# An Effective Transformer Simulation Technique using PSIM Magnetic Elements

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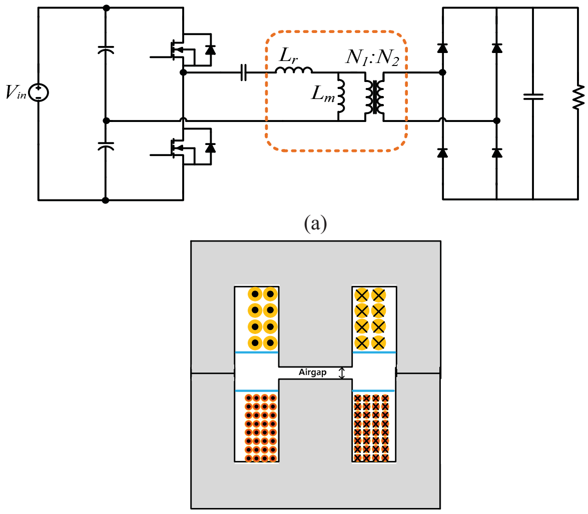
***Abstract*— Magnetic circuit is a powerful tool in the design of power transformers, especially for a priori evaluation of leakage and magnetizing inductance before actual production of the components. This paper investigates an alternative modeling approach using PSIM magnetic circuit library to remove 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. Because of its accuracy as well as simplicity, this approach is attractive for analysis and design of LLC resonant transformers whose leakage and magnetizing inductance are very critical to circuit operation.**

***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][2]. It utilizes a magnetic transformer that incorporates leakage and magnetizing inductors into a single core with moderate turn-ratio. Moreover, it is not strange to use custom-made structures instead of standard off-the-shelf core parts, to achieve low profile or low cost power supplies. Because of its critical role in the circuit operation, a priori evaluation of leakage and magnetizing inductance before actual production is essential in the design stage, and this can be achieved by establishing appropriate transformer model describing the core and winding structure in various shapes.

While modeling approach with field simulator such as Maxwell 2D/3D shows highly accurate results, it has disadvantages in cost and simulation time [3][4]. For this reason, this paper only focuses on the circuit simulator approach. In circuit simulation programs, a magnetic component can be modeled first by a magnetic circuit, and then its terminal characteristics are utilized. Magnetic circuit is constructed by the concept of electro-magnetic analogy so that it preserves original physical meaning such as material property, core dimension, and winding structure, and thus it is suitable to magnetic component design process. On the contrary, terminal parameters characterize the electrical behaviors such as leakage and magnetization inductances, where it is useful in circuit analysis and device measurement.



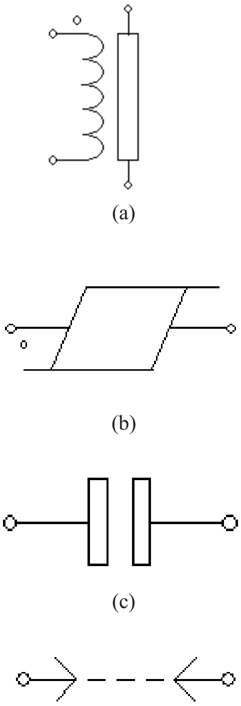
(a)

(b)

Fig. 1. Full wireless power system based on C-WPT
(a) LLC converters, (b) a LLC transformer structure with side-by-side winding

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 because user should manually transform its node to mesh or vice versa before placing them in the circuit simulator, in order to resolve inherent duality between magnetic and electric energy [5][6]. 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 [7][8][9]. Recently, PSIM, a circuit simulator specialized in power electronics, has introduced the magnetic elements library that adopts this kind of model. However, they have not been commonly used because of limited information on this library.

The purpose of this paper is to investigate feasibility of using PSIM magnetic circuit library as a design and analysis



(a)

(b)

(c)

(d)

Fig. 2. PSIM's magnetic element library
(a) winding, (b) linear core, (c) air gap, (d) leakage path

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 as shown in Fig. 2: 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 [10][11][12]. In this section, modeling is studied in detail.

