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A Common Mode Choke Using Toroid-EQ Mixed Structure

Wenhua Tan, Carlos Cuellar, *Member*, *IEEE*, Xavier Margueron, *Member*, *IEEE*, and Nadir Idir, *Member*, *IEEE*

***Abstract*— Electromagnetic interference (EMI) filters are main solutions to suppress the conducted emissions from static power converters. For some years, integration techniques for EMI filters have been widely investigated to realize more compact systems. In this letter, a common mode (CM) choke with toroid-EQ mixed structure is presented. This structure is constituted of a toroidal CM choke embedded into an EQ core. The proposed toroid-EQ CM choke presents three-fold advantages. First, it effectively increases the leakage inductance of the toroidal CM choke and hence increases the DM inductance. Secondly, it reduces the parasitic coupling between the choke and the filter capacitors. Finally, the component can be easily fabricated with low cost. Experimental verifications have been carried out to validate the effectiveness of the proposed toroid-EQ CM choke.**

***Index Terms*—Choke, electromagnetic interference, filter, integration, leakage inductance.**

I. Introduction

WITH the increase of switching frequency, power converters generate severer electromagnetic interferences (EMI), which is a challenging issue for designers. In the past ten years, many techniques have been reported to mitigate the conducted EMI noise, among which the EMI filters are the most practical and reliable solutions [1]–[3]. A typical topology of passive EMI filters is shown in Fig. 1. In this filter, the common mode (CM) choke L_{CM} is realized by coupled inductors while the differential mode (DM) chokes L_{DM} can be yielded by the leakage inductance of the CM choke or by independent discrete coils. In recent years, many integration techniques have been proposed to combine L_{CM} and L_{DM} together [4]–[8]. In [4], flexible multilayered foils are wound around two UU ferrite cores to integrate L_{CM}, L_{DM} and CM capacitances, resulting in a very compact EMI filter. However, parasitic elements due to the closely wound foil layers deteriorate the high frequency (HF) performances of the filter. In [5], a ferrite polymer composite layer is inserted inside a planar CM choke for providing leakage path and thereby increases the L_{DM}. Though planar components are more adapted for integration, the low thickness and long length of winding traces increase the copper loss that reduces the efficiency of filters [4].

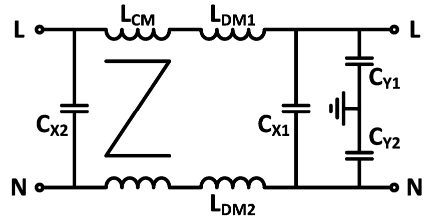

Fig. 1. Typical topology of EMI filter

Note that the most commonly used chokes in commercial EMI filters are still based on toroidal cores due to their low cost and wide availability [9]. In the literature, integration techniques have also been reported for toroidal cores. In [6], [7], CM and DM chokes are wound on toroidal cores with different radius so that the smaller core (DM choke) is inserted into the window of the bigger one (CM choke). These methods combine the CM and DM choke together and thereby significantly reduce the volume of the filters.

Another integration technique consists in increasing the leakage inductance of the toroidal CM choke for DM noise suppression [8]. According to [10], the leakage inductance of a toroidal CM choke can be estimated by:

$$L_{\mathrm{DM}} = \mu_{\mathrm{DM\_e}} \frac{0.4\pi N^2 A_{\mathrm{e}}}{l_{\mathrm{e}}\sqrt{\left[(\theta/360)+(\sin(\theta/2)/\pi)\right]}} \tag{1}$$

where $\mu_{\mathrm{DM\_e}}$ is the effective permeability for leakage flux, N is the number of turns in the winding, θ is the winding angle, A_{e} is the effective cross section area and l_{e} is the effective mean length of the core. From (1), it can be seen that L_{DM} mainly depends on the winding turn number N, the core geometry, and the effective permeability for the DM leakage flux. Usually, the value of L_{DM} is very small. Recently, nanocrystalline material receives many concerns in EMI filtering applications [11]. Compared to MnZn ferrite, nanocrystalline material has a very high initial permeability, high saturation level, high operating temperature and low temperature sensibility. Therefore, to achieve the same inductance L_{CM} for a given current, using nanocrystalline core allows the miniaturization of the filter with smaller core and less winding turn number, leading to an even smaller L_{DM}. This reduction of leakage inductance is adverse for DM noise suppression. In [8], magnetic epoxy mixture is used for coating a CM choke. This mixture outside the choke can increase the $\mu_{\mathrm{DM\_e}}$ and hence enlarge the leakage inductance

