Original CM Noise Suppression in SMPS

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Abstract **– Based on the CM noise model in SMPS, several CM noise suppression approaches are introduced. The approaches mentioned in this paper include structure and compensation. The effectiveness of the techniques is verified for prototypes in common use in reducing CM noise, filter size and in creasing power density.**

Ⅰ. INTRODUCTION

Switched Mode Power Supplies (SMPS) generate high frequency noise because of their switching action. As we know, for any electric or electronic equipment, it is necessary to meet the Electromagnetic Interference (EMI) standards, such as CISPR, IEC, EN, FCC, etc. In a continuous effort to increase converter power density, switching frequency becomes higher and higher. As a result, EMI noise of the power supply is much larger. So EMI problem becomes into prominence in the power supply design cycle.

To solve the EMI problem, two ways are usually adopted. One is suppressing the noise source and the other is cutting off the coupling path. A line filter is always used for the latter way, but the former one is better for smaller prototype size, and thus be benefit to high power density. Usually Common-Mode (CM) noise is more difficult to be solved, and needs large inductance to suppress it. So if the original CM noise can be reduced to a small level, the filter size will be decreased effectively. Some researchers have disclosed several methods about it [1] [2] [3] [4]. In this paper, two approaches are mentioned, including structure and compensation. They are verified to be effective in original CM noise suppression in engineering applications.

In section Ⅱ of this paper, the structure approach is introduced, which include heatsink grounding and transformer shielding. In section Ⅲ, compensation approach is introduced. There are three methods: noise source balance, noise source quasi-balance, and active compensation. In section Ⅳ, experimental results are shown, and the conclusions are given in section Ⅴ.

Ⅱ. STRUCTURE APPROACH FOR ORIGINAL CM NOISE SUPPESSION

Fig.1 shows the approaches of original EMI noise suppression. In this paper, we focus on the former two approaches, which are structure and compensation, for CM noise suppression.

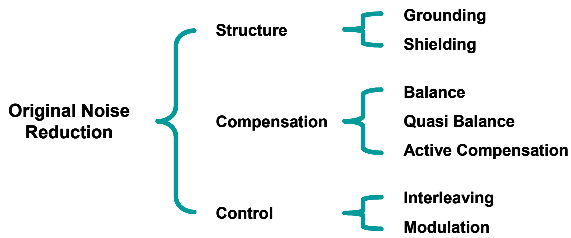


Fig.1 Original Noise Suppression Approaches

In this section, the structure approach is introduced, including grounding, method about heatsink, and shielding, method about transformer.

a) *Grounding (Heatsink)*

Fig.2 shows the CM noise current paths in a flyback converter. There are two key hot-voltage points, V_P and V_S. For the primary side, there are mainly two coupling paths: one is through the parasitic capacitor of switch and heatsink, we denote it i_{P_H}. And the other is through the parasitic capacitor of transformer, we denote it i_{P_Tr}. For the secondary side noise, it is mainly the noise current through the transformer, we denote it i_{S_Tr}.

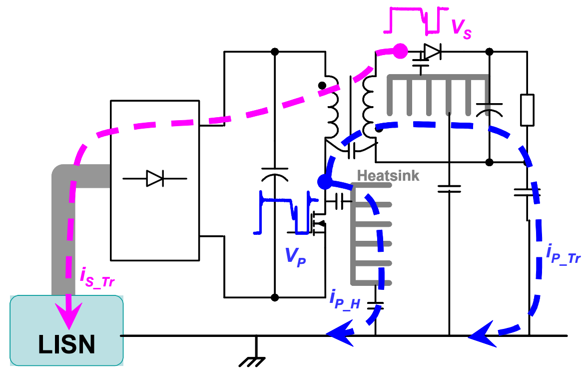
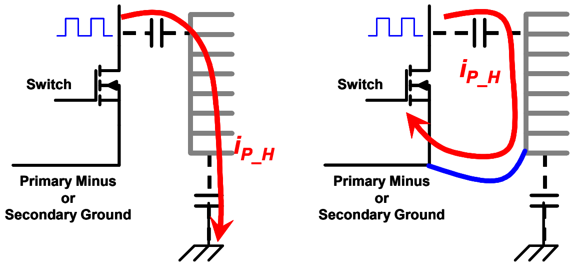


