Active EMI filters to reduce size and cost of EMI filters in automotive systems

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Introduction

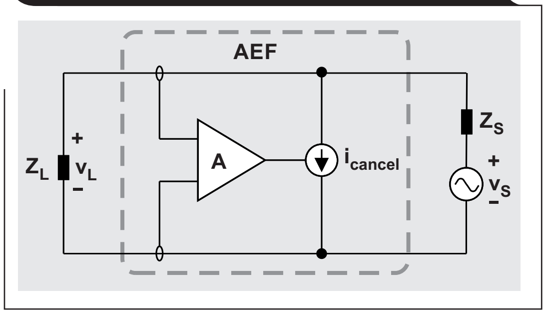
Electromagnetic interference (EMI) is an inherent problem in all modern electronic devices, hence most electronic devices have to pass stringent EMI regulations in order to be on the market. As the automotive industry moves to autonomous driving, more advanced infotainment systems, and hybrid or all-electric cars, automotive power converters need to process more power and be smaller and more sophisticated. As a result, EMI has become a major challenge for power electronics designers. Conventional passive EMI filters, which are comprised of inductors and capacitors, can be one of the biggest volumetric parts in automotive power electronics systems.

A promising solution to this challenge is an integrated active EMI filter (AEF), which uses active circuits to sense noise and inject an appropriate cancellation signal to reduce EMI. This article provides an overview of a differential-mode AEF implementation based on the LM25149-Q1, a buck controller with an integrated AEF. Test results show that when compared to a traditional passive filter, the EMI filter of a designed 400-kHz converter with AEF is nearly 50% smaller in area and has a volume reduction of over 75%.

AEF concepts

Figure 1 shows the equivalent circuit of an AEF; v_S is a noise source, Z_S is the internal impedance and Z_L represents the load.

Figure 1. Equivalent circuit of an AEF



The AEF senses the noise voltage, v_L, amplifies the noise voltage and injects a cancellation current, i_{cancel}, into the system. Assuming that the gain from v_L to i_{cancel} is A, Equation 1 expresses the equivalent impedance of the AEF as:

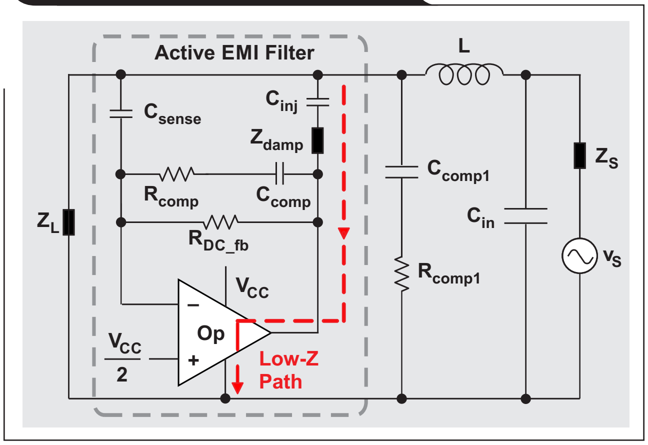
$$Z_{eq} = \frac{v_L}{i_{cancel}} = \frac{v_L}{Av_L} = \frac{1}{A} \tag{1}$$

Having a large gain creates a low-impedance path to shunt noise current, which makes it possible to reduce V_L.

AEF implementation

Figure 2 shows an implementation of an AEF where Z_L represents the impedance of line-impedance stability networks or power sources; C_{in} represents the input capacitors of power converters; L is the differential-mode inductor; C_{sense} and C_{inj} are the sensing and injection capacitors, which also isolate the amplifier circuit from the power supply; C_{comp}, R_{comp}, C_{comp1} and R_{comp1} ensure system stability; and Z_{damp},which is comprised of a small resistor in parallel with a capacitor, is a damping network used to damp the resonance between the AEF and L.

Figure 2. AEF implementation



For this implementation, Equation 2 expresses the equivalent impedance of the AEF as:

$$Z_{eq\_AEF} = \frac{Z_{op} + Z_{damp} + Z_{C\_inj}}{1 + G_{op\_amp}} \tag{2}$$

where Z_{op} is the output impedance of the operational amplifier (op amp), G_{op_amp} is the voltage gain from the sensing node to the output of the op amp, and Z_{C_inj} is the impedance of the injection capacitor.

Inductor selection criteria

As shown in Figure 2, the AEF needs to work with L for noise filtering. There are two main criteria for selecting L: noise attenuation and op-amp saturation.

