Use of a C_z Common-Mode Capacitor in Two-Wire and Three-Wire Offline Power Supplies

Hung-I Hsieh, *Student Member, IEEE*, Liom Huwang, Tien-Chi Lin, and Dan Chen, *Fellow, IEEE*

***Abstract*—In a two-wire (no chassis ground) input offline power supply system, a filter capacitor C_z is often connected between the primary side and the secondary side of the transformer for common-mode electromagnetic interference reduction. For three-wire offline power supplies, such a capacitor is also sometimes used for the same purpose. It is unclear how this filter capacitor works. In this paper, an explanation of the noise suppression mechanism of such a capacitor is given. From the understanding of the mechanism, it is noted that when properly connected, C_z works fine, but when improperly connected, it makes the noise performance even worse. Suggestions were made with regard to a proper C_z connection for a variety of converter configurations with different variations.**

***Index Terms*—Common-mode (CM) electromagnetic interference (EMI) noise, mixed-mode (MM) EMI noise, three-wire system, two-wire system.**

I. Introduction

TWO-WIRE input offline power supplies are popular in many battery charger applications for handheld electronic devices. In such a system, there is no "chassis ground" connection point, which is available in a three-wire system. Fig. 1 shows a circuit diagram of a three-wire offline flyback power supply in which the two so-called "Y capacitors" C_y are connected across line L and neutral N to chassis ground G. Y capacitors are normally effective and necessary for common-mode (CM) electromagnetic interference (EMI) reduction. Modeling of the effectiveness of the Y capacitor has been reported [1]–[4]. In a two-wire system, however, there is no chassis ground available, and therefore, Y capacitors cannot be connected as such. In such a system, a substituting capacitor C_z is often connected between the primary and the secondary of the transformer to reduce CM noise. In fact, a similar connection using C_z, as shown by the dotted-line connection in Fig. 1, has been found even for some three-wire systems.

To the knowledge of the authors, there has never been a clear explanation given in the literature about how the capacitor C_z works [4]. In this paper, an explanation of the noise suppression mechanism of C_z will be given for both the two-wire and three-wire systems. Understanding of such a mechanism leads to suggestions for an alternative C_z connection for a variety of power converter configurations. Discussion of the effects of output choke placement and transformer winding techniques will be given. A comparison of the effectiveness of C_y and C_z will be given. Throughout this paper, the term "Z capacitor" or C_z will be used for the capacitor connecting the primary and the secondary, whereas "Y capacitor" or C_y will be used for the capacitor connecting either line or neutral to chassis ground.

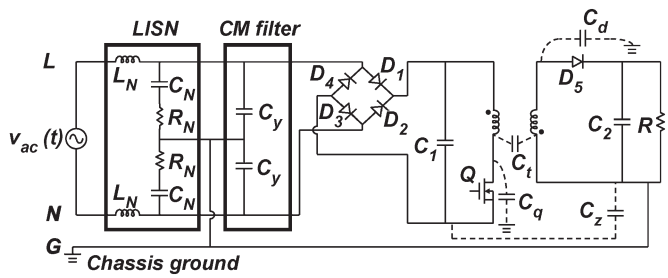


Fig. 1. Using Y capacitors for CM EMI reduction in a three-wire system. Capacitor C_z is sometimes used for the same purpose.

II. Noise Suppression Mechanism of C_z

For a three-wire system, as shown in Fig. 1, Y capacitors C_y are connected between chassis ground G and line L/neutral N. Thus, both L and N are always connected from a C_y to G. The CM noise current flows from the transformer interwinding capacitances C_t and the transistor and diode parasitic capacitances C_q and C_d to ground and return via ground to the line impedance stabilization network (LISN) resistors R_N. A C_y provides a lower impedance noise–frequency path for the CM noise when compared with the LISN impedance and therefore shunts the part of the noise current from flowing through R_N and achieves a noise reduction effect.

For a two-wire system, an EMI noise measurement is normally conducted under the condition that is shown in Fig. 2, in which the secondary-side point X is connected to the LISN ground, which, in turn, is connected to ground G in the measurement setup. Because there is no chassis ground for connecting C_y, a C_z is connected between the primary side and the secondary side. It is not easy to see how C_z can shunt the noise current from the LISN like a C_y and achieve a noise reduction effect. This will be explained in the following. Depending on the state of the diode bridge, the primary side of C_z is effectively connected to the line and/or the neutral

Manuscript received August 8, 2006; revised August 15, 2007. This work was supported by the National Science Council of Taiwan, R.O.C., under Award NSC93-2218-E-002-143 and Award NSC94-2218-E-002-084.

H.-I Hsieh, L. Huwang, and D. Chen are with the Department of Electrical Engineering, National Taiwan University, Taipei 106, Taiwan, R.O.C. (e-mail: d92921005@ntu.edu.tw).

T.-C. Lin was with the National Taiwan University, Taipei 106, Taiwan, R.O.C. He is now with System General Corporation, Taipei 231, Taiwan, R.O.C.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TIE.2007.896263

0278-0046/$25.00 © 2008 IEEE

Authorized licensed use limited to: National Taiwan University. Downloaded on March 9, 2009 at 02:22 from IEEE Xplore. Restrictions apply.

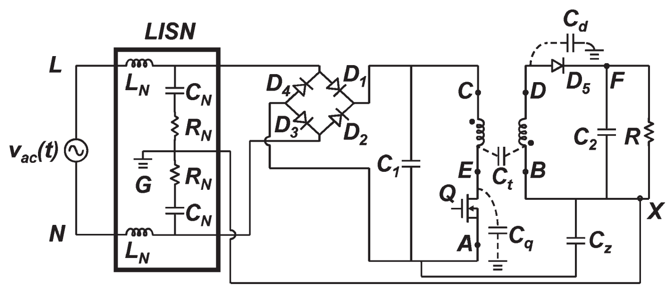


Fig. 2. Measurement of EMI noise in a two-wire system.

