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Study of Load Side Harmonics Sources Effects and Elimination

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Abstract

The power quality problems in power utility distribution systems are not new, but recently their effects have gained public awareness. Advances in semiconductor device technology have fuelled a revolution in electronics and power electronics over the past decade, many factories and heavy loads which are recently installed highly affect power quality due to their non-sinusoidal current. In this paper different harmonics sources such as electric ballast, magnetic ballast, vapor mercury, halogen spot light and halogen with dimmer and their effects and two methods of harmonics elimination are studied. The results obtained show that at incidence of harmonics the currents waveform are not sinusoidal, THD values are out of limits, there is a set of high order harmonics, the current values are higher and power factor is lower. However, the results obtained when the harmonics are eliminated show that THD values are reduced, the currents values are reduced, the power factor is improved and values of current harmonics orders are reduced.

1. Introduction

The objective of the electric utility is to deliver sinusoidal voltage at fairly constant magnitude throughout their system. This objective is complicated by the fact that there are loads on the system that produce harmonic currents. These currents result in distorted voltages and currents that can adversely impact the system performance in different ways. As the number of harmonic producing loads has increased over the years, it has become increasingly necessary to address their influence when creating any additions or changes to an Installation.

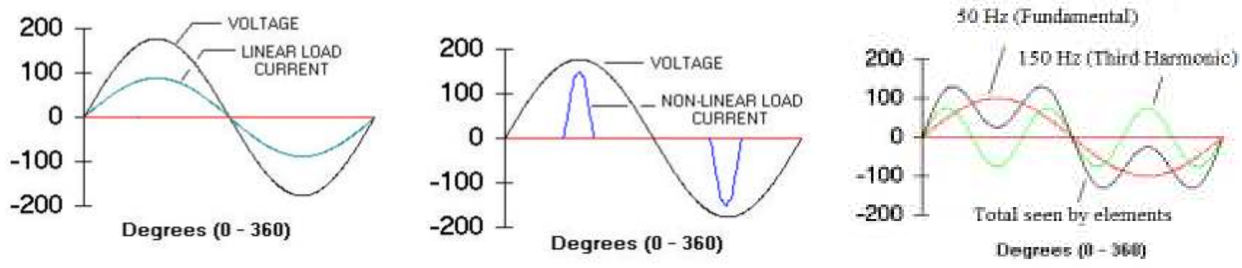
Power electronics equipments are responsible for raising the power quality problems. These nonlinear loads appear to be prime sources of harmonic distortion in a power distribution system. Harmonic currents produced by nonlinear loads are injected back into power distribution systems through the point of common coupling (PCC). As the harmonic currents pass through the line impedance of the system, harmonic voltages appear, causing voltage distortion at the PCC [1], [2], [3].

Harmonics have a number of undesirable effects on the distribution system. They affect both technically and economically. They increase resistive losses and eddy current and hysteresis losses. Also, harmonics worsen the load power factor. In addition, the harmonic currents produced by nonlinear loads can interact adversely with a wide range of power system equipment, most notably capacitors, transformers and motors causing additional losses, overheating and overloading [4]. Presence of harmonics requires increasing the conductors' size and circuit breaker capacity. Presence of harmonics in power system limits the system capacity.

2. Linear and Non-linear Loads

A linear element in power systems is a component that draws a current waveform which is same as the voltage as shown in Figure (1-a). On the other hand, the current waveform on a non-linear load is not the same as the voltage as shown in Figure (1-b). Typical examples of non-linear loads include rectifiers, uninterruptable power supply (UPS) units, discharge lighting, adjustable speed motor drives, electric ballast, vapor mercury, halogen spot light, halogen with dimmer and arcing equipment.

The current drawn by non-linear loads is not sinusoidal but is periodic. Periodic waveforms can be described mathematically as a series of sinusoidal components that have been summed together as shown in Figure (1-c). The sinusoidal components are integer multiples of the fundamental (50 or 60 Hz). The only way to measure a voltage or current that contains harmonics is to use a true-RMS reading meter.



(a) (b) (c)

Figure (1) Waveforms of linear, nonlinear and the symmetrical harmonic components

Symmetrical waves contain only odd harmonics and un-symmetrical waves contain even and odd harmonics. A symmetrical wave is one in which the positive portion of the wave is identical to the negative portion. An un-symmetrical wave contains a DC component or the load is such that the positive portion of the wave is different than the negative portion. An example of un-symmetrical wave would be a half wave rectifier.

Most power system elements are symmetrical. They produce only odd harmonics. There are exceptions, and normally-symmetrical devices may produce even harmonics due to component mismatches or failures. Arc furnaces are another common source of even harmonics but they are notorious for producing both even and odd harmonics at different stages of the process.

