

Design of a Colour Consistent LED Driver Considering Temperature Effect

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Abstract Light Emitting Diodes (LEDs) has become the next generation lighting solutions due to rapid advancement of solid-state lighting technology. Colour consistency is the main issue for multi-colour LEDs. Change in temperature of the LED pn junction leads to changes in light output, wavelength and spectral width. Changing colour consistency creates adverse effects on human perception and comfort. So it is essential to maintain the colour consistency of LED string. This paper proposes a LED driver that controls colour (CCT) by considering the temperature effect on LED voltages. By Nonlinear optimization of LED voltages and the LED currents, CCT deviation are minimized. The optimum LED currents are fed to the feedback controller which adjusts the current to obtain the desired light output for least CCT deviation. Power parameters like Power Factor and THD have been improved to reduce power loss. The system stability has been determined. System performances show that the LED driver is working well.

Keywords: CCT, LED, photodiode, feedback controller

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1. Introduction

Advances in solid-state lighting technology have made light-emitting diodes (LEDs) the next generation of light source [1]. Red, green, and blue (RGB) LEDs are vastly used for colour mixing as those can vary colour in wide chromatic range and has been applied in architectural, commercial and residential lighting. Combining RGB LEDs to form a light source is an attractive proposition. There are however, challenges to overcome before a high-quality multi-colour LED light source can be produced [2,3]. However, the tunable light outputs have been found to induce light consistency issues for RGB LED lighting, because the luminous intensity and color outputs are easily influenced by junction temperature variations caused by self-heating of the LEDs and disturbances in ambient temperatures. Therefore, proper control strategies are required to stabilize light output in order to counteract temperature variations.

Since the driving current and LED brightness are intimately related, an LED needs a constant output current to have a consistent luminance. But when the temperature rises, LED emission intensity drops [4,5,6,7,8].

Maintaining the LED color point is essential for high-end applications, even when the LED junction temperature varies due to ambient temperature variations and dimming levels. There have been reports on color control techniques for RGB LED systems based on voltage-

junction temperature curves and current-voltage empirical models [9,10]. A lookup table was employed in [11] as the multivariable robust control to account for junction temperature variations and control the RGB LED lighting system's color and luminous intensity outputs. As a result, the thermal coupling effect will impact the LED's color and luminous intensity [12]. Lighting technology still faces a significant issue in accurately controlling the color of RGB LED systems.

A key consideration in controlling RGB LED lighting systems is feedback signal selection. Color coordinates were measured by photodiodes using color filters and fluxes in Muthu et al. [13,14,15]. Furthermore, for temperature feed forward adjustment, the junction temperature was estimated using the heat sink temperature and thermal resistance. Hoelen et al. [16,17,18] went into more detail about light outputs and used four control mechanisms in situations where the system's junction temperature varied. However, the discrepancy between the spectra of the color matching function and the filtered-sensor limits the accuracy of feedback signals. Different passive approaches [19,20] and active approaches [21,22] have been recently implemented to provide constant currents. A large power loss are generated when the current sensing LED string is turned on.

This paper proposes LED driver where colour (CCT) control method by considering the temperature effect on LED currents and voltages. The range of temperature is observed from the lookup table and optimum temperature is determined with corresponding LED

string voltages and currents by optimization method. Optimum LED currents are maintained by using appropriate feedback circuit. This LED driver prevents microcontroller, photodiode, colour filter.

This paper is organized as follows: Basic LED Characteristics in section 2, Analysis and Design of LED driver circuit in 3, Photo power stabilization circuit in 4, Power parameter improvement in 5, Stability analysis in section 6, Results and discussions in 7 and Conclusion in section 8.

2. Basic LED Characteristic

The LED characteristics were designed to be a lookup reference for the generated LED photo power. They were based on electrical and optical measurements that varied with temperature. Electrical Characteristics. The LED driver circuit consists of two parts. First one is power stage and the second one is colour management stage..

