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Design and Verification of proposed Operation Modes of LLC Converter

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***Abstract*—The subject is a comprehensive research on issues of power electronic converters operating at very high switching frequency. This is a group of inverters applicable particularly in the power supply, respectively automotive products. The main purpose of the use of high switching frequency is a high value of power density and reduced weight and dimension parameters of the device.**

***Index Terms*—communication system control, telecommunication services, internetworking, switching converters.**

I. INTRODUCTION

Purpose the paper is verification of operation modes and the influence of parasitic elements proposed of LLC converter with output power of 1 kW and switching frequency of 500 kHz for telecommunications distributions. LLC resonant converter is multi-resonant converter and is characterized by its unique DC - gain characteristic, which has two resonant frequencies (f_0 and f_p). This converter has several advantages compared to standard serial LC resonant topology. One of them is possibility of stable regulation of output voltage in a wide range of input voltages together with the change of output power from 1% to 100%. The next advantage is achievement of ZVS switching mode during various operational modes. LLC resonant converter is composed of three functional parts (Fig. 1). It deals about pulse generator, resonant circuit with high-frequency transformer and rectifier with capacitive filter.

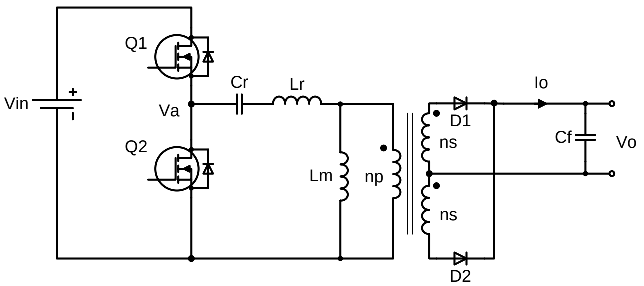

Fig. 1. Principle schematic of LLC converter.

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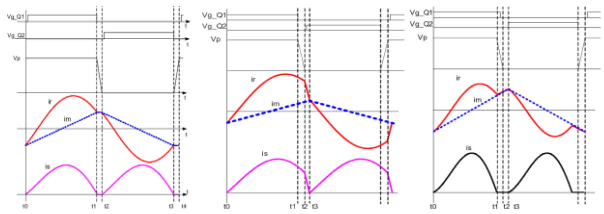
II. OPERATION MODES

Operation of LLC converter in different operational modes is described by DC gain characteristic, which should be divided into ZVS and/or ZCS region [1]. ZVS region in dependency on the switching frequency can be further divided into:

- Region with switching frequency equal to resonant ($f_s = f_0$);
- Region with switching frequency higher than resonant ($f_s > f_0$);
- Region with switching frequency lower than resonant ($f_s < f_0$).



a) b) c)

Fig. 2. Waveforms of currents and voltages of LLC converter at different operating conditions: a – $f_s = f_0$, b – $f_s > f_0$, c – $f_s < f_0$.

According to the operational modes of resonant converters the operation of LLC resonant converter is rather difficult [2]. The principal waveforms of transformer and output diode during each operating mode are shown in Fig. 2. The impedance of series resonant circuit at the resonant frequency is equal to zero. Therefore the reflected output voltage is equal to the input voltage, what is described by the unity of voltage gain thus the circuit then operates optimally. LLC resonant converter can achieve gain greater, less or equal to 1. If the switching frequency is less than the resonant frequency, magnetization inductance is involved into the resonance of the circuit so the converter can deliver higher gain.

III. DESIGN PARAMETERS OF THE MAIN CIRCUIT

Target of the design is to determine the active and passive elements of the proposed converter. Is the need estimated efficiency, determination of the maximum and minimum input voltage, determination of maximum and minimum voltage gains, determinations of transformer turns ratio, determination of equivalent load resistance and design of the resonant network. The final design of LLC power stage only the three parameters are necessary to be optimally chosen:

– Ratio of magnetizing and resonant inductance

$$m = \frac{L_m}{L_r}, \tag{1}$$

where L_m is magnetizing inductance and L_r is resonant inductance.

– Quality factor

$$Q = \sqrt{\frac{L_r}{L_m}} \cdot \frac{\pi^2}{8.n^2.R_L}, \tag{2}$$

where n is transformer ratio and R_L is equivalent load.

– Resonant frequencies

$$f_0 = \frac{1}{2.\pi.\sqrt{L_r.C_r}}, \quad f_p = \frac{1}{2.\pi.\sqrt{(L_r + L_m).C_r}}. \tag{3}$$

In terms of design it is important to made the compromise in selection of the inductance ratio m.

