FR-PM-5 - EMI/EMC for Power Electronics Systems

Design of Compact Active EMI Filters to Reduce the CM Conducted Emissions

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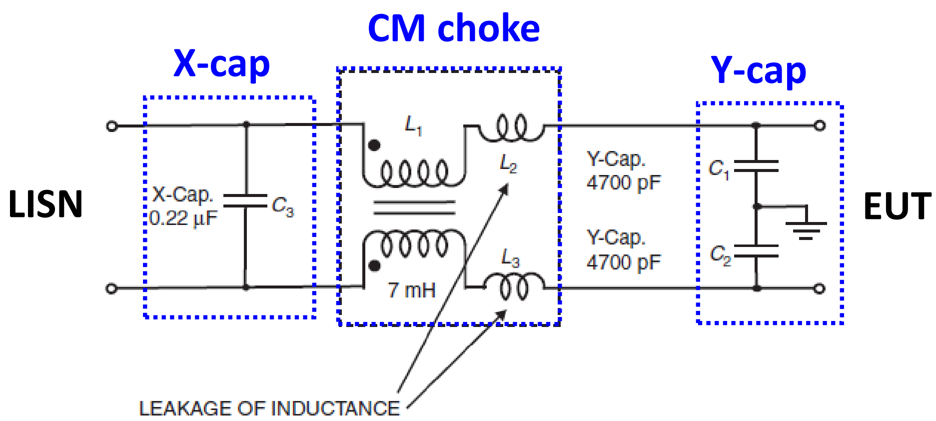
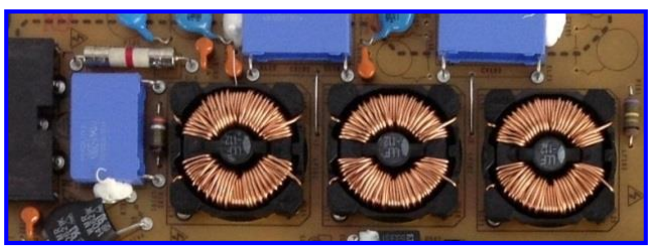
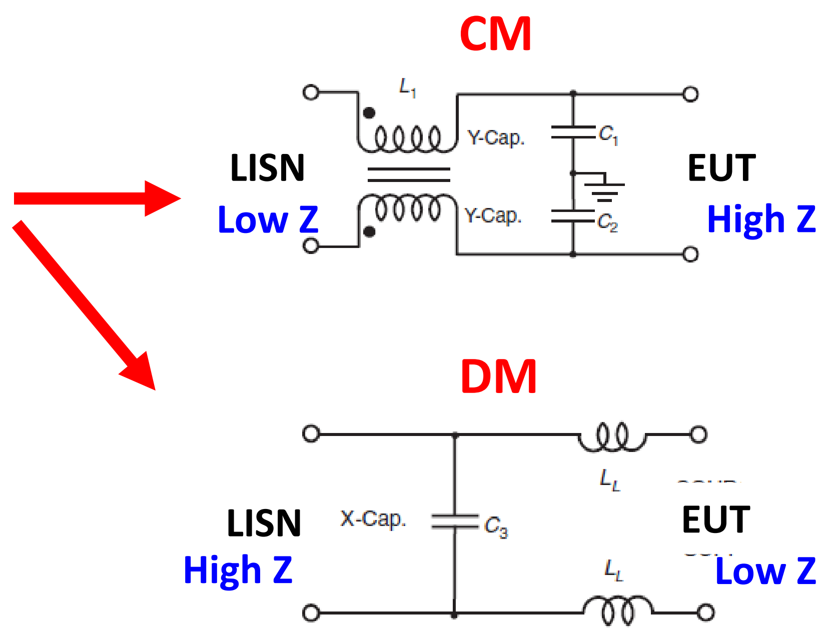
Outline

- Introduction
- Feed-Forward Voltage-sense Voltage-compensation (FF-VSVC) AEF
- Voltage-sense Current-compensation (VSCC) AEF
- Other types AEFs
- Conclusion

A Passive EMI Filter for both CM and DM







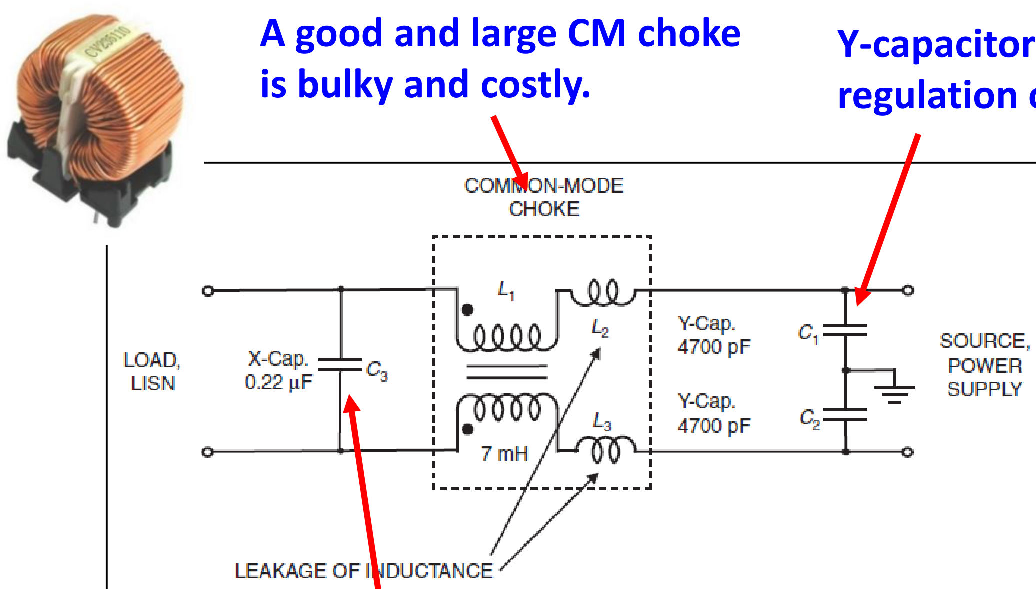
- A typical passive EMI filter consists of a X-cap, CM choke, and Y-cap.
- The leakage inductance of CM choke can be used as the DM inductance.
- Each filter generates a large impedance mismatching.

[ref] H. W. Ott, Electromagnetic Compatibility Engineering, 2009, Wiley

Limitation in a Passive CM EMI Filter

A good and large CM choke is bulky and costly.

Y-capacitor is limited by the safety regulation on leakage currents.

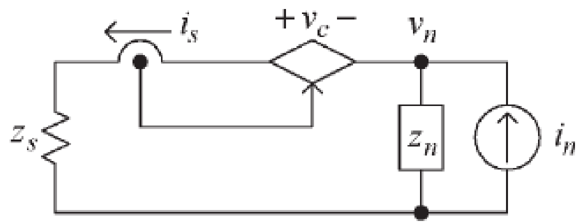


Attenuation of DM noise by using X-cap is relatively easier.

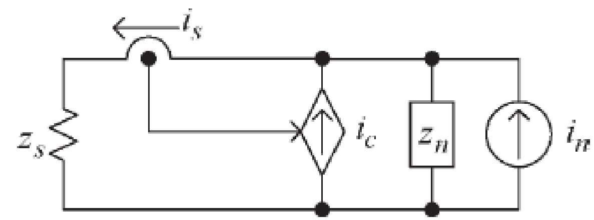
- For sufficient CM noise reduction, the passive EMI filter with a large CM choke, a large Y-capacitor, or multi-stage filters are necessary.
- Active EMI filters (AEFs) employing active circuit components are also proposed to reduce the low-frequency CM noise in a compact-size and low-cost.

Topologies of Active EMI Filter (AEF)

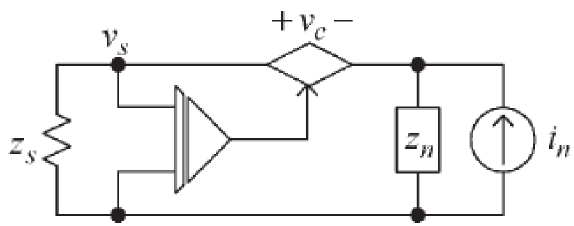
Feed-back



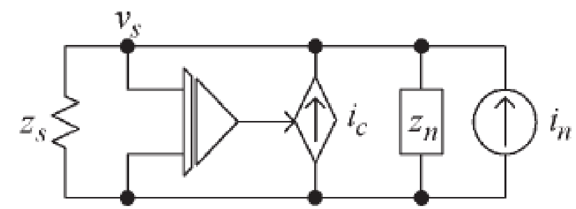
Current-sense Voltage-compensation



Current-sense Current-compensation

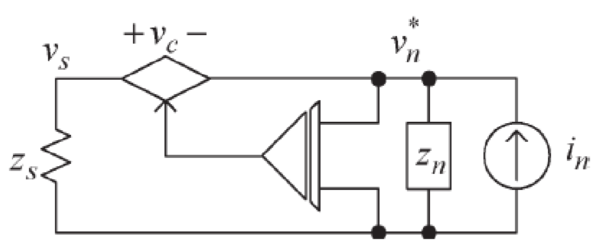


Voltage-sense Voltage-compensation

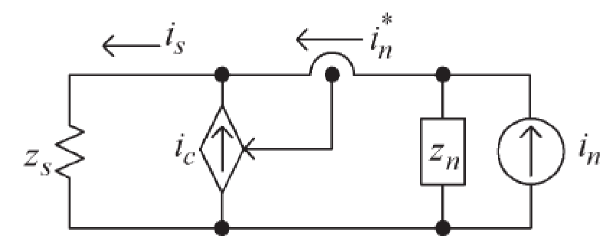


Voltage-sense Current-compensation

Feed-forward



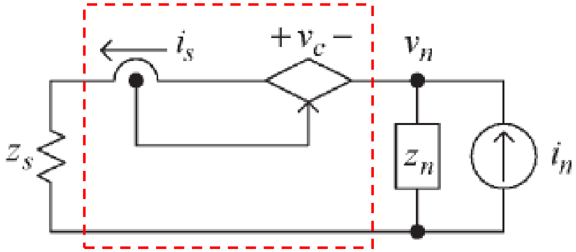
Voltage-sense Voltage-compensation



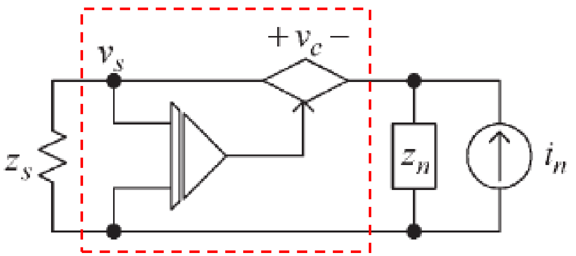
Current-sense Current-compensation

[ref] Y. Son, S. Sul, "Generalization of active filters for EMI reduction and harmonics compensation," *IEEE Trans. Ind. Appl.*, vol.42, no.2, pp.545-551, March./April 2006

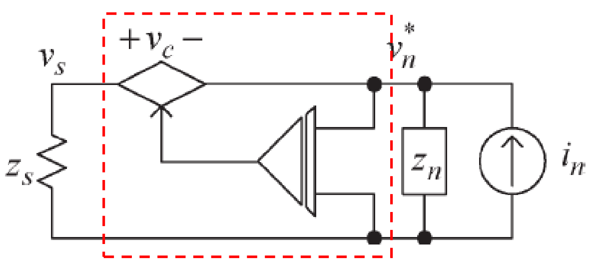
Voltage-Compensation AEFs



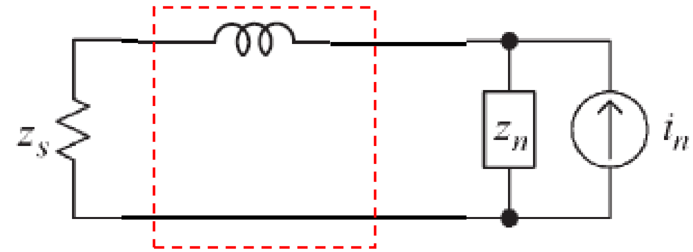
Current-sense Voltage-compensation



Voltage-sense Voltage-compensation

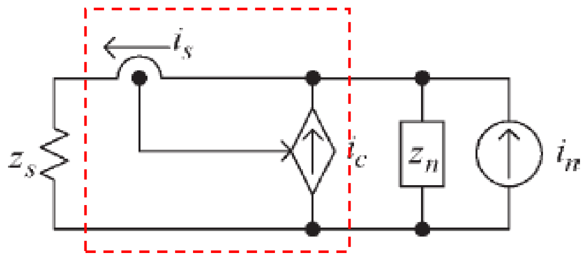


Voltage-sense Voltage-compensation

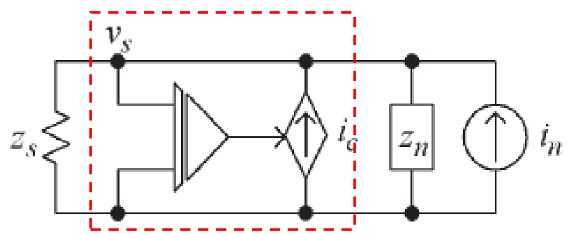


- The voltage-compensation AEFs behave as a series impedance, such as a CM choke.
- It should be used with other passive filter components.

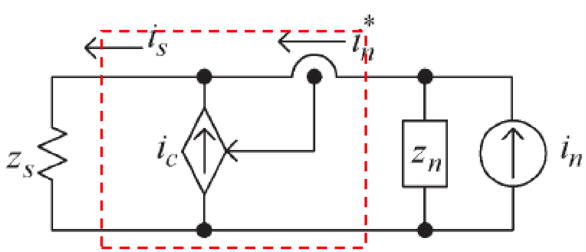
Current-Compensation AEFs



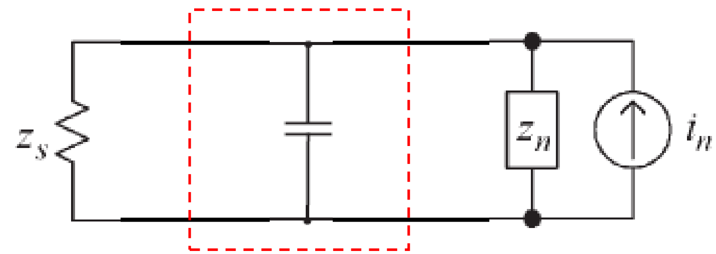
Current-sense Current-compensation



Voltage-sense Current-compensation



Current-sense Current-compensation



- The voltage-compensation AEFs behave as a shunt impedance, such as a Y-cap.
- It should be used with other filter components.

Critical Issues in applying AEF to AC lines

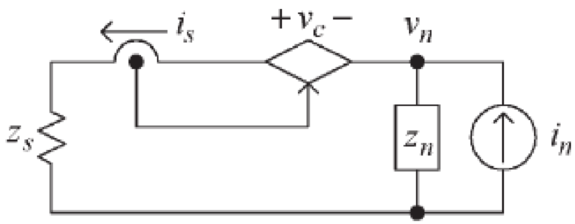
- Immunity against high voltage transient (e.g. surge)
  - Protection circuits are required, but it should not affect the performance

- Power supply generation for AEF
  - A DC voltage for AEF can be separately made, but it increases cost and size.
  - A proper DC voltage is usually available from a gate switching control board.

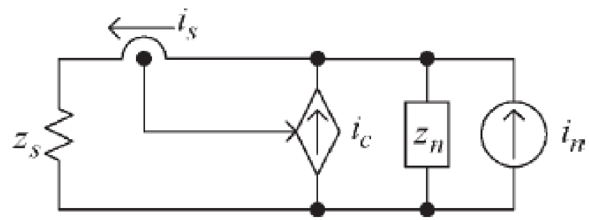
- Stability in the target applications
  - Because AEF should be used with other filter components, the stability condition depends on the condition of filter and EUT.

