Performance Evaluation of DC-DC Converter Using Fuzzy PID Controller for LED Lighting Applications

MuthuvelV[1,*], AnanthamoorthyNP[2], ManikandanBV[3], MarikkannanA[4]

Abstract

A high-power white LED (HPWLED) is widely considered the future trend in lighting, because of its high reliability, efficiency, and other exceptional features, including shock/vibration resistance, chromatic variability, etc. A boost converter has some limitations when driving a long LED string, despite being able to match each LED's current perfectly. A high duty cycle and a low efficiency are the two most significant drawbacks of these systems. Due to this, new power supplies are needed to boost and make use of their respective characteristics. This paper proposes a Fuzzy Proportional-Integral-Derivative (Fuzzy-PID) controller-based transformer-less DC-DC high voltage gain converter drive to regulate the luminosity of the HPWLED string. The transformer-less DC-DC high voltage gain converter is used here as a driver for HPWLED strings due to its high voltage gain with a small duty ratio. Here, the Fuzzy PID controller provides robust and highly efficient luminous control for the HPWLED without any chance of exceeding the safe current limit of individual high-power LEDs. Controller performance is analyzed and validated with a traditional PID controller. Simulation works are using a Matlab/Simulink environment. Also, to ascertain the supremacy of the suggested controller for the HPWLED string, a hardware prototype is fabricated for a suitably scaled-down wattage rating incorporating ARDUINO Mega 2560 microcontroller.

Key Words: DC-DC converter, Luminous regulator, High power white LED (HPWLED), Proportional integral controller, Fuzzy logic controller, Fuzzy PID controller.

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Introduction

Continuous research and development in the optoelectronics field make high-power LED lighting mercury-free, high efficiency, long life cycle, reliable, and cost-effective new generation lighting solutions for domestic, industrial, automotive, agricultural, defense (Chris Richardson., 2007) and medical applications (Alexandre Campos et al., 2015) To lessen global warming and reduce the impact of green homes, it plays a crucial role. High-power LED lighting technology is continuously developing its new dimensions to find various applications i.e., television and projector display technologies. In addition, high-power LED can be easily controlled the spectral composition and achieve desired wavelengths for suitable applications. But it needs proper and efficient control strategies with protection. High-power LED light replaces almost all filamentsheating, discharging, and fluorescent-based lighting technology.The amount of energy needed for LED is minimum than others such as laser, intense pulse light, and other coherent light systems.High-power LED emits visible light very fast when powered as compared to its counterparts. High power LED is a current-driven device and is available at various power levels starting from a 1W chip. High-power LEDs are arranged in arrays form where individual LEDs are in series in a fixture to give sufficient light output. A High-power LED's forward current decides its luminous intensity and chromaticity level. This makes to design a driver circuit to drive High power LED with constant current control. Various light intensity control techniques (Chris Richardson., 2007; W.A Rodrigues et al., 2011; Alexandre Campos et al., 2015) are available. A simple constant voltage source with a resistor has given constant current control. But it has poor current regulation resulting in a huge loss of energy.

It has been focused on the performance of high-power LED lighting instruments, including the effectiveness of LED drivers and device reliability features. A linear voltage regulator with internal constant current feedback control is used as a driver for high-power LED. It has good regulation but with poor efficiency, more loss and occupies large space and it is not suitable for driving high-power LED. Switch-mode DC-DC regulator gives promising constant current control with higher efficiency as high as 96% at higher ambient temperature environment and occupies lesser space. A constant current output and wide input voltage range are part of the DC-DC switching regulator. Voltage mode control is a more common control strategy employed in DC-DC converter output voltage regulation. Constant current output can be effectively maintained by voltage mode control. Many different LED string combinations are possible due to the wide output range of the DC-DC switching regulator.

Various topology of the switching-mode regulator is available such as sepic, cuk, buck-boost, boost, and buck DC-DC converter based on its output voltage level for its input voltage (Julio Cesar Rosas-Caro et al., 2009; Lung-Sheng Yang et al., 2009; Arnab Ghosh et al., 2015; Munir Al-Absi et al., 2017; Yijie Wang et al., 2017; Omer Saleem et al., 2018; IttiponLaoprom et al., 2020). In (Yong-Nong Chang et al., 2013) high efficiency illumination of LED street lighting is designed (Behnam Abbasi Soltani et al., 2021; David Katzin et al., 2021) using a class-E resonant inverter.

