Loss Analysis and Optimization Design of Half-Bridge LLC Resonant Converter

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Abstract. The efficiency improvement of switching converters has always been a research hotspot. This paper analyzes the loss of LLC resonant converter including magnetic components loss and Switching loss. For easier analysis, a mathematical model of the switching tube is established, and then derive the formula of the loss. The synchronous rectification technology is used to improve the efficiency of the LLC, and finally established a simulation model to verify the correctness of the technology to improve the efficiency of the converter.

Keywords: LLC Resonant Converter, synchronous rectification technology, MATLAB simulation

1. Introduction
With the rapid development of power electronics technology, the requirements for power supplies in various fields are getting higher and higher. Therefore, high efficiency, small size, high power density, high withstand voltage and high reliability have become hot research circles in the industry. From the perspective of reducing the size of the switching converter, increasing the switching frequency is one of the most effective methods. However, increasing the switching frequency will increase the switching loss and reduce the switching efficiency. This paper analyzes the loss of each part of the LLC converter, which has important significance for improving the efficiency of the converter.

2. The Basic Working Principle of LLC Resonant Converter
The topology of the LLC resonant converter is shown in Figure 1, where Q1 and Q2 are two MOSFET switching transistors. \(L_r\) is a resonant inductor, which can be replaced by the leakage inductance of the transformer? \(L_m\) is the magnetizing inductance of the transformer, \(C_r\) is the resonant capacitor, \(L_r\), \(L_m\) and \(C_r\) form the resonant cavity [1], and their resonant frequencies are:

\[
f_1 = \frac{1}{2\pi\sqrt{L_r C_r}}
\]  

(1)
\[ f_2 = \frac{1}{2\pi \sqrt{(L_r + L_m)C_r}} \] (2)

![Figure 1. Topology of LLC resonant converter](image1.png)

A switching cycle of the switch can be divided into 8 stages [2], as shown in Figure 2. Where VQ1 and VQ2 represent the driving pulses of the switching tubes Q1 and Q2, \( i_r \) represents the current of the resonant cavity, \( i_m \) represents the excitation current of the excitation transformer, and VD1, VD2 and \( i_{D1}, i_{D2} \) respectively represent the voltage and current of the secondary rectifier diode. \( C_1 \) and \( C_2 \) represent the parasitic capacitance of Q1 and Q2.

![Figure 2. main waveform when \( f_2 < f_s < f_1 \)](image2.png)

Stage 1\( (t_0 < t < t_1) \): Q2 is turned off at \( t_0 \) and then enter dead time, \( C_1 \) discharge while \( C_2 \) charging. Reverse current \( i_r < i_m \). The primary winding voltage of the transformer is forward voltage, and the secondary rectifier diode D1 is turned on.

Stage 2\( (t_1 < t < t_2) \): The body diode of Q1 is turned on, creating conditions for ZVS of Q1. The voltage of the primary winding of the transformer is forward voltage, and the secondary rectifier diode D1 is turned on. The voltage of \( l_m \) is clamped at \( nV_0 \) and does not participate in resonance. When \( i_r \) becomes 0, the process ends.

Stage 3\( (t_2 < t < t_3) \): At time \( t_2 \), Q1 is turned on, and \( i_r > i_m \), \( l_m \) is linearly charged at this stage. This process ends until \( i_r = i_m \).

Stage 4\( (t_3 < t < t_4) \): At time \( t_3 \), \( i_r = i_m \), the transformer has no energy transfer, the secondary rectifier is turned off, and the excitation winding \( l_m \) participates in resonance.

Stage 5\( (t_4 < t < t_5) \): At time \( t_4 \), Q1 is turned off and enters the dead time. At this stage, \( C_1 \) is charged, \( C_2 \) is discharged, \( i_r < i_m \), the primary winding voltage of the transformer is reverse voltage, and the secondary rectifier diode D2 is turned on.

Stage 6\( (t_5 < t < t_6) \): At time \( t_5 \), \( C_2 \) discharge is completed, and the body diode of Q2 is turned on to create conditions for ZVS of Q2. The state of the transformer and rectifier diode is the same as that of the previous stage.

Stage 7\( (t_6 < t < t_7) \): At time \( t_6 \), Q2 is turned on, and the secondary side rectifier D2 is turned on, and the voltage of \( l_m \) is clamped at \(-nV_0\) and \( l_m \) is linearly charged at this voltage. This process ends until \( i_r = i_m \).
Stage 8(t_7<t<t_0): At time t_7, i_r = i_m, the working state is the same as Stage 4, and then Enter the next cycle.

3. Loss Analysis of LLC Resonant Converter

The loss of the LLC resonant converter mainly includes two parts, one is the loss caused by the magnetic component such as the transformer, and the other is the loss caused by the switching tube.

