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# STRING DIMMING MODEL WITH CURRENT CONTROL FOR HIGH EFFICIENT PARALLEL STRING LED DRIVER

Chris Batara, Salama Manjang, Faizal Arya Samman*
and A. Ejah Umraeni Salam

Department of Electrical Engineering
Universitas Hasanuddin
Jl. Perintis Kemerdekaan Km.10, Tamalanrea, Makassar 90245, Indonesia
chrisbatara@ukipaulus.ac.id; { salamamannjang; ejah }@unhas.ac.id
*Corresponding author: faizalas@unhas.ac.id

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Abstract. *This article proposes an LED driver design consisting of a boost converter, a Constant Voltage Regulator Circuit (CVRC), a String Current Adjuster Circuit (SCAC), and a Dimming Control Circuit (DCC). The boost converter provides voltage for multiple LED strings, while the CVRC keeps $V_{bus}$ constant according to the load demand. The SCAC precisely regulates the current of each string with minimal power loss compared to a conventional linear regulator, thus improving energy efficiency. The DCC is used to adjust the dimming level as needed. Verification through PSIM simulations shows that the conventional driver produces $V_{bus}$ = 21.6 V, $I_{str}$ = 9.80-29.90 mA, and an efficiency of 49.29%. Meanwhile, the proposed driver with a duty cycle of 0.5-0.7 produces $V_{bus}$= 22.01-23.68 V, $I_{str}$ = 10.4-59.25 mA, and $V_s$ = 1-5 V, providing high flexibility in brightness adjustment. This system is capable of maintaining LED voltage with high precision and achieving energy conversion efficiency of up to 97.71%, demonstrating optimal performance and significant improvement over conventional designs.*

**Keywords:** Boost converter, Constant voltage regulator, Current balancing circuit, Dimming control, High-efficiency LED driver

1. **Introduction.** The use of Light Emitting Diodes (LEDs) for lighting is currently experiencing rapid growth, including applications in liquid crystal displays, backlighting, commercial lighting, residential lighting, automotive lighting, and general lighting. This is due to LEDs' advantages over conventional lighting, such as low power requirements, environmental friendliness, long durability, and dimmability.

LEDs exhibit similar properties to P-N junction diodes but demonstrate nonlinearity and temperature dependence, where increased temperature reduces barrier voltage and elevates current at constant voltage [1]. Therefore, LEDs cannot be operated directly by a voltage source, the output current must be precisely controlled [2,3]. Lighting improvements usually arrange several LEDs in series or parallel, series arrangement requires high voltage and parallel arrangement is more widely used because it requires low power [4]; however, it causes current non-uniformity in parallel LEDs so that a current uniformity control circuit is required [5,6]. There are two methods of uniformity control, which are passive and active. The passive method is simpler but causes additional power losses.

The active method uses active components to form constant current regulator that is installed in series with the LED circuit, thus producing precise current as needed and is implemented in a switch or linear type (Figure 1) [7]. Figure 1(a) shows a switch-type regulator that uses a non-isolated DC/DC converter (Boost-Buck) with the number of converters equal to the number of LED strings. Although this circuit has high efficiency, it has a complex and expensive circuit. To avoid complex and expensive circuits, a SIMO

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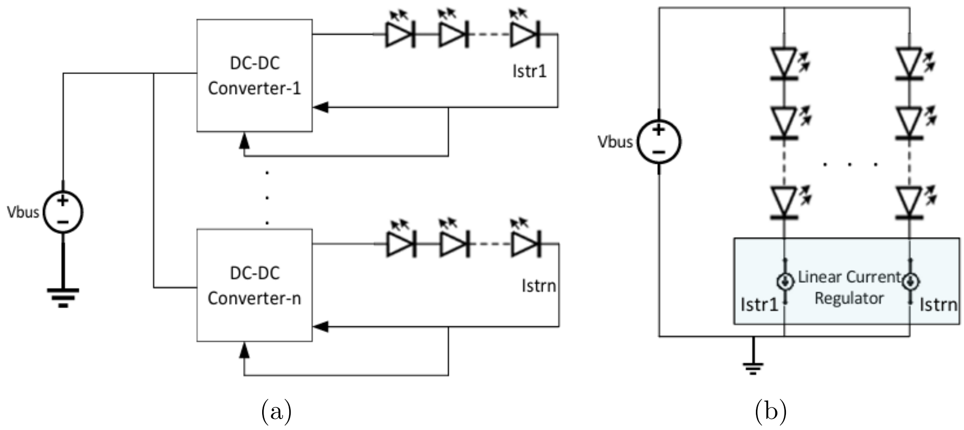



