

High Power Density EMI Mitigation in Power Electronics Converters: Active and Integrated Solutions

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Abstract

Traditional bulk passive EMI filters are the “necessary evil” for modern power electronics systems yet they are also the bottle-neck for the improvement of power density. This limitation is caused by the low power-density of passive components themselves and the conventional passive components are structurally optimized when assembled together. Use of active circuits and integration approach in EMI noise filtering have been proven to be effective in shrinking the size and weight of traditional EMI filters. This paper presents an overview of the latest works in the area of active EMI filtering, passive integration and a combination of both techniques. The paper compares passive volume reduction with active EMI filtering and summaries a list of materials and processes involved in the passive integration techniques. These new approaches provide potential high density solutions for EMI mitigation in power electronics converters.

1 Introduction

Modern power electronics converters provide flexible efficient energy conversion yet it also generates strong electromagnetic interferences during its high dv/dt and di/dt switching operation. This undesired “bi-product” significantly increases the demand of passive EMI Filters in order to ensure compliance with EMC standards. With the advent of Wide bandgap devices, power stages with power density of up to 34 kW/kg have been demonstrated [1-2]. While the power stage has high power density, the high switching frequency and high switching speeds require careful design of both the system [4-5] and EMI filters to ensure high power density of the entire power converter. However, passive components have not kept up with the developments in the power semiconductors. Therefore, passive EMI filters are still a major bottleneck for power density and could occupy up to 30% of system volume and weight. Use of Active EMI filters and integrated passive components can potentially enable high density EMI filtering solutions for next generation power converters.

Active EMI filters use an active circuit to generate a “reverse signal” to cancel or eliminate the EMI noises. Active EMI filters involve noise sensing and injecting the “reversed” noise back into the system. The active EMI filter circuit comprises of three parts – noise-sensing circuit, noise-processing active circuit and the noise-injection circuit. Different topologies of active EMI filter can be categorized depending on types of control, and current or voltage sensing and cancellation. The bandwidth of these sub-circuits are limited due to the parasitics of the passive components, and the stability considerations of the active circuit [6-8]. Therefore, active EMI filters are typically implemented with another passive component to form the hybrid EMI filters. A survey of different active EMI filters for different power converters, their implementation, performance (attenuation), and power loss was presented in [9].

Passive components are used widely in a power converter in different capacities. However, the design of the passives

involved in the EMI filter are different from that of other passives that are used for energy storage and transfer[10]. The passive EMI filters are typically built with discrete components that come in different forms from different manufacturers and therefore are typically not optimized to fit well with each other. Passive integration enables better spatial design, improves the filter form factor, and simplifies system assembly. It could also enable lower cost due to fewer manufacturing steps and simplify processes [10].

Both active EMI filters and passive integration help to reduce the volume passive EMI filters. Moreover, adopting both the techniques together may even enable further volume reduction. This paper summarizes some of the significant works in the area of active EMI filters, passive integration for EMI filters and combination of both techniques. For passive integration, the processes and the materials involved in the passive integration and active plus passive integration are also summarized.

The organization of the paper is as follows. Section2 presents a literature survey in the area of active EMI filters for passive volume reduction and passive integration, while section 3 introduces the literature in the area of passive integration for EMI filters. The key processes involved in the manufacturing and assembly of passive integration in summarized in Section 4. Conclusion is presented in Section 5.

