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Analyzing the Impact of Rectifier-based LED Lighting Fixtures on the Electrical Power Distribution System

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A B S T R A C T

The widespread use of single-phase rectifiers, particularly in residential buildings for LED lighting fixtures, has led to an increase in harmonics in power distribution systems. These harmonics pose significant challenges to power grids and require a thorough assessment of their impact on distribution networks. Therefore, the purpose of this work is to clarify how higher capacitance values at rectifiers' output, which are essential for reducing DC voltage waveform ripple, affect the quality of the input power supply. This study employs analyses and simulations conducted via MATLAB/Simulink to investigate the AC/DC converter circuit and its associated load. The analysis includes calculating output current and voltage ripples, as well as evaluating the total harmonic distortion (THD) in the input current with different capacitor values. The results highlight the adverse consequences of increasing filter capacitance values, which affect both the input current purity and the power factor. Notably, the THD showed a significant increase, reaching approximately 134%, with a low power factor of 0.5 when the output ripple voltage decreased from 307 V to 64 V using a capacitor filter of 1500 μF.

1. Introduction

Nonlinear loads, such as single-phase and three-phase rectifiers, whether controlled or uncontrolled, introduce a significant amount of lower-order harmonics into the electrical power distribution system. These harmonics can lead to voltage distortions at the common coupling point [1]. This is particularly problematic in weak microgrids with high source impedance, as the numerous harmonics in the source current cause disproportionate voltage drops across the source impedance, impacting the overall system.

Difffrent types of loads such as LED (light emitting diode) lighting loads or in general switch-mode power supply based devices, use rectifier circuits in the first stage to convert AC signals into DC signals [2][3]. In high-power applications, use of controlled power semiconductor devices like MOSFET or IGBT is needed with an additional sensor to regulate the output circuit voltage and the input current. However, such designs can be expensive [4]. For lower-power applications, uncontrolled rectifier circuits based on rectifier diodes with capacitive filters are commonly used. Filters are utilized to further enhance the output performance by eliminating ripples. In practice, two types of filters are commonly used in circuits: inductors or capacitors[5], with capacitors being the predominant choice. Interestingly, by increasing the capacitor value beyond a certain threshold, it is possible to achieve a DC output voltage equal to or greater than the transformer output voltage, resulting in a pure DC output without ripples [1]. In theory, using a high value capacitor is recommended to reduce ripple and achieve a more consistent voltage output. To ensure the proper functioning of LED lighting loads, it is crucial to maintain low DC output voltage ripple. However, the high value of the filter capacitor contributes to a high-quality DC output while simultaneously introducing significant harmonics into the input supply. Consequently, it is necessary to minimize the injection of harmonics into the power distruibution system [6]. Therefore, there are several studies conducted to reduce these harmonics that appear on the input current. In [7], Mokhtar, A., et al. developed a power factor correction (PFC) circuit for a single-phase LED driver for lighting Streets. They used a SEPIC PFC modulator with continuous conduction mode (CCM), achieving high efficiency and a wide power operating range while minimizing harmonic distortion. In [8], Vinod, K., et al. introduced a two-stage AC-DC drive circuit for powering LED lighting loads. The circuit comprisesa buck converter driven by a modified synchronous semi-bridgeless rectifier. The circuit incorporates voltage feed-forward control at the front end and the K factor control method at the back end to ensure stability. It is noteworthy that the proposed configuration meets the standards specified in IEC61000-3-2 for LED lighting loads connected to universal AC mains, achieving THD of less than 5% and nearly unity power factor. In [9], Wen, T. T., et al. introduce a novel PFC circuit tailored for LED lighting applications. Their innovative design integrates a forward converter with a multi-winding transformer flyback converter. The flyback converter operates in series with the rectified AC mains voltage to mitigate harmonic current distortion and achieve a high power factor. The results showed that the proposed circuit complies with the standards and has low current harmonics and a power factor close to unity over a universal input voltage range.