Figure 1. Active current balance method: (a) Switching mode; (b) linear type

(Single-Inductor Multiple-Output) circuit is used [8-10]. Figure 1(b) shows a linear regulator, which experiences higher power losses due to the voltage difference between the bus voltage ($V_{bus}$) and the forward voltage of the LED string that drops across the internal linear switch, resulting in lower efficiency. To solve this, adaptive output voltage control has been proposed and can improve efficiency, but is less effective when the forward voltage between parallel LEDs varies.

Intelligent lighting systems use dimming via amplitude or pulse-width modulation, where AM is simpler but affects the light's color spectrum [11], while PWM preserves color stability but may cause flicker at narrow duty cycles and low frequencies [12].

One crucial aspect of current LED driver research is improving efficiency. Table 1 shows research results related to efficiency improvement.

This paper presents a multi-string LED driver based on SIMO boost converter to overcome the complexity, voltage instability, current imbalance, and power losses of linear regulators. The design maintains constant voltage, uniform current, adaptive dimming, and high efficiency. This paper is composed of a review of conventional drivers (Section 2), the design of the proposed system (Section 3), experimental results (Section 4), analysis of the results (Section 5), and conclusions (Section 6).

2. **Conventional LED Driver.** In Figure 2, the voltage required by the LED string can be controlled by adjusting the duty cycle on the MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor) switch. For example, with a Duty Cycle (DC) of 0.5, the output voltage $V_{bus}$ is 21.6 Volts and the current per LED string ($I_{str}$) reaches 29.9 mA. This value is sufficient to meet the operating needs of the LED string with a voltage range between 21 to 24.5 Volts and a current between 10 to 60 mA. To adjust the brightness level, the amount of current flowing to the LED string can be controlled, and the current is regulated by adjusting the reference voltage ($V_{ref}$).

Conventional LED drivers are limited in duty cycle range because they rely solely on PWM control to adjust the output voltage. This often leads to unstable voltages and current surges before steady state, potentially damaging the LED string. Furthermore, there is power loss in the current regulator for each string. The average power loss in the current regulator is [17]

$$P_{loss} = \sum_{n=1}^{N} V_{dim} \cdot I_{str,avg} \tag{1}$$

where $P_{loss}$ is the average power dissipated in the current regulator, $V_{dim}$ is the voltage across each string (str) and $I_{str,avg}$ represents the average current through each LED string. The value of $I_{str,avg}$ is controlled to adjust the brightness of the LEDs.

Table 1. Research on efficiency improvement

| No | Ref | Efficiency improvement methods | Efficiency | Advantage | Disadvantage |
|---|---|---|---|---|---|
| 1. | [13] | SIMO LED driver, dimming control with phase-shift PWM switching. | 85% | Large dimming range. | Control complexity, limited scalability. |
| 2. | [14] | Efficiency improves through optimal WLED arrangement and sensing to set the minimum output voltage in real time. | 91% | High system efficiency, excellent inter-string current accuracy (0.2%). | Design complexity increases due to the use of programmable resistors and amplified current sinks. |
| 3. | [10] | The ARIC method adds freewheeling phase per cycle to reduce cross-regulation and dynamically adjust inductor current for optimal efficiency. | 92.9% | Using SIMO architecture which can reduce complexity. | Using a resistor to set string current leads to power loss and heat generation. |
| 4. | [15] | The digital control system utilizes resistive DAC as analog feedback on the DC-DC converter, with an input voltage of 24 V and an output range of 35-38 V. | 93.9% | Flexible control methods. | System complexity increases due to the application of digital logic to the feedback loop. Disadvantages of linear current regulators. |
| 5. | [16] | The proposed method uses a passive snubber circuit consisting of two capacitors, two diodes, and an inductor. | 94.80% | Reduction of switching losses. | Complexity of the snubber circuit. Optimization is limited to high duty cycle. |
| 6. | [17] | Proposes Current Balancing Circuits (CBC) and boost converter with Drain Voltage Balance (DVB) control scheme installed on each string and Phase-Shifted PWM (PSPWM). | 95% | Can improve string current balance. | Complex circuit. The driving current setting on the LED string has not been done. |
| 7. | [18] | This driver applies a half-bridge topology with switched capacitors to forming a double resonant network, so that the current can be divided evenly and proportional dimming between the networks can be maintained. | 95.56% | Simple switched-capacitor based design, proportional dimming capability. | Although it supports proportional dimming, its lifespan is narrow and it is difficult to scale to multi-string systems due to potential inter-network instability. |
| 8. | [19] | The proposed LED driver is based on a Single-Inductor Multiple-Output (SIMO) DC-DC converter. A Pulse Width Modulation (PWM) control strategy is applied to the LED driver to flexibly and precisely control the LED brightness. | 97% | Precise current distribution between LED strings. | Complexity in large multi-channel, diode arrays and complex paths. |

