A Modeling of Integrated Transformer using PSIM Magnetic Elements

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***Abstract*— Magnetic circuit is a powerful tool in the design of power transformers, especially for a priori evaluation of leakage and magnetizing inductance before actual production of the components. This paper investigates an alternative modeling approach using PSIM magnetic circuit library to remove duality transformation used in a conventional reluctance model and establishes formula to determine the permeance-capacitors in both core and leakage path. A simulation jig is devised to automate the parameter determination process and the derived formula has been verified by measurement results.**

Keywords—PSIM, Magnetic Circuit, Magnetizing Inductance, Leakage Inductance

I. INTRODUCTION

Integrated magnetic structure is popular in high power density dc/dc converters. Among them, LLC resonant converter shown in Fig. 1 has been attractive in small to medium power applications such as audio, TV, server system, etc [1]. It utilizes a magnetic transformer that incorporates leakage and magnetizing inductors into a single core with moderate turn-ratio.

There are two common ways to construct a magnetic circuit – one is performed by reluctance model and the other is by permeance-capacitor model. Even though the former is widely used in the industry, it is less convenient to use than the latter. [2]. On the other hand, adopting ideal gyrator, permeance-capacitor model is more insightful because it retains the original shape of magnetic structure and automatically perform duality transformation function [3].

The purpose of this paper is to investigate feasibility of using PSIM magnetic circuit library as a design and analysis tool for magnetic components through automated terminal parameter extraction process. Moreover, this paper establishes user guidance and formula to determine the individual permeance-capacitors in both core and leakage path from design specifications.

II. TRANSFORMER MODELING

PSIM provides one coupling element and three linear magnetic elements: the former describes the energy conversion and is implemented as a winding block, the latters are used to model magnetic path and consist of a linear core, an airgap, and a leakage path. In this section, modeling are studied in detail.

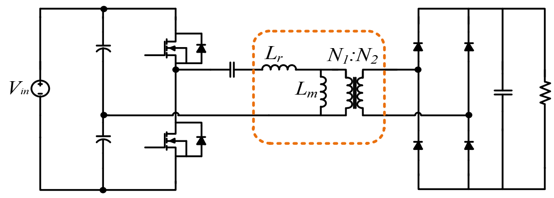

Fig. 1. Full wireless power system based on C-WPT

A. Electro-magnetic coupler modeling

PSIM winding block provides the exactly same function as an ideal gyrator whose the input-output relation is

$$\frac{d\phi}{dt} = I_m = \frac{V_e}{N} \tag{1}$$

$$F_{mmf} = V_m = N \times I_e \tag{2}$$

where N is the number of turns in each winding. In the permeance-capacitor model, the electric voltage, V_e [V], is transformed to the magnetic current, I_m [Weber/sec]. that describes the rate of flow in magnetic flux, Φ (Faraday's law). At the same time, the electric current, I_e [A], is mapped to the magnetic potential variable, V_m [A·turn], that describes ampere-turns, or magneto-motive force, F_{mmf} (Ampere's law).

B. Magnetic modeling

In linear magnetic elements, the permeance-capacitance named as inductance factor inside PSIM block, is defined as following formula.

$$P = \mu_r \mu_o \frac{A_{eff}}{l_{eff}} \tag{3}$$

where, P is the permeance[Henry/turn^2], A_{eff} is the effective core cross sectional area[m^2], l_{eff} is the effective magnetic flux length[m]. Deriving the pearmeance-capacitance as a whole body can be performed simply with the effective dimension supplied by core datasheets. However, it is common to use custom-made structure other than standard core parts.

