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Detailed analysis of common mode and differential mode conducted emission generation in switch mode power supplies

Abstract. In this paper the basic mechanisms behind conducted emission generation in switch mode power supplies are analyzed. For the analyses a buck converter circuit is used. Separate equivalent models are introduced for differential mode and for common mode noise and the main parameters influencing the emission levels for both modes are identified. A detailed evaluation is performed to show which part of the emission spectrum is affected by a given parameter. Simulation in Matlab is performed to visualize the effect of these parameters on the spectrum. The results of theoretical analysis and simulation are verified experimentally through bench measurements performed on a buck converter.

Streszczenie. W artykule przeanalizowano podstawowe mechanizmy powstawania emisji przewodzonej w przetwornicach impulsowych. Do analiz użyty został układ przetwornicy obniżającej napięcie. Wprowadzone zostały osobne układy zastępcze dla składowej różnicowej i składowej wspólnej, a następnie główne parametry wpływające na poziom emisji dla obydwu składowych zostały zidentyfikowane. Przeprowadzona została szczegółowa analiza pokazująca na którą część wyemitowanego widma wpływa dany parametr. W celu zobrazowania wpływu tych parametrów na widmo emisji układy przesymulowano w środowisku Matlab. Rezultaty analizy teoretycznej i symulacji zostały zweryfikowane poprzez pomiary eksperymentalne do których użyta została przetwornica obniżająca napięcie. (Szczegółowa analiza powstawania zakłóceń przewodzonych w przetwornicach impulsowych).

Keywords: electromagnetic compatibility, common mode, differential mode, conducted emission, switch mode power supply, buck converter
Słowa kluczowe: kompatybilność elektromagnetyczna, składowa wspólna zakłóceń, składowa różnicowa zakłóceń, emisja przewodzona, przetwornice impulsowe, przetwornica typu Buck

Introduction

Switching converters are inherent generators of electromagnetic emission because of high dV/dt of the switching waveform, high voltage amplitudes and large currents flowing through the circuit. Before a product is placed on the market it must be ensured that it complies with applicable EMC standards, which means that the emission must be limited below specified limits. During the design phase of the converter several trade-offs must be made including efficiency, thermal properties [1], size, cost etc., and all of them may have impact on the EMC performance. By understanding the main mechanisms causing emission in the switching converters proper decisions can be made at an early stage of the design. This helps to avoid additional costs of "patching" an incorrectly designed product, delays caused by lengthy debugging and major redesigns when it finally appears to be unavoidable.

Theory of switch mode converters is well described in literature [2], [3], [4], however, the problem of electromagnetic compatibility is out of the main focus in these positions. Some more guidance regarding electromagnetic compatibility concepts of switch mode converters is given in [5], [6].

Because of relatively low frequencies used in switching converters the radiated emission mostly stems from the cables attached to the converter and not directly from the PCB [7]. Therefore it is crucial to understand and counteract the conducted emission on the cables as in many cases it can solve both conducted and radiated emission problems.

Often, the importance of common mode reduction is emphasized, neglecting the differential mode. This is correct when considering radiated emission, as the common mode is the major contributor there. However, in conducted emission measurement using LISN method [8] no distinction is made between both propagation modes, so both of them are equally important. Common mode and differential mode noise sources have largely distinct characteristics and different measures should be applied when dealing with each of them. An attempt to solve a conducted emission problem without the knowledge about which mode creates the problem may appear to have little or no effect. A method to separate common mode and differential mode components in a real circuit with the use of a current probe is described in [5].

