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Prediction of the Conducted EMI from DC-DC Switched-Mode Power Converters

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***Abstract* – This paper presents theoretical estimation of the conducted electromagnetic emissions from a SMPS, based on Fourier analysis. The theory is applied to a buck converter. The comparison between the theoretically estimated and measured EMI shows that the CM EMI was well predicted. Up to 3 MHz the measured DM noise was much lower than the predicted one, which could be because of unknown DM noise source impedance. Further research is needed to find out whether a proper model of the noise source impedance can improve the accuracy of the DM noise prediction.**

I. INTRODUCTION

Switched-mode power supplies (SMPSs) are widely used for powering today's electronics loads. Unfortunately, they are often cited as one of the main sources of *electromagnetic interference* (EMI). Usually a SMPS cannot comply with the strict *electromagnetic compatibility* (EMC) regulations, which are in force nowadays. In order to meet the limits set for conducted EMI, a SMPS normally requires a power line filter at its input. Such filter can be quite bulky and can easily take most of the power converter space. The design of an input filter starts with the measurements of the common mode (CM) and differential mode (DM) noise coming from the source of EMI – the SMPS in this case. This means that the power converter must be physically build before its input filter can be designed. If the emissions from of a *switched-mode power converter* (SMPC) could be predicted before it is physically built, that would allow the EMI filter design to start early enough and the space reserved for the SMPS with its filter could be optimized.

The 2nd section of this paper presents theoretical discussion on the conducted emissions, which could be expected from a SMPC. In the 3rd section the EMI that could be expected based on the theory is compared with the measurements of the EMI from a buck converter prototype. The conclusions are summarized in the last section 4.

II. CONDUCTED EMISSIONS FROM DC-DC CONVERTERS

Conducted EMI from a SMPC can be narrowband and broadband. The latter is caused by diode recovery, reconducted radiated emissions and other, mostly parasitic phenomena, which are difficult, even impossible to predict theoretically. The way to minimize the broadband noise is to follow good design practices, i.e. proper layout, grounding, etc. If these are followed, the broadband emissions are unlikely to exceed the standard limits.

Because of the difficulty to deal with the broadband noise the attention in the following discussion is on the narrowband conducted EMI, caused by the switching actions in the converter. Also, it is normally the narrowband noise, which is larger and exceeds the limits.

A. Conducted EMI Measurements

In accordance with the regulations, conducted EMI is measured using *line impedance stabilization network* (LISN), as shown in Fig. 1. The DM current flows through two 50 Ω resistors in series, i.e. 100 Ω in total. These resistors appear in parallel for the CM current, resulting in 25 Ω load. This is true only if the impedances on the return paths of the CM current components, i.e. from line and neutral to the CM EMI source, are equal. It is an open question to what extent such symmetry is justified, but this is the usual assumption in the literature because very seldom the assumption for symmetry is mentioned.

The *equipment under test* (EUT) fulfils the EMC specifications if the EMI measured at the line and neutral is under the limit set in the standard. The conducted emissions limits used in this paper are those set in the European standard EN50081, which consider the frequency range from 150 kHz up to 30 MHz.

The measured line and neutral noise levels are in fact the voltage drop over the corresponding 50 Ω resistor, measured in dBμV. This voltage drop is partly caused by the

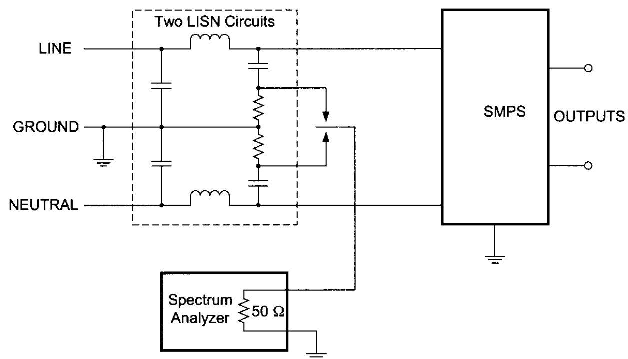

Fig. 1. Measuring conducted EMI from a dc-dc SMPS.

