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Research Article

Optimization for Spectral and Power Characteristics of Bicolour LED Driver

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Abstract

LED-powered luminaires have the ability to offer cutting-edge features like temperature adjustment and color management. Color shift creates discomfort in human eyes. So it is essential to design a LED driver which will precisely control the color parameters of the LED driver. Precise control of color parameters like CRI, CCT, color intensity is very complex and challenging. This paper describes the nonlinear optimization methodology for the design of blended LED light sources. This paper presents the methodology that enables LED strings regarding various parameters, e.g. high color rendering index (CRI) and high luminous efficacy of a blended bi-color (namely red CCT-2500K and blue CCT-9000K) LED driving system. Due to the applied optimization, the obtained CRI is maintained 98.03%. The overall luminous intensity depends upon the combined luminous flux which depends upon the current control of both LED sources. These optimized LED currents ensure the desired CCT. The achieved luminous efficacy is 90% at two optimal peak wavelengths 601 nm and 426 nm respectively. Power loss is minimized by frequency optimization. At the same time power parameters i.e. low THD and high P. F. is also maintained. The nonlinear optimization is verified in Ltspice simulations and experimentally for two different luminaire strings.

Keywords

LED, CCT, CRI, THD, Frequency, Power Loss

1. Introduction

For the advent of LEDs solid state lighting has become the most popular for their advantages such as low power consumption, less expensive, robust, environment friendly, long lifetime compared to conventional lamps in the recent years [1]. LEDs are mostly used in general purpose lighting. It is an effective lighting solution for attractive atmospheric consequence [2]. Some features are required cognizance when LEDs come for multicolor lighting like co-related color temperature (CCT), color rendering index (CRI), luminous efficacy (LE) and luminous intensity. In multicolor LEDs variation in one color can change target color point significantly. A universal method for white light LEDs is wavelength transformation methodology which is discerning to the excitation spectrum and also undergoes mixing the light of different colors emitted from two or more primary LED chips [3, 4]. Full color regulation is a lucrative feature for multichip LEDs [5]. In case of reality and expense, it is convenient to have only three independent monochromatic LEDs [6]. Temperature variations, aging effects and process deviations influence the performance of a LED lighting system and

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causes visible color shifts and changes in luminous intensity [7-9]. Several researchers have proposed some approaches to compensate the color shifts, e.g. [8, 10]. A lot of efforts have been done for CCT control [11-13], but CCT deviations are higher. Again, CRI represents an important measure for light quality since it indicates the color rendering of illuminated objects [13]. The difficulty is that color rendering and luminous efficacy are general in a trade-off relationship [5, 14].

Luminous efficacy is an important measure for brightness. Color control involves in power supply, thermal and optical issues [15, 16]. Low THD, high P.F. and high efficiency are essential for the design of LED driver. A number of endeavours have been made for achieving low harmonics in the input current [17-20]. Power loss minimization is a vital issue for a reliable LED driver. Switching losses in MOSFETs and switching losses in diodes account for most of the losses in high frequency applications [21, 22]. Power loss minimization technique described in [23] but nothing mentioned about power quality parameter. Ref. [24] enhanced efficiency 93.5%. Precise colour control of multicolour LED system is still a challenging job for the lighting industry [25-27].

In this paper, a bicolor LED driver has been proposed where CCT, CRI and luminous efficacy are maintained for composite LED light with blended CCT-2500K and CCT-9000K. By regulating LED string currents, desired CCT is obtained. These string currents are obtained from nonlinear optimization of LED currents. CRI is determined. Desired luminous efficacy is achieved by optimizing wavelength of the mentioned two colors. At the same time, minimized THD and reduced power loss have been achieved by nonlinear optimization of parameters of SEPIC and switching frequency respectively. And thus efficiency of the LED driver is enhanced.

The remainder paper is organized in the following order - overview of driver topology in section 2, nonlinear optimization for color issues in section 3, optimization for power parameters in 4, and result and discussion in 5, conclusion in section 6.

