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The Influence of Parasitic Components on LLC Resonant Converter

Fang Li , Ruixiang Hao *, Haodong Lei , Xinyi Zhang and Xiaojie You

School of Electrical Engineering, Beijing Jiaotong University, Beijing 100044, China; hahalifang@163.com (F.L.); leihaodong@bjtu.edu.cn (H.L.); 17121536@bjtu.edu.cn (X.Z.); xjyou@bjtu.edu.cn (X.Y.)

* Correspondence: haorx@bjtu.edu.cn; Tel.: +86-137-1774-2934

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Abstract: In recent years, the LLC resonant converter has been widely used in DC–DC conversion applications. However, the parasitic components of the LLC resonant converter have a significant impact in practical applications, such as influence on the conduction loss and the soft-switching of power devices, the voltage oscillation across rectifier diodes, the unregulated output voltage at light load condition and so on. It is hard to analyze the higher-order circuits by the conventional analysis methods. Focusing on the operational principle of the LLC converter with parasitic components, the differential equation model is presented and solved by the numerical method in this paper. The simulation results verify the correctness of the theoretical analysis. The causes of two different frequency oscillations and the voltage spike are clarified. The design considerations and a specific example of the LLC converter are given. The experimental results are consistent with the simulation results, and the soft-switching of primary-side switches can be achieved in the prototype.

Keywords: LLC resonant converter; parasitic components; differential equation model; numerical solution; design consideration

1. Introduction

The LLC resonant converter has been widely used in the electric vehicle charger, server power supply, and uninterrupted power supply conditions for its advantages, such as isolation, adjustable voltage, soft switching, high switching frequency, and high efficiency [1,2]. In the ideal case, the resonant inductance, resonant capacitance, and magnetizing inductance operate together to achieve energy transfer. Frequency modulation control with half duty cycle is usually adopted. And when the switching frequency is lower than the resonant frequency, zero voltage switching (ZVS) turn-on of primary-side switches and zero current switching (ZCS) turn-off of rectifier diodes can be achieved [3,4].

However, in practical applications, the parasitic components of the LLC resonant converter have a significant impact. The secondary-side parasitic capacitance may influence the ZVS transient in the LLC resonant converter [5]. The transformer capacitance may have an impact on the conduction loss of primary-side switches, and the optimal dead time should be longer [6,7]. In the LLC converter with center-tapped transformer, unbalanced leakage inductances may cause the imbalanced rectifying currents [8,9]. At the switching transitions, the voltage oscillation across rectifier diode may emerge by the transformer leakage inductance and the parasitic capacitance [10,11]. The practical phenomena that the output voltage is unregulated at light load condition cannot be explained by the ideal analysis. The essential reason may be the effect of junction capacitances of rectifier diodes, or the output capacitances of primary-side switches [12–14].

Besides the fundamental harmonic approximation method, the graphical state-trajectory analysis method is clear and useful to analyze the resonant converters [15]. There are also some analysis methods based on time-domain solution [16,17]. However, if the output capacitance or other parasitic

components are considered, the order of the circuit will be higher, and it is difficult to get the time domain solution. Hence, simplified analysis has been used, such as assuming that the current of magnetizing inductance and the voltage of resonant capacitance remain unchanged to ignore the resonant devices, or only considering a single or several parasitic components [18,19]. The consequence is that the analysis is partial and not accurate. While in the study of silicon carbide (SiC) metal oxide semiconductor field effect transistor (MOSFET) behavior, the circuit-level analytical model with device parameters and parasitic values is proposed [20,21]. That provides another referential analysis method for the LLC converter considering the parasitic components.

This paper mainly focuses on the analysis of the operational principle of the LLC converter that considers parasitic components comprehensively. Section 2 presents the full-bridge LLC resonant converter circuit with parasitic components. The differential equation models of each stages are established in Section 3. The numerical solutions are solved, and the waveforms are discussed in Section 4. Design considerations and an example of the LLC convert are given in Section 5. The conclusion is in Section 6.

