Reducing Differential-mode EMI and Low-frequency Common-mode Voltage in Switching-mode Power Converters

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Abstract — This paper presents a design for an electromagnetic interference (EMI) power filter which is serially-cascaded with a conventional off-line switching-mode power converter to reduce the non-intrinsic differential-mode (DM) EMI and low-frequency common-mode (CM) output voltage in switching-mode power converters (SMPCs). The circuit configuration is extremely simple so that the size of the component can be reduced as well as its cost. Additionally, the operating principle of the proposed EMI power filter is also quite straightforward. An off-line flyback-type power converter, using the proposed EMI power filter, is analyzed in detail. Finally, some experimental results are provided in order to verify the performance and effectiveness of this converter.

I. INTRODUCTION

Due to the development of semiconductor technology, more and more switching-mode power converters (SMPCs) are being used in industrial applications. However, the high power-output switching devices, such as MOSFETs and diodes etc., interfere with nearby equipment through conduction or radiation of electricity causing unwanted electromagnetic emissions from the SMPCs. [1, 2]. There are several types of electromagnetic emission with the most common types being electromagnetic interference (EMI) and radio frequency interference (RFI). The switching frequency of the SMPCs is usually in a range from several dozen kHz to values exceeding 100 kHz. Hence, not only the electromagnetic compatibility (EMC) aspects related to the arc welding equipment of power converters are regulated in EN 60974-10, but also the EMI Standard CEI 61000 of the international commission establishes to tolerance limits for electromagnetic for disturbances in electrical communication. The EN55022 standard is also driving the study and research of minimizing and containing the conducted EMI. [3-5]

It is well known that EMI can negatively affect the effectiveness of power supply devices and have a harmful effect on sensitive equipment such as sensors, DSP or MCU chips, and the power switches. Passive filtering is the most common method for EMI attenuation. However, due to the existence of parasitic capacitors in high- frequency switching devices, the inherent functionality of passive components with higher frequency characteristics results in the less attenuation of the EMI. In fact, it can also produce other resonances in the conducted EMI frequency range. In the radio frequency (RF) range, a second filter stage must be implemented to attenuate at frequencies higher than the bandwidth of the first stage. [5, 6] In addition, for power converters having many inductors and capacitors, this makes them costly, bulky and space-consuming. In other words, the impractical space utilization will result in the economic benefit being greatly downscaled.

A variety of techniques are proposed to reduce the EMI emissions of a power converter, including, for example, active filtering, [6, 7] shielding and grounding, [8, 9] noise balancing or canceling [10-12], soft switching technique [4, 8], switching frequency modulation [13, 14] as well as packaging design [15]. However, it is really the necessity, of implementing ways to reduce the cost drastically, shorten production time, and enhance the reproducibility of a filter or layout designthat must be considered addressing any EMI issues in the solution process. On the other hand, although the issue of low-frequency CM output voltage has been pointed put[16], if appears as though no cost-effective method has been presented to deal with this issue.

In view of the above facts, an EMI power filter for off-line SMPCs is proposed in switching-mode power converter. It is found that the proposed EMI power filter not only can suppress the input DM EMI but also reduce the low-frequency CM output voltage of the off-line power converter. Hence the size and cost of the converter can be reduced significantly. The detailed illustration of the proposed EMI power filter with some experimental results are given to verify the effectiveness of the propose EMI power filter.

II. BRIEF REVIEW OF EMI AND LOW-FREQUENCY CM VOLTAGE IN SMPCS

1. EMI in SMPCs

Generally speaking, EMI noise is classified into two common types. One is CM noise which is the radiation being caused by the charge difference between live lines and neutral lines with respect to the ground line. Another one is DM noise that is also radiation but being by the charge difference between the live line and neutral line. [4, 5] Typically, DM noise leads to the major filter and is therefore the main determer of the power density of the converter. The sources of EMI in SMPCs are the power switches, power diodes and input power sources. Usually, the electromagnetic coupling paths in SMPCs include input power source, public ground loops and coupling capacitors located between wires or PCB components. The EMI noises nearby switching frequency and multiple switching frequencies are produced by the SMPCs. Furthermore, noised with dozens or hundreds of MHz are produced by the switching devices during the switching transients. During the switching transients, the power peaks will occur between parasitic inductors and parasitic capacitors, and then the RF noises in dozens or even hindreds of MHz noises, are generated. Since many power switches and power diodes are utilized in SMPCs is compact. The SMPCs are not only a major source of EMI emissions affecting the grid and loaders, but also are interfered by the elements of themselves. Hence, particular must be paid to EMI generation in SMPCs.

