Application Note

Turn Ratio Correction Factor for Integrated Transformer LLC Design

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ABSTRACT

In the LLC design, we found the turn ratio is not matched our target when we designed the resonant inductor which is integrated inside the transformer. In this application note, we will go through the modification of the transformer model, and then updated the First Harmonic Approximation (FHA) model to find out the correction factor, which helps us to reduce the design cycles.

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1 Introduction

SRC LLC design is a popular topology for the high efficiency application. Normally, we design the power supply based on FHA. It provides very good results when the switching frequency is close to the resonant frequency. In real design experience, we found the result is not correct when we implement the leakage inductance of the transformer as the resonant inductance, especially those designs with split windings in primary and secondary side. In this application note, we find out the correction factor which helps engineers to speed up their design cycles.

In the first part of the application note, we roughly go through the FHA, and then modify the transformer model by putting secondary leakage inductance into the system. In the third part, we rewrite the transfer function and find out the correction factor for the turn ratio. In the fourth part, we use a design example, and compare the result based on calculation, simulation and the real system for confirmation.

2 Detailed Description

2.1 LLC Design

LLC is very popular design due to its ZVS operation in whole range and supports very high efficiency design. Most of the time, we design the system using FHA method which provides pretty good results when the switching frequency is close to the resonant frequency of the system. We don't address the detailed FHA process. Figure 2-1 shows the transfer procedure from original circuit (A), simplify the model into square wave (B), and through the FHA transfer, we get sine wave system (C). It becomes very easy to define the system thorugh the impedance analysis.

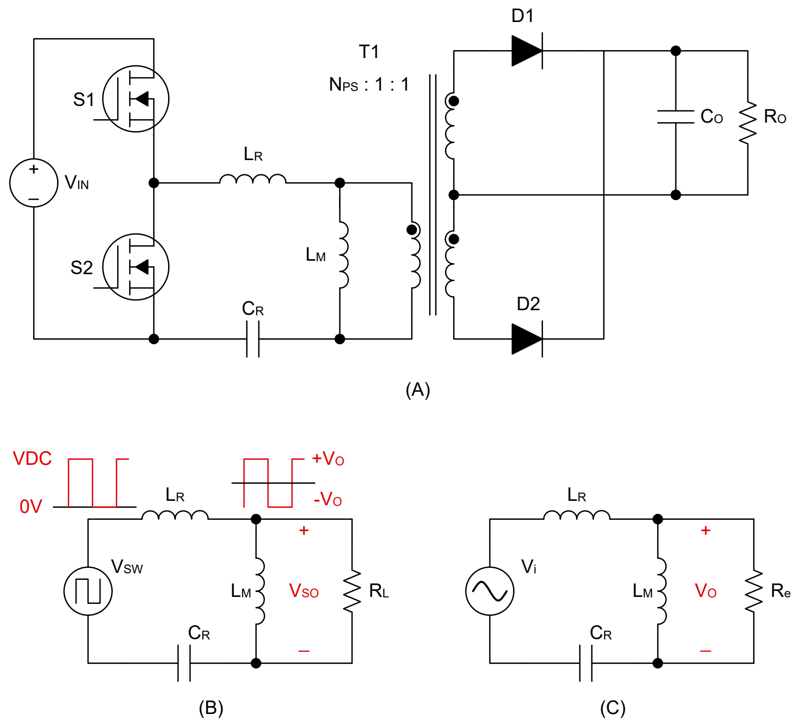

Figure 2-1. Procedure of FHA. (A) shows a LLC circuit with secondary center tape. (B) shows the simplified model from A. (C) takes FHA from B to get sine wave model

Based on this model, we can easily write the transfer function of the system design.

$$M_g = \frac{V_{OUT}}{V_{IN}} = \left| \frac{Z_{Lm} || R_e}{Z_{Lm} || R_e + Z_{Lr} + Z_{Cr}} \right| \quad (1)$$

