New Measurement Methods to Characterize Transformer Core Loss and Copper Loss In High Frequency Switching Mode Power Supplies

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Abstract - **New measurement methods to characterize transformer core loss and copper loss in high frequency switching mode power supplies are proposed. Experimental results for a planar transformer used in a DC/DC converter are presented. A time-domain finite element analysis transient solver is adopted to verify the measurement results. In addition, a detailed error analysis on each of the error sources of the proposed measurement methods is provided.**

Key Words - **core loss measurement, copper loss measurement, planar magnetics, loss characterization**

I. INTRODUCTION

Measurement methods are widely used for transformer core loss and copper loss characterization due to the potential for higher accuracy in comparison to simple conventional analytical methods. Unfortunately, no measurement methods are available that can measure the transformer core loss and copper loss under the actual operation conditions in switching mode power supplies (SMPS).

The existing measurement methods determine transformer core loss under sinusoidal excitation using an impedance or network analyzer [1],[2]. However, the pulse width modulation (PWM) waveforms in SMPS are not sinusoidal, but are rectangular. In addition, converters such as the flyback and asymmetrical half-bridge (AHB) contain a DC bias in the magnetizing current, but these methods cannot account for the DC bias. Furthermore, due to the highly non-linear nature of the B-H property of ferrite materials, Fourier analysis can yield completely erroneous results. Therefore, the impedance or network analyzer method cannot be applied to accurately determine the core loss in high frequency switching converters.

In [3] and [4], two measurement setups were designed to experimentally determine transformer core loss. In [3], sine waveforms were used to obtain the core loss curves for the ferrite materials. In addition, no core loss results for switching converters are provided. In [4], a method is proposed to measure transformer core loss for a SMPS using a waveform generator and a power amplifier. Unfortunately, using these techniques, the core loss cannot be determined if the transformer under test operates with a DC bias in the magnetizing current. It is also noted that an error analysis of the proposed methods was not conducted and the corresponding measurement accuracy was not provided. Therefore, if these techniques are used, the user cannot interpret the accuracy of their results. To overcome the limitations of the existing methods, an improved method to determine transformer core loss in high frequency SMPS is proposed, which is suitable for core loss measurement under PWM excitation, with or without a DC bias.

In [5], a method is proposed to calculate transformer copper loss by measuring winding AC resistance for each harmonic in the PWM current. The method uses sinusoidal waveforms in the measurement and not the rectangular PWM waveforms under the transformer operating conditions. The drawback to this technique is that it does not replicate the field pattern within the transformer. In addition, the measurements are time-consuming. Another disadvantage of this method is that the results only provide information about winding self-resistance. When both the primary and secondary windings have current flowing through them at the same time, the field interaction due to proximity effect induces a mutual resistance between them, which can significantly reduce the total transformer copper loss. Therefore, an "in-component" measurement scheme for transformer AC winding resistance is proposed. The method uses the PWM current waveforms, so, the mutual resistance between windings is inherently included, which yields increased accuracy.

In section II, the core loss measurement method is proposed. In section III, the proposed copper loss measurement method is presented. The experimental verification is provided in section IV. In section V, a detailed error analysis is presented for each method. The conclusions are presented in section VI.

II. PROPOSED CORE LOSS MEASUREMENT METHOD

The proposed transformer core loss measurement test setup is shown in Figure 1. With the secondary side open-circuit, the averaged core loss P_{Core} over one switching period T can be determined from the primary voltage v_{pri}(t) and the magnetizing current i_M(t) using (1).

$$P_{Core} = \frac{1}{T}\int_0^T v_{pri}(t) \cdot i_M(t)\,dt \tag{1}$$

Due to the leakage inductance and resistance associated with the primary winding, the winding voltage cannot be measured directly. However, the secondary side voltage v_{sec}(t) can be measured and reflected back to the primary side using the turns ratio. Since the secondary winding is open circuit, the only primary terminal current is the magnetizing current, which is sensed using a resistor R_{Sense}. By measuring the secondary voltage and the voltage across a sensing resistor, we can obtain the averaged core loss over one switching period T using (2).

