The Influence of LED Street Lighting Upon Power Quality in Electrical Networks

Radu-Dumitru Pentiuc, Andrei Dascălu, Cezar-Dumitru Popa, Pavel Atănăsoae
"Ștefan cel Mare" University of Suceava
Faculty of Electrical Engineering and Computer Science
Suceava, Romania
radup@eed.usv.ro

Abstract-**The study also aims the electricity consumed, the ilumination achieved and the study of harmonics introduced in the network and the role of ballast circuits in this problem. An important criteria in choosing the proposed solutions is the economic criteria, we calculate the investment and depreciation costs if they consider replacing the conventional apparatus equipped with LEDs.**

Keywords-energy efficiency, LED, power quality

I. INTRODUCTION

However in recent years were improved LEDs lighting sources. Manufacturers and their distributors say that are more efficient in terms of energy consumption and superior features in terms of luminous efficacy. Thus we could have an alternative, applicable to larger scale.

There are proposals to replace conventional lighting sources. Luminaires equipped with LEDs, bring to the fore some drawbacks, some can be analyzed easily, others are more complex and require more time to be understood. The cost of LEDs is still high in comparison with classical lumps existent in the market, the influence upon power quality, the voltage waveforms variations and current waveform are not completely determined. The way they behave over time and lifespan in outdoors in a real operation environment, are only estimates.

Nobody knows the long time effect of LED light on human retina, wildlife and so on.

In this paper we analyze the influence that new light sources have on the electrical distribution networks, especially in urban communities. In general, the electrical parameters that characterize the electrical grid are approximately sinusoidal. The deviations from the ideal waveform mark the system as a system in a distorted regime. In reality generators do not produce strictly sinusoidal voltage waveform. Most of the nonlinear distortions occur due to consumers (core coils, rectifiers, inverters, magnetic amplifiers, electric arc furnaces, lighting installations with fluorescence tubes or with LED s). These types of consumers distort the waveform of the current, which causes non-sinusoidal voltage drops, thus favoring the occurrence of voltage harmonics.

Improving the power factor to the neutral value requires additional investment.

So we propose the study and compares the different aspects of power quality in both types of lighting with normal and LED sources, in electrical streets networks.

II. POWER QUALITY

A. *The mathematical description of a non-sinusoidal waveform*

The harmonic [1] analysis is based on the decomposition of the signal in Fourier series, thus the study of the waveform in the frequency domain. This involves the description of the signal according to its harmonic components as follows:

$$y(t) = Y_0 + \sum_{n=1}^{\infty} \left(Y_n \sqrt{2} \sin(n\omega t + \gamma_n\right) = Y_0 + \sum_{n=1}^{\infty} y_n ; \quad (1)$$

were Y_0 is the *DC* component or the mean value of the waveform, Y_n the root-mean square of the harmonic of rank n, ω the fundamental angular frequency, γ_n the initial phase of the harmonic of rank n.

The *root mean square* of a sinusoidal signal is:

$$Y_{ef} = \sqrt{\frac{1}{T}\int_0^T y(t)^2 dt} ; \quad (2)$$

Using the above relation for a non-sinusoidal signal, we obtain the following relationship for the total RMS:

$$Y_{ef} = \sqrt{Y_0^2 + Y_1^2 + Y_2^2 + Y_3^2 + \cdots} = \sqrt{Y_0^2 + \sum_{n=1}^{\infty} Y_n^2} ; \quad (3)$$

What remains after subtracting the fundamental frequency from the initial signal is:

$$y_d(t) = y(t) - y_1(t) = Y_0 + \sum_{n=2}^{\infty} Y_n ;$$

The RMS of the residue is:

$$Y_{ef} = \sqrt{Y_0^2 + \sum_{n=2}^{\infty} Y_n^2} = \sqrt{Y_{ef}^2 - Y_1^2}\,; \qquad (4)$$

Total harmonic distortion factor (THD) is defined as:

$$THD = \frac{\sqrt{Y_1^2 + Y_2^2 + Y_3^2 + \cdots}}{Y_1} \cdot 100; \qquad (5)$$

The total harmonic distortion factor, *THD*, is less than 1 but greater than 0. For a *THD* less than 0.005%, in practice the waveform is considered to be sinusoidal. The *THD* is defined for voltage and current waveforms and its accepted values in practice are set in power quality standards and legislations.

