TI *Live!* INDIA AUTOMOTIVE SEMINAR

ORLANDO MURRAY

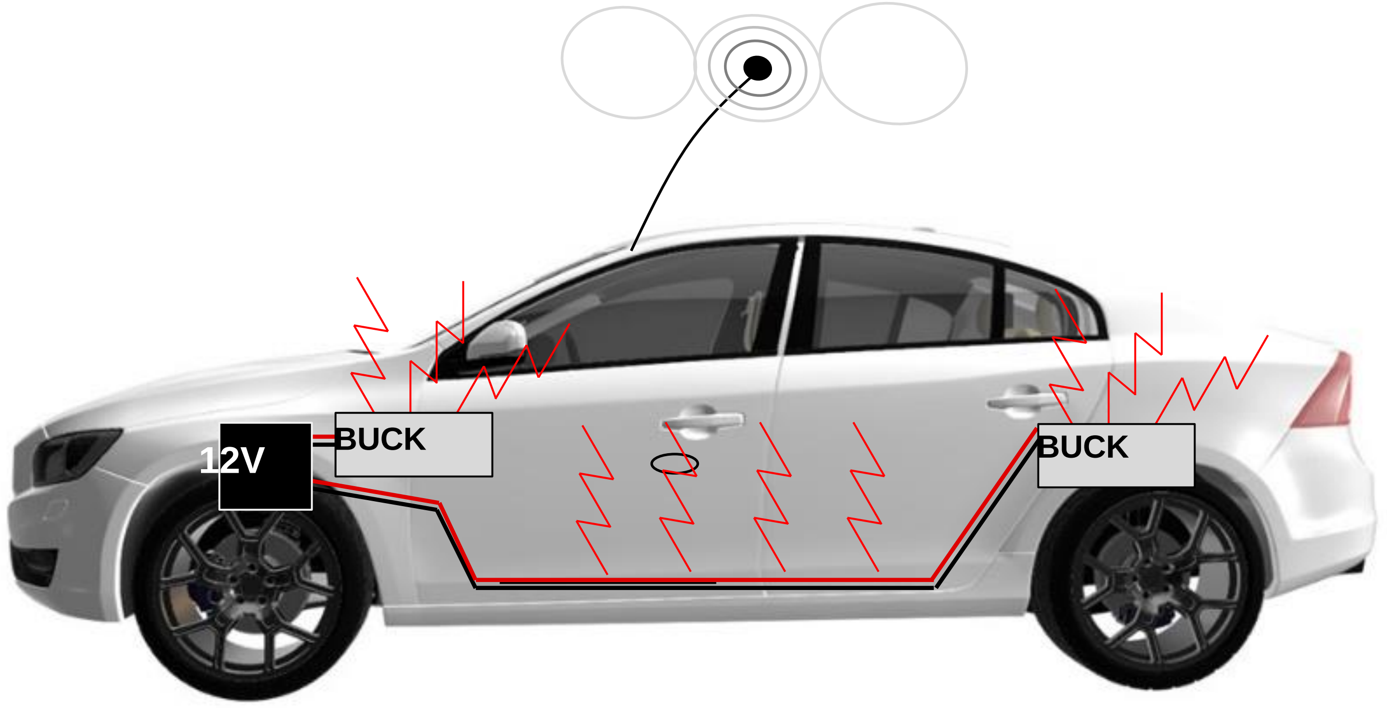
USING AN ACTIVE EMI FILTER IN POWER CONVERTERS TO REDUCE EMI FILTER SIZE AND COST

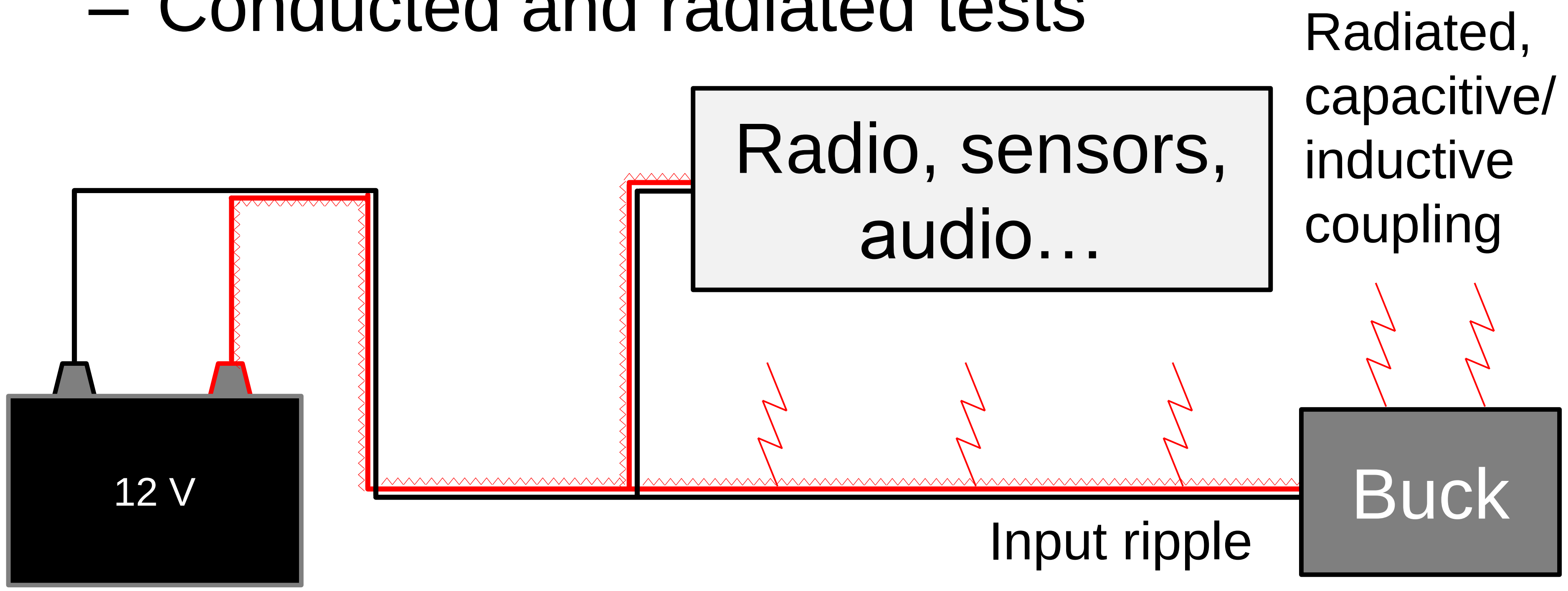
Outline

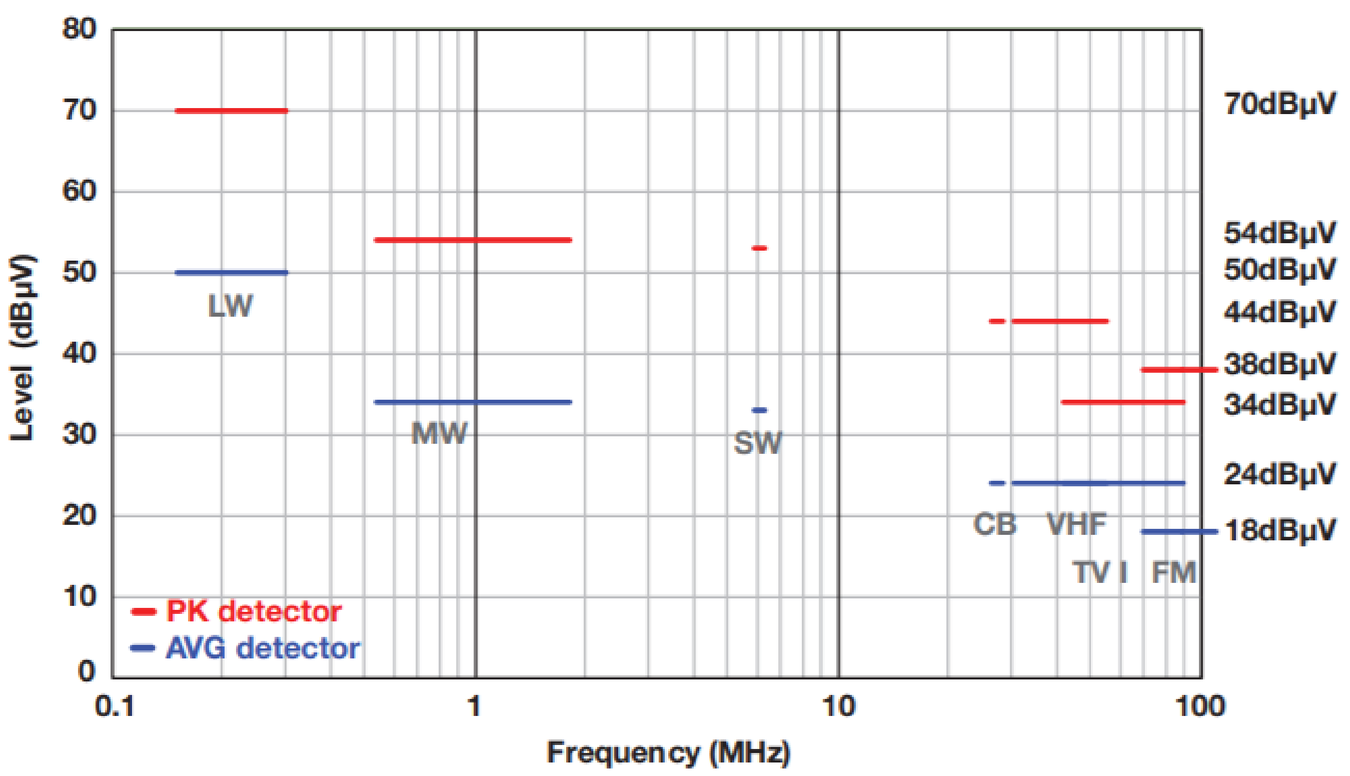
- Background and context:
  - What is electromagnetic interference (EMI)
  - How to mitigate EMI
  - EMI filters and limitations
- Active EMI filter
  - Active EMI filter (AEF)
  - AEF compensation
  - AEF damping
- Results

Background: What is EMI and why do we care?

- EMI: Unwanted noise and signals that cause capacitive coupling, inductive coupling, or radiation onto a conductor
- Can interfere with other systems
- Standards limit how much we can emit
  - CISPR 25, CISPR 11… standards
  - Conducted and radiated tests



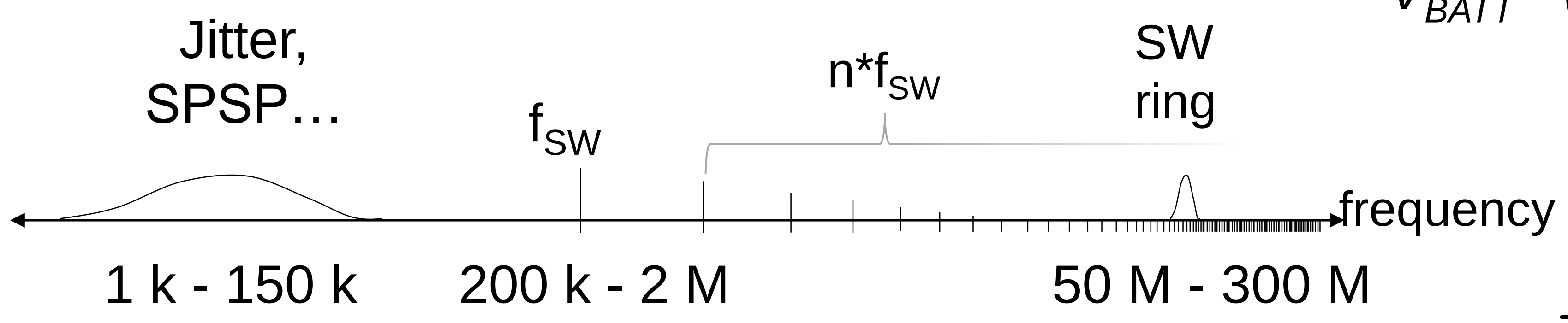


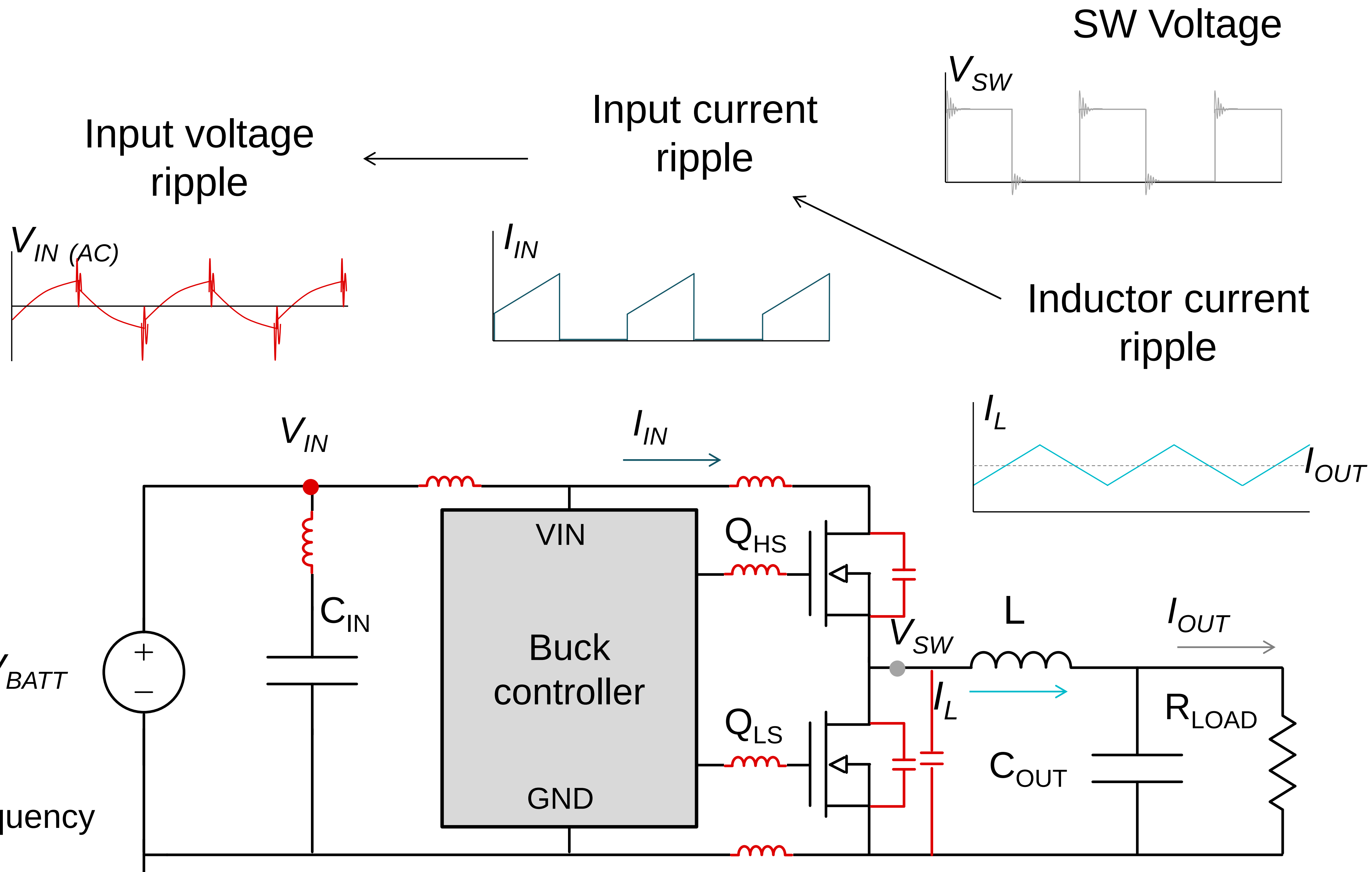


Conducted EMI limits – CISPR 25 Class 5

Context: What causes EMI in a buck regulator?