However, the majority of LED lighting fixtures in local markets lack a PFC unit, mainly due to economic constraints and market competition. To the best of the authors knowledge, the quality of LED lighting fixtures available in these markets has not been investigated. Therefore, this study aims to conduct an initial survey and testing of the power quality of selected LED lighting fixtures. In addition, the study attempts to elucidate the detrimental effects of rectifier-based LED Lighting Fixtures on the quality of the input power supply, particularly focusing on THD and PFC issues.The study investigates in detail the effects of capacitor filters used to reduce the voltage ripple of the rectified DC output on the input AC current.

In addition to this introduction, this paper contains four additional sections. Section 2 presents the theoretical foundations and equations required for the work. The proposed circuit is explained and presented in Section 3. The obtained results and corresponding discussions are included in Section 4. Finally, the last section concludes with references.

2. Harmonics and Power Factor in Nonlinear Circuits

A sinusoidal component of a periodic voltage or current waveform with frequencies that are an integral multiple of the fundamental frequency is referred to as harmonics. The fundamental frequency in the majority of systems is 50 Hz (such as Iraqi national power network). Voltage and current waveform distortion is the main issue with harmonics. There are multiple harmonic frequencies produced by nonlinear load such as

LED lighting devices. However, by taking the square root of the sum of the squares of all harmonics produced by a single load and dividing it by the value of the fundamental component at 50 Hz, we can determine the relationship between the fundamental and distorted waveforms. In fact, the Fast Fourier Transform Theorem (FFT) and some simple mathematical calculations allow us to achieve this.

THD percentage due to nonlinear current waveform is calculated using this formula. [10]:.

$$\%THD = \sqrt{(\frac{Is}{Is1})^2 - 1} \quad (1)$$

where Is stand for the rms value of the input total current, and I_s1 is the main frequency component is

In fact, THD measures the amount of harmonic distortion in a signal and serves to describe the electric power systems' power quality.

Input power factor (PF) is generally defined as the ratio of the active power (measured in W) to the apparent power (measured in VA) of an electrical load [11].

$$PF = \frac{Active\ power}{Apparent\ power} \quad (2)$$

When the voltage and current waveforms are both sinusoidal for linear circuits, the power factor is equal to the displacement factor (DF), which is the cosine angle between the voltage and the current.

$$PF = DF = COS\emptyset \quad (3)$$

In other words, nonlinear loads cause deviations from the sine waveform in current waveforms, resulting in the presence of harmonic components. This phenomenon can be expressed as follows:

$$i(t) = i_1(t) + ih(t) \quad (4)$$

where i_1 (t) is the instantaneous fundamental current and ih(t) is its associated harmonics.

Moreover, i_1 (t) can be written as:

$$i_1(t) = I_{1max}Sin(wt - \emptyset_1) \quad (5)$$

Where, $\emptyset_1$ is the angle between the fundamental of voltage waveform and the fundamental of current waveform.

Displacement power factor (DPF) is equal to $\cos\emptyset_1$. By taking into consideration such key components as:

$$Active\ Power = V_{(rms)} \times I_{1(rms)} \times cos\emptyset_1 \quad (6)$$

When calculating the active power, only the fundamental current component is taken into account. The apparent power can be deduced as:

$$Apparent\ Power = V_{rms} * I_{rms} \quad (7)$$

$$PF = \frac{I_{1rms}}{I_{rms}} cos\emptyset_1 \quad (8)$$

In fact,I_1rms/I_rms , is defined as distortion factor

Thus, PF can be derived in terms of THD as follows:

$$PF = \frac{COS\emptyset}{\sqrt{1+THD_i{}^2}} \quad (9)$$

$$PF = \frac{DPF}{\sqrt{1 + THD^2}} \quad (10)$$

In fact,I_1rms/I_rms , is defined as distortion factor

In fact, the last equation establishes that for a pure sinusoidal waveform, i.e. THD = 0, PF will be equal to displacement factor. However, for non-sinusoidal waveforms, the lesser the PF, the larger the THD.

3. Light-Emitting Diode (LED)

The light-emitting diode (LED), known for its compact size, high efficiency and long life, has become one of the most popular light sources[12]. Modern LEDs offer a lifespan of 50,000 to 60,000 hours [13] which is a stark contrast to the 1,000 hours typical of incandescent lamps. This remarkable property confirms the ability of LED technology to significantly reduce the energy consumption of electric light. When designing LED systems, it is important to consider compliance with technical specifications within practical constraints, including cost, form factors, reliability, power factor, harmonic distortion, and compliance with international regulations such as the Energy Star program, IEC 61000-3-2, and other mandated standards.

