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 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.

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)

Current-sense Voltage-compensation

Voltage-sense Voltage-compensation

Feed-forward

Voltage-sense Voltage-compensation

Current-sense Current-compensation

Voltage-Compensation AEFs

- 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

- 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

Two Types of VSVC AEF

**Feed back type**

\[
\begin{align*}
Z_{\text{in}} &= (1 + A)(Z + sL) \\
1 + A &
\end{align*}
\]

**Input Impedance**

**Impedance Boosting**

\[
Z_n + \frac{(1 + A)(sL + Z)}{Z + sL + Z_n}
\]

**Noise Attenuation**

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

- High turn ratio transformer required
- High Gain amplifier required

**Feed forward type**

\[
\begin{align*}
Z_{\text{in}} &= \frac{Z + sL}{1 - A} \\
\frac{1}{1 - A} &
\end{align*}
\]

**Input Impedance**

**Impedance Boosting**

\[
Z_n + \frac{sL + Z}{Z + sL + Z_n}
\]

**Noise Attenuation**

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

\[
\text{LoopGain} = -\frac{V_{oc}}{V_{t}} = \frac{Z_{1} \parallel \frac{1}{sC_{in}}}{Z_{in1} + Z_{1} \parallel \frac{1}{sC_{in}}} A_{v}
\]

\[Z_{in1} = Z_{cm} + Z_{inj} + Z_{LISN}\]

\[A_{v} = -\frac{sM_{inj}A_{op}}{sL_{inj} + R_{o} + \frac{1}{sC_{o}}}\]

- Stability and noise attenuation can be analyzed from the feedback loop gain.
Noise Attenuation by Impedance Boosting

- **Input Impedance**

\[
Z_{in} = \frac{1}{1 + \text{LoopGain}} = \frac{\frac{1}{sC_{in}} \parallel Z_{in1}}{1 - A_v} = Z_1 \parallel \frac{\frac{1}{sC_{in}} \parallel Z_{in1}}{1 - A_v} = Impedance\ boosting\ when\ A_v = 1
\]

- **Noise Attenuation Factor**

\[
NA = \frac{i_{CM, w/ AEF}}{i_{CM, w/o AEF}} = \frac{Z_{in1}}{1 - A_v} + \frac{1}{sC_{in}} || \frac{Z_1}{Z_n} = \frac{Z_{in1}}{1 - A_v} + \frac{Z_1}{sC_{in}} || \frac{Z_n}{Z_L + Z_{LISN}}
\]

- 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) - $C_{\text{in}}$ and $C_{\text{sen}}$

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

\[
(Z_n \parallel Z_1) \gg \frac{1}{sC_{\text{in}}} \geq \frac{1}{sC_Y} \quad \frac{1}{sC_{\text{sen}}} \geq \frac{1}{sC_Y}
\]
Design of FF-VSVC AEF (2) – Compensation Part

Design of $C_o$, $A_{\text{amp}}$, $f_o$, $R_o$, $L_{\text{inj}}$

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

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

Minimum operation frequency

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

Considering the max current of the OP amp

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

- $A_{\text{amp}}$ is designed to be $1/k_{\text{inj}}$, and the ratio of $L_{\text{inj}}$ and $R_o$ is determined by the minimum operation frequency $f_o$.

- Small $R_o$ and $L_{\text{inj}}$ 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**

- $R_1$ 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.

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

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

\[
|A_{amp}| \approx \frac{R_2}{R_1} = \frac{1}{k_{inj}}
\]
Design of FF-VSVC AEF (4) – Stability Check

- 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

\[ 1/Y_{21} = \frac{V_1}{I_2} \mid_{V_2=0} \]

\[ S_{21} = \frac{V_2^-}{V_1^+} \mid_{V_2^+=0} \]

![Graph of impedance vs. frequency](image1)

![Graph of S21 magnitude vs. frequency](image2)
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 VSVCAEF

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.

Overcurrent path to the compensation part

- Induced 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.
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.

**When the diode is **Turn-off**: \[ I_d = 0, \quad I_{o1} = I_{o2}, \quad V_{br} > \frac{R_{o,p2}}{R_{o,p1} + R_{o,p2}} V_{Linj} \Rightarrow V_{Linj} < \frac{R_{o,p1} + R_{o,p2}}{R_{o,p2}} V_{br} \]

\[ I_{op.out} = \frac{V_{Linj}}{R_{o,p1} + R_{o,p2}} < \frac{V_{br}}{R_{o,p2}} \]

$V_{br}$ : Diode break down voltage

**When the diode is **Turn-on**: \[ V_{br} < \frac{R_{o,p2}}{R_{o,p1} + R_{o,p2}} V_{Linj}, \quad \Rightarrow \quad V_{Linj} > \frac{R_{o,p1} + R_{o,p2}}{R_{o,p2}} V_{br} \]

\[ I_{o1} = \frac{V_{LO} - V_C}{R_{o1}} \]

\[ I_{op.out} \approx I_{o2} = \frac{V_C}{R_{o,p2}} \]

$V_{C}$ : Diode clamping voltage
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.