2. Overview of LED Driver Topology

The bicolor LED driver circuit consists of two parts. First one is power stage i.e. SEPIC and the second one is color management stage. Figure 1 shows the bicolor combination LED lighting system of blended CCT 2500K and CCT 9000K.

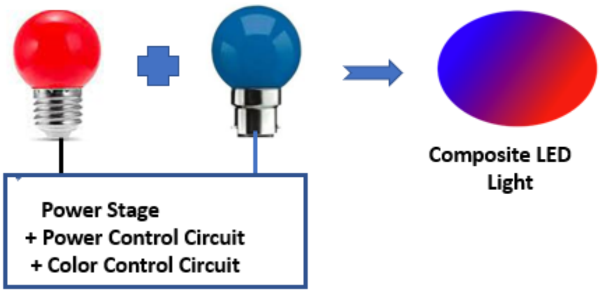


Figure 1. *Combination of the bicolor (CCT 2500K and CCT 9000 K) color for LED lighting system.*

In the power circuit outer loop regulates total LED current and inner loop controls input current waveshape. It enhances power factor and reduces harmonics. SEPIC provides the sum of the two LED strings' currents. The SEPIC is chosen for PFC due to positive dc output and good Power Factor Corrector.

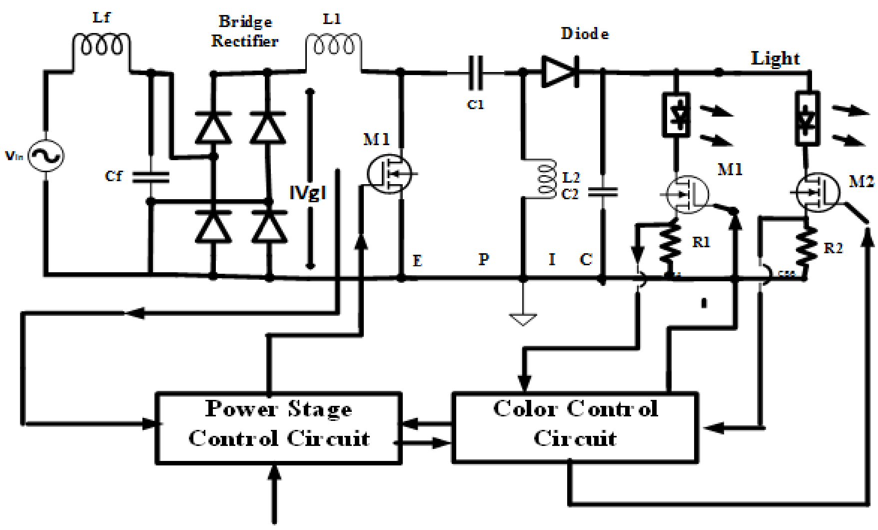


Figure 2. *Schematic of the basic SEPIC and color control system.*

Figure 2 shows details of LED color control system. The current (color) controller regulates LED current in each of the two strings which controls luminous flux.

The desired color parameters as CRI, luminous efficacy and power parameters as efficiency, THD all can be maintained in the bicolor LED driver circuit at the same time. By maintaining the optimized value of LED currents in two branches, CCT deviation can be reduced. Target CCT is ensured by current regulation through feedback control loop [28]. Good CRI is achieved from minimization of color distance. CRI is measured w.r.t. reference CCT. The desired luminous efficacy is achieved by optimization of wavelengths of the above mentioned two colors.

Efficiency is enhanced by reducing power loss of the driver circuit. By deploying nonlinear optimization of switching frequency, switching power loss is minimized. THD reduction can be done by applying the optimum parameters in the SEPIC circuit of the LED driver. The values of optimized parameters found from nonlinear optimization technique.