The inverter has provided galvanic isolation by using multiple serial-linked transformers to drive the LED. The size of the complete structure of the system is a serious issue here due to the number of transformers. Stand-alone solar PV-powered LED lighting with a DC-DC SEPIC converter is presented (Jose Antonio Barros Viera et al., 2013). The battery is also used for storing PV power during the daytime and is also the main source for driving LED lighting at night. The new invention of various types of batteries in the field of energy storage opens the way for LED lighting solutions and applications. Non-isolated and isolated types are used depending upon the applications. In isolated types, push-pull, full-bridge, half-bridge, and fly-back topologies are used. Bridge converter topologies have multistage power conversion which makes them handle high power levels. But it depends on the power requirements of particular applications. Generally, Pulse width modulation (PWM) control is the traditional and main control strategy in the DC-DC converter. But today's applications demand fast and robust control strategies in addition to PWM control. Various control strategies such as proportional integral, sliding mode (Said Oucheriah et al., 2013) fuzzy logic (LipingGuoa et al., 2012), and adaptive fuzzy logic controls (Cetin Elmas et al., 2009) are employed to regulate the output voltage of the converter. In boost topologies, transformerless DC-DC high voltage gain DC-DC converter (Lung-Sheng Yang et al., 2009) has wider popularity since it provides high voltage gain without the need for a large duty ratio. It increases efficiency and reduces stresses on switches even in hard switching. High switching frequency makes this converter simple, very fast, and able to provide wide output voltage control. An efficient and fast responding controller makes this converter most suitable for constant current control of high-power white LEDs. Constant current control in the DC-DC switching regulator is maintained with constant voltage control and for this, the converter has to operate in voltage mode control.

High power LED is a non-linear device and if a low value of forwarding voltage is given across LEDs, it will not emit light. As soon as the forward voltage crosses its threshold value, high power LED starts to emit light, and its current increases sharply. Thereafter, forward voltage continues to increase, leading to a larger increment of current and rapid overheating. It creates thermal instability which will damage the high-power LEDs. If the current increases, light intensity also will increase proportionally, but the current, not within the safe limit of LEDs, leads to thermal issues. Constant current within the safe limit increases the operating life of high-power LEDs at the required light intensity

level. This creates a space for designing constant current-controlled drivers for high-power LEDs (Nguyen DinhPhu et al., 2020; Chun-Tang Chao et al., 2019).

A small change in voltage doubles the variation in the intensity of light and therefore maintaining constant voltage across high-power LED is essential. These factors pose a great challenge to the performance of LEDs and it has opened up new avenues for research in this domain.

Traditionally, headlights consume a lot of power, are inefficient, and also struggle with voltage fluctuations. This is a simply modified half-bridge converter (Sureshkumar et al, 2021) designed for automotive lighting applications. Converters like this can work in buck and boost modes, which is great for varying sources. However, the converter is relatively inefficient. For street-lighting applications, (Soltani et al, 2021) a two-input boost converter coupled with an impedance network is offered. As a lab prototype, (Quintana-Barcia et al, 2021) an emergency lamp with a series resonant current regulator based a ballast and a battery charger is presented. A power converter acts as a non-dissipative impedance controllable by the LED array in this circuit. To accommodate input voltages over a wide range, a transformer-less DC-DC multi-configurable series loaded resonant converter-based LED driver is proposed (Vaidyanadhan et al, 2021). For these topologies, implementing high-power applications with wide input voltage ranges is difficult due to unsymmetrical power device stresses and large inductance requirements.

In this paper, fuzzy PID controller-based voltage mode control operation for HPWLEDs is proposed and it is driven by novel transformer less DC-DC converter. The objective of this work is to attain high voltage gain with small duty ratio on proposed fuzzy PID based transformer less DC-DC converter for LED applications.

The following are the contributions of this paper:

- Fuzzy PID controller plays the role of luminous regulator with fast and efficient voltage mode control action in the converter for HPWLED light string.
- The Fuzzy PID controller is too capable of tolerating many more wrong selections or inappropriate implementations of controller gains that could create instability in conventional controllers.
- In addition to having a high capability and low voltage stress on the active elements, the suggested topology has moderate efficiency and low voltage stress on the active devices.

