Integrated Magnetic Circuits for Differential-mode and Common-mode Chokes of EMI Filters

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ABSTRACT

In this paper, two magnetic circuits to integrate common-mode (CM) and differential-mode (DM) chokes of an electromagnetic interference (EMI) filter are proposed. The DM and CM chokes are integrated by using UIU and EI ferrite core shapes. To evaluate the EMI reduction performances of proposed approaches, the conducted EMI reduction performances of proposed integrated DM and CM chokes are compared with the conventional CM choke and traditional separated DM and CM chokes. From the experimental results, it ensures the advantages of the use of proposed approaches. Although some magnetic parts are eliminated by proposed approaches, the amount of DM and CM EMI attenuation rate is comparable to the case of traditional separated DM and CM chokes, except the highest peak is located at different frequencies.

Keywords: Common-mode Chokes, Differential-mode Chokes, EMC, EMI, EMI Filters, Integrated Magnetics.

1. INTRODUCTION

With the tremendous improvement in terms of performance, reliability, and cost of power electronic device technology such as wide band gap power devices [1], power electronic systems dramatically penetrate into: commercial products, electrical/electronic industries, electric power generations and distributions, vehicle transportations, medical equipments, and military applications and etc. [2]. Despite the fact that power electronic systems can convert electrical energy efficiently; the extremely fast switching operations of power electronic circuits pollute the power quality of the electric utilities. The electrical pollution problems can be divided by frequency ranges i.e. harmonics (low-frequency range) and electromagnetic interference (EMI) (high frequency range). As a result, in order to control the generating EMI emissions from power electronic systems which operate at a switching frequency higher than 9 kHz, electromagnetic compatibility (EMC) recommendations
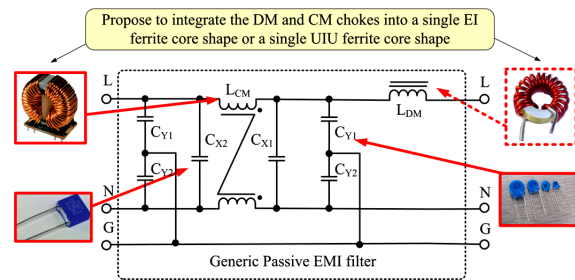

Fig.1: *Generic passive EMI filter.*

and regulations are enforced by both local and international organizations. Generally, to comply with conducted emission standards, EMI filters are used [3-6]. Although, there are three types of EMI filters i.e. passive, active, and hybrid EMI filters used nowadays, the most used in commercial one is still a passive EMI filter [7]. Fig. 1 shows an example of a generic EMI filter which composes of: differential-mode choke (DM choke), common-mode choke (CM choke), X-capacitors, and Y-capacitors. It should be noted that all EMI filter topologies used in commercial products are derived from Fig. 1 [8].

The function of EMI filters is to limit the differential-mode (DM) and common-mode (CM) emissions generated by any electrical/electronic products whose operating switching frequency exceeding 9 kHz (such as switching power supplies, electric drive applications, etc.) lower than the standard limit lines. It is worth to note that, currently, EMI filters are still the most effective tool to suppress the conducted emissions, although, it increases the total size, weight, and production cost of products [3-6]. Obviously, as shown in Fig. 1, the bulkiest and most expensive components are DM and CM chokes. Thus, several techniques were proposed to solve the mentioned disadvantages of EMI filters [9 - 15]. Although, there are some researches proposed techniques to integrate all EMI filter components i.e. DM and CM chokes as well as X- and Y-capacitors using flexible multilayer foils with planar magnetic technology [14-15], nowadays, in a commercial EMI filter, a traditional ferrite core (discrete components) is still the most preferable because it is easy to find and cost competitive [11]. With this reason, in this paper, only the integration of DM and CM chokes into one single core is focused.

To reduce the total size of EMI filters, in [9-11], two toriodal ferrite cores are used as DM and CM chokes; The DM and CM chokes are integrated by placing a DM choke within an open window of a CM choke. However, the production cost of this technique is still high because it comprises of two separated toroidal ferrite cores. In [12], the approach to achieve compact size with lower cost of EMI filters is presented. One EI ferrite core shape is used instead of commonly-used two separated ferrite cores for DM and CM chokes. The EMI reduction performance of [12] is evaluated and studied in [13]. However, the EMI reduction performance of proposed technique in [12] is completely dependent on adjusting air-gap of EI ferrite core shape which is limit the maximum DM and CM reduction performances [13]. To solve such a limitation, a new magnetic circuit for effective integration of DM and CM chokes of EMI filters is presented in this paper.