In here, Z_{Lm}, Z_{Lr} and Z_{Cr} are the impedance of the magnetizing inductor, resonant inductor and the resonant capacitor as:

$$Z_{Lm} = j \times \omega_{SW} \times L_M \quad (2)$$

$$Z_{Lr} = j \times \omega_{SW} \times L_r \quad (3)$$

$$Z_{Cr} = \frac{1}{j \times \omega_{SW} \times C_R} \quad (4)$$

And Re is:

$$R_e = \frac{8}{\pi^2} \times {N_{PS}}^2 \times R_L \quad (5)$$

By defined the Lm, Lr and Cr, we can provide good results for the system.

2.2 Model of Real Transformer

In real transformers, it includes the leakage inductance in primary and secondary side. The transformer model can be simplified as Figure 2-2 (A) which ignores parasitic resistance and capacitance. This model is including an ideal transformer with turn ratio N_{PS}, magnetizing inductance L_M, primary leakage inductance L_{KP}, and secondary leakage inductance L_{KS}. We can even further to simplify the model as (B) without the ideal transformer but use $N_{PS}{}^2$ ratio to transfer the secondary leakage inductance into primary.

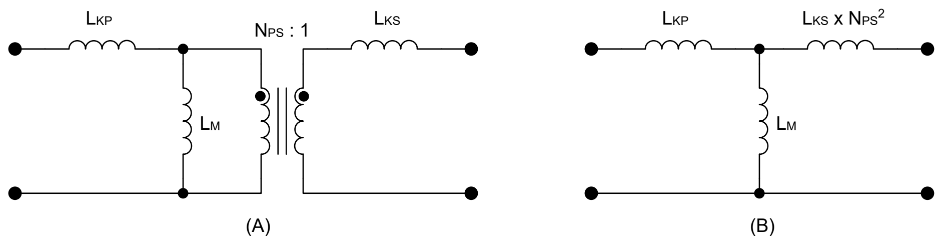

Figure 2-2. Simplified model of transformer.

In inductance measurement, we defined primary inductance L_P as the value when secondary terminal is open, and it shows as:

$$L_P = L_M + L_{KP} \tag{6}$$

And leakage inductance L_K as the value when secondary terminal is "shorted", , and it shows as:

$$L_K = L_{KP} + L_M || L_{KS} \times N_{PS}{}^2 \tag{7}$$

To simplify the formula, we assume:

$$L_R = L_{KP} = L_{KS} \times N_{PS}{}^2 \tag{8}$$

Based on this assumption we can calculate the L_M as:

$$L_M = L_P \times \sqrt{1 - \frac{L_K}{L_P}} \tag{9}$$

We can put L_M result into eq (6) to get L_R Value.

2.3 Integrated Transformer in LLC and Correction Factor

Now, we put the new transformer model with secondary leakage inductance into the model and the new model is shown in Figure 2-3.

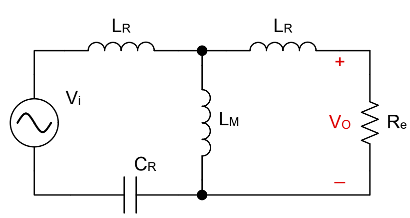

Figure 2-3. FHA model with secondary leakage inductance

We can write the gain of the integrated design M_{g_int} as:

$$M_{g\_int} = \frac{V_O}{V_I} = \left| \frac{Z_{Lm} || (R_e + Z_{Lr})}{Z_{Lm} || (R_e + Z_{Lr}) + Z_{Lr} + Z_{Cr}} \times \frac{R_e}{R_e + Z_{Lr}} \right| \tag{10}$$

It can be simplified as:

$$M_{g\_int} = \frac{L_n \times f_n^{\,2}}{\left[f_n^{\,2} \times (L_n + 1) - 1\right] + j \times f_n \times Q_e \times \left[f_n^{\,2} \times (2 \times L_n + 1) - (L_n + 1)\right]} \quad (11)$$