3. **Proposed LED Driver.** The proposed LED driver, as illustrated in Figure 3, is designed to improve energy efficiency by minimizing power losses typically caused by conventional resistors. The CMOS (Complementary Metal-Oxide-Semiconductor) method uses current mirror to balance the LED current, reducing power loss and improving reliability, while a flip-flop circuit allows for broader dimming control to support energy efficiency.

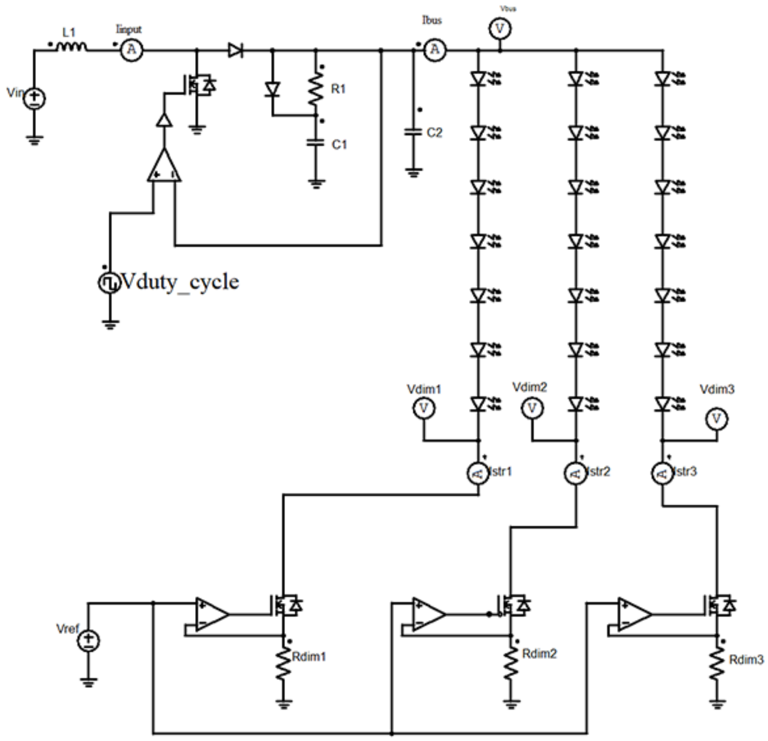



FIGURE 2. Conventional LED driver

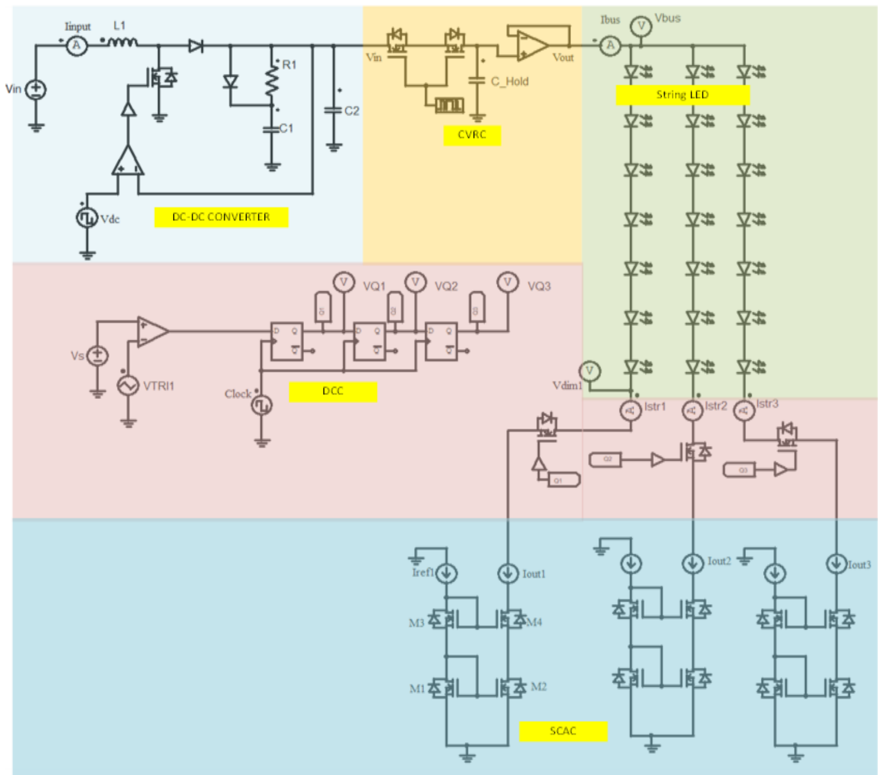



FIGURE 3. Proposed LED driver with constant voltage regulator, string current adjustment circuit and dimming regulator circuit

3.1. **Constant Voltage Regulator Circuit (CVRC).** A CVRC is a circuit used to maintain a constant $V_{bus}$ output voltage according to the voltage required by the LED string. A CVRC adopts and improves the Sample and Hold (S/H) working principle [17] applied to each LED string, which increases complexity and cost. This study implements

CVRC based on MOSFET, capacitor, and op-amp to maintain output voltage stability despite load variations.

