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Design of Digital Linear Power Supply with Low Current Ripple

Che-Min Kung, Yeh-Chen Yeh and Wen-Tien Tsai

Department of Green Energy and Environment Research Labs, Industrial Technology Research Institute, Hsinchu County 310401, Taiwan

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Abstract: A linear power supply is a circuit architecture directly driven by AC. Multiple high-voltage LEDs (light-emitting diodes) are connected in series to withstand the input voltage. The LEDs are divided into multiple segments through a segment switching mechanism to adapt to the pulsating DC changes after bridge rectification. Due to imperfect switching between control signals, there may be signal overlap or misalignment, which reduces circuit performance and component lifespan. Firstly, signal overlap occurs when the next segment opens before the previous segment is about to close. This state causes overlapping intervals where two segments of current combine, resulting in a high combined current that can lead to significant power losses and generate heat, potentially reducing the lifespan of the components. Secondly, signal misalignment occurs when the next segment prepares to open after the previous segment has completely closed. In this state, there is a time gap with no current flow, resulting in reduced output power and exacerbating LED flickering. Both of these undesirable phenomena introduce ripple into the LED output current. In this paper, a digitalized design is proposed to precisely compensate for the timing between alternating signals, significantly reducing output current ripple. This approach helps enhance power supply performance, extend component lifespan, and reduce LED index flicker.

Key words: LED, linear, flicker, direct AC, current ripple.

1. Introduction

According to TrendForce's "Global LED Industry Database and Quarterly Update of LED Manufacturers" report, the demand for high-spec LED (light-emitting diodes) products in the lighting market will enter a climbing stage, because the recent rise in global raw material prices has led to a trend of increasing product unit prices. The energy-saving demand of governments in various countries is soaring. It is estimated that the output value of the lighting LED market in this year (2022) may reach 8.11 billion US dollars, with an annual increase of 9.2%. In the next few years, driven by factors such as human health lighting and smart lighting, the lighting LED market will continue to grow and is expected to reach US $11.1 billion by 2026, with a CAGR (compound annual growth rate) of 8.4% from 2021 to 2026 [1] shown in Fig. 1.

TrendForce further stated that despite the continuous impact of the epidemic this year, with the popularization of vaccines and the recovery of economic activities, coupled with the rigid demand for people's livelihood necessities in the lighting market, and the global carbon neutrality and energy-saving needs are gradually being put on the agenda, major powers have followed suit in recent years. Net-zero emissions are achieved through measures such as energy efficiency and low-carbon heating. However, lighting is a major energy-consuming item in buildings, accounting for 20% to 30% of total building energy consumption. Driven by the high demand for energy saving and the upgrade of policies and regulations, LED will further penetrate. In addition, smart lighting can also achieve the purpose of timely energy saving. Therefore, commercial lighting, home lighting, outdoor lighting and industrial lighting have strong demand for LED lighting introduction and smart

Corresponding author: Che-Min Kung, Ph.D., research field: LED lighting.

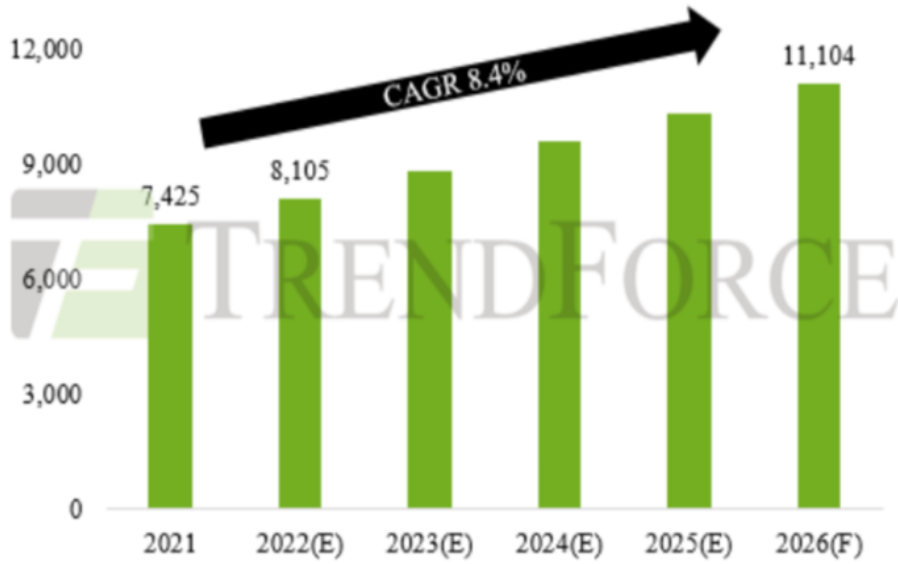

Fig. 1 LED market trends.

lighting upgrades, further pushing up the demand for high-standard LED products, including high luminous efficiency, high color rendering and color saturation, low blue light human factors health lighting and smart lighting.