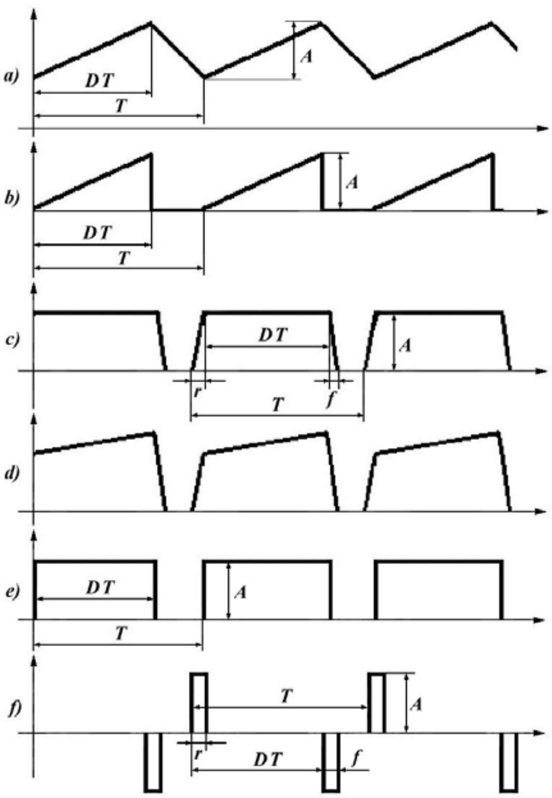

Fig. 2. Some waveforms.

DM current and partly by the half of the CM current, assuming the above-mentioned symmetry. The vector sum of the CM and DM currents multiplied by the resistance, expressed in dBμV, should give the noise level.

The broadband current components have stochastic nature and their phases cannot be known – one more reason to exclude the broadband noise from the analysis.

The narrowband DM and CM noise although different in nature, is caused by the same switching actions, taking place in the SMPC. This may suggest that when the phases of the CM and DM current harmonics are known, the total currents in line and neutral, as well as the EMI can be calculated. Unfortunately, this is not true, because the phase of the CM harmonics depends from different factors than the DM current harmonics. This should not disappoint too much because for the design of power line filter, it is the CM and DM EMI components, which are needed, not the total EMI [1]. The reason is that EMI filter components target either the CM or the DM noise.

B. DM current estimation

The switch in a SMPC chops the line current, which is the reason for the DM noise current. Depending on SMPC's topology, its input current can be approximated with either a triangular wave, as in Fig. 2a), or as the waveform shown in Fig. 2d). Converter topologies with inductor at their input, like boost and Ćuk converter, have triangular input current waveform. The waveform in Fig. 2d) is typical for dc-dc converter where the switch is directly in series with the input power line, e.g. the buck converter.

The Fourier series of the waveforms in Fig. 2 a), b), c), e), and f) are given by equations (1), (2), (3), (4), and (5) respectively:

$$I_n = \frac{A}{n^2\pi^2 D(1-D)}\sin(n\pi D) \tag{1}$$

$$I_n = \frac{AD\sqrt{2}}{(2n\pi D)^2}\sqrt{\begin{aligned}&2[1-\cos(2n\pi D)]+\\&\quad+2n\pi D[2n\pi D-2\sin(2n\pi D)]\end{aligned}} \tag{2}$$

$$\begin{aligned}I_n = A\sqrt{2}\left(D+\frac{r+f}{2}\right)&\frac{\sin(n\pi r)}{n\pi r}\\&\frac{\sin[n\pi(D+r)]}{n\pi(D+r)}\frac{\sin[n\pi(f-r)]}{n\pi(f-r)}\end{aligned} \tag{3}$$

$$I_n = \frac{\sqrt{2}\cdot A}{n\cdot\pi}\cdot\left|\sin(n\cdot\pi\cdot D)\right| \tag{4}$$

$$I_n = \frac{A\sqrt{\begin{aligned}&\{\sin(nr)-\sin[n(2\pi D+f)]+\sin(2n\pi D)\}^2+\\&+\{\cos[n(2\pi D+f)]-\cos(2n\pi D)-\cos(nr)+1\}^2\end{aligned}}}{\sqrt{2}n\pi}$$

$$\text{with } r=f\text{, it simplifies to:} \tag{5}$$

$$I_n = \frac{\sqrt{2}\cdot A}{n\pi}\sqrt{[1-\cos(2n\pi D)][1-\cos(nr)]}$$

In equations (1)-(4) A is the amplitude of the respective waveform, D is the duty ratio, r is the rise time, and f is the fall time. In (5) and waveform f), D is the displacement between the positive and negative pulses, because of the relationship between waveforms c) and f), which will become clear later in the discussion of the generation of the CM current. The dc-component is not included in equations (1)-(5) because it does not play any role in the conducted noise currents under consideration.