2. PROPOSED INTEGRATION TECHNIQUES FOR DIFFERENTIAL-MODE AND COMMON-MODE CHOKES

In this paper, two magnetic circuits, i.e. UIU and EI ferrite core shapes for the integration of CM and DM chokes, are presented as shown in Figs. 2 (c)-(d), respectively. For comparison purpose, the conventional CM choke and traditional separated CM and DM chokes are also shown in Figs. 2 (a)-(b), respectively. For sake of simplicity, the constraints of magnetic circuit calculation of proposed circuits are defined as follows:
1. The CM and DM fluxes are decoupled completely.
2. The leakage fluxes are not taken into account.
3. The number of turns of CM and DM chokes are set to be equal to N .
4. The reluctance of air-gap is much larger than that of magnetic circuits ($\Re_g \gg \Re_1 \Re_2 \Re_c$).

By these simplifications, the CM and DM inductances of proposed circuits can be approximated as follows:

2.1 Integration technique using an UIU ferrite core shape

From proposed integrated CM and DM chokes using the UIU ferrite core shape as shown in Fig. 2 (c), it can be converted into magnetic circuits as shown in Fig. 3. Using these magnetic circuits, it yields the approximation of CM and DM inductances as follows:

- *Common-mode Inductance Approximation*

In Fig. 3 (c), as the CM currents at line and neutral wires are equal ($I_{CM1} = I_{CM2}$) the CM inductance can be approximately calculated:

$$L_{CM(UIU)} = \frac{N^2}{2(\Re_1 + \Re_2)} \tag{1}$$

- *Differentail-mode Inductance Approximation*

The DM inductance can be roughly determined using equivalent circuit as shown in Fig. 3 (d); it yields:

$$L_{DM(UIU)} = \frac{N^2}{2\Re_g} \tag{2}$$

2.2 Integration technique using an EI ferrite core shape

Similarly, the CM and DM inductances of proposed integrated CM and DM chokes by the EI ferrite core shape as shown in Fig. 2 (d) can be converted into magnetic circuits as shown in Fig. 4. The CM and DM inductances can be estimated using magnetic circuits as shown in Fig. 4 (c) and (d), respectively.

- *Common-mode Inductance Approximation*

In Fig. 4 (c), as the CM currents at line and neutral wires are equal the CM inductance can be estimated:

$$L_{CM(EI)} = \frac{N^2}{4\Re_1} \tag{3}$$

- *Differentail-mode Inductance Approximation*

With the magnetic circuit in Fig. 4 (c), the DM inductance can be found as follows:

$$L_{DM(EI)} = \frac{N^2}{\Re_g} \tag{4}$$

3. EXPERIMENTAL VALIDATIONS AND DISCUSSIONS

To evaluate the conducted EMI reduction performances of proposed integrated CM and DM chokes using UIU and EI ferrite core shapes, the experimental setup is conducted as shown its block diagram and photograph in Figs. 5-6, respectively. The noise source is a 250 W switched-mode power supply (SMPS) where it is powered through the line impedance stabilization network (LISN) which includes DM/CM discrimination network [16]. For the EMI chokes under test, it is composed of: conventional CM choke, traditional separated CM and DM chokes, integrated CM and DM chokes using an UIU ferrite core shape, and integrated CM and DM chokes using an EI ferrite core shape. Since this paper is focused only on the comparison of EMI reduction performances of EMI chokes under test, as a result for comparison purposes, all EMI chokes are used the same magnetic core size (EI50A) and copper wire size (AWG♯18) where the number of turns of each windings is equal to 15 turns.
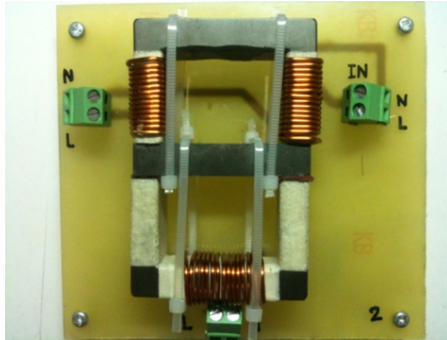
In order to evaluate the EMI reduction performances of proposed integrate CM and DM chokes techniques, three experiments are conducted as follows:
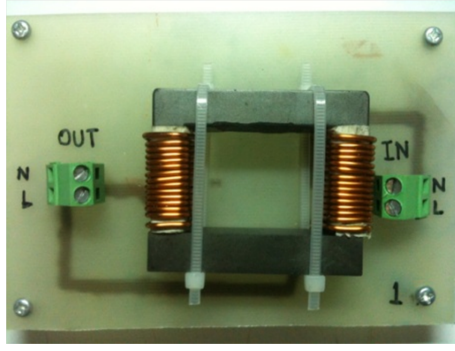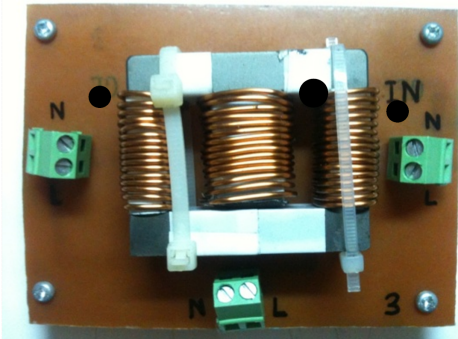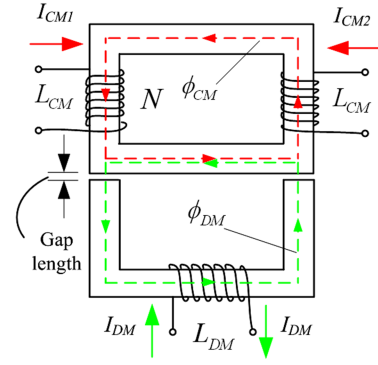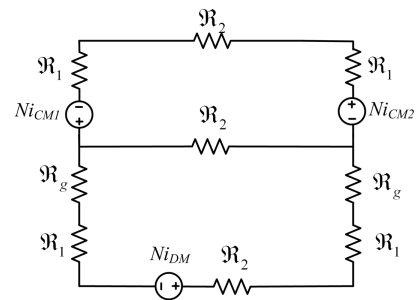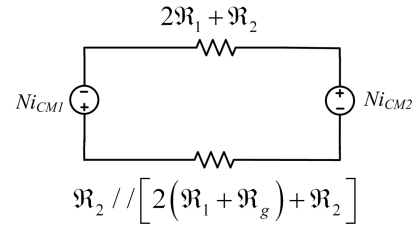
(a)
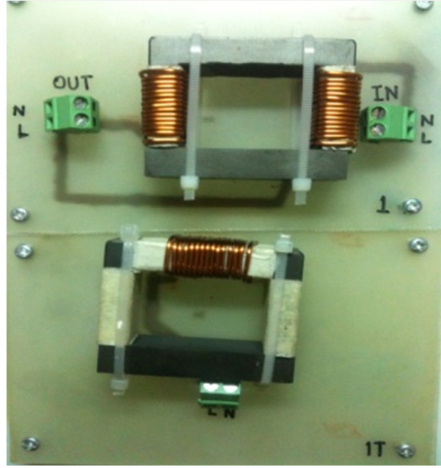
(b)

(c)

(d)

Fig.2: *Prototype of : (a) conventional CM choke; (b) Traditional separated CM and DM chokes; (c) Integrated DM and CM chokes using an UIU ferrite core shape; (d) Integrated DM and CM chokes using an EI ferrite core shape.*
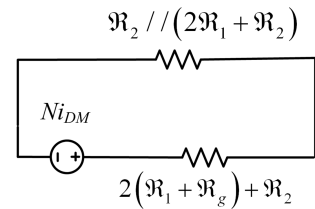

(a)

(b)

(c)

(d)

Fig.3: *Proposed UIU ferrite core topology; (a) Winding configuration; (b) magnetic circuit derivation. Simplified magnetic circuit derivation under: (c) CM current; (d) DM current.*

