Efficiency optimization strategy of LLC resonant converter based on Hybrid PWM and PFM digital control mode

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Abstract. There is a problem that the overall efficiency of LLC resonant converter decreases due to large switching loss under light load, in order to solve it, an efficiency optimization strategy based on hybrid PWM and PFM digital control mode was proposed to improve the efficiency of LLC Resonant Converter in the full load range. In order to adapt to different loads, Boost LLC converter circuit topology was proposed. The former Boost circuit was controlled by pulse width modulation (PWM), and the latter LLC was controlled by pulse frequency modulation (PFM). Pulse width modulation (PWM) control of the front Boost circuit can improve the bus voltage of the rear LLC circuit and adapt to different loads. Under the pulse frequency modulation (PFM), the efficiency of the rear LLC resonant converter under light load can be further improved by adjusting the resonant frequency. The experimental results showed that the proposed digital control efficiency optimization method could enable the Boost LLC converter to achieve high efficiency in the whole load range, and the overall conversion efficiency was not less than 94%.

1. Introduction
LLC resonant converter has been widely concerned and applied because of its advantages of simple circuit topology, high switching frequency, small electromagnetic interference and high efficiency, such as switching power supply in communication equipment, driving power supply for LED lamp, power supply for electric vehicle charging pile, etc.

However, with the increase of input voltage range, the conduction loss of LLC resonant converter will increase rapidly due to the increase of switching frequency, and the efficiency of LLC resonant converter will decrease. Therefore, a Buck LLC cascaded converter is proposed in reference [4]. Based on the inductance current of buck circuit and the output voltage of LLC converter, the efficiency of LLC converter is improved by double loop constant frequency control to compensate the efficiency reduction of Buck converter. In reference [5], a dual output LLC two-stage DC-DC converter topology is studied, which can use wide voltage input characteristics and has high conversion efficiency. However, when the load changes greatly, the soft switching operating point of LLC resonant converter is difficult to control. In reference [6], the two-stage topology suitable for wide voltage input is analyzed, and a new two-stage circuit topology is proposed. In reference [7-8], a Boost LLC resonant converter with wide input range is studied. The input current ripple is significantly reduced, and the voltage gain range is also significantly increased. Although LLC resonant converter improves the...
conversion efficiency of the converter, it also has some shortcomings. With the increasing of power and load, the output voltage of LLC resonant converter also further increases, which makes the resonant frequency decrease. When the load is light load, the output bus voltage of Boost circuit is constant. In order to ensure the output voltage stability of the converter, it is necessary to increase the working frequency, so that the switching off loss increases, resulting in low efficiency in light load. When the load is particularly light, the output voltage of the converter is not adjustable due to the limitation of the working frequency [9]. Therefore, this paper proposes an efficiency optimization strategy of LLC Resonant Converter Based on hybrid PWM and PFM digital control mode. The circuit topology is Boost LLC structure. The front Boost converter adopts PWM control, and the bus voltage can be adjusted by load current compensation. The later LLC resonant circuit realizes PFM control by output voltage, which stabilizes the resonant frequency and achieves efficiency in different load ranges Rate optimization [9-11].

2. Working principle

2.1. Analysis of circuit working state

The circuit topology of Boost LLC resonant converter is shown in Figure 1. The Boost circuit consists of inductor L, switch Q and diode D1. MOS tubes S1 and S2, resonant inductor Lr, resonant capacitor Cr and primary excitation inductor Lm of transformer T form a LLC resonant network. The secondary side of the transformer uses MOS switches SR1 and SR2 to realize synchronous rectification and reduce output loss.

The input voltage Vin is Boosted by the Boost converter, and then output to the LLC converter, and then output to the load. The output value of Boost converter is also called the bus voltage of LLC converter. By adjusting the duty cycle of the switch Q of the Boost converter, the bus voltage can be adjusted. By using the boost characteristics of the Boost converter, the wide range input voltage can be increased and stabilized, so as to reduce the requirements of the input side capacitance. The latter half bridge LLC circuit is always at the resonant frequency under the switching frequency regulation, so as to achieve the low voltage regulated output of the converter, and realize the isolation of modular voltage input and output.