Due to demand for high-standard LED products, the choice of LED driver power supply is crucial. In the field of LED driver power supplies, two main architectures are widely used: switching converters and linear power supply architectures. Switching converters typically use high-frequency switching operations to regulate output voltage or current, enabling efficient power conversion. However, switching converters involve the use of components such as transformers, inductors, and large electrolytic capacitors, which result in increased size and cost. Moreover, they are prone to electromagnetic interference issues [2, 3].

In contrast, linear power supply architectures have gained attention for their unique advantages and application areas. Linear power supplies have simpler designs and operate at lower frequencies, eliminating the need for complex switching components and reducing electromagnetic interference. Another advantage of linear power supplies is their lower cost and ease of design. Compared to switching converters, linear power supplies have simpler circuitry, eliminating the need for complex control circuits and high-frequency transformers. This reduces the overall cost of the power supply and simplifies system setup and maintenance costs [4, 5].

In response to the modern LED lighting demands of low cost and small volume, linear power supplies have become the new mainstream for lighting power sources. This paper focuses on the improvement and design of specifications based on linear power supplies. Traditional linear power supplies are prone to generate significant current ripple, which is an important indicator in power supply specifications. Large fluctuations in the current ripple may affect circuit performance and component lifespan, and can also aggravate LED flickering. Therefore, this paper adopts digital precision control and utilizes control algorithms to specifically reduce the current ripple of the linear power supply, improve hardware specifications and lifespan, and reduce LED flicker index.

2. Hardware Architecture and Design

The proposed linear power supply circuit architecture is shown in Fig. 2, which consists of five parts, namely bridge rectifier, valley filling circuit, linear circuit, constant current and digital controller (microcontroller, named MCU).

