A Current-Source 5-Level DC-DC Used for Capacitor-less LED Driver

Shuang Xu\textsuperscript{1}, Jianyu Bao\textsuperscript{2, *}

\textsuperscript{1}School of Information and Engineering, Nanchang University, Nanchang, China
\textsuperscript{2}School of Mechanical and Engineering, Ningbo institute of finance and economics, Ningbo, China

*Corresponding author e-mail: jianyu_bao@126.com

Abstract. Traditional lighting emitting diode (LED) driving circuits generally use electrolytic capacitors as the filter component, and the lifetime of electrolytic capacitor becomes the main limiting factor for extending the lifetime of LED lighting. Therefore, this paper proposes a new current-source 5-level DC-DC circuit to construct the LED driver. It can not only remove large electrolytic capacitors to improve the service life of LED driver, but also the high input power factor can be achieved by 5-level PWM modulation. Finally, the feasibility and effectiveness of such LED driver are verified by simulation results.

1. Introduction

With the fast development of semiconductor technology, light-emitting diode (LED) as a new type of lighting source with the advantages of energy conservation, environment friendly, high safety and reliability, long lifetime, etc., has become the leading product in the market \cite{1}. Most LED drivers are supplied by AC power, so it is necessary to convert alternating current to the required direct current, and to generate a controllable dc current-source to drive LED. In the traditional conversion circuit, electrolytic capacitors are generally used as energy storage element to maintain the balance of input and output power. The lifetime of conventional electrolytic capacitor is only about 10000 hours at \(50^\circ\text{C}\), while LED’s lifetime can be up to 100000 hours. It can be seen that the electrolytic capacitor has become a key factor restricting the lifetime of LED driver. Therefore, how to remove the electrolytic capacitor or decrease its value has become a research focus for LED driver application.

At present, the circuit scheme removing electrolytic capacitor for LED mainly deals with the imbalance of input and output power from the following three aspects. The harmonic modulation method \cite{2} reduces the peak-average ratio of the input current by the injection of third and fifth harmonics into the input current, the power fluctuation between the input and output is decreased, and thus the capacitance value of electrolytic capacitor can be reduced. The advantage of such scheme is that the circuit structure is simple, and its disadvantage is that the harmonic injection will lower the power factor. The pulsating current method \cite{3} can make the ripple value of the output power synchronize with the instantaneous power at the input by controlling the output ripple current. The drawback of such method is that the output current contains a large second harmonic component. The third method is to add auxiliary energy storage element to of balancing the input/output power difference is implemented by inserting auxiliary energy-storage element. The excess energy is transferred to the energy storage device by the auxiliary circuit when the input power is larger than the output power, and when the input power is lower than the output power, the storage energy will be released. The energy transmission needs two transformations, so the circuit efficiency is relatively low.
In this paper, a high-power LED driving circuit removing electrolytic capacitor is proposed, which is mainly consisted of a current-source five-level DC-DC circuit [4]. Since the current-source converter is adopted, the electrolytic capacitor filter circuit after the diode rectifier can be omitted, thereby greatly improving the lifetime of the LED driver. Multi-level PWM modulation technology [5,6] is applied in this current-source DC-DC circuit to make the input current as the 5-level PWM waveform with low harmonic content. Simultaneously, the phase of input current is basically consistent with the line voltage, that is, high power factor can be obtained without additional power factor correction circuit.

2. Operational Principle

2.1. Main Circuit Topology
The current-source 5-level DC-DC circuit is shown in Fig.1. The whole circuit is mainly consisted of the following parts: single-phase diode rectifier circuit, current-source 5-level dc-dc circuit, LED array, and two inductors.

![Figure 1. The main circuit topology.](image)

2.2. Operational Principle
The working process of the current-source 5-level dc-dc circuit can be divided into five stages during the positive half cycle, and the corresponding equivalent circuit of each stage is illustrated in Fig. 2.

Assuming that all switches are in an ideal state, the operational mechanism of its 5-level current is as follows:

Stage 1: $\omega t = [0 \sim \alpha]$ ($Q_1=0, \quad Q_2=0$): $i_0$ is 0; Energy stored in $L_2$ is supplied to the load, $L_1$ is short-circuited by $D_1$ and $D_2$.

Stage 2: $\omega t = [\alpha \sim \alpha + \phi]$ ($Q_1=1, \quad Q_2=0$): $i_0$ is $I/2$; Energy stored in $L_2$ is supplied to the load; $L_1$ is charged by $U_i$, thus $i_{L1}$ increases.

