EMI Filter Design Part I: Conducted EMI Generation Mechanism

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1 author:

V. Tarateeraseth
Srinakharinwirot University

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Vuttipon Tarateeraseth, Member, IEEE, Department of Electrical Engineering, Srinakharinwirot University, Thailand. E-mail: vuttipon@ieee.org

Abstract—An electromagnetic interference (EMI) filter design procedure for switched-mode power supplies will be described in three parts: Part I) conducted EMI generation mechanism, Part II) measurement of noise source impedances, and Part III) a selection of passive filter topology for optimal performance. This article is the first part of the three-part series.

1. Introduction

Switched-Mode Power Supplies (SMPS) -also known as Switching Power Supplies (SPS) or Isolated DC-DC converters- are of widespread use in modern days because there are significant benefits in reduction of the physical sizes and high efficiency comparing to the linear power supplies [1]. The main function of the SMPS is to convert the AC input power to different level of regulated DC output voltages. Although there are several types of SMPS, all of them can be derived from the three basic DC-DC converters namely buck converter, boost converter, and buck-boost converter [2]. The main difference between SMPS and DC-DC converters is that the SMPS uses the high frequency transformer to make an isolation. For the sake of simplicity, to understand why SMPS generate significant noise, the boost converter and its switching waveforms are shown in Fig. 1 for explanation. In order to obtain the required DC output voltage, the semiconductor switch e.g. Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) of the boost converter must be switched "ON" and "OFF" by varying its duty-cycle at the switching frequency. Since the boost converter operates under extremely high switching frequency, the fast-transition voltage and current waveforms at the switching devices are resulted, as shown in Fig. 1. These fast-transition voltage and current waveforms are main noise sources and generate a wide spectrum of electromagnetic disturbance (EMD) [3]–[4]. Such electromagnetic noise propagates through the power cord connected to it and can also radiate in open space [5].