The problem of electromagnetic emission in power converters is widely discussed in literature for traditional hard switching converters [9], more recently for soft switching converters [10], [11], as well as for other types of power converters such as uninterruptible power supplies [12]. Several methods for reduction of electromagnetic interference are proposed, including passive methods: high frequency filter design [13], transformer optimization [14], balanced structures [15], [16], common mode cancellation [17] and active methods like special control algorithms [18]. However, a detailed analysis and identification of parameters influencing the emission together with simulation and experimental verification was not given. The aim of this paper is to identify the main parameters influencing conducted emission generation in common and differential mode and analyze how do they impact the measured spectrum. Equivalent simulation models for both propagation modes are implemented in Matlab. At the end experimental verification is performed to confirm the results obtained in simulation.

Parasitic components like wire inductance and common-mode choke interwinding capacitance are not included in the models. In real circuits these parameters may cause resonances and alter the measured characteristics of the circuit. However, the presence and character of such effects depends largely on a particular design whereas the basic mechanisms presented here will always be present. To keep the discussion general these effects are omitted.

The models presented in this paper are developed on the example of the buck converter. In other topologies the discussed effects may differ. For example in the buck converter the input capacitor is placed in series with the main switch (for AC) and in the boost converter in series with the inductor. The methods presented in this paper can be used for any topology after adjusting the appropriate parameters.

Differential Mode Emission

Differential mode is also called the normal mode of propagation. The flow of differential mode current is intended and is necessary for the circuit to operate. Path of differential current flow in a buck converter is illustrated in Fig. 1.
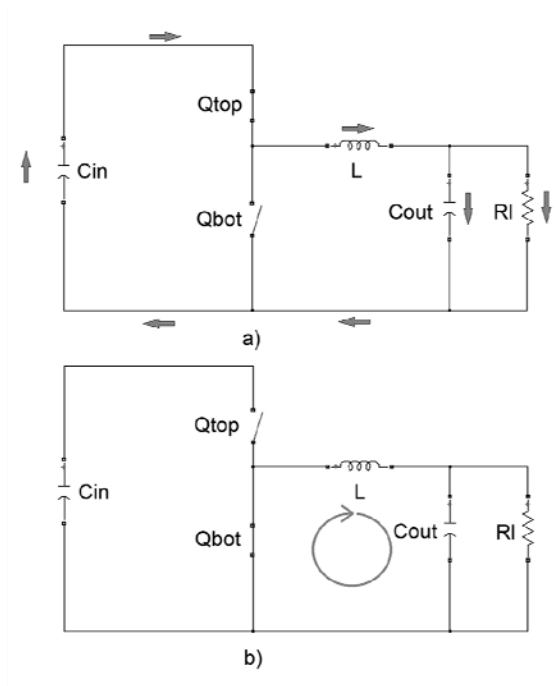

Fig.1. Differential current flow in a buck converter: during turn-on time of the main switch (a) and during turn-off time (b)

As shown in Fig. 1 the current flowing in the converter during the on-time of the top switch creates a voltage drop over the input capacitor. In the case when an additional input filter is not present and wire inductances are omitted the differential part of conducted emission measured by the LISN is in fact the voltage across the input capacitor. Basing on that an equivalent model is introduced, as shown in Fig. 2.
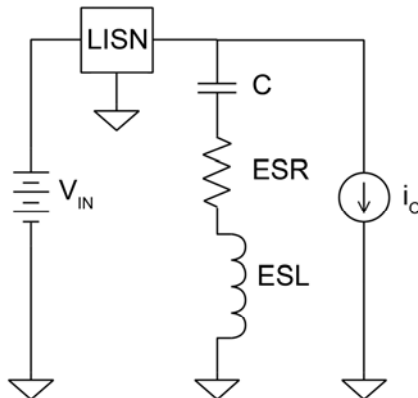
Fig.2. Equivalent model for differential mode emission

Differential emission generator is modeled as a capacitor connected in parallel with a current source. The current source simulates the current drawn by the buck circuit, so it is equal to the coil current during on-time of the main switch and zero during off-time.

$$(1) \qquad i_C = \begin{cases} i_L, 0 \leq t < \tau \\ 0, \tau \leq t < T \end{cases}$$

where: T – period, τ – conduction time of the top MOSFET and i_L is the coil current.
Slope of the coil current is given by:

$$(2) \qquad \alpha_{i_L} = \frac{V_{IN} - V_{OUT}}{L}$$

Turn-on and turn-off transition times of the switch are also included in the model. LISN is modeled as infinite impedance for AC and zero impedance for DC. In this way the whole AC current is drawn from the input capacitor and the DC current re-charging the input capacitor during off-time is drawn from the input voltage source. The impedance of the differential mode generator as seen by the LISN is low, therefore it can be said that the character of this generator is voltage source.

