Investigation and Reduction of Common Mode Current in Center-Tapped Transformer of LLC Resonant Converters

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2022 IEEE Applied Power Electronics Conference and Exposition (APEC) | 978-1-6654-0688-8/22/$31.00 ©2022 IEEE | DOI: 10.1109/APEC43599.2022.9773439

***Abstract*—This paper investigates the effects of resonant tank arrangements on the common mode (CM) noise current. CM noise reduction methods with symmetrical transformer winding structure and split resonant tank are proposed for full bridge (FB) LLC converters. For half bridge (HB) LLC converters, CM noise cancellation capacitor C_{can} is proposed to fully cancel the CM noise current flowing through the transformer. The corresponding extraction and calculation techniques of C_{can} are provided. Both techniques are lossless and easy to implement. The capabilities and excellence of aforementioned methods are verified by experiments.**

Keywords—Common mode, LLC converter, resonant tank, transformer

I. Introduction

Among various DC-DC topologies, LLC resonant converter is gaining more and more attention than ever before owing to its simplicity and inherent features, such as excellent zero-voltage-switching (ZVS) and zero-current-switching (ZCS) performance, galvanic isolation, and high efficiency [1][2]. The HB and FB with the center-tapped transformer rectifier are the most commonly used topologies of LLC resonant converters. With the center-tapped transformer, only two rectifying diodes are necessary at the secondary side.

The interwinding capacitance of the transformer is one of the major paths for conducted CM noise. This is due to the CM noise displacement currents produced by adding high *dv/dt* to the parasitic interwinding capacitances. To reduce the CM noise flowing through transformers, various CM noise reduction techniques have been proposed. The shielding technique is widely to reduce the CM noise directly [3]-[5]. However, this will result in complicated manufacture process of the transformer, introduce additional power loss, and enlarge the size of the transformer. The CM noise current can also be reduced by changing the transformer winding arrangement [6]-[9]. The basic idea is to ensure that the overlapping primary and secondary winding turns have the same voltage distributions. However, this will increase the leakage inductance of the transformer, which is critical to the LLC converter circuit design. Besides, this technique is not suitable for wire-wound transformer. The winding loss and the transformer size could be large. For HB LLC converters, balance method can used to reduce the CM noise by generating a Wheatstone bridge network [10]. However, additional balance inductor is needed which increase the cost and complexity.

In this paper, for HB and FB LLC converters, influences of resonant tank arrangements on CM current are analyzed. It is found that, for HB LLC converters, the CM noise source of the center-tapped transformer can only be related to the magnetizing inductor voltage with appropriate resonant tank arrangement. For FB LLC converters, the CM noise current flowing through the transformer can be fully cancelled with symmetrical interleaved transformer winding structure and split resonant tank. This method is lossless and can also reduce the transformer leakage inductance. For HB LLC converters, the CM noise current flowing through the transformer can be fully cancelled by using a CM noise cancellation capacitor C_{can}. This method is also lossless and the corresponding extraction and calculation techniques of C_{can} are provided.

II. CM Noise Analysis of LLC Converters

A. CM noise modeling

CM noise propagation paths of FB LLC converters are shown in Fig. 1. The CM noise currents generated by switching nodes will couple into the PE (Protective Earth) through parasitic capacitances of the LLC converter, which will be detected by the line impedance stabilization network (LISN). LISN is a passive network that serves the purpose of isolating the test system with a reference impedance and provide measurement points to the EMI receiver. Noise separator is used to separate the original noise into DM (Differential Mode) and CM noise.

In Fig. 1, SG (Secondary Ground) is connected to PE. C_{Q2} (C_{Q4}) is the parasitic capacitor between the drain of Q_2 (Q_4) and PE. C_A, C_B, C_{D1} and C_{D2} denote the parasitic capacitors between switching terminals of center-tapped transformer and PE. i_{CM_ps} represents the CM noise displacement current flowing through the interwinding capacitance C_{ps} of the transformer.