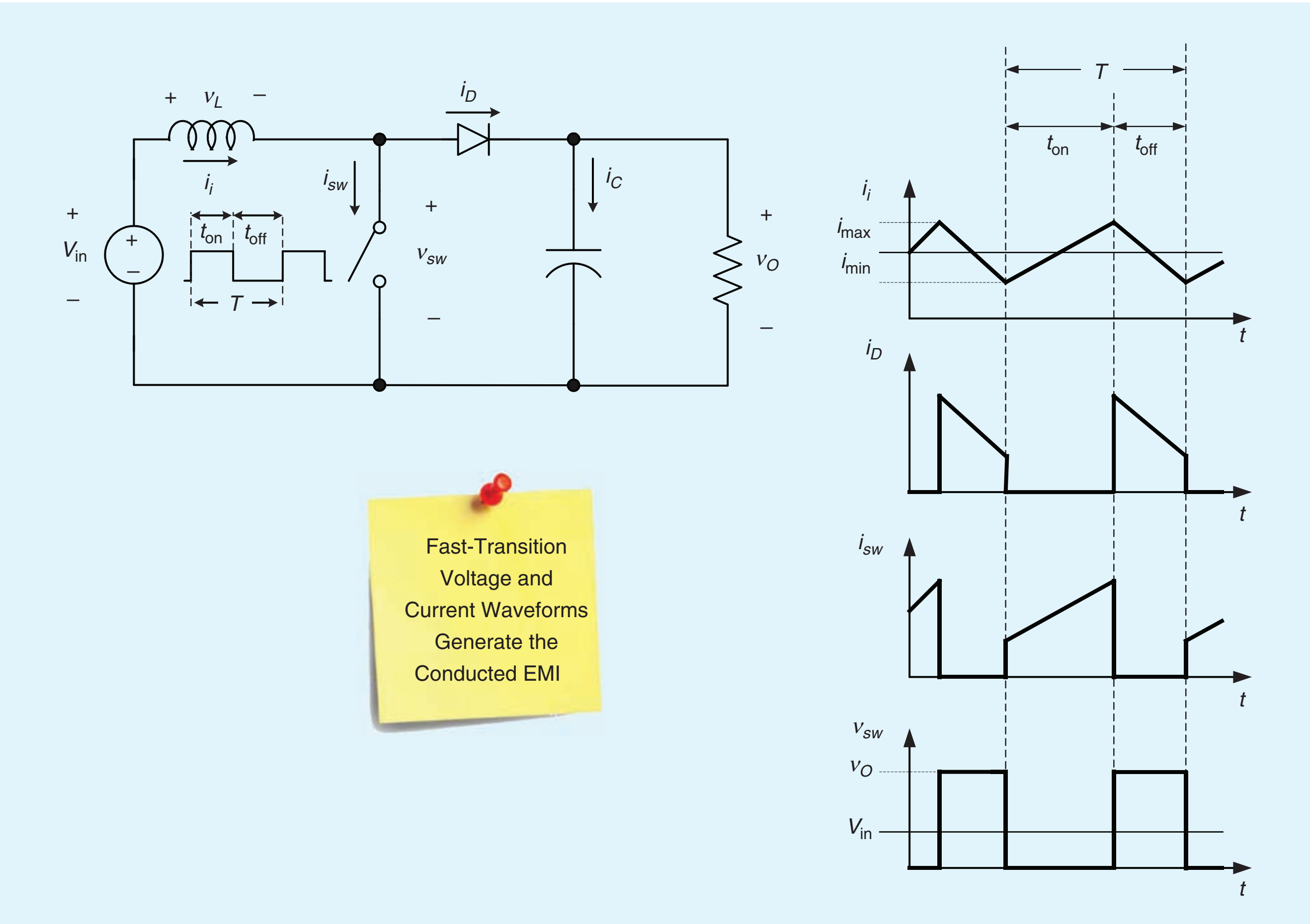

Fig. 1. Noise Source: switching operation of the converter.

Moreover, the cause of EMD is not only the switching operation of SMPS but also the parasitic elements of the passive components such as capacitor, resistor, inductor, transformer and power cord as shown in Fig. 2. In addition, the parasitic elements also come from the device leads, printed circuit board (PCB) traces, and device installations. For example, a heat sink is usually connected to the body of the MOSFET, which introduces a parasitic capacitance between the MOSFET and the heat sink as shown in Fig. 3. Those parasitic elements can cause a ringing voltage and current superimposed on the original switching waveforms which tend to enhance certain region of the original EMD [6]. The parasitic elements cause a ringing voltage across the switching device, during turn-off periods, while the diode reverse recovery causes a ringing current passing through the switching device during turn-on periods, as shown in Fig. 4. Therefore, it can be concluded that it is not only high *dv/dt* and *di/dt* during turn-off and turn-on periods having great influence on EMD problems, but the ringing voltage and current too.

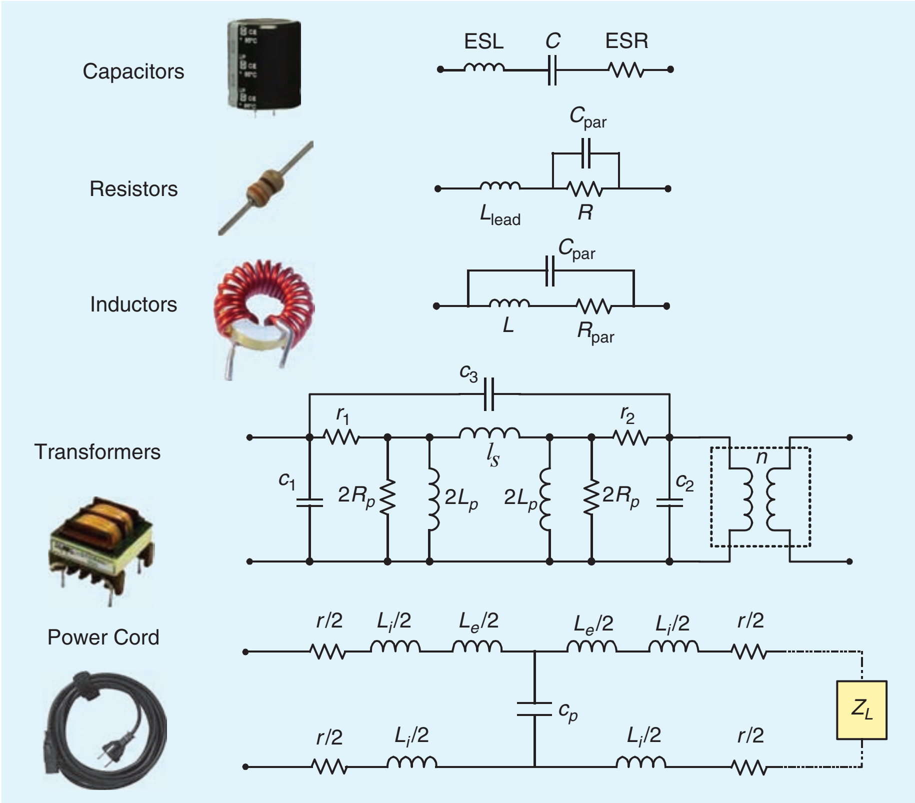

Fig. 2. Noise Source: parasitic elements of passive components.

The generated EMD might degrade the performance at device, equipment, or system level, either because the apparatus is powered by the same commercial power system and/or its location is very close to the power supply. If the performance of a device, an equipment, or a system is degraded by EMD, we commonly talk of electromagnetic interference (EMI).