3.1 Loss analysis of magnetic components

Transformer losses are clearly a major part of the loss of magnetic components. It mainly includes iron loss and copper loss. Iron loss refers to the energy lost during transformer magnetization, including hysteresis loss and eddy current loss. Iron loss has a great relationship with core selection. Therefore, the selection of high frequency transformer core material is very important for the design of the converter.

The core loss P includes hysteresis loss $P_h$, eddy current loss $P_c$, and residual loss $P_r$, that is,

$$ P = P_h + P_c + P_e $$ (3)

3.1.1 Hysteresis loss. The loss in the static magnetic field is mainly hysteresis loss. The hysteresis loss is proportional to the area enclosed by the hysteresis loop [3], which can be expressed by

$$ P_h = \oint B dH $$ (4)

The hysteresis loss is generally calculated by the following formula.

$$ P_h = K_h f B_m^{1.6} $$ (5)

$K_h$ is the proportionality factor and is related to the material.

3.1.2 Eddy current loss. In the dynamic alternating magnetic field, there is eddy current loss, which can be calculated by the following formula:

$$ P_c = \frac{\pi^2 f^2 B^2 d^2}{6\rho} $$ (6)

Where d is the material density, unit g/cm³ $\rho$ is the resistivity, the unit is Ω·m.

3.1.3 Residual loss. The residual loss is due to the magnetization hysteresis caused by the post-magnetic effect. That is, when B→0 and f→0, the part of the loss whose total loss is not zero is the residual loss, which is related to the type of material and the excitation condition.

3.2 Power switch tube loss

3.2.1 Loss of the primary side switch of the transformer. Generally speaking, the loss of the power tube is divided into on-state loss and switching loss. The on-state loss is the loss caused by the switch tube when it is turned on, and the switch loss means that the switch tube is turned from on to off or from off to on. The resulting transition loss. In the first section, the primary side switch of the LLC resonant converter can be analyzed to achieve ZVS, so the turn-on loss is not considered. Then, only the on-state loss and the turn-off loss need to be considered.

During time $t_0<t<t_3$, the voltage across the magnetizing inductance $L_m$ is $nV_0$, which is clamped by the secondary side without participating in resonance. In this stage, the exciting inductor current $i_m$ can be expressed as:
At time $t_3$, the excitation current reaches the maximum value $I_{m\text{max}}$, that is:

$$i_m(t_3) = -I_{m\text{max}} + \frac{nV_0}{L_m} \cdot t$$

At this time $t_3 = \pi/w_r$. Then

$$i_m(t_3) = -I_{m\text{max}} + \frac{nV_0}{L_m} \cdot \frac{\pi}{w_r} = I_{m\text{max}}$$

So $I_{m\text{max}} = \frac{nV_0}{L_m} \cdot \frac{\pi}{w_r}$

At time $t_3$, $i_m = i_r$, the voltage across the magnetizing inductance $L_m$ is no longer clamped, and participates in resonance with $L_r$ and $C_r$. Since the value of the magnetizing inductance $L_m$ is much larger than the resonant inductor $L_r$, the resonant current $i_r = I_{m\text{max}}$ can be considered in the stage of $t_3 < t < t_4$.

Therefore, the expression of the resonant current $i_r(t)$ in the first half of the cycle is as follows:

$$i_r(t) = \begin{cases} 
\frac{V_{im} - nV_0}{Z_r} \sin(w_r t - \theta) & t_0 < t < t_3 \\
I_{m\text{max}} & t_3 < t < t_4
\end{cases}$$

where $Z_r = \sqrt{\frac{L_r}{C_r}}$ is resonant network impedance, $\theta = \sin^{-1}(I_{m\text{max}})$.

The on-state loss during Q1 conduction can be divided into two parts, one part is the loss caused by the body diode of Q1, and its size is the product of the on-voltage drop $V_d$ of the body diode and the current $i_d$. This process occurs at $t_1 < t < t_2$ period, $i_d = i_r$, its loss can be expressed as:

$$P_{ssd} = \int_{t_1}^{t_2} i_d \cdot V_d \, dt$$

The other part is the on-state loss. This process occurs during the period $t_2 < t < t_3$, and it can be expressed as:

$$P_{dt} = \frac{1}{2} \int_{t_2}^{t_3} (i_r(t))^2 \cdot R_{on} \, dt$$

$R_{on}$ is the on-resistance, which can be found in the device manual.