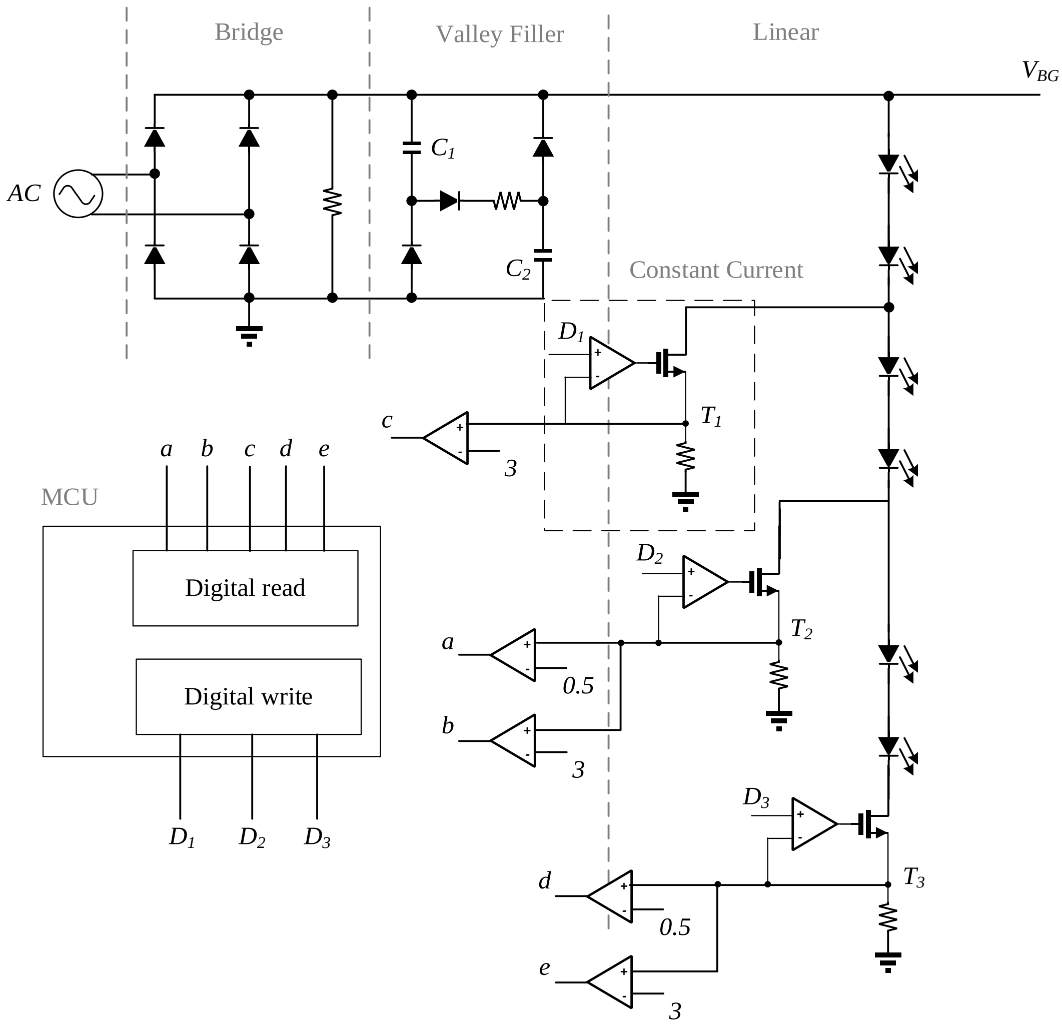

Fig. 2 The proposed linear power architecture.

The bridge rectifier is used to convert the AC power supply into a DC power supply for the LED driver circuit. It consists of four electronic switches (usually diodes or MOSFETs) configured in a bridge configuration. When the positive half-cycle of the AC voltage appears, two diagonally-opposite switches close, allowing current to flow to the LED driver circuit. Conversely, when the negative half-cycle of the AC voltage appears, the other two diagonally-opposite switches close, still supplying current to the LED driver circuit but in the reverse direction. This way, the bridge rectifier achieves the rectification of the AC power supply, enabling the LED driver circuit to operate using a DC power supply.

The valley filling circuit is utilized to fill in the peaks and valleys of the DC output voltage from the bridge rectifier, aiming to achieve a more stable output current. By monitoring the output voltage, the valley filling circuit inserts current between the peaks and valleys, striving to maintain the output current as constant as possible. This ensures that even with fluctuations in the input voltage, the valley filling circuit can maintain a stable output current, guaranteeing uniformity and stability of the LED's brightness [6, 7].

The segmented linear LED driving involves dividing the LED into multiple sections and driving each section separately. Each section is controlled by a constant current circuit to ensure a constant current under different input voltage conditions. This approach achieves uniform brightness for the entire lighting fixture and enhances efficiency and stability. In summary, the bridge rectifier converts the AC power supply to DC, the valley filling circuit maintains the stability of the output current, and the segmented linear LED driving ensures uniform brightness for the LED. This driving scheme effectively improves the performance and stability of LED lighting fixtures and finds wide applications in the LED lighting industry.

The constant current circuit, as shown in Fig. 3, is composed of an operational amplifier, power switch elements, resistors, and a reference voltage source [8]. In the constant current circuit, the non-inverting input of the operational amplifier is typically connected to a stable voltage source, such as a reference voltage source, to provide a reference current value. The switch elements used in the constant current circuit can be transistors, field-effect transistors, or other types of switches. The states of these switch elements can be controlled by voltage to modify the current path. When the switch is closed, the current flows through the controlled load, generating a constant current. On the other hand, when the switch is open, the current path is interrupted, and the current no longer flows through the load. By controlling the open and closed states of the switch, a constant current can be delivered to the load for a specific period, achieving the function of maintaining a constant current. The constant current circuit is commonly used in applications that require a stable current supply, such as LED drivers and electrochemical reaction control.