Noise attenuation

The AEF provides a low-impedance path and forms a voltage divider with L to reduce noise. In the concerned frequency range, the impedance of C_{in} is much smaller than that of L and the load impedance Z_L is much larger than the equivalent impedance of the AEF. As a result, Equation 3 calculates the noise reduction of L and AEF as:

$$A_{atten} = \frac{Z_{L\_inductor}}{Z_{eq\_AEF}} \tag{3}$$

where $Z_{L\_inductor}$ is the impedance of L.

Based on Equation 3, the following steps are a guide to design L for a given converter with the AEF:

1. Obtain the bare noise of the power converter—the noise of the power converter without any filtering—through actual measurements or simulations.
2. Determine the noise attenuation required according to Equation 4:

   $$A_{atten}\left[dB\right] = v_{bare}\left[dB\mu V\right] - v_{limit}\left[dB\mu V\right] + m\left[dB\right] \tag{4}$$

   where v_{bare} is the bare noise of the power converter, v_{limit} is the limit specified by related EMI standards and m is the safety margin (such as 6 dB).
3. Calculate the equivalent impedance of the AEF based on Equation 2.
4. Obtain the impedance of L based on Equation 3 and select the inductor.

The fundamental EMI spur at the switching frequency is typically higher than other spurs and determines the inductor value. For example, consider a 400-kHz converter with a dominant fundamental spur of 96 dBμV. If the related EMI standard limits the 400-kHz spikes to 56 dBμV, the noise attenuation needed with a 6-dB margin would be 46 dB, or 200 times.

For the LM25149-Q1 controller, the typical AEF configuration for 400-kHz converters is 100-nF C_{sense}, 50-kΩ R_{DC_fb}, 1-kΩ R_{comp}, 1-nF C_{comp} and 470-nF C_{inj}; Z_{damp} is a 220-nF capacitor in parallel with a 15-Ω resistor. With this configuration, at 400 kHz, $R_{comp}/Z_{C\_sense} = 2\omega f \times R_{comp}C_{sense}$ estimates G_{op_amp}, which is about 250; Z_{damp} is about 1.8 Ω; Z_{inj} is about 0.8 Ω; the open-loop output impedance of the integrated op amp is about 1 Ω; and the closed-loop output impedance, Z_{op}, is an estimated 0.5 Ω. Thus, according to Equation 2, the equivalent impedance of the AEF, Z_{eq_AEF}, is about 12.4 mΩ. And according to Equation 3, the impedance of L needs to be about 2.5 Ω at 400 kHz, which corresponds to a 1-μH inductance.

Op-amp saturation

Because the output voltage and current of the op amp are limited, another criterion is to make sure that the op amp will not saturate with the selected inductor. An AEF is typically saturated by the output current instead of the output voltage, which is attributed to the low impedance of the injection path. Equation 5 calculates the noise current flowing through the inductor as:

$$i_{op\_amp} = \frac{v_{bare}}{Z_{L\_inductor}} \tag{5}$$

If the voltage spur at the fundamental switching frequency, v_{bare_fund}, is higher than those at other frequencies, v_{bare_fund} would mainly determine the current flowing into the op amp. However, a certain margin needs to be left for the cumulative contributions of other frequency components. For 400-kHz converters, the margin should be about 25 mA and for 2-MHz converters, the margin should be about 35 mA. The minimum output-current capability of the AEF integrated in the LM25149-Q1 is about 65 mA. When using the AEF in a 400-kHz converter, the 400-kHz component of the current flowing through the AEF should be less than 40 mA. Assuming a dominant fundamental (400 kHz) bare noise spur of 100 mV, the impedance of the inductor needs to be greater than 2.5 Ω to prevent saturation of the AEF.

PCB layout considerations

For effective high-frequency performance of the AEF, care should be taken during printed circuit board (PCB) layout to prevent coupled noise from contaminating the AEF output. Table 1 lists the AEF-related pins of the LM25149-Q1.