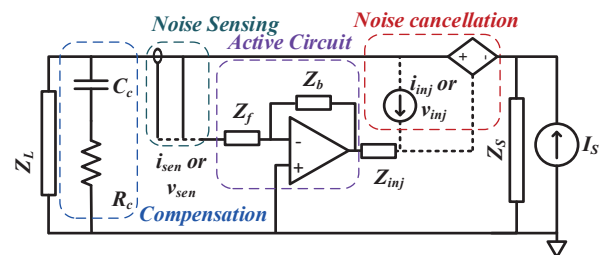


Figure 1 Equivalent circuit of an active EMI filter

Table I. Summary of active/hybrid EMI filter in literature

Reference	Converter and power level	Methodology	Topology of Active EMI filter	Volume Reduction
[11]	230 W dc-dc buck	Hybrid EMI filter	Feedback + feedforward voltage-sense voltage-cancellation topology	50% reduction of DM capacitor
[12]	600 W boost PFC	Hybrid EMI filter and passive integration	Feedback voltage-sense current-cancellation topology	40% volume reduction of overall filter
[13]	1.1 kW induction motor drive	Hybrid EMI filters	Feedback voltage-sense voltage-cancellation topology	96% smaller CM choke
[14]	30 W dc-dc converter	Hybrid EMI filter and passive integration	Feedback voltage-sense voltage-cancellation topology	75% volume reduction of overall filter
[15]	200 W ac-dc converter	Hybrid EMI filter	Feedforward voltage-sense voltage-cancellation topology	50% smaller CM choke
[8]	30 W ac-dc converter	Hybrid EMI filter	Feedback voltage-sense current-cancellation topology	64% small DM capacitor
[16]	350 W ac-dc converter	Hybrid EMI filter	Feedback voltage-sense current-cancellation topology	49.5% overall volume reduction

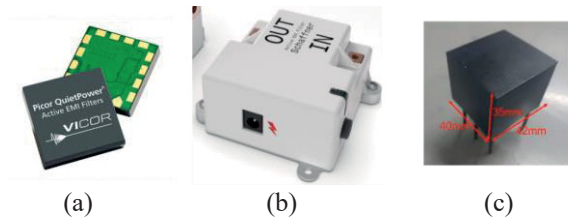


Figure 2 Commercial active and hybrid EMI filters from (a) Vicor Picor QuietPower for dc-dc converters [17] (b) Schaffner active EMI filters for automotive applications [18] (c) EMcoretech active EMI filters for SMPS [15]

2 Active EMI filters

Active EMI filters and hybrid EMI filters have been used to achieve passive volume reduction. A generic equivalent circuit of an active EMI filter is shown in Fig. 1. Commercial active EMI filters available are shown in Fig. 2. Selection of a particular topology of active or hybrid EMI filter depends upon the type of noise source (I_s), noise source impedance (Z_s) and load impedance (Z_L). Because, this determines the impedance mismatch criteria. Besides the impedance mismatching, the stability of the active EMI filter is also decided by the noise source and load impedance. In addition, the feasibility of a particular topology of active EMI filter is also dictated by the type of converter employed [9].

Ideally, the active EMI filter should provide the same attenuation as that of the passive EMI filter it replaces. However, the passive EMI filters are typically oversized to maintain lower order filter topology, low cut-off frequency, and still provide attenuation at higher frequency. When using an active EMI filter, the active stage provides the attenuation up to a few MHz, therefore, a relatively small passive filter with less parasitics could be used to provide attenuation at high frequency (a few MHz and up).

2.1 Performance and Volume Reduction

The attenuation provided by the active EMI filter is one of the key performance metrics. However, the overall volume reduction is further dictated by additional components used for compensation (such as a high voltage capacitor C_c in Fig. 1) to ensure stability of the active EMI filter. Some of the significant works in the literature are summarized in Table. I. From the Table. I, it can be seen that active EMI filters enable about 50% volume reduction. But by adapting passive integration along with active EMI filters up to 75% volume reduction could be achieved.

3 Active and Passive Integrated EMI filters

3.1 Passive integration

In [19], an inductor was integrated along with the dc-link capacitor (based on electrolytic capacitor technology) and demonstrated in a 2.2 kW industrial drive. The implementation is shown in Fig. By adding an inductor on the dc-link, the volume of the EMI filter on the ac line was reduced. Overall passive volume reduction of 45% was reported. The two versions of the filter are shown in Fig.3a and 3b respectively. The first version used low-frequency and EMI filters separately and used nano-crystalline cores. The second version uses different uses different parameters (number of turns, dimensions etc.) for the integrated inductor.

In [12], the passive hybrid integrated EMI filters shown in Fig. 3c was demonstrated for a 600 W PFC. In this work, the entire EMI filter is integrated in a PCB. All the inductor windings and all the capacitors with the exception of the DM capacitor. The DM capacitor is realized by using multiple SMD-X7R capacitors with X2 rating. The name passive hybrid integrated EMI filter due to the combination of integrated and discrete passive components.