2. Equivalent Circuit of LLC Resonant Converter with Parasitic Components

Figure 1 shows the circuit diagram of a full-bridge LLC resonant converter which considers the parasitic components. The circuit contains the resonant inductance L_r , resonant capacitance C_r , and magnetizing inductance L_m of the transformer T , and also includes the output capacitance C_o . In addition to these four necessary ideal passive devices, the parasitic components needing to be considered are:

- the output capacitances of the primary-side SiC MOSFET devices, named as $C_{in1} \sim C_{in4}$;
- the equivalent capacitance C_{eq} of the transformer;
- the junction capacitances of the rectifier diodes, named as $C_{o1} \sim C_{o2}$;
- the equivalent series inductance L_{ok} of the output capacitance branch;
- the on-resistance of the switch and the parasitic resistance in the print circuit board (PCB) line of the primary circuit loop are combined and equaled to R_1 ; the influence of the diode voltage drop and the parasitic resistance of the secondary circuit are similarly combined and equaled to R_2 .

Figure 1. Full-bridge LLC resonant converter circuit with parasitic components.

3. Analysis of Operational Principle with Parasitic Components

The most common control strategy for LLC resonant converters is variable frequency control with half duty ratio. To make sure the converter is operating in the ZVS region, the switching frequency is usually lower than the resonant frequency. The circuit waveforms are shown in Figure 2, including the driving waveform v_{gs} , the voltage v_{Cin1} across the switch Q_1 , the resonant current i_{Lr} , and the voltage v_{Co2} across the rectifier diode D_{02} .

Figure 2. Key waveforms of full-bridge LLC resonant converter considering parasitic components.

There are several stages in the waveforms:

- $[t_0, t_1]$, positive resonant stage. L_r resonates with C_r , and energy is transferred from the primary side to the secondary side. This stage ends when the resonant current is equal to the magnetizing current.
- $[t_1, t_2]$, since the switching period is longer than the resonance period, there is a freewheeling stage after the end of the resonance. In this stage, the statuses of switches are not changed, and the voltage applied to the resonant network is still V_{in} . This stage ends when the switches Q_1 and Q_4 turn OFF.
- $[t_2, t_4]$ is the dead time. The voltage across the capacitances of the primary-side switches and the rectifier diodes are changing. This time interval is divided into two stages, the front voltage-establish stage and the rear voltage-establish stage. There are two different voltage-establish modes at different situations.

After t_4 , the relative switches turn ON, and the converter enters the negative resonant stage.

3.1. Freewheeling Stage

When the resonant current is equal to the magnetizing current, the current of the rectifier diode D_{o1} crosses to zero, and D_{o1} turns OFF naturally. Then the converter operates in the freewheeling stage, in which the input voltage of the resonant network is still V_{in} for the switches Q_1 and Q_4 are still ON. The equivalent circuit in $[t_1, t_2]$ is shown in Figure 3.

Figure 3. The equivalent circuit of the freewheeling stage.

Assume the voltage on the output capacitance is v_o , and V_{Ro} is the average voltage value on the load R_o at steady state. Therefore, the initial voltages of v_{Co1} and v_{Co2} are 0 and $2 V_{Ro}$ on the freewheeling stage. According to the positive direction shown in Figure 3, the relationships of voltages and currents of the LLC converter are list as Equation (A1) in the Appendix A. In which i_{pri} is the primary current of the transformer, i_{sec1} and i_{sec2} are the currents in the two secondary windings respectively. Equation (A1) is complicated and cannot be written as the matrix form directly. To

simplify the analysis, several assumptions are made as follows: the voltage V_{Ro} is constant, and the voltage change rate of the secondary-side of the transformer is equal to the voltage change rates of v_{Co2} :

$$\frac{dv_{sec}}{dt} = \frac{1}{N} \frac{dv_{pri}}{dt} = -\frac{dv_{Co1}}{dt} = \frac{dv_{Co2}}{dt}, \quad (1)$$

in which the transformer turns ratio is $N:1:1$. Therefore, the resonant current can be solved as:

$$i_{Lr} = i_{Lm} + C_{eq} \frac{dv_{pri}}{dt} + i_{pri} = i_{Lm} + \left(C_{eq} + \frac{C_{o1}}{N^2} + \frac{C_{o2}}{N^2} \right) \frac{dv_{pri}}{dt}. \quad (2)$$

