Design of a Fuzzy PI Controller for Peak-to-Average Reduction in Output Current of LED Drivers

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Abstract—This paper presents an optimal gain-scheduling fuzzy PI controller applied to an AC-DC discontinuous conduction mode (DCM) flyback converter to achieve a high performance electrolytic capacitor-less LED driver with high efficiency and high power factor. The proposed system consists of seven PI controllers for seven different load currents which are designed based on Particle Swarm Optimization (PSO) algorithm. By using the obtained data, a fuzzy system is trained to give suitable PI gains for any load condition. Employing the proposed controller significantly improves the peak-to-average ratio of the output current to 1.05 while the LED driver reaches to a high power factor of 90.8% and its input current THD is equal to 11.88% meeting the IEC 61000-3-2 class C standard.

Keywords—flyback converter; electrolytic capacitor; fuzzy PI controller; PSO algorithm; peak-to-average ratio; THD; power factor.

I. INTRODUCTION

Due to the growing popularity of LEDs in brightness systems, designing appropriate control methods to improve the performance of LEDs is essential. It should be noted that LEDs are sensitive to their driving current changes and thus this limits their lifetime. Any increment in the output current ripple increases the peak-to-average ratio of the output current [1]. Therefore, control methods have to limit the ripple of output current. On the other hand, electrolytic capacitors used in LED drivers are another reason to reduce the lifetime of these types of lamps [1], [2]. Table I demonstrates three types of capacitors and their lifetime, indicating the lower lifetime of electrolytic capacitor in comparison to the other types [3]. Thus, to increase the lifetime the electrolytic capacitors should be reduced or eliminated. However, this will increase the ripple of output current. The power factor is another important characteristic in designing of LED drivers. Higher power factor is more favorable. In [4], by injecting odd harmonics into the input current a method is presented to decrease the storage capacitance and reach to a desirable power factor. Although, the power factor is decreased from 1 to 0.9, the storage capacitance declined by 65.6%. To this end, the presented topology has two-stage converter which consists boost converter for correcting power factor and flyback converter. However, the amplitude of the third harmonic current in this method is higher than the IEC 61000-3-2 class C standard [5]. In [1], by extending the method in [4] the electrolytic capacitor is fully eliminated and it is shown that the peak-to-average of output current becomes 1.4, while keeping the power factor more than 0.9.

In order to increase the lifetime of LED drivers which can be achieved by eliminating electrolytic capacitors and at the same time guarantee reaching to a desirable peak-to-average ratio and power factor using adaptive controllers are essential. One of these controllers is the combination of fuzzy system and PI controller presented in [6]-[8]. In [6], by using error and its variation is utilized as the inputs of a rule base fuzzy system. The optimal ratio between these two inputs is derived by using genetic algorithm. Then, the fuzzy system determines the parameters of the PI controller adaptively. In [7], a robust fuzzy PID controller is presented to control a PWM based DC-DC buck converter. The rule of fuzzy system is considered such that the maximum overshoot and steady state error are decreased significantly. Meanwhile, the method does not need the linearized model of the converter. A fuzzy logic controller based for maximum power point tracking (MPPT) is proposed in [8] for a DC-DC SEPIC converter. It has been shown that the proposed fuzzy logic controller has superior performance in comparison to the conventional PI controller.

In this paper, a fuzzy PI controller, which leads us to an optimal gain-scheduling PI controller is proposed for AC-DC DCM flyback converter. Meanwhile, the proposed topology is a capacitor-less one-stage converter, which significantly decreases the complexity, and at the same time increases the lifetime of the system. At the beginning, seven PI controllers are designed for seven different output load currents, using PSO algorithm. Each PI controller is designed to minimize the output ripple for the each corresponding load current. Then the fuzzy system is trained by the achieved data which then it can calculate the suitable coefficients of PI controller for any output load changes. The proposed fuzzy PI controller is able to mitigate the output current ripple significantly in a wide range of load variations. Meanwhile, simulation results indicate significant improvement in performance by using the proposed driver. Comparing with [1], by using the proposed driver the maximum peak-to-average ratio of output current in the whole range of load variations is decreased significantly from 1.4 to 1.05.