The application of S/H increases efficiency and voltage stability, keeps the current and LED intensity constant, reduces the risk of damage, and saves power through more efficient system operation.

With CVRC, if dimming control is carried out by changing the $V_s$ voltage from 1 Volt to 5 Volts, the average string current flowing through the LED string will be maintained at $V_{bus} = 22.01$ Volts. If the duty cycle = 0.5, $V_{in} = 10$ Volts with variations in the average string current $I_{str}$ from 10.6 mA to 59.25 mA, the $V_{bus} = 22.01$ Volts will be maintained, as in Figure 4.

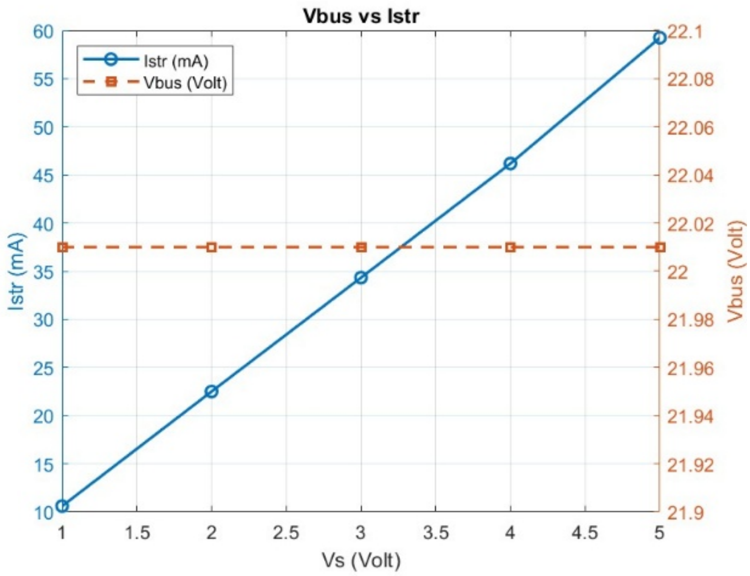



FIGURE 4. Comparison of average $V_{bus}$ and $I_{str}$ at duty cycle = 0.5; $V_{in}$ = 10 Volts

3.2. **String Current Adjuster Circuit (SCAC).** This study proposes current regulator model for each LED string that eliminates the use of resistors as current regulating elements. The proposed SCAC regulates the current in the LED string as needed between 10 mA and 60 mA. The SCAC is designed using MOSFETs to eliminate the use of resistors that can cause excessive power loss [20].

