Hybrid Common-Mode EMI Filter With Active Impedance Multiplication

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Abstract—This paper presents a novel hybrid common-mode (CM) electromagnetic interference filter for a military power supply. The proposed filter is composed of an active impedance multiplication circuit cascaded with a benchmark CM inductor. The active impedance multiplication circuit is very effective in boosting the impedances of both the benchmark CM inductor and the noise source. Thus, the total equivalent impedance of the filter is enlarged by the active booster to a great extent. An important advantage of this approach is that only a small-size CM choke is used as the passive filter instead of a traditional CLC filter. Furthermore, the noise source is turned to be an inevitable part of the hybrid filter by the impedance multiplication effect. Experimental results were carried out according to MIL-STD-461. It is shown that the proposed approach can acquire good noise attenuation performance within a wide frequency range.

Index Terms—Active filter, common mode (CM), electromagnetic interference (EMI), hybrid filter, impedance multiplication.

I. INTRODUCTION

Electromagnetic interference (EMI) filters have been widely used for years to solve conducted EMI problems for many electronic applications. A typical three-order common-mode (CM) EMI filters is shown in Fig. 1. It is acknowledged that minimizing shunt-path impedance and maximizing series-path impedance at high frequencies are an effective way to achieve good noise attenuation.

However, CM noise cannot be reduced by using an arbitrarily large value of \( C_Y \), since this capacitor is usually limited by the safety standard that specifies the maximum leakage current allowed flowing to the ground. Therefore, in most instances, designers have to resort to a larger CM inductance. For this reason, the size and weight of PEFs or even the whole equipment are very huge.

Hybrid EMI filters (HEFs) are proposed to overcome these problems [1]-[9]. A planar passive filter with an active filter is reported in [5]. A HEF designed for a motor drive system is introduced in [3], where active filters were used to optimize the passive filter performance. Detailed analysis and quantitative calculation of the hybrid filter parameter are reported in [2].

Moreover, the impedance feature and the connection between passive and active filters are studied in [8]. What is more, Zhu et al. [6] proposed a hybrid ripple filter in dc/dc converters. Furthermore, an intensive study of the hybrid filter has just been made by Ostroznik et al. recently [1]. Nevertheless, in the authors’ opinion, there are still two major problems that need to be paid more attention to. First, for the hybrid filter system, active EMI filters (AEFs) and PEFs are often treated as two separated parts in most reported papers. The following questions are therefore raised: How will these two filter types (AEFs and PEFs) perform when placed in one hybrid filter system? Is there any cooperation or interrelation between them? Second, when selecting a power line filter, the designer must be aware that the performance of the filter is dependent on the source and load impedance to a great extent. Another question also comes into mind. If HEFs have also such problems, then are there any approaches to maximize the HEF noise attenuation in a real environment?

In an effort to obtain insight into these questions, investigations are carried out in this paper. A novel approach that uses an active circuit to increase the impedances of both the inductor and the noise source is proposed. A distinguished advantage of this approach is that the equivalent CM impedance of the passive component, as well as that of the noise source, is boosted by the active circuit entirely. Thus, only a small-size CM inductor but not a traditional CM filter (shown in Fig. 1) is used in the novel hybrid filter system. In addition, the increased noise impedance can also act as a necessary part of the whole filter system.

Section II explains the principle of the active impedance multiplication method. The design considerations of the proposed HEF for a military power supply is presented in Section III. Section IV gives experimental results. Conclusions are presented in Section V.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{Fig1.png}
\caption{Typical three-order CM EMI filter.}
\end{figure}

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II. PRINCIPLE OF THE ACTIVE IMPEDANCE MULTIPLICATION METHOD

A. Basic Active Multiplication Structure

The principle of the active impedance multiplication method is shown in Fig. 2. It is a current-controlled current source (CCCS) $A_i$ in parallel with a benchmark impedance $Z$. An important feature of this structure lies in the controlling current $i$ that is not on the impedance branch but on the input port AB. According to Thevenin’s theorem, the input impedance $Z_{in}$ of port AB can be calculated as follows:

$$Z_{in} = \frac{u}{i} = \frac{Z}{(A+1)i} = Z + AZ.$$  

(1)

Thus, if the original input impedance of port AB is $Z$, then, by introducing an active circuit in parallel with it, the impedance of $Z$ can be boosted by a factor of $A$, where $A$ is the current gain of the CCCS. This approach is called the active impedance multiplication method in this paper.