The change rates of voltages are:

$$\begin{cases} \frac{dv_{pri}}{dt} = \frac{i_{Lr} - i_{Lm}}{C_A} \\ \frac{dv_{Co1}}{dt} = -\frac{dv_{sec}}{dt} = -\frac{1}{N} \frac{dv_{pri}}{dt} = -\frac{1}{N} \frac{i_{Lr} - i_{Lm}}{C_A} \\ \frac{dv_{Co2}}{dt} = \frac{dv_{sec}}{dt} = \frac{1}{N} \frac{dv_{pri}}{dt} = \frac{1}{N} \frac{i_{Lr} - i_{Lm}}{C_A} \end{cases}, \quad (3)$$

in which $C_A = \left(C_{eq} + \frac{C_{o1}}{N^2} + \frac{C_{o2}}{N^2} \right)$.

Then, the current change rate of output capacitance branch meets:

$$L_{ok} \frac{di_{Lok}}{dt} = -R_o C_{o1} \frac{dv_{Co1}}{dt} - R_o C_{o2} \frac{dv_{Co2}}{dt} - i_{Lok} - v_{Co}. \quad (4)$$

In the end, the relationships of voltages and currents in the freewheeling stage can be written as the matrix form of differential equations and list in Equation (A2) in the Appendix A.

3.2. Front Voltage-Establish Stage

After the freewheeling stage, the primary switches Q_1 and Q_4 turn OFF, the voltages on capacitances of the primary-side switches and the rectifier diodes are both changing. The equivalent circuit of this stage is shown in Figure 4.

Figure 4. The equivalent circuit of the front voltage-establish stage.

In the traditional analysis, C_{in1} and C_{in2} are the same, and the currents in those capacitances are at the same value with the opposite direction. However, considering the variation of junction capacitances with the drain-source voltage v_{ds} , C_{in1} and C_{in2} are no longer equal for the initial voltage of Q_1 is 0 and the initial voltage of Q_2 is V_{in} . And the currents of the capacitances are no longer same, which satisfy:

$$i_{Cin1} - i_{Cin2} = i_{Lr}. \quad (5)$$

Under variable frequency control with half duty ratio in the LLC converter, it can be considered that the voltage change of Q_4 is consistent with that of Q_1 synchronously. And Q_3 is the same as Q_2 . Therefore, the calculation can be simplified and written as:

$$\begin{cases} \frac{di_{Lr}}{dt} = \frac{v_{Cin2} - v_{Cin1} - v_{Cr} - v_{pri} - R_1 i_{Lr}}{L_r} \\ \frac{dv_{pri}}{dt} = \frac{i_{Lr} - i_{Lm}}{C_A} \end{cases} \quad (6)$$

The matrix form of differential equations of voltages and currents are list in Equation (A3) in the Appendix A.

3.3. Rear Voltage-Establish Stage

The LLC converter enters to rear voltage-establish stage either v_{Cin2} or v_{Co2} drops to zero in the front voltage-establish stage. However, the equivalent circuit became different in the next. Two situations need to be discussed separately: primary capacitance voltage-establish mode and secondary capacitance voltage-establish mode. No matter which mode the converter is operating in, after the rear voltage-establish stage, the converter reaches the same stage, i.e., the negative resonant stage.

3.3.1. Primary Capacitance Voltage-Establish Mode

At t_3 , the voltage of C_{o2} drops to zero and D_{o2} turns ON, and the primary-side voltage of the transformer drops to $-NV_o$ synchronously. Then the energy transfers from the primary side to the secondary side. The equivalent circuit of this mode is shown in Figure 5.

Figure 5. The equivalent circuit of the primary capacitance voltage-establish mode.