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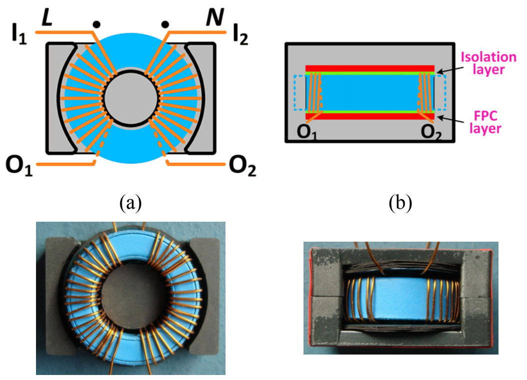


(a) (b)

(c) (d)

Fig. 2. T-EQ CM choke. (a) Structure: top view. (b) Structure: front view. (c) Realized T-EQ choke: top view. (d) Realized T-EQ choke: front view.

TABLE I
PARAMETERS OF THE MAGNETIC CORES USED IN THE T-EQ CM CHOKE

	Nanocrystalline core	**Ferrite EQ core**
Reference	Magnetec M-307	EPCOS EQ30 N97
Dimensions	OD=22.5 mm ID=12.5 mm H=7.5 mm	L=30 mm W=20 mm H=16mm
Initial Permeability	30000	2200
Saturation Level	1.2 T	0.4 T

L_{DM}. However, this kind of integrated component is expensive due to the fabrication of the magnetic epoxy mixture and the coating process.

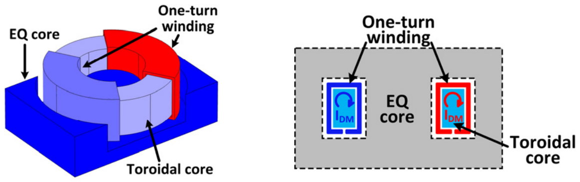
In this letter, a CM choke with toroid-EQ (referred as T-EQ hereinafter) mixed structure is presented. It consists of the association of two magnetic cores with different geometries and materials for realizing the CM choke, i.e. nanocrystalline toroid and ferrite EQ cores. The nanocystalline core is used as CM choke to provide large L_{CM} whereas the ferrite core can significantly increase the leakage inductance of the CM choke, namely L_{DM} for filtering DM noise. Moreover, it exhibits less parasitic magnetic coupling between itself and filter capacitors in its vicinity. At last, the T-EQ CM choke can be easily fabricated. To verify the design, a prototype is realized using a nanocrytalline toroidal core and a MnZn ferrite EQ core. Measurements are carried out to demonstrate the effectiveness of the design.

This paper is organized as follows. In Section II, the design of the T-EQ CM choke is briefly introduced. Besides, some physical characteristics of this component are studied by simulations and measurements. In Section III, experimental verifications are presented to validate the design.

I. DESIGN OF THE TOROID-EQ CM CHOKE

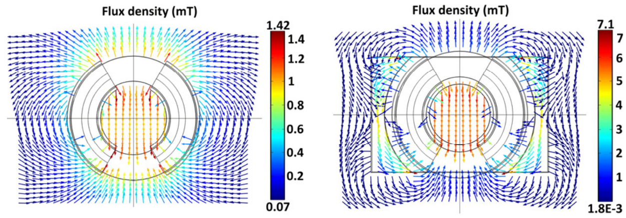
A. Design Description

To increase L_{DM} one can augment the value of μ_{DM_e} according to (1). The proposed T-EQ CM choke incorporates a nanocystalline toroidal core as CM choke and an EQ core for increasing the μ_{DM_e}. The basic design of this component is illustrated in Fig. 2(a)(b). As seen, the toroidal CM choke is wound as an ordinary one and it is subsequently embedded



(a) (b)

Fig. 3. T-EQ CM choke model for simulation. (a) One-turn equivalent model. (b) Cross section view.



