DC-DC CONVERTERS

Stability measurement: the voltage injection method

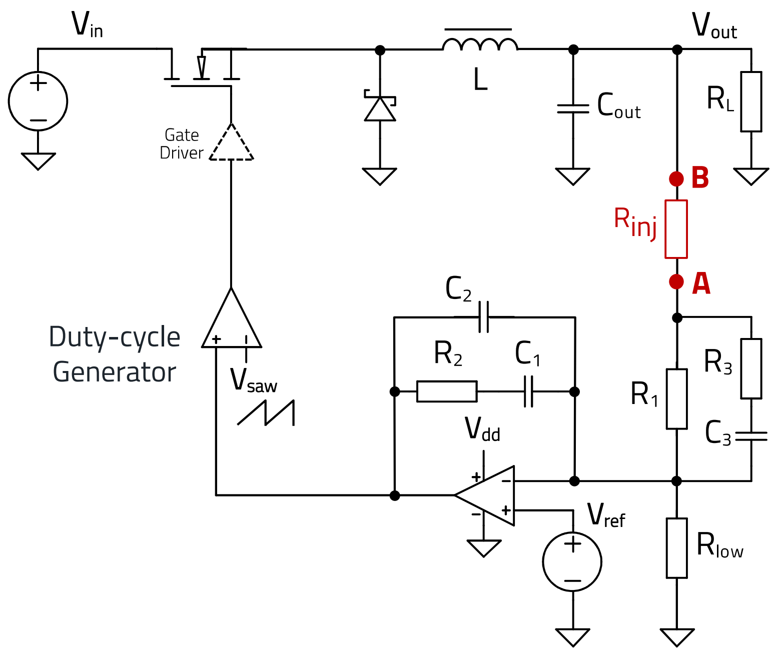
How we will be measuring it:
Inversion is included in the measured compensator frequency response (negative feedback). It cannot be separated.



Open−loop TF → $G_{OL}(s)=-C(s)\cdot H(s)$

$\Phi(GOL(fc))>-360°$ (not -180°!)

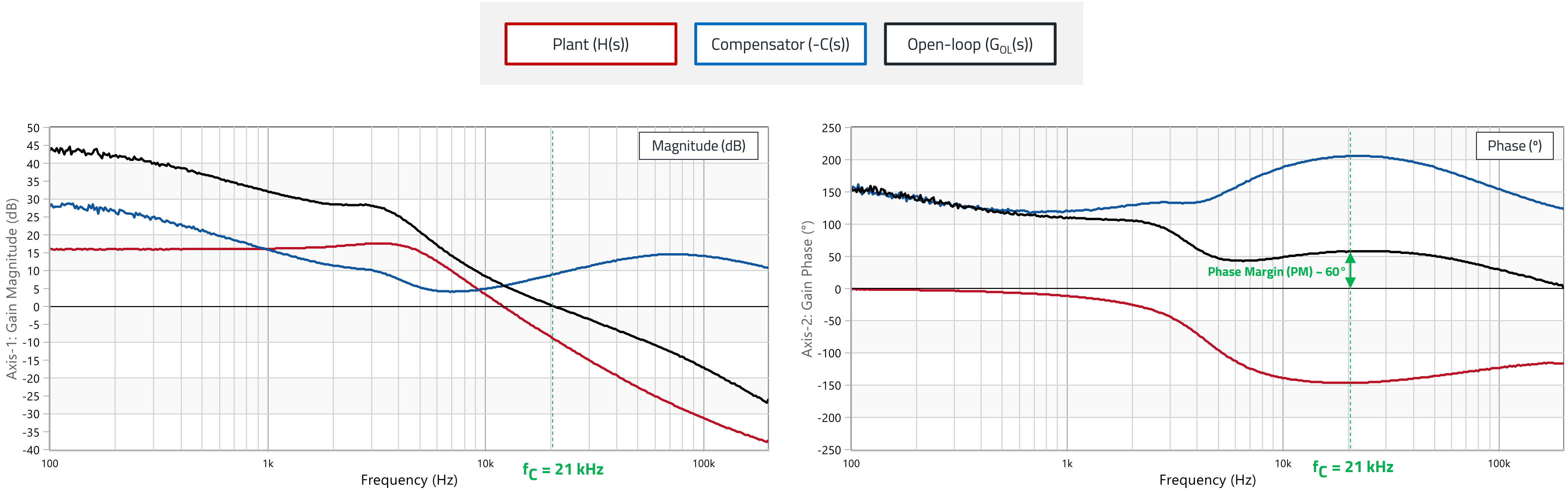
Voltage-mode buck converter with op-amp based type-3 compensator



(*) See for reference: *DC-DC Converter Stability Measurement*, V3.3, Application Note, Omicron Lab

REVIEW OF BASICS - FEEDBACK LOOP STABILITY OF DC-DC CONVERTERS

A measurement example: plant, compensator and open-loop response with stability margin



THE OUTPUT CAPACITOR IN A VM-CCM BUCK CONVERTER

THE OUTPUT CAPACITOR IN A VM-CCM BUCK CONVERTER

The plant or control-to-output transfer function of a VM-CCM Buck converter

DC–Gain → $G_0=\frac{V_{in}}{V_{saw}}$

ESR Zero → $\omega_z=\frac{1}{r_{Cout}\cdot C_{out}}$

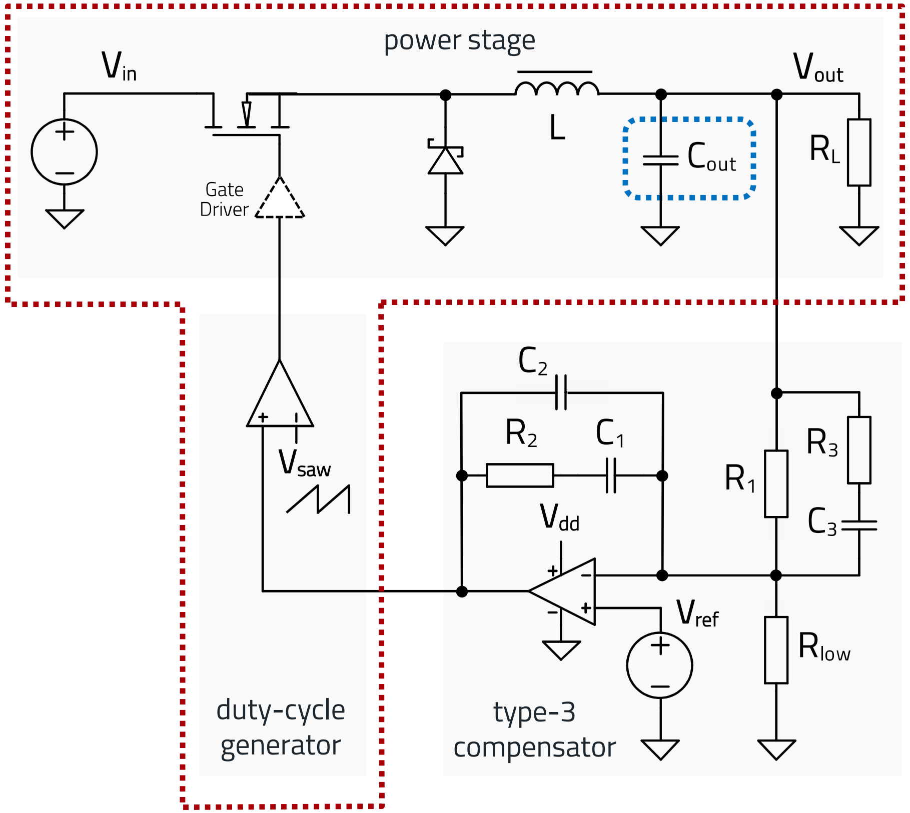
$$H(s)=\frac{v_{out}(s)}{v_c(s)}=G_0\cdot\frac{\left(1+\frac{s}{\omega_z}\right)}{\left(1+\frac{s}{Q\cdot\omega_0}+\frac{s^2}{\omega_0{}^2}\right)}$$

Resonant double–pole

$$\omega_0=\frac{1}{\sqrt{L\cdot C_{out}\cdot\frac{R_L+r_{Cout}}{R_L+r_{Ldcr}}}}$$

$$Q=\sqrt{\frac{L}{C_{out}}}\cdot\frac{1}{\frac{L}{C_{out}\cdot(r_{Ldcr}+R_L)}+r_{Cout}+\frac{r_{Ldcr}\cdot R_L}{r_{Ldcr}+R_L}}$$

H(s) → Plant or Control-to-output TF



(*) See for reference: *Switch-Mode Power Supplies: SPICE Simulations and Practical Designs*, Second Edition McGraw-Hill Professional, 2014, written by C. Basso

THE OUTPUT CAPACITOR IN A VM-CCM BUCK CONVERTER

The DC or low-frequency gain term

DC–Gain $\rightarrow G_0 = \dfrac{V_{in}}{V_{saw}}$

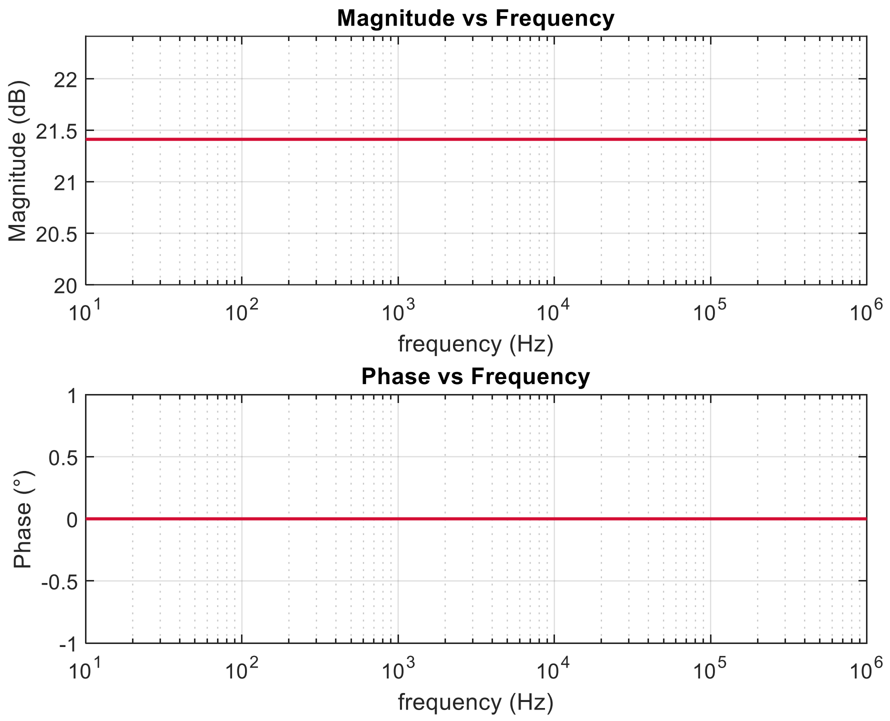
ESR Zero $\rightarrow \omega_Z = \dfrac{1}{r_{Cout} \cdot C_{out}}$

$$H(s) = G_0 \cdot \frac{\left(1 + \frac{s}{\omega_Z}\right)}{\left(1 + \frac{s}{Q \cdot \omega_0} + \frac{s^2}{\omega_0^2}\right)}$$

Resonant double–pole

$$\omega_0 = \frac{1}{\sqrt{L \cdot C_{out} \cdot \frac{R_L + r_{Cout}}{R_L + r_{Ldcr}}}} \qquad Q = \sqrt{\frac{L}{C_{out}}} \cdot \frac{1}{\frac{L}{C_{out} \cdot (r_{Ldcr} + R_L)} + r_{Cout} + \frac{r_{Ldcr} \cdot R_L}{r_{Ldcr} + R_L}}$$

Example G_0=21.2 dB



THE OUTPUT CAPACITOR IN A VM-CCM BUCK CONVERTER

The ESR zero

DC–Gain $\rightarrow G_0 = \frac{V_{in}}{V_{saw}}$

ESR Zero $\rightarrow \omega_z = \frac{1}{r_{Cout} \cdot C_{out}}$

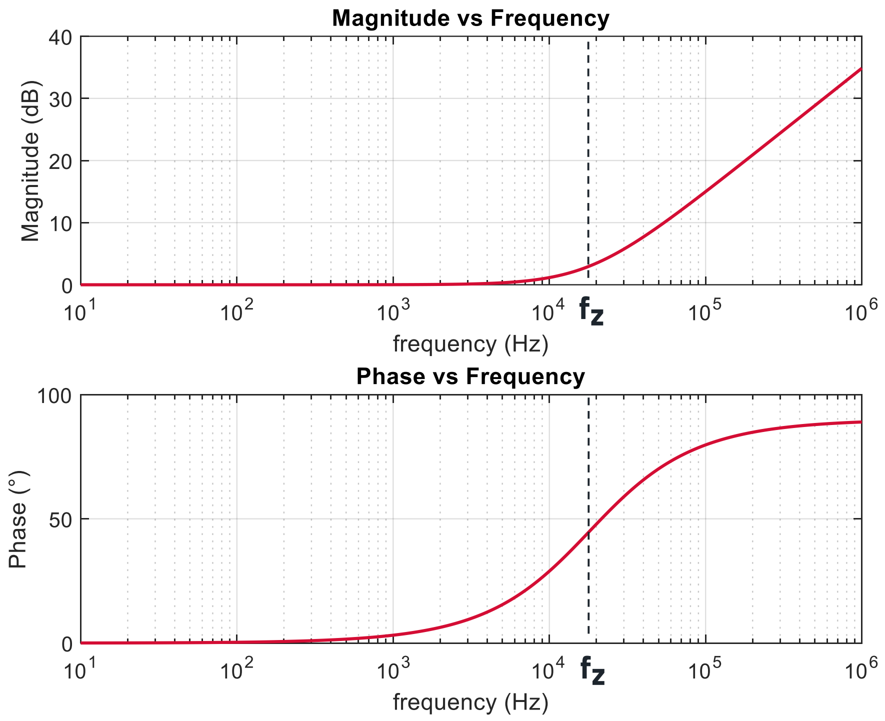
$$H(s) = G_0 \cdot \frac{\left(1 + \frac{s}{\omega_z}\right)}{\left(1 + \frac{s}{Q \cdot \omega_0} + \frac{s^2}{\omega_0^2}\right)}$$

Resonant double–pole

$$\omega_0 = \frac{1}{\sqrt{L \cdot C_{out} \cdot \frac{R_L + r_{Cout}}{R_L + r_{Ldcr}}}}$$

$$Q = \sqrt{\frac{L}{C_{out}}} \cdot \frac{1}{\frac{L}{C_{out} \cdot (r_{Ldcr} + R_L)} + r_{Cout} + \frac{r_{Ldcr} \cdot R_L}{r_{Ldcr} + R_L}}$$

Example f_z=18 kHz



THE OUTPUT CAPACITOR IN A VM-CCM BUCK CONVERTER

The resonant double-pole

DC–Gain $\rightarrow G_0=\frac{V_{in}}{V_{saw}}$

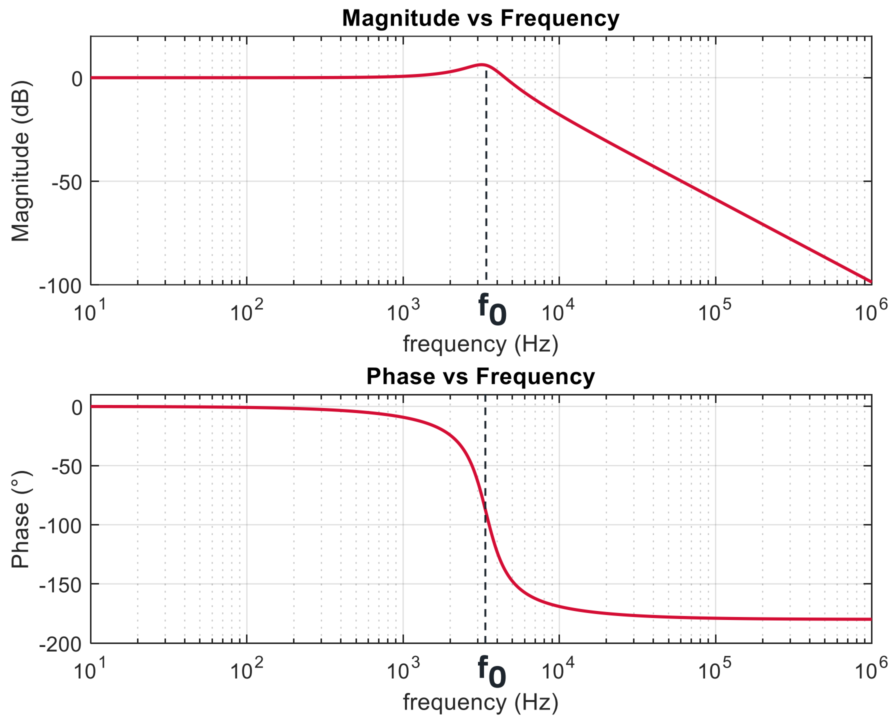
ESR Zero $\rightarrow \omega_Z=\frac{1}{r_{Cout}\cdot C_{out}}$

$$H(s)=G_0\cdot\frac{\left(1+\frac{s}{\omega_Z}\right)}{\left(1+\frac{s}{Q\cdot\omega_0}+\frac{s^2}{\omega_0^2}\right)}$$

Resonant double–pole

$$\omega_0=\frac{1}{\sqrt{L\cdot C_{out}\cdot\frac{R_L+r_{Cout}}{R_L+r_{Ldcr}}}}\qquad Q=\sqrt{\frac{L}{C_{out}}}\cdot\frac{1}{\frac{L}{C_{out}\cdot(r_{Ldcr}+R_L)}+r_{Cout}+\frac{r_{Ldcr}\cdot R_L}{r_{Ldcr}+R_L}}$$

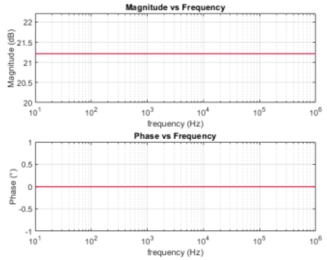
Example f_0=3.4 kHz, Q=1.7



THE OUTPUT CAPACITOR IN A VM-CCM BUCK CONVERTER

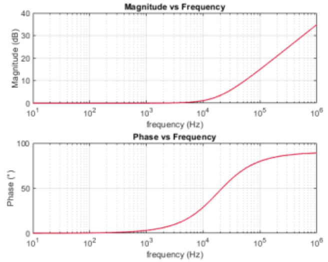
Adding magnitude and phase curves of each term to obtain the plant frequency response

