Design of High-efficiency LED Driver Power Supply Based on Improved Particle Swarm Optimization

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Abstract. The photoelectric properties of LED are affected by driving current and ambient temperature. To solve the problem of light wane caused by excessive current and overheating, LLC resonant converter with soft switching was chosen as the main topology, improving the power efficiency, and reducing the heat of the LED driver. Firstly, the soft-switching conditions of the LLC resonant converter are analyzed, and the constraint equation is obtained. Then, an improved particle swarm optimization algorithm is proposed to optimize the resonant parameters. The weight of particles is dynamically and adaptively changed to balance the global and local optimization performance of particles. Finally, the controller is designed to realize constant current. This design improves the efficiency of the LED driver. At the same time, the light wane is effectively suppressed by stable output current, and the rationality of the selected parameters is verified by simulation and experiment.

1. Introduction
LED lighting has the advantages of high efficiency, low loss, long life, and no pollution, so it is more and more widely used in lighting occasions [1]. As an important part of the LED lighting system, the driving power supply affects the quality of the light source, and its performance directly determines the service life of LED [2]. The current LED electro-optical conversion efficiency is only 30%~40%, so a large part of the energy is released in the form of heat energy. The constant pressure control method will make the driving current increase with the rise of the junction temperature. However, excessive current will lead to the continuous rise of the junction temperature, so the vicious cycle will accelerate the LED light decline, resulting in the LED life shortened. Therefore, the high-power LED driving power supply must adopt the constant current driving mode to avoid the adverse effects of environmental temperature changes on LED photoelectric characteristics [3][4][5]. Compared with other topologies, resonant converters are widely used in high-power LED drivers because of their high conversion efficiency. LLC takes resonant capacitor, resonant inductor, and
leakage inductance of transformer as a resonant element, and Zero Voltage Switching (ZVS) is used to realize variable frequency soft Switching, which improves the overall efficiency and EMI performance of the power supply, and then improves the power density of the power supply [6]. Appropriate LLC resonant parameters are necessary to ensure the operation of the soft switch, and the selection of resonant parameters directly affects the efficiency of the drive. At present, the most widely used method is to design resonant parameters based on the fundamental wave analysis method. When the resonant frequency is far away, the gain curve derived from the fundamental wave analysis method deviates greatly from the actual value [7].

To improve the efficiency of the LLC converter and reduce the influence of driver heating on LED performance, this paper proposes an improved Particle Swarm Optimization (PSO) method to optimize LLC resonant parameters. This algorithm has the characteristics of fewer parameter Settings and faster convergence speed. The improved particle swarm optimization algorithm can conduct global optimization randomly and in parallel, and the inertia weight of the velocity update formula is changed continuously according to the change of iteration times, to realize the flexible search of solution space.

2. Photoelectric characteristics of LED

Figure 1 shows the voltage-current characteristic curve of the LED, which is essentially the same as the characteristic curve of the PN junction, including four states: conduction region, dead region, cutoff region, and breakdown region. The normal operation requires a certain positive voltage drop between the anode and cathode of the LED, that is, it works in the positive guide pass region. When the forward voltage of LED is greater than a certain threshold value, the current of LED increases exponentially with the voltage, so the instability of the voltage will have a great impact on the output current.

\[ i_{LED} = I_s \left( e^{\frac{qU_{th}}{kT}} - 1 \right) \]  

(1)

The volt-ampere characteristic formula can be expressed as:

Fig.1 Voltametric characteristics of LED

The formula \( I_s \) represents the reverse saturation current, which is influenced by semiconductor materials and processes as well as temperature. It can be seen from Figure 1 that the reverse
saturation current increases with the increase of temperature. \( q \) represents the electronic quantity; \( K \) is the Boltzmann constant; \( T \) is temperature; \( U_{D_{\text{on}}} \) is the LED opening voltage; \( U_{D} \) is the voltage added to both ends of the LED; \( i_{\text{LED}} \) is the value of current flowing through the LED. At the same time, the volt-ampere characteristic curve is related to temperature. If the driving current is too small, the LED luminescence intensity will not meet the application requirements. If the driving current is too large, the PN junction temperature will be too high, which will lead to light failure and shorten the life of the LED.

3. The working principle of LLC converter

3.1. Operating process of LLC converter

Set LLC circuit working in the first resonance frequency, figure 2 for each variable work waveform, figure 3 for the working process of the LLC, a single cycle, among them, \( V_{g1} \), \( V_{g2} \), the said tube and pipe under the driving waveform, \( I_{c} \) for cavity current, \( I_{m} \) for excitation current, and \( I_{d1}, I_{d2} \) current of rectifier tube, \( D_1, D_2 \) respectively, \( f_{k} \) said switch frequency, \( f_{\alpha} \) said the first resonance frequency.