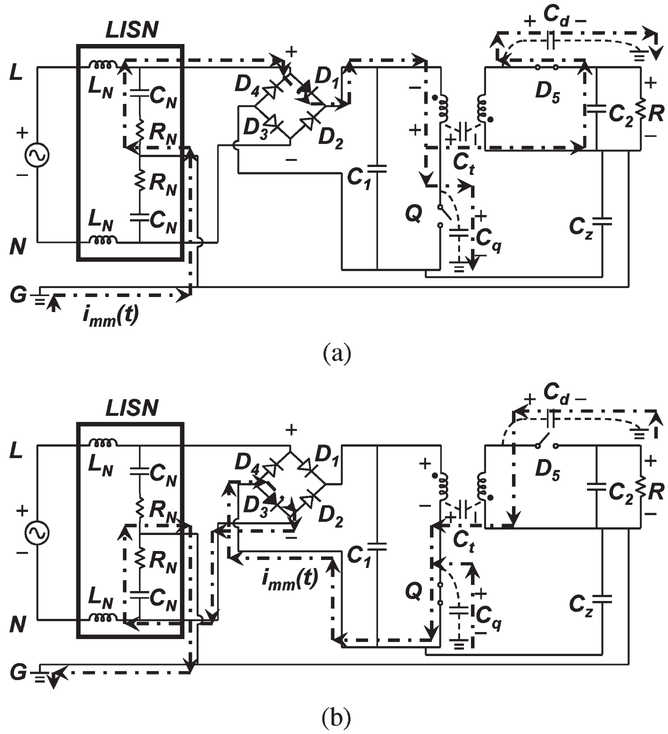


Fig. 3. One of the diodes conducts, and C_z is connected to the primary side, either L or N. (a) Coupling mechanism of mixed-mode (MM) noise when parasitic capacitors are being charged. (b) Coupling mechanism of MM noise when parasitic capacitors are being discharged.

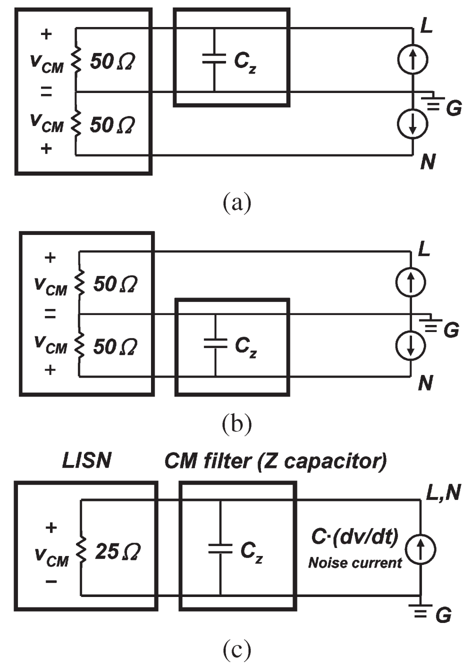


Fig. 4. Equivalent circuit models of CM noise coupling when one Z capacitor is used. (a) Z capacitor connected between ground and line sides because of MM noise coupling. (b) Z capacitor connected between ground and neutral sides because of MM noise coupling. (c) Z capacitor connected between ground and both line/neutral sides during the period when one pair of rectifying diodes is conducting.

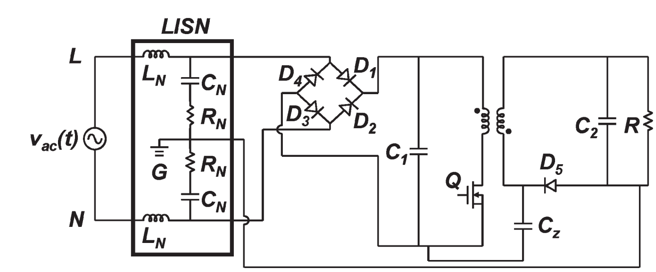


Fig. 5. Improperly connected C_z makes noise even worse.

and therefore serves as a C_y capacitor. This is explained in Sections II-A and B.

A. When All the Four Bridge Diodes Cut Off a 60-Hz Current

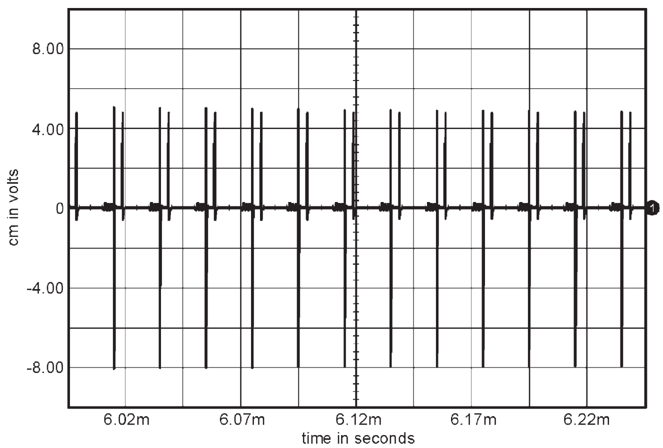
Under this condition, one diode still conducts a switching-frequency current, which flows through the LISN and causes EMI. This phenomenon, as illustrated in Fig. 3, has been explained in [5]–[8]. Therefore, C_z is also connected across ground point G and either line L or neutral N. This means that C_z is effectively tied between G and L/N, therefore working just like a "time-sharing" Y capacitor. Fig. 4(a) and (b) shows the equivalent noise circuit.

B. When a Pair of Bridge Diodes Conducts a 60-Hz Current

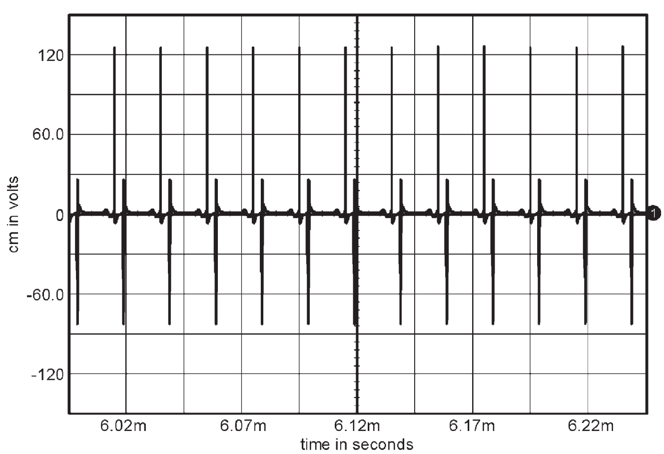
The diodes conduct according to a 60-Hz voltage when one pair of diodes (D_2, D_4) conducts. Point A of C_z is connected to line through D_4 and is connected to neutral through C_1 and D_2. Because of a relatively large C_1 value, C_z is effectively connected to both L and N, just like a Y capacitor. When the other diode pair (D_3, D_1) conducts, the same thing happens. Fig. 4(c) shows a simplified equivalent circuit of CM noise coupling to the LISN resistors. The $C(dv/dt)$ current source represents the displacement current going through a variety of parasitic capacitances in the system, including the semiconductor switching device package-to-ground capacitances, transformer interwinding capacitances, and parasitic capacitances between other components and ground point G. Z capacitor is used to provide a path to divert part of the $C(dv/dt)$ noise current from flowing into the LISN and achieve CM noise reduction.