(a) (b)

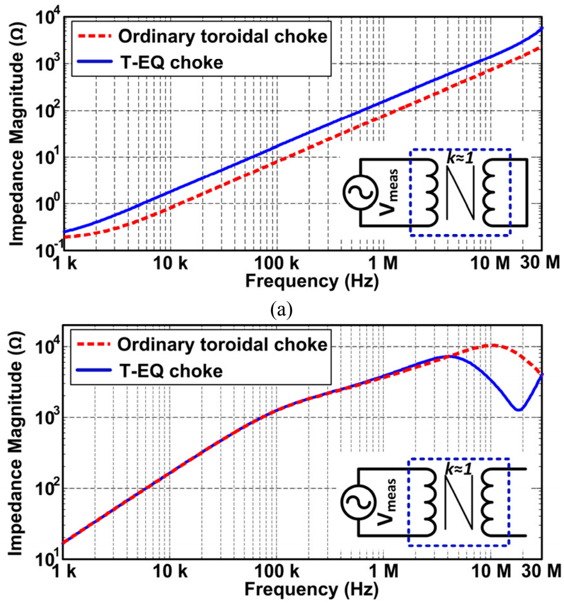
Fig. 4. Finite elements simulation results for the CM choke models. (a) Ordinary toroidal choke. (b) T-EQ choke.

into an EQ core. Giving matched sizes of the toroidal and EQ cores, the implementation of this component is simple since it does not require particular winding or fabrication process. The basic operating mechanism of this component for CM filtering is the same as an ordinary toroidal CM choke. The flux due to DM currents is cancelled in the toroidal core. The CM inductance L_{CM} of the component is given by: $L_{CM} = A_L \cdot N^2$, where A_L denotes the inductance ratio of the toroidal core and N denotes the number of turns in the winding. The leakage inductance of the CM choke is used for filtering the DM conducted noise. As the CM choke is surrounded by the MnZn ferrite EQ core, the value of μ_{DM_e} is significantly increased.

According to this structure, a prototype is realized, as shown in Fig. 2(c)(d). The toroidal core for CM choke uses Nanoperm alloy from Magnetec [12] whereas the EQ core uses EPCOS N97 ferrite material [13]. The properties of both cores are summarized in Table I. The toroidal CM choke is wound with 21 turns of AWG 26 wire. An isolation layer of silicone varnish is coated on the inner surface of the EQ core to avoid the contact between the windings and the core. To further increase the leakage inductance, ferrite polymer composite (FPC) C350 material [13] is used for filling the space between the CM choke and the EQ core.

B. Component Characteristics

The study of the component characteristics begins with numerical simulations. In fact, the windings of the toroidal choke can be approximately regarded as two one-turn coils having the same winding angle and the same ampere-turns [14], as shown in Fig. 3. Based on this approximation, a simplified 3D model of the component is built in COMSOL multiphysics and magnetostatic analyses are carried out. It is supposed that the DM currents passing through the 21-turn CM choke is 0.5 A (peak), so the DM currents in the one-turn model are set to be 10.5 A to keep same ampere-turns value.



(a)

(b)

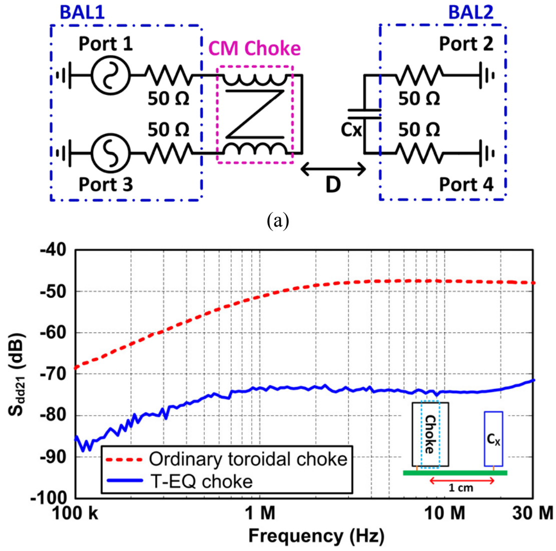
Fig. 5. Impedance measurement results. (a) Short-circuit configuration. (b) Open-circuit configuration.