SCAC is the circuit that copies the same reference current $I_{ref}$ or modifies its value according to the bias requirements of the amplifier stage. MOSFETs M3 and M4 are biased with the same gate-to-source voltage $V_{GS}$, so both MOSFETs must operate in the saturation region to maintain a constant output current. The reference current and output current equations for MOSFETs M3 and M4 operating in the saturation region can be given as

$$I_{out} = I_{D4} = 0.5\mu_n cox \left(\frac{W}{L}\right)_4 (V_{GS} - V_T)^2 (1 + \lambda V_{DS4}) \quad (2)$$

$$I_{ref} = I_{D3} = 0.5\mu_n cox \left(\frac{W}{L}\right)_3 (V_{GS} - V_T)^2 (1 + \lambda V_{DS3}) \quad (3)$$

where, $I_{out}$ is the output current, $I_{ref}$ is the reference current, $W/L$ is called the MOSFET aspect ratio and $\lambda$ is the line length modulation coefficient.

Equations (2) and (3) show that the reference current and output current depend on the MOSFET aspect ratio as well as the channel length modulation coefficient. If the aspect ratio changes, it causes a proportional change in the reference current and output current. Similarly, both currents also depend on $V_{DS}$ due to the channel length modulation effect. Neglecting the channel length modulation effect,

$$I_{out} = I_{D4} = 0.5\mu_n cox \left(\frac{W}{L}\right)_4 (V_{GS} - V_T)^2 \tag{4}$$

$$I_{ref} = I_{D3} = 0.5\mu_n cox \left(\frac{W}{L}\right)_3 (V_{GS} - V_T)^2 \tag{5}$$

therefore,

$$I_{out} = \frac{\left(\frac{W}{L}\right)_4}{\left(\frac{W}{L}\right)_3} I_{ref} \tag{6}$$

From Equation (6), it can be observed that the output current of the current mirror $I_{out}$ only depends on the aspect ratio of each MOSFET and the reference current value $I_{ref}$. If the aspect ratio of both MOSFETs remains the same, i.e., $(W/L)_3 = (W/L)_4$, then the output current is equal to the reference current, i.e., $I_{out} = I_{ref}$.

The current through M1 and M3 is the same because they are connected in series:

$$I_{ref} = I_{D3} = I_{D1} \tag{7}$$

$$I_{ref} = I_{D3} = 0.5\mu_n cox \left(\frac{W}{L}\right)_3 (V_{GS} - V_T)^2 = 0.5\mu_n cox \left(\frac{W}{L}\right)_1 (V_{GS} - V_T)^2 \tag{8}$$

Equation (8) shows that the reference current in the MOSFET based reference current source depends on the aspect ratio of MOSFET M3 as well as the current mirror MOSFET M1.

The use of SCAC reduces power dissipation, supports integrated system integration, and provides energy efficiency, current stability, and high compatibility for modern, energy-efficient and reliable LED drivers.