The following is the organization of this paper: Section 2 provides the characteristics of a high-power white LED system. Section 3 describes the transformer less

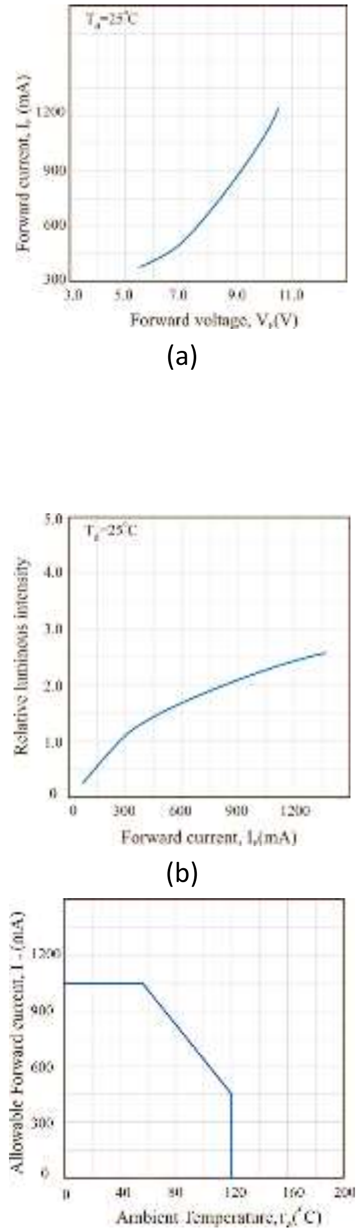
DC-DC converter design and its operation. Section 4 provides the proposed fuzzy PID controller design. Chapter 6 demonstrates the result and discussions. Chapter 5 discusses the conclusion.

High Power White Led (Hpwled) And Its Characteristics

Each HPWLED emits cool white light with a maximum forward voltage of 12V and a maximum forward current of 1050 mA. Forward Voltage and current characteristics of LED at a temperature level of 25oC are shown in Figure. 1(a). It resembles diode V-I characteristics. After threshold voltage, the current rises rapidly with a small incremental change in voltage. This gives a narrow region of operation for HPWLED. Utmost importance is given to the design of the current control scheme for the DC-DC converter to drive HPWLED. The light intensity of HPWLED depends upon its forward current of it. If the forward current through LED increases, the light intensity level also rises proportionally as shown in Figure. 1(b). The light intensity of HPWLED decreases considerably by increasing the ambient temperature as shown in Figure. 1(c). Ambient temperature, a limiting factor for forwarding current greatly affects the light intensity output of LED as shown in Figure. 2(a). The Wavelength characteristics of HPWLED are drawn between relative light intensity and wavelength of LED and shown in Figure. 2(b). Some technical specifications for high-power 10W LED are shown in table 1. Each LED is mounted on a suitable individual heat sink.

Table 1. Technical specification of 10W HPWLED

Parameters	Value
Forward voltage, V_F	9-12V
Forward current, I_F	1050 mA
Reverse voltage, V_R	50V
Power dissipation, P_D	10W
Luminous intensity	720 lm

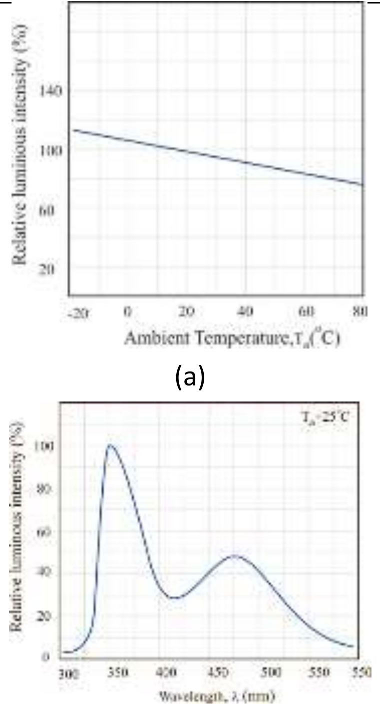


(a)

(b)

(c)

Figure 1.(a) V-I characteristic (b) Current-Intensity characteristic and (c) Temperature-Current characteristic



(a)

(b)

Figure2.(a) Temperature-intensity characteristics and(b) Wavelength-intensity characteristic

Transformer less DC-DC High Voltage Gain Converter

This converter is used to drive a single high-power
LED string with voltage-mode control. The circuit diagram of the converter is shown in Figure 3.