The frequency-domain method is used in this paper to build the CM EMI model for the FB LLC converter as shown in Fig. 1. With the frequency-domain method, only one CM noise source should be used at a time. The phase information will be

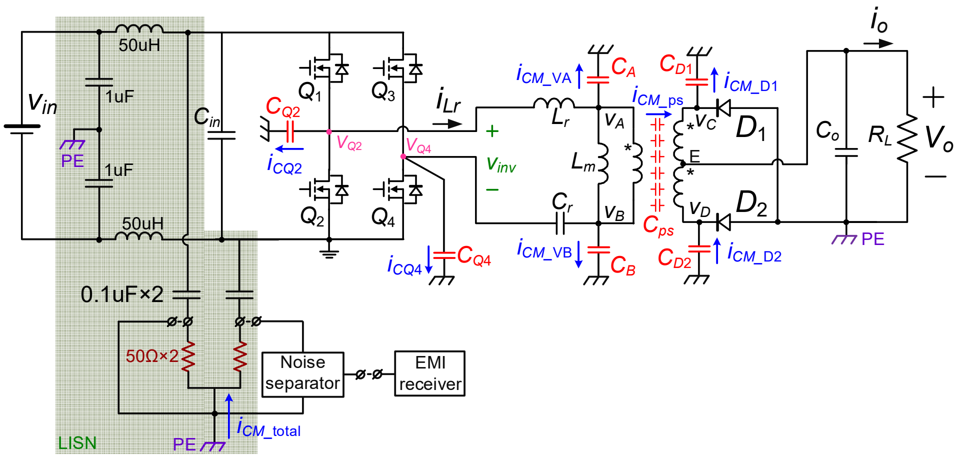


Fig. 1. CM noise paths of FB LLC converter

lost if all the CM noise sources are replaced by their spectrum. It is worth noting that when there are more than one noise sources, by substituting the noise sources with their time-domain waveforms, the model developed by the frequency-domain method is still valid. The analysis methodology can also be applied to HB LLC converters.

In order to linearize the circuit, the substitution theory is used to substitute the noise sources for the original circuit elements. It is noted that the substitution should avoid voltage loops and current nodes. The main switch Q_2 (Q_4) is substituted with a voltage source v_{Q2} (v_{Q4}). The main switch Q_1 (Q_3) is substituted with a current source i_{Q1} (i_{Q3}). The diodes D_1 and D_2 are substituted with the current sources i_{D1} and i_{D2}, respectively. C_{in} and C_o is considered as short circuit within the conducted CM noise frequency range (150kHz-30MHz). The LISN can be approximately modeled as a 25ohm resistor. Resonant inductor L_r is substituted with a current source i_{Lr} based on the resonant current. The transformer turns ratio of primary and secondary windings is denoted by n. Magnetizing inductance L_m is substituted with a current source i_{Lm}. L_p is substituted with a current controlled current source i_{Lp}, which is equal to $n(i_{D1}+i_{D2})$. The primary winding voltage is equal to v_A-v_B, so the rest of the other windings can be replaced with corresponding controlled voltage sources. Fig. 2 gives the CM noise equivalent circuit of FB LLC converters.