Pico (Raspberry Pi Pico) is a microcontroller board launched by the Raspberry Pi Foundation, powered by the RP2040 chip designed by Raspberry Pi. RP2040 is a high-performance dual-core ARM Cortex-M0+ microcontroller with a maximum clock frequency of 133 MHz. It comes with 264 KB of SRAM and 2 MB of flash memory. Additionally, it features 16 sets of GPIO (general purpose input/output) pins and integrates communication interfaces such as I^2C (Inter-Integrated Circuit), SPI (Serial Peripheral Interface), and UART (Universal Asynchronous Receiver-Transmitter), making it highly suitable for various embedded systems and IoT (Internet of Things) applications. This paper uses the Pi Pico as the control core (MCU) and utilizes its 8 sets of GPIO pins for digital input and output purposes. These GPIO pins allow for digital signals to be received as input and to be sent as output to interact with external devices and components [9].

3. Control Logic and Design Methodology

Traditional linear power supplies use analog control, which offers advantages such as better tolerance to interference, lower cost, and the absence of a need for firmware development by specialized personnel. However, due to the reliance on analog circuitry throughout the system, these power supplies tend to have a higher component count and larger physical size. Additionally, analog components are more susceptible to temperature and other environmental factors, leading to output voltage drift that can affect system stability and reliability. On the other hand, digital power supplies exhibit characteristics opposite to those of analog power supplies. They come with higher costs and require expertise in firmware development, but offer advantages such as higher precision, flexible design capabilities, fast response times, and remote monitoring capabilities. In this paper, where the suppression of current ripples during the segmented switching process demands rapid voltage detection and response, a digital control core is adopted to manage the segmented switching of the linear circuitry.

According to the circuit diagram shown in Fig. 2, this paper utilizes the MCU’s digital-read pins to detect voltage parameters from *a* to *e*. Through the logical decisions and built-in algorithms specified in Table 1, the MCU provides signals D1 to D3 digital-write pins to control the constant current regulators in the linear circuit. This enables real-time adjustment of current variations during switching, aiming to effectively suppress current ripples.

Initialization state: D1 to D3 are first set to 1 to enter the steady state. State 1: When c=1 and a=b=d=e=0, it

Table 1 The state table for the three-segment switching process.

	D1	D2	D3	a	b	d	e	c
Initial state	1	1	1	0	0	0	0	0
State 1	1	1	0	0	0	0	0	1
State 2	0	1	0	1	0	0	0	0
State 3	0	1	1	1	1	0	0	0
State 4	0	0	1	0	0	1	0	0
State 5	0	0	1	0	0	1	1	0
State 6	0	1	0	0	0	1	0	0
State 7	0	1	0	1	1	0	0	0
State 8	1	0	0	1	0	0	0	1

indicates that the current pulsating DC voltage is in the first segment steady state. D1 and D2 are set to 1, and D3 is set to 0. State 2: When b=d=e=c=0 and a=1 simultaneously, it indicates that the current state is at the transition point between the first and second segments (rising half-cycle of pulsating DC). D2 is set to 1, and D1 and D3 are set to 0. State 3: When a=b=1 and d=e=c=0, it indicates that the current state is in the second segment steady state. D1 is set to 0, and D2 and D3 are set to 1. State 4: When d=1 and a=b=e=c=0, it indicates that the current state is at the transition point between the second and third segments (rising half-cycle of pulsating DC). D3 is set to 1, and D1 and D2 are set to 0. State 5: When d=e=1 and a=b=c=0, it indicates that the current state is in the third segment steady state. D3 is set to 1, and D1 and D2 are set to 0. State 6: After the third segment steady state, when d=1 and a=b=e=c=0 is encountered again, it indicates that the current state is at the transition point between the second and third segments (falling half-cycle of pulsating DC). Subsequently, State 7: When a=b=1 and d=e=c=0 is encountered, it indicates that the current state is in the second segment steady state. D2 is set to 1, and D1 and D3 are set to 0. State 8: Finally, when a=c=1 and b=d=e=0, it indicates that the current state is at the transition point between the second and first segments (falling half-cycle of pulsating DC). D1 is set to 1, and D2 and D3 are set to 0, allowing this logic design to connect back to state 1, completing a full cycle.

4. Measurement Result

Figs. 3a-3c illustrate the results of three different switching states. Fig. 3a shows that the control signal D2 lags behind D1. According to the circuit diagram in Fig. 2, during this lagging delay period, both the D1 and D2 controlled constant current sources are simultaneously turned off, resulting in an instantaneous drop in the output current (I_{out}) and generating a large downward current spike. On the other hand, Fig. 3b demonstrates that the control signal D2 leads D1. In this leading interval, the D1 and D2 controlled constant current sources are both turned on, causing the current to accumulate and leading to an instantaneous increase in the output current (I_{out}), producing a large upward current spike. To address these issues, this paper employs digital control to precisely capture the moment of switching between the states of control signals D1 and D2. This allows a smooth transition where the D1-controlled constant current source gradually decreases before the D2-controlled constant current source slowly rises. Consequently, this approach effectively suppresses the current spikes (current ripples) caused by switching between constant current sources, as illustrated in Fig. 3c.