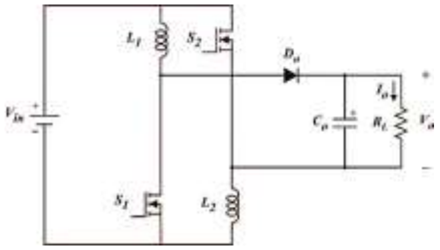
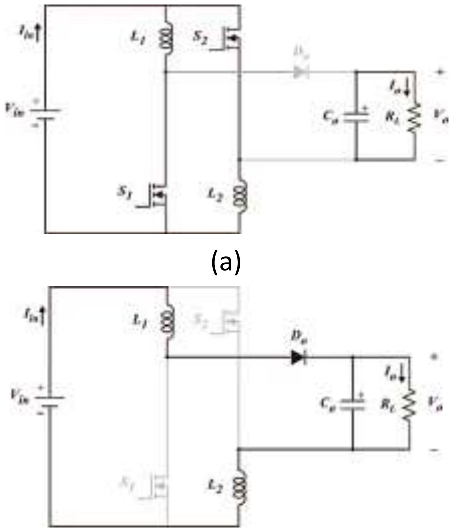


Figure 3. Transformer less DC-DC high voltage gain converter



(a)

(b)

Figure 4. (a) Mode-1 operation and (b) Mode-2 operation

It has an extensive input voltage range. It is constructed with two power MOSFET as switches (S_1 and S_2), one output capacitor C_o, two ideal inductors (L_1 and L_2) and one output diode D_o. Switches S_1 and $S_2$are turned on and off simultaneously by using one control signal. The converter can be operated both in continuous current (CCM) and discontinuous current (DCM) modes. But for driving a high-power LED, it must be operated in continuous conduction mode to maintain enough current level for a visible level of illumination. In continuous current mode (CCM) converter has 2 modes of operation. In mode 1 switches S_1 and S_2 are turned on and inductors L_1 and L_2 get energy from the source, V_{in} as shown in Figure. 4(a). At this condition, capacitor C_o delivers stored energy into the load, R_L. Switches S_1 and S_2 are turned off at mode 2 and source V_{in}, inductors L_1 and L_2 deliver energy in series to capacitor C_o and load R_L as shown in Figure. 4(b). In this system, the converter is controlled with voltage-mode control. Voltage mode control maintains constant voltage even if there is a change in load conditions. The output current of the converter depends upontheconnected load i.e., illumination level. The voltage gain equation of this converter for continuous current mode is given by

$$M_{ccm} = \frac{V_o}{V_{in}} = \frac{1+D}{1-D} (1)$$

Specifications and components used in this converter are V_{in}=12V, V_o=60-100V, f_S=100kHz, P_O=50W, L_1=L_2=100µH, and C_O=68µF.

Fuzzy PID Controller

Classical PID controller has given very effective control with linear system completely modeled by mathematical equations. If a system is nonlinear or too complex to model by mathematical equations, a classical PID controller is ineffective to control. Precise gain calculations are not a simple task for effective control of the particular system by a classical PID controller and it also gives unpredictable responses under the situation of dynamic conditions. To determine accurate gain values of the PID controller, a fuzzy inference module of the fuzzy logic controller is constructed to tune the gain values of the PID controller online with the inputs of error, *e,* and change of error, *Δe*. A fuzzy PID controller is a combination of fuzzy logic and classical PID controllers (Mohan et al., 2008). As exposed in Figure 5, the fuzzy logic system employs two inputs and three outputs based on the Mamdani inference method and its Matlab/Simulink model is shown in Figure. 6. Error, *e,* and change of error, *Δe* are given as inputs to the fuzzy inference system and increments of PID gains outputs. The fuzzy PID tunes PID k_P, k_I, and k_D parameters through fuzzy logic knowledge by establishing the following equation:

$$k_P=k_{P0}+\Delta k_P (2)$$

$$k_I=k_{I0}+\Delta k_I (3)$$

$$k_D=k_{D0}+\Delta k_D (4)$$

where k_{Po}, k_{Io}, and k_{D0} represents the initial values of PID controller gains.

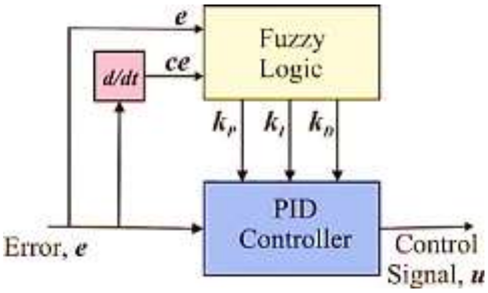


Figure 5. Fuzzy PID controller block diagram

To convert input and output data into proper semantic values, input and output variables are fuzzified. There are seven semantic variables in this work that describe the fuzzy range of inputs and outputs, and related fuzzy subsets are [PB, PM, PS, Z, NB, NM, NS,]. Where PB is positive big, PM is positive maximum; PS is positive small; Z is zero; NS is negative small; NB is negative big; NM is negative maximum.