In here, f_n is the normalized the switching frequency by resonant frequency which is the factor about the real switching frequency compared to the resonant frequency.

$$f_n = \frac{f_{SW}}{f_{RES}} \quad (12)$$

f_{SW} is switching frequency and f_{RES} is the system resonant frequency as:

$$f_{RES} = \frac{1}{2\pi \times \sqrt{L_R \times C_R}} \quad (13)$$

L_n is the ratio between the magnetizing and the resonant inductance:

$$L_n = \frac{L_M}{L_R} \quad (14)$$

Qe is the quality factor of the system:

$$Q_e = \frac{\sqrt{\frac{L_R}{C_R}}}{R_e} \quad (15)$$

Based on eq (11), we can get the maximum gain on different Qe and Ln and we can plot as Fig 2-4. It shows the difference from discrete resonant inductance which the gain curve gets flat at 1, but 1.1225 by integrated transformer design.

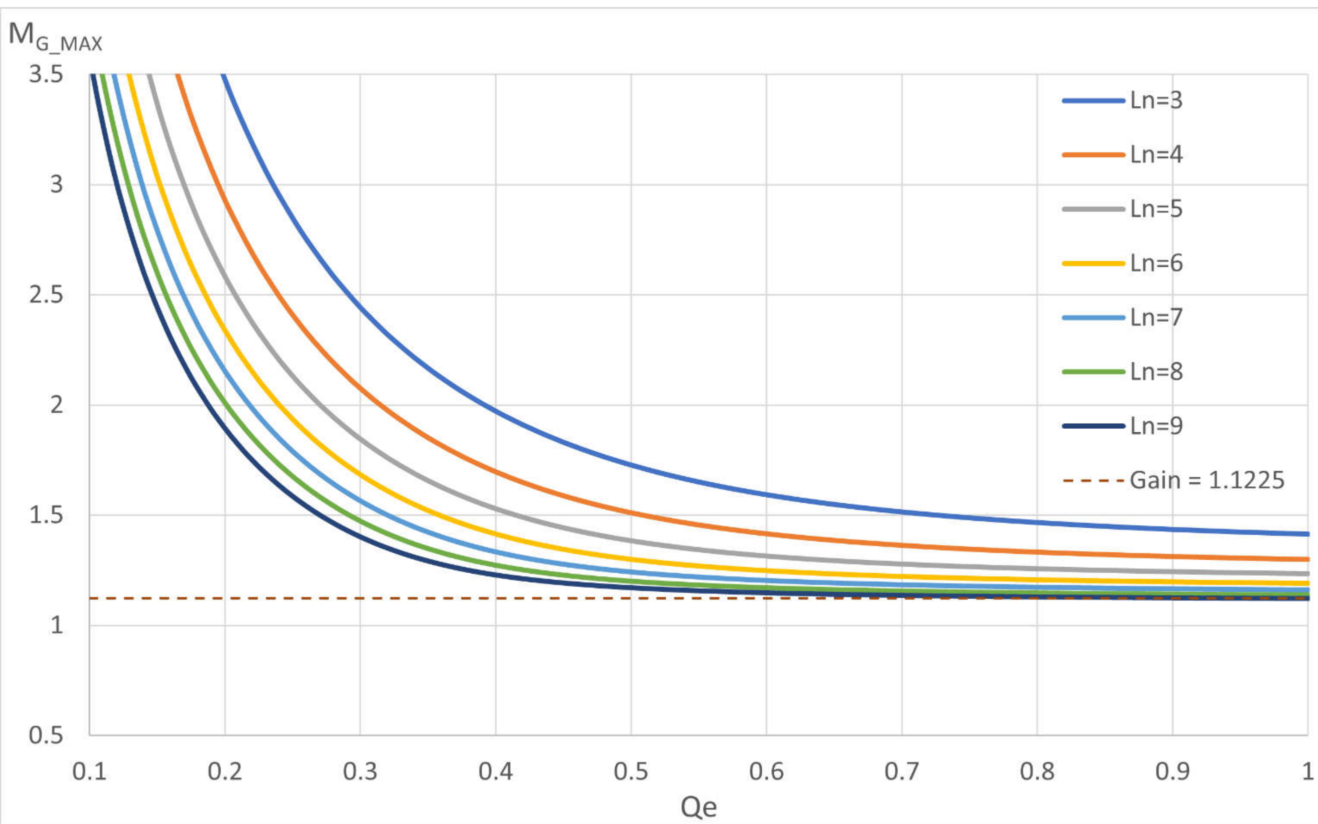

Figure 2-4. Maximum Gain curve of the system by putting secondary leakage inductance into the system

And the gain curve based on different fn and Qe with L_K = 85μH, and L_P = 510μH shows in Figure 2-5.

