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Current THD and Output Voltage Ripple Characteristics of Flyback PFC Converters with LED Lamp and Nonlinear RL Loads

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Abstract: This study analysed the characteristics of total harmonic distortion (THD) and output voltage ripple in a flyback PFC converter circuit under two different loads, which are the LED lamp modules and nonlinear RL loads. The converter was designed to step down the AC input voltage (90 V-265 V) to a DC output voltage of 80 V DC for both loads, each with an output power of 16 W. The main objectives were to observe and assess current THD and output voltage ripple for both loads using two different capacitances of the output capacitor, which are 2400 µF and 6 µF, respectively. The results demonstrated that using smaller capacitors (6 µF), it increased output voltage ripple, which it increased for the LED lamp load from 10% to 25% and for the nonlinear RL load it increased from 15% to 70%. However, with the same smaller capacitors (6 µF), it reduced current THD for both loads, which for the LED lamp load it reduced from 12% to 10.3%, and for the nonlinear RL load it reduced from 13.7% to 8.3%. From these results, with 2400 µF of the output capacitor, it provided better performance in terms of current THD and output voltage ripple for both load types.

Keywords: Flyback PFC converter, LED lamp load, nonlinear RL load, current THD, output voltage ripple

1. Introduction

Light-emitting diode (LED) lamps are becoming increasingly popular as a lighting source due to their energy efficiency, long lifespan, and low maintenance requirements. However, LED lamps are nonlinear loads, which means that their current waveform is not a pure sine wave [1]-[4]. This is because LEDs require a high-frequency current to operate. In addition, nonlinear loads, such as switching power supply, variable speed drive and electronic ballast resistive-inductive loads showing current waveform of not a pure sine wave as well [5].

The non-linear current waveform of LED loads and nonlinear loads can cause problems with power quality, such as low power factor, increased current THD and output voltage ripple. Increased current THD can cause problems with the power system, such as increased losses and decreased efficiency [1]-[5]. In addition, Increased output voltage ripple can cause problems with other equipment connected to the same power system, such as computers and motors [6], [7]. There are a number of ways to tackle the issues of current THD and output voltage ripple. One way is to use a power converter

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that can control the input current waveform. The power converter can be used to control the input current waveform of LED lamps and nonlinear loads by shaping it into a pure sine wave. This can help to reduce current THD and output voltage ripple.

Flyback PFC converters are one of the options that can be used for LED drivers because it has a transformer (galvanic isolation) that provides electrical isolation between the AC source and the output DC for safety purposes [8]-[11]. Depending on the transformer ratio or duty cycle, the output voltage of the flyback PFC converter can be stepped up or stepped down. Other advantages include ground separation from the utility grid, simple circuit configuration, ease of control and implementation, and low cost. However, combination of flyback PFC converters with LED lamp module load or other nonlinear loads cause low power factor (PF), high current total harmonic distortion (THD), and necessitates a bulky input and output filters.

The characteristics of the flyback PFC converter are investigated using two different loads, namely the LED lamp load and the nonlinear RL load. The output voltage of the flyback PFC converter is controlled by adjusting the transformer ratio and duty cycle. This converter using single switch topology and PWM switching signal is used to varies the duty cycle. An 18 W experimental prototype was considered to compare and observe the characteristics of voltage waveforms, current waveforms, current THDs and spectrum of current THDs.

2. Principle of Flyback PFC Converter

A flyback converter is a buck-boost converter with an isolation element that allows the output voltage to be stepped up and down. The flyback converter design improves on the buck-boost converter, which used two parallel inductors without changing the input-to-output voltage ratio. The two parallel inductors are used as an isolation element. Nonetheless, the two parallel inductors can be replaced with a transformer by changing the polarity of the secondary winding to obtain a noninverted output voltage. The operation of a flyback converter is similar to that of a buck-boost converter, except that the output voltage is always with positive polarity. Furthermore, if the main supply is AC source, the flyback converter can be integrated with a full-bridge rectifier (flyback PFC converter), Fig. 1.