3. Nonlinear Optimization for Color Issues

Problem based nonlinear optimization methodology efficiently determines the value of CRI and luminous efficacy. Maximum CRI is obtained, maintaining minimum perceivable color distance ΔE. This can be achieved by minimizing color distance i.e. (x, y) coordinates. The minimum color distance can be achieved by obtaining desired CCT through LED current optimization. This LED current closely approximates the CCT to the desired value. Luminous efficacy can be maximized by using nonlinear optimization of wavelengths of the two colors (CCT 9000K and CCT 2500K). Again, Power losses are minimized by optimization of switching frequency f_s. Further, optimization methodology effectively finds out the parameters of SEPIC L_1, L_2, C_1 and filter parameters L_f, C_f for minimization of THD. All the above parameters minimization is essential for maintaining color consistency and power quality respectively.

Optimization method for reduction of color and power parameters are described in the following sections. Non-linear optimization works into the following distinct steps. Cost function generation, applying constraints for optimization and solving the problem with iteration until it converges and determines the result.

In the nonlinear optimization methodology, the change of chromaticity and illuminance are independent to each other. Changing color consistency hampers human sensation and weal. Therefore, it is important to choose the right color parameters based on the pleasant disposition. Block diagram of the nonlinear optimization methodology are shown in Figure 3. Optimization procedure for CRI and luminous efficacy are described in the following.

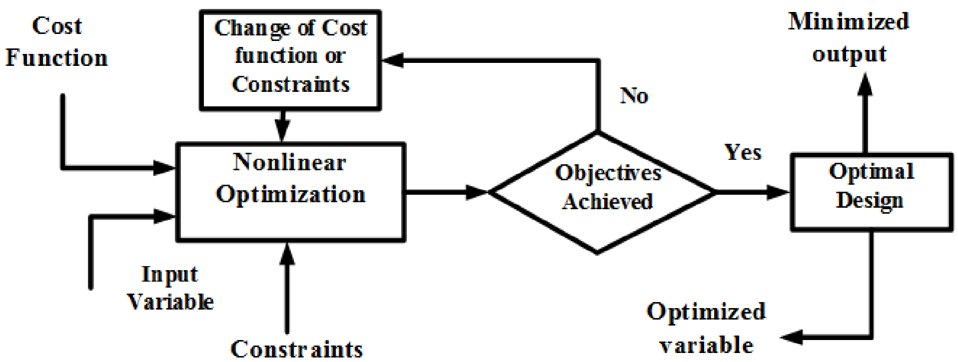


Figure 3. *Functional block diagram of the nonlinear optimization methodology.*

3.1. Color Rendering Index

This refers to the ability of the source to illuminate surfaces such that their colors appear as natural as possible. *The International Commission for Illumination (CIE)* has standardized and developed multiple color spaces for computation, measurement and illustration of displayable colors [29]. Most of these color spaces can be converted into each other by non-linear transformations [30]. CRI is measured w.r.t. the CCT of incandescent light or daylight.

Expression of Optimization Problem with Constraint

The special color rendering indices R_i for each color sample is given by

$$R_i = 100 - 4.6 * \Delta E_i \quad (1)$$

$$i = 1,2,3, \ldots \ldots \ldots \ldots \ldots 14$$

Here eqn. (1) is the cost function. CIE defines color difference as a Euclidean distance between two color points in a CIE. The constraint of the optimization is

$$\Delta E_i = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

where (x_1, y_1) point stands for test point co-ordinate. (x_2, y_2) point stands for reference point co-ordinate. For maximizing CRI, (x_1, y_1) and (x_2, y_2) should be optimized. x_1 varies within the (0.3-0.6), y_1 varies within (0.25-0.35) and x_2 varies from (0.3-0.4) and y_2 varies (0.25-0.35) with corresponding CCT. The nonlinear optimization methodology has been performed in MATLAB. The calculated blended CCT i.e. estimated CCT, CCT_{est} = 4238.25 and calculated CRI is 98.03.

