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Characterization and SPICE modelling of a transformer for LLC converter based on GaN transistors

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Abstract. The paper describes a method how to measure the high-power, high-voltage transformer that is used in LLC converter based on GaN transistors. These transistors allow high frequency switching which reduces the power losses and minimizes the form factor. On the other hand, this high frequency is challenging due to the parasitic parameters of the transformer. To achieve soft switching with Zero Voltage Switching (ZVS) on the primary side and Zero Current Switching (ZCS) on the secondary side it must have predictable properties and it must be considered in the controller design. This paper presents measurement of real parameters of given transformer and how to consider its properties in the converter's design using the SPICE simulations.

Key words. LLC converter, Real transformer, SPICE simulation, GaN transistors, Electric Vehicle on-board charger

1. Introduction

The resonant converters are ideal for Electric Vehicle on-board chargers and for energy storage applications. It enables to effectively control power flow between the energy source, the battery or high-power load. The simple LLC converter can be extended to bidirectional CLLLC converter that allows intelligent power control and increases the effectivity of the devices [1]. In order to reduce the switching losses and reduce the form factor it is necessary to use high frequency switching devices such as GaN transistors. The GaN transistors have low $R_{DS(ON)}$ parameter compared to the silicon or silicon carbide equivalent transistors which leads to small conduction losses [2]. The zero revers recovery, fast switching speed and lower dead-time make the GaN transistor ideal candidate for the converted design [3]. The design of such converters is described e. g. in [4, 5]. Besides the H-bridge switch made from the transistors, also the transformer has crucial influence on the functionality and power effectivity. The real parameters of the transformer must be considered in the design – namely the self-resonance frequency because it affects the maximum operating frequency of the converter [6]. This paper presents measurement of real parameters of given transformer and how to consider its properties in the converter's design using the SPICE simulations.

2. Resonance Converter Simulation

It can be used different kinds of the software for simulations and verifications of the design. Simulations in this paper aims on standard devices with well-known models. This is why the simple software such as LTspice can be used [7, 8]. Figure 1 presents the LTspice model of the LLC converter that should be able to regulate output voltage between 250 VDC and 450 VDC while the input voltage can vary between 375 VDC and 425 VDC. So, it must be possible to set the voltage transfer between 0.588 and 1.2 by changing the operating frequency. The model deals only with the AC analysis and input voltage source V_{in} represents the H-bridge consisting of the GaN transistors. AC voltage is set to be 1 V in order to obtain the converter's transfer on the output. Resistor R_{aux} is an auxiliary resistor for setting the DC operating point in the primary winding – it has no effect on the simulation result. The voltage sources *V2 - V5* serve only for reading the calculated parameters of the model.

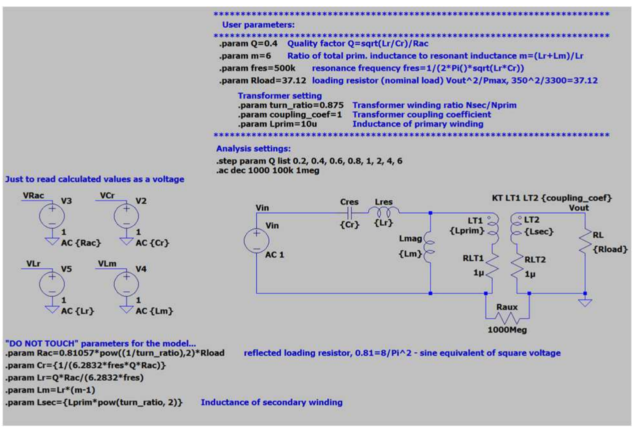

Fig.1. Simulation schematic of the converter with ideal transformer, small signal AC analysis

The parameters of the model are calculated using the user parameters Q – the quality factor, m – ratio of total primary inductance to the resonant inductance, f_{res} – the resonance frequency, R_{load} – maximum load, coupling coefficient and turn ratio of the transformer. These parameters are used for optimization of the converter which is described in [5].

An iterative process should be used to find an optimal value of the parameter m and Q. Increasing the parameter m, the efficiency of the converter increases, but regulation frequency band goes wider. Increasing the Q, the magnetizing inductance goes to be bulky and potentially lossy due to parasitic resistance.

Figures 2 and 3 show examples of the simulation results of the converter for different parameters m and Q. In this case only the ideal transformer is considered (coupling coefficient is 1 and just a minimum serial resistance of the windings is considered).