Clearly, no matter which waveform represents converter's input current waveform, it always consists of harmonics, which are multiples of the frequency of repetition of the waveform, i.e. multiples of the fundamental frequency, which in a SMPC is the switching frequency. At a given switching frequency, the peak-to-peak amplitude has the most significant impact on the harmonic values, at least at the lower side of the harmonics spectrum. Therefore, for a given average current, the buck type topologies are the worst case.

The buck converter input current waveform could be approximated to the one in Fig. 2d), which can be viewed as a sum of waveforms b) and c). However, in practice the rise and fall times, as well as the change of the plateau are insignificant. Therefore, the square waveform, shown in Fig. 2e) with Fourier series (4), can serve as a basis for estimation of the DM current harmonics, which are the reason for the narrowband DM EMI.

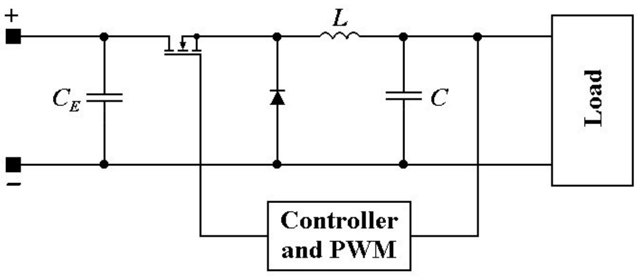

Fig. 3. Buck converter used in the measurements:
$f_s = 250$ kHz, $U_{in} = 35 \div 70$ V, $U_o = 12$ A, $I_{o,max} = 4$ A, $L = 190\ \mu H$,
$C = 100\ \mu F$, $C_E = 220\ \mu F$.

According (4), the DM current harmonics depend on the duty ratio (max is at $D = 50$ %), but for a given D, the amplitude A is proportional to the average input current. Therefore, the DM current harmonics are largest when the average input current is largest, i.e. when the SMPC supplies maximum load from minimum input voltage.

C. CM current Estimation

If the broadband CM noise is ignored, as in the discussion of the DM current, the CM current is the result of fast switching voltages in the SMPC across the parasitic capacitance to ground:

$$i_{CM} = C_{par} \frac{du}{dt} \tag{6}$$

From (6) one can conclude that minimizing C_{par}, or du/dt are the ways to minimize the CM noise. Reducing du/dt is not a good solution, because it increases the switching losses. Furthermore, too large switching delays, can compromise the stability of the SMPC. Therefore, it is best to minimize the C_{par} [2], by using proper layout and grounding.
If the voltage over the switch is approximated as the waveform in Fig. 2c), then from (6) the CM current waveform is

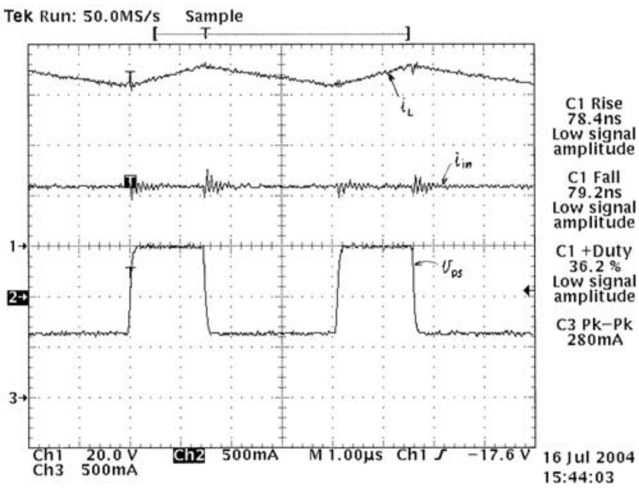

Fig. 4. Measured waveforms: Ch1 is the voltage over the switch, u_{DS}; Ch2 is the input current, i_{in}; and Ch3 is the inductor current, i_L.
The right hand side column shows a snapshot of the measured rise time, fall time and duty cycle of the switch voltage, as well as the peak-to-peak value of the inductor current.