D_{o2} turns ON and $v_{Co2} = 0$, then the secondary-side voltage of the transformer satisfies:

$$v_{sec} = -v_{Co1} + v_{Ro} + R_2 \left(i_{Lok} + \frac{v_{Ro}}{R_o} \right) = 0 - v_{Ro} - R_2 \left(i_{Lok} + \frac{v_{Ro}}{R_o} \right). \quad (7)$$

Make simplification and get:

$$\begin{cases} v_{sec} = -\left(1 + \frac{R_2}{R_o}\right) v_{Ro} + R_2 i_{Lok} = -\frac{1}{2} v_{Co1} \\ v_{Ro} = (-v_{sec} - R_2 i_{Lok}) \frac{R_o}{R_o + R_2} = \left(-\frac{v_{pri}}{N} - R_2 i_{Lok}\right) \frac{R_o}{R_o + R_2} \end{cases} \quad (8)$$

Because v_{Ro} is the sum of the voltages of the output capacitance and parasitic inductance, as:

$$v_{Ro} = v_{Co} + L_{ok} \frac{di_{Lok}}{dt}. \quad (9)$$

By calculating, the current changing rate of output capacitance branch is:

$$\frac{di_{Lok}}{dt} = -\frac{R_o}{NL_{ok}(R_o + R_2)} v_{pri} - \frac{1}{L_{ok}} v_{Co} - \frac{R_o R_2}{L_{ok}(R_o + R_2)} i_{Lok}. \quad (10)$$

The resonant current and the secondary-side currents are:

$$\begin{cases} i_{Lr} = i_{Lm} + C_{eq} \frac{dv_{pri}}{dt} + i_{pri} = i_{Lm} + C_{eq} \frac{dv_{pri}}{dt} - \frac{i_{sec1}}{N} + \frac{i_{sec2}}{N} \\ i_{sec1} = C_{o1} \frac{dv_{Co1}}{dt} \\ i_{sec2} = -i_{sec1} - i_{Lok} - \frac{v_{Ro}}{R_o} \end{cases}, \quad (11)$$

and the change rate of resonant current is:

$$\frac{di_{Lr}}{dt} = \frac{v_{Cin2} - v_{Cin1} - v_{Cr} - v_{pri} - R_1 i_{Lr}}{L_r}. \quad (12)$$

Then,

$$\frac{dv_{pri}}{dt} = \frac{i_{Lr} - i_{Lm} + \frac{1}{N} i_{Lok} - \frac{1}{N^2(R_o + R_2)} v_{pri} - \frac{R_2}{N(R_o + R_2)} i_{Lok}}{C_B}, \quad (13)$$

in which $C_B = C_{eq} + \frac{4C_{o1}}{N^2}$. The matrix form of differential equations can be list as Equation (A4) in the Appendix A.

3.3.2. Secondary Capacitance Voltage-Establish Mode

The other possibility is that v_{Cin1} and v_{Cin2} change to V_{in} and zero earlier, then the current is freewheeling through the body diodes of primary switches, and the voltage of the input-side of the resonant network is clamped to $-V_{in}$. At this mode, since the secondary-side voltage of the transformer is lower than the output voltage, the diode D_{o2} is still reverse blocking. The equivalent circuit of secondary capacitance voltage-establish mode is shown in Figure 6.

Figure 6. The equivalent circuit of the secondary capacitance voltage-establish mode.

Comparing the equivalent circuit of this mode to that of the free-wheeling stage, it can be found that only the voltage of the input-side of the resonant network changes from V_{in} to $-V_{in}$. Therefore, modify the corresponding coefficient of Equation (A2) can get the differential equations of secondary capacitance voltage-establish mode as Equation (A5) in the Appendix A.

3.4. Negative Resonant Stage

After the rear voltage-establish stage, the voltage of the input-side of the resonant network is clamped to $-V_{in}$. The rectifier diode D_{o2} is conducting forward, and the energy is transferred from the input to the output of the converter. The equivalent circuit is shown in Figure 7.

Figure 7. The equivalent circuit of the negative resonant stage.

The differences from Figure 7 to Figure 5 are the voltage of the input side of the resonant network becomes $-V_{in}$, and the change rates of v_{Cin1} and v_{Cin2} are both zero. The differences from Figure 7 to Figure 6 are v_{Co2} is clamped to zero, and D_{o2} is conducting forward. Then, the matrix form of differential equations of the negative resonant stage can be easily listed as Equation (A6) in the Appendix A.