The input capacitor is modeled as a series connection of capacitance, ESL (equivalent series inductance) and ESR (equivalent series resistance). Contribution of each of these three components on the voltage across input capacitor are given by the formulas:

$$(3) \qquad v_C = C \cdot \int_0^T i \cdot dt$$

$$(4) \qquad v_{ESL} = ESL \cdot \frac{di}{dt}$$

$$(5) \qquad v_{ESR} = ESR \cdot i$$

The total voltage across the input capacitor:

$$(6) \qquad v_{Ctotal} = v_C + v_{ESL} + v_{ESR}$$

Exemplary waveforms are presented in Fig. 3 to illustrate how each of these components influence the total voltage.
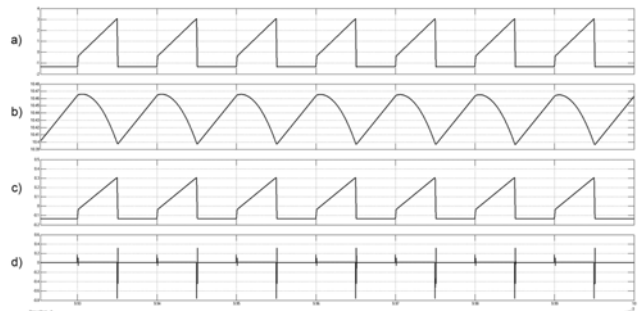

Fig.3. Input capacitor waveforms: a) capacitor current, b) voltage across capacitive reactance, c) ESR voltage, d) ESL voltage

The main parameters influencing the shape of the voltage and thus the measured emission spectrum can now be identified:

• Capacitance. Typically the value of the input capacitance is large (>1μF) so the capacitive reactance quickly decreases with frequency becoming negligible in the low megahertz range. Therefore this parameter influences only the lower part of the measured spectrum, where it is significant relatively to ESR.

• Equivalent series resistance. The value of ESR varies a lot depending on capacitor type: from single miliohms for ceramic capacitors up to ohms for electrolytic capacitors. ESR will influence the middle range of the spectrum – where it becomes comparable with the capacitive reactance but where ESL is still not significant.

• Equivalent series inductance. Voltage across this component reflects only rapid current changes which occur during turn-on and turn-off of the main switch. Typically the value of the series inductance is in the range from single

nanohenries to hundreds of nanohenries. This parameter influences the spectrum at higher frequencies where it starts to dominate ESR.

• Load current. The AC part of the load current flows through the input capacitor, so by changing the load the voltage across capacitor is directly changed. Changes in the load current influences the complete spectrum equally.

• Edge steepness of the main switch. The steeper the edges the more the high frequency content is contained in the measured voltage. Therefore this parameter changes the higher part of the spectrum.