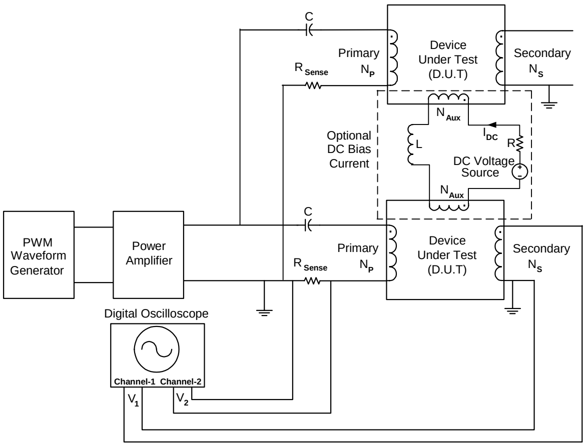


Figure 1 Proposed core loss measurement test setup

Using a digital oscilloscope with channel math capabilities, (2) can be evaluated directly using the oscilloscope. In (2), N_P and N_s are the primary and secondary winding turns; v_{1i} and v_{2i} are the ith sample of the measured voltage values of the secondary side and current sensing resistor; N is the number of the samples in one switching period.

$$P_{Core} = \frac{N_p}{N_s}\frac{1}{N}\sum_{i=1}^{N} v_{1i}\cdot\frac{v_{2i}}{R_{sense}} \qquad (2)$$

The practical implementation issues of the measurement setup are explained as follows:

1) Power Source

A PWM waveform generator (function generator) and an RF power amplifier (3MHz bandwidth) are used to provide the PWM voltage source to the transformer.

2) Current Sensing Device

A low-inductive metal film resistor is used to measure the magnetizing current. In order to minimize the distortion on the waveform and at the same time to reduce the phase-shift error, ten 10Ω±1% metal film resistors were connected in parallel. The impedance characteristic of the resistor combination is flat up to 5MHz.

3) DC Bias Current

An optional auxiliary winding can be introduced to provide the equivalent DC magnetomotive force to the core for transformers that operate with a DC bias component in the magnetizing current. A 2mH inductor was connected in the auxiliary circuit to reduce the high frequency AC ripple. In addition, two auxiliary windings with the same number of turns were connected with opposite polarities to eliminate the AC voltage from the primary winding. The second auxiliary winding is connected into the same transformer as the one under test.

In order to ensure the measurement of the transformer core loss is accurate and to eliminate error from a variety of sources, three key steps are proposed in the following sub-sections.

A. Calibration of the Winding Turns Ratio

The proposed core loss measurement method has two-ports. Due to the non-ideal magnetic coupling, parasitic air flux and the winding terminations, the primary and secondary winding terminal voltage ratio can vary slightly from the designed turns ratio. In order to minimize this error, the winding turns ratio should be calibrated. For the turns ratio calibration, a sinusoidal wave can be used to simplify the process. The turns ratio result can be applied to the rectangular PWM waveforms under test. The terminal voltages (peak or peak-to-peak value) of the primary and secondary windings are measured and the actual turns ratio is calculated using (3), which is then used in (2). The calibration should be conducted over a range of frequencies.

$$N_{Turns-Ratio} = V_{\Pr i} / V_{Sec} \qquad (3)$$

B. Current Sensing Resistance Calibration

Some error will be introduced into the core loss measurement due to the tolerance and the associated inductance of the current sense resistor. A good approach is to calibrate the resistor's frequency response using the impedance analyzer to ensure its frequency response remains flat for several harmonics of the switching frequency.

C. Averaging Data

Averaging should be adopted for the data processing. The core loss for each operating condition should be tested ten times and then the values should be averaged.

III. PROPOSED COPPER LOSS MEASUREMENT METHOD

The objective of transformer copper loss measurement is to obtain an equivalent AC resistance for each winding under the actual operating conditions. To proceed, it is important to clarify the following two concepts:

1) We need to define the current wave shape used in the measurement under the SMPS operating conditions. By analyzing the SMPS circuits, the currents flowing through the windings can usually be well approximated as a rectangular wave shape (unipolar or bipolar) of the corresponding duty ratio by neglecting the small ripple [6]. Therefore, a rectangular PWM current can be used in measuring the transformer copper loss. In this paper, a bipolar rectangular PWM waveform is used.

2) A transformer is a multi-winding structure, so, the field interaction between the primary and secondary windings induces a mutual resistance. Fortunately, we don't need to obtain the mutual resistance information. What we need is an equivalent AC resistance of each winding under the operating condition, which includes the mutual resistance information.

The proposed transformer winding AC resistance measurement scheme is shown in Figure 2. By applying the rectangular PWM voltage in the primary side from the waveform generator and power amplifier, the corresponding magnetic field is established within the transformer and a PWM voltage is induced in the secondary side. If a resistive load is connected on the secondary side, a rectangular current will flow through the load resistor and the secondary winding equivalent AC resistance. The secondary side current i_{Sec} can be obtained by measuring the voltage across the load resistor. An auxiliary winding is added to measure the secondary winding terminal voltage. This winding can be easily added externally around the core since it does not carry any current. The two voltages are then measured using a digital oscilloscope. Then the averaged power of the secondary winding P_{Sec} and the power of the load resistor P_{Load} can be calculated over one switching period. Therefore, the secondary winding equivalent AC resistance can then be calculated using (4), where N_{Sec} and N_{Aux} are the the secondary and auxiliary winding turns; v_{1i} and v_{2i} are the ith sample of the voltage values; and N is the number of the samples in one switching period.

