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An Examination of Parasitic Processes in DC/DC Power Converters

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Introduction

Direct current (DC) power supply of today's electronics (especially that of portable and handheld products) to a large extent is connected with DC/DC converters or switch mode power supply (SMPS) units. Such a shift in the supply from traditional linear ones (having low efficiency η – typically less than 50% and the considerable troubles with their weight, size, and remove of generated heat) is caused by clear operational advantages of SMPS: they are much more effective (now η can be greater than 90%), they exhibit high volumetric characteristics (thus, the boundary of $3000\,W/dm^3$ is already overcome). But the price of these and high rating values of the mentioned principal parameters is of less quality of SMPS energy, e.g., rather high ripples on the load, the emergence of more severe problems with electromagnetic interference (EMI) and the onset of lower electromagnetic compatibility (EMC) on the whole.

The problems related to EMI and EMC first of all arise from the fundamental essence of SMPS – from switch-mode power energy delivery which involves the conversion of DC by the use of controlled switching process into pulses of rather high frequency f_{sw} (typically $200\ldots500\,kHz$ for industrial units and above $1\,MHz$ for experimental ones). These power transmitting pulses are carrying on a reach harmonic content of f_{sw} which is extending up to several tens or even hundreds of *MHz*. The actions of these harmonics have become a serious concern in electronics. For the mitigation of these problems the switching process is modified: realized as resonant, or quasi-resonant [1], or with randomized switching frequency (in spread spectrum approach) [2]; in addition appropriate shielding and filtering needs to be applied [3].

The aim of the study – parasitic processes of magnetic origin

The mentioned general problems of SMPS still continue to be under intensive investigations [4]. But in addition to them there are more specific problems related to the non-idealities of real components used in SMPS units.

In this study particular interests are with inductive processes: manifestations of parasitic processes of power inductors and their interconnections. For practice such an aim is not too restricted since the inductors (chokes, transformers, a.o.) have a substantial role in SMPS: along with the power semiconductors and the control circuitry they form the three traditional pillars of power electronics [5]. Several typical parasitic actions in which the inductors are involved are rather well known (e.g., the ringing in buck and boost converters in the case of their discontinuous current mode operation: the involved inductance L of non-energized inductors and barrier layer capacitances of commutating (freewheeling) diode and switch may give oscillations [6]). On the contrary several other aspects especially ones with participation of self-capacitance (or self-resonance) of power inductors of SMPS units are less analyzed. But it is pertinent to note that these characteristics are not possible to eliminate fully by some specific design of inductor – greater or lower self-capacitance is always with all inductors: bulk, planar, integrated, etc. (some proposals for parasitic action compensation of filter inductors recently have appeared [7, 8, 9] but they are connected with the introduction of several additional passive elements that is not practical in power applications). In relation to such a situation J.D.Lenk [10] stated that "self-resonance should be between 5 to 10 times the switching frequency f_{sw} (but not an exact multiple of switching frequency!)". But what happens when it does not hold is not clear; moreover, the fulfillment of this cited condition principally is not possible with new SMPS units where converters with randomized switching frequency are used: in this case separate harmonics spectrum is transformed into continuous one [2]. Answers to these obscurities are searched in this study.

Experimental setup

For investigation of mentioned parasitic processes in SMPS the experimental setup was made which by interchange of components allows assembling of usual buck (Fig. 1) or boosting converter topologies. In the following experiments mainly the buck converter is used the control circuit of which was disconnected form output and was organized in the way in order to allow hand operated control of f_{sw} ($120\ldots500\ kHz$) as well as of duty ratio D. The intent of such a control first of all is the hope that it will allow to equate the frequency of a particular harmonic of f_{sw} with the self-resonant frequency f_0 of inductor L. In addition, all principal components of setups (except MOSFET switch IRF9520N and regulating pulse-width modulator SG2524) were replaceable: diodes – p-n-junction and Schottky; capacitors – electrolytic, film, ceramic; inductors – the characteristics of them are presented in the next section. Through the use of different resistive load values it was possible to go from continuous current mode to discontinuous one.