To meet the EMC requirements, the EMD must be classified and analyzed because different EMC solutions are applicable to different frequency ranges. The EMD generated by any power electronic systems can be classified by frequency spectrum contents as shown in Fig. 5. The frequency spectrum contents from the power frequency (50 Hz or 60 Hz) to 2 kHz is defined as "harmonics" which can strongly distort the input current and voltage waveforms of the systems; in other words, it can decrease the power factor of the system and degrade the "quality" of power. The International Electrotechnical Committee (IEC) has issued the IEC-1000-3-2 standard to limit the harmonic contents of the electrical and electronic appliances. Generally, to comply with the given standard, there are two approaches: passive power factor correction (passive PFC) and active power factor correction (active PFC) [5]. Practically, the passive PFC is used for high power applications while the active PFC is applied for low power applications. Both approaches might be used to counteract the distortion and raise power factor. However, the PFC solutions will not be addressed in this article.

The frequency spectrum contents from 150 kHz to 30 MHz are defined as "conducted electromagnetic disturbance (conducted EMD)" or "conducted electromagnetic interference (conducted EMI)", as shown in Fig. 6. Typically, the conducted

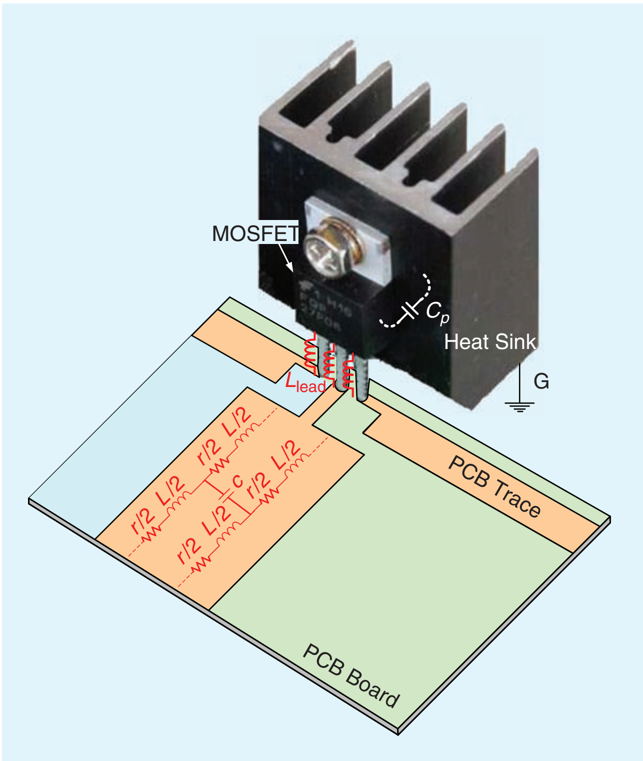

Fig. 3. Noise Source: parasitic elements of the circuit layout [8].

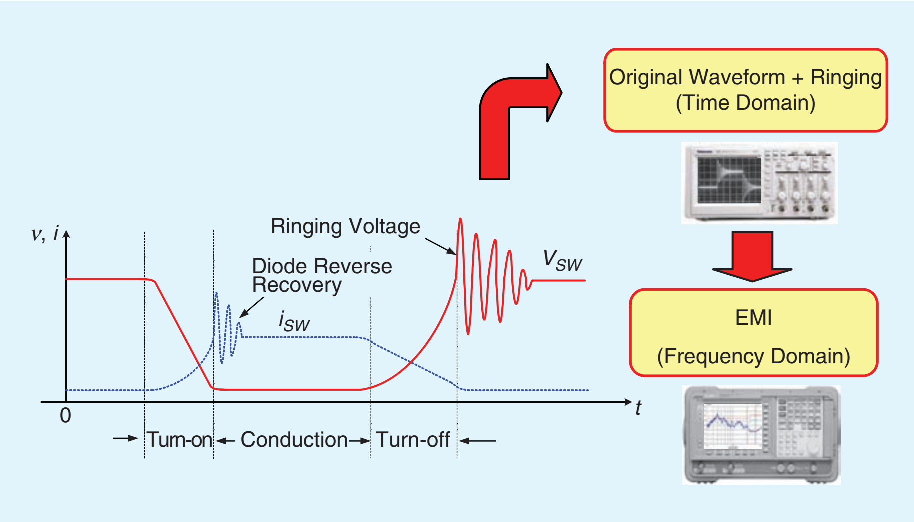

Fig. 4. Noise Source: fast-transition of switching devices.

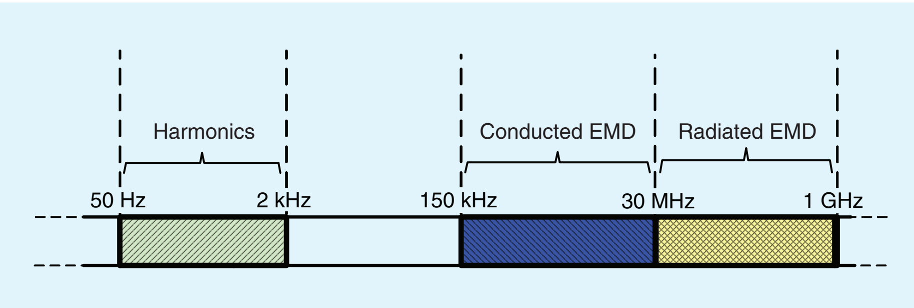

Fig. 5. Classification of electromagnetic disturbance by frequency {9}.

be minimized at the design stage if the product is designed based on EMC principles. This subject is out of scope of this article. In this article, the filter design to suppress the conducted EMI generated by a switched-mode power supply (SMPS) will be the main focus.

