Analysis and Simulation of a Current Mirror Balancing Circuit for AC LED Lighting

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Abstract

This paper presents the design, operation, and analysis of a current mirror balancing circuit for AC LED lighting applications, a technique aimed at ensuring uniform current distribution across multiple LED strings. In conventional AC-driven LED systems, mismatches in forward voltage and device tolerances often cause unequal current sharing, leading to non-uniform brightness, reduced efficiency, and shortened lifespan. The proposed circuit utilizes bipolar junction transistor (BJT)-based current mirrors to replicate and balance the reference current across parallel LED branches, thereby maintaining consistent illumination. Through simulations performed in eSim software, the circuit demonstrates effective current equalization and improved stability under alternating supply conditions. The results confirm the role of current mirror balancing in providing accurate current control, enhancing LED reliability, and minimizing thermal stress, emphasizing its importance in solid-state lighting and energy-efficient illumination systems.

Keywords:LED Balancing, Current Mirror, AC LED Driver, Solid-State Lighting, Reliability

I. INTRODUCTION

A current mirror balancing circuit is designed to maintain equal current distribution across multiple LED strings in AC lighting systems, preventing variations in brightness and improving overall reliability. Unlike simple resistor-based balancing methods, which waste power and provide only approximate control, a current mirror ensures precise replication of a reference current in each branch. This accurate current control minimizes mismatch effects caused by LED forward voltage variations and device tolerances.

The circuit typically employs bipolar junction transistors (BJTs) arranged in a current mirror configuration, with one branch setting the reference current while other branches mirror it. When the AC supply drives the LEDs alternately during positive and negative half cycles, the current mirror actively maintains uniform current flow, ensuring consistent illumination. This behavior not only enhances efficiency but also reduces thermal stress, preventing premature degradation of the LEDs. By providing predictable and stable current balancing, the circuit improves the performance, lifespan, and energy efficiency of AC-driven LED lighting systems.

II. PURPOSE OF CURRENT BALANCING

The purpose of current balancing in AC LED circuits plays an important role in ensuring reliable and efficient operation of lighting systems:

-Uniform Brightness: Prevents variations in light output by ensuring equal current through each LED string.

- Protecting LEDs from Stress: Avoids overdriving certain LEDs while others remain underutilized, reducing the risk of damage.

-Improved Efficiency: Eliminates unnecessary power loss compared to resistor-based balancing methods

-Thermal Stability: Reduces localized heating and prevents hotspots, thereby enhancing system safety.

-Extended Lifespan: Ensures LEDs operate within safe electrical limits, increasing durability and long-term reliability.

III. WORKING PRINCIPLE

The working principle of a current mirror balancing circuit revolves around ensuring equal current distribution among parallel LED strings in AC-driven lighting systems. Unlike simple resistor balancing, which passively drops excess current, a current mirror actively replicates a reference current, resulting in precise and controlled balancing. This allows each LED branch to operate under uniform electrical stress, improving reliability and performance.

When an AC voltage is applied, the LED strings conduct alternately during positive and negative half-cycles. A reference current is established in one branch, and the current mirror—implemented using bipolar junction transistors—forces the same current through the mirrored branch. This action prevents current imbalance that would otherwise arise from forward voltage mismatches among LEDs. The circuit therefore ensures smooth, consistent brightness across all LEDs while minimizing power loss.

1. **Input Signal Application:** An AC supply is applied to the LED array. During each half-cycle of the AC waveform, one group of LEDs conducts depending on the polarity, while the current mirror circuit actively regulates current flow.

2. **Reference Current Establishment**: A reference LED branch, usually containing a series resistor, sets a stable current level. This current acts as the baseline for balancing across other branches.

3. **Current Mirroring Action**: Bipolar junction transistors (BJTs) form the current mirror. One transistor senses the reference current, and the other(s) replicate this current into parallel LED branches, forcing them to carry nearly identical currents.

4. **Equal Current Distribution:**By mirroring the reference current, the circuit ensures that all LED strings share the supply evenly, preventing one branch from drawing excessive current due to forward voltage mismatch.