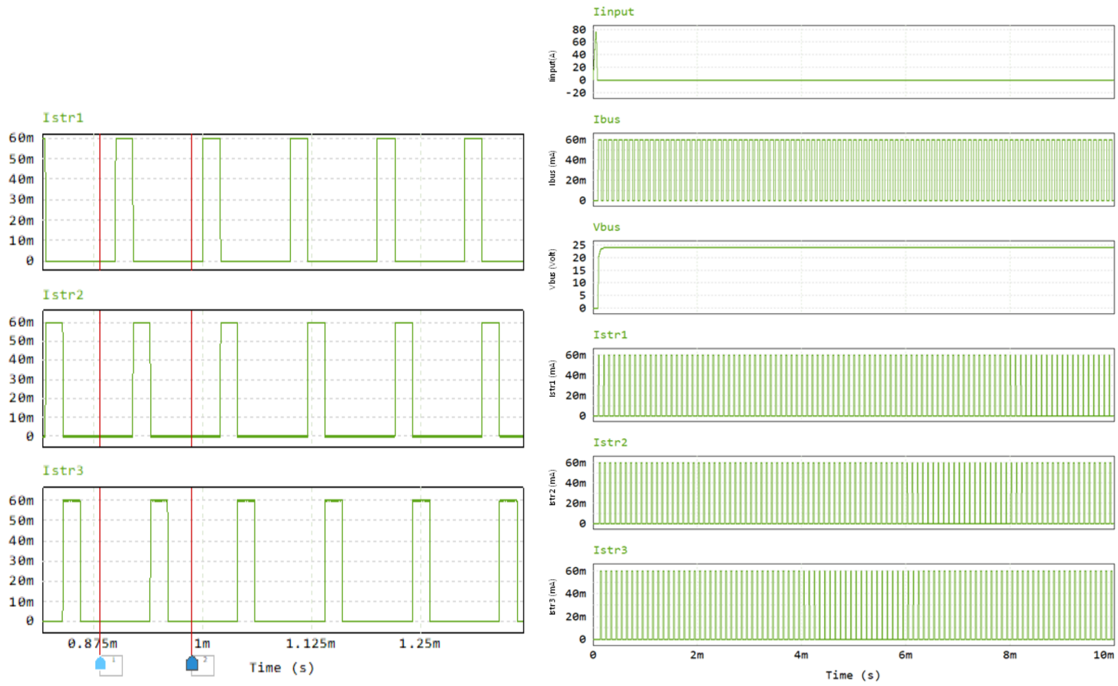
SCAC is used to balance the current of each LED string and regulate the current according to the needs of the LED string, namely 10 mA-60 mA. With this circuit, the maximum current is determined at 60 mA so that the current at $I_{out}$ ($I_{str}$) is equal to the current $I_{ref}$, namely = 60 mA.

3.3. **Dimming Control Circuit (DCC).** The DCC consists of a comparator and a Serial Input Parallel Output (SIPO) shift register. The comparator compares the variable input voltage $V_s$ and the reference voltage $V_{ref}$. By comparing the sense voltage ($V_s$) and $V_{ref}$, the output of the comparator becomes PWM signal with a duty cycle pulse width depending on the value of $V_s$. If $V_s = 2.5$ V, the comparator output is a PWM pulse with a duty cycle of 50%.

The PWM pulse generated by the comparator is the D input to the D Flip-Flop (SIPO), with a clock frequency of 50 kHz. When the clock rises (rising edge), the D value is passed to Q. When the clock falls (falling edge), the Q output retains its previous value. Because the PWM has a duty cycle that depends on $V_s$, the D Flip-Flop will capture this changing pattern and change its output according to the PWM duty cycle.

The D Flip-Flop output controls MOSFET as the series switch on the LED string to regulate the current. When Q is HIGH, the switch supplies current to the LED, when it is LOW, the current stops. Flip-Flop D follows the PWM duty cycle to regulate brightness. Figure 5(a) shows the LED dimming process by regulating the average current through changing the pulse width and sense voltage ($V_s$).

The dimming frequency in this study was 10 kHz. The frequency was selected by considering the technical and physiological aspects of the user's visual comfort. Based on literature studies, dimming frequencies above the human perception threshold, which is generally below 100 Hz to 500 Hz, can effectively avoid visual side effects such as imperceptible flicker, eye fatigue, and potential long-term negative impacts on visual health




(a) (b)

FIGURE 5. (a) Current waveforms of each string and (b) waveforms of $I_{input}$, $I_{bus}$, $V_{bus}$, $I_{str1}$, $I_{str2}$, $I_{str3}$, with duty cycle = 0.5 and $V_s = 1$ Volt

[21,22]. Therefore, the use of a dimming frequency of 10 kHz is far above the human retinal sensitivity threshold and is included in the flicker-free operation category, making it suitable for lighting applications requiring high visual comfort, such as in work environments, study rooms, and adaptive lighting systems.

4. **Experimental Results.** The performance of the proposed LED driver is verified through simulation using PSIM software with parameters: input voltage of 10 V, switching frequency of 10 kHz, and maximum output current of 177.76 mA. Passive elements include a 19.8 μH inductor and capacitors $C_1 = 100$ μF, $C_2 = 12$ μF, and $C_{HOLD} = 33$ μF. The load consists of three LED strings containing seven LEDs in series. Current regulation is done by controlling the sense voltage (1-5 V) and adjusting the duty cycle in the range of 0.5-0.7.