2. LOW-FREQUENCY CM VOLTAGE IN SMPCS

The size of the switching power supply is usually very small in the high-frequency trend, and the sandwich winding method is usually adopted due to the consideration of the coupling effect between the windings of the transformer, so the parasitic capacitor of the transformer is usually larger. In addition, in order to satisfy the electromagnetic compatibility (EMC) and EMI, a bridging capacitor has to be added between the primary side and the secondary side of the transformer. The bridging capacitor in an equivalent circuit is connected in parallel to a capacitor between the parasitic capacitance. When the input voltage is electrically connected to the filtering capacitor through the input filtering device and the bridge rectifier by a live line, the positive terminal of the filtering capacitor has an AC voltage with a positive half cycle relative to the ground. Similarly, when the input voltage is electrically connected to the filtering capacitor through the input filtering device and the bridge rectifier by a neutral line, the negative terminal of the filtering capacitor has an AC voltage with a negative half cycle relative to the ground. The positive half cycle and the negative half cycle are coupled to the secondary side through the bridging capacitor, thereby causing an AC low-frequency CM voltage in the circuit in the secondary side relative to the ground. When unit is being tested for the leakage-current, the CM voltage of the primary side is coupled to the node of the secondary side through the bridging capacitor and is then discharged to the ground through the loop formed by the testing equipment because the method and the object of the testing equipment and the equivalent circuit are used to simulate the behavior of the human body. Because the CM voltage exists at each node of the secondary side, a current flows through the testing equipment to generate the leakage-current. Thus, when the CM voltage is low, the generated leakage current is low, and the danger to the human body is also low.

In addition, when this AC low-frequency carrier voltage is supplied to a load, which may be an analog or digital audio amplifier, a home appliance serving as an audio transfer medium (e.g., a phone or even an advanced VoIP phone), or medical equipment, which may contact the human body, the following problems occur. Firstly, when the human body touches the circuit on the secondary side, the voltage of the secondary side is coupled with the ground through the human body so that a loop is formed, and the energy stored in the bridging capacitor is discharged through the human body such that the human body tends to shock. This is because the human body itself is a conductive object R and the human body is in the position to be a ground. Then, if the load is an audio product, the CM voltage enters an analog or digital signal amplifier circuit through a DC output wire. Then, the low-frequency CM voltage and the analog or digital signal are mixed and then enter the amplifier circuit, which amplifies the mixed signal multiple times. Finally, a low-pass filter(LPF) boarders the amplified signal, and an audio signal with a low-frequency carrier is generated by the speaker such that a low-frequency AC hum is generated.

It is to be noted that the secondary-side low-frequency CM noise generated by the switching power supply can be theoretically reduced using a multi-stage filter. However, implementing a high-current secondary-side multi-stage filter in an electronic apparatus product with the competitive is very challenging or even cannot be implemented under the actual considerations of the cost and the space.