Fig.2 Flyback Converter CM Noise Path

To delete i_{P_H}, the primary side heatsink can be connected to the primary minus. In this case the CM noise current through the parasitic capacitor of heatsink can circum-flow, as Fig.3 shown.



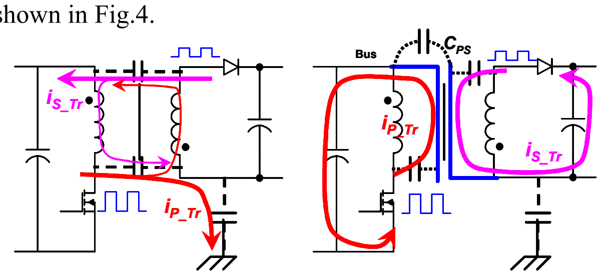
(a) Heatsink without Grounding (b) Heatsink with Grounding

Fig.3 CM Noise Current through Heatsink

Please note, the heatsink can't be connected to the earth ground, otherwise the CM noise will be much larger.

b) *Shielding (Transformer)*

Now let's reduce the CM noise current through the parasitic capacitor of the transformer. The suppression mechanism is similar to the heatsink grounding. The shielding between the primary windings and secondary windings is needed. The CM noise current in transformer is shown in Fig.4.



(a) Transformer without Shielding (b) Transformer with Shielding

Fig.4 CM Noise Current through Transformer

In Fig.4 (b), the voltage of C_{PS} is not hot-point, so there is no displace current through the transformer.

The CM noise has been reduced 10~20dBμV when use structure approach, but it is only the passive suppression, so the decrease is not enough. In section Ⅲ, compensation approach is disclosed to reduce the CM noise further.

Ⅲ. COMPENSATION APPROACH FOR ORIGINAL CM NOISE SUPPRESSION

There are three methods in compensation approach. If in a circuit there exits two noise sources which produce the noise currents with same amplitudes but counteractant phases, it is called noise source balance. If the amplitudes of two noise currents are not same, the large one can be decreased to the smaller one, or the small one can be increased to the large one. This method is denoted noise source quasi-balance. The third method is active compensation. It is used in the case that there are no counteractant phases noise sources in a circuit, and we need to build an additional noise source to balance the original one. Fig.5 shows these three methods, and they will be introduced in detail, respectively.

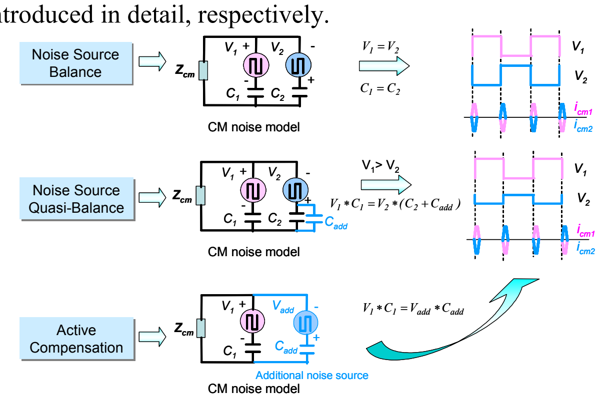


Fig.5 Three Methods of Compensation Approach

a) *Noise Source Balance*

There are two key factors in noise counteracting. One is phase shift of the two noise source, θ. The other is magnitude uniformity of $V*C$, β. As shown in Fig.6, if $\theta=\pi$, it means the phases of V_1 and V_2 are exactly counteractant. If $\beta=1$, it means $V_1*C_1=V_2*C_2$.