3.2. Luminous Efficacy

Expression of Optimization Problem

In order to enhance LE, the radiant power of the LED driver should be maximized. First cost function is generated. The equation (2) is the cost function i.e. expressed [11] as follows –

$$LE = \frac{K_m \int V(\lambda)S(\lambda)d\lambda}{P_{opt}} \tag{2}$$

Where, Km is a normalization factor, P_{opt} is the total optical power emitted by a light source, S (λ) is the spectral power distribution, and V(λ) is the human eye sensitivity function for photopic vision standardized by CIE. To maximize luminous efficacy, radiant power should be maximized. Nonlinear optimization of wavelength λ, is used in order to maximize electrical power consumption.

For our bicolor LED luminaire, the spectral distribution model has been found from curve fitting. This model is almost accurate. The spectra power distribution (SPD) of a model bicolor LED is the constraint of the optimization problem and it is given as follows-

$$S(\lambda) = a_1 e^{\left\{\frac{\lambda_1 - b_1}{c_1}\right\}^2} + a_2 e^{\left\{\frac{\lambda_2 - b_2}{c_2}\right\}^2} \tag{3}$$

Here, a_1, b_1, c_1 and a_2, b_2, c_2 are the constants of the humps of the curve of spectral power distribution of bicolor (red and blue) LED light which follows the Gaussian distribution. Here, a_1, b_1, c_1 and a_2, b_2, c_2 are the constants of the humps of the curve of spectral power distribution of bicolor LED light which follows the Gaussian distribution. Figure 4 shows the spectral distribution of red (R) and blue (B) color of LED light with Gaussian fitting. The average luminous efficacy of LED luminaires will certainly continue to improve since there are luminaires on the market with a luminous efficacy of 50 – 70 lm/W which can still be optimized.

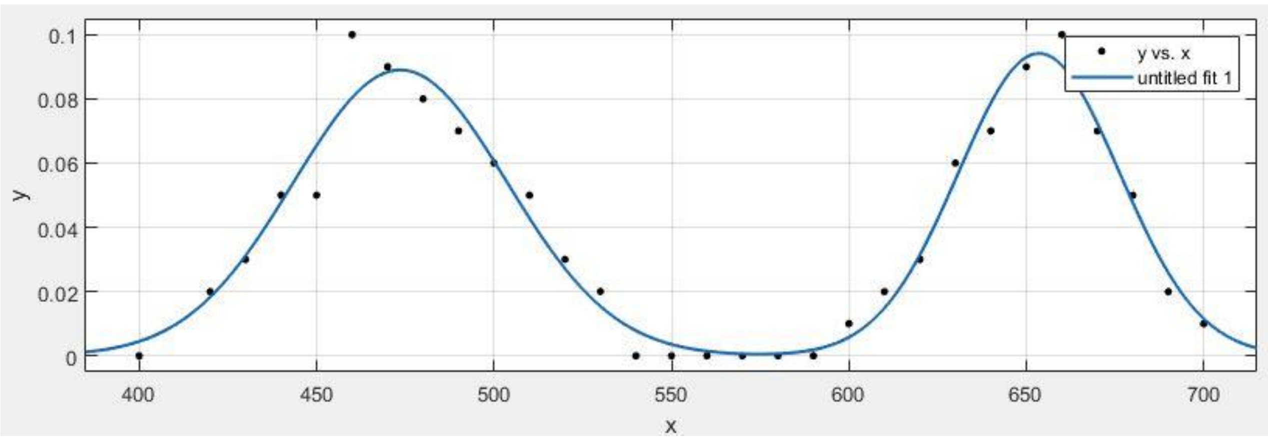


Figure 4. *Spectral Distribution of R B (curve fitting) LEDs.*

Formation of constraint with boundary

In order to simulate bicolor systems, two spectral regions are chosen, whose wavelength ranges are 425-500nm, 600-700nm. By nonlinear optimization of wavelengths λ_1 and λ_2, obtained luminous efficacy 90%. λ_1 and λ_2 are the wavelengths of red and blue LED lights. The boundary limits of wavelengths variation are 425-500 nm and 600 - 700 nm for CCT 9000K (λ_2) and CCT 2500K (λ_1) respectively. Luminous efficacy is 90% with optimized wavelength 601nm and 426 nm for red and blue LEDs respectively.

