Analytical Design and Simulation for Switching Transformer in High-Voltage Applications

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***Abstract*—Resonant converters are interesting topologies for high voltage power supplies because of their advantages such as soft switching and high power density. In order to increase the voltage to dozens of kilovolts or even more, it is necessary to use a high step-up transformer in high voltage power supplies; therefore, the parasitic parameters of the transformer cannot be neglected. So, the most important part in the high voltage resonant converter is high voltage transformer. This paper presents a method for LCLC resonant converter designing according to employing parasitic parameters of transformer as resonant circuit components in order to reduce weight and size of the converter. Converter behavior cannot be predicted without calculating the exact value of parasitic parameters of the transformer such as leakage inductance and stray capacitance. This case is focused on calculating the parasitic parameters of transformer, simulation using Finite Element Method (FEM) and using the results for design an LCLC converter. The experimental results that obtained from 250W, 12KV prototype verified simulation results for LCLC fixed frequency resonant converter.**

***Index Terms*—High Voltage, Transformer, Parasitic Parameters, FEM, Resonant Component**

I. INTRODUCTION

RESONANT converters have more importance today since benefits like soft switching, compact size and high power density. Resonant converters are interesting for some applications of high voltage power supplies such as medical imaging and radar systems because these applications have sensitive loads and EMI and ripple issues are very important [1-5].

Resonant converters can be divided into three main categories with respect to their resonant tank topologies. These categories are: Series Resonant Converters (SRC), Parallel Resonant Converters (PRC) and, Series-Parallel Resonant Converters (S-PRC) [1] and [7].

SRC and PRC are studied in [1] and those are not suitable for high voltage applications. S-PRC has different topologies such as LLC, LCC and LCLC [2] and [8]. In this case, studies are focused on S-PRC with LCLC topology because in high voltage applications parasitic components of high voltage transformer cannot be neglected and this topology can absorb all of the parasitic components of high voltage transformer in resonant tank (Figure 1).

Schematic of LCLC resonant converter is shown in figure 3. The converter is made of three part: resonant inverter, high voltage transformer and, output rectifier. The resonant inverter is divided to two subdivision: full bridge MOSFET switches and resonant tank. As shown in figure 3, the resonant tank includes two inductors and two capacitors in series and parallel.

As shown in figure 1.b, there are three main parasitic parameters in high voltage transformer: Leakage inductance, Magnetizing inductance and, Stray capacitance (Figure 2). LCLC resonant converter can absorb parasitic components of high voltage transformer in resonant tank since leakage inductance, magnetizing inductance and, stray capacitance are employed as series inductor, parallel inductor and, parallel capacitor respectively. More detail and steady state analysis of LCLC resonant converter are studied in [2] and [8].

High voltage transformer design has the most importance in converter design. Therefore, this paper is focused on high voltage transformer design according to simulation parasitic parameters of the transformer and employing them as components of the

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resonant converter. In section II the parasitic parameters of the transformer are introduced. Converter design is reviewed in section III including two subdivision: topology selection and transformer design. Parasitic parameters are studied using FEM simulation in section IV. Finally a 12KV, 250W prototype is designed using FEM simulation results and experimental results are compared with simulation results in section V.

II. PARASITIC PARAMETERS OF HIGH VOLTAGE TRANSFORMER

The parasitic parameters in a transformer can be modeled by the parasitic components. This is an acceptable approximate for studying transformer behavior as a part of the system. Detailed model of a transformer is shown in figure 1 [9-16]. This model includes leakage inductance, magnetizing inductance, stray capacitance, intra-winding capacitances, copper loss and, core loss. Each application needs a suitable model and in many cases, it's not necessary to consider all of the parasitic parameters. Using complete model makes calculations more complicated and as a consequence, simulations takes longer. In this case, only three parasitic parameters are modeled: leakage inductance, magnetizing inductance and, stray capacitance. Losses and other parasitic parameters are neglected.

Passing alternating current in primary winding makes magnetic flux. According to the shape of core and type of windings, most of the flux flow in the core and induces in the secondary winding. By the way, part of flux flows around the winding. This flux is known as leakage flux. There is leakage flux around both of primary and secondary but the effect of both of them can be modeled by a series inductor in transformer model (L_{LK}). The main part of flux makes magnetizing inductance and modeled by a parallel inductor ($L_m^{'}$).