- Switching causes ripple/noise at f_{SW} and harmonics
- Parasitics cause high-frequency SW ring and spikes
- Jitter, spread spectrum can add low-frequency noise

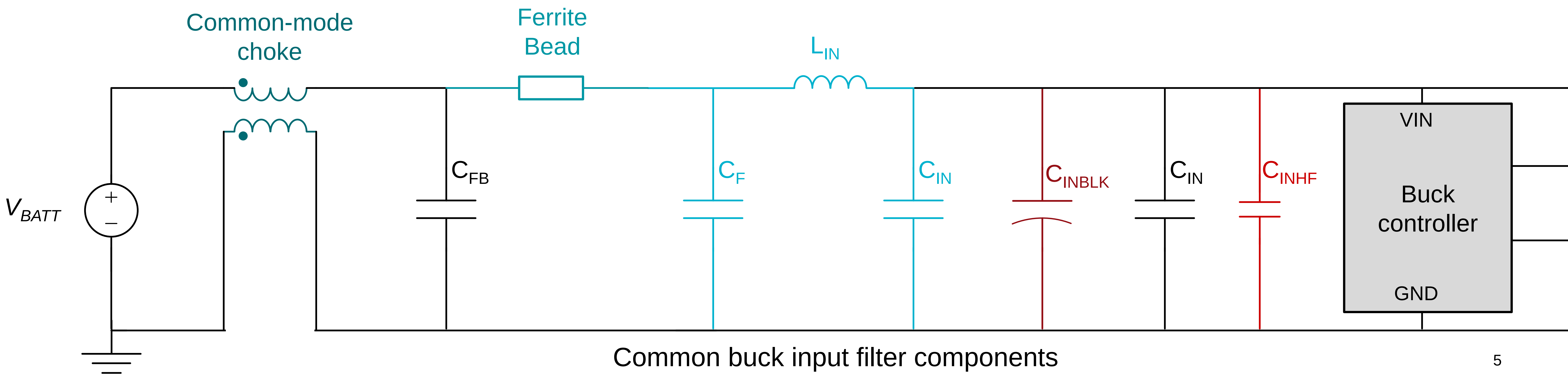




Simplified buck schematic

EMI filtering: Common passive components

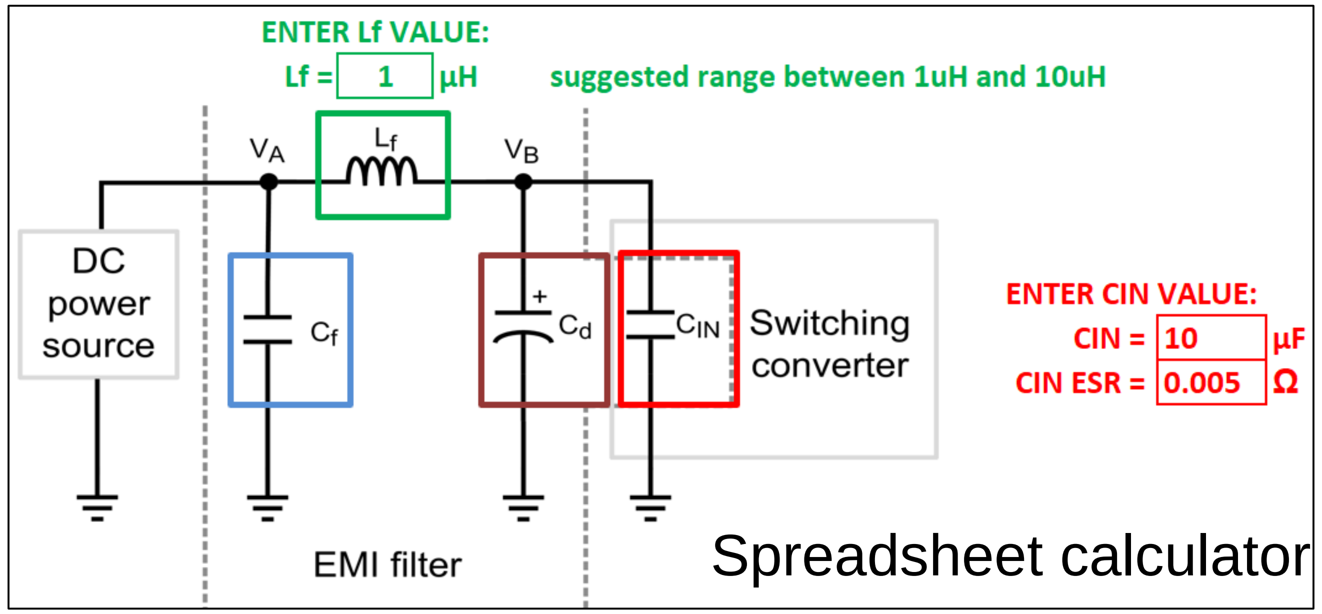
- **HF ceramic input capacitor** - Reduces SW ringing, improves >10 MHz
- **Bulk capacitor** - ESR damps resonance with filter components at <1 MHz
- **CLC/LCL π/T-filter** - Filters up to 10 -100 MHz
- **Ferrite bead** - Filters >2 MHz, spec'd at 100 MHz
- **Common-mode choke** - Filters common-mode noise up to ~100-300 MHz



Common buck input filter components

EMI filtering: Designing a CLC π filter

- Three methods:
  - A. Check the evaluation board or a reference design
    - Check data sheet and user's guide for EMI results and filter
    - Use something similar or adjust to your specs
  - B. Calculate/measure
    - Calculate attenuation using equation (1) or measure necessary attenuation
    - Use AN-2162 application note and spreadsheet to calculate component values
  - C. Test in lab and adjust until the filter is optimized



$$|Att|_{dB} = 20\log\left(\frac{\frac{I_{peak}}{\pi^2 f_{SW} C_{IN}}\sin(\pi D)}{1\mu V}\right) - V_{MAX} \quad (1)$$

Where:

f_{SW} = *Switching frequency*

D = *Duty cycle*

V_{MAX} = *Max allowed dBµV for the particular EMI spec*

EMI filtering: Designing a CLC π filter

- After measuring or using (1) to calculate required attenuation in dB
- Use (2) to design EMI filter cutoff frequency
- Use (3) to select C_F and L_{IN} components
  - Typically select L_{IN} 0.1–10 µH with input current rating
  - Typically parallel multiple C_F to get required value
- Test and adjust as needed

$$|Att|_{dB} = 20\log\left(\frac{\frac{I_{peak}}{\pi^2 f_{SW} C_{IN}}\sin(\pi D)}{1\mu V}\right) - V_{MAX} \quad (1)$$

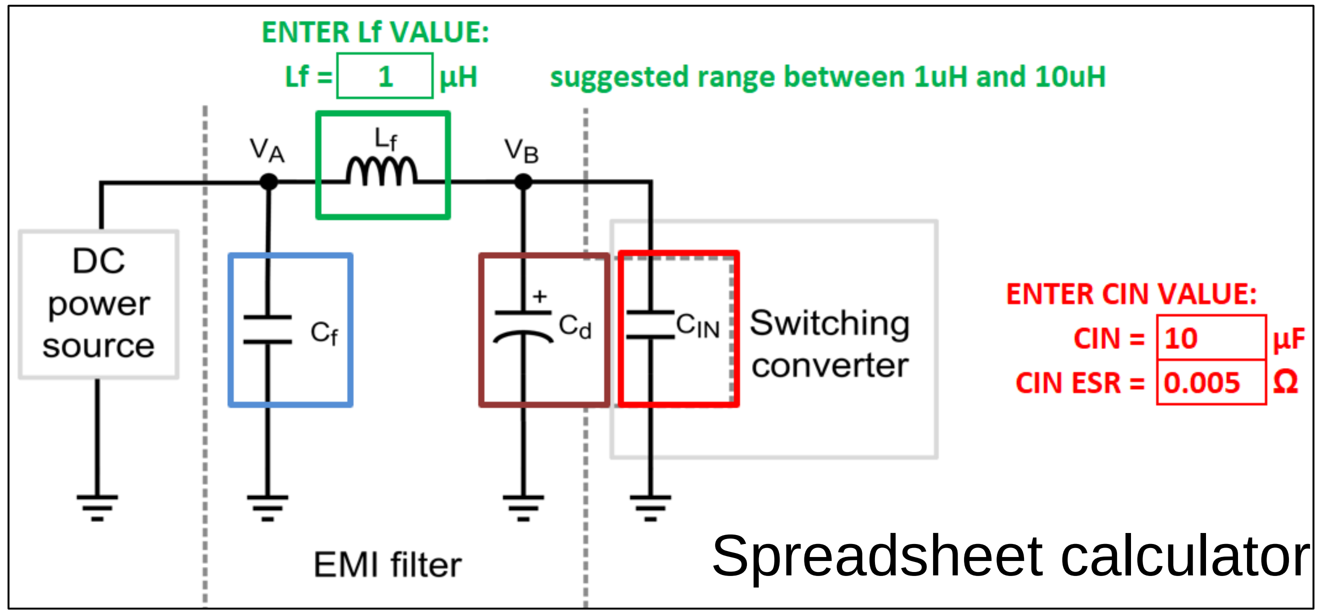
Where:
f_{SW} = *Switching frequency*
D = *Duty cycle*
V_{MAX} = *Max allowed dBµV for the particular EMI spec*

$$f_c = \frac{f_{sw}}{10^{|Att|/40}} \quad (2)$$

Where:
f_c = *EMI filter cutoff frequency*

$$L_{IN} C_F = \frac{1}{(2\pi f_c)^2} \quad (3)$$

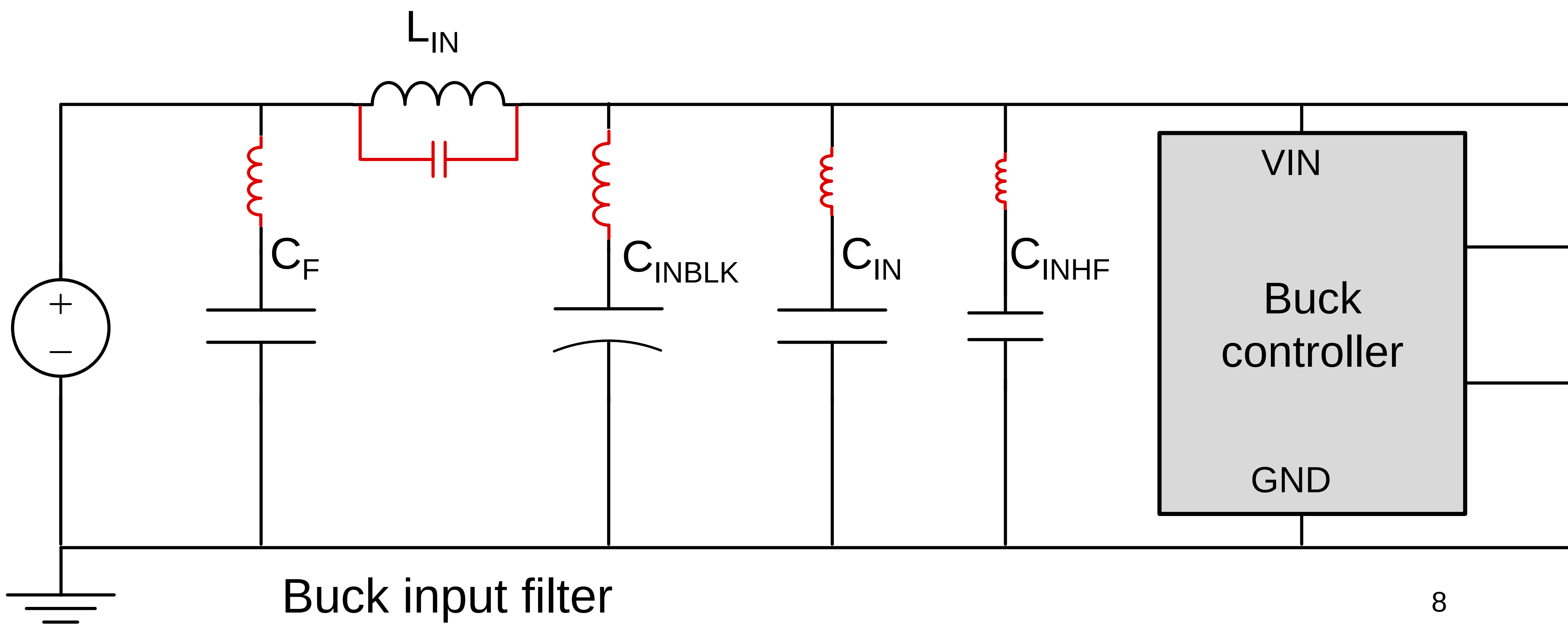
Where:
L_{IN} = *EMI filter inductor*
C_F = *EMI filter inductor*



Spreadsheet calculator

EMI filtering: Passive filter component limitations

- Concerns:
  - Cost – Filter cost can add up. Larger filter for more attenuation means more money!
  - Size – Filter can take large board area depending on necessary components
- Considerations:
  - Capacitor voltage rating must > V_{IN_MAX}
  - Inductor current rating must > I_{IN_MAX} (at V_{IN_MIN})
  - Filter components' parasitics limit filtered frequencies to less than self-resonant frequency (SRF)
  - Larger package = more parasitics
    - 1210 capacitor ~ 1–2 nH
    - 0402 capacitor ~ < 1 nH

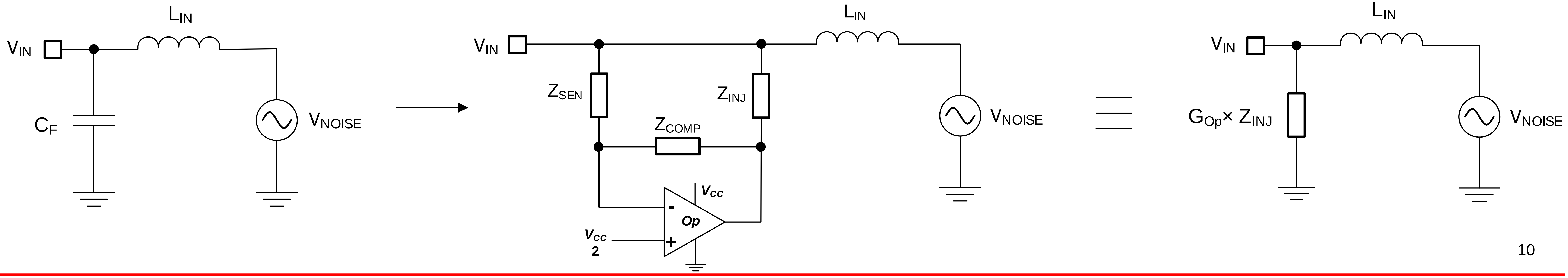


Buck input filter

Active EMI filter

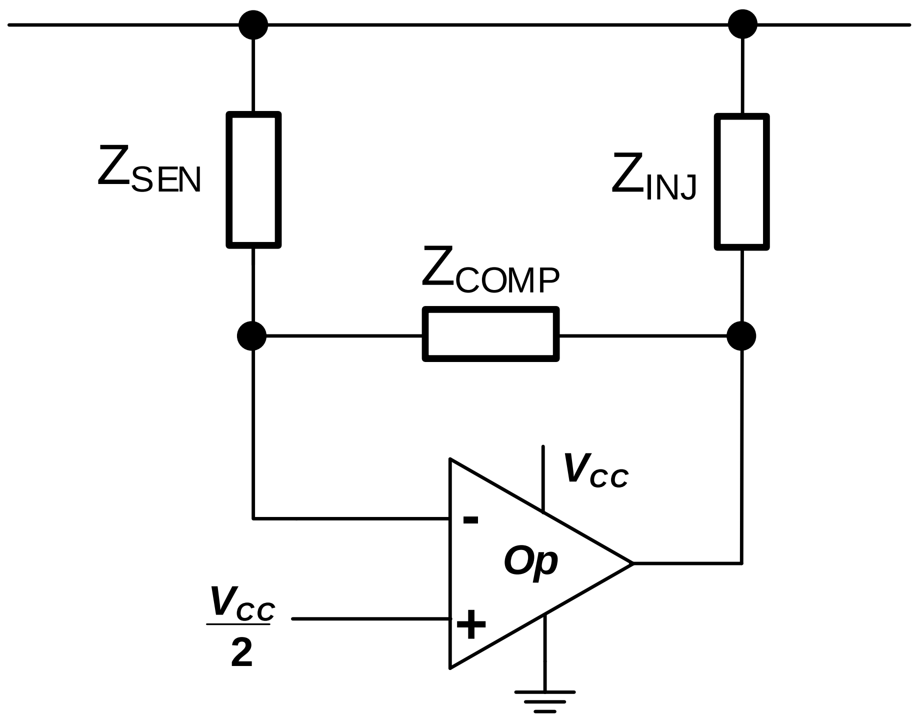
Active EMI fundamentals

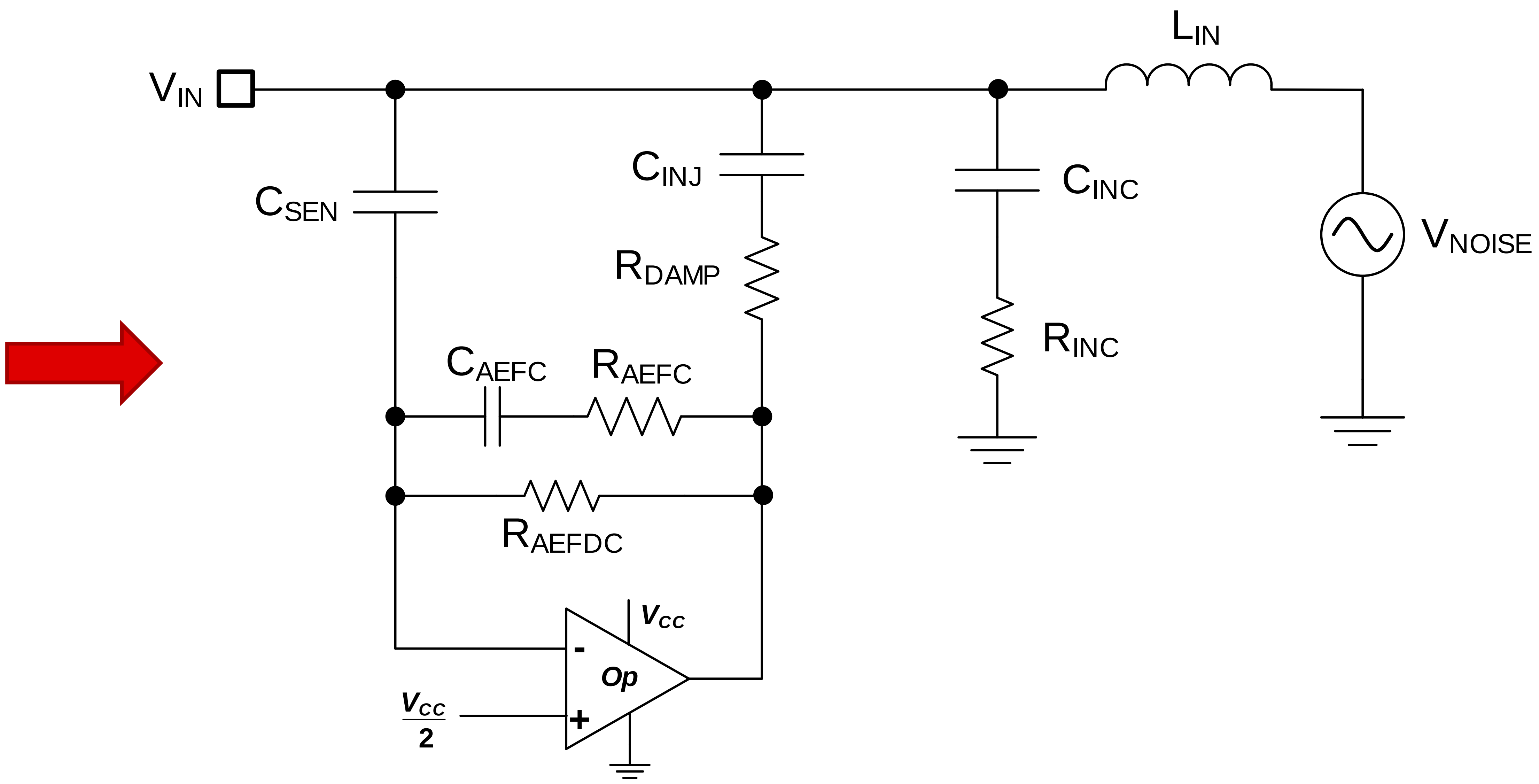
- View Active EMI filter (AEF) as an "active capacitor" compared to passive C_F.
- AEF uses an operational amplifier to sense AC-perturbations on the input rail and inject an 180º out-of-phase signal to cancel the noise.
- Replace passive EMI filter C_F with active EMI network; Op-amp requires feedback and compensation components but these are much smaller in capacitance, footprint, and cost.
- Op-amp can be integrated in DC/DC controller IC, such as LM25149-Q1.



