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RESEARCH ARTICLE

Ultra-Low Percentage Flicker High-Efficiency Direct AC LED Driver Using Constant Power Technology

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ABSTRACT According to California's 2016 Building Energy Efficiency Standards, the percentage flicker of light-emitting diode (LED) lighting fixtures should be below 30%. However, the percentage flicker of commercially available linear power supplies is generally between 25% and 99.9%; thus, some LED lighting fixtures that use linear power supplies have been unable to enter the European or American markets. The traditional method of effectively reducing flicker involves increasing the capacitance of the electrolytic capacitor of the power supply, which causes an increase in the height of the lamp board components as well as shadowing and dark band phenomena. This paper presents a power supply circuit that uses only electrolytic capacitors with low capacitance and exhibits constant power, constant light output, and a lamp board thickness of only 8 mm; it can achieve a percentage flicker of less than 10%, which exceeds international standards. Power efficiency is a crucial performance indicator of linear power supplies. Because linear power supplies are mostly integrated circuits (ICs) with extremely small package volumes, higher power efficiency results in lower heat loss. The international standard for the power efficiency of linear power supplies is approximately 75%. A multistage switching mechanism is used in the proposed power supply to achieve an overall efficiency of $> 88\%$. Under an input power of 12 W, a 10% increase in efficiency reduces the heat by 1.2 W, which can considerably reduce the difficulty and cost of heat dissipation in IC packages. By combining the aforementioned technologies, the proposed power supply can achieve high efficiency and low percentage flicker, thereby improving the shortcomings of traditional linear power supplies. Currently, the driver-on-board (DOB) module of the proposed power supply is in the trial production phase, and its market entry will be accelerated to expand the market share of linear power supplies.

INDEX TERMS High efficiency, linear converter, percentage flicker, constant power, DOB.

I. INTRODUCTION

According to TrendForce's 2022 Global LED Lighting Market Analysis Report, the penetration rate of light-emitting diode (LED) smart lighting is expected to continually increase over time. With the application of new technologies, LED smart lighting has redefined the growth of the lighting market. TrendForce estimates the global market value of LED lighting to be US$64.95 billion in 2022 (Figure 1). Because of the booming development of this market, the demand for LED power or control integrated circuits (ICs) has increased considerably. Power specifications are crucial indicators for differentiating between different LED lighting products.

LED power supplies are commonly divided into two categories: switching converters [1], [2] and linear converters. Because lighting products are generally thin and small, power ICs constitute a crucial technology in the development of LEDs. Switching power supplies contain transformers,

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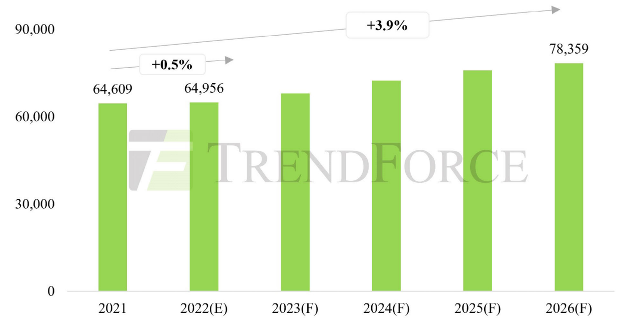
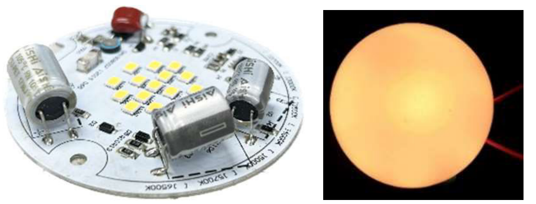


FIGURE 1. Trend of the market value of LED lighting.

TABLE 1. Percentage flicker specifications.

DLC	PST < 1, SVM < 0.4	
California	Percentage Flicker < 30%	
EU draft	SVM < 1.0	
CQC	f ≤ 10 Hz	10 Hz < f ≤ 90 Hz
	PF < 0.1	PF < f ×0.01