4. Optimization for Power Parameters

4.1. Power Loss Analysis

In order to improve the LED driver efficiency, it is important to define a power loss model considering the parasitic effects of each component. Power losses in SEPIC can be divided into two main parts: losses in active components and losses in passive components. MOSFET, diode power losses are active power losses and resistive and parasitic resistive losses in inductors and capacitors are passive power losses.

Basic SEPIC circuit has been shown in Figure 2. The factors that influence on the power losses are the mode of conduction, the temperature, the voltage and the current ripples. The power losses in SEPIC are of three types such as switching, conduction and gate losses. The power losses in the switch are mainly caused by the, on state and the gate-drain charge Q_{Gate}. The switching loss and conduction loss of MOSFET and diode in SEPIC are discussed in [10, 11].

The lower forward voltage, the smaller internal resistance and the high frequency operation are the main characteristics needed to reduce the power dissipation in the diode.

Switching power loss

P_{sw1}, P_{sw2}, P_{sw3}, P_{Dsw} are the switching power losses due to rise and fall time, to charge gate loss, due to output capacitor and diode switching power loss respectively [10]. To minimize the switching power losses of the SEPIC the following outlined as in (4)

$$P_{SWLOSS} = P_{SW1} + P_{SW2} + P_{SW3} + P_{DSW} \tag{4}$$

Here P_{sw1}, P_{sw2}, P_{sw3} denotes three types of switching power loss in MOSFET, P_{Dsw} is diode switching loss.

To minimize the overall power losses of the SEPIC the following outlined (5) as cost function.

$$P_{LOSS} = P_{SWLOSS} + P_D + P_{rc} + P_{rL} + P_{filter} + P_{rsense} + P_{divider} \tag{5}$$

In order to reduce the switching power losses, frequency optimization is required. The other power losses are minimized by different ways like using less no. of components, using low on resistor MOSFET, proper on-off switching, reducing THD, improving P.F. etc.

4.2. Frequency Optimization for Power Loss Minimization

Power loss minimization is the utmost desire of a reliable and efficient LED driver. Power loss is minimized by deploying the nonlinear optimization of switching frequency. The switching losses of MOSFETs vary with switching frequency.

A nonlinear optimization method is used for improving the efficiency of SEPIC based LED driver. In the proposed method, at the optimized frequency when the converter is delivering power to the load for minimum power loss that corresponds to the maximum conversion efficiency. The problem based nonlinear optimization methodology has been applied by using MATLAB. For this purpose, the SEPIC frequency optimization problem is formulated first. Power loss is defined in terms of parameters of SEPIC. achieving the least power loss is the optimization problem.

Expression of Optimization Problem

To minimize the overall power loss objective function is obtained as follows-

$$P_{LOSS} = P_{MOS}(f, q_{MOS}) + P_D(f, q_D) + P_{rc} + P_{rL} + P_{filter} + P_{rsense} + P_{divider} \tag{6}$$

The SEPIC efficiency is given by the following equation

$$\eta = \frac{P_{LED}}{P_{LED}+P_{LOSS}} \times 100\% \tag{7}$$

By minimizing the power loss, efficiency can be maximized.

Formation of constraint with boundary

In order to enhance efficiency, power loss is minimized with nonlinear optimization of switching frequency. Optimization is executed in MATLAB and the constraint boundary limit is defined from 10kHz to 500kHz considering the device tolerance limit of the modified SEPIC operation.

The minimized power loss is obtained from the solution of nonlinear optimization problem by using MATLAB. Obtained minimized Switching Power Loss = 0.84watt, Total Power loss =2.96 % for f= 10 kHz. The least value of power loss is achieved at 10 kHz switching frequency and efficiency is 97.04%.

4.3. Nonlinear Approach for Harmonic Reduction

Minimization of THD is mandatory to maintain power quality. Problem based nonlinear constrained optimization method successfully finds out the parameters of SEPIC L_1, L_2, L_f, C_1 and filter parameters L_f, C_f for which THD is minimized. SEPIC parameters are optimized incorporating over current protection parameters and input filter parameters, to make input current deformation to zero to reduce THD.