EMI filtering: Active EMI filter

- Active EMI filter uses an op-amp to replace passive C_F with “active capacitor”



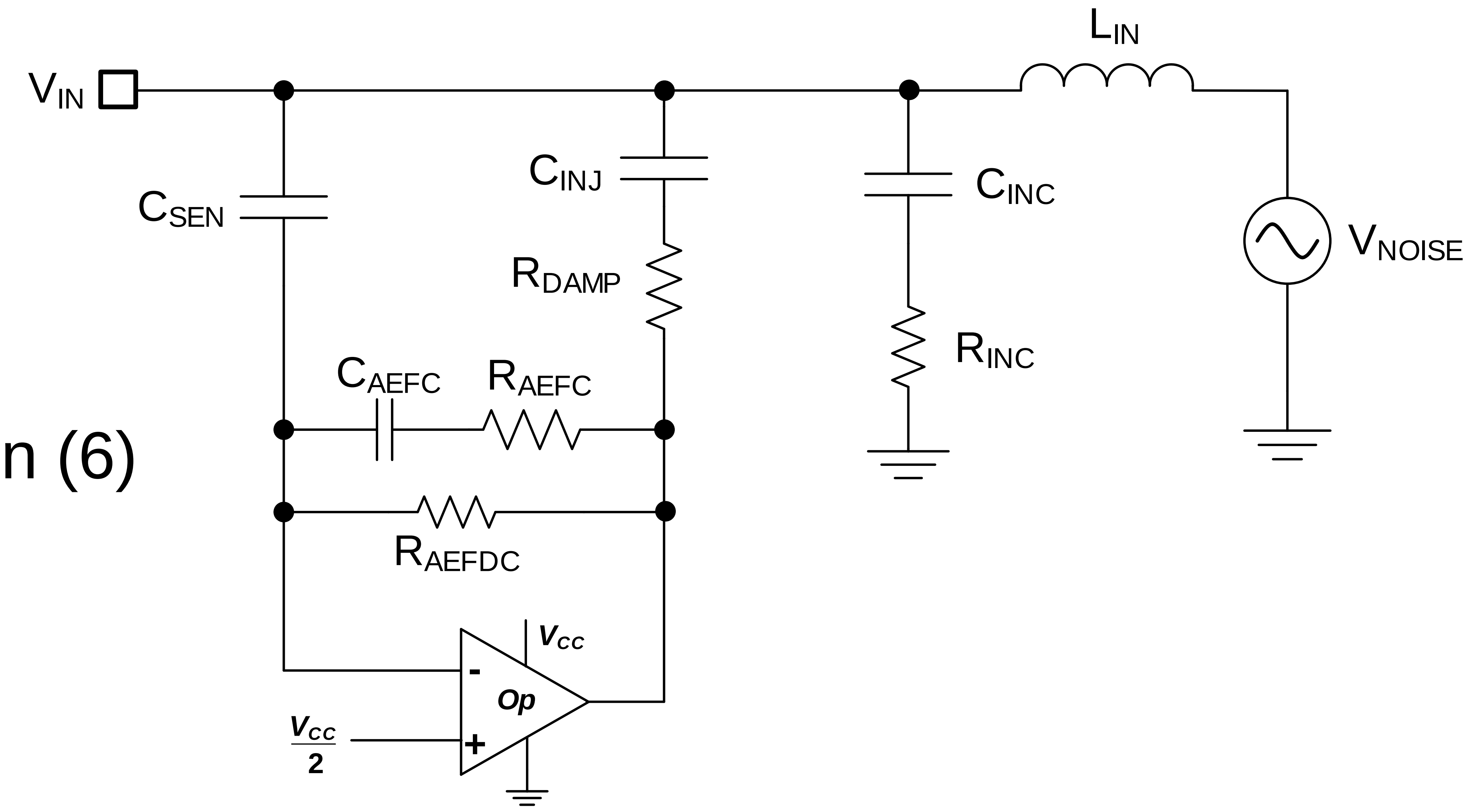


EMI filtering: Active EMI filter

- Active EMI filter uses an op-amp to replace passive C_F with "active capacitor"
- Op-amp gain term (5)

$$G_{Op} \approx C_{SEN}/C_{AEFC} \qquad (5)$$

Where:
C_{SEN} = *AEF sensing capacitor*
C_{AEFC} = *AEF compensation capacitor*



- Active filter L_{IN} and C_{INJ} selection (6)

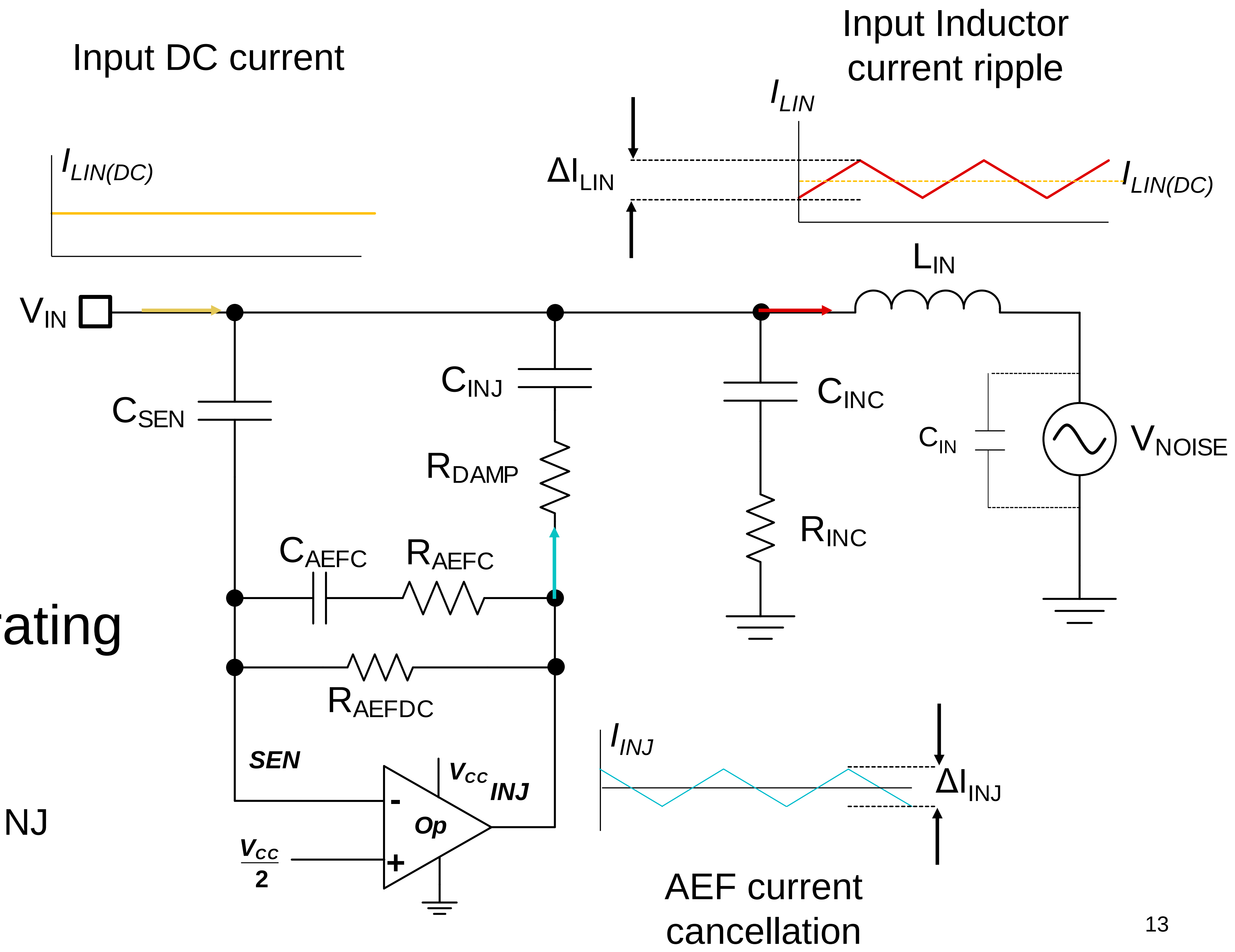
$$L_{IN}C_{INJ} = \frac{1}{G_{Op}(2\pi f_c)^2} \qquad (6)$$

Where:
C_{INJ} = *AEF injection capacitor*

- With $G_{Op} = 100$, filter can reduce L_F and C_{INJ} one-tenth compared to passive!

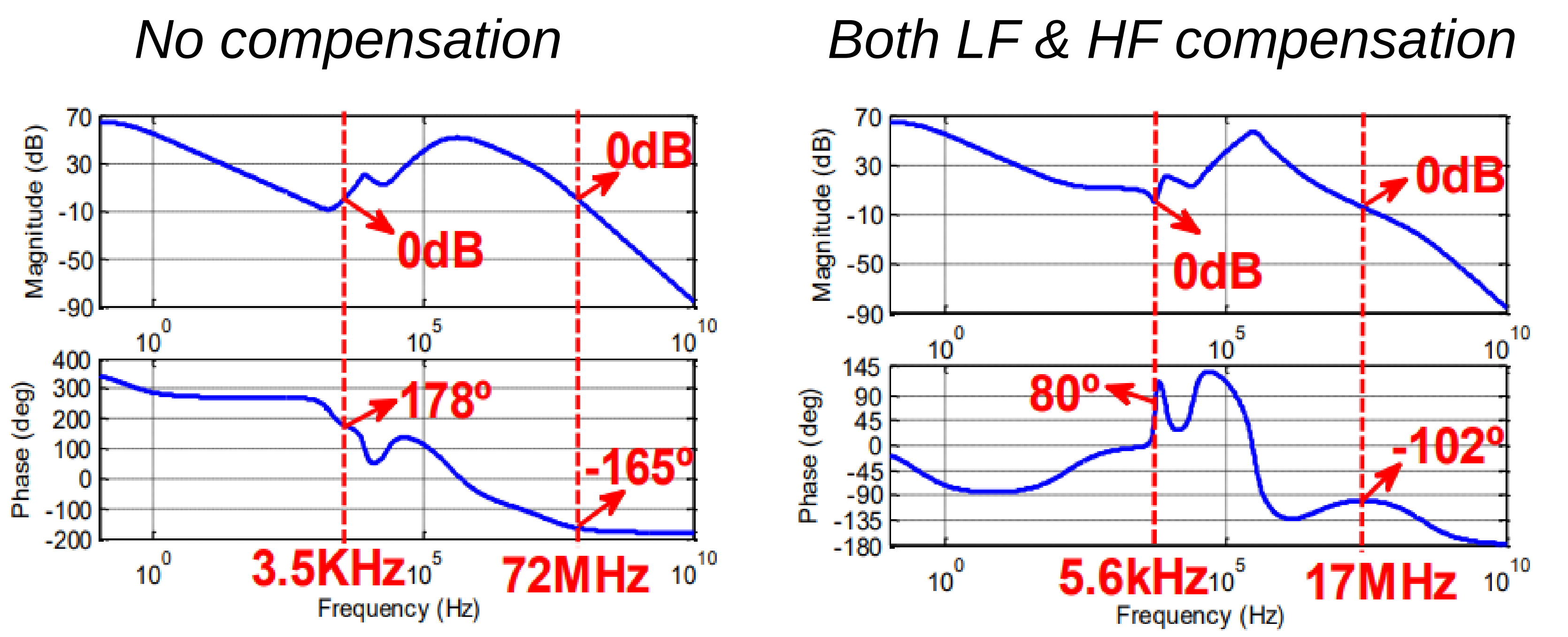
EMI filtering: Active EMI filter

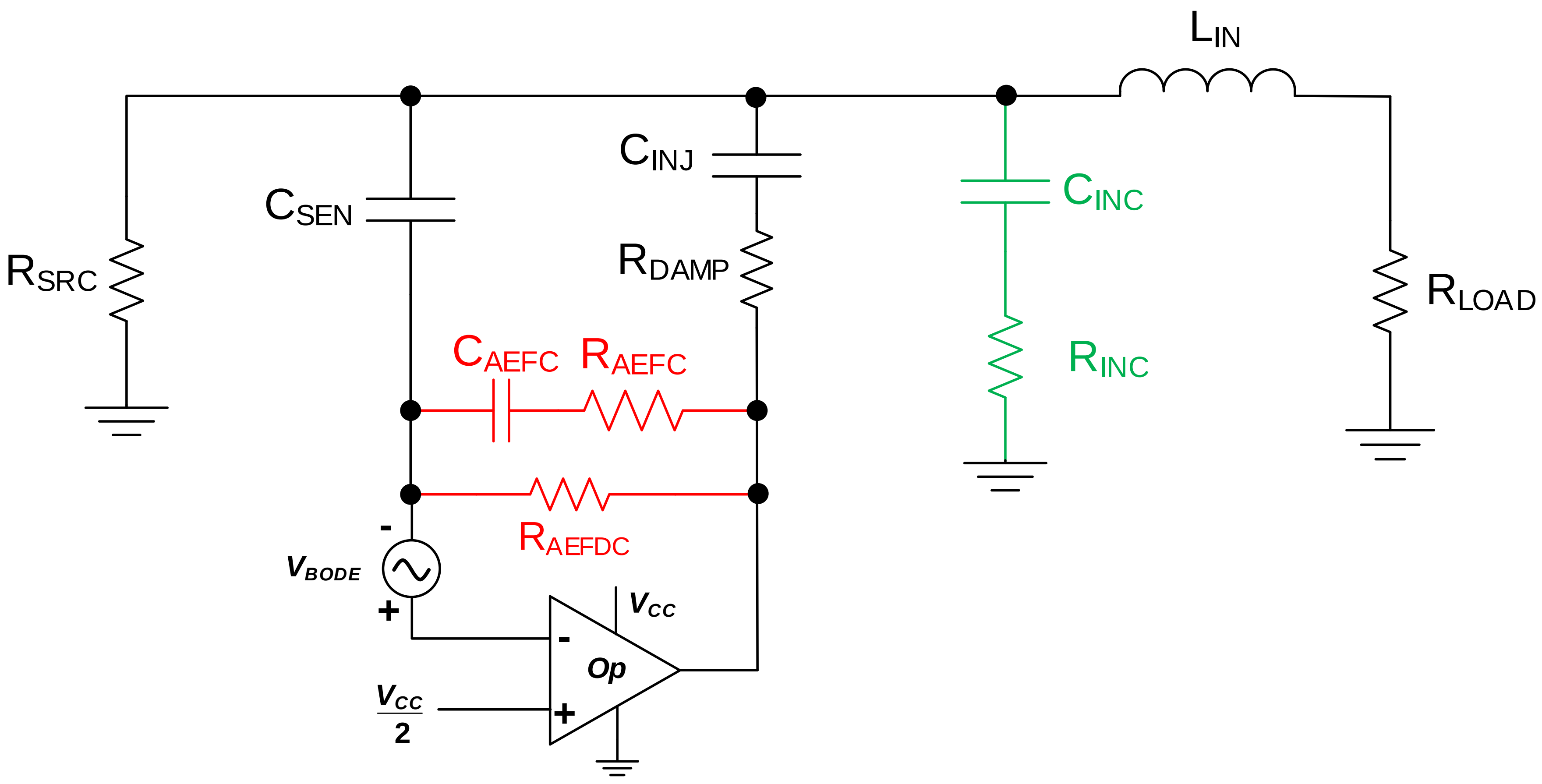
- Input voltage and current ripple cause EMI. Lowest ripple will result in lowest EMI
- Capacitive sensing and injection
  - No DC current into AEF
- AEF ripple current cancels ripple current of input inductor
- AEF is NOT limited to DC power rating
  - Limited to ΔI_{INJ} canceling ΔI_{LIN}
- L_{IN} or C_{IN} can be sized to meet ΔI_{INJ} requirement