Figure 2 depicts the DC gain characteristics of the flyback converter. To identify an appropriate duty cycle for a specific output voltage, the DC gain characteristic graph must be referred to in order to avoid the condition of zero output voltage or infinite output voltage, as shown in Fig. 2. Additionally, the following technical issues must be considered when designing a flyback converter: parasitic capacitance, leakage inductance, switching losses, EMI, snubber circuit, and design complexity [12]-[14]. If the converter operates outside of the operating conditions, a short circuit at the input side may occur and the converter circuit will not function correctly. Furthermore, the structure depicted in Fig. 1 consists of buck and boost operations, with the duty cycle for the buck operation must be less than 0.5 and the duty cycle for the boost operation must be greater than 0.5. Figure 1 shows the flyback PFC converter circuit with important parameters of input voltage V_{AC}, input current I_{AC}, output voltage V_{out}, output current I_{out}, input inductors L_1 and L_2, input capacitor C_1 and output capacitor C_o.

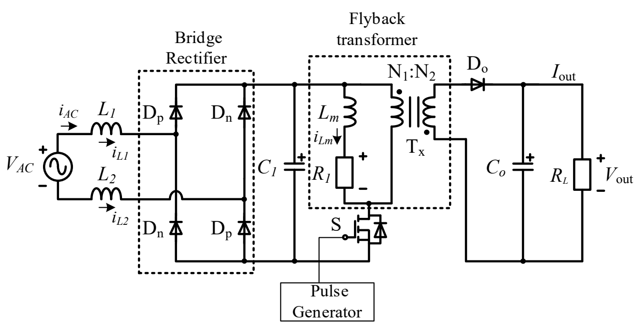


Fig. 1 - Flyback PFC converter

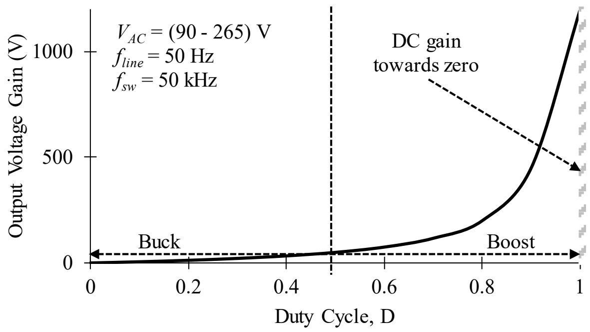


Fig. 2 - DC gain characteristics

The flyback PFC converter circuit as illustrated in Fig. 1 using a single switch topology for controlling output parameters. The first step in the operation of the flyback PFC converter is to convert the AC source into DC power by the bridge rectifier circuit. The DC power is then fed to the primary winding of the transformer through the switch. The switch is turned on and off in a controlled manner to regulate the output DC voltage. The three modes of operation of the circuit are illustrated in Fig. 3. Specifically, in mode-1, the input capacitor C_1 and primary winding of the transformer are charged and the output capacitor C_o is discharged to the load R_L. The energy stored in transformer is subsequently transferred to the output side in mode-2, i.e., the output capacitor C_o get charged and other part of energy is transferred to the load R_L. During mode-3, the switch S is turned off, allowing for the charging of the input capacitor C_1 and the transformer's primary winding in preparation for mode-1 operation. The process of transferring energy from AC source to output side will be referring to these 3 operation modes. Table 1 shows the expressions for determining the important parameters. Transfer function of the output voltage (V_o) is shown in Eqn. (1). Meanwhile, for the input inductor (L_1 and L_2), input capacitor (C_1) and output capacitor (C_o) parameters design, Eqn(s). (2), (3) and (4) are used.