(AEF Type 1) : FF-VSVC AEF

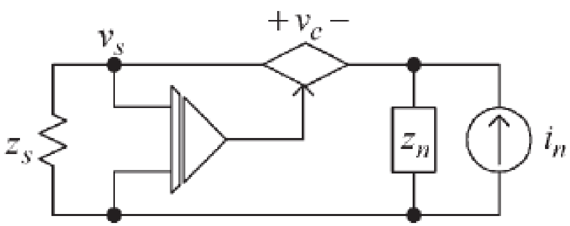
Feed-back



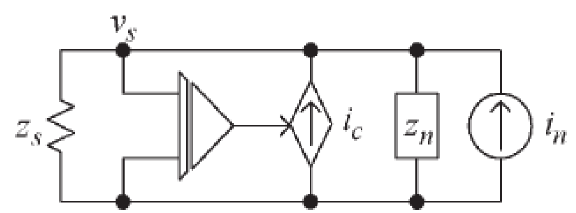
Current-sense Voltage-compensation



Current-sense Current-compensation

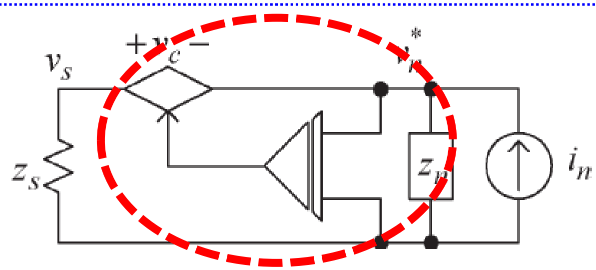


Voltage-sense Voltage-compensation

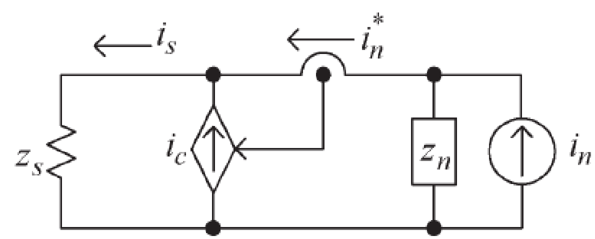


Voltage-sense Current-compensation

Feed-forward



Voltage-sense Voltage-compensation

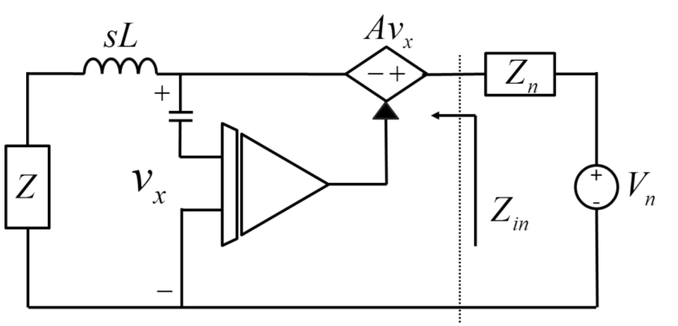


Current-sense Current-compensation

- Dongil Shin, et al., and Jingook Kim, "Analysis and Design Guide of Active EMI Filter in a Compact Package for Reduction of Common-Mode Conducted Emissions", IEEE Trans on EMC, vol. 57, no. 4, pp. 660-671, Aug. 2015.

Two Types of VSVC AEF

Feed back type



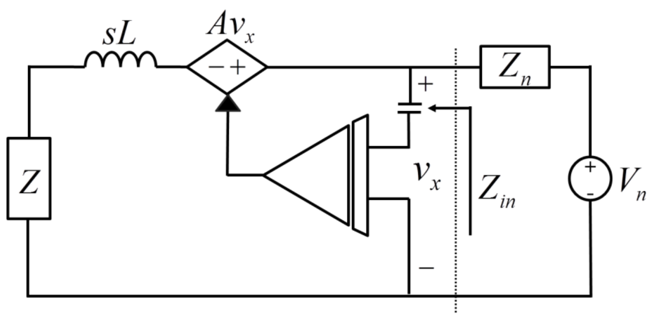
Input Impedance	$Z_{in} = (1+A)(Z+sL)$
Impedance Boosting	$1+A$
Noise Attenuation	$\frac{Z_n + (1+A)(sL+Z)}{Z+sL+Z_n}$

The attenuation performance increases with the voltage gain (A).

➔ High turn ratio transformer required

➔ High Gain amplifier required

Feed forward type



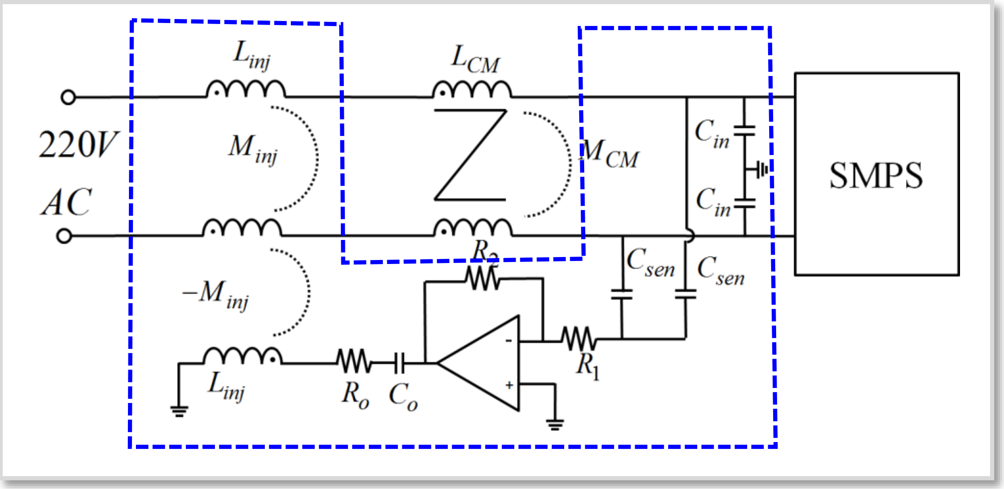
Input Impedance	$Z_{in} = \frac{Z+sL}{1-A}$
Impedance Boosting	$\frac{1}{1-A}$
Noise Attenuation	$\frac{Z_n + \frac{sL+Z}{1-A}}{Z+sL+Z_n}$

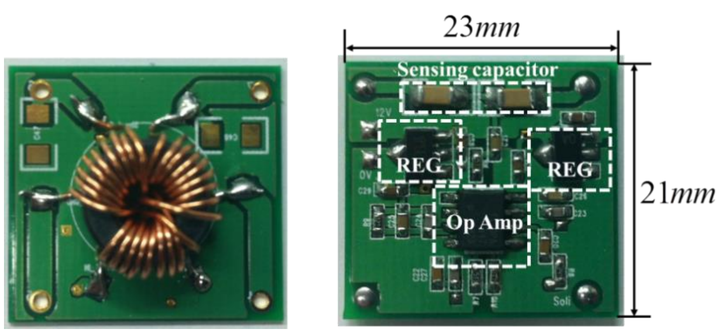
The attenuation performance is highest at the unity gain.

➔ 1:1 turn ratio transformer

➔ unity gain amplifier

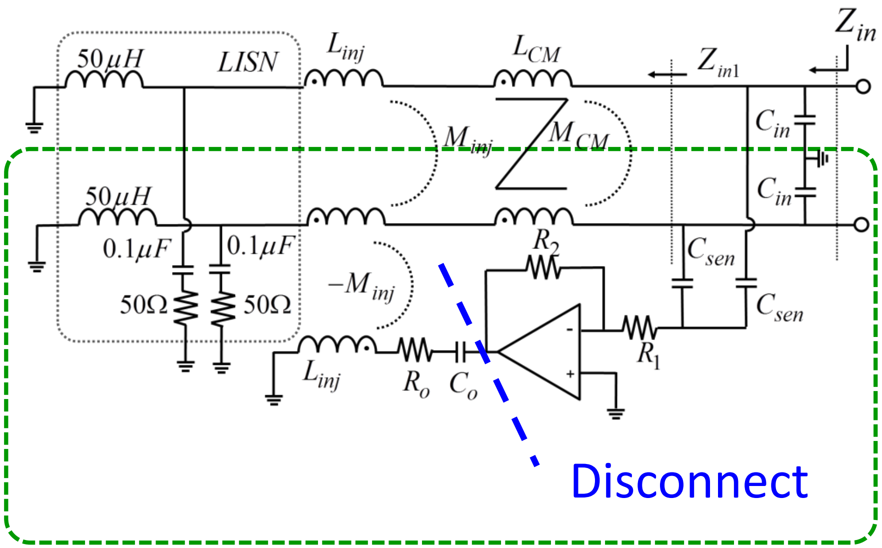
Structure of the Designed CM FF-VSVC AEF

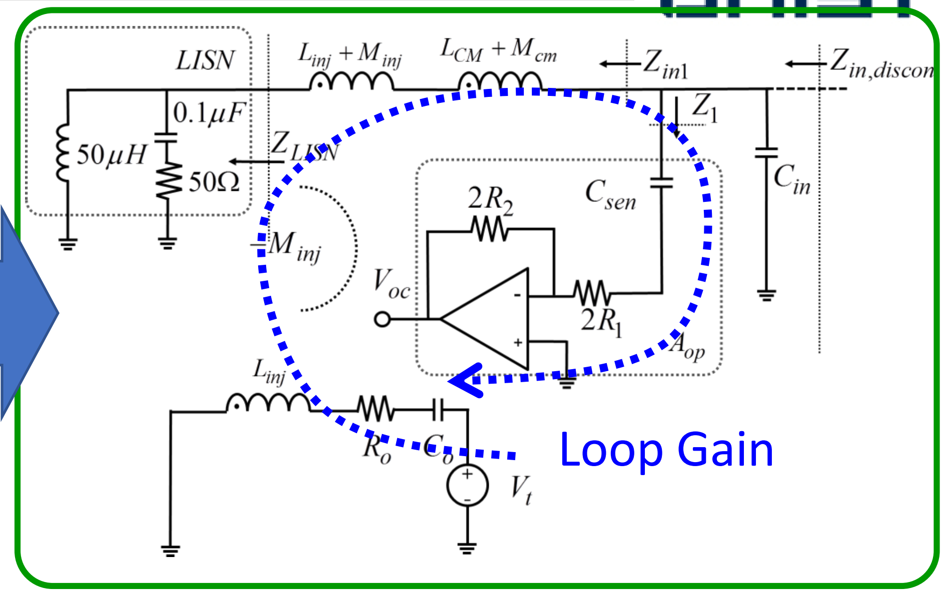




- Common-mode Feed-forward VSVC
  - The AEF output for voltage compensation is coupled to both power lines through a transformer, and isolated from the high power voltage.
  - The AEF input for voltage sensing is connected to both power lines through capacitors and a resistor.

Feedback Loop Gain of the AEF





$$LoopGain = -\frac{V_{oc}}{V_t} = \frac{Z_1 \parallel \frac{1}{sC_{in}}}{Z_{in1} + Z_1 \parallel \frac{1}{sC_{in}}} A_v$$

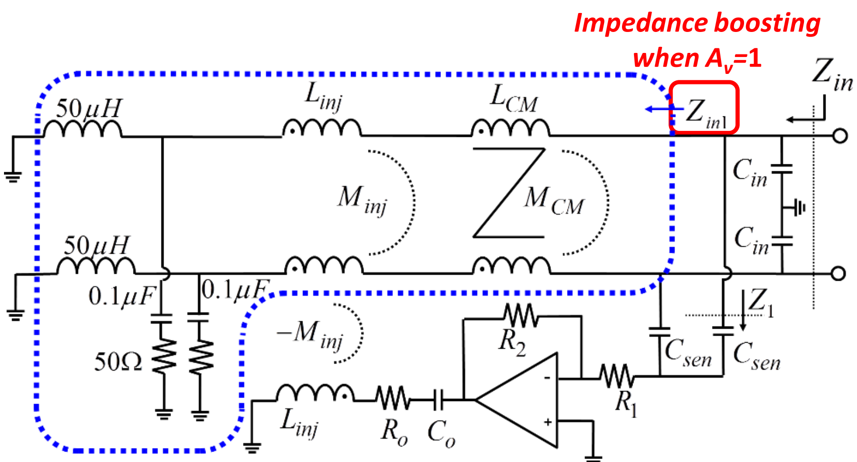
$$^* Z_{in1} = Z_{cm} + Z_{inj} + Z_{LISN} \qquad ^* A_v = -\frac{sM_{inj} A_{op}}{sL_{inj} + R_o + \frac{1}{sC_o}}$$

Impedance boosting
(Feedback input impedance)

Stability
(Gain margin)

- Stability and noise attenuation can be analyzed from the feedback loop gain.

Noise Attenuation by Impedance Boosting



$$^*Z_{in1} = Z_{cm} + Z_{inj} + Z_{LISN}$$

- Input Impedance

$$^*A_v = -\frac{sM_{inj}A_{op}}{sL_{inj} + R_o + \frac{1}{sC_o}}$$

$$Z_{in} = Z_{in,discon}\frac{1}{1+LoopGain} = \frac{\left(Z_1 \parallel \frac{1}{sC_{in}}\right)\cdot\frac{Z_{in1}}{1-A_v}}{\left(Z_1 \parallel \frac{1}{sC_{in}}\right)+\frac{Z_{in1}}{1-A_v}} = Z_1 \parallel \frac{1}{sC_{in}} \parallel \frac{Z_{in1}}{1-A_v}$$

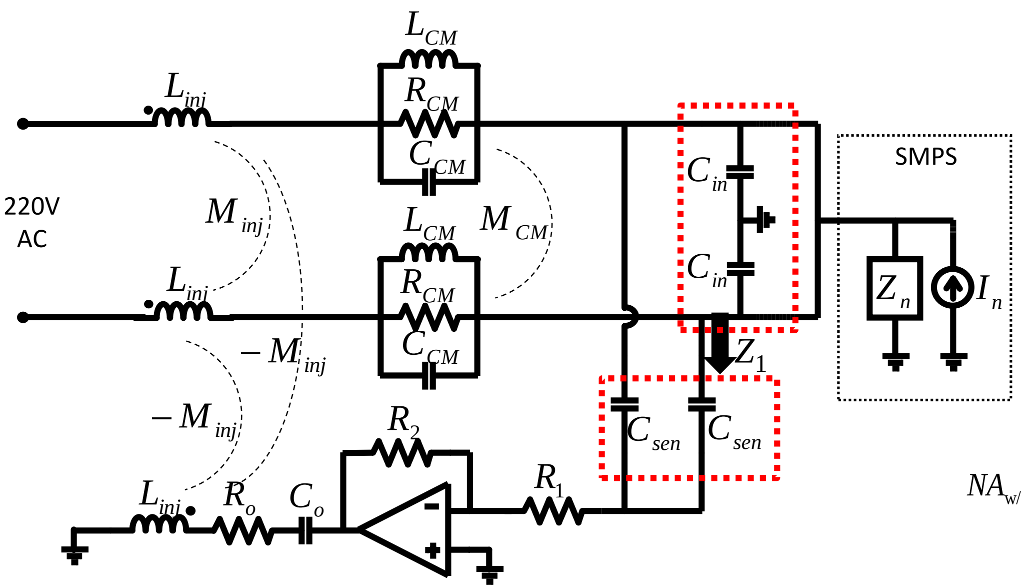
Impedance boosting when A_v=1

- Noise Attenuation Factor

$$NA = \frac{i_{CM,\text{w/ AEF}}}{i_{CM,\text{w/o AEF}}} = \frac{\frac{Z_{in1}}{1-A_v} + Z_1 \parallel \frac{1}{sC_{in}} \parallel Z_n}{\left(Z_{Lcm} + Z_{LISN} + \frac{1}{sC_{in}} \parallel Z_n\right)\cdot\frac{Z_1}{\frac{1}{sC_{in}} \parallel Z_n + Z_1}}$$

- The line impedance of the CM choke (Z_{in1}) is amplified by $\frac{1}{1-A_v}$
- The closed-loop gain (A_v) should be close to **1** for high impedance boosting.
- The noise attenuation performance of the AEF is achieved by impedance boosting.