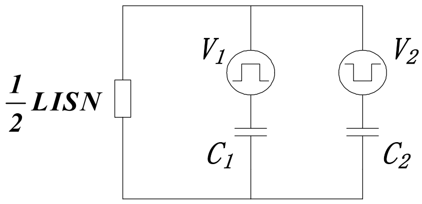
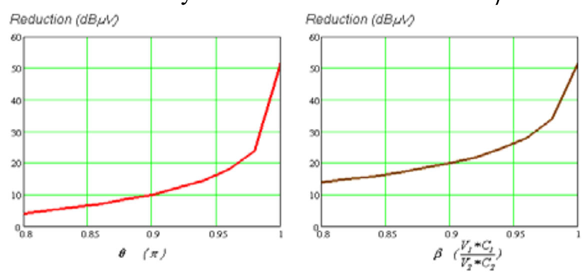


Fig.6 Noise Source Balance

In Fig.7, the reduction is referred to:

$$Reduction = 20\log(\frac{V_1*C_1}{V_1*C_1+V_2*C_2}) \qquad (1)$$

Suppose $\beta=1$, the reduction is only the function of θ, and the curve is shown as Fig.7 (a). If $\theta=\pi$, the reduction is only the function of β, as Fig.7 (b) shown. From Fig.7, it can be seen obviously that θ is more sensitive than β.



(a) $\beta=1$ (b) $\theta=\pi$

Fig.7 CM Noise Current through Transformer

We use LLC circuit for example as shown in Fig.8. In order to achieve noise source balance, half bridge topology is changed to full bridge topology.

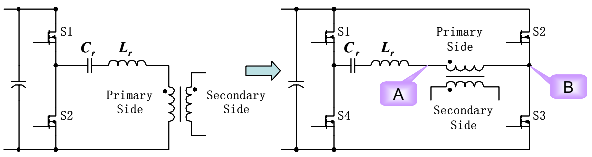
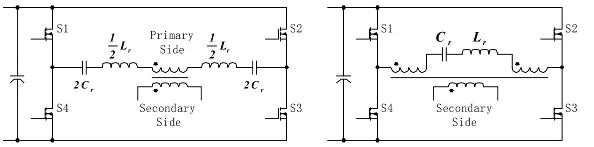


Fig.8 LLC Circuit with Noise Source Balance

Because the resonance capacitor C_r and the resonance inductor L_r will influence the voltage waves of point A, so the circuit as shown in Fig.9 (a) is adopted. In high power application, usually two transformers are used. To make θ of V_A and V_B close to π, the two transformers can be coupled together, as Fig.10 (b) shown.



(a) Single Transformer (b) Coupled Transformer

Fig.10 Modified Full Bridge LLC Circuit

b) Noise Source Quasi-Balance

Noise source balance needs two noise currents with same amplitude and counteractant phases in a circuit, but most circuit topologies are without such characteristic.

We still take flyback for example, and suppose the primary side voltage is higher than the secondary side voltage. When the heatsink is grounding, the main CM noise current paths are i_{P_Tr} and i_{S_Tr}. Usually in engineering application, only primary windings will be fully shielded because of V_P>V_S. In this case, equivalent C_{PS} is reduced much, but C_{SP} which between the shielding and secondary windings is very large. So i_{P_Tr} may be smaller than i_{S_Tr}, the main noise source is in the secondary side, as Fig.11 shown.