2. Common-mode and Differential-mode Conducted EMI Generation Mechanisms

Generally, the conducted EMI can be categorized into two conduction modes: the differential mode (DM) emission and common mode (CM) emission as shown in Fig. 6 [9]. The DM current flows out of the live wire and returns via the neutral wire. The CM current takes the live and neutral wires as one outgoing conductor and returns via the ground wire. Hence, the DM currents in the live and neutral wires are equal in magnitude but opposite in phase, while the CM currents are equal in both magnitude and phase as shown in Fig. 8 (a) and Fig. 9 (a), respectively [10].

Although many different SMPS topologies exist as discussed earlier, the flyback converter is presented as an example of the DM and CM noise coupling paths associated with the SMPS. In the flyback converter, as shown in Fig. 8 (b) and Fig. 9 (b), a diode bridge rectifies the ac voltage which is filtered by a bulk capacitor C_B producing a dc voltage. The required DC output voltage is chopped by the MOSFET, which is controlled by the pulse width modulation (PWM) controller. The MOSFET switches on and off at switching frequency but the duty-cycle is varied to regulate the output voltage. Due to the switching operation, the DM and CM noise currents are resulted. The normal operation of the circuit causes a DM noise, whereas the CM noise results from of the circuit's parasitic capacitances [7]. Fig. 8 (b) and Fig. 9 (b) show the DM and CM emissions propagating in an off-line flyback converter, respectively.

The objective of the conducted EMI test is to measure the total noise currents generated by the electrical and electronic appliances which are powered through a Line Impedance Stabilization Network (LISN). For measurement repeatability, CISPR 16-1 requires a LISN to prevent external conducted EMI on the ac mains from contaminating the measurement and to stabilize the ac mains impedances (line-to-ground and neutral-to-ground) at 50 Ω over the frequency range 150 kHz–30 MHz [11]. The noise currents across the 50 Ω instrument, which are the combination of the DM and CM disturbances, are measured as the conducted EMI. The DM noise depends on the equivalent series resistance (ESR) and equivalent series inductance

EMI produced by electrical and electronic appliances can be minimized if EMC principles are taken into account at the design stage. However, to ensure that the products can comply with the conducted EMI limits, the filtering techniques (passive filtering and/or active filtering) are normally used to suppress the conducted EMI. The different solutions between the PFC and the conducted EMI are illustrated in Fig. 7.

The "radiated electromagnetic disturbance (radiated EMD)" or "radiated electromagnetic interference (radiated EMI)" is from frequency above 30 MHz. In this frequency range, the product begins to radiate electromagnetic interference in space. Similar to the conducted EMI problem, the radiated EMI can

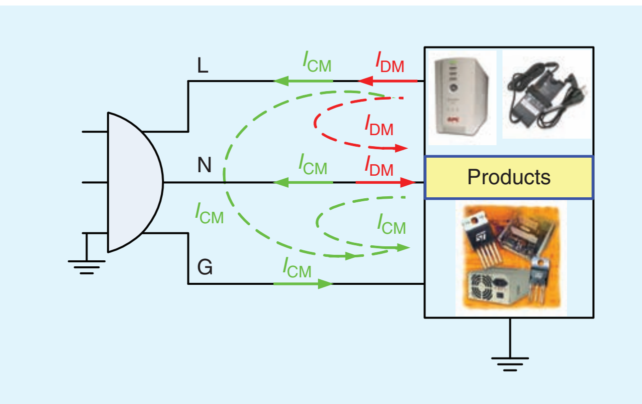

Fig. 6. Conducted EMI emission definition.

(ESL) of the bulk capacitor (C_B); the CM noise, instead, is coupled through the parasitic capacitance (C_p) of the switching devices due to their switching phenomena and transformer interwinding capacitance [7]. The measured total disturbances (combination of the DM and CM noises) at a line-to-ground and neutral-to-ground ports of a LISN are monitored by a spectrum analyzer as shown in Figs. 8 (b) and 9 (b).

Although either DM or CM noise measurements are not required by the EMI regulations, the total noises should be decomposed into the DM noise and the CM noise not only for facilitating the systematic EMI filter design but also for a noise diagnosis purpose. Many noise discrimination techniques have been developed, either by frequency domain measurement [12]–[14] or by time domain measurement [15].