5. **Balancing Behavior:** The current mirror adjusts dynamically with the input waveform. As the AC signal rises and falls, the mirror continuously regulates branch currents, maintaining uniform brightness and reducing stress on individual LEDs.

This current-balancing principle is particularly valuable in AC LED lighting systems, where it minimizes brightness variations, prevents thermal stress on individual LEDs, and enhances both efficiency and long-term reliability.

CIRCUIT DIAGRAM

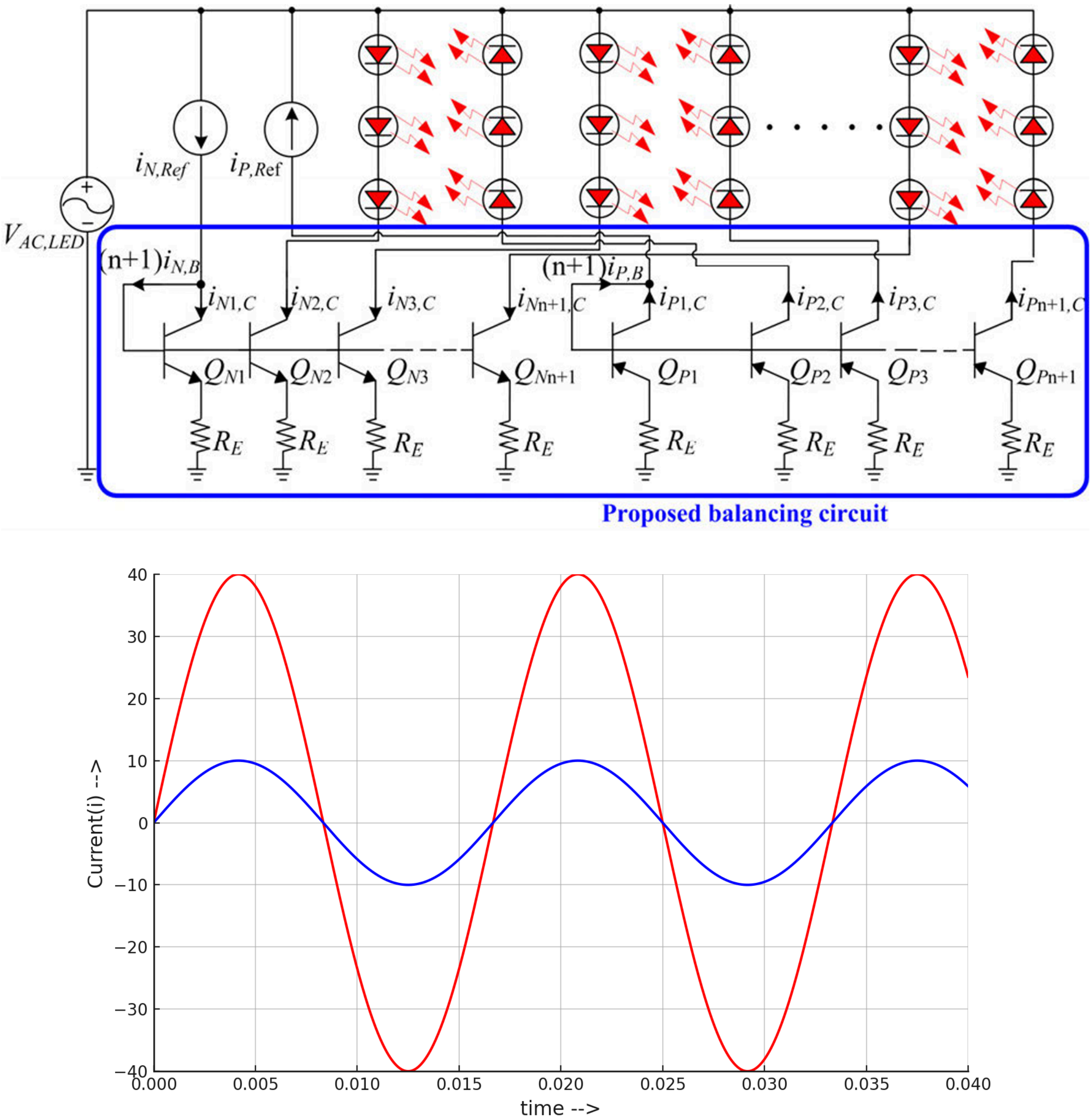

Fig. 1: Current Mirror Balancing Circuit for Uniform LED Current Distribution

The current mirror balancing circuit is designed to ensure equal current distribution across multiple LED strings in an AC-driven lighting system. In this design, a reference branch sets a controlled current, which is mirrored by paired transistors into the other LED branches. When the AC input voltage is within the conduction range of the LEDs, the reference current flows and the mirrored branches replicate it, ensuring uniform current sharing.

Unlike simple resistor-based balancing methods, which allow variations due to forward voltage mismatches, the current mirror actively maintains equalized currents. This prevents some LEDs from being over-driven while others remain under-driven. As a result, the circuit enhances brightness uniformity, reduces thermal stress, and extends the lifespan of the LED array. This makes the current mirror balancing circuit highly valuable in AC LED lighting applications where efficiency, reliability, and consistency are critical.

IV. PROPOSED SYSTEM

The proposed system introduces a **Current Mirror Balancing Circuit** implemented using eSim software. This circuit is designed to demonstrate the concept of current equalization and reliability improvement in AC LED lighting. The current mirror employs a transistor pair to replicate a reference current across multiple LED strings, ensuring that each branch receives nearly identical current. Unlike resistor-only balancing methods that suffer from voltage mismatch issues, the current mirror provides accurate current control with minimal power loss.

By maintaining equal currents during both positive and negative half-cycles of the AC supply, the circuit achieves uniform brightness across the LEDs, reduces thermal stress, and extends device lifespan. This makes the design highly suitable for solid-state lighting applications such as AC LED bulbs, streetlights, and industrial lighting systems, where efficiency and consistency are essential.