TABLE II
PARAMETERS OF THE CHOKES

	Ordinary choke	T-EQ choke
Number of turns	21	21
L_{CM} (@10 kHz)	2.6 mH	2.6 mH
L_{DM} (@100 kHz)	6.3 µH	13.6 µH
Volume	4.3 cm^3	9.6 cm^3

Fig. 4 compares the simulated flux densities on the median cross-sections (without the flux density in the toroidal core) for an ordinary toroidal CM choke and the T-EQ CM choke. Compared to the ordinary choke, the leakage flux for the T-EQ choke mainly travels inside the EQ core, especially through the central cylinder leg. As a result, the flux density outside the T-EQ CM choke is significantly reduced. The space between the toroid and EQ cores forms an air-gap, which avoids the saturation of the EQ core in this setup.

Next, impedances of the T-EQ CM choke are measured with an impedance analyzer (HP 4294A). Short and open circuit impedances are measured to determine the value of CM inductance and leakage inductance of the component. The measured results are compared with those of an ordinary CM choke in Fig. 5. Based on these impedance measurements, the parameters of the T-EQ CM choke as well as the ordinary CM choke are summarized in Table II. The T-EQ choke exhibits a leakage inductance of 13.6 µH, which is more than twice the one of the ordinary choke. Meanwhile, the CM inductance at 10 kHz is 2.6 mH, which is the same for both cases. It should also be noted that the MnZn ferrite of the EQ core has a high intrinsic relative permittivity ε_r, normally in the order of 10^4 [15]. In turn, it increases the parasitic capacitances of the T-EQ CM choke. As can be seen from Fig. 5(b), the resonance of the open-circuit impedance for the T-EQ CM choke is moved to lower frequency due to this raise of the parasitic capacitances. However, this parasitic capacitance problem for CM choke can be circumvented by parasitic capacitance cancellation techniques [16].



(a)

(b)

Fig. 6. Measurements of the parasitic magnetic coupling between the choke and DM capacitors. (a) Test setup. (b) Measurement results.

C. Parasitic Magnetic Coupling Between CM Choke and Filtering Capacitors

Parasitic elements are one of the main factors that impair the HF performances of an EMI filter. Apart from the extensively studied self-parasitic elements, parasitic coupling between components in an EMI filter is dominant for the effectiveness of such filter [17]. One solution for reducing the parasitic coupling is to use magnetic shield. In the T-EQ CM choke, the ferrite EQ core acts as a shield by covering the CM toroidal choke inside. Instead of travelling in air, a great portion of the leakage flux is enclosed inside the EQ core, resulting in a reduced magnetic coupling between the choke and other components in its vicinity such as filter capacitors. The simulated results for T-EQ CM choke in Fig. 4 show that the flux is well confined inside the EQ core. Moreover, the flux density outside the component is significantly reduced with respect to that of the ordinary toroidal choke, resulting in lower coupling between the choke and capacitors.

Experimental measurements are then performed to further support the simulated results. Four-port mixed mode S parameter measurements are carried out with a vector network analyzer (Agilent 5071C) to study the small-signal characteristics of filters. The fixture simulator of the analyzer is enabled and is set to BAL-BAL mode with port 1 and 3 being BAL1 and port 2 and 4 being BAL2. The test setup is shown in Fig. 6(a). The distance D between the choke and the capacitor is kept at 1 cm. The CM choke is excited by balanced RF outputs (BAL1) from the analyzer. This RF signal is coupled to the DM capacitor C_X through magnetic coupling and captured by another balanced RF input (BAL2). The value of S_{dd21} is then measured and it reflects the

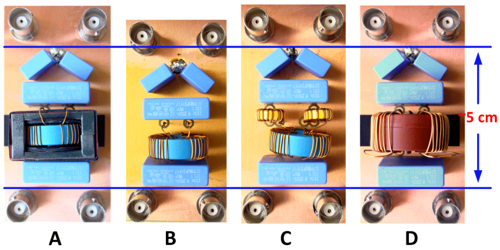


Fig. 7. Four different EMI filters for comparison.