For a three-wire system, C_z is sometimes used to replace C_y. The noise suppression mechanism of C_z in a three-wire system is similar to that described previously for a two-wire system.

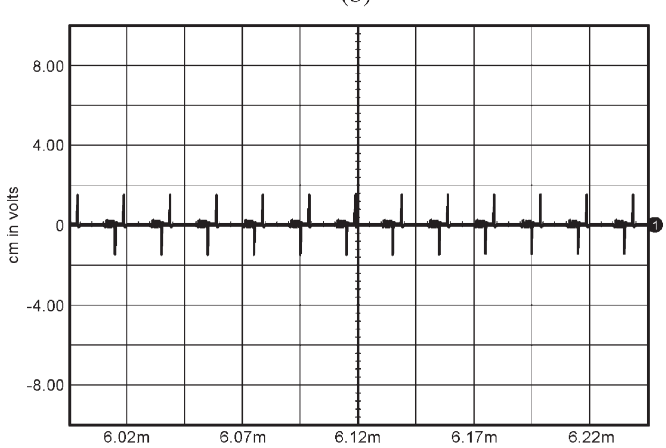
Authorized licensed use limited to: National Taiwan University. Downloaded on March 9, 2009 at 02:22 from IEEE Xplore. Restrictions apply.



(a)

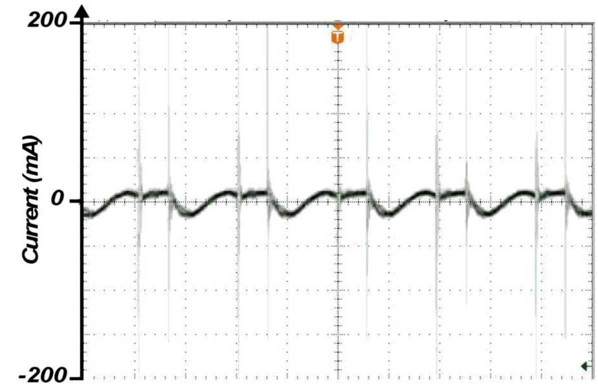


(b)

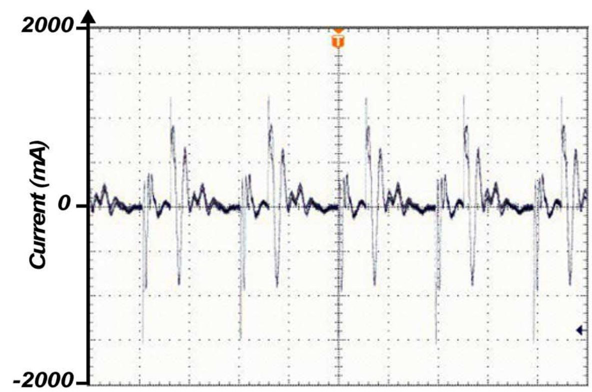


(c)

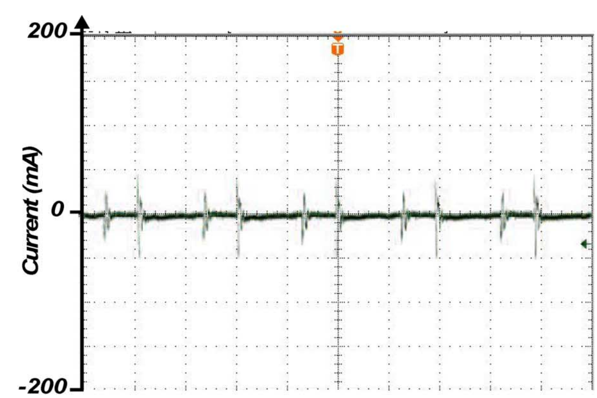
Fig. 6. Comparison of properly and improperly connected C_z's. The simulated CM voltage of a flyback converter configuration is shown in Fig. 2. Converter operation condition: $P_o = 40$ W, $V_o = 12$ V, $f_s = 50$ kHz, and $C_z = 3300$ pF. (a) CM noise voltage (without C_z). (b) CM noise voltage with an improperly connected C_z (between points E and B). (c) CM noise voltage with a properly connected C_z (between points A and B).



(a)



(b)



(c)

Fig. 7. Comparison of properly and improperly connected C_z's. The measured CM current of a flyback converter configuration is shown in Fig. 2. Converter operation condition: $P_o = 40$ W, $V_o = 12$ V, $f_s = 50$ kHz, and $C_z = 3300$ pF. (a) CM noise current (without C_z). (b) CM noise current with an improperly connected C_z (between points E and B). (c) CM noise current with a properly connected C_z (between points A and B).

III. Suggestions for a Proper C_z Connection

Based on the explanation given in the previous section, suggestions are made for a proper connection of C_z. If properly connected, C_z can serve as an effective CM noise filter. If improperly connected, however, the use of C_z would not only be ineffective but also make noise even worse. This phenomenon will be described in Sections III-A and B.

A. Recommended Connection Points

In general, to be effective, C_z must be connected between either terminal of C_1 (bulk capacitor) and that of C_2 (output capacitor). This is because the two terminals of C_1 are connected to line or neutral through rectifying diodes, as described

Authorized licensed use limited to: National Taiwan University. Downloaded on March 9, 2009 at 02:22 from IEEE Xplore. Restrictions apply.

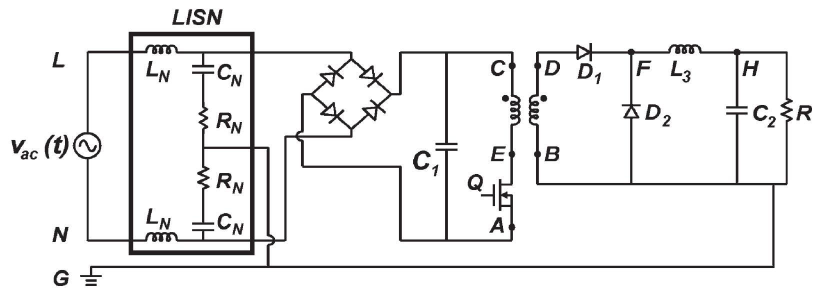


Fig. 8. Proper C_z connections for a forward isolated converter: points A–B, A–H, C–B, and C–H.

