How to ensure the stability and performance of an active EMI filter

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Introduction

As an excellent alternative to traditional bulky and expensive passive filters, active electromagnetic interference filters (AEFs) can help designers deal with ever-increasing EMI challenges, improve power density, and reduce the cost of power solutions. References [1] and [2] demonstrate an approximate 50% size reduction and >75% volume reduction with an AEF implemented in the Texas Instruments **LM25149-Q1** buck controller.

Most AEFs use operational amplifier (op amp)-based active circuits to sense noise and inject an appropriate cancellation signal to reduce EMI, such as the AEF integrated into the **LM25149-Q1**. To achieve the best performance with this kind of AEF, the op-amp circuits need to be stable and the op amp should not saturate. Otherwise, the AEF would have worse performance and may even inject additional noise into the system [3]. This article discusses the proper compensation and damping techniques to achieve stability and the best performance of an AEF.

AEF compensation

Figure 1(a) shows an AEF with no compensation. In **Figure 1**, V_S is a noise source, Z_S is the internal impedance, 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, R_{DC_fb} is to provide DC feedback for the Op_amp and C_{para} is the parasitic capacitance between the power trace and ground.

As an op amp-based feedback circuit, the AEF in **Figure 1**(a) could become unstable, which would saturate the op amp. In such cases, the performance of the AEF could be significantly affected, and the AEF may consume more power and inject extra noise into the system [3]. Since the loading network of the op amp is complex, the AEF in Figure 1a could be unstable at both low and high frequencies.

At low frequencies (such as between 10 kHz and 50 kHz), the phase of the loop gain can go to positive 180 degrees and the system can become unstable, primarily because of the voltage dividers formed by C_{inj} and L, and by C_{sen} and R_{DC_fb}. One method for low-frequency compensation is to add R_{comp} and C_{comp} in parallel with R_{DC_fb}, as shown in **Figure 1**(b). C_{comp} is for low-frequency compensation by making the feedback network capacitive at low frequencies. R_{comp} is to ensure the performance of the AEF. In addition, there are typically electrolytic capacitors at the input of the converter to store energy and ensure converter stability. The equivalent series resistance (ESR) of the electrolytic capacitors also helps with low-frequency stability.

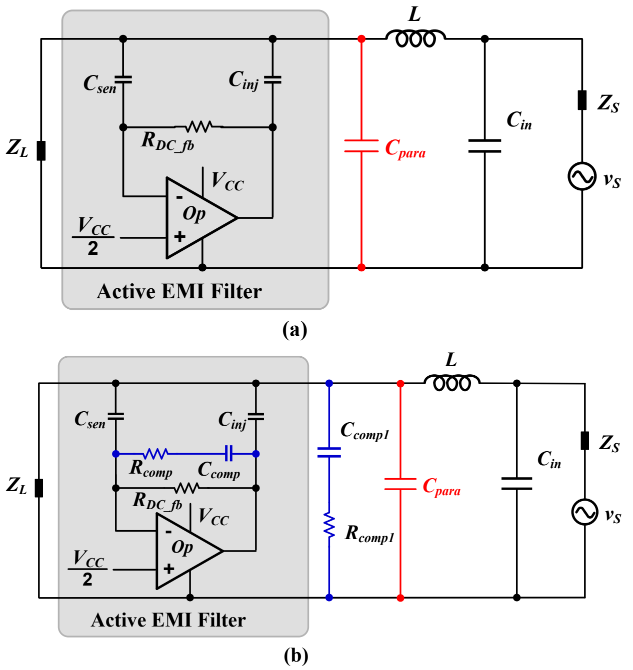

Figure 1. *An AEF with no compensation (a); with compensation (b).*

At high frequencies, the output impedance of the op amp and C_{para} will generate a pole and cause phase lag of the loop gain. In addition, op amps typically have a low-frequency pole. As a result, the loop gain will have two poles at high frequency and its phase goes close to negative 180°, which can cause high-frequency instability. R_{comp1} and C_{comp1} in **Figure 1**(b) are for high-frequency compensation, which can be 100 nF and 0.5 Ω. R_{comp1} and C_{comp1} can boost the phase of the loop gain at high frequencies so that the system has enough phase margin to ensure high-frequency stability. In certain applications, high-frequency ceramic capacitors (such as 10 nF or 100 nF) are necessary for high-frequency noise filtering or for protection circuits, such as smart diodes for reverse protection. In such cases, there are several ways to maintain high-frequency stability:

- Insert ferrite beads between the sense/inject node and the high-frequency ceramic capacitors to decouple them.
- Add small resistors in series with the high-frequency capacitors for compensation.
- Place high-frequency capacitors far from the AEF, since the ESRs and equivalent series inductances (ESLs) of the ceramic capacitors and printed circuit board traces can also help with high-frequency stability.