TABLE I. MAGNETIC CORE FLUX CALCULATION

Permeance	l_{eff}	A_{eff}
P_{o1}	h	$c_2 w$
P_{o2}	$\frac{\pi}{8}(c_1 + c_2)$	$\frac{w}{2}(c_1 + c_2)$
P_{o3}	b_w	$c_1 w$
P_{o4}	$\frac{\pi}{8}(c_1 + \frac{d}{2})$	$\frac{w}{2}(c_1 + \frac{d}{2})$

TABLE II. LEAKAGE FLUX CALCULATION

Permeance	l_{eff}	A_{eff}
1	$b_w{}'$	$l_w(\frac{h_1}{3})$
2	$b_w{}'$	$l_w \times h_\Delta$
3	$b_w{}'$	$l_w(\frac{h_2}{3})$

Therefore, to analyze exactly the core structure, it is always best to use divide-and-conquer approach.

However, without an accurate guideline, the modeling accuracy is not guaranteed. This section proposes the effective guideline to use such a divide-and-conquer rule. For an effective explanation, a typical two winding LLC transformer structure with side-by-side winding configuration shown in Fig. 2 (a) is used as an example. It should be noted that the proposed strategy can be applied to any other structure with slight modification.

For a magnetic flux in core, finding a permeance-capacitance of the linear core block is rather straight-forward. As shown in Fig. 2 (a), the core structure is partitioned unit elements, P_{o1}~P_{o4} and P_{c1} [4]. Using Table 1 and Eq. (3) inductance factor is calculated. For an airgap in the magnetic flux path, it can be modelled in the similar fashion by air gap element.

Most challenges in the modeling process exists in calculating the leakage magnetic flux because it heavily depends on winding structure. Fig. 2 (b) indicates the distribution of F_{mmf} built by each winding. In this figure, P and S indicate the window space occupied by primary and secondary winding, respectively. First, we can divide the leakage path into three regions – the primary winding, the secondary winding, and the intermediate region. In the primary winding region, according to Ampere's law, the F_{mmf} is linearly proportional to the position of evaluation and the following holds.

$$\oint H ds = N_1 I_1 \frac{x}{h_1} \tag{4}$$

where x is the position along the core axis, s is the distance along the core axis, N_1 is the number of primary turns, and I_1 is the primary current. From the differential volume in Fig. 2 (c), the stored energy relation [5] states that

$$\frac{\mu_o}{2}\int_0^h H^2 l_w b_w dx = \frac{1}{2} N_1^2 P_1 I_1^2 \tag{5}$$

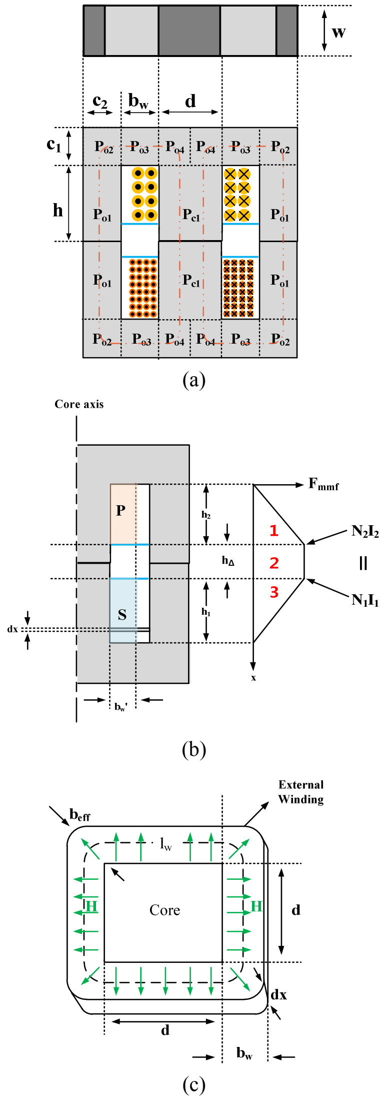

Fig. 2. Full wireless power system based on C-WPT
(a) core partitioning, (b) leakage flux distribution, (c) differential volume

where P_1 is the permeance-capacitance evaluated in the primary winding region and l_w is the mean length turn (MLT). In the intermediate region, F_{mmf} is constant and thus independent of the position of evaluation. Likewise, similar analysis can be performed in the secondary region. Therefore, it is possible to define the permeance capacitance of the leakage three section and the results are summarized in Table 2. This paper recommends the following formula to calculate MLT, where b_{eff} represents the diagonal length from outermost winding to innermost winding.

$$l_w = 4d + \pi b_{eff} \tag{6}$$

C. *Transformer parameter extraction*

All-primary-referenced (APR) model in Fig. 3(a) is very useful to extract the terminal characteristics of transformers. For the purpose of test and evaluation, a simulation jig in Fig. 3 (b) is devised to measure the inductances and perform short and open terminal test on the PSIM magnetic circuit model.