Design of FF-VSVC AEF (1) - C_{in} and C_{sen}



$$NA_{\text{w/o Cin}} = \frac{\frac{Z_{in1}}{1-A_v} + Z_1 \parallel 2Z_n}{\left(Z_{Lcm} + Z_{LISN} + 2Z_n\right)\cdot\frac{Z_1}{2Z_n + Z_1}} \approx \frac{\frac{Z_{in1}}{1-A_v} + 2Z_n}{Z_{Lcm} + Z_{LISN} + 2Z_n}$$

$$(Z_n << Z_1)$$

$$NA_{\text{w/ Cin}} = \frac{\frac{Z_{in1}}{1-A_v} + Z_1 \parallel \frac{1}{sC_{in}} \parallel Z_n}{\left(Z_{Lcm} + Z_{LISN} + \frac{1}{sC_{in}} \parallel Z_n\right)\cdot\frac{Z_1}{\frac{1}{sC_{in}} \parallel Z_n + Z_1}} \approx \frac{\frac{Z_{in1}}{1-A_v} + \frac{1}{sC_{in}}}{Z_{Lcm} + Z_{LISN} + \frac{1}{sC_{in}}}$$

$$\frac{1}{sC_{in}} << (Z_n \parallel Z_1)$$

- A large impedance of CM noise source degrades the noise attenuation.
- C_{in} is required to decrease the effective impedance of CM noise source.
- Both C_{in} and C_{sen} should be smaller than the Y-cap regulation standard.

$$(Z_n \parallel Z_1) >> \frac{1}{sC_{in}} \geq \frac{1}{sC_Y} \qquad \frac{1}{sC_{sen}} \geq \frac{1}{sC_Y}$$

Design of FF-VSVC AEF (2) – Compensation Part

Design of Co , A_{amp}, fo, Ro, L_{inj}

$$A_v = -\frac{sM_{inj}A_{amp}}{sL_{inj} + R_o + \frac{1}{sC_o}} \approx -\frac{sM_{inj}A_{amp}}{sL_{inj} + R_o}$$

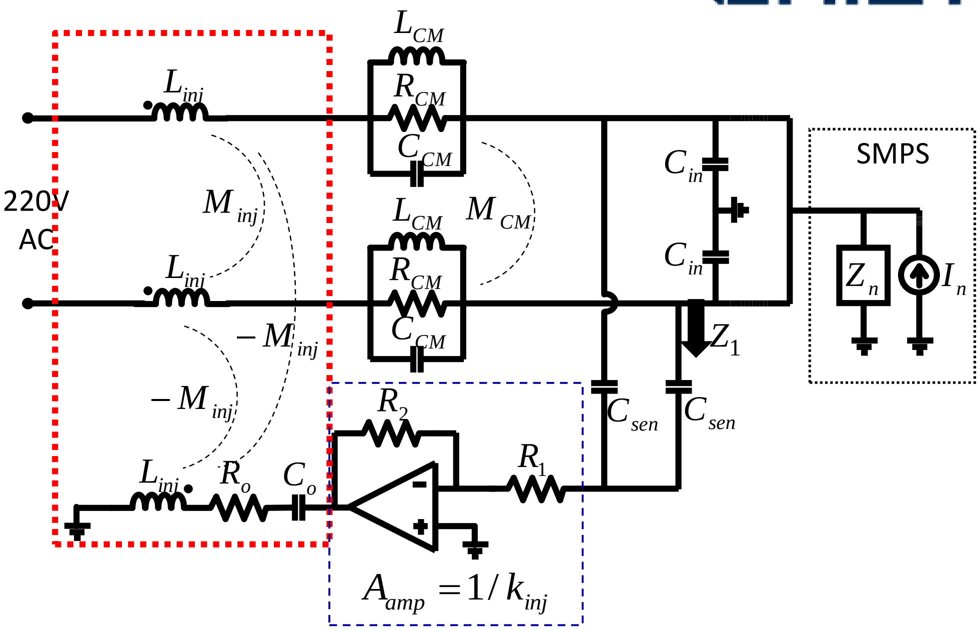
$$A_v(f_o) \approx \frac{2\pi f_o L_{inj} k_{inj} A_{amp}}{2\pi f_o L_{inj} + R_o} = \frac{2\pi f_o L_{inj}}{2\pi f_o L_{inj} + R_o} \equiv \frac{1}{2}$$

Minimum operation frequency

$$f_o \approx \frac{R_o}{2\pi L_{inj}}$$

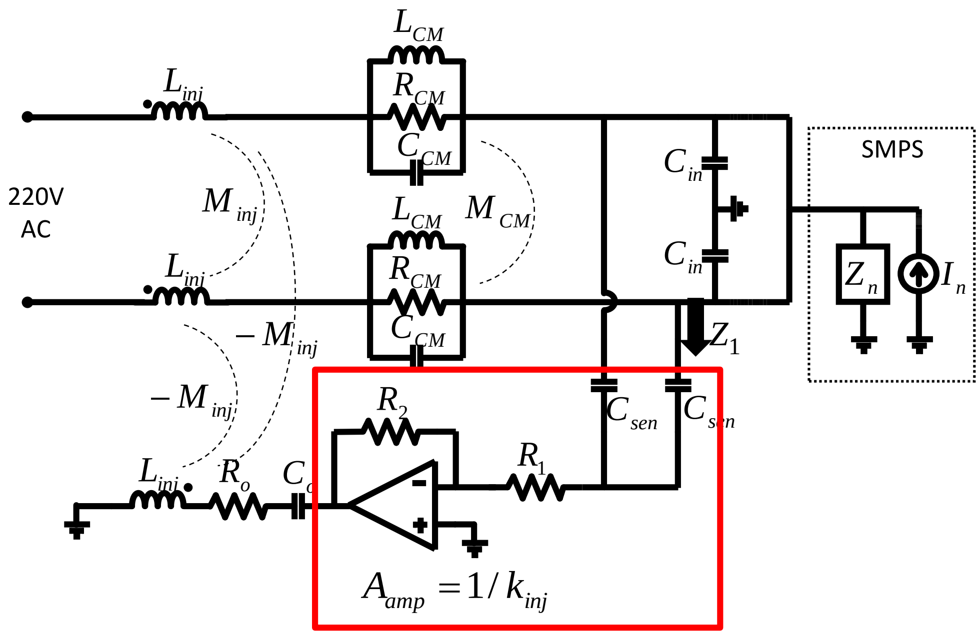
Considering the max current of the OP amp

$$\frac{V_o}{2\pi f L_{inj} + R_o} \le I_{\max, OPamp}$$



- A_{amp} is designed to be $1/k_{inj}$, and the ratio of L_{inj} and R_o is determined by the minimum operation frequency f_o.
- Small R_o and L_{inj} are desired for compact size, but they should be sufficiently large for the OP amp output current not to exceed the limit.

Design of FF-VSVC AEF (3) – Sensing Part



Design of A_{amp}, R_1, R_2

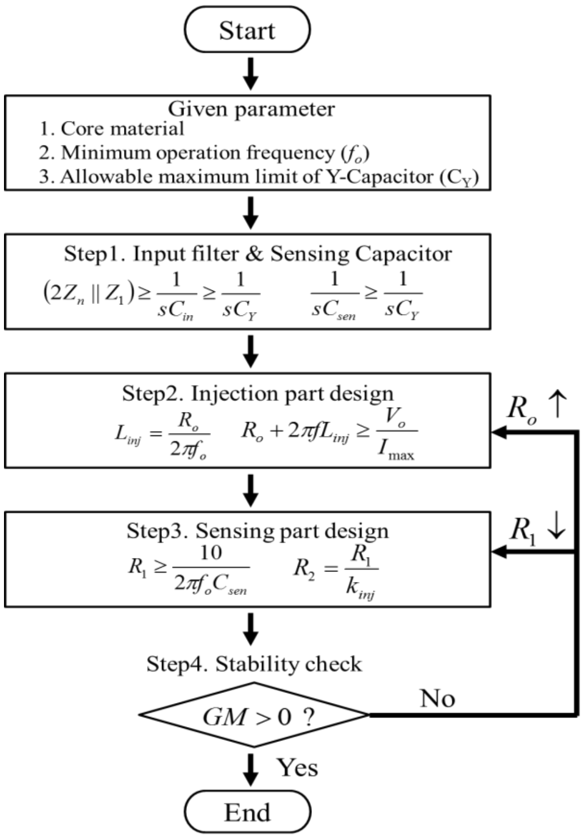
$$A_{amp} \approx -\frac{2R_2}{2R_1 + \frac{1}{sC_{sen}}}$$

$$2R_1 \geq 10 \cdot \frac{1}{2\pi f_o C_{sen}}$$

$$|A_{amp}| \approx \frac{R_2}{R_1} = \frac{1}{k_{inj}}$$

- R_1 should be much larger than $1/sC_{sen}$ even at the minimum operation frequency f_o.
- The amplifier gain A_{amp} should compensate the coupling coefficient.

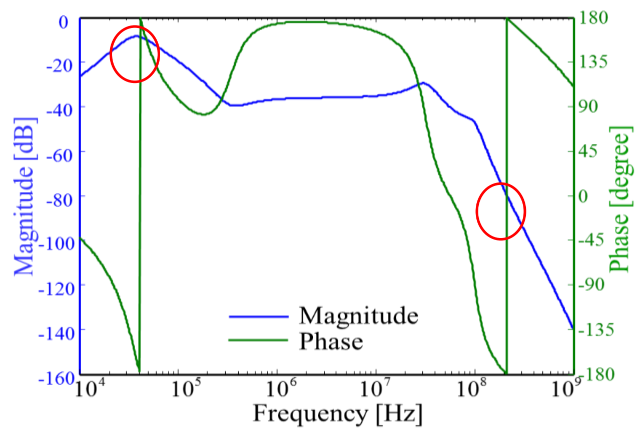
Design of FF-VSVC AEF (4) – Stability Check



Fine tune of R_o and R_1 according to Gain Margin

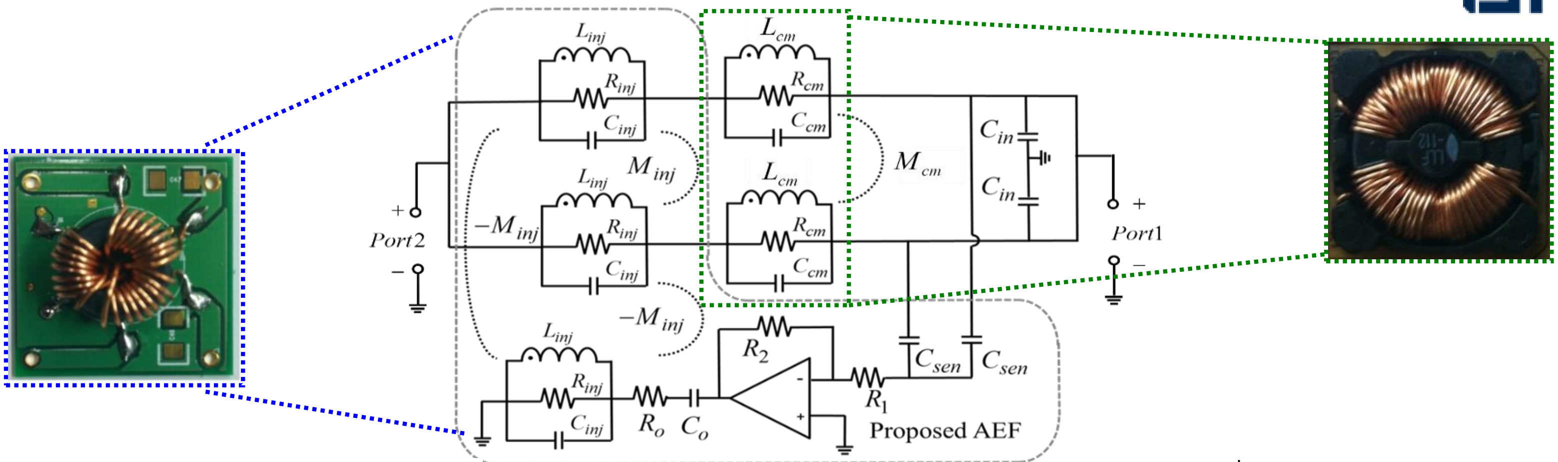
$$GM = \left| \left(1 + \frac{Z_{Lcm} + Z_{Linj} + Z_{LISN}}{2R_1 \| \frac{1}{j\omega_{180}(C_{in} + C_p(\omega_{180}))}} \right) \cdot \left(2R_1 \| \frac{1}{j\omega_{180} C_p(\omega_{180})} \right) \cdot \frac{R_o + j\omega_{180} L_{inj} + \frac{1}{sC_o}}{j\omega_{180} M_{inj} 2R_2} \right| [dB]$$

$$C_p(\omega) = \frac{C_{sen}}{1 + (2\omega C_{sen} R_1)^2} \qquad \omega_{180} \approx \sqrt{\frac{1}{C_{in}} \left[\frac{1}{(L_{cm} + M_{cm} + L_{inj} + M_{inj})} - \frac{1}{4C_{sen} R_1^2} \right]}$$



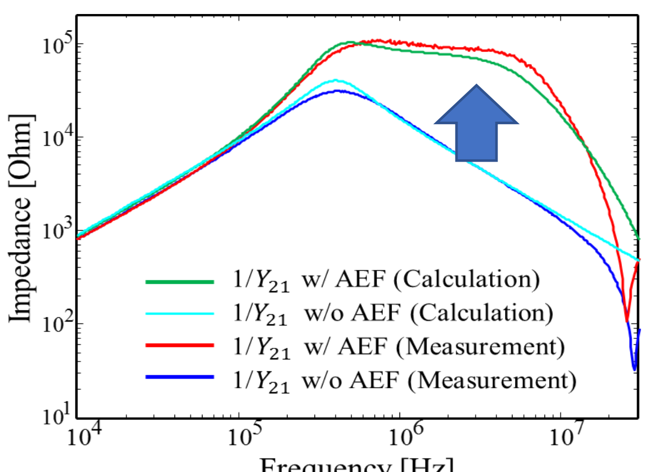
- If the feedback system is unstable, the AEF does not work properly or even damaged.
- After the initial design, the stability should be confirmed by checking the gain margin.
- The gain margin increases, as R_1 decrease and R_o increases.