Table 1. AEF-related pins of the LM25149-Q1

Pin Name	Description
AVSS	Active EMI bias ground connection
INJ	Active EMI injection output
SENSE	Active EMI sense input
AEFVDDA	Active EMI bias power. Connect a ceramic capacitor between AEFVDDA and AVSS
REFAGND	Active EMI reference ground
CNFG	Connect a resistor to ground for single- or multi-phase operation, spread spectrum enable/disable or interleaved operation. After start-up, CNFG is used to enable AEF

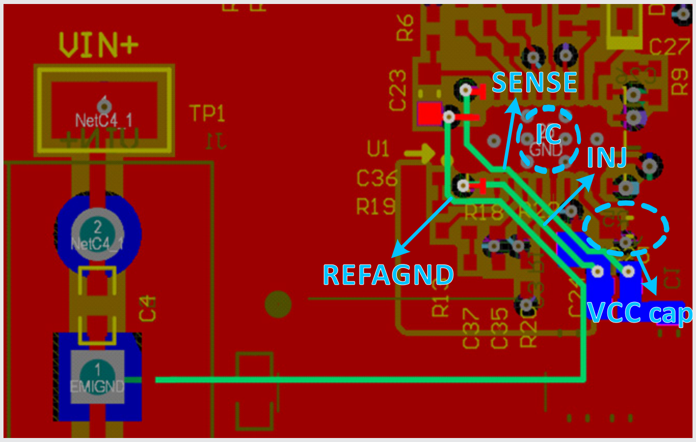
For effective AEF performance in the LM25149-Q1, follow these guidelines during PCB layout:

- The SENSE, INJ and REFAGND traces should be in parallel, on a quiet layer and as close together as possible to minimize near-field coupling. Avoid noisy layers or layers carrying high-voltage traces. REFAGND should not be between SENSE and INJ traces. Do not route these three traces under the integrated circuit (IC) or close to noise traces or components, such as the V_{CC} capacitor of the IC.
- Route REFAGND directly to a quiet ground, perhaps the ground near the sense/inject node. REFAGND is the most critical pin from noise perspective. A noisy REFAGND pin could significantly affect the performance of the AEF. Do not ground any capacitor to the REFAGND pin or REFAGND trace.

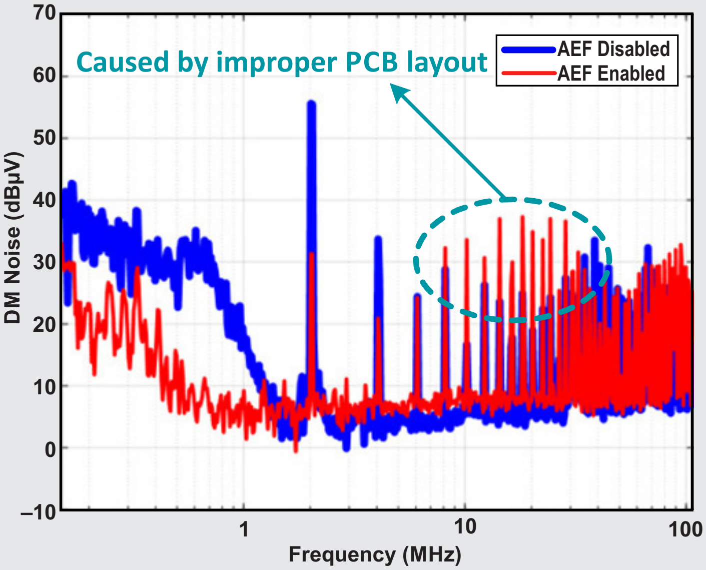
- Connect AVSS to a quiet ground connection as well, further from the IC if possible. Do not directly connect AVSS to the grounding/thermal pad of the power-controller IC. Keep the decoupling capacitor of the AEF bias supply close to the AEFVDDA pin and AVSS ground connection.
- Place the high-frequency compensation components, R_{comp1} and C_{comp1}, near the other AEF components. Ensure that the ground connection is far away from any noise source; in other words, do not ground this branch near the power stage or input capacitors.

Figure 3a shows an improper PCB layout, where the SENSE, INJ and REFAGND traces are too close to the IC and V_{CC} capacitor. This would introduce coupling to the AEF and affect its performance. Figure 3b shows the measurement results with this layout, where the increased noise between 8 MHz and 30 MHz with AEF enabled is visible. Figure 4 shows a good PCB layout that can fix this issue.