It can be calculated the amount of each harmonic, based on the fundamental, for example, for the rank i we have the following formula:

$$f_i = \frac{Y_i}{Y_1} \cdot 100;$$

Electric power under a non-sinusoidal voltage and current is analyzed using this theory, decomposing all the signals in Fourier series.

$$u(t) = U_0 + \sum_{n=1}^{\infty} \left(U_n \sqrt{2} \sin(n\omega t + \alpha_n\right) = U_0 + \sum_{n=1}^{\infty} u_n\,;$$

$$i(t) = I_0 + \sum_{n=1}^{\infty} \left(I_n \sqrt{2} \sin(n\omega t + \beta_n\right) = I_0 + \sum_{n=1}^{\infty} i_n\,;$$

α_n-initial phase voltage of the rank *n* harmonic;
β_n- initial current phase of the rank *n* harmonic;

Multiplying the above relations we obtain the instantaneous power:

$$p(t) = ui =$$

$$= U_0 I_0 + \sum_{n=1}^{\infty} u_n i_n + U_0 \sum_{n=1}^{\infty} i_n + I_0 \sum_{n=1}^{\infty} u_n + \sum_{k=1}^{\infty} \sum_{n=1}^{\infty} u_k i_n\,;$$

The real power:

$$P = \frac{1}{T} \int_0^T p(t)dt = U_0 I_0 + \sum_{n=1}^{\infty} U_n I_n \cos\varphi_n; \quad [W] \qquad (6)$$

Where: $\varphi_n = \alpha_n - \beta_n$;,,

φ_n - the phase difference between voltage and current harmonic of rank *n*;

The reactive power:

$$Q = \sum_{n=1}^{\infty} U_n I_n \sin\varphi_n\,; \quad [VAR] \qquad (7)$$

The apparent power:

$$S = U_{ef} I_{ef} =$$

$$= \sqrt{U_0^2 + U_1^2 + U_2^2 + U_3^2 + \cdots} \sqrt{I_0^2 + I_1^2 + I_2^2 + I_3^2 + \cdots}\,; \quad [VA]$$

The deformed power:

$$D = \sqrt{S_0^2 - (P^2 + Q^2)}; \quad [VAD] \qquad (8)$$

The power factor:

$$k = \frac{P}{S} = \frac{P}{\sqrt{S_0^2 + P^2 + D^2}} \leq 1; \qquad (9)$$

The power factor is a measure of the harmonic content in the waveforms of voltage and current [2] because as the distortion grows it lowers the power factor. A comparison between the power factor and the phase [3] difference between voltage and current can give us a first indication of deviations from the ideal waveforms.

III. Power Quality Parameters Monitoring

In the study we present the harmonic analysis [4] that was performed on lighting electrical network in the city *A* (where LEDs are used as light sources) [5] and in city *B* (which still uses classical light sources, sodium-vapor lumps).

In the city *A*, in collaboration with the engineers from the company E-ON Moldova, we installed in an electrical panel the Chauvin Arnoux power analyzer *CA* 8334

The electrical hookups used to connect the *CA* 8334 are presented in Fig.2

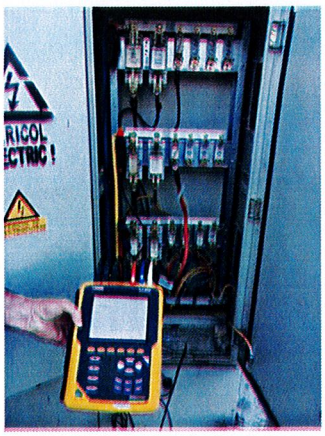


Figure 1. *C.A* 8334 Power analyser

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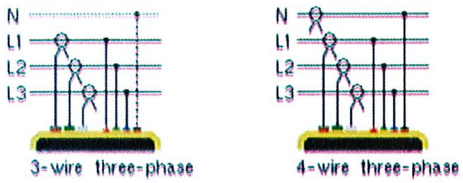