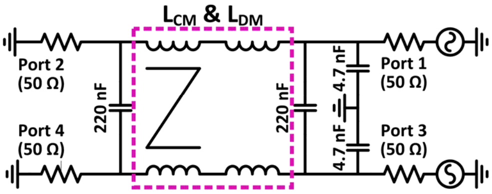
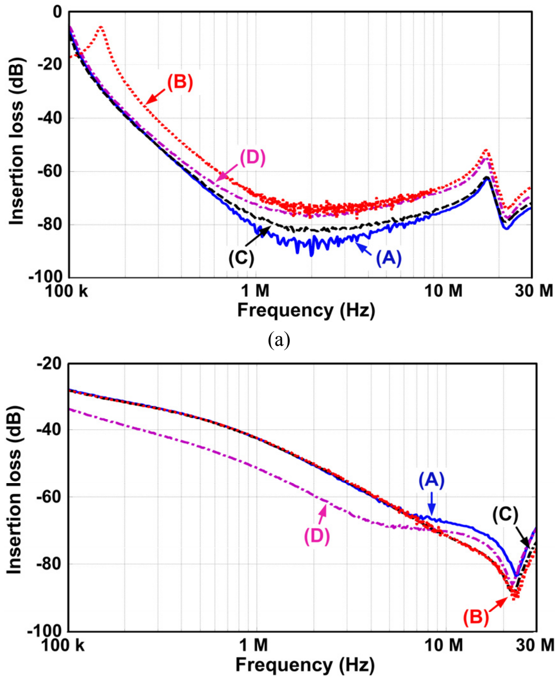


Fig. 8. Configuration of the four-port mixed mode S parameter measurements.

magnetic coupling strength between the CM choke and the C_X capacitor. The measured results for ordinary choke and T-EQ choke are compared in Fig. 6(b). It can be seen that the coupling between the choke and the capacitor is considerably reduced in the T-EQ choke case.



(a)
(b)

Fig. 9. Comparison of the insertion losses. (a) DM. (b) CM.

II. Experimental Validations and Discussion

A. *Comparison of Different Solutions for Increasing L_{DM}*

To show the benefits of the T-EQ CM choke solution for EMI filtering, the topology of Fig. 1 with four different solutions are compared: (A) the proposed T-EQ CM choke; (B) same toroidal nanocrystalline CM choke without EQ core; (C) same toroidal nanocrystalline CM choke with separate DM coils for increasing L_{DM}; (D) toroidal CM choke with larger nanocrystalline core for increasing L_{DM}. The realized EMI filters are shown in Fig. 7. The values of the DM capacitors C_X and the CM capacitors C_Y are 220 nF and 4.7 nF respectively for every filter. In filter (C), iron powder core should be used for the separate DM coils to avoid saturation and two MULTICOMP 8.2µH/2A inductors are chosen to achieve comparable L_{DM} as (A). In (D), a Magnetec M-449 nanocrystalline core is chosen and wound (with 26 turns, L_{CM}=6.4 mH@10 kHz) so that it has the same L_{DM} as (A). It can be seen that the filter (B) has the smallest volume while the filters (A), (C) and (D) occupy almost the same area on PCB. However, it should be mentioned that solution (C) increases the winding length by 45% (from 110 cm to 160 cm) and solution (D) increases the height of the filter by 25% (from 2.4 cm to 3 cm) and almost doubles the winding length (from 110 cm to 210 cm).

B. *Small Signal Insertion Loss Measurements*

One major difference between (A) and the other filters is that the toroidal CM choke is covered by the ferrite core. As stated previously, the ferrite EQ core can effectively reduce the magnetic coupling between the choke and the capacitors and thereby improve the performance of the filter. To further support this, four-port mixed-mode S parameter measurements are again performed with the Agilent 5071c network analyzer to evaluate the insertion losses (IL) of the EMI filters in Fig. 7 from 100 kHz to 30 MHz. The measurement configuration is presented in Fig. 8. The DM IL is given by S_{dd21} whereas the CM IL is given by S_{cc21}, as presented in Fig. 9. Comparing the DM ILs of filters (A) and (B), it can be seen that the use of the EQ ferrite core improves the performances of the filter for more than 8 dB from 100 kHz to 30 MHz, which is due to the increased L_{DM} and reduced parasitic magnetic coupling between components. Moreover, as same L_{DM} are realized in filters (A), (C) and (D), the DM ILs below 400 kHz are almost the same for the three cases. Nevertheless, the filters (C) and (D) exhibit inferior performances beyond 1 MHz due to the magnetic parasitic coupling between the choke and the DM capacitors [17]. Regarding the CM ILs, the filters (A),(B) and (C) has almost the same CM IL below 5 MHz, and beyond, the CM IL for the filter (A) is degraded by parasitic capacitances for about 8 dB. Filter (D) has larger CM attenuation below 8 MHz since it has greater CM inductance due to the larger size and winding turn numbers of the choke.