eSIM CIRCUIT

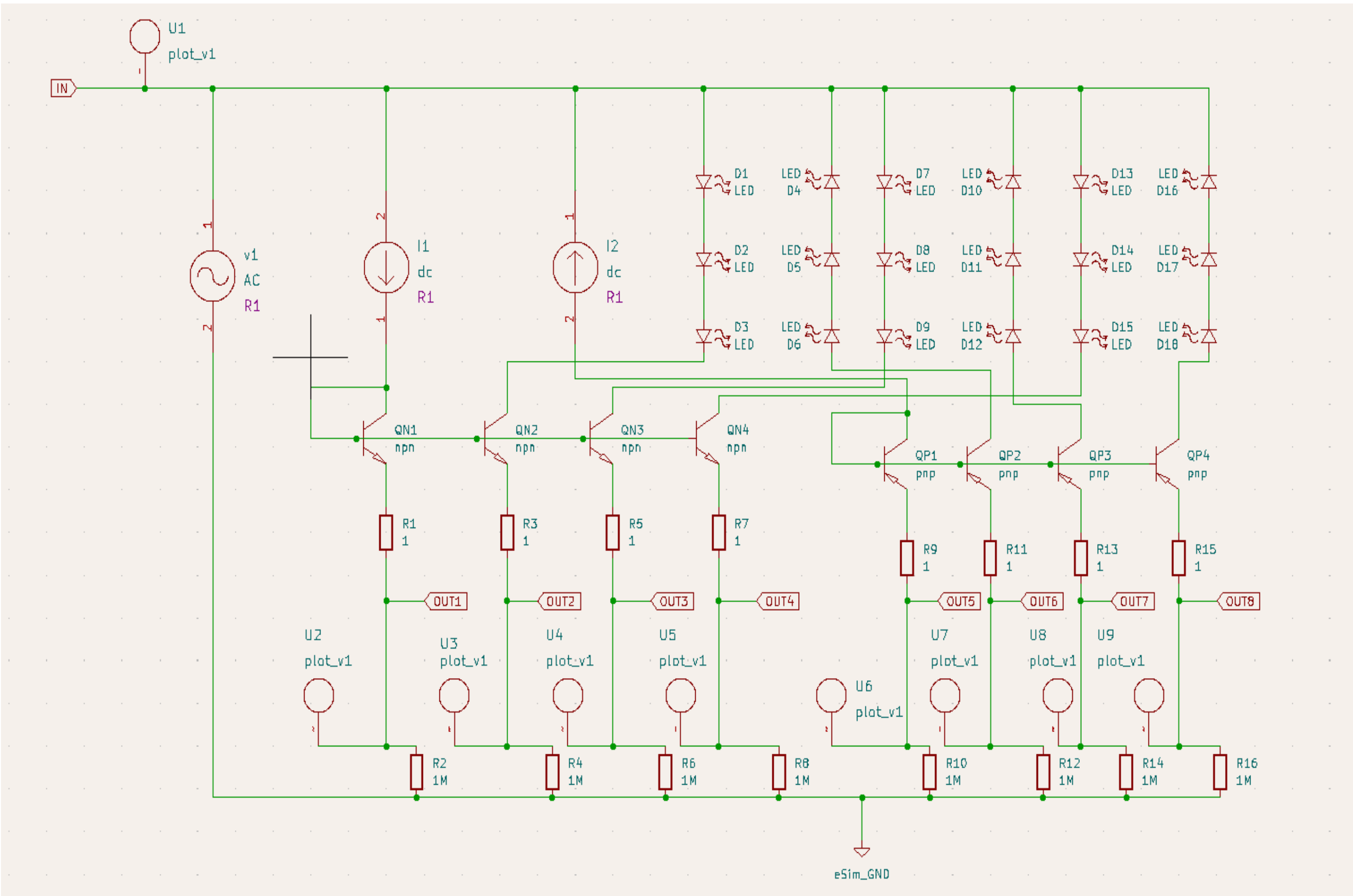

Fig. 3: Current Mirror Balancing Circuit for AC LED Lighting in eSim

Figure 3 presents the circuit diagram of a Current Mirror Balancing Circuit for AC LED Lighting designed within the eSim software environment. Key components include multiple LED strings connected in parallel and transistor-based current mirror stages to control current distribution. The transistors act as the balancing elements: when the AC supply is applied, one set of LEDs conducts during the positive half cycle and the complementary set conducts during the negative half cycle, while the current mirror replicates the reference current across each branch.

As a result, every LED string receives nearly equal current regardless of forward voltage mismatches, ensuring consistent brightness and preventing thermal stress. This arrangement provides uniform illumination, minimizes power loss compared to simple resistor balancing, and enhances the overall reliability of the LED system. The circuit effectively demonstrates how **current mirror balancing** can be applied in AC LED drivers to improve efficiency, brightness uniformity, and long-term stability in solid-state lighting applications.