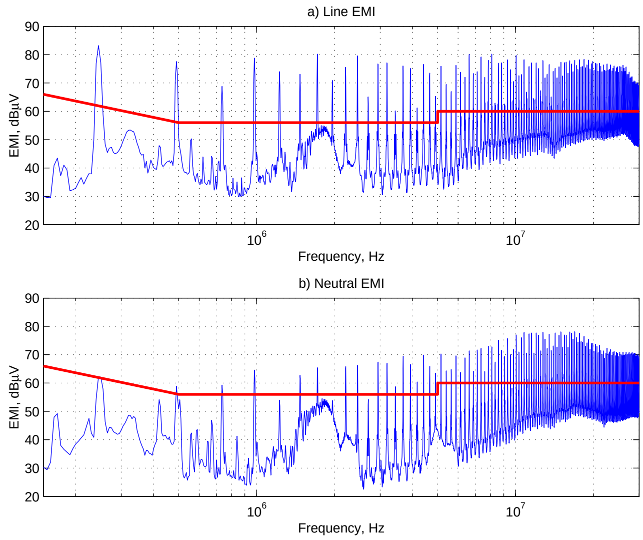

Fig. 5. EMI from the buck converter.

a square waveform like the one in Fig. 2f) with Fourier series (5).
It is worth nothing that unlike DM, the CM noise is strongest when the input voltage is largest. Assuming that the load does not affect switch turn on and off times, i.e. rise and fall time intervals do not change when the load is changing, the maximum du/dt is reached when U_{in} is largest.

III. MEASUREMENTS AND COMPARISON

A. The Buck Converter Prototype

One of the points mentioned in the previous section was that buck type dc-dc converters could be expected to be the worst EMI sources. To test the theory, we have built a buck converter with main characteristics shown in Fig. 3. Unfortunately, the converter needed a large electrolytic input capacitor C_E, which was coupled with a good ceramic one. Due to C_E and the LISN, the measured input current (Fig. 4) is quite smooth. It would have been very good, if a place for a current probe to measure the switch current were reserved, as it was done for the inductor current, shown in the same Figure. The third waveform in Fig. 4 is the voltage over the switch.

B. Measured EMI from the Buck Converter

The EMI from the buck converter was measured according the set up in Fig. 1 using EMI test receiver ESCS 30 and the 50 µH / 50 Ω LISN ESH3-Z5. The line and neutral noise levels are shown in Fig. 5.

C. Measured CM and DM EMI

Conducted noise measurements in Fig. 5 are the net result from the CM and DM noise currents on the LISN's precision resistors. Separating the two EMI components is not easy and there are number of publications dedicated to the topic. The process requires additional equipment. With

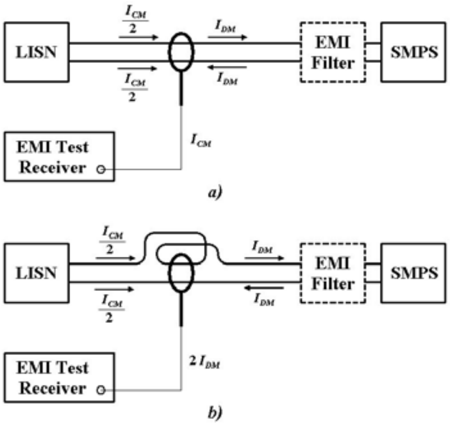

Fig. 6. Measuring CM and DM conducted EMI from a dc-dc SMPS using current probe.

differential mode rejection network (DMRN) [3] the DM noise is rejected and only the CM EMI is measured. By summing and/or subtracting simultaneously the signals from the LISN's resistors at line and neutral, both the CM and DM components of the EMI can be obtained. This can be done using transformers [4], power combiners/splitters [5], or operational amplifiers [6].