Break-down voltage of external TVS diode should be lower than that of internal ESD diode.
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.

R₁ or R₁,p₁ should be strong against the overvoltage surge pulse.

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

\[ V_{Linj} < \frac{R_{o1} + R_{o2}}{R_{o1}} V_{br} \]

\[ V_{Linj} > \frac{R_{o1} + R_{o2}}{R_{o2}} V_{br} \]

\[ I_{op, out} < \frac{V_{br}}{R_{o2}} \]

\[ I_{op, out} = \frac{V_{C}}{R_{o2}} \]

- \( R_{o,p1} \) 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)
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.

### Measured Waveform of Sensing Part

#### Circuit Diagram

- $V_{cc}$
- $I_{op,in}$
- $V_{op,in}$
- $R_{op,in}$
- $C_{sen}$
- Option 1: $n1$ to $n2$
- Option 2: $n2$ to $n3$

#### Waveform Plots

- **$I_{op,in}$**
  - The internal ESD-diode turn on and inrush current increases.
  - Graph shows $I_{op,in}$ vs. time (msec).

- **$V_{op,in}$**
  - Graph shows $V_{op,in}$ vs. time (msec) for different protection options.

- **$V_{op,in}$**
  - Graph compares $V_{op,in}$ vs. time (msec) for different protection options.
Performance Degradation Effect of Diode

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

Voltage-sense Voltage-compensation

Current-sense Current-compensation

Voltage-sense Current-compensation

Feed-forward

Current-sense Current-compensation

Voltage-sense Voltage-compensation

Voltage-sense Voltage-compensation

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 BJT.

The proposed AEF can enhance the Y-cap in the LCL filter.
Loop Gain and Impedance Analysis

(Closed-loop transfer function) = \[ \frac{V_{AEF}}{I_n} = \frac{A}{1 + A\beta_i} \]

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

(AEF impedance) = \[ \frac{V_{AEF}}{I_b + I_o + I_f} = \frac{A}{1 + A(\beta_1 + \beta_2 + \beta_3)} \]

\[ A = \frac{Z_{BJT}Z_{sen,FB}}{Z_f || Z_{BJT}} \]

\[ \beta_i = \frac{Z_f || Z_{BJT}}{Z_{sen,FB} || Z_{BJT}} \left( \frac{Z_\pi}{\alpha} \right) \]

\[ \beta_1 = \frac{Z_f || Z_{BJT}}{Z_{sen,FB}} \frac{1}{Z_f} \]

\[ \beta_2 = \frac{Z_f || Z_{BJT}}{Z_{sen,FB}} \frac{1}{Z_f} \left( \frac{\alpha}{Z_\pi} \right) \]

\[ \beta_3 = \frac{Z_f || Z_{BJT}}{Z_{sen,FB}} \frac{1}{Z_f} \left( \frac{g_m - \alpha}{Z_\pi} \right) \]
Noise Attenuation by the AEF

- The effective Y-cap impedance, is much decreased compared to \((Z_{\text{sen}} || Z_{\text{inj}})\), which results in a large increase of the NA.

- However, \(Z_{\text{AEF}}\) 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

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

- **at the low frequency**

\[ Z_{AEF0,low} \approx Z_{sen} || Z_{inj} = \frac{1}{s(C_{sen} + C_{inj})} \]

- **at the high frequency**

\[ Z_{AEF0,high} \approx \frac{Z_{sen}Z_{inj}}{Z_{bias}} + \frac{1}{g_m} + R_e + \frac{2}{sC_L} + 2R_L \]

- 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

• $R_e$ of 1~4 $\Omega$ 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.

$\text{BJT emitter voltage at the sat. region}$

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

$\text{CM noise current } I_n$ \[ \gg I_n \]

$\text{The amplifier maximum output current}$

$\text{DC bias analysis of the BJT}$

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

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

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.
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.
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

1. Maximum capacitance with in safety regulation ($C_{T_{max}}$)
2. CM choke
3. The operation frequency ($f_{op}$)

**Step1. Sensing and injection Capacitor**
- $C_{inp}$, $C_{sen}$, $C_{inp}$, and $C_{DC}$ are designed by using (20), (26) and (27)

**Step2. Push-pull Amplifier Design**
- The selection of complementary BJT by using (28), (29)
- Bias Circuit Design by using (30), (31), (32), (34)

**Step3. Damping Circuit Design**
- The circuit parameters in $Z_f$ are selected by using (40), (41), (43)
- The circuit parameter in $Z_m$ are selected by using (38), (42)

\[ \angle LoopGain \neq 180^\circ \]

- $R_m$ \uparrow
- $C_f$ \uparrow

**Step4. Protection Circuit Design**
- $T_1$ is selected by using (45) and (48)
- $M_3$ is selected by using (46) and (47)

- 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

Huge, heavy, and expensive EMI filter... No more!

Most of the critical issues have been resolved now.
(Reliability, immunity, power, stability)

We use IC design technology in EMI filter.

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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.