It should be noted that, even by eliminating electrolytic capacitor, the system has reached to high power factor and high efficiency equal to 90.8% and 87.26%, respectively. Meanwhile, the THD of the input current follows the IEC 61000-3-2 class C standard.

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TABLE I. The three types of capacitor and their property

Type	Lifetime at 85°C (hours)	Available range
Electrolytic	< 18,000	1 μF ~ 15 mF
Polyester Film	> 100,000	10 pF ~ 400 μF
Ceramic	> 50,000	1 pF ~ 10 μF

This paper is organized as follows, Section II, presents the preliminaries about the flyback converter, the peak-to-average of output current, controller and optimization method. Section III, focuses on the proposed method and states the design of the proposed controller for a flyback converter and it also accomplishes simulations and discussions. Finally, Section IV concludes the main advantages of the proposed controller.

II. PRELIMINARIES

A. Flyback Converter

The flyback converter is utilized in this paper due to its simple structure which consists of just one single switch, and self-power factor correction property in DCM mode, making it suitable for medium power LED drivers. Thus, this single stage converter can correct the power factor and convert the input voltage to the desired output voltage. In addition, working in the DCM mode needs a smaller transformer and provides faster transient response while the primary and secondary winding currents have triangular waveforms [9], [10]. By selecting the system parameters which include the minimum and maximum input voltage, efficiency, output power and switching and line frequencies, the DCM flyback converter can be designed. Firstly, the maximum input power, DC link capacitor, and minimum DC input voltage are calculated based on Eqs. (1)-(3), respectively, as follows:

$$Pin_{max} = \frac{Pout_{max}}{\eta} \quad (1)$$

$$C_{DC} = \alpha\, Pin_{max} \quad (2)$$

$$VDC_{min} = \sqrt{2{V_{ac}}^2 - \frac{Pin_{max}\,(1-d_{charge})}{C_{DC}\, f_{line}}} \quad (3)$$

where Pin_{max} and $Pout_{max}$ are the input and output power and η is the efficiency. C_{DC} and d_{charge} are the DC link capacitor and its charging duty ratio, typically around 0.2, respectively. α is the coefficient equal to capacitance per watt of input power which is equal to 2- 3 $\frac{\mu F}{w}$ for the input voltage between 85 V_{ac} and 265 V_{ac}. On the other side, the maximum DC input voltage can be estimated according to (4) when the capacitor peak charge voltage reaches the peak of the AC input voltage.

$$VDC_{max} = VAC_{max}\sqrt{2} \quad (4)$$

where VAC_{max} is the peak of the AC input voltage. In the next step, the maximum duty cycle is estimated based on Eq. (5) in which the transformer is assumed to be designed in the boundary of DCM and continuous conduction mode (CCM).

$$D_{max} = \frac{V_R}{V_R + VDC_{min}} \quad (5)$$

where V_R is the reflected voltage from the secondary winding of the transformer and is equal to:

$$V_R = n\,(V_{out} + V_D) \quad (6)$$

where n is the primary to secondary turns ratio of the transformer, V_{out} is the output voltage and V_D is the secondary diode voltage drop. Finally, the value of the peak current and the primary inductance of the transformer can be determined as follows:

$$I_p = \frac{2Pin_{max}}{VDC_{min}\, D_{max}} \quad (7)$$

$$Lp_{max} = \frac{VDC_{min}\, D_{max}}{I_p\, f_{sw}} \quad (8)$$

where f_{sw} is the switching frequency. In order to guarantee that the flyback converter does not work in the CCM mode, the amount of primary inductance should be selected lower than Lp_{max}.

B. Peak-to-Average Ratio of Output Current

Peak-to-average ratio of the output current is a suitable criterion for measuring the output current ripple. As it is known, the ideal value of the peak-to-average ratio is one. As a result, the closer to one, the lower output current ripple will be achieved [1-2], [4].

