A Method for Inductor Core Loss Estimation in Power Factor Correction Applications

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***Abstract* – Conventional core loss estimation methods exhibit limitations in dealing with important aspects of switching power converter applications such as different duty cycles, discontinuous-conduction-mode, variable switching frequency, or variable duty cycle operation. These limitations are particularly evident when trying to estimate boost inductor core loss in Power Factor Correction circuits. This paper first presents a core loss estimation method that addresses these limitations and then demonstrates an effective technique to estimate core losses in Power Factor Correction circuits. Finally, we show examples of how this method can be conveniently incorporated into simulation software to automate the core loss estimation process. The inductor models that are developed to facilitate this automatic core loss estimation and the approaches to implement the calculation in simulation software, especially a program called SIMPLIS, are also provided.**

I. INTRODUCTION

Accurate estimates of the magnetic core loss are important when designing the magnetic devices used in switching power converters. Besides time-consuming direct hardware measurements, the most common estimation methods in practice rely on rough calculations based on core manufacturer's data book [1-4]. Because these data are typically taken under sine wave excitation conditions, they are very difficult to apply to switching power conversion applications. This is especially true in Power Factor Correction (PFC) circuits where duty-cycle and switching frequency can vary with the instantaneous input voltage of the converter. In addition, the very wide input voltage variation can cause the converter to transition back and forth from discontinuous to continuous conduction mode operation. This paper presents a method of estimating core losses that can address switching power conversion applications where duty cycle and/or frequency may vary with operating conditions. This method can be applied equally well to the continuous or discontinuous conduction mode of operation. We then show how this method can be applied to Power Factor Correction circuits where duty cycle, frequency and conduction mode may vary with instantaneous input voltage through out the AC line cycle. Although it is quite straightforward to implement this method of core loss estimation manually, even for PFC circuits, we also demonstrate that this method is well suited for implementation with circuit simulation tools allowing the process to be automated.

Usually in the data sheet of the core, a cluster of curves can be found, which show the core loss per unit volume (or weight) under sine wave excitation versus the maximum flux density for different values of switching frequency. Look up a value in these curves, multiply it by the volume (or weight) of the core, and that is the estimation of the core loss. In some data books, those core loss curves are also fit into a so-called Steinmetz equation as follows:

$$P_{\mathrm{v}} = \mathrm{C} f_{\mathrm{s}}^{\mathrm{X}} B_{\mathbf{max}}^{\mathrm{Y}}, \tag{1}$$

where P_{v} is the power loss density, f_{S} is the switching frequency, and specific value of C, X and Y are listed as core loss parameters for each material.

This traditional core loss estimation method is far from satisfactory as:

1) The curves that manufacturers provide were obtained through measurement under sine wave excitations, which could result in certain error in this core loss estimation method as in most cases the inductors in the switching power converters are operating under square wave excitations [5].
2) This method does not reflect the core loss difference between Continuous-Conduction-Mode (CCM) operation and Discontinuous-Conduction-Mode (DCM) operation, the core loss difference caused by different switching duty cycle, or in DCM mode, the core loss difference caused by different zero-voltage time on the inductor.
3) This method is difficult to apply to circuits with variable switching frequency operation. For example, critical conduction mode operation and quasi-square-wave mode operation in single-phase boost Power Factor Correction (PFC) circuit are both variable switching frequency cases [6, 7].
4) This method does not reflect the core loss difference between constant duty cycle operation circuit and

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variable duty cycle operation circuit. E. g., the popular single-phase CCM boost PFC circuit is a typical variable duty cycle operation circuit;

Paper [3] and [4] made good efforts to address the first two points. But the need to find a more effective core loss estimation method is still essential to cover all the above issues.

In seeking an improved core loss estimation method, another important aspect is the feasibility of implementing the method using available switching power converter simulation tools. It is very desirable that core loss estimation method can be embedded into the switching power converter simulation program and can automatically calculate the inductor core loss for the customers as they investigate a converter circuit through computer simulation.