3. Harmonics Measurement Indices

They give full idea about the level of harmonics in the power system, comparing values of these indices with the standards [5], the state of the system can be determined. The Total Harmonic Distortion (*THD)* is the Total Harmonic Distortion of Voltage (THD_V) and current (THD_I) which are given by (1) and (2). In case of pure sinusoidal waves $THD_V = THD_I = 0$.

$$THD_V = \frac{\sqrt{\sum_{n=2}^{\infty} V^2(n)}}{V_{(1)}} \tag{1}$$

Where:

$V_{(1)}$ Is the rms value of voltage with the fundamental frequency.

$V_{(n)}$ Is the rms value of voltage with the harmonic frequency.

$$THD_I = \frac{\sqrt{\sum_{n=2}^{\infty} I^2(n)}}{I_{(1)}} \tag{2}$$

Where:

$I_{(1)}$ Is the rms value of current with the fundamental frequency.

$I_{(n)}$ Is the rms value of current with the harmonic frequency.

The distortion power (*D*) produced by load nonlinearity, It is given by (3), in case of being free of harmonics *D* = 0.

$$D = \sqrt{S^2 - P^2 - Q^2} \quad (3)$$

Where:
S Is the apparent power (kVA).
P Is the active power (kW).
Q Is the reactive power (KVAR).

The Distortion Factor (*DF) i*s the ratio of distortion power *D* to the apparent power *S*, the distortion factor is given by (4), in case of being free of harmonics *DF* = 0.

$$DF = \frac{D}{S} \quad (4)$$

The Power Factor Ratio (*PFR)* is the ratio of the fundamental power factor (DPF) and the total power factor (TPF), both fundamental and total power factors are given below, in case of being free of harmonics *PFR* = 1.0.

$$PFR = \frac{DPF}{TPF} \text{ Where } DPF = \cos\varphi_{(1)} = \frac{P_{(1)}}{U_{(1)} \,.\, I_{(1)}} \text{ and } TPF = \frac{P}{S} \quad (5)$$

The Crest Factor (CF) is the ratio between the maximum value of the voltage(V_m) or current(I_m) to the RMS value of the voltage(V_{rms}) or current(I_{rms}). In case of being free of harmonics *CF*= $\sqrt{2}$

$$CF_V = \frac{V_m}{V_{rms}} \quad (6)$$

$$CF_I = \frac{I_m}{I_{rms}} \quad (7)$$

4. Load Side Sources of Harmonics

Many types of non-linear loads appeared and their usage rate increased rapidly. Non-linear loads such as rectifiers, power supplies, UPS units, TV's, Video recorders, Computers, Printers, Micro wave ovens, discharge lighting, adjustable speed motor drives, electric ballast, vapor mercury, halogen spot light, halogen with dimmer and arcing equipment became widely used these days besides the rapid increase of the industrial non-linear loads such as that in metal factories. In this paper different types of non-linear loads are considered, different measurements have been made, wave forms and spectrum of different harmonic orders have been shown for each of the non-linear loads considered.

The experimental works have been performed in the Advanced Power Systems and Control Laboratory, Sudan University of Science and Technology. Different types of sources have been studied, effects of harmonics have been investigated and two harmonics eliminations methods have been applied. A power analyzer device has been used to obtain all required measurements.

4.1. Dimmer Controlled Halogen Lamp

Figure (2) shows a dimmer controlled Halogen lamp (150 W, 230 V) supplied by a sinusoidal voltage source. The dimmer firing angle set to ($\alpha = 90^\circ$). Figures (3-a) and (3-b) show the current waveform and the spectrum of harmonics. Table (1) shows values of the current, *I*, *THD_I, CF_I, DF, FPF, TPF and PFR.*

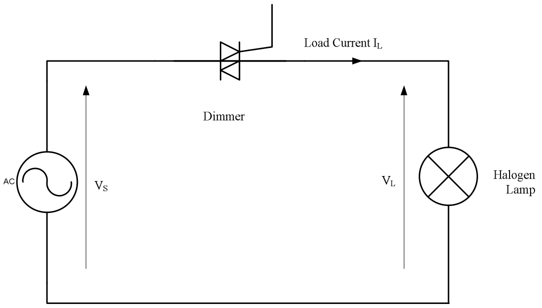


Figure (2) a dimmer controlled Halogen lamp supplied by a sinusoidal voltage source