C. *EMI Conducted Noise Measurements*

The EMI filters (A) and (B) are tested with a DC-DC converter using SiC power semiconductor operating at 100 kHz with an R(30 Ω)-L(6 mH) load. The input voltage is 100 V_{DC} and the input current is about 1 A. The measurement setup is shown in Fig. 10. The DM and CM noises are picked up by a current probe (FCC F-35, 100 Hz–100 MHz) and sent to an EMI test receiver (ROHDE & SCHWARZ, 9 kHz–3 GHz). The DM and CM noises are measured from 150 kHz–30 MHz under peak detection mode. After correction of the

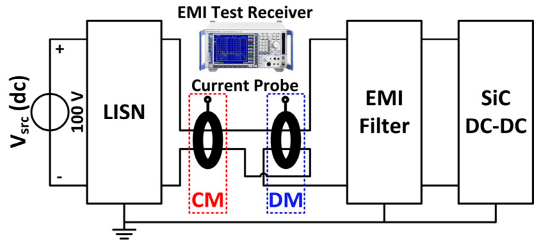
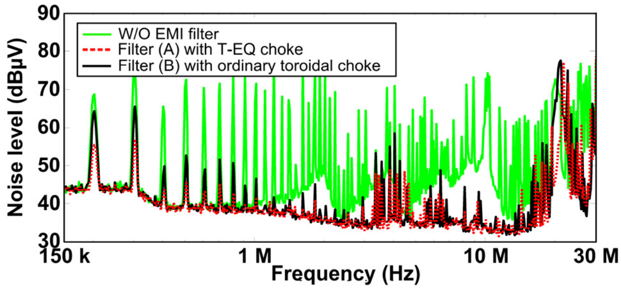
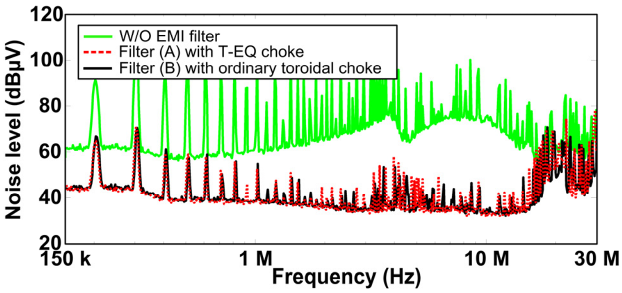


Fig. 10. Setup for conducted noise measurements.



(a)



(b)

Fig. 11. Conducted noise measurement results. (a) DM noises. (b) CM noises.

measured data from the current probe, the final conducted EMI noise levels are compared in Fig. 11. For differential mode, the filter (A) with the T-EQ CM choke exhibits an improvement of 6–8 dB from 150 kHz to 10 MHz in comparison with the filter (B) using the ordinary toroidal choke. Moreover, the use of the ferrite EQ core has almost no influence on the CM performances of the filter as both filters achieve almost the same attenuation for CM (see Fig. 11(b)).

D. Discussions

As an additional ferrite EQ core is used in the proposed CM choke, there are many other ways to further improve the performances of the component. First, to obtain a higher inductance value, additional windings on the EQ core are also feasible to form coupled DM inductors. Nonetheless, as this will cause saturation of the ferrite EQ core, air-gap should be added on its central cylinder leg. Besides, as the surface of the EQ core is flat, one can stick additional magnetic shield (copper or μ-metal foil) directly on the EQ core to reduce the parasitic coupling between components, which is not possible with toroidal core. The EQ core presented in this letter can be replaced by many other cores such as P core, PQ core, etc., which can enclose the leakage flux of the toroidal CM choke as well. To extend the technique for higher power applications, cores with customized sizes and material can be employed for thicker wire and higher current.

III. Conclusion

In this letter, a CM choke using toroidal and EQ mixed structure is presented. The toroidal nanocrytalline core, acting as a CM choke is embedded into a MnZn ferrite EQ core that is used to increase the leakage inductance for DM filtering. The proposed structure can effectively augment the leakage inductance without additional DM chokes and the fabrication of such component is simple. Experimental verifications are performed and the results show that this solution is very interesting for EMI filtering applications.

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