• Input voltage, output voltage, inductance of the output filter – these three parameters will determine the inductor current ripple amplitude. The lower this amplitude is the flatter the inductor current becomes until it starts resembling a square waveform. Therefore if the output filter inductance is increased or the difference between input and output voltage is decreased then the even harmonics in the spectrum will be reduced (like in a square wave), without much influence on odd harmonics.
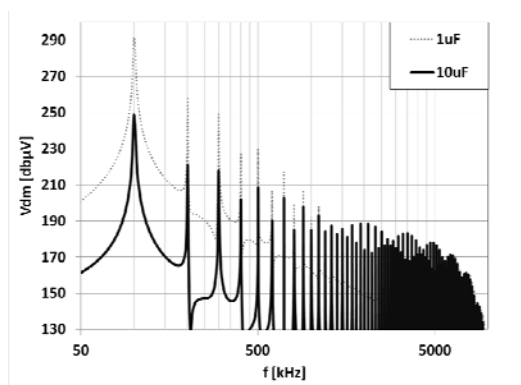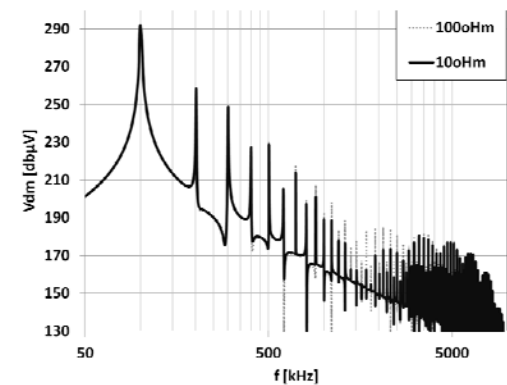
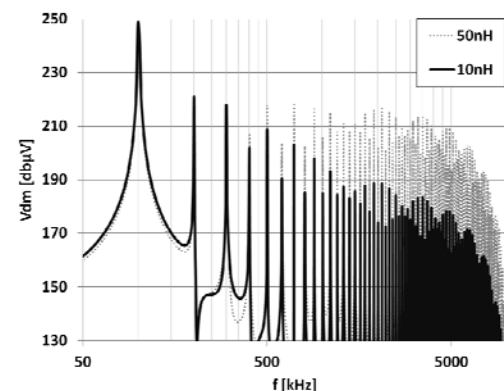Fig.4. Variation of capacitance

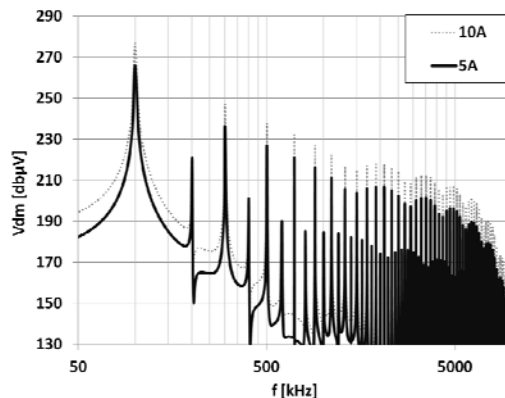Fig.5. Variation of ESR

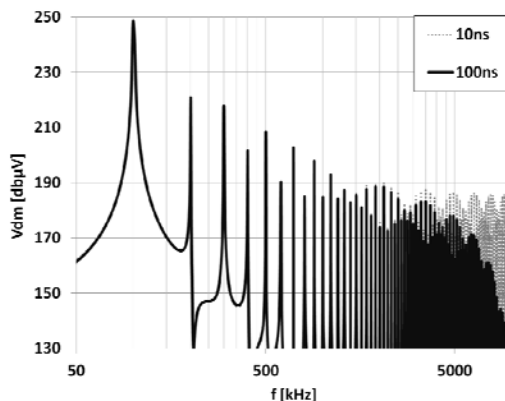Fig.6. Variation of ESL

Fig.7. Variation of load current

Fig.8. Variation of edge steepness

An important parameter is also the switching frequency which will shift the complete spectrum either way.

The parameters listed above are now simulated to visualize their influence on the differential mode emission spectrum. Parameters of the simulated circuit, except for the parameter being under investigation, are following:
f=100kHz, V_{IN}=12V, V_{OUT}=5V, t_r=100ns, t_f=100ns, DC=50%, I_{OUT}=1A, L=10uH, C_{IN}=100uF, ESR=100mOhm, ESL=10nH
Simulation results are presented in Fig. 4 to 8.