Electrical characteristics of a p-n junction are described by Shockley's equation

$$I_{LED} = I_0 \left(e^{\frac{V_{LED}}{nV_T}} - 1 \right) \quad (1)$$

where I and V diodes current and voltage respectively and n is the ideality factor. In order to compare the theoretical electrical model for single p-n junction with structures used in high intensity light emitting diodes available on the market, the basic I-V characteristics of Red and Green LEDs are shown in Figure 1

Thermal Characteristics:

LEDs are highly temperature dependent device. The rise of heatsink temperature corresponds to the rise of junction temperature. The relation between junction and heatsink temperature is not linear as LED losses depends on junction temperature. The emission of LEDs strongly depends on junction temperature. The spectrum of all LEDs shifts toward longer wavelength. Shift in longer wavelength will increase luminous flux of green and blue LEDs, decreases flux of red LEDs. As the peak of eye sensitivity is at 555 nm, closer to it increases luminous flux and away from it decreases luminous flux. Again, luminous flux decreases with increase of temperature.

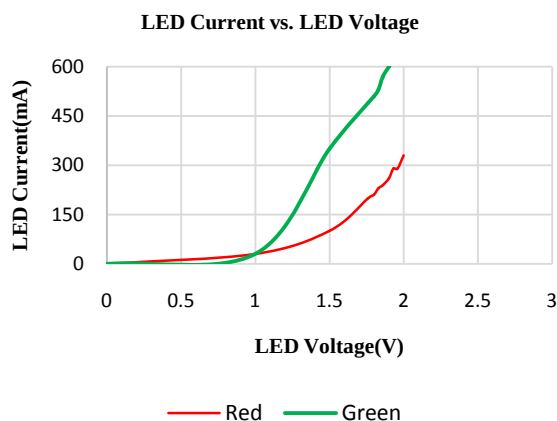


Figure 1. Current-voltage characteristics of Red and Green LEDs

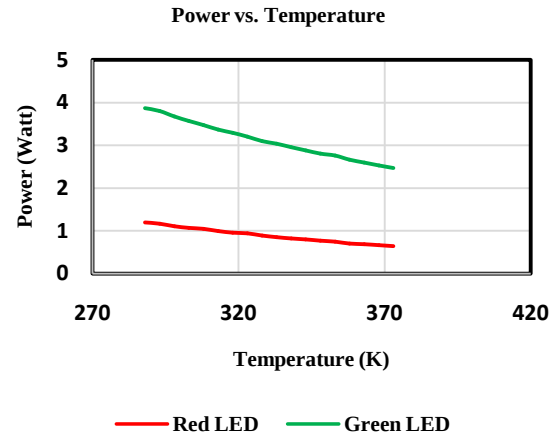


Figure 2. LED Power variation with junction temperature

Again, Radiant flux is almost proportional to LED current. Figure 2 shows the variation of luminous power with temperature.

The following displays the typical emission spectra of InGaN and AlGaInP LEDs. The broadest emission spectrum is shown by Green GaN LEDs because of their high indium-rich semiconductor fluctuation. The density of states and carrier distribution in the permitted band, which is defined by a Boltzman distribution, are the products that yield the theoretical emission spectrum of a bulk semiconductor. Maximum emission is theorized to occur at $FWHM = 1.8 kT$ and $E = E_g + kT/2$. In practice, alloy broadening uses the spectral width of LED transitions in the region of 2 - 4 kT. Real-world diodes exhibit photon emission at far lower energies than those anticipated by theory. Specifically, in InGaN diodes, where the bandgap energy depends on composition and doping variations can lead to spectrum broadening. Figure 3 shows the emission spectra of red and green LEDs. The wavelength range of green LEDs is of 500–565 nm and the wavelength range of red LEDs is of 625–740 nm. In the wavelengths of the spectrum, only certain wavelength (the spikes) are strongly present. From the SPD curve, it can be seen that the peaks of the green (LED₂) region are greater than those of the red (LED₁) region.