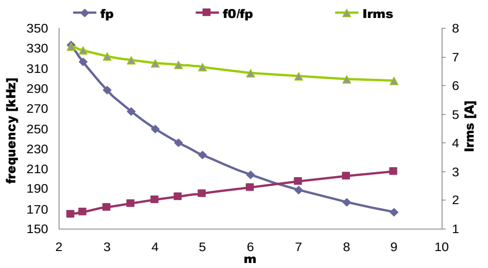


Fig. 2. Dependency of parallel resonant frequency (f_p), ratio of f_0/f_p and I_{RMS} on the value of m.

IV. SIMULATION ANALYSIS OF THE OPERATIONAL MODES OF PROPOSED LLC RESONANT CONVERTER

Operational modes of LLC resonant converter has been verified in OrCAD PSpice simulation software.

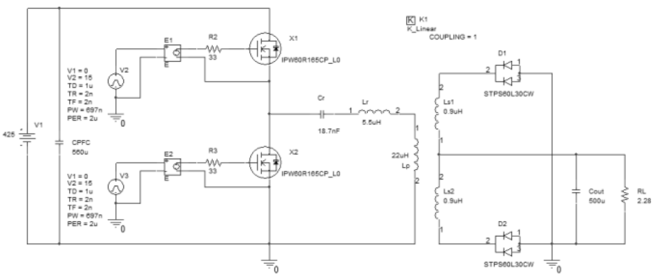


Fig. 3. Simulation model of main circuit of proposed LLC converter.

Input/Output parameters of LLC resonant:

– Input voltage: 425 V;
– Output voltage: 48 V;
– Output current: 21 A;
– Output power: 1008 W;
– Switching frequency ≈ 500 kHz.

Simulation waveforms in the Fig.4, Fig.5, Fig.6. confirm the theoretical assumptions. Another simulation test verified the properties of LLC resonant converter at change load and change the input voltage [3].

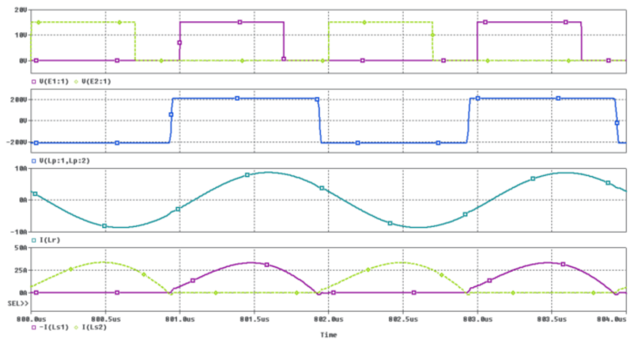


Fig. 4. Time waveforms during the simulation experiment at $f_s = f_0$ (from top – driving signals of transistors X1, X2, voltage on the primary side of transformer, current on the primary side of transformer, currents of the output diodes D1, D2).

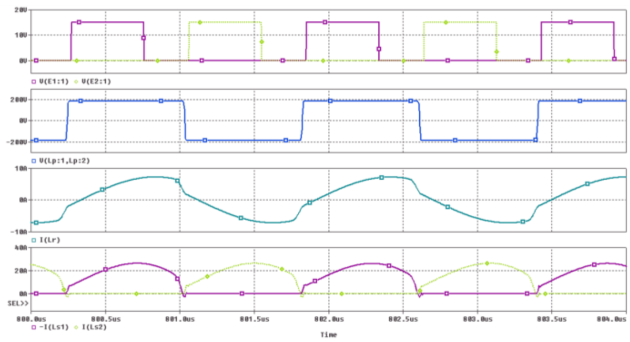


Fig. 5. Time waveforms during the simulation experiment at $f_s > f_0$ (from top – driving signals of transistors X1, X2, voltage on the primary side of transformer, current on the primary side of transformer, currents of the output diodes D1, D2).

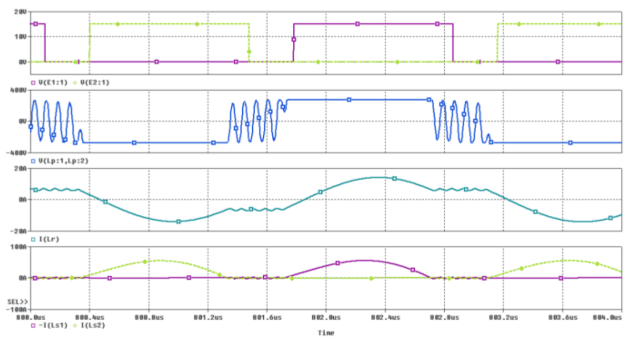


Fig. 6. Time waveforms during the simulation experiment at $f_s < f_0$ (from top – driving signals of transistors X1, X2, voltage on the primary side of transformer, current on the primary side of transformer, currents of the output diodes D1, D2).