In the negative resonant stage, the simplified analysis is adopted. No matter whether the primary-side switches Q_2 and Q_3 are ON or not, the equivalent circuit is regarded as the same. The body diodes of primary-side switches could also conduct the resonant current. In practice, the voltage drop of body diode is much higher than that of the on-resistance of the switches. To improve efficiency, the body diode conducting time should be shortened.

In the ideal case, L_r and C_r are resonating during the resonant stage, and primary-side voltage of the transformer is reflected as $-NV_o$. With parasitic components, the negative resonant stage of the LLC converter becomes different. The damping oscillation between parasitic components and the voltage spikes and fluctuations may emerge. Those are both reflected on the voltages of the rectifier diode and the transformer. As a consequence, the voltage stress of the rectifier diodes will increase, and the output voltage will be distorted.

4. Numerical Solution and Simulation Results

4.1. Numerical Solution

Calculate the numerical solution of the differential equations in MATLAB, and Figure 8 shows the flow chart processes of the four stages after the positive resonant stage. The converter parameters and the voltage and current values at time t_1 are set at the initialization. Choose two different operating points of the LLC resonant converter to calculate, which correspond to the two kinds of modes. Then, draw the waveforms with changing time as shown in Figures 9 and 10.

In Figure 9, v_{Co2} drops to zero first, while in Figure 10, v_{Cin2} drops to zero earlier. Besides the resonance between L_r and C_r , there are two other oscillations in the waveforms of the numerical solution.

One oscillation is emerging in the freewheeling stage. The participant components are L_r , L_m , and the capacitance C_A . C_A includes the C_{eq} and the reflected capacitances of C_{o1} and C_{o2} . It is hard to calculate the resonant frequency between these participant components. Since the value of C_A is much smaller than the capacitance of C_r , the oscillation frequency is higher than the resonant frequency f_r of the LLC converter.

Figure 8. The flow chart of the solution processes in MATLAB.

Figure 9. The waveforms of the numerical solution with primary capacitance voltage-establish mode.

Figure 10. The waveforms of the numerical solution with secondary capacitance voltage-establish mode.

The other oscillation is emerging after v_{Co2} drops to zero. In Figure 9, the oscillation is in the primary capacitance voltage-establish mode. And in Figure 10, the oscillation is in the negative resonant stage. From the waveform of i_{Lok} , it can be seen that there is a significant current step at this time, which leads to a voltage spike. Then, the participant components start to oscillate. Since the parasitic inductance of output capacitance branch is little and the equivalent capacitance C_B is small, the oscillation frequency is high. Under the damping effect of R_1 and R_2 , the oscillation decays slowly, overlaying on the main resonance waveform. In Figure 10, due to the secondary capacitance voltage-establish mode, the difference value between the resonant current and the magnetizing current is more significant. As a consequence, a higher spike emerges on the diode voltage and output voltage.

It should be noted that there is an inevitable error, because the error of initial values exists and the influence of the dead time is not considered. Anyway, the deviation is small, and the calculation results of the numerical solution can reflect the operation of the LLC converter considering parasitic components.

4.2. Simulation Results

LTspice software is used to verify the theoretical analysis for it has the advantages such as being free, fast, and easy to converge. And the mathematical model of SiC devices can be imported to LTspice directly. The junction capacitance of the rectifier diode can be represented as a variable current source controlled by variable voltage. To simplify the simulation, the open-loop waveform is simulated with unique driving signals. The LTspice simulation waveforms corresponding to the two kinds of modes are shown in Figures 11 and 12, respectively.

Figure 11. The LTspice simulation results of the LLC converter with primary capacitance voltage-establish mode.

Figure 12. The LTspice simulation results of the LLC converter with secondary capacitance voltage-establish mode.

In the LTspice simulation model, all of the parasitic components in the full-bridge LLC resonant converter circuit are considered. The magnetizing current cannot be extracted due to the coupling inductance model of the transformer in LTspice. Compared with the waveforms of the numerical solution of MATLAB, the results are mainly the same with two other oscillations and spikes. However, the length of the freewheeling stage set in the LTspice simulation is slightly larger than that of MATLAB, so the number of oscillation cycles is increased.

