Letters

A Novel Neutral Point-Based Active EMI Filter for Common Mode Noise Attenuation

Yongxing Zhou, *Student Member, IEEE*, Wenjie Chen, *Senior Member, IEEE*, Xu Yang, *Senior Member, IEEE*, Zheyuan Yu, *Student Member, IEEE*, Xin Meng, *Student Member, IEEE*, Pengyuan Ren, *Student Member, IEEE*, Yuxuan Chen, *Student Member, IEEE*, and Xingwei Huang, *Student Member, IEEE*

***Abstract*—This letter proposed a new configuration of neutral point-based common mode (CM) active electromagnetic interference (EMI) filter (NP-CM-AEF). It is achieved by setting the reference of filtering system to the neutral point of equipment under test. Therefore, CM noise could be sensed across neutral point and ground. Meanwhile, compensation signal could be built by op-amp and re-injected to cancel the initial CM noise. The main advantage of the proposed NP-CM-AEF lies in that no more noise separation such as bulky passive CM transformer is needed to get pure CM noise. The whole filter becomes smaller, lighter, and more compact compared with traditional CM AEF. Working principle is analyzed in details and hardware experimental tests are also performed. It shows that the proposed NP-CM-AEF has a good attenuation to CM noise and total size is pretty tiny.**

***Index Terms*—Active electromagnetic interference (EMI) filters, common mode noise, EMI attenuation.**

I. Introduction

FAST transient caused by swift changing of current and voltage waveforms is widely regarded as the source of electromagnetic interference (EMI). With the usage of wide bandgap devices, switching frequency has increased a lot which deteriorates the EMI environment. The general method to cope with this problem is to use passive filters. This method is universal in practical applications due to its simplicity, reliability, and low cost. But passive filters themselves contradict the developing tendency of high power density converters due to their bulky volume, heavy weight, and poor performance during high frequency range.

Recently, scholars start to pay attention to another kind of active EMI filter (AEF) to better solve the severe EMI problem [1]. AEF mainly consists of the sensing part, amplifying part, and injection part. With proper design, the compensation signal will have the same magnitude as initial noise signal but in the reverse phase. In this way, those two parts will cancel each other ideally. Without bulky inductors and capacitors, the total volume of AEF could be dramatically reduced compared to traditional passive filters.

Similar to passive filters, AEF could also be classified into a common mode (CM) AEF and differential mode (DM) AEF. The injection path connections and reference settings of those two kinds of AEFs will be different due to the intrinsic propagation path difference of CM and DM noise. Except this classification, AEFs could also be classified according to their noise sensing method and noise cancellation method. Noise sensing and noise cancellation could be performed in current or voltage forms. Therefore, four combination topologies suit different applications and have different noise attenuation abilities. It is generally accepted that AEF with voltage sensing-current cancellation (VSCC) topology will occupy less space.

Nowadays, the analysis and implementation of AEF are not the bottlenecks for engineers. Chu *et al.* [2] and [3] reported the modeling of AEF based on functional parts and systematic level considering stability issues. They provided us good guidelines for key components choosing and parameter setting. In [4], the design of AEF on the motor control systems was comprehensively discussed. Several implements and features related to practical applications were introduced. Combinations of AEFs have also been well illustrated in literature to further improve the noise attenuation ability [5], [6]. A novel integration topology of AEF for both CM noise and DM noise attenuation has also been put forward in [7]. In this reference, CM AEF and DM AEF were well combined with tiny size the first time.

Although many problems of AEF are solved, there still exist some challenges. For example, the configuration of conventional CM AEF is more complicated compared to DM AEF. It has to separate pure CM noise and inject compensation signals into two power lines. Those will inevitably involve two RC sensing paths and two RC injection paths for conventional VSCC AEF [7]–[11]. To cope with this problem, this letter proposes a new neutral point-based compact CM AEF topology.

The main contributions of this letter are listed as follow.