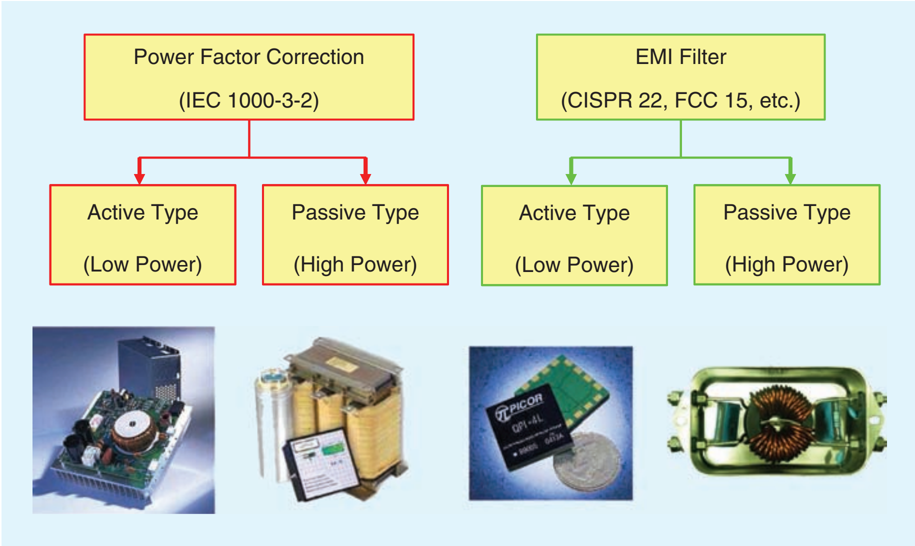

Fig. 7. The different solutions between PFC and conducted EMI.

3. Why Do We Need EMI Filters?

Since SMPS can produce the DM and CM noises in a wide frequency range, to suppress the conducted EMI effectively, the typical conducted EMI characteristic of SMPS must be analyzed. Typical emissions of SMPS, as shown in Fig. 10, are composed of the switching frequency of switching devices which is about 70 kHz–100 kHz [1]. Below 2 MHz, it is dominated by the DM noise. For frequency above 2 MHz, it is mainly contributed by the CM noise, and the self-resonant-frequency (SRF) of the components and PCB layout resonances occur at higher frequency [10]. In order to comply with the conducted EMI regulations, various conducted EMI reduction techniques for SMPS have been proposed [16]–[17]. However, there are virtually no electronic products today that can comply with the conducted EMI emission regulatory requirements without an EMI filter inserted [6]. The EMI filter needs to attenuate both DM and CM noises with good attenuation with reliability.