Common Mode Emission

Common mode current flow is unintended, it is not needed for the circuit to operate and it is always the result of parasitic components present in the circuit. To derive a model for common mode noise propagation a method similar to presented in [19] is used, but adjusted to buck converter. At first parasitic capacitances from each node of the circuit to earth are drawn: C_1, C_2, C_3, C_{SW}, as shown in Fig. 9.
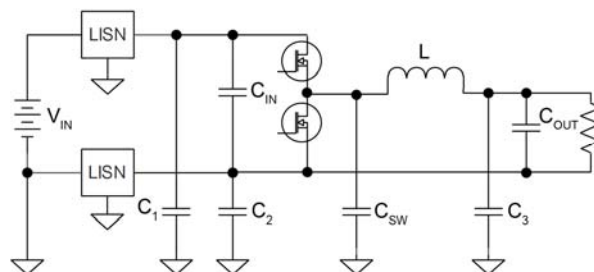
Fig.9. Parasitic capacitances to earth in a buck converter

Then it can be noted that the voltages across capacitances C_1, C_2 and C_3 are constant or nearly constant, whereas the voltage amplitude across C_{SW} is large. Also, large PCB area is often used for the switching node in order

to absorb heat generated in the bottom switch, so Csw is also large relative to capacitances of other nodes. Additional structures (e.g. heatsinks) attached to the switching node will further increase C_{SW} and contribute to emission generation. Effect of heatsinks on electromagnetic emission is investigated in [20]. Therefore, C_{SW} is the main contributor to the common mode current generation in a buck converter and other parasitic capacitances will be omitted in the analysis.

C_{IN} is replaced with a short for common mode. For common mode both LISNs are effectively connected in parallel. Switching node is replaced with a trapezoidal waveform generator which is then connected in series with the capacitance C_{SW} to earth.

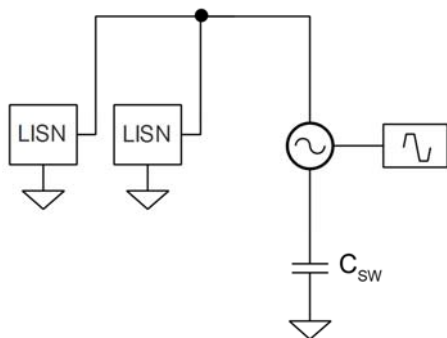Basing on the above an equivalent model can be derived, as shown in Fig. 10.

Fig.10. Equivalent model for common mode emission

Current flowing through capacitance C_{SW} is:

$$i_C = C_{SW} \cdot \frac{dv}{dt}$$
(7)

Because the value of C_{SW} is low the internal impedance of the common mode generator is high. Taking an exemplary C_{SW} value of 50pF the impedance at 100kHz can be calculated as about 30kOhm, which is high relative to other impedances in the circuit. Therefore it can be said that the character of the common mode source is current source.

To illustrate how the common mode current is generated an exemplary waveform is presented in Fig. 11.
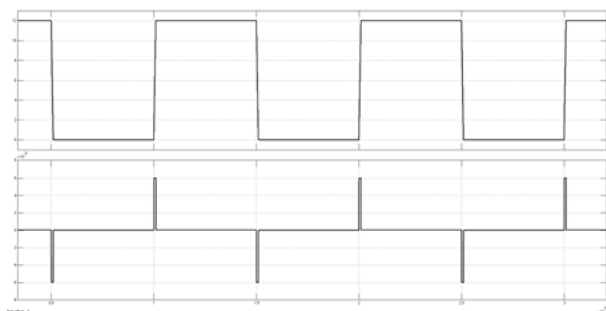

Fig.11. Common mode current generation: switch node voltage (top), C_{SW} current (bottom)

The main parameters influencing the common mode current generation can now be identified:
- Capacitance C_{SW}. According to formula the larger the parasitic capacitance between the switch node and earth the higher current will be generated. The complete spectrum is equally influenced.
- Edge steepness. According to formula the steeper the edges the higher current will be generated.