inductors, or large capacitor components that cannot be integrated into ICs, thus increasing the height of the lamp board. Some thin or uniquely shaped lamps cannot use such components. Therefore, this study focused on developing a linear converter that has the advantages of low cost, high reliability, and low electromagnetic induction. However, the efficiency and flicker percentage of linear power supplies are lower and higher, respectively, than those of switching power supplies. In extremely small IC packages, higher power efficiency results in lower heat loss, which can reduce the difficulty and cost of IC package cooling. According to California's 2016 Building Energy Efficiency Standards, the flicker percentage of LED lamps sold on the European and American markets should be less than 30%. As presented in Table 1, the flicker percentage of commercially available linear converters is generally between 25% and 99.9% [3]. Although increasing the capacitance of electrolytic capacitors can suppress the flicker percentage, it also increases the height of lamp board components and causes shading and dark band phenomena. Figure 2(a) displays a commercially available linear converter with a driver-on-board (DOB) module. This power supply has a total thickness of 15 mm and contains three electrolytic capacitors with a thickness of 10 mm each. Figure 2(b) indicates that the light output of the lamp board is uneven and that dark band phenomena occur, which results in poor lighting efficiency and visual aesthetics. Therefore, improving power



(a) DOB (b) Light effect

FIGURE 2. Commercially available linear converter with a DOB module.

efficiency and reducing percentage flicker are crucial directions for improving power supplies for LED lighting.

The rest of this paper is organized as follows. Section II describes the circuit of the proposed high-efficiency linear converter with an ultra-low percentage flicker. Section III presents the experimental results. Finally, Section IV provides the conclusion.

II. CIRCUIT DESCRIPTION

A. VALLEY FILLER CIRCUIT

The bridge rectifier is used to convert AC voltage to DC voltage [4], [5], while the valley filler circuit (shown in Figure 3) is used to improve power factor and eliminate current dead zone, providing a more stable output power source. When the DC voltage output of the bridge rectifier is rising, C1 and C2 are in the charging phase. In this situation, the compensation loop in the valley filler circuit enters the charging mode, and D2 is in the conducting state (D1 and D3 are in the cutoff state). The voltage across C1 and C2 reaches up to half of the peak value of the pulsating DC voltage. When the pulsating DC voltage drops below the voltage across C1 and C2, D1 and D3 turn on (D2 is in the cutoff state). In this case, the compensation loop in the valley filler circuit enters the discharging mode. This causes C1 and C2 to start releasing the previously stored energy. The capacitors C1 and C2 discharge in parallel, releasing energy to the output circuit. The resistor R1 connected in series with D2 helps smooth the input current spikes and also limits the current flowing into C1 and C2 to improve the power factor. Figure 4 shows the output waveform of the valley filler circuit, where the red line represents the AC input voltage waveform, and the green line represents the output voltage waveform of the valley filler circuit.

When studying or evaluating the flicker intensity of a light source, the Percentage Flicker formula (Equation 1) can be used to quantify its flicker strength, which is a common assessment method. In this formula, we have two key variables: A and B. A represents the maximum luminance value of the light source within one complete flicker cycle, indicating the highest point the brightness reaches. B represents the minimum luminance value of the light source within one complete flicker cycle, indicating the lowest point the brightness reaches, as shown in Figure 5 [6]. The primary purpose of this formula is to calculate the flicker amplitude, which