ENERGY STAR® Which includes aspects such as LED loading and AC-DC LED drive. This regulation distinguishes between two types of LED loads: LED lamps and LED lighting fixtures (so-called LED lamps), but also excludes some products such as semiconductor retrofits, high-beam lamps, street and outdoor lighting, and party or entertainment lighting. However, they include a wide range of LED lighting products designed for both residential and commercial environments. Rated life and power factor (PF) stand out as the most restrictive constraints, with total luminaire input power ≥ 5 W: PF ≥ 0.5. Total luminaire input power > 5W: PF ≥ 0.7.

Harmonic injection standard, IEC 61000-3-2 In order to maintain the quality of the network and prevent its deterioration, the International Electrotechnical Commission (IEC) has introduced various regulations aimed at limiting the injection of low-frequency harmonics from electronic devices into the network. In this context, compliance with the IEC 61000-3-2 standard, which limits the injection of harmonics into devices with input currents of ≤ 16 A per phase, is considered an essential requirement when developing AC-DC LED drivers for this application area [3]. In single-phase AC power grids, lighting equipment is classified as Class C, specifying limits for current harmonics. For instance, the third harmonic current, expressed as a percentage of the fundamental current, should not exceed 86%, and the fifth harmonic current should not surpass 61%.

4. Modeling and Simulation of Full-bridge Diode Rectifier

The single-phase diode full-wave rectifier changes AC current into DC current. By converting both the positive and negative portions of the AC waveform, a full-wave rectifier converts all input signals into a signal with a constant positive value at its output[14]. Uncontrolled full-wave rectification of the load is achieved by using four diodes (D1,D2,D3, and D4), as shown in Figure. 1.

During each half cycle, only one pair of diodes conducts, and these diodes are connected in pairs in series. A typical AC-DC power supply interface includes a rectifier in conjunction with a filter capacitor. The filter capacitor efficiently minimizes the ripple in the output voltage waveform.

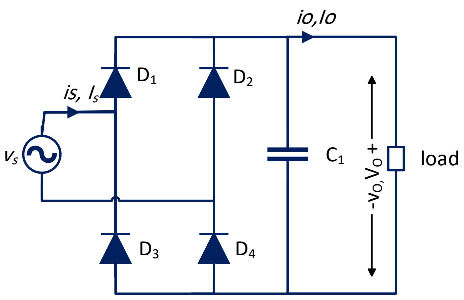

Fig 1. Full-wave bridge rectifier circuit.

The initial state of the capacitor is uncharged. During the first quarter cycle, diodes D1 and D4 are forward biased, initiating charging of the capacitor. Charging continues until the input voltage Vs reaches its maximum value[15]. The capacitor voltage Vo begins to increase. As soon as the input voltage falls below Vs, the voltage of the capacitor exceeds the input voltage, causing the diodes to turn off. When the diodes are turned off, the capacitor discharges across the load resistor, supplying the load current Io until the next peak value is reached. When the subsequent peak occurs, diodes D3 and D4 temporarily conduct and charge the capacitor to its maximum value.

Figure 2 shows the modeling of a uncontrolled single-phase diode rectifier with a filter capacitor using MATLAB/Simulink software. In fact, simulation experiments with different capacitance values to observe how they affect the output waveform and input current are conducted. In this circuit, an AC power supply of Vs=220V (RMS) value is used along with a full wave bridge rectifier circuit. The equivalent LED loads is represented with a resistive load. A filter capacitor with different capacitance values is connected in parallel with the load, covering the range from 100 µF to 1500 µF in increments of 100 µF for each test. Initially, the test began with a capacitance value of zero, and then the capacitance value was incrementally increased to analyze its impact on both the input and output sides.

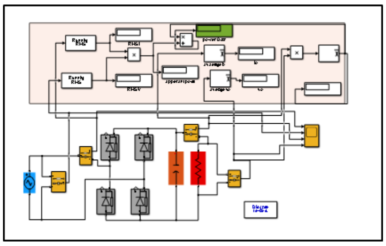

Fig 2. Modeling of the single phase diode rectifier with filter capacitor.