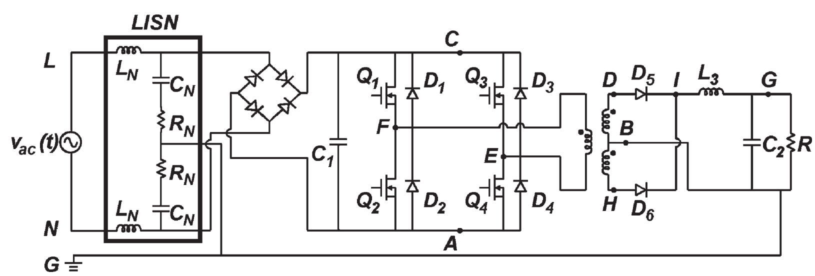


Fig. 9. Proper C_z connections for a full-bridge isolated converter: points A–B, A–G, C–B, and C–G.

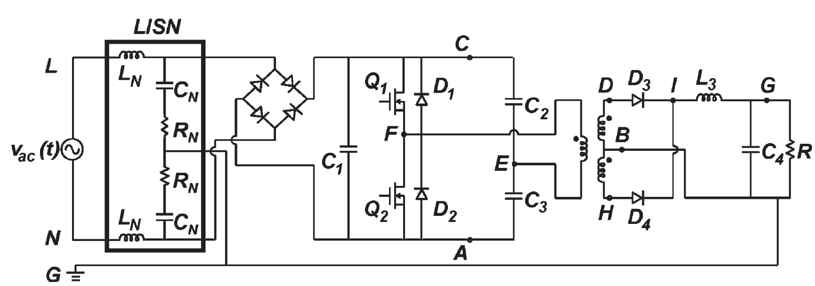


Fig. 10. Proper C_z connections for a half-bridge isolated converter: points A–B, A–G, C–B, C–G, E–B, and E–G.

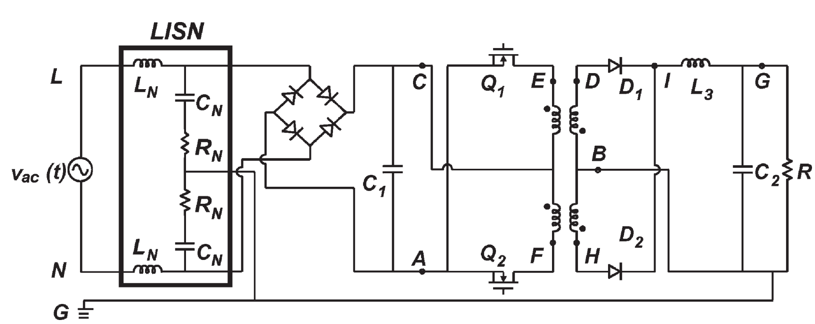


Fig. 11. Proper C_z connections for a push–pull isolated converter: points A–B, A–G, C–B, and C–G.

in Section II, and the two terminals of C_2 are both effectively connected to ground because of the low impedance of C_2 at noise frequencies. Therefore, a C_z works just like C_y's. For example, referring to Fig. 2, a C_z that is connected between points C and B is effectively connected between L/N and G, through D_1/D_2, and should therefore work as a CM capacitor. Other such connections include points C–F, A–B, and A–F. This basic connecting rule also applies to other converter configurations.

B. Connection Points to be Avoided

Referring to Fig. 2, a C_z connection between the following pairs should be avoided: points E–B, E–D, E–F, C–D, and A–D. None of these connecting schemes lead to those connections given in Section III-A. Even more, all of these condition schemes make CM noise even worse because of the high dv/dt across C_z, which makes the noise $C(dv/dt)$ current to the LISN without the benefit of a bypassing effect that a C_y

Authorized licensed use limited to: National Taiwan University. Downloaded on March 9, 2009 at 02:22 from IEEE Xplore. Restrictions apply.

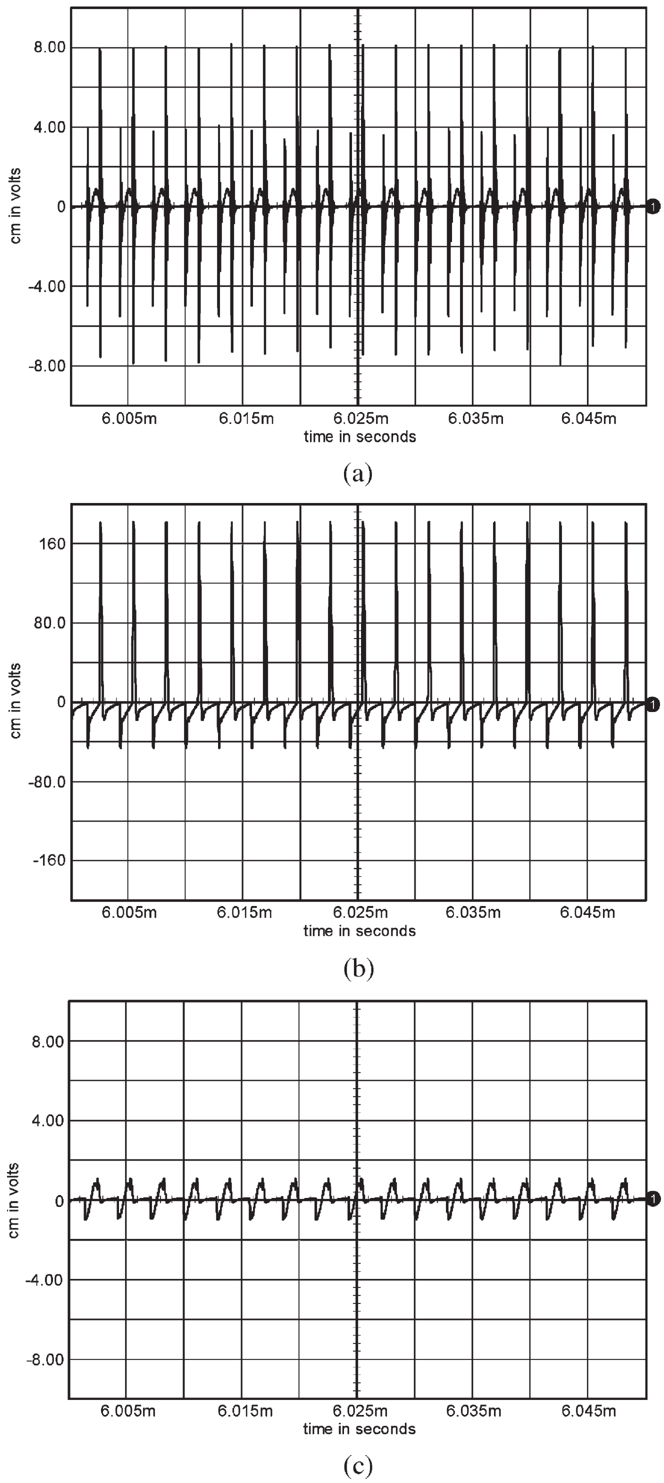


Fig. 12. Comparison of properly and improperly connected C_z's. The simulated CM voltage of a forward converter configuration is shown in Fig. 8. Converter operation condition: $P_o = 40$ W, $V_o = 18$ V, $f_s = 350$ kHz, and $C_z = 3300$ pF. (a) CM noise voltage (without C_z). (b) CM noise voltage with an improperly connected C_z (between points E and D). (c) CM noise voltage with a properly connected C_z (between points C and B).