Figure 2 is the key waveform of Boost LLC resonant converter, [t0, t12] is a switching cycle, including 12 working modes. The analysis of each stage is as follows.

In the [t0, t6] stage, the switch Q is disconnected, and the input power flows through the inductor L, diode D1 and LLC converter to the load. Figure 3 is the circuit diagram of each working mode.

In the [t0, t1] stage: before t0, the charging and discharging process of parasitic capacitors of switch S1 and S2 has been completed, and the voltage of switch S1 and S2 is equal to the voltage Vbus of capacitor Cbus; at t1, switch S1 is on, inductance Lm is clamped, and does not participate in resonance. The excitation current im rises linearly, and the resonance current ir reverses to negative. In this mode,
Inductor $L_r$ and Capacitor $C_r$ participate in resonance, the primary side of the transformer provides energy to the secondary side, and the secondary side synchronous rectifier diode $SR_1$ is on to provide power for the load.

[t1, t2] stage: LLC resonant current $i_r$ reverses to be positive until $t_2$ when the current $i_m$ decreases to zero. When the inductance $L_m$ is clamped continuously, it still does not participate in the resonance. The secondary side $SR_1$ of the transformer is on, and the energy transmitted from the primary side to the secondary side is provided by a resonant network composed of inductance $L_r$ and capacitance $C_r$.

[t2, t3] stage: the current $i_m$ is from top to bottom, the inductance $L_m$ is still clamped, does not participate in resonance, the current $i_r$ changes sinusoidally, the primary side of the transformer provides energy to the secondary side, the secondary side diode $SR_1$ is on, and the energy is output to the load.

[t3, t4] stage: the excitation current $i_m$ reaches the maximum value, and at $t_3$, the current $i_r$ drops to equal to $i_m$. In this stage, the inductance $L_m$ is no longer clamped, and it participates in resonance together with the inductance $L_r$ and the capacitance $C_r$. The switches $SR_1$ and $SR_2$ are cut off in reverse, in which $SR_1$ realizes ZCS shutdown. There is no energy transmission between the primary and secondary sides of the transformer, and the secondary side load is powered by the filter capacitor $C_o$.

[t4, t5] stage: the switch $S_1$ is turned off and enters the dead time. The resonant current $i_r$ charges the parasitic capacitance of switch $S_1$ and discharges the parasitic capacitance of switch $S_2$ until $t_5$. The primary and secondary sides of the transformer are separated and no longer transmit energy. The filter capacitor $C_o$ provides energy for the load.

[t5, t6] stage: the inductance $L_m$ is clamped and does not participate in the resonance, the current $i_m$ changes linearly, the input power supply no longer provides energy, the resonance network $L_r$ and $C_r$ fully provide the transmission energy of the original secondary side of the transformer, and the secondary side switch $SR_2$ is on; at $t_5$, the charging and discharging is completed, the parasitic capacitance voltage of switch $S_2$ drops to zero, the current $i_r$ flows through the body diode of switch $S_2$ to complete the freewheeling, and at $t_6$, the switch $S_2$ is on. The ZVS of switch $S_2$ is realized.

![Figure 3. The Circuit diagram of each working mode.](image-url)
(t6-t12) phase enters the second half cycle of switch Q, the working principle is similar to the first half cycle, switch S1 can realize ZVS opening.

2.2. Control strategy

The control signal of the converter adopts the digital control method, as shown in Figure 4, which is the circuit block diagram of Boost LLC converter. In the Figure 4, Vbus is the bus voltage, Vref is the given reference voltage, Verror is the error voltage. The feedback signal is sampled by the DSP system, in which the PWM feedback control signal comes from the bus voltage and the output load current, and the PFM feedback signal comes from the system output voltage.

When DSP system works, the system samples Boost output voltage (bus voltage), LLC output voltage and output current. When the load changes, the system adjusts the duty cycle of the Boost circuit according to the sampling bus voltage and the output current signal. Under the PWM control, the Boost output voltage is stabilized at the set value. The LLC circuit adjusts the working resonant frequency of the PFM according to the output voltage, so that the system can adjust the LLC resonant converter according to different loads, and achieve high performance in the whole load range conversion efficiency.