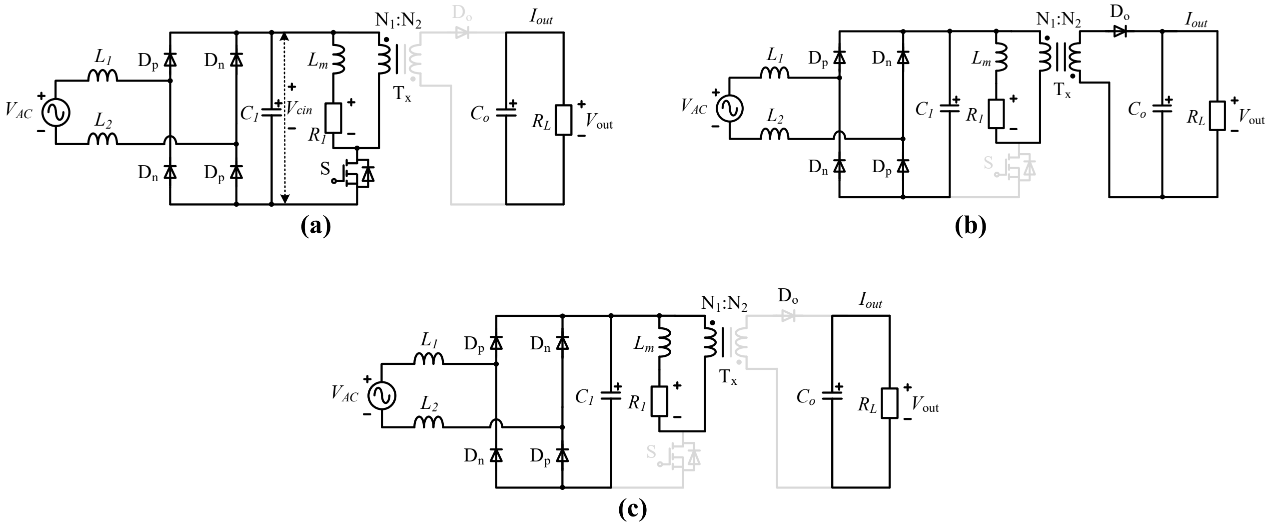


Fig. 3 - Equivalent circuit of flyback PFC converters operation modes (a) mode-1; (b) mode-2, and; (c) mode-3

Table 1 - Parameters

Parameter	Expression	
DC output voltage, V_{out}	$V_{out} = \frac{D}{1-D}\frac{N_s}{N_p}V_{AC}$	(1)
Input inductors, L_1 and L_2	$L_1 = L_2 = \frac{V_{AC}(t)\cdot D}{\Delta I_{Lx}\cdot f_{SW}}$	(2)
Input capacitor C_1	$C_1 \approx \frac{1}{2f_{Line}\cdot R\left(\Delta V_{out}/V_m\right)}$	(3)
Output capacitor, C_o	$C_o = \frac{P_o}{4f_{Line}\cdot V_o\cdot \Delta V_o}$	(4)

Table 2 - Specifications

Parameters	Values
AC Source Voltage, V_{AC}	90 - 265 V
DC Output Voltage, V_{out}	80 V
Output Power, P_{out}	16 W
Switching Frequency, f_{sw}	50 kHz
Line Frequency, f_{line}	50 Hz
Nonlinear RL load, R_L	400 Ω and 4 mH
LED lamp module load, LED	18 W
Input Inductors, L_1 and L_2	2 mH
Magnetization Inductor, L_m	42 μH
Input Capacitor, C_1	1 μF
Duty cycle, D	60%
Output Capacitor, C_o	6 μF and 2400 μF

3. Experimental Specifications and Results

The specifications of the flyback PFC converter are presented in Table 2. Due to limitation of the maximum current rating of 0.5 A, the output power is set at 16 W and AC voltage source is limited to between 90 V - 265 V with a fixed output voltage of 80 V. Switching frequency is fixed at 50 kHz with 60% of duty cycle. In addition, the allowable maximum output voltage ripple is limited to 25% from an average of the output voltage.

The experiments were conducted using both a LED lamp module and nonlinear RL loads, with a switching frequency of 50 kHz and a DC output voltage of 80 V. In this setup, variable voltage transformer was used. Two different output capacitors of 2400 μF and 6 μF were considered in this experimental setup to observe the current THD and output voltage ripple characteristics. Current THD data were measured and captured using power analyzer equipment. The experimental setup of the flyback PFC converter with LED lamp load is depicted in Fig. 4.