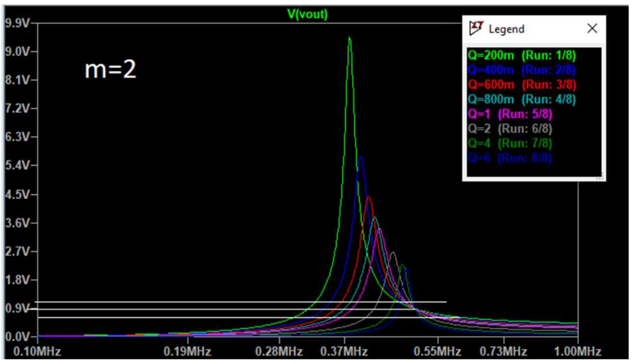

Fig.2. Simulation of the converter's transfer for parameter m=2 and different parameters Q

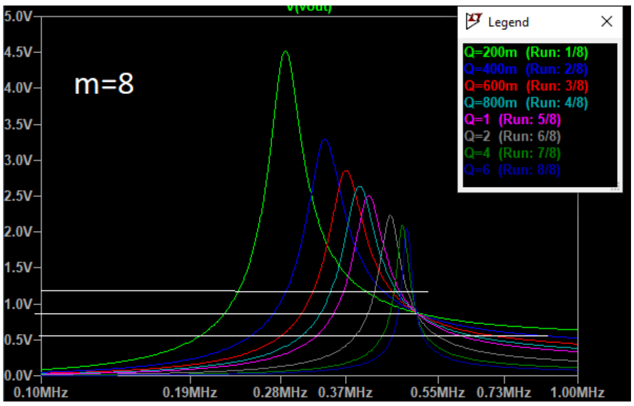

Fig.3. Simulation of the converter's transfer for parameter m=8 and different parameters Q

As a possible combination can be selected m = 12, Q = 0.4 at which the minimum voltage transfer for maximal load is achieved at 970 kHz and maximum transfer for 411 kHz. When the converter is unloaded (R_{load} = 10 kΩ), the regulation frequency band is 499.5 kHz – 500.9 kHz.

The parameters of the converter can be resolved using the equations in the spice model (fig. 1).

$$C_{res} = \frac{1}{2\cdot\pi\cdot f_r\cdot Q\cdot R_{ac}} = 20.25\ nF \quad (1)$$

$$L_{res} = \frac{Q\cdot R_{ac}}{2\cdot\pi\cdot f_r} = 5\ uH \quad (2)$$

$$L_{mag} = L_{res}\cdot(m-1) = 55\ uH \quad (3)$$

The operating frequency between 411 kHz and 970 kHz is reasonable for the GaN transistors. Nevertheless, the design must also consider the real properties of the transformer which can limit the operating frequency or it will affect the controller design because it will incorporate some phase shift close to its resonance.

3. Real transformer

Figure 4 presents the transformer used in this project and figure 5 shows its basic parasitic properties. It consists of two windings realized using the parallel loops. The serial resistances of the windings are very low even at high frequencies because the Litz wires are used.

Fig.4. The transformer under test (WE 750320587 A2334 REV00)

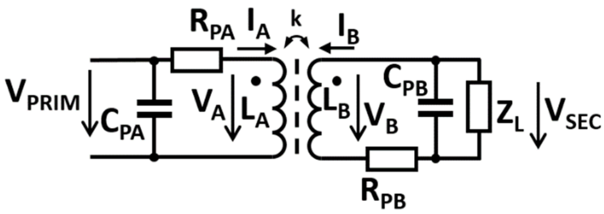

Fig.5. Transformer with basic parasitic properties

Analysing the equivalent model and using the basic circuit theory it can be derived an equation 4 which describes how to measure the coupling coefficient.

$$k = \sqrt{\frac{L_{AOC}-L_{ASC}}{L_{AOC}}} \quad (4)$$

When the loading resistor is disconnected and the parasitic capacitors are neglected, the transformer is unloaded and its winding A behaves only as an inductor L_{AOC}. For shorted side B the winding A behaves as an inductor L_{ASC}. The coupling coefficient can be calculated from these measurements but it must be far away from the self-resonance of the transformer (only then the capacitors C_{PA} and C_{PB} can be neglected).