Figure 2. The *CA* 8334 electrical hookups

A. Measurement results for LED road lighting

Quantitatively, the measured voltages (Fig. 3) are relatively symmetric and is in the domain (quantitative) accepted by the regulatory authority National Regulatory Authority for Energy-ANRE

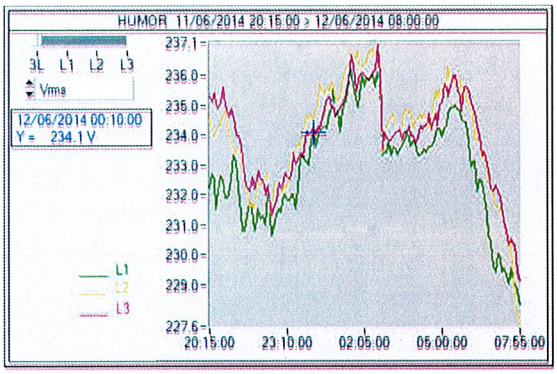


Figure 3. The voltage of the all three phases

The voltage harmonics on each phase (Fig. 4) falls in the 1,6 ÷ 2,4%. Subsequently we evaluate and weight of each voltage harmonic in the LED street lighting electrical network.

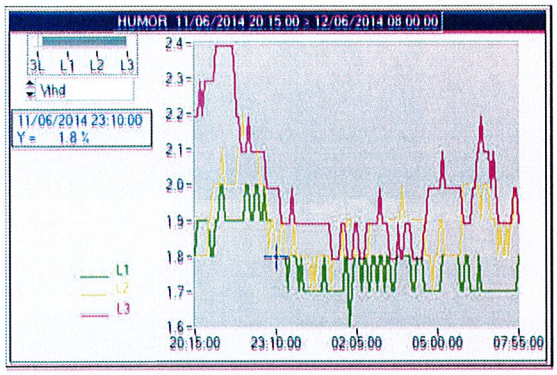


Figure 4. *THD* (V) for each phase

Quantitative, the three phase currents measured (Fig. 5) are asymmetric, after loading each phase of the circuit. As a remedy, it is recommended a load balance.

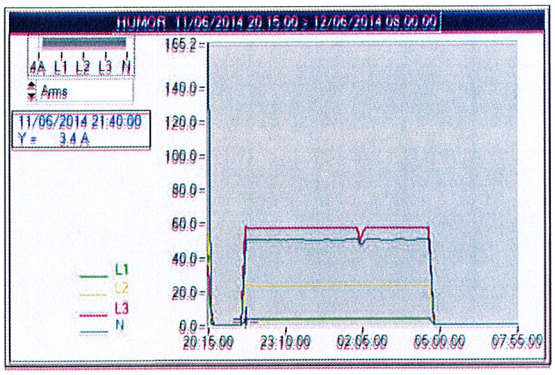


Figure 5. The currents (*RMS*) on each phase

The current total harmonic distortion, *THD* (I), on each phase (Fig. 6) falls in the range 0 ÷ 40,7%. We also want to evaluate the weight of each current harmonic.

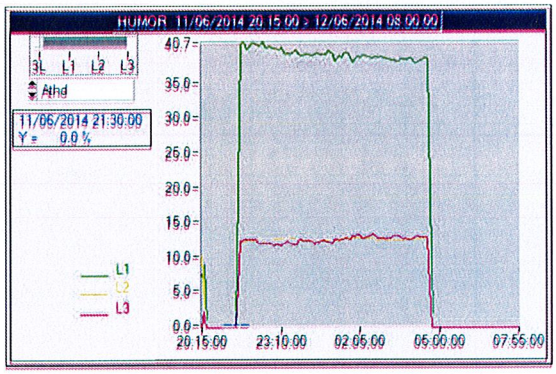


Figure 6. *THD* (A) for each phase

As shown in (Fig. 7) the most important influence of the voltage waveform distortion is the rank 7 harmonic with values: phase *R* is 1,3%, phase *S* is 1,1%, phase *T* is 1,3%.