The input voltage is defined as:

$$v_{in}(t) = v_m \sin\omega_L t \quad (9)$$

where v_m is the peak value and ω_L is the angular frequency of the input voltage. Assuming that the power factor is one, the input current is obtained as below:

$$i_{in}(t) = I_1 \sin\omega_L t \quad (10)$$

where I_1 is the peak value of the input current. Therefore, the instantaneous input power can be achieved as follows:

$$p_{in}(t) = v_{in}(t)\, i_{in}(t) = \frac{v_m I_1}{2}(1 - \cos 2\omega_L t) \quad (11)$$

Assuming that the efficiency is 100%, the output current can be achieved as below:

$$i_o(t) = \frac{p_{in}(t)}{v_o} = \frac{v_m I_1}{2v_o}(1 - \cos 2\omega_L t) \quad (12)$$

where v_o is the peak value of the output voltage. The estimated peak-to-average ratio of the output current is equal to 2, which is quite high and undesirable in practical applications.

C. PI Controller

PI control is one of the conventional control methods employed in the LED drivers. It controls the switches of the driver based on comparing the selected signal and the desired value. The transfer function of a PI controller is given by:

$$G(s) = K_p + K_i(\frac{1}{s}) \quad (13)$$

where the coefficients K_p and K_i are the proportional and integral gains, respectively, and their correct tuning is mandatory for LED drivers.

D. PSO Algorithm

PSO algorithm is a kind of optimization algorithm evolved from society of birds which is simple and high accurate in reaching the goal (minimization of the amount of errors). It is started with a population of random solutions. Then, by updating the generation, the system searches for the best solution. In each iteration, the new location of particles is dependent on the position and the velocity of a particle weighted in the program [11]. The new position and velocity are given by:

$$V_i^{k+1} = WV_i^k + C_1 r1\left(Pbest_i^k - X_i^k\right) + C_2 r2\left(Gbest^k - X_i^k\right) \quad (14)$$

$$X_i^{k+1} = X_i^k + V_i^{k+1} \quad (15)$$

where V_i^k and X_i^k are the velocity and location of the ith particle until kth iteration, W is weight parameter and C_1 and C_2 are weight factors. $r1$ and $r2$ are two random numbers uniformly chosen in [0,1]. $Pbest^k$ and $Gbest^k$ are the best position of the ith particle and the group until kth iteration, respectively. Here, the PSO algorithm is used to estimate the best coefficients of the PI controller for different loads by using a defined cost. Then, the obtained coefficients are used to tune the fuzzy algorithm.

E. Fuzzy System

Two single input single output fuzzy systems are adapted here to control the driver with the obtained coefficients from the previous step. The specifications of the fuzzy systems are: fuzzy rule base: Mamdani; inference engine: product; fuzzifier and defuzzifier: singleton and center average, respectively. The output of the fuzzy system is as follows:

$$y = \frac{\sum_{l=1}^{M} y^{-l}\,\omega_l}{\sum_{l=1}^{M} \omega_l} \quad (16)$$

where y^{-l} is the vector of the centers of output membership function, ω_l is the degree of input membership functions and M is the number of applied rules. The output current of the LED driver is fed to the fuzzy systems as their input to generate suitable coefficients for the PI controller. By defining the best cost using the optimized coefficients of the PI controller, y^{-1} can be calculated through the PSO algorithm. Therefore, by calculating the degree of input membership functions according to the output current and the optimized y^{-1}, suitable coefficients of PI controller can be calculated.

III. Proposed Method, Simulations and Discussions

The flyback converter is designed in DCM mode while the designed topology parameters are shown in Table II. In order to improve THD, the ratio of switching frequency and signal frequency is chosen multiple of 3 [12]. The signal frequency after the diodes of the bridge is equal to 120 Hz and the switching frequency is chosen 25.2 KHz. In order to improve removing higher harmonics transported to the input source and consequently results in a better THD an input filter is designed. Due to the THD of the input current and the range of its harmonics, the inductor and the capacitor of the input filter are selected 1 mH and 1 μF, respectively. The proposed topology is shown in Fig.1. For this system the variation range of the output current is considered between 200 mA to 700 mA. Then, by dividing the interval between 300 mA to 600 mA into seven points, seven PI controllers designed for the different currents as explained. Each PI controller is designed to minimize the output current ripple corresponding to each of these seven currents. To this end, the integral absolute error between the desired and actual voltages is considered as the cost function. To minimize this cost function, which is a nonlinear optimization problem, PSO algorithm is used. The optimal K_p and K_i corresponding to each PI controller obtained using PSO algorithm are shown in Table III. It should be noted that the number of iterations, the number of populations and the range of gains are considered 100, 20 and [-2,2], respectively.