DC-Gain



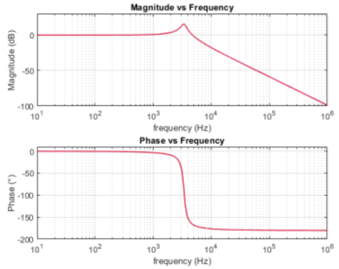
+

ESR-zero



+

Double-pole



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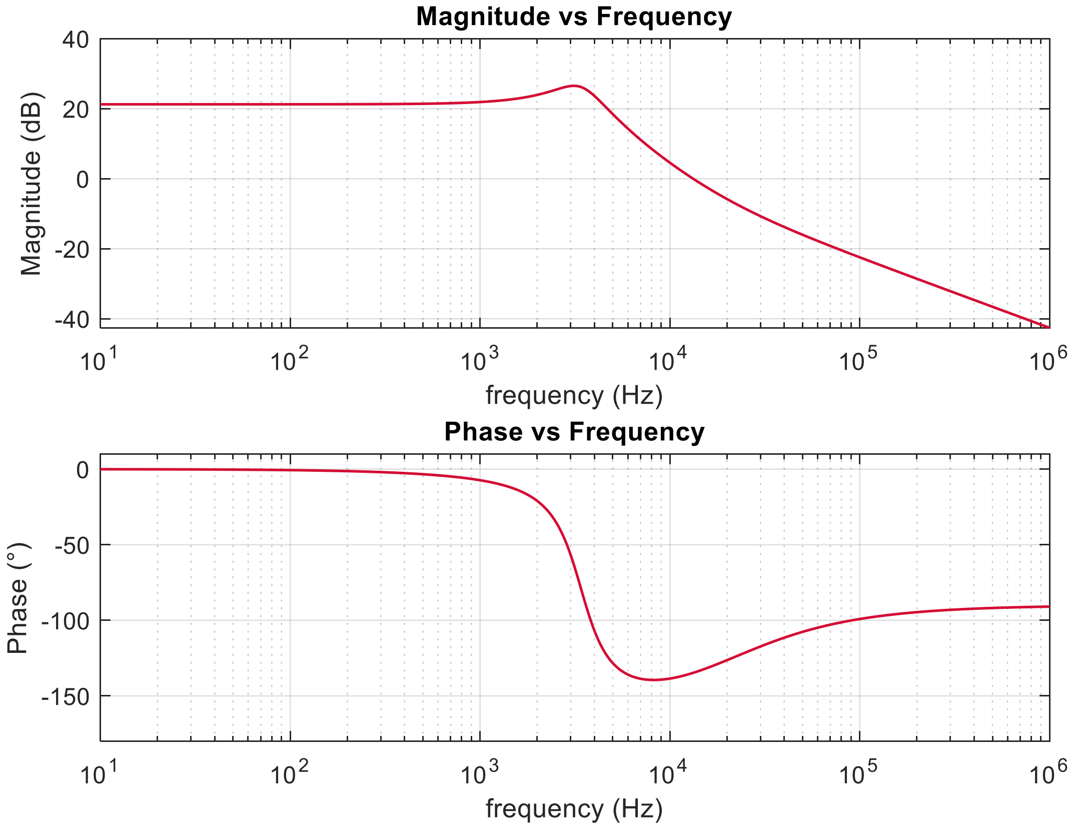


THE OUTPUT CAPACITOR IN A VM-CCM BUCK CONVERTER

VM-CCM buck specification used for the example

Example Specification:

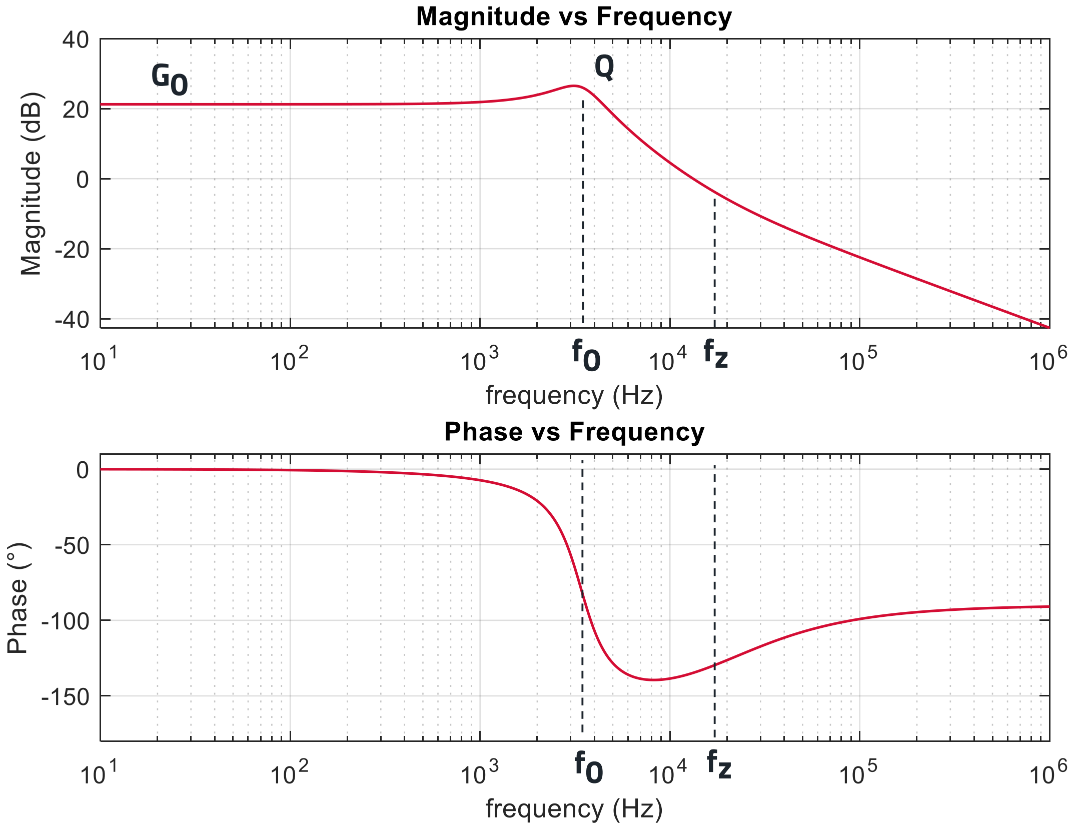
- $V_{in} = 24$ V
- $V_{out} = 5$ V
- $I_{out} = 2$ A
- $F_{sw} = 500$ kHz
- L = 10 µH
- DCR = 50 mΩ
- $C_{out} = 220$ µF
- ESR = 40 mΩ
- $V_{saw} = 2$ V

G_0=21.24 dB

f_Z=18 kHz

Q=1.73

f_0=3.4 kHz



THE OUTPUT CAPACITOR IN A VM-CCM BUCK CONVERTER

Selecting target crossover frequency range of the open-loop transfer function based on plant characteristic

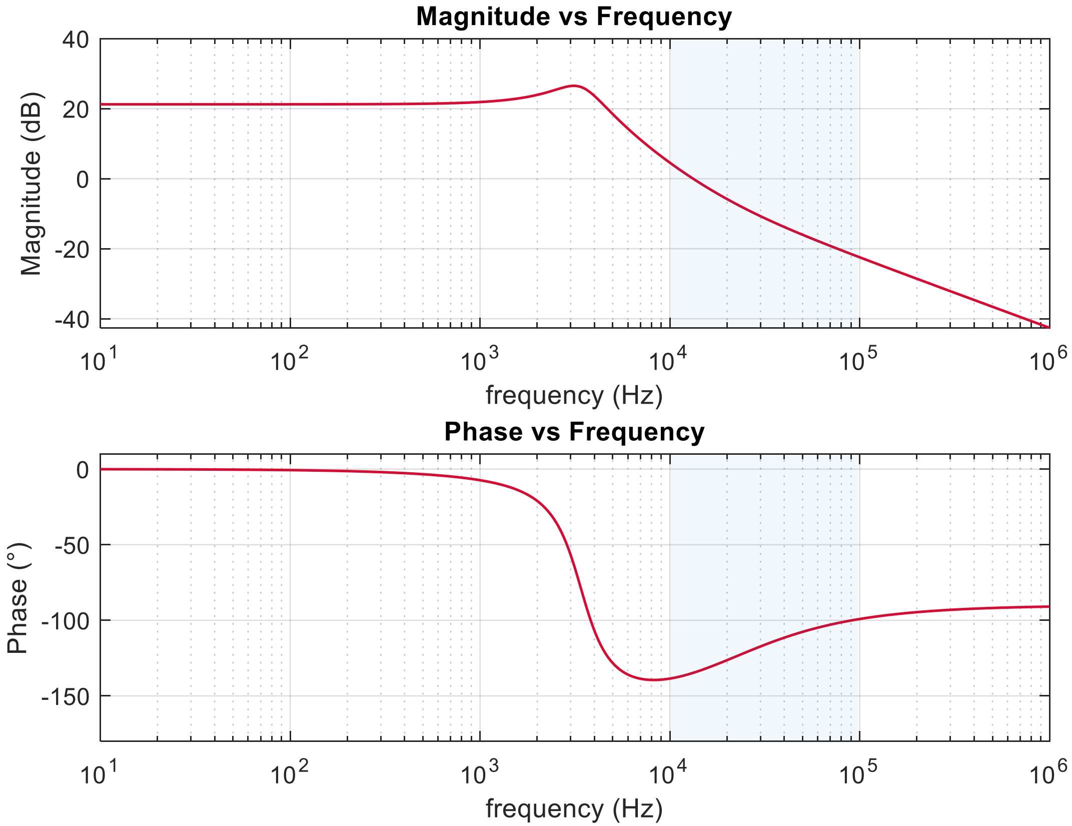
- Target crossover frequency range

  $f_0/3 < f_C < f_{sw}/5$

- In this example:

  $f_0 = 3.4$ kHz and $f_{sw} = 500$ kHz

  10 kHz $< f_C <$ 100 kHz



HOW VARIATIONS IN OUTPUT CAPACITOR PARAMETERS IMPACT THE PLANT CHARACTERISTIC

HOW OUTPUT CAPACITOR VARIATIONS AFFECT THE PLANT RESPONSE

Example: Impact of capacitance variations with fixed ESR

Fixed ESR = 10 mΩ

C_{out1} = 22 µF ⟶ f_{Z1}=723 kHz, f_{01}=11 kHz, Q_1=1.65

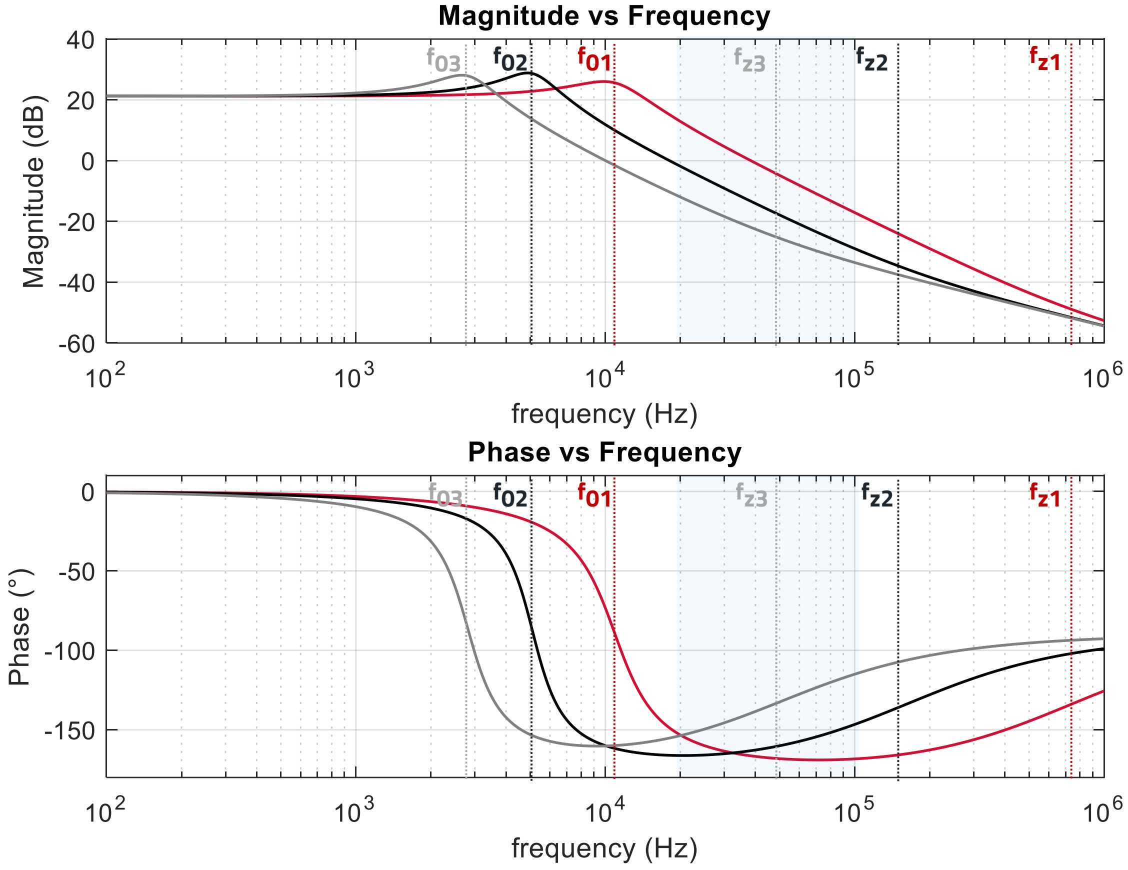
C_{out2} = 100 µF ⟶ f_{Z2}=160 kHz, f_{02}=5.1 kHz, Q_2=2.3

C_{out3} = 330 µF ⟶ f_{Z3}=48 kHz, f_{03}=2.8 kHz, Q_3=2.1

Large change of f_Z and f_0 - Small change of Q

Gain difference up to ~ 25 dB (@20 kHz)

Phase difference up to ~ 65° (@100 kHz)



HOW OUTPUT CAPACITOR VARIATIONS AFFECT THE PLANT RESPONSE

Example: Impact of ESR variations with fixed capacitance

Fixed C_{out} = 47 µF

ESR_1 = 10 mΩ ⟶ f_{Z1}=340 kHz, f_{01}=7.5 kHz, Q_1=2.1

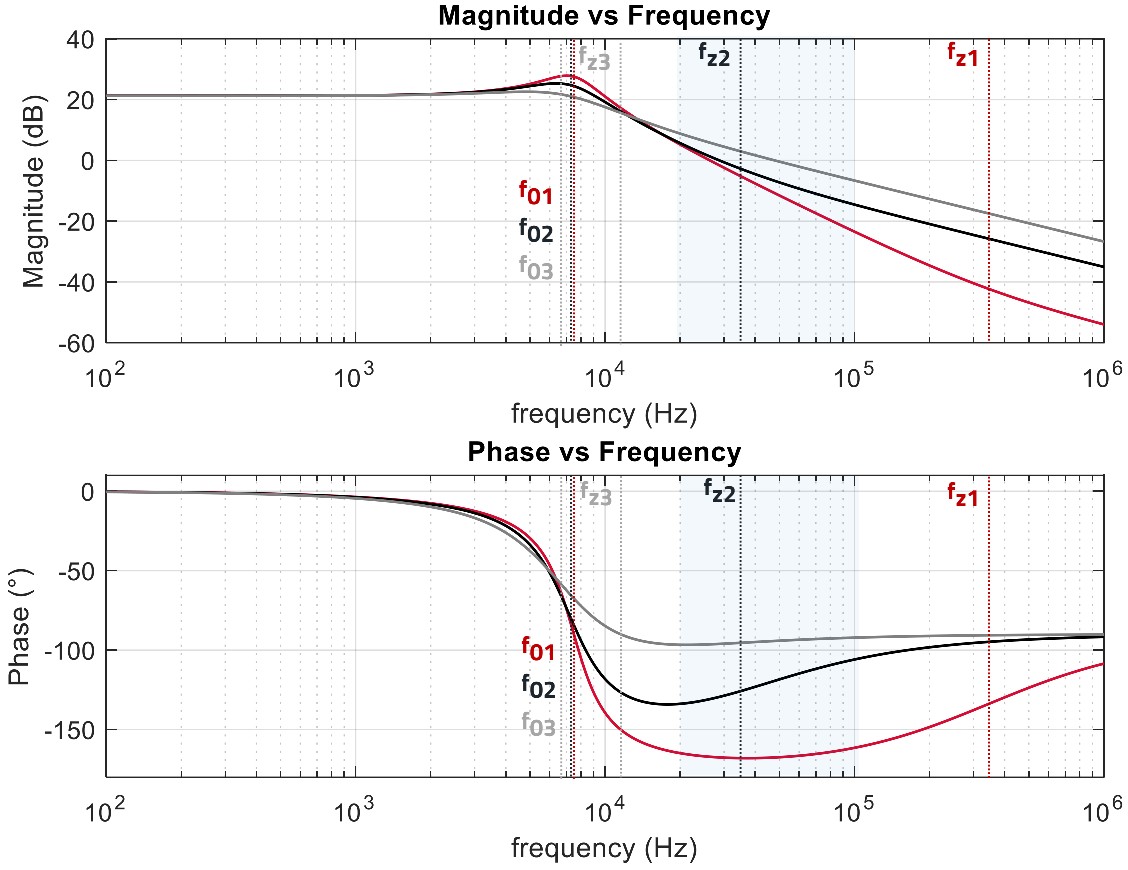
ESR_2 = 100 mΩ ⟶ f_{Z2}=34 kHz, f_{02}=7.2 kHz, Q_2=1.5

ESR_3 = 300 mΩ ⟶ f_{Z3}=11.3 kHz, f_{03}=6.7 kHz, Q_3=0.9

Large change of f_Z - Small change of f_0 and Q

Gain difference up to ~ 18 dB (@ 100 kHz)

Phase difference of~ 90° (entire range)



DESIGN CASE EXAMPLE:
IMPACT OF BULK CAPACITOR

DESIGN CASE EXAMPLE: IMPACT OF BULK CAPACITOR

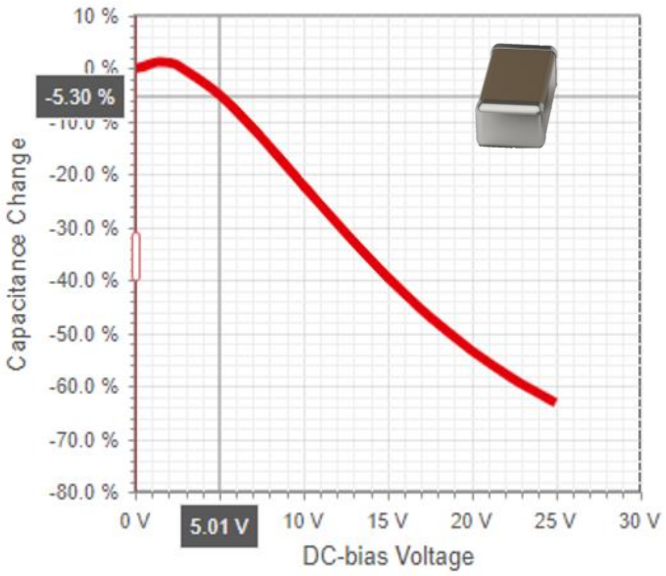
Selecting output capacitor(s) for switching frequency ripple attenuation (Co1)