1. The EMI reduction performances of: without any filter inserted, with conventional CM choke, with traditional separated CM and DM chokes, and with integrated CM and DM chokes using an UIU ferrite core shape are compared.
2. The EMI reduction performances of: without any filter inserted, with traditional separated CM and DM chokes and with integrated CM and DM chokes using an EI ferrite core shape (with air-gap length equal to 0.14 mm at center leg) are compared.
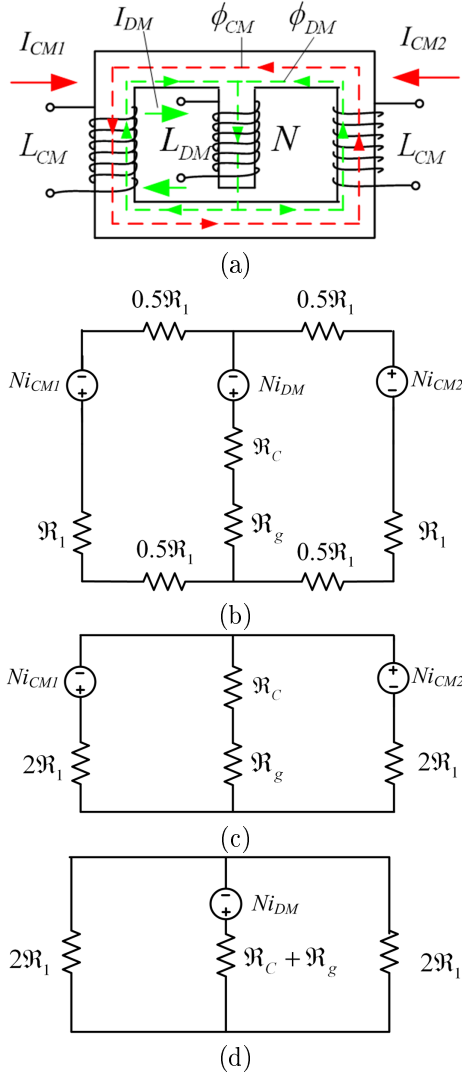
Fig.4: *Proposed EI ferrite core topology; (a) Winding configuration; (b) magnetic circuit derivation. Simplified magnetic circuit derivation under: (c) CM current; (d) DM current.*

3. The EMI reduction performances of without any filter inserted and integrated CM and DM chokes using an EI ferrite core shape with varying air-gap length at center leg from 0.1 mm, 0.12 mm, and 0.14 mm are demonstrated.

Although, the integrated CM and DM chokes using an EI ferrite core shape can minimize the use of ferrite cores than that of the integrated CM and DM chokes using an UIU ferrite core shape. However, the EMI reduction performances of integrated CM and DM chokes using an EI ferrite core shape is dependent on air-gap length [9]. As a result, the effect of air-gap length to EMI reduction performance of the integrated CM and DM chokes using an EI ferrite core shape is evaluated in the last experiment;

Figs. 7 (a) and (b) show the comparison of CM and DM emissions of without any filter inserted, with conventional CM choke, with traditional separated CM
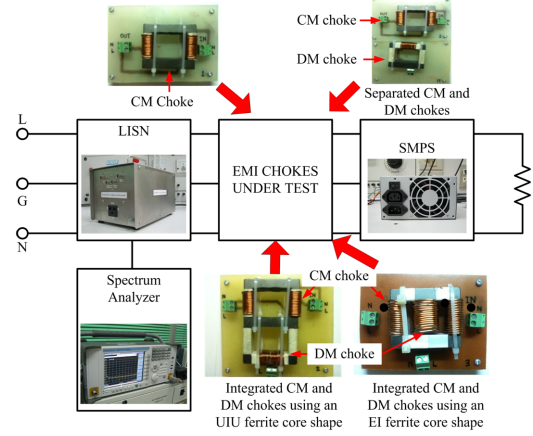

Fig.5: *The block diagram of experimental setup to verify the EMI reduction performances of proposed integrated CM and DM chokes.*
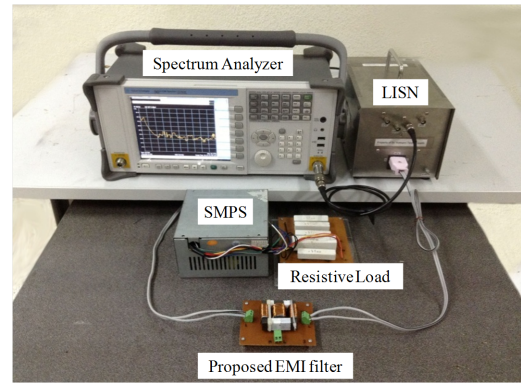

Fig.6: *The photograph of experimental setup to verify the EMI reduction performances of proposed integrated CM and DM chokes.*

and DM chokes, and with integrated CM and DM chokes using an UIU ferrite core shape, respectively. It can be seen that the amount of DM and CM EMI attenuation rate of integrated choke using UIU core shape is comparable to that of the traditional separated CM and DM chokes.

