A New Active EMI Filter with Virtual Impedance Enhancement

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***Abstract*—In this paper, a novel topology and control scheme for active electromagnetic interference (EMI) filter based on the idea of virtual impedance enhancement is proposed. To ease analysis, a general and simplified equivalent circuit is introduced to predict the conducted emissions incurred from switched-mode power converters. In addition, theoretical analysis is given to show how the proposed active EMI filter (AEF) should be designed along with simulation validation. A prototype of proposed AEF is implemented and tested to verify its effectiveness on proof-of-concept test setup. It is shown that the proposed AEF is capable of attenuating conducted emissions.**

Keywords—Electromagnetic interference (EMI), active EMI filter, conducted emissions, feedforward control, virtual impedance transform

I. Introduction

Power semiconductors with pulse width modulation (PWM) have been extensively used in switch-mode power converters. The emergence of wide-bandgap semiconductors such as silicon carbide (SiC) and gallium nitride (GaN) devices has enabled the switching frequency of power converters to increase from several kHz to hundreds of kHz or even up to several MHz. Thus, higher power density and smaller size of power converters can be achieved due to the reduction in size of passive components at the higher switching frequency. However, significant electromagnetic interference (EMI) induced by the rapid transients during switching (high *dv/dt* and/or *di/dt*) would inevitably and severely affect the system's operation.

EMI can be in the form of either radiation or conduction [1]. For conductive EMI, there are two conduction modes: differential mode (DM) and common mode (CM) whose propagation paths can be identified as shown in Fig. 1. The noise flowing between power line and ground is taken as CM noise and the noise flowing between two power lines is called DM noise. While DM noise can be relatively easy to mitigate, many researchers have been focusing on reducing CM noise since it has greater contribution to the generation of radiated emissions [3]. A feasible solution to eliminating conducted emissions can be installing EMI filters in power converters. A typical passive EMI filter shown in Fig. 2 is composed of several CM chokes and X and Y capacitors which can take up significant size and weight, which may be impractical for certain applications.

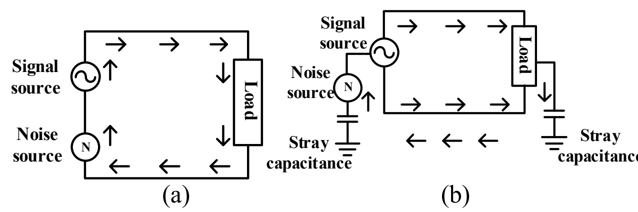

Fig. 1. (a) DM and (b) CM noise.

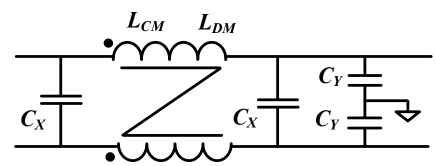

Fig. 2. Typical passive EMI filter.

The technique of active filtering was first introduced in [4] by Thomas Farkas, which later gave rise to the emergence of active EMI filters (AEFs). It is believed that AEFs have the potential to reduce or even eliminate the bulky passive filtering components so that reduced total volume and high power density of a converter might be achieved. Many researchers have so far focused on reducing CM noise in power converters. Either current or voltage can be sensed and compensated for with AEF implementation. Krishna and Ramesh present a comprehensive survey on EMI mitigation techniques [5]. In [6], analysis has been given to evaluate the performance of the four general types of AEF based on different sensing and compensation schemes. In [7]-[11], different implementations of AEF utilizing CM transformer as a voltage compensation method have been proposed to mitigate CM noise. In [12], an AEF without a transformer has been proposed to perform current compensation instead. Different control schemes such as feedforward (FF) and feedback (FB) control can also be applied in AEF. In [13], AEFs with feedforward, feedback and combination of these two control schemes are analyzed and developed.

This paper adopts the idea of virtual impedance transform and applies it to the AEF implementation. Theoretical analysis has been performed on the proposed AEF with feedforward control. Simulation and experiment on a proof-

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of-concept test setup have verified the proposed AEF's effectiveness.

II. Simplified Equivalent Circuit for EMI Prediction

For EMI testing, a line impedance stabilization network (LISN), which can provide isolation from the main and known impedance to the equipment under test (EUT), is indispensable. The standard diagram of a typical LISN is shown in Fig. 3 below.