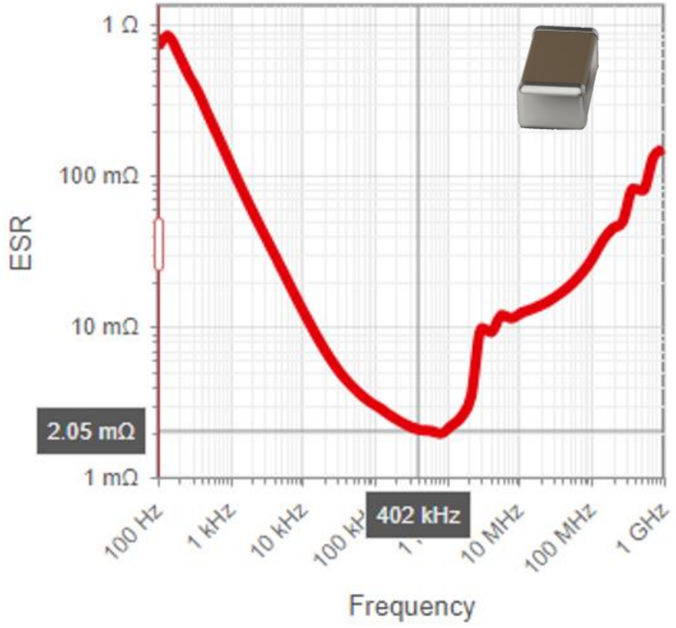
- V_{in} = 12 V
- V_{out} = 5 V
- I_{out} = 4 A
- F_{sw} = 400 kHz
- L = 4.7 µH (MAPI 74438367047)
- ΔV_{out} < 0.5 % of V_{out} (i.e. 25 mV)

$$C_{o1} > \frac{\Delta I_L}{8 \cdot f_{sw} \cdot \Delta V_{out}} = \frac{1.7}{8 \cdot 400k \cdot 0.025} \approx 22\ \mu F$$

- Co1 = 3 x WCAP-CSGP 885012209028
- Equivalent: 28 µF, 0.7 mΩ

REDEXPERT DATA: WCAP-CSGP-885012209028





$0.947 \cdot 10\mu F \approx 9.45\ \mu F$

DESIGN CASE EXAMPLE: IMPACT OF BULK CAPACITOR

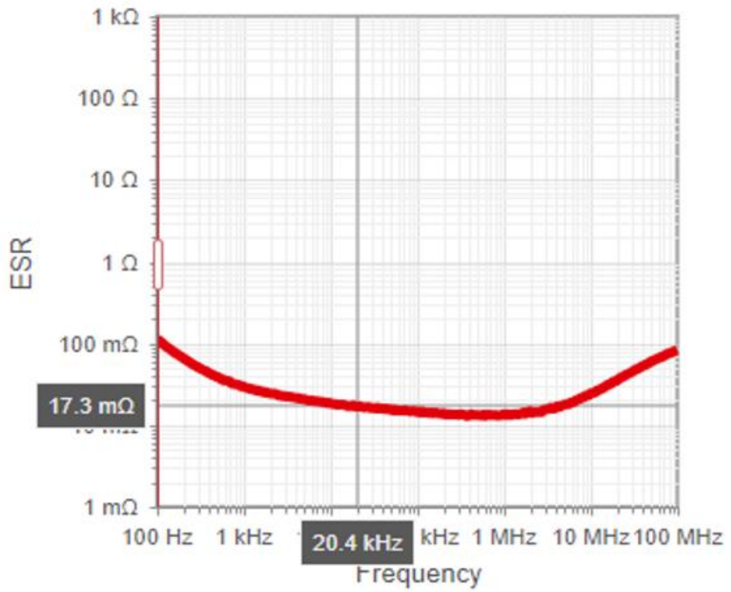
Selecting output capacitor for transient response (a.k.a. bulk capacitor) (Co2)

- Transient Specification:
  - Load current step: 1.5 to 3.5 A (1 A/µs)
  - V_{out} undershoot < 100 mV
- Open-loop crossover frequency: 20 kHz

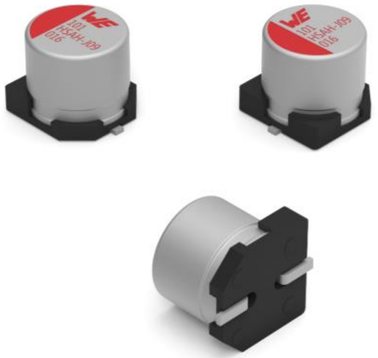
$$C_{o2\_min} \approx \frac{\Delta I_{out}}{2 \cdot \pi \cdot f_C \cdot \Delta V_{out}} = \frac{2A}{2 \cdot \pi \cdot 20k \cdot 0.1V} \approx 160\ \mu F$$

- Co2 = WCAP-HSAH 875585345004
- 220 µF, 16 V, 17 mΩ (@ 20 KHz)

REDEXPERT DATA: WCAP-HSAH-875585345004



Hybrid-Polymer Capacitor



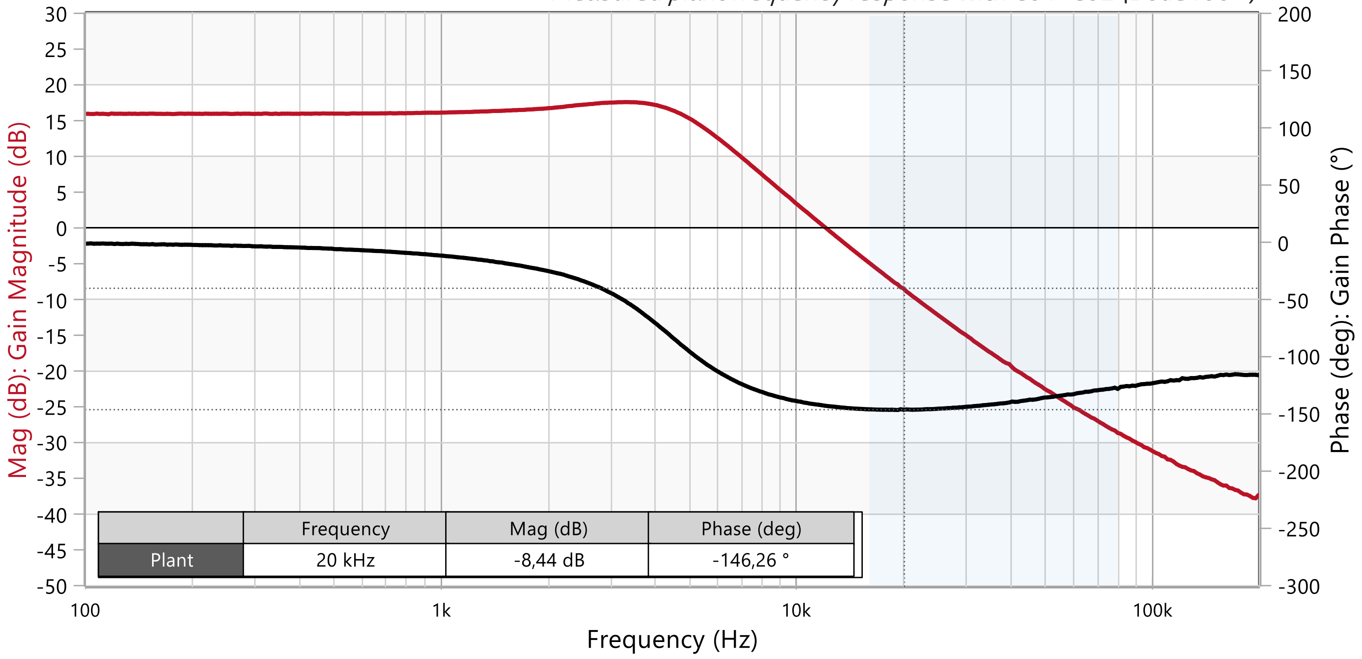
(*) See for reference: *Switch-Mode Power Supplies: SPICE Simulations and Practical Designs*, Second Edition McGraw-Hill Professional, 2014, written by C. Basso

DESIGN CASE EXAMPLE: IMPACT OF BULK CAPACITOR

The plant or control-to-output transfer function of VM-CCM Buck with Co1 and Co2 (bulk capacitor)

- Bode plot of plant TF:
  - $f_Z \approx 50$ kHz
  - $f_0 \approx 4$ kHz
  - $Q \approx 1.2$
- f_C selection range: 15 to 80 kHz
- Selected: 20 kHz
- Magnitude: -8.44 dB, Phase: -146°
- Target PM = 60°
- Required compensator phase lead: 116°
- Need of a type-3 compensator …

Measured plant frequency response with Co1+Co2 (Bode100™)



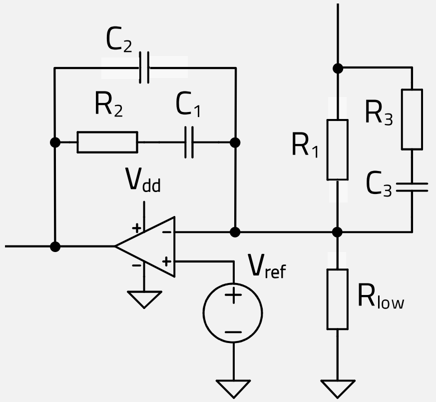
	Frequency	Mag (dB)	Phase (deg)
Plant	20 kHz	-8,44 dB	-146,26 °

DESIGN CASE EXAMPLE: IMPACT OF BULK CAPACITOR

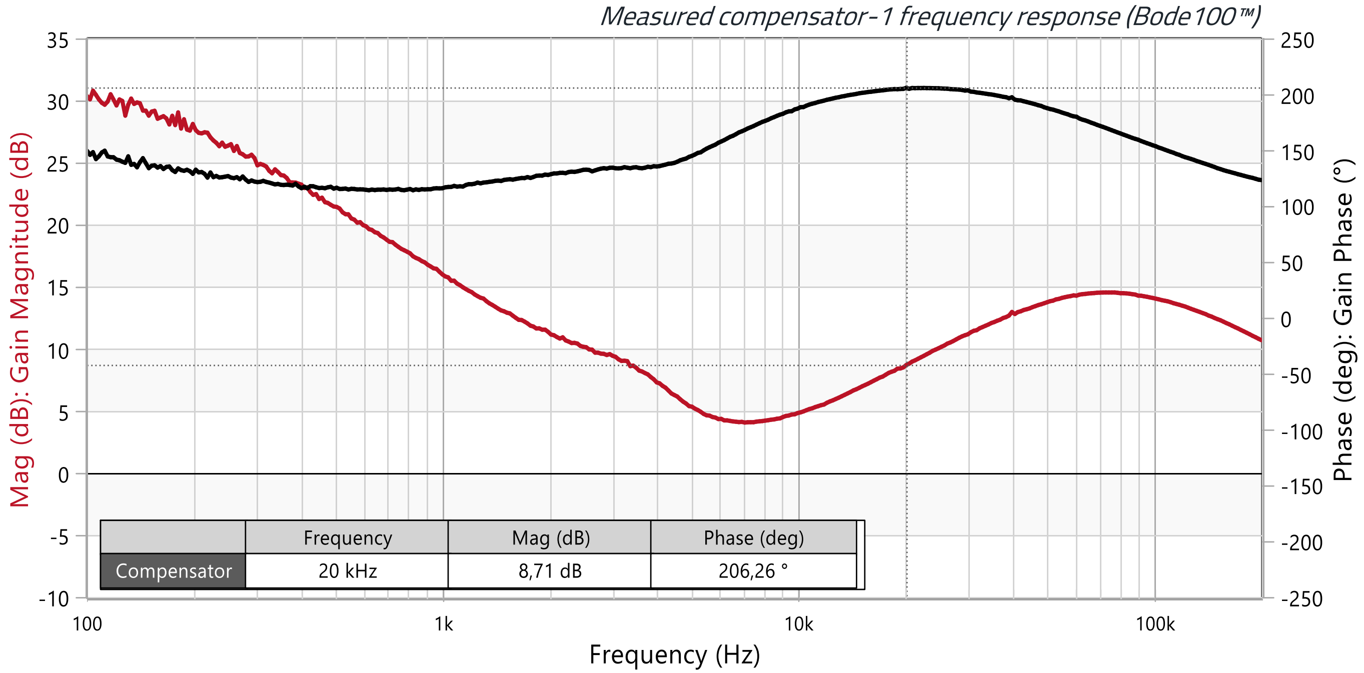
Type-3 compensator design and frequency response

Compensator-1 circuit component values:

- R_1 = 73.2 kΩ
- R_{low} = 10 kΩ
- R_2 = 68 kΩ
- R_3 = 4.7 kΩ
- C_1 = 470 pF
- C_2 = 33 pF
- C_3 = 330 pF



Gain ≈ 8.7 dB, Phase ≈ 206°, Phase lead ≈ 116°



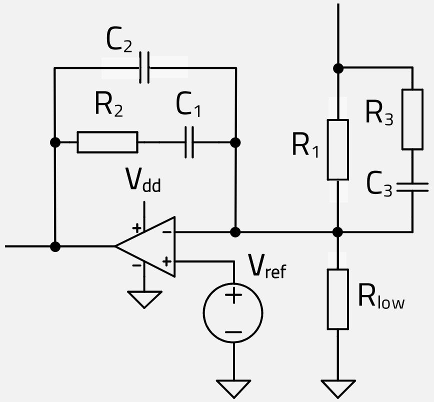
(*) See for reference: *Designing Control Loops for Linear and Switching Power Supplies: A Tutorial Guide,* Artech House, 2012, written by C. Basso

DESIGN CASE EXAMPLE: IMPACT OF BULK CAPACITOR

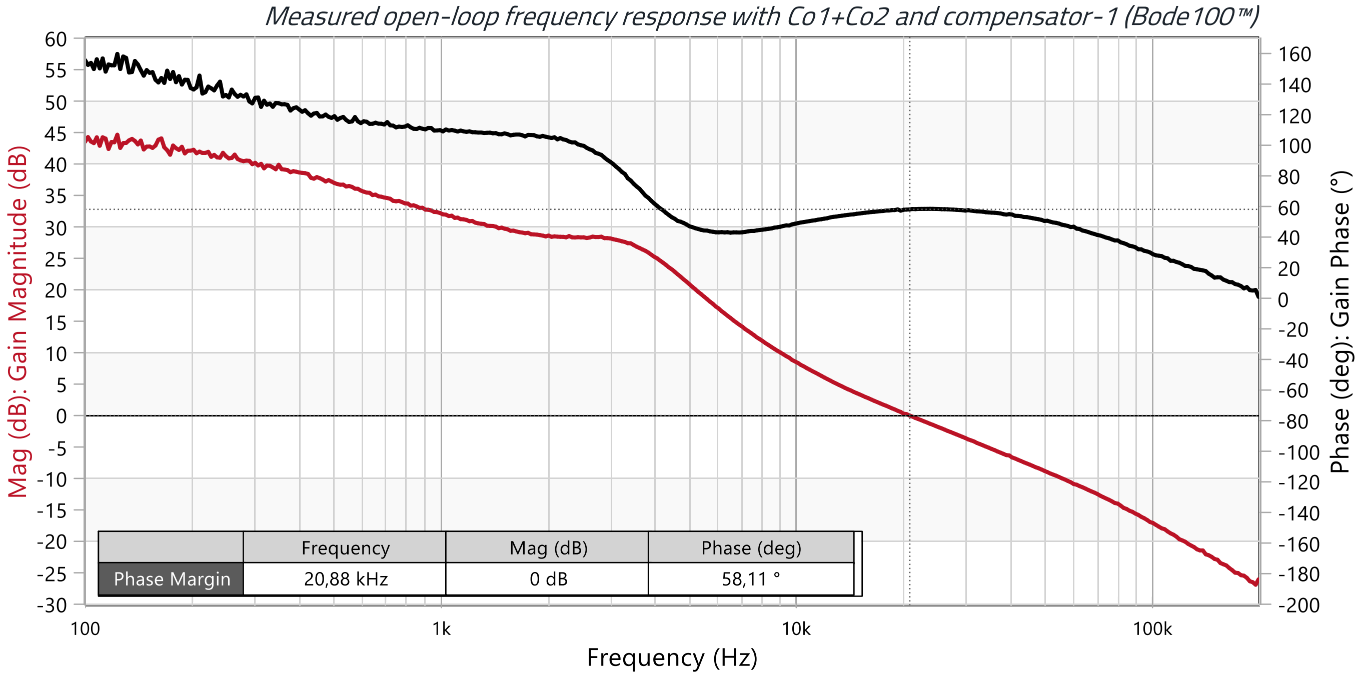
Open-loop response and stability margins: Co1+Co2 with compensator-1

Compensator-1 circuit component values:

- R_1 = 73.2 kΩ
- R_{low} = 10 kΩ
- R_2 = 68 kΩ
- R_3 = 4.7 kΩ
- C_1 = 470 pF
- C_2 = 33 pF
- C_3 = 330 pF

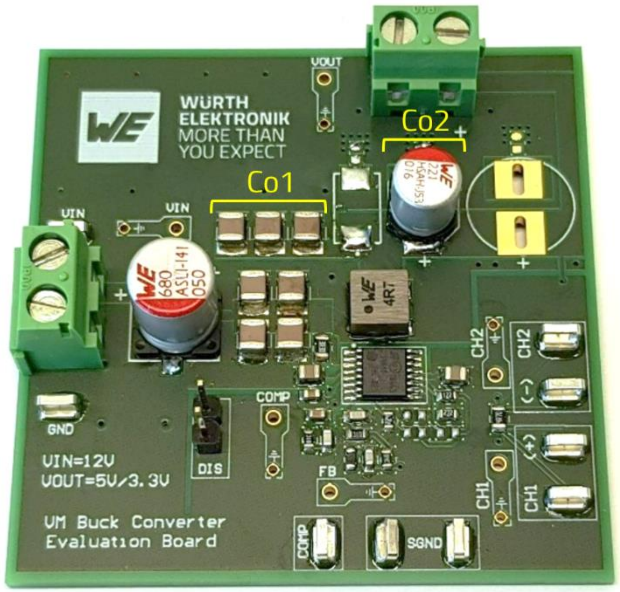


$f_C \approx$ 21 kHz, PM ≈ 58° and GM ≈ 25 dB



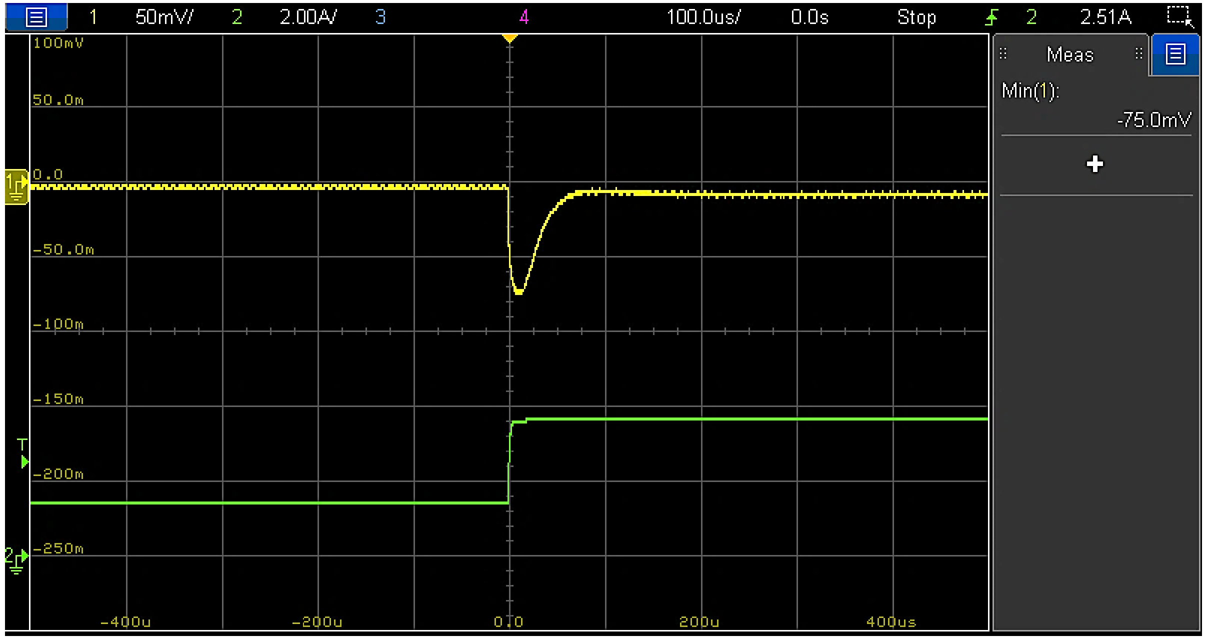
DESIGN CASE EXAMPLE: IMPACT OF BULK CAPACITOR