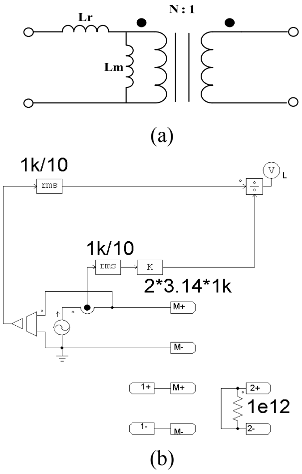

Fig. 3. Extraction of terminal characteristics
(a) APR model, (b) simulation jig

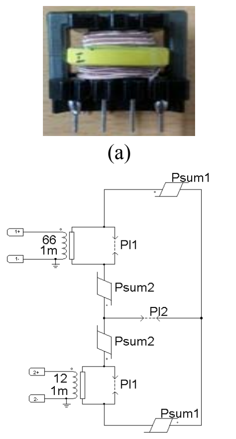

Fig. 4. PSIM implementation for a prototype LLC transformer
(a) transformer sample, (b) PSIM magnetic model

With the help of calculation blocks in PSIM, the simulated inductance is automatically plotted in time simulation. Leakage inductance is obtained by shorting the opposite terminal, while the sum of magnetizing and leakage inductance is obtained by opening it.

III. PERFORMANCE VERIFICATION

For verification of the proposed method, a prototype transformer with a structure shown in Fig. 2 (a) is constructed [6]. The specifications are listed in Table 3 and the transformer sample is shown in Fig. 4(a). In order to closely examine the leakage inductance formula, prototype transformers are constructed in two different window fill factors: 50% and 100% of the window size are occupied by windings, respectively. Fig. 4(b) shows a PSIM simulation model for the transformer samples. It is constructed by the method presented in the Section II.

In order to extract the terminal parameters in the all-primary-referenced (APR) model, a sequence of short and open circuit tests are performed on the prototype transformers and

TABLE III. DESIGN SPECIFICATION OF A TEST TRANSFORMER

	50% winding	100% winding
core	EE2519	
turn ratio	5.56 : 1	5.27 : 1
num. of turns (pri.)	33	66
num. of turns (sec.)	6	12
insulation gap	3.3mm	
wire size (pri.)	0.06/20 litz	
wire size (sec.)	0.1/40 litz	
relative permeance	2400 (PL-7)	

TABLE IV. DESIGN EVALUATION

	category	L_r	L_m
50% winding	measurement	44.47uH	2.202mH
	simulation	45.92uH	2.16mH
	error	2.70%	-1.90%
100% winding	measurement	283.1uH	8.63mH
	simulation	232.5uH	8.61mH
	error	-17.87%	-0.23%

the corresponding inductance has been measured by LCR meter. For a comparison, a simulation jig in Fig. 3 (b) is used to test the constructed PSIM magnetic circuit model. Table 4 summarizes the comparison results between the measurement and the simulation. Model error is less than 2% for magnetizing inductance while becomes about 20% for leakage inductance, which is very accurate result as for lumped model approaches.

IV. CONCLUSION AND FUTURE WORK

This paper proposes an effective modeling approach using PSIM magnetic circuit library for integrated magnetic components. Because of its accuracy as well as simplicity, this approach is attractive for analysis and design of transformers. This paper also establishes user guide and formula to determine the permeance-capacitors in both core and leakage path from design specifications. The derived formula has been verified by measurement results. It is concluded that the proposed method simplifies the modeling, gives a lot of design insight with good accuracy, and provides a valuable design and analysis techniques for magnetic components.

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