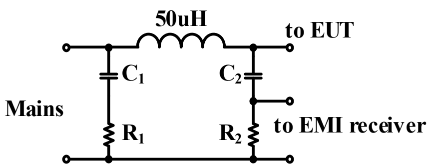


Fig. 3. Schematic of a LISN.

To model the EMI that arises from rapid transients of a switching device in a power converter, a Thevenin equivalence or a Norton equivalence can be used to model a single device or a bridge leg for any converter as shown in Fig. 4. Thus a general and simplified equivalent circuit for conducted EMI prediction can be obtained as shown in Fig. 5 based on noise source modeling. For ease of analysis, Norton equivalence is used while $\boldsymbol{Z_{line}}$ and $\boldsymbol{Z_{LISN}}$ are used to model the line and LISN impedances, respectively.

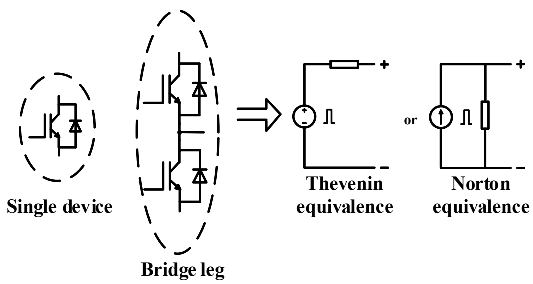


Fig. 4. Noise source modeling.

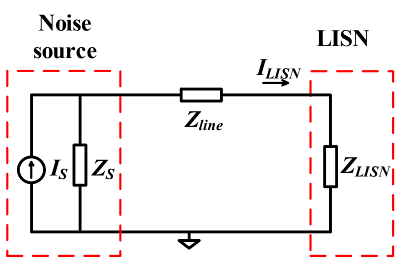


Fig. 5. Simplified equivalent circuit for EMI prediction.

III. Proposed AEF

In this section, the idea of virtual impedance transform is first introduced. Then we will show how the idea can be applied to realize the proposed AEF. Besides that, we also explore feedforward and feedback control schemes for the proposed AEF's compensation. Finally, a prototype of the proposed AEF is built using operational amplifiers.

A. Virtual impedance transform

Take an ideal capacitor *C* as an example. The voltage across two terminals of an ideal capacitor and the current flowing through the capacitor should follow (1). Suppose a controlled voltage source also follows the same equation, which means the output voltage is the integration of the current, the controlled voltage source is showing characteristic of a capacitor.

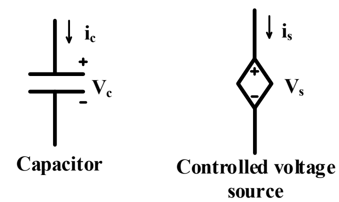


Fig. 6. Virtual impedance transform.

$$V_c = Z(s)i_c \quad Z(s) = 1/sC \tag{1}$$

This idea could play an important role in AEFs since the controlled voltage source can act as a capacitor to bypass the conducted noise. Moreover, the effective capacitance can be easily changed by adjusting the integral gain.

B. Feedforward and feedback control analysis for proposed AEF

The proposed AEF is in the form of current-sense current-compensation (CSCC). Feedforward and feedback control can be used to perform compensation. To evaluate the performance of a filter, the open loop gain $G_{OL}(s)$ and the insertion loss (*IL*) derived from Fig. 5 are shown in (2)-(3).

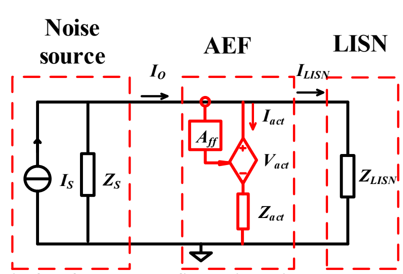
$$G_{OL}(s) = Z_s(s)/(Z_s(s) + Z_{LISN}(s)) \tag{2}$$

$$IL_{dB} = I_{LISN} / I_s \tag{3}$$

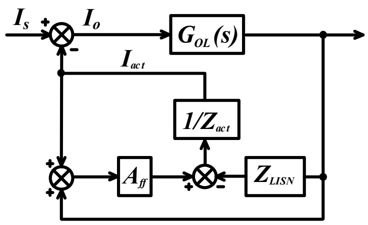
The equivalent circuit and corresponding signal flow diagram for feedforward and feedback control are shown in Fig.7 and Fig. 8, respectively. The insertion loss for these two control schemes can be expressed in (4)-(5), where Z_{act} is the impedance of compensation branch, A_{ff} and A_{fb} are the feedforward and feedback gain of active filter, respectively. Ideally, we would like the insertion loss to be zero, which means the AEF is able to provide a low impedance path for high-frequency conducted noise.