Buck converter board and load transient response: Co1+Co2 with compensator-1



Prototype VM-CCM buck board with Co1 and Co2

Load step: 1.5 to 3.5 A at 1 A/µs A (V_{out} (), I_{out} ())



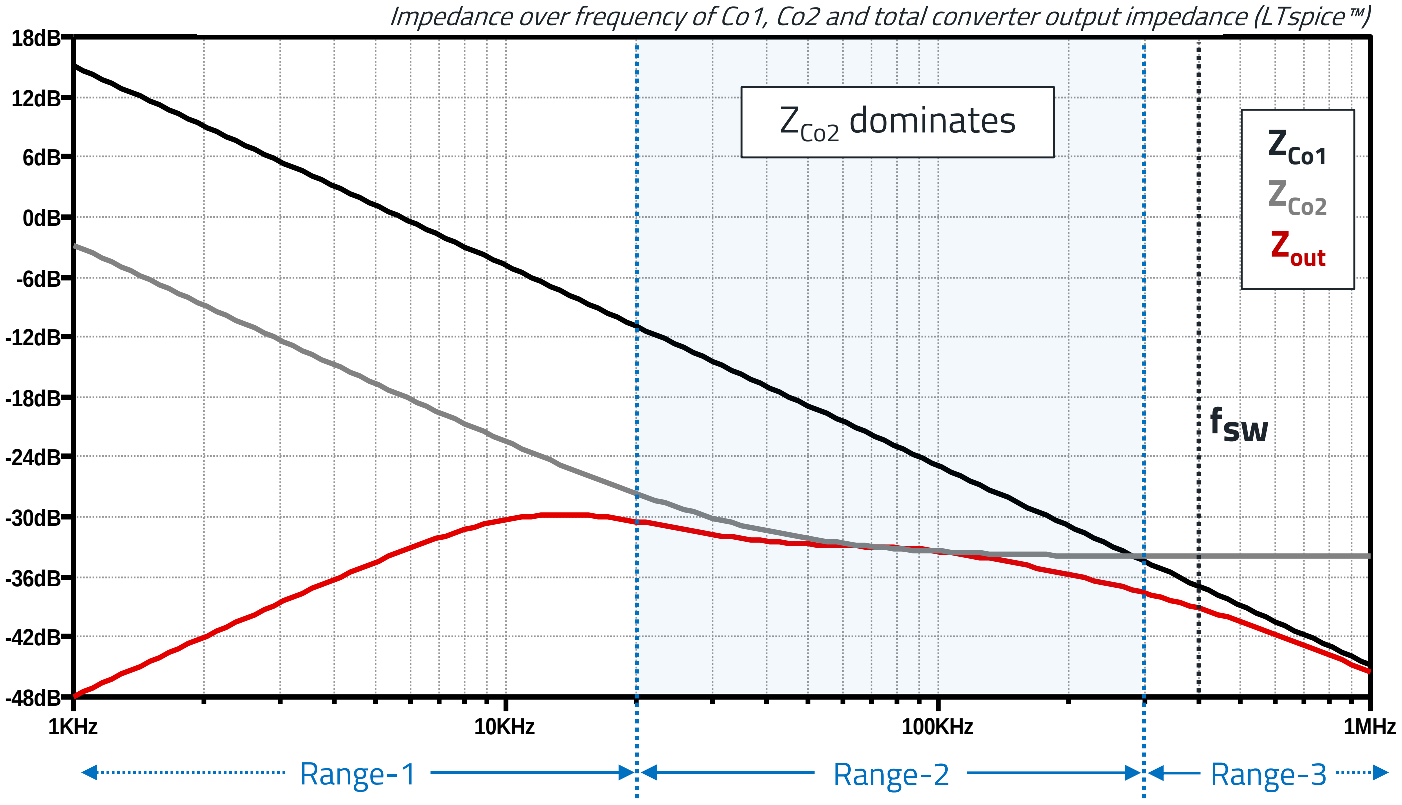
V_{out} undershoot of 75 mV (maximum was 100 mV)

DESIGN CASE EXAMPLE: IMPACT OF BULK CAPACITOR

Impedance curves: Co2 does not affect switching frequency ripple

- Range-1: $f<f_C$ (=20 kHz)
  - Z_{out} set by closed control loop
- Range-2: 20 kHz < f < 300 kHz
  - Z_{out} set by Co2
- Range-3: f > 300 kHz
  - Z_{out} set by Co1

- Fsw = 400 kHz → Z_{Co1}
- Co2 does not almost affect ΔV_{out}
- Relaxed transient requirement:
  - **Co2 can be removed**



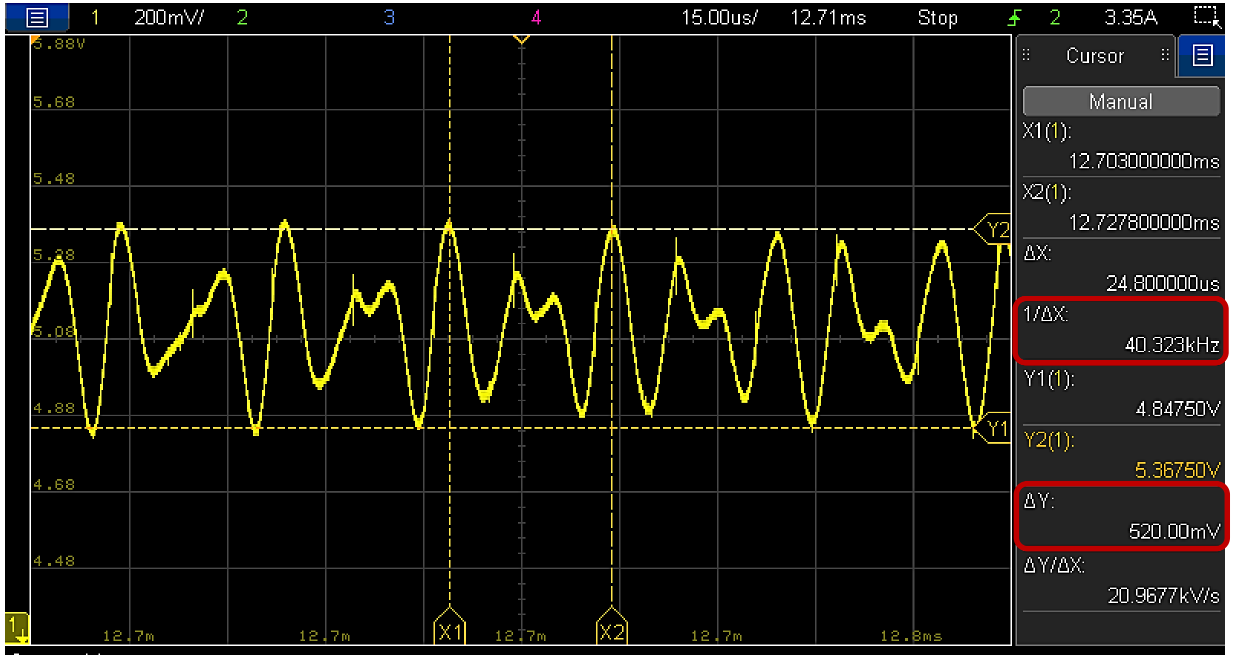
DESIGN CASE EXAMPLE: IMPACT OF BULK CAPACITOR

Removing Co2 with compensator-1: unstable operation

Co2 removed ...

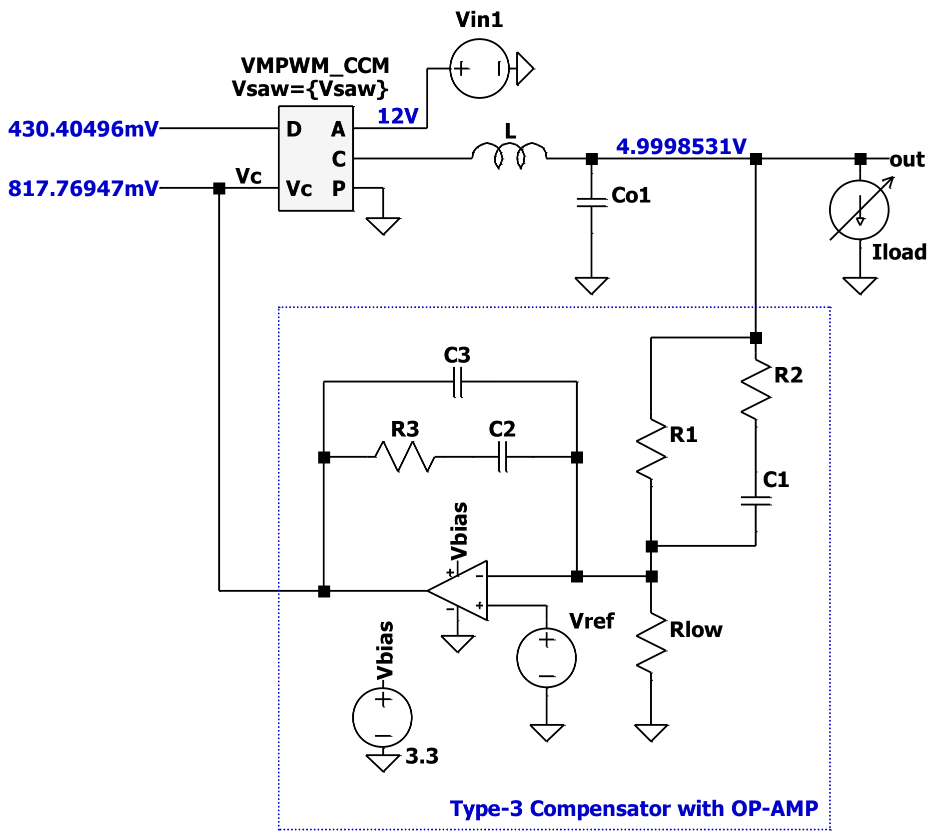
- Oscillation at 80 kHz
- Around 520 mV amplitude
- Erratic behavior (turn switching on/off)

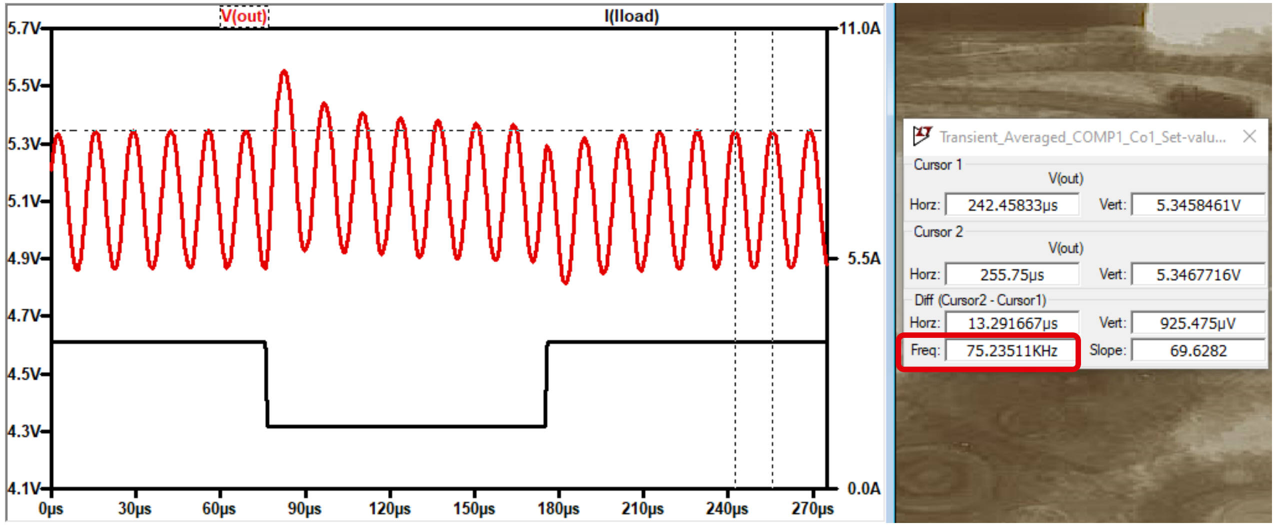
Oscillation on power-up at 2 A (V_{out} (!))



DESIGN CASE EXAMPLE: IMPACT OF BULK CAPACITOR

LTspice™ transient simulation with averaged PWM switch model: unstable operation





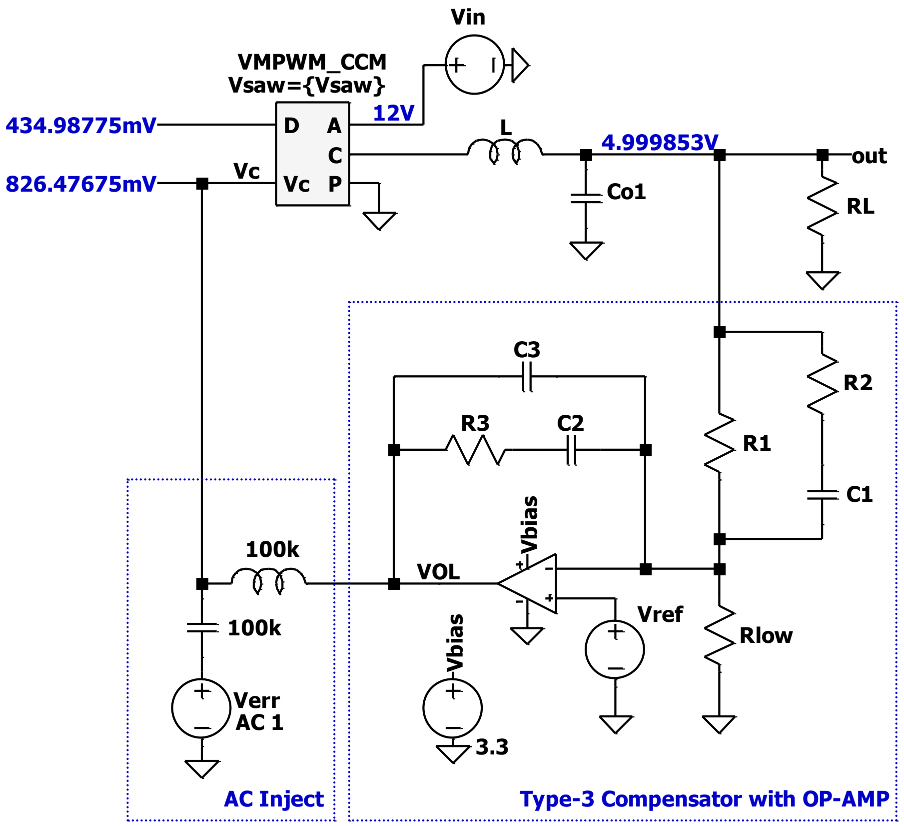
- Oscillation at ~ 75 kHz
- Amplitude ~ 550 mV

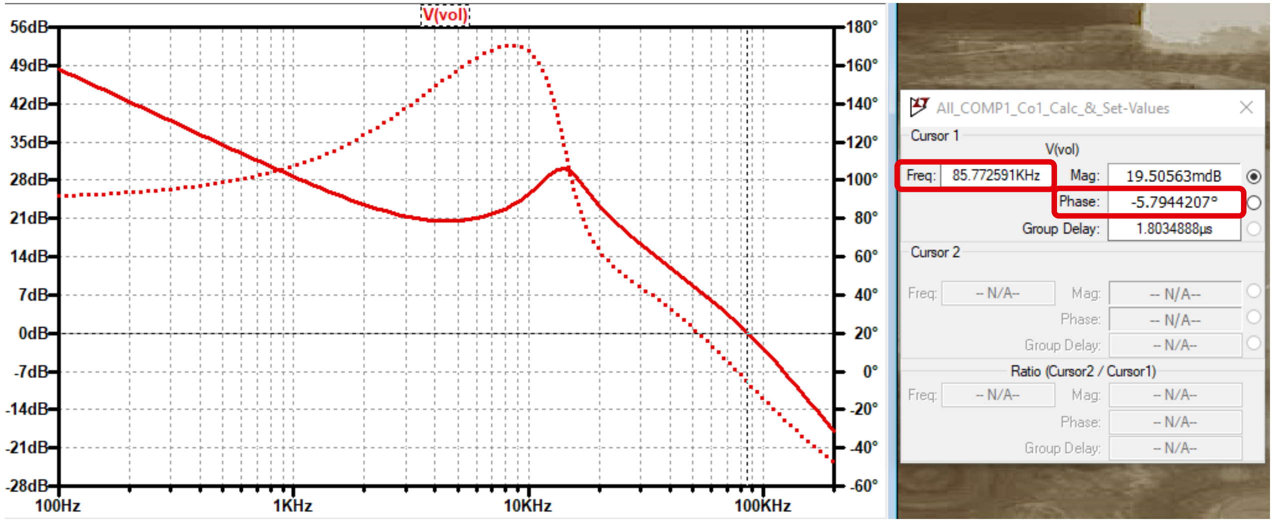
In line with measurement …

(*) See for reference: *Switch-Mode Power Supplies: SPICE Simulations and Practical Designs*, Second Edition McGraw-Hill Professional, 2014, written by C. Basso

DESIGN CASE EXAMPLE: IMPACT OF BULK CAPACITOR

LTspice™ .AC simulation with averaged PWM switch model: open-loop response confirms instability





- f_C ~ 85 kHz
- PM ~ -6°

Unstable control loop confirmed …

(*) See for reference: *Switch-Mode Power Supplies: SPICE Simulations and Practical Designs*, Second Edition McGraw-Hill Professional, 2014, written by C. Basso

DESIGN CASE EXAMPLE: IMPACT OF BULK CAPACITOR

How did the plant response change?