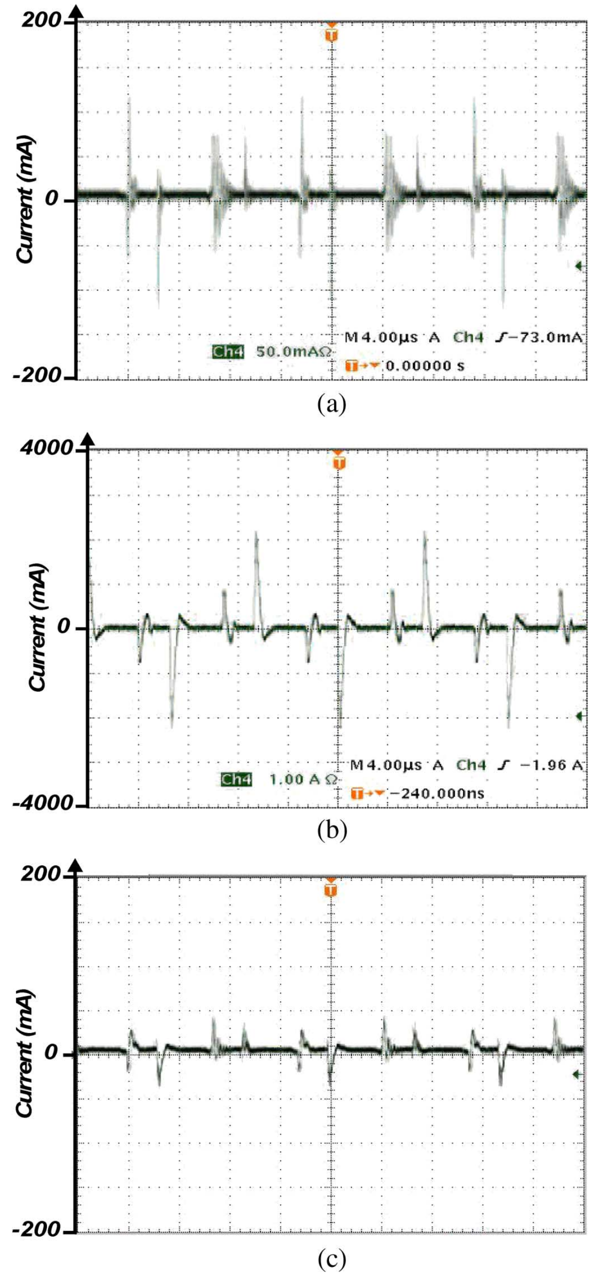
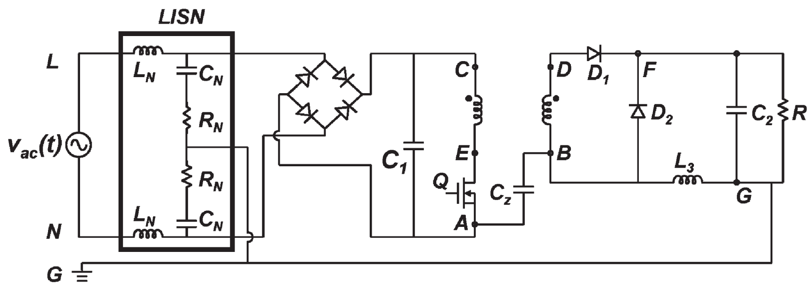


Fig. 13. Comparison of properly and improperly connected C_z. The measured CM current of a full-bridge converter configuration is shown in Fig. 9. Converter operation condition: $P_o = 80$ W, $V_o = 12$ V, $f_s = 70$ kHz, and $C_z = 3300$ pF. (a) CM noise current (without C_z). (b) CM noise current with an improperly connected C_z (between points E and D). (c) CM noise current with a properly connected C_z (between points A and G).

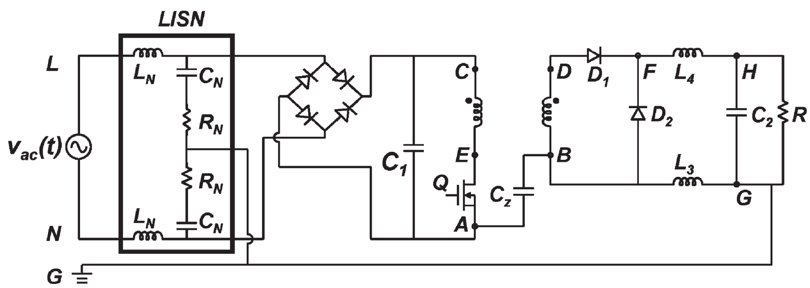
provides. The displacement current $C(dv/dt)$ flows through C_z, point X, ground, and LISN and causes CM noise. Take the case of a C_z that is connected in Fig. 5 as an example. The only difference between the two configurations that are shown in Figs. 2 and 5 is that D_5 is differently placed. C_z is effective in Fig. 2, but it makes things even worse in Fig. 5 because a high-frequency $C(dv/dt)$ noise current flows through C_z and LISN and causes CM noise.

The aforementioned assertions in points A and B have been verified by experiments or simulations. Figs. 6 and 7 show the results of simulations and experiments. One can see in both figures that a properly connected C_z suppresses CM noise and an improperly connected C_z makes CM noise even larger. It is noted that the simulation results were all obtained under the nonideal conditions in which parasitic capacitances and inductances were incorporated [9].

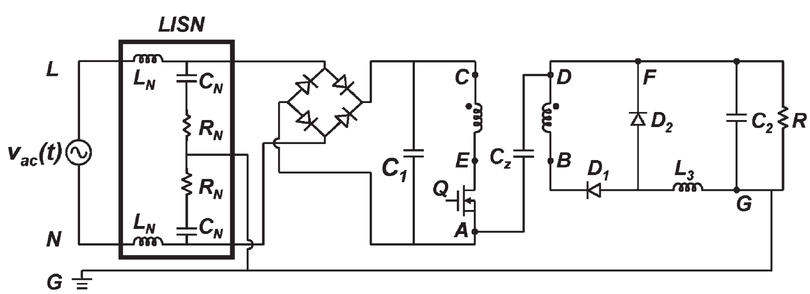
Authorized licensed use limited to: National Taiwan University. Downloaded on March 9, 2009 at 02:22 from IEEE Xplore. Restrictions apply.