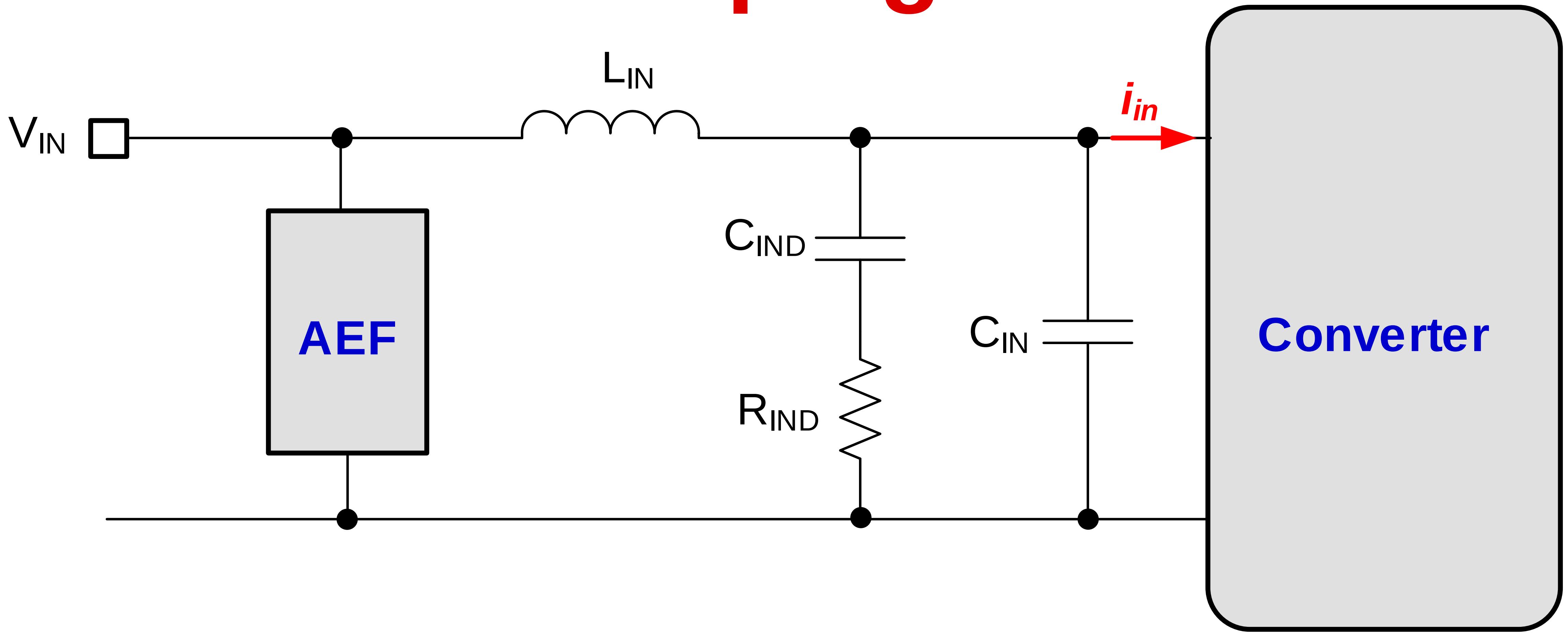
EMI filtering: Active EMI filter Compensations

- Loop has two crossovers to compensate
- Two compensations:
  - Feedback compensation (AEFC)
  - Input compensation (INC)
- R_{AEFDC} and C_{AEFC} set LF crossover
  - Gain could cross 0 dB close to 180º of phase
- R_{INC} and C_{INC} set HF-crossover
  - Provides phase boost at high-frequency
  - C_{INJ} parasitics limit SRF ~20 MHz





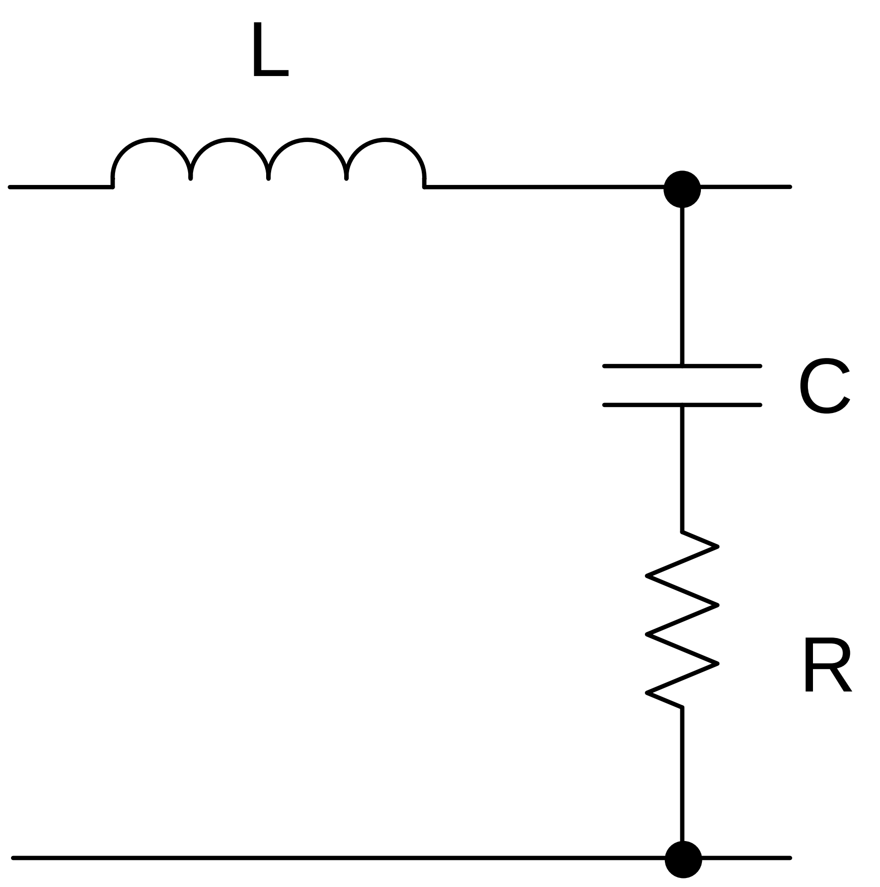
Why do we need damping?

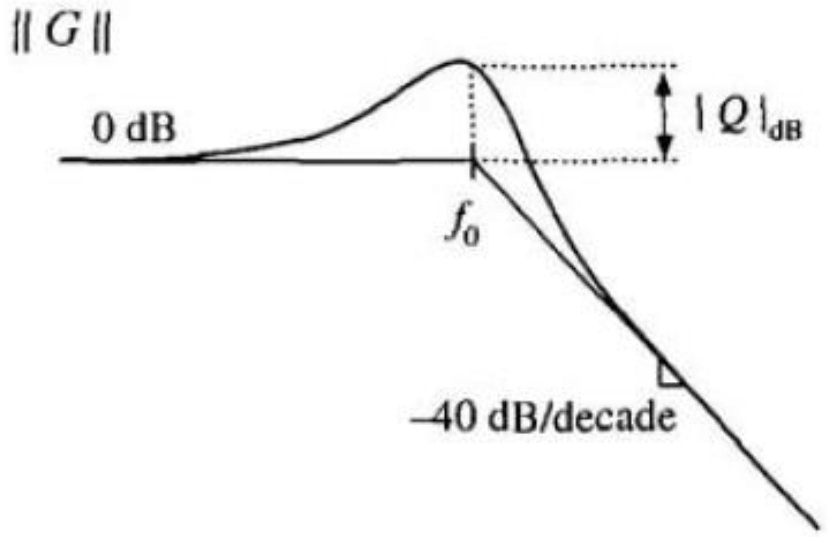


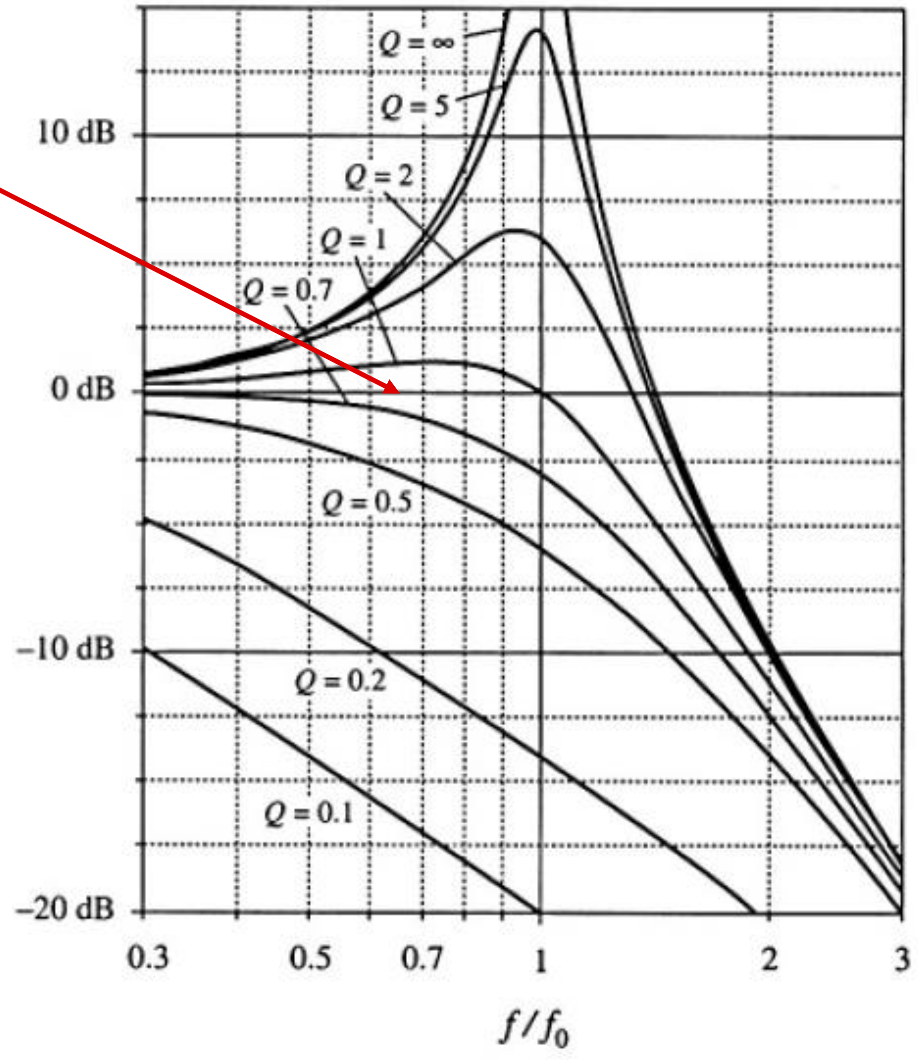
- Jitter, transients, or any other perturbation can cause an undamped response on an L-C filter.
- C_{IN} and L_{IN} can resonate from regulator perturbations. A damping capacitor, C_{IND}, with ESR or resistor R_{IND}, is in parallel with C_{IN} for damping.
- AEF can be purely capacitive and resonate with L_{IN} if undamped. This may cause saturation and increased power loss.

Damping basics

For the filter to be damped against resonance,
we need a Q between 0.7 to 1.0.



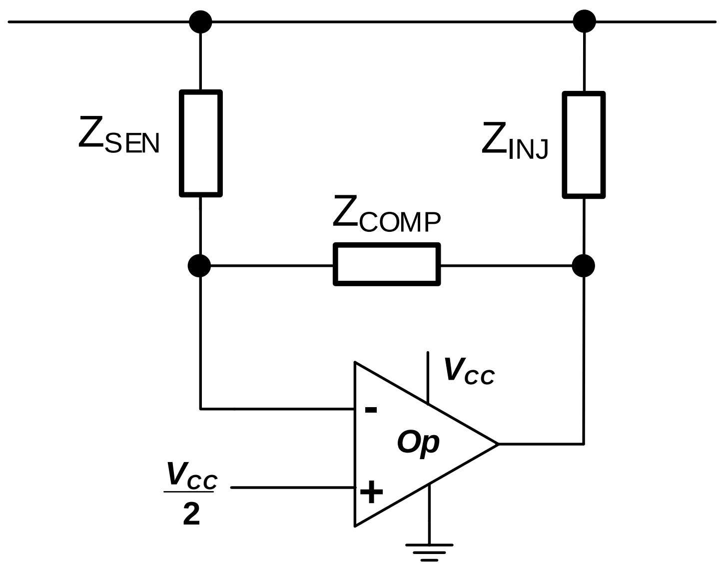




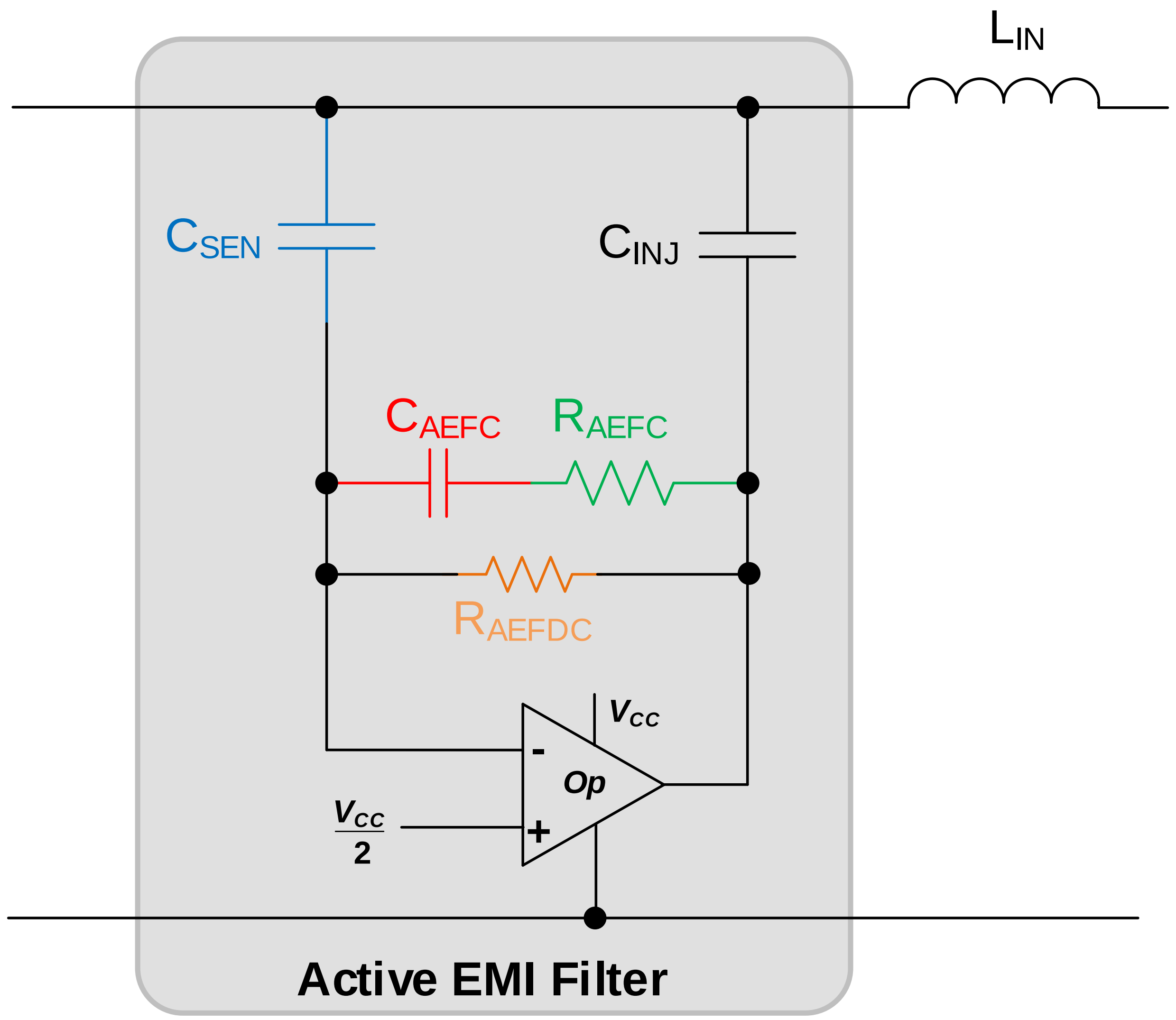
$$Q = \frac{1}{R}\sqrt{\frac{L}{C}}$$

Quality factor

AEF undamped response



$$G_{Op} = \frac{Z_{COMP}}{Z_{SEN}}$$



$$G_{Op} = \frac{(Z_{CAEFC} + Z_{RAEFC}) \,||\, Z_{RDC}}{Z_{CSEN}}$$

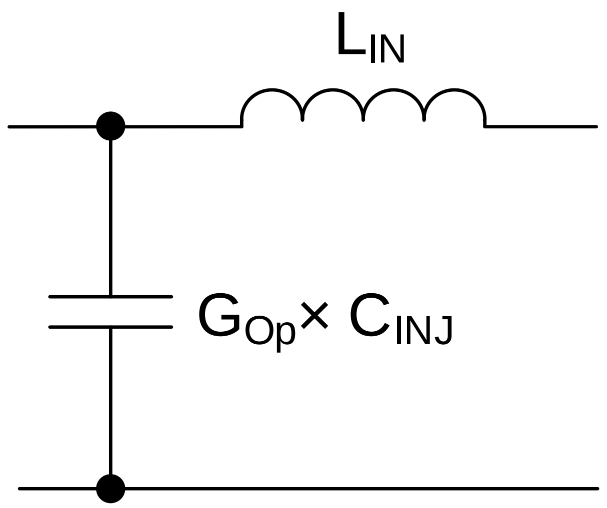
$$\approx \frac{Z_{CAEFC} + Z_{RAEFC}}{Z_{CSEN}} \approx \frac{Z_{CAEFC}}{Z_{CSEN}} \approx \frac{C_{SEN}}{C_{AEFC}}$$