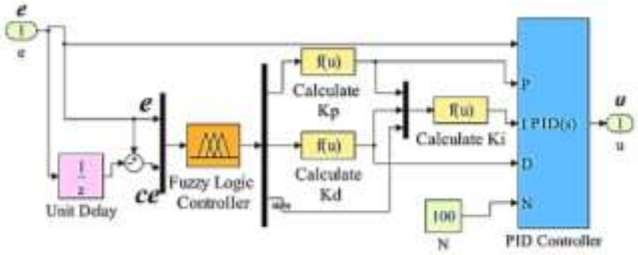


Figure 6.Matlab/Simulink model of Fuzzy PID controller

Seven Gaussian membership functions are used to implement the membership functions of two inputs and scale within the range of [-1, 1]. There are seven triangular membership functions corresponding to three outputs and they scale within the range [-1, 1]. Figure. 7 and 8 shows the membership functions. Self-tuning fuzzy PID control can be understood by using expert experience or input-output data to understand the relationship between inputs and outputs. As indicated in the form given, fuzzy rules are used to infer relation between I/O.

Rule: If e is L_i and ce is M_j, Then Δk_P is N_{ij},Δk_I is O_{ij} and Δk_D is P_{ij} . Where L_i, M_i, N_{ij}, O_{ij}, P_{ij} (L_i, M_i, N_{ij}, O_{ij}, $P_{ij} \in$ [PB, PM, PS, Z, NS, NM, NB]) are linguistic values of inputs and outputs. All 49 possible rules are included in Figure 9. The fuzzy implication and synthesis calculations are managed by the product-inference rule and the center average defuzzifier, correspondingly. The output of $\Delta k_P$from the fuzzy inference system is:

$$\Delta K_p (e, Ce) = \frac{\Sigma_n^N \omega^n \Delta\, \mathrm{Kp}^n}{\Sigma_n^N \omega^n} \quad (5)$$

$$\omega^n = \mu L_i^n(e) \mu M_j^n(ce) \quad (6)$$

Where, N is the number of rules, and n is the nth fuzzy rule. $\Delta k_P^n \in$ U is any point at which $\mu_{N_{ij}^n(\Delta k_P)}$ attain its highest value, $\mu_{N_{ij}^n(\Delta k_P)} = 1$. $\mu_{L_i}(e)$ and $\mu_{M_i}(ce)$ are the Gaussian membership function of the input e and ce, correspondingly.

$$L_i^n(e) = \exp\left[-\left(\frac{e-N_i}{\sigma_j}\right)^2\right] \quad (7)$$

$$M_j^n(ce) = \exp\left[-\left(\frac{ce-N_i}{\sigma_j}\right)^2\right] \quad (8)$$

Where, σ_i $and c_i$ are the standard deviations of Gauss membership functions and corresponding centers, correspondingly.

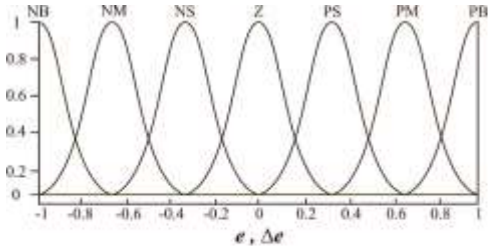


Figure 7.e and Δe membership functions

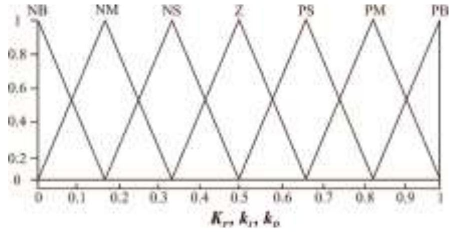
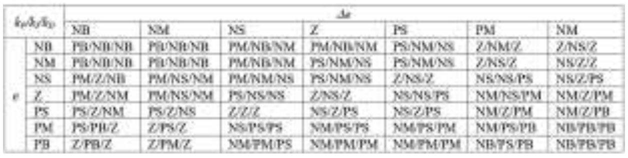