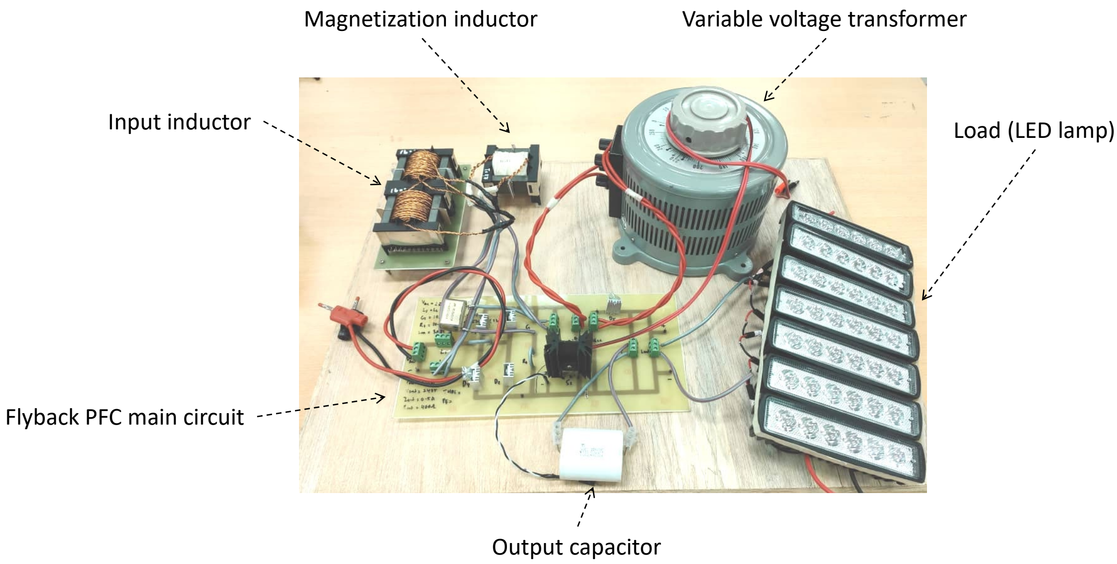


Fig. 4 - Experimental setup of the flyback PFC converter with LED lamp load

3.1 Voltage and Current Waveforms Characteristics without Output Capacitor

Figure 5 shows the output voltage V_{out} and output current I_{out} waveforms without an output capacitor connected in parallel with two different loads, a LED lamp module load and a nonlinear RL load.

For the LED lamp module load, the peak-to-peak AC current source is 0.56 A and the peak-to-peak AC voltage source is 250 V, as shown in Fig. 5(a). The maximum output voltage and output current are 80 V and 0.22 A, respectively. From these results, the output voltage ripple for the LED lamp load is 76 V (95%) and the output current ripple is 0.16 A (72.7%), as shown in Fig. 5(a). In addition, the output voltage waveform has positive and negative spike voltage noises. Thus, appropriate filtering circuits or components are required to filter out unwanted noises during operation when the LED lamp module load is considered.

Besides, for the nonlinear RL load, the peak-to-peak AC voltage source and peak-to-peak AC current source are 0.68 A and 322 V, respectively, as shown in Fig. 5(b). The maximum output voltage and output current are 90 V and 0.24 A, respectively. From the same waveform, the output voltage ripple is 88 V (25%) and the output current ripple is 0.16 A (66.67%). From these results, the output voltage has spike voltage noises on both the positive and negative sides. Thus, for the nonlinear RL loads, it requires appropriate filtering circuits or components to reduce or eliminate the voltage spike noises as well.

Furthermore, for one cycle of the output voltage ripple frequency is half of the line frequency for both loads. Thus, based on this condition, the size of the passive components for the filtering circuit can be smaller due to the output voltage ripple frequency becoming double from the line frequency.