1) A new neutral point-based compact CM active EMI filter topology (NP-CM-AEF) is proposed. By means of

Manuscript received December 17, 2021; revised January 20, 2022 and February 20, 2022; accepted March 11, 2022. Date of publication March 23, 2022; date of current version May 23, 2022. This work was supported by the National Natural Science Foundation of China under Project 51977175. *(Corresponding author: Wenjie Chen.)*

The authors are with the State Key Laboratory of Electrical Insulation and Power Equipment, Xi'an Jiaotong University, Xi'an 710049, China (e-mail: zhouyongxing@stu.xjtu.edu.cn; cwj@xjtu.edu.cn; yangxu@mail.xjtu.edu.cn; weizheyuan@stu.xjtu.edu.cn; msx414@stu.xjtu.edu.cn; 1420396971@qq.com; cyx1998@stu.xjtu.edu.cn; huangxw867046635@stu.xjtu.edu.cn).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TPEL.2022.3161288.

Digital Object Identifier 10.1109/TPEL.2022.3161288

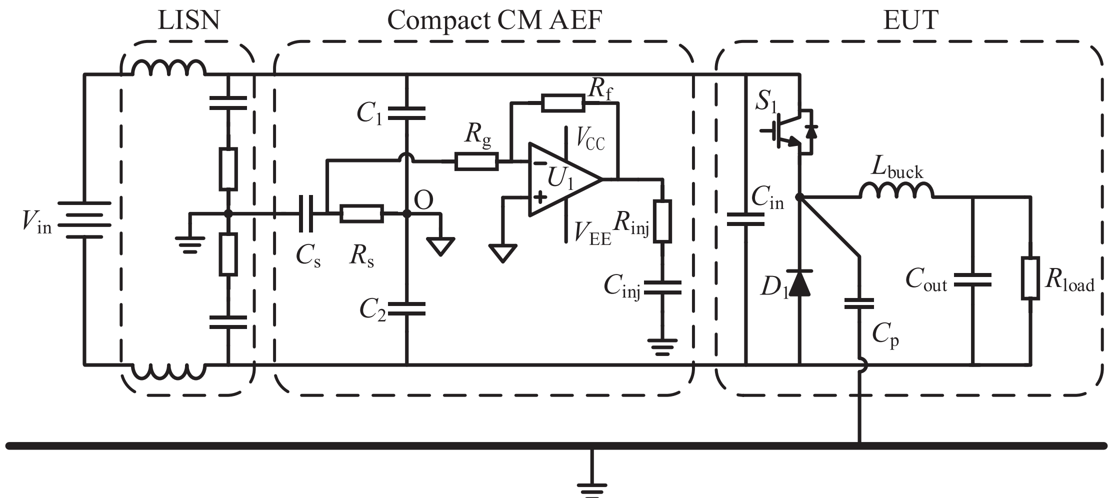

Fig. 1. Schematic of neutral point based compact CM AEF.

building a neutral point in the input terminal of equipment under test (EUT), the CM noise could be detected and reconstructed, and reinjected back to the ground of EUT. The proposed NP-CM-AEF has advantages of less components, without a bulky current transformer, smaller size, and is easy to be implemented.

2) Moreover, due to the neutral point clamp capacitors, the NP-CM-AEF could share the same dc power supply with most low voltage dc EUT. Which, in turn, make the whole filter more compact. Meanwhile, using the neutral point clamp capacitors, the proposed NP-CM-AEF could also reduce certain DM noise.

The rest of this letter will be organized as follow. First, the topology of the proposed CM AEF is put forward and the main functional parts are introduced in Section II. In Section III, the noise model and detailed information about the working principle are well analyzed. Corresponding insertion loss is also derived. A prototype is designed and manufactured in Section IV. Further experimental tests are executed and tested performance shows good agreement with expected results. Finally, conclusion is given in Section V.

II. Schematic of Proposed CM AEF

Fig.1 shows the schematic of the proposed neutral point-based compact CM AEF. Line impedance stabilization network (LISN) is inserted between power input and EUT. Here, a dc–dc converter with buck topology is used. The proposed NP-CM-AEF also has three main functional parts sensing part, amplifying part, and injection part. Different from traditional CM AEF, the reference of neutral point-based CM AEF is not connected to the ground. Besides, sensing networks and injection networks are not built across power lines and ground.

Neutral point clamp capacitors C_1 and C_2 work as neutral point building circuits between two power lines. Those two capacitors are connected in series and the mid-point of two capacitors is defined as neutral point O. This neutral point will be used as the reference for the CM AEF system. Those two capacitors could also contribute to DM noise attenuation.