Stage 3: $\omega t = [\alpha + \phi \sim \pi - (\alpha + \phi)]$ ($Q_1=1, \quad Q_2=1$): $i_0$ is $I$; $U_i$ charges $L_2$ and supplies for the load via $L_2$, $i_{L2}$ increases slightly, when $L_1$ is short-circuited by $Q_1$ and $Q_2$.

Stage 4: $\omega t = [\pi - (\alpha + \phi) \sim \pi - \alpha]$ ($Q_1=0, \quad Q_2=1$): $i_0$ is $I/2$; $U_i$ charges $L_2$ and supplies for the load via $L_2$, $i_{L2}$ increases slightly; $i_{L1}$ freewheels through $D_1$, and thus $i_{L1}$ decreases.

Stage 5: $\omega t = [\pi - \alpha \sim \pi]$ ($Q_1=0, \quad Q_2=0$): $i_0$ is 0; Same as stage 1.
3. PWM Control Strategy

The most effective strategy to modulate such current-source 5-level DC-DC is POD-PWM, because it obtains the optimum harmonic cancellation [7]. Figure 3 shows its operational principle, where the modulation signal ($W_m$) is compared with two triangular carriers ($w_{C1}$, $w_{C2}$). Since the input DC voltage is a sine half-wave, only two triangular carriers can be used. Therefore, the improved multilevel PWM modulation strategy is: in one cycle of the modulated wave, the modulated wave is compared with two carriers that are 180 degrees out of phase. When the modulated wave is greater than one carrier, a positive step current is output, otherwise zero current is output.

Each carrier is ceaselessly compared against the modulating signal, and the results of these comparing operations are applied to select the required switching-combinations. Table 1 shows how the two outputs of comparator determine the current-source 5-level DC-DC switching sequences that generate the required 5-level output current.

![Figure 3. POD-PWM Scheme.](image-url)
Table 1. Switch State Decoding for POD-PWM.

| Comparator State | Switching Combinations | Input Current |
|------------------|-------------------------|---------------|
| \( W_m > W_{c1}, W_m > W_{c2} \) | \( Q_1=0, Q_2=0 \) | \( I \) |
| \( W_{c2} < W_m < W_{c1} \) | \( Q_1=1, Q_2=0 \) | \( I/2 \) |
| \( W_{c1} < W_m < W_{c2} \) | \( Q_1=0, Q_2=1 \) | \( I/2 \) |
| \( W_m < W_{c1}, W_m < W_{c2} \) | \( Q_1=0, Q_2=0 \) | 0 |

4. Simulation Results

The main parameters of the simulation system, which is used to investigate the current-source 5-level DC-DC topology are as follows:

The input AC supply voltage \( U_i \) is equal to 220V; the converter circuit parameters were \( L_f =1\text{mH}, C_f =10\mu\text{F}, L_1=10\text{mH}, L_2=100\text{mH}, R_f=3.3\Omega \); for the current-source 5-level DC-DC, the modulation index is 0.9, output frequency is 50 Hz, and the PWM switching frequency is 3000 Hz (pulse ratio = 60).

Figure 4 (a) is the input current with 5-level PWM waveform, which validates the feasibility of the multi-carrier PWM modulation technology. Figure 4(b) are the waveforms of line voltage and the filtered line current at the AC side. Obviously, the input current waveform after filtering is very close to the sine wave, and its power-factor (PF) is approximately equal to 1. The simulation results show that such current-source 5-level DC-DC converter can achieve high grid-side power factor without adding power factor correction circuit.

![Figure 4](image)

(a) Current waveform with 5-level PWM  
(b) The input current and voltage at the grid-side

Figure 4. Simulation performance of the current-source 5-level DC-DC.

Figure 5(a) shows the total dc current waveform filtered by the smoothing inductor \( L_2 \). Figure 5(b) shows the waveform of the sharing-inductor current \( i_{L1} \). It can be seen that \( i_{L1} \) can be basically stabilized at \( 1/2 i_{L2} \) by applying the current-balancing control (not described in detail in paper for page limited). By simple calculation, the current ripple is almost maintained at 5% of the average current.

![Figure 5](image)

(a) \( i_{L2} \)  
(b) \( i_{L1} \)

Figure 5. The DC current flowing through \( L_2 \) and \( L_1 \).
5. Conclusion
In this paper, a current-source 5-level DC-DC without electrolytic capacitor used for LED driver is presented, the large electrolytic capacitor can be neglected and thus the service life of LED driver is improved. In addition, the current-source 5-level DC-DC PWM modulation technology is adopted to make the input current as 5-level PWM waveform with low harmonic content, which can achieve high input power factor on the grid-side without additional power factor correction circuit. Finally, the feasibility and effectiveness of the above scheme are verified by the simulation results.

Acknowledgments
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