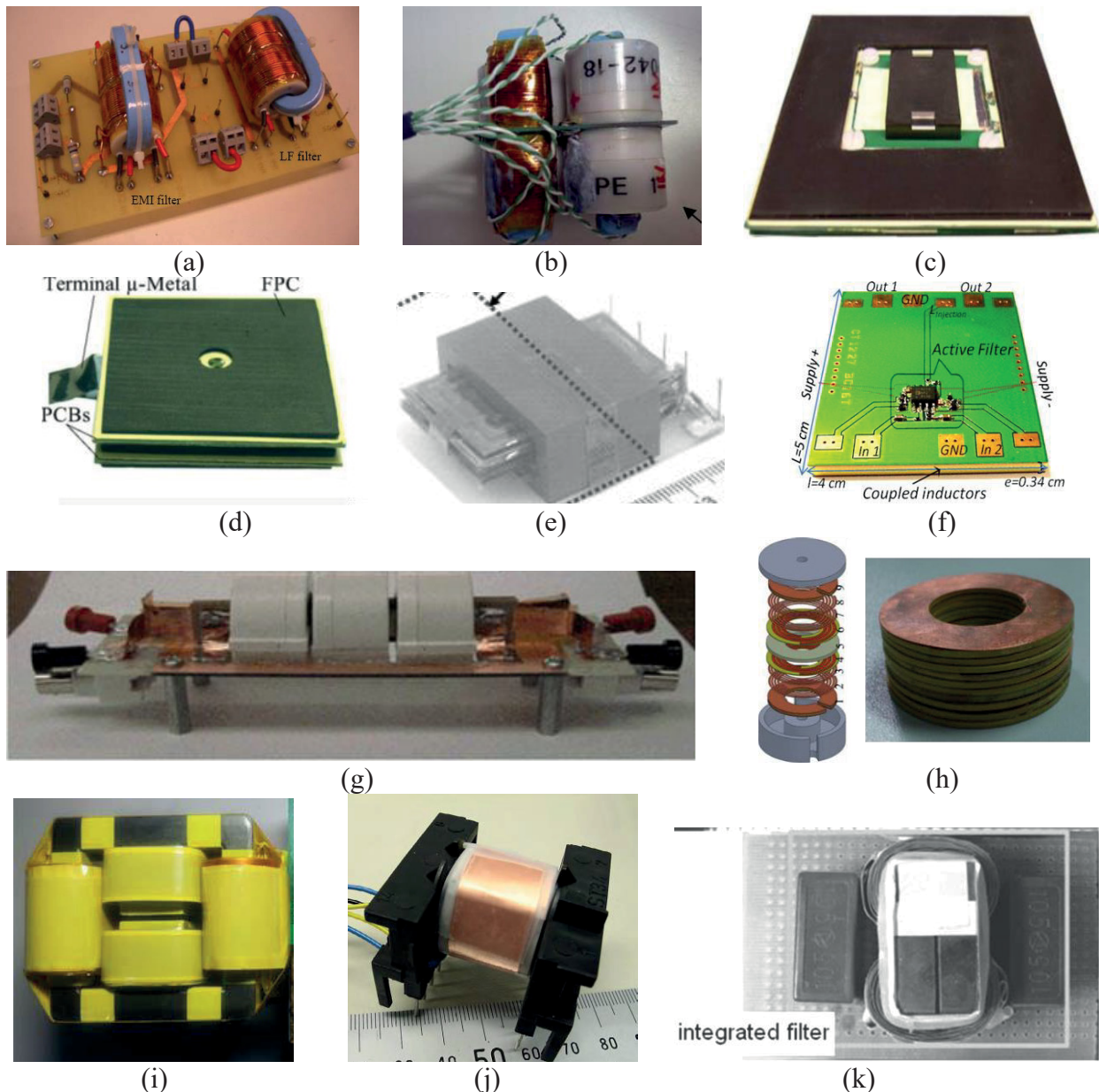


Figure 3 Different implementations of passive integration and active & passive integration in literature (a) Integrated inductor in electrolytic capacitor technology version-1 and (b) version-2 [19] (c) Passive integrated EMI filter with integrated inductor [12] (d) active and passive integrated EMI filter for ac-dc converter [12] (e) passive integrated EMI filter using transmission line filter [20-22] (f) active and passive integrated EMI filter for dc-dc converter [14] (g) busbar filter using combination of transmission-line filter and a one-turn inductor for dc-fed motor drives [23] (h) passive integrated EMI filter based on annular integrated inductor-capacitor unit [24] (i) flexible multi-layer foil based integration of EMI filters and boost inductor [25] (j) air-core flexible multi-layer foil based integrated filter [26] (k) integrated EMI filter with flexible multi-layer coils [27]