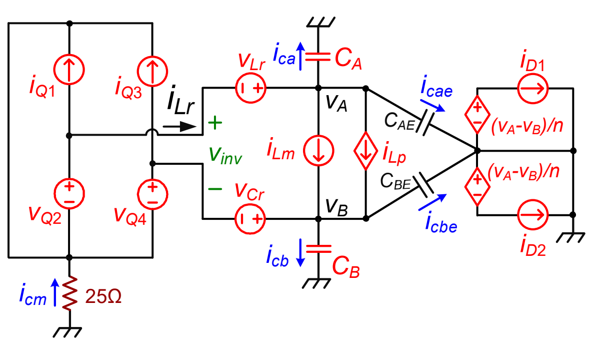


Fig. 2. CM noise equivalent circuit of FB LLC converter

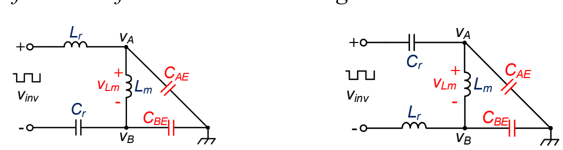
Since Q_2 and Q_4 are switched at 50% duty and 180 degree out of phase with each other, v_{Q2}=-v_{Q4}. Considering the same packaging and fabrication process of Q_2 and Q_4, C_{Q2}=C_{Q4}. In this case, The CM noise currents generated by C_{Q2} and C_{Q4} can be canceled by each other, which means i_{CQ2}=-i_{CQ4}. The same applies to C_{D1} and C_{D2} (i_{CM_D1}=i_{CM_D2}). C_{Q2}, C_{Q4}, C_{D1} and C_{D2} are removed from following CM noise analysis, as shown in Fig. 2.

The next step is to apply the superposition theory to the noise sources. When analyzing a noise source, the other voltage sources and current sources are treated as the short circuit and open circuit, respectively. According to this, the current sources i_{Q2}, i_{Q3}, i_{D1}, i_{D2}, i_{Lp} and i_{Lm} are shorted. In this case they do not contribute to the CM noise current and can be ignored. Also, secondary side two voltage-controlled voltage sources do not generate CM noise current. There are four remaining CM noise sources that are v_{Q2}, v_{Q4}, v_{Lr}, and v_{Cr}, respectively.

It is noted that lumped two-capacitor model [11] is used to illustrate the distributed interwinding capacitors of the transformer, as shown in Fig. 2. The sum of C_{AE} and C_{BE} equals to the total static interwinding capacitance C_{ps} between transformer primary and secondary windings. The total CM current flowing through the transformer can be calculated as shown in (1).

$$i_{CM\_transformer} = C_{AE}\frac{dv_A}{dt} + C_{BE}\frac{dv_B}{dt} \quad (1)$$

B. Influences of resonant tank arrangements on CM current



(a) Model I (b) Model II

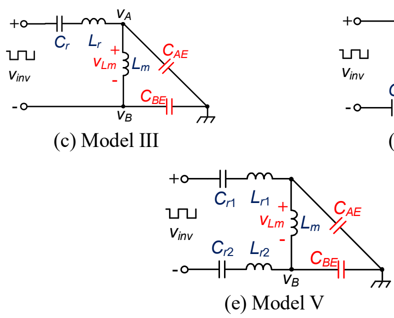


Fig. 3. Possible models for the resonant tank arrangement

There are 5 possible models for the resonant tank arrangements, as shown in Fig. 3. Model I is used in Fig. 1. As can be observed from Fig. 2, the resonant tank arrangements will influence the CM noise current by changing the voltages of v_A and v_B.

Based on (1), there are two different ways to fully cancel the CM noise current in the transformer. The first one is to achieve zero parasitic capacitance, which means C_{AE}=C_{BE} =0. This can be achieved by add copper foil shielding between primary and secondary windings. However, it is undesirable because this will introduce extra loss, enlarge the size of transformer and increase the leakage inductance which is critical to the LLC converter resonant tank design. The second one is to achieve the equation as shown in (2). In this case, the total CM noise current in the transformer can be calculated as 0.