Now, in order to have a gain-scheduling PI controller two Mamdani-type fuzzy systems as in (16) are considered to give K_p and K_i, respectively for any load condition. The first and the second columns in Table III are used as a training set for the first fuzzy system. Similarly, the first and the third columns in Table III are the training set for the second fuzzy system. For each fuzzy system $\bar{y}^l$ is assumed free and derived using PSO algorithm in order to minimize the error between the desired and the actual values. The triangular input membership functions are used to partition the interval between 200 mA to 700 mA. The number of input membership functions or correspondingly the number of rules is assumed differently for each number of input membership functions the training is accomplished. Fig. 2 and 3 demonstrate that for both fuzzy systems four is a suitable choice as the number of input membership functions. Fig. 4 shows the input membership functions with the centers demonstrated in Table IV. Table V, shows the optimal centers of output membership function, derived by PSO. Now, the input of fuzzy systems is the output current and their outputs are K_p and K_i of PI controller, respectively. The flowchart of the proposed control method is shown in Fig.5.

Applying the proposed controller for the maximum output power in 128 Ω of output load, the RMS value of the output current and its peak value will be 625.5 mA and 657.5 mA. Thus, the peak-to-average ratio of output current will be 1.05. This results a significant improvement in comparison to [1]. Fig. 6 depicts the output voltage and output current of 128 Ω output load. Since the flyback converter is in DCM mode, Fig. 7a shows the primary current and Fig. 7b shows the secondary current of the transformer. The input voltage and the input current are shown in Fig. 8. Considering Fig. 8, the power factor and the THD of the input current is equal to 90.8% and 11.88%, respectively. The harmonic spectrum of the input current is shown in Fig.9. It can be seen that the THD follows the IEC 61000-3-2 Class C standard. Meanwhile, the efficiency of system is 87.26% which is satisfactory.

TABLE II. The system parameters.

Input Voltage	220 [V_{rms}]
Output Voltage	80 [V_{rms}]
Output Power	50 [w]
Line frequency	60 [Hz]
Switching frequency	25.2 [KHz]
Inrush Resistor	30 [Ω]
Input Filter Inductor	1 [mH]
Input Filter Capacitor	1 [μF]
Turns ratio	2
Primary Inductance	1.086 [mH]
Output Filter Capacitor	200 [μF]

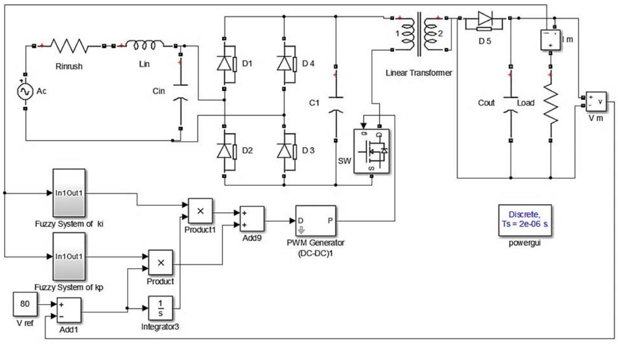


Fig.1. The proposed topology.

TABLE III. The obtained coefficients of PI controller by PSO algorithm.

I (mA)	K_p	K_i
300	0.0030	0.6131
350	0.0026	0.8615
400	0.0025	0.9196
450	0.0024	0.9675
500	0.0023	1.0135
550	0.0022	1.0261
600	0.0021	1.0698

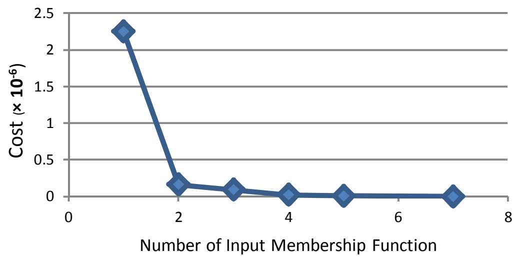


Fig.2. The cost of estimating the K_p by PSO algorithm.