Figure 8.KP,KI and KD membership functions



$k_P/k_I/k_D$		Δe						
		NB	NM	NS	Z	PS	PM	NM
e	NB	PB/NB/NB	PB/NB/NB	PM/NB/NM	PM/NB/NM	PS/NM/NS	Z/NM/Z	Z/NS/Z
	NM	PB/NB/NB	PB/NB/NB	PM/NB/NM	PS/NM/NS	PS/NM/NS	Z/NS/Z	NS/Z/Z
	NS	PM/Z/NB	PM/NS/NM	PM/NM/NS	PS/NM/NS	Z/NS/Z	NS/NS/PS	NS/Z/PS
	Z	PM/Z/NM	PM/NS/NM	PS/NS/NS	Z/NS/Z	NS/NS/PS	NM/NS/PM	NM/Z/PM
	PS	PS/Z/NM	PS/Z/NS	Z/Z/Z	NS/Z/PS	NS/Z/PS	NM/Z/PM	NM/Z/PB
	PM	PS/PB/Z	Z/PS/Z	NS/PS/PS	NM/PS/PS	NM/PS/PM	NM/PS/PB	NB/PB/PB
	PB	Z/PB/Z	Z/PM/Z	NM/PM/PS	NM/PM/PM	NM/PM/PM	NB/PS/PB	NB/PB/PB

Figure 9. The fuzzy rules for PID gains

Simulation Results and Discussion

The proposed HPWLED system was simulated using the Matlab/Simulink toolbox and the complete simulation diagram is shown in Figure. 10. To validate the results and to prove the commercial viability of the proposed system for HPWLEDs, a proportionally scaled-down wattage-rated experimental setup is fabricated and analyzed. Proposed Fuzzy PID controller-based luminous regulator performance is evaluated with traditional proportional-integral (PI) controller and fuzzy logic controller (FLC). A resistive load is used to meet the parameters suitable for HPWLED. Rated current of 1050mA is maintained and the voltage across each load is kept between 9V to 12V as per the specifications of data sheet. For illumination control, the current value of the load is varied between 850mA to 1050mA, and the load current value of 1050mA is maintained constant for line regulation. To imitate the varying intensity level of LED string, the load value can be altered. For voltage-mode control, A resistor is measured, the voltage across it is compared to a reference voltage, and the output of this measurement is fed into an error amplifier.

Reference voltage decides the required voltage across the load resistor. The error signal, e, and change of error signal, ce are given into fuzzy PID controller and controller produces required control signal, u to pulse width modulator (PWM). The control signal, u iscompared to the ramp signal to generate the required PWM gate pulse to control the current flow through the string. Control responses of the PI, FLC, and Fuzzy PID controller for the step-change in current and voltage are plotted and revealed in Figures 11, 12, and 13. For voltage-mode control, the voltage across the resistor is calculated and evaluated with the reference voltage, and the output is given to the error amplifier. Voltage and current responses have been obtained for both step changes in current and voltage applied to load. Current has been increased in step from 850 mA to 1050 mA and back to 850 mA. Similarly, the input voltage has been increased in step from 8 V to 16 V and back to 12 V.

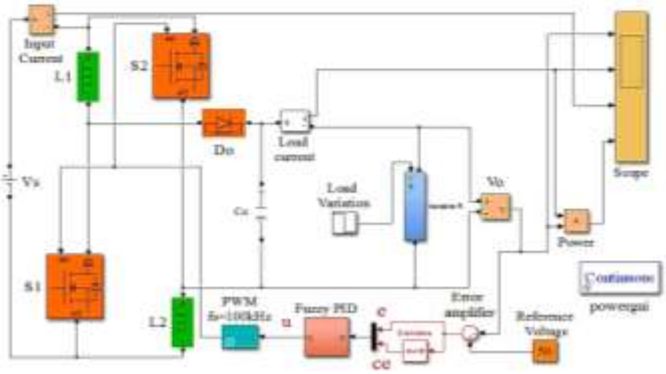
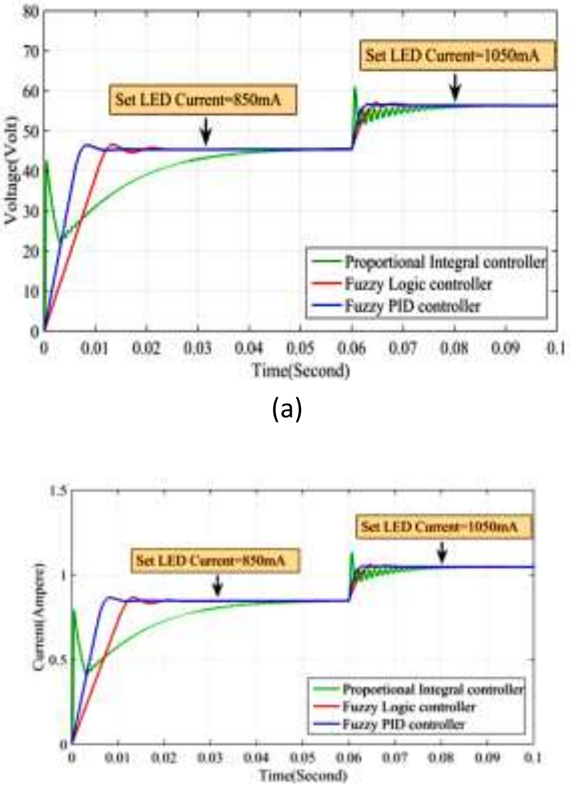