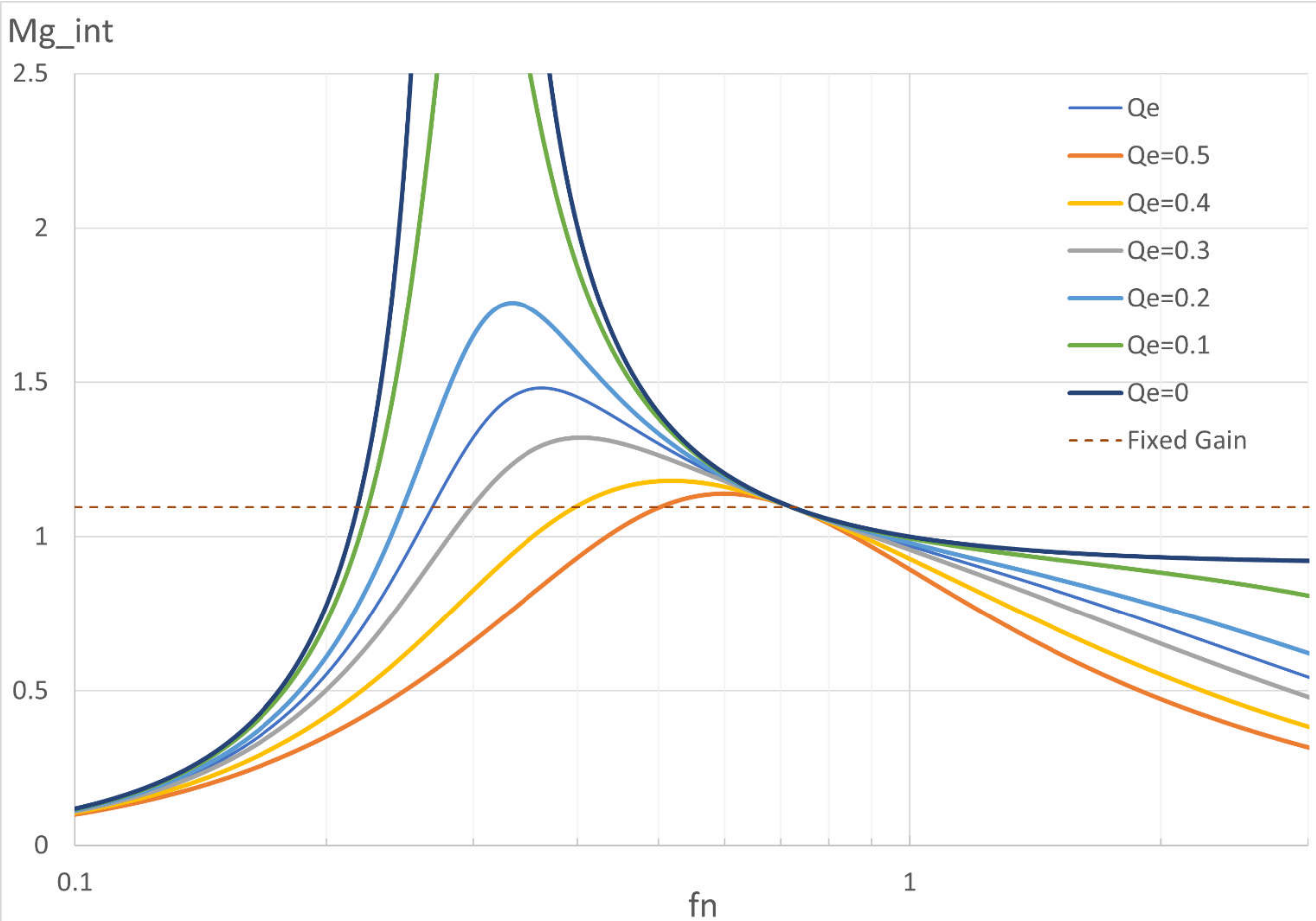

Figure 2-5. Gain curve by putting secondary leakage inductance into the system. L_K = 85μH, and L_P = 510μH

Based on the result, we can find:

1. Compared with the original Gain Curve, the fixed gain's frequency shifts to low. It is reasonable because the real resonant inductance is $L_R + L_R||L_M$ which equal to L_K (according to our definition). The relationship between L_K and L_R can be rewritten from eq (9) as:

$$L_K = \left(1 - \frac{{L_M}^2}{{L_P}^2}\right) \times L_p = \left(\frac{2 \times L_n + 1}{L_n + 1}\right) \times L_R \tag{16}$$

   The actual resonant frequency f_{RES}' can be rewritten as:

$$f_{RES}' = \sqrt{\frac{L_n + 1}{2 \times L_n + 1}} \times f_{RES} \tag{17}$$

   It means the real resonant frequency shift to f_{n_int} as:

$$f_{n\_int} = \sqrt{\frac{L_n + 1}{2 \times L_n + 1}} \tag{18}$$

2. In LLC design, when $f_{SW} = f_{RES}'$, we can find the point where the gain is fixed at any Qe value. In here, the real system resonant frequency is f_{RES}'. We put f_{n_int} it into eq (11), and we can get the fixed gain at any Q_e value $M_{g\_int\_fixed}$ as:

$$M_{g\_int\_fixed} = \frac{L_n + 1}{L_n} = \frac{L_P}{L_M} \quad (19)$$

In LLC design, we try to make the system working at this operation point by adjusting the perfect turn ratio as:

$$N_{PS} = M_{g\_fixed} \times \frac{V_{DC}}{2 \times V_{OUT}} \quad (20)$$

In the discrete resonant inductor design, M_{g_fixed} = 1 and the turn ratio is equal to the $(V_{DC}/2)/V_{OUT}$. In the integrated design, we need to modify the turn ratio according to the correction factor as $M_{g\_int\_fixed}$ which is equal to L_P/L_M as:

$$N_{PS\_int} = \frac{L_P}{L_M} \times \frac{V_{DC}}{2 \times V_{OUT}} \quad (21)$$

2.4 Real Design for Performance Confirmation

In here, we used UCC25661EVM-128 to be our bench mark for the comparison.

In the UCC25661EVM-128 (Links in Reference 3), the system works in 390VDC input and 12V-15A output. The L_P = 510µH, L_K = 85µH and C_R = 30nF. The turn ratio is 33:2:2 which is 16.5. According to eq (5), we can get:

$$L_M = L_P \times \sqrt{1 - \frac{L_K}{L_P}} = 510\mu H \times \sqrt{1 - \frac{85\mu H}{510\mu H}} = 465.56\mu H \quad (22)$$

We can get the correction factor as:

$$M_{g\_int\_fixed} = \frac{L_P}{L_M} = \frac{510\mu H}{465.56\mu H} = 1.095 \quad (23)$$

For VDC = 390V, Vout = 12V, with forward voltage of Schottky diode as 0.7V, the original turn ratio should be:

$$N_{PS} = \frac{V_{DC}}{2 \times V_{OUT}} = \frac{390V}{2 \times (12V + 0.7V)} = 15.35 \quad (24)$$