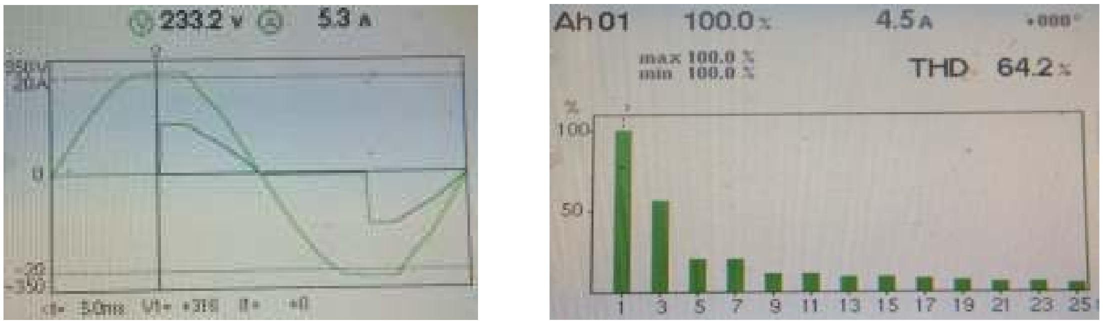


Figure (3-a), (3-b) current and voltage wave forms and current harmonics spectrum

Table (1) Values of the Readings

V(V)	I(A)	THD_I	CF_I	P(W)	Q(VAR)	S(VA)	D(VAD)	DF	DPF	TPF	PFR
233.2	0.53	64.2	2.0	90	55.8	125.2	66.8	0.53	0.85	0.71	0.84

4.2 Vapor Mercury Lamp

Figure (4) shows a Vapor mercury lamp (80 W, 230 V) supplied by a sinusoidal voltage source. Figures (5-a) and (5-b) show the current wave form and the spectrum of harmonics. Table (1) shows values of the current, *I*, *THD_I, CF_I, DF, FPF, TPF and PFR.*

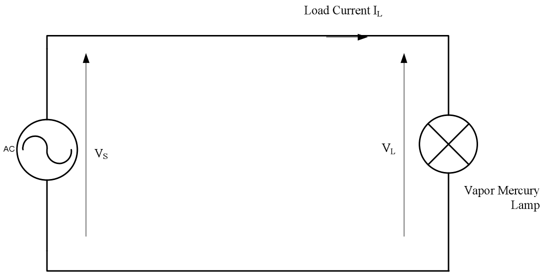


Figure (4) a Vapor mercury lamp supplied by a sinusoidal voltage source

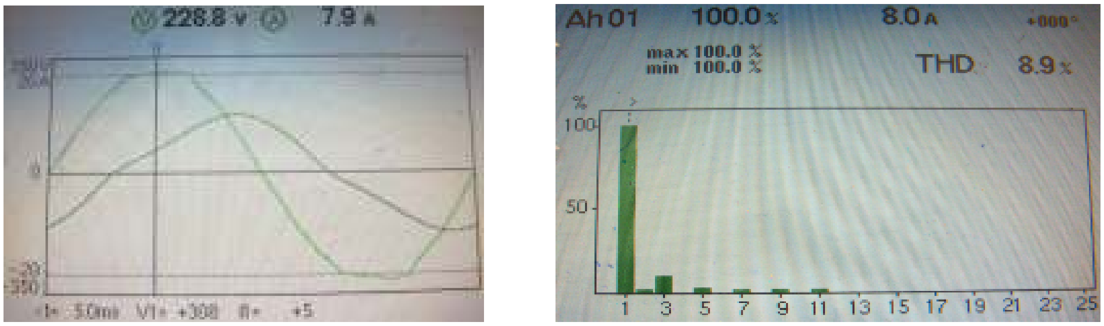


Figure (5-a), (5-b) current and voltage wave and currents harmonics spectrum

Table (2) Values of the Readings

V(V)	I(A)	THD_I	CF_I	P(W)	Q(VAR)	S(VA)	D(VAD)	DF	DPF	TPF	PFR
228.8	0.79	8.9	1.5	91	172	196	23.5	0.12	0.47	0.46	0.98

4.3 Halogen Spot Light Lamp

Figure (6) shows a Halogen spot light lamp (50W, 12V) supplied by a sinusoidal voltage source. Figures (7-a) and (7-b) show the current wave form and the spectrum of harmonics. Table (3) shows values of the current, *I, THD_I, CF_I, DF, FPF, TPF and PFR*.

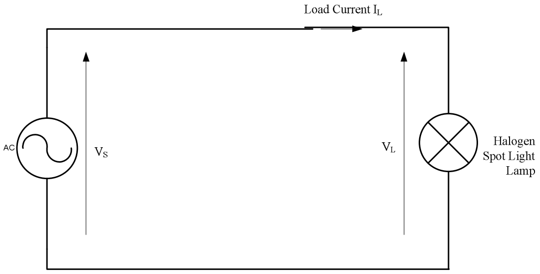


Figure (6) a Halogen spot light lamp supplied by a sinusoidal voltage source.