This paper proposes an improved inductor core loss estimation method for switching power converters. It overcomes the drawbacks that are listed and can be easily embedded into power electronics circuit simulation software to realize automatic core loss calculation. The core loss model and the calculating equation of this method are first introduced. Then the inductor models that are developed to facilitate the automatic core loss calculation in simulation programs based on this method are described in detail. The approaches to implement the calculation are also introduced. One of them is particularly suitable for realization in a fast simulation tool—SIMPLIS [8] from Transim Technology.

II. THE PROPOSED CORE LOSS ESTIMATION METHOD

A. *The Core Loss Model and Calculating Equation*

The energy loss per unit volume of a core in one switching cycle is the area enclosed by the B-H loop during that switching cycle as shown in Fig. 1. The following observations reveal that core loss is not inherently related to switching frequency and flux density variation as it looks. The width of the B-H loop is related to *dB/dt*, the rate at which the flux density changes, increasing as *dB/dt* increases. In most cases, inductors in high frequency switching power converter circuits are operating under square wave or quasi-square wave voltage excitations, where *dB/dt* is constant when the power switch is on and while the power switch is off and the rectifying diode is conducting. But typically, the voltage across the inductor is different during these two intervals as is *dB/dt*. Consequently, we expect the core losses to be greater during the interval when *dB/dt* is greater.

Based on the above ideas, we propose that the core loss of an inductor can be calculated as:

$$P = \alpha V \left[\left(\Delta B^{\,m} / (2t_{ON})^{\,n} \right) t_{ON} / T_S + \left(\Delta B^{\,m} / (2t_{OFF1})^{\,n} \right) t_{OFF1} / T_S \right], \qquad (2)$$

where

t_{ON} is the interval when switch is on and flux density B is increasing;

t_{OFF1} is the interval when switch is off and flux density is decreasing;

t_{OFF2} is the zero-voltage time, the interval when switch is off and flux density is not changing;

T_S is the switching period, which is the sum of t_{ON} , t_{OFF1} , and t_{OFF2};

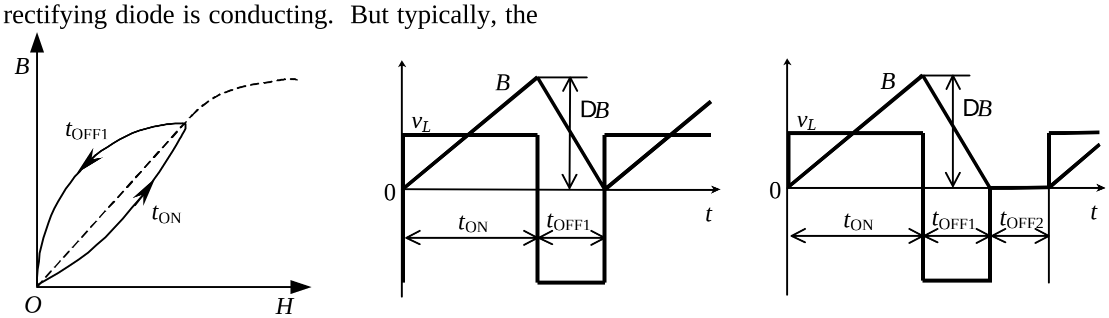
V is the volume of the core.

α, m and n are constants for each core material, and can be obtained through appropriate measurement under square wave excitation and then corresponding curve fitting. For a 50% duty cycle square wave, (2) reduces to the same form as the Steinmetz equation (1)

$$P = \alpha V \Delta B^{\,m} f_S^{\,n}, \qquad (3)$$

where f_S is the switching frequency. This means that the proposed core loss model and calculating method can be simplified to the same form of the previous core loss estimation method when the circuit operates at CCM mode with constant frequency and a constant 50% duty cycle. Of course, the parameters α, m, and n are different from the corresponding parameters in (1) because there are significant differences in the core losses under square wave excitation and sine wave excitation even with same ΔB and f_S [5].