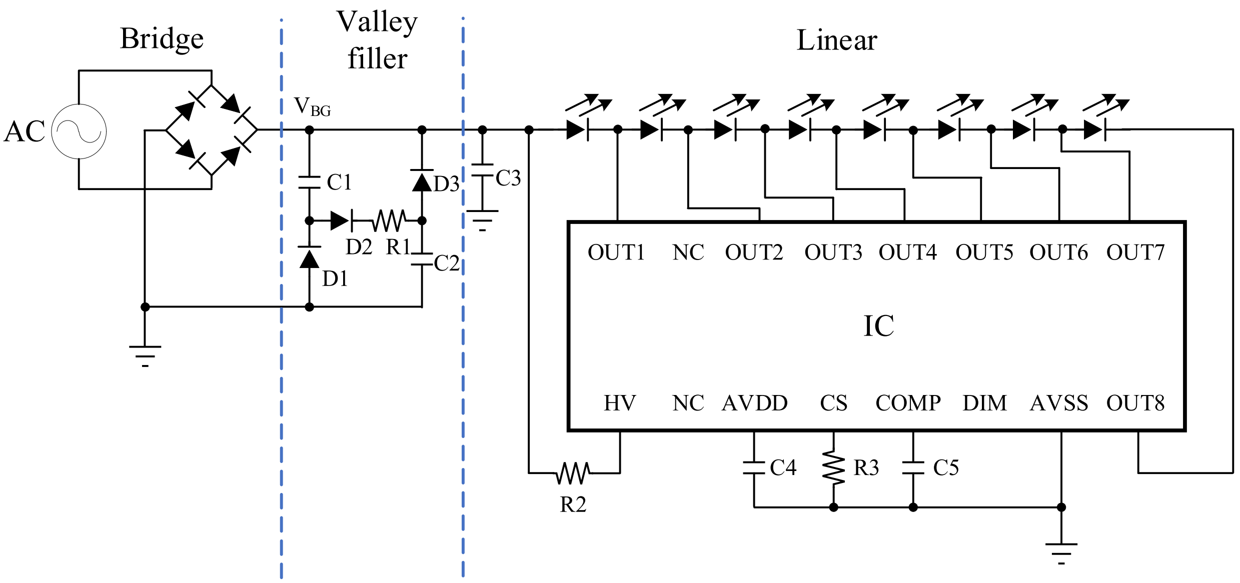


FIGURE 3. Block diagram of the proposed circuit architecture.

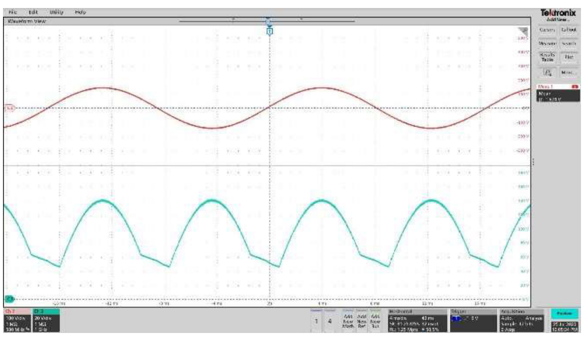


FIGURE 4. The output waveform of the valley filler circuit.

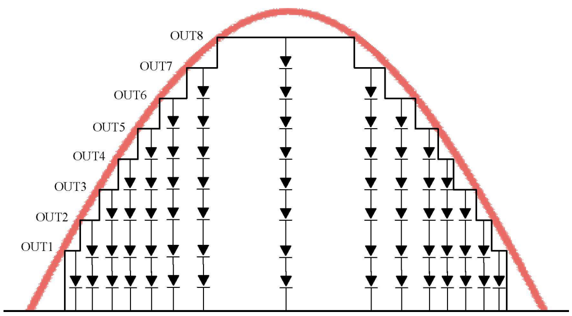


FIGURE 6. Schematic of the eight-segment switching process in the proposed linear converter.

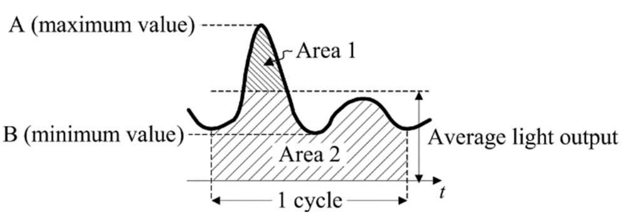


FIGURE 5. Illustration of the percentage flicker.

measures the variation in brightness during one flicker cycle. The numerator (A - B) represents the change in luminance within one flicker cycle, while the denominator (A + B) represents the overall range of luminance. Multiplying this ratio by 100% gives the percentage value of the flicker intensity. When the value of Percentage Flicker is 0%, it means that there is no flicker, and the brightness of the light source remains stable without significant fluctuations. Conversely, as the value of Percentage Flicker increases, the flicker intensity of the light source becomes stronger, and the amplitude of brightness variation also increases.

$$\text{Percentage Flicker} = 100\% \times (A - B)/(A + B) \quad (1)$$

When B is close to or equal to 0, the percentage flicker tends to approach 100%, indicating a very high flicker intensity. To improve percentage flicker, it is essential to keep B as far away from 0 as possible. The valley filler circuit plays a crucial role in achieving this by increasing the minimum luminance point (B) of the light source, effectively reducing the flicker value. During the charging phase, the valley filler circuit stores excess energy in the capacitors, leading to an increase in the value of B, which corresponds to a higher minimum luminance point. In the discharging phase, the valley filler circuit releases the previously stored energy back into the output circuit, maintaining a relatively higher B value. By operating the valley filler circuit in this manner, B's value increases, resulting in a reduction of the numerator (A - B) in the flicker formula, thus lowering the flicker value. This effectively mitigates flicker and provides a more stable and less flickering illumination.