The objective function is obtained in eqn. (i) by using equations from ref. [10]. To achieve minimized THD, SEPIC parameters L_1, L_2, C_1 and filter parameters L_f, C_f are optimized and the constraint boundary limit is defined in the practical reign.

Considering the practical limitations of the circuit like inductor current variation, size, cost, availability of component values etc., the minimized THD is obtained from the solution of nonlinear optimization problem by using MATLAB. Obtained THD = 2.28% for SEPIC parameters L_1=10.0mH, L_2=40.0μH, C_1=0.01μF, L_f =10.0 mH, C_f =0.6μF. From the above simulations it is clear that without parametric optimization harmonics in the input current becomes higher and this technique is good to determine least THD.

5. Result and Discussion

In order to achieve perfect luminous and power characteristics a bicolor LED driver is proposed based on nonlinear optimization scheme in MATLAB. The constraints are considered as the availability and suitability of size of the components. The control circuit strictly regulates the total LED current by using color feedback circuits. Desired luminous efficacy is achieved by optimization of wavelengths (426λ and 601 λ) is 90%. LEDs made by semiconductor material InGaN (blue) and In-GaAlP (red) emit light of wavelength 425-500nm and 600-700nm respectively. It should be mentioned here, that LEDs have unique quality to emit at specific wavelength. Any wavelength can be produced by changing composition of semiconductor material. In this case a dedicated LED driver can be designed where LED lights with optimized wavelengths are used with the desired performances. Proper CCT and CRI are maintained. CCT varies with luminous flux and LED current. The minimum CCT deviation 138.25K is obtained from nonlinear algorithm in MATLAB.

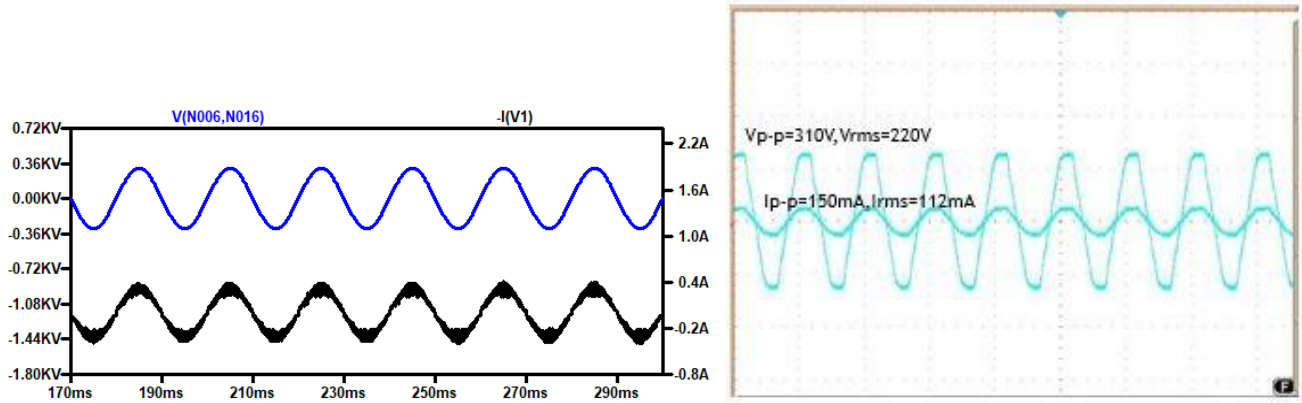
By applying the closed-loop control scheme specified currents 300mA and 200mA flow can be made through the two LEDs with CCT 2500K and 9000K strings respectively at input 220V in Ltspice simulator software.

According to ref. [10], where the non-perceivable CCT variation at target set point (5000K) is about +/-283K. But calculated CCT deviation is 138.25K, which is within the limit. Therefore, LED driver is designed in such a way that by ensuring flow of current 300mA, 200mA to get minimum CCT deviation. This prevents the color shift of the composite color LED driver. Good CRI is also maintained.