It can also be done using current probe. In this work current probe EZ-17 was used. The concept is shown in Fig. 6. Note that it is current in dBμA, which is measured, not voltage. Therefore, the measured data need to be converted to voltage, in dBμV. To obtain the CM EMI:

$$EMI_{cm} = 20 \cdot \lg(I_{cm} \cdot 25) = 20 \cdot \lg I_{cm} + 20 \cdot \lg 25 \qquad (7)$$

Similarly for the DM EMI:

$$EMI_{dm} = 20 \cdot \lg\left(\frac{2 \cdot I_{dm}}{2} \cdot 100\right)$$
$$EMI_{dm} = 20 \cdot \lg(2 \cdot I_{dm}) + 20 \cdot \lg 50 \qquad (8)$$

From (7) and (8), it follows that the conversion from current to voltage involves just adding an appropriate constant. The theoretically calculated CM current harmonics also must be converted to voltage. If the parasitic impedance to ground is assumed to be only the parasitic capacitance to ground C_{par}, then the predicted CM current harmonics can be converted to voltage by using (7). This is not the case with the theoretical DM current, because of the input electrolytic capacitor.

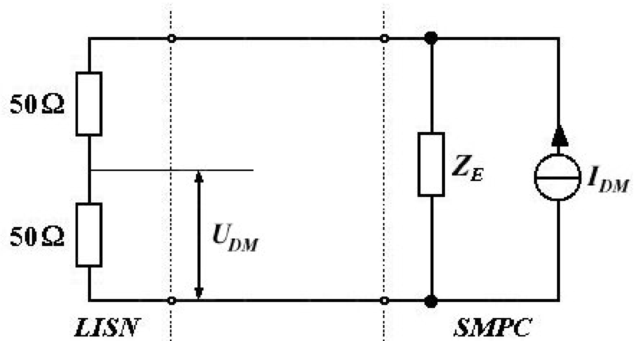

Fig. 7. The DM harmonic current source is terminated with the input capacitor's impedance in parallel with the LISN's resistors.

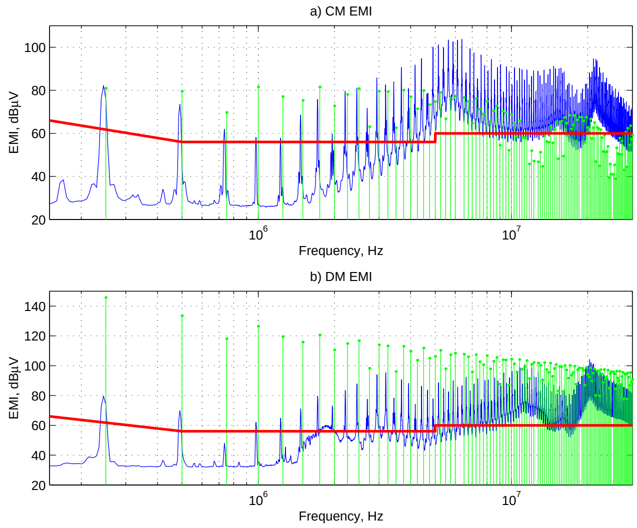

Fig. 8. Measured and predicted CM and DM EMI.

Using Fig. 7 the voltage over the LISN's resistor is:

$$EMI_{dm} = 20 \cdot \lg\left(\frac{50 \cdot Z_E}{2 \cdot 50 + Z_E} \cdot I_{dm}\right) \qquad (9)$$

Buck converter's input capacitor consists of 220 μF electrolytic capacitor, coupled with a good ceramic capacitor. Then impedance Z_E is assumed to be the equivalent circuit of a capacitor [2]. In the prediction calculations shown later, the *equivalent series resistance* (ESR) is 1 mΩ and resonant frequency 10 MHz, which would mean parasitic inductance of 1.15 pH.

The theoretically calculated CM and DM noise are plotted in Fig. 8a) and b) together with the corresponding measured noise components.