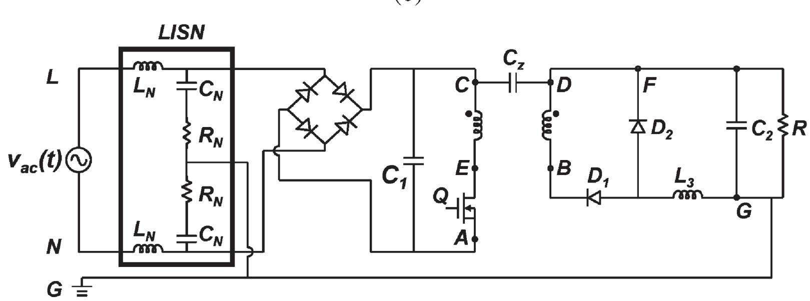
(a)



(b)



(c)



(d)

Fig. 14. Properly connected C_z for different variations. (a) Improperly connected C_z. (b) Improperly connected C_z. (c) Properly connected C_z. (d) Properly connected C_z.

IV. Suggested C_z Connection Schemes for Other Converter Configurations

Using the concept that was described in Section III-A, proper C_z connection schemes are suggested for other commonly used power converter configurations. Forward (Fig. 8), full-bridge (Fig. 9), half-bridge (Fig. 10), and push–pull converter configurations are included in the discussion (Fig. 11). The suggested C_z connection schemes are indicated in the figure captions. C_z must be properly connected to be effective in all these power converter configurations. If improperly connected, C_z could make things even worse. This fact is confirmed again from the simulated waveforms for a forward converter, as shown in Fig. 12, and from the measured waveforms for a full-bridge converter, as shown in Fig. 13.

V. Effects of Output Choke Placement and Transformer Winding Techniques

A. Output Choke Placement

Output choke placement may affect the effectiveness of C_z in that particular circuit. When the output choke L_3 is placed in the bottom rail, as shown in Fig. 14(a), then there is a

Authorized licensed use limited to: National Taiwan University. Downloaded on March 9, 2009 at 02:22 from IEEE Xplore. Restrictions apply.

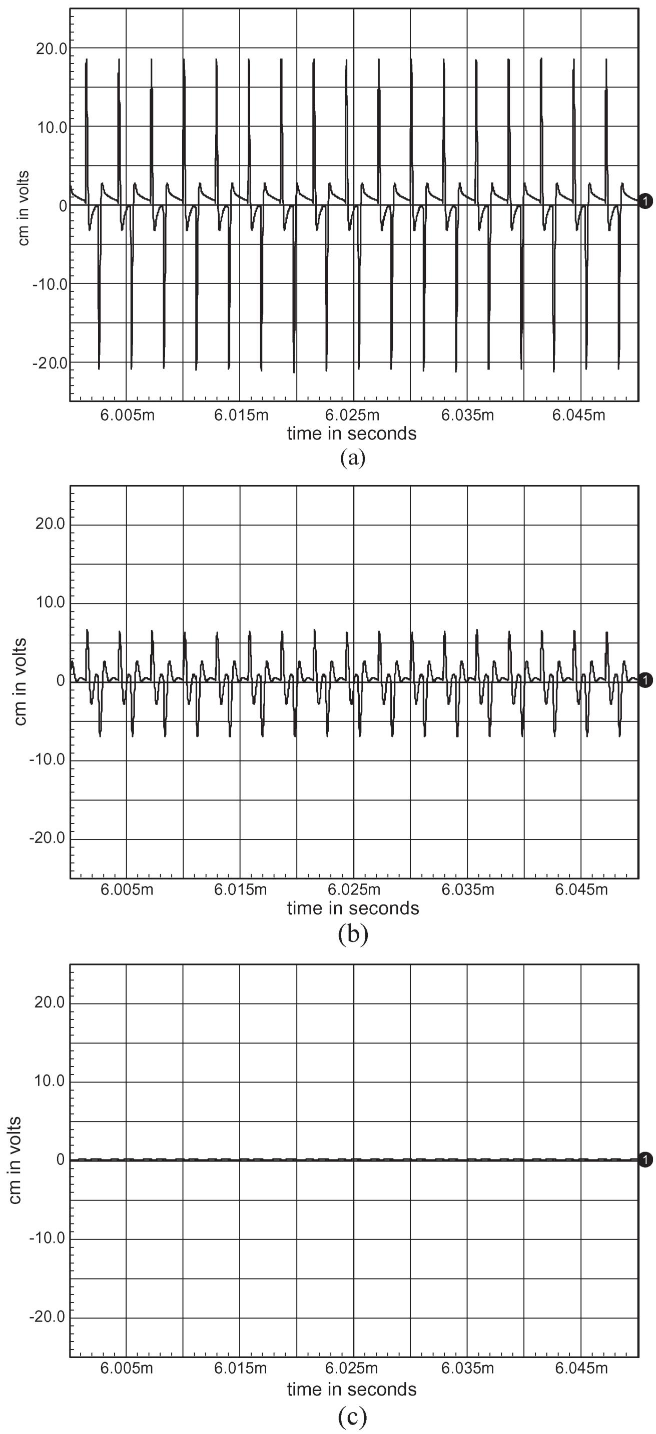


Fig. 15. Comparison of the effects of output choke placement for a forward converter (simulated results). Converter operation condition: $P_o = 40$ W, $V_o = 18$ V, $f_s = 350$ kHz, and $C_z = 3300$ pF (refer to Fig. 14). (a) Improperly connected [between points A and B; refer to Fig. 14(a)]. (b) Improperly connected [between points A and B; refer to Fig. 14(b)]. (c) Properly connected [between points A–D and C–D; refer to Fig. 14(c) and (d)].

high-frequency voltage at point B. Therefore, the connection of C_z between points A and B in Fig. 14(a) would increase the CM noise current. The same C_z would reduce the CM noise current if L_3 is placed on the top rail. The same theory applies to Fig. 14(b). However, if both D_1 and L_3 are placed on the bottom part, as shown in Fig. 14(c) and (d), then the connection

