Transformer Harmonics Simulation and the Effect of Leakage Inductance on it

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Abstract--Nowadays, switching power supplies are used in almost all electronic devices to change the voltage amplitude into different levels of values. The only obstacle on using these devices is the production of high frequency harmonics that violates different standards such as (FCC, VDE, 461). In this paper the sources various noises in switching power supplies will be introduced and then, the method of high frequency simulation of switching converters will be considered and appropriate model of transformers to be implemented at high frequencies will be presented. Then the effect of leakage inductance on current and voltage waveforms of the input and output switches, which are the main cause of common mode differential mode noises and radiations, will be discussed and harmonically analyzed. Finally the experimental results will confirm the simulation conclusions.

I. INTRODUCTION

Today, due to the high efficiency, low weight, size and cost, switching power supplies have totally taken the place of linear power supplies and are used in almost every electronic device to convert the voltage amplitude to different levels of values. The basic principles of the operation of these switching devices is cutting dc voltage or current (and converting them into AC voltage) that unfortunately causes many harmonics to be produced. The only negative side of switching power supplies is that they act as a source of noise that, in case of not taking appropriate measures, will violate the standards of electromagnetic disturbances (FCE, VDE, 461). Usually, common mode and differential mode filters and shielding and grounding are designed and implemented to get over this obstacle [1, 2]. The best way to get rid of harmonic problems and electromagnetic disturbances in switching power supplies is to accurately identify the sources of noises and to cancel them out.

In these devices the current harmonics are clearly known and fall into two categories: common mode and differential mode. Noise or differential harmonics are in fact the Fourier series coefficients of the switch current, so it can be concluded that the sources of differential mode harmonics are the main switch current waveform at the input and that of the rectifying diode at output.

Furthermore, common mode noise radiations in switching power supplies contradict the standards and are produced because the Mosfet drain chassis (and also the anode of diode at the output) are connected to the heat sink via an electric insulation. The drain can be considered as a voltage source that is connected to the heat sink through a capacitance made up of Mosfet chassis, heat sink and electric insulations. The heat sink, in turn, acts as an antenna and causes the creation of radiations and common mode noises [3]. On the other hand, due to its electric and magnetic fields and intrinsic capacitance between its windings, transformer is among the sources of common mode noise in switching power supplies. Therefore the voltage across the main switch (and the output diode) is the origin of common mode noise and radiations and so it's of great significance to harmonically analyze it.

Basically the structure and topologies of switching power supplies are similar and their operation principle is to cut the voltage or current waveforms, so simulation of different topologies will differ slightly from one topology to another. The topologies fall into two groups: flyback and forward. In flyback topology, transformer bears the task of storing energy in each cycle, in addition to changing the voltage amplitude and insulating the two sides of power supply, so some measures should be taken, such as creating an air gap, to prevent it from saturation. However, in the forward topology, the transformer only carries out the voltage conversion and insulation. Anyway, the transformer used in these devices needs to be an ideal one. The parameters separating an ideal transformer from the actual one are leakage inductance, capacitance and winding resistance which are substantially dependent on the operating frequency. The winding resistance only causes the transformer losses to increase and doesn't have any role in harmonics production. But the leakage inductance and the capacitance between windings are the effective cause of noise in switching power supplies that will be addressed in this paper.

In order to study the effect of leakage inductance and intrinsic capacitance of transformer on the generated harmonics, a single-switch forward topology power supply has been considered here. Figure 1 shows the considered topology. The circuit's operation is elucidated in [4].