III. PROPOSED EMI POWER FILTER

Figure 1 illustrates the system configuration of the proposed EMI power filter capable of reducing DM EMI and LFCM output voltage using an off-line flyback-type SMPC as an example. As shown in Fig. 1, the proposed EMI power filter is serially-cascaded with a conventional off-line flyback-type SMPC. When the input voltage is at the positive half cycle, i.e. the voltage supply line L is positive with respect to that of the neutral line N, both diode DF1 and DF2 are forward biased, and thus start up line current to charge the filtering capacitor CF. At this moment, the low-frequency CM voltage with the positive half cycle still exists. When the input voltage is at the negative half cycle, i.e. the voltage supply line N is positive with respect to that of the neutral line L, the input voltage is blocked using the DF2. Hence, no current path passes through the CF. Thus, only the positive half cycle of the CM voltage is obtained at the positive terminal of the CF, and the voltage with the negative half cycle originally existing between the negative terminal of the CF and the ground has disappeared. As a result, only the positive component is left in the voltage of the CF relative to the ground, and the low-frequency CM voltage contained in the transformer TR and switch SW inherently has the isolation function. In other words, the DC component on the capacitor CF cannot be electrically coupled to the output terminal through the transformer TR, and thus the effective CM voltage at the node of the output terminal can be greatly reduced.

On the other hand, in order to illustrate the significance of the reducing output low-frequency CM voltage of the proposed EMI power filter, as shown in Fig. 2. The EMI power filter together with a simplified circuit of the line impedance stabilization network (LISN) is connected to Spectrum Analyzer through CM noise and DM noise separator to observe the spectrums of CM noise, DM noise and total noise. In addition, a fairly high capacitance Cp between the drain and the chassis ground is utilized to analysis the behavior of emissions. When SW is on, Cp is simply tied to the negative DC bus. When the SW is off, the is tied to the primary side of the transformer; the voltage across the transformer is clamped by the output capacitor Co. Since the two LISN inductors allow only 60Hz of current to pass to the mains side, additionally, they and everything to the left of them in the circuit diagram can be ignored. Fig. 3 shows the resulting simplified emission circuit, in which N denotes the turn ratio of the transformer TR.

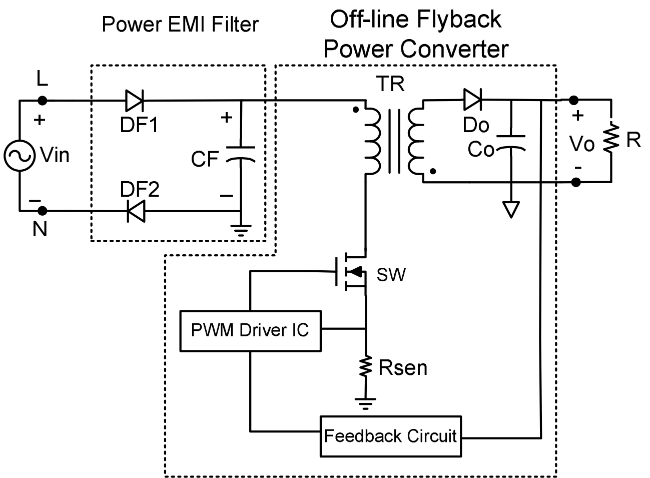

Fig. 1. Overall system configuration of the proposed EMI power filter with an off-line power converter.

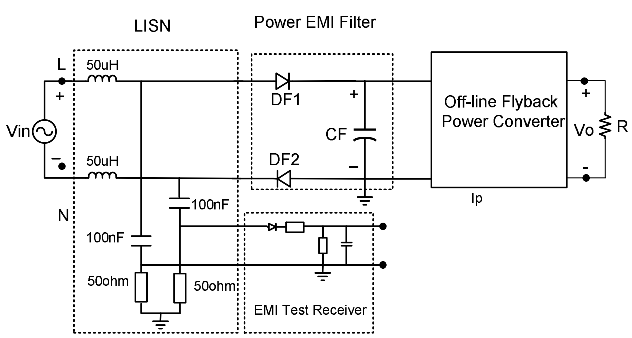

Fig. 2. The simplified LISN is shown together with the proposed EMI power filter for off-line power converter.