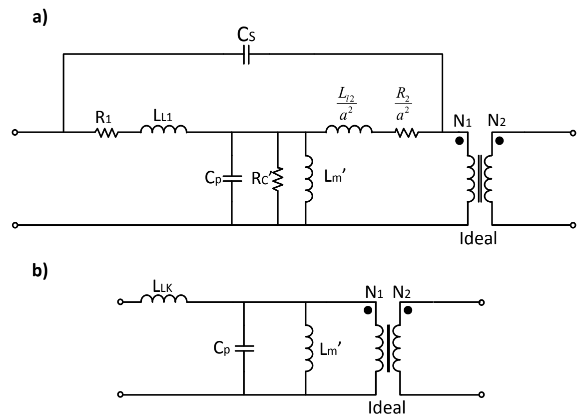

Fig.1 a) Detailed model b) Proposed model for high voltage transformer

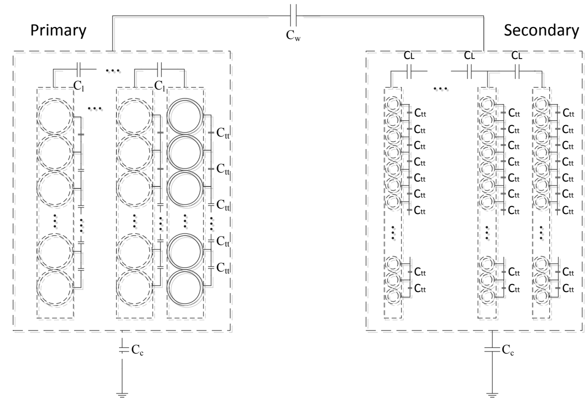

Fig.2 Parasitic capacitances in transformer

There are different capacitances in transformer due to distributed electrical potential in conductors. These capacitances are listed as follow [10-12]:

a) Turn to turn capacitance which is appear between two parallel approximate turn in transformer winding (C_{tt}).
b) Turn to core capacitance which is appear between each turn and magnetic core (C_c).

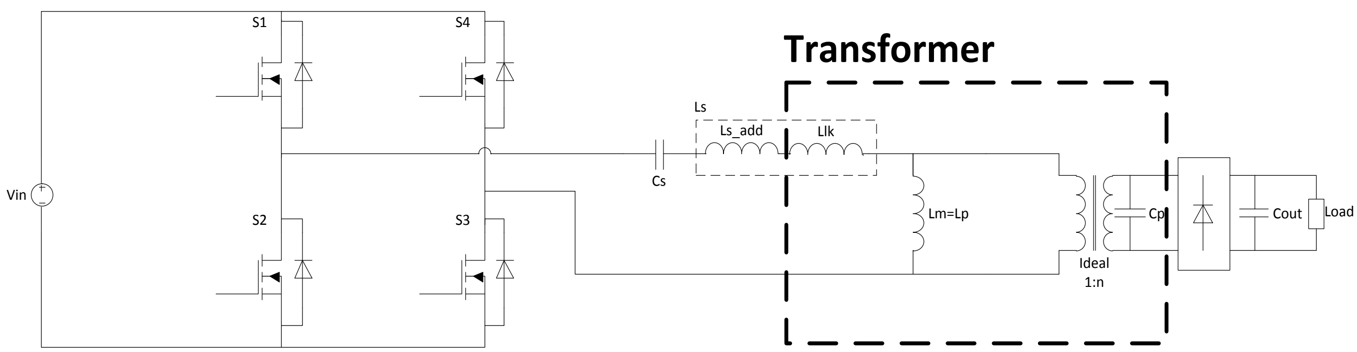

Fig.3 LCLC Resonant Converter

c) Layer to layer capacitance for multi-layer windings (C_l).
d) Winding to winding capacitance between primary and secondary windings or even other windings if exist (C_w).

These capacitances are shown in figure 2. Parasitic capacitances have essential effect in converter behavior due to the step-up ratio of transformer. Parasitic capacitances can be modeled by a parallel capacitor (C_p) in transformer model.

Simulation of parasitic parameters of the transformer is subject to next sections.

III. CONVERTER DESIGN

A. Topology Selection

The soft-switching condition is important due to decrease output ripple, passing EMI requirements and insulation stress reduction [1]. In high voltage applications soft-switching has more importance because hard switching requires high-level insulation and as a result, the size, weight and, cost of the converter have been increased.

Resonant converters can be used to achieve soft-switching condition. There are various kinds of resonant converter; but, because of the significant value of parasitic components in the step-up transformer, high order resonant converters with 3, 4 or more storage elements in the resonant tank are interesting for high voltage applications [1], [2]. In this study LCLC resonant converter is selected for prototype due to it can absorb all of the parasitic components of high voltage transformer.