The square wave with a fixed duty cycle is used as the driving signal of the switch tube, and the upper and lower axle arms are complementarily switched on, and the dead zone is designed to prevent straight through. The LLC working process \( f_{k} = f_{\alpha} \) is analyzed as follows:

- \( t_0 \sim t_1 \) stage: before \( t_0 \) time, the lower tube closes, the resonant inductance makes the current maintain the original direction, and the body diode of the upper tube conducts, providing conditions for the zero-voltage opening of the upper tube. At the time of \( t_0 \), the upper tube is opened, the excitation current is less than the resonant current, the energy is transferred to the secondary side, the rectifier tube on the secondary side \( D_1 \) is on, the voltage of the excitation
inductor $L_m$ is clamped by the output voltage, the current rises linearly, only $C_t$ and $L_t$ participate in the resonance process.

$t_1 \sim t_2$ stage: the upper and lower tubes close, known as the dead section. At this time, the parasitic capacitor of the upper tube is charged, and the parasitic capacitor of the lower tube is discharged. Only in this stage can the parasitic capacitor charge be discharged completely; can the zero voltage of the lower tube be turned on. The excitation current is equal to the resonant current, so the primary energy at this stage is no longer transmitted to the secondary, the rectifying tube $D_1$ zero current is turned off, and the electrolytic capacitor supplies power to the load.

$t_2 \sim t_3$ stage: the lower tube is on, the upper tube is off, the rectifier tube $D_2$ on the secondary side is on, and the voltage of the excitation inductor $L_m$ is clamped by the output voltage. Only $C_t$ and $L_t$ participate in the resonance process.

![Figure 3: Operation process of LLC with $f_k = f_{i1}$](image)

3.2. Operating conditions of LLC converter soft switch
The voltage gain of LLC resonant converter can be expressed as:
The normalized input impedance of LLC resonant converter is shown in Equation (5), and the real and imaginary parts of the impedance are shown in Equation (6) and (7) respectively.

\[
Z_{in} = \frac{x^2 k^2 Q}{1 + x^2 k^2 Q^2} + j\left(x - \frac{1}{x} + \frac{xk}{1 + x^2 k^2 Q^2}\right)
\]  

Re = \frac{x^2 k^2 Q}{1 + x^2 k^2 Q^2}  

Im = x - \frac{1}{x} + \frac{xk}{1 + x^2 k^2 Q^2}  

LLC resonant converter in order to realize ZVS, the first thing to do is to ensure that the converter works in the inductive region under the condition of maximum load and minimum input voltage, that is, the input impedance Angle should meet the following equation:

\[
\theta = \arctan\left(\frac{\text{Re}}{\text{Im}}\right) > 0
\]  

Simplify:

\[
x - \frac{1}{x} + \frac{xk}{1 + x^2 k^2 Q^2} > 0
\]  

Guarantying that the converter always works in the inductive region is only a necessary condition to realize ZVS. The key to LLC resonant converter to realize ZVS is whether the parasitic capacitor stored in the switch tube can be fully released in the dead zone time. Therefore, it is necessary to design parameters to make the resonant current in the dead zone time greater than the minimum discharge current required by the parasitic capacitor of MOSFET. The minimum discharge current required for the parasitic capacitance of LLC resonant converter switch tube is:

\[
i_j = \frac{2C_{sw} V_{in}}{t_{dead}}
\]
Because the dead time of the converter is very short, it can be considered that the resonant current is constant in the dead time, that is, the peak value of the excitation current is maintained:

$$L_{pk} = \frac{nV_i T_i}{4L_m}$$  \hspace{1cm} (11)

Another necessary condition to realize the soft switch is obtained as follows:

$$\frac{nV_i T_i}{4L_m} \geq \frac{2C_{cos} V_m}{I_{dead}}$$  \hspace{1cm} (12)

Namely, the resonant inductance shall meet the following requirements:

$$L_m \leq \frac{T_i I_{dead}}{16C_{cos}}$$  \hspace{1cm} (13)

The above content deduces the conditions for LLC resonant converter to realize soft switching in the working process, which is sorted into the form of equation set:

$$\begin{cases}
L_m \leq \frac{T_i I_{dead}}{16C_{cos}} \\
x - \frac{1}{x} + \frac{\sqrt{x}}{1 + \sqrt{x} Q} > 0 \\
G(f_{s, min}) \geq 2n \frac{V_o}{V_{dc, min}} \\
G(f_{s, max}) \leq 2n \frac{V_o}{V_{dc, max}}
\end{cases}$$  \hspace{1cm} (14)

4. Parameter optimization using improved particle swarm optimization

The particle swarm optimization algorithm simulates the foraging behavior of birds. Resonant parameters $L_m$, $L_s$ and $C_r$ are set as parameters to be optimized. Firstly, the particle swarm is initialized, and the fitness of each particle is calculated respectively. When the maximum number of iterations is reached or the current solution stops searching within the allowable error range, the power consumption of the converter is mainly concentrated on the switch tube, rectifier tube, and high-frequency transformer, and the power consumption of the transformer largely depends on the design and selection of magnetic components, which is not within the scope of this paper. Therefore, it is considered that the loss of the converter is related to the sum of the excitation current, resonance current, and secondary side current.

