Analysis and Measurement of Resonant Tank Current on LLC

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Power Management/Field Application

ABSTRACT

Wide input voltage range and high efficiency of front-end converters are required in many applications. Most PWM DC-DC converters cannot meet these requirements because of low efficiency at the wide input voltage range. As a result, LLC is put forward to achieve both high efficiency and wide input voltage range capability because of its voltage gain characteristics and small switching loss[1]. This application report presents analysis of resonant tank current on LLC. Three current measurements of power resistance, current transformer, and current probe are discussed and compared, and the advantages, disadvantages, and applications of these current measurements are presented. The experiment result matches theoretical analysis.

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1. Introduction

LLC is the best candidate of front-end DC-DC converter for wide input voltage range and high efficiency. UCC25600 is designed for DC/DC applications utilizing resonant topologies, especially the LLC half bridge resonant converter. This highly integrated controller has only 8 pins and small package, which will greatly simplify the system design, layout and accelerate product time to market [2]. So LLC half bridge resonant converter is as example to analyze resonant tank current.

2. Analysis of Resonant Tank Current

Figure 1 is an LLC resonant half-bridge converter circuit.

- S_1 and S_2 are primary MOSFETs.
- C_{S1} and C_{S2} are parasitic capacitors between drain and source of MOSFET.
- D_{s1} and D_{s2} are body diodes of MOSFET.
- L_r and C_r are resonant inductor and resonant capacitor.
- L_m is the magnetic inductor of transformer.
- n is the turns ratio of primary and secondary turns.
- The secondary rectifier contains D_1 and D_2.
- C_o is the output capacitor.
- R_L is the load.
- V_{in} is input voltage and V_o is output voltage.

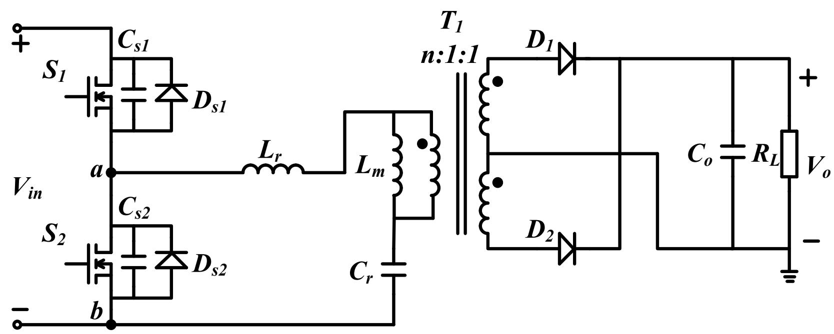


Figure 1. LLC Resonant Half-bridge Converter

There are two resonant frequencies on the LLC resonant converter: one is produced by L_r and C_r, which is shown as equation 1; the other is produced by L_r, L_m, and Cr, which is shown as equation 2. Generally, LLC is designed to operate at f_r for nominal input voltage, thus the best efficiency will be achieved. Switch frequency is larger than f_r. ZVS of primary MOSFET can be realized, but ZCS of secondary diode cannot be achieved; it is called LC series resonance. When switch frequency is lower than f_r but higher than f_m, both ZVS and ZCS can be realized. Because the resonance of L_r, L_m, and C_r occurs in a period, it is called LLC series resonance. In reference [3], switch frequency at most of the load range is lower than f_r, so the operation where frequency is lower than f_r is analyzed in this application report.

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{1}$$

$$f_m = \frac{1}{2\pi\sqrt{(L_r + L_m)C_r}} \tag{2}$$

Figure 2 is the waveform at $f_m<f_s<f_r$, half period is divided into four parts. A voltage spike of t_2 to t_3 is concerned, so this period is described in the following paragraphs. All equations show the relations of power parameters.