For traditional converters, it is important to decrease leakage inductance of the transformer, but the resonant tank in LCLC resonant converter needs significant inductor in series and it is possible to use leakage inductance as series inductor in resonant tank. So, increasing the leakage inductance is one of design goals and UU, UI and CC cores are interesting for transformer fabrication.

B. Transformer Design

Switching power supplies operate in switching frequency from 20 KHz to more than 250 KHz generally. In this frequency range, various kinds of ferrite cores present significant advantages such as acceptable loss and remarkable maximum flux density. Therefore, usually, ferrite cores are selected for the transformer in power supplies.

In order to provide reliable electrical insulation between primary and secondary windings in high voltage transformers, sandwiched windings are not suitable. One winding in each separate leg of core instead of sandwich windings is more interesting in high voltage transformers. Furthermore, LCLC resonant converter needs a significant inductor as the series inductor in the resonant tank and this winding plan provide greater leakage inductance compare sandwich windings. For these reasons UU, UI and, CC cores are considering in high voltage resonant converters (Figure 3). In this study, the transformer is made by UU93/152/30 and its mechanical characteristics are summarized in table 1.

Core loss in ferrite cores determined by loss vs. frequency in each work point. In this case, the core loss calculated 29 W in room temperature.

TABLE I
MECHANICAL CHARACTERISTICS OF UU93/152/30

Symbol	Discretion	Value
le	Effective Magnetic Length	354 mm
Ae	Cross-Section Area	840 mm^2
Ve	Volume	297000 mm^3
m	Wight	1500 g/set
A	-	153 mm
B	-	93 mm
C	-	28 mm
D	-	34.6 mm

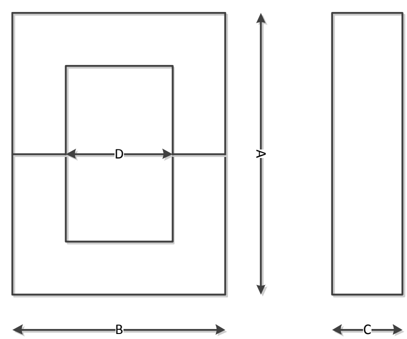

Fig.4 UU magnetic core

For calculating the loss of windings, first, must calculate windings resistance. DC resistance is given by:

$$R_{dc} = \rho \frac{\ell}{A} \quad (1)$$

Where ρ , ℓ and, A are resistivity of conductor, length of wire and, the cross-section area of wire respectively.

When an alternating current passes through the wire, the current flows mainly at the skin of the conductor, between the outer surface and a level called the skin depth. This fact called "Skin Effect". Increasing the frequency makes the effective cross-section of the conductor smaller and as a sequence, the

TABLE 2
PARAMETERS OF TRANSFORMER

Symbol	Discretion	Value
N_p	Number of primary turns	7
N_s	Number of secondary turns	329
a	Transfer ratio	47
Insulation	-	20 KV

effective resistance becomes larger. The skin depth is given by [7]:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} \tag{2}$$

Where μ is permeability of the conductor and ω is angular velocity.

The resistivity and permeability of copper are $1.68*10^{-8}$ and $1.256*10^{-6}$ respectively; therefore, (2) can be turned to:

$$\delta = \frac{2837}{\sqrt{f}} \tag{3}$$

According to (3), the AC resistance is given by:

$$R_{ac} = \frac{\left(\frac{r}{\delta}\right)^2}{\left(\frac{r}{\delta}\right)^2 - \left(\frac{r}{\delta}-1\right)^2} R_{dc} \tag{4}$$

Where r is the radius of the conductor and R_{dc} is calculated by (1).

The primary winding is made of AWG18 and the secondary winding is made of 0.15mm magnet wire. Due to (4), the resistance of primary calculates 3.2 mOhms and resistance of secondary calculates 47 Ohms. Therefore whole copper loss calculates less than 0.1 W.

There is a trade-off between magnetic characteristics of core and number of turns in each winding. A minimum number of primary turns is limited by maximum flux density in the core to avoid saturation. The minimum number of turns, in this case, is given by [9]:

$$N_{p,\min} = \frac{E_{peak}}{4B_{\max}A_e f} \tag{5}$$

Where E_{peak} is the peak of voltage pulse, B_{max} is maximum flux density, A_e is effective cross-section area of the core and, f is switching frequency.

As E_{peak}=255V, B_{max}=120mT, A_e=840mm^2 and, f=90 kHz minimum number of the primary is 7.