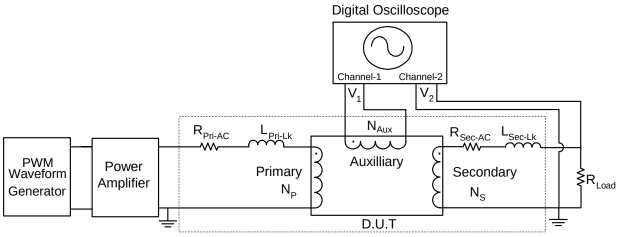


Figure 2 Proposed copper loss measurement test setup

$$R_{Sec-AC} = \frac{P_{Sec} - P_{Load}}{I^2_{SecRMS}} = \frac{\frac{N_{Sec}}{N_{Aux}}\frac{1}{N}\sum_{i=1}^{N} v_{1i}\cdot\frac{v_{2i}}{R_{Load}}}{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{v_{2i}}{R_{Load}}\right)^2} - R_{Load} \tag{4}$$

By defining the corresponding functions in the digital oscilloscope, the power of the measured winding and the RMS current value over one switching period can be obtained easily and used in the winding resistance calculation. In order to measure the primary winding AC resistance, the secondary winding should be excited.

In order to ensure the measurement of the transformer copper loss is accurate and to eliminate error from a variety of sources, three key steps are proposed in the following sub-sections.

A. Calibration of the Winding Turns Ratio

In the proposed transformer winding AC resistance measurement method, a third winding is used to obtain the terminal voltage of the measured winding. The actual winding turns ratio between the measured winding and the third winding should be calibrated in order to achieve accurate results. This can be achieved using the procedure outlined in section II.

A. Load Resistance Calibration

Since a resistor is used as the load in measuring the winding AC resistance, the resistor's tolerance and frequency response can have a significant impact on measurement results. In order to minimize any error introduced by the resistor, the resistor's frequency response should be measured using an impedance analyzer to obtain an accurate resistance value and phase response.

B. Averaging Data

As in the core loss calculation, the copper loss data in the winding AC resistance measurement should be averaged in order to minimize any random error in the measurements.

IV. MEASUREMENT RESULTS AND VERIFICATION

A high frequency planar transformer was tested to verify the proposed core loss and copper loss methods. In order to verify the loss measurement results, a time-domain Finite Element Analysis solver from ANSOFT was used.

A multi-winding planar transformer was used in an AHB DC/DC converter with unbalanced secondary windings [7]. The converter diagram is shown in Figure 3. The specifications of the converter and the transformer parameters are:

Input: 35-75V, nominal at 48V, output: 5V/25W

Switching frequency: 400kHz

Main winding turns: N_p: N_{s1}: N_{s2} = 6:1:3

Core: E18/4/10 planar cores (EE combination)

Winding: 1oz (35μm) copper on a 10-layer PCB

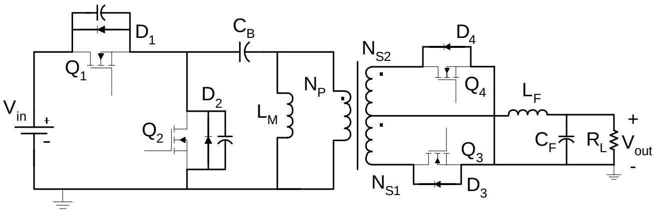


Figure 3 AHB converter diagram

Due to the complementary duty cycle operation and unbalanced secondary windings, the converter operates with a DC bias (I_{M-DC}) in the magnetizing current. It can be calculated using (5).

$$I_{M-DC} = (1-D)I_o\frac{N_{s2}}{N_p} - DI_o\frac{N_{s1}}{N_p} \tag{5}$$

In the transformer design, an air gap of 67μm was added to the core central leg to avoid saturation. The proposed optional circuit to create the DC bias current for the test setup was used in the core loss measurement.