5. Results and Discussions

The following subsections present the results and introduce their discussion to underline the main findings of the paper.

The Impact of filter capacitor. Figure 3 and Figure 4 respectively show the input supply current and its spectrum and the output load voltage and its current for the case without using a filter capacitor. The output waveform exhibits noticeable fluctuations, reaching peak-to-peak ripple value of 307V ΔV (Vmax-Vmin) with ripple factor equal to 0.49%, and maintains an average load voltage of 196V. Meanwhile, the input current takes on a purely sinusoidal shape with an almost negligible THD. This observation underscores the significance of filter capacitors in mitigating voltage ripple and stabilizing the output voltage, thereby enhancing the overall quality of the power supply.

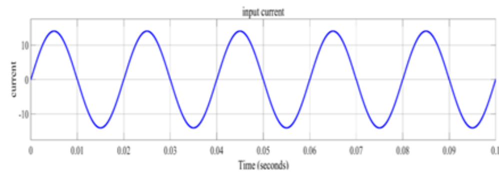

Fig 3.a. Modeling of the single phase diode rectifier with filter capacitor.

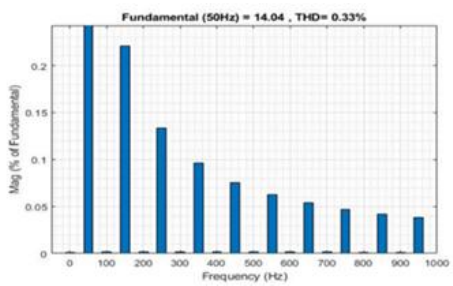

Fig 3.b. FFT analysis of the input current without filter capacitor.

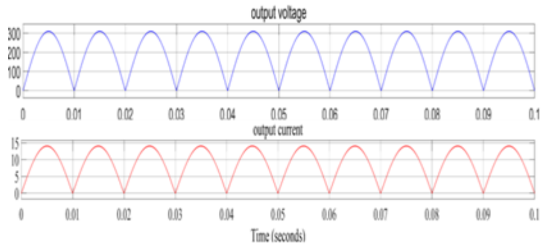

Fig 4. Output voltage and its current without filter capacitor.

Figure. 5 and figure. 6 respectively show the input supply current and its harmonics and the output load voltage and its current when using a 1000 µF filter capacitor. The peak-to-peak ripple value ΔV reaches 86V with a ripple factor of 0.1%, and the input current has a distorted sinusoidal shape with about 115% THD. It can also be observed that the proportion of the third harmonic dominates over the harmonic components with a value of around 82%. This value was measured as a percentage of the peak fundamental component, which corresponds to 23.83 A, as in Figure. 5-b. Due to the waveform similarity along the x-axis, only the odd harmonics appeared.

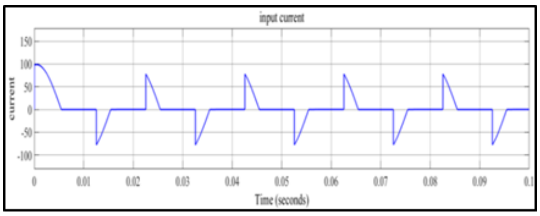

Fig 5.a. Input current with filter capacitor 1000 µF.

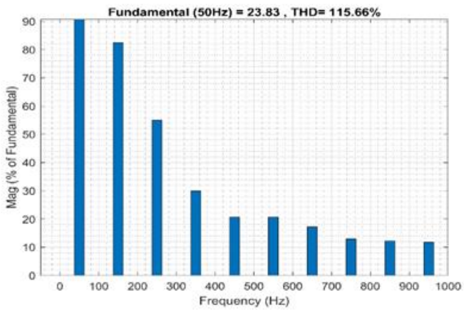

Fig 5.b. Input current and FFT analysis with filter capacitor 1000 µF.

Shown below Figure 6 output voltage and current with filter capacitor1000 µF.