Fig. 7 presents the results from the simulation experiment, when LLC resonant converter operates at full load (P_{OUT} = 1008W) when input voltage U_{IN} = 425V. In this mode, transistors are operating with ZVS conditions and output diodes with character of ZCS switching. The unwanted effect of reverse recovery was eliminated by utilization of Schottky rectifier diodes.

Fig. 8 is showing the simulation experiment at 25% of load at the input voltage U_{IN} = 425V. In the picture shows that even at the reduced output power the switching transistors are maintaining excellent operating characteristics of the ZVS mode. In the case of output diodes the ZCS switching character is also still achieved.

Fig. 9 shows the simulation experiment, when LLC resonant converter operates at minimal supply voltage U_{IN} =

325V and at full load condition. Simulation experiment confirmed proper design of converter. Transistor's current has sinusoidal shape until magnetizing inductance became participating in resonance with other circuit parameters. Output diodes are operating in discontinuous ZCS mode. The last experiment has been done at the input voltage U_{IN} = 325V and at output power P_{OUT} = 252W. As can be seen in this operation mode the inverter is still able to achieve ZVS conditions for the main transistors. Soft commutation with ZCS conditions are also achieved for output rectifier diodes, which are operating in discontinuous mode.

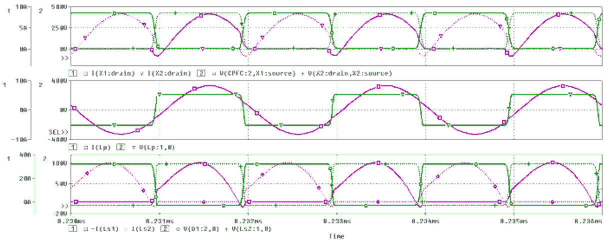


Fig. 7. Time waveforms of voltages and currents during the simulation experiment: U_{IN} = 425V, P_{OUT} = 1008W (from top - transistor X1a X2, transformer primary side, output diode D1 and D2).

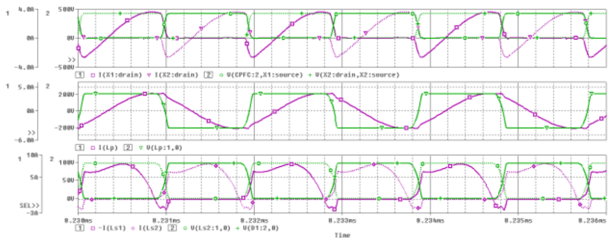


Fig. 8. Time waveforms of voltages and currents during the simulation experiment: U_{IN} = 425V, P_{OUT} = 252W (from top - transistor X1a X2, transformer primary side, output diode D1 and D2).

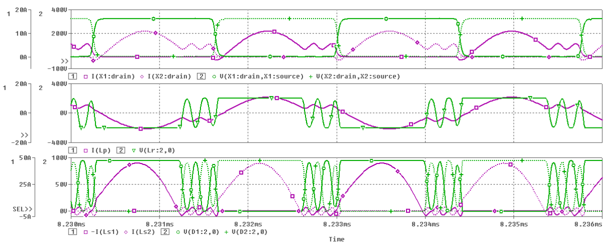


Fig. 9. Time waveforms of voltages and currents during the simulation experiment: U_{IN} = 325V, P_{OUT} = 1008W (from top - transistor X1a X2, transformer primary side, output diode D1 and D2).

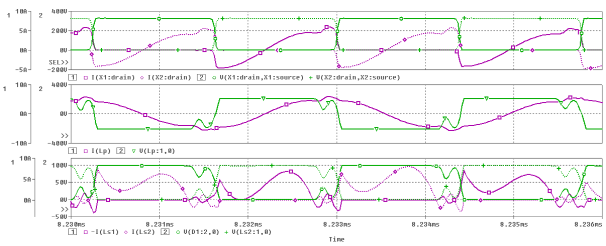


Fig. 10. Time waveforms of voltages and currents during the simulation experiment: U_{IN} = 325V, P_{OUT} = 252W (from top - transistor X1a X2, transformer primary side, output diode D1 and D2).

After simulation experiments have been made, we have made multiple graphic interpretation of converter's efficiency in dependency on converter's output power and input voltage. These results are good indicators of converter design and are good starting point for experimental verifications.