- Input voltage. The input voltage sets the amplitude of the trapezoidal waveform at the switching node. Assuming constant rise and fall times the input voltage determines the dv/dt. The higher the input voltage the larger common mode current will be generated.

Similarly as in differential mode a change in the switching frequency will shift the complete spectrum.

It is interesting to note that the load of the converter does not influence the common mode emission.

The parameters listed above are now simulated to analyze their influence on the common mode spectrum. Parameters of the simulated circuit, except for the parameter being under investigation, are following: f=100kHz, V_{IN}=12V, t_r=100ns, t_f=100ns, DC=50%, C_{SW} =50pF

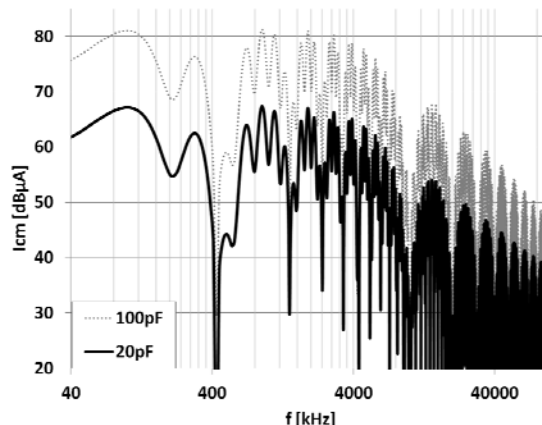Simulation results are presented in Fig. 12 to 14.

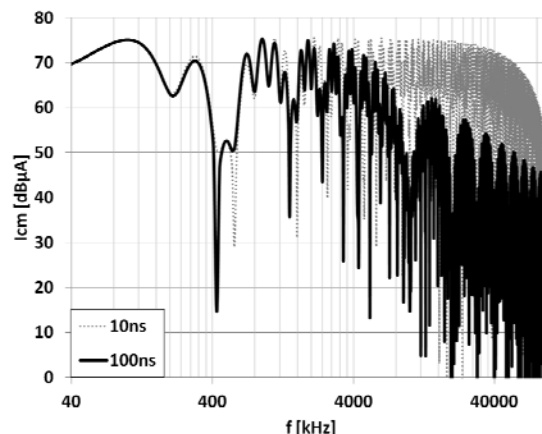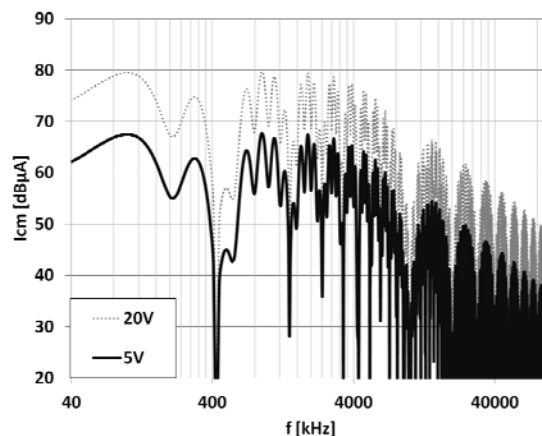Fig.12. Common mode, influence of switch node capacitance

Fig.13. Common mode, influence of rise time and fall time

Fig 14. Common mode, influence of input voltage

Experimental Verification

Experimental verification is performed in order to confirm the simulation results. For the measurements a synchronous buck dc-dc converter with MOSFET switches is used. Input voltage is 5V and output voltage is 2.5V. Switching frequency is 300kHz. Input capacitor is ceramic type X7R 10µF in 0805 package. The storage inductor is 3.3µH.