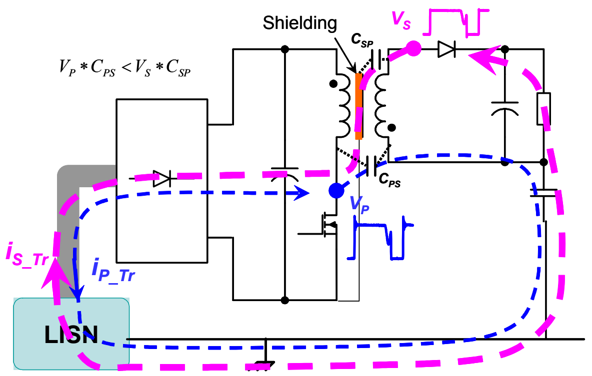


Fig.11 Noise Currents with Primary Windings Fully Shielding

It can be seen that the phase of primary side noise current is counteractant to the phase of secondary side noise current, so if equation (2) is satisfied, the two noise currents can be counteracted each other, thus the total CM noise will be reduced. This technique is called noise source quasi-balance.

$$V_P * C_{PS} = V_S * C_{SP} \tag{2}$$

We have discussed above that with primary windings fully shielded, $V_P * C_{PS} < V_S * C_{SP}$, so if C_{PS} can't be reduced so much, it means incomplete primary windings shielding shall be used to meet equation (2).

Fig.12 shows the structure of the transformer with one primary windings layer and one secondary windings layer. W is winding width; d is diameter of shielding layer. U_{P1} and U_{P2} are the voltages of the first primary winding and the last primary winding respectively. U_{S1} and U_{S2} are the voltages of the first secondary winding and the last secondary winding respectively.

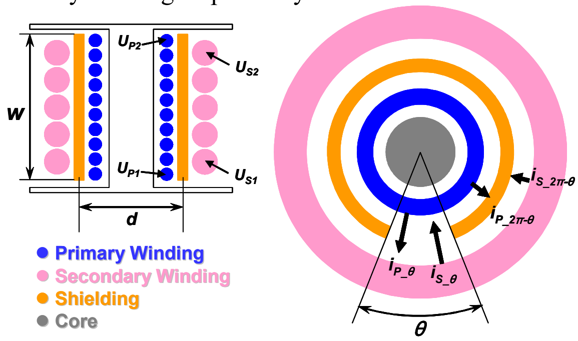
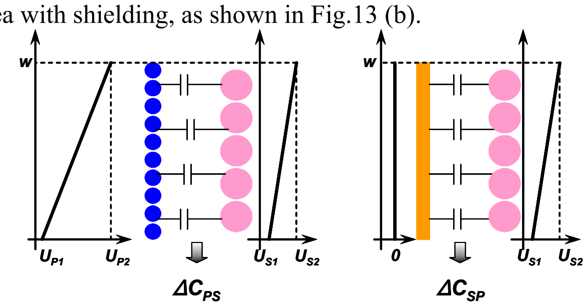


Fig.12 Transformer with Incomplete Shielding

In Fig.12, there is a non-conductive blank area in shielding length. In the area with shielding, there exit displace currents between primary windings and shielding, $i_{P\_2\pi\text{-}\theta}$; and between secondary windings and shielding, $i_{S\_2\pi\text{-}\theta}$. In the area without shielding, there exit displace currents between primary windings and secondary windings, i_{P_θ} and i_{S_θ}. It has been supposed that V_P>V_S, so the shielding is connected to the primary minus, $i_{P\_2\pi\text{-}\theta}$ has no contribution to noise current. In this case, ΔC_{PS} refers to the parasitic capacitance between primary windings and secondary windings of unit area of each winding in the area without shielding, as shown in Fig.13 (a); and ΔC_{SP} refers to the area with shielding, as shown in Fig.13 (b).