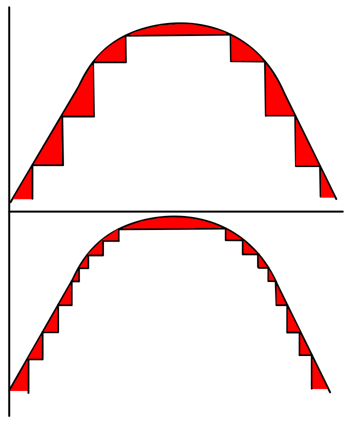
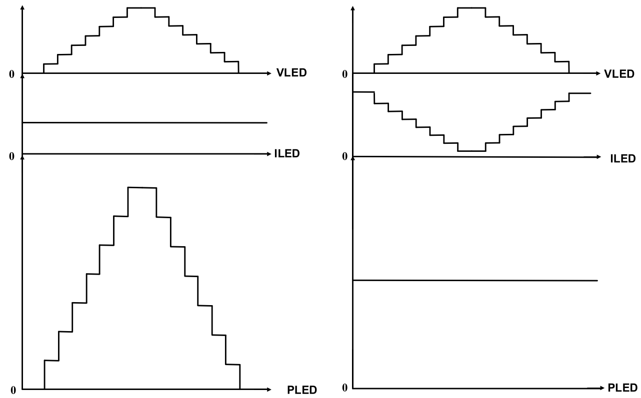


FIGURE 7. Power consumption charts for four- and eight-stage switching.



(a) (b)

FIGURE 8. Constant-power design.

FIGURE 9. Layout of the adopted IC.

B. INTERNAL ARCHITECTURE OF LINEAR POWER ICs AND MULTISTAGE DESIGN FOR INCREASING POWER EFFICIENCY

A schematic of the segmented switching of the proposed linear converter is displayed in Figure 6. An eight-segment switching scheme is adopted in this power supply. In Figure 6, the red waveform represents the pulsating dc voltage (V_{BG}). When this voltage is greater than the voltage of a certain LED segment, the linear converter switches on the LED segment. For example, if the pulsating dc voltage is greater than the voltage of the first LED segment, the power supply switches on this segment. The same process is then repeated for the remaining seven segments. The number of conducting LEDs increases with the pulsating dc voltage.

Most commercial linear converters use four-stage switching and have an overall power efficiency of approximately 75% to meet international standards [7]. This study conducted a comprehensive energy analysis, identified energy consumption problems, optimized electrical performance, and implemented eight-stage switching to increase power efficiency. As displayed in Figure 7, the waveform of four-stage switching contains a red area that represents the difference between the pulsating dc voltage and the LED segmented voltage, and this area corresponds to the heat loss (unused voltage). A larger red area in one cycle indicates higher heat loss and lower overall efficiency. Eight-stage switching is used in the proposed power supply (Figure 7, lower panel) to reduce the red area by dividing it into eight segments, which results in lower heat loss and higher overall power efficiency compared with those achieved in four-stage switching.

C. CONSTANT-POWER DESIGN FOR ACHIEVING ADVANCED PERCENTAGE FLICKER SUPPRESSION

In the commonly used traditional constant-current method, the same current value is set for each segment. As displayed in Figure 8(a), because LEDs are illuminated in segments, the total voltage drop across the LEDs resembles a segmented staircase pattern and varies with the pulsating dc voltage. If the current for each segment is constant, the LED power also exhibits a segmented staircase pattern [8]. A higher LED power fluctuation is associated with a higher percentage flicker. To effectively suppress flicker, a constant-power driving method is used in the proposed circuit shown in Figure 8(b). The LED segment current is inversely proportional to the LED segment voltage. Therefore, the average power is consistent across all LED segments. The brightness of each LED segment is thus ideally the same, which can considerably reduce the percentage flicker.

D. COMPARISON OF LINEAR AND SWITCHING CONVERTER

Table 2 compares linear and switching converters. Switching converters have higher efficiency and lower percentage flicker. However, due to the need for energy storage components such as transformers, inductors, and large electrolytic capacitors, they are larger in size and more expensive. These larger power supplies make it difficult to integrate them into integrated circuits (ICs). The operating principle of a linear converter is to directly drive the load LED with the input pulsating direct current (DC). In other words, it uses segmented LED voltages to adapt to pulsating DC.