$$1/IL_{dB} = 1 + Z_{LISN}/Z_s + (Z_{LISN} - A_{fb})/Z_{act} \tag{4}$$

$$1/IL_{dB} = Z_{LISN}/Z_s + (Z_{LISN} + Z_{act})/(Z_{act} + A_{ff}) \tag{5}$$

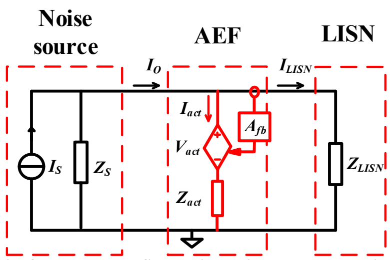


(a) AEF in feedforward configuration with Norton equivalence.

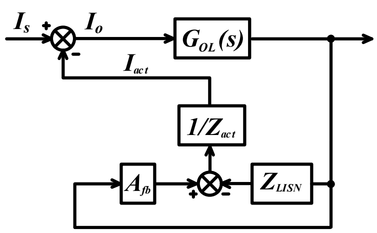


(b) Signal flow diagram of feedforward AEF.

Fig. 7. AEF model in feedforwad control mode.



(a) AEF in feedback configuration with Norton equivalence.



(b) Signal flow diagram of feedback AEF.

Fig. 8. AEF model in feedback control mode.

By analyzing (4)-(5), it is found that $A_{ff} \approx -Z_{act}$ and $A_{fb} \to \infty$ for feedforward and feedback control. As we can see, the feedback gain should be as close to infinity as possible while the feedforward gain should be close to negative impedance of compensation branch.

C. Proposed AEF design

A current sense amplifier followed by a high-pass filter with Sallen-Key topology as shown in Fig. 9 can be used to sense conducted noise. Controlled voltage source can be realized with operational amplifiers and a capacitor is used as compensation branch. Feedforward control is adopted here since we would like to avoid the infinite feedback gain discussed previously.

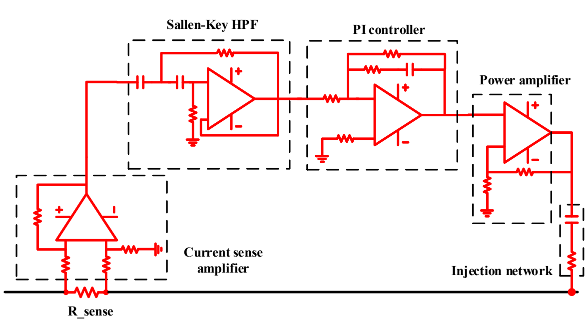


Fig. 9. Proposed AEF implementation.

The cut-off frequency of HPF is set to 5kHz and the op-amp used to perform feedforward control has a unit-gain at 20MHz. The corresponding control diagram is shown in Fig.10.

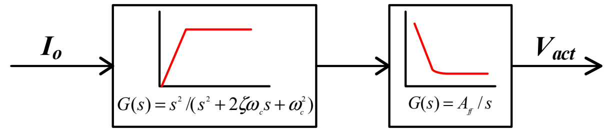


Fig. 10. Control block diagram of proposed AEF.

IV. SIMULATION AND EXPERIMENTAL VERIFICATION

Simulation as well as experiments was performed on a proof-of-concept circuit to validate the proposed AEF design's effectiveness.

A. PSIM simulation on proof-of-concept circuit

A 10V peak-to-peak 60Hz sinusoidal voltage source is in series with a 1V peak to peak 100kHz square-wave voltage source to feed a standard 50Ω resistive load. The square-wave voltage source is aimed at mimicking conducted noise present in the circuit.