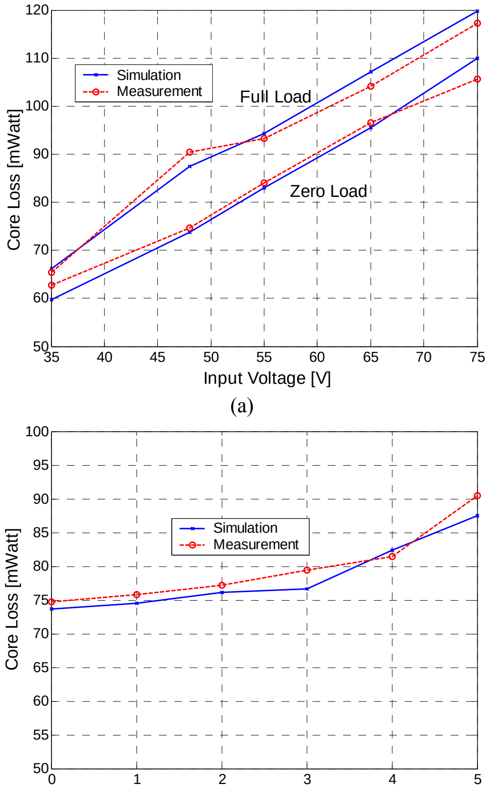
A. Core Loss Measurement Results

The following three operating conditions of the AHB transformer were tested using the proposed method.

1) V_{in}=35-75V range @ no load
2) V_{in}=35-75V range @ 5A load
3) V_{in}=48V @ 0-5A load range

The measurement results and FEA simulation results are provided in Figure 4. In order to illustrate the effect of the DC bias current on the ferrite core loss, Figure 4(a) shows the core loss measurement and simulation results under operating conditions 1) and 2). Figure 4(b) provides the results for operating condition 3). The core losses under the equivalent 400kHz sine waveform and bipolar square waveform (D=50%) with no DC bias current condition were also tested for comparison purposes.

Some typical core loss measurement waveforms under operating condition 1) are shown in Figure 5. The digital oscilloscope math functions implement (2). The results are indicated on the right side of the figure.



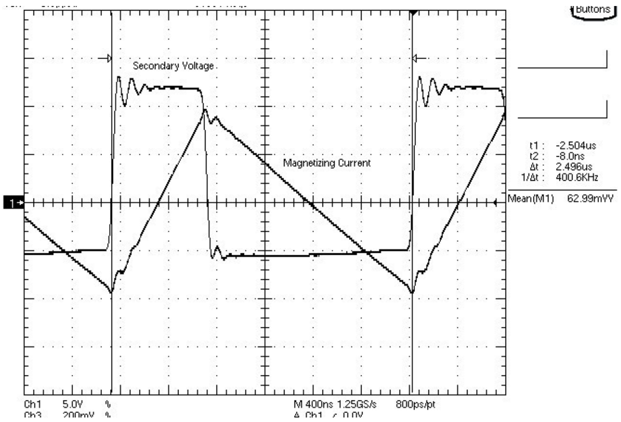
(a)

(b)

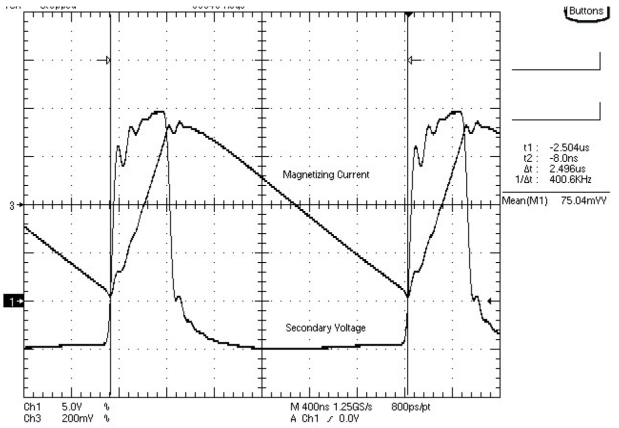
Figure 4 AHB transformer core loss results

It is clear from the test results that the core loss under PWM waveform excitation increases as the duty ratio decreases and that the addition of a DC bias current increases core loss.

Using the FEA simulation result as the reference, the difference between the measurement and the FEA simulation is within ±5% for all the measurement conditions.



(a)



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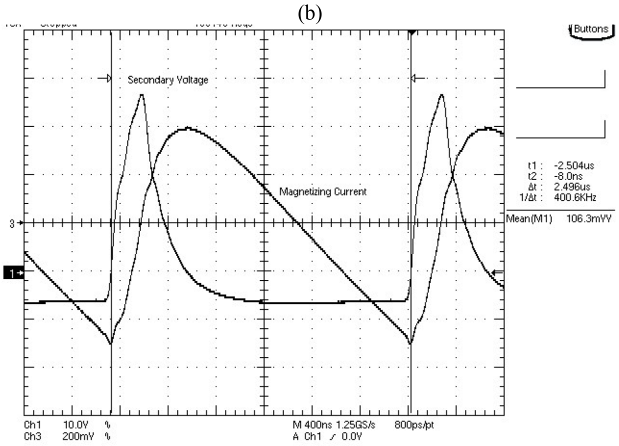


(c)