Proposed Filter Topology With Active Impedance

Based upon that idea, a topology of a HEF for CM noise reduction is proposed in Fig. 3. $R$ represents the CM impedance of the load—a standard line impedance stabilization network (LISN). $Z_n$ is the equivalent impedance of the noise source or equipment under test (E.U.T.). To achieve the function of the active multiplication method, the controlling current $i$ of the CCCS should be sampled on the load branch, and the CCCS should also be placed beside it. A single CM inductor $sL$, instead of a traditional three-order filter (as shown in Fig. 1), is used in the proposed system. It is because there is a CCCS to boost up the passive impedance, so only a small passive filter component is used here. Additionally, since the size of the CM inductor is usually much larger than that of the CM capacitor, reducing the passive filter size would be best to start from reducing the CM inductor size.

According to the active impedance multiplication method, it can be clearly observed that the impedances of both the inductor $sL$ and the noise source $Z_n$ are all increased by $A$ times. The equivalent impedance model is shown in Fig. 3(b). The physical meaning of this circuit can be explained as adding a boosted inductor $A sL$ and a boosted source impedance $AZ_n$ between the load $R$ and the noise source $Z_n$. Therefore, the larger the multiplication factor $A$, the greater the series component value $A sL$ and $AZ_n$, and the better the noise reduction effect. In a word, it is only by means of the correlation between the active multiplication circuit and the passive component followed that the filter impedance can be increased to a large extent.

Moreover, the increased noise impedance $AZ_n$ also acts as a necessary part of the whole filter system. It is noticed in Fig. 3(b) that there is always a certain part of noise voltage damped on the equivalent component $AZ_n$. Therefore, the noise source impedance, whether it may be large or not, will be a useful part of the filter.

Quantitative Comparison of Filter With and Without Impedance Multiplication

Insertion loss (IL) is generally used to characterize an EMI filter. IL is defined as the ratio of the signal level in a test configuration without the filter installed ($U_1$) to the signal level with the filter installed ($U_2$). In the proposed scheme, the IL of the single inductor is

$$IL_p = \frac{U_1}{U_2} = \frac{RZ_n}{R+Z_n+sL} \left(1 + sL R+Z_n \right).$$  

(2)
By means of impedance multiplication, the $IL$ of the novel filter system is described as follows:

$$IL_n = \frac{U_1}{U_2} = \frac{RZ_n}{R+Z_n+R+LZ_n}$$

$$= 1 + \frac{AsL}{R+Z_n}$$

$$= 1 + \frac{AsL}{R+Z_n} + R + LZ_n + R + Z_n.$$  \hspace{1cm} (3)

It can be seen from (2) and (3) that an additional insertion loss is introduced by cooperation among impedance multiplication $A_i$, inductor $sL$, and noise source $Z_n$.

$$IL' = \frac{AsL}{R+Z_n} + AZ_n.$$  \hspace{1cm} (4)

D. Simulation Analysis of Different Filter Types

Simulations are carried out first under ideal conditions without the knowledge of noise source. The passive component value $L$ is chosen as 50 mH. The factor of the active multiplication circuit is defined as a simplified open-loop transfer function $A(s)$, which will be discussed in detail later. Furthermore, the source impedance is modeled as constant $Z_{in_1} = 300 \Omega$ and $Z_{in_2} = 30 \Omega$. The simulated insertion loss of the CM inductor, the hybrid filter with an active booster, and the entire active circuit are shown in Fig. 4. It consists of the following features:

1) The noise attenuation of the hybrid filter with impedance multiplication is always higher than that of the single passive inductor or the active booster.