The transformer was measured using the BODE 100 analyser from Omicron LAB and using the B-AMP 12 external power amplifier probe for AC measurements. The DC resistance of the windings were measured using the Agilent 34410A multimeter and at 4 wires connection. Figures 6 and 7 present the measurement with unloaded and shorted secondary winding. The inductances L_{AOC} and L_{ASC} are recorded for 100 kHz which is in safe distance from the self-resonance at 1.3 MHz.

The transformer exhibits the resonance behaviour when the parasitic capacitances take the effect.

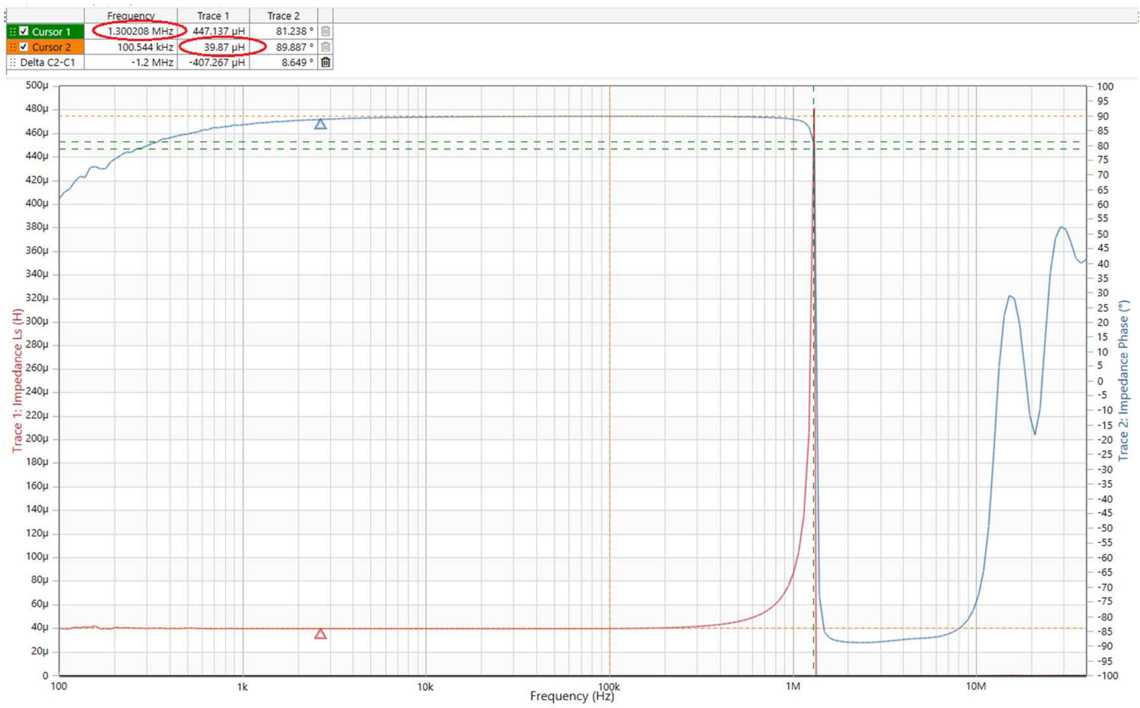

Fig.6. Main transformer – winding A measurement with unloaded secondary winding (winding B)