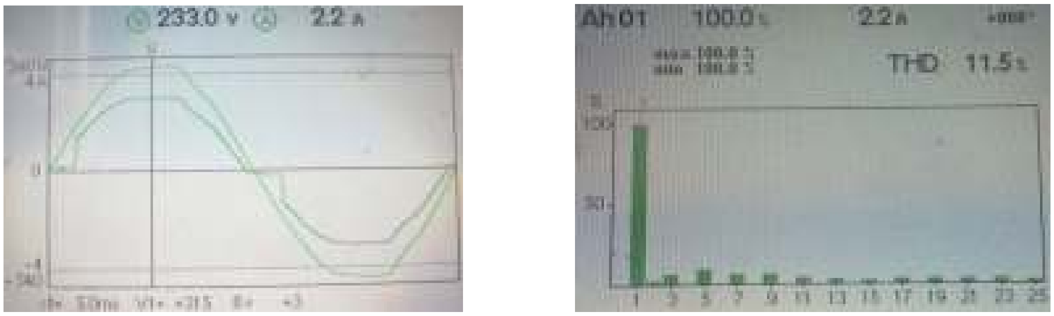


Figure (7-a), (7-b) current and voltage wave forms and current harmonics spectrum

Table (3) Values of the Readings

V(V)	I(A)	$\mathrm{THD_I}$	$\mathrm{CF_I}$	P(W)	Q(VAR)	S(VA)	D(VAD)	DF	DPF	TPF	PFR
233.0	0.22	11.5	1.39	512	1.6 Cap.	515.6	60.8	0.12	1.0	0.99	0.99

4.4 Electric Ballast Lamp

Figure (8) shows an electric ballast lamp (23W, 230V) supplied by a sinusoidal voltage source. Figures (9-a) and (9-b) show the current wave form and the spectrum of harmonics. Table (4) shows values of the current, *I, THD_I, CF_I, DF, FPF, TPF and PFR*.

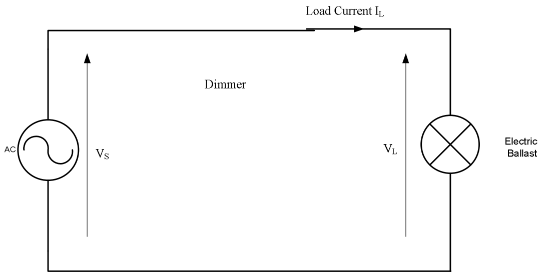
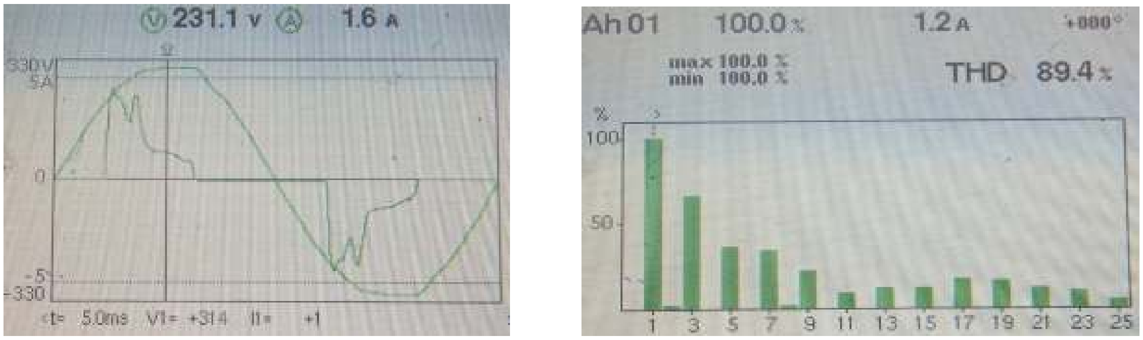


Figure (8) an Electric Ballast lamp supplied by a sinusoidal voltage source.