Figure 5(b) displays the steady-state waveform when duty cycle = 0.5 and sense voltage ($V_s$) = 1 V. The input current is shown as $I_{input}$, the bus output current as $I_{bus}$, and the output voltage as $V_{bus}$. The average current of each LED string is represented by $I_{str1}$, $I_{str2}$, and $I_{str3}$, respectively for LED strings 1-3. All measurements were performed at $V_s = 1$ V, while Table 2 presents the simulation results with varying duty cycle and $V_s$.

The equations used to develop the efficiency calculations can be found in [23]. The efficiency calculations are calculated using the formula:

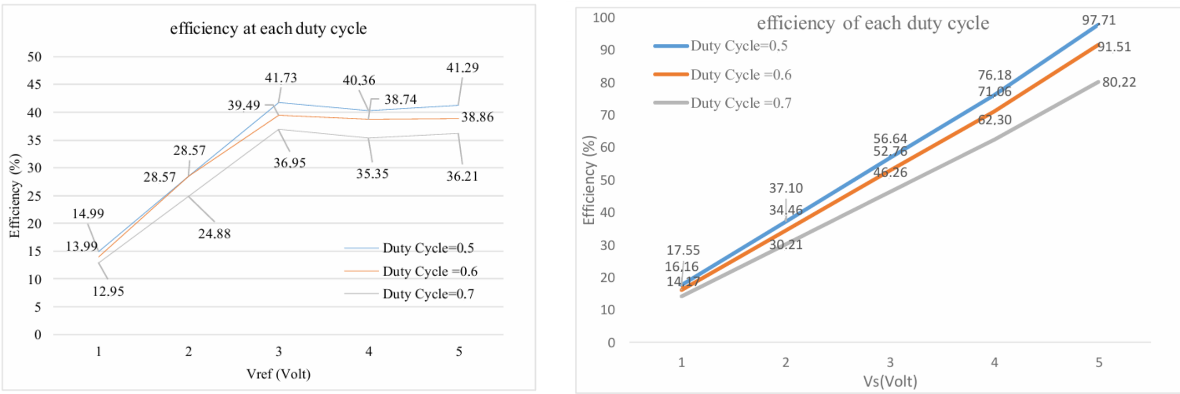
$$efficiency = \frac{P_{output}}{P_{input}} \times 100\% \tag{9}$$

where $P_{input}$ is the input power and $P_{output}$ is the output power.

Figure 6(a) shows the simulation results of a conventional LED driver, with a maximum efficiency of 41.29% at a duty cycle of 0.5 and $V_{ref} = 5$ V, and a minimum efficiency of 12.95% at duty cycle of 0.7 and $V_{ref} = 1$ V. Meanwhile, Figure 6(b) displays the performance of the proposed LED driver, which achieves a maximum efficiency of 97.71% at a duty cycle of 0.5 and $V_s = 5$ V, and minimum efficiency of 14.17% at a duty cycle of 0.7 and $V_s = 1$ V.

TABLE 2. Simulation results

| Duty cycle | $V_s$ (Volt) | $I_{input}$ (mA) | $I_{bus}$ (mA) | $V_{bus}$ (Volt) | $I_{str1}$ (mA) | $I_{str2}$ (mA) | $I_{str3}$ (mA) |
|---|---|---|---|---|---|---|---|
| 0.5 | 1 | 400.38 | 31.93 | 22.01 | 10.6 | 10.6 | 10.6 |
| | 2 | 400.38 | 67.48 | 22.01 | 22.5 | 22.49 | 22.48 |
| | 3 | 400.38 | 103.03 | 22.01 | 34.33 | 34.35 | 34.34 |
| | 4 | 400.38 | 138.57 | 22.01 | 46.18 | 46.2 | 46.19 |
| | 5 | 400.38 | 177.75 | 22.01 | 59.25 | 59.25 | 59.25 |
| 0.6 | 1 | 458.79 | 31.38 | 23.62 | 10.4 | 10.4 | 10.4 |
| | 2 | 458.78 | 66.93 | 23.62 | 22.32 | 22.32 | 22.3 |
| | 3 | 458.78 | 102.48 | 23.62 | 34.15 | 34.17 | 34.16 |
| | 4 | 458.78 | 138.03 | 23.62 | 46 | 46.02 | 46.01 |
| | 5 | 458.79 | 177.75 | 23.62 | 59.25 | 59.25 | 59.25 |
| 0.7 | 1 | 524.68 | 31.39 | 23.68 | 10.47 | 10.46 | 10.45 |
| | 2 | 524.67 | 66.94 | 23.68 | 22.32 | 22.31 | 22.3 |
| | 3 | 524.68 | 102.49 | 23.68 | 34.15 | 34.17 | 34.16 |
| | 4 | 524.68 | 138.04 | 23.68 | 46.00 | 46.02 | 46.01 |
| | 5 | 524.69 | 177.75 | 23.68 | 59.25 | 59.25 | 59.25 |