TABLE 3
SIMULATIONS RESULTS

Symbol	Discretion	Value
L_{LK}	Leakage Inductance	19.65 uH
L_m	Magnetizing Inductance	223.11 uH
C_p	Parasitic Capacitance	2.08 pF

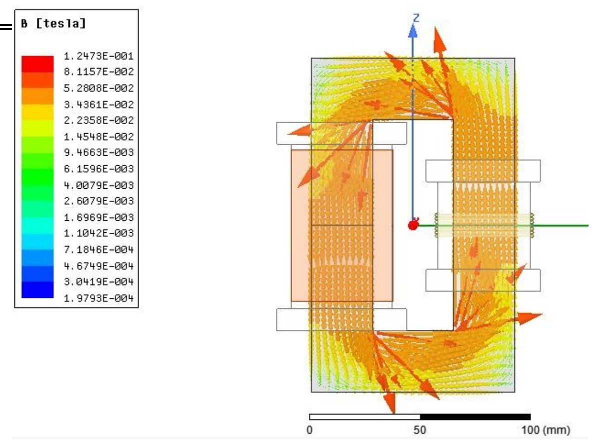

Fig.5. Flux density through the core by magnetostatic simulation

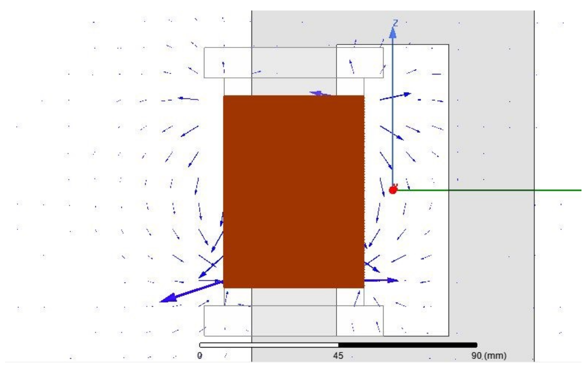

Fig.6 Electric field around the secondary winding in electrostatic simulation.

Transformer ratio is 47 then secondary contain 329 turns.

Ferrite characteristics can be changed through temperature changes. Because of the fact that, it is suitable to consider a small gap in the core. In this case, there is a 0.03mm gap in each leg.

According to provide the required insulation, the frame that is made of PTFE Teflon is used as insulation between each winding and core and KAPTON tapes are used as insulation between primary and secondary to avoid leakage current and electrical arcing. Transformer design is summarized in table 2.

IV. SIMULATION OF PARASITIC PARAMETERS

Simulation of high voltage transformer before fabrication can reduce overall price and fabrication

TABLE 4
THE CONVERTER DETAILS

Symbol	Discretion	Value
V_{in}	Input voltage	270 Vdc
V_{out}	Output voltage	12 KV
P_{out}	Output Power	250 W

TABLE 5
RESONANT TANK VALUES

Symbol	Discretion	Value
Ls	Series Ind.	275 uH
L_p	Parallel Ind.	225 uH
C_s	Series Cap.	15 nF
C_p	Parallel Cap.	4.5nF

time due to errors can be recognized and resolved before fabrication progress. A powerful analysis for simulation electromagnetics system is based on Finite Element Method (FEM). In this case, parasitic parameters of high voltage transformer are simulated using FEM in two different type. Leakage and magnetizing inductances are simulated using Magnetostatic solver and parasitic capacitance simulated using Electrostatic solver. All calculated parameters are for the transformer that designed in the previous section. Magnetostatic simulation results are given in inductance matrix form as follow:

$$\begin{pmatrix} V_1 \\ V_2 \end{pmatrix} = \begin{pmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{pmatrix} \begin{pmatrix} di_1/dt \\ di_2/dt \end{pmatrix} \quad (6)$$

Leakage and magnetizing inductances can be calculated by:

$$L_{lk} = L_{11} - \frac{L_{12}^{\ 2}}{L_{22}} \quad (7)$$

$$L_m = L_{11} \quad (8)$$

Parasitic capacitance is calculated using energy method. Electric field energy is given by:

$$W_e = \frac{1}{2}\varepsilon_0 \int \left| \vec{E} \right| \, dv \quad (9)$$

Where ε_0 and, E are permittivity of free space and electric field respectively. The integral is calculated on volume of the whole problem space.

The value of We is calculated by the software; then, the value of parasitic capacitance is given by:

$$C_p = \frac{2W_e}{V^2} \quad (10)$$

Where V is electrical potential between secondary winding turns. Magnetostatic and electrostatic fields are shown in figure 5 and figure 6 respectively. Simulation results are summarized in Table 2.

V. EXPERIMENTAL RESULTS

The converter details are summarized in Table 4. The converter has been designed through the parasitic parameters of the transformer from table 3 and details of Table 4. Design of LCLC resonant converter is discussed in [2], [3] and, [4]. In this case, the design is according to the routine that studied in [2].