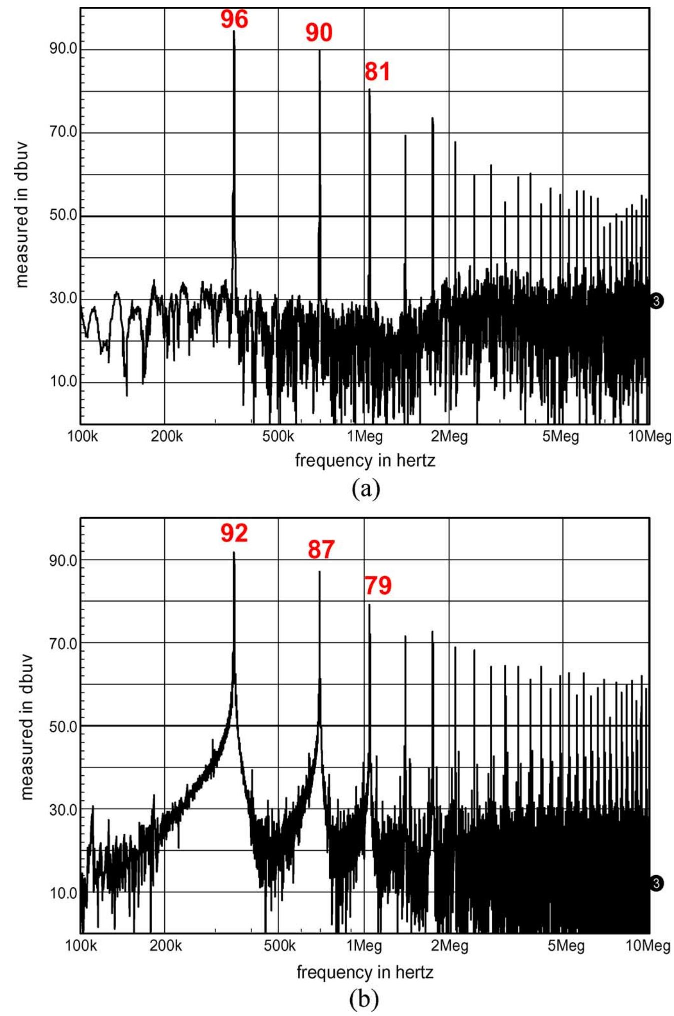


Fig. 16. Comparison of filter effectiveness between one C_z and two C_y's. The simulated CM EMI noise of a forward converter configuration is shown in Fig. 8. Converter operation condition: $P_o = 40$ W, $V_o = 18$ V, and $f_s = 350$ kHz. (a) CM EMI noise when $2 \times C_y$, each of 22 200 pF, are used. (b) CM EMI noise when $1 \times C_z$ of 44 400 pF is used.

between points A–D and C–D would work. The simulation results that are shown in Fig. 15(a)–(c) verify the theory. The same theory applies to the half-bridge and push–pull converter configurations that are shown in Figs. 10 and 11.

B. Effects of Transformer Winding Techniques

Transformer interwinding capacitance plays a role in CM noise. From the aforementioned discussion, it is clear that some interwinding capacitances help but some hurt the CM noise performance, depending on the circuit configuration. Referring to Fig. 2, the interwinding capacitances between points E–B, C–D, and E–D hurt the CM noise performance because there are high-frequency voltages across the interwinding capacitances, which therefore contribute to the CM noise current flow from the capacitance to the LISNs. These capacitances are called "bad" capacitances in this paper. However, the capacitance between points C and B reduces the CM noise current because it essentially works like a C_z. This is called a "good" capacitance. This opens up a possibility of exercising winding termination to increase the "good" and also reduces "bad" capacitances.

Authorized licensed use limited to: National Taiwan University. Downloaded on March 9, 2009 at 02:22 from IEEE Xplore. Restrictions apply.

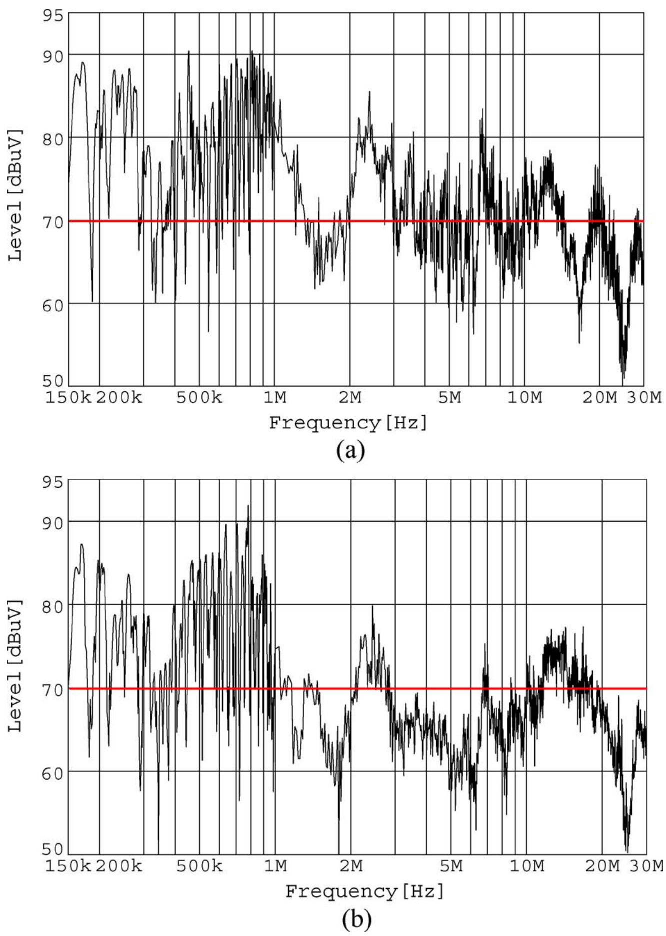


Fig. 17. Comparison of filter effectiveness between one C_z and two C_y's. The measured CM EMI noise of a flyback converter configuration is shown in Fig. 1. Converter operation condition: $P_o = 40$ W, $V_o = 12$ V, and $f_s = 50$ kHz. (a) CM EMI noise when $2 \times C_y$, each of 22 200 pF, are used. (b) CM EMI noise when $1 \times C_z$ of 44 400 pF is used.

In circuit configurations such as Fig. 14(a) and (b), however, all interwinding capacitances are "bad" capacitances. If the circuit is rearranged, as shown in Fig. 14(d), however, the interwinding capacitance between points C and D becomes a "good" capacitance, which makes the option of using an interwinding capacitance to reduce CM noise a possibility.