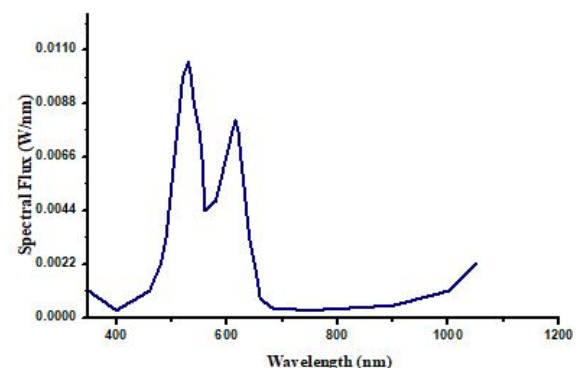


Figure 3. Emission Spectra for Red and Green LEDs

These spikes indicate the dominance of the rendering of color for objects illuminated by the light source. Relative radiant flux is almost proportional to LED current [23].

Xi.et.al [24,25] analyzed the temperature dependence of forward voltage. Again, the bandgap energy E_g of semiconductors decreases with increasing temperature.

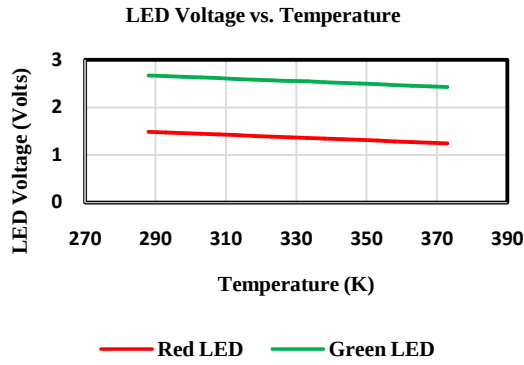


Figure 4. LED voltage variation with temperature

Figure 4 shows the LED voltage variation with temperature. From the above observation it is clear that even constant current source cannot maintain constant radiant flux of the LEDs when the ambient temperature is increased. And thus color consistency hampers. Therefore, this paper proposes a LED driver where the colour (CCT) control is performed by Nonlinear optimization considering the temperature effect on LED currents and voltages. Here we consider the CCT of the two LEDs of green and red are 6000K and 1500K respectively. Those are blended to generate composite CCT. The CCT deviation is the difference between target CCT and estimated CCT. By using nonlinear optimization methodology CCT deviation is minimized for composite LED driver where the effect of temperature is counted as constraint in the voltage optimization. Obtained optimized currents of red and green LEDs are maintained by proper feedback control circuit.

3. Analysis and Design of LED Driver Circuit

3.1. Nonlinear Optimization for Color Stability

Color temperature is a characteristic of visible light. In this paper, the system is configured based on two different color temperatures. The combined CCT of the composite LED light is determined considering the effect of temperature on LED voltages and currents. The CCT deviation is minimized through the nonlinear optimization of the LED currents and LED voltages of the two LED strings.

Creation of Optimization Problem

For the two LED modules with color temperatures of 1500 K and 6000 K, the chromaticity coordinates of the emitted light according to CIE 1931 are (x_1, y_1) and (x_2, y_2) with luminous fluxes ϕ_1 and ϕ_2 respectively. Referring to Figure 1, the currents that flow through the mentioned LED strings are I_{LED1} and I_{LED2} , and their corresponding voltages are V_{LED1} and V_{LED2} respectively. In order to find the desired CCT within the infinite number of possible solutions, an objective function is introduced to the system of equations. Equations (4) and (5) illustrate the mathematical model of the CCT. The CCT deviation is found from [26].