D. Predicted and Measured CM Comparison

The theoretical CM EMI can be calculated from (6), (5), and (7). The *du/dt* is calculated from 35 V voltage over the

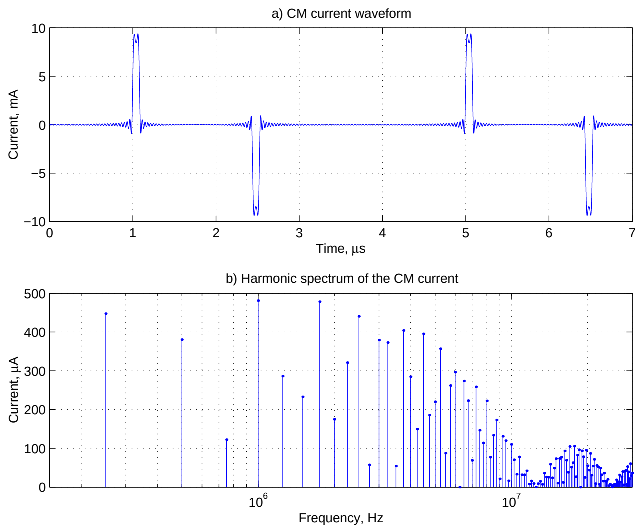

Fig. 9. CM current: a) waveform b) spectrum. The harmonic components are calculated using (5) where $r = f = 80$ ns, A = 8.75 mA, and $D = 0.36$

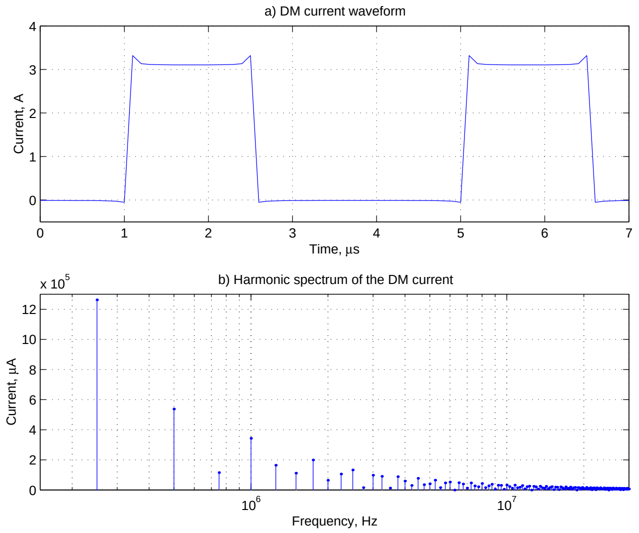

Fig. 10. DM current: a) waveform b) spectrum.
The harmonic components are calculated using (4) where
A = 3.1 A, and $D = 0.36$

switch, assuming equal rise and fall times $t_r = t_f = 80$ ns, and $C_{par} = 20$ pF. This gives amplitude $A = 8.75$ mA for the CM current waveform, which is potted in Fig. 9a). The harmonic components of this CM current are plotted in Fig. 9b). These harmonic currents, in μA, are inserted in (7) to obtain the predicted CM EMI, shown in Fig. 8a).

Overall the predicted CM EMI and the measured one are close to each other. The differences at some frequencies reach about 20 dB, but that is not a surprise, after the assumptions and simplification made.

E. Predicted and Measured DM EMI Comparison

The DM current harmonics, plotted in Fig. 10b), are calculated using (4) with the data for worst operating regime, i.e. duty ratio $D = 36$ % and current amplitude equal to the load current $A = 3.1$ A. The predicted DM current waveform, plotted in Fig. 10a), is obtained by summing all the harmonic components up to 30 MHz.

After the DM current harmonics are found, the DM EMI is calculated from (9) and plotted in Fig. 8b) together with the measured DM EMI. Up to 3 MHz the predicted DM EMI was surprisingly higher than the measured one. One reason can be the simplified model of the input capacitor. In fact two capacitors in parallel should be considered, instead of one. Another reason could be the assumption for the DM noise source to be an ideal current source. In practice there is some source impedance, which reduces the measured EMI in practice.

IV. CONCLUSIONS

Fourier analysis was used to try and predict the EMI from a buck converter. The predicted EMI was compared with that measured from a real buck converter. The results show good match between the predicted and measured CM noise, whereas the predicted DM EMI was much higher than the measured one in the lower frequency band up to 3 MHz. A proper model of the DM noise source impedance might provide more accurate prediction of the DM noise level.

The noise level from a SMPS is very sensitive to changes in layout and parasitic components, which can easily make any prediction effort useless. Detailed studies on the noise levels from particular converter topologies and comparisons with some theoretical prediction models might prove worthwhile.

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