Figures (9-a), (9-b) current and voltage wave forms and current harmonics spectrum

Table (4) Values of the Readings

V(V)	I(A)	$\mathrm{THD_I}$	$\mathrm{CF_I}$	P(W)	Q(VAR)	S(VA)	D(VAD)	DF	DPF	TPF	PFR
231.1	0.16	93.3	2.9	255	112 Cap.	384	264.4	69%	0.92	0.66	0.72

4.5 Magnetic Ballast Lamp

Figure (10) shows a magnetic ballast lamp (23W, 230V) supplied by a sinusoidal voltage source. Figures (11-a) and (11-b) show the current wave form and the spectrum of harmonics. Table (5) shows values of the current, *I*, THD_I, CF_I, *DF, FPF, TPF and PFR.*

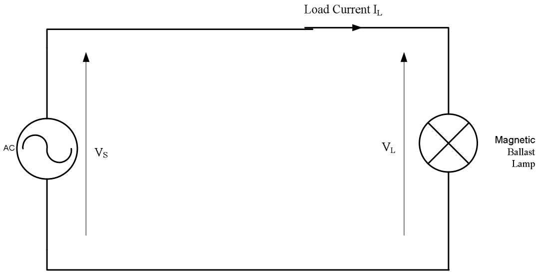


Figure (10) a Magnetic Ballast lamp supplied by a sinusoidal voltage source.

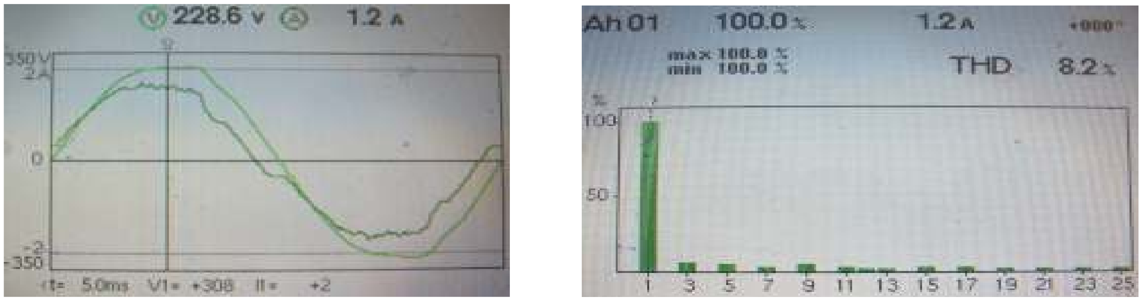


Figure (11-a), (11-b) current and voltage wave forms and current harmonics spectrum

Table (5) Values of the Readings

V(V)	I(A)	THD_I	CF_I	P(W)	Q(VAR)	S(VA)	D(VAD)	DF	DPF	TPF	PFR
228.6	0.12	8.2	1.51	260	69 Cap.	271	32.9	12.1%	0.97	0.96	0.99

5. Effects of Load Side Harmonics

The existence of harmonics produces many problems in the power systems; it increases noise of electric machines and highly affects its iron loss, besides increasing the current as given by (8).

$$I = \sum_{n=1}^{\infty} \sqrt{I_n^2} \tag{8}$$

Where, I_n is the rms current value of the nth harmonic order.

Due to current increase the active power loss increases in generators, transmission lines, transformers and load resistances. Harmonics frequencies increase the eddy current and hysteresis loss, these lead to equipment heating and malfunctioning and fuse and circuit breaker miss-operation.

The existence of harmonics frequencies increases the absorption of reactive power due to current increase and more clearly due to appearance of a new reactance $X_{L(n)}$ for each harmonic's frequency $f_{(n)}$ as given by (9).

$$X_{L(n)} = 2\pi f_{(n)} L \tag{9}$$

The existence of harmonics reduces the total power factor (TPF) due to the increasing of reactive power absorption and distortion power. It also causes current flow in the neutral conductor and power elements over-age, power system capacity reduction, power system over-stress and maintenance and installations cost increase the thing makes it essential to eliminate the harmonics level in the power systems.

In this paper, the effects of load side harmonics are illustrated by studying the operation of a 0.5A circuit breaker in three load cases. In Figure (12) the first case represents a linear (150 W) load by closing switches S_1, S_2 and S_3, the second and third cases represent a single phase two and three dimmer controlled halogen lamps respectively (150 W) each case, in the second case switches S_1, S_2 and S_4, are closed, while in the third case switches S_1, S_2, S_4 and S_5 are closed. The firing angle is set to maintain the active power equal to 150 W in each of case two and three. The time of circuit breaker tripping is examined in the three mentioned cases; the results are illustrated in Table (6).