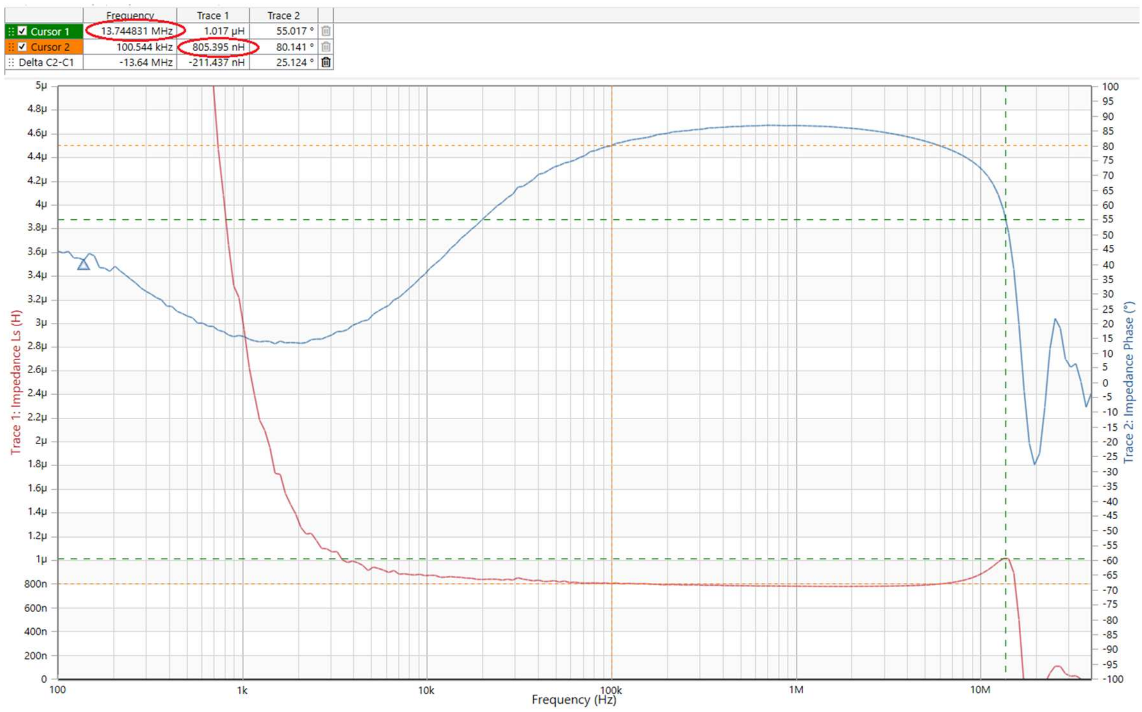

Fig.7. Main transformer – winding A measurement with shorted secondary winding (winding B)

Neglecting the parasitic resistances ($R_{PA} \rightarrow 0$, $R_{PB} \rightarrow 0$), considering the unloaded transformer ($Z_L \rightarrow \infty$) and considering ideal coupling ($k \rightarrow 1$), the transformer reduces to parallel combination of L_A, C_{PA} and C_{PBE}. Capacitor C_{PBE} is capacitor C_{PB} transformed to the primary side using the equation (5). The resonance frequency is then given by (6).

$$C_{PBE} = C_{PB} \cdot \frac{L_B}{k^2 \cdot L_A} \tag{5}$$

$$f_r = \frac{1}{2 \cdot \pi \sqrt{L_A \cdot (C_{PA} + C_{PBE})}} \tag{6}$$

Parasitic capacitance is caused mainly by the capacitances between the transformer winding's loops. Let us consider that the ratio between the parasitic capacities of the windings is approximately equal to the radio between the inductances (7). Then the parasitic capacitances of the winding can be calculated using the equations (8) and (9) that were derived combining (5), (6) and (7).

$$\frac{C_{PA}}{C_{PB}} \approx \frac{L_A}{L_B} \tag{7}$$

$$C_{PA} = \frac{L_A}{4 \cdot \pi^2 \cdot f_r^2 \cdot (L_A^2 + L_B^2)} \tag{8}$$

$$C_{PB} = \frac{L_B}{4 \cdot \pi^2 \cdot f_r^2 \cdot (L_A^2 + L_B^2)} \tag{9}$$

Table 1 presents the transformer's measured and calculated parameters according to the schematic in figure 5.

Table I. - Measured Parameters of the Transformer

PARAMETER		VALUE
Inductance of winding A	L_A	39.87 µH
Inductance of winding B	L_B	49.42 µH
Windings ratio	TR	1.113
Coupling coefficient	k	0.99
Self-resonance frequency	f_{res}	1.3 MHz
Winding A capacitance	C_{PA}	147.8 pF
Winding B capacitance	C_{PB}	183.6 pF
Winding A resistance	R_{PA}	< 2 mΩ
Winding A resistance	R_{PB}	< 3 mΩ

4. Converter with Real Transformer

The self-resonance of the transformer was measured to be relatively close to maximum operating frequency of the converter. This is why it should be verified the previous simulation in time domain, that the converter is possible to work at this frequency. Figure 8 shows the LTspice simulation schematic which considers the real properties of the transformer and it includes also the full-bridge rectifier consisting of ideal diodes. There are the same parameters like in the previous model plus the parameter of the switching frequency f_{sw} and input voltage amplitude are included. The input voltage is represented by the square voltage now.