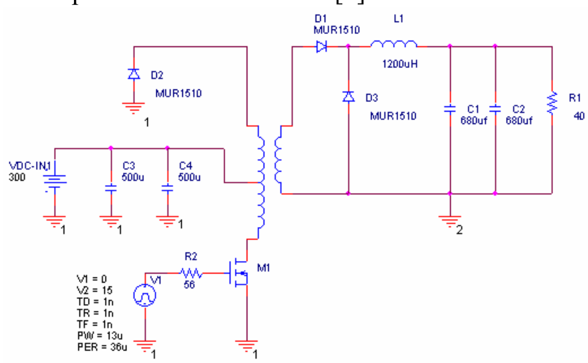

Fig. 1. Single switch forward topology

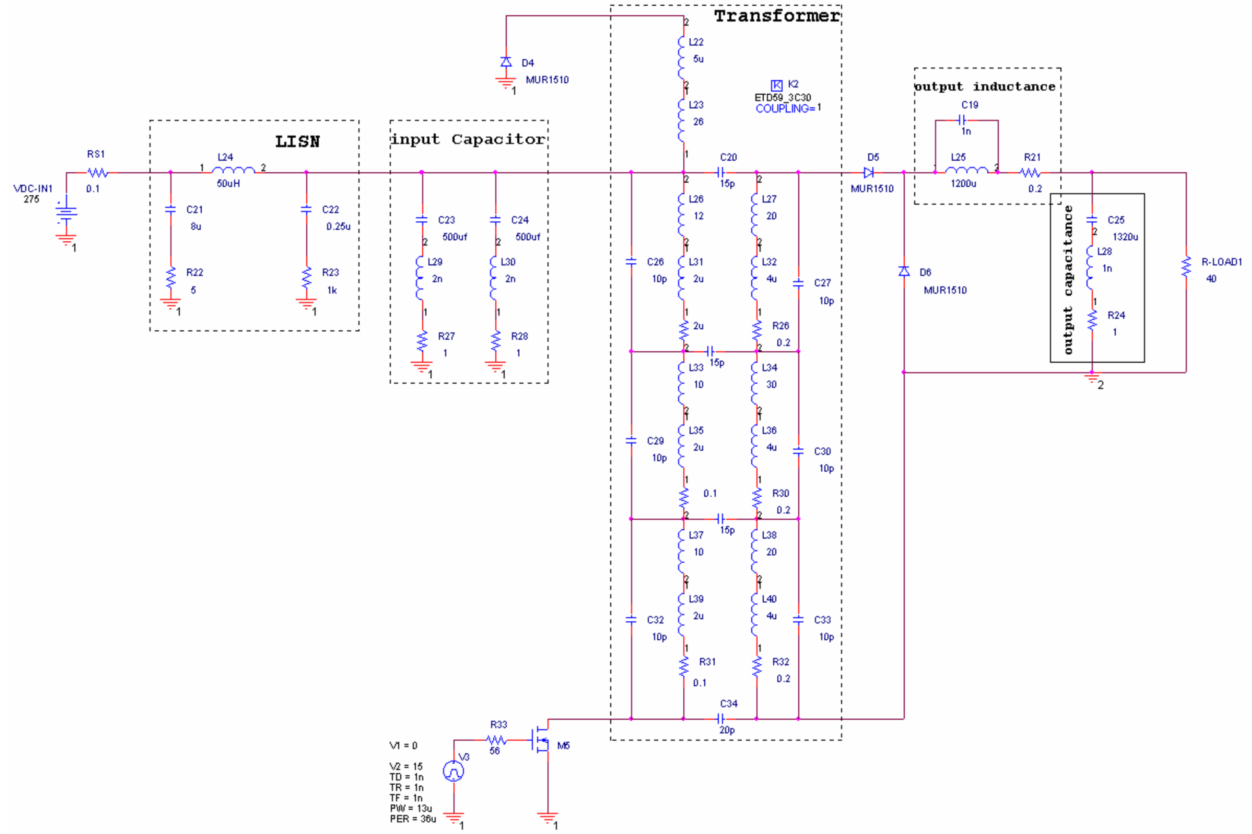

Fig. 2. High frequency model for (fig. 1)

II. Harmonics Simulation of Switching Power Supplies.

Since the measurement of high frequency harmonics is a complex process and needs expensive tools [5], it's preferred to carry out a precise harmonics simulation prior to the Standard test so that the possible errors are avoided. Therefore the harmonics simulation or high frequency analysis of the circuit has a great significance. In [6] harmonic analysis of a flyback topology switching power supply has been carried out and it has been shown that simulating by the PSpice software can yield reasonable results. But, in the said simulation, the intrinsic transformer parameters have not been considered and so an ideal transformer has been simulated. In this work a suitable model in the transformer at the above conditions is introduced and then the effect of leakage inductance on the harmonic generation in switching power supplies is considered.

The first step in an accurate simulation is to pick a suitable model for the elements used in the circuit. For this purpose, the intrinsic parameters of each element must be determined using measuring bridges and network analyzer. In [6] model selection and the proper method for measuring inductance and capacitance has been presented and is shown in fig. 2. The model for simulation of high frequency transformer is also shown in fig. 2. in this model, in order to properly distribute the intrinsic capacitance and leakage inductance, each layer or each turn of the winding can be modeled as a separate winding coupled with the other windings (L23, L31, L33, L34, L37, L38) whereas the leakage inductances don't have any coupling with each other (L22, L31, L32, L35. L36, L399, L40).