Plant TF with **Co1+Co2**

$f_{Z1} \approx 50$ kHz

$f_{01} \approx 4$ kHz

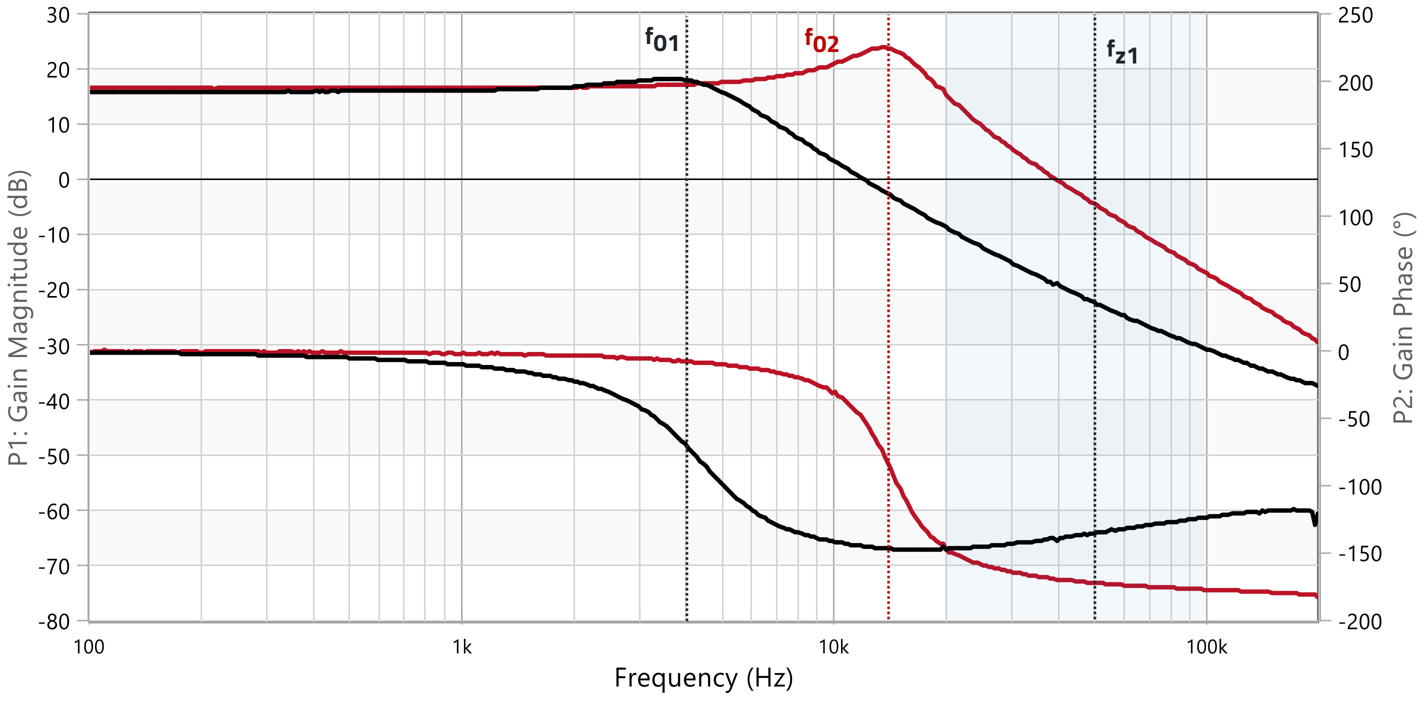
$Q_1 \approx 1.2$

Plant TF with **Co1**

$f_{Z2} \approx 8$ MHz

$f_{02} \approx 14$ kHz

$Q_2 \approx 2.5$



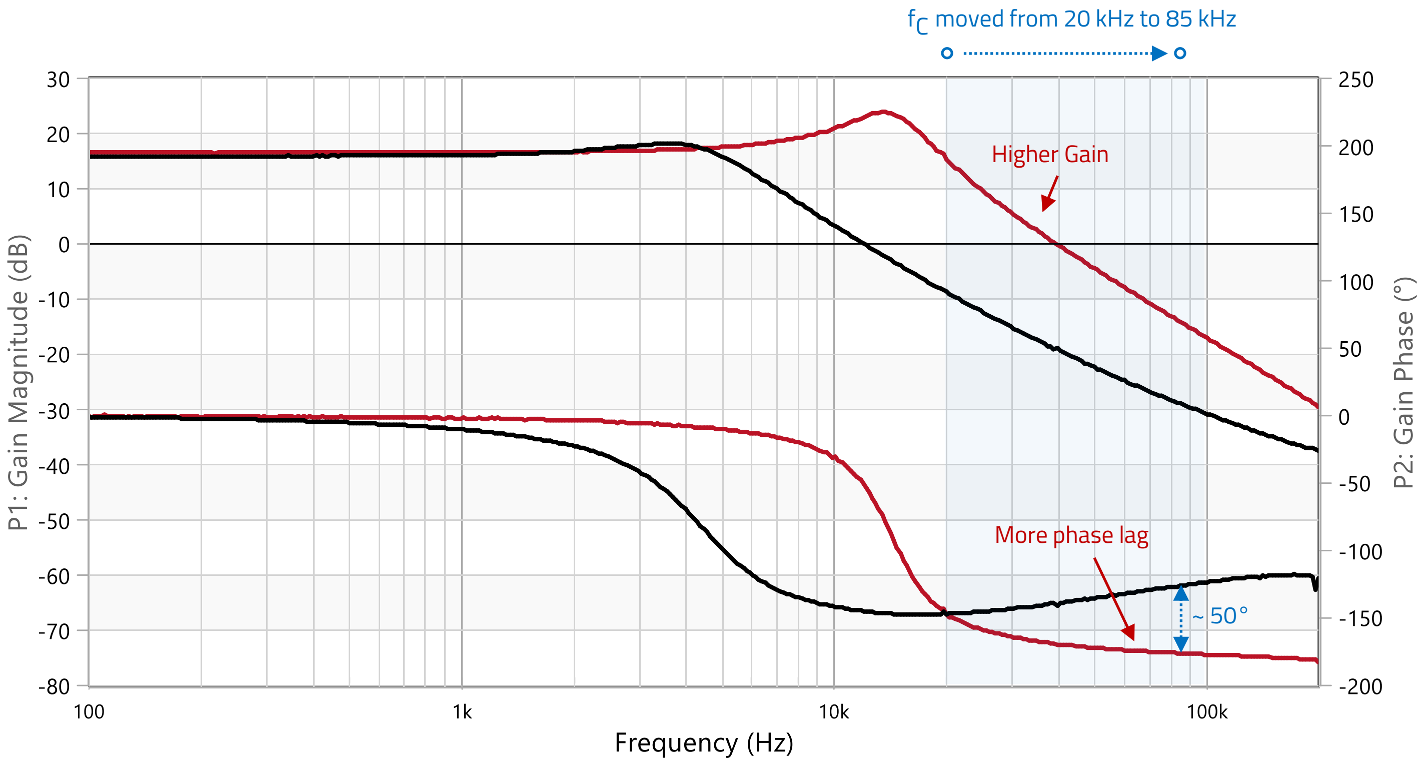
DESIGN CASE EXAMPLE: IMPACT OF BULK CAPACITOR

How did the plant response change?

Plant TF with **Co1+Co2**	Plant TF with **Co1**
$f_{Z1} \approx 50$ kHz	$f_{Z2} \approx 8$ MHz
$f_{01} \approx 4$ kHz	$f_{02} \approx 14$ kHz
$Q_1 \approx 1.2$	$Q_2 \approx 2.5$

Fixed compensator-1, Co2 removed ...

- Higher gain → Higher crossover f_C
- Higher crossover:
  - Higher phase lag (no ESR zero)
  - Compensator:
    - Maximum phase lead at 20 kHz
    - Lower phase lead at 85 kHz

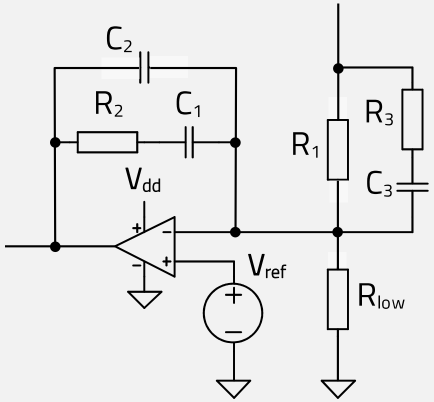


DESIGN CASE EXAMPLE: IMPACT OF BULK CAPACITOR

Compensator redesign for stability without Co2

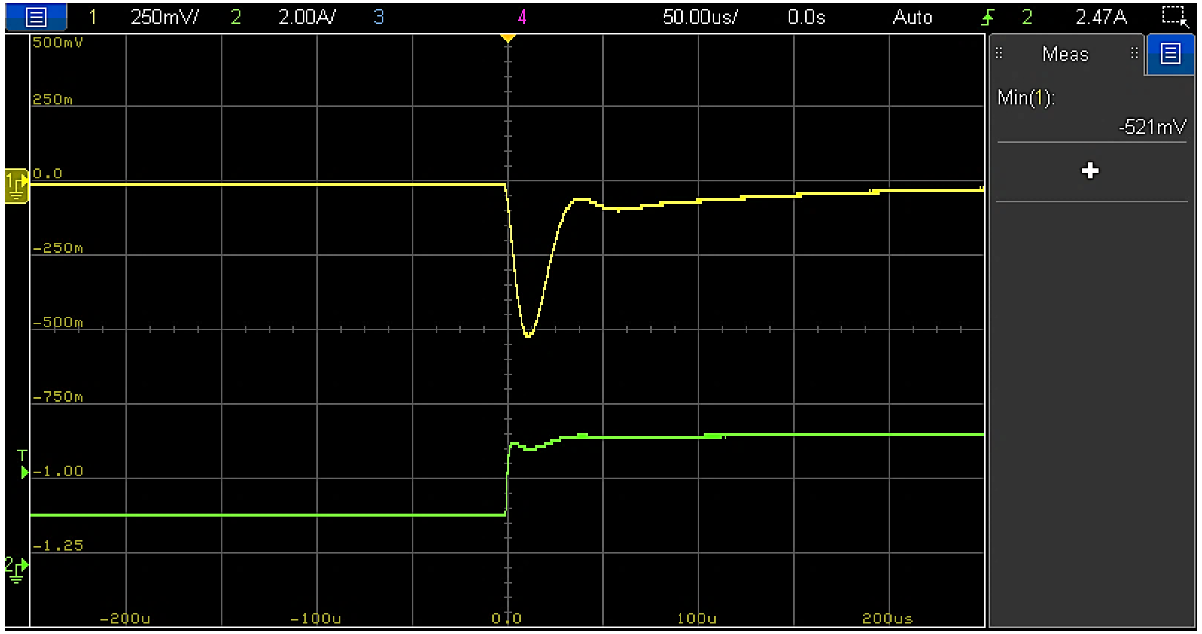
Compensator-2 circuit component values:

- R_1 = 73.2 kΩ
- R_{low} = 10 kΩ
- R_2 = 4.7 kΩ
- R_3 = 4.7 kΩ
- C_1 = 6.8 nF
- C_2 = 470 pF
- C_3 = 330 pF



f_C ≈ 21 kHz, PM ≈ 59.8° and GM ≈ 18 dB

Load step: 1.5 to 3.5 A at 1 A/µs A (V_{out} (/), I_{out} (/))



Stable, but much higher undershoot (0.52 V) due to no bulk capacitor …

DESIGN CASE EXAMPLE:
SAME CAPACITANCE - DIFFERENT ESR

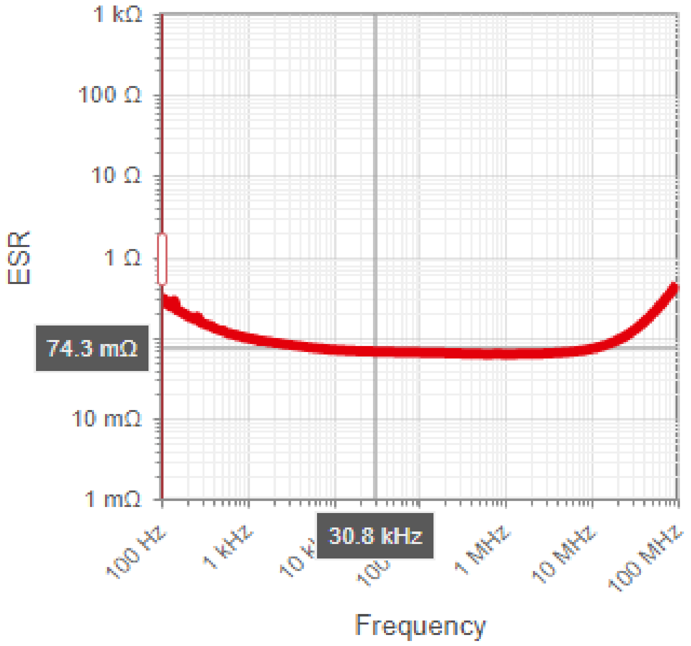
DESIGN CASE EXAMPLE: IMPACT OF ESR

Specification and output capacitors

- V_{in} = 12 V
- **V_{out} = 3.3 V**
- I_{out} = 4 A
- F_{sw} = 400 kHz
- L = 4.7 µH (MAPI 74438367047)
- ΔV_{out} < 0.4 % of V_{out} (i.e. 20 mV)
- Use same Co1 for ΔV_{out} as previous design

- Bulk capacitor (Co3):
  - WCAP-ATLI 860080474010
  - 220 µF, 25 V, 75 mΩ (@ 30 kHz)

REDEXPERT DATA: WCAP-ATLI 860080474010



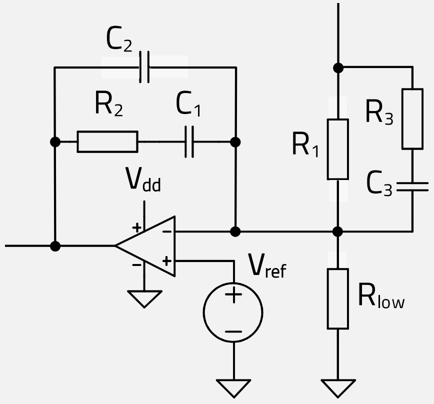
Aluminum electrolytic capacitor

DESIGN CASE EXAMPLE: IMPACT OF ESR

Open-loop response and stability margins: Co1+Co3 and compensator-3

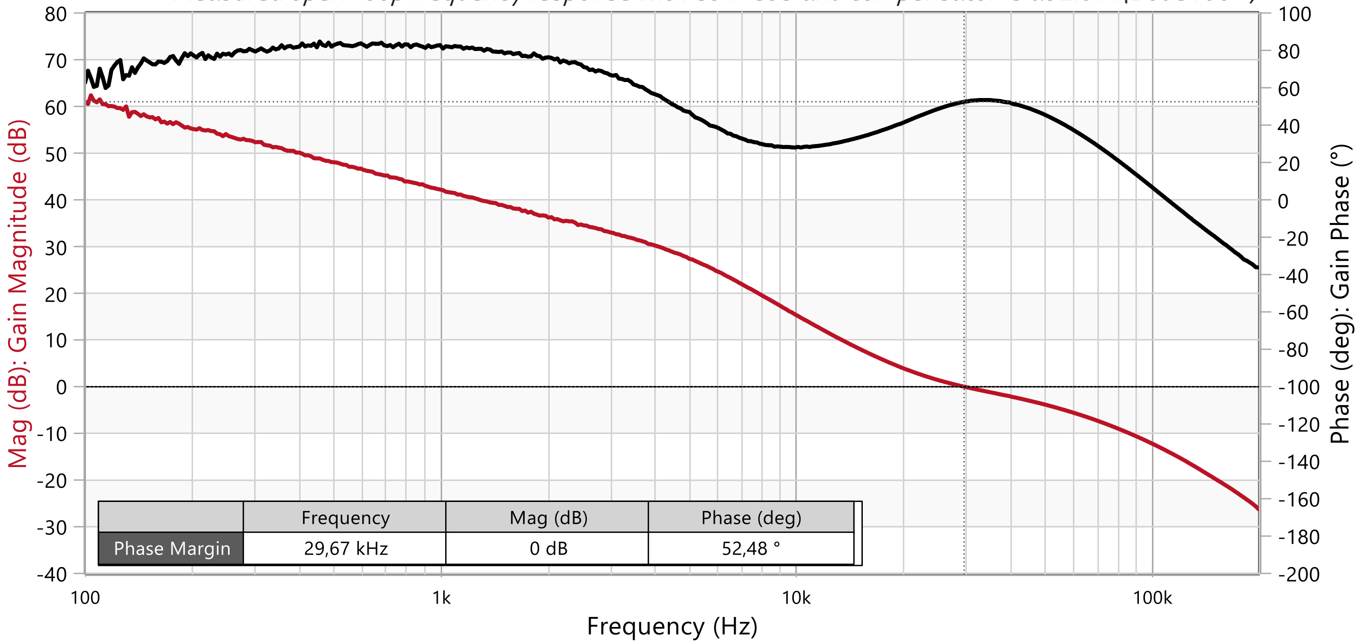
Compensator-3 design (f_C=30 kHz, PM>50 °)

- R_1 = 45.5 kΩ
- R_{low} = 10 kΩ
- R_2 = 73.2 kΩ
- R_3 = 13 kΩ
- C_1 = 150 pF
- C_2 = 33 pF
- C_3 = 100 pF



f_C ≈ 30 kHz, PM ≈ 52.5° and GM ≈ 15 dB

Measured open-loop frequency response with Co1+Co3 and compensator-3 at 2.5 A (Bode100™)



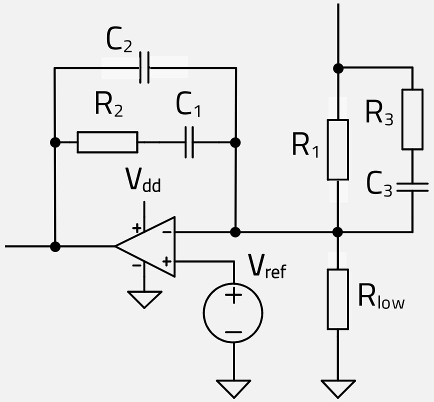
	Frequency	Mag (dB)	Phase (deg)
Phase Margin	29,67 kHz	0 dB	52,48 °