Put additional correction factor and the turn ratio should be

$$N_{PS}' = M_{g\_int\_fixed} \times N_{PS} = 1.095 \times 15.35 = 16.8 \quad (25)$$

Based on L_K and C_R , the resonant frequency is:

$$f_{RES}' = \frac{1}{2 \times \pi \times \sqrt{L_K \times C_R}} = \frac{1}{2 \times \pi \times \sqrt{85\mu H \times 30nF}} = 99.67KHz \quad (26)$$

Next, we run the Simplis model based on the input parameters, and we can see the system running at boundary mode, and the operation frequency is 100.42KHz. The simulation result shows in Figure 2-6.

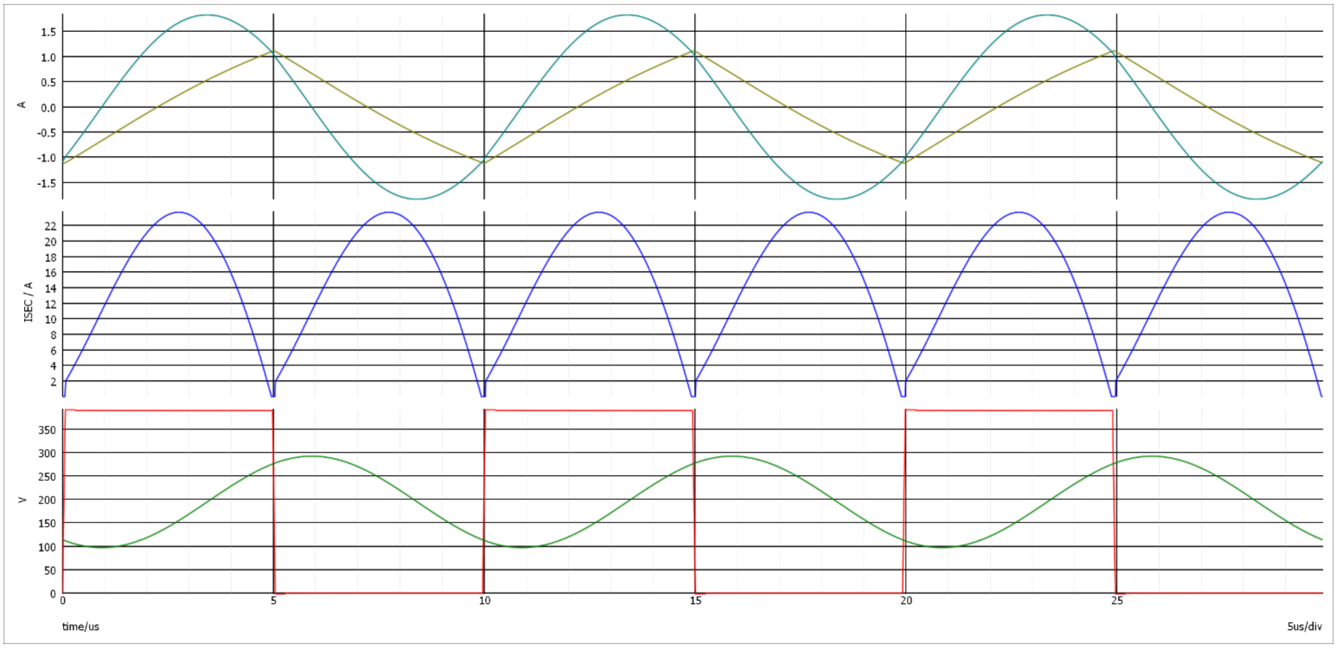

Figure 2-6. Simplis simulation result based on the input parameters with correction factor. The system runs at 100.42KHz in critical resonant frequency

If we set the turn ratio to be 15.5 without correction and keep others parameters to be the same, we get the operation frequency to be 115.53KHz and the result shows in Figure 2-7. It looks the system working in the above resonant frequency condition.