Resistor R_s together with capacitor C_s form a high-pass filter and they are connected between ground and neutral point O to capture CM noise. During practical applications, the voltage across this sensing part is achieved by high-frequency noise and system input power does not contribute. So, the voltage rating for those two components will be low.

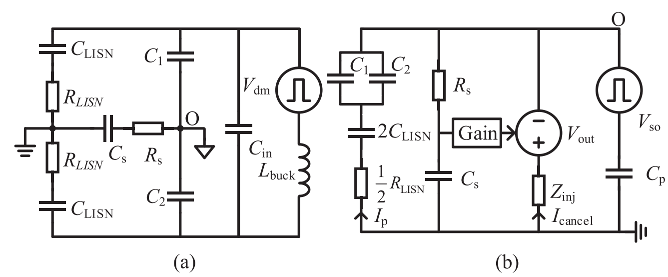

Fig. 2. Equivalent noise model for CM and DM noise. (a) equivalent model for DM noise. (b) equivalent model for CM noise.

The amplifying part of neutral point-based compact CM AEF consists of two resistors R_g,$R_\mathrm{f,}$ and an op-amp U_1. With the feedback control method, the gain of this part should be sufficient enough to guarantee good attenuation ability with stable working conditions.

Injection part is combined with a resistor R_inj and a capacitor C_inj. Similar to sensing networks, their voltage stress of them is low. The total impedance of the injection path equals to the sum of impedance of resistor R_inj and capacitor C_inj.

III. Working Principle of Proposed CM AEF

As mentioned that the functional parts of neutral point-based CM AEF also contain sensing parts. Pure CM noise is sensed by sensing network and no more noise separation is demanded the proposed CM AEF. Fig.2 shows the equivalent models of CM and DM noise propagation. R_LISN and C_LISN refer to the model of LISN during the test.

In Fig. 2(a), V_dm represents the voltage source of DM noise in EUT. L_buck refers to the buck inductor. Those two parts together compose the noise source and source impedance for DM noise analysis. C_in is defined as an input capacitor. With this DM noise model, it could be found that when C_1 and C_2 are set with the same value, there exists a balanced Wheatstone bridge. Based on this fact, the voltage signal between ground and neutral point

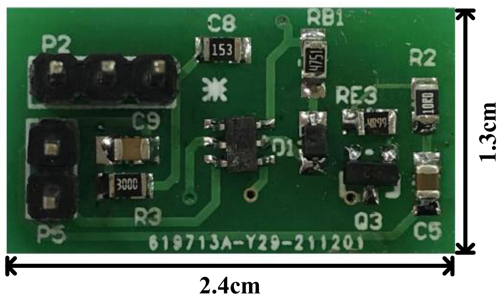

Fig. 3. Prototype of neutral point-based CM AEF.

O equals to zero. So, DM noise will not be captured by the sensing network of the proposed neutral point-based CM AEF. Similarly, main power flow will also not affect.

When it comes to CM noise as shown in Fig.2(b), noise flowing path is different. So the balanced Wheatstone bridge will not work. Here, C_1 and C_2 could be regarded as a short circuits to simplify the analysis. V_{so} is defined as the voltage across the source terminal of the switching device and neutral point O. C_{p} represents the parasitic capacitance between the voltage changing point and ground. When proposed CM AEF is not added into the circuit, CM current I_{p} will directly flow through the parasitic capacitor to the ground. Then it passes LISN and neutral point O without any attenuation. After the proposed CM AEF inserted into circuit, pure CM noise across ground and neutral point O will be captured by the sensing part. And it will be further amplified by the gain of amplifying part (Gain) which has a negative polarity. Finally, the output voltage V_{out} will provide a cancellation current I_{cancel} to compensate initial noise signal through the injection path. Z_{inj} refers to the total impedance of the injection path. Based on the feedback control method, a bigger cancellation current will result in better noise attenuation. Equation (1) shows the calculation of cancellation current I_{cancel}. Z_{LISN} is defined as the impedance of LISN during the CM test and Z_{p} represents the impedance of capacitor C_{p}. Insertion loss (IL) defined as the ratio of noise signal with and without proposed CM AEF is also derived as (2).