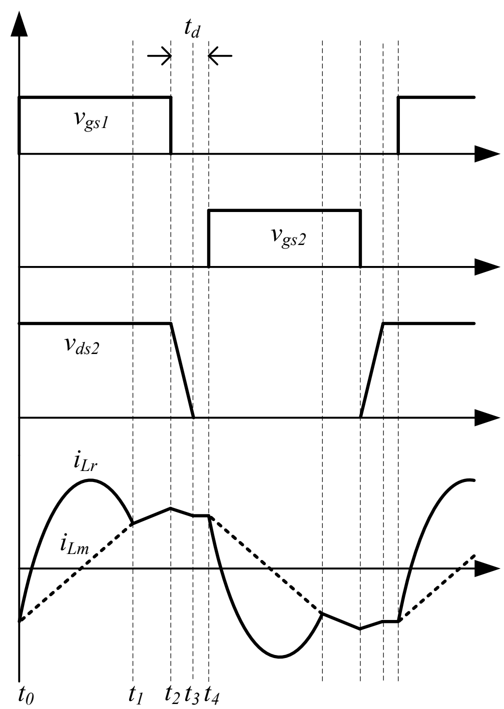


Figure 2. Waveform at $f_m<f_s<f_r$

At t_2, high-side MOSFET S_1 is turned off, but low-side MOSFET is still off, so t_2 is the beginning of dead time. During this period, resonant tank current cannot flow through MOSFET; it charges C_{s1} and discharges C_{s2}. C_{s1} and C_{s2} participate resonance. C_{s1} and C_{s2} are equal and small, so this period is very short. ZVS is achieved quickly. In real systems $C_r >> C_{s1}$, so in this period, V_{Cr} nearly does not change; it could be regarded as a DC voltage source. Figure 3 shows a simplified circuit.

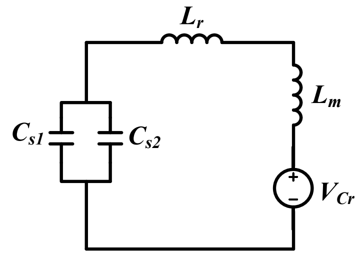


Figure 3. Simplified Circuit at $t_2<t<t_3$

All parameters are shown as equations 3 and 4, and the resonant frequency is equal to equation 5. Because of C_{eq}, fr_3 is extremely larger than fr_1 and fr_2.

$$v_{Ceq} + (L_r + L_m)C_{eq}\frac{\mathrm{d}^2 v_{Ceq}}{\mathrm{d}t^2} = V_{Cr} \tag{3}$$

$$i_{Lr} = i_{Lm} = C_{eq}\frac{\mathrm{d}v_{Ceq}}{\mathrm{d}t} \tag{4}$$

$$f_{r3} = \frac{1}{2\pi\sqrt{(L_r + L_m)C_{eq}}} \tag{5}$$

Where, $C_{eq} = C_{s1} + C_{s2} = 2C_{s1}$

The value of the change in the resonant tank current in this period is researched, so an equation to describe resonant tank current at the time domain is required. The actual beginning time of this period is t_2 and the ending time is t_3. To simplify calculation, assume the beginning time of this period is 0 and the ending time of this period is t_a. At 0, the voltage of v_{Ceq} is $\frac{1}{2}V_{in}$, the resonant tank current is I_{Lr}, so $v_{Ceq}(0) = \frac{1}{2}V_{in}$, $i_{Lr}(0) = I_{Lr}$. At t_a, the voltage of v_{Ceq} is $-\frac{1}{2}V_{in}$, so $v_{Ceq}(t_a) = -\frac{1}{2}V_{in}$.

According to equation 3, $v_{Ceq}(t)$ could be obtained as follows:

$$v_{Ceq}(t) = p_1 \cos\left(\frac{1}{\sqrt{(L_r + L_m)C_{eq}}}t\right) + p_2 \sin\left(\frac{1}{\sqrt{(L_r + L_m)C_{eq}}}t\right) + V_{Cr} \tag{6}$$

Where, p_1 and p_2 are constants. We define $\omega_{rm} = \frac{1}{\sqrt{(L_r + L_m)C_{eq}}}$, so equation 6 is simplified.

$$v_{Ceq}(t) = p_1 \cos(\omega_{rm} t) + p_2 \sin(\omega_{rm} t) + V_{Cr} \tag{7}$$

$i_{Lr}(t)$ is expressed as equation 8.

$$i_{Lr}(t) = -i_{Ceq}(t) = -C_{eq} \frac{\mathrm{d}v_{Ceq}(t)}{\mathrm{d}t} = C_{eq} p_1 \omega_{rm} \sin(\omega_{rm} t) - C_{eq} p_2 \omega_{rm} \cos(\omega_{rm} t) \tag{8}$$

$v_{Ceq}(0) = \frac{1}{2} V_{in}$ and $i_{Lr}(0) = I_{Lr}$ are put into equations 7 and 8 separately, the constant coefficients p_1 and p_2 are derived as follows:

$$p_1 = \frac{1}{2} V_{in} - V_{Cr} \tag{9}$$

$$p_2 = -\frac{I_{Lr}}{C_{eq} \omega_{rm}} \tag{10}$$

$v_{Ceq}(t_a) = -\frac{1}{2} V_{in}$ is put into equation 6.

$$p_1 \cos(\omega_{rm} t_a) + p_2 \sin(\omega_{rm} t_a) + V_{Cr} = -\frac{1}{2} V_{in} \tag{11}$$

According to equation 11, $\sin(\omega_{rm} t_a)$ and $\cos(\omega_{rm} t_a)$ can be deduced.