We can see that the proposed method separates the core loss into two parts, the on-time t_{ON} and off-time t_{OFF1}, so the difference between CCM mode and DCM mode and the difference caused by different switching duty cycles can all be clearly reflected. Even more, in the DCM mode, given the switching period T_S and on-time t_{ON} , the calculated core loss will also vary with the off-time t_{OFF1} . Or, in other words, it also clearly reflects the difference caused by different zero-voltage time t_{OFF2}. When t_{OFF2} gets zero, or in other word t_{ON} plus t_{OFF1} equals T_S , circuit gets into CCM mode.



a) B-H loop b) CCM waveform c) DCM waveform

Fig. 1 Typical B-H loop and waveform of inductor in switching power converters

Another good feature of the proposed method is the calculation can be carried out cycle by cycle. That means the switching period T_S , on-time t_{ON} , and the off-time t_{OFF1} could be different for each switching cycle, and the result of (2) is just the average core loss over each switching cycle. Therefore, the overall average core loss during k switching cycles can be calculated as

$$p = \frac{\mathbf{1}}{\sum_{j=\mathbf{1}}^{k} T_{Sj}} \sum_{j=\mathbf{1}}^{k} T_{Sj} P_j \ , \tag{4}$$

where T_{Sj} is the period of the number j switching cycle, and P_j is the average core loss during the number j switching cycle based on the computation of (2). This shows that the proposed method can easily deal with variable switching frequency, and variable duty cycle situations. For the constant switching frequency and constant duty cycle case, (4) just simplifies to (2).

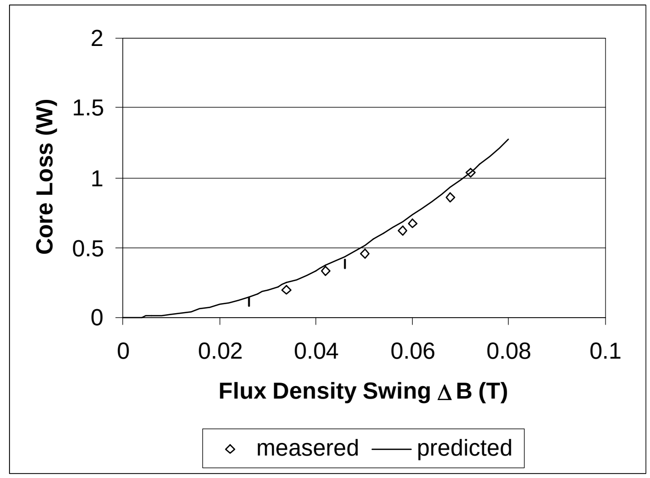
B. Experimental Verification

Core loss measurement is a very elaborate and time-consuming work. Recent published core loss measurement data in [4] are cited to compare with the prediction based on the proposed estimation method. The experiments were done on a buck-boost converter operating at CCM mode at different duty cycles. Philips EFD20 core sets with 3F3 material were used. The core loss parameters are α=1.214, m=1.923, and n=1.503, which are transferred from parameters in [4] under 50% duty cycle condition. Fig. 2 shows that the predicted results are all very close to the measured data.