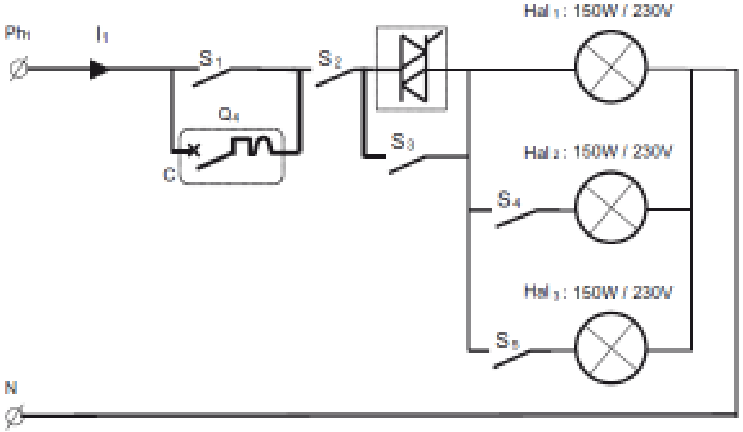


Figure (12) Dimmer controlled Halogen Lamps with selective switches and circuit breaker

Table (6) Circuit breaker tripping time for three different cases (150W)

	Case 1 Linear load	Case 2 Non-linear load	Case 3 Non-linear load
I (A)	0.66	1.02	1.32
CB tripping time (s)	6000	33	15
THD_I	2.7 equal to THD_V	75.3	95.1

6. Elimination of Load Sides Harmonics

Harmonic distortion in power distribution systems can be suppressed using two approaches namely, passive and active filters. The passive filtering is the simplest conventional solution to mitigate the harmonic distortion [6]-[8]. Another approach is using (Δ/Y) transformers. In this paper, both of the last two methods have been used. The harmonics case considered for the process of harmonics elimination is shown in Figure (13), it represents a dimmer controlled 3-

phase Halogen lamps (3X150 W, 230 V) supplied by a sinusoidal voltage source with two choices of filtering (Δ/Y Transformer and passive filter). To generate the harmonics, switches S_1 and S_3 have been closed and the dimmer firing angle set to ($\alpha = 90^{\circ}$). Figures (14-a) and (14-b) show the current wave form and harmonics spectrum. The results for this case without filtering are given in Tables (7) and (8).

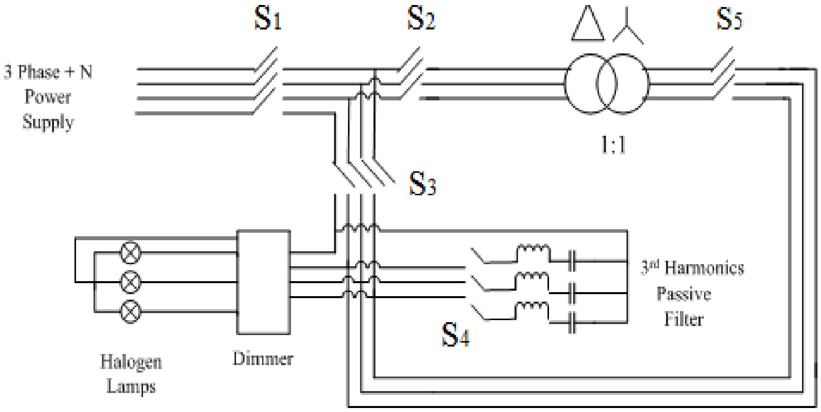
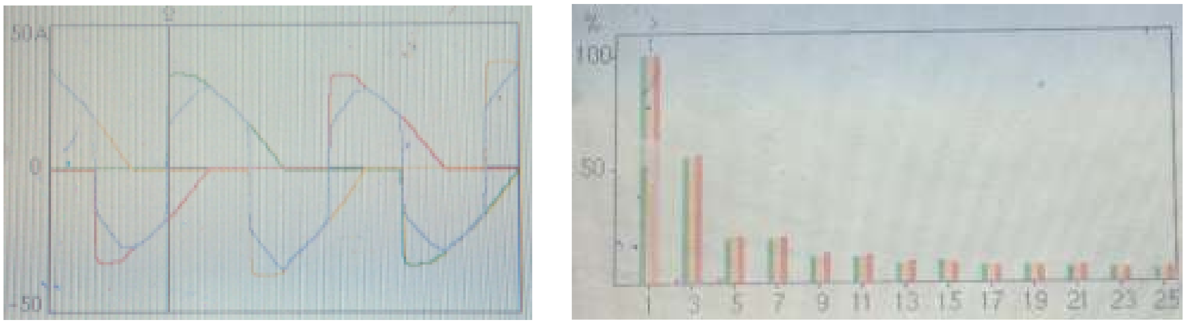


Figure (13) a dimmer controlled 3Φ Halogen supplied by a sinusoidal voltage source with two choices of filtering ((Δ/Y) Transformer and passive filter).