$i_{Lr}(t_a)$ is shown is equation 12. Because all parameters are derived, the exact value of $i_{Lr}(t_a)$ can be obtained.

$$i_{Lr}(t_a) = C_{eq} p_1 \omega_{rm} \sin(\omega_{rm} t_a) - C_{eq} p_2 \omega_{rm} \cos(\omega_{rm} t_a) \tag{12}$$

The change of the resonant tank current in this period is called Δi_{Lr}, which is shown as follows:

$$\Delta i_{Lr} = i_{Lr}(t_a) - I_{Lr} \tag{13}$$

Generally, Δi_{Lr} is omitted in analysis of resonant tank current, because its value is smaller than the peak value of resonant tank current and the period of this transition is extremely shorter than the switch period. However, this quick transition introduces noise to the measurement circuit. The preceding equations can verify if the result of the measurement is true. When it is false, the measurement circuit should be improved.

3. Resonant Tank Current Measurement Method

When current waveform is required, three methods can be adopted to measure the current.

- Power resistance with small tolerance
- Current transformer (CT)
- Measure resonant tank current directly by current probe

The first method is power resistance with small tolerance, which is in series with other components in the resonant loop. The resistance must have high resolution and good temperature performance. Normally, the resonant loop is connected to ground by one terminal, which can reduce common mode noise when measured. This method is also an easy way to measure resonant tank current. However, it increases power loss especially at high current. On the other hand, it changes the resonant parameter and makes the operation deviate from the original design. This method also has a high price because of the high performance required.

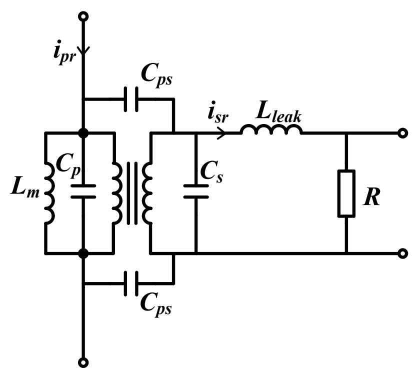


Figure 4. Equivalent Model of Current Transformer

The second method is CT, where the primary side is in series in the resonant loop. Compared with power resistance (the first method), this method has low resistance and its power loss is lower than the power resistance. Moreover, compared with L_r and L_m of the resonance loop, the magnetic inductance of CT is small enough and can be ignored. However, CT is not an optimal solution because of many parasitic parameters. Figure 4 is the equivalent model of CT. Because the secondary leakage inductance is much larger than the primary leak inductance, leakage inductance is set at the secondary side.

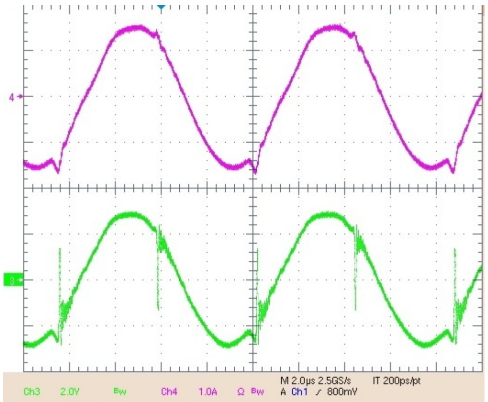
In Figure 4:

- C_{ps} is the parasitic capacitance between primary turns and secondary turns.
- C_p is the parasitic capacitance of the primary side.
- C_s is the parasitic capacitance of the secondary side.
- L_m is the magnetic inductance of CT.
- R is the sample resistance.