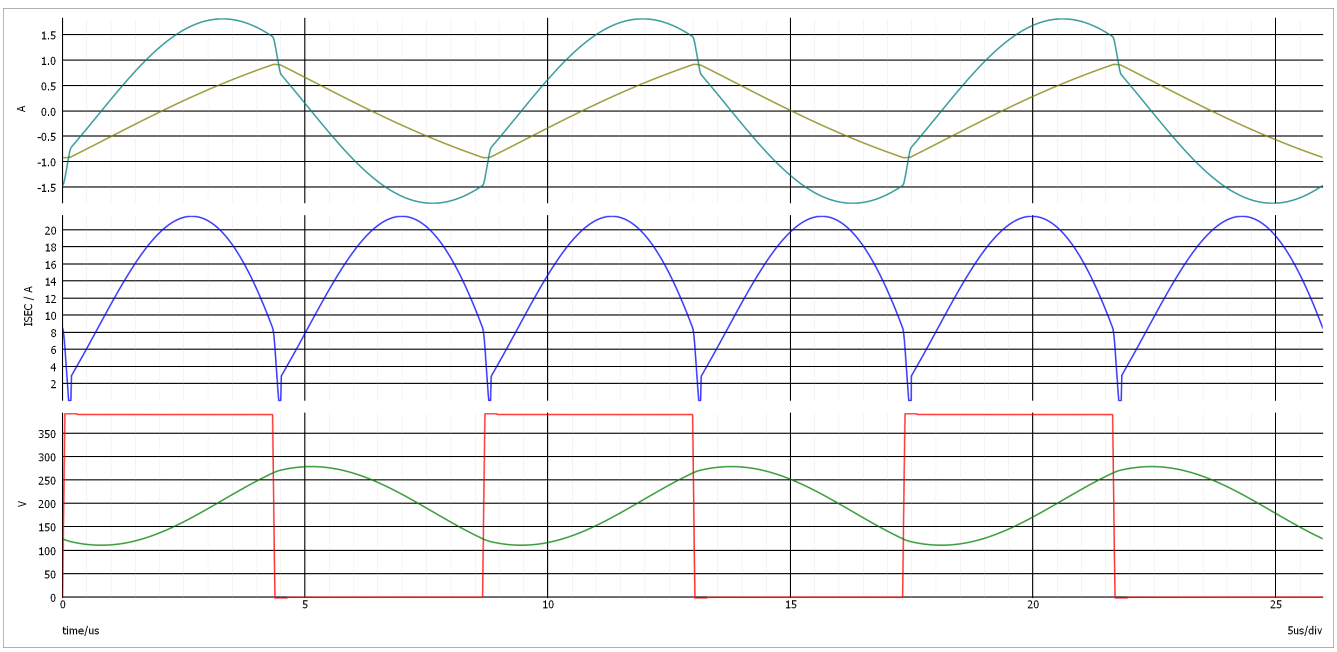

Figure 2-7. Simplis simulation result based on the input parameters without correction factor. The system runs at 115.53KHz in above resonant frequency.

Finally, we make the comparison between the calculation, simulation and the measurement result. Figure 2-8 shows the full load waveform in the UCC25661EVM-128 user's guide [3], the switching frequency is close to the 100KHz, and the system runs close to boundary mode. It means the correction factor matches the real system.