Figures (14-a), (14-b) the current wave form and harmonics spectrum without filtering

Table (7) Values of the Readings without filtering

Phase	V(v)	I(A)	THD_I	CF_I	P(W)	Q(VAR)	S(VA)	D(VAD)	DF	DPF	TPF	PFR
1	238	1.72	63.0	1.97	291.1	+ 181.8	406.7	218	0.54	0.85	0.72	0.85
2	236	1.88	65.5	1.99	309.0	+ 200.0	441.1	243	0.55	0.84	0.70	0.83
3	231	1.65	65.4	2.00	271.0	+ 175.0	386.0	212	0.55	0.84	0.70	0.83

Table (8) Values of the current harmonics orders without filtering

Current Harmonics order		3^{rd} (A)	5^{th} (A)	7^{th} (A)	9^{th} (A)
Neutral current = 2.54 Neutral temperature = 90°C	Ph1	0.78	0.26	0.26	0.15
	Ph2	0.87	0.30	0.29	0.17
	Ph3	0.76	0.26	0.26	0.15

6.1. Elimination by Passive Filter

Closing switches S1, S3 and S4 in Figure (13), the 3-phase Halogen Lamps lit up having the firing angle set to ($\propto = 90^{\circ}$) with the passive filter inserted. To eliminate the third order current harmonics, value of the inductance (L) is selected $L = 92$ mH and value of the capacitance (C) is calculated using (11) and get $C = 12.24$ µF for each phase. Figures (15-a) and (15-b) show the current wave form and the spectrum of harmonics. The results for this case with passive filter are given in Tables (9) and (10).

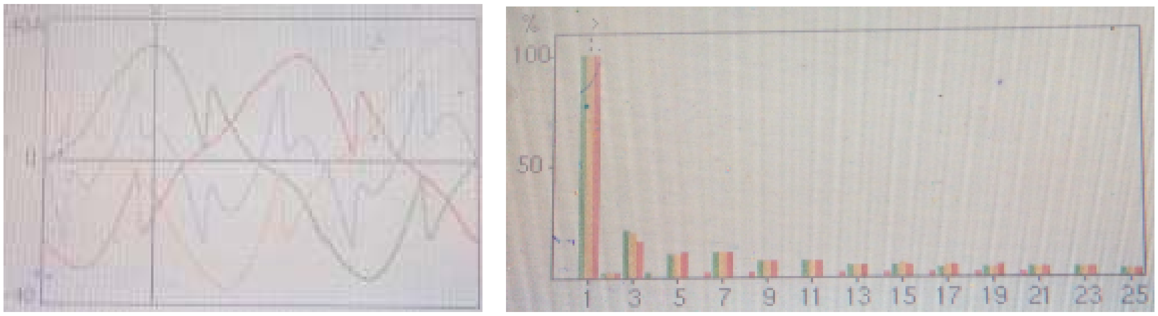
$$\omega_o = 2\pi f_o = \frac{1}{\sqrt{LC}} \tag{10}$$

Where:

f_o : The frequency wanted to be filtered.

L and C : The passive filter elements.

$$C = \frac{1}{L(2\pi f_o)^2} \tag{11}$$



Figures (15-a), (15-b) the current wave form and the spectrum of harmonics with passive filter

Table (9) Values of the Readings with passive filter

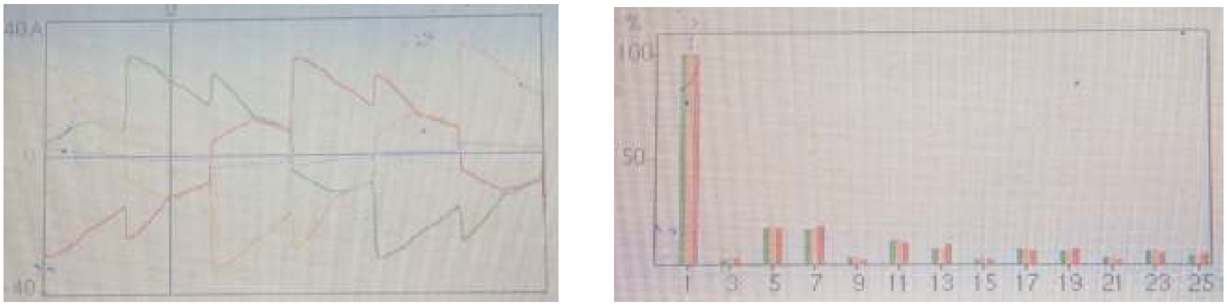
Phase	V(v)	I(A)	THD_I	CF_I	P(W)	Q(VAR)	S(VA)	D(VAD)	DF	DPF	TPF	PFR
1	238	1.72	25.0	1.67	317.9	- 316.1	464.0	119.7	0.26	0.71	0.69	0.97
2	241	1.86	23.8	1.65	351.4	- 347.0	500.0	78.2	0.16	0.70	0.68	0.97
3	230	1.66	23.9	1.62	285.9	- 300.0	431.0	118.4	0.27	0.70	0.68	0.97