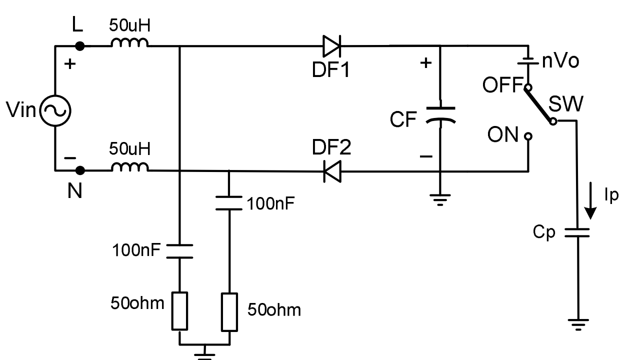

Fig. 3. The simplified DM EMI emission model.

For clarity and brevity, the following analysis ignores the ESR of the elements and focuses only on the DM noise emission.

A. Mode 1: (Vin>0 and SW being turned off)

As shown in Fig. 4, the SW is turned off. The accompanying noise emission current flow is described in Fig. 4. Since two paths with almost identical impendence exist in the LISN, the two currents are almost the same, and the result is that measured DM EMI is almost zero.

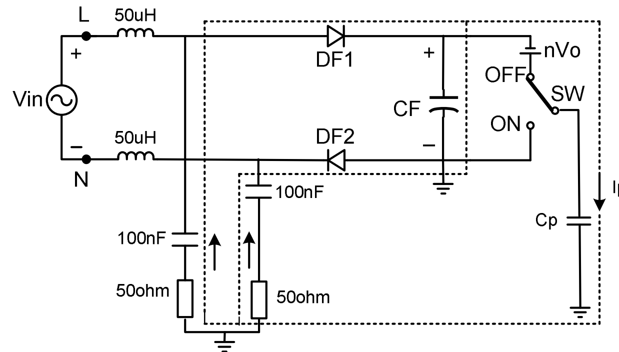

Fig. 4. The resulting equivalent circuit in mode 1

B. Mode 2: (Vin>0 and SW being turned on)

As depicted in Fig. 5, the SW is turned off. The accompanying noise emission current flow is described in Fig. 5. Similarly, the two currents passing through the LISN are almost balanced and nearly equal. Hence the measured DM EMI is almost zero, theoretically speahing.

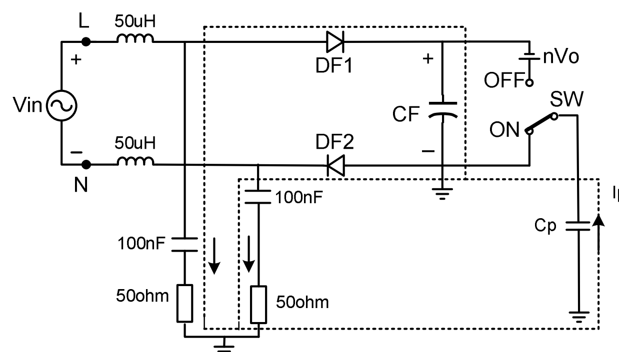

Fig. 5. The resulting equivalent circuit in mode 2

C. Mode3: (Vin<0 and SW being turned off)

The resulting power flow is illustrated in Fig. 6. During this mode, both diode DF1 and DF2 are reverse-biased and no current goes to the LISN branches. Hence the measured DM EMI is almost zero, theoretically.

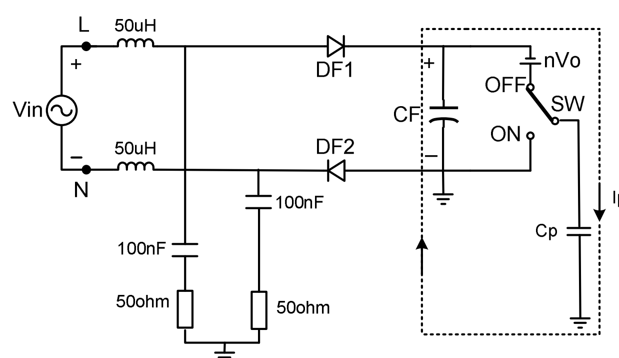

Fig. 6. The resulting equivalent circuit in mode 3

D. Mode4: (Vin<0 and SW being turned on)

As shown in Fig. 7, the SW is turned on. The accompanying noise emission current flow is described in Fig. 7. No current goes through the LISN branches and the result is that the measured DM EMI is almost zero.