It is worth to note that the obtained results agree well with the theoretical one because one passive element, i.e. one inductor in this case, has an insertion loss (IL) equal to 20 dB/decade as shown in Eq. (5) [3-6], [8].

$$IL = 20 \log \sqrt{1 + (\omega\tau)^2} \qquad (5)$$

where

$$\tau = \frac{L}{Z_s + Z_L} \qquad (6)$$

and the cutoff frequency is equal to

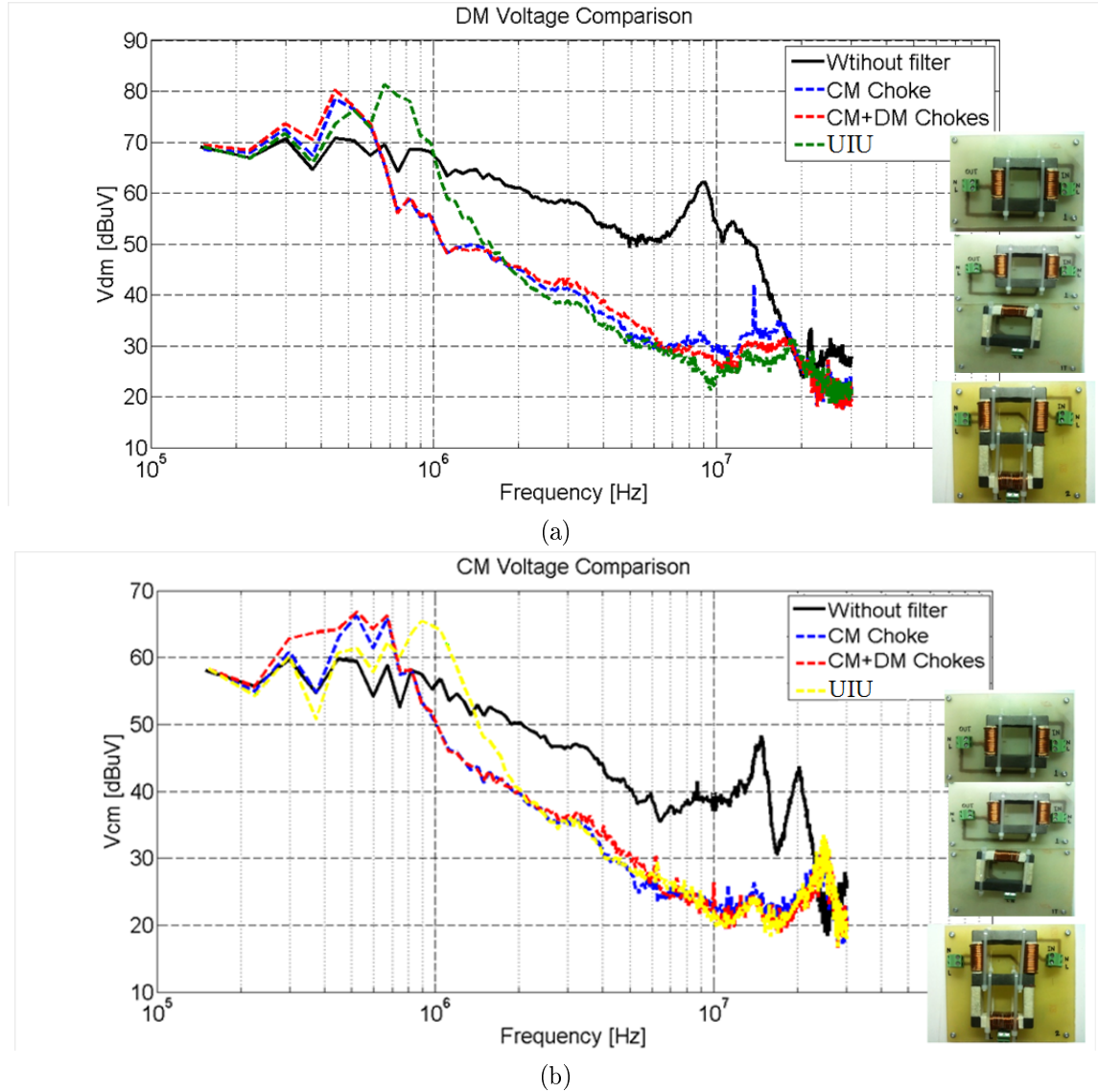$$f_r = \frac{1}{2\pi}\left[\frac{Z_s + Z_L}{L}\right] \qquad (7)$$

(a)

(b)

Fig.7: *EMI emission comparisons of without any filter inserted, with conventional CM choke, with traditional separated CM and DM chokes, and with integrated CM and DM chokes using an UIU ferrite core shape: (a) DM; (b) CM.*

where Z_s and Z_L are the source and load impedances, respectively.