DESIGN CASE EXAMPLE: IMPACT OF ESR

Transient response with Co1+Co3 and compensator-3

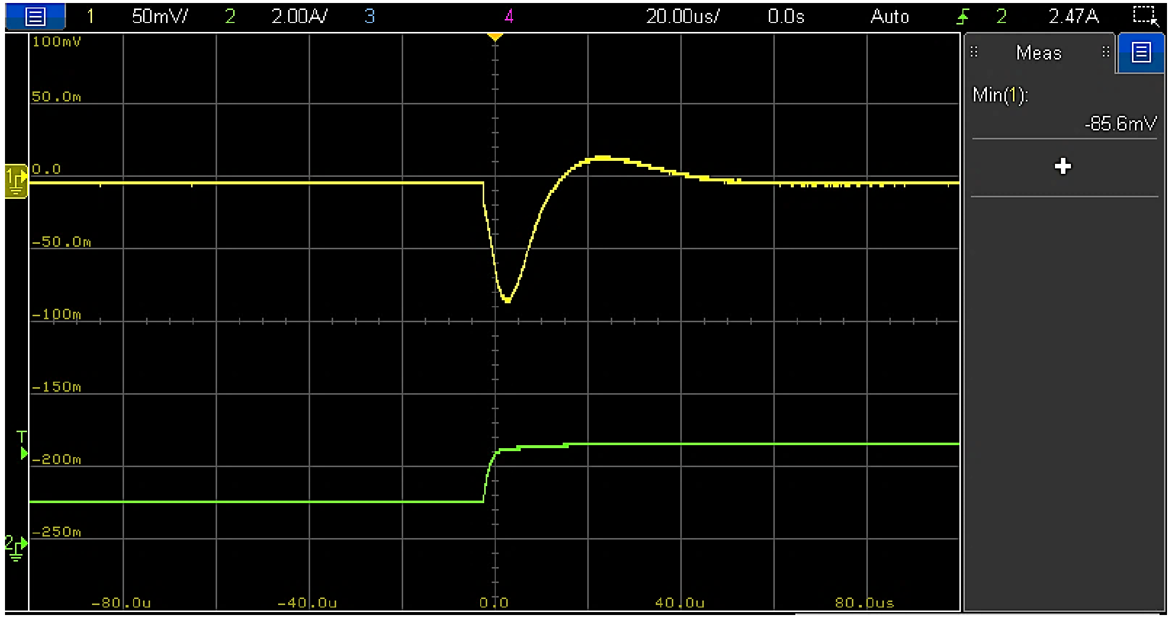
Compensator-3 circuit component values:

- R_1 = 45.5 kΩ
- R_{low} = 10 kΩ
- R_2 = 73.2 kΩ
- R_3 = 13 kΩ
- C_1 = 150 pF
- C_2 = 33 pF
- C_3 = 100 pF



Undershoot ~ 85 mV

Load step: 1.2 to 2.7 A at 1 A/µs (V_{out} (/), I_{out} (/))



DESIGN CASE EXAMPLE: IMPACT OF ESR

Replacing Co3 by an equivalent SMD, low-profile part (Co4)

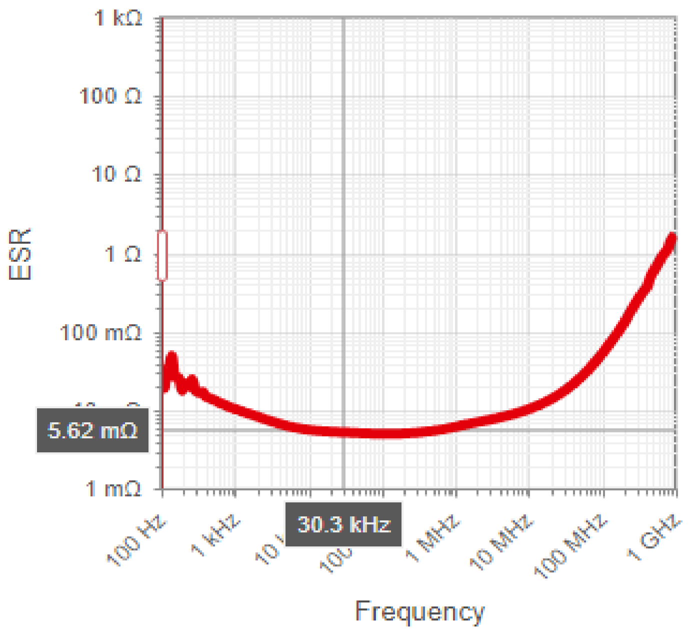
Typical requirements change:

- THT to SMT
- Mechanical constraints
- Stock availability
- Cost reduction

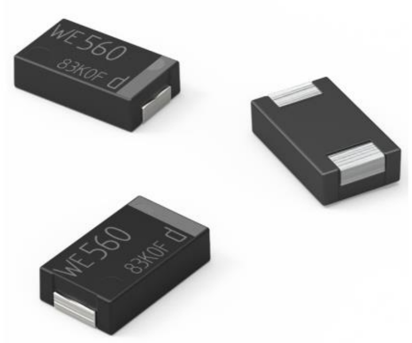
Example: All-SMT, Max. Height 4 mm

- Co4: WCAP-PHGP 875015119006
  - H-chip polymer, SMT, height: 2 mm
  - 220 µF, 6.3 V, 6 mΩ (@ 30 kHz)
- Co3 replaced by Co4

REDEXPERT DATA: WCAP-PHGP 875015119006

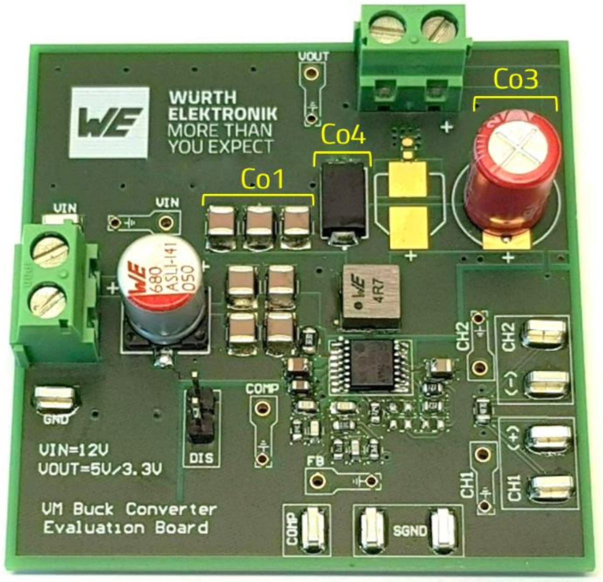


H-chip polymer capacitor

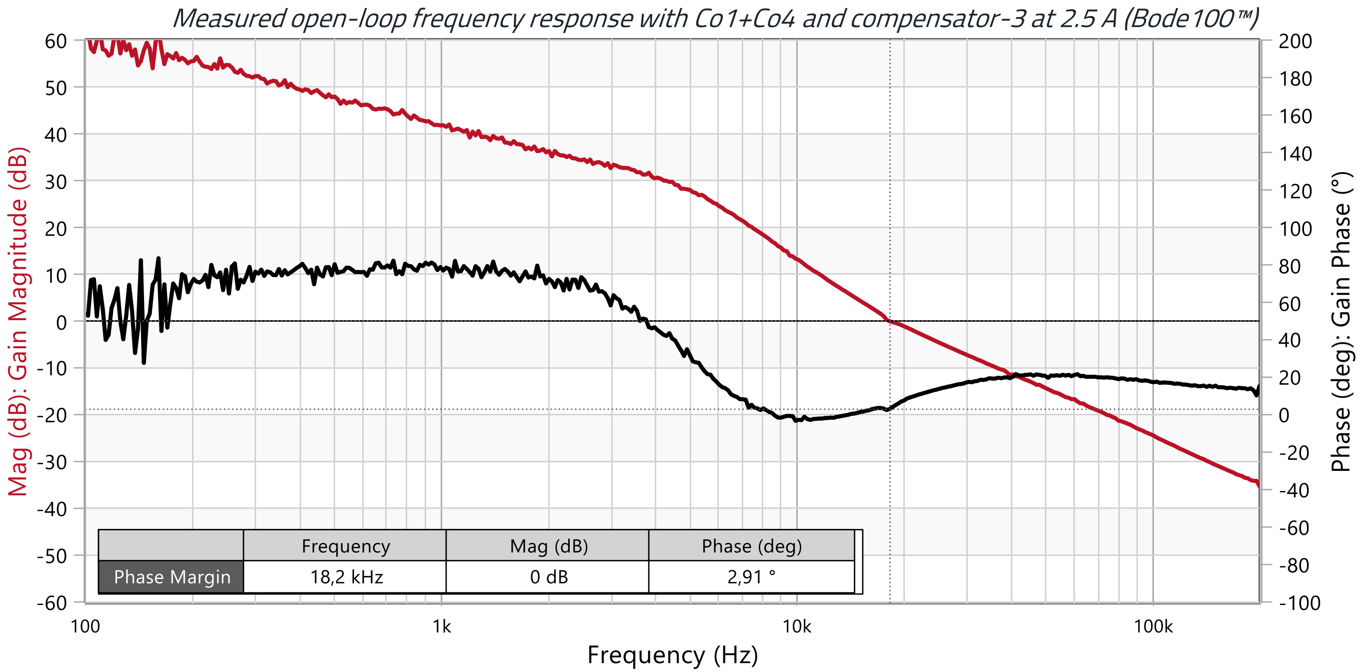


DESIGN CASE EXAMPLE: IMPACT OF ESR

Buck converter board and open-loop response with Co1+Co4 and compensator-3



Prototype VM-CCM buck board with Co1, Co3 and Co4



PM below 10º - On the brink of instability !

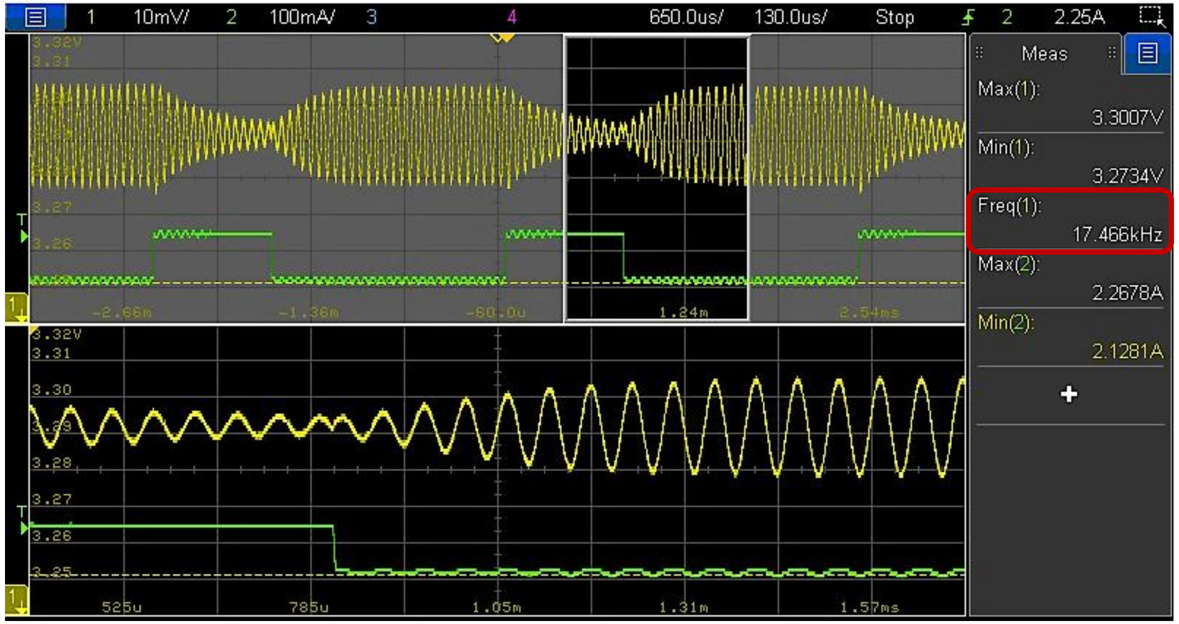
DESIGN CASE EXAMPLE: IMPACT OF ESR

Small load transient steps

Small load transient step:

- From 2.15 A to 2.3 A
- Load step up: decaying oscillation
- Load step-down: permanent oscillation
- Above ~ 2.2 A → Stable
- Below ~ 2.2 A → Unstable
- Oscillation frequency ≈ 17.5 kHz
- Remember OL crossover f_C ≈ 18 kHz

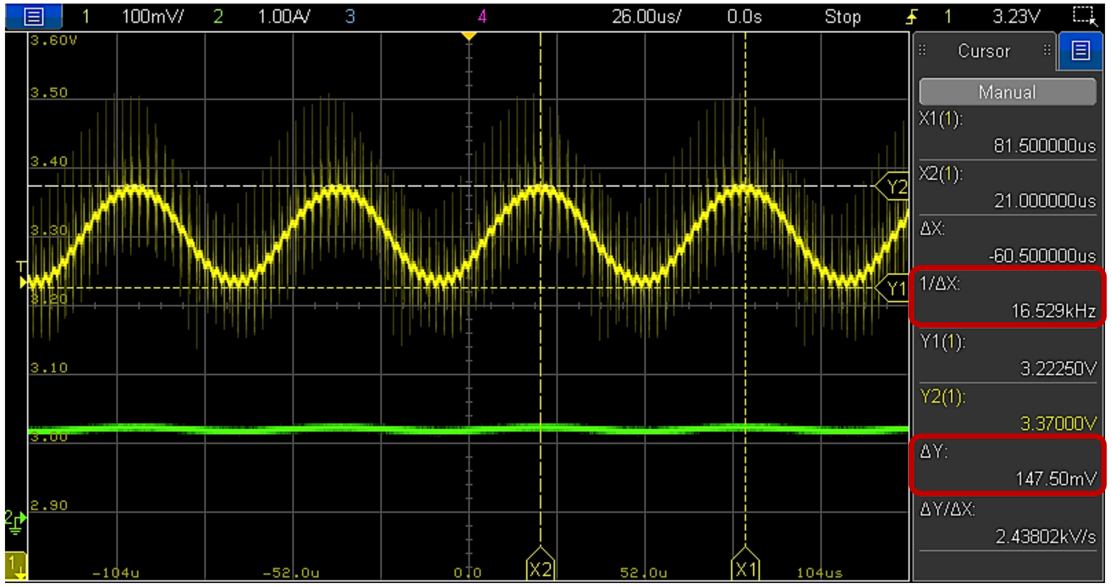
Load step: 2.15 to 2.3 A at 1 A/µs (V_{out} (/), I_{out} (/))



DESIGN CASE EXAMPLE: IMPACT OF ESR

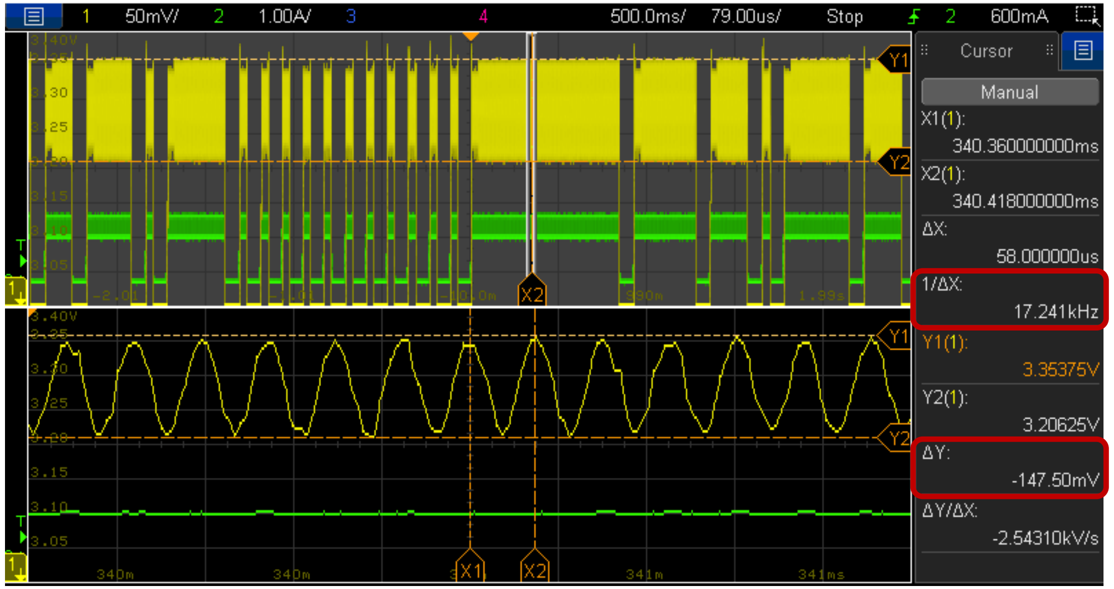
Power-up at 1.2 A load: Oscillation and erratic behavior

Oscillation on power-up at 1.2 A (V_{out} (/), I_{out} (/))



Unstable operation at constant 1.2 A load
Oscillation at ~ 16.5 kHz with amplitude ~ 150 mV

Behavior after single load step 1.2 to 1.9 A at 1 A/µs (V_{out} (/), I_{out} (/))



Erratic behavior after a small load transient applied
Oscillation at ~ 17 kHz with amplitude ~ 150 mV

DESIGN CASE EXAMPLE: IMPACT OF ESR

How did the plant response change?

Plant TF with **Co1+Co3**

$f_{Z1} \approx$ 9 kHz

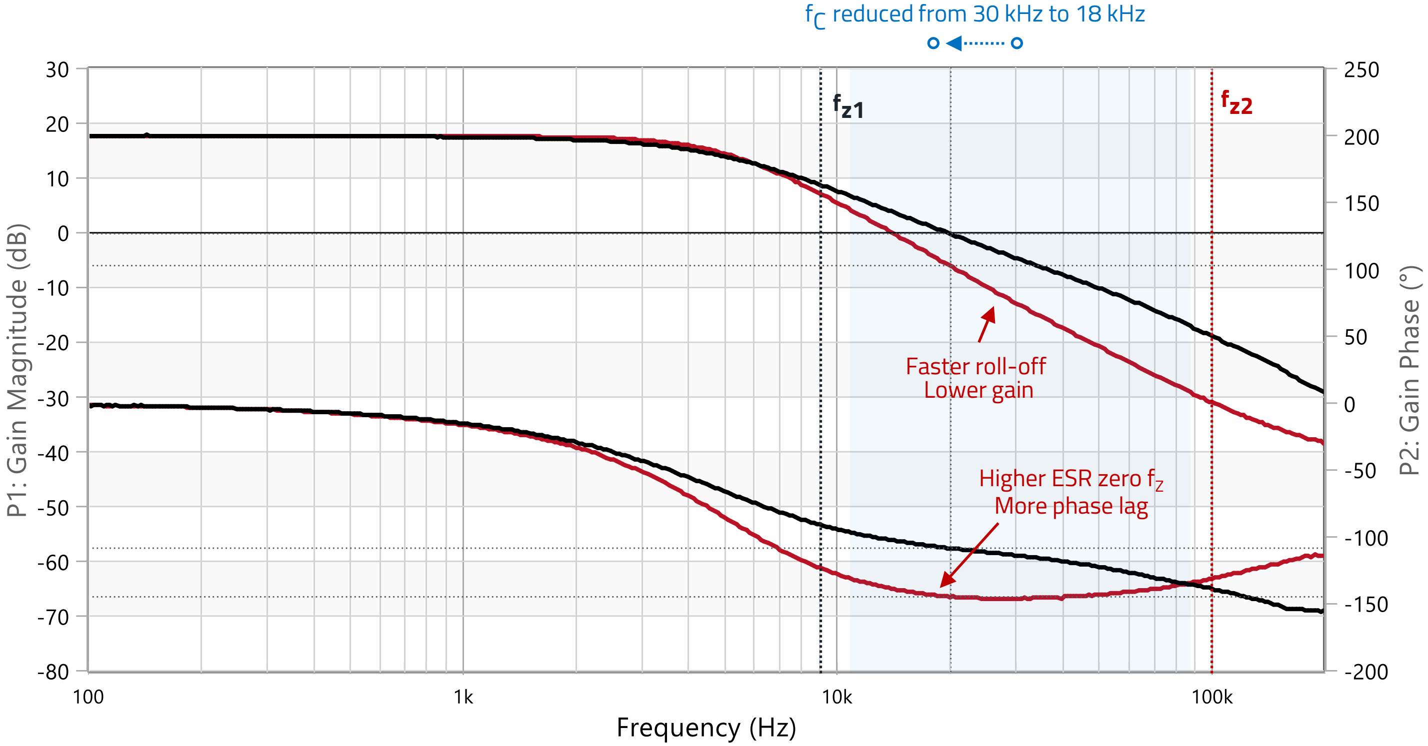
Plant TF with **Co1+Co4**

$f_{Z2} \approx$ 100 kHz

- f_0 and Q are similar

Replacing Co3 by Co4 ...