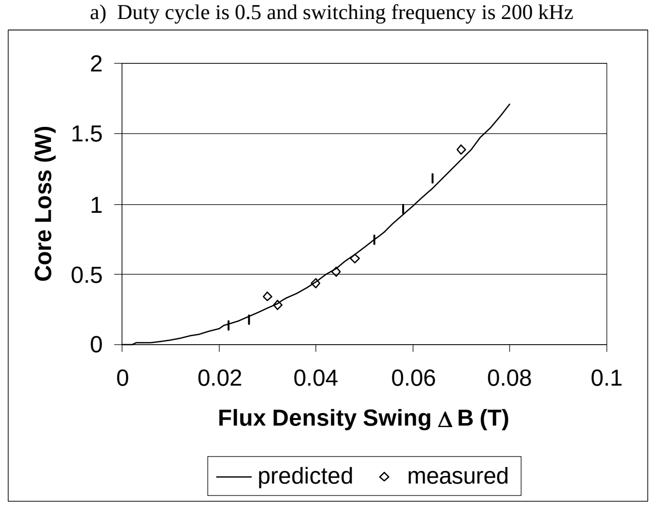
III. CORE LOSS ESTIMATION FOR SINGLE PHASE PFC APPLICATIONS PFC

To implement the proposed core loss estimation method in a computer simulation program, first, a special inductor model is needed. This inductor model should include flux density as one of its variables (not just the voltage across it and the current through it), so that the time-domain flux density data can be obtained through simulation. Second, an implementation algorithm is needed for (2) and (4), so that the core loss can be calculated by computer according to the simulated time-domain flux density data.

The following part shows the inductor models the authors developed to get the time-domain flux density data, and the algorithms used to calculate core loss based on the flux density waveform.



a) Duty cycle is 0.5 and switching frequency is 200 kHz



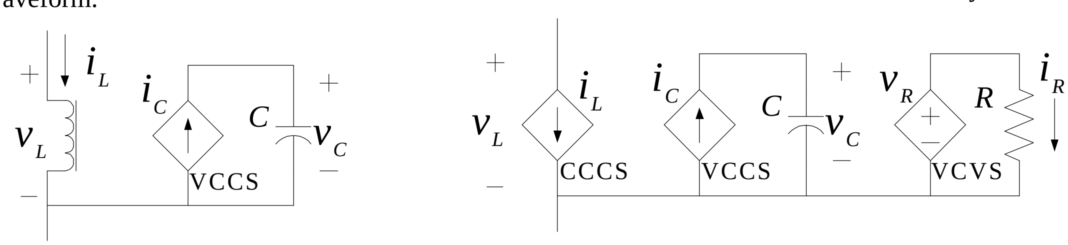
b) Duty cycle is 0.4 and switching frequency is 240 kHz

Fig. 2 Comparison of measured data from Chung et al [4] and predicted results from the proposed method

All the simulation results are done with SIMPLIS, although these models and algorithms could also be incorporated into other simulation software. Finally, a simplified implementation approach for estimating the core loss of inductor in single-phase PFC circuits is also developed, that is particularly effective for SIMPLIS simulations.

A. Inductor Models to Obtain Time-Domain Flux Density Data

Fig. 3 shows the inductor models the authors developed to obtain the time-domain flux density.



a) Model I b) Model II

Fig. 3 Inductor models to obtain time-domain flux density data

For model I, we define

$$i_C = v_L \text{, and } C = NA \text{,}$$

where N is the number of turns and A is the core area. Then

$$v_C = \frac{\mathbf{1}}{C}\int i_C\,dt = \frac{\mathbf{1}}{NA}\int v_L\,dt = B\,. \qquad (5)$$

That means the voltage v_C is numerically equal to the flux density of the core in Tesla. The nonlinear B-H characteristics of the core could be emulated by replacing the liner inductor L with a Piece Wise Linear (PWL) inductor.

For model II, We define

$$i_C = v_L\,,\ \ v_R = v_C\,,\ \ i_L = \frac{l}{N} i_R\,,$$

$$C = NA\,,\ \text{ and }\ R = \mu_e \mu_0\,,$$

where l is the length of magnetic path and μ_e is the equivalent relative permeability. Then (5) is also valid and the nonlinear B-H characteristics of the core can be emulated by replacing the liner resistor R with a PWL resistor.