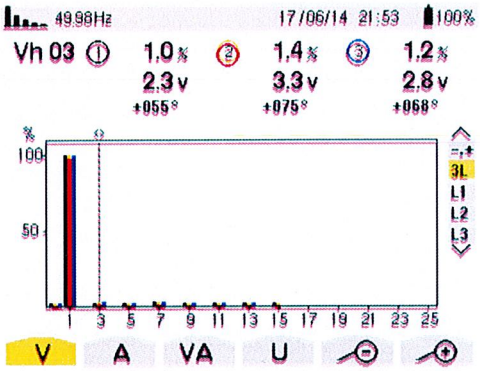


Figure 7. The voltage waveform spectrum.

In the case of the currents (Fig. 8) the most important influence of the current waveform distortion is the rank 3 harmonic (the phase *R* has the lowest value of the load): phase *R* is 30%, phase *S* is 9%, phase *T* is 8 %.

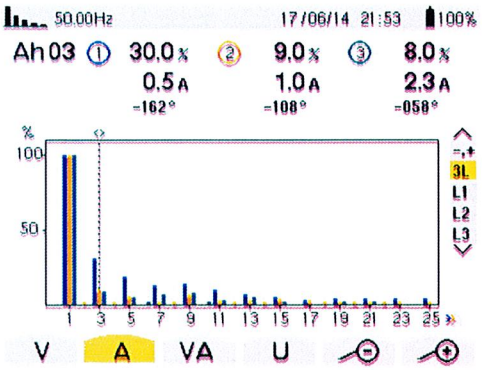


Figure 8. The current waveform spectrum.

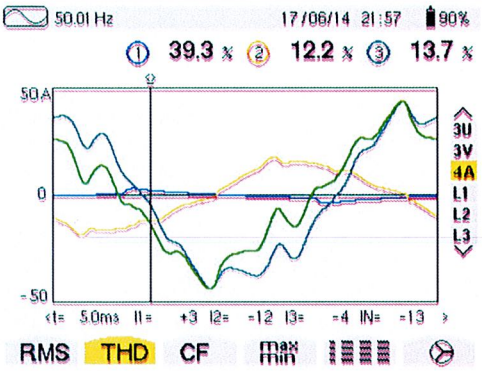


Figure 9. The THD(I) for all three currents

The ANRE Order-28 2007 - Performance standard for electricity distribution service, shows in Chapter VI the technical power quality standards for voltage. According to the Art.19. Table 1, the voltage variations permissible for low voltage networks are ± 5% of nominal voltage. In the measurements mentioned above are shown, in (Fig. 4), that the voltage of the lighting electrical networks in the city *A*, fall within the accepted range. Art. 22 from the same chapter, presents the maximum distortion factor for voltage waveform, *THD* (V), and the maximum percentage values of the each voltage harmonics. The maximum of *THD*'s (V) is 8%. According to the schedule *THD* (V) (Fig. 4), its maximum is 2,4% for *T* phase, which is framed by the STAS's rules invoked.

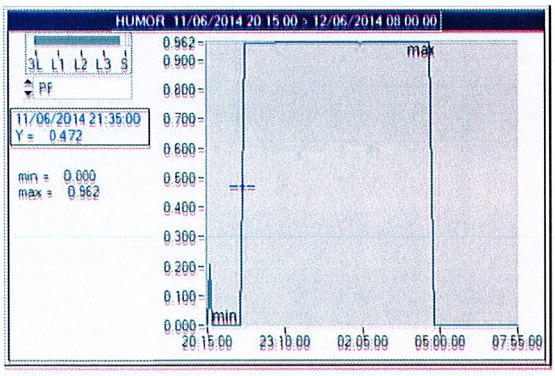


Figure 7. The average power factor

B. Measurement results for sodium-vapor street lighting system (city C)

In town *C*, were made the same types of measurements as in town *A*. The data is summarized in tables and its variation over time is illustrated in the following graphs: quantitatively, the measured voltages (Fig. 8) are asymmetric but they are