- Lower gain ⟶ Lower crossover f_C
- Lower crossover (18 kHz):
  - Higher phase lag (higher f_Z)
  - Compensator:
    - Lower phase lead at 18 kHz

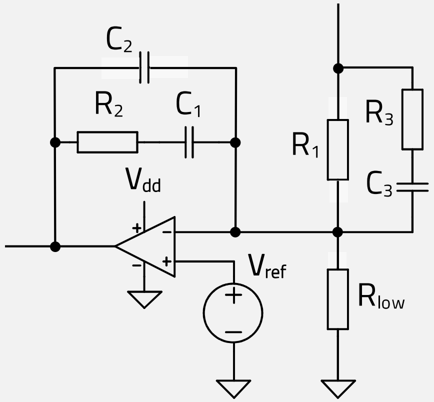


DESIGN CASE EXAMPLE: IMPACT OF ESR

Compensator redesign for stability with Co1+Co4

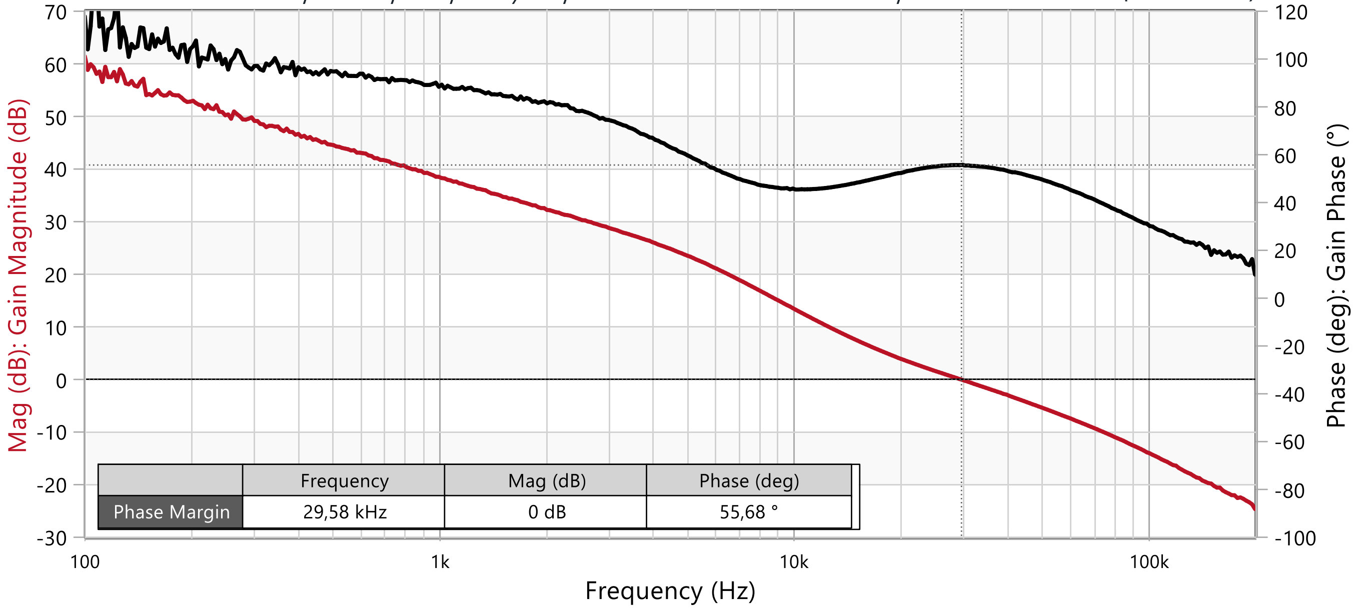
Compensator-4 circuit component values:

- R_1 = 45.5 kΩ
- R_{low} = 10 kΩ
- R_2 = 73.2 kΩ
- R_3 = 2.7 kΩ
- C_1 = 220 pF
- C_2 = 33 pF
- C_3 = 330 pF



f_C ≈ 30 kHz, PM ≈ 55° and GM ≈ 25 dB

Measured open-loop frequency response with Co1+Co4 and compensator-4 at 2.5 A (Bode100™)

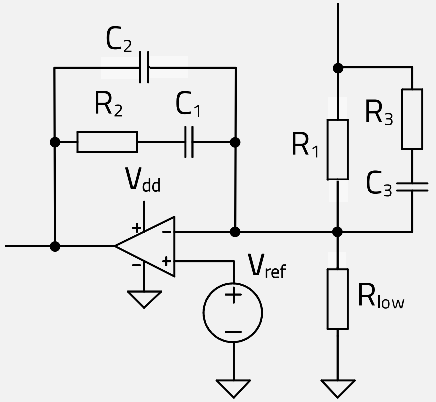


DESIGN CASE EXAMPLE: IMPACT OF ESR

Transient response with Co1+Co4 and compensator-4

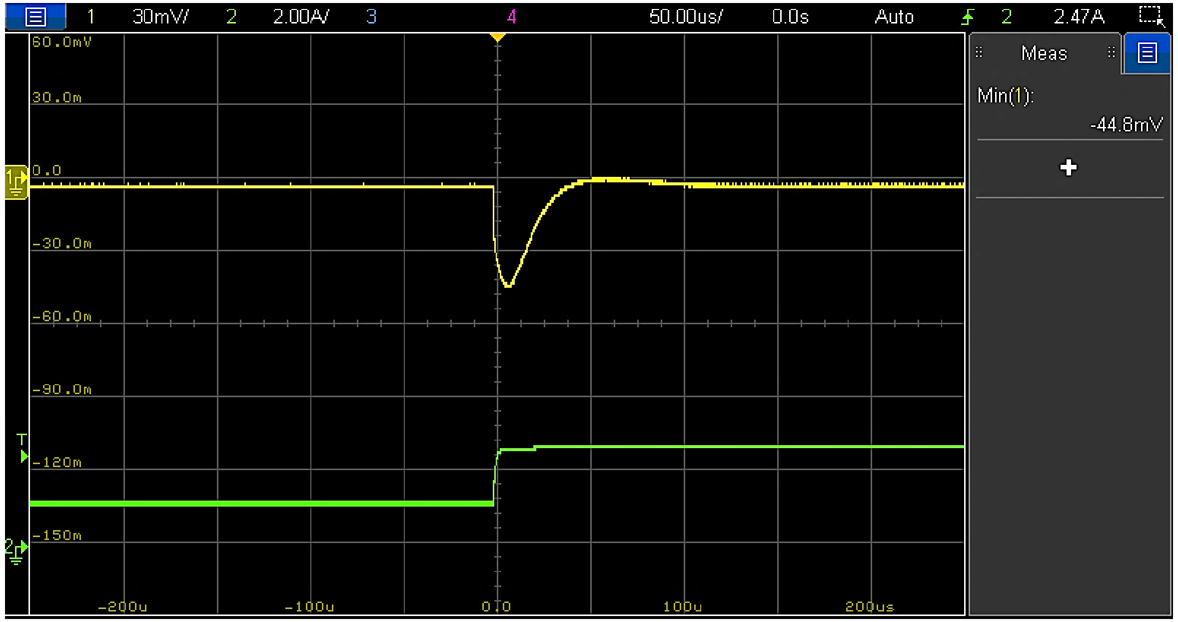
Compensator-4 circuit component values:

- R_1 = 45.5 kΩ
- R_{low} = 10 kΩ
- R_2 = 73.2 kΩ
- R_3 = 2.7 kΩ
- C_1 = 220 pF
- C_2 = 33 pF
- C_3 = 330 pF



Undershoot ~ 45 mV

Load step: 1.2 to 2.7 A at 1 A/µs (V_{out} (/), I_{out} (/))



Lower undershoot than Co3, thanks to lower ESR

A STABLE CONTROL LOOP FOR A WIDE RANGE OF OUTPUT CAPACITORS?

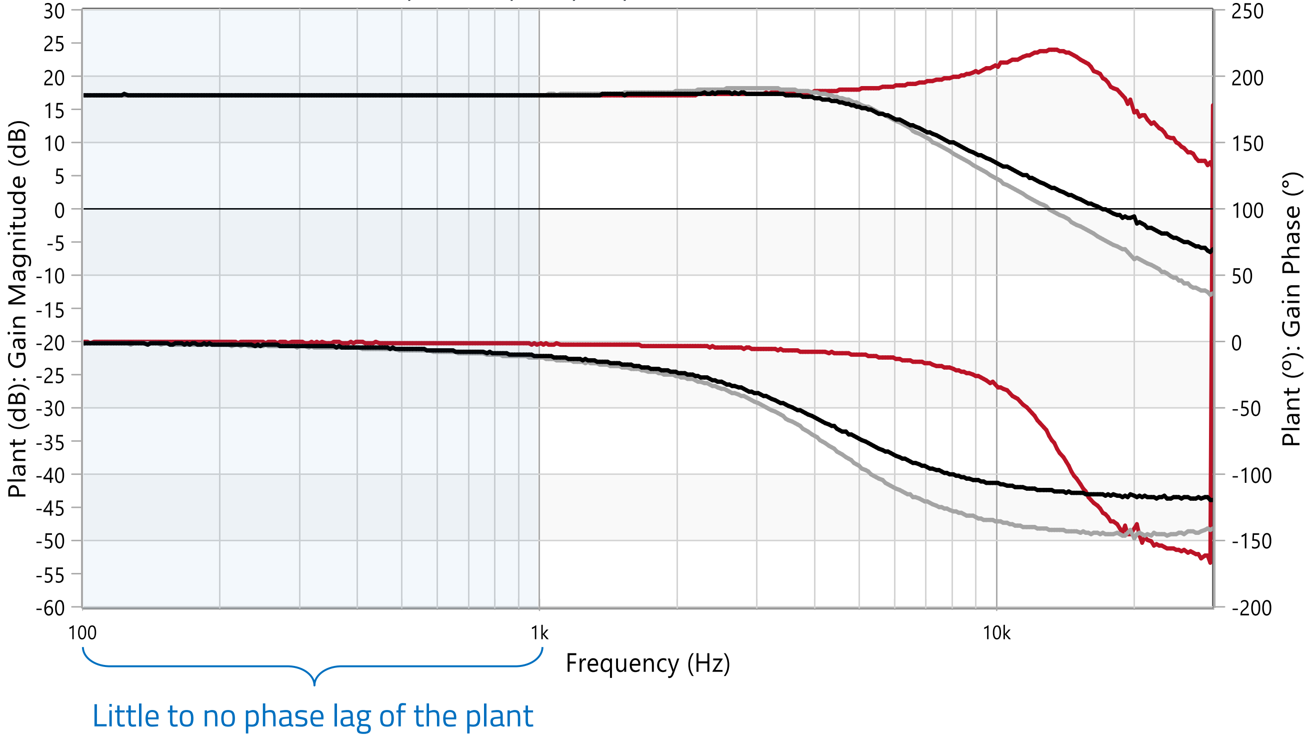
A STABLE CONTROL-LOOP FOR ANY OUTPUT CAPACITOR?

The plant response with different capacitors

Co1 only | Co1+Co2 | Co1+Co3

- Co4 not shown → Very similar to Co2
- Below f ≈ 1 kHz:
  - Plant dominated by G_0 ≈ 17 dB (≈7)
  - No effect of f_0 and f_Z
  - Little to no phase lag
- **What if we select f_C below 1 kHz?**

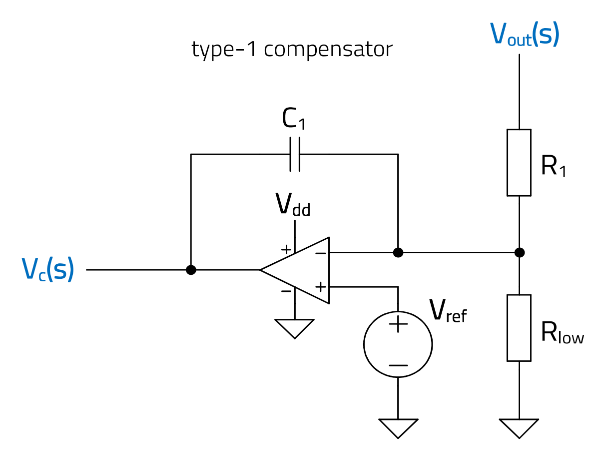
Measured plant frequency response with Co1, Co1+Co2 and Co1+Co3 (Bode100™)



A STABLE CONTROL-LOOP FOR ANY OUTPUT CAPACITOR?

A type-1 compensator for 1 kHz crossover frequency

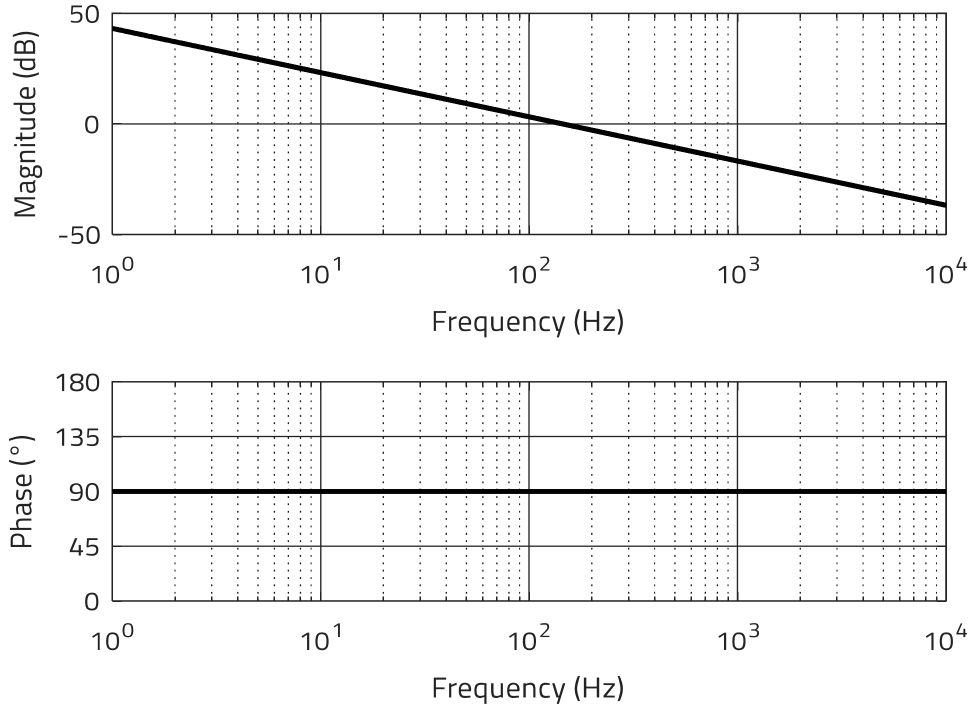
- Type-1 Compensator
- Integrator C_1-R_1
- High DC-gain
- No phase lead
- Phase margin ~ 90°



- R_1 and R_{low} set V_{out}=5 V
- C_1 calculated for f_C=1 kHz:

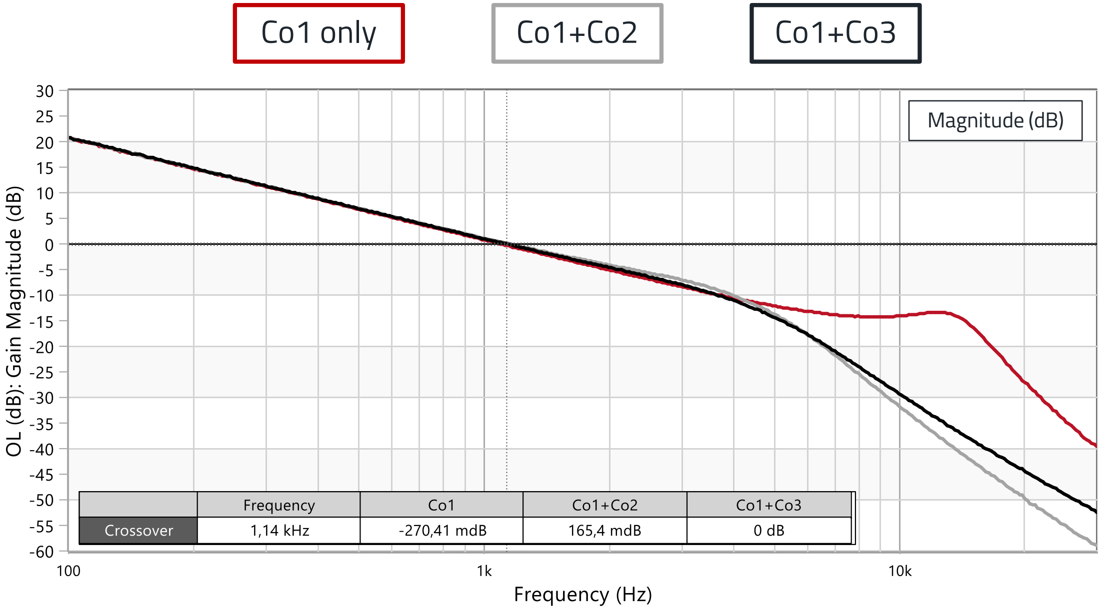
$$C_1 \approx \frac{G_0}{2 \cdot \pi \cdot f_C \cdot R_1} = \frac{7}{2 \cdot \pi \cdot 1k \cdot 73.2k} \approx 15\ nF$$

Type-1 compensator frequency response with R_1=73.2 kΩ and C_1=15 nF (MATLAB™)

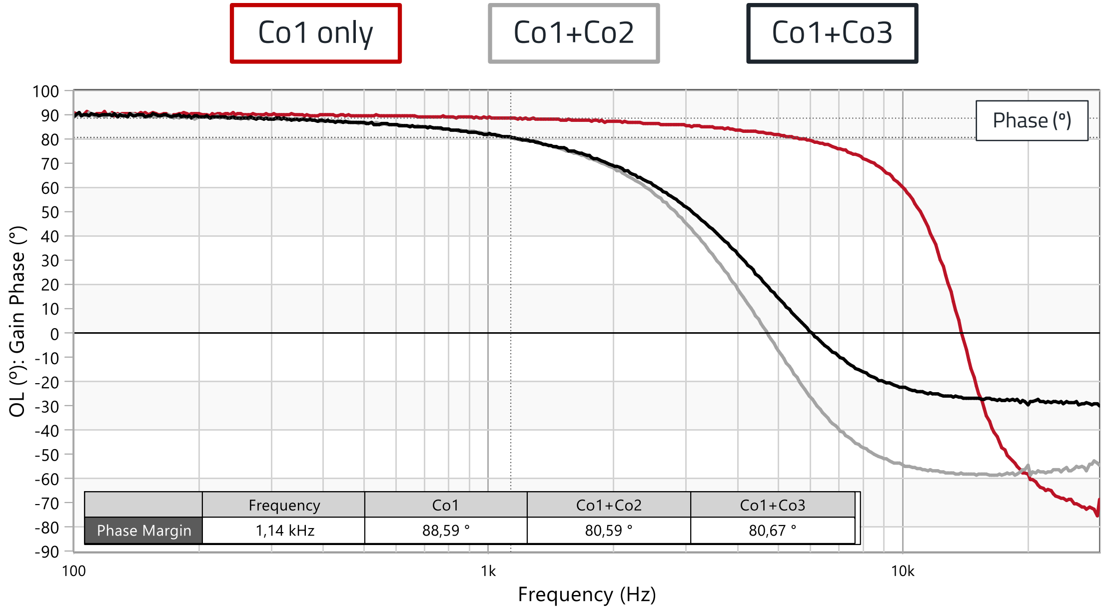


A STABLE CONTROL-LOOP FOR ANY OUTPUT CAPACITOR?