In order to get better convergence in SIMPLIS simulation, model II is chosen to obtain the time-domain flux density data although it is slightly more complicated than model I. Simulation results have verified the effectiveness of this model. Fig. 4 shows the simulated waveform of this model when incorporated into a boost DC/DC circuit as a boost inductor during a transient process. The waveform simulated with a regular inductor model is also shown as comparison. The following is some of the inductor data:

EE75 core, $N = 50$, $L = 500\ \mu$H,
$l = 0.107$m, and $A = 3.36\times10^{-4}\ \mathrm{m}^2$.

B. Calculation of Core Loss based on Flux Density Data

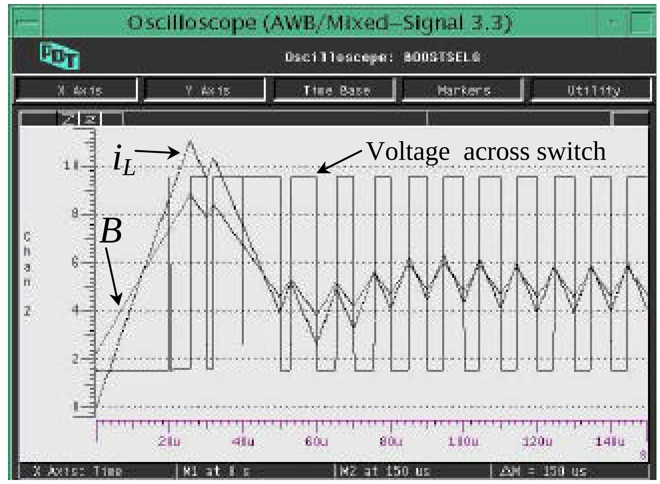
For constant frequency and constant duty cycle operation, the calculation of the overall average core loss based on (4) is very simple and can be simplified as just calculating (2). This can even be implemented by manual calculation once ΔB, T_S, t_{ON}, and t_{OFF1} are read out from the flux density waveform.

For other cases, ΔB, T_S, t_{ON}, and t_{OFF1} have to be identified for each switching cycle. Then the average core loss over each switching cycle can be calculated out based on (2), and the overall average core loss can be obtained through (4).

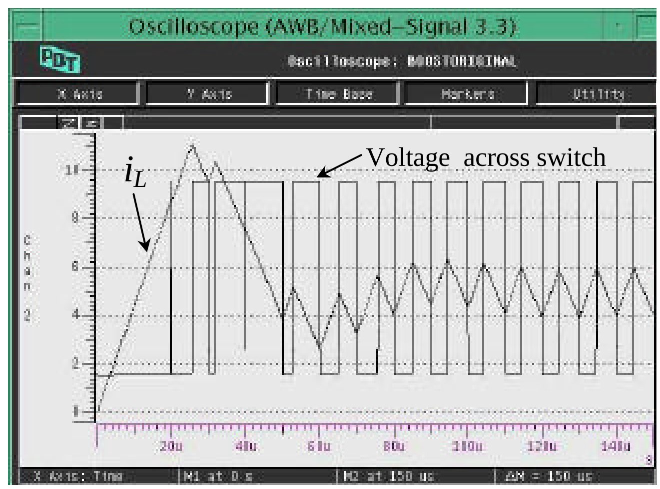
In fact, looking at (2), if we notice that the ΔB for the time interval t_{OFF2} is zero, then (2) is actually the summation of three similar items. These three items are respectively related to the three time intervals t_{ON}, t_{OFF1}, and t_{OFF2}, which separate the flux density waveform into three segments, each with a constant dB/dt. Keeping this in mind with (4), we can extend the core loss calculation equation to a more general form. Assume there are k segments of the flux density waveform identified by k+1 break points of time-domain flux density data

$$(t_0, B_0), (t_1, B_1), \ldots\ldots, (t_k, B_k),$$

if each segment is of constant dB/dt, and between any two adjacent segments there is a sign change of dB/dt or there is a



a) Using inductor model II



b) Using regular inductor model

Fig. 4 Simulated waveform of a boost inductor

segment in which dB/dt is zero, then the overall average core loss during t_0 to t_k can be calculated as

$$p = \alpha V \sum_{i=\mathbf{0}}^{k-\mathbf{1}} \left\{ \left|B_{i+\mathbf{1}} - B_i\right|^m \left[\frac{\mathbf{1}}{\mathbf{2}(t_{i+\mathbf{1}} - t_i)}\right]^n \frac{(t_{i+\mathbf{1}} - t_i)}{(t_k - t_{\mathbf{0}})} \right\}. \qquad (6)$$

(2) and (4) are just special cases of this equation.