The intrinsic capacitances can be placed between different layers. In order to measure the leakage inductance, as described in [7] one of the two windings should be properly short-circuited and the measurement be done on the other side.

The analyzed circuit of a 1500W forward power supply with the following specification is shown in fig. 3

V_{in}=220v_{ac}±15%, V_{out}=220v_{dc}, I_{out}=7.5A_{dc}.

For harmonics evaluation, as described in [6], one and a half cycle of the switching period is simulated in the time domain and then its first half cycle is discarded, then FFT is taken from the remaining waveform. Harmonics analysis is carried out from 10 kHz to 30 MHz as in [8] and the LISNs in [5] is used to measure the current harmonics. Also in the simulation, since the aim is to study the effect of leakage inductance on harmonics, no EMI filter is introduced.

III. The Effects of Leakage Inductance on the Generated Harmonics

The calculation method and its influence on the forward topology are discussed in [9]. The leakage inductance causes the main switch current at the device input to vary at a low slope between the rated value and zero and reduces the rate of commutation between output diodes. In addition, the stored energy in the leakage inductance leads to the generation of voltage spikes on the main switch which, besides creating harmonic problems, increases the switching losses and so lowers the efficiency.

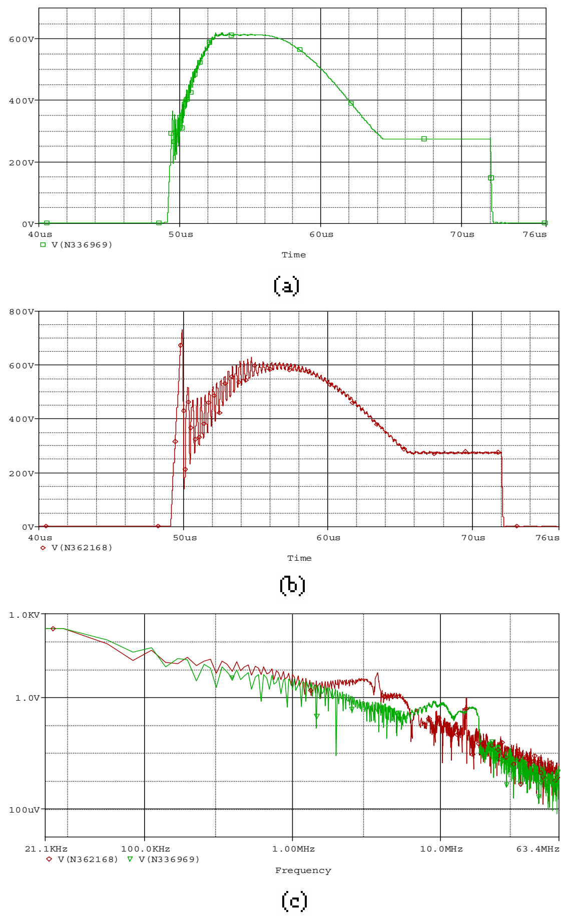

Fig. 3. Voltage across switch a) converter with interleaved transformer winding b) converter with ordinary transformer c) their respective FFTs.