Each color LED features a different spectral distribution and luminous output. If P is the consumed electrical power of each LED string and ϵ_i is the luminous efficacy of LED light source, then

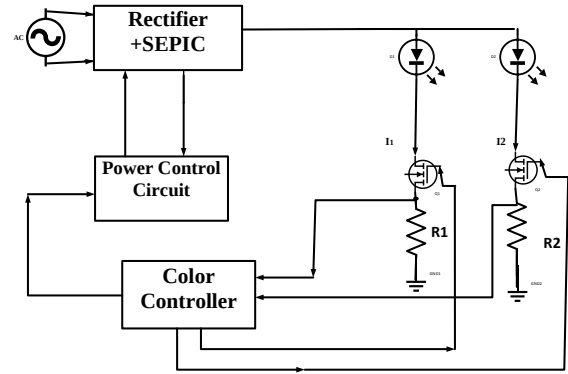


Figure 5. Bicolor LED driver color control system

$$CCT = f(\phi_i) = f(V_{LED}, I_{LED}) \quad (\phi_i = \epsilon_i P_{elec i})$$

where $i = 1, 2$ for bicolor LED string

The target CCT is obtained from (x, y) co-ordinate of the blackbody curve. By putting the values of V_{LED} , estimated CCTest [26] can be obtained.

$$V_{LED} = -0.00287T_d + 2.3145$$

This CCTest model is used in order to get least CCT deviation.

Graphical Analysis

The common approach to maintain the radiant flux of the LED by driving it with a constant current source. According to the forward current versus voltage characteristics of LED shown in Figure 1. The graphical result demonstrates that the electrical power of LEDs (red and green) decreases with increasing ambient temperature as illustrated in Figure 2. When the forward voltages of the red and green LED were driven by varying the ambient temperature shown in Figure 4 we find that the forward voltage decreases with increasing temperature. We know that the change of radiant flux and the LED current are proportional. The forward voltage may also be represented as V_F using the basic characteristics of the LED. Therefore, the radiant flux of the red and green LEDs can be described by the following way -

$$\Phi = \eta \cdot V_F \cdot I_F$$

$$V_F = (-0.00287T + 2.3145) \quad (2)$$

where η represents the power efficiency of the constant current drive.

Formation of Constraint with boundary --The constraint equation represents the I-V relationships of the LEDs.

In practice, the reverse saturation current I_0 is equivalent to 10 μA . Color shift is lessened when the CCT deviation is decreased. Based on their observed I-V characteristics, we examined the I-V characteristics of restricted LEDs, 1500 K (LED₁) and 6000 K (LED₂). When the LED₁ voltage fluctuates between 23 and 24 volts, we calculated that the current limit of I_{LED1} is between 90 and 320 mA, and when the LED₂ voltage fluctuates between 23 and 25 volts, the current limit of

I_{LED2} is between 310 and 390 mA. The output varies within the feedback control limit in response to changes in temperature and AC input.

By using MATLAB to solve the nonlinear optimization issue, we were able to acquire the least CCT deviation. For two optimized LED currents, $I_{LED1} = 90$ mA and $I_{LED2} = 390$ mA, desired CCT=5700K, $\Delta CCT = 77.5$ K. To ensure the least amount of CCT deviation, the color control circuit in the bicolor LED driver should be constructed so that the LED₁ and LED₂ strings will get 90 mA and 390 mA of current, respectively.

4. Photo Power Stabilization Circuit

4.1. Description of the Driving Circuit

The output current of the SEPIC is split into two LED strings based on the equivalent resistor of each branch, resulting in a constant current that is equal to the total of the intended currents in the two LED strings. This driver contributes to lowering input current harmonics and increasing power factor. A multiplier's output and a sawtooth carrier signal at 100 kHz are compared to create the PWM signal. The color controller, which regulates color point and intensity, is part of the color control stage. Figure 5 shows the color control system of bicolor LED driver.

The color control feedback loop controls the average currents in each LED string separately. The parts that follow provide a description of the detailed color scheme.