This process and calculation based on (6) is well suited for single phase PFC circuits where there are a large number of switching cycles in an AC line cycle and the duty cycle and even the switching frequency can vary from one conversion cycle to the next.. Fortunately it is not difficult to program this process and calculation into a computer and have these done automatically once the time-domain flux density data is obtained through simulation.

To verify the effectiveness of (6), measurement data from [3] are cited to compare with estimation data based on (6). Paper [3] provided the measured core losses data of Philips E42/21/15 core sets with 3C85 ferrite material under the flux density waveform as shown in Fig. 5. Here T_0 is 50 μs, and the integer n_0 is set to different value to get different switching period T. It is a constant frequency and constant duty cycle case, but with 4 segments of flux density waveform in each cycle (PFC cases are actually hundreds or thousands of segments of flux density waveform in each line cycle). Paper [3] did not provide any core loss parameters under square wave excitation. We just use the parameters of a similar MnZn ferrite material instead, obtained from measurement and curve fitting [9], where α=21.11, m=2.08, and n=1.02. Fig. 6 shows the comparison of the measured data from [3] and predicted results based on (6). The results are fairly close if we keep in mind that we introduced a certain error using core loss parameters from a slightly different ferrite material.

C. A Simplified Implementation Approach in SIMPLIS for Single-Phase PFC circuits

Using (6) we are now able to estimate core loss based on a simulation of a PFC circuit over the course of ½ of an AC line cycle These results are presented later in this section in Table I. This brute force approach is tractable, but it is computationally intensive. For single-phase PFC circuits, Fig. 7 suggests how we can simplify this task and speed up the process by an order of magnitude while still obtaining very accurate results. In fact, this method is even amenable to hand calculations where the brute force approach is not.

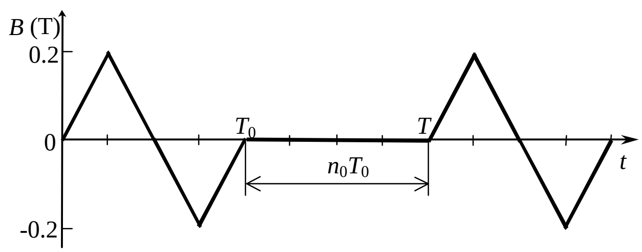


Fig. 5 Experimental flux density waveform provided in [3]

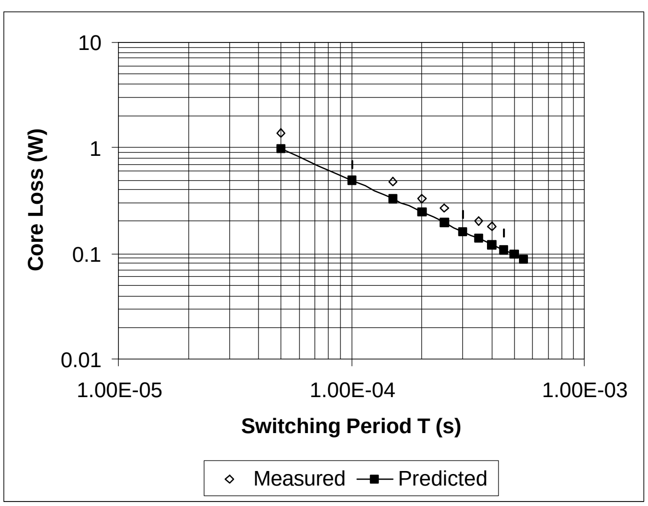


Fig. 6 Comparison of measured data from Albach et al [3] and estimation data from the proposed method