5. Design Considerations and Experimental Verification

5.1. Design Considerations of the LLC Converter

Based on the differential equation model and the numerical results, some design considerations of the LLC converter can be given.

- The dead time for achieving the soft-switching of primary-side switches is related to their output capacitances. However, the output capacitance of switches changes with the drain-source voltage. In the datasheet, the output capacitance is usually given as a curve and the specific value of output capacitance under the specific test condition. In order to simplify the calculation, 2 or 3 times of the specific value of the output capacitance can be used as the equivalent output capacitance in general.
- The maximum load power should be used in designing the converter parameters. When the load power is maximum, v_{cr} is high and i_{Lr} is low in the freewheeling stage. Thus, it is the most serious condition to realize soft-switching of the primary-side switches.
- The equivalent capacitance of the transformer and the junction capacitance of the rectifier diodes deteriorate the soft-switching of the primary-side switches, and they are both participating in the two oscillations. When designing transformers, the equivalent capacitance should be reduced seriously.
- The equivalent series inductance L_{ok} of the output capacitance contributes to the voltage spike in the high frequency oscillation, especially for the situation with high output current. Therefore, the output capacitance with small equivalent series inductance should be selected, and the parasitic inductance of the circuit loop should be minimized.

5.2. Experimental Results

In order to verify the assistance of this paper on the design and application of the LLC converter, the specific and concise design procedure based on an application example is given. The design requirements are shown in Table 1.

Table 1. The parameters of the LLC experimental prototype.

Parameters	Value
Input voltage	700–800 V
Output voltage	48 V
Rated power	8000 W
Primary switches	C2M0025120D
Rectifier diodes	VB60170G

According to the relationship of the input and output voltages, the transformer turns ratio is defined as 18:1:1. The LLC converter works below the resonant frequency. Set the resonant frequency f_r as 255 kHz, and the dead time between switches t_{dead} is 300 ns. The primary-side switches are SiC MOSFETs C2M0025120D. In the datasheet, the output capacitance C_{oss} is 220 pF under the test condition as $v_{gs} = 0$ V, $v_{ds} = 1100$ V, $f = 1$ MHz, and $v_{AC} = 25$ mV.

The traditional LLC resonant converter parameter design process has been given in the references [22,23]. Ignoring the voltage drop of the rectifier diodes, the amplitude of magnetizing current at resonant frequency can be calculated as:

$$I_{Lm} = \frac{1}{2} \frac{NV_{Ro}}{L_m} \frac{1}{2f_r}. \quad (14)$$

The required dead time to charge and discharge the C_{oss} is:

$$t_{dead} = 2C_{oss} \frac{V_{in}}{I_{Lm}}. \quad (15)$$

Therefore, the upper limit value of L_m satisfies:

$$\frac{1}{2} \frac{NV_{Ro}}{L_m} \frac{1}{2f_r} = 2C_{oss} \frac{V_{in}}{t_{dead}}. \quad (16)$$

By calculating the parameters of the LLC converter, L_m should be less than $668 \mu\text{H}$. However, the soft-switching of primary-side switches cannot be achieved due to the loose restrictions. According to the design considerations proposed in this paper, the actual value of L_m is taken as one sixth to one quarter of the upper limit value calculated by Equation (16), considering the influence of the output capacitance of switches, transformer equivalent parasitic capacitance, and diode junction capacitance. Based on the switching frequency range 160–250 kHz and the voltage gain curves under different switching frequencies, L_m is determined as 6–7 times of L_r in the prototype. Therefore, the final value of L_r is $19.18 \mu\text{H}$, and L_m is $111.4 \mu\text{H}$. According to the resonant frequency, the value of C_r is 20.25 nF .

In the final design of the prototype, there are two transformers whose primary windings are in series and secondary windings are in parallel after rectifier diodes. The two transformers are the same, in which the turns ratio is 18:2:2 and magnetizing inductances is $55.7 \mu\text{H}$. In the design process, the equivalent parasitic capacitance of the transformer should be minimized. When the PCB is drawn, the length of the secondary circuit should be minimized to reduce parasitic inductance. And the symmetry of each secondary circuit should be guaranteed. Those specific optimization methods will not be detailed here. Figure 13 shows the experimental prototype of the LLC converter.