OUTPUT WAVEFORM

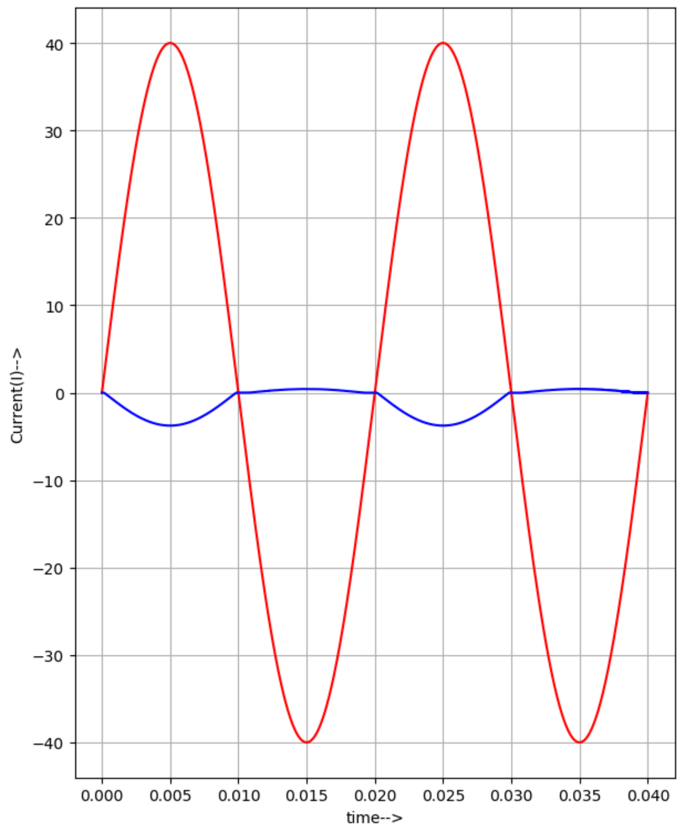

Fig. 4: Output Waveform of Current Mirror Balancing Circuit in eSim

Figure 4 showcases the output waveform of the Current Mirror Balancing Circuit simulated using eSim software. The graph illustrates the effect of current balancing on multiple LED strings driven by an AC supply. The input waveform is sinusoidal, representing the applied AC source, while the output waveforms correspond to the LED branch voltages.

The results demonstrate that the current mirror action ensures nearly uniform current distribution across all LED strings, even when there are forward voltage mismatches. Each branch conducts alternately during the AC half-cycles, yet the output waveforms remain consistent in amplitude, confirming the balancing effect. This prevents any single LED string from being overdriven or underutilized, maintaining steady brightness across the array.

This behavior highlights the circuit's ability to achieve **controlled current sharing, improved reliability, and uniform illumination** in AC LED lighting systems

KEY OBSERVATIONS FROM THE GRAPH:

- **Current Balancing:** The LED branch waveforms show nearly equal amplitude, confirming that the current mirror effectively balances current across all strings.

- **Symmetry in Conduction:**Each LED string conducts alternately during positive and negative half-cycles of the AC supply, ensuring consistent operation.

- **Uniform Brightness:** The balanced current distribution prevents any single LED string from being overdriven or underutilized, maintaining steady illumination.

- **Reliability:**The circuit eliminates current mismatch effects, reducing thermal stress and improving the lifespan of the LEDs.

- **Efficiency:** Unlike resistor-based balancing, minimal power is wasted, demonstrating the energy-efficient nature of the current mirror approach.

In summary, this graph shows that the current mirror balancing circuit equalizes the current flowing through multiple LED strings in an AC-driven system. At lower supply levels, the LED strings conduct normally, while the current mirror ensures that no single branch is overdriven. As the AC input varies across its cycle, the balanced operation maintains nearly identical current waveforms in all strings, resulting in uniform brightness. This controlled current distribution reduces mismatch, minimizes thermal stress, and preserves efficiency. The behavior demonstrates the effectiveness of the current mirror circuit in achieving reliable and consistent LED performance in solid-state lighting applications.

APPLICATIONS OF CURRENT BALANCING CIRCUIT :

1. **AC LED Lighting Systems:** Ensures uniform current distribution across LED strings, providing consistent brightness.
2. **Street and Outdoor Lighting**: Improves reliability and lifespan of large LED arrays under varying supply conditions.
3. **Consumer Electronics**: Maintains stable performance of LED displays and indicator circuits.
4. **Industrial Illumination**: Protects LED assemblies from current imbalance, reducing maintenance in high-demand environments.
5. **Smart Lighting Solutions**: Supports energy-efficient designs by minimizing thermal stress and maximizing LED utilization.
6. **Automotive Lighting**: Enhances durability of LED headlights and interior lighting by preventing uneven current stress.

VI . CONCLUSION

In conclusion, the design and simulation of a Current Mirror Balancing Circuit for AC LED systems using eSim provided valuable insights into the principle of current equalization in parallel LED strings. By replicating a reference current through transistor-based current mirrors, the circuit ensures uniform current distribution across all LED branches, thereby preventing brightness variations and reducing thermal stress. The simulation results confirmed its effectiveness in maintaining balanced operation even under forward voltage mismatches, achieving higher efficiency and extended lifespan compared to resistor-based balancing methods. This study highlights the importance of current mirror techniques in modern solid-state lighting applications, where stability, reliability, and energy efficiency are essential.

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