2) The insertion loss of the inductor increases with the increase of frequency, while for the active booster, the insertion loss curve is comparatively flattened. Thus, the hybrid filter with impedance multiplication combines the advantage of both of these filter types. At low-frequency range, the boosted impedance can provide a comparatively high insertion loss decibel, while at high-frequency range, the intrinsic high-attenuation feature of the inductor will be further amplified.

3) Although, for a fixed-value inductor, larger noise impedance will result in smaller insertion loss, this bad characteristic can be weakened in the hybrid filter. It is simulated under low-noise-impedance conditions, and the hybrid filter still maintains a decent attenuation decibel by the same filter parameters. This is because the insertion loss of the hybrid structure mainly comes from the boosted inductor and the boosted source impedance. For this reason, the noise attenuation of the proposed one is not only dependent on the value of passive filter component $sL$ but also highly dependent on the gain $A$ of the active multiplication circuit.

III. BASIC STRUCTURE OF THE PROPOSED EMI FILTER

The basic structure of the proposed EMI filter is shown in Fig. 5. To be as a benchmark of the active impedance booster, the CM inductor must be placed near the E.U.T.; otherwise, the multiplication approach will not be accomplished. The active circuit consists of a current-transformer (CT)-based sensor, an operational amplifier block, and a current injection branch. The active circuit plays two kinds of roles. On the one hand, it is used to accomplish the active multiplication method together with the followed inductor and the noise source so as to increase the impedance of these parts. On the other hand, it is constructed as an active filter. The CM noise is detected by the CT and then amplified and injected by the op-amp and capacitors, respectively.

In general, both feedback and feedforward control can be used in the active circuit. Although most reported filters use feedforward control, the reason why feedback control is chosen here comes from the following considerations.

1) The feedback control structure obtains the noise current at the process output, but the feedforward one obtains data at the process input. As a result, feedback control takes into account any possible disturbance that might cause EMI noise at the LISN terminal.

2) Feedback control does not require detailed knowledge about the noise source. Although the frequency range of EMI noise is wide, the feedback control architecture ensures the desired performance by altering the inputs immediately once deviations are observed regardless of what caused the disturbance.

3) In order to maximize the effect of impedance multiplication, the control factor $A$ of the CCCS is ideally infinite. Since the active circuit is essentially a single-loop system, it is comparatively easy for the op-amp to achieve
large gain in feedback control. While for feedforward control, \( A = 10 \) means that the op-amp gain will be 0.1. In addition, if \( A = 100 \), the op-amp gain will be 0.01. In most cases, such a high accuracy is difficult to implement and maintain for the op-amp.

4) Feedback control is a closed-loop system, which is essentially different from “open-loop” feedforward control. Therefore, by careful design and analysis, unstable processes may be stabilized through feedback control.

**PRACTICAL DESIGN CONSIDERATION OF THE HYBRID FILTER**

In this section, a detailed consideration of several practical issues related to the design of the hybrid filter is presented. To acquire an accurate result, the CM noise impedance of the E.U.T. is tested first. Then, the value of inductor \( L_{CM} \) is determined by taking into account the noise impedance, the forthcoming multiplication effect, and the limit of EMI regulation. Finally, the selection and specification of the components used in the active circuit are studied in detail.

**Description of the CM Noise Source Used in the Experiment**

It has long been recognized that noise impedance has a significant impact on the attenuation performance of the EMI filter, no matter what kind of filter it may be. Thus, in order to effectively attenuate the EMI noise over the frequency range of interest, the EMI filter must be designed to match the noise impedance.

A 1-kW power supply for military aviation is used as the noise source in our experiment. The rated output current is 5 A, and the output frequency is 15-2000 Hz. The system setup is shown in Fig. 6. According to the requirements for the control of the EMI characteristics of the power supply, a standard GJB152 is chosen for this application. It is defined from 10 kHz to 10 MHz for the conducted EMI noise and can be equivalently exchanged with MIL-STD-461 CE102.