$$I_{\text{cancel}} = \frac{I_{\text{p}} Z_{\text{LISN}} \left(1 - Gain\right)}{Z_{\text{inj}}} \quad (1)$$

$$\text{IL} = \frac{1}{1 + \frac{Z_{\text{p}}}{Z_{\text{p}} + Z_{\text{LISN}}} \frac{Z_{\text{LISN}}(1 - Gain)}{Z_{\text{inj}}}} \quad (2)$$

IV. Experimental Verification

To validate the feasibility and performance of the proposed neutral point-based compact CM AEF, a prototype is manufactured. To enhance the current driving capability, an extra class AB amplifier is used. Fig.3 shows the prototype with its size. Based on the abovementioned analysis, the main power flow will not affect the sensing and injection parts, so the voltage rating of the main components is low. Less components together with low voltage rating will result in about 80% volume reduction for sensing and injection networks. Detailed parameter settings of components and op-amp are listed in Tables I and II.

Fig.4 shows the connections of the testing setup. LISN is inserted between the input supply and the proposed AEF. A buck converter with 20 V input and 7.2 V output is taken as EUT. It is a typical application controlled by LM2596. A noise separator is used to separate pure CM or DM noise and deliver it to the EMI receiver. Dc voltage across capacitor C_1 and capacitor C_2 could be used to power the AEF with a suitable value and this voltage is sufficient enough to cover the input noise signal and compensation signal. Here, for the simplicity of test, an extra dc power supply is taken to provide the dc voltage for AEF.

Fig.5 refers to the CM voltage waveforms across neutral point O and ground tested with and without proposed CM AEF. From the observation, we could find that spikes are well removed which means high-frequency CM noise is dramatically attenuated by AEF. Besides, the maximum value of noise signal is pretty small. It is immune to the high voltage from the input supply, so the feasibility of using low voltage rate components for sensing and injection parts is verified. Corresponding CM

TABLE I
Detailed Parameters of Components

Components	Value	Components	Value
R_s	300Ω	C_1	680nF
C_s	0.1µF	C_2	680nF
R_g	750Ω	R_{inj}	10Ω
R_f	15kΩ	C_{inj}	1µF

TABLE II
Main Features About OP-AMP

Parameters	Value
Bandwidth	71MHz
Slew rate	55V/µs
Input voltage noise	$10\text{nV}/\sqrt{Hz}$
Input resistance	8MΩ
Input capacitance	1.5pF

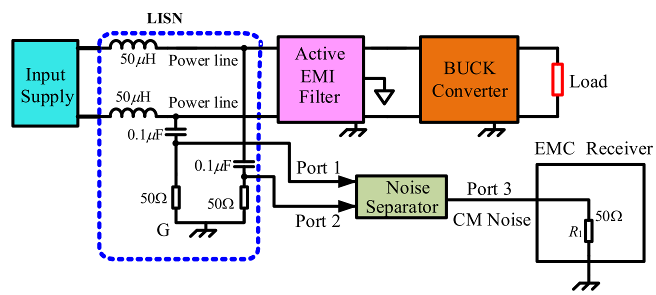

Fig. 4. Testing configuration of neutral point based compact CM AEF.

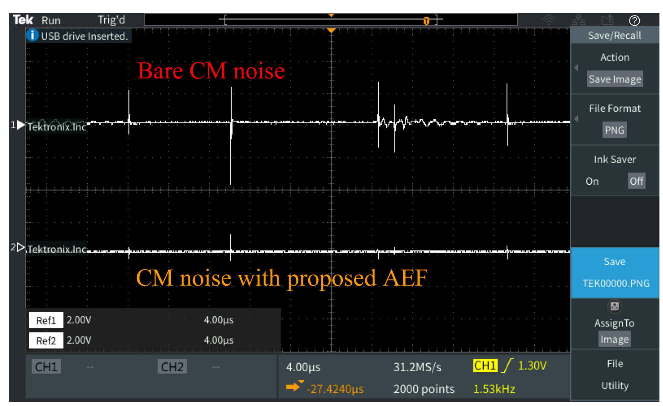

Fig. 5. CM noise signals in time domain tested with and without CM AEF.