Figure 13. The experimental prototype of the LLC converter.

The experimental results of the LLC converter are shown in Figure 14. In case one, the time interval of the freewheeling stage is longer. And i_{Lr} and v_{Co2} are oscillating at a frequency higher than the resonant frequency of the LLC converter. v_{Co2} drops to zero first, and then v_{Cin2} drops to zero. When the rectifier diode is conducting forward, there is high-frequency oscillation in the beginning of the resonant stage. It is corresponding to the numerical solution and the simulation results. In case two, the time interval of the freewheeling stage is shorter and less than a resonant period. v_{Cin2} drops to zero a little earlier than v_{Co2} . The spike of high-frequency oscillation in the waveforms of diode voltage is a little larger than that of case one.

Figure 14. The experimental results of the LLC converter.

The experiment results verify the correctness of the differential equation model and its numerical solution. What's more, the soft-switching of primary-side MOSFETs is achieved based on the parameter design considerations proposed in this paper.

6. Conclusions

The operational principle of the LLC resonant converter with parasitic components is proposed in this paper. Besides the three resonant components, the output capacitance and its parasitic inductance, the capacitance of primary-side switches, the capacitance of rectifier diodes, and the equivalent capacitance of the transformer are all considered. By establishing differential equations and solving numerical solutions, the causes of two different frequency oscillations and the voltage spike are clarified. The simulation results verify the correctness of the theoretical analysis. The influence of the parasitic components and the design considerations are proposed. The experimental results of a specific example of the LLC converter are given. The analysis is helpful in the design and application of the LLC converter.

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Appendix A

The voltage and current expressions of freewheeling stage:

$$\begin{cases}
 V_{in} = L_r \frac{di_{Lr}}{dt} + v_{Cr} + v_{pri} + R_1 i_{Lr} \\
 i_{Lr} = i_{Lm} + C_{eq} \frac{dv_{pri}}{dt} + i_{pri} \\
 v_{pri} = L_m \frac{di_{Lm}}{dt} \\
 i_{Lr} = C_r \frac{dv_{Cr}}{dt} \\
 v_{Cin1} = 0, v_{Cin2} = V_{in} \\
 v_{sec} = -v_{Co1} + v_{Ro} + R_2 \left(i_{Lok} + \frac{v_{Ro}}{R_o} \right), v_{pri} = N v_{sec} \\
 v_{sec} = v_{Co2} - v_{Ro} - R_2 \left(i_{Lok} + \frac{v_{Ro}}{R_o} \right) \\
 i_{sec1} = C_{o1} \frac{dv_{Co1}}{dt}, i_{sec2} = C_{o2} \frac{dv_{Co2}}{dt} \\
 i_{pri} = -\frac{i_{sec1}}{N} + \frac{i_{sec2}}{N} \\
 C_o \frac{dv_{Co}}{dt} = i_{Lok} \\
 v_{Ro} = v_{Co} + L_{ok} \frac{di_{Lok}}{dt} = R_o \left(-C_{o1} \frac{dv_{Co1}}{dt} - C_{o2} \frac{dv_{Co2}}{dt} - i_{Lok} \right)
 \end{cases} \quad (A1)$$

The differential equation model of freewheeling stage:

$$\begin{pmatrix} \dot{i}_{Lr} \\ \dot{v}_{Cr} \\ \dot{i}_{Lm} \\ \dot{v}_{pri} \\ \dot{v}_{Cin1} \\ \dot{v}_{Cin2} \\ \dot{v}_{Co1} \\ \dot{v}_{Co2} \\ \dot{i}_{Lok} \\ \dot{v}_{Co} \end{pmatrix} = \begin{pmatrix} \frac{-R_1}{L_r} & \frac{-1}{L_r} & 0 & \frac{-1}{L_r} & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{C_r} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{L_m} & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{C_A} & 0 & \frac{-1}{C_A} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-1}{NC_A} & 0 & \frac{1}{NC_A} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{NC_A} & 0 & \frac{-1}{NC_A} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{R_0(C_{o1}-C_{o2})}{NC_A L_{ok}} & 0 & \frac{-R_0(C_{o1}-C_{o2})}{NC_A L_{ok}} & 0 & 0 & 0 & 0 & \frac{-R_0}{L_{ok}} & \frac{-1}{L_{ok}} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{C_o} & 0 & 0 \end{pmatrix} \begin{pmatrix} i_{Lr} \\ v_{Cr} \\ i_{Lm} \\ v_{pri} \\ v_{Cin1} \\ v_{Cin2} \\ v_{Co1} \\ v_{Co2} \\ i_{Lok} \\ v_{Co} \end{pmatrix} + \begin{pmatrix} \frac{V_{in}}{L_r} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}. \quad (A2)$$