### A. *Electro-magnetic coupler modeling*

PSIM winding block in Fig. 2 (a) 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). Additional resistance field in the PSIM winding element is reserved for loss analysis, but it will not be used in this paper for model simplicity.

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 | $b_w'$ | $l_w(\frac{h_2}{3})$ |

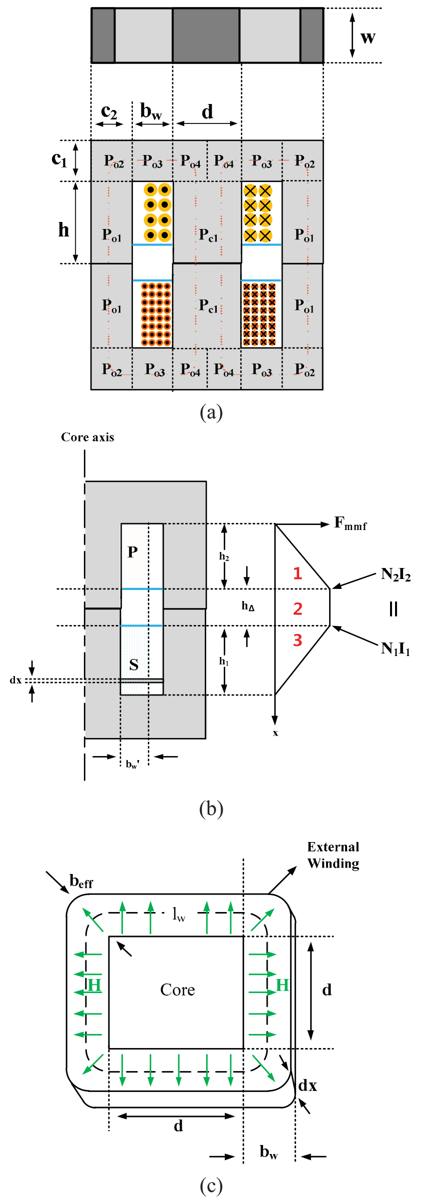
### B. *Magnetic circuit modeling*

In linear magnetic elements, the permeance-capacitance named as inductance factor inside PSIM block, is defined as the 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. Therefore, to analyze exactly the core structure, it is always best to use divide-and-conquer approach. In other words, at first the whole core body is divided into unit elements to calculate individual permeance-capacitance. In the final stage, they are connected to recover the original core structure.

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. 1 (b) is used as an example. It should be noted that the



(a)

(b)

(c)

Fig. 3. Full wireless power system based on C-WPT
(a) core partitioning, (b) leakage flux distribution, (c) differential volume

proposed strategy can be applied to any other structure with slight modification.

For a magnetic flux in the core, finding a permeance-capacitance of the linear core block is rather straight-forward. As shown in Fig. 3 (a), the core structure is partitioned unit elements, $P_{o1}$~$P_{o4}$ and $P_{c1}$ [14]. 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. 3 (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. Here also applies the divide-and-conquer rule. 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.

$$\oint \cdot Hds = N_1 I_1 \frac{x}{h_1} \tag{4}$$

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. 3 (c), the stored energy relation [15] states that

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

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.