$$R_{DC} \gg Z_{AEFC}$$

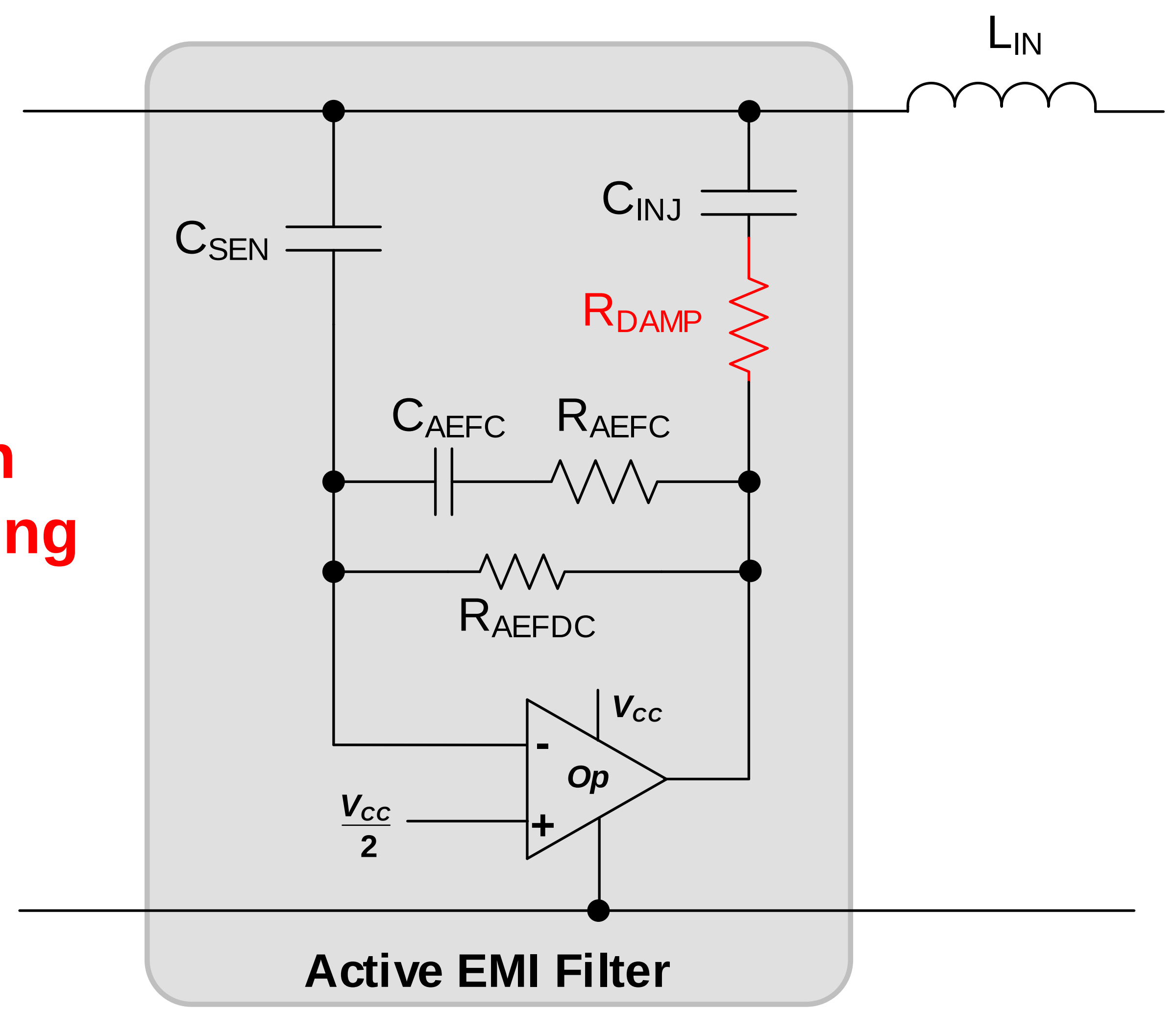
$$Z_{CAEFC} \gg Z_{RAEFC}$$

$$Z_{EQ} = \frac{Z_{CINJ}}{G_{Op}} = \frac{1}{sC_{INJ}G_{Op}}$$

(equivalent to a $G_{Op} \times C_{INJ}$ capacitor)



Damping method 1 (series damping)

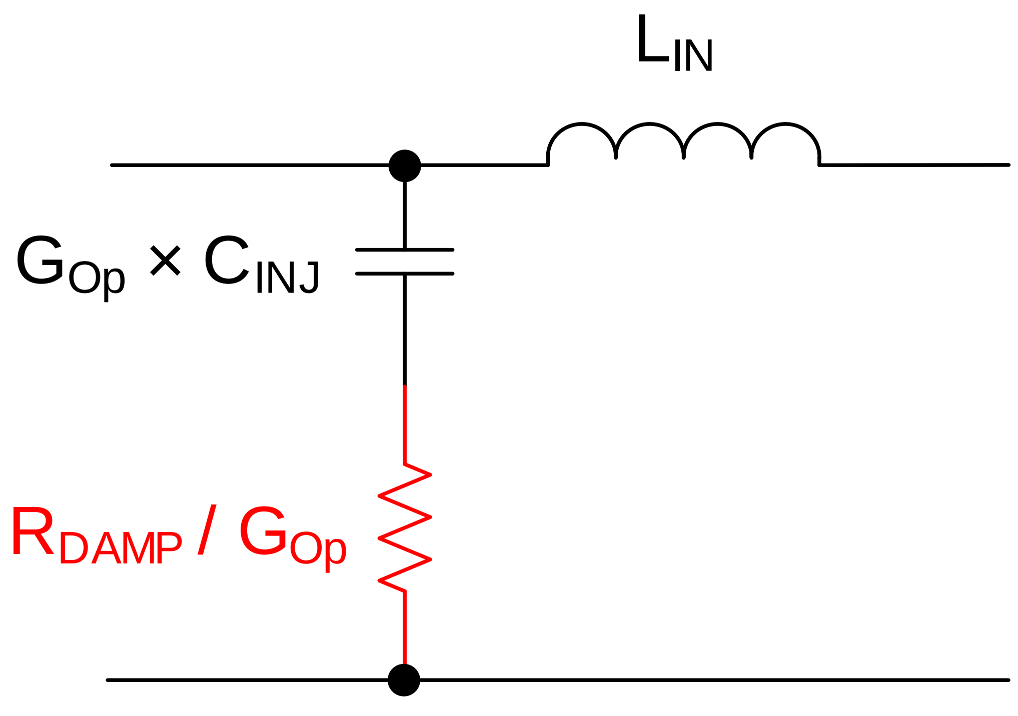


With damping

Equivalent impedance with series damping:

$$Z_{EqDamped} = \frac{Z_{RDAMP} + Z_{CINJ}}{G_{Op}}$$

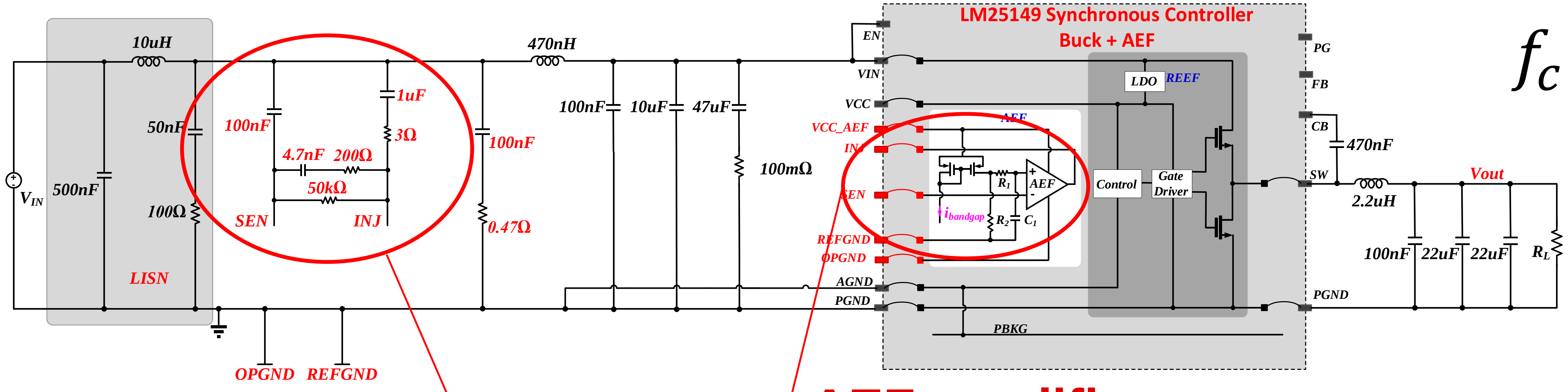
$$= \frac{R_{DAMP}}{G_{Op}} + \frac{1}{sC_{INJ}G_{Op}}$$



Low-frequency equivalent circuit with damping

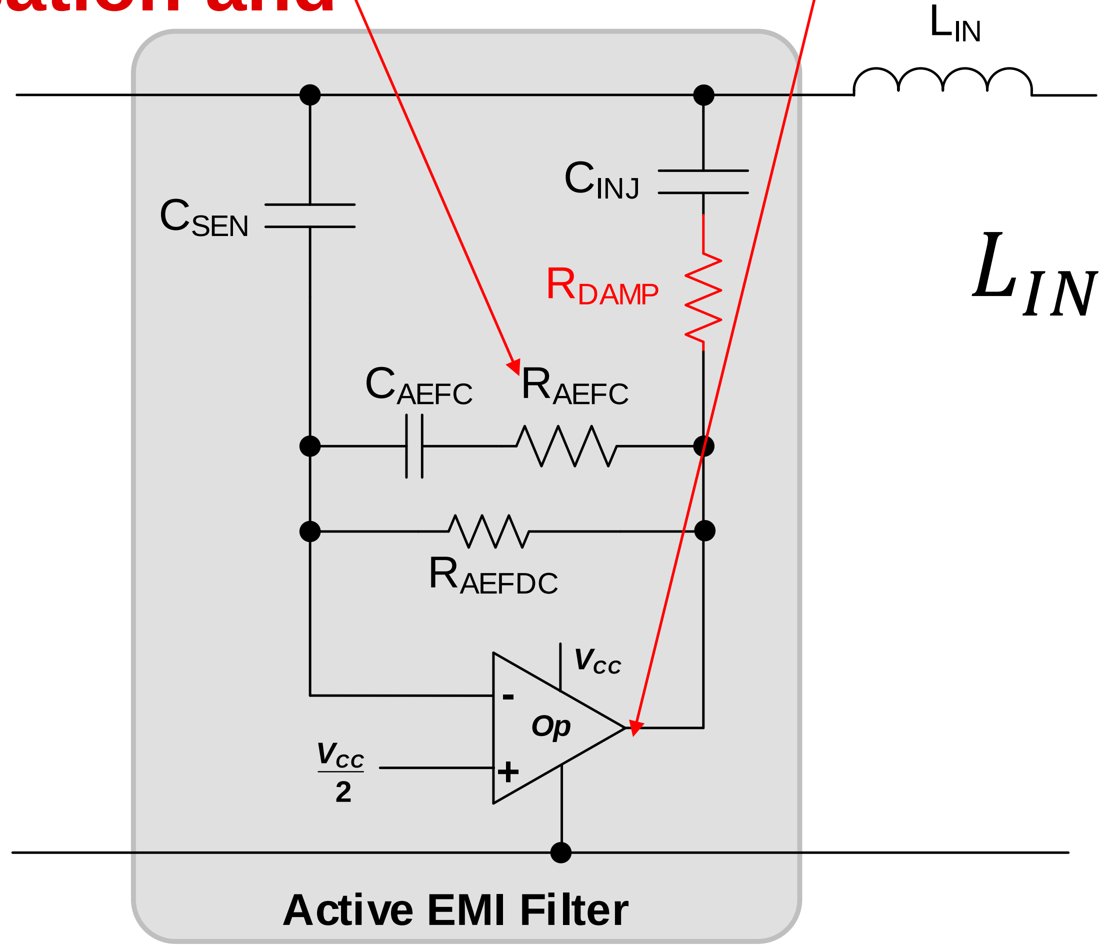
$$Q = \frac{1}{R}\sqrt{\frac{L}{C}} = 1,\ R = \sqrt{\frac{L}{C}} \Rightarrow \frac{R_{DAMP}}{G_{Op}} = \sqrt{\frac{L_{IN}}{C_{INJ} \cdot G_{Op}}} \Rightarrow R_{DAMP} = \sqrt{\frac{L_{IN} \cdot G_{Op}}{C_{INJ}}}$$

Damping method 1 example, f_{SW} = 2 MHz



Compensation and damping

AEF amplifier



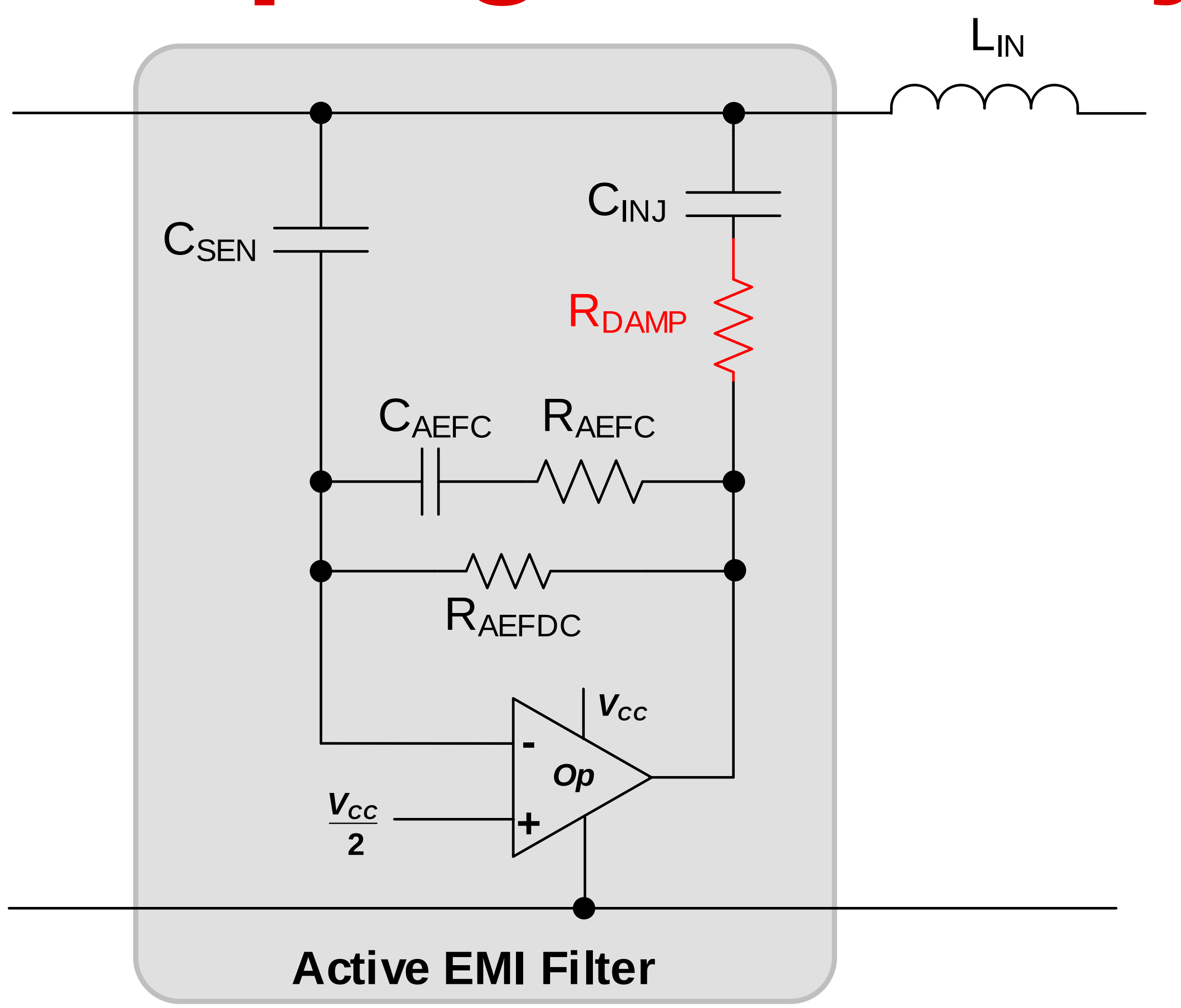
$$f_c = \frac{f_{SW}}{10^{|Att|/40}} = \frac{2\text{ MHz}}{10^{|60|/40}} = 63\text{ kHz}$$

$$G_{Op} \approx \frac{C_{SEN}}{C_{AEFC}} = \frac{100\,nF}{4.7\,nF} = 21$$

$$L_{IN}C_{INJ} = \frac{1}{G_{Op}(2\pi f_c)^2} = \frac{1}{21(2\pi * 63\text{ kHz})^2} = 304\ [\text{nH}\cdot\mu\text{F}]$$

$$R_{DAMP} = \sqrt{\frac{G_{Op}\cdot L_{IN}}{C_{INJ}}} = \sqrt{\frac{21\cdot 470\,nH}{1\,\mu F}} = 3.1\,\Omega$$