However, the highest EMI peaks of both cases are located at different frequencies because the number of winding turns is set to be equal, as a result, the DM and CM inductances of both cases are different that affect to the shift of cutoff frequency of EMI filters as shown in Eq. (7).

Furthermore, for the DM comparison, it obviously shows that the DM reduction performances of integrated CM and DM chokes using an UIU ferrite core and traditional separated CM and DM chokes are better than that of conventional CM choke about 5 dBuV at frequency range 10 MHz - 20 MHz due to the effect of additional DM choke.

Similarly, Fig. 8 (a)-(b) show the comparison of DM and CM reduction performance of without any filter inserted, with traditional separated CM and DM chokes, and with integrated CM and DM chokes using an EI ferrite core shape (air-gap = 0.14 mm). For DM reduction performance, it shows a similar result between integrated and traditional separated CM and DM chokes. However, for CM reduction performance, the amount of CM attenuation rate of integrated and traditional separated CM and DM chokes are comparable, unless the highest peak is located at different frequencies.

In Fig. 9 (a)-(b), the DM and CM reduction performances of integrated CM and DM chokes using an EI ferrite core shape are evaluated and studied by varying the air-gap length at center leg from 0.1 mm, 0.12 mm, and 0.14 mm, respectively. It should be note that, for comparison purpose, the integrated CM and DM chokes using an EI ferrite core shape
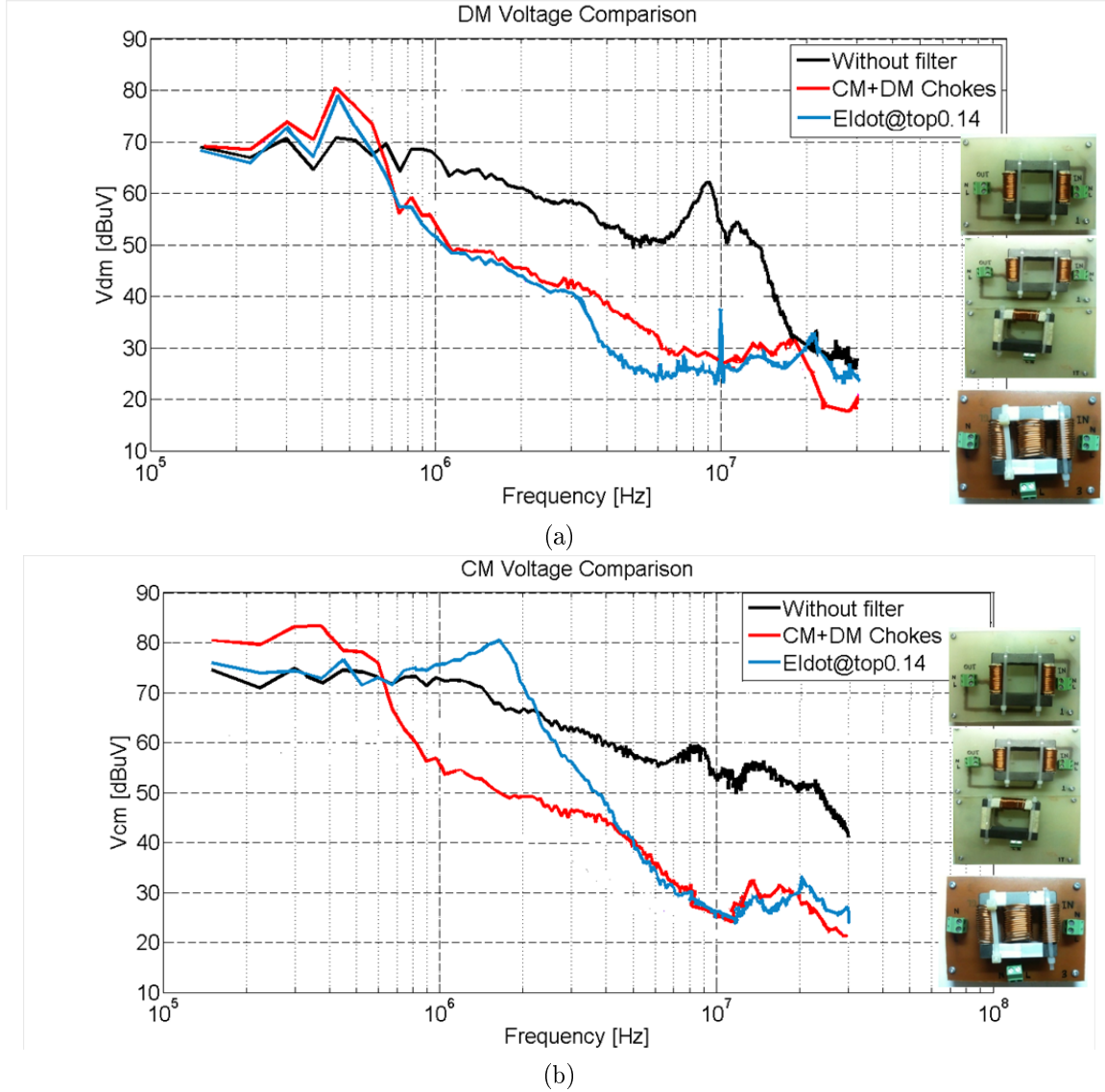
(a)