4.2. Color Stability of RG LEDs

Conventional LEDs do not create color points or lumen output with a high degree of consistency. As a result, there is a growing demand for a certain amount of consistency in the lighting domain. Although seemingly identical LEDs might have different light outputs. Furthermore, luminescence is unpredictable and changes with temperature as well as time. Each of these factors has an impact on the color point and light intensity. This problem can be solved by putting in place an adequate feedback strategy. The LED current feedback approach can be used to alter the color point and intensity of an LED. Figure.6 shows the block diagram of LED Lighting system with feedback. This LED current is amplified. The current error amplifier maintains the output according to the reference value for each colour component to maintain the colour point and colour intensity. This reference value determines the brightness level. The control voltage is the output of the current error amplifier. PWM is to generate comparing control voltage with sawtooth wave. Generated pulse is fed to the gate of the MOSFET of LED string.

The proposed control method is applied to a bicolor (Red-R, Green-G) LED system connected in parallel with a SEPIC-based LED driver. The multi-channel LED system in reference [12] requires a multi-power converter in order to operate correctly. In order to properly drive RG LED strings without the need for an additional power converter, this suggested solution generates varying bus voltages. A color filter and a heat sink are used in ref. [13,14,15]. A color filter and heat sink are not required with this technology. A color filter applies a lot of

electricity. An abundance of electricity. As so, both system volume and complexity substantially drop. A color light sensor, an analog to digital converter integrated circuit (IC), and a microcontroller or CPU are needed for a multi-channel LED system [27]. A microcontroller or microprocessor, an analog to digital converter integrated circuit, a color light sensor, and an LED system with several channels are necessary components. This approach eliminates the need for a color light sensor, an analog to digital converter integrated circuit, and a microcontroller or microprocessor. Compared to previous control techniques, this color control mechanism is really distinct.

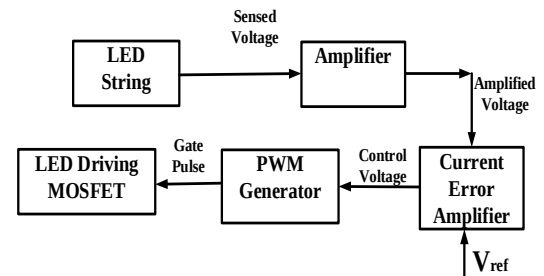


Figure 6. Block diagram of LED Lighting system with feedback

5. Power Parameter Improvement

Methodology

Low PF and high THD are the main factor for low efficiency. Power parameters like power factor (PF) and Total Harmonic Distortion (THD) are improved by taking different attempts. This work presents a SEPIC-based constant current LED driver that reduces harmonics through parameter adjustment. Because of its positive dc output, high-low output level, low switching stress, and low output ripple current, the SEPIC is used in PFC. Another excellent power factor corrector is SEPIC. Three things have been done to obtain good power factor. One is after rectification no input capacitor is used. Output inductor and capacitor are optimized to enhance power factor and reduce harmonics [28]. In the control circuit multiplier block is used to make current follow the input voltage shape and thus enhance power factor. Figure 7 shows the PFC functional

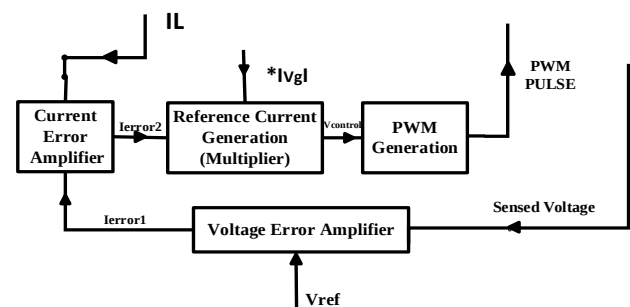


Figure 7. PFC Functional Block diagram

block. LC filter is used to reduce harmonics. Optimization of SEPIC parameters reduces harmonics and output current ripple [28].