Figure 10. Simulation diagram of the proposed Fuzzy PID based converter system

For the load regulation as well as line regulation aspect, the proposed fuzzy PID controller has outperformed the other two controllers. Specific performance indices are observed and given in Table 2 for all controllers to identify fast and best-performing controllers for the proposed system.

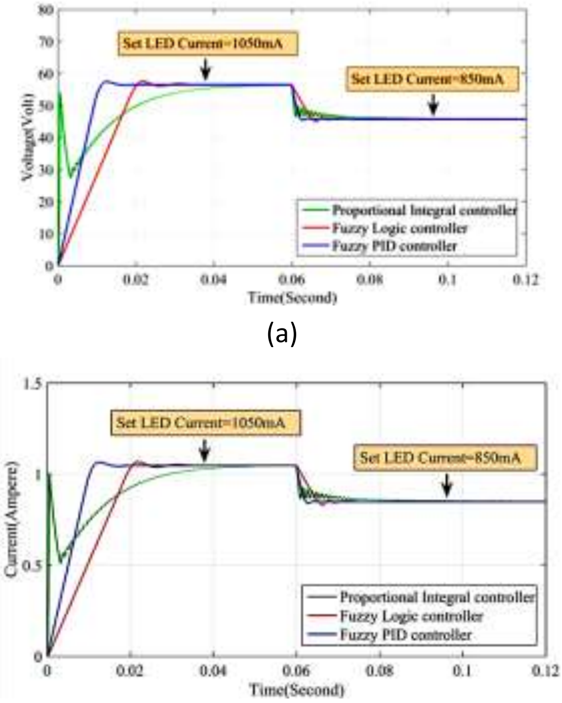
The fuzzy PID controller has provided superior and convincing results compared to the other two controllers considered for comparison. The fuzzy PID controller has given fast and remarkable transient responses for the proposed system.



(a)

(b)

Figure 11.(a)Voltage response and (b) Current response for step-change in current from 850mA to 1050mA



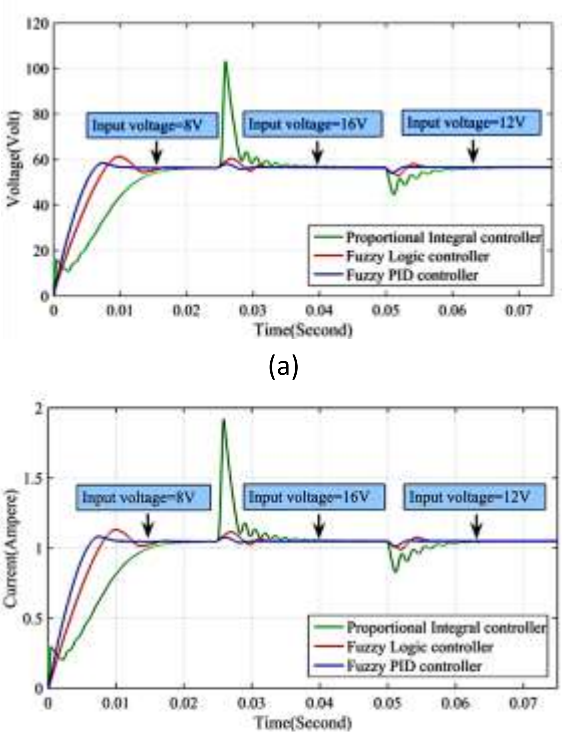
(a)

(b)

Figure 12.(a)Voltage response and (b) Current response for a step change in current from 1050mA to 850mA

Table 2. Performance parameters observed from simulation results

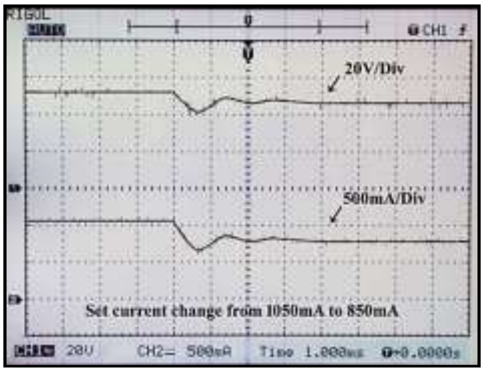
Controller	Rise time in (secs)	Settling time in (secs)	Overshoot in (mA)	Steady-state error (mA)
PI Controller	0.0101	0.0133	2	-1.46
Fuzzy Logic Controller	0.0069	0.0107	3	- 1.34
Proposed Fuzzy PID Controller	0.0044	0.0065	3	-0.66