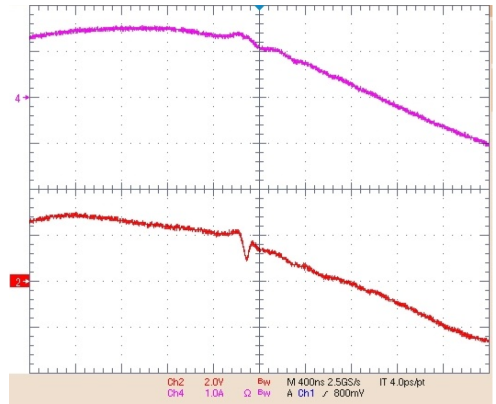
When MOSFET turns on or turns off at hard switch, the state of the circuit changes instantly and fiercely. Much switch noise is produced at this time. This noise is coupled to the secondary side of CT through C_{ps}. Noise also flows through C_p and C_s. L_m and L_{leak} are also affected. If a generic voltage probe is used to measure the voltage of R, normally a high voltage spike occurs; however; if a differential voltage probe is adopted, the common mode noise coupled by C_{ps} is eliminated, and only differential mode noise remains. Voltage spike is reduced efficiently. However, waveform measured by differential voltage probe is still not the real current waveform.

The third method is to measure resonant tank current directly by current probe. Normally, current probe has a high bandwidth, which is enough for power system test. For example, TCP202 designed by Tektronix is a DC-coupled current probe, which has a bandwidth of DC to 50 MHz. The LLC resonant tank current frequency is 100 kHz. Current probe has a good performance, which can display a nearly real current waveform. Only a short wire is needed, and it is in series with other components in loop, so this is the least expensive method to view current waveform. However, the current signal measured by current probe cannot be used for other purpose, such as loop control, protection, and so forth.

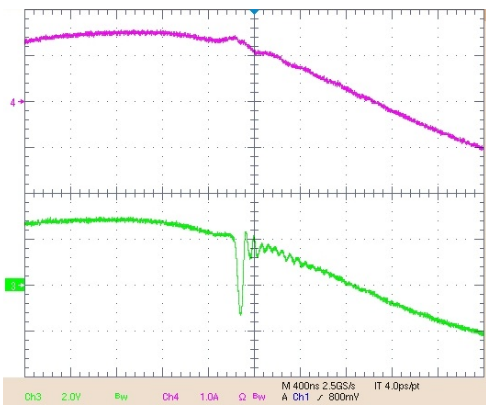
UCC25600 300W EVM demonstrates the preceding analysis. In Figure 5, resonant tank current is measured by different methods. CH2 and CH3 are both measured by CT, the difference is that a *differential* voltage probe is used to sample voltage signal which is the voltage at the output side of CT in CH2, but a *common* voltage probe is used to sample voltage signal, which is the voltage at the output side of CT in CH3. CH4 is measured by current probe directly. In Figure 5(b) and 5(c), CH2 and CH3 are measured separately, but in Figure 5(d), they are measured at the same time. In Figure 5(a), compared with CH4, large current pulse can be seen in CH3, which is big noise. In Figure 5(b) and Figure 5(c), compared with CH3, current pulse of CH2 is reduced greatly because common mode noise is eliminated; however, differential mode noise still exists, so current pulse of CH2 is larger than that of CH4. In Figure 5(d), CH2 and CH3 are measured at the same time, because all of the grounds of the probes of the oscilloscope are connected at the internal oscilloscope. Common mode noise of CH3 will affect CH2. The waveforms of CH2 and CH3 are the same in Figure 5(d), which proves that in Figure 5(b) and Figure 5(c), CH3 equals the result that CH2 pulses common mode noise.



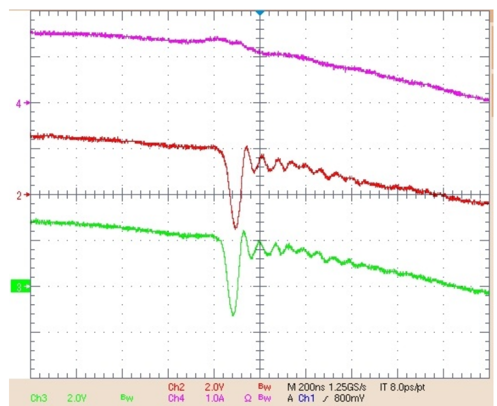
(a) CH3: CT, Common Voltage Probe, CH4: Current Probe



(b) CH2: CT, Differential Voltage Probe, CH4: Current Probe



(c) CH3: CT, Common Voltage Probe, CH4: Current Probe



(d) CH2: CT, Differential Voltage Probe, CH3: CT, Common Voltage Probe, CH4: Current Probe

Figure 5. Resonant Tank Current Measured by Different Methods

According to experiment result, the preceding analysis is certified. Power resistance is used at the condition of low current, and sampled current signal could be used for other functions. CT is adopted at the condition of high current, and sampled current signal could be used for other functions. If compensation and filter are added on the CT, it is better. Current probe is applied at all conditions, but its sampled current signal cannot be used for other functions.