Regarding differential mode the influence of input capacitance, ESR, ESL, and load was measured. ESR was varied by adding a 10mΩ 0805 resistor and ESL was varied by adding a 1nH 0402 inductor in series with the input capacitor. Regarding common mode the influence of the switch node capacitance and input voltage was measured. The switch node capacitance was varied by connecting a copper plate of dimensions 3x3cm to the switch node. Together with changing the input voltage also the output voltage is changed in order to keep duty cycle constant. Additionally a measurement with varying load current is performed to confirm that common mode emission is not load dependent. Also, a measurement of common mode current vs. switch node voltage in time domain is shown.
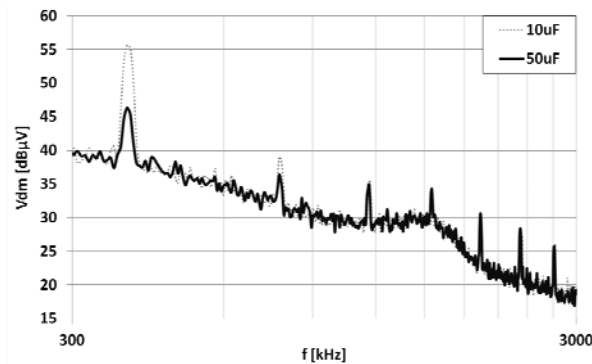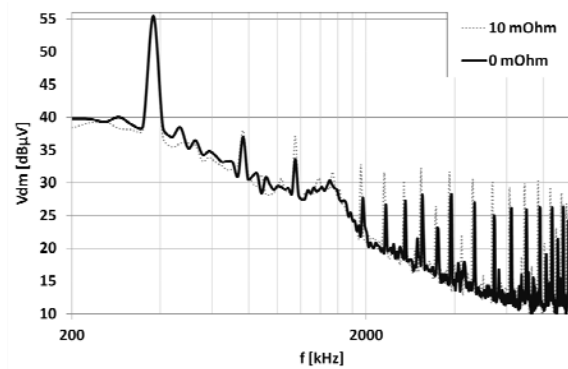

Fig.15. Differential mode, influence of capacitance
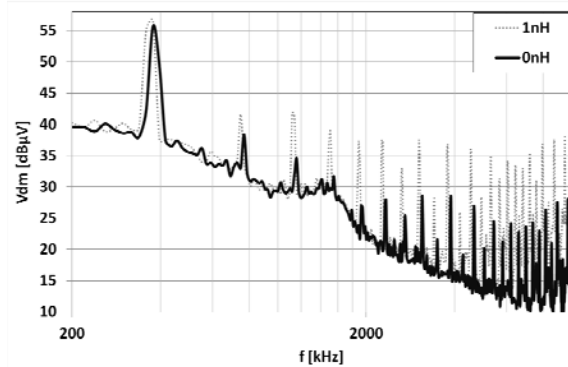

Fig.16. Differential mode, influence of ESR
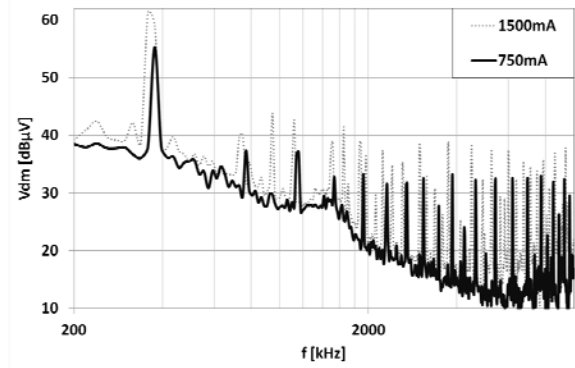