6. System Stability Analysis

The SEPIC converter consists of two capacitors C_1 , C_2 and two inductors L_1 , L_2 with equivalent series resistors r_{c1} , r_{c2} and r_{L1} , r_{L2} respectively. MOSFET on resistance r_{ds} and diode on resistance r_d are also important factor in achieving stability. Figure 8 shows LED driving system with small signal parameters.

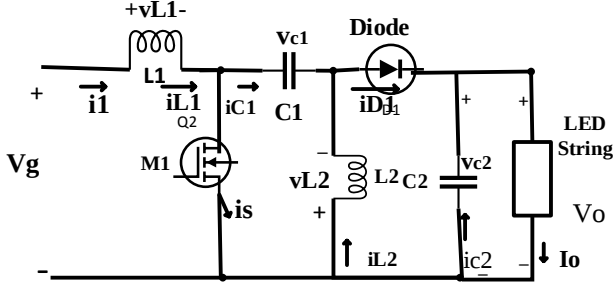


Figure 8. LED driver circuit with small signal parameters

The capacitors and inductors exchange energy through the SEPIC. The output voltage levels are altered in this manner. MOSFET M_1 regulates the quantity of transmitted energy. If the current flowing through the inductor L_1 stops for a portion of the switching process, a SEPIC is operated in DCM.

Output voltage varies with the change of duty cycle. The duty cycle of the SEPIC can be varied during operation by using a controller. Considering the colour control scheme of the LED Driver the SEPIC's two output LED strings R and G. Considering all the matters the control to output of the SEPIC is obtained by [28].

$$G_{dv}(s) = \frac{12.94s^3 - 0.07303s^2 - 5.503e^{-6}s + 7.187e^{-15}}{s^4 + .005621s^3 + 1.197e^{-6}s^2 + 9.625e^{-14}s + 4.772e^{-18}} \quad (3)$$

Output to input transfer function

$$G_{vv}(s) = \frac{0.01897s^3 + 1.412e^{-6}s^2 + 5.424e^{-14}s + 1.427e^{-18}}{s^4 + .005621s^3 + 1.197e^{-6}s^2 + 9.625e^{-14}s + 4.772e^{-18}} \quad (4)$$

Step response of the SEPIC system obtained from transfer function using Matlab software is shown in Figure 9(a) without compensator. From step response it is found that without compensation the system achieves stability at 1.5×10^8 seconds. Figure 9(b) shows that step responses of compensated model reaches to steady state within only 1ms.

The open loop transfer function of the whole system can be defined

$$T(s) = T_{ea}(s)G_{dv}F_r \quad (5)$$

F_r is the transfer function of PWM.

The parameters of the color compensator have been optimized for stable operation of the designed LED driver. The transfer function of the color compensator of the designed LED driver is obtained

$$T_{ea}(s) = \frac{2.7s + 100}{s} \quad (6)$$

The overall open loop transfer function for the system with color compensator is found from eqn. (6).

$T_{rgb} =$

$$\frac{6.988s^4 + 258.8s^3 - 1.461s^2 - 0.0001101s + 1.438e^{-13}}{s^5 + .005622s^4 + 1.197e^{-6}s^3 + 9.627e^{-14}s^2 + 4.773e^{-18}s} \quad (7)$$