$$C_{AE}\frac{dv_A}{dt}=-C_{BE}\frac{dv_B}{dt} \tag{2}$$

To achieve this, model V is preferred for FB LLC converters. Fig. 4 gives the simplified CM noise model when using model V resonant tank for FB LLC converters. Based on Kirchhoff Voltage Law (KVL), v_A and v_B can be calculated as shown in (3). v_{Zr1} and v_{Zr1} can be calculated as shown in (4), where Z_{r1} and Z_{r2} are defined in (5). If Z_{r1}=Z_{r2} (L_{r1}=L_{r2} and C_{r1}=C_{r2}), voltages of v_A and v_B can be rewritten as shown in (6) since v_{Q2}=-v_{Q4}. It is observed that v_A=-v_B and the total CM noise current can be calculated as shown in (7). It is observed the CM noise current can be fully cancelled if C_{AE}=C_{BE}, which means symmetrical transformer winding structure. Another benefit of model V FB LLC converters is that i_{ca} will be fully cancelled by i_{cb} by assuming C_A=C_B, as shown in Fig. 4.

$$\begin{cases} v_{Q2}-v_{Zr1}=v_A \\ v_{Q4}+v_{Zr2}=v_B \end{cases} \tag{3}$$

$$\begin{cases} v_{Zr1}=i_{Lr}\cdot Z_{r1} \\ v_{Zr2}=i_{Lr}\cdot Z_{r2} \end{cases} \tag{4}$$

$$Z_{r1}=sL_{r1}+\frac{1}{sC_{r1}},\quad Z_{r2}=sL_{r2}+\frac{1}{sC_{r2}} \tag{5}$$

$$\begin{cases} v_{Q2}-v_{Zr1}=v_A \\ -v_{Q2}+v_{Zr1}=v_B \end{cases} \tag{6}$$

$$i_{CM\_transformer}=(C_{AE}-C_{BE})\frac{dv_A}{dt} \tag{7}$$

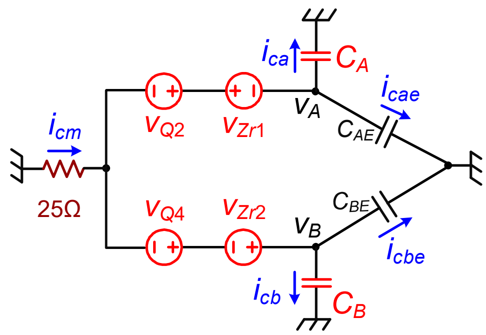


Fig. 4. Simplified CM noise model when model V resonant tank applied

Since the output voltage of the FB inverter is a two-level square wave with same amplitude, models I and II will have same impacts on the CM noise current if C_{AE} is equal to C_{BE}. The same applies to models III and IV.

Fig. 5 gives the CM noise equivalent circuit of HB LLC converters after using substitution theory. It is noted that model V resonant tank arrangement can not be used for HB LLC converters to fully cancel the CM noise currents. The reason is that the resonant tank input voltage is v_{Q2}, whose negative pole is always connected to the PG (Primary Ground). In this case, v_A will not be equal to v_B even with split resonant tank parameters. In Fig. 5, It is worth noting that i_{Lr}, i_{Q1}, i_{Lp}, i_{D1}, i_{D2} and two secondary side voltage-controlled voltage sources are removed from following CM noise analysis. The reason is that they do not contribute to the CM noise current after using superposition theory analysis.

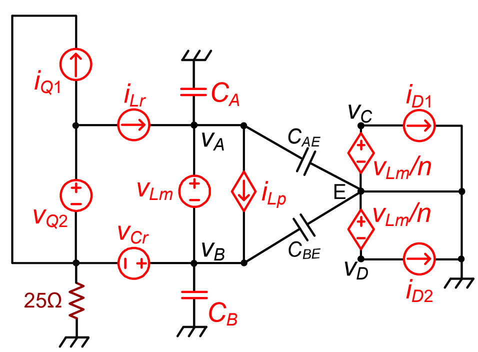


Fig. 5. CM noise equivalent circuit of HB LLC converter

Fig. 6 gives the simplified CM noise model with different resonant tank arrangements for HB LLC converters. The corresponding CM noise current calculations when using different resonant tank arrangements can be shown as (8)-(12). It is noted that the *dv/dt* of PG is considered as 0 when doing the calculation. v_{Zr2} denotes the resonant tank (C_{r2} and L_{r2}) voltage source.