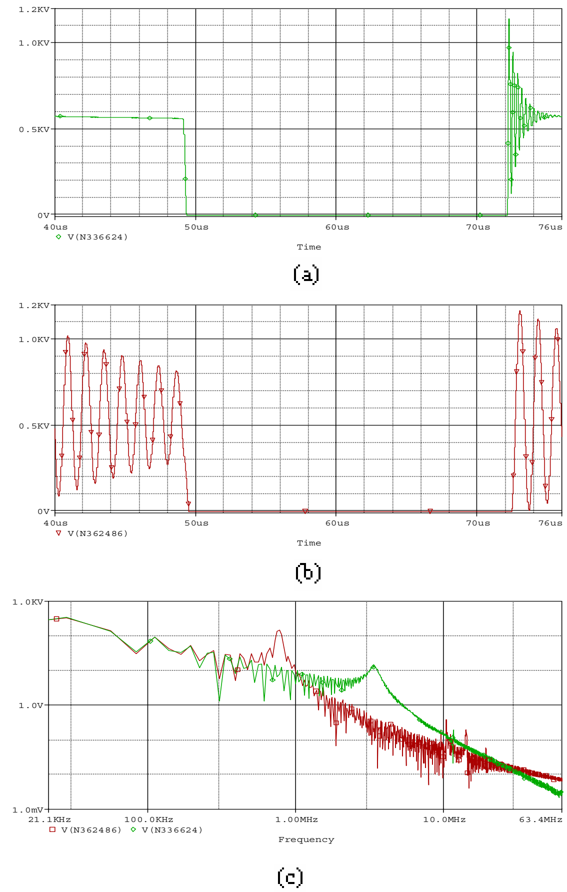

Fig. 4. Voltage across the freewheeling diode a) converter with interleaved transformer b) converter with ordinary transformer c) the respective FFTs.

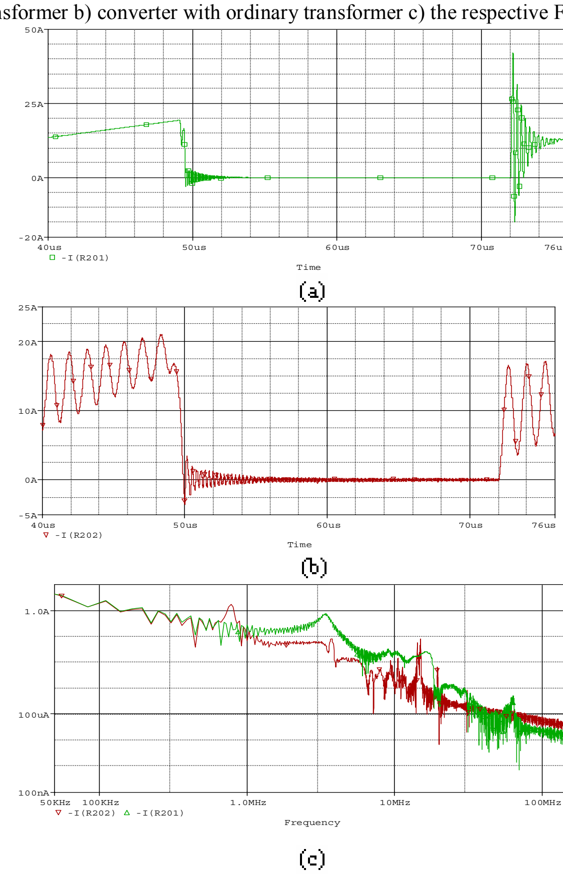

Fig. 5. Switch current a) converter with interleaved transformer winding b) converter with ordinary transformer c) their respective FFTs.

Interleaved winding can be used to reduce the leakage inductance [10]. To consider the effect of the leakage inductance on the generated harmonics, the simulation of the considered converter is carried out twice. In the first one, interleaved winding is used in the transformer and the equivalent leakage inductance become 2μH; in the second simulation, the ordinary winding is used in the transformer and hence the equivalent leakage inductance on the primary becomes 15 μH. That is expanded and embedded in the transformer.

Fig. 3 illustrates the voltage across the main switch under the above two conditions and the respective FFTs. The voltage spike due to leakage inductance is clearly observed in fig. 3-b and is responsible for the increase of harmonics up to 5MHz and beyond 25MHz. in the range of 5MHz~25MHz the harmonic contents of fig. 3-a is larger. This is due to the quick rise of voltage.

The voltage across the freewheeling diode, which is connected to heat sink, under the two conditions and the respective FFTs are shown in fig. 4. It's obvious from this figure that below 1MHz, converter with interleaved transformer winding has a better performance compared to that of converter with ordinary transformer winding. However at the higher frequencies the story is the other way round, that is, the leakage inductance makes the common mode noise increase but reduces the radiations.