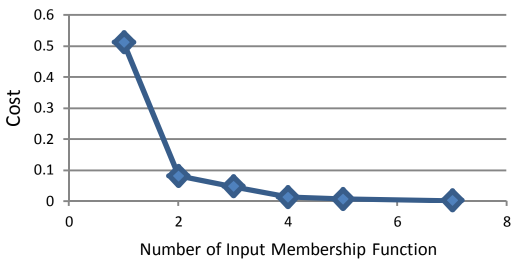


Fig.3. The cost of estimating the K_i by PSO algorithm.

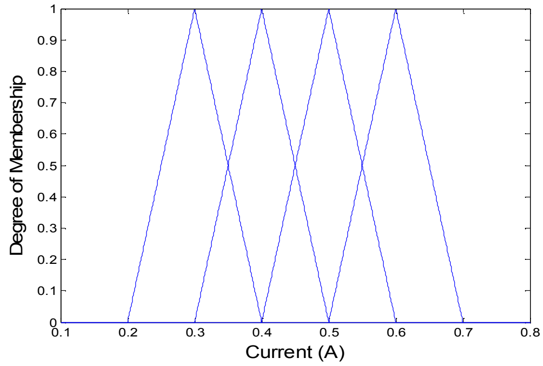


Fig.4. The input functions of fuzzy algorithm.

TABLE IV. The center of input membership functions of fuzzy systems.

Input membership function number	Center of input membership function (A)
1	0.3
2	0.4
3	0.5
4	0.6

TABLE V. The optimized center of output membership functions of fuzzy systems.

Output membership function number	Optimized center of output membership function of K_p	Optimized center of output membership function of K_i
1	0.0030	0.6131
2	0.0025	0.9206
3	0.0023	1.0135
4	0.0021	1.0698

In order to study the robustness of the proposed controller in sudden output load variations, the output load changes abruptly from 210 Ω to 128 Ω at $t = 0.15$ s. It can be seen form Fig. 10a that the controller can keep output voltage to its desired value with satisfactory performance. Fig. 10b shows that the output current has increased rapidly to keep the output voltage to its desired value. It should be noted that in the whole of this process the peak-to-average ratio of output current is equal or lower than 1.05. Unlike the classical PI controller, the proposed controller can control system for sudden output load variations and keep the peak-to-average ratio in acceptable level.