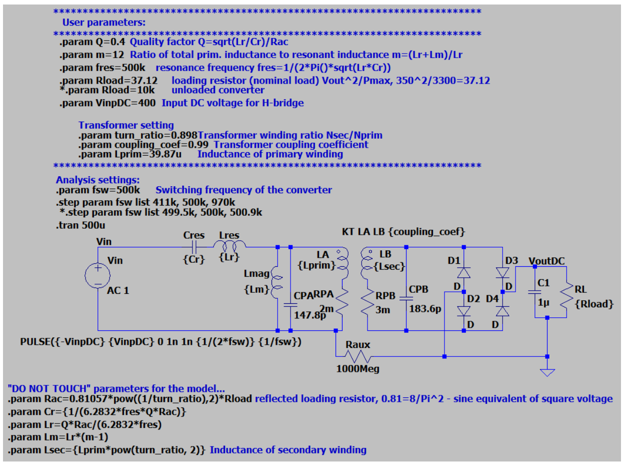

Fig.8. LTspice model of the converter in time domain and considering the real properties of the transformer

Parasitic capacitors C_{PA} and C_{PB} can be set to consider the self-resonance effect of the transformer. Figure 9 shows the simulation result of the output voltage depending on the operating frequency and where the capacitors are neglected. The steady value of the converter's output voltage varies between 230 VDC and 400 VD depending on the operating frequency.

When the parasitic properties are considered, the output voltage range is reduced as it is evident from the figure 10. For input voltage 400 VDC the output voltage can be regulated only in the range from 270 VDC to 400 VDC by the switching frequency change between 411 kHz and 970 kHz. This regulation range is smaller than expected and for correct operation the frequency range must be changed to 340 kHz – 1.1 MHz.

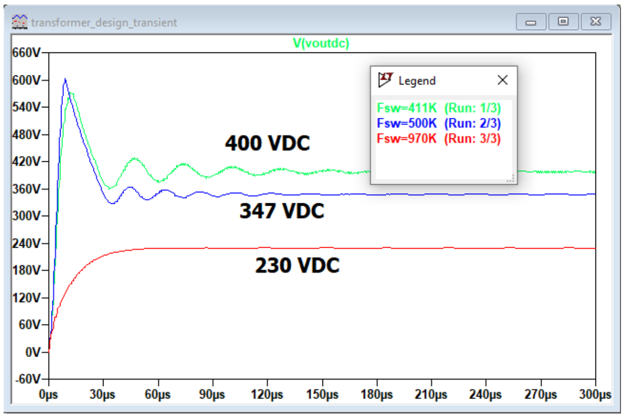

Fig.9. Simulation results of the converter with ideal transformer (no parasitic capacitances considered) for 3 different frequencies 411 kHz, 500 kHz and 970 kHz and loading resistor 37.12 Ω.

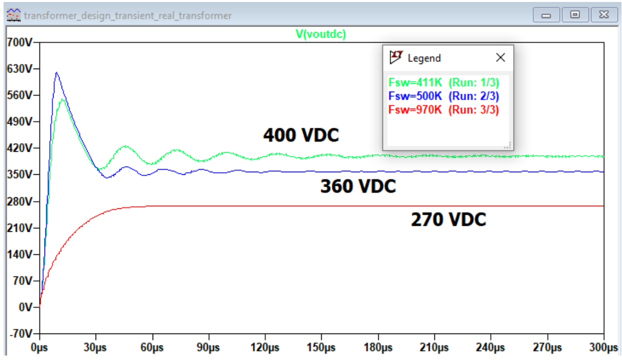

Fig.10. Simulation results of the converter with parasitic capacitances of the windings for 3 different frequencies 411 kHz, 500 kHz and 970 kHz and loading resistor 37.12 Ω.

5. Conclusion

The paper described method how to simulate the LLC convertor for Electric Vehicle on-board chargers and how to consider the real properties of the transformer used. The basic components of the converter are found by iterating the parameters in the schematic. The goal is to find optimum ratio between the primary inductance and the magnetizing inductance. The input parameters are the basic operating frequency and demanded regulation range. This first part of the design considers only the ideal transformer. When the basic parameters of the circuit are found, the real properties of specific transformer must be also considered. The paper presents how to measure the real properties using the BODE 100 analyser and how to calculate the parasitic properties of the primary and secondary winding of the transformer. The parasitic properties are then added into the LTspice simulation and performance of the converter can be verified also in the time domain.

Due to self-resonance behaviour of the transformer and due to fact that the operating frequency is close to it, the parameters of the converter must be accommodated. The simplest way is to change the frequency range of the converter. If the frequency change is not enough, also the other parameters such as *m*, *Q* or f_{res} can be changed.

Acknowledgement

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