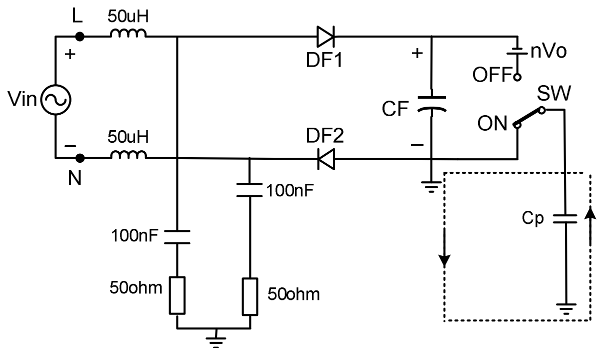

Fig. 7. The resulting equivalent circuit in mode 4

It can be concluded from the above statements that the high-frequency current can be balanced by the proposed power EMI filter. Therefore, the DM EMI is eliminated effectively.

IV. EXPERIMENTAL RESULTS

To further illustrate the significance and facilitate the understanding of the proposed power EMI filter, a hardware prototype shown in Figure 8, with the following parameters was constructed.

Vin: 220Vrms;
Vo: 12V/1A;
DF1, DF2: LT2A07(2A/1000V);
SW: STP4NK60ZFP(4A.600V);
CF: 47uF;
Rsen: 5ohm;
Co: 220uF;
Do: SB3100(3A/100V)x2;
PWM driver IC: LD7550B0 (switching frequency is 55 kHz);
Feedback circuit: LTV817B;
CPF: 0.1uF;
LPF1, LPF2: 30mH.

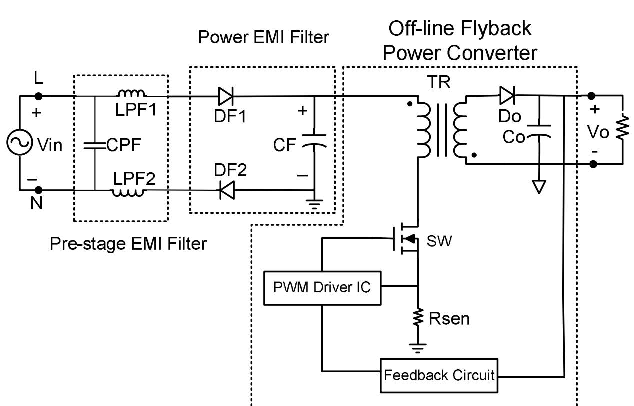

Fig. 8. The hardware prototype of the experimental off-line SMPC.

Figures 9 and 10 show the off-line switching power converter with respect to the attenuation of low-frequency output-voltage with to the measured waveforms both with and of without the proposed EMI power filter and with the proposed EMI power filter to be used with the off-line SMPC. From Figs. 9 and 10, it is obvious that the peak value of the LF CM voltage of the apparatus of the proposed power converter is about 35 volts, which is attenuated to about 1/5 that (about175 volts) when the EMI power filter is not used. Figures 11 and 12 show the measured spectrums of output noise emitted by the off-line SMPC in conjunction with the conventional full-bridge rectifier EMI filter and with the proposed EMI filter power, respectively. Obviously, within the range of 9kHz-30kHz, the voltage output of the SMPC, used together with the proposed EMI power filter, will improve by approximately 40dBs, with regard to the EMI levels compared to the case of a conventional full-bridge rectifier EMI filter used with an off-line switching power converter. The test results are rather in good agreement with the expected results.