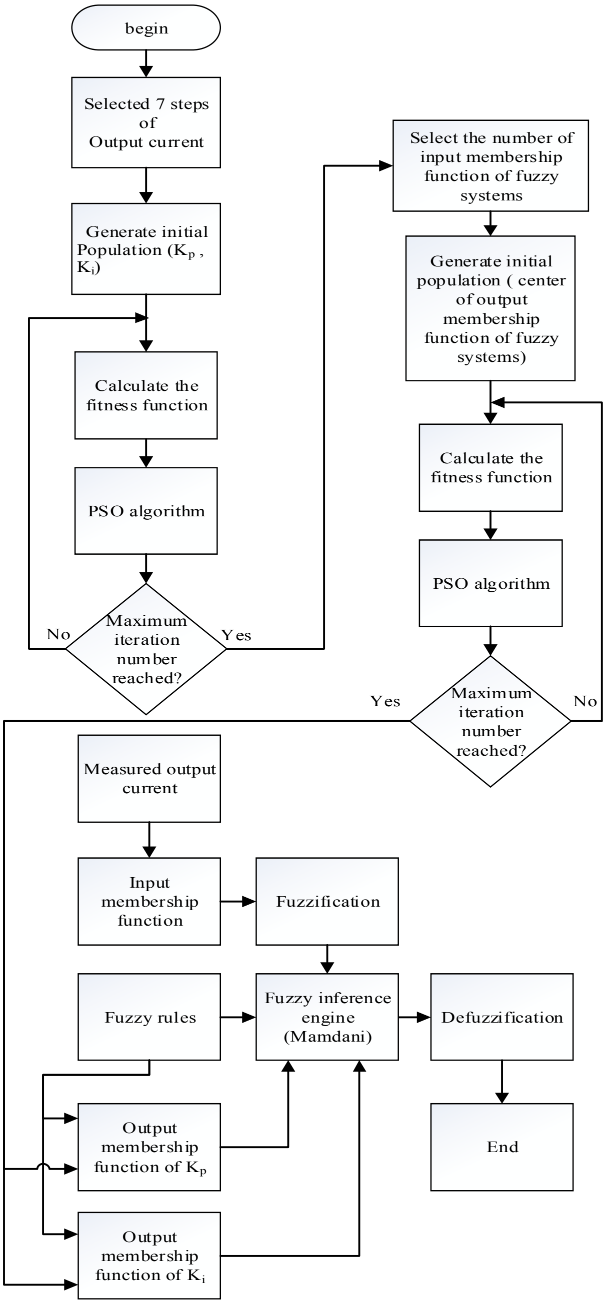
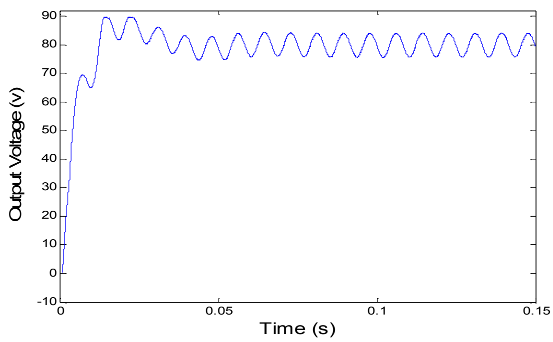
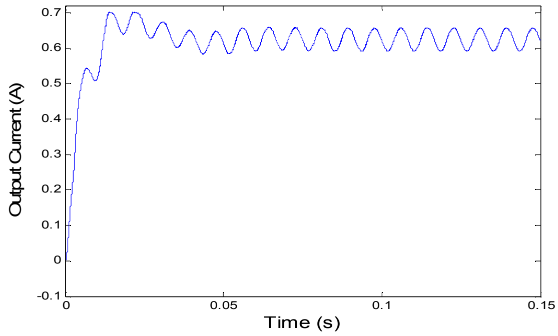


Fig.5. Flowchart of the proposed control method.

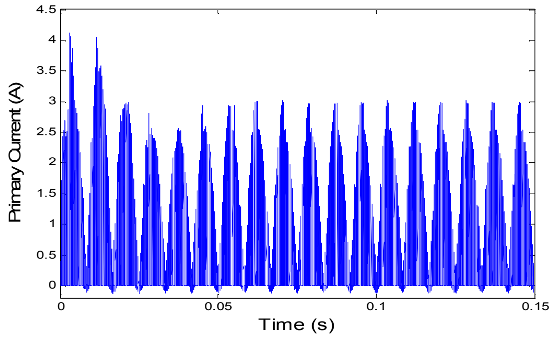


(a)

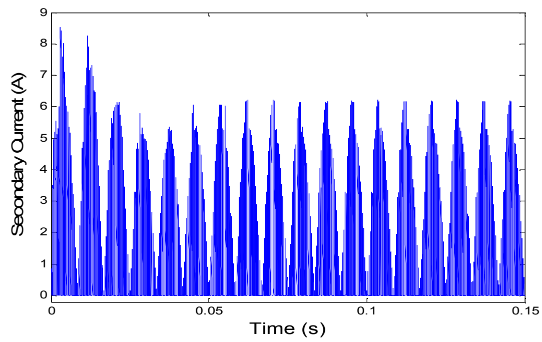


(b)

Fig.6. The output waveforms for 128 Ω output load. (a) The output voltage. (b) The output current.