(a)

(b)

Figure 13. (a)Voltage response and (b) Current response for a step-change in voltage from 8V to 16V and back to 12V



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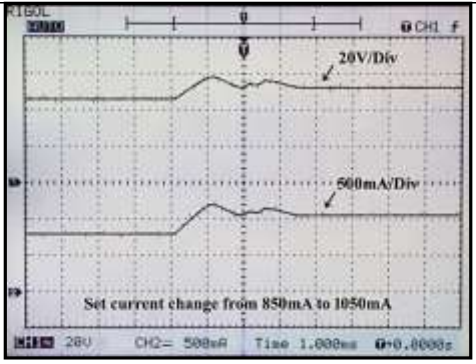
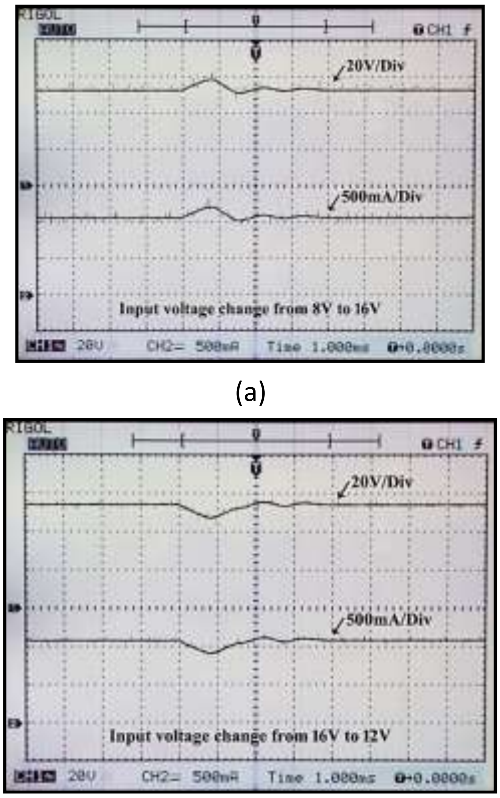


(b)

Figure 14. Voltage and current response for step change in current from (a) 1050mA to 850mA and (b) 850mA to 1050mA



(a)

(b)

Figure 15. Voltage and current response for input voltage step change from (a) 8V to 16V and (b) 16V to 12V

Experimental Results and Discussion

Five numbers of each 10W, 9V-12V high power white LED are used for ascertaining the performance of the fuzzy PID controller. The implementation of that fuzzy PID controller has been done with the widely used ARDUINO Mega 2560 microcontroller. Experimental responses of the proposed HPWLED system for step-change in current from 1050mA to 850mA and back to 1050 mA have been obtained and shown in Figures 14 (a) and (b). Similarly, the response for the input voltage step change from 8 V to 16 V and 16V to 12 V is shown in Figure. 15(a) and (b). The obtained results are almost replicas of obtained simulation results. Therefore, it has been proved experimentally, that it is capable of providing fast and good dynamic performance. Controlling and maintaining the illumination level of LEDs with a safe limit of maximum LED current has been easily done with the proposed fuzzy PID controller.

Conclusion

A Fuzzy PID controller-based transformer less DC-DC high voltage gain converter drive to regulate the luminosity of HPWLED string is proposed in this work.

Simulation works are using a Matlab/Simulink environment. The output results demonstrate the effectiveness of a Fuzzy PID controller for use as a luminous regulator for high-power white LED string. The fuzzy PID controller has maintained constant voltage across the LED string without any chance of exceeding the safe current limit of individual high-power LEDs. Compared with the traditional PI controller and fuzzy logic controller, the proposed controller regulates the luminous level of high-power LED string with fast, efficient, and robust controlling action. In addition, the incorporation of a Transformer-less DC-DC high voltage gain converter with a wide input voltage range feature supports a Fuzzy PID controller for variable and constant luminous regulation. Both the simulation results and the suitably scaled-down wattage-based experimental setup results are in favour of the proposed fuzzy PID controller. Commercial implementation of this proposed work will add a new dimension to the performance enhancement of high-power white LED strings.

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Conflicts of interests

Authors do not have any conflicts.

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