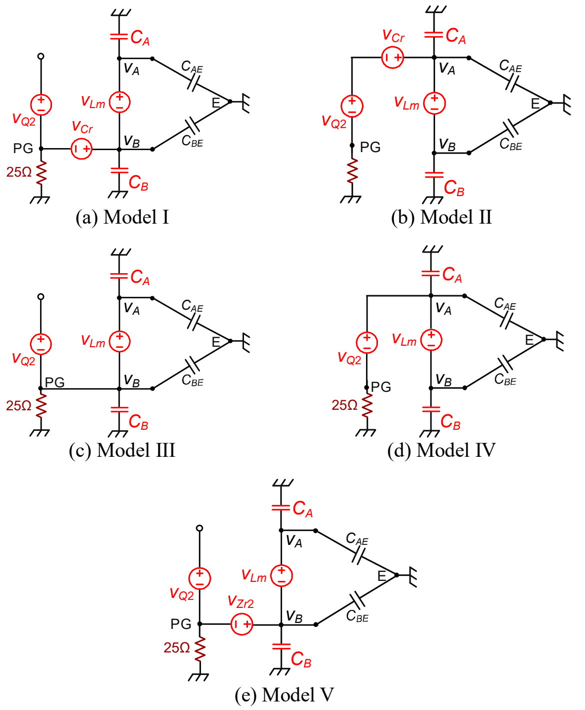


Fig. 6. Simplified CM noise model with different resonant tank arrangements for HB LLC converter

$$i_{CM\_HB\_I} = (C_{AE}+C_{BE}+C_A+C_B)\frac{dv_{Cr}}{dt} + (C_{AE}+C_A)\frac{dv_{Lm}}{dt} \quad \text{model I} \tag{8}$$

$$i_{CM\_HB\_II} = (C_{AE}+C_{BE}+C_A+C_B)\frac{d(v_{Q2}+v_{Cr})}{dt} - (C_{BE}+C_B)\frac{dv_{Lm}}{dt} \quad \text{model II} \tag{9}$$

$$i_{CM\_HB\_III} = C_{AE}\frac{dv_{Lm}}{dt} \quad \text{model III} \tag{10}$$

$$i_{CM\_HB\_IV} = (C_{AE}+C_{BE}+C_A+C_B)\frac{dv_{Q2}}{dt} - (C_{BE}+C_B)\frac{dv_{Lm}}{dt} \quad \text{model IV} \tag{11}$$

$$i_{CM\_HB\_V} = (C_{AE}+C_{BE}+C_A+C_B)\frac{dv_{Zr2}}{dt} + (C_{AE}+C_A)\frac{dv_{Lm}}{dt} \quad \text{model V} \tag{12}$$

Based on above analysis, it can be concluded that model III is preferred for HB LLC converters. Since the v_B will connect to the primary ground directly, *dv/dt* of v_B is zero. In this case, the CM noise will only be related to v_{Lm}, as shown in (10). The other resonant tank arrangement models will introduce extra CM noise variables, which will deteriorate the CM EMI performance. Besides, it will be difficult to fully cancel the CM noise current generated by the switching nodes.

III. CM Current Reduction in Transformers

A. CM noise cancellation capacitor C_{can} for HB LLC converters

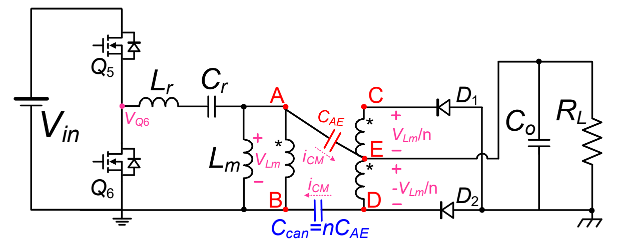


Fig. 7. CM noise cancellation capacitor for HB LLC converter

Fig. 7 gives the implementation of CM noise cancellation capacitor for HB LLC converters. Based on (10), a CM noise cancellation capacitor C_{can} can be placed between terminals B and D to generate a reverse extraction current to cancel the CM noise current flowing through the C_{AE}. The value of C_{can} can be calculated as shown in (13), where n denotes the transformer turns ratio.