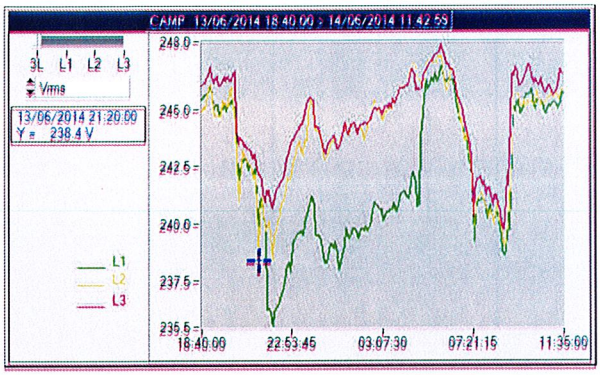


Figure 8.The voltage variations for all three phases

in the (quantitative) range accepted by the Regulatory Authority for Energy - ANRE.

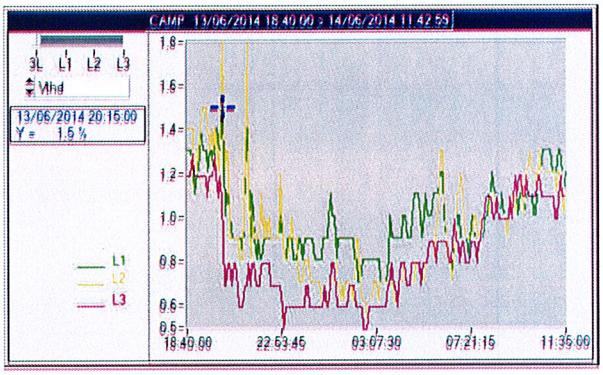


Figure 9. *THD* (V) for all three phases

The total harmonic distortion, *THD* (V), on the three phases (Fig. 9) falls in the range 0.5 ÷ 1.8%. In this case also we evaluate and weight of each harmonic.

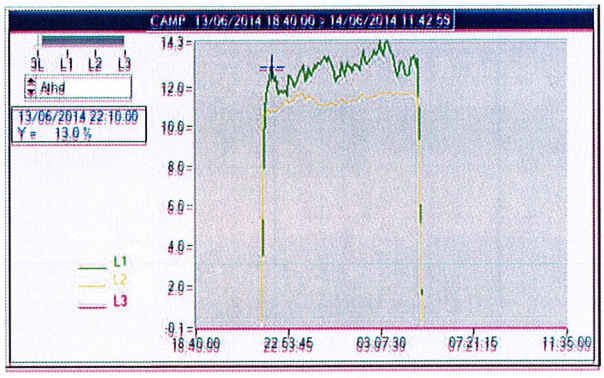


Figure 10. THD (I) for all three currents

Quantitative, after loading, the three-phase currents measured (Fig. 10) are asymmetric. The all three phases system is clearly unbalanced.

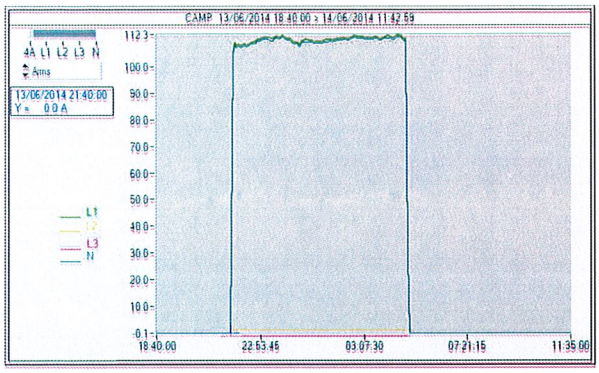


Figure 11. The currents on all three phases

This time the power factor is much lower (Fig. 12) then in the case of the system with LEDs.