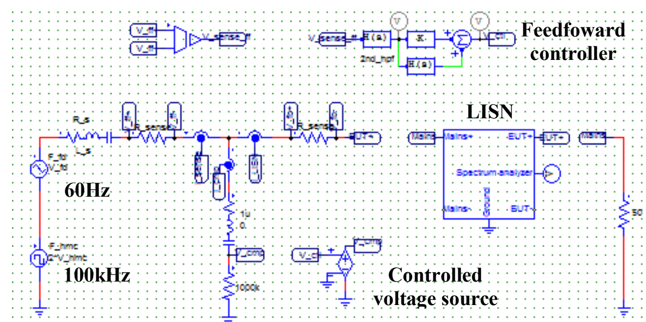
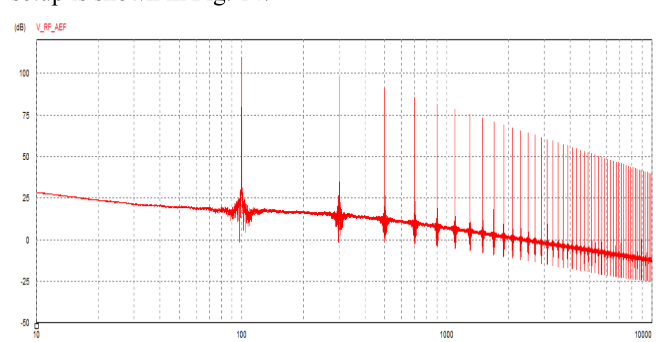


Fig. 11. Simulation circuit in PSIM.

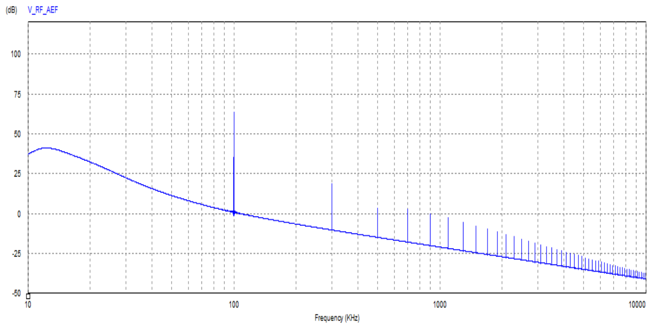
A LISN model is also built in the simulation to provide baseline measurement for conducted emissions. The measured conducted spectrum without and with the proposed AEF are shown in Fig. 12 where significant attenuation can be clearly observed at different harmonic frequencies.

B. Hardware test on proof-of-concept circuit

A prototype of proposed AEF was built as shown in Fig. 13. Two function generators are used to represent the two voltage sources, and a spectrum analyzer measured the conducted emission picked up from a LISN. The whole test setup is shown in Fig. 14.



(a) Measured spectrum without AEF.



(b) Measured spectrum with AEF.

Fig. 12. Measured conducted emission from LISN.

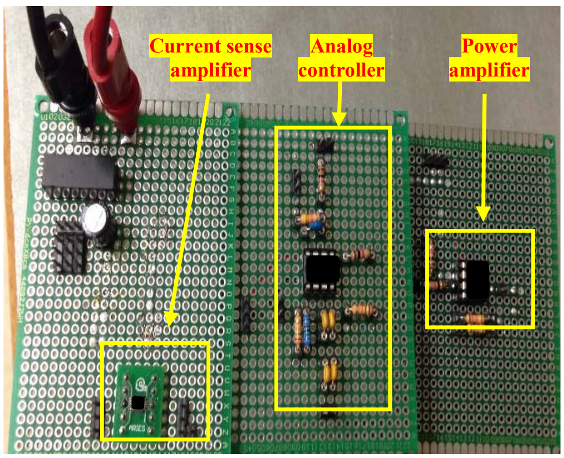


Fig. 13. Proposed AEF.