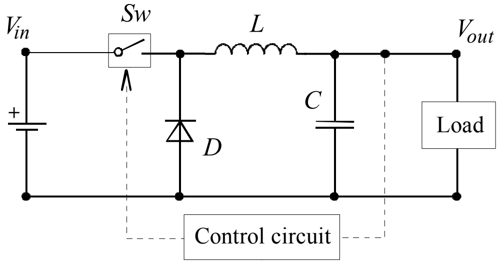

Fig. 1. Buck topology used in experiments

Power inductors

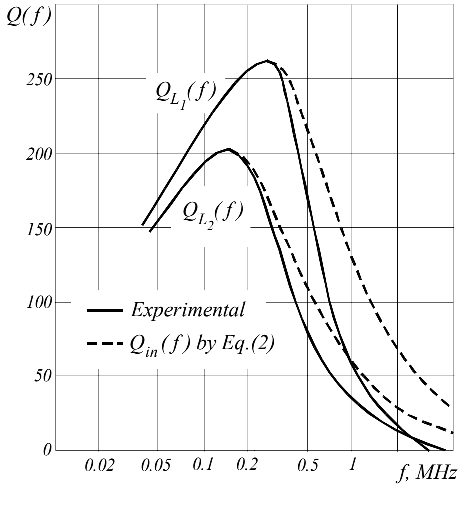

Fig. 2. Quality factor of inductors L_1 and L_2

Since the parasitic processes related to the power inductors are of primary interest in this study hence more detailed characteristics of two type inductors applied here are presented. In both inductors as a core material is used ferrite. One of the inductors (which characteristics from here on are with subscript 1, e.g., inductance L_1) is of gaped ($g_1 = 0.15\ mm$) standardized pot-core (Б30, ferrite *1500HM2*); the another (with subscript 2) is of gaped ($g_2 = 0.2\ mm$) E-core (E36/18/9, ferrite *2000HM*). Windings are of copper wire (diameter $0.7\ mm$), inductances $L_1 = 0.18\ mH$ and $L_2 = 0.17\ mH$; measured self-resonance frequencies: $f_{01} = 3.6\ MHz$ and $f_{02} = 4.6\ MHz$. In general, intensity of parasitic processes largely depends on the losses involved. To account for them in the case of named inductors in the frequency f region of interest the reciprocal characteristic – quality factor $Q(f)$ was measured (Fig.2). These curves show typical bell-shaped frequency dependence of $Q(f)$. Along with it $Q(f) = 0$ at f_0 but this in fact is the value between two terminals of the component (because meters, in this particular case – Q-meter, as a rule allow providing measurements in accordance to series equivalent circuit). In actuality it does not mean that the inner quality factor Q_{in} of LC_0-circuit (C_0 – self-capacitance) as a hole is so low. Estimation of this inner $Q_{in}(f)$ is possible by the use of relations obtained in [11] where two dominating types of the losses were accounted for, namely, loss in magnetic material (R_{core} in Fig. 3) and that in winding ($R_{wind.}$); such an account has resulted in the relation:

$$Q(f) = \left(4Q_{\max}^2 a\, f / f_u\right) / \left(1 + 4Q_{\max}^2 a^2 f^2 / f_u^2\right) , \qquad (1)$$

where $Q_{\max}$ is the maximum value of $Q(f)$ at frequency $f_{\max} = f_u / 2a\, Q_{\max}$; a shows the effectiveness of use of magnetic material: $a = \mu_e / \mu_{st}$ (with μ_e and μ_{st} as the effective and the static permeability correspondingly; f_u is the frequency of the maximum of imaginary part of complex permeability. Thus it is possible to equate $Q(f)$ from Eq.(1) with $Q_{in}(f)$; for convenience of calculations Eq.(1) is possible to simplify:

$$Q_{in}(f) = 2Q_{\max} / \left(f_{\max} / f + f / f_{\max}\right) . \qquad (2)$$