VI. Effectiveness of C_z

Due to the safety leakage current limitation, it is well known that each of the two C_y's must be no more than 3300 pF for a 60-Hz application. The C_z value is also limited by the same safety concern. The maximum allowable C_z is 6600 pF (i.e., 2×3300 pF). Therefore, a fair comparison of filtering effectiveness should be made between $1 \times C_z$ of 6600 pF and $2 \times C_y$, each of 3300 pF. From the description of Section II, during the period when a pair of bridge diodes conducts, C_z is equivalent to two C_y's, as indicated in Fig. 4(c). Therefore, C_z is as effective as two C_y's during this period. During the period when a bridge diode conducts, then C_z is connected to line or neutral, as shown in Fig. 4(a) or (b). During this same period, only one C_y is connected to L or N, which is similar to the case of using C_z except that C_z is two times the size of C_y. Therefore, C_z is more effective in this regard during this period. Because of the time-varying feature of the circuit, it is difficult to theoretically predict the effectiveness of C_z filtering attenuation, but it can be concluded from the aforementioned arguments that $1 \times C_z$ of 6600 pF is no worse than $2 \times C_y$, each of 3300 pF in filtering effectiveness. Experiments and simulations have been conducted to verify this assertion. Figs. 16 and 17 show results of simulated and measured CM EMI noise for verification. Unusually large C_y and C_z values were used in the experiments and simulations to show the effect.

VII. Conclusion

A theory is given to explain the noise suppression mechanism of a "Z capacitor" for both two-wire and three-wire offline power supplies. From the proposed theory, suggestions were made for a proper connection of C_z to achieve a noise suppression effect. It is noted that an improper connection of C_z amplifies the CM noise, which makes things worse. It is also concluded that a properly connected C_z is at least as equally effective as commonly used Y capacitors in suppressing CM noise. With the guidance provided in this paper, designers can effectively use C_z for a variety of converter configurations.

References

[1] F.-Y. Shih, D. Chen, Y.-P. Wu, and Y.-T. Chen, "A procedure for designing EMI filters for AC line applications," *IEEE Trans. Power Electron.*, vol. 11, no. 1, pp. 170–181, Jan. 1996.

[2] W. Chen, X. Yang, and Z. Wang, "Analysis of insertion loss and impedance compatibility of hybrid EMI filter based on equivalent circuit model," *IEEE Trans. Ind. Electron.*, vol. 54, no. 4, pp. 2057–2064, Aug. 2007.

[3] J. Meng, W. Ma, Q. Pan, Z. Zhao, and L. Zhang, "Noise source lumped circuit modeling and identification for power converters," *IEEE Trans. Ind. Electron.*, vol. 53, no. 6, pp. 1853–1861, Dec. 2006.

[4] P. Chen, H. Zhong, Z. Qian, and Z. Lu, "The passive EMI cancellation effects of Y capacitor and CM model of transformers used in switching mode power supplies (SMPS)," in *Proc. Power Electron. Spec. Conf.*, Aachen, Germany, Jun. 2004, pp. 1076–1079.

[5] S. Qu and D. Chen, "Mixed-mode EMI noise and its implications to filter design in offline switching power supplies," *IEEE Trans. Power Electron.*, vol. 17, no. 4, pp. 502–507, Jul. 2002.

[6] M. Jin and M. Weiming, "A new technique for modeling and analysis of mixed-mode conducted EMI noise," *IEEE Trans. Power Electron.*, vol. 19, no. 6, pp. 1679–1687, Nov. 2004.

[7] H.-I Hsieh, J.-S. Li, and D. Chen, "Effects of X capacitors on EMI filter effectiveness," *IEEE Trans. Ind. Electron.*, vol. 55, no. 2, pp. 949–955, Feb. 2008.

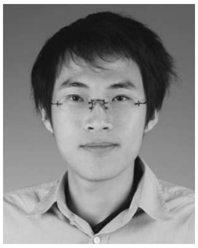
[8] H.-I Hsieh, D. Chen, and S. Qu, "A filter design procedure incorporating mixed-mode EMI noise for off-line switching power supplies," in *Proc. Power Electron. Motion Control Conf.*, Xi'an, China, Aug. 2004, pp. 1527-1532.

[9] P.-H. Liu, D. Chen, C.-W. Liu, and S.-Y. Wang, "Simulation and analysis of conducted EMI for a commercial DC/DC power module," in *Proc. Taiwan Power Electron. Conf. Exhib.*, Hsinchu, Taiwan, R.O.C., Sep. 2005, pp. 705–710.

Hung-I Hsieh (S'00) received the B.S.E.E. degree from Chung Hua University, Hsinchu, Taiwan, R.O.C., in 2000 and the M.S.E.E. degree from the National Chiao Tung University, Hsinchu, in 2002. He is currently working toward the Ph.D. degree in the Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan.

His research interests include EMI in switching circuits, resonant power converters, modeling and control of switching power converters, digital PWM controllers for power circuits, and power management IC design.

Authorized licensed use limited to: National Taiwan University. Downloaded on March 9, 2009 at 02:22 from IEEE Xplore. Restrictions apply.



Liom Huwang received the B.S.E.E. degree from Zhong Zheng University, Taipei, Taiwan, R.O.C., in 2005, and is currently working toward the Ph.D. degree at the Department of Electrical Engineering, National Taiwan University, Taipei.

Tien-Chi Lin received the B.S.E.E. degree from the National Taiwan University of Science and Technology, Taipei, Taiwan, R.O.C., in 2004 and the M.S.E.E. degree from the National Taiwan University, Taipei, in 2006.

Since July 2006, he has been a member of Technical Staff with System General Corporation, Taipei, where he is involved in the development of PWM ICs for low-power switching converters.

Dan Chen (S'72–M'75–SM'83–F'02) received the B.S.E.E. degree from the National Chiao Tung University, Hsinchu, Taiwan, R.O.C., in 1969 and the Ph.D. degree in electrical engineering from Duke University, Durham, NC, in 1975.

From 1975 to 1979, he was with GE Corporate Research Center, Schecnectady, NY, where he worked on solid-state power applications, including electronic ballasts for fluorescent lamps, electric cars, and switching power supply applications for computer and communication equipment. From 1979 to 2003, he was with the Department of Electrical Engineering, Virginia Polytechnic Institute and State University, Blacksburg, and was a Core Professor with the Center for Power Electronic Systems, National Science Foundation. Since August 2003, he has been a Professor with the Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan. He is the author or coauthor of one IEEE Press book, more than 100 papers, and one tutorial article in the *IEEE Spectrum* magazine. He is the holder of seven U.S. patents, which are all in the field of power electronics. His recent research interests include piezoelectric transformers, high-power semiconductor device characterization, EMI in switching circuits, modern magnetic amplifiers for switching power supplies, and power management IC architecture and design.

Dr. Chen was a recipient of the Barry Carlton Award from the IEEE Aerospace Society in 1973 and the Best Paper Award from the IEEE Power Electronics Society in 1998.

Authorized licensed use limited to: National Taiwan University. Downloaded on March 9, 2009 at 02:22 from IEEE Xplore. Restrictions apply.