$$l_w = 4\mathrm{d} + \pi \mathrm{b}_{eff} \tag{6}$$

### *C. Transformer parameter extraction*

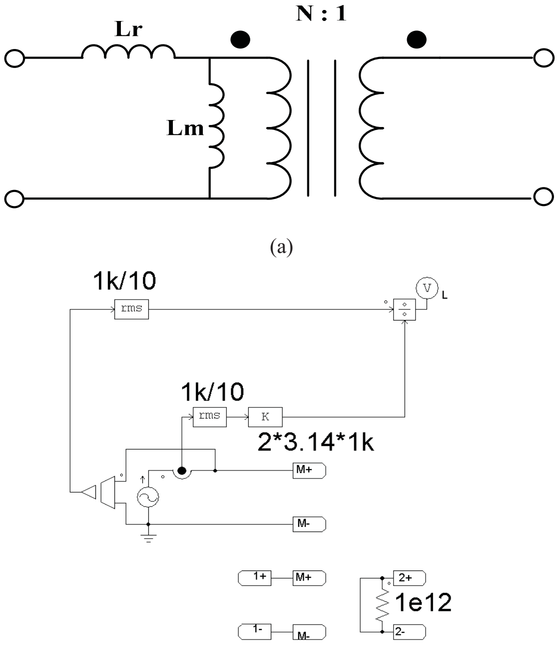
All-primary-referenced (APR) model in Fig. 4 (a) is very useful to extract the terminal characteristics of transformers where $L_r$ is an effective series inductance, $L_m$ is an effective parallel inductance and N is the effective turn ratio of APR model. Their formulas are shown as follows.

$$L_r = (1 - k^2) L_{s1} \tag{7}$$

$$L_m = k^2 L_{s1} \tag{8}$$

$$N = \frac{M}{L_{s2}} = \sqrt{\frac{L_m}{L_{s2}}} \tag{9}$$

In the above formulas, $L_{s1}$ is the primary self-inductance, $L_{s2}$ is the secondary self-inductance, M is the mutual inductance, and k is the coupling coefficient of windings.



(a)

(b)

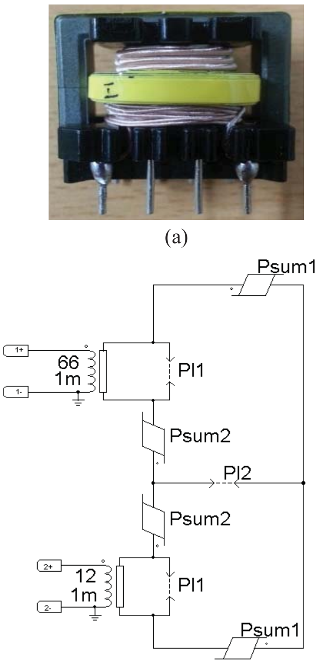
Fig. 4. Extraction of terminal characteristics
(a) APR model, (b) simulation jig

For the purpose of test and evaluation, a simulation jig in Fig. 4 (b) is devised to extract the inductances by performing short/open terminal test on the PSIM magnetic circuit model.

$$L = \frac{V}{I \times 2\pi f} \tag{10}$$

The inductances are easily calculated by the PSIM jig according to Eq. (10). With a sinusoidal alternating current source injected to the either terminal pair of the PSIM transformer model block, both the input current and the voltage applied between the terminals are measured using 'rms' blocks shown in the figure. For the test frequency, arbitrary value can be chosen and the fundamental frequency of the rms block is set to one-tenths of the driving frequency to average the output value. In this paper, 1KHz has been used for the test frequency.

Electrical terminal characteristics of a given transformer can be completely described from the simulation jig. First, primary side measurements are performed by making the secondary terminal open. Because PSIM fails to work with an open terminal, a dummy resistor with very large resistance value is placed instead on the secondary side. With the secondary side open, the equivalent inductance seen from the primary is the sum of the series inductance, $L_r$ and the parallel inductance, $L_m$. Secondly, with the secondary side short, all the winding elements are completely opened and only the series inductance of the transformer is visible. And thus, $L_r$ and $L_m$ are solved using the simultaneous equations. Finally, the secondary self-inductance, $L_{s2}$ can be obtained by switching between the terminals, (1+,1-) and (2+,2-) in Fig. 4 (b) to measure the inductance from the secondary side with the primary open. It can be used to calculate the effective turn ratio, N, as well as the coupling coefficient, k, by using Eqs. (7)-(9), which completes the transformer characterization.