In order to achieve good quality of power, high P.F., low THD are essential. Efficiency enhancement is another objective of the LED driver. Reduced power loss is obtained by nonlinear optimization of switching frequency. The result from frequency optimization shows- efficiency 98.27%, power loss 1.73% at 10 kHz switching frequency. The reduced THD is obtained by nonlinear optimization of parameters of SEPIC. The minimized THD is obtained from the solution of nonlinear optimization problem by using MATLAB. From this optimization the least value of THD is achieved. After Ltspice simulation P.F.=0.98 and THD=3.67% are obtained at 220V. Crest factor is obtained 1.4. The results are satisfactory.

The proposed LED driver shows low THD and high PF and relatively high efficiency for optimization of SEPIC parameters and well-designed feedback control circuit. The average LED voltage and LED current of two branches are
60 V, 300 mA and 60V, 200 mA are needed for obtaining optimized CCT respectively.

Figure 5(a) shows the simulated waveforms of input voltage (v_s), input current (i_s) in the steady state condition where input current follows the input voltage. Obtained P.F. = 0.98, THD = 3.67%. The experimental is shown in Figure 5(b).



a b

Figure 5. *(a, b) The simulated input current and input voltage at THD=6.51%, P.F.=0.96,6(b) Experimental input current and input voltage.*

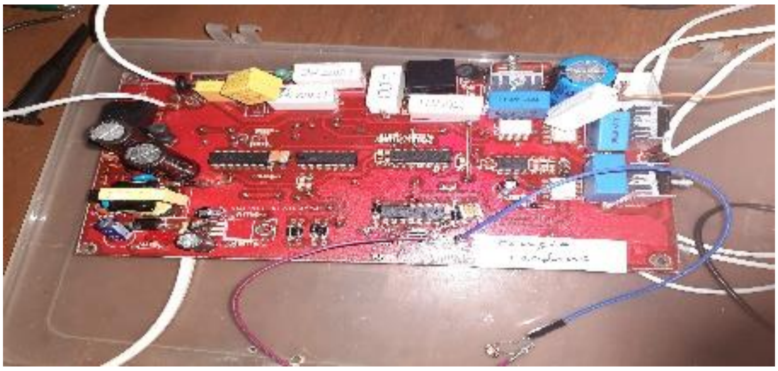


Figure 6. *Prototype of Bicolor LED Driver.*

The prototype of bicolor LED driver is shown in Figure 6. The experimental result are - P.F.=0.96, THD = 4.47%, Efficiency 93.90% at 10kHz at rated voltage. For efficiency enhancement the components (MOSFET, Diode) have been chosen with the loss related parameters of minimum value. Table 1 shows the obtained simulated power parameters.

Table 1. *Simulated and Experimental data of LED driver.*

Item	Proposed LED Driver (simulated)	LED driver (Experimental data)
InputVoltage (V)	220	220
MOS Switches	3	3
Frequency (kHz)	10	10
Power Factor	0.98	0.96
THD	3.67%	4.47%
Efficiency	97.04%	93.90%

6. Conclusion

In this paper, a bicolor composite LED driver has been proposed based on the nonlinear optimization for achieving both desired color parameter and power parameter. Desired luminous parameters like CCT, CRI, LE and reduced power loss and reduced THD have been achieved. The simulated CCT deviation 138.25K, CRI = 98.03, LE = 90%. So, the proposed bi-color LED lamp prevents color shift. The experimentally obtained power quality parameters - THD = 4.47%, P.F.= 0.98, efficiency = 93.90% are satisfactory. These results provide an important basis for the design and manufacture of bicolor composite LED driver with high performances.

Abbreviations

CCT	Corelated Color Temperature
THD	Total Harmonic Distortion
PF	Power Factor
LED	Light Emitting Diode
CRI	Color Rendering Index

Author Contributions

Fouzia Ferdous: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Software, Visualization, Writing – original draft

ABM Harun-ur Rashid: Supervision, Validation, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

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