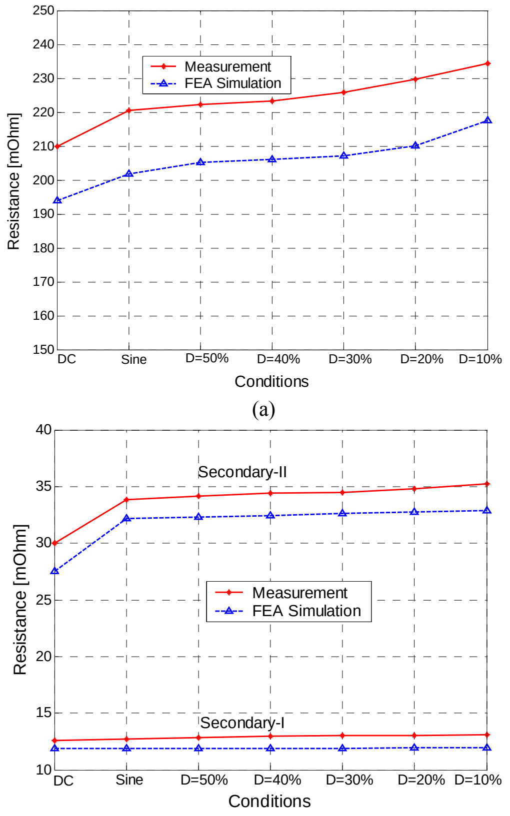
Figure 5 AHB core loss measurement waveforms: (a) Vin=35V, (b) Vin=48V, (c) Vin=75V

A. Winding AC Resistance Measurement Results

The AC resistance of the AHB transformer power windings were measured and 3D FEA simulations were conducted to compare the results. The measurement and FEA simulation results are illustrated in Figure 6. The DC resistances are also provided as a reference.

Using the simulation results as reference, the difference between the measurement and FEA simulation results are within ±10% for the three AHB transformer powertrain windings. The measurement waveforms are shown for the secondary-I winding in Figure 7.

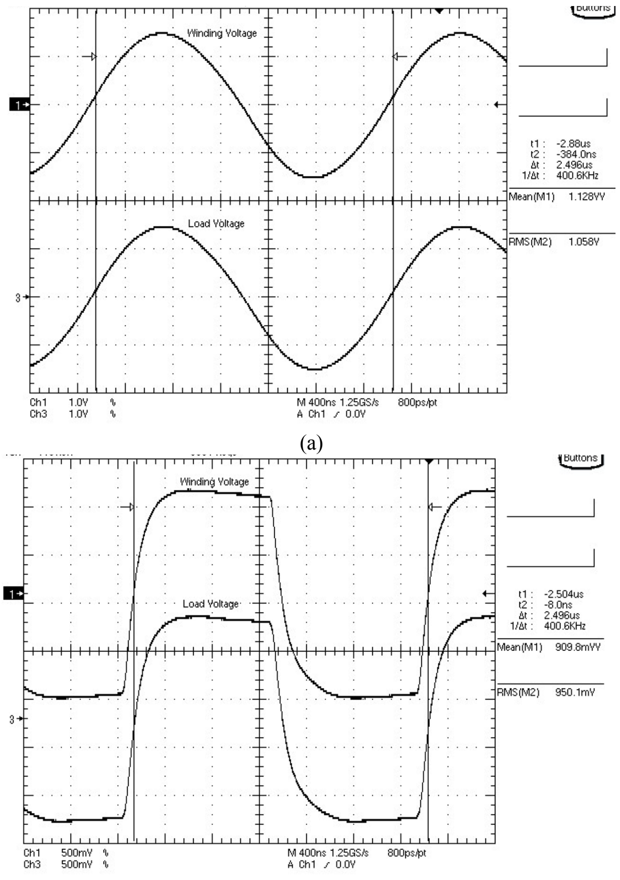
We can observe from the test results that the winding equivalent AC resistance under PWM waveform excitation is larger than that under sinusoidal excitation. In addition, the resistance increases as the duty ratio decreases.



(a)

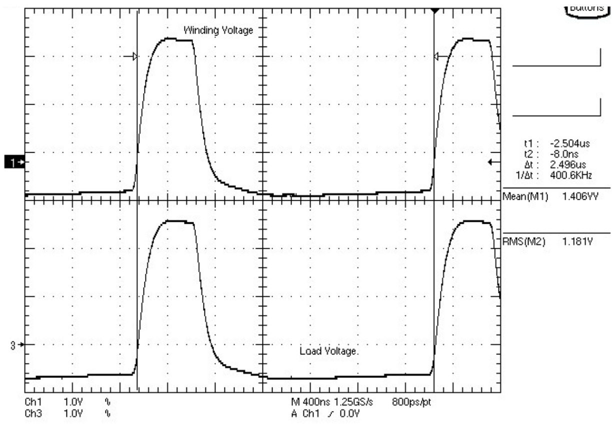
(b)

Figure 6 AHB transformer winding AC resistance; (a) primary winding, and (b) secondary windings



(a)

(b)



(c)

Figure 7 AHB transformer secondary-I winding AC resistance measurement waveforms; (a) sinusoidal, (b) D=50%, and (c) D=20%

V. ERROR ANALYSIS

In order to ensure that the core loss and winding AC resistance measurements are accurate and valid, it is necessary to analyze the various error sources in the measurements to obtain the loss measurement accuracy.