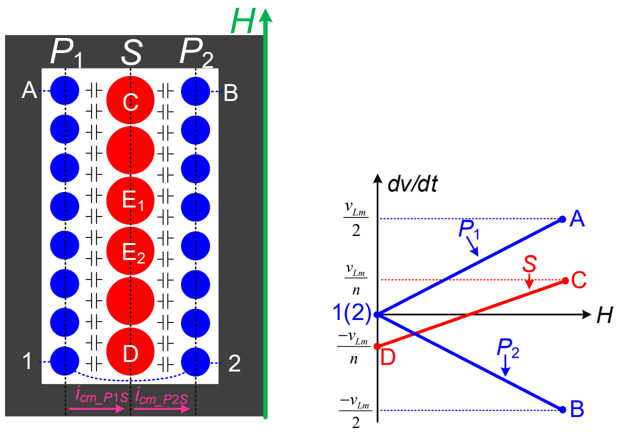
$$C_{AE}\frac{dv_{Lm}}{dt} - C_{can}\frac{dv_{Lm}/n}{dt} = 0, \quad C_{can} = nC_{AE} \tag{13}$$

B. Interleaved transformer winding with split resonant tank for FB LLC converters

For FB LLC converters, Fig. 8 (a) gives the example of interleaved transformer winding structure. It is assumed that the total interwinding capacitance is C_{ps}. The interwinding capacitance between layer P_1 (P_2) and S can be estimated as $C_{ps}/2$. The original voltage distribution of winding layers is given in Fig. 8 (b). By using superposition theory, the total CM noise current consists of two components. One component is the currents coupled from primary winding to secondary winding. By assuming the *dv/dt* of layer S is 0 in Fig. 9 (a), the CM noise current can be calculated as shown in (14). The other component is the currents coupled from secondary winding to primary winding. By assuming the *dv/dt* of layer P_1 (P_2) is 0 in Fig. 9 (b), the CM noise current can be calculated as shown in (15). It can be concluded that, for FB LLC converters, the CM noise current can be fully cancelled by using interleaved transformer windings with split resonant tank.

$$\int_0^L \frac{C_{PS}}{2L}\frac{d}{dt}\left(\frac{xv_A}{L}+\frac{xv_B}{L}\right)dx = \frac{C_{PS}}{4}\frac{d(v_A+v_B)}{dt} = \frac{C_{PS}}{4}\frac{d}{dt}\left(\frac{v_{Lm}}{2}-\frac{v_{Lm}}{2}\right) = 0 \tag{14}$$

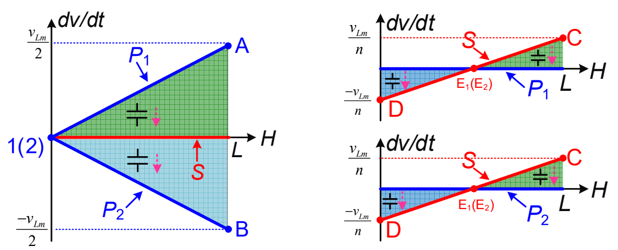
$$\int_0^L \frac{C_{PS}}{2L}\frac{d}{dt}\frac{x(v_C+v_D)}{L}dx = \frac{C_{PS}}{4}\frac{d(v_C+v_D)}{dt} = \frac{C_{PS}}{4n}\frac{d(v_{Lm}-v_{Lm})}{dt} = 0 \tag{15}$$