As a result, an EMI filter remains a very important part of SMPS to

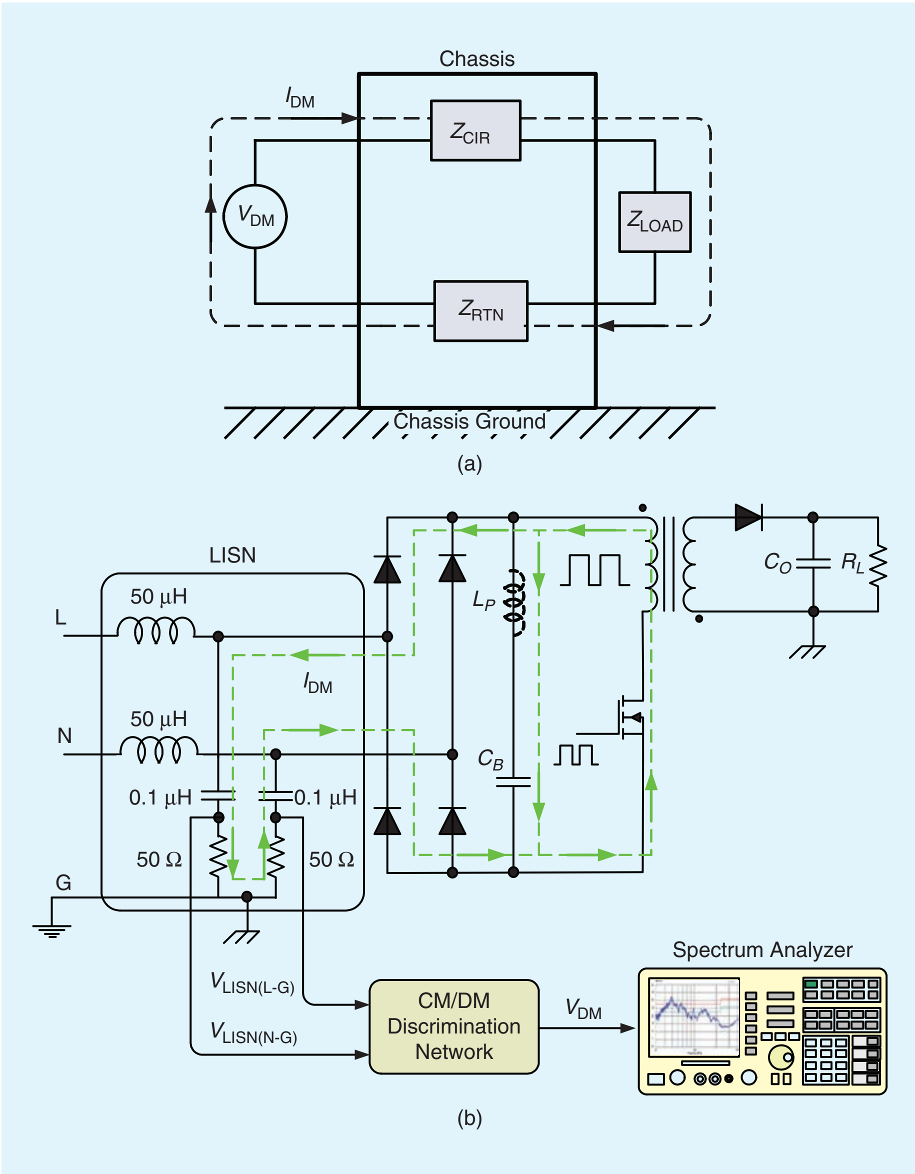

Fig. 8. Conducted EMI conduction modes. (a) DM path; (b) DM path in SMPS.

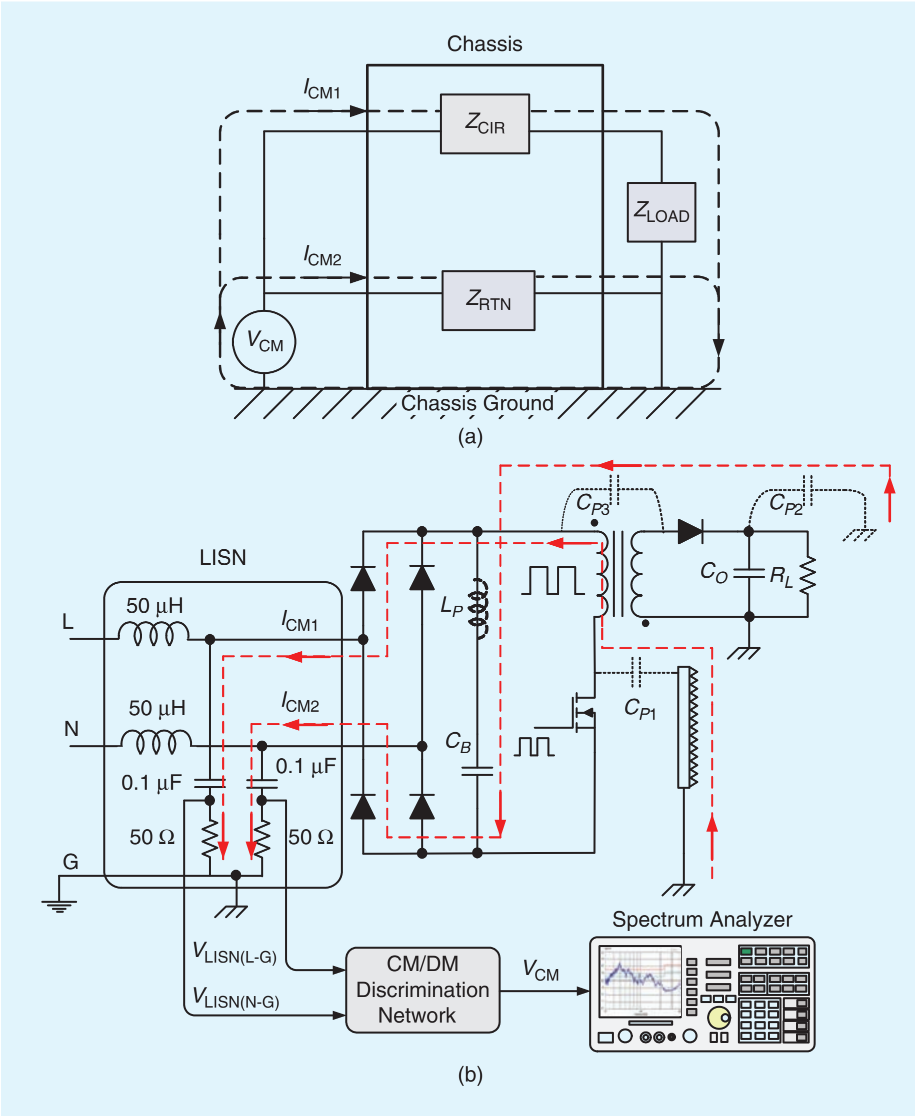

Fig. 9. Conducted EMI conduction modes. (a) CM path; (b) CM path in SMPS.