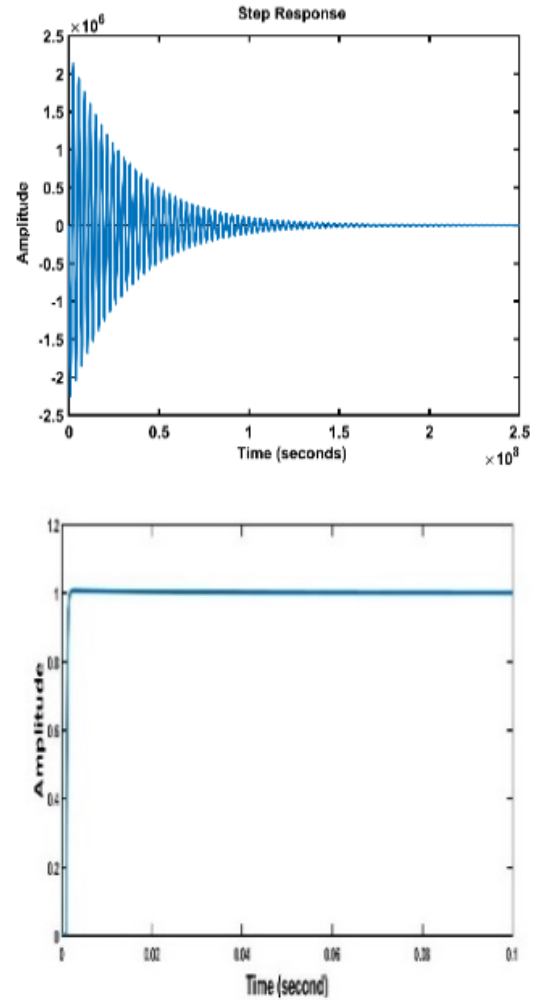
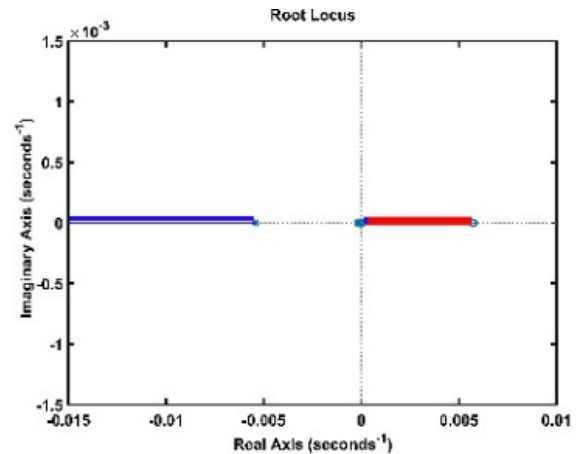


Figure 9. a) Step response before compensation (steady state achieves at 1.5×10^8 seconds) and b) Step response after compensation (steady state achieves at 1ms) by light feedback loop



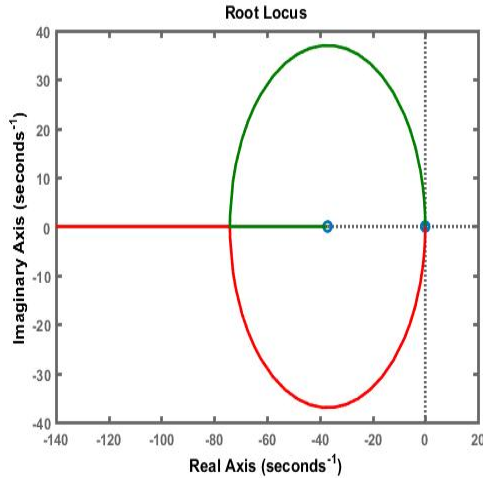


Figure 10. a) Root locus before compensation and b) Root locus after compensation by light feedback loop.

Figure 10(a) depicts the root locus of the SEPIC without compensation. It indicates that a zero is discovered in the R.H.S. of the imaginary axis in the s plane instead of a pole. There is stability in the system. The color-compensated system operates steadily in Figure 10(b) the root locus because the imaginary axis' right side is devoid of poles on the left side of the imaginary axis lies the root locus.

7. Result and Discussion

The proposed LED driver based on SEPIC topology. In the bicolor system two LED strings consist of 12 and 8 LEDs in series respectively. In order to get realistic estimate of the color LED driver, simulations are carried out in Ltpice. The design has been implemented to maximize the LED driver's performance.