Overall, it is essential to make sure that the impedance of the sense/inject node to ground is not dominated by capacitance at high frequencies (between 10 MHz to 50 MHz).

AEF damping

Because of thermal variation or switching jitter, power converters may generate noise at frequencies lower than their switching frequencies, which is referred to as low-frequency disturbance in this article. For the AEF in **Figure 1**(b), **Equation 1** expresses its equivalent impedance as:

$$Z_{eq\_AEF} = \frac{Z_{op} + Z_{C\_inj}}{1 + G_{op\_amp}} \qquad (1)$$

where Z_{op} and G_{op_amp} are the output impedance and voltage gain from the sensing node to the output of the op amp and Z_{C_inj} is the impedance of the injection capacitor [**2**].

According to **Equation 1**, the equivalent impedance of the AEF in **Figure 1**(b) is capacitive at low frequency. As a result, the AEF can resonate with differential mode inductor L at low frequencies, such as between 10 kHz to 100 kHz. Given the resonance, the low-frequency disturbance could lead to a large op-amp output voltage and output current. As the op amp has limited output swing and output current capability, the op amp could enter the nonlinear region or even become saturated, potentially affecting AEF performance and causing the AEF to inject additional noise into the system.

Dealing with this problem requires damping the resonance. **Figure 2** shows two damping methods by making the AEF less capacitive at the resonant frequency. In **Figure 2**(a), a damping resistor, R_{damp}, is inserted in the injection path. In this way, the larger R_{damp}

is, the better the resonance damping. With the damping network inserted, however, **Equation 2** expresses the equivalent impedance of the AEF as:

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

where Z_{damp} is the impedance of the damping network [2].

A large R_{damp} would increase Z_{eq_AEF}, thus affecting the performance of the AEF. So this damping method mainly works for high-frequency switching converters, such as 2 MHz. To effectively damp the resonance, the quality factor should be around or below 1. To get the quality factor near 1, calculate R_{damp} according to **Equation 3**:

$$R_{damp} = \sqrt{\frac{G_{op\_amp}L}{C_{inj}}} \quad (3)$$

To improve the performance of the AEF shown in **Figure 2**(a), place a capacitor, C_{damp}, in parallel with the damping resistor, R_{damp}, as shown in **Figure 2**(b). At the resonant frequency, resistor R_{damp} dominates the impedance of the damping network to damp the resonance. At high frequencies where the AEF needs to attenuate noise, capacitor C_{damp} dominates the impedance of the damping network, thereby ensuring the performance of the AEF. Following a similar optimization method as described in [4], **Equation 4** and **Equation 5** express a good combination of R_{damp} and C_{damp} for the resonance damping:

$$C_{damp} = \frac{1}{2}C_{inj} \quad (4)$$

$$R_{damp} = \sqrt{\frac{G_{op\_amp}L}{C_{inj}}} \quad (5)$$

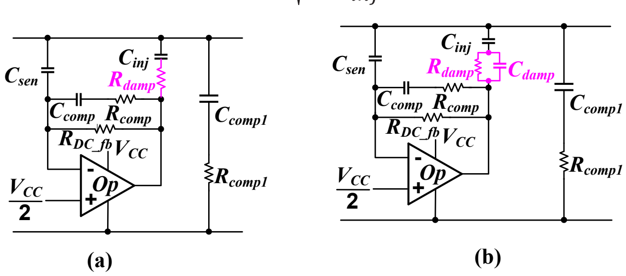

Figure 2. *Methods to damp the differential mode inductor and AEF resonance: resistor damping (a); resistor and capacitor parallel damping (b).*

Figure 3 shows the spectrum test results from 10 kHz to 1 MHz of a 400-kHz buck converter with AEF off, with AEF on but no damping, and with AEF on and with resistor-capacitor parallel damping where R_{damp} and C_{damp} are selected based on **Equation 4** and **Equation 5**. In **Figure 4**, without damping, there is a spike at about 30 kHz from the resonance, which affects the AEF performance and increases the noise floor. With the damping network, the resonance spike is now at 45 kHz but with its magnitude greatly reduced, which means that the resonance is successfully damped. As a result, the AEF effectively suppresses the high-frequency noise and the noise floor is much lower.