(a) Area without Shielding (b) Area with Shielding

Fig.13 Parasitic Capacitor in Transformer

The displace current of unit area integral with width in transformer produced by V_P can be calculated with equation (3), and the displace current produced by V_S can be calculated with equation (4).

$$\Delta i_P = \Delta i_{P\_\theta} - \Delta i_{S\_\theta} = \frac{\omega * \Delta C_{PS} * w}{2}(U_{P1} + U_{P2} - U_{S1} - U_{S2}) \tag{3}$$

$$\Delta i_S = \Delta i_{S\_2\pi-\theta} = \frac{\omega * \Delta C_{SP} * w}{2}(U_{S1} + U_{S2}) \tag{4}$$

The shielding length can be calculated with equation (5), and the length without shielding can be calculated with equation (6). Use equation (7), the shielding length can be got.

$$l_P = \frac{d}{2} * \theta \tag{5}$$

$$l_S = \frac{d}{2} * (2\pi - \theta) \tag{6}$$

$$\Delta i_P * l_P = \Delta i_S * l_S \tag{7}$$

Above is designing shielding length to adjust displacement currents i_P and i_S, and it also means adjusting equivalent C_{PS} and C_{SP}. Incomplete shielding can also be designed with shielding width, as Fig.14 shown.

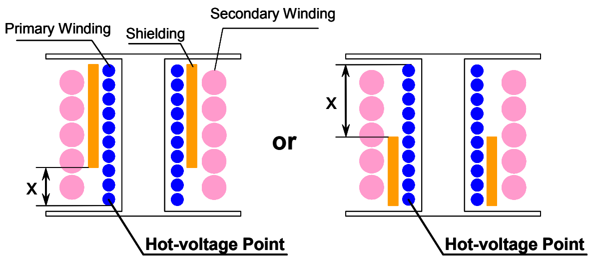


Fig.14 Incomplete Shielding with Designed Length

As we know, i_P and i_S are relative with voltage of each winding, and the voltages of different winding turns are variety, so the shielding position is very sensitive in shielding width design. As a result, the uniformity will be worse, so adjusting shielding width is less used in engineering application.

Another way to achieve noise source quasi-balance is adding an additional capacitor, C_{add}. The connection of C_{add} is shown in Fig.15. To achieve noise source quasi-balance, equivalent (8) must be satisfied.

$$V_P * C_{PS} = V_S (C_{SP} + C_{add}) \tag{8}$$

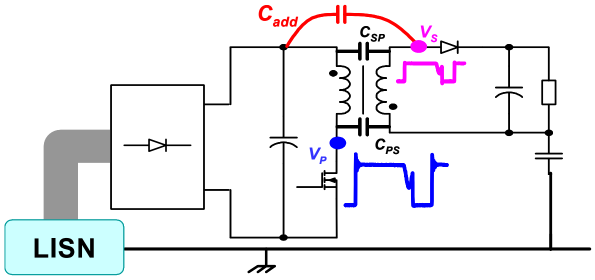


Fig.15 Flyback with C_{add}

The different effect between incomplete shielding and additional C_{add} is analyzed in [5].

Noise source quasi-balance technique can not only be used in flyback topology, but also can be used in forward and half bridge LLC topology, etc. Fig.16 and Fig.17 show C_{add} connection and shielding design is also suitable.

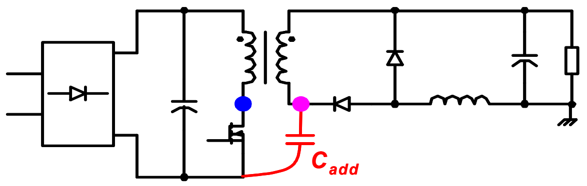


Fig.16 Noise Source Quasi-Balance Applied in Forward

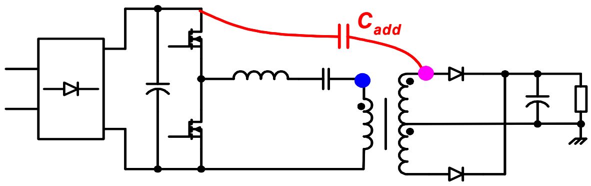


Fig.17 Noise Source Quasi-Balance Applied in HB LLC

Above analysis are based on primary side voltage higher than secondary side voltage. In the case that secondary side voltage is higher than primary side voltage, or secondary side noise is larger than primary side noise, the application of this technique is similar.

c) Active Compensation

Based on above analysis, it is known that whether noise source balance or noise quasi-balance, it needs two noise sources producing noise currents with counteractant phases in the circuit. If there is no such characteristic, active compensation technique is adopted to reduce the original CM noise.