(b)

Fig.8: *EMI emission comparisons of without any filter inserted, with conventional CM choke, with traditional separated CM and DM chokes, and with integrated CM and DM chokes using an EI ferrite core shape: (a) DM; (b) CM.*

with varying air-gap length at center leg of EI ferrite core shape is compared only with the case of without any filter inserted.

From experimental result as shown in Fig. 9 (a), the DM reduction performance of integrated CM and DM chokes using an EI ferrite core shape improves when the air-gap length is increased especially at frequency range 400 kHz - 1 MHz. On the contrary, as shown in Fig. 9 (b), it can be seen that the CM emission reduction performance of integrated CM and DM chokes using an EI ferrite core shape slightly change when the air-gap length is increased at the frequency range about 150 kHz - 1 MHz.

The measured results as shown in Fig. 9 (a) and (b) are in a good agreement with the theoretical one. When the air-gap length is increased, the DM inductance is also increased as shown in Eq. (4) ($\Re_g$ de-

crease), but as shown in Eq. (3) it does not affect to the CM inductance. As a result, only the DM attenuation is improved. Moreover, it should be noted that for switching power supplies the DM emission is dominant at low frequency 150 kHz - 1 MHz while CM emission is dominant at high frequency 1 MHz - 30 MHz [6]. With this reason, it explains that why when the air-gap length is increased, DM attenuation is improved at frequency rage about 400 kHz - 1 MHz.