The actual complete circuit prototype is shown in Fig. 4, which includes the bridge rectifier, valley filler circuit, LED board, comparator, constant current source circuit, and the digital control core (MCU).

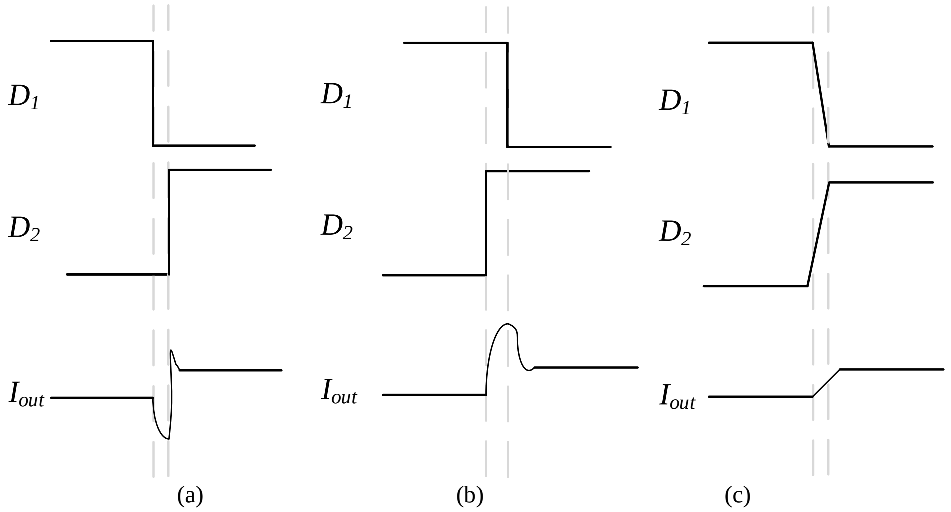

Fig. 3 Schematic comparison diagram of switching state.

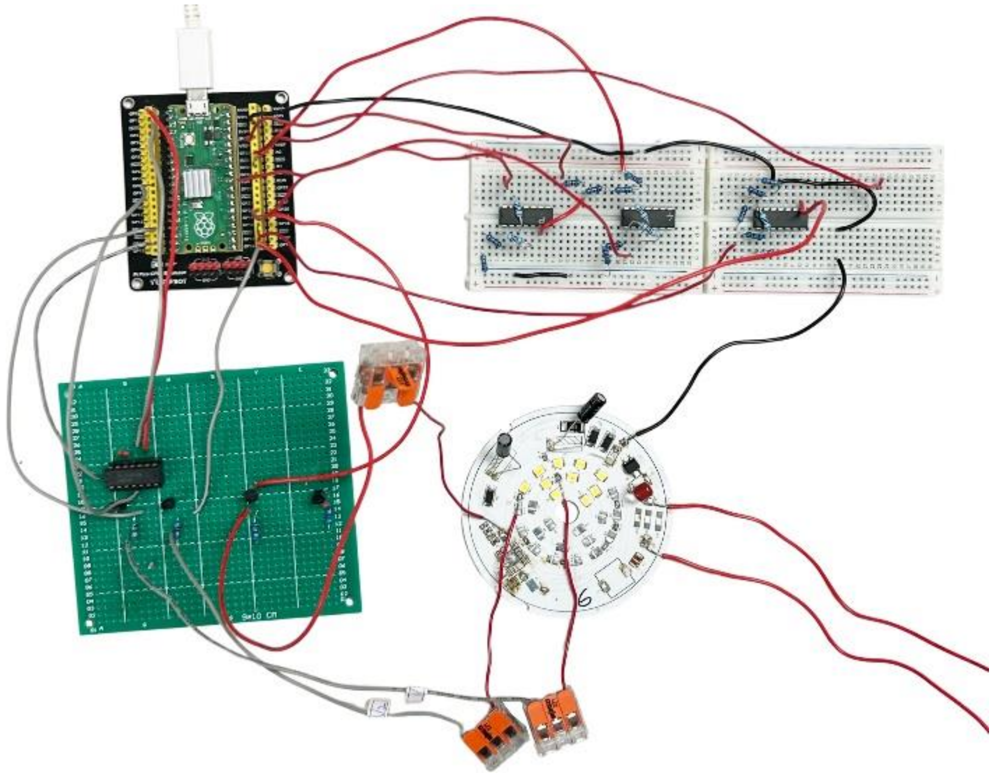

Fig. 4 Complete circuit prototype.