Series damping summary



$$f_c = \frac{f_{sw}}{10^{|Att|/40}}$$

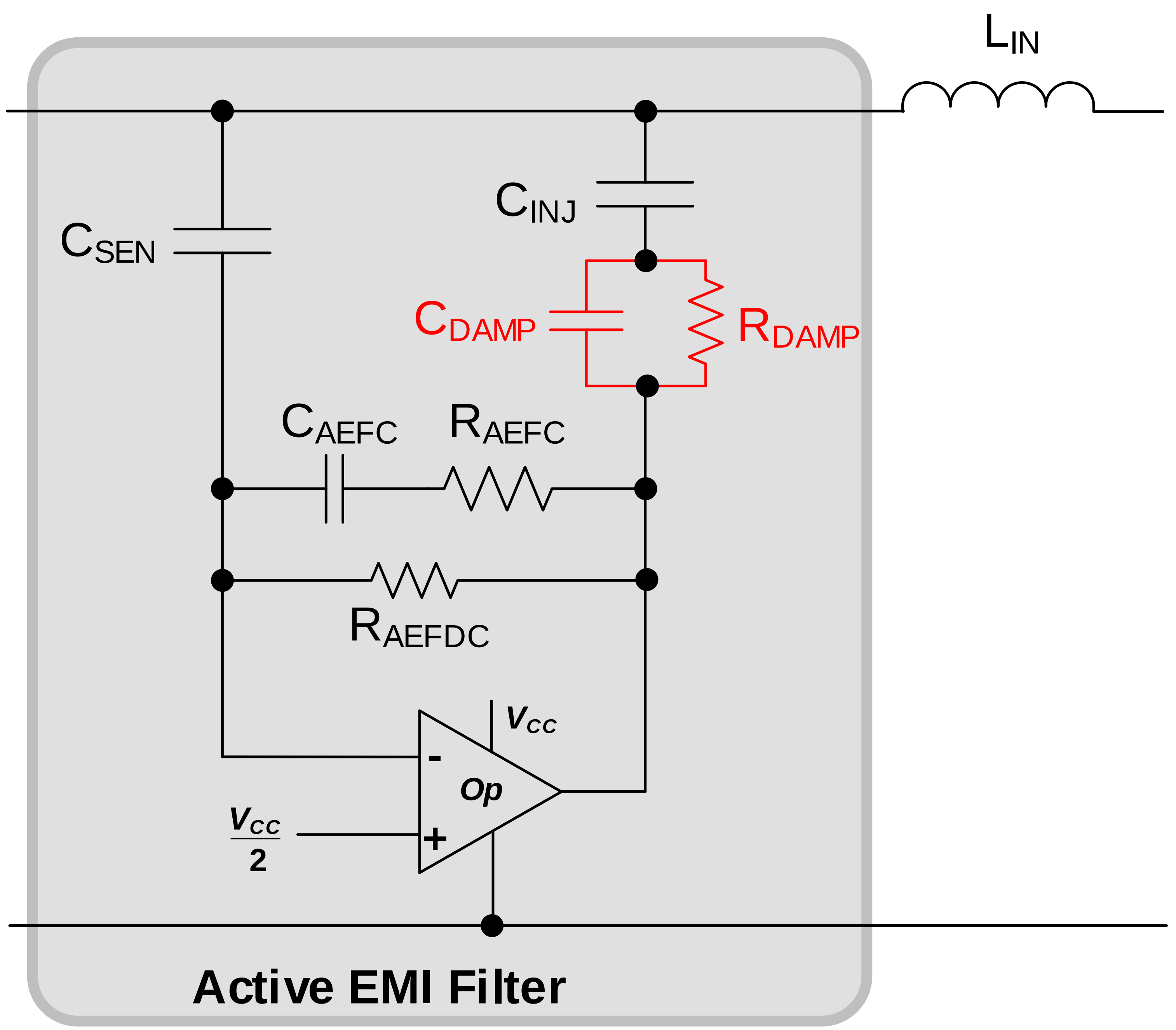
$$G_{Op} \approx \frac{C_{SEN}}{C_{AEFC}}$$

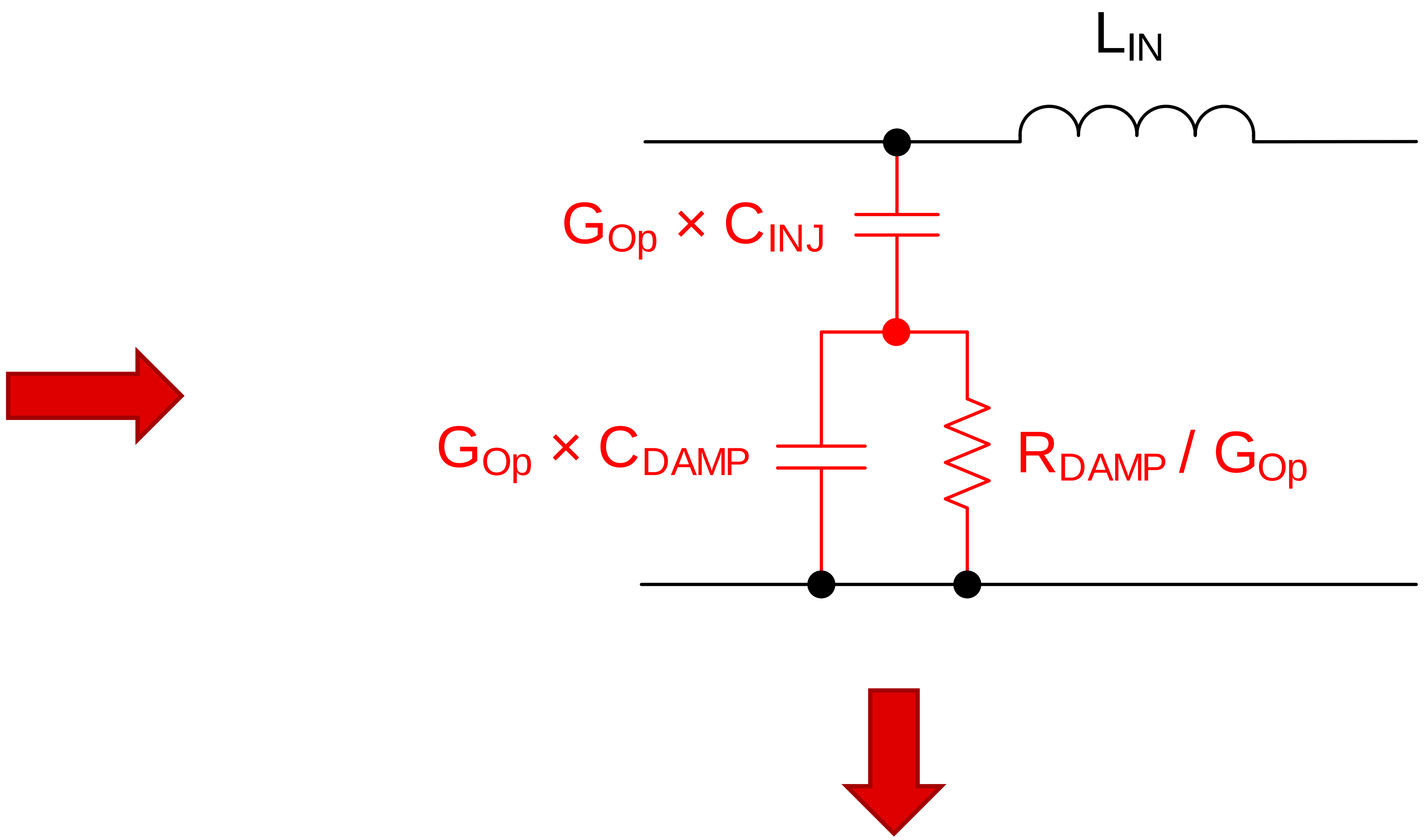
$$L_{IN} C_{INJ} = \frac{1}{G_{Op}(2\pi f_c)^2}$$

$$R_{DAMP} = \sqrt{\frac{G_{Op} \times L_{IN}}{C_{INJ}}}$$

- Damping method 1 is simple
- G_{Op} acts like a capacitive multiplier
- This method can be applied for ~2MHz f_{SW}
- Other damping methods can be used for lower switching frequency

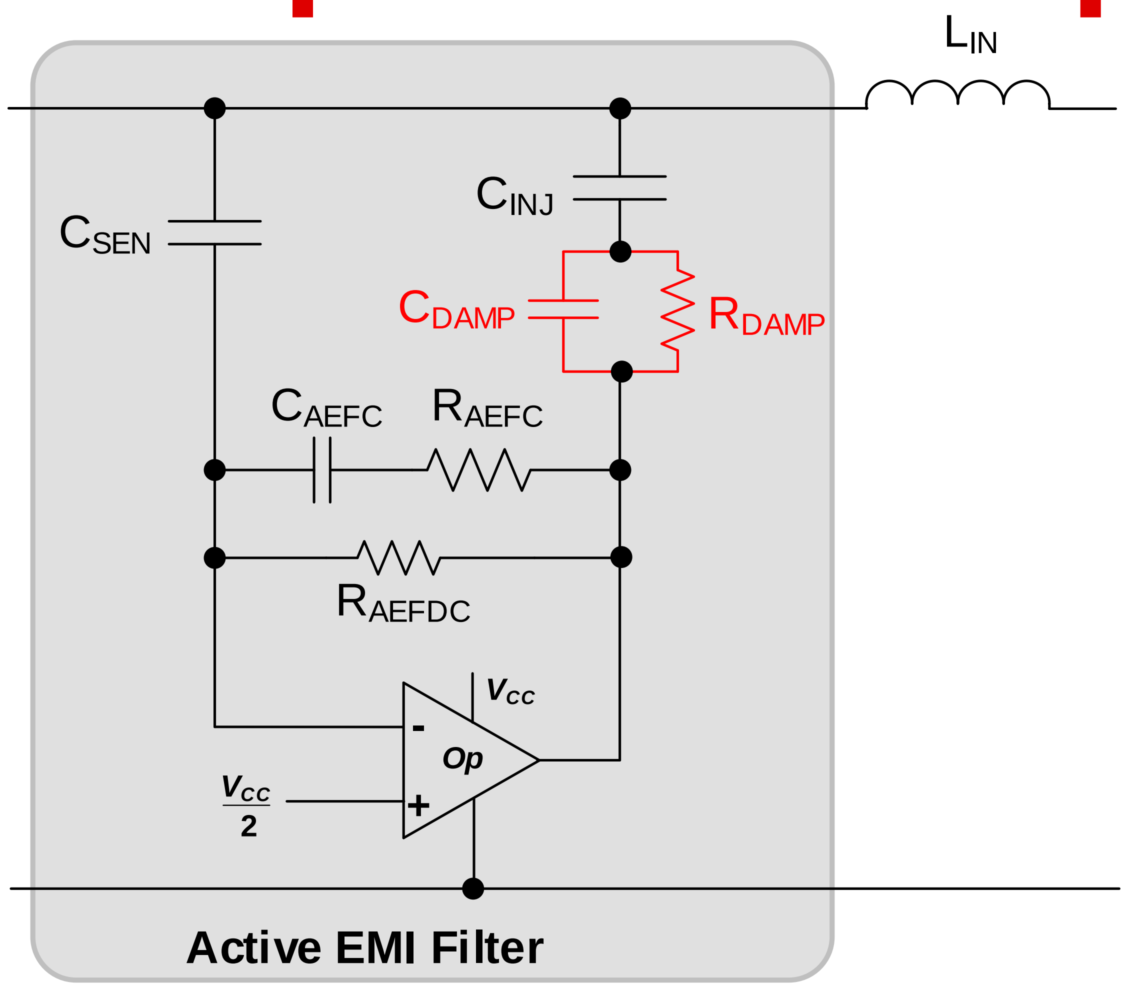
Damping method 2 – parallel capacitor (440 kHz)





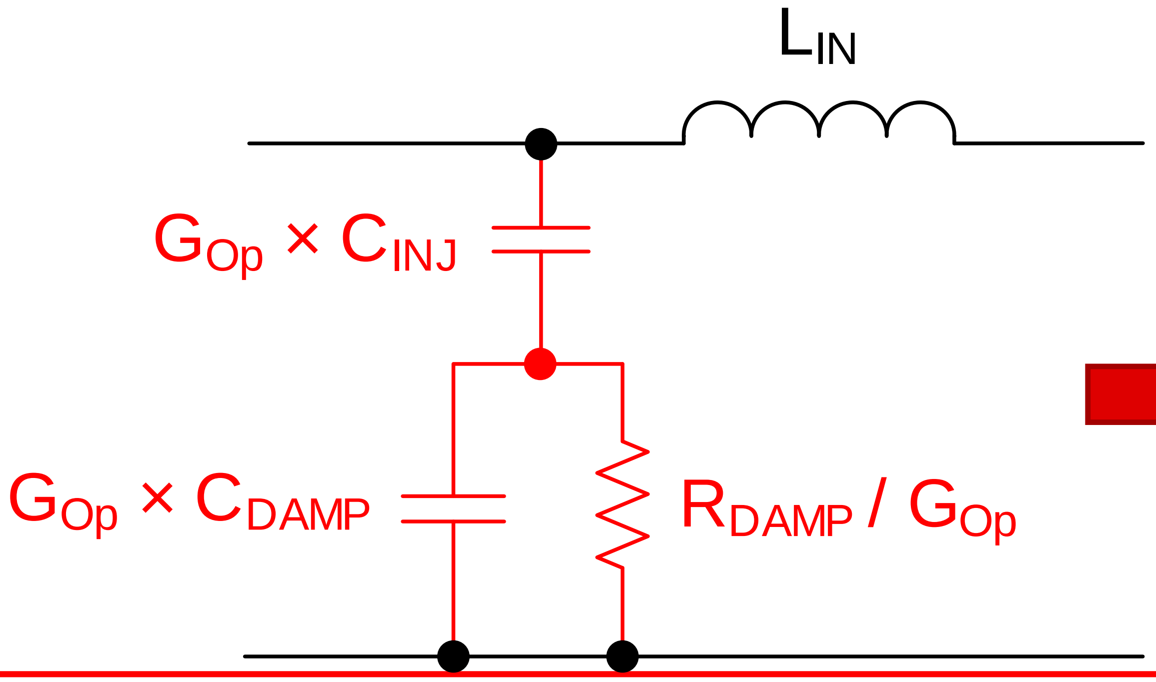
Third-order system, the optimal point for R_{DAMP} needs to be found

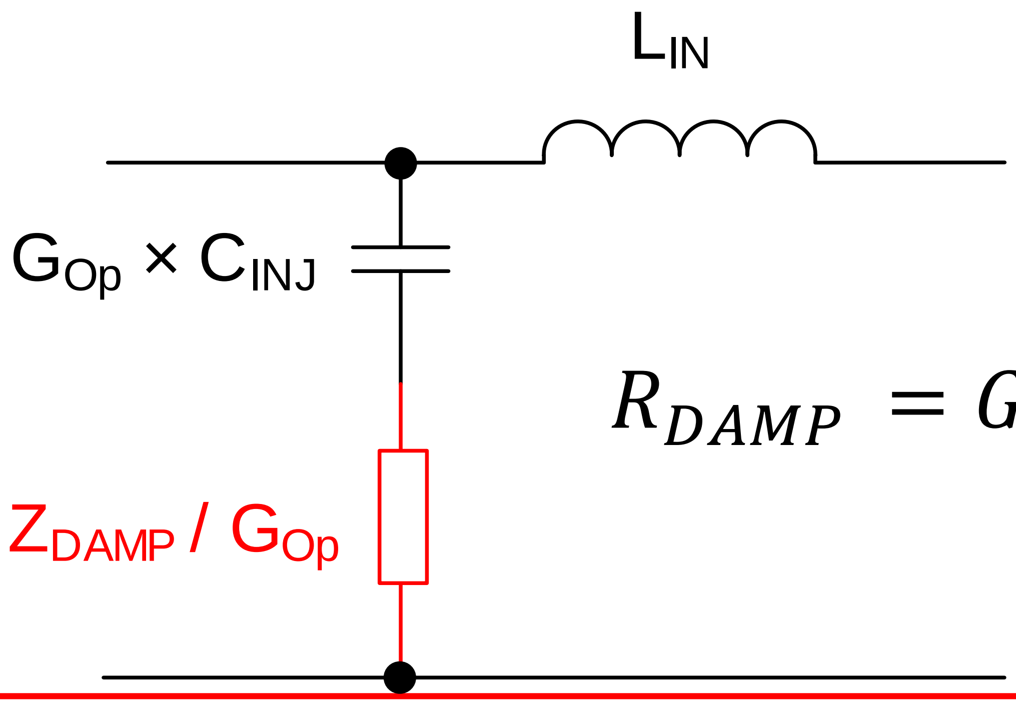
AEF optimal damping for a third-order system



$$Z_{DAMP} = \frac{1}{\sqrt{\left(\frac{1}{R_{DAMP}}\right)^2 + (2\pi f_{SW} \cdot C_{DAMP})^2}}$$