(a) Transformer structure with interleaved windings

(b) Original *dv/dt* distribution

Fig. 8. Transformer structure and original *dv/dt* distribution



(a) Assume *dv/dt* of layer *S* is 0

(b) Assume *dv/dt* of layer P_1 and P_2 is 0

Fig. 9. CM current calculation with superposition theory

IV. Experimental Verification and Discussion

A. Verification of CM noise cancellation capacitor for HB LLC converters

This experimental verification is conducted with a 120W AC to DC HB LLC converter. It has a switching frequency range from 150 kHz to 200 kHz (below resonant frequency), with 220Vac input and 30V output. To extract the values of C_{AE} and C_{BE} of the transformer, a signal generator is added to the primary winding, as shown in Fig. 10. The measured waveforms are shown in Fig. 11. The total static interwinding capacitance C_{ps} is measured by LCR meter which is around 15pF. C_{AE} and C_{BE} can be solved by (16), which are 7pF and 5pF. So, the C_{can} be calculated by nC_{AE}, which is around 50pF.

$$\begin{cases} C_{AE} + C_{BE} = C_{ps} \\ \dfrac{v_{C\_AE}}{v_{AB}} = \dfrac{C_{BE}}{C_{AE} + C_{BE}} \end{cases} \tag{16}$$

A 47pF C_{can} is added according to Fig. 7. Fig. 12 gives the CM noise reduction with different C_{can} for the prototype. By adding derived 47pF C_{can} between terminals D and B in Fig. 7, the total CM noise can be reduced by around 8 dB. It is noted that when C_{can} is greater than 47pF, CM noise will be over canceled. It will generate more reverse current that flows into LISN. 100pF is used between D and B to verify this over cancellation phenomenon. It can be observed that the total CM noise will increase by 6 dB if C_{can} is put between terminals C and B, which verifies the analysis in Section III.

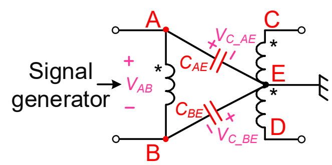


Fig. 10. Extraction of C_{AE} and C_{BE}

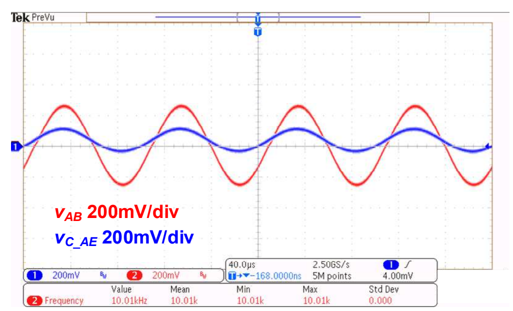


Fig. 11. Measured waveforms

B. Verification of interleaved transformer windings with split resonant tank for FB LLC converters

This experimental verification is conducted with a 120W AC to DC FB LLC converter. It has a switching frequency range from 150 kHz to 200 kHz (below resonant frequency),