A. Error Analysis for Core Loss Measurement

Using (2), the core loss is determined using the winding voltage and magnetizing current. Therefore, the error analysis of the proposed core loss measurement method is based on (2). The various error sources and their effect on the core loss measurement accuracy are analyzed as follows.

1) Voltage Measurement Error

The Tektronix TDS5054 digital oscilloscope was used for the tests. It has an 8-bit ADC. The averaging acquisition mode was used in the measurement, so, the effective sampling resolution can be as high as 11-bit. Both the digitizing and the linearity errors in the measurement are ±1/2LSB at full scale. Combining these factors, we can assume that the voltage measurement error is ±1LSB at full scale.

For the measurements, the location of the peak value of the voltage waveform measured on the oscilloscope determines the voltage measurement error. In the measurement, the peak value is always kept above 10% of the full scale (for the worst case). For the vertical scale, the voltage measurement error of the oscilloscope is less than 0.489%. Therefore, from (2), the relative error of the worst case core loss due to the voltage measurement is given by (6), which is less than 1% for the given test setup.

$$\frac{\Delta P_{Core}}{P_{Core}} = \left| \frac{\frac{N_p}{N_s}\frac{1}{N}\sum_{i=1}^{N} v_{1i}(1\pm 0.489\%)\cdot\frac{v_{2i}(1\pm 0.489\%)}{R_{sense}}}{\frac{N_p}{N_s}\frac{1}{N}\sum_{i=1}^{N} v_{1i}\cdot\frac{v_{2i}}{R_{sense}}} - 1 \right| = 0.98\% \qquad (6)$$

2) Turns Ratio Error

As explained in section II, calibration of the turns ratio between the primary and secondary windings helps to minimize error. In the turns ratio calibration procedure, (3) is used for the calculation. The peak voltage is kept close to the full scale of the oscilloscope, so, the digitizing error in the voltage measurement for the turns ratio calibration can be considered as ±1LSB of the ADC, which is 2^{-11}. Therefore, based on (3), the worst case relative error for the turns ratio calibration is less than 0.1%.

In this paper, the digitizing error is neglected, so, we can assume that no error is introduced into the calibration procedure of the turns ratio. Using this calibration method, the turns ratio between the primary and secondary-II winding in the AHB transformer is 2.04 from 400kHz to 2MHz. Without this turns ratio calibration, a relative error of 2% will be introduced into the core loss measurement results.

3) Tolerance of the Current Sensing Resistor

The metal film resistor used in the core loss measurement has a tolerance of ±1%. Therefore, a 1% relative error is introduced due to the current sensing resistor.

4) Time Delay Error

Another important error source is time delay error due to the inductance of the current sensing resistor. For SMPS transformers, ideally, the voltage and current waveforms are in the wave shapes as shown in Figure 8 by the solid lines.

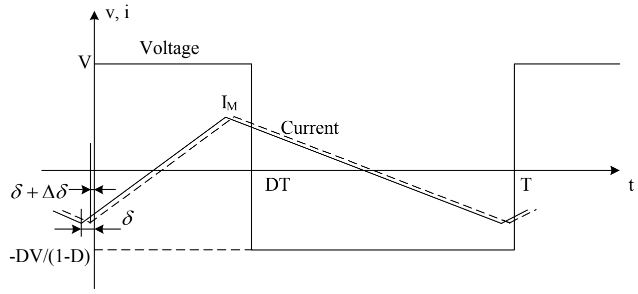


Figure 8 Ideal and typical transformer voltage and magnetizing current

The time delay between the voltage and the magnetizing current can be defined as δ. Then, from (1), (7) can be derived. In (7), V is the amplitude of the positive part of voltage waveform; I_M is the amplitude of the magnetizing current; D is the duty ratio of the PWM waveform; T is the switching period of the circuit; and δ is the time delay between the voltage and the magnetizing current.

$$P_{Core} = V \cdot I_M \cdot \frac{2D\delta T - 2D^2\delta T - \delta^2}{(1-D)^2 DT^2} \tag{7}$$