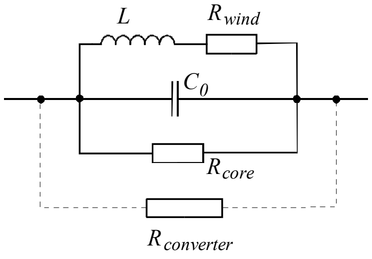

Fig. 3. Equivalent circuit of power inductor L and its situation in the converter

The calculated curves (Fig.2) show that $Q_{in}(f_0)$ actually is not zero: $Q_{in}(f_{01}) \approx 40$, $Q_{in}(f_{02}) \approx 15$. This means that from loss point of view of power inductor there is potential for parasitic inductive process to manifest itself, but the details will depend on actual value of C_0 as well as on averaged shunting resistance from the circuitry of converter $R_{converter}$ (Fig. 3).

The results and their discussion

To the first approximation experimentally recorded signals from aforementioned buck converter under test were typical. In addition to it no specific process related with power inductors were observed even by steady change of f_{sw} from 120 to $500\,kHz$ (thus quasi-simulating the spread spectrum approach). However more careful examination of inductors' current i_L reveals several specific details (Fig. 4): typical ripple current is accompanied by quickly rising spikes. In [12] without explanation it is simply mentioned that these spikes result from high energy rapidly switching power elements within switching regulator. The observation of the spikes with higher resolution shows that they in fact involve short duration ringing process in form of oscillations near $20\,MHz$ (Fig. 4, b). Moreover, such a ringing process was observed on the several other components of converter (e.g., on diode, even when the power inductor was removed from the converter).

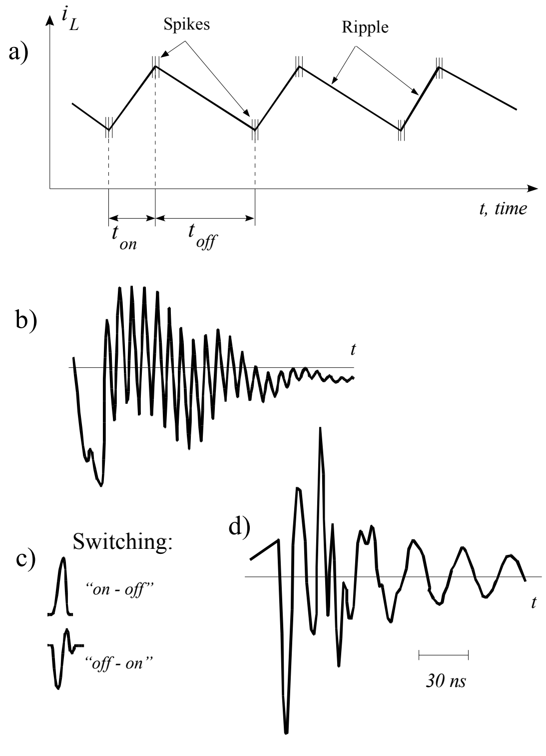

Fig. 4. Diagrams of: (a) typical current through power inductor with the spikes; (b) experimentally recorded structure of spikes; (c) spikes structure given by simplified PSPICE simulation; (d) spikes structure given by account of wires inductances in PSPICE simulation

In order to clear up the origin and give an interpretation of spikes the converter was simulated by PSPICE, first of all using the components of the converter as nominal ones (without any their non-idealities except the power inductor L which is used as in Fig.3). Simulation gives short duration spikes as well (Fig.4, c) the reason of which is the discharge of self–capacitance C_0 at the time moments when the voltage across power inductor is reversing its sign; the intensity of spikes weakly depend on Q–factor of inductor (it clearly shows on rather low averaged resistance of the converter's circuitry $R_{converter}$ parallel to power inductor, Fig. 3). Besides, the spikes more pronounced at the switching "on-off" (Fig. 4, c) (in the due correlation with the more energized state of the power inductor).