Fig. 5 displays the measurement results of the traditional analog control method (the schematic diagram of the effect is shown in Fig. 3a), clearly indicating significant downward current spikes/current ripples. Excessive output current ripple can affect flicker, causing discomfort during human eye reading. In contrast, Fig. 6 illustrates the measurement results of the digital control method proposed in this paper (the schematic diagram of the effect is shown in Fig. 3c). The results demonstrate that the control logic presented in this paper is highly effective in suppressing current ripples, leading to a substantial reduction in flickering phenomena.

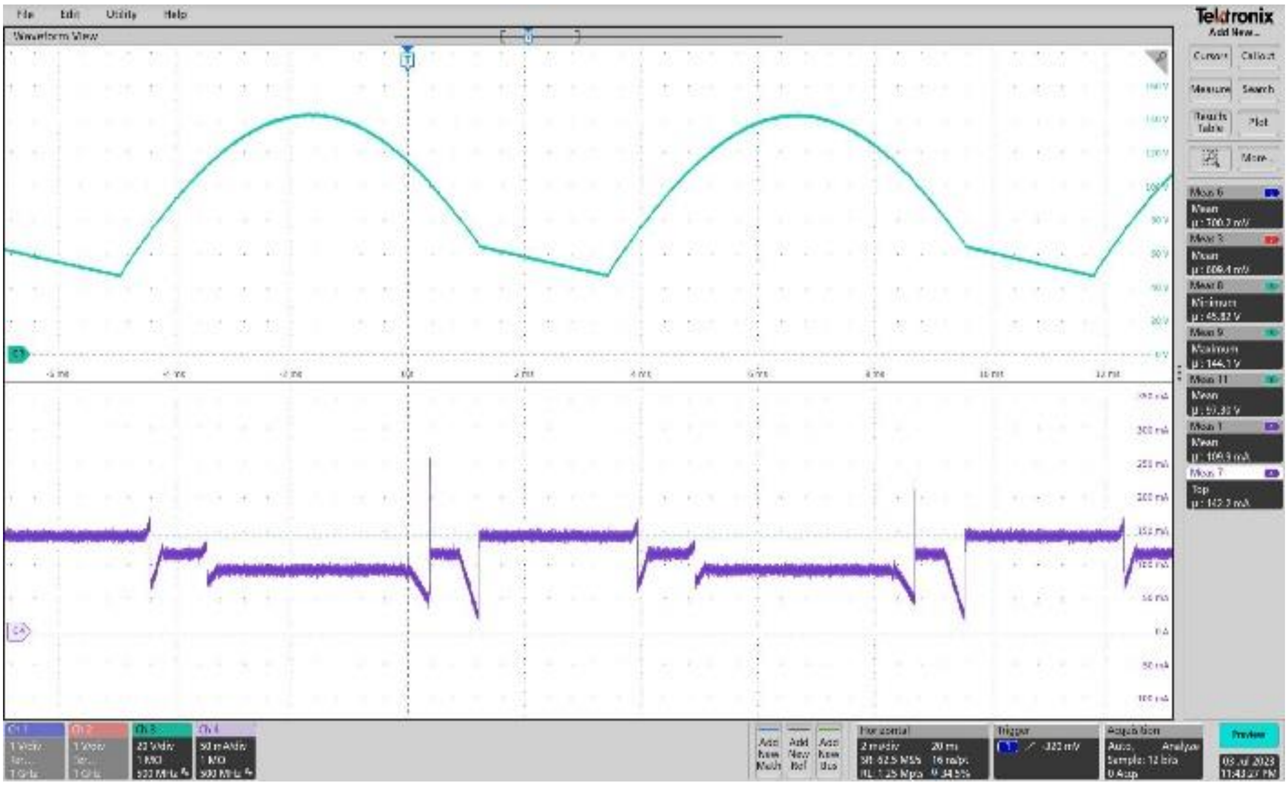

Fig. 5 Measurement results of traditional analog control methods.