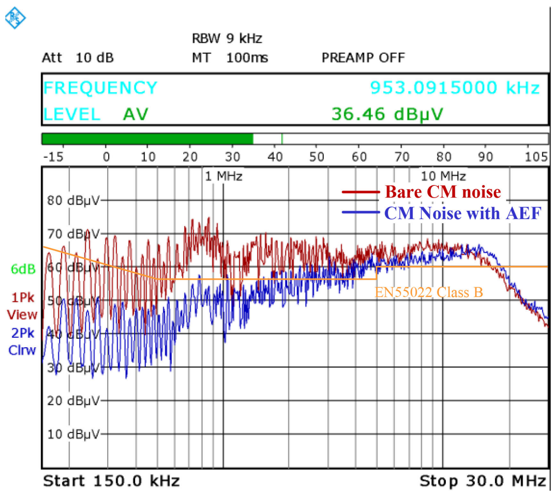

Fig. 6. CM noise signals in frequency domain tested with and without CM AEF.

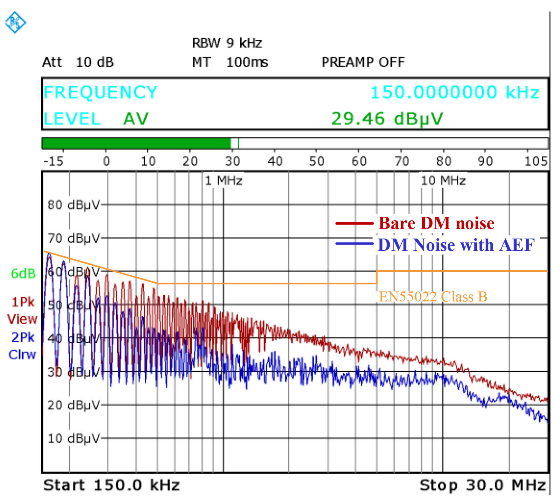

Fig. 7. Tested DM noise with and without proposed CM AEF.

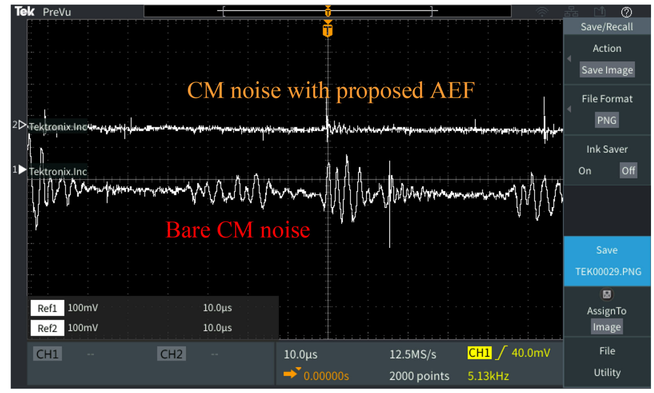

Fig. 8. CM noise signals in time domain tested with and without CM AEF on inverter system.

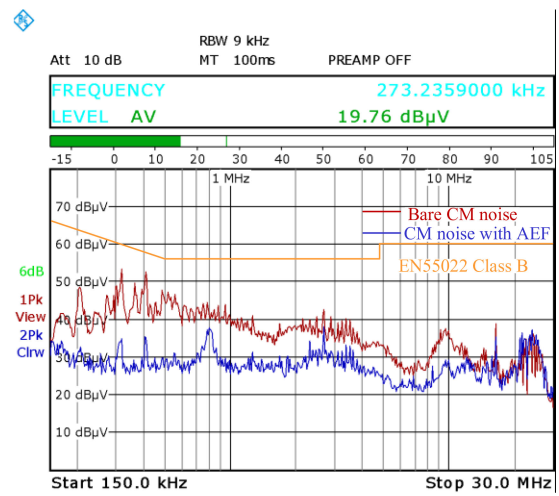

Fig. 9. CM noise signals in frequency domain tested with and without CM AEF on inverter system.

noise signals in the frequency domain are also derived in Fig. 6. The red curve refers to the bare CM noise and the blue curve is defined as the CM noise with the proposed CM AEF. The achieved noise attenuation is about 20dB within a wide frequency range. With this AEF, a small CM choke could easily cope with high-frequency noise to pass the EMC regulation.