At the next step the converter was PSPICE simulated with the account of non-idealities of interconnections – their inductances (in the range of $50\ldots100\,nH$). This simulation (Fig. 4, d) gives ringing comparable with that of measurements (Fig. 4, b). Thus it is possible to say that the dominant reason of the spikes on i_L ripple are the inherent inductances of interconnections (especially the leads of components since printed circuit board wires were of considerable width and thus with low inductance). This statement is largely strengthened by the observations that the ringing is possible to attenuate considerably by the use of ferrite beads on the leads of components.

Conclusions

The experimental investigations and PSPICE simulations of the buck converter and the analysis of the results show that the typical parasitic processes observed have at least two components.

One, in the form of short spikes on the ripple of power inductor's current is generated by the power inductor and its self-capacitance and is in a weak correlation with the inductor's quality factor Q (most likely because of low value of overall averaged resistance of converter $R_{converter}$, Fig. 2, b). So the self-capacitance manifests itself in the low intensity spikes at the moments when the switching occurs and when the sign of voltage on inductor reverses; as such the spikes don't contribute considerably to EMI. In this case it is possible to conclude that at times strictly declared conditions in relation to interrelationships between the values of self-resonance and harmonics of power pulses in fact is not so strong.

The other component of the parasitic process is of the design origin: the ringing arises from capacitances of semiconductor devices (switch, diode) and parasitic inductances of the interconnections. This ringing process, as such, is possible to eliminate practically by the use of leadless components (e.g., surface mounted units) or by the use of appropriate ferrite beads on the leads of leaded components.

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Parasitic processes related to the magnetics of DC/DC converter – power inductors and interconnections (having inherent inductances) are studied by the use of buck converter. The study involves both experimental measurements and PSPICE simulation approaches. The results show that there is ringing having two components. The one, in the form of short duration spikes arises from discharge of self-capacitance of the power inductor. Another, in the form of high frequency ringing process arises from parasitic resonances set out mainly by capacitances of semiconductor devices and parasitic inherent inductances of the interconnections. Ill. 4, bibl. 13 (in English; summaries in English, Russian and Lithuanian).

Я. Янковский, Д. Степин. Исследование паразитных процессов в импульсных силовых преобразователях // Электроника и электротехника. – Каунас: Технология, 2006. – № 4(68). – С. 15–18.

Паразитные процессы, связанные с магнитными элементами преобразователя – силовым индуктором и межсоединительными элементами (обладающими индуктивностью), исследуются при использовании понижающего преобразователя. Исследование включает в себя как эксперименты, так и моделирование с использованием PSPICE. Полученные результаты показывают, что паразитный процесс наблюдается в виде высокочастотного звона, имеющего две компоненты. Одна – в виде короткого всплеска, возникающего в результате разряда собственной емкости силового индуктора, а другая – из-за паразитных колебаний, порождаемых емкостями полупроводниковых приборов и индуктивностями межсоединений. Ил. 4, библ. 13 (на английском языке; рефераты на английском, русском и литовском яз.).

J. Jankovskis, D. Stepins. Parazitinių procesų DC/DC galios keitikliuose tyrimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2006. – Nr. 4(68). – P. 15–18.

Parazitiniai procesai, susiję su nuolatinės srovės keitiklio magnetiniais elementais – galios induktoriais ir jungiamaisiais elementais (pasižyminčiais savuoju induktyvumu) tyrinėti naudojant žeminantį keitiklį. Tyrimas apima tiek eksperimentinius matavimus, tiek modeliavimą naudojant PSPICE. Rezultatai rodo, kad parazitinis procesas pasireiškia aukštadažniu triukšmu, kuris susideda iš dviejų komponenčių. Viena pasireiškia trumpo impulso forma, kurie atsiranda dėl galios induktoriaus savosios talpos. Kita pasireiškia dėl parazitinio rezonanso, kurį daugiausiai lemia puslaidininkių įtaisų talpos bei tarpusavio jungčių savieji induktyvumai. Il. 4, bibl. 13 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).