Short-circuit protection of LLC resonant converter using voltages across resonant tank elements

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Abstract: This paper describes two methods for the short-circuit protection of the LLC resonant converter. One of them uses the voltage across the capacitor and the other uses the voltage across the inductor of the resonant tank. These voltages can be processed (integrated or differentiated) to recover the resonant tank current. The two circuits illustrated in the described methods make it possible to develop a robust LLC converter design and to avoid using lossy current measurement elements, such as a shunt resistor or current transformer. The methods also allow measuring resonant tank current without breaking high-current paths and connecting the measuring circuit in parallel with the inductor or capacitor of the resonant tank. Practical implementations of these indirect current measurements have been experimentally tested for the short-circuit protection of the 1600 W LLC converter.

1 Introduction

The LLC series resonant converter (the two inductors and one capacitor) is very attractive for medium-level isolated power conversion. It has advantages such as a soft switching, a high-power density, high efficiency in the wide range of loads and low electromagnetic interference [1, 2]. The short-circuit protection is one of the important issues for the reliability of LLC resonant converter. Many techniques have been presented to protect the LLC converter against short circuit and over current [3–7]. Some of them use additional hardware functionality such as increasing the switching frequency [3], implementing clamping circuits [3, 5] and monitoring voltage across the resonant capacitor [4, 5]. Other approaches change the control of pulse-width modulation [3, 6]. All these solutions either increase the size of the converter or complicate the development of the resonant controller.

This paper illustrates two ways to protect LLC converter against short circuit on the output. Both of them use indirect measurement of resonant tank current. The first way is based on the differentiation of the voltage across the capacitor of the resonant tank (capacitor sensing method). The second way is based on the integration of the voltage across the inductor of the resonant circuit (inductor sensing method). For both methods, a calculation strategy, simulation results and experimental data are presented.

2 Description of the methods

The schematic of the full-bridge LLC resonant converter is illustrated in Fig. 1. To effectively protect it from the short circuit on the output, it is necessary to monitor the resonant tank current \( I_r \). To measure this current indirectly, it is possible to use the voltage across resonant capacitor \( C_r \) and differentiate it as was offered in [8]. The development of this idea gives one more way: to use the voltage across resonant inductor \( L_r \) and integrate it. To select the circuits for indirect resonant tank current measurement, the following specific requirements should be taken into account: (a) high common and differential modes voltages on the resonant tank elements; (b) high-voltage change rate \((dv/dt)\) on the resonant tank elements; (c) a small occupied size on the printed circuit board; and (d) additional circuit solution should be of low cost.

Considering the above-illustrated requirements, the isolated RC-circuit differentiator and the integrator based on the operational amplifier (OPAMP) have been selected for the differentiation and integration, respectively (see Fig. 2). Using the OPAMP for differentiation in this case is not beneficial because of the high voltages and high \( dv/dt\) on its inputs.

The basic current sensor schematic for the capacitor sensing method is shown in Fig. 2a. It represents an RC-circuit differentiator. The transformer TR is used to galvanically isolate the flying resonant capacitor and over-current protection logic. The output sensing voltage can be found from the following equation

\[
V_{\text{sense}} = \frac{I_r}{3\omega C_r} (R + (1/\omega RC)) \simeq \frac{I_r RC}{C_r}, \quad \text{if } \omega RC \ll 1 \tag{1}
\]

The basic current sensor schematic for the inductor sensing method is shown in Fig. 2b. It represents the integrator based on the OPAMP. The output sensing voltage can be found as follows

\[
V_{\text{sense}} = \frac{I_r \omega L_r (R_2/(1 + \omega R_2 C))}{R_1} \simeq \frac{I_r L_r}{R_1 C}, \quad \text{if } \omega R_2 C \gg 1 \tag{2}
\]

In these equations, \( I_r \) is the resonant tank current and \( V_{\text{sense}} \) are the sensors output voltages equal to the scaled resonant tank current. \( L_r, C_r, R, R_1, R_2 \) and \( C \) are values of corresponding elements in Fig. 2.

3 Practical implementation of short-circuit protection of LLC converter

The two described indirect current measurement approaches can be used for the short-circuit protection of LLC converter.