It is mentioned that the proposed CM AEF could help to attenuate DM noise due to the existence of C_1 and C_2. To better illustrate the effect of DM noise attenuation, a small DM inductor is inserted between the proposed AEF and EUT. The inductance is 15 μH and it is made by ferret core. Tested spectrums of DM noise are shown in Fig. 7. The red curve represents the bare DM noise with a small DM inductor and the blue curve refers to the DM noise with small inductor and proposed AEF. The AEF contributes extra 10 dB attenuation to DM noise within the mid-frequency range. By increasing the value of C_1 and C_2, low-frequency spikes could be further attenuated.

Except for the application on Buck converter, this proposed NP-CM-AEF could also be used on other kinds of converters. Here, similar tests are also performed on an inverter system. Following Figs. 8–10 show the corresponding results tested on the inverter system. From the observation, we could find that the tested CM noise in the time domain and frequency domain shows the same characteristic as tested on the Buck converter. And the DM noise attenuation achieved by NP-CM-AEF is also decent as expected.

Based on the above analyses and tested results, a conclusive comparison between the proposed CM AEF and traditional CM AEF is performed as shown in Table III. From the comparison, we could find that the proposed CM AEF is much better than the traditional CM AEF from many perspectives. Besides, this proposed CM AEF is promising for both a low voltage converter and high voltage converter; however, the voltage rating of components should be noticed. Table IV shows the detailed voltage rating of components for those two kinds of converters. Capacitor C_1 and capacitor C_2 are connected across two power lines, so they have to hold the input voltage with a voltage rating higher than 1/2 V_{in}. The voltage rating for capacitor C_{s} and capacitor C_{inj} should have sufficient margin under high voltage conditions considering the unbalance of the Wheatstone bridge caused by the tolerance of components. Safety is guaranteed when those two components are set with a voltage rating above $1/5V_{\text{in}}$. Resistors including R_{s}, R_{g}, R_{f}, and R_{inj} are related to signal processing, and a 15 V voltage rating is enough to cover

TABLE III
CONCLUSIVE COMPARISON OF PROPOSED NEUTRAL POINT BASED CM AEF AND TRADITIONAL CM AEF

Compared Features	Neutral Point based CM AEF	Traditional CM AEF[7]-[11]
Sensing network	1-stage RC network	Two pairs of 2-stage RC network
Injection network	1-stage RC network	Two pairs of 1-stage RC network
Voltage rating of components	Low	High
Attenuation to DM noise	Yes	No
Size	Small	Medium
Reference setting	Neutral point	Ground
Convenience of power supply	Easy	Medium

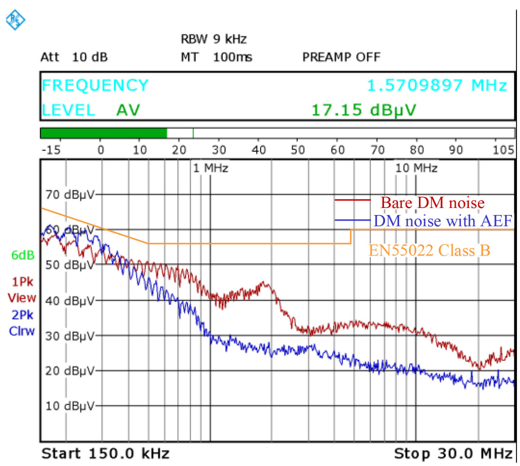

Fig. 10. Tested DM noise with and without proposed CM AEF on inverter system.

TABLE IV
VOLTAGE RATING OF COMPONENTS FOR LOW VOLTAGE CONVERTER AND HIGH VOLTAGE CONVERTER

Components	Voltage rating for low voltage converter	Voltage rating for high voltage converter
Capacitor C_1,C_2	>1/2 V_{in}	>1/2 V_{in}
Capacitor C_s, C_{inj}	About 15V	About 1/5 V_{in}
Resistor R_s,R_g,R_f,R_{inj}	About 15V	About 15V
Amplifier U_1	>1/2 V_{in}	According to extra DC supply

the applications. Meanwhile, the voltage rating for the amplifier is flexible. If it is used for a low voltage converter, the voltage rating of the amplifier higher than 1/2 V_{in} will contribute to a compact system as the voltage across capacitor C_1 and capacitor C_2 could be directly used as dc power supply for active part. If the AEF is used on high voltage converters, the voltage across capacitor C_1 and capacitor C_2 could not be directly used and an extra dc power supply is needed. Under this situation, the voltage rating for an amplifier is according to the extra dc power supply.