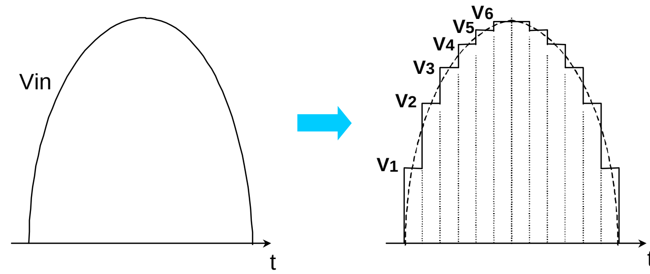
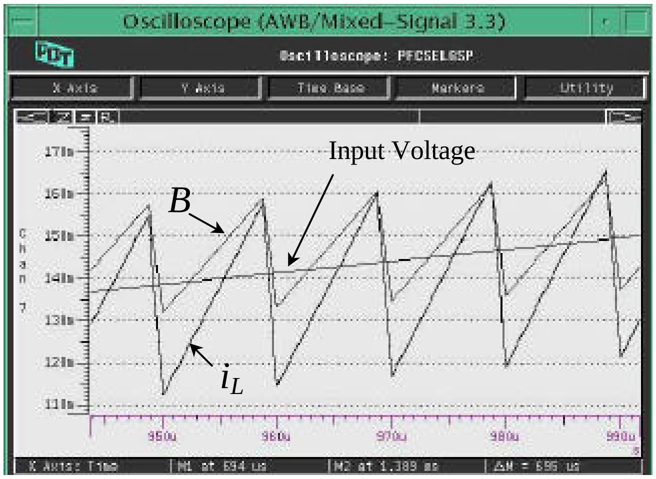


Fig. 7 6-step DC input approach for single-phase PFC circuits

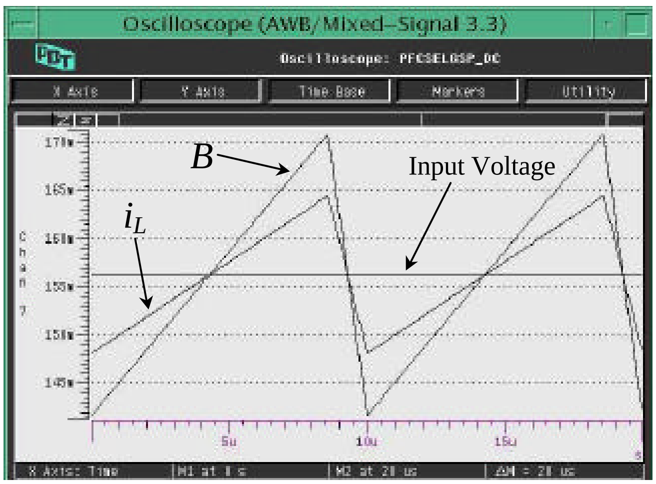
As shown in Fig. 7, similar to the methodology for semiconductor loss evaluation in [10], the idea is just to evenly divide each quarter line cycle into 6 time intervals and replace the AC voltage input with a 6-step DC input voltage for every quarter line cycle period. Specifically the DC input voltage of each step is set at the RMS value of the replaced AC input voltage during that time interval. Since for each step we want to look at the steady-state waveform of 1/6 of quarter line cycle and the voltage control loop of the PFC is much slower than this, we have to break the voltage loop and replace the DC bulk capacitor with a battery of the same steady-state DC voltage value. Therefore, for each step, the circuit is just a DC/DC converter with only the current control loop. Usning SIMPLIS, we can automatically and very quickly find out the steady state waveforms using the Periodic Operating Point (POP) analysis [8]. Because the DC/DC converter is in steady state, we only need to simulate one switching cycle to compute the time-domain flux density waveform. We can then estimate the average core loss during each step. The overall average core loss is just the arithmetic average of the average core losses of the 6 steps. So, this simplified method requires simulating only one cycle of steady-state converter operation at six different DC input voltages.