The practical sensor schematic implementation for the capacitor sensing approach (Fig. 2a) is presented in Fig. 3. The scale factor for this sensor can be found from (1): \( K_{CS} = 0.022 \text{ V/A} \). The schematic illustrates the same elements \( R, C \) and TR as in Fig. 2a and some additional auxiliary components. The common mode filter LCM as well as the capacitor CF play a filtering role against high \( dv/dt\) present on the resonant capacitor ends. The diode bridge rectifier makes it possible to protect LLC converter from any polarity of the basic-circuit resonant current. Transformer TR should have low capacitance between the primary and secondary windings \((C_{\text{w}} \leq 10 \text{ pF})\), low-leakage inductance \((L_{\text{leak}} \leq 10 \mu\text{H})\), corresponding isolation voltage and high magnetising inductance. It might be sensitive to external noise and should either have a shielded design or be placed far from high-current paths.

The practical schematic implementation of the sensor for the inductor sensing method (Fig. 2b) is presented in Fig. 4. The scale
The factor for this sensor can be found from (2): \( K_{LS} = 0.023 \text{ V/A} \). The circuit with single power supply and two OPAMPs is implemented for rectification purposes and simplifying the circuit. Each OPAMP in this circuit works in active mode during half the switching period. Thus, these OPAMPs should be fast enough to exit saturation on their outputs. In current solution LT1801 OPAMPs are implemented. There will be some output distortions because of voltage drop (\( \approx 0.3 \ldots 0.5 \text{ V} \)) on the diodes \( D_2 \) that can be taken into account when selecting the short-circuit threshold, or the scale factor can be adjusted to compensate this voltage drop.

### 4 Experimental results

Both methods and schematics presented in Figs. 3 and 4 have been simulated and tested as a part of the LLC converter. The prototype sensor board for each method has been assembled and connected to the existing 1600 W LLC converter prototype (Fig. 5). The output of the short-circuit sensor under test is connected to the over-current protection pin of the resonant mode controller (Texas Instruments...
UCC25600). When the voltage on this pin is above 1 V the gate signals turn off.

Experimental data for the capacitor sensing method are presented in Fig. 6. Experimental data for the inductor sensing method are presented in Fig. 7.

5 Conclusion

This paper has presented two solutions for measuring resonant tank current and short-circuit protection of LLC resonant converter. The Letter methods are based on the differentiation of the resonant capacitor voltage and the integration of the resonant inductor voltage. The illustrated solutions allow simplifying the development of a robust LLC converter using a small amount of additional components. The capacitor and inductor sensing boards have been experimentally tested with the 1600 W LLC converter prototype. Both the sensors proved to be effective in the short-circuit protection of this LLC converter.

The given approaches allow to avoid lossy current measurement elements, such as a shunt resistor or current transformer and can be further developed for implementing short-circuit protection in other switch-mode power supplies topologies where the access is available to power inductors or capacitors.

6 References

[1] Liu R., Lee C.Q.: ‘Analysis and design of LLC-type series resonant convertor’, Electron. Lett., 1988, 24, (24), pp. 1517–1519
[2] Liu R., Batarseh I., Lee C.Q.: ‘Comparison of performance characteristics between LLC-type and conventional parallel resonant converters’, Electron. Lett., 1988, 24, (24), pp. 1510–1511
[3] Yang B., Lee F.C., Concannon M.: ‘Over current protection methods for LLC resonant converter’. Applied Power Electronics Conf. and Exposition, 9–13 February 2003, vol. 2, pp. 605–609
[4] Xie X., Zhang J., Zhao C., Zhao Z., Qian Z.: ‘Analysis and optimization of LLC resonant converter with a novel over-current protection circuit’, IEEE Trans. on Power Electron., 2007, 22, (2), pp. 435–443
[5] Figge H., Grote T., Fröhleke N., Böcker J., Schafmeister F.: ‘Overcurrent protection for the LLC resonant converter with improved hold-up time’: Applied Power Electronics Conf. and Exposition (APEC), 2011, pp. 13–20
[6] Liu S., Ren R., Meng W., Zheng X., Zhang F., Xiao L.: ‘Short-circuit current control strategy for full-bridge LLC converter’. Energy Conversion Congress and Exposition (ECCE), 2014, pp. 3496–3503
[7] Sheng H., Wang F., Tipton C.W.: ‘A fault detection and protection scheme for three-level DC-DC converters based on monitoring flying capacitor voltage’, IEEE Trans. Power Electron., 2012, 27, (2), pp. 685–697
[8] Kim S.K., Han H.S., Woo Y.I., Cho G.H.: ‘A low-cost high-efficiency CCFL inverter with new capacitive sensing and control’, IEEE Trans. Power Electron., 2006, 21, (5), pp. 1444–1451