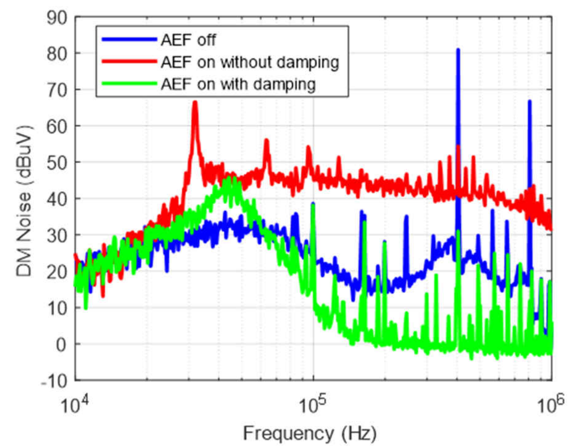

Figure 3. *Test results with and without damping.*

AEF performance with both compensation and damping

With proper compensation and damping, an AEF can achieve significant noise reduction, as shown in **Figure 4**. The measurement with a 440-kHz power converter was conducted, an input voltage of 12 V and an output of 5 V/5 A. Both the AEF and the converter are implemented with the LM25149-Q1. L is 1 µH, C_{sense} is 100 nF, R_{DC_fb} is 50 kΩ and C_{inj} is 470 nF. For compensation, 1-kΩ R_{comp} and 1-nF C_{comp} are used for low-frequency compensation, and 0.5-Ω R_{comp1} and 100-nF C_{comp1} are used for high-frequency compensation.

For damping, a resistor and capacitor parallel damping is used; R_{damp} is 15 Ω and C_{damp} is 220 nF. As shown in **Figure 4**, the AEF can achieve about 50 dB of noise attenuation at 440 kHz. Compared to a passive filter with similar performance, it is possible to achieve about a 50% size reduction and about a 75% volume reduction [1], [2].

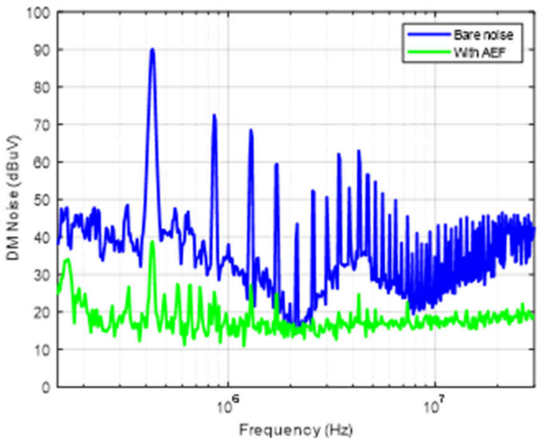

Figure 4. *Noise reduction of a properly compensated and damped AEF.*

Conclusion

Compensation and damping are important in achieving the best AEF performance. The methods discussed in this article can all be easily implemented with the AEF integrated into the LM25149. With proper compensation and damping, an AEF can achieve significant noise reduction. Power electronics designers should take advantage of AEFs for higher power density, high efficiency and lower cost.

References

1. Murray, Orlando. **How to reduce EMI and shrink power-supply size with an integrated active EMI filter**. TI E2E™ design support forums technical article, April 5, 2021.
2. Texas Instruments: ***Active EMI filters to reduce size and cost of EMI filters in automotive systems***.
3. Chu, Yongbin, Shuo Wang, and Qinghai Wang. **Modeling and Stability Analysis of Active/Hybrid Common-Mode EMI Filters for DC/DC Power Converters**. Published in IEEE Transactions on Power Electronics 31, no. 9 (September 2016): pp. 6254-6263. doi: 10.1109/TPEL.2015.2502218.
4. Xing, Lei, Frank Feng, and Jian Sun. **Optimal Damping of EMI Filter Input Impedance**. Published in IEEE Transactions on Industry Applications 47, no. 3 (May-June 2011): pp. 1432-1440.

Related Websites

Product information:

- **LM25149-Q1**

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