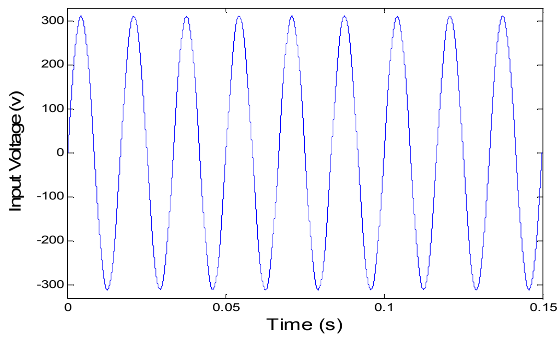


(a)

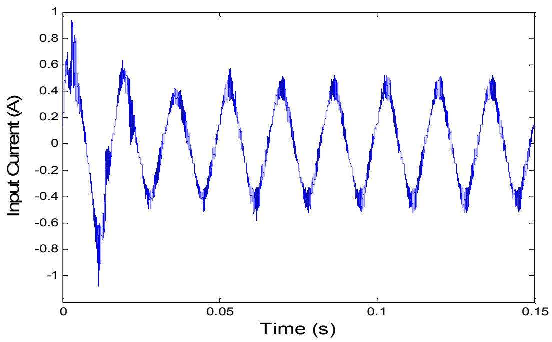


(b)

Fig.7. The waveforms of current of transformer. (a) The primary current. (b) The secondary current.

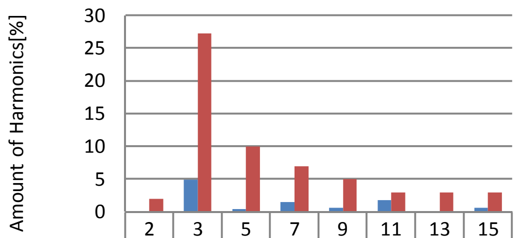


(a)



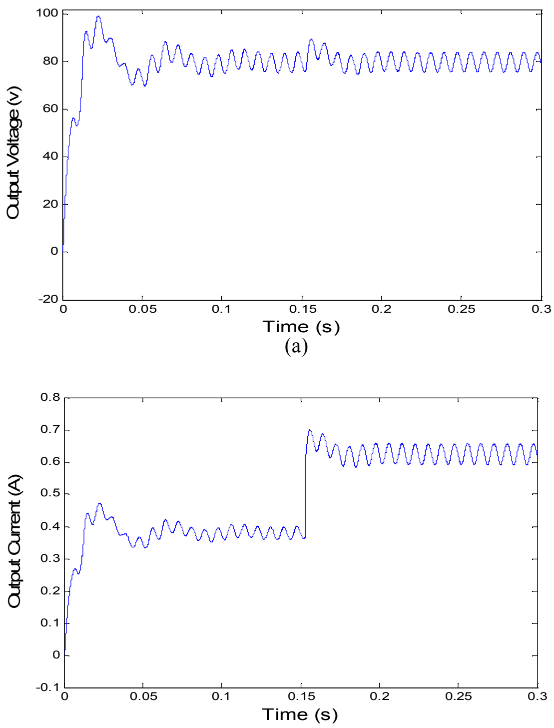
(b)

Fig.8. The input waveforms for 128 Ω output load. (a) The input voltage. (b) The input current.



	2	3	5	7	9	11	13	15
measurment [%]	0.05	4.98	0.49	1.53	0.67	1.8	0.1	0.61
IEC 61000-3-2 [%]	2	27.2	10	7	5	3	3	3

Fig.9. The spectrum of the input current.



(b)

Fig.10. The output waveforms for load changes from 210Ω to 128Ω. (a) The output voltage. (b) The output current.

IV. CONCLUSION

This paper presents a method for controlling the output current of a LED driver. The lifetime of LED drivers is highly limited by the ripples in the driving current. In this paper, by eliminating the electrolytic capacitors the lifetime of the driver is significantly increased. However, this increases the ripple in output current which consequently increases the peak-to-average ratio. In order to cope with this drawback, an optimal fuzzy PI controller is proposed to keep the value of the peak-to-average ratio of output current in a desired level. To this end, the PSO algorithm is used to derive the optimal parameters of seven PI controllers for different current load conditions. The derived data are used to train a Mamdani fuzzy system using PSO algorithm. The trained fuzzy system can calculate values of K_p and K_i of the main PI controller and it can control the system for different output current in range of 200 mA to 700 mA. The proposed controller is able to cope with sudden load changes and keep the peak-to-average ratio of output current on 1.05, that it is closer to ideal value. Meanwhile, the power factor of input current becomes 90.8%, the THD of input current is 11.88%, and the efficiency of the system reaches to 87.26% which all are satisfactory under IEC 61000-3-2 Class C standard.

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