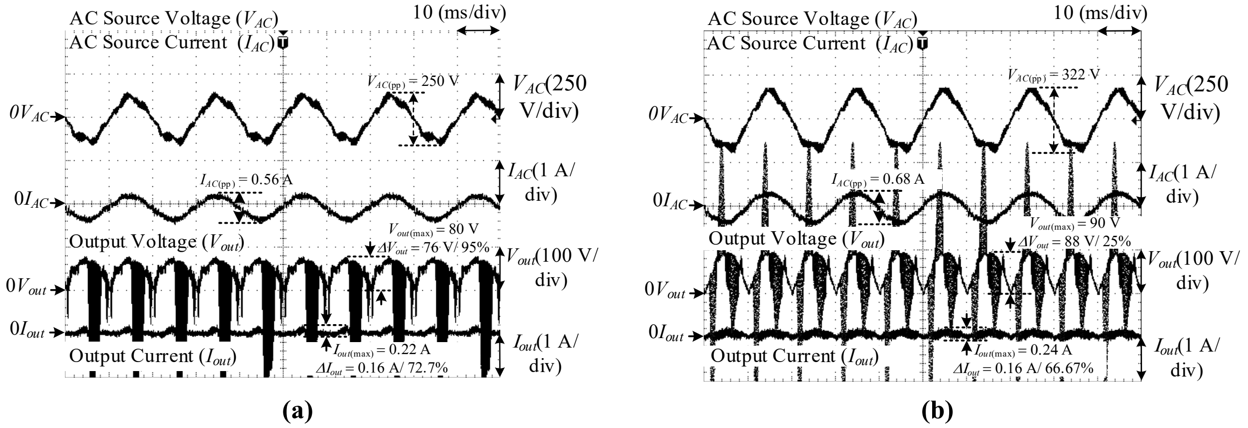


Fig. 5 - Voltage and current waveforms characteristics without output capacitor (a) LED lamp load; (b) nonlinear RL load

3.2 Voltage and Current Waveforms Characteristics with Output Capacitor Consideration

In order to observe reduction of the output voltage ripple and spike voltage noises for both loads (LED lamp module and nonlinear RL loads), two different output capacitors have been selected which are 2400 µF (electrolytic type) and 6 µF (film type).

In Fig. 6(a), the maximum output voltage and output current for the LED lamp module load are 80 V and 0.22 A, respectively. From Fig(s). 6(a) and 6(b), the output voltage ripple is reduced from 20 V (25% of the maximum output voltage) to 8 V (10% of the maximum output voltage) when the output capacitor is changed from 6 µF to 2400 µF. The output current ripple is also reduced from 0.2 A (91% of the maximum output current) to 0.12 A (60% of the maximum output current) with the same capacitor arrangement.

For the nonlinear RL load, the maximum output voltage and output current for the LED lamp module load are 80 V and 0.22 A, respectively as shown in Fig. 6(c). The output voltage ripple is reduced from 56 V (70% of the maximum output voltage) to 12 V (15% of the maximum output voltage) with the same capacitor arrangement as LED lamp load, from 6 µF to 2400 µF as shown in Fig(s). 6(c) and 6(d). Meanwhile with the arrangement of the capacitor, the output current ripple is also reduced from 0.24 A (75% of the maximum output current) to 0.08 A (22.22% of the maximum output current).

The output voltage and current ripples are almost eliminated for both loads when a 2400 µF output capacitor is used. However, an electrolytic capacitor of 2400 µF will cause higher equivalent series resistance (ESR) and poorer suppression of electromagnetic interference (EMI) compared to a film or ceramic capacitor, since a flyback PFC converter uses an active switch to operate.

The results of the experiment have confirmed that adding a larger capacitance of the capacitor in parallel with the load eliminates spike voltage noises and reduces output voltage ripple. The effectiveness of using different capacitors in reducing output voltage ripple and noise is highlighted in Figure 6. The capacitors to be used for filtering voltage ripple must be appropriately selected, and Eqn. (6) can be used to estimate the appropriate capacitance of the capacitor.

3.3 Input Current Harmonic Spectrum Characteristics for Current THD Observation

Figure 7 shows the spectrum of harmonic components for the input current of different loads (LED lamp load and nonlinear RL load) with different output capacitors (2400 µF and 6 µF). The third harmonic component is typically the most significant harmonic created by power converters, and it can cause non-sinusoidal input current, which can create harmonics in the power system.