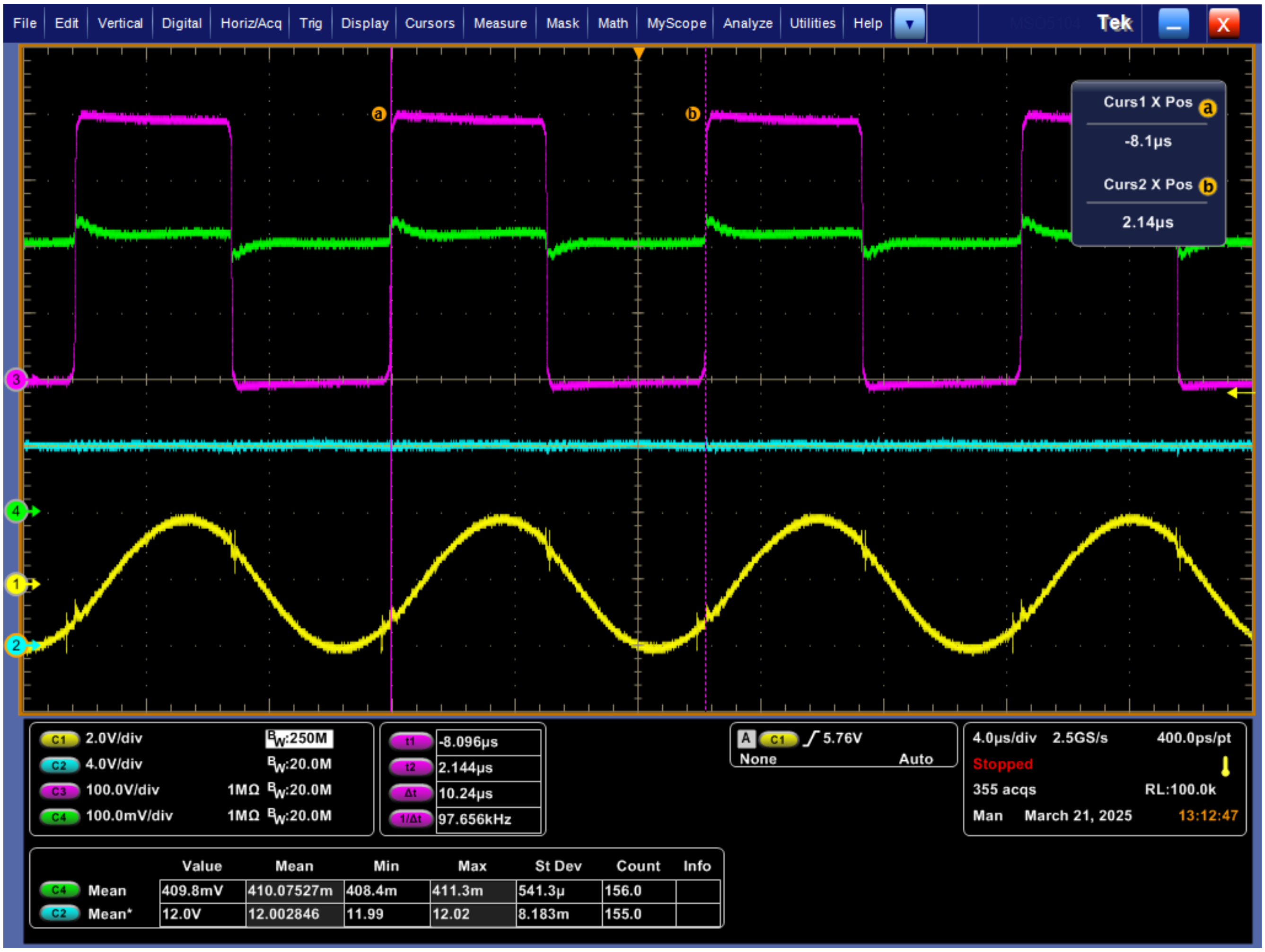

Figure 2-8. Measurement result from UCC25661 EVM [2], the switching frequency is 97.66KHz

3 Summary

In this application note, we put the models with leakage inductance in both primary and secondary side into FHA for system analysis. In here, we find the correction factor for the turn ratio which is equal to the ratio of L_P and L_M. By putting the correction factor and the system matched our prediction. Through this correction factor, we can design the transformer with correct turn ratio in to shorten the design cycle.

4 References

1. Texas Instruments, *Power Tips: Why Is Your LLC Resonant Converter Frequency Way, Way off*, technical article.
2. IEEE, *Analysis and Design of LLC Resonant Converter with Integrated Transformer*
3. Texas Instruments, */UCC25661EVM-128*, product page.