When the converter works in PFM modulation mode, the duty cycle of S1 and S2 switches is 0.5, and the voltage of Cbus capacitor is higher. With the increase of input voltage, the voltage stress of field effect switches and Cbus capacitor will increase, which increases the difficulty of device selection. At the same time, the gain range of LLC resonant converter will increase greatly, which increases the difficulty of parameter design of magnetic components. In order to effectively reduce the Cbus voltage and narrow the switching frequency range, the efficiency optimization strategy of LLC Resonant Converter Based on hybrid PWM and PFM digital control mode is used to realize the dual loop hybrid control based on PWM and PFM.

The error comparison between the bus voltage sampling value Vbus and the given bus voltage value Vbref is used as the input of the PI 1 controller. The voltage Vbus_f is obtained by proportional integral operation. When Vbus is lower than the given value Vref, The voltage Vbus_f will be clamped to (Vupper+Vlower)/2, and the duty cycle of the switch Q is 0.5. At the same time, when the output voltage V0 is compared with the reference voltage value. The error value is the input of PI 2 controller, and the feedback control signal is obtained after proportional integral operation, the frequency of the resonant converter is adjusted by PFM.

When the input voltage increases further, the bus voltage Vbus increases. When the bus voltage tends to exceed the given value, the output current I0 will also increase and feed forward to PWM to adjust the duty cycle of switch Q, and then the duty cycle of the switch Q decreases, so the bus voltage is stabilized at the given value. At the same time, the output voltage gain decreases with the decrease of the duty cycle. Therefore, in order to improve the voltage gain, the output voltage is compensated. The control loop will call back the switching frequency. That is, the switching frequency of the

![Figure 4. System control signal block diagram.](image-url)
converter will decrease with the increase of the input voltage. At this time, the working mode of the converter is converted into PFM and PWM modulation mode.

It can be seen from the two compensation loops that: before the bus voltage does not exceed the set value, the duty cycle of the switch Q is limited to 0.5, and the output voltage \( V_0 \) remains stable under the control of PFM; when the bus voltage tends to exceed the set value, the duty cycle of the switch Q is adjusted by the output current \( I_0 \) feed forward and bus voltage \( V_{bus} \) compensation part, and the output voltage compensation loop adjusts the switching frequency, at this time, The converter is under the common modulation of PFM and PWM. The experiment shows that whether \( V_{bus} \) and \( V_{bus-f} \) are equal or not is the key point to judge the modulation mode of PFM and PWM. When it is reached, the switching frequency has reached the maximum. When the input voltage further increases, the duty cycle of the switch tube Q decreases due to the output current feed-forward compensation network, so as to maintain the bus voltage stability; and the decrease of the duty cycle will reduce the output voltage. At this time, the output voltage control circuit will reduce the switching frequency, and increase the voltage gain to ensure the stability of the output voltage.

2.3. Gain analysis

When the system works, the output voltage of the front Boost circuit is

\[
V_{bus} = \frac{1}{1-D} V_{in}
\]  

(1)

The AC gain of the later LLC converter is

\[
G_{LLC} = \sin(d\pi) \frac{1}{\sqrt{\left(\frac{1}{f_n}-f_s\right)^2 Q^2 + \left(1 + \frac{1}{\lambda} - \frac{1}{\lambda f^2_s}\right)}}
\]  

(2)

Where, \( D \) is the duty cycle and quality factor \( r_{ac} C L R Q = \frac{1}{R_{ac}} \); \( R_{ac} = \frac{8N^2R_s}{\pi^2} \) is the equivalent resistance converted from the secondary side of the transformer to the primary side; \( f_n = f_s / f_r \) is the switching frequency; \( \lambda = L_m / L_r \) is the ratio of excitation inductance to resonant inductance.