Since the magnetizing current is sensed by a resistor, (7) can be written as (8).

$$P_{Core} = V \cdot \frac{V_R}{R_{Sense}} \cdot \frac{2D\delta T - 2D^2\delta T - \delta^2}{(1-D)^2 DT^2} \tag{8}$$

If some error, $\Delta\delta$ is introduced into the time delay, δ the magnetizing current waveform will be shifted with respect to the actual waveform as illustrated by the dashed line in Figure 8. Then the incremental core loss due to this error can be calculated using (9).

$$\Delta P_{Core} = \frac{\partial P_{Core}}{\partial \delta}\Delta\delta \tag{9}$$

Using (8) and (9), the relative error of the core loss power due to $\Delta\delta$ is given by (10).

$$\left|\frac{\Delta P_{Core}}{P_{Core}}\right| = \left|\frac{2DT - 2D^2T - 2\delta}{2D\delta T - 2D^2\delta T - \delta^2}\right| \left|\Delta\delta\right| \tag{10}$$

When $\delta \ll DT$ and $D \ll D^2T$, (10) can be approximated by (11).

$$\left|\frac{\Delta P_{Core}}{P_{Core}}\right| \approx \left|\frac{\Delta\delta}{\delta}\right| \tag{11}$$

It is clear that the relative error is very sensitive to small values of δ. In this case, if large time delay error is introduced, the relative error will become large. Therefore, care should be taken to minimize time delay error.

Sources of time delay error can be: poor frequency response of the current-sensing device; and trigger jitter and delays for different channels introduced by the oscilloscope. For the digital oscilloscope used, the trigger jitter is typical at 8 ps, so, it can be ignored. The probes used for the voltage measurement are originally from the same oscilloscope and are matched to each other, so, the phase delay between channels of the oscilloscope can be neglected. The inductance associated with the current sensing resistor is the important source of the phase delay error. Therefore, in experiments, care should be taken to reduce these error sources and small inductance metal film resistor is used.

Using an impedance analyzer, phase shift less than 0.01° is observed for the current sensing resistor at 400kHz. It is less than 0.02° at 800kHz and 0.05° at 2MHz. Using the phase shift at 400kHz and transferring it to delay time for 400kHz, the time error can be calculated as given by (12).

$$\Delta\delta = \frac{0.01^\circ}{360^\circ} \times 2.5\mu\text{s} = 69.5\text{ps} \tag{12}$$

The relative error depends on the time delay and the error introduced due to the time delay, so the value changes for different operating conditions. For example, the time delay between the voltage and magnetizing current can be calculated as δ=59ns using (8) for the AHB transformer operating at 48V input. With a time delay error of $\Delta\delta$=69.5ps introduced by the current sensing resistor, we can obtain the relative core loss error as less than 0.12% using (10). This calculation procedure can be applied for other operating conditions and a relative error of less than 0.2% is obtained for all the operating conditions.

B. Error Analysis for Copper Loss Measurement

The main error sources in the winding resistance measurement are: (1) voltage measurement error, (2) turns ratio error, (3) tolerance of the load resistor, (4) time delay introduce into the load current measurement.

By manipulating (4), (13) can be derived.

$$R_{Sec-AC} = R_{Load} \cdot \left(\frac{\frac{N_{Sec}}{N_{Aux}} \cdot \sum_{i=1}^{N} v_{1i} \cdot v_{2i}}{\sum_{i=1}^{N} (v_{2i})^2} - 1 \right) \tag{13}$$

The effect of each error source on the winding AC resistance measurement is analyzed as follows.

1) Voltage Measurement Error

The TDS5054 uses one ADC for all four channels. Therefore, the digitizing errors of the voltage measurement for each channel can be considered equal. Furthermore, the digitizing error will cancel out in the numerator and denominator in the first item in (13), so we can assume that the digitizing error can be neglected.

2) Turns Ratio Error

An auxiliary winding is used to obtain the winding voltage. Since a calibration of the turns ratio is carried out to obtain the actual turns ratio, this error can be ignored.

3) Tolerance of the Load Resistor

The load resistor used in the measurement has a tolerance of ±1%, so a relative error of 1% is introduced into the winding AC resistance measurement.

4) Time Delay Error

In the load current measurement, a pure resistor value is assumed as the load. However, the inductance of the resistor and the inductance induced in the measurement circuit will introduce some time shift error for the current.