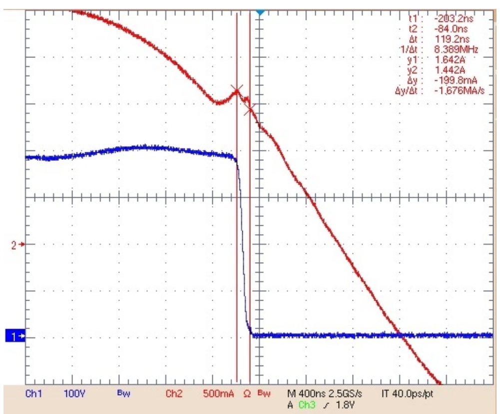
NOTE: Small range current probe is recommended to measure low current. Similarly, large range current probe is recommended to measure high current.

4. Experiment

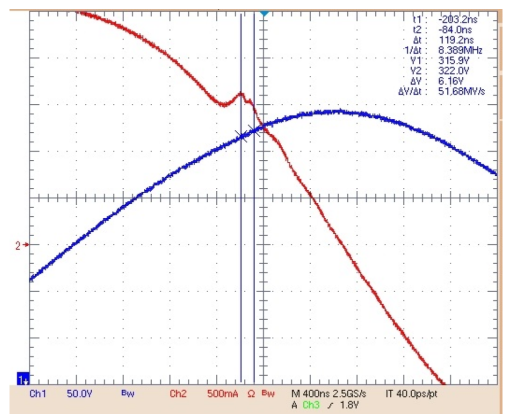
To validate the analysis of Section 2, LLC resonant half-bridge converter 300-W evaluation module of TI is used to obtain data of seven groups. All parameters have been designed and optimized, L_r = 55 µH, L_m = 280 µH, C_r = 24 nF, C_{s1} = 340 pF, V_{in}, V_{Cr} and I_{Lr} must be measured.

Figure 6 shows resonant tank current, DS voltage and V_{Cr} waveform during ZVS, where, CH2 is resonant tank current waveform. In Figure 6(a), CH1 is DS voltage waveform. In Figure 6(b), CH1 is the voltage of C_r waveform. Resonant tank current is measured by current probe, DS voltage and C_r voltage are measured by differential voltage probe.

All data are listed in Table 1: I_{Lr1} is the value of I_{Lr} at the beginning of ZVS, I_{Lr2} is the value of I_{Lr} at the end of ZVS, $\Delta I = I_{Lr1}$-I_{Lr2}, and ΔI_{cal} is the result calculated by from equation 13 to equation 20. Because these equations are too complex, Mathcad is adopted to make calculation easy. Comparing ΔI and ΔI_{cal}, ΔI_{cal} approaches ΔI, which certifies that the analysis of reference [3] in Section 2 is correct and reasonable. The differential value of ΔI and ΔI_{cal} is caused by parasitic parameters and measurement error.



(a) CH1: DS voltage waveform
CH2: resonant tank current waveform



(b) CH1: C_r voltage waveform
CH2: resonant tank current waveform

Figure 6. Resonant Tank Current, DS Voltage and V_{Cr} Waveform During ZVS

Table 1. The Value of Parameters

V_{in}(V)	V_{Cr}(V)	I_{Lr1}(A)	ILr2(A)	ΔI(A)	ΔI_{cal}(A)
392.7	237.4	1.517	1.32	0.197	0.130
392.6	249.9	1.541	1.358	0.183	0.135
390.5	268.0	1.550	1.357	0.193	0.144
390.5	288.3	1.584	1.375	0.209	0.152
390.6	307.7	1.623	1.440	0.183	0.158
390.6	328.1	1.659	1.460	0.199	0.165
390.6	348.2	1.677	1.476	0.201	0.174

5. Conclusion

LLC can provide high efficiency at a wide input voltage range. Resonant tank current of LLC is analyzed, and numerous equations specify the relations of all power parameters. Three current measurements are discussed and their applications, advantages, disadvantages are presented. The analysis is certified by experiment results.

References:

[1] Ya Liu. High Efficiency Optimization of LLC Resonant Converter for Wide Load Range. Blacksburg, Virginia: Master's Degree Thesis of Virginia Polytechnic Institute and State University, 2007.

[2] 8-Pin High-Performance Resonant Mode Controller. Texas Instruments UCC25600 Data Sheet, SLUS846B, September 2008, Revised July 2011.

[3] LLC Resonant Half-Bridge Converter 300-W Evaluation Module. Texas Instruments User's Guide, SLUU361, April 2009.

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