Open-loop response and phase margin



	Frequency	Co1	Co1+Co2	Co1+Co3
Crossover	1,14 kHz	-270,41 mdB	165,4 mdB	0 dB



	Frequency	Co1	Co1+Co2	Co1+Co3
Phase Margin	1,14 kHz	88,59 °	80,59 °	80,67 °

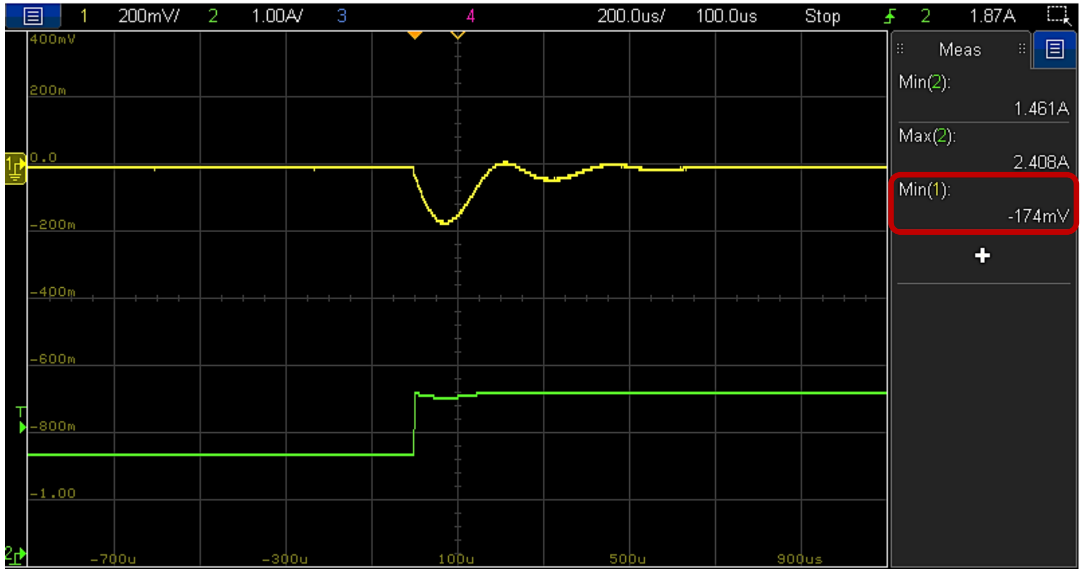
Crossover frequency f_C ~ 1 to 1.2 kHz

Minimum phase margin ~ 80°

A STABLE CONTROL-LOOP FOR ANY OUTPUT CAPACITOR?

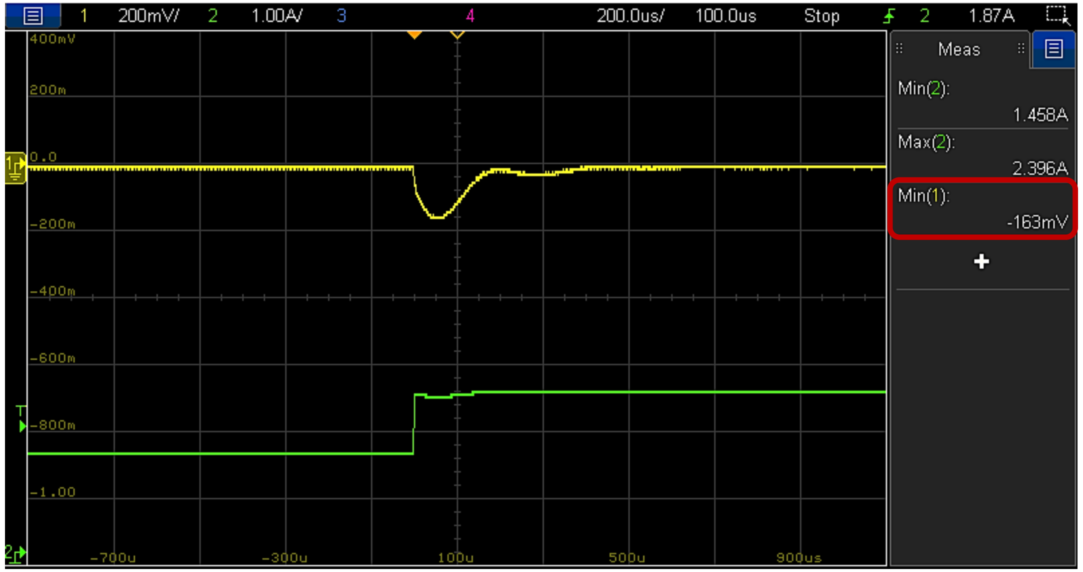
Transient response for Co2 and Co3 cases with type-1 compensator

Co1+Co2



Load step: 1.2 to 2.4 A at 1 A/µs (V_{out} (/), I_{out} (/))

Co1+Co3



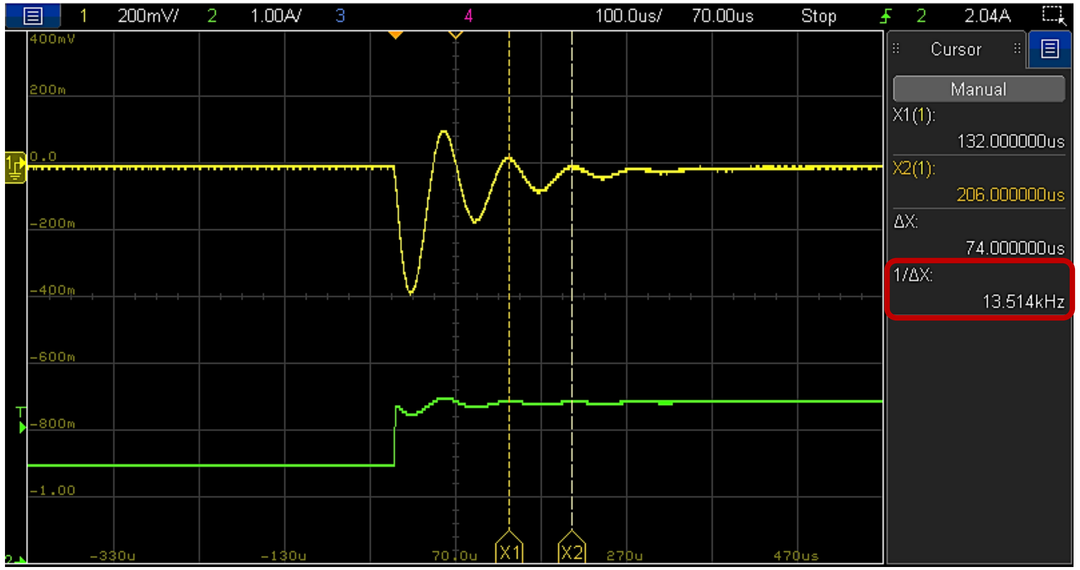
Load step: 1.2 to 2.4 A at 1 A/µs (V_{out} (/), I_{out} (/))

Despite smaller load step: longer settling time and higher undershoot than before. Degraded transient performance.
There is a small underdamped oscillation with Co2 and not with Co3, despite same phase margin ~ 80° … Let us see …

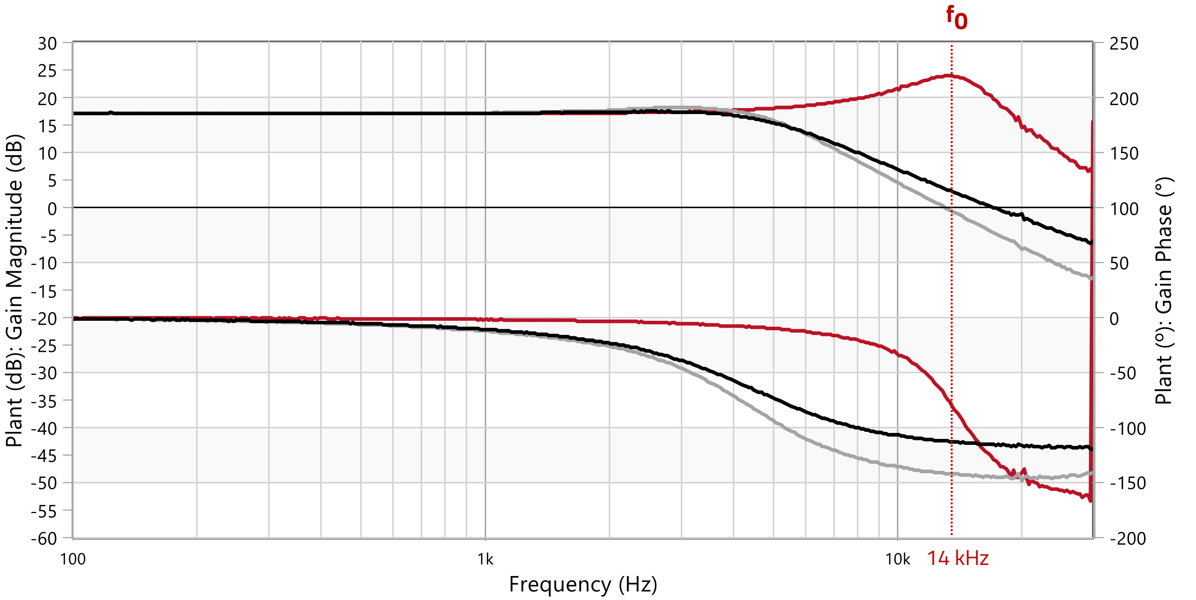
A STABLE CONTROL-LOOP FOR ANY OUTPUT CAPACITOR?

Transient response for Co1-only case: underdamped oscillation despite high phase margin

Co1 only



Load step: 1.2 to 2.4 A at 1 A/µs (V_{out} (/), I_{out} (/))



Stable, but with some underdamped oscillation at ~ 14 kHz

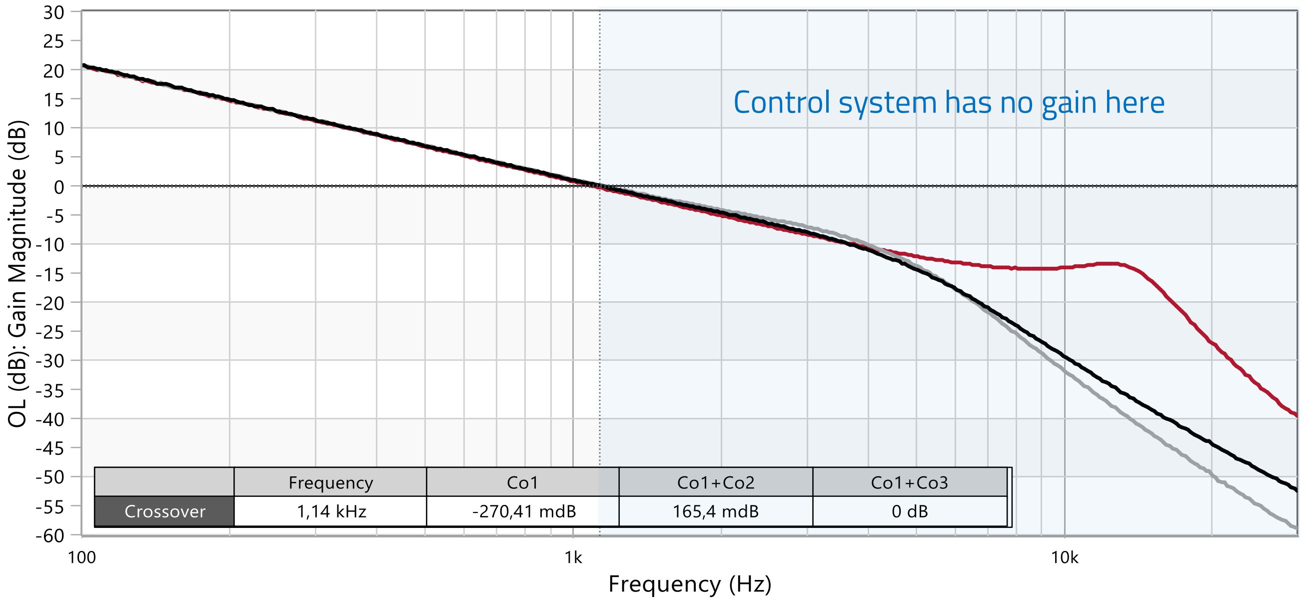
LC resonant double-pole with **Co1-only** is at ~ 14 kHz with a Quality factor ~ 2.5

A STABLE CONTROL-LOOP FOR ANY OUTPUT CAPACITOR?

Lack of gain of control system above crossover

- Closed-loop bandwidth $f_{C\_CL} \approx f_{C\_OL}$
- No gain above f_C
- System cannot correct for oscillations above f_C
- Issues for high Q (underdamped double-pole)
- Very high Q ⟶ Could cross over again at 0 dB !

- Must be careful with Q if using this approach!

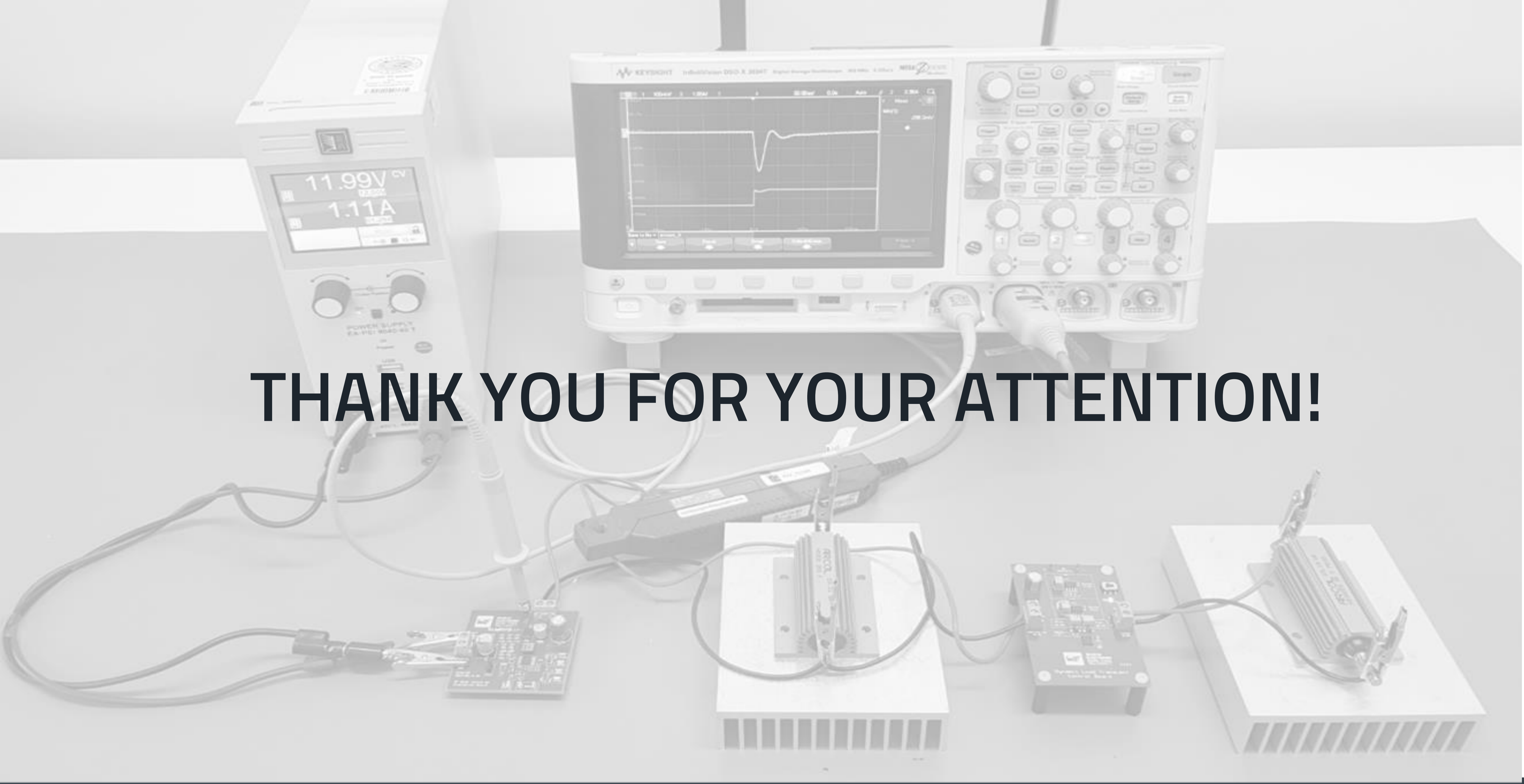


	Frequency	Co1	Co1+Co2	Co1+Co3
Crossover	1,14 kHz	-270,41 mdB	165,4 mdB	0 dB

SUMMARY - KEY TAKEAWAYS

SUMMARY AND KEY TAKEAWAYS

- Output capacitor(s) parameters shape the converter plant transfer function: Capacitance and ESR values
- For a fixed compensator, changes in the output capacitors will affect the stability margins
- Transient performance degradation and even full-blown instability are possible
- Always check feedback loop stability margins after changes in output capacitor(s)
- Redesign compensator to keep good stability margins
- Very-low crossover frequency: stability for many different output capacitor and power inductors
- But … degraded transient response and oscillation for high quality factors
- A compensator tailored to a specific plant characteristic will provide the best performance



THANK YOU FOR YOUR ATTENTION!