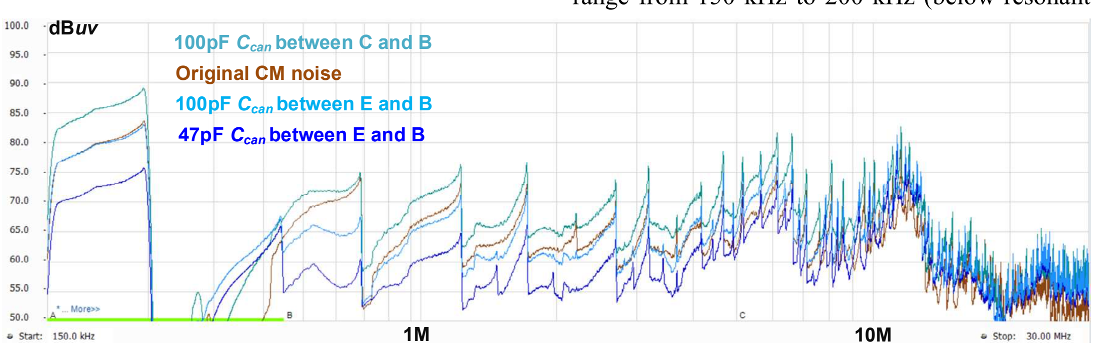


Fig. 12. CM noise reduction with different C_{can}

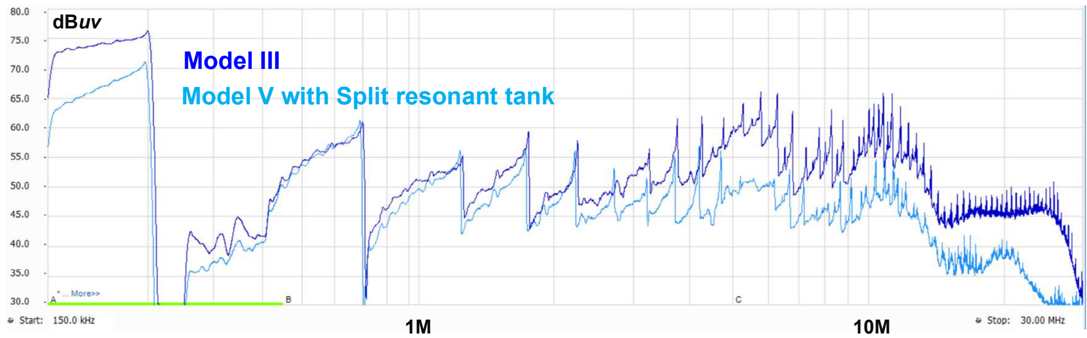


Fig. 13. CM noise reduction with molder V resonant tank and interleaved transformer winding

with 110Vac input and 30V output. For comparison, the FB LLC converter is first tested with the model III resonant arrangement. The transformer winding structure is non-interleaved. Then, the original resonant inductor and capacitor are both split into two equal components, respectively. And the transformer winding structure is changed into interleaved winding structure. The corresponding parameters of resonant tank and transformer are listed in Table I.

TABLE I. PARAMETERS COMPARISON

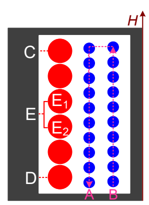
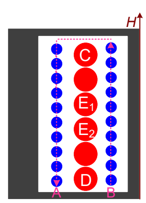
Parameter	Original	Proposed
Resonant inductor	11 uH	6.5 uH×2
Resonant capacitor	11 nF	22 nF×2
Transformer turns ratio	20:3:3	20:3:3
Transformer leakage inductance	5.5 uH	3 uH
Transformer winding structure	Non-interleaved 	Interleaved 

Fig. 13 gives the CM noise testing results. It is noted that the actual CM noise will be 20dB larger since a 20dB attenuator is used during tests to protect the EMI receiver. It can be observed that the total CM noise can be reduced by around 6dB within fundamental switching frequency range. Above 5MHz, around 10dB CM noise reduction can be achieved which means lower radiation CM EMI noise.

V. CONCLUSIONS

This paper investigates the effects of resonant tank arrangements on the CM noise current. The CM noise sources and coupling paths of HB and FB LLC resonant converters are analyzed analytically. Preferred resonant tank arrangements for HB and FB LLC resonant converter are analyzed and provided. For HB LLC resonant converter, CM noise cancellation capacitor is proposed based on preferred resonant arrangement, which is lossless and easy to implement. For FB LLC resonant converter, interleaved transformer windings with split resonant tank is proposed to fully cancel the CM noise current generated in the center-tapped transformer. The transformer can achieve lower CM noise current while maintaining lower leakage inductance. Through experimental verification, around 6dB CM noise reduction can be achieved within fundamental switching frequency range. Around 10dB CM noise reduction can be achieved at high frequency range (above 5MHz).

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