Phase Shift Full Bridge (PSFB) topology is in common use in DC/DC stage. We had got the conclusion before that because the duty cycle is 0.5 in primary side, the odd frequency harmonic noise is mostly come from the primary side, and the even frequency harmonic frequency noise is mostly come from the secondary side because of the full wave rectifying [6]. So the primary side noise current and the secondary side noise current can't be counteracted each other. It means noise source balance or noise source quasi-balance can't be adopted in this topology. To reduce CM noise, active compensation technique is adopted in primary side and secondary side, respectively.

Fig.18 shows the primary side noise compensation circuit. There are mainly two hot-voltage points: V_{P1} and V_{P2}, and phase shift of these two voltages are not zero or π, so inverters are used to build counteractant noise sources V_{add} for V_{P1} and V_{P2} respectively. Additional capacitors C_{add} are needed to couple the noise current to the secondary ground. To achieve noise counteracting, equation (9) and (10) must be satisfied.

$$V_{P1} * C_{PS1} = V_{add1} * C_{add1} \tag{9}$$

$$V_{P2} * C_{PS2} = V_{add2} * C_{add2} \tag{10}$$

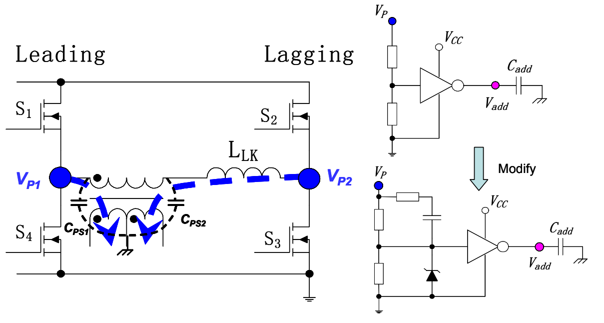
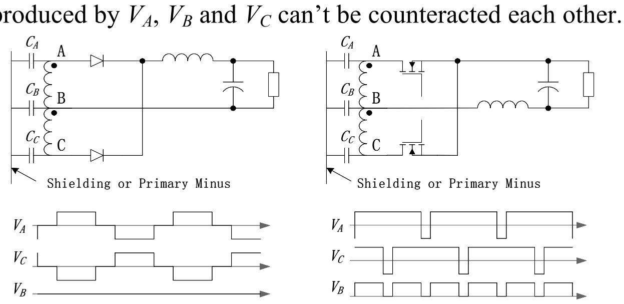


Fig.18 PSFB Primary Side Noise Compensation

Because of the parasitic parameters exiting, the compensation circuit needs modification, in order to get the counteractant V_{add} exactly.

For the secondary side topology, it has been analyzed in [6] that the balanced structure is better to get small CM noise, as Fig.19 (a) shown. But if the output voltage is low, synchronized rectifier is adopted. In this case, the topology shown as Fig.19 (b) is usually used, so the CM noise will be much larger, because the noises produced by V_A, V_B and V_C can't be counteracted each other.



(a) Balance (b) Unbalance

Fig.19 PSFB Secondary Side Topologies and Waveforms

To reduce the CM noise, the compensation circuit shown in Fig.20 is adopted. In the period of t_1, equation (11) must be satisfied; and in the period of t_2, equation (12) must be satisfied. Usually the amplitudes of V_A and V_C are the same, so if C_A=C_C, the compensation effect will be the best.