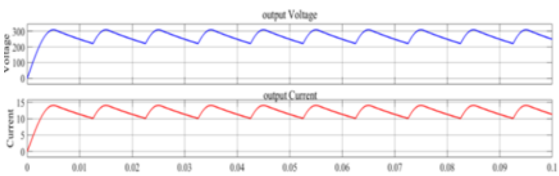

Fig 6. Output voltage and current with filter capacitor1000 µF.

On the other hand, Figures 7 and 8 show the input supply current and its harmonics as well as the output load voltage and output load current when using a 1500 µF filter capacitor. The peak-to-peak ripple value reaches 64V (Vmax-Vmin) with a ripple factor of 0.07%, while the input current has a distorted sinusoidal shape with THD of about 134%. In addition, it is worth noting that the third harmonic predominates among the harmonic components, accounting for about 88% of the peak fundamental, shown at 24.94 A in the figure. 7-b.

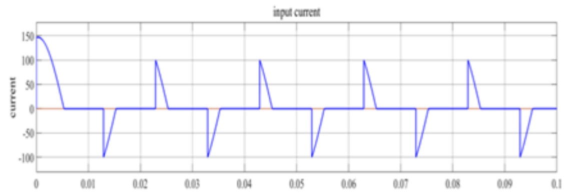

Fig 7.a. Input current with using value an Capacitor value of 1500µF.

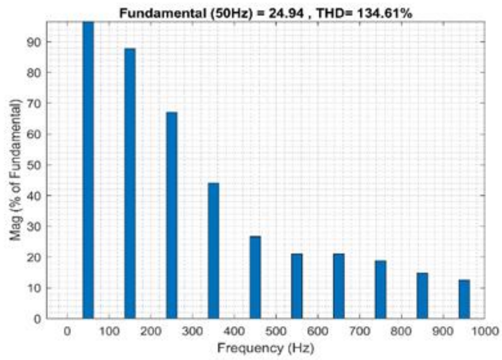

Fig 7.b. Input current and FFT analysis with filter capacitor 1500 µF.

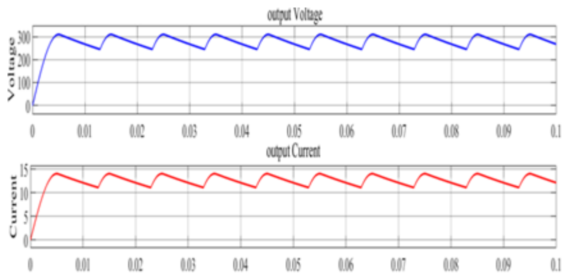

Fig 8. Output voltage and current using an capacitor value of 1500 µF.

From the figure above, it can be seen that the ripple in the output waveform is less than in the previous case, that is, when the amplitude was 1000 µF. In summary, increasing the filter capacitors reduces the output voltage ripple while simultaneously increasing the THD% and reducing the input power factor (PF). Therefore, selecting the appropriate capacitor filter value requires careful consideration to find a balance between input distortion and output voltage ripple.

Table (1) summarizes the various values of capacitor, average output current, average output voltage, root mean square for voltage and current, THD, ΔV(vmax-vmin), ripple factor, displacement angle Φ, peak value of the fundamental and third harmonics for the input current. Displacement power factor (DPF) and input power factor (PF).

Table 1. Result analysis of Diode Bridge and capacitor filter.