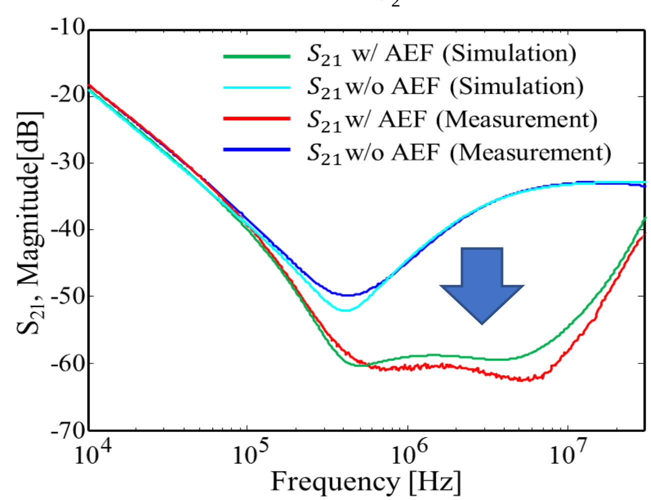
VNA Measurement vs. Model



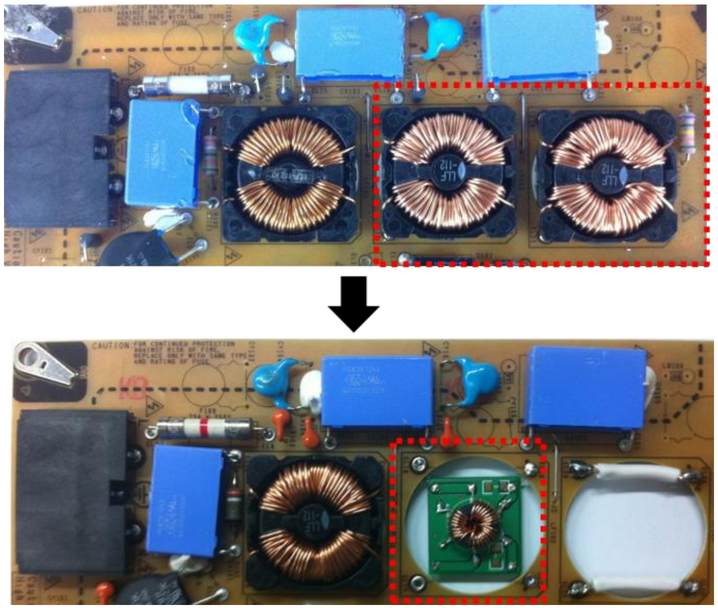
$$1/Y_{21} = \left.\frac{V_1}{I_2}\right|_{V_2=0}$$

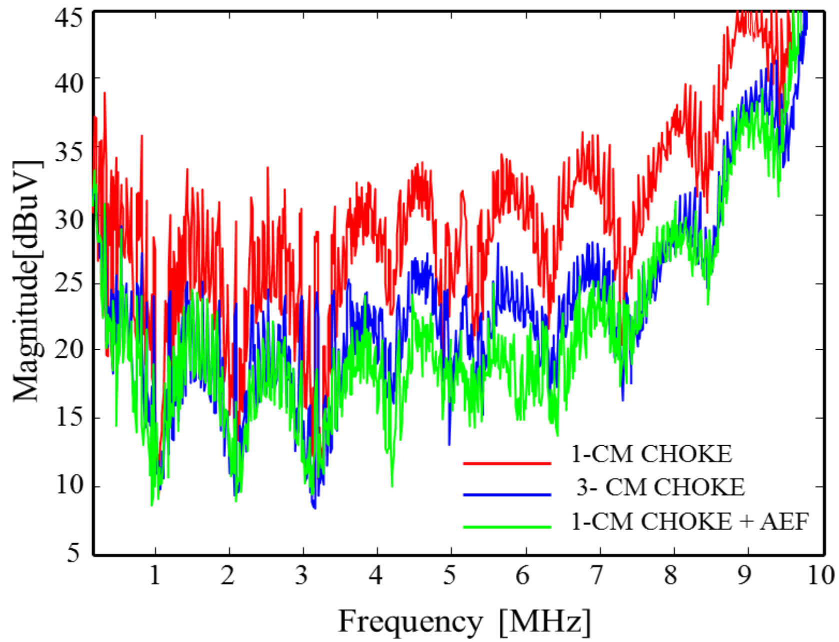
$$S_{21} = \left.\frac{V_2^-}{V_1^+}\right|_{V_2^+=0}$$





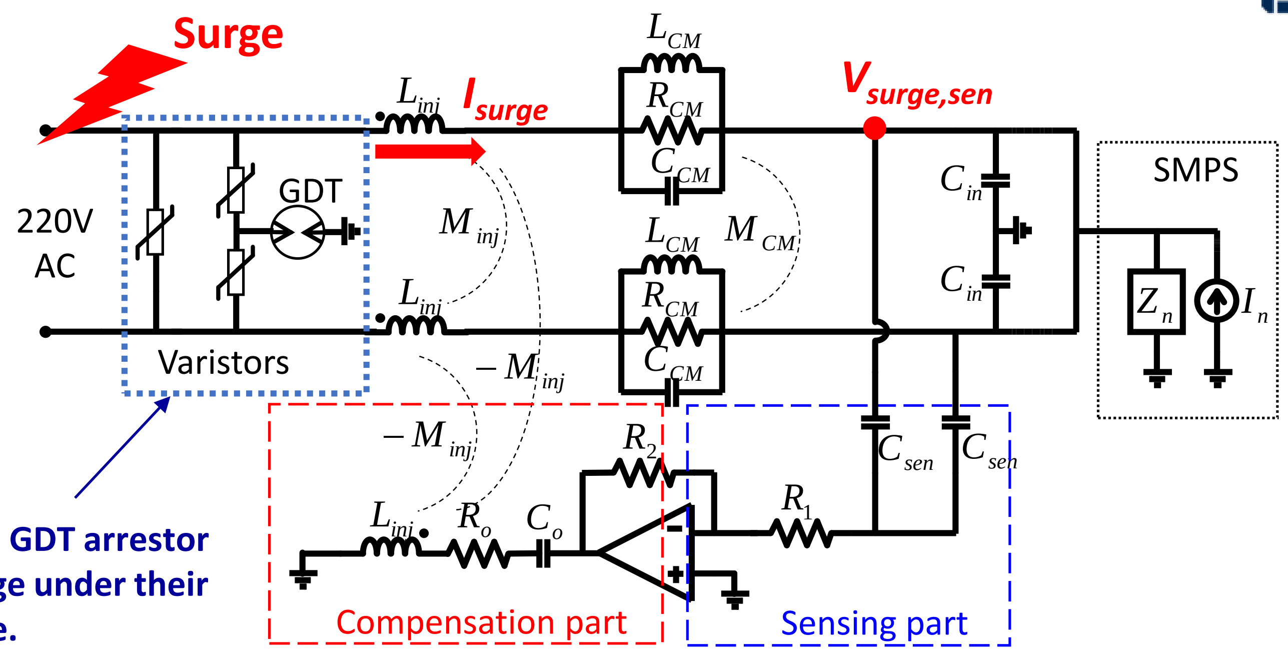
CE Measurements of the AEF installed on a SMPS





- The OP amp supply is supplied by the SMPS board using regulators.
- Two CM Chokes are replaced by the AEF, and the space is greatly reduced.
- The AEF has the noise attenuation about 10 ~ 12dB.
- The performance of the (AEF + 1 CM choke) is comparable to 3 CM chokes.
- The size is greatly reduced!

Surge Inflow Path to VSVC AEF

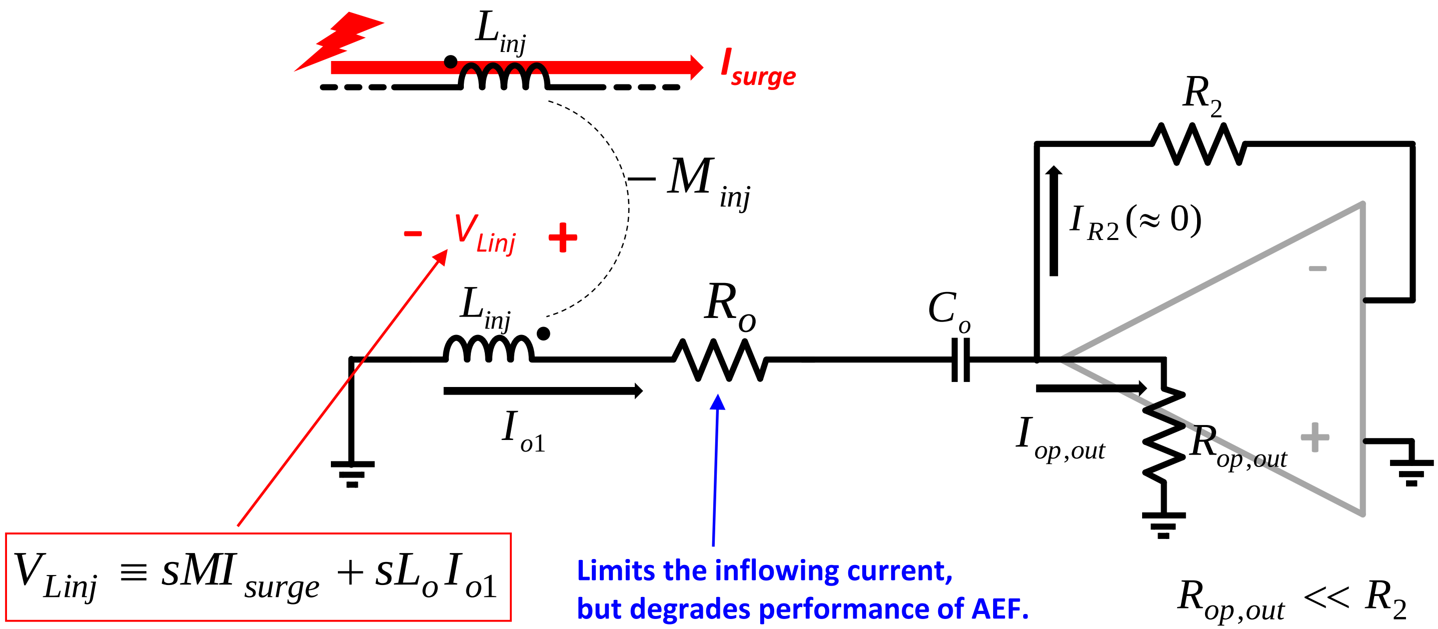


The varistors and GDT arrestor cannot block surge under their operating voltage.

- Mostly, the varistors and gas discharge tube (GDT) arrestors are installed to primarily suppress the surge voltage and current.
- However, they usually operate only for very high surge voltages over several kV.
- Surge protection circuits for the AEF should be separately prepared against the surge voltage or current that the varistors and arrestors cannot suppress.

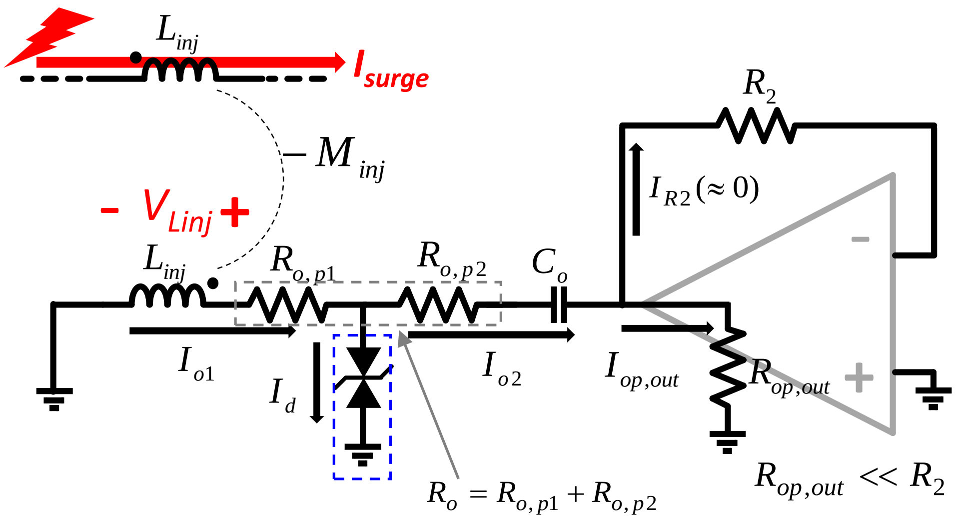
[Ref] Sangyeong Jeong, Dongil Shin. Jongpil Kim and Seokjoon Kim, and Jingook Kim, "Design of Effective Surge Protection Circuits for an Active EMI filter", 2017 Asia Pacific EMC conference, Seoul, Korea, June 2017.

Overcurrent path to the compensation part



- Inducted voltage and current can be generated through the injection transformer.
- The current flowing to R_2 is almost negligible since R_2 is usually much higher than output impedance of Op-amp.
- The current injection into the op-amp output stage can be limited by a high value of R_o, but higher R_o degrades the noise attenuation performance at low frequency range.

Surge Protection Circuit for Compensation Part



When the diode is **Turn-off** :

$$I_d = 0, \quad I_{o1} = I_{o2}, \quad V_{br} > \frac{R_{o,p2}}{R_{o,p1} + R_{o,p2}} V_{Linj} \;\Rightarrow\; V_{Linj} < \frac{R_{o,p1} + R_{o,p2}}{R_{o,p2}} V_{br}$$

$$\Rightarrow\; I_{op,out} = \frac{V_{Linj}}{R_{o,p1} + R_{o,p2}} < \frac{V_{br}}{R_{o,p2}}$$

V_{br} : Diode break down voltage

When the diode is **Turn-on** :

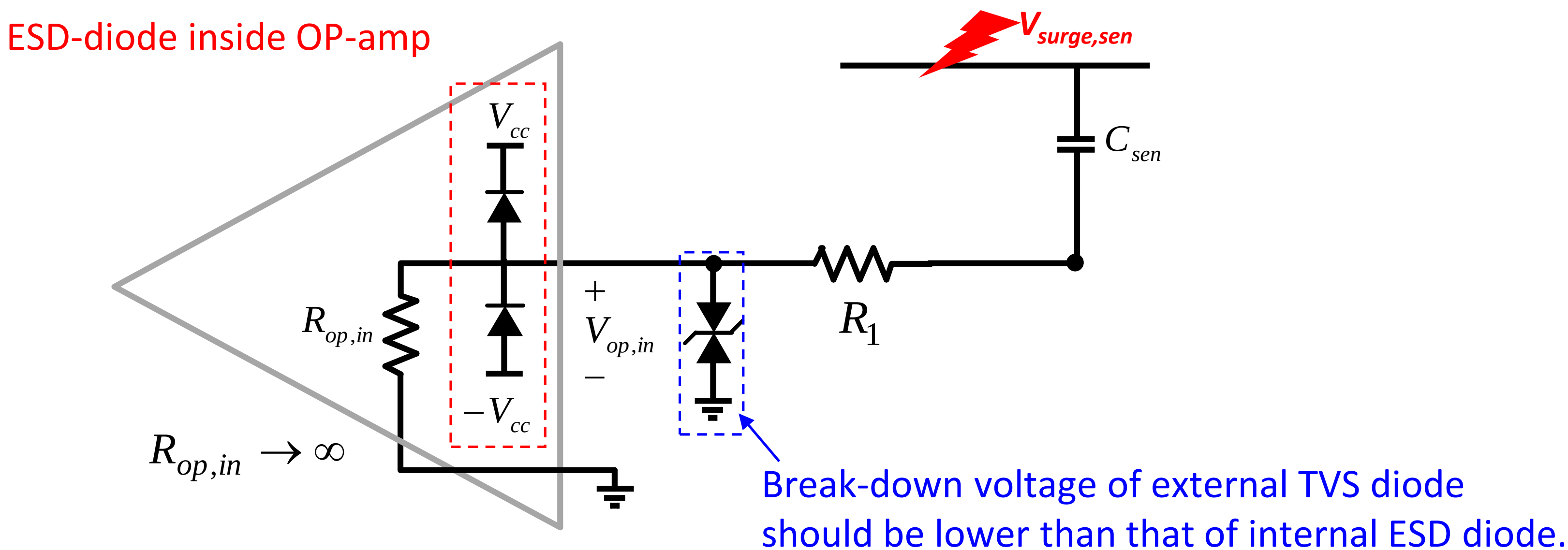
$$V_{br} < \frac{R_{o,p2}}{R_{o,p1} + R_{o,p2}} V_{Linj}, \;\Rightarrow\; V_{Linj} > \frac{R_{o,p1} + R_{o,p2}}{R_{o,p2}} V_{br}$$

$$I_{o1} = \frac{V_{LO} - V_C}{R_{o1}} \qquad I_{op,out} \approx I_{o2} = \frac{V_C}{R_{o,p2}}$$

V_C : Diode clamping voltage

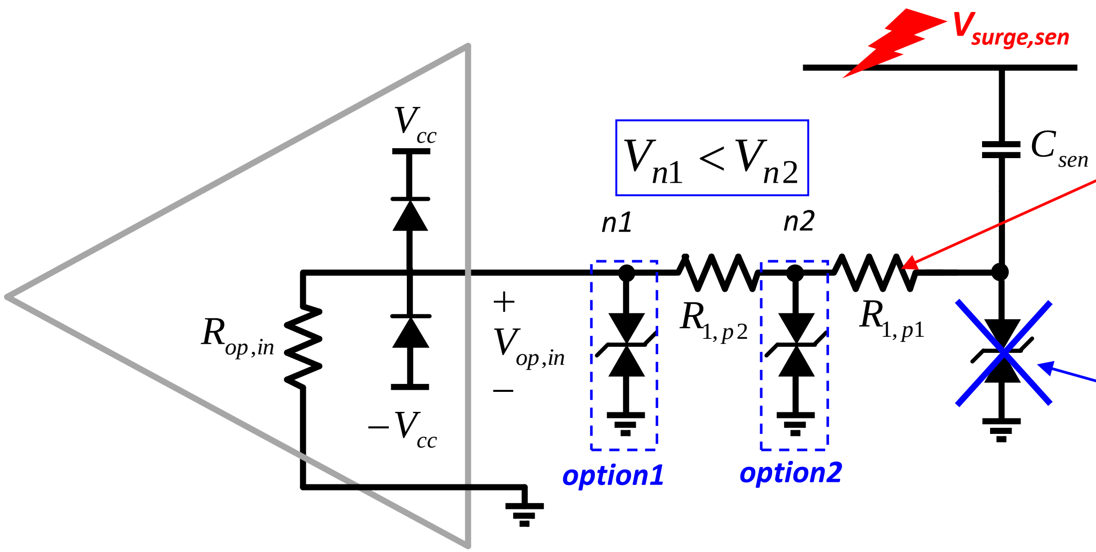
- A transient voltage suppression (TVS) diode is installed to limit the current and maintain the design freedom of R_o.
- The diode limits the op-amp current as shown in the right expressions.
- The resistor of $R_{o,p1}$ should be sufficiently robust against a large voltage pulse.