V. CONCLUSIONS

In this paper, an EMI power filter serially-cascaded with a conventional off-line flyback SMPC is proposed to reduce not only the non-intrinsic DM EMI noise but also low-frequency CM output-voltage in SMPC. The low-frequency CM output-voltage cannot be smoothly transformed to the secondary side, so the low-frequency AC hum can be isolated. Even if the actual circuit has a small low-frequency CM output-voltage transformed to the secondary side, the low-frequency CM output-voltage generating the leakage current has been greatly reduced. Thus, the leakage-current cannot be increased even if the parasitic capacitor is increased. As a result, when the load is a phone or an IP phone, the low-frequency CM output-voltage, which originally passes through the DC output terminal, has been greatly reduced since the proposed EMI power filter circuit eliminates the low-frequency AC hum originally existing in the microphone of the phone. The operation of the proposed EMI power filter is quite straightforward and thus the circuit configuration of the proposed SPMC is extremely simple under the actual considerations of cost and size.

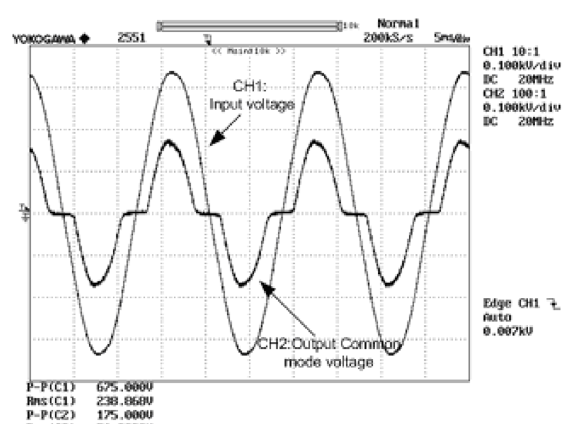

Fig. 9. Low-frequency CM output-voltage without the proposed EMI power filter.

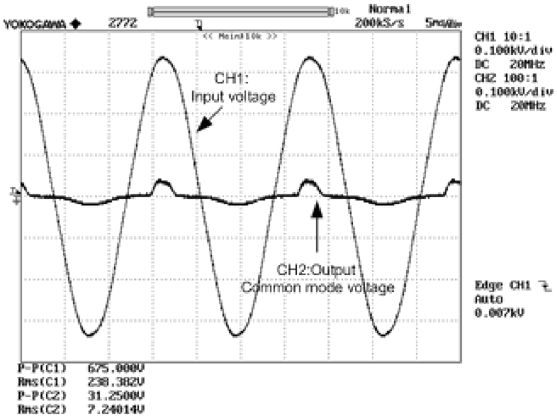

Fig. 10. Lw-frequency CM output-voltage with the proposed EMI power filter.

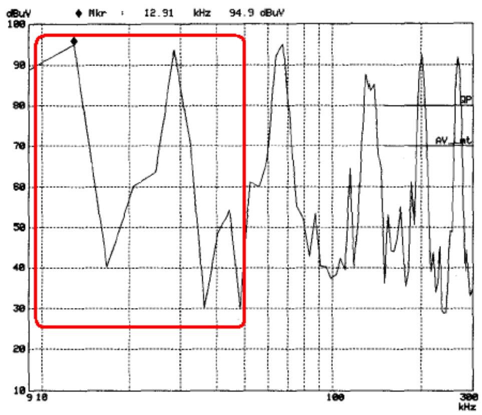

Fig. 11. Output-voltage and EMI performance using a conventional full-bridge rectifier EMI filter.

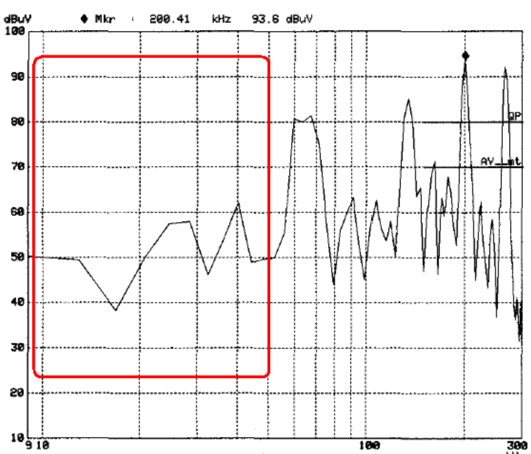

Fig. 12. Output-voltage and EMI performance with the proposed EMI power filter.

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