The total gain of the two-stage circuit is

\[
G = \sin(d\pi) \frac{1}{1-D} \frac{1}{\sqrt{\left(\frac{1}{f_n}-f_s\right)^2 Q^2 + \left(1 + \frac{1}{\lambda} - \frac{1}{\lambda f^2_s}\right)}}
\]  

(3)

Figure 5 shows the gain curve of the two-stage circuit while keeping \( d \) constant.
As can be seen from Figure 5, when the switching frequency is fixed, adjusting the duty cycle can further reduce the voltage gain of the converter, so as to achieve fine adjustment of the voltage gain; and when the duty cycle is adjusted in the range of 0.45-0.5, the fine degree of the voltage gain is higher. It can be found that the fine adjustment of voltage gain can be achieved by adjusting the frequency and duty cycle at the same time, so as to reduce the impact on the output voltage.

3. Experimental design and result analysis
In order to verify the rationality of the proposed efficiency optimization method, a 1.2kW DSP digital control prototype is designed. Figure 6 and Figure 7 is the physical drawing of the prototype. The main components and specifications of the prototype are shown in Table 1. In order to verify whether the proposed efficiency optimization method can achieve high transmission efficiency in the full load range, the transmission efficiency under different loads is measured under the input voltage of 200V, 340v and 420v.
Table 1. Parameters of main experimental components of the prototype.

| Parameter                        | Values  |
|----------------------------------|---------|
| Input voltage Vin (V)            | 200–420 |
| Resonant inductor Lr (μH)        | 10      |
| Resonant capacitor Cr (μF)       | 33      |
| Excitation inductance Lm (μH)    | 120     |
| Switching frequency fr (kHz)     | 90      |
| Output filter capacitor Co (μF)  | 1000    |
| Output voltage V0 (V)            | 14      |
| Maximum output power P0 (W)      | 1200    |
| Transformer ratio n              | 14:1    |

Figure 8 shows the voltage and current waveform between electrodes when switch S1 is turned on at zero voltage. It can be seen from Figure 8 that the MOSFET switch voltage VGS is triggered after the voltage VDS drops to zero, which indicates that the switch on the primary side of the transformer has achieved ZVS. ZVS mode of switch can reduce the loss of switch in turn-on and turn off, and improve the efficiency.

![Figure 8](image1.png)

**Figure 8.** The voltage and current waveform between electrodes.

![Figure 9](image2.png)

**Figure 9.** Waveform of output voltage and current when load changes suddenly.

The test of different loads is shown in Figure 9. The load switching from 50W to 500W is carried out in the experiment. As shown in Figure 9, the output voltage drops by about 2V. After load shedding, the output voltage returns to be stable about 150VAS, which proves that the output voltage of any load can be kept constant.

The experiment of testing transmission efficiency under different input voltage and power is shown in Figure 10. The input voltage of the experiment is 200VDC, 340vdc and 420vdc respectively, and the load is increased from 300W to 1200W. The output power and input power are measured under the condition of heat engine balance, and then the conversion efficiency is calculated. As can be seen from Figure 10, when the input voltage is high, the conversion efficiency is high; when the load is light, the conversion efficiency is high, and the conversion efficiency decreases with the increase of the output power. The overall system has high transmission efficiency under wide voltage input and wide load, which is more than 90%, and the highest is nearly 94%. Experiments show that boost LLC converter
not only achieves wide input voltage range, but also has high conversion efficiency in the full load range.

As can be seen from Figure 11, compared with the traditional PFM control mode, the conversion efficiency of the system based on PWM and PFM hybrid control mode is greatly improved in the full load range.

4. Conclusions
In this paper, the efficiency optimization strategy of LLC Resonant Converter Based on hybrid PWM and PFM digital control mode was adopted to realize the double loop control of two-stage Boost LLC converter. The load current loop can adjust the bus voltage by changing the duty cycle, and the output voltage loop can adjust the resonant frequency. It can not only realize ZVS control of switch tube under wide range input voltage, but also improve the energy transmission efficiency under light load. The experimental results showed that the efficiency of the two-stage Boost LLC converter was improved by 3% under light load, and the converter had high conversion efficiency in the full load range under wide input voltage range.

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