The primary goal is to keep voltage and current constant while taking temperature variations into account. Additionally, it maintains a high power factor when the right input filter, feedback circuit, and circuit settings are used. At 460 mA, LED current is kept constant. Both the crest factor and input current THD are within tolerance. The power factor is almost at one.

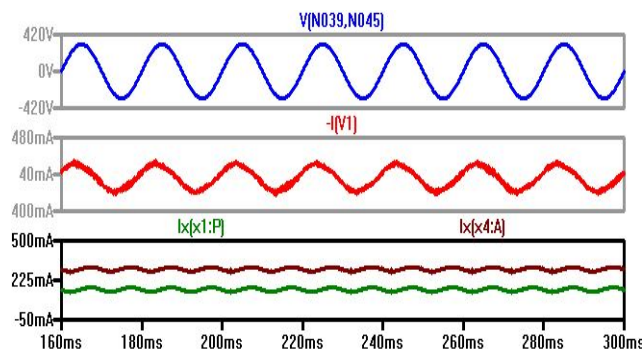


Figure 11. Input voltage, Input current and output currents of red and green LED strings respectively at 220 V

Figure 11 shows the waveforms of input voltage (vs), input current (is) and output currents in the steady state condition. Obtained P.F.=0.89, efficiency is 91.5%, THD

11.27% at 220V. The Simulated Power losses are shown component wise in Figure 12.

The LED driver with proposed techniques can reduce the power losses. Thus, the efficiency can be effectively enhanced about 2-3% for an LED current of 470 mA [29].

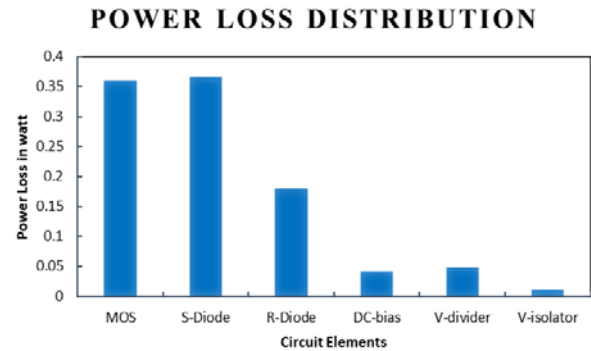


Figure 12. Power loss components in LED driver

Table 1. Performance Comparison with Previous Works

Item	LED driver in [30]	Designed LED driver
Input Voltage No. of LEDs	240	220
	LED array for 19inch module	2 LED strings 15 LEDs in each string
Power Switches	5	6
Total Current	$I_R=500\text{m A}$ $I_G=375\text{mA}$ $I_B=330\text{m A}$	$I_R=90\text{m A}$ $I_G=390\text{mA}$
Diodes	7	5
Capacitors	2	2
Inductors	2	3
Transformer	1	No need
Frequency	50 kHz	100kHz
Power Factor	Not given	0.89(220V)
THD	Not given	11.27%
Efficiency	90.0%	91.5%

Table 1 shows comparisons with LED driver presented in [30] and the proposed one. The proposed LED Driver shows the feature of better input current THD compared to [30] and it offers less number of components with same efficiency.

8. Conclusion

In order to drive RG LEDs with the appropriate CCT, this research suggests a low-cost Bicolor (RG) LED driver that preserves color consistency while taking the temperature effect into account. An LED current feedback control circuit is used to maintain color consistency in the LED driver even when the current varies with temperature. The necessary color stabilization, or maintaining CCT = 5623.5K, where $\Delta\text{CCT} = 77.5$, and electrical power parameters i.e. PF = 0.89, THD = 11.27%, efficiency = 91.5%, obtained from nonlinear optimization methodology and maintained in the bicolor RG LED driver, were determined from the electrical and optical characteristic data on a commercial bicolor LED. Using the acquired values, theoretical formulations were created

for system performance and stability. Lighting that is ornamental can be achieved using this kind of LED driver.

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