Fig.17. Differential mode, influence of ESL
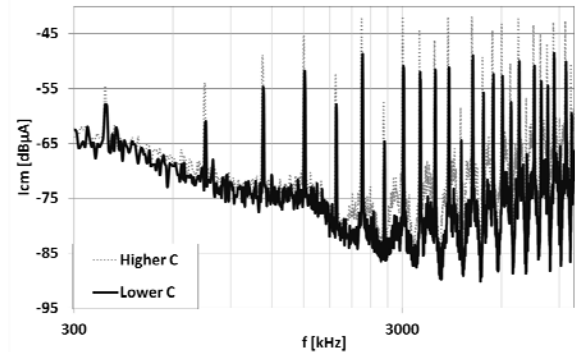

Fig.18. Differential mode, influence of load

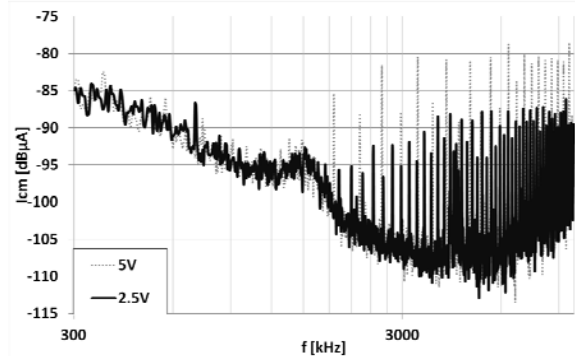Fig.19. Common mode, influence of switch node capacitance

Fig.20. Common mode, influence of input voltage
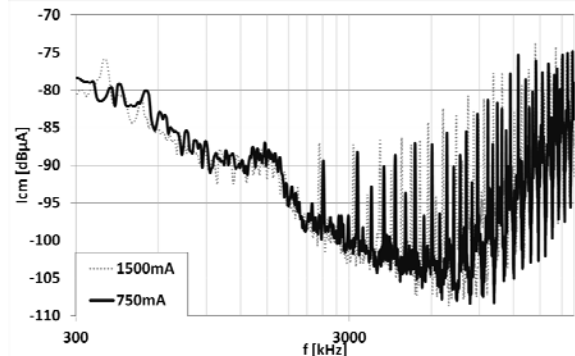
Fig.21. Common mode, influence of load current

Fig. 15 shows the influence of input capacitance. By changing its value from 10µF to 50µF only the first two harmonics are reduced and the remaining ones are not influenced. After increasing ESR (Fig. 16) the first two harmonics are not influenced, the middle part of the spectrum is increased and around 10MHz the amplitude of the harmonics approaches the ones with no additional ESR. After increasing ESL (Fig. 17) the first harmonic is not

influenced but higher harmonics are significantly increased. By increasing the output current all the harmonics are equally increased (Fig. 18).

Fig.22. Common mode current (top) and switch node voltage (bottom) in time domain

Regarding common mode current generation, after increasing the switch node capacitance (Fig. 19) or the input voltage (Fig. 20) all measured harmonics are equally increased. Fig. 21 shows the impact of load current. Although the amplitude of the current is increased two times the measured amplitudes of harmonics remain comparable, what confirms that the common mode current is essentially not dependent on the load current. Fig. 22 shows the switch node voltage and common mode current in time domain to verify simulation results shown in Fig. 11.

Conclusions
The main mechanisms behind common mode and differential mode conducted emission generation are discussed. The main parameters influencing the emission spectrum for each mode are identified and simulated with the use of Matlab models. Behavior of experimental circuit used for measurements match the results of simulation what confirms correctness of the models.
As shown, the character of the source and parameters influencing the emission levels are different for both propagation modes. With the knowledge of the basic mechanisms described here the proper measures can be applied when solving a problem in a real circuit.
This paper does not discuss secondary effects caused by other parasitic components, like e.g. cable inductance, common mode choke interwinding capacitance, PCB trace inductance, MOSFET capacitances (G-S, D-S, D-G), etc. In a real circuit these parameters may alter the measured emission spectrum or cause oscillations in some circuit parts resulting in additional emission in other parts of the spectrum. These effects depend on things such as component choice, enclosure construction and PCB layout and have to be identified and analyzed for a particular design.

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