The turn-off loss occurs during the period of $t_4 < t < t_5$. After the Q1 is turned off, the resonant current cannot be rapidly dropped to 0 due to the leakage inductance of the transformer, so loss occurs, and $t_4$ enters the dead time, and $C_1$ is charged at this stage. $C_2$ discharge, establish its mathematical model as shown in Figure 3:

![Figure 3. Mathematical model when Q1 is turned off](image)

When Q1 is turned off, the current $i_{Q1}$ decreases linearly, and its size is:

$$i_{Q1}(t) = i_b - \frac{i_b}{t_f} \cdot t$$
Where $i_b$ is the initial current, the magnitude of which is equal to the current at time $t_4$, $i_b = I_{m \cdot \text{max}}$ and $t_f$ is the fall time. According to the model, you can get:

$$\begin{align*}
    \begin{cases}
        i_m = i_{c1} + i_{c2} + i_{Q1} \\
        i_{c1} &= \frac{c_1 dV_{c1}}{dt} \\
        i_{c2} &= \frac{c_2 dV_{c2}}{dt} \\
        V_{c1} + V_{c2} &= V_{in} \\
        C1 &= C2 \\
        i_{c1} &= -i_{c2}
    \end{cases}
\end{align*}$$

(13)

we can get $i_{c1} = \frac{i_m}{2t_f} \cdot t$

$$V_{s1}(t) = V_{c1}(t) = \left(\frac{i_m \cdot t^2}{4C_1 t_f}\right)$$

(14)

Where $V_{c1}$ $V_{c2}$ is the capacitor voltage, and $V_{s1}$ is the voltage of Q1. The loss of the MOS tube is thus:

$$P = \frac{1}{T} \int_0^{t_f} V_{s1}(t) i_{Q1}(t) dt = \frac{i_m^2 t_f^2 t_f}{4C_1}$$

(15)

3.2.2 Secondary side rectifier diode loss. Generally, the voltage drop of the rectifier diode is 0.7V, and the conduction time of each diode of the secondary side is $\pi / \omega_r$ so the conduction loss of the two rectifiers is:

$$P_{D1, D2} = 2 \cdot 0.7 \cdot \frac{\pi}{\omega_r} = 0.7l = 0.7 \frac{V_0}{R_0}$$

(16)

The diode rectification conduction voltage drop is about 0.7V. If the secondary side output voltage is as low as a few volts, the loss due to this diode voltage drop becomes very large. The synchronous rectification technology is very suitable for this low voltage and high current occasion. Greatly reduce the loss of the diode [4].

![Figure 4. Simulation model of LLC resonant converter](image)

4. Simulation Verification of Secondary Side Synchronous Rectification Technology
The relevant parameters of this simulation are as Table 1:
Table 1. Simulation parameters

| Input voltage $V_{in}$ | Load $R_o$ | 5Ω |
|------------------------|------------|----|
| 400                    |            |    |

Magnetizing inductance $L_m$ | Dead time | 125nS |
|---------------------------|-----------|------|
| 879                       |           |      |

Resonant inductor $L_r$ | Transformer ratio |
|-----------------------|------------------|
| 122                   | 4                |

Resonant capacitor $C_r$ | |
|------------------------|------|
| 22n                    |      |

The simulation model is established as shown in Figure 4. When the secondary diode is rectified on the secondary side, the output voltage waveform is shown in Figure 5. The average output current is $I_o = 9.5A$, and the average input current is $I_{in} = 1.3A$, so the efficiency of normal diode rectification can be calculated.

$$\eta = \frac{VoIo}{Vin} \times 100\% = \frac{47.6 \times 9.5}{400 \times 1.3} \times 100\% = 86.9\%$$

(17)

Figure 5. Output voltage waveform when rectifying with a common diode

The output waveform when using the synchronous rectification technique on the secondary side is shown in Fig. 6. At this time, the output voltage $V_o = 49.97V$, the output average current is $I_o = 10.0A$, and the average input current is $I_{in} = 1.38A$ and the efficiency is:

$$\eta = \frac{VoIo}{Vin} \times 100\% = \frac{49.97 \times 10.0}{400 \times 1.38} \times 100\% = 90.5\%$$

(18)
It can be seen that the efficiency of the secondary side is greatly improved after using the synchronous rectification technology. The simulation results in $i_m$ and $i_r$ waveforms as shown in Figure 7.

![Figure 7. Resonant current $i_r$ and excitation current $i_m$ waveform](image)

5. Conclusion
Nowadays, with the increasing demand for power supply in various fields, it is urgent to improve the efficiency of switching converters. In this paper, the loss of LLC resonant converter is analyzed, including the loss of magnetic component of the transformer and the loss of the switching tube, and a mathematical model is established to analyze the on-state loss and turn-off loss of the switch. At the same time, the LLC resonant converter simulation model is established, and used MATLAB software simulation to verify that the synchronous rectification technology can improve the efficiency of the LLC resonant converter.

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