In these results, the third harmonic component in Fig. 7(a) is 9.69% for the LED lamp load with a 2400 µF output capacitor. Meanwhile, in Fig. 7(b), the third harmonic component is reduced to 6.13% for the same load with a 6 µF output capacitor. These findings show that reducing the third harmonic component also reduces the current THD from 12% to 10.3% when the output capacitor is decreased.

For the nonlinear RL load as shown in Fig(s). 7(c) and 7(d), results of the current THD are reduced from 13.7% to 8.3% when the output capacitor is reduced from 2400 µF and 6 µF. In addition, the third harmonic component is reduced from 12.87% to 4.72% as well.

From these results it shows that, for both loads, the current THD will be reduced when smaller capacitance of the output capacitor is considered. At the same time, the third harmonic component is reduced as well, thus, with this condition the conductor heating, power factor (PF) and interference with communication signal problems can be improved.

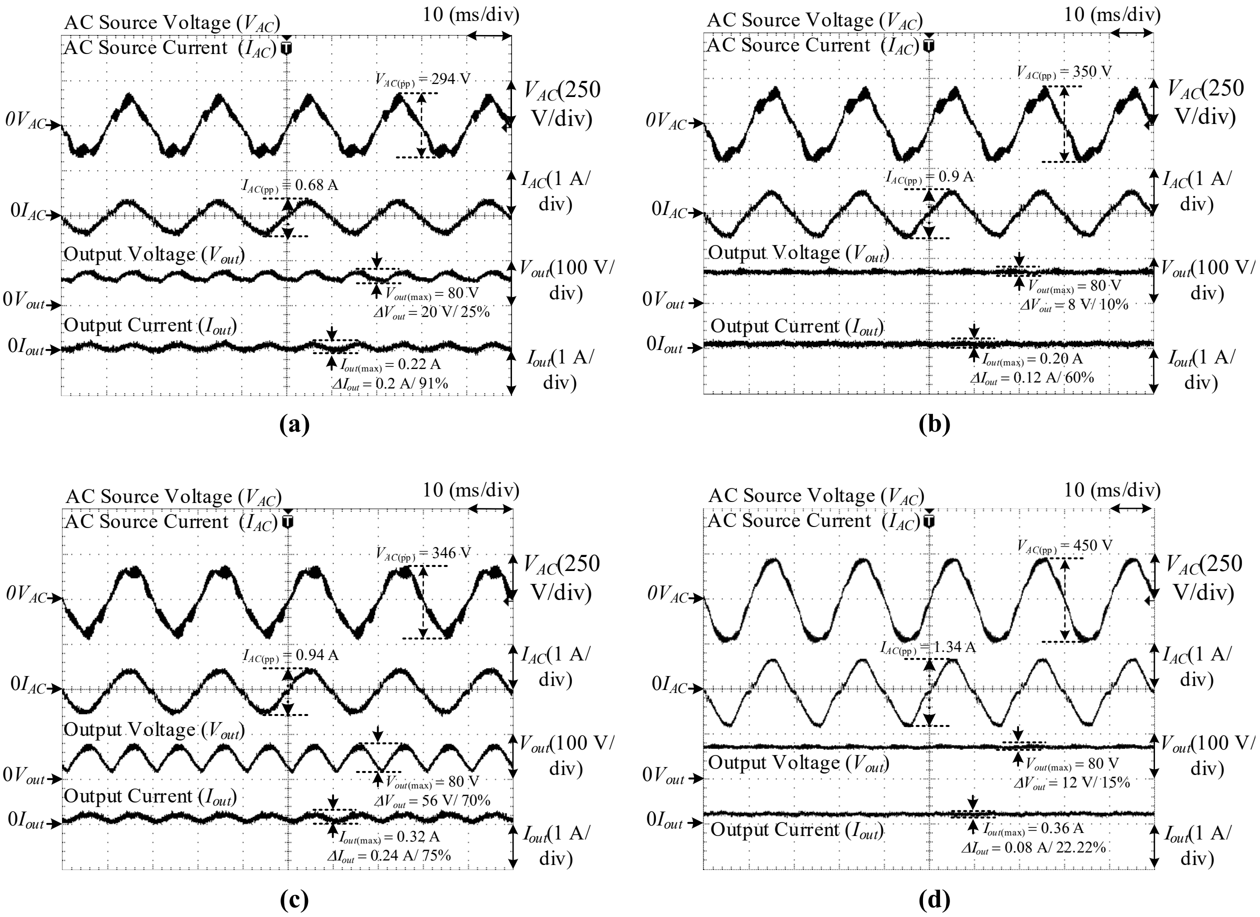
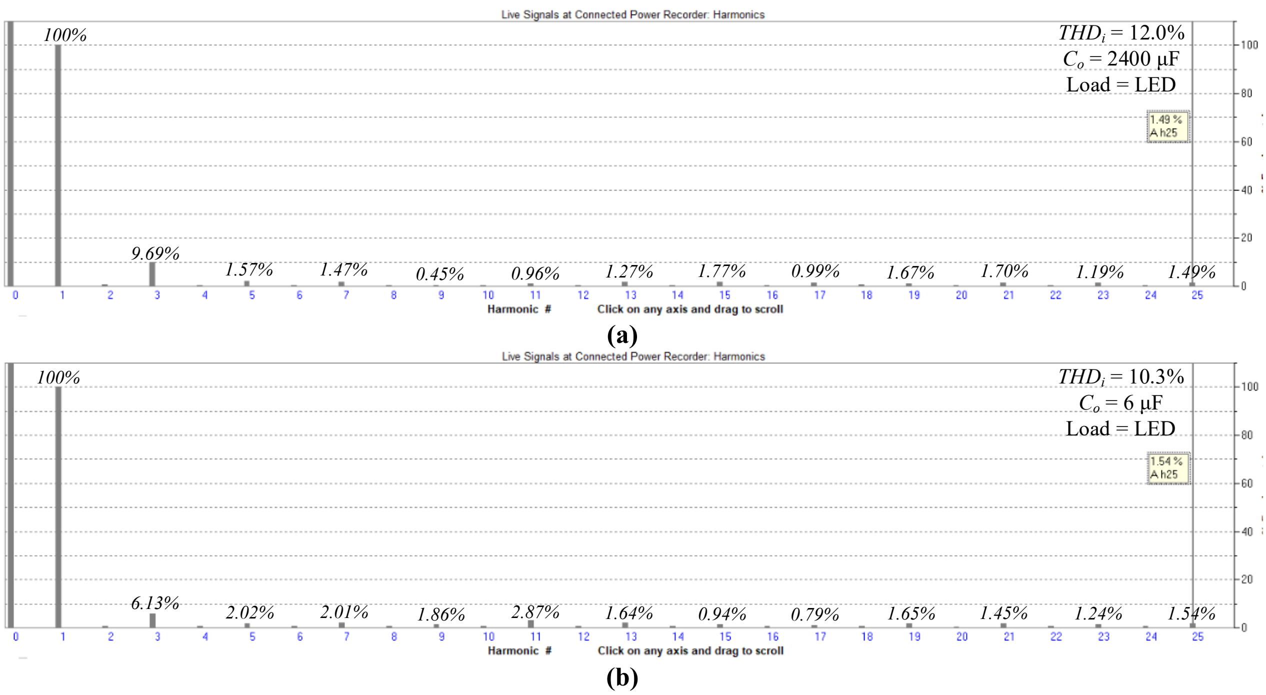
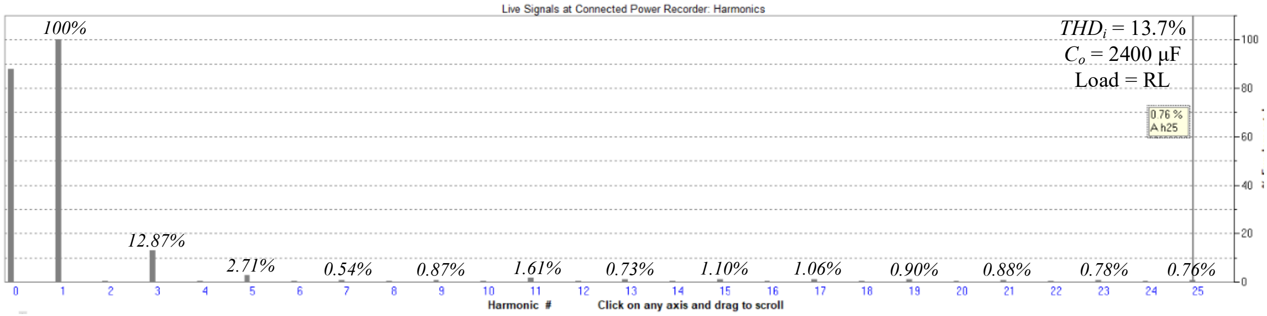
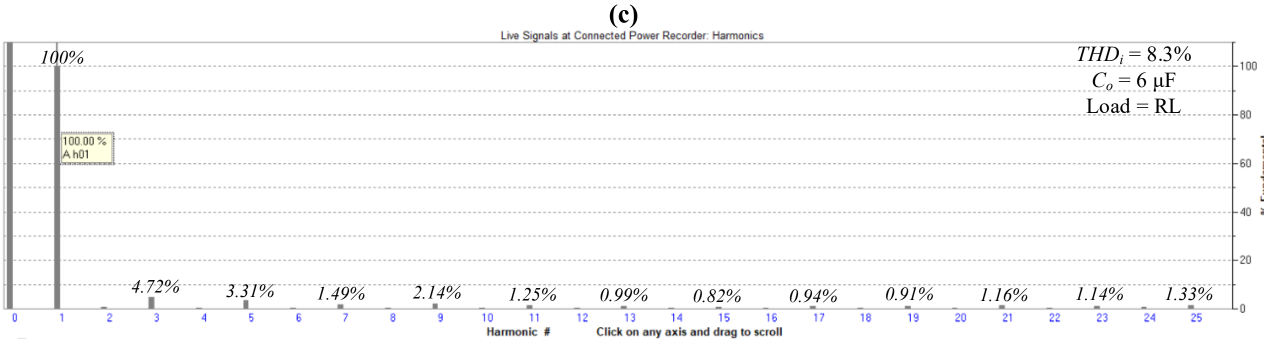