The integrated EMI filter technology [20-22] as shown in Fig. 3e was proposed for the EMI filter of a DPS front-end converter to realize structural, functional and process integration. It can achieve smaller size, lower profile, better performance and reduced fabrication time and cost compared to discrete EMI filter. All the filter components were integrated into one module, constructed by using standard semiconductor processing, printed circuit board (PCB) and packaging techniques. The high frequency performance of the EMI filter is limited by the structural parasitic parameters, such as the equivalent parallel capacitance (EPC) of

inductors and the equivalent series inductance (ESL) of capacitors. In [21], an EPC cancellation technique for the integrated inductor is proposed. A conductive ground layer is embedded in the planar inductor windings and the structural capacitance between the inductor winding and this embedded layer is utilized to cancel the EPC. The experimental results show that the embedded conductive layer can effectively cancel the parasitic winding capacitance; hence, ideal inductor characteristics can be obtained. With

the help of this embedded conductive layer, the improved integrated EMI filter has much smaller volume and profile and much better characteristics over a wide frequency range than the discrete EMI filter.

The transmission-line EMI filter, as shown in Fig. 3e, was proposed in reference [20]. In traditional power electronics systems, LC filters using lumped inductors and capacitors are used to attenuate the noises. However, in the LC filters, the useful power current and the noises share the same conductive path. The LC filter has to have the same power level as the power converter. The transmission-line EMI filter provides different conductive paths for low frequency power current and high frequency noise current. The low-frequency power current mainly goes in the copper conductors. The high-frequency noise current, due to the proximity effect, it will go in the nickel conductors. The nickel conductor is more lossy than copper. Thus, the transmission-line filter combines the reflective and absorptive effects, which makes its attenuation less dependent upon the source and load impedances. Conventional transmission-line filters used rectangular cores. A planar integrated LC

filter with annular inductor-capacitor unit was proposed in [24] and is shown in Fig. 3h.

The transmission-line filter was combined with a one-turn inductor to further enhance the attenuation of the EMI filter in [23] as is shown in Fig. 3g. This method allows the user to select the structure of the bus-bar filter based on the attenuation required in different frequency ranges. Recently, flexible multi-layer foils based passive integration is published in [25-27]. The flexible foil includes a dielectric layer, two copper layers, and an insulation layer. Thus it can integrate both the inductor and capacitor into a single component. Further, the flexible multi-layer foils are easy to wind around any form of magnetic component. The use of flexible multilayer foils simplifies the processes required. Using conventional gapped EE cores, flexible multilayer foils, the EMI filter and the boost inductor was integrated into a single structure [25] and is shown in Fig. 3i. Flexible film with air was used to integrate CM EMI filter for attenuation at frequencies above 1 MHz in [26] and is shown in Fig. 3j. A detailed model and verification of the integrated filter designed for a 1 kW SMPS with flexible

Table II. Summary of materials used in different passive integration technology

Technology	Materials
Integrated filter in electrolytic capacitor technology	FR4/Plastic (Substrate), Copper/Aluminum (Conductor), Ferrite/Nanocrystalline (Magnetics)
Passive hybrid integrated EMI filter	FR4 (Substrate), Copper/Carbon paste/ μ Metal (Conductor), Ferrite/FPC [EPCOS]/MagLam [ISOLA]/ μ Metal [VAC] (Magnetic), X7R/C-Lam [ISOLA]/RO3210 [Rogers]/HiK [DuPont] (Dielectric)
Active hybrid integrated EMI filter	FR4 (Substrate), Copper/Carbon paste/ μ Metal (Conductor), Ferrite/FPC [EPCOS]/LTCC tape (Magnetic), X7R/C-Lam [ISOLA]/RO3210 [Rogers]/HiK [DuPont] (Dielectric)
Integrated EMI filter technology	Copper/Titanium (Conductor), Ferrite/FPC [EPCOS]/MagLam [ISOLA]/ μ Metal [VAC] (Magnetic), Al ₂ O ₃ /Kapton [Hik]/NP0/X7R/Y5V (Dielectric)
Transmission-line EMI filter	Al ₂ O ₃ (Substrate), Copper/Titanium/Nickel (Conductor), NP0/Y5V (Dielectric)
Integrated EMI filter with flex PCB winding	FR4/Flex PCB (Substrate), Copper (Conductor), Ferrite/UF33 (Magnetic), Polypropylene (Dielectric)
Flexible Multilayer Foils	Copper (Conductor), UF33-R10K [DEMAG] (Magnetic), PP (Dielectric)