$$Z_{DAMP} = \sqrt{\frac{L_{IN}}{G_{Op} \cdot C_{INJ}}}$$

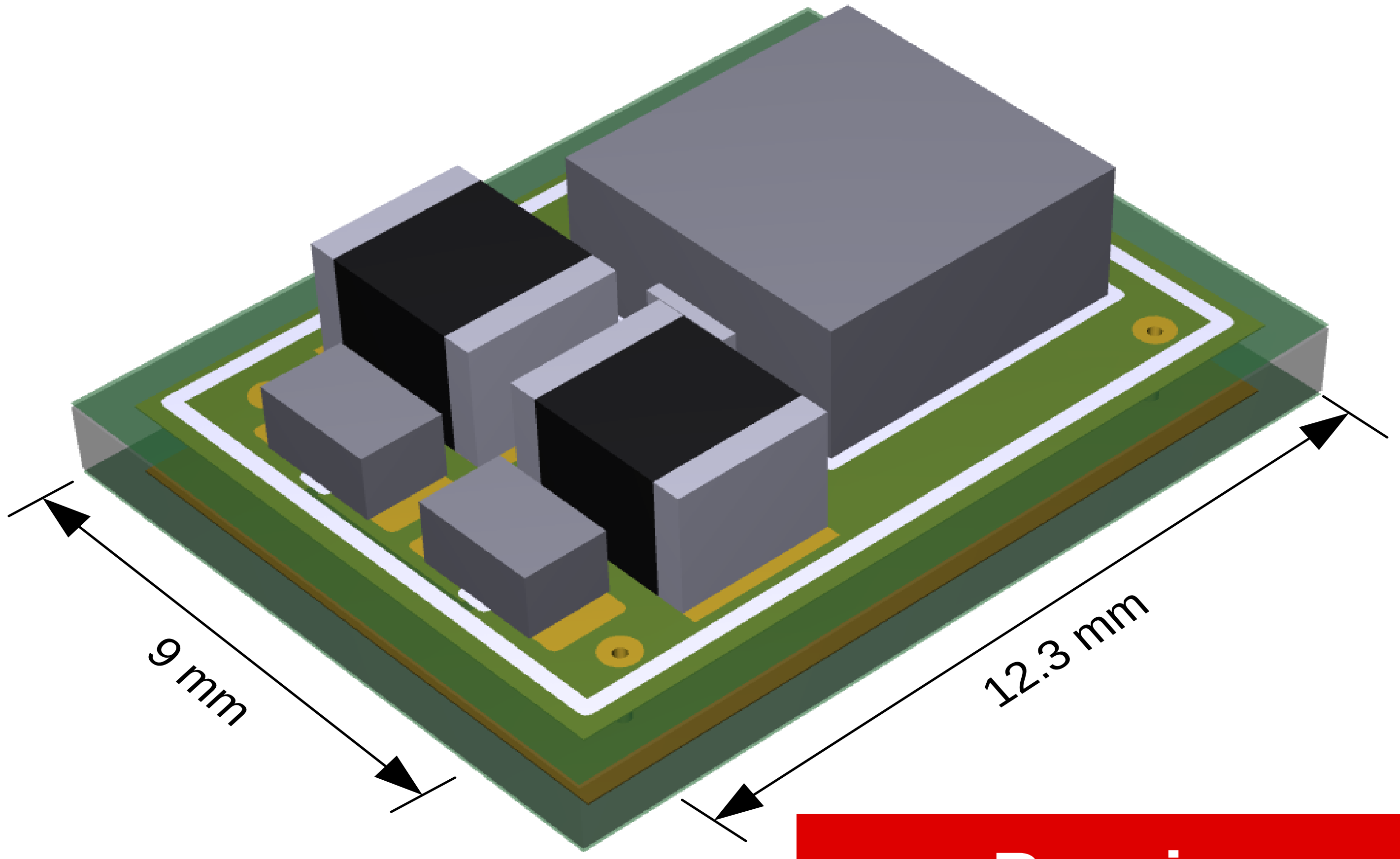


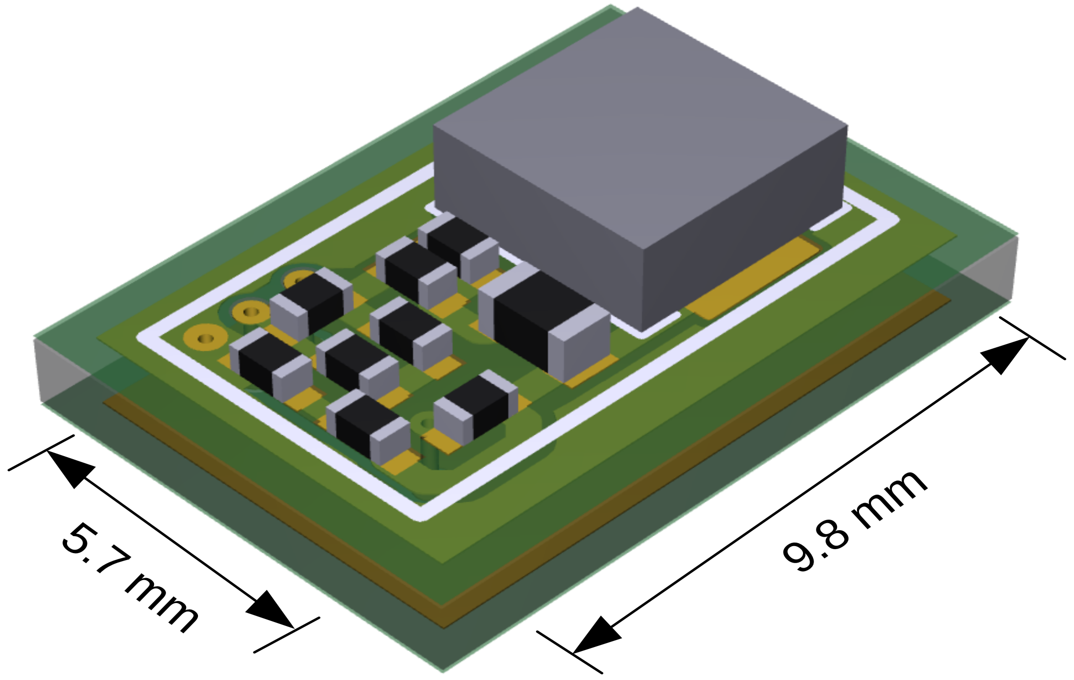


$$R_{DAMP} = G_{Op} \sqrt{\frac{L_{IN}}{G_{Op} \cdot C_{INJ} - (2\pi f_{SW} \cdot C_{DAMP})^2}}$$

Passive vs active filter optimized layouts

- Traditional passive layout (left) uses a taller inductor and larger capacitors.
- Active EMI filter (right) uses smaller and cheaper components with improved filter performance.





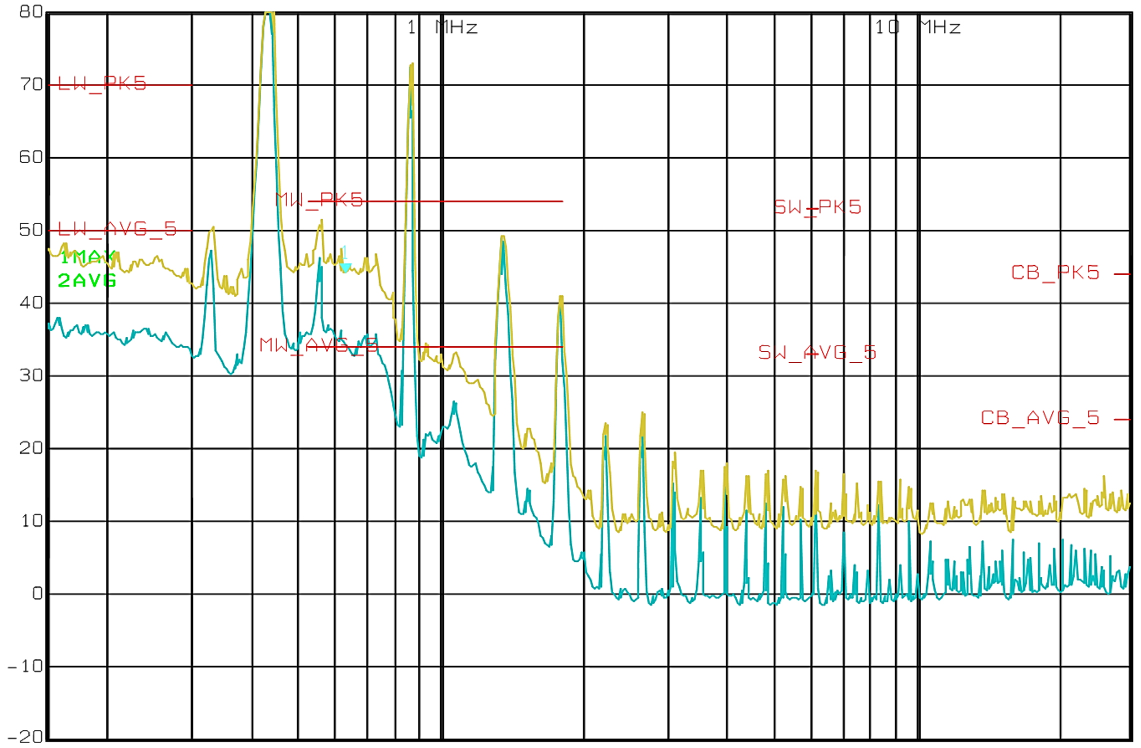
Passive	Active
110 mm^2	56 mm^2
$2.71*	$1.70*

*as of April 2021

Passive vs active CISPR 25 results comparison

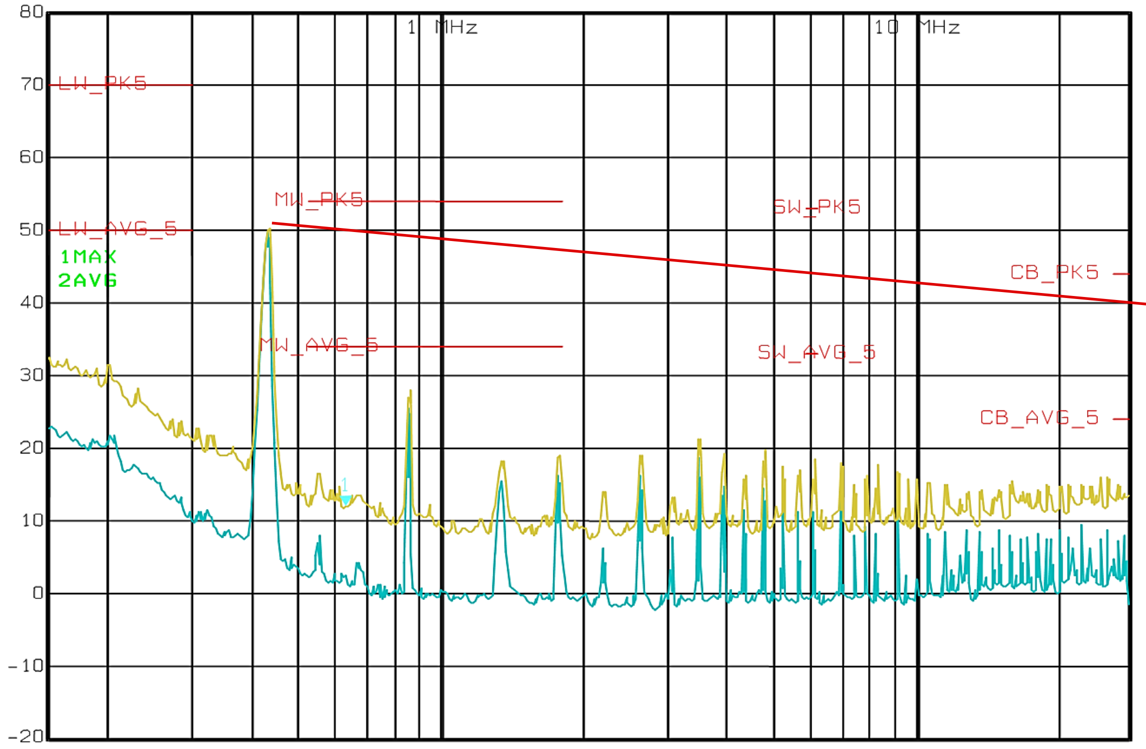
V_{IN} = 13.5 V, V_{OUT} = 5 V, I_{OUT} = 5 A F_{SW} = 440 kHz