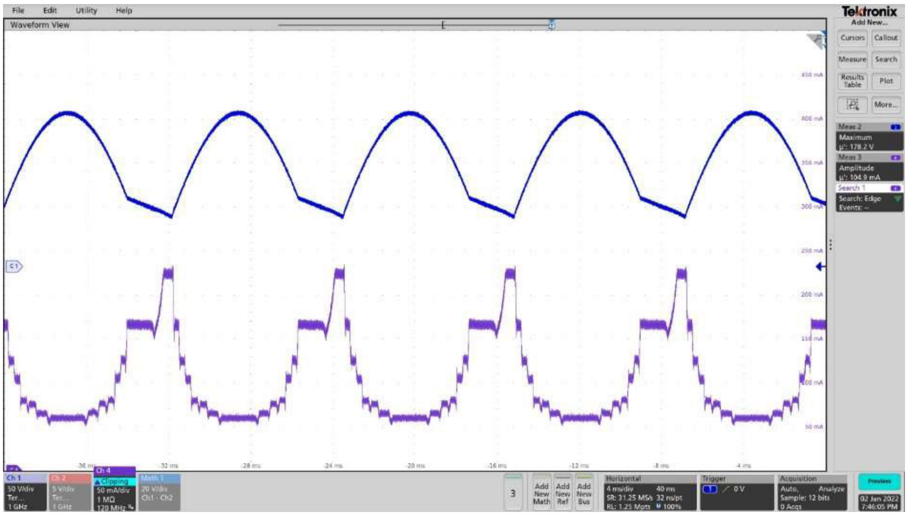
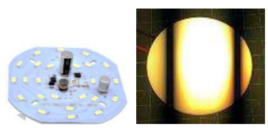


FIGURE 10. Output voltage and current waveforms of the proposed linear converter.

TABLE 2. Comparison of linear and switching converters.

	Switching converter	Commercially Linear converter	This work
Schematic diagram			
EMC	Yes	No	No
Light board thickness	> 60 mm	> 40 mm	<9 mm
10 W driver cost	> 40 NTD	~ 20 NTD	~ 20 NTD
Power efficiency	< 90%	75~85%	88.179%
Percentage flicker	< 5%	25 ~ 100%	< 10%
Dimming method	Analog/Digital	TRIAC	Analog/Digital
Uniformity of light emitting surface	Excellent	Bad	Good

When the pulsating DC voltage is higher, more segmented LEDs are turned on, and vice versa, when the pulsating DC voltage becomes lower, the number of LEDs turned on is reduced. Therefore, linear converters do not require energy storage components, eliminating the need for transformers and inductors that are difficult to integrate into ICs. Due to the rising demand for low-cost, small size, and low flicker percentage in the market, the development of linear converters has become crucial. As shown in Table 2, the efficiency of commercial linear converters ranges from 75% to 85%, with percentage flicker between 25% and 99.9%. The proposed linear converter adopts a multi-stage switching and constant power design, improving the drawbacks of linear converters, achieving an overall efficiency of $>$ 88%, and a percentage flicker of $<$ 10%. Therefore, the proposed linear converter exceeds international product standards.

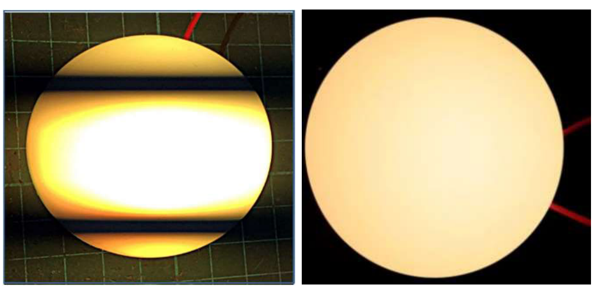
III. EXPERIMENTAL RESULTS

In this paper, the chip design was implemented using the Nuvoton HV 0.5-micron process. The layout diagram of the designed chip is shown in Figure 9, with a surface area of 3267 μm $\times$ 2150 μm. The input AC voltage range is 220 $\pm$ 10 V, and the chip can withstand a power transistor voltage of 500 V. Figure 10 illustrates the waveforms, where the blue waveform represents the output voltage of the valley filler circuit, and the purple waveform represents the current of the eight-segment LED. As observed from Figure 10, when the pulsating DC voltage increases (decreases), the current in

FIGURE 11. Measured percentage flicker of the proposed linear converter.

TABLE 3. Measured efficiency results.