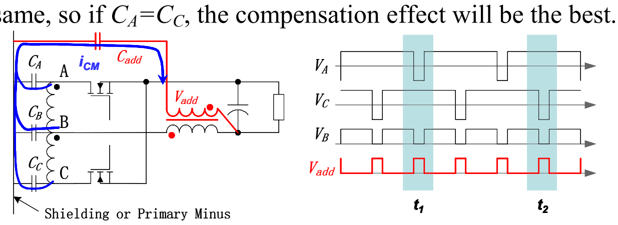


Fig.20 PSFB Secondary Side Noise Compensation

$$V_A * C_A + V_B * C_B = V_{add} * C_{add} \tag{11}$$

$$V_C * C_C + V_B * C_B = V_{add} * C_{add} \tag{12}$$

This compensation circuit can also be used in other topologies. Fig.21 is Interleaved Dual Forward (IDF). The primary side noise source is symmetric with traditional control, so the CM noise is small. In order to reduce the reverse recovery issue, new control is adopted [7]. In this case, the primary side noise will be much larger. After noise source compensation in new control IDF, its original CM noise will be reduced to the lower level.

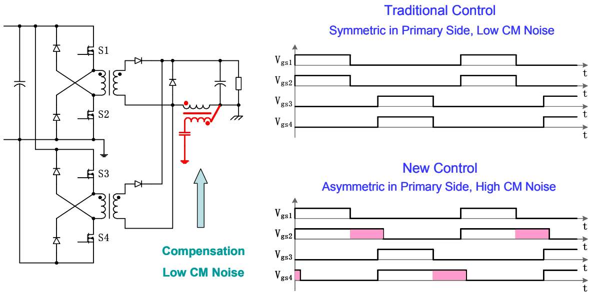


Fig.21 Noise Compensation Applied in New IDF

IV. EXPERIMENTAL RESULTS

In this section, several prototypes are tested to verify the compensation approach. Structure approach has been verified before, so only experimental results with compensation approach will be shown in this paper. EMI noise curves shown in Fig.23~Fig.25 are original CM noise, without any filters in the prototypes. Class A and Class B limitations are also shown to make out the effect more clearly.

Fig.22 shows the CM currents in a 2500w Telecom Power with LLC Circuit. It shows the noise balance effect. Fig.23 and Fig.24 show the noise levels of different prototypes with noise source quasi-balance technique. Fig.25 shows the noise compensation effect.

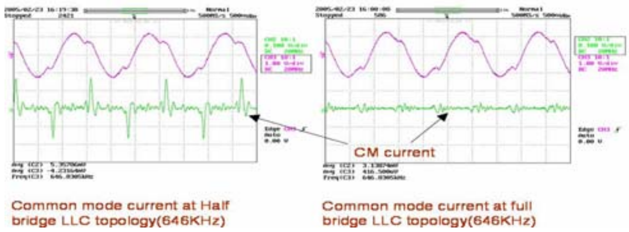
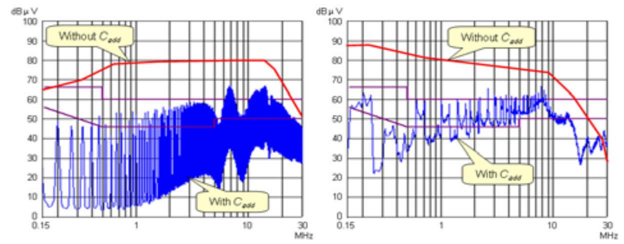
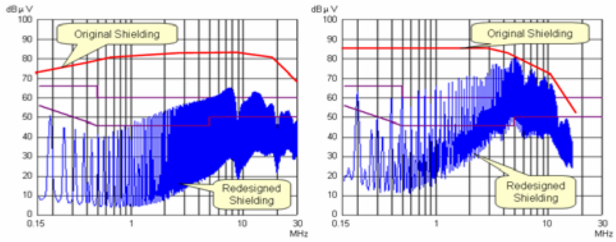