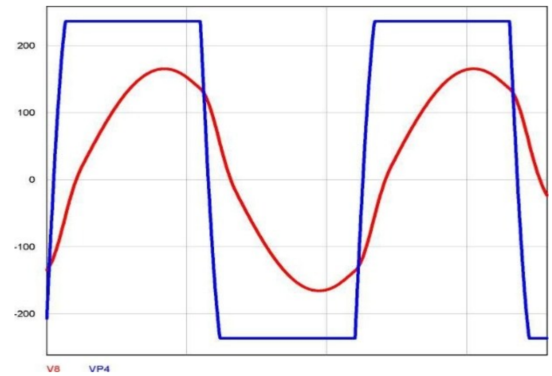

Fig.7 Simulation results: Inverter voltage vs. resonant tank current

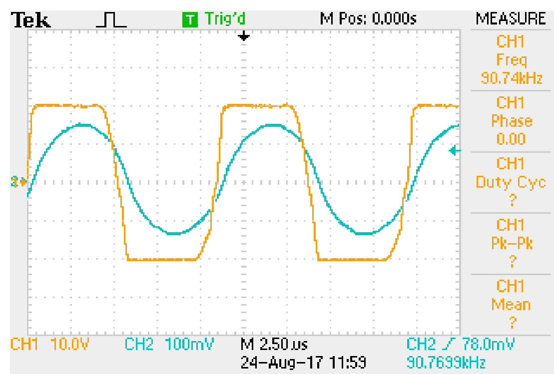

Fig.8 experimental results: Compared inverter voltage and resonant tank current

The natural frequency of resonant tank circuit is given by:

$$f_0 = \frac{1}{2\pi\sqrt{L_s C_s}} \quad (11)$$

In order to simplify the calculations, three normalized value are defined as follows:

$$L_n = \frac{L_s}{L_p} \quad (12)$$

$$C_n = \frac{C_s}{C_p} \quad (13)$$

$$f_n = \frac{f_s}{f_0} \quad (14)$$

Where f_s is switching frequency.

In [2], L_n, C_n and, f_n are assumed 1, 0.5 and, 1 respectively; but, in order to improve zero current switching (ZCS), L_n and C_n are assumed 0.82 and 0.3 respectively. Simulation results for the designed converter are shown in figure 7. Switching frequency set to 90 KHz, then according to (11), (12), (13) and, simulation results, the value of resonant tank components are designed as summarized in Table 5.

Since the value of L_m=225uH is obtained from simulation, L_m can be used as the parallel inductor; but, it is necessary to add an extra inductor in series to the transformer to acclaim designed value of L_s. The value of the extra inductor is 255uH and then, the series inductor is 275uH. The value of simulated C_p is 2.08pF and it transfers to primary by-product to turns ratio to the power of two. Therefore, parasitic capacitance can be used as the parallel capacitor. The series capacitor is added subsequently.

Note that the simulation results of the transformer are proved by measurements using LCR meter with less than 4 percent error.

The prototype converter is shown in figure 9. Waveguides of the converter are shown in figure 7 where inverter voltage and resonant tank current are compared. ZVS is reached for various loads and converter is worked stable.

VI. CONCLUSION

This paper presented an analytical method for high voltage transformer that used in switching power supplies. The Parasitic parameters of transformer introduced and the transformer were modeled. Parasitic parameters of transformer was calculated using Finite Element Method (FEM). In order to decrease the size and weight of the converter, an interesting topology, LCLC resonant converter was selected because this topology could absorb all parasitic components as resonant tank element. Since high voltage insulation was required, an UU93/152/30 magnetic core was selected. Leakage inductance, magnetizing inductance and, parasitic capacitance were calculated from FEM simulation results and their value was 19.56uH, 223.1uH and, 2.08pF respectively. These values proved by measurements using LCR meter and experimental results through the 12KV, 250W prototype converter.

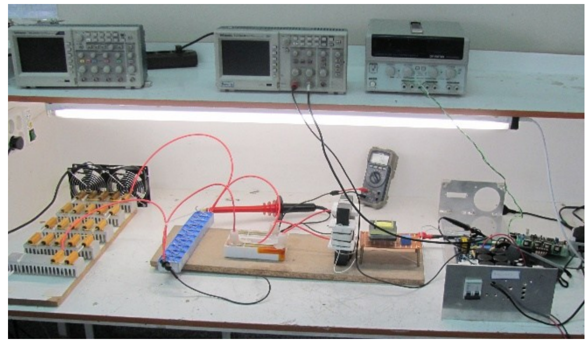

Fig.9 Prototype converter

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