	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9
	AC	First stage	Second stage	Third stage	Fourth stage	Fifth stage	Sixth stage	Seventh stage	Eighth stage
Vrms (V)	125.12	-	-	-	-	-	-	-	-
Arms (mA)	121.9	-	-	-	-	-	-	-	-
Vmn (V)	-	43.77	61	75.468	87.725	98.767	109.76	118.84	125.35
Amn (mA)	-	76.997	68.305	40.114	29.533	25.834	26.113	26.033	30.252
W (W)	12.565	1.2676	1.9605	1.1243	0.81	0.904	1.171	1.5156	2.3267
PF	0.905	-	-	-	-	-	-	-	-
DOB Efficiency	88.179%								



(a) (b)

FIGURE 12. Light caused by flickering.

FIGURE 13. DOB module.

the eight LED segments decreases (increases). After amplification, the LED power and brightness are approximately constant, resulting in a reduction in percentage flicker. The measured flicker values are presented in Figure 11, where

TABLE 4. Comparison table.

	[9]	[10]	[11]	[12]	[13]	[14]	[15]	This Work
Process	No	0.35 um 120 V HVCMOS	0.18 um 85 V BCDMOS	NO	NO	0.5 um 500 V LDMOS	NO	0.5 um 600 V BCDMOS
Power	3.6 W	2~7.8 W	34 W	6.8 W	4 W	9 W/16 W	15 W	12 W
Vac	110 V	110 V	120 V	110 V	110 V	110/220 V	80-140 V	110 V
Dimming method	TRIAC	NA	NA	NA	DPWM	TRIAC	TRIAC	Analog/PWM
PF	0.72	0.925	0.996	0.95	0.99	0.98/0.96	0.973	0.905
Percentage Flicker	28%	17.3%	~100%	NA	NA	~100%	18.6%	9.42%
Efficiency	NA	87.6%	83%	80%	85%	85%/87%	84.7%	88.179%

FIGURE 14. Thickness of DOB module.

the measured percentage flicker (Percent Flicker) was 9.42%, and the flicker index was 0.023; these values exceed relevant international specifications. In Figure 12(a), the measured luminous flux of a linear DOB module with a flicker percentage of 66% is displayed. When recorded with a phone camera, this flux appears as zebra patterns. In contrast, Figure 12(b) illustrates the measured luminous flux of the proposed structure, which had a flicker percentage of only 9.42%; as a result, the flux does not exhibit zebra patterns when captured by the phone camera, facilitating the reading process.

The prototype circuit of the Driver-on-Board (DOB) used in the proposed linear converter is illustrated in Figure 13, which includes a bridge rectifier, a valley filler circuit, protection components, a linear power IC, and LEDs. The overall thickness of the DOB along with the aluminum substrate is 8.15 millimeters (as shown in Figure 14). However, the DOB itself, excluding the aluminum substrate (with a thickness of 2 millimeters), has a thickness of only 6.15 millimeters, meeting the requirements of an ultra-thin design. Table 3 presents the measurement results for the eight segments of the linear converter in this paper. As the input is an AC signal, the root mean square (rms) values are used for calculation (Vrms and Arms). CH2 to CH9 represent segments 1 to 8 of the LED, and as the LED segment voltages are DC, mean values are used for calculation (Vmn and Amn). In this paper, a power meter (Voltech PM6000) was employed to measure the root mean square (rms) and mean values of the input (CH1) and the eight segment outputs (CH2 to CH9). Finally, the sum of the eight segment powers (C2 to CH9) is divided by the input power of CH1 to obtain an efficiency of 88.179%. The comparison table shown in Table 4 demonstrates that our approach outperforms other reference papers in both power efficiency and percentage flicker performance.

IV. CONCLUSION

In order to effectively reduce percentage flicker, this paper employs a valley filler circuit with constant power driving design and avoids the use of large-capacity electrolytic capacitors. The overall depth of the driver-on-board (DOB) is only 8.15 mm, which avoids the occurrence of shading and dark bands and ensures uniform light output. The percentage flicker is less than 10%, which exceeds the international standard. This study utilizes a multi-stage switching mechanism, achieving an overall efficiency greater than 88%. Under the condition of 12 W input, a 10% increase in efficiency reduces 1.2 W of heat, greatly reducing the difficulty and cost of IC packaging heat dissipation. Through these technologies, this study simultaneously achieves high efficiency and low flicker characteristics, improving the shortcomings of traditional linear converters. Currently, the DOB is in the trial production phase and will be rapidly introduced to the market to expand the market share of linear converter.

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