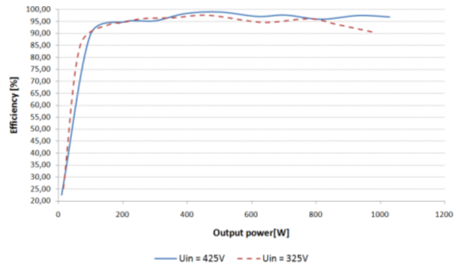


Fig. 11. Efficiency of the proposed converter in dependency on output power and input voltage (U_{IN} = 425 V, U_{IN} = 325V).

Time waveforms voltage and current may be deformed influence parasitic components. At higher switching frequencies the sensitivity of the parasitic leakage inductances and capatities becomes serious problem. The parasitic components inclusive in the simulation model of main circuit of LLC resonant converter are:

- C_{OSS}: output capacitance of MOSFET;
- C_{TR}: transformer winding capacitance;
- C_{jc}: junction capacitance of rectifier diode;
- L_{lks}: leakage inductance at transformer secondary side.

The simulation model LLC resonant converter include parasitic components is shown in Fig. 12.

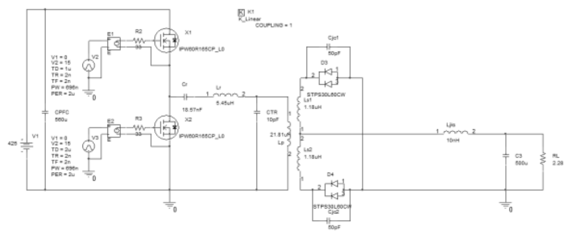


Fig. 12. Simulation model of main circuit of proposed LLC resonant converter with parasitic components.

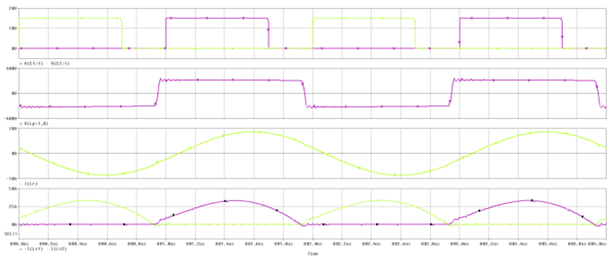


Fig. 13. Time waveforms during the simulation experiment LLC resonant converter inclusive parasitic components at fs = f_0 (from top – driving signals of transistors X1, X2, voltage on the primary side of transformer, current on the primary side of transformer, currents of the output diodes D1, D2).

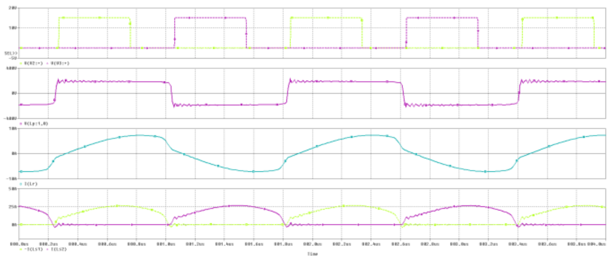


Fig. 14. Time waveforms during the simulation experiment LLC resonant converter inclusive parasitic components at fs > f_0 (from top – driving signals of transistors X1, X2, voltage on the primary side of transformer, current on the primary side of transformer, currents of the output diodes D1, D2).

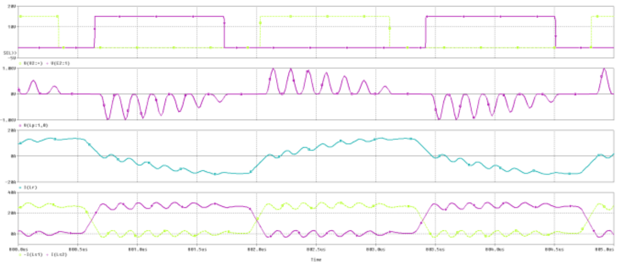


Fig. 15. Time waveforms during the simulation experiment LLC resonant converter inclusive parasitic components at fs < f_0 (from top – driving signals of transistors X1, X2, voltage on the primary side of transformer, current on the primary side of transformer, currents of the output diodes D1, D2).

V. CONCLUSIONS

This paper describes the design of the LLC resonant converter, which is done by means of fundamental harmonic approximation (FHA). Output power of proposed converter is 1kW output voltage 48V and switching frequency is 500 kHz. Performance of converter at different operational conditions were verified through simulation analysis by utilization of OrCAD PSpice software. The simulation results of multiple parametrical experiments were obtained and consequently evaluated into graphical interpretation of efficiency of proposed converter. Future work will be focusing on the design of the physical samples, verification activities and influence of the parasitic components on the operation of LLC converter.

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