In contrast, using the brute force simulation of the full AC input requires much more CPU time to run the circuit through enough AC line cycles to reach steady state. Then once the circuit is close enough to steady state, we need the additional time-domain data of all the switching cycles within the quarter line cycle to calculate the core loss.

The simulations of Fig. 8 are done with a CCM mode single-phase boost PFC circuit using the same inductor as mentioned in subsection A to compare these two implementation approaches. The comparison results shown in Table I verify that the 6-step DC input approach is much faster while the calculated core loss is satisfactorily close to the regular AC input approach. Fig. 8 shows the simulated waveform from the two different approaches. Table I shows the comparison of calculated losses of this inductor between the 6-step DC input approach and the regular AC input approach. The difference in each time interval is within 6% and the final averaged loss for a quarter line cycle is within 2.5%. The total consumed CPU time during the time-domain simulation by the regular AC input approach is 66 CPU seconds while the 6-step DC input approach is just 7.6 CPU



a) Using the regular AC input approach



b) Using the proposed 6-step DC input appoach

Fig. 8 Simulated waveform of an inductor in CCM mode single-phase boost PFC circuit

TABLE I COMPARISON OF CALCULATED CORE LOSSES IN A PFC CIRCUIT

Time intervals	AC input Approach (W)	6-step DC input approach (W)	Error (%)
1	0.00926	0.00977	5.2
2	0.0528	0.0616	5.9
3	0.125	0.129	3.6
4	0.180	0.183	1.8
5	0.212	0.217	2.4
6	0.227	0.230	1.5
Average	0.135	0.138	2.5
CPU time	66 seconds	7.6 seconds	

seconds on a Sun Ultra 10 machine. This does not take into account the extra time the regular AC input approach needs to run the circuit to steady state yet. Additionally the 6-step DC input approach also saves much time in the calculation of core loss based on the simulated flux density data, because it only needs to calculate one switching cycle for each time interval.

IV. CONCLUSIONS

This paper presents a method for estimating the core loss of magnetic devices used in switching power converters. It addresses drawbacks of previous core loss estimation methods and can be easily embedded into a power electronics circuit simulation to automate core loss calculation process. By appropriately estimating the core loss for each time interval in the power conversion switching cycle, we are able to take into account that the rate of change of flux density can vary significantly from one time interval to the next. As a result, the core loss model is sensitive to changes in duty cycle and conversion frequency as well as being able to address both continuous and discontinuous conduction modes of operation.

With this capability, we are able to effectively estimate boost inductor core loss in Power Factor Correction circuits. We first use this method to estimate core loss for an entire AC mains line cycle. We demonstrate that a very good estimate of core loss can be made by dividing one quarter of the AC line cycle into six equal time intervals and replacing the input AC line voltage with a DC voltage source equal to the RMS value of the AC line voltage during each respective time interval. We then look at the core loss under steady-state conditions with a fixed DC input voltage during each time interval. We show that the average core loss during each of these intervals with an AC input voltage source is very close to the core loss for each time interval with the equivalent DC input voltage. When we average results together over all six time intervals the results of the six-step DC input voltage technique are well with in 5% of the analysis of the full flux density wave shape.

This core loss estimation method is very tractable using hand calculations. Even the six-step DC input voltage technique for estimating core loss in PFC boost inductors can be done by hand. However, we show that this method is also very suitable for use with simulation tools. We show an example of a PFC application using the SIMPLIS simulator where we are able to obtain very useful results with the six-step DC input voltage method using much less CPU time compared to the CPU time required to simulate the circuit operation over a complete AC line cycle.

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