Fig.22 Noise Source Balance



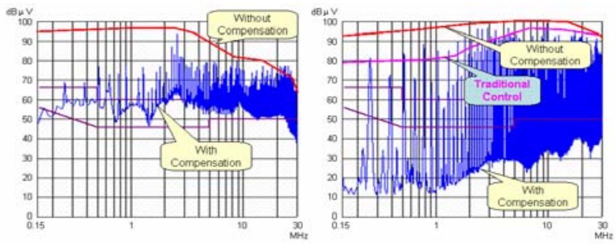
(a) ADP-65KP (Flyback) (b) Low Profile Adaptor (HB LLC)

Fig.23 Noise Source Quasi-Balance with C_{add}



(a) ADP-60AB (Flyback) (b) XBOX Power(Forward)

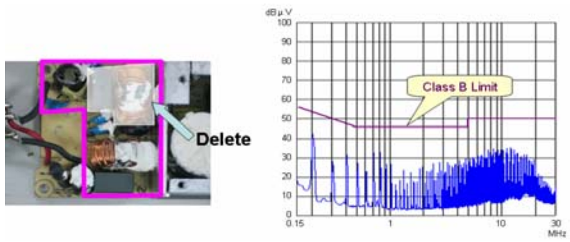
Fig.24 Noise Source Quasi-Balance with Shielding



(a) ERP700w (PSFB) (b) New IDF

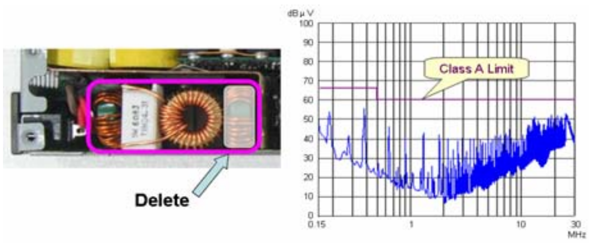
Fig.25 Noise Compensation

The noise impendence will be change when with compensation, but its influence to the insertion loss of the filter is very small, so the reduction of the original noise means the fewer filter component. Fig.26 and Fig.27 show the EMI noise with filter.



(a) Filter (b) EMI Noise

Fig.26 XBOX Power EMI Noise



(a) Filter (b) EMI Noise

Fig.27 ERP700w EMI Noise

V. CONCLUSIONS

Structure and compensation approaches for original CM noise suppression are introduced. The structure approach includes grounding and shielding. The grounding refers to heatsink and the shielding refers to transformer. The compensation approach includes three methods. The first is noise source balance. It means in a circuit there exits two noise sources which produce the noise currents with same amplitudes but counteractant phases. There are two key factors, phase shift of two noise source, θ, and the other is magnitude uniformity of two noise source, β. θ is more sensitive than β. The secondary method is noise source quasi-balance. It can be used in the case that the phases of two noise currents are counteractant, but the amplitudes are not the same. The large noise current can be decreased to the smaller one, or the small noise current can be enlarged to the large one, so then the noise is "balanced". Noise source quasi-balance technique can be achieved by incomplete shielding design in transformer or use additional lump capacitor between hot-voltage point and static point. The third method is active compensation, and it can be used if there are no counteractant phases noise sources in a circuit. The method of it is building an additional noise source to balance the original one.

Several experimental tests have been done to verify the techniques mentioned in this paper. Two telecom power prototypes with the same power rating but different topologies are built. One is with half bridge LLC topology and the other is with full bridge LLC topology. CM noise currents of them have been measured and compared. CM noise current in full bridge is much smaller. Noise source quasi-balance technique is verified effective in flyback, forward and LLC topologies. The tests are based on notebook adaptor and game box power. For active compensation technique, original CM noises of two server power prototypes with PSFB and IDF topology are measured, respectively. All experimental results show the techniques effective for original CM noise suppression. The reduction is about 10~20dBμV. Especially some prototype's CM noise is under Class B limitation in low frequency range even without filters.

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