The differential equation model of rear voltage-establish stage with secondary capacitance voltage-establish mode:

$$\begin{pmatrix} \dot{i}_{Lr} \\ \dot{v}_{Cr} \\ \dot{i}_{Lm} \\ \dot{v}_{pri} \\ \dot{v}_{Cin1} \\ \dot{v}_{Cin2} \\ \dot{v}_{Co1} \\ \dot{v}_{Co2} \\ \dot{i}_{Lok} \\ \dot{v}_{Co} \end{pmatrix} = \begin{pmatrix} \frac{-R_1}{L_r} & \frac{-1}{L_r} & 0 & \frac{-1}{L_r} & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{C_r} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{L_m} & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{C_A} & 0 & \frac{-1}{C_A} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{-1}{NC_A} & 0 & \frac{1}{NC_A} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{NC_A} & 0 & \frac{-1}{NC_A} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{R_0(C_{01}-C_{02})}{NC_A L_{ok}} & 0 & \frac{-R_0(C_{01}-C_{02})}{NC_A L_{ok}} & 0 & 0 & 0 & 0 & \frac{-R_0}{L_{ok}} & \frac{-1}{L_{ok}} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{C_o} & 0 & 0 \end{pmatrix} \begin{pmatrix} i_{Lr} \\ v_{Cr} \\ i_{Lm} \\ v_{pri} \\ v_{Cin1} \\ v_{Cin2} \\ v_{Co1} \\ v_{Co2} \\ i_{Lok} \\ v_{Co} \end{pmatrix} + \begin{pmatrix} -\frac{V_{in}}{L_r} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}. \quad (A5)$$

The differential equation model of negative resonant stage:

$$\begin{pmatrix} \dot{i}_{Lr} \\ \dot{v}_{Cr} \\ \dot{i}_{Lm} \\ \dot{v}_{pri} \\ \dot{v}_{Cin1} \\ \dot{v}_{Cin2} \\ \dot{v}_{Co1} \\ \dot{v}_{Co2} \\ \dot{i}_{Lok} \\ \dot{v}_{Co} \end{pmatrix} = \begin{pmatrix} \frac{-R_1}{L_r} & \frac{-1}{L_r} & 0 & \frac{-1}{L_r} & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{C_r} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{L_m} & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{C_B} & 0 & \frac{-1}{C_B} & \frac{-1}{N^2 C_B (R_0 + R_2)} & 0 & 0 & 0 & \frac{R_0}{N C_B (R_0 + R_2)} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{2}{NC_B} & 0 & \frac{2}{NC_B} & \frac{2}{N^3 C_B (R_0 + R_2)} & 0 & 0 & 0 & \frac{-2R_0}{N^2 C_B (R_0 + R_2)} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{-R_0}{N L_{ok} (R_0 + R_2)} & 0 & 0 & 0 & \frac{-R_0 R_2}{L_{ok} (R_0 + R_2)} & \frac{-1}{L_{ok}} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{C_o} & 0 & 0 \end{pmatrix} \begin{pmatrix} i_{Lr} \\ v_{Cr} \\ i_{Lm} \\ v_{pri} \\ v_{Cin1} \\ v_{Cin2} \\ v_{Co1} \\ v_{Co2} \\ i_{Lok} \\ v_{Co} \end{pmatrix} + \begin{pmatrix} -\frac{V_{in}}{L_r} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}. \quad (A6)$$

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