The EMI noise detected by LISN will be separated into CM and DM by a noise separator. Since the CM noise, as well as the CM filter, is the main concern of this paper, only CM equivalent impedance is tested here. An insertion loss method proposed in [10] is used to measure the noise impedance. The equivalent CM impedance curve is shown in Fig. 7. The test results showed that the CM impedance of the E.U.T is within several kilohms.

In the whole hybrid filter system, the passive filter component is mainly used as a basic benchmark that needs further increase through the impedance multiplication circuit. Because of this, an appropriate value of \( L_{CM} \) will play an important role in the whole hybrid filter system.

Fig. 8 shows the measured spectrum of the E.U.T. when no filter is installed.
The injection network and CT are very small, which will give little help for improving the total gain $A(s)$. However, the curve of the op-amp circuit maintains a high gain level within a wide frequency range, which will play a very significant role in the whole filter system. The solid lines are the insertion losses of the CM inductor, the active circuit, and the hybrid filter. It can be seen that the CM noise is greatly reduced by the hybrid filter because of the active multiplication effect. There is a 20-30-dB improvement in the whole frequency range compared with the single CM inductor. At high frequency, it should be noted that the hybrid filter performance is not as good as that at low frequency. It is mainly because the benchmark impedance of the passive inductor decreases with the increase of frequency. That is, although the inductor is boosted by “$A$” times, the multiplication impedance cannot be too large. The parasitic cancellation method reported in [11] can be used to optimize the high-frequency performance of the inductor.

**Experiment**

In our experiment, an Agilent E7401A spectrum analyzer is used to measure the CM noise. First, measurements were conducted with a pure passive inductor and a pure active circuit. Fig. 18 shows the noise spectrum when only CM inductor $L_{CM}$ is installed. Although a 22-mH inductor is not a small-size component, dominant peaks can still be seen at the fundamental switching frequency (40 kHz). A reduction of about 10-15 dB is achieved by this entirely passive inductor when compared with the original CM noise. The experimental result of the active multiplication circuit is shown in Fig. 19. It can be seen that 20-30-dB attenuation is achieved, as predicted by the model. In practical design, special attention has to be paid for the stability of the closed-loop system. Another set of measurements were taken with the HEF. It can be clearly observed from Fig. 20 that the HEF successfully attenuates the CM noise within a wide frequency range.

### Table II

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>Insertion loss of the passive inductor (dBuV)</th>
<th>Insertion loss of the hybrid filter (dBuV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>16</td>
<td>43</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
<td>45</td>
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<tr>
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<tr>
<td>6000</td>
<td>30</td>
<td>38</td>
</tr>
</tbody>
</table>

In order to provide a comparison to the traditional CM filter, a three-order CLC CM filter shown in Fig. 1 is also built. The component values of the CLC filter are selected as $C_Y = 4700$ pF and $L_{CM} = 50$ mH. Fig. 21 shows the measured spectrum for the CLC filter. It can be seen that, at a frequency near 40 kHz, the noise spectrum still cannot pass the EMI limit. In order to fulfill this acquirement, the value of the CM
inductor should be enlarged further. However, the diameter of the 50-mH CM inductor is larger than 6 cm, although it is made of nanoscale crystalline cores. Thus, the advantage of the proposed hybrid filter over the traditional EMI filter lies not only in noise attenuation effect but also in size.

**CONCLUSION**

In this paper, a HEF with a benchmark CM inductor and an active booster that operate through feedback control has been built based on the active impedance multiplication approach. The design and compensation performance of the hybrid filter have been discussed in detail. Quantitative analysis and simulations of both the passive element and active components have been carried out, and the limitations and design tradeoffs have also been addressed. The experimental results for a military power supply have been presented according to MIL-STD-461. It has been proven that the proposed active impedance multiplication approach is able to boost the impedances of both the inductor and the noise source simultaneously. Thus, the cascade of passive component and active booster allows for better CM noise attenuation performance.

**REFERENCES**