Figure 3. Poor PCB layout example

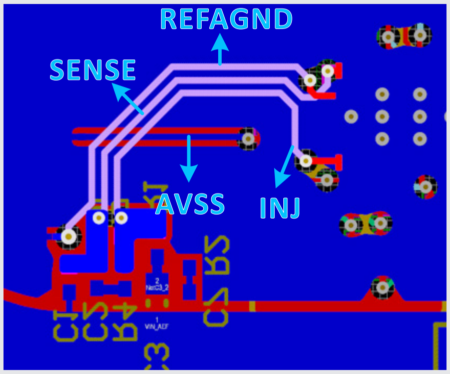


(a) Poor layout of AEF traces



(b) Measurement results with poor layout

Figure 4. Example of a proper PCB layout for superior AEF performance



Size and volume reduction with an AEF

The AEF implemented in the LM25149-Q1 offers excellent EMI reduction with reduced filter components, as shown in the measurement results in Figure 5. We conducted the measurements with a 440-kHz switching frequency, an input voltage of 12 V and an output of 5 V/5 A. For the AEF, L is 1 µH, C_{sense} is 100 nF, C_{comp} is 1 nF, R_{comp} is 1 kΩ, C_{comp1} is 100 nF, R_{comp1} is 0.5 Ω, R_{DC_fb} is 50 kΩ, C_{inj} is 470 nF and the damping network is a 220-nF capacitor with a 15-Ω resistor in parallel.

For comparison, the passive EMI filter is a 3.3-µH differential-mode inductor with two 10-µF differential-mode capacitors and two 100-nF differential-mode capacitors in parallel. Between the AEF and passive filter solutions the size and volume of the AEF for the same attenuation is about 50% and 75% smaller, respectively, as listed in Table 2. The estimates in Table 2 consider all of the external components needed by the AEF and the increase in size from the actual PCB layout. Along with density benefits, the AEF also offers a lower-cost solution by not needing large inductors and capacitors.

Figure 5. Differential-mode noise spectrum with a passive filter and an AEF

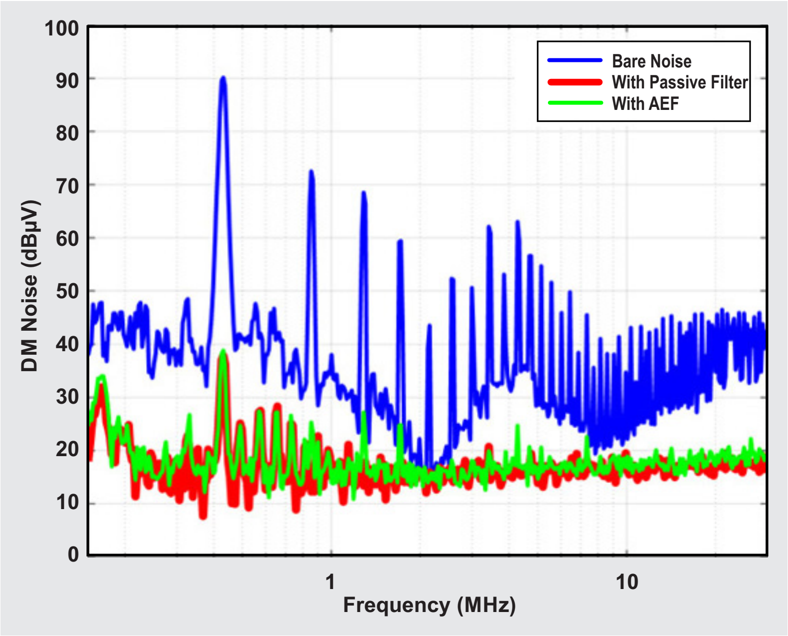


Table 2. Size and volume comparison of a passive filter and an AEF

	Size	Volume
Passive filter	110.7 mm^2	136.3 mm^3
AEF	55.9 mm^2	32 mm^3
Reduction	~50%	>75%

Conclusion

Active EMI filters are an excellent alternative to traditionally bulky and expensive passive filters. Power electronics designers can take advantage of the AEF integrated into TI's automotive controller, the LM25149-Q1, to deal with EMI challenges in automotive environments, and to improve the power density and reduce the cost of their power solutions.

References

1. Y. Chu, S. Wang and Q. Wang, "Modeling and Stability Analysis of Active/Hybrid Common-Mode EMI Filters for DC/DC Power Converters," in IEEE Transactions on Power Electronics, vol. 31, no. 9, pp. 6254-6263, Sept. 2016, doi: 10.1109/TPEL.2015.2502218.
2. Orlando Murray, "How to reduce EMI and shrink power-supply size with an integrated active EMI filter," TI E2E™ blog, April 5, 2021.

Related Web sites

Product information:
LM25149-Q1

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