Table (10) Values of the current harmonics orders with passive filter

Current Harmonics order		3rd (A)	5th (A)	7th (A)	9th (A)
Neutral current = 1.02 Neutral temperature = 42°C	Ph1	0.33	0.17	0.18	0.10
	Ph2	0.36	0.17	0.20	0.11
	Ph3	0.24	0.18	0.18	0.10

6.2. Elimination by (Δ/Y) Transformer

In Figure (13), closing switches S_1,S_2 and S_5, the 3-phase Halogen Lamps being fed through the Δ/Y Transformer with unity transformation lit up having the firing angle set to ($\propto = 90^{\circ}$). Figures (16-a) and (16-b) show the current waveform and the spectrum of harmonics. Figures (24) and (25) show the current waveform and the spectrum of harmonics. The results for this case with (Δ/Y) Transformer are given in Tables (11) and (12).



Figures (16-a) and (16-b) the current wave form and the harmonics spectrum with (Δ/Y) Transformer

Table (11) Values of the Measurements and Calculations with (Δ/Y) Transformer

Phase	V(v)	I(A)	THD_I	CF_I	P(W)	Q(VAR)	S(VA)	D(VAD)	DF	DPF	TPF	PFR
1	239	1.72	27.1	1.73	327	226	413	112.1	0.27	0.82	0.79	0.96
2	239	1.86	28.1	1.75	364	229	446	118.2	0.27	0.85	0.81	0.95
3	237	1.66	28.0	1.75	310	214	392	108.5	0.28	0.82	0.79	0.96

Table (12) Values of the current harmonics orders with (Δ/Y) Transformer

Current Harmonics order	3rd (A)	5th (A)	7th (A)	9th (A)
Ph1	0.02	0.26	0.25	0.02
Ph2	0.05	0.29	0.28	0.03
Ph3	0.03	0.24	0.27	0.01

7. Results Discussion

The set of nonlinear-loads which is studied draw non-sinusoidal currents and produce odd high order harmonics, current waveforms are distorted. The THD_I values are out of the standard limits and the contents of harmonics are high. The effects of harmonics have been studied; the results tables' show that harmonics reduce the power factor and produce distortion power. In three phase non-linear loads neutral current increases and in single phase non-linear loads phase and neutral current increases, this increases the voltage drop and resistive power loss besides increasing of iron and reactive power losses. Current increase result in cable size increases and circuit breakers cost.

The 3rd harmonics tuned passive filters reduced the 3rd harmonics current component to about 42% also reduced the 5th to 65%, 7th to 69% and 9th to 67%. The delta-star transformer highly reduces the 3rd order harmonics and its multiples; it reduced the 3rd harmonics current component to about 2.5% and 9th to 13.3%. The reduction of the 5th and 7th order harmonics is very low.

Table (13) shows a comparison of different load types using values of THD_I, DF, CF_I and PFR for different types of non-linear loads. Table (14) shows upper ordered harmonics without filter, with third harmonics tuned passive filter and with delta-star transformer for three phases dimmer controlled halogen lamps, values of one of the three phases are given.

Table (13) Comparison of different load types

Load Type	THD_I (%)	DF (%)	CF_I	PFR (%)
Dimmer controlled halogen lamp ($\alpha=90^o$)	64.2	53	2.0	84
Vapor mercury lamp	8.9	12	1.5	98
Halogen spot light lamp	11.5	12	1.4	99
Electric Ballast lamp	93.3	69	2.9	72
Magnetic Ballast lamp	8.2	12.1	1.5	99

Table (14) harmonics without filter, with passive filter and with delta-star transformer

Case	THD_I (%)	DF (%)	I (3rd) (A)	I (5th) (A)	I (7th) (A)	I (9th) (A)	I_N (A)
Without Filter	63.0	55	0.78	0.26	0.26	0.15	2.54
With 3rd harmonic Passive Filter	25.0	26	0.33	0.17	0.18	0.10	1.02
With a delta-star transformer	27.1	27	0.02	0.26	0.25	0.02	---

8. Conclusion

Harmonics have a number of undesirable effects on the distribution system. They affect both technically and economically. In this paper, different harmonics source loads have been studied. The current waveforms and harmonics spectrum have been given. The harmonics effects have been studied and two methods of harmonics elimination have been tested and the results of current waveforms and harmonics spectrum have been obtained. Upper harmonics orders are obtained for cases of no filters system and the two types of filters.

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