V. CONCLUSION

Traditional CM AEF is not concise enough in implementation and demands many components. To better reduce the size of CM AEF, this letter proposed a new neutral point-based compact CM AEF topology. The reference is set by a rebuilt neutral point. With this special design, noise separation is not needed. A prototype is built and experimental results show that this proposed NP-CM-AEF has a good attenuation to CM noise and the total size is pretty tiny. Besides, the proposed AEF also can contribute to DM noise attenuation. This neutral point-based compact AEF is a good solution for portable dc adapters and small motor drive systems.

REFERENCES

[1] B. Narayanasamy and F. Luo, "A survey of active EMI filters for conducted EMI noise reduction in power electronic converters," *IEEE Trans. Electromagn. Compat.*, vol. 61, no. 6, pp. 2040–2049, Dec. 2019, doi: 10.1109/TEMC.2019.2953055.

[2] Y. Chu, S. Wang, and Q. Wang, "Modeling and stability analysis of active/hybrid common-mode EMI filters for DC/DC power converters," *IEEE Trans. Power Electron.*, vol. 31, no. 9, pp. 6254–6263, Sep. 2016, doi: 10.1109/TPEL.2015.2502218.

[3] R. Goswami and S. Wang, "Modeling and stability analysis of active differential-mode EMI filters for AC/DC power converters," *IEEE Trans. Power Electron.*, vol. 33, no. 12, pp. 10277–10291, Dec. 2018, doi: 10.1109/TPEL.2018.2806361.

[4] S. Wang, Y. Y. Maillet, F. Wang, D. Boroyevich, and R. Burgos, "Investigation of hybrid EMI filters for common-mode EMI suppression in a motor drive system," *IEEE Trans. Power Electron.*, vol. 25, no. 4, pp. 1034–1045, Apr. 2010, doi: 10.1109/TPEL.2009.2033601.

[5] R. Goswami and S. Wang, "Investigation and modeling of combined feedforward and feedback control schemes to improve the performance of differential mode active EMI filters in AC–DC power converters," *IEEE Trans. Ind. Electron.*, vol. 66, no. 8, pp. 6538–6548, Aug. 2019, doi: 10.1109/TIE.2018.2883264.

[6] Y. Zhou, W. Chen, and X. Yang, "Investigation of cascade connection method to improve the insertion loss of DM active EMI filters," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 10, no. 1, pp. 1084–1094, Feb. 2022, doi: 10.1109/JESTPE.2021.3112576.

[7] Y. Zhou *et al.*, "A new integrated active EMI filter topology with both CM noise and DM noise attenuation," *IEEE Trans. Power Electron.*, vol. 37, no. 5, pp. 5466–5478, May 2022, doi: 10.1109/TPEL.2021.3130113.

[8] D. Hamza, M. Qiu, and P. K. Jain, "Application and stability analysis of a novel digital active EMI filter used in a grid-tied PV microinverter module," *IEEE Trans. Power Electron.*, vol. 28, no. 6, pp. 2867–2874, Jun. 2013, doi: 10.1109/TPEL.2012.2219074.

[9] D. Shin *et al.*, "Analysis and design guide of active EMI filter in a compact package for reduction of common-mode conducted emissions," *IEEE Trans. Electromagn. Compat.*, vol. 57, no. 4, pp. 660–671, Aug. 2015, doi: 10.1109/TEMC.2015.2401001.

[10] J. Ji, W. Chen, X. Yang, and J. Lu, "Delay and decoupling analysis of a digital active EMI filter used in arc welding inverter," *IEEE Trans. Power Electron.*, vol. 33, no. 8, pp. 6710–6722, Aug. 2018, doi: 10.1109/TPEL.2017.2758682.

[11] D. Hamza and M. Qiu, "Digital active EMI control technique for switch mode power converters," *IEEE Trans. Electromagn. Compat.*, vol. 55, no. 1, pp. 81–88, Feb. 2013, doi: 10.1109/TEMC.2012.2213590.