No EMI filter



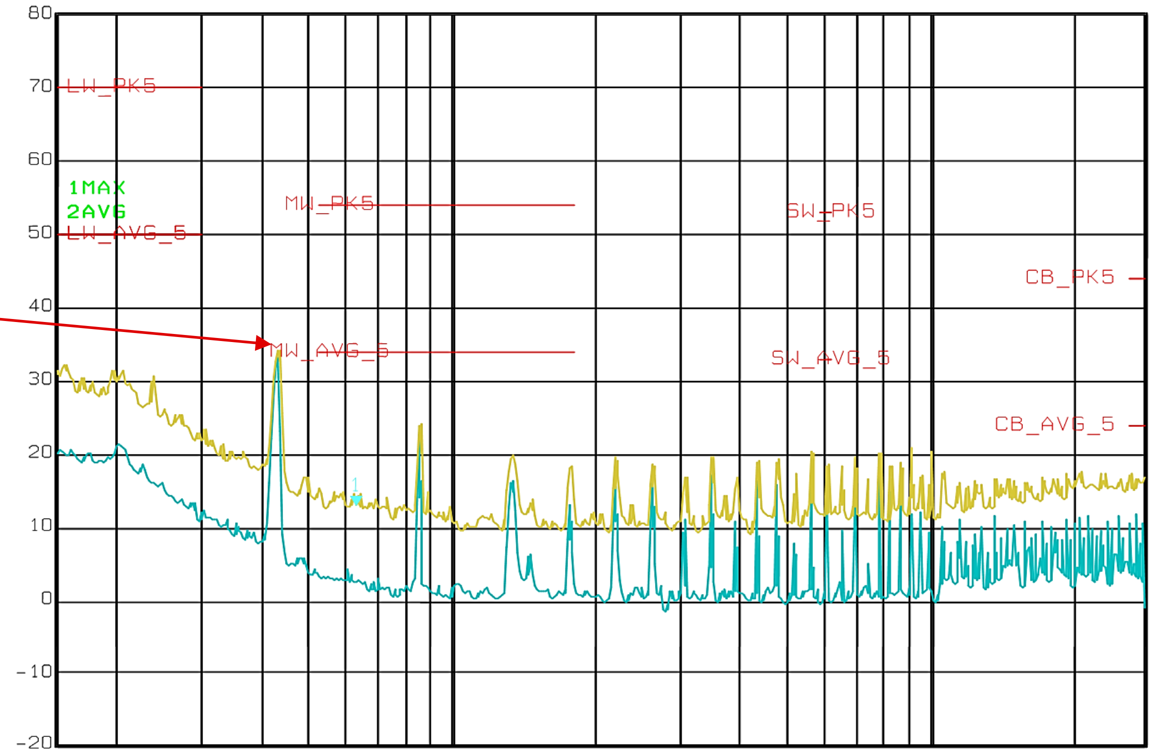
Passive EMI filter

L_{IN} = 2.2 µH, C_F = 2 x 10 µF



Active EMI filter

L_{IN} = 1 µH, C_{INJ} = 0.47 µF



Start: 150 kHz

CISPR 25 Class 5 peak

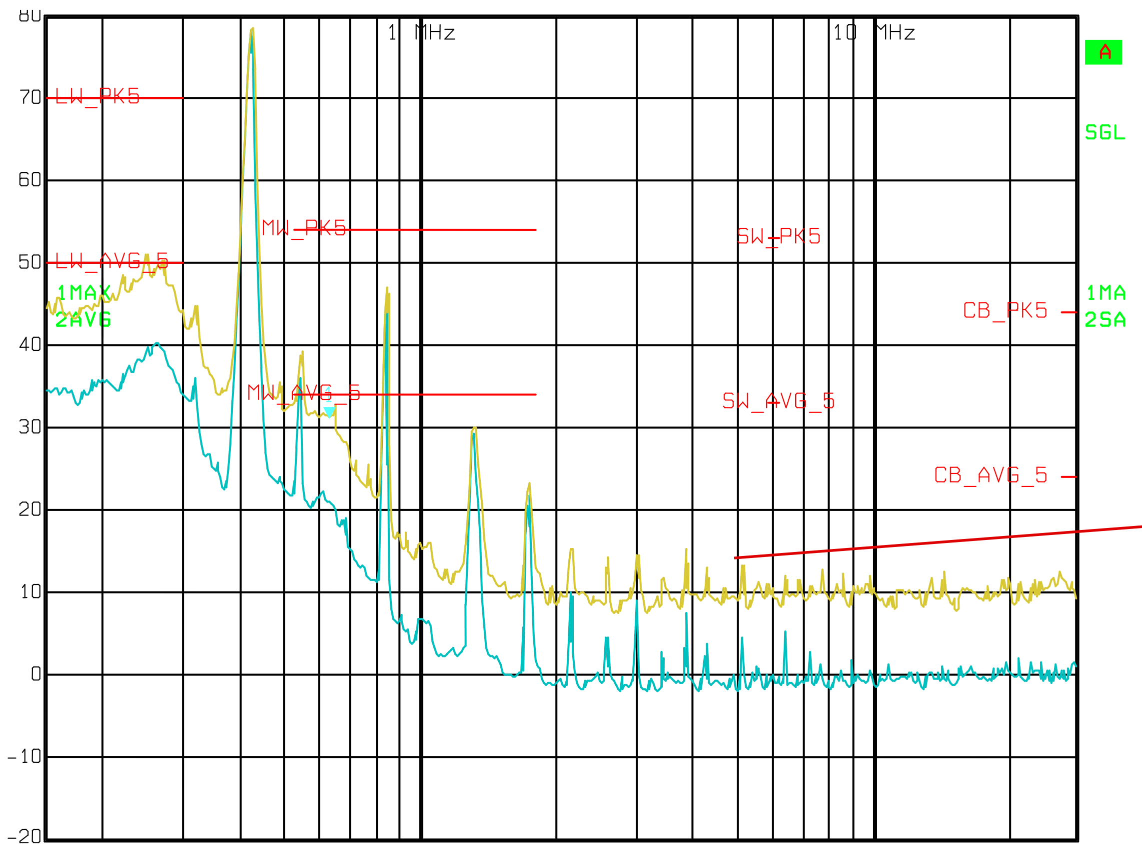
CISPR 25 Class 5 average

Stop: 30 MHz

EMI filtering: Active EMI filter components

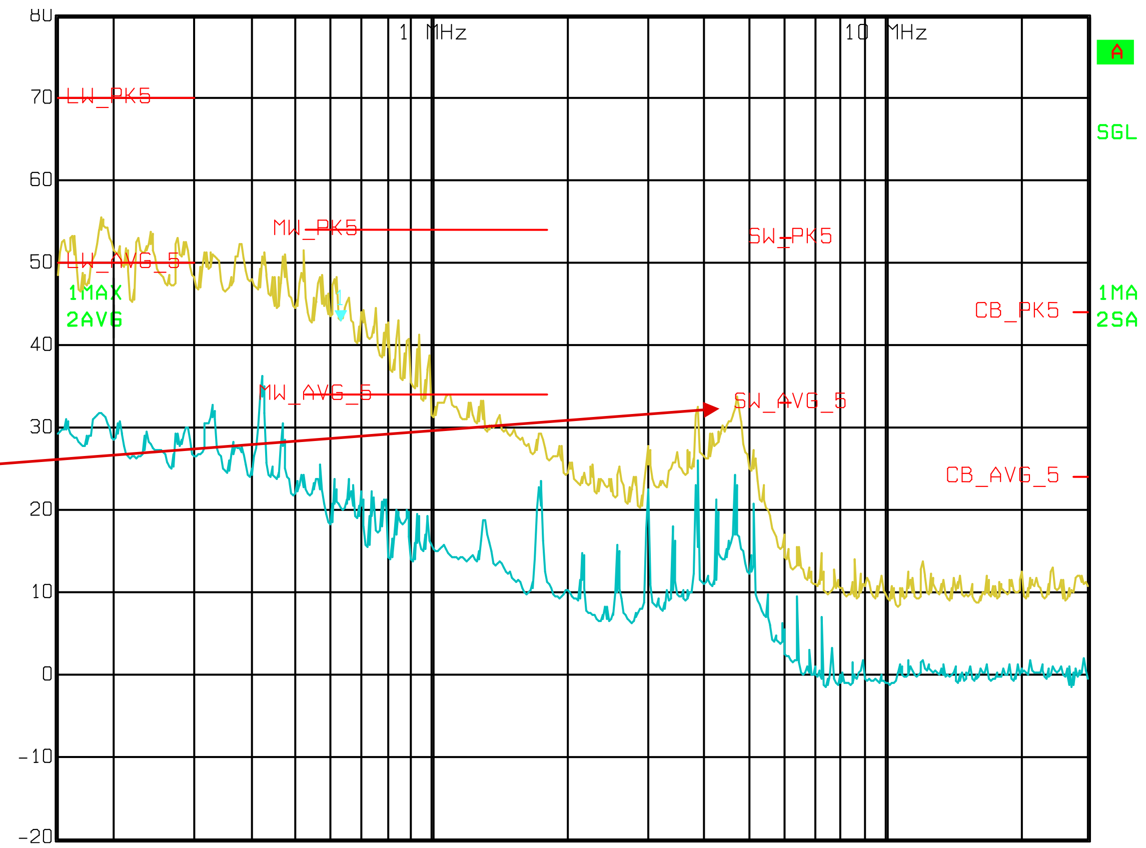
- Poorly selected AEF components can negatively impact EMI:
  - C_{INJ} with SRF **<u>5 MHz</u>** caused resonance (*less than system loop crossover of 20 MHz*).
    - Use a HF crossover **lower** than the SRF of active EMI components

AEF disabled



Start: 150 kHz
CISPR 25 Class 5 peak
CISPR 25 Class 5 average
Stop: 30 MHz

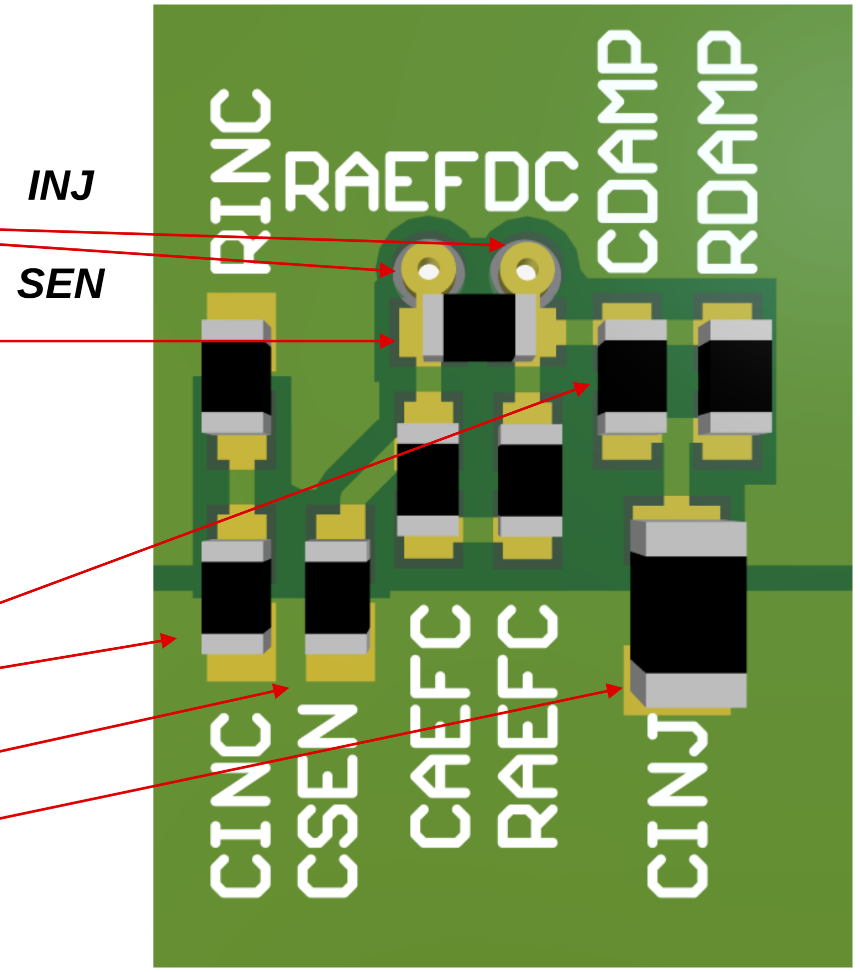
AEF enabled with poor components



Start: 150 kHz
CISPR 25 Class 5 peak
CISPR 25 Class 5 average
Stop: 30 MHz

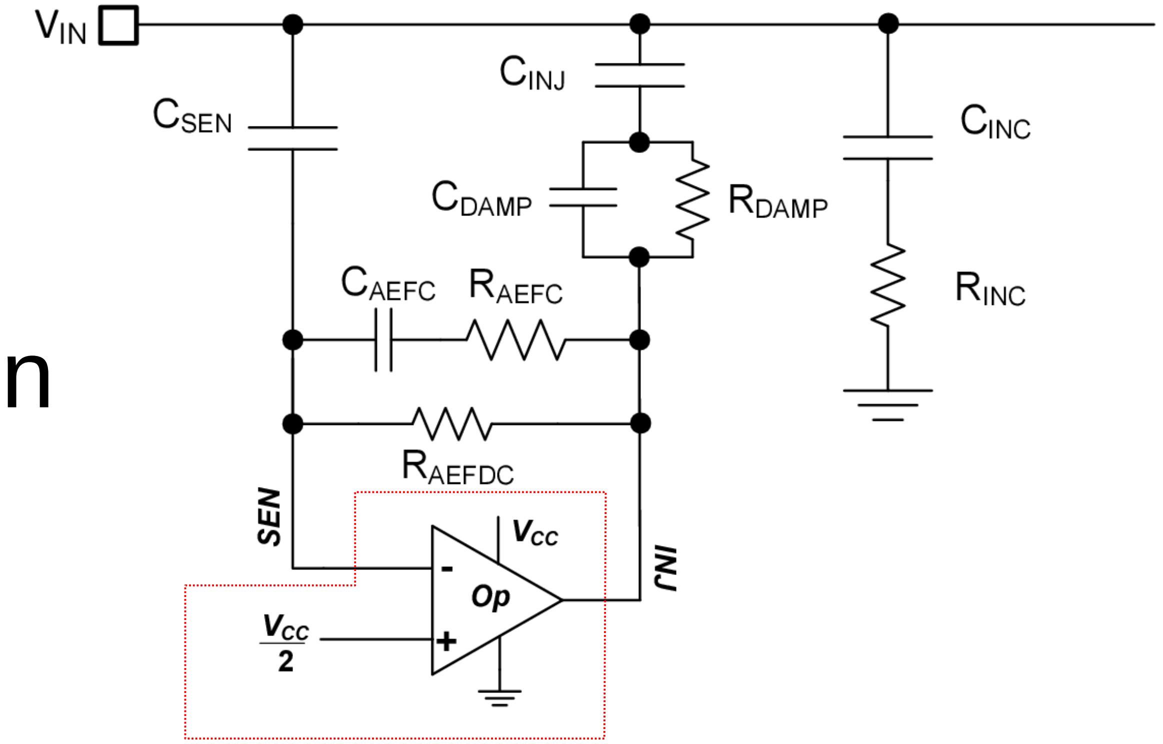
EMI filtering: AEF layout and other considerations

- Route SEN and INJ traces differentially
- Place R_{AEFDC} at SEN and INJ vias
  - Place C_{AEFC} and R_{AEFC} to form tight loop
- C_{DAMP} & R_{DAMP} close to AEF compensation *(AEFC)*
- R_{INC} and C_{INC} away from noisy ground
- C_{SEN} close to AEF compensation
- C_{INJ} close to damping



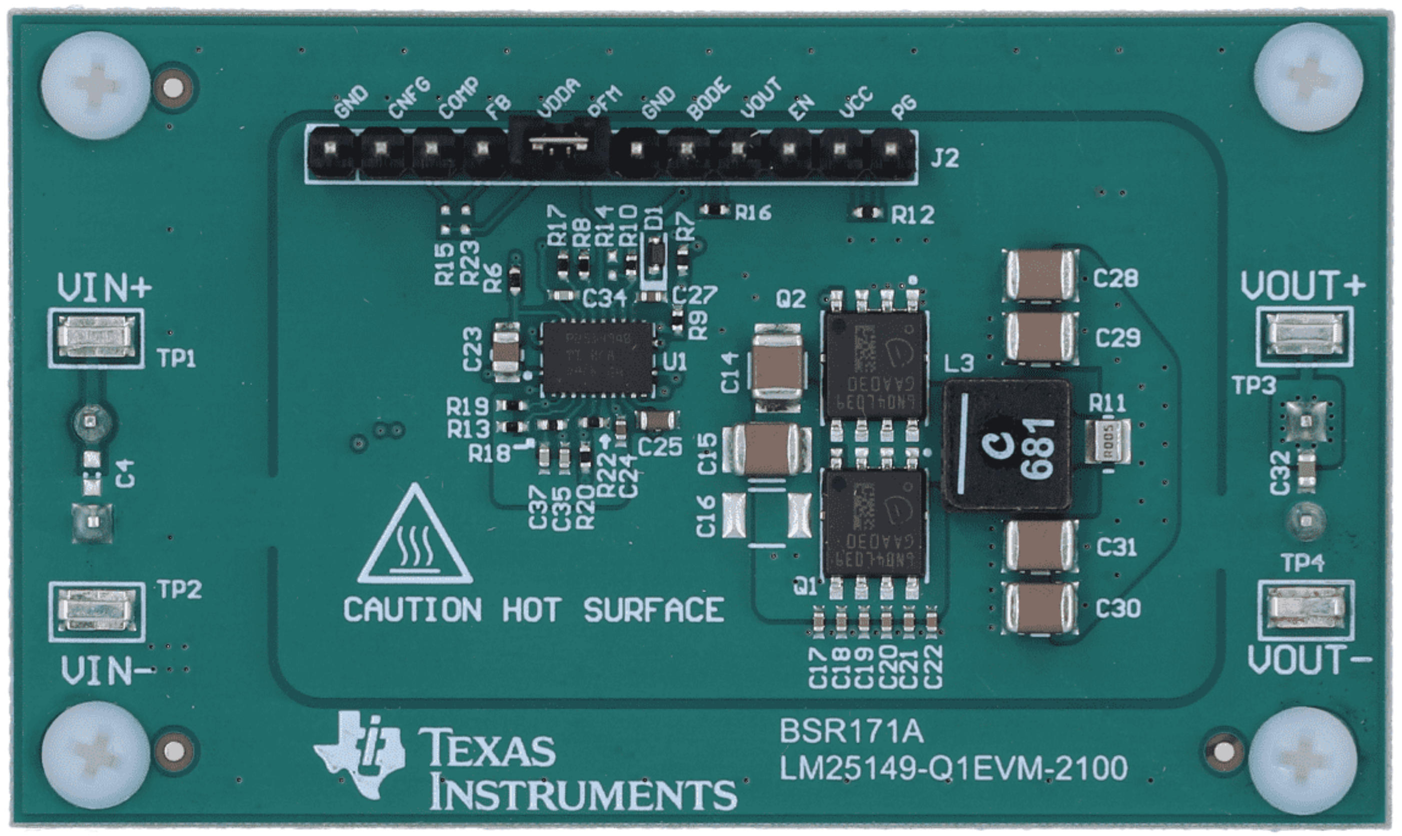
At the Op-amp / IC:

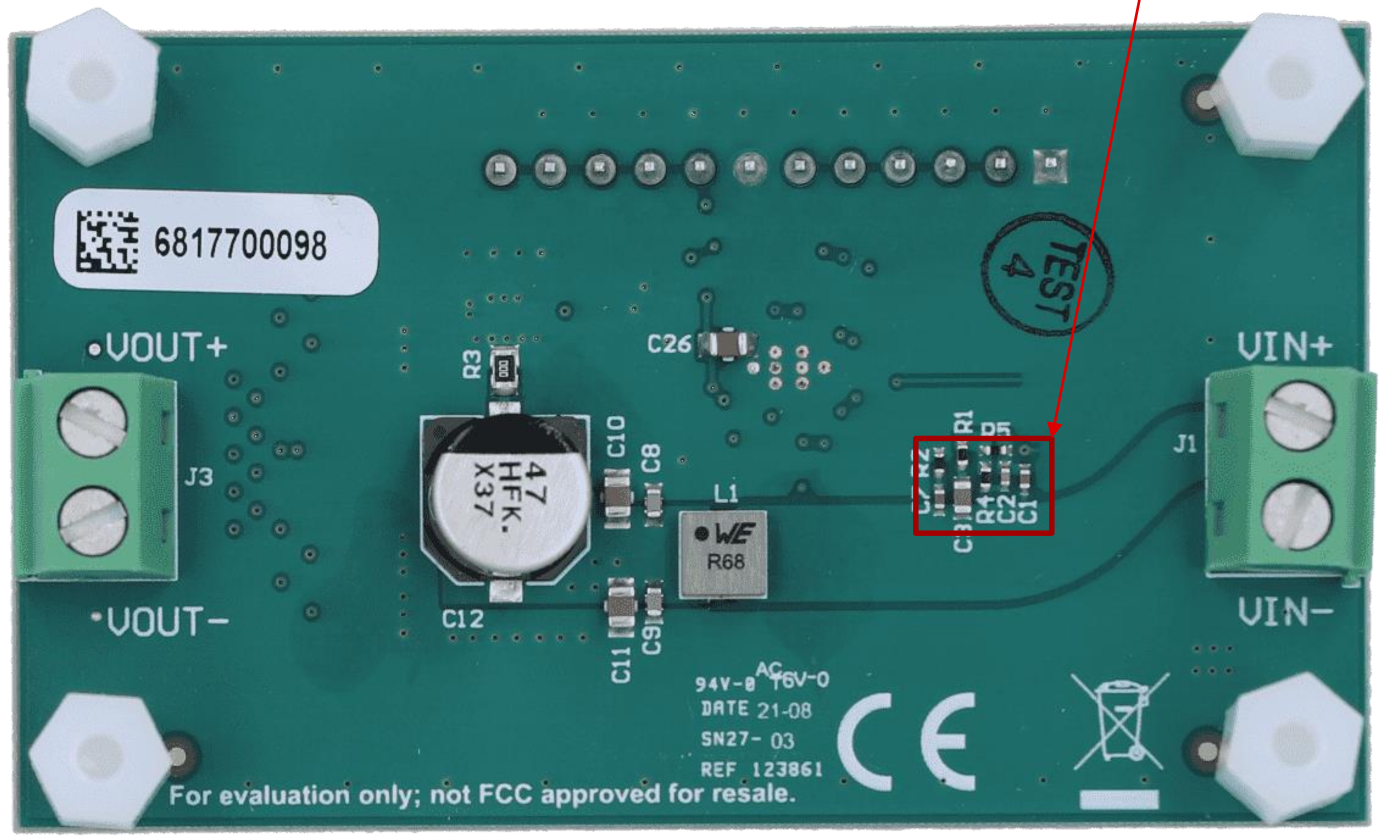
- AEF amplifier VCC decoupling capacitor close to pin
- AEF amplifier AVSS grounded on quiet ground



LM25149-Q1EVM-2100 Buck controller with AEF

- LM25149-Q1EVM-2100 evaluation board uses LM25149-Q1 synchronous buck controller with integrated AEF.





Summary

- EMI can cause unwanted interference between electronics
- EMI filters are typically used to mitigate EMI
- EMI filters take cost and size, and come with limitations
- Active EMI filter uses an op-amp as an active capacitor
- AEF compensation
- AEF damping
- Results
- Layout guidelines

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