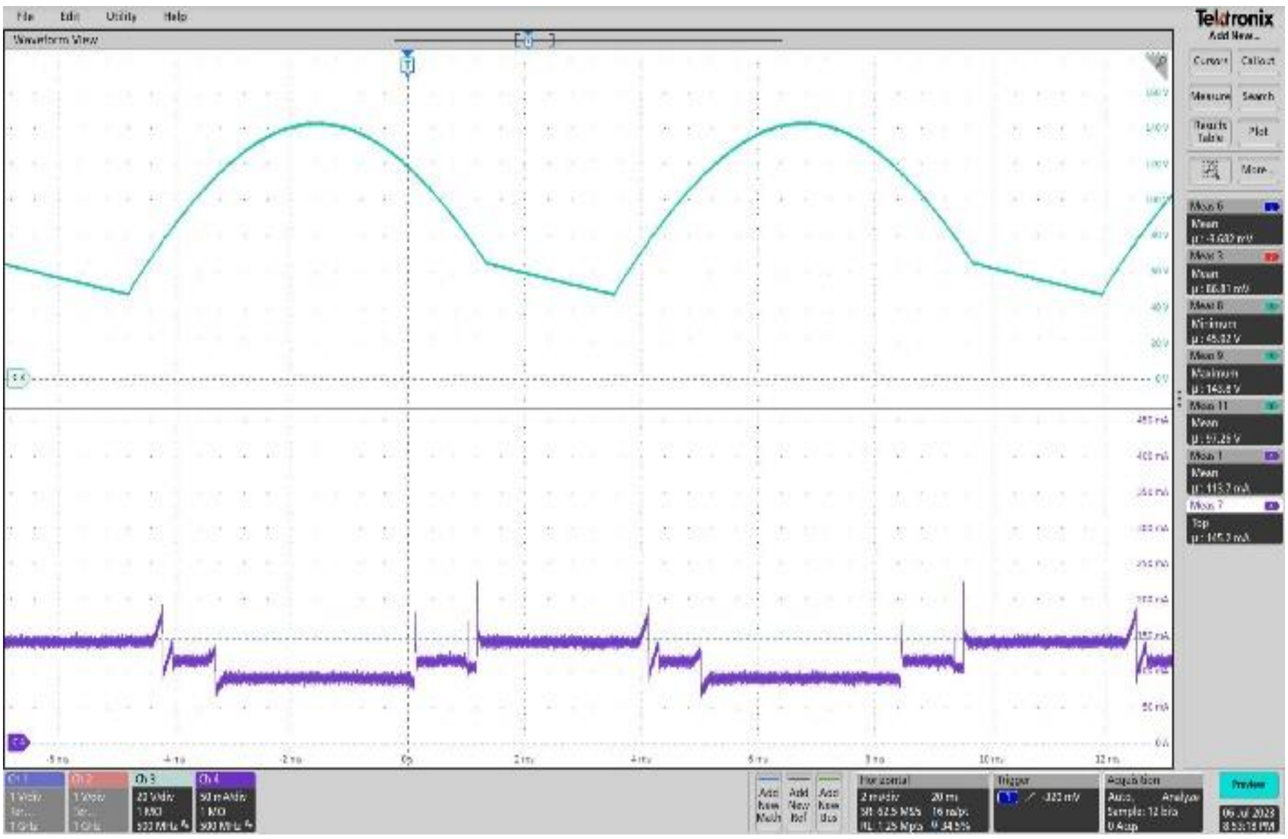

Fig. 6 The measurement results of the digital control method in this paper.

5. Conclusion

The linear power supply is a circuit architecture directly driven by AC. Multiple high-voltage LEDs are connected in series to withstand the input voltage. It divides the LEDs into multiple segments to adapt to the pulsating DC changes after bridge rectification. Due to imperfect switching of control signals, there can be instances where two signals are out of alignment, causing the output current to experience momentary and significant current ripple. This current ripple can impact the LED flickering phenomenon. In this paper, a digitalized design is proposed to precisely compensate for the differences between alternating signals, significantly reducing output current ripple. This approach helps enhance power supply performance, extend component lifespan, and reduce LED flickering.

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