Capacitor Value (μF)	I_O average (A)	$V_{O,average}$ (V)	$I_{0\ RMS}$ (A)	$V_{o\ RMS}$ (V)	$I_{S\ RMS}$ (A)	%THD_{IS}	ΔV(V)	Ripple factor	∅(deg)	%I1 (A)	%I3 (A)	DPF	PF
0	8.926	196	9.93	218.5	9.931	0.33	307	0.49	0.2	14.04	0.22	0.99	0.99
100	9.264	203.8	10.03	220.5	11.58	26	252.6	0.4	24.8	15.77	17.62	0.9	0.87
200	9.868	217.1	10.36	227.8	14.22	49	205.8	0.31	31.1	17.84	39.4	0.85	0.76
300	10.41	229	10.74	236.2	16.74	64	175.3	0.25	32.1	19.39	53.3	0.84	0.71
400	10.85	238.6	11.06	243.7	19	76	154.3	0.2	31.7	20.53	62.31	0.85	0.67
500	11.19	246.2	11.38	250	21.06	85	132.2	0.17	30.8	21.41	68.4	0.85	0.65
600	11.47	252.4	11.6	255.3	22.97	93	121.9	0.176	29.8	22.1	72.79	0.86	0.63
700	11.7	257.4	11.8	259.7	24.67	99	108.9	0.133	28.8	22.66	76.1	0.87	0.62
800	11.89	261.6	11.98	263.5	25.48	105	101.9	0.12	27.9	23.11	78.69	0.88	0.6
900	12.05	265.2	12.13	266.8	28.12	110	92.7	0.11	27	23.5	80.77	0.89	0.59
1000	12.19	268.2	13.25	269.6	29.72	115	86	0.1	26.2	23.38	82.47	0.89	0.58
1100	12.31	270.9	12.36	272	31.28	120	80.6	0.09	25.5	24.11	83.9	0.9	0.57
1200	12.42	273.2	12.46	274.2	32.82	124	76.4	0.085	24.8	24.36	85.11	0.9	0.56
1300	12.51	275.2	12.55	276.1	34.33	127	71.7	0.08	24.2	24.58	86.14	0.91	0.56
1400	12.59	277.1	12.63	277.8	35.82	131	67.9	0.071	23.6	24.77	87.04	0.91	0.55
1500	12.67	278.7	12.7	279.4	28.12	134	64	0.07	23	24.94	87.84	0.92	0.55

Figure 9 shows the relation of Vo, PF, ΔV and THD% /100, i.e. THD with the varation of capacitor values As the capacitance increases, THD also increases, reaching 1.34, i.e THD%= 134%.

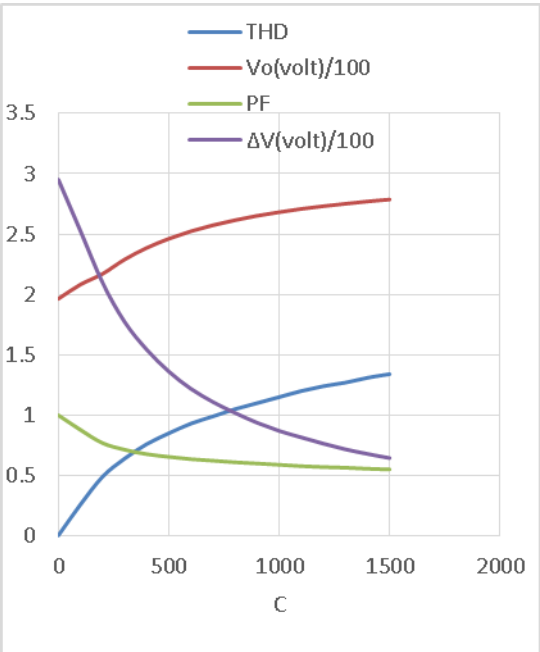

Fig 9. Varaition of THD, Vo, PF, and ΔV with filiter capacitor values.

The relationship between input power factor (PF) and the filter capacitance is inverse. As capacitance increases, the power factor decreases. With zero capacitance, the PF approaches unity. However, when the capacitance value reached 1500°F, the PF decreased to 0.55 from 0.9 before adding capacitance. In addition, increasing the capacitance value causes the average output voltage to rise, reaching 278.7V at maximum capacitance. The output ripple decreases as the filter capacitance increases, eventually reaching about 64 volts from 307 volts when the capacitance was zero. These observations provide valuable insights into the interaction between these variables within the circuit.

Field Survey. While the rectifier circuit presented is straightforward, it finds extensive use in various applications. LED lighting fixtures, particularly those with lower power ratings, are prominent practical examples. Given the widespread use of LED fixtures today, a field survey utilizing the AEMC Instruments power quality meter model 8220 was conducted. This survey encompassed various brands of LED lighting fixtures with varying power levels, accessible in the local market of Mosul city. The outcomes of the field surveyrevealed that a majority of the assessed luminaires, particularly those rated below 25 watts, Demonstrated poor quality, surpassing THD limits, and low PF. Table 2 summarizes the brands and their respective nominal power for 37 survey samples of various LED lighting fixtures with power levels below 25W.

Table 2. Samples of the field survey.