4. CONCLUSION

Two magnetic circuits to integrated CM and DM chokes by using UIU and EI ferrite core shapes are proposed in this paper. The approximation of CM and DM inductances of proposed circuits is also derived mathematically.
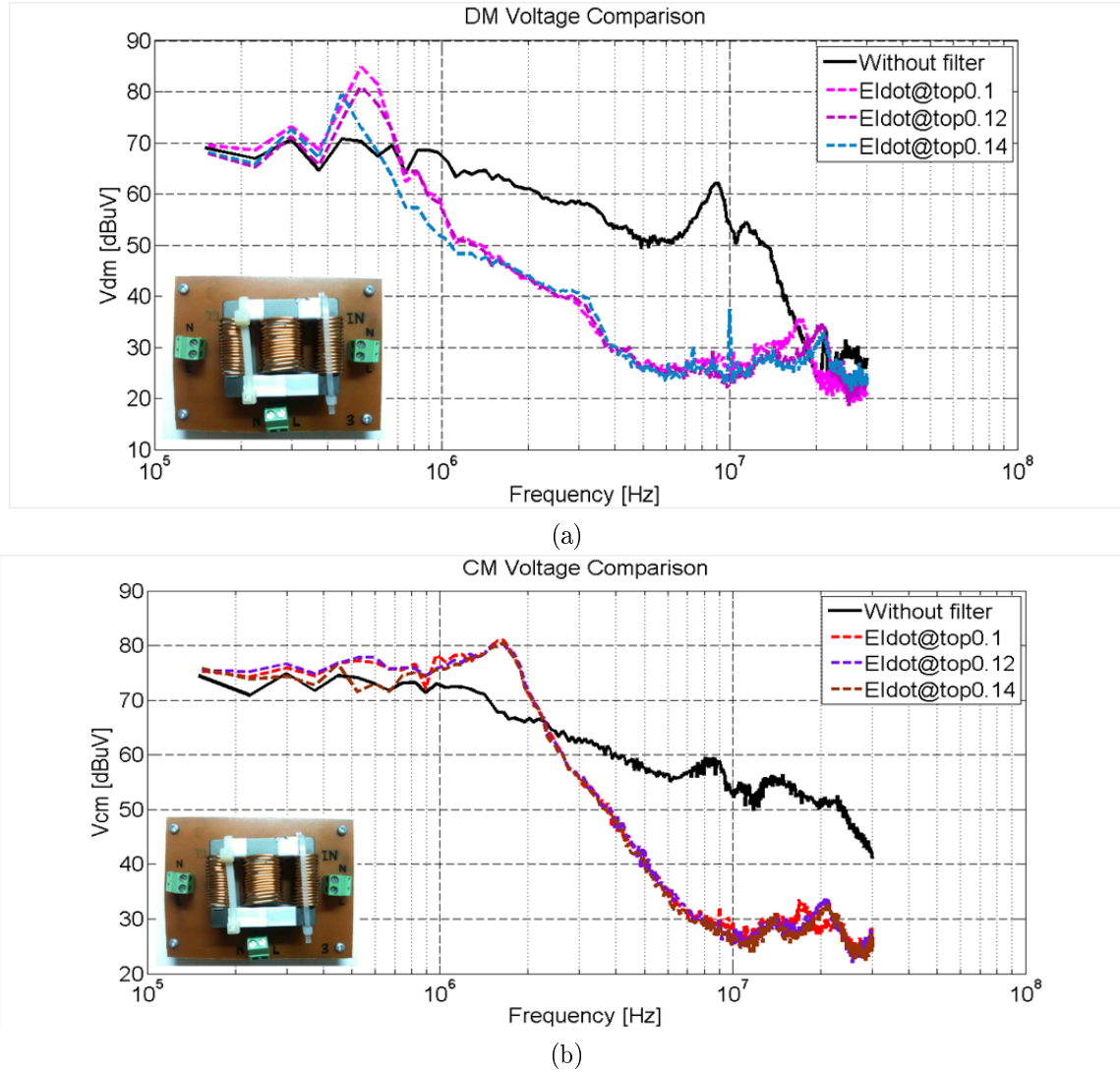
(a)

(b)

Fig.9: *EMI emission comparisons of integrated CM and DM chokes using an EI ferrite core shape by varying the air-gap length at center leg from 0.1 mm, 0.12 mm, and 0.14 mm.*

In order to verify the EMI reduction performances of proposed circuits, three experiments are conducted. The First experiment is focused on the use of an UIU ferrite core shape comparing to without any filter inserted and with traditional filter inserted. The left two experiments are focused on the use of EI ferrite core. In second experiment, the EMI reduction performances of with an EI ferrite core shape is compared to without any filter inserted and with traditional filter inserted. However, the EMI reduction performances of integrated CM and DM chokes using an EI ferrite core shape is dependent on air-gap length. As a result, the effect of air-gap length to EMI reduction performance of the integrated CM and DM chokes using an EI ferrite core shape is further evaluated in the last experiment.

From the experimental results, it ensures the advantages of the use of proposed approaches. Although some magnetic parts are eliminated by proposed ap-

proaches, the amount of DM and CM EMI attenuation rate of integrated CM and DM chokes using an UIU ferrite core shape is roughly equal to the case of traditional separated CM and DM chokes, except the highest peak is located at different frequencies. Moreover, in case of integrated CM and DM choke using an EI ferrite core shape, it shows a similar result between integrated and traditional separated CM and DM chokes for DM reduction performance. However, for CM reduction performance, the amount of CM attenuation rate of integrated and traditional separated CM and DM chokes are comparable, unless the highest peak is located at different frequencies. Furthermore, by using an EI ferrite core shape, the DM attenuation can be improved by increasing the air-gap length where it slightly affects to the CM attenuation.

Finally, it is worth to note that he EMI reduction performance, especially to the CM reduction performance, of integrated chokes is strongly affected by

parasitic parameters [14-15]. As a result, to improve the EM reduction performance of proposed integrated CM and DM chokes, various parasitic cancellation techniques can be applied [17].

5. ACKNOWLEDGMENT

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