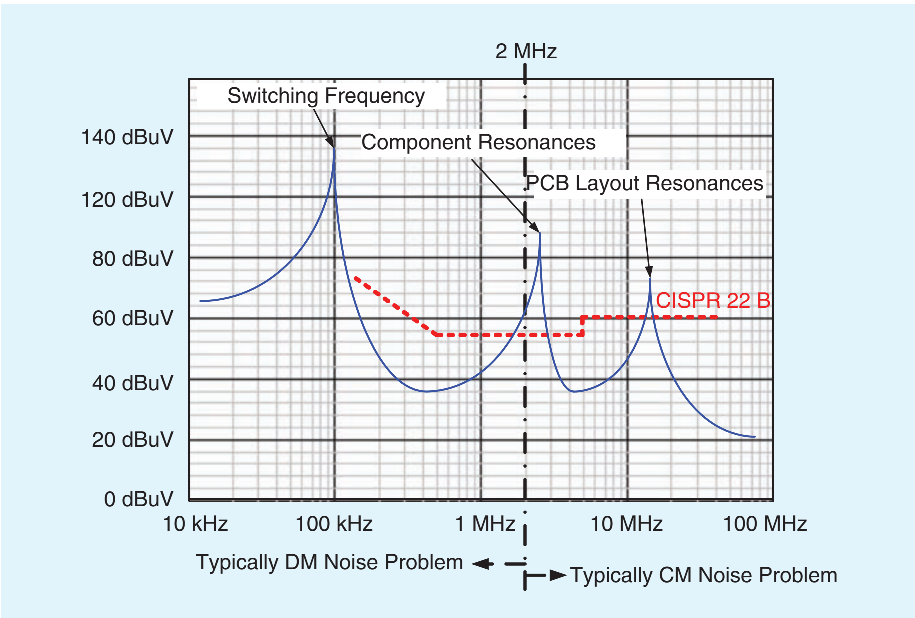

Fig. 10. Typical conducted EMI problem areas of the SMPS [10].

suppress the conducted EMI [6]. To prevent the disturbances of SMPS emitting through the ac power line, the EMI filter is always located right at the AC input of SMPS as shown in Figs. 11 (a) and (b).

EMI filters can be categorized into three types: active, passive, and hybrid EMI filters [20]–[21]. Although an active EMI filter is an alternative choice to mitigate the conducted EMI with a compact size, it is not extensively used in SMPS because several unsolved limitations still exist. For example, since the operational amplifier bandwidth is limited, the active EMI filter alone is ineffective at high frequency [18]. In addition, for a good attenuation, the types of active EMI filter must be chosen appropriately, i.e. a voltage canceling for a low impedance DM noise source and a current canceling for a high impedance CM noise source [19].

Existing research has demonstrated the benefit of an active EMI filter by integrating it with the passive EMI filter, thus producing a "hybrid EMI filter" [20]–[21]. An active EMI filter is used not only to improve the passive EMI filter performance but also to reduce the size of the passive EMI filter components by replacing large passive components (i.e. common mode chokes) with smaller passive components and some active control circuitry [22].

Unlike an active EMI filter and a hybrid EMI filter, a passive EMI filter is bulky and heavy, but it presents the advantages of suppressing both DM and CM noises with very good attenuation [16]. A passive EMI filter is a superposition of the CM and DM equivalent filters. The CM noise propagating through the parasitic capacitances within the SMPS is eliminated by the CM equivalent filter while the DM equivalent filter suppresses the DM noise which propagates between the line and neutral wires [9], [2]. However, we should point out at the limitations on the maximum inductance of series inductor to prevent the excessive voltage drop and maximum capacitance