Fig. 6 - Voltage and current waveforms characteristics with output capacitor (a) LED lamp load with C_o = 6 µF; (b) LED lamp load with C_o = 2400 µF; (c) nonlinear RL load with C_o = 6 µF; (d) nonlinear RL load with C_o = 2400 µF





(c)



(d)

Fig. 7 - Harmonic spectrum of input current different output capacitors; (a) LED lamp load with C_o = 6 μF; (b) LED lamp load with C_o = 2400 μF; (c) nonlinear RL load with C_o = 6 μF; (d) nonlinear RL load with C_o = 2400 μF

4. Conclusion

This paper observes and accesses the characteristics of voltage waveforms, current waveforms, output voltage ripples, current THD and harmonic spectrum of input current with variation of load combinations using a flyback PFC converter as a power converter. In this study, two output capacitors with capacitances of 2400 μF and 6 μF, are considered as passive filter components at the output side. The output voltage ripple results show that the voltage ripple increases from 10% to 25% for LED lamp module loads, and for nonlinear RL loads, it increases from 15% to 70% when both loads are connected to the output capacitor in parallel, from 2400 μF to 6 μF, respectively. Meanwhile, the results show that the current THD is reduced from 12% to 10.3% for the LED lamp module load, and for the nonlinear RL load, it is reduced from 13.7% to 8.3% with the same arrangement of the output capacitor connected. From these results, it can be seen that the output voltage ripple is suddenly increased to 70% when a 6 μF output capacitor is used. Therefore, it shows that the loads connected with 2400 μF show better results in terms of current THD and output voltage ripple with 16 W of output power.

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