(a)

(b)

Fig. 5. PSIM implementation for a prototype LLC transformer
(a) transformer sample, (b) PSIM magnetic model

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% |

## III. PERFORMANCE VERIFICATION

For verification of the proposed method, a prototype transformer with a structure shown in Fig. 1 (b) is constructed

[16]. The specifications are listed in Table 3 and the transformer sample is shown in Fig. 5 (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. 5(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 the corresponding inductance has been measured by LCR meter. For a comparison, a simulation jig in Fig. 4 (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 $L_m$ while becomes about 20% for $L_r$, 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. In the subsequent work, loss factor will also be discussed.

## REFERENCES

[1] B. Yang, F. C. Lee, A. J. Zhang, and J. Y. Lee, “LLC resonant converter for front end DC/DC conversion,” in Proc. IEEE Appl. Power Electron. Conf., 2002, pp. 1108-1112

[2] G. M. Kim, J. U. Yoo, T. K. Kim, C. H. Kang, and T. W. Chun, ″ Development of Battery Charger for Electric Vehicle using the LLC Resonant Converter,″ Transaction of the korean inititu. of Power Electronics, Vol. 18, No. 5, pp. 443-447, Oct. 2013

[3] N. H. Kim, J. H. Nam, and K. H Choi, ″A Study on Flux Barrier of Permanent Magnet Assisted Reluctance Synchronous Moter Design using FEM, ″ Transaction of the korean inititu. of Power Electronics, pp. 298-302, Aug. 2008

[4] C. Alvarez-Marino, F. de Leon and X. M. Lopez-Fernandez, "Equivalent Circuit for the Leakage Inductance of Multiwinding Transformers: Unification of Terminal and Duality Models," IEEE Transactions on Power Delivery, vol. 27, no.1, pp. 353-361, 2012

[5] Lloyd Dixon, “Deriving the Equivalent Electrical Circuit form the Magnetic Device Physical Properties,” Oct. 1994

[6] Gerald W. Ludwig and Sayed-Amr El-Hamamsy, "Coupled Inductance and Reluctance Models of Magnetic Components," IEEE Transsactions on Power Electronics, vol. 6, no.2, pp. 240-250, Apr. 1991

[7] David C. Hamill, “Lumped Equivalent Circuits of Magnetic Components: The Gyrator-Capacitor Approach,” IEEE Trans. on Power Electronics, vol. 8, no.2, pp. 97-103, Apr. 1993

[8] David C. Hanmill, "Gyrator-Capacitor Modeling: A Better Way of Understanding Mganetic Components," Applied Power Electronics Conference and Exposition, pp. 326-332, 1994

[9] Liang Yan and Brad Lehman, "A Capacitor Modeling Method for Intgegrated Magnetic Components in DC/DC Converters," IEEE Transsactions on Power Electronics, vol. 20, no.5, pp. 987-996, Sep. 2005

[10] PSIM User′s Guide, Ver. 9, May, 2010, POWERSIM.

[11] Tutorial on How to Define the Saturable Core Element, July, 2006, POWERSIM

[12] Eaton, M. E. ″Adding Flux Paths to SPICE's Analytical Capability Improves the Ease and Accuracy of Simulation Power Circuits,″ Applied Power Electronics Conf., vol. 1, pp. 386-392, 1998

[13] Calculation of the Effective Parameters of Magnetic Piece Parts, British Standard 60205, 2009.

[14] E. C. Snelling., 1969, Soft Ferrites-Properties and Applications, second ed., London Iliffe Bbooks ltd., pp.337-358.

[15] De Simone, C. Adragna, C. Spini, “Design guideline for magnetic integration in LLC resonant converters,” International Symposium on Power Electronics, pp. 950-957, 2008

[16] N. Y. Abed and O. A. Mohammed, ″Physics-Based High-Frequency Transformer Modeling by Finite Elements,″ IEEE Transactions on Magnetics, vol. 46, no.8, pp.3249-3252, 2010