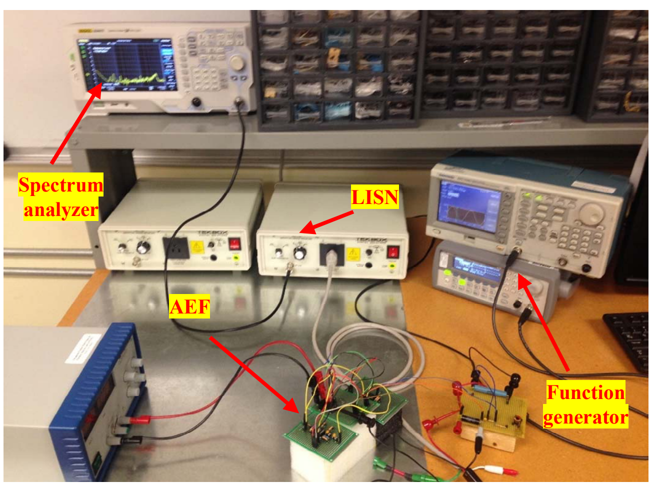
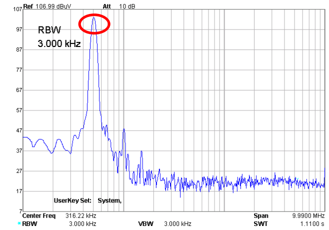
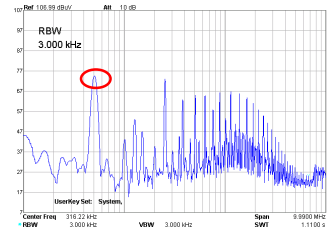


Fig. 14. Proof-of-concept test setup.

Test results of the proposed AEF over different frequencies (50kHz-250kHz) are shown in Fig. 15-Fig. 18, which demonstrates the effectiveness of the proposed AEF. These results show that on average, approximately 25dBμV attenuation can be achieved with proposed AEF for a fundamental square wave (noise) frequency ranging from 50kHz to 250kHz.

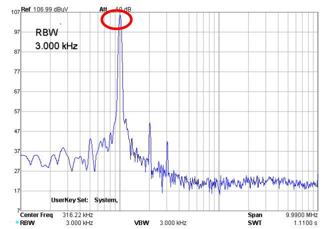


(c) Measured spectrum without filter.

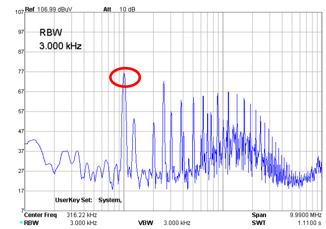


(d) Measured spectrum with filter.

Fig. 15. Measured conducted emission from LISN at 50kHz.

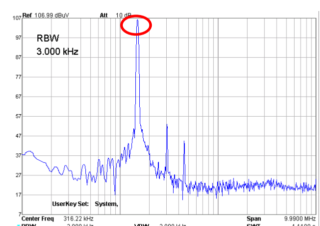


(a) Measured spectrum without filter.

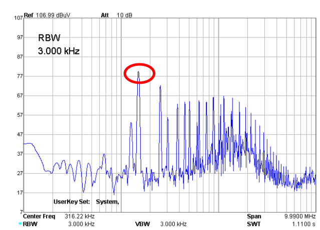


(b) Measured spectrum with filter.

Fig. 16. Measured conducted emission from LISN at 100kHz.

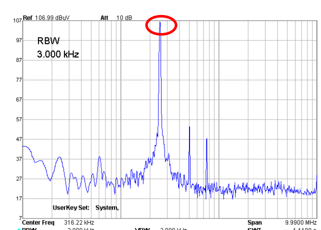


(c) Measured spectrum without filter.

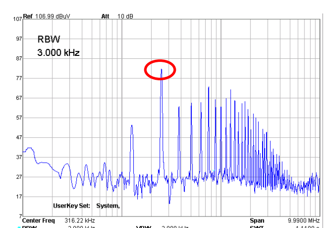


(d) Measured spectrum with filter.

Fig. 17. Measured conducted emission from LISN at 150kHz.



(a) Measured spectrum without filter.



(b) Measured spectrum with filter.

Fig. 18. Measured conducted emission from LISN at 250kHz.

V. CONCLUSIONS

In this paper, a novel AEF is proposed based on the idea of virtual impedance transform to mitigate CM EMI. Both simulation and experiments on proof-of-concept circuit have verified that the proposed AEF is capable of mitigating conducted noise.

ACKNOWLEDGMENT

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