For a SMPS with a rectangular PWM voltage and current waveform as shown in Figure 9 (the leakage inductance can be neglected because it is very small), the winding AC resistance can be calculated using (14), where, V_1 is the positive amplitude of the auxiliary winding voltage; V_2 is the positive amplitude of the load resistor voltage; and $N_{Turn\text{-}Ratio}$ is the actual turns ratio between the auxiliary and the measured windings after calibration.

$$R_{Sec-AC} = R_{Load} \cdot \left(N_{Turn-Ratio} \cdot \frac{V_1}{V_2} - 1\right) \tag{14}$$

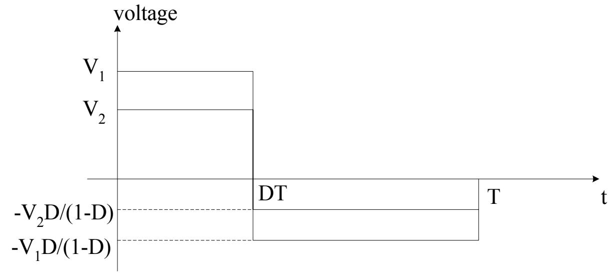


Figure 9 Typical and ideal PWM voltage and current waveform in measuring winding AC resistance

Due to the parasitic inductance, some time delay will be introduced into the load current measurement as shown in Figure 10. With this time delay, the winding AC resistance is given by (15).

$$R_{Sec-AC} = R_{Load}\left[N_{Turn-Ratio} \cdot \frac{V_1}{V_2}\left(1 - \frac{\delta}{D(1-D)T}\right) - 1\right] \tag{15}$$

Then, the relative error due to the time delay can be calculated using (16).

$$\frac{\Delta R_{Sec-AC}}{R_{Sec-AC}} = \frac{\dfrac{\delta}{D(1-D)T}}{1 - \dfrac{V_2}{N \cdot V_1}} \tag{16}$$

If the load resistor is much larger than the winding AC resistance, then the ratio of V_2/V_1 in (16) will be very close to one. In this case, the relative error will be very sensitive to the time delay and care should be taken to minimize the parasitic inductance in the measurement.

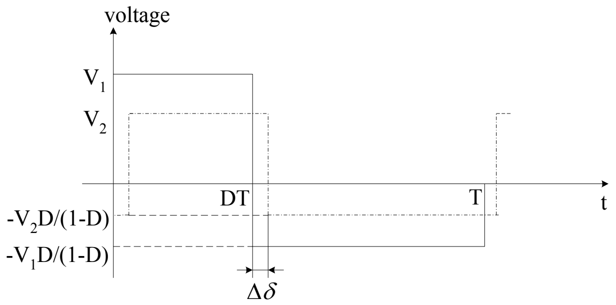


Figure 10 Time delay introduced into the load current measurement

VI. CONCLUSIONS

New measurement schemes to characterize transformer core loss and copper loss for SMPS were proposed. Measurement results were presented for a planar transformer operating in a DC/DC power converter. FEA simulation using a time-domain solver was used to verify the measurement results. In addition, a detailed error analysis has been provided for the proposed core loss and copper loss measurement methods. The results show that the proposed methods can provide accurate measurement of transformer core loss and copper loss for high frequency SMPS.

Using the error analysis results, the relative error was calculated to be less than 5% for all the measurement conditions for the AHB transformer core loss; For the winding AC resistance, the measurement accuracy is: <2% for the primary winding, <5% for the secondary-I winding and <4% for the secondary-II winding.

REFERENCES

[1] F. D. Tan, Jeff L. Vollin, and Slobodan M, Cuk, "A Practical Approach for Magnetic Core-Loss Characterization", IEEE Trans. Power Electronics, vol. 10, No. 2 pp. 124-129, Mar. 1995;

[2] V.J. Thottuvelil, T.G. Wilson, H.A. Owen, "High-frequency measurement techniques for magnetic cores," IEEE Trans. Power Electronics, v5, No.1, pp.41-53, Jan. 1990;

[3] D. K. Conory, G. F. Pierce, and P. R. Troyk, "Measurement techniques for the design of high frequency SMPS transformers", IEEE APEC Proc., pp. 341-353, 1988;

[4] Jieli Li, T. Abdallah, and C. R. Sullivan, "Improved Calculation of Core Loss with Nonsinusoidal Waveforms," IEEE IASA, pp. 2203-2210, 2001;

[5] James H. Spreen, "Electrical Terminal Representation of Conductor Loss in Transformers," IEEE Trans. on Power Electronics, Vol. 5, No. 4, October 1990;

[6] P. S. Venkatraman, "Winding Eddy Current Losses in Switching Mode Power Transformers Due to Rectangular Wave Currents," Proceedings of POWERCON 11, A-1 pp. 1-11, Power Concept, Inc., April 1984;

[7] W. Eberle, Y. F Liu, "A Zero Voltage Switching Asymmetrical Half-Bridge DC/DC Converter with Unbalanced Secondary Windings for Improved Bandwidth," IEEE PESC, 2002.