Overvoltage path to the Sensing part



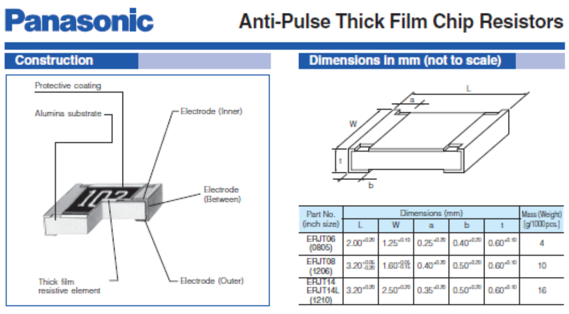
- The sensing part has basically a high input impedance from the AC line, the current is not critical issue but an overvoltage can be induced at the op-amp input, $R_{op,in}$.
- Most commercial op-amps include internal diodes on each pin for electrostatic discharge (ESD) protection, but the on-chip ESD-diode is not suitable for preventing surges.
- External TVS diodes are necessary for reliability from the surges.

Surge Protection Circuit for Sensing Part



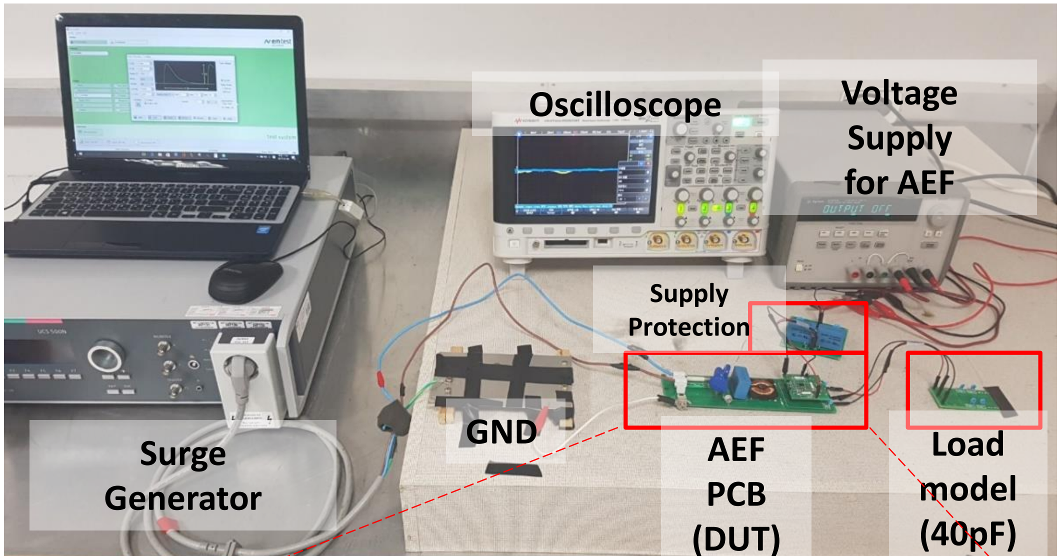
(not recommend this placement since overcurrent can flow to the diode.)

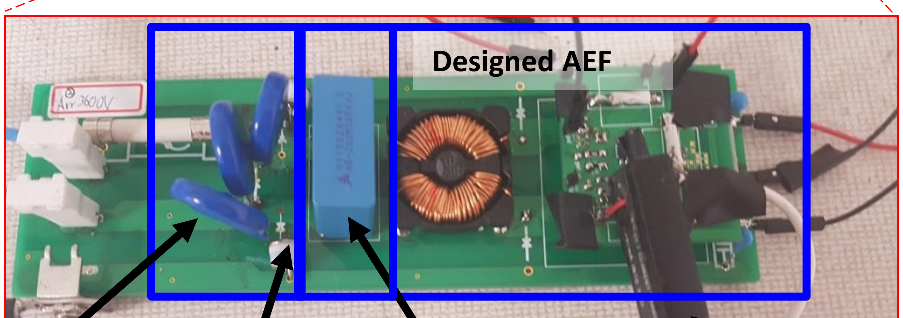
e.g. Anti-surge resistor



- The TVS diode can be connected to the node '*n1*' ***(option1)*** and '*n2*' ***(option2).***
- The voltage at the node n2 is larger than the node n1 so the voltage can be more effectively limited in the option 2. However, the junction capacitance of the diode at the 'option2' position can degrade the noise attenuation performance of AEF
- R_1 or $R_{1,p1}$ should be strong against the overvoltage surge pulse.

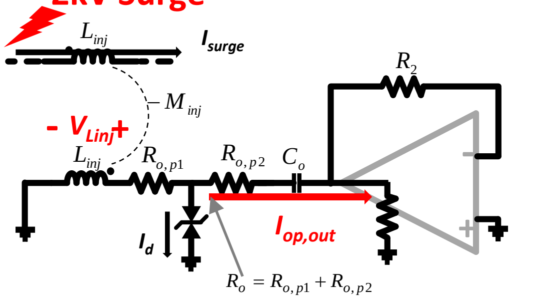
2kV Surge Test Set-up



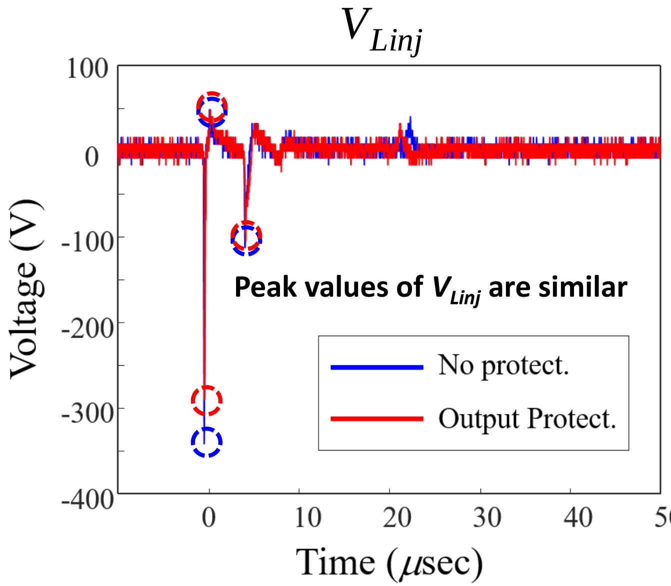


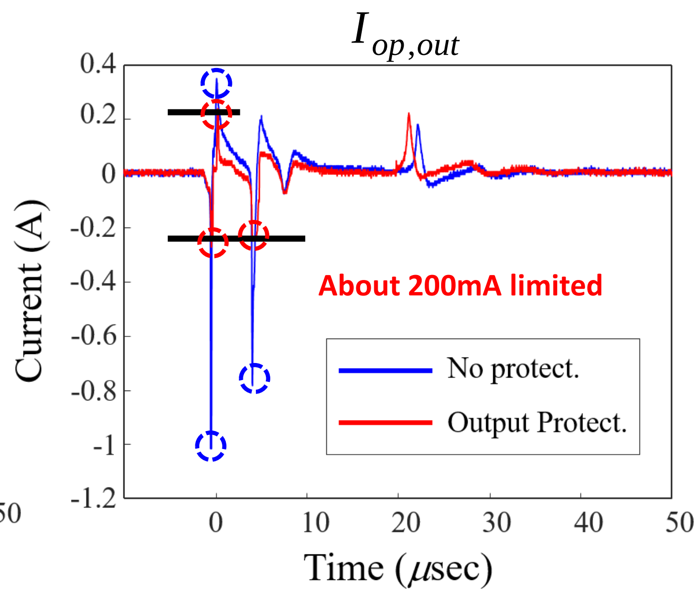
- 2kV common mode (LINE-GND) surge tests had been performed, and the waveforms are measured using an oscilloscope.
- The impedance of the CE noise source is modeled as a capacitor of 40pF, which represents the parasitic capacitance between switching transistors and heat sinks in SMPS.

Measured Waveform of Compensation Part



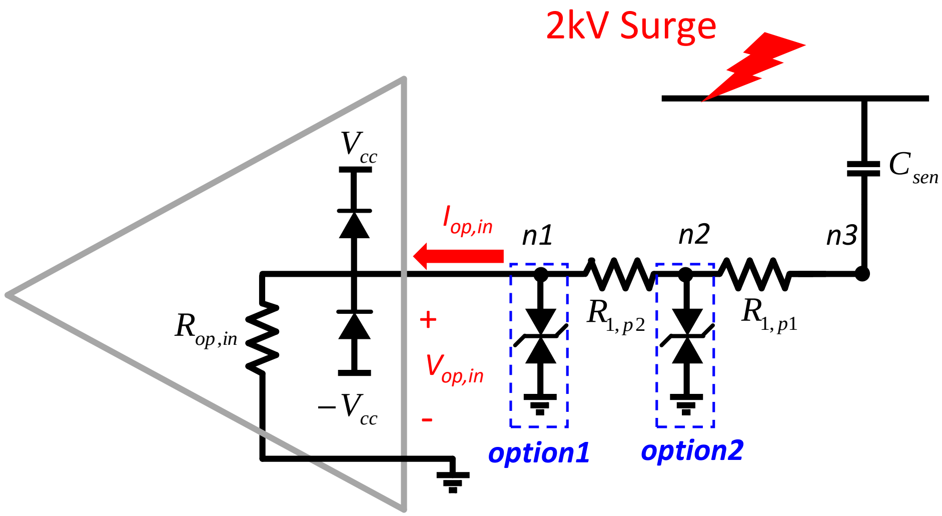
$V_{Linj} < \frac{R_{o1}+R_{o2}}{R_{o2}} V_{br}$	$V_{Linj} > \frac{R_{o1}+R_{o2}}{R_{o2}} V_{br}$
$I_{op,out} < \frac{V_{br}}{R_{o2}}$	$I_{op,out} = \frac{V_C}{R_{o2}}$



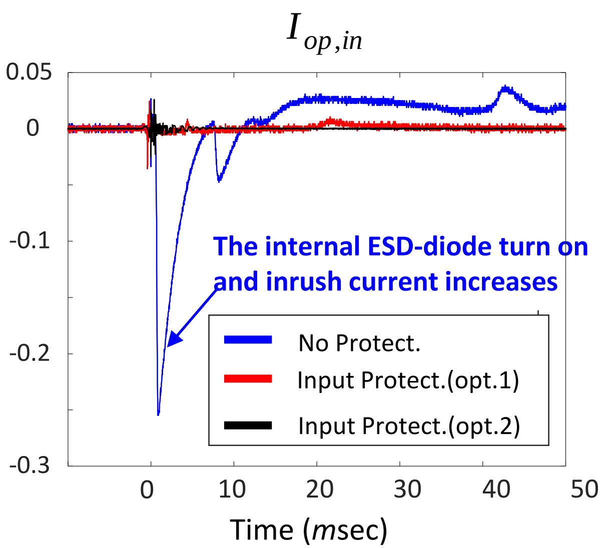


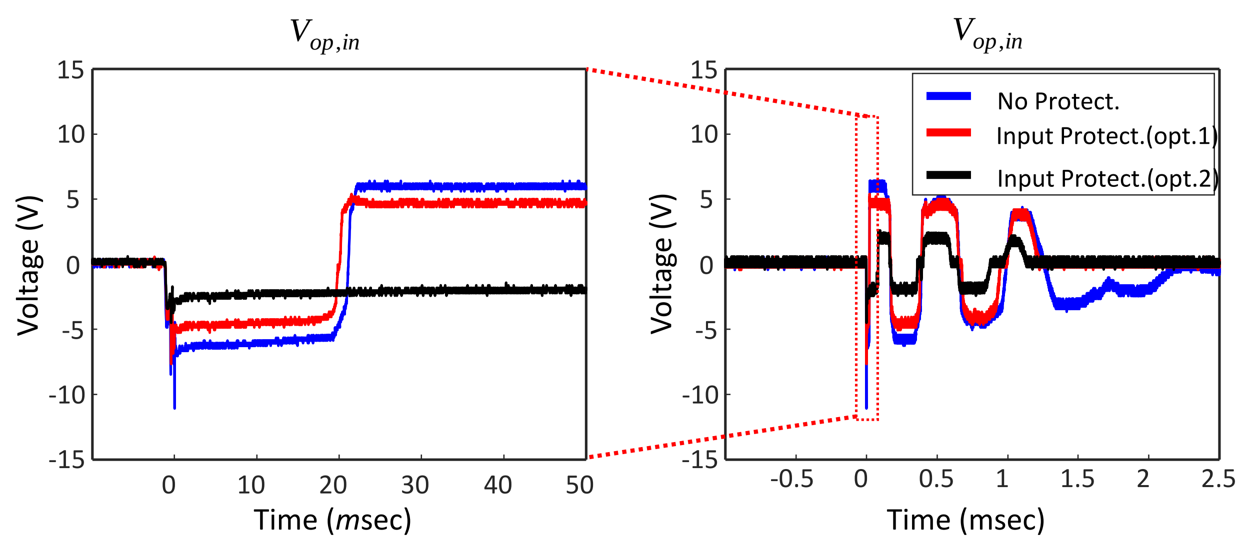
- $R_{o,p1}$ and $R_{o,p2}$ are designed as 100Ω and 30 Ω, respectively, and the clamping voltage of bidirectional TVS diode is around 6V.
- The output current of op-amp is limited to about 200mA when large V_{Linj} is induced as shown in the above figures.
- When V_{Linj} is small and diode is turn-off, current level is similar. (last peak of current)

Measured Waveform of Sensing Part



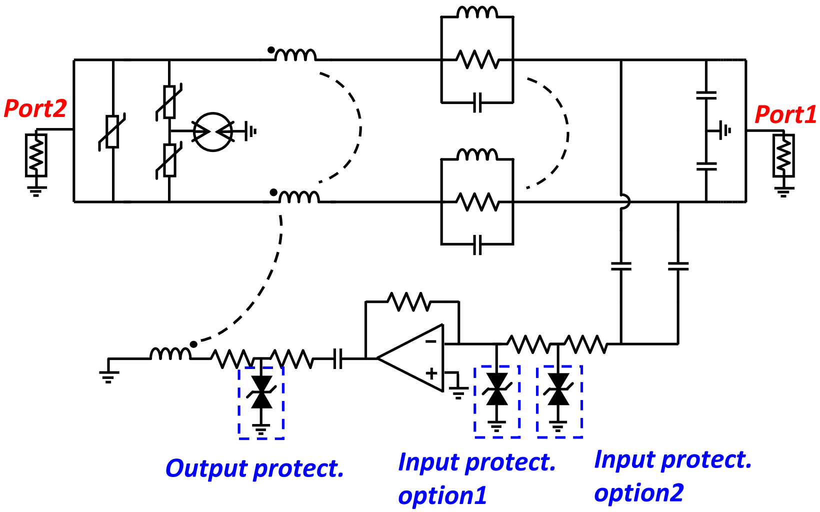
- The op-amp input voltage and current are compared according to the diode position.
- The internal ESD-diode are turned on at around 6V, while the external TVS diode with the break-down voltage of 3.5V was implemented
- $R_{1,p1}$ and $R_{1,p2}$ are 3.6kΩ and 2kΩ, respectively.