(a) (b)

FIGURE 6. Graph of the relationship between efficiency and duty cycle and $V_{ref}$ of (a) the conventional LED driver and (b) the proposed LED driver

5. **Results and Discussion.** The simulation results in Table 2 show that the Boost Converter-based LED driver operates stably at a duty cycle of 0.5-0.7, with an output voltage range of 22.01-23.68 V, still within the specification limits of 21-24.5 V. This stability reflects the precise performance of the PWM in regulating $V_{out}$, while improving the linearity and resolution of power regulation for optimal lighting performance. The average current per string ($I_{str}$) is in the range of 10.4-59.25 mA, in accordance with the LED current requirement (10-60 mA), which is controlled by varying $V_s$ between 1-5 V. At $V_s = 1$ V, a minimum current of 10.4 mA is obtained, while at $V_s = 5$ V, the current increases to 59.25 mA for maximum lighting. Compared to conventional drivers that only produce current of 19.70-31.75 mA, this system shows significant improvement in the dimming control range. With high sensitivity to $V_s$ changes, this driver not only maintains output current stability, but also supports energy efficiency, visual comfort, and minimizes flicker and light non-uniformity through effective control strategies.

Dimming in the LED driver is realized through voltage regulation $V_s$ compared with $V_{ref}$ to control the input of a 50 kHz flip-flop circuit as a power MOSFET control signal. The variation of $V_s$ allows stepwise regulation of the LED current in the range of 10.4-59.25 mA, allowing for dynamic adjustment of the luminance intensity. This medium-frequency flip-flop-based control mechanism provides fast response, reduces flicker, and maintains dimming stability, making it effective for adaptive and efficient lighting systems.

Medium frequency flip-flop control reduces flicker and maintains dimming stability. Otherwise, conventional PWM dimming methods simultaneously turn on the entire string, causing the bus current ($I_{bus}$) to fluctuate sharply from maximum to zero, forcing the boost converter to alternate between full-load and no-load conditions. This creates transient ripple in the bus voltage and LED current fluctuations.

To solve it, stable dimming scheme based on sliding flip-flops is used that alternately distributes the PWM signal among the strings. Figure 5 shows the timing diagram for each LED string. Dimming is controlled by changing the current pulse width through $V_s$, regulating the current and the LED light intensity precisely.

6. **Conclusion.** Based on the simulation results of the conventional LED driver, it was obtained that the efficiency was 46.29%, $V_{bus} = 21.6$ Volts, $I_{str}$ range 9.80 mA-29.90 mA. While in the proposed LED driver, the maximum efficiency of 97.71% was achieved at the duty cycle condition of 0.5, an input voltage ($V_{in}$) of 10 V, a bus current ($I_{bus}$) of 177.75 mA, a sense voltage ($V_s$) of 5 V, and the average of LED string current ($I_{str}$) of 59.25 mA. The bus voltage ($V_{bus}$) is in the range of 22.01 V to 23.68 V, which can be adjusted to the needs of the LED string configuration. The dimming feature can be realized by adjusting the sense voltage ($V_s$) in the range of 1 to 5 V, which results in an average LED string current in the range of 10.4 mA to 59.25 mA. Further research will focus on developing adaptive, stable, energy-saving dimming methods and integrating intelligent lighting systems.

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