Sample No.	LED lighting fixture Brand	Nominal power (watt)
1	AIKO	5
2	S0UL	3
3	AIKO	6
4	HALLEY STAR	5
5	VIP	7
6	HALLEY STAR	7
7	QUANTA	7
8	B.G	9
9	QUANTA(Mayar)	9
10	HOROZ ELECTRIC	10
11	Braytron	10
12	DRD	12
13	VIP	12
14	HALLEY STAR	12
15	B.G LED LAMP	15
16	VIP	15
17	DRD	15
18	VETRA	16
19	VIP	18
20	HALLEY STAR	18
21	QUANTA(Jasmine)	18
22	QUANTA(Mayar)	18
23	BG	18.
24	MJD	18
25	DF	20
26	DRD	20
27	VIP	20
28	VETRA	20
29	energetic	21
30	BG	24
31	QUANTA(Mayar-A)	24
32	HALLEY STAR	24
33	ENZO	22
34	VIP	24
35	GIVIS-PP	24
36	FSE	24
37	24W	24

As shown in Figures (10) and (11) respectively, the power factor and THD of the tested samples vary from one sample to another depending on the performance of these installations and their manufacturer. Power less than 25 watts has a low power factor, poor quality, and high harmonic distortion, and power more than 25 watts has a better power factor, lower harmonic distortion, and better quality, as shown in the figures above. In fact, most of the lighting fixtures available in the market are of poor quality for reasons of price.

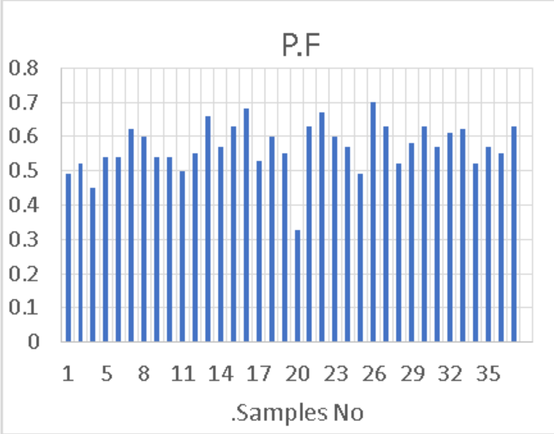

Fig 10. PF for different samples of of LED lighting fixtures.

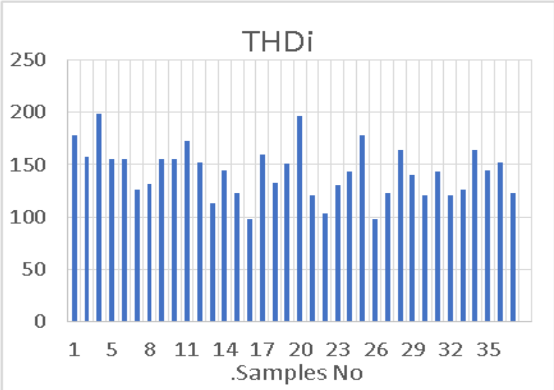

Fig 11. THD for different samples of LED lighting fixtures.

6. Conclusion

Using capacitor filters in an AC-DC converter is a common method to enhance the quality of the DC output voltage. These filters effectively smooth out the pulsating DC voltage, resulting in a more stable and less flickering output voltage, which is particularly beneficial for powering LED lighting fixtures. It is important to note that the efficacy of the filter increases with a higher capacitance value. The presented study revealed the detrimental effects of increasing filter capacitance values, impacting both input current purity and power factor. However, these findings can be expressed quantitatively to enhance the precision of the conclusion. For instance, THD exhibited a notable rise, reaching approximately 134%, while the power factor decreased to 0.5 when the output ripple voltage was reduced from 307 V to 64 V with a capacitor filter of 1500 μF. Therefore, selecting the appropriate capacitor filter value requires careful consideration to strike a balance between input distortion and output voltage ripple. Additionally, the survey results and tests conducted on available LED lighting fixtures in the Mosul city markets revealed poor quality for the majority of them. Consequently, there is a pressing need for stricter quality monitoring of imported devices by authorized entities.

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Competing Interests

There are no competing interests.

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