The effective value of resonant current is:

$$I_{rms} = \frac{V_o}{8nR_i} \sqrt{8\pi^2 + \frac{2n^4 R_i^2}{L_m f_e^2}}$$  \hspace{1cm} (15)

The conduction loss of MOSFET is:

$$P_{Q, on} = \frac{R_{on} V_o^2}{32n^2 R_i} \left( \frac{n^4 R_i^2 T_i^2}{L_m^2} + 4\pi^2 \right)$$  \hspace{1cm} (16)

Where, $R_{on}$ is the on-resistance of MOSFET. The larger the excitation inductance is, the smaller the resonant current is, and the smaller the on-loss of the switch tube is.

Excitation current is a periodic triangular wave, and a single period can be expressed as:
\[
I_m(t) = \begin{cases} 
\frac{V_{nt}}{L_m} - \frac{V_{n}n}{4L_m f_r}, & 0 \leq t < \frac{1}{2f_r} \\
\frac{V_{nt}}{L_m} + \frac{3V_{n}}{4L_m f_r}, & \frac{1}{2f_r} \leq t < \frac{1}{f_r} 
\end{cases}
\]
(17)

The effective value of the current through the excitation inductor is:
\[
I_{m_{\text{rms}}} = \frac{\sqrt{2}nV_n}{\pi f_r L_m}
\]
(18)

The effective value of secondary side current is:
\[
I_{2_{\text{rms}}} = \frac{\pi V_n}{4R_i} \sqrt{1 + \frac{n^4 R_i^2 (5\pi^2 - 48)}{12\pi^4 I_{m_{\text{rms}}}^2 f_r^2}}
\]
(19)

Therefore, the on-state loss of rectifier tube is:
\[
P_{d_{\text{on}}} = \frac{0.7\pi V_n}{4R_i} \sqrt{1 + \frac{n^4 R_i^2 (5\pi^2 - 48)}{12\pi^4 I_{m_{\text{rms}}}^2 f_r^2}}
\]
(20)

Considering the soft switching condition, the fitness function is:
\[
\min \text{Fitness} = I_{r_{\text{rms}}} + I_{m_{\text{rms}}} + I_{2_{\text{rms}}} - \alpha \times \text{logic}
\]
(21)

Where, \(\alpha\) is a positive number of orders of magnitude far greater than the resonance current, excitation current, and secondary side current. \(\text{logic}\) is related to the inequality constraints, when the resonance parameter value meets all constraints, \(\text{logic}\) value is 1, otherwise is -1, to ensure that the optimal parameter value is generated in the range that satisfies the constraints.

5. Simulation and experimental verification

5.1. Simulation verification

To verify the stability of the algorithm, this paper verifies the optimization ability of the improved algorithm and the conventional algorithm under the experimental times of 50, 200, 500, and 600 respectively, as shown in the figure. From the simulation results, the improved algorithm can jump out of the local optimal solution and has a good performance of global optimization in the later stage. It is shown that the improved particle swarm optimization has a good performance in balancing global and local optimization. To be more precise, the improved algorithm proposed in this paper has good stability through comparison of different groups of experiments.
5.2. Circuit design and experimental verification

A set of optimal resonant parameters, namely $\text{Parameter}_1$, was finally obtained from the output of the improved particle swarm optimization algorithm. In order to verify the rationality of the obtained parameters, the driving circuit was designed. The designed AC input voltage was 220V, the rated output voltage was 24V, the rated output current was 1.25A, the transformer turn ratio was 6.235, and the resonant frequency was 100kHz.

The circuit is shown in Figure 5. NCP1397B is selected as the control chip of the power supply. This circuit converts the output current into voltage through the sampling resistance. At the same time, the circuit also has soft start, Undervoltage protection, overcurrent protection, and intermittent operation mode under light load conditions, which improves the reliability of the circuit and reduces the circuit loss.

![Circuit diagram of the driving power supply](image-url)
Fig. 6 is the experimental waveform to verify the soft switch. After the voltage $V_{ds}$ between the drain and the source reaches zero, the MOS driving voltage $V_{gs}$ reach a high level, and the switch tube can be turned on at zero voltage. Figure 7 shows the output voltage waveform. The output voltage can be started within the $0.6s$, and the output voltage is stable at 24V under the action of closed-loop regulation.

![Fig. 6 Waveform of soft switch experiment](image)

![Fig. 7 Experimental waveform of $V_o$](image)

6. Conclusions
To LLC converter as the main topology of driving power supply can realize soft switch, at the same time design improved the resonance parameters of particle swarm optimization (PSO), a combination of both can effectively reduce the wastage of the converter, the optimization parameters of the proposed method has strong portability and can be extended to other switching power supply topology structure, the design of 30 w drive circuit, Finally, the feasibility of the scheme is verified by simulation and experiment.

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