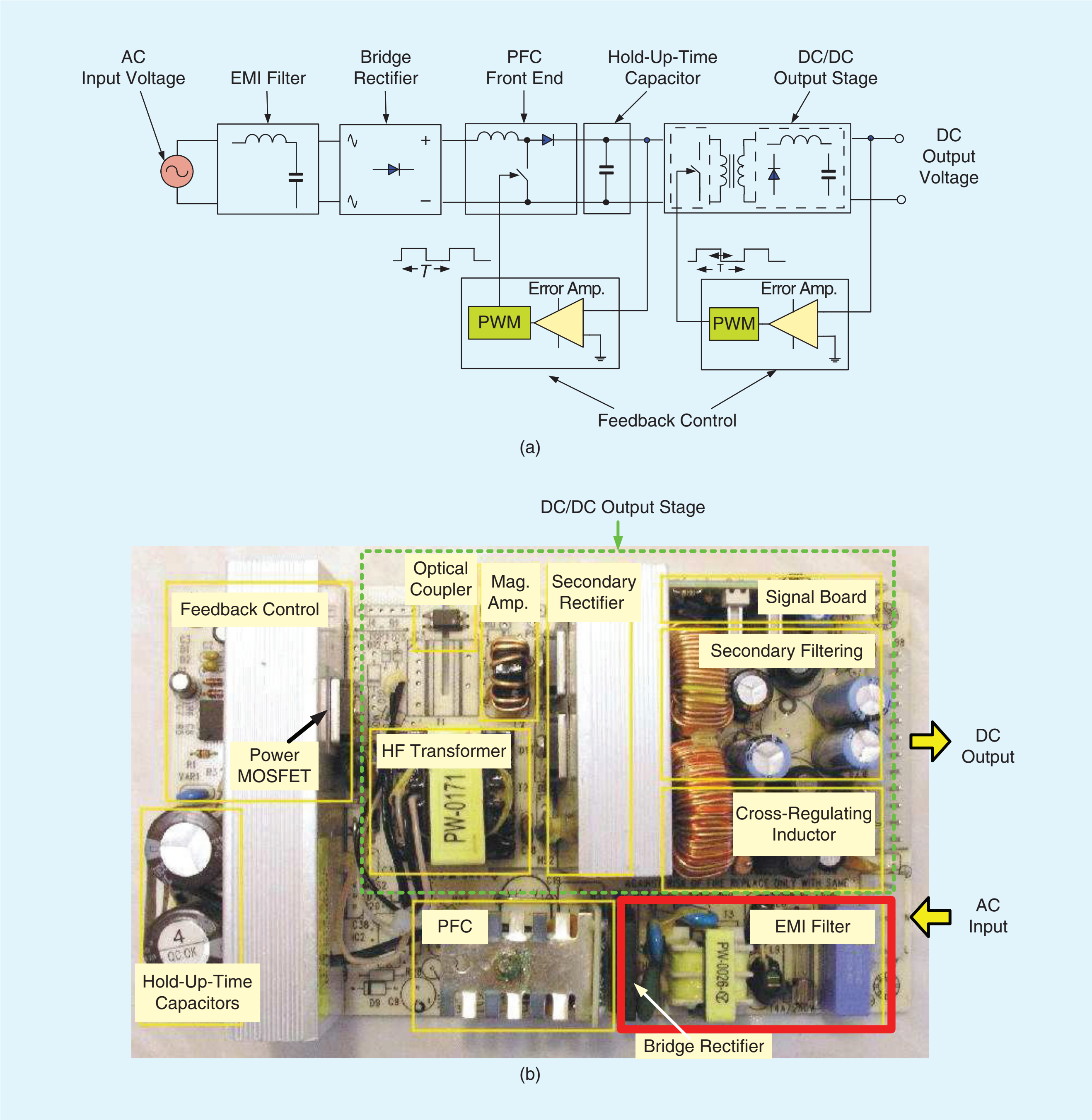

Fig. 11. Typical SMPS. (a) Block diagram of general SMPS; (b) SMPS prototype {http://www.convectron.com/smps/LambdaSMPS.htm}.

of parallel capacitor connected to ground for safety hazard consideration.

To meet the conducted EMI limitations, the passive EMI filter is still popular in SMPS design. However, one challenging task is to design the EMI filter effectively, optimally and systematically with a minimum guess. A few papers exist on a systematic design procedure of SMPS EMI filters [23]–[24]. The main difference between the two approaches is that in [23] the noise source and load impedances are taken into account in the EMI filter design procedure, but they are not considered in [24]. Without the noise source and load impedances in the design process, the EMI filter might lead to an over-design because the filter performance is strongly dependent on the connecting impedances [25]–[26]. Although reference [23] proposes a systematic EMI filter design procedure, the method to extract the noise source and load impedances is not accurate enough and some a-priori assumptions must be made. Without precise information of the noise source and load impedances, it makes designing EMI filter optimally a difficult task.

Conclusion

In this article, we present conducted EMI generation mechanisms and the need of EMI filters. In the second paper, we will present a method to extract the DM and CM impedances of noise source and termination load impedances under actual operating conditions by means of a direct clamping two-probe approach. Finally, in the third paper, a systematic design procedure for single-stage passive power line EMI filters to be used in SMPS applications by applying the insertion loss concept with the accurate amplitude and phase information of the SMPS and LISN impedances will be presented. The effectiveness of the proposed procedure will be validated and demonstrated by various practical design examples.

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Biography

***Vuttipon Tarateeraseth** received the B. Eng. (second-class honors) and M. Eng. degree both in electrical engineering from King's Mongkut Institute of Technology Ladkrabang (KMITL), Thailand, and Ph.D. in electronics and communications engineering from Politecnico di Torino, Italy. Since 2011, he is a lecturer at Department of Electrical Engineering, Srinakharinwirot University, Thailand. From 2010–2011, he was a lecturer at College of Data Storage Innovation, KMITL. Prior to 2007, he worked as a head of environment testing laboratory at Delta Electronics (Thailand) for three years. He also worked as an EMC engineer for 2 years under the Joint Development of Teaching Materials to Improve EMC Skills of Academic Staff and Postgraduate Electronic Designers Project funded by European Commission. He was a lecturer for 2 years at Department of Electrical Engineering, Srinakharinwirot University, Thailand. His research interests are mainly in the fields of EMI reduction techniques, EMC/EMI modeling, EMC instruments and measurements and EMI filter design. He is author or coauthor of more than 40 technical papers published in international journals and conference proceedings and one book chapter.*

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