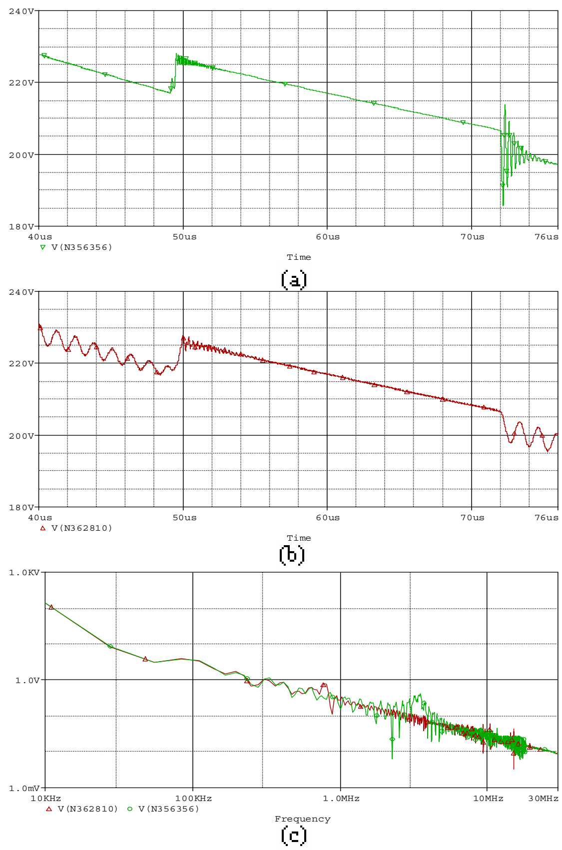

Fig. 6. LISN output voltage a) converter with interleaved transformer winding b) converter with ordinary transformer c) their respective FFTs.

The main switch current and the output voltage of LISN circuit at the two conditions and their respective FFTs are depicted in fig. 5 and fig. 6 respectively. As can be seen from these figures, due to the fluctuating nature of figs 5-b and 6-b, the harmonic content of this circuit below 1MHz is higher than that of converter with interleaved transformer winding but this is reversed beyond 1MHz frequency. Since high frequency filtering is much simpler than the low frequency filtering, the leakage inductance increases the differential mode noise of the device input

Fig. 7 shows the output voltage at the two states and the respective FFTs, it's also clear from this figure that below 1MHz frequency, the (differential mode) harmonic contents of converter with ordinary transformer is higher than converter with interleaved transformer winding and above this limit the story is reversed. Since high frequency filtering is simpler than that of the low frequency, the leakage inductance raises the amount of output harmonics.

IV. CONCLUSION

The method for switching power supplies simulation was presented and an appropriate high frequency model for transformer simulation was recommended. Then the effect of transformer leakage inductance on generation of high frequency harmonics at the input and output of switching power supplies was discussed and it was observed that the leakage inductance does make the radiation and common mode noise increase and also shifts the high frequency noise to lower frequencies that would make the filter size bigger. So the use of interleaved winding and reduction of leakage inductance will both raise the efficiency and reduce harmonics generated by the switching power supplies.

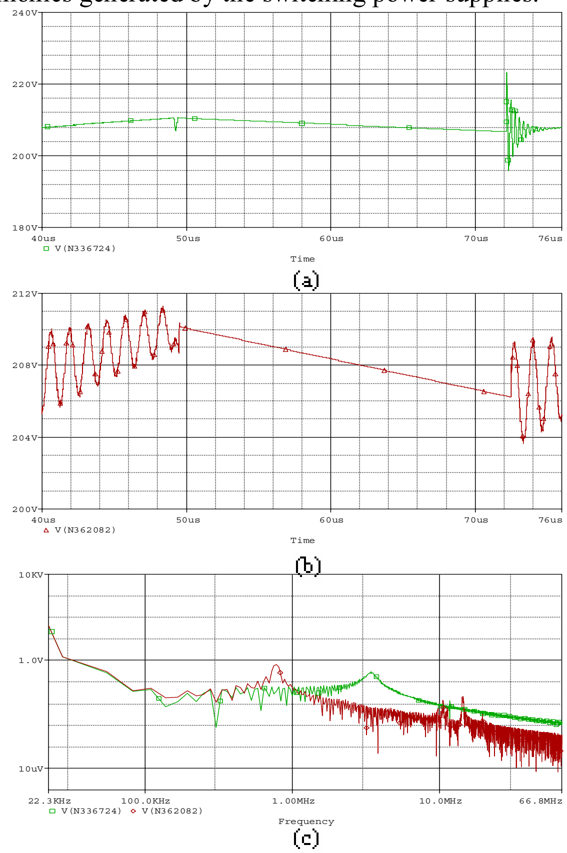

Fig. 7. Output voltage a) converter with interleaved transformer winding b) converter with ordinary transformer c) their respective FFTs.

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