Table III. Summary of processes used in different passive integration technology

Technology	Process
Integrated filter in electrolytic capacitor technology	Soldering, Electrolytic capacitor manufacturing, Cold pressure welding, Plastic molding, Photolithography, Ohmega Ply process (Ruwel)
Passive hybrid integrated EMI filter	Soldering, PCB manufacturing process, Ohmega Ply process (Ruwel)
Active hybrid integrated EMI filter	Soldering, PCB manufacturing process, Ohmega Ply process (Ruwel)
Integrated EMI filter technology	Soldering, One-step etching, Lamination, Stencil printing, Low temperature co-fire, Plasma cleaning, Sputtering, Laser drilling/cutting, Electroplating, Photolithography
Transmission-line EMI filter	Soldering, One-step etching, Plasma cleaning, Sputtering, Laser drilling/cutting, Electroplating, Photolithography
Integrated EMI filter with flex PCB winding	Soldering, Flex PCB manufacturing process

film coil was presented in [27] and is shown in Fig. 3k. The integrated filter helped achieve 45% lower volume in comparison to the discrete components based filter.

3.2 Active and Passive integration

An active and passive integrated filter was proposed in [12]. In this integrated filter, the above passive hybrid integrated structure is combined with an active EMI-filter and is shown in Fig. 3d. With the active EMI filter stage the required inductance and capacitance values of the components decrease significantly compared to the passive integrated filter. This results in reduced magnetics requirement for the additional ferrite core for this integrated filter. The components of the active filter are mounted on top of the PCB, where the passive filter is integrated. This new approach results in a very compact construction (around 40% volume reduction in comparison to a discrete solution) and is called active hybrid integrated EMI filter. Fig shows the 3D drawing of the active hybrid integrated EMI filter that was designed for a 600W PFC-converter. Another implementation of the active and passive integrated filter was demonstrated in [14] for a 30 W dc-dc converter and is shown in Fig. 3f. The active stage consists of a feedback voltage-sense voltage-cancellation active EMI filter. The filter consists of a planar coupled inductor that forms the CM choke and as well as the DM voltage injector in a single structure.

4 Manufacturing and Assembly Processes for Passive Integration

The integrated filter in electrolytic capacitor technology makes use of similar materials as the electrolytic capacitor technology. Besides those materials, the integrated filter uses magnetic materials, such as nano-crystalline and ferrite. The key materials for the passive hybrid integrated EMI filter and the active hybrid integrated EMI filter are similar, including magnetic materials, dielectric materials, and resistive materials. The possible magnetic materials include ferrite, FPC, MagLam, μ -metal and etc. The possible dielectric materials include C-Lam and HiK. The key materials for the integrated EMI filter technology include magnetic materials and dielectric materials. The magnetic materials include ferrite core, FPC tape and LTCC tape. The fired LTCC tape can be used as the leakage layer in the integrated EMI filters. The key materials in the transmission line EMI filter include the nickel conductor and the high-permittivity dielectric material, such as Y5V. The key materials in the integrated EMI filter with flex PCB winding include the flex PCB, the ferrite core and the polypropylene dielectric material. The key materials for the flexible multi-layer foils consisting of a 2 layers of copper and a dielectric layer between them. These are then covered by PI insulating layer. This is then wound on any magnetic core.

5 Conclusion

This paper presents an overview of advanced solution for high power density EMI mitigation which are potentially beneficial for future power electronics system. The paper has summarized the key progresses in the area of active EMI filters, passive integration and a combination of both methods. From the literature it can be seen that either methods when used separately can help lower the passive filter volume by about 50%. Whereas by combining both active EMI filters and passive integration could help achieve up to 75% overall filter volume reduction. The materials and processes used for the different integration methods in the literature are also summarized. These advanced EMI filtering solutions provide promising performance with tremendous improvement on filter power density, while the emerging of these ideas can potentially flip the design and manufacturing paradigm for passive filters in power electronics converters. More research effort are still required in depth to understand the integration of these advanced approaches to achieve even better performances. Further research in integrated passive materials is also in demand to support higher level of filter integration.

6 Literature

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