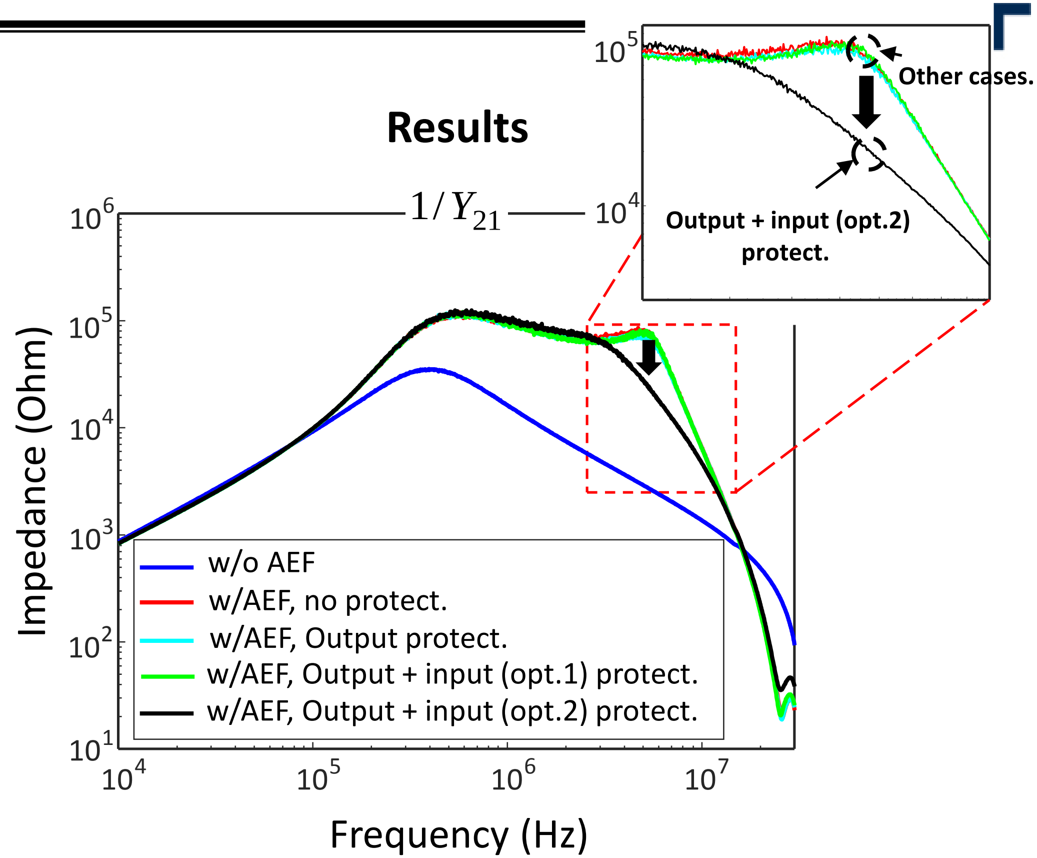
Performance Degradation Effect of Diode

VNA Measurement Set-up



$$1/Y_{21} = \left.\frac{V_1}{I_2}\right|_{V_2=0}$$

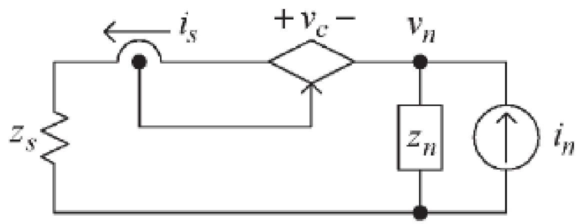
Results



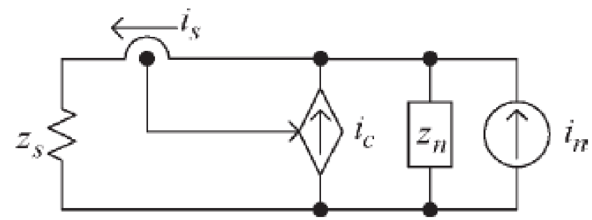
- The $1/Y_{21}$ parameter measured by the vector network analyzer (VNA), which can demonstrate the boosting of the power line impedance by the AEF.
- Junction capacitance of 2.5pF can cause performance degradation at high frequency since the additional pole is added in the transfer function.

(AEF Type 2) : VSCC AEF

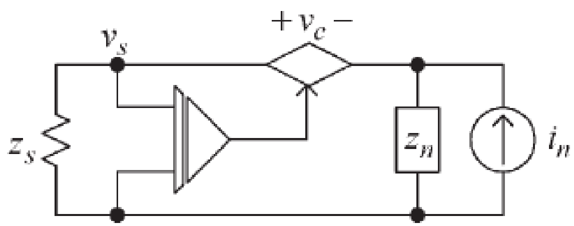
Feed-back



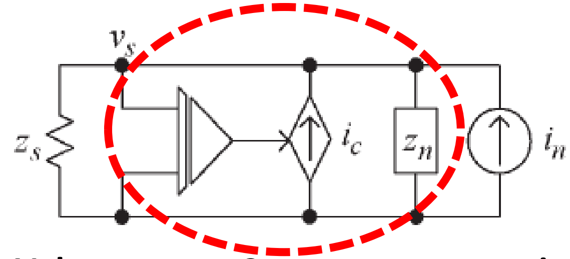
Current-sense Voltage-compensation



Current-sense Current-compensation

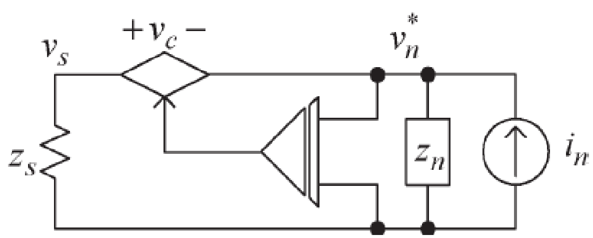


Voltage-sense Voltage-compensation

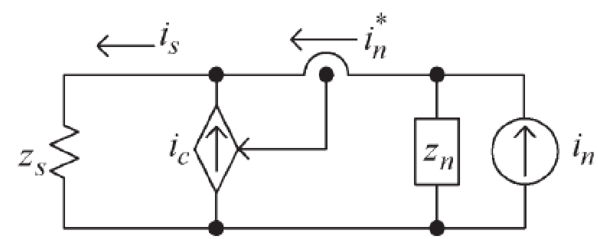


Voltage-sense Current-compensation

Feed-forward



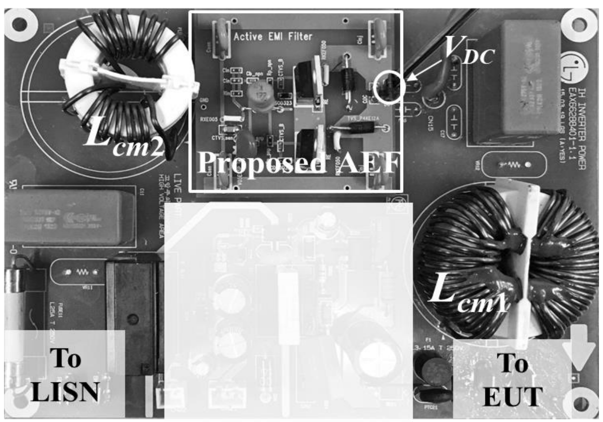
Voltage-sense Voltage-compensation

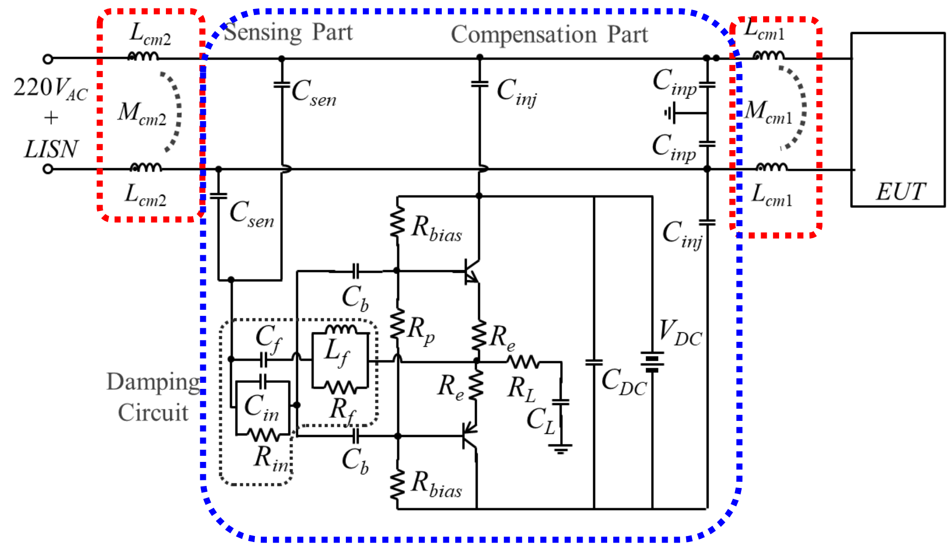


Current-sense Current-compensation

- Dongil Shin, Sangyeong Jeong, and Jingook Kim, "Quantified Design Guidelines of Compact Transformer -less Active EMI Filter for Performance, Stability, and High Voltage Immunity", IEEE Trans on Power Electronics, vol. 33, no. 8, pp. 6723-6737, Aug. 2018.

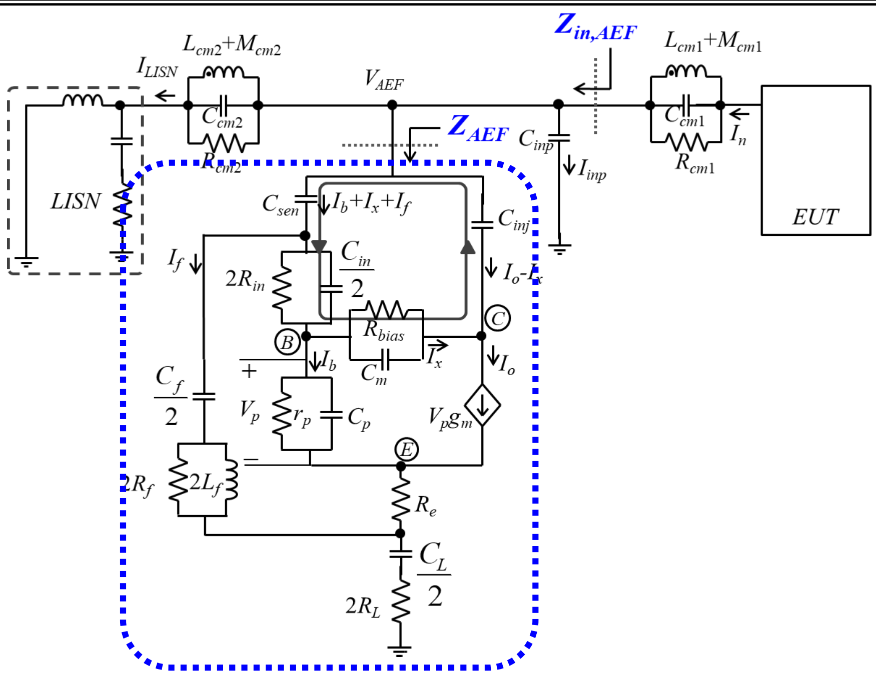
Structure of the Designed VSCC AEF

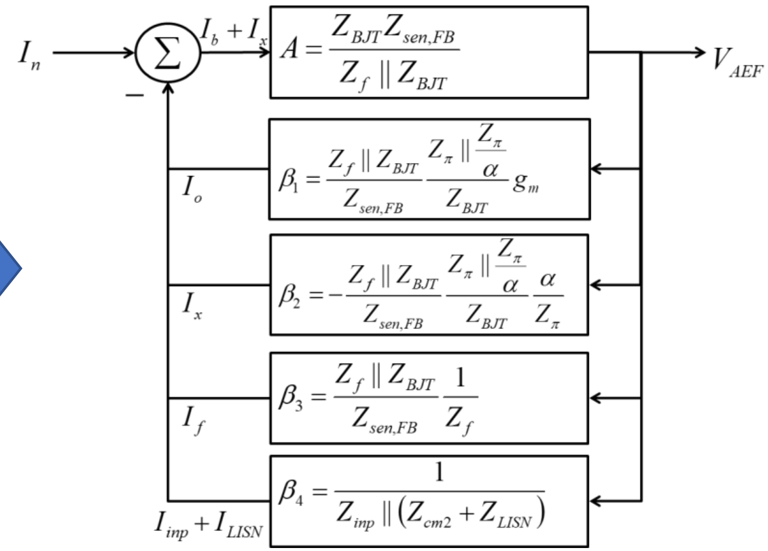




- A simple low-cost compact AEF of the VSCC type without transformers is proposed.
- The amplifier part is designed as a push-pull amplifier with two BJTs.
- The proposed AEF can enhance the Y-cap in the LCL filter.

Loop Gain and Impedance Analysis



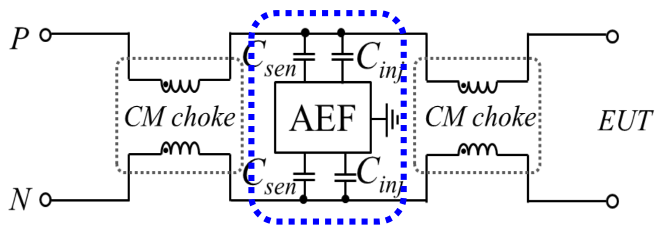


(Closed-loop transfer function) = $Z_{in,AEF} = \frac{V_{AEF}}{I_n} = \frac{A}{1+A\beta_t} = \frac{A}{1+A(\beta_1+\beta_2+\beta_3)} \| \frac{1}{\beta_4} = Z_{AEF} \| Z_{inp} \| \left(Z_{cm2}+Z_{LISN}\right)$

(Loop gain) = $A\beta_t = \left(Z_\pi \| \frac{Z_\pi}{\alpha}\right)\left(g_m - \frac{\alpha}{Z_\pi}\right) + \frac{Z_{BJT}}{Z_f}\left(1+\frac{Z_{sen,FB}}{Z_{inp}\|\left(Z_{cm}+Z_{LISN}\right)}\right) + \frac{Z_{sen,FB}}{Z_n \| \left(Z_{cm}+Z_{LISN}\right)}$

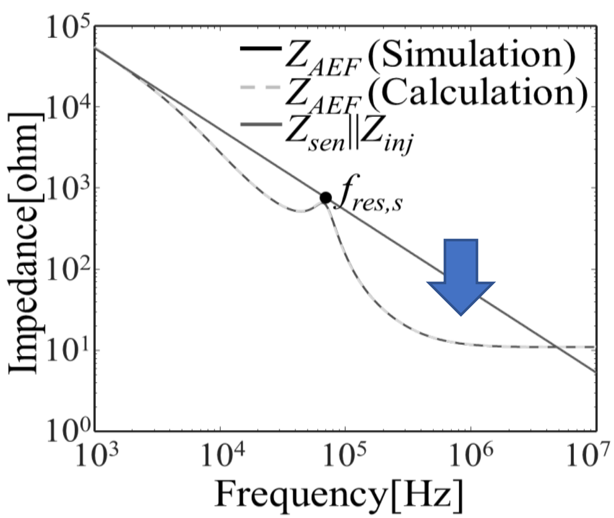
(AEF impedance) = $Z_{AEF} = \frac{V_{AEF}}{I_b+I_o+I_f} = \frac{A}{1+A(\beta_1+\beta_2+\beta_3)} = \frac{Z_{sen,FB}}{1+\left(\frac{Z_f\|Z_{BJT}}{Z_{BJT}}\right)\left(Z_\pi\|\frac{Z_\pi}{\alpha}\right)\left(g_m-\frac{\alpha}{Z_\pi}\right)}$

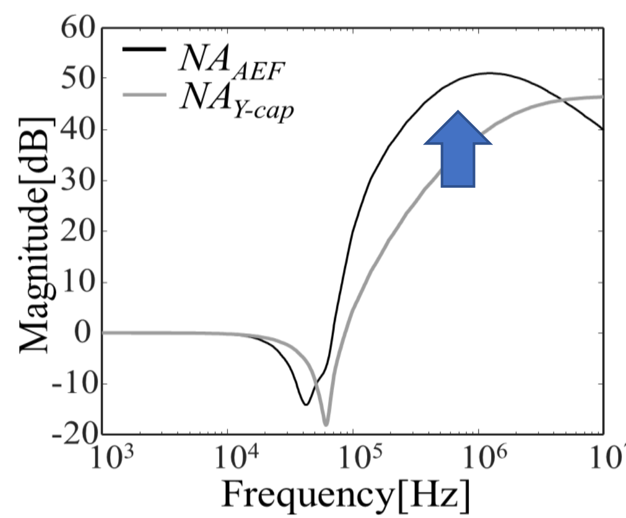
Noise Attenuation by the AEF



$$NA_{Y-Cap} = \frac{I_{LISN,w/oY-cap}}{I_{LISN,w/Y-cap}} = \frac{Z_{cm2} + Z_{LISN} + Z_{sen} \| Z_{inj} \| Z_{inp}}{Z_{sen} \| Z_{inj} \| Z_{inp}}$$

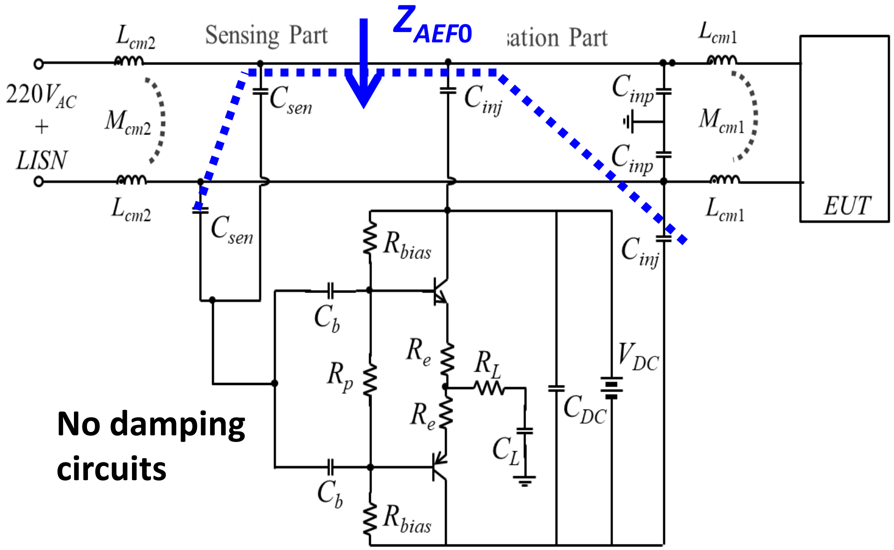
$$NA_{AEF} = \frac{I_{LISN,w/oAEF}}{I_{LISN,w/AEF}} = \frac{Z_{cm2} + Z_{LISN} + Z_{AEF} \| Z_{inp}}{Z_{AEF} \| Z_{inp}}$$

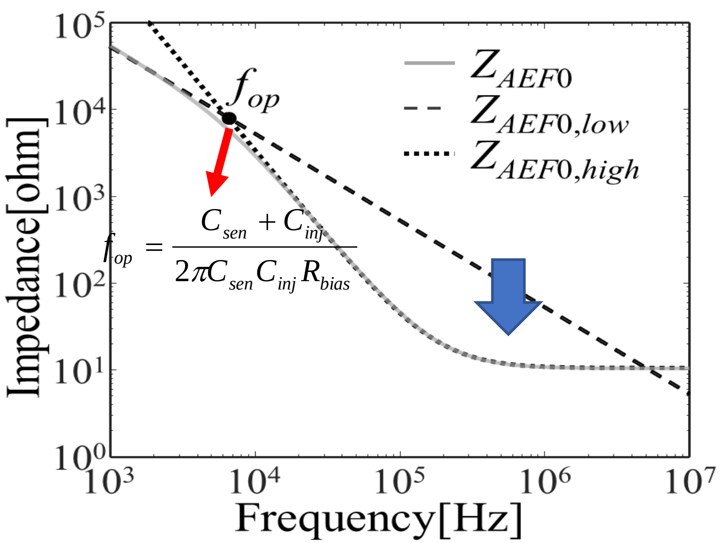




- The effective Y-cap impedance, is much decreased compared to ($Z_{sen}||Z_{inj}$), which results in a large increase of the NA.
- However, Z_{AEF} below 1kHz is rarely affected by the AEF, and the influence of the AEF on the safety requirements for the leakage current is very small.

Design Target of VSCC AEF





Z_{AEF} without the damping circuits

$$Z_{AEF0} \approx \frac{Z_{sen}}{Z_\pi g_m}\alpha_0 + \frac{1}{g_m} + R_e + \frac{2}{sC_L} + 2R_L$$

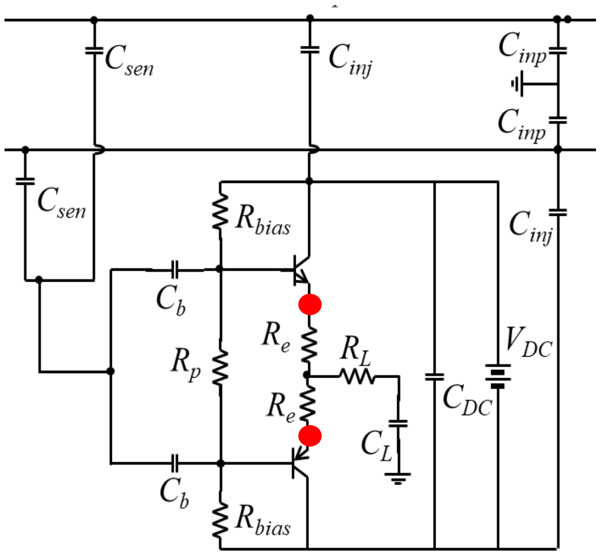
at the low frequency $Z_{AEF0,low} \approx Z_{sen} \parallel Z_{inj} = \frac{1}{s(C_{sen}+C_{inj})}$

at the high frequency $Z_{AEF0,high} \approx \frac{Z_{sen}Z_{inj}}{Z_{bias}} + \frac{1}{g_m} + R_e + \frac{2}{sC_L} + 2R_L$

g_m : current gain of the BJT

- The values of $Z_{AEF0,high}$ and f_{op} should be reduced as much as possible while maintaining the sum of C_{inp}, C_{sen}, and C_{inj} to be under the safety limit.
- C_{inp} are used to screen out the noise source impedance, Z_{EUT} .

Design of Class AB Push-Pull Amplifier



$$f_{op} = \frac{C_{sen} + C_{inj}}{2\pi C_{sen} C_{inj} R_{bias}}$$

BJT emitter voltage at the sat. region

CM noise current I_n

$$\frac{\frac{V_{DC}}{2} - V_{ce,sat}}{R_e + 2R_L} \leq I_{c,\max} >> I_n$$

The amplifier maximum output current

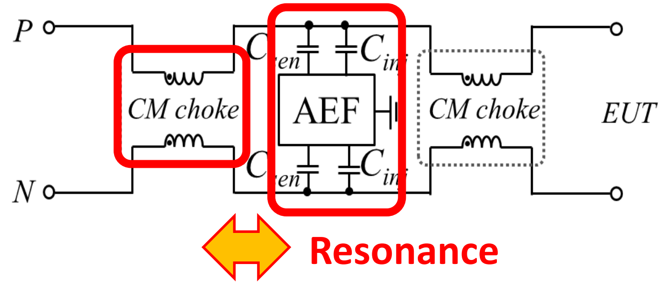
the max limit of the BJT collector current

DC bias analysis of the BJT

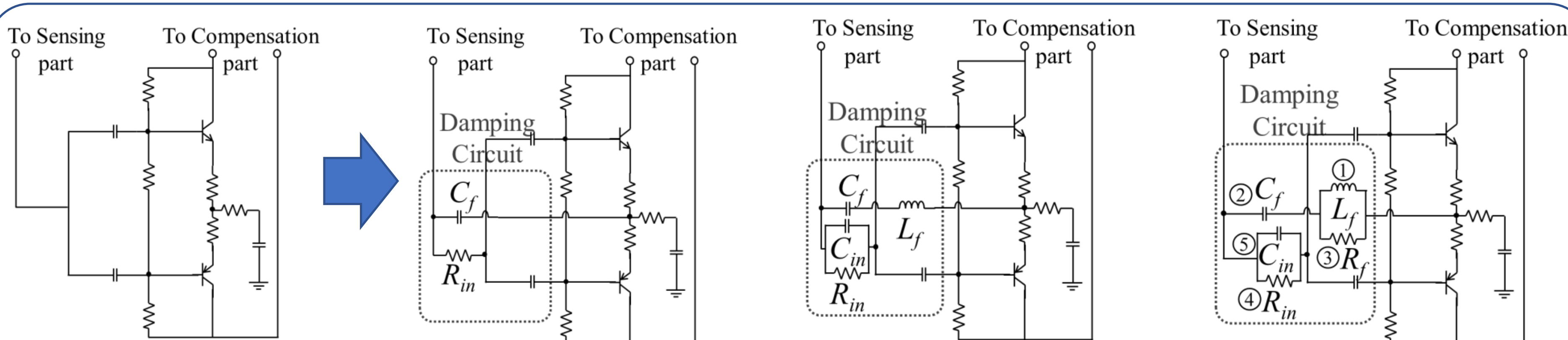
$$\frac{\frac{R_p}{2}}{R_{bias} + \frac{R_p}{2}} \frac{V_{DC}}{2} = I_B\left(R_{bias} \parallel \frac{R_p}{2}\right) + V_{BE} + (I_C + I_B)R_e$$

- R_e of 1~4 Ω is necessary to stabilize the BJT bias and the thermal runaway of a BJT.
- R_L should be as small as possible while satisfying the BJT current limit.
- R_{bias} can be determined from the target f_{op}.
- DC bias point of the BJT in the class AB amplifier is located slightly above the cutoff, and R_p can be extracted by solving the KVL from the base to the emitter.

Damping Circuit Design for System Stability (1)



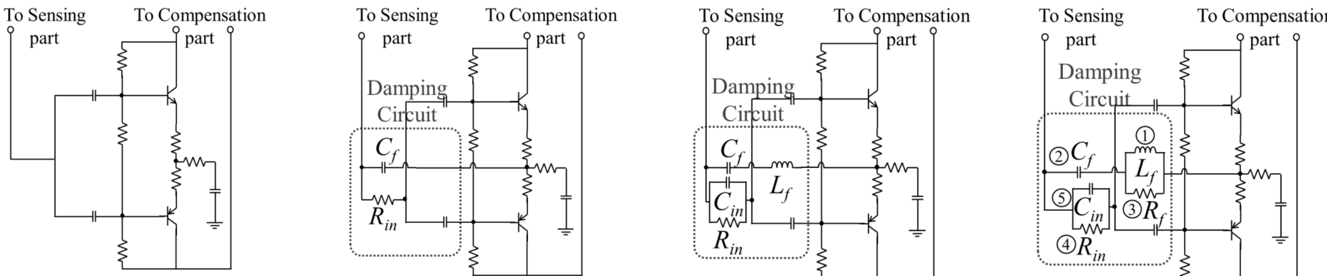
- The resonance between the CM choke2 and AEF most likely causes the system instability.
- The damping circuits are essential for feedback stability of this AEF.



Case0: Unstable
Case1: Stable, Poor Performance
Case2: Acceptable Performance, But risk of instability at $f_{res,s}$
Case3: Stable, Optimized Performance

- In Case 1, after C_f and R_{in} are added, the filter becomes stable, but its *NA* performance is poor.
- In Case 2, L_f and C_{in} are inserted at each damping branch to recover the filter performance, but the resonance between L_f and C_f causes a risk of feedback instability.
- In Case 3, R_f is also added to suppress the Q-factor of the resonance. Finally, both stability and performance of the AEF are optimized.

Damping Circuit Design for System Stability (2)

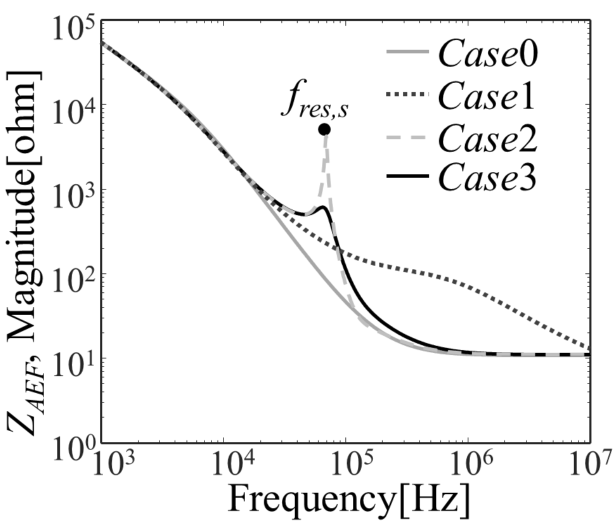


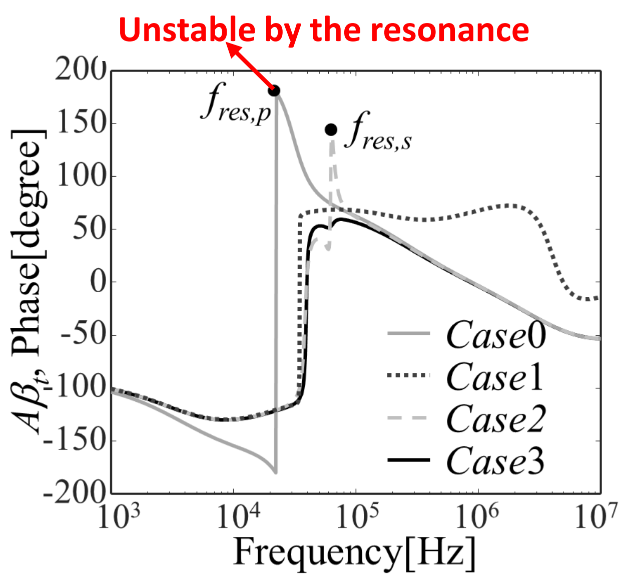
Case0: Unstable

Case1: Stable, Poor Performance

Case2: Acceptable Performance, But risk of instability at $f_{res,s}$

Case3: Stable, Optimized Performance





Design equations for Damping circuits

$$L_f > \frac{1}{4\pi f_L}\left(r_\pi \parallel \frac{1}{2\pi f_L C_\pi}\right)$$

$$C_f \le \frac{1}{20\pi^2 f_{res,p}^2 L_f}$$

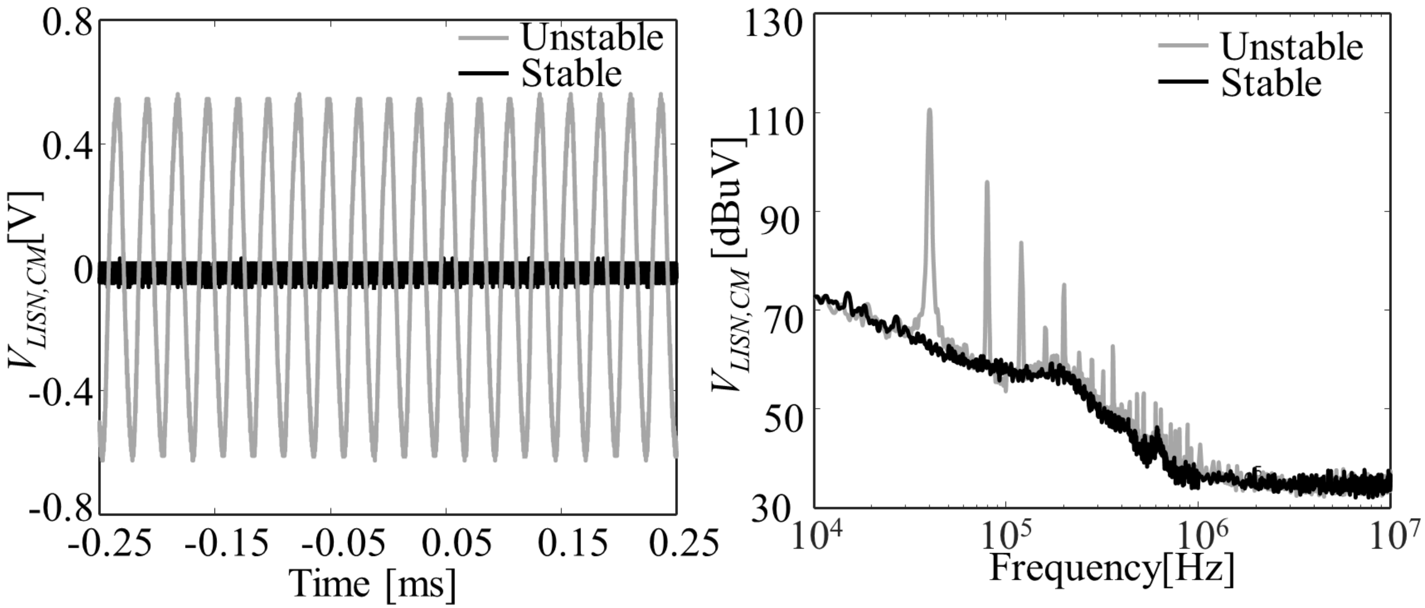
$$10\pi f_{res,p} L_f \le R_f \le 20\pi f_{res,s} L_f$$

$$R_{in} \ge \frac{1}{2\pi f_{res,p} C_f}$$

$$\frac{1}{2\pi f_L \left(r_\pi \parallel 1/(2\pi C_\pi f_L)\right)} \le C_{in} \le \frac{1}{10\pi f_{res,p} R_{in}}$$

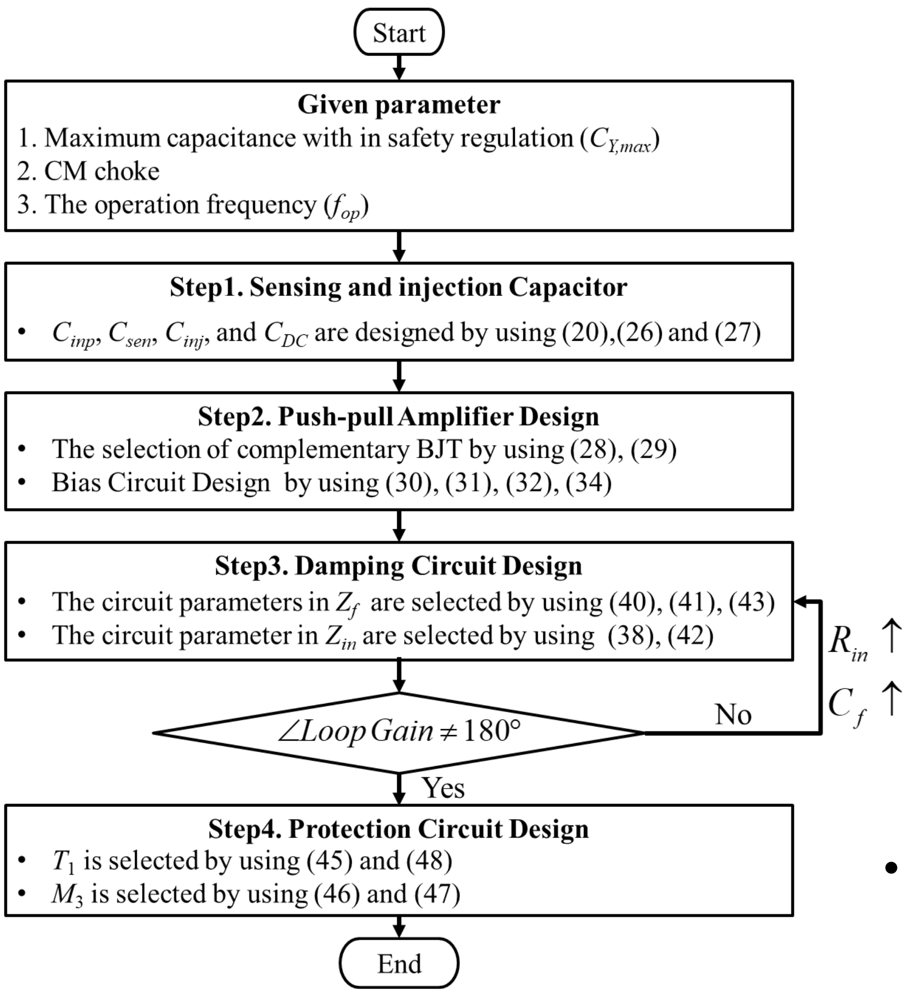
- For the system to be stable, the phase of the loop gain, Ab_t, should remain below 180˚.
- The damping circuits should make the filter stable, while maintaining the performance.

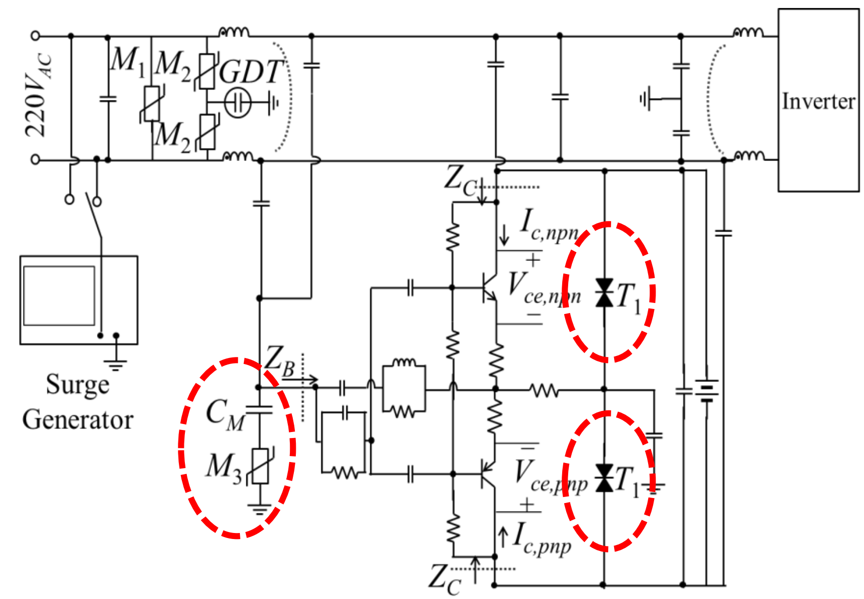
Effects of AEF Stability on CE Noises



- The CM noises were measured in both time and frequency domains, when the EUT was turned off and only the AEF turned on.
- Without the damping circuits, the oscillation due to the instability occurs. After applying the damping circuits, all the oscillations and harmonic peaks disappear.

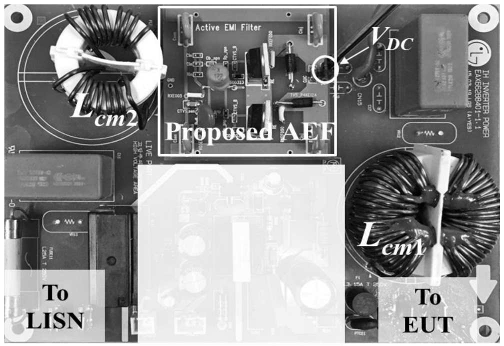
Design Flow of the VSCC AEF with Surge Protection



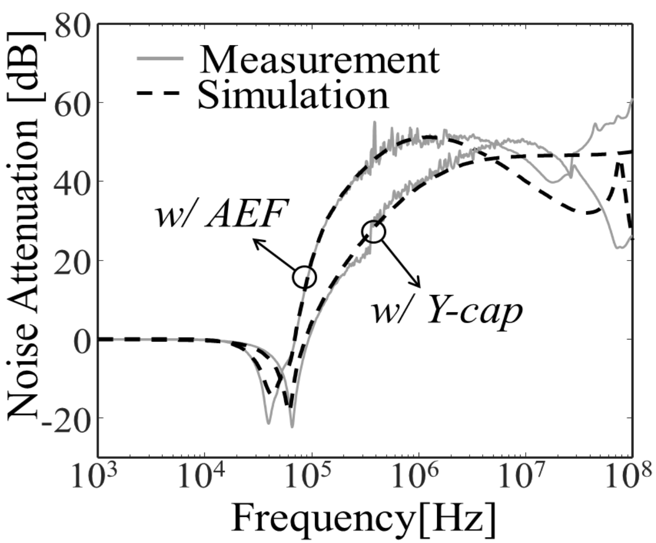


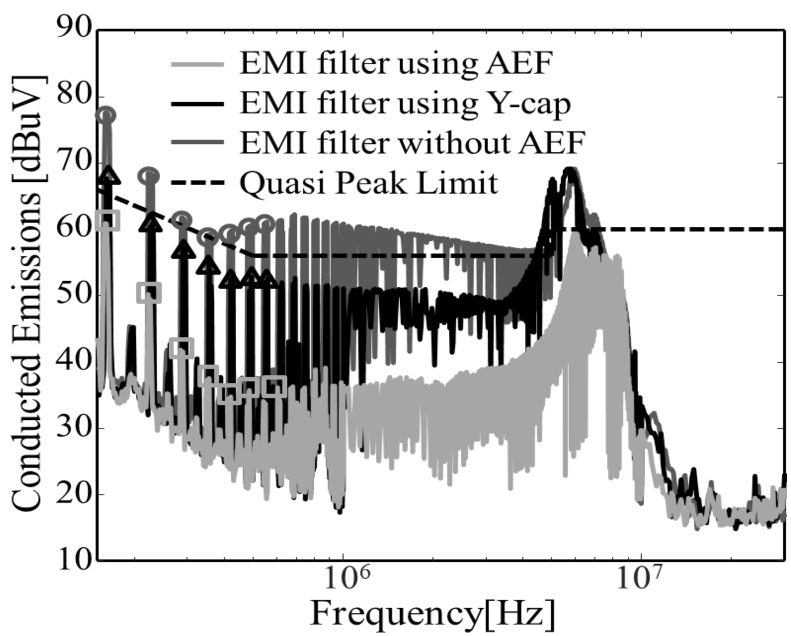
- The AEF's immunity against high voltage surge transients is tested and guaranteed.

CE Measurements of the AEF installed on an Inverter

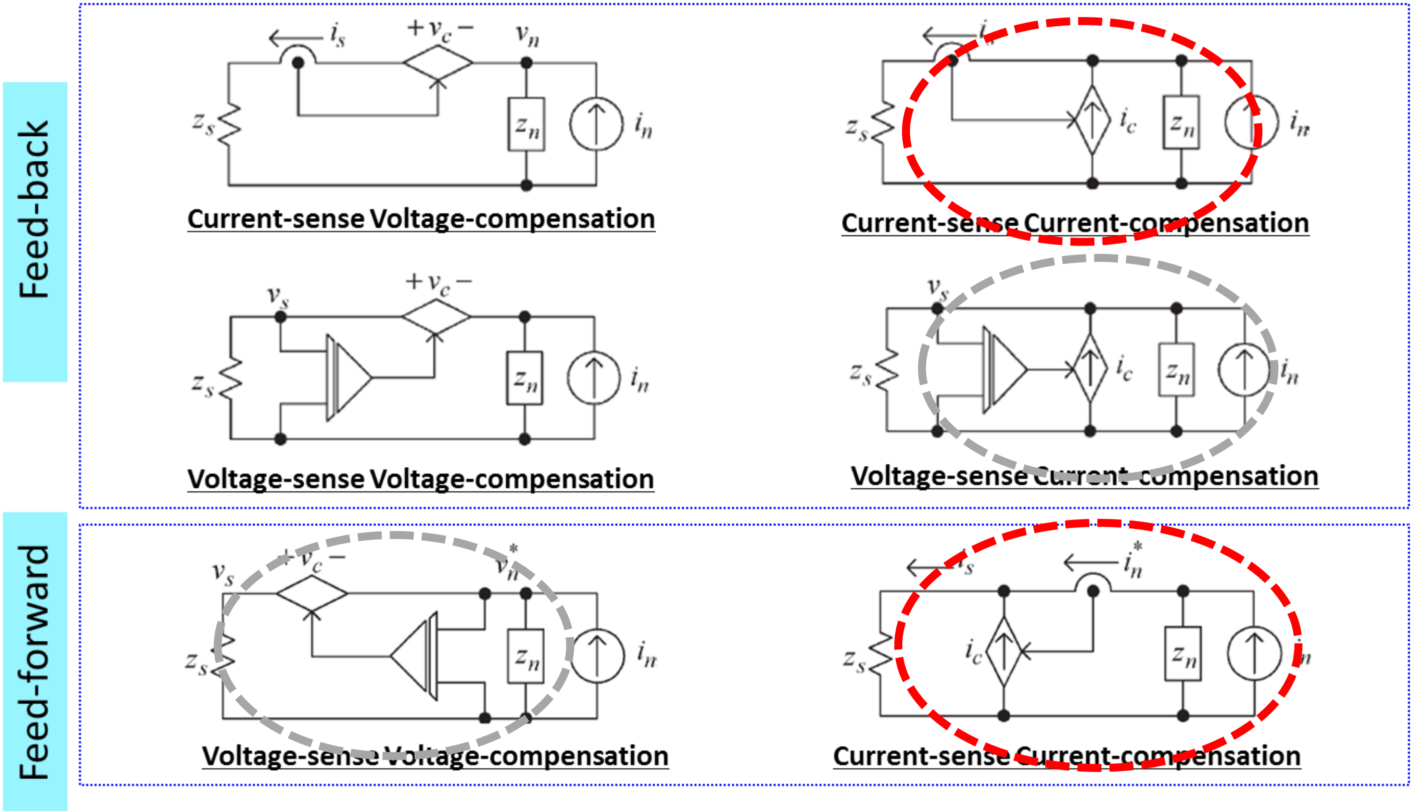


- For a fair comparison, the value of C_Y is set as the sum of C_{sen}, C_{inj}, and C_{inp}, which are utilized in the filter with the AEF.
- The AEF is implemented into a real 2.2 kW current resonant inverter, and the CE are reduced by 5dB to 25 dB at a frequency range from 150 kHz to 6 MHz.
- The AEF can be embedded inside a real product without increasing the size and cost.





Other developed AEFs



- Sangyeong Jeong, et al, Jingook Kim, "A Transformer-Isolated Common-Mode Active EMI Filter without Additional Components on Power Lines", Early Access Articles, IEEE Transactions on Power Electronics, 2018.
- Dongil Shin, et al, Jingook Kim, “A Balanced Feedforward Current-Sense Current-Compensation Active EMI Filter for Common-Mode Noise Reduction”, under revision, IEEE Transactions on EMC, 2018.

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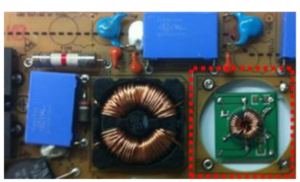

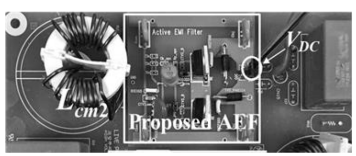

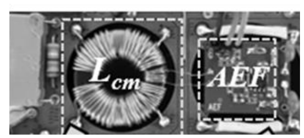

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Conclusion

- An EMI filter employing the AEF can be smaller, cheaper, and lighter than a passive-only filter.
- The design guidelines for two types of compact AEFs were derived for performance, stability, and high voltage immunity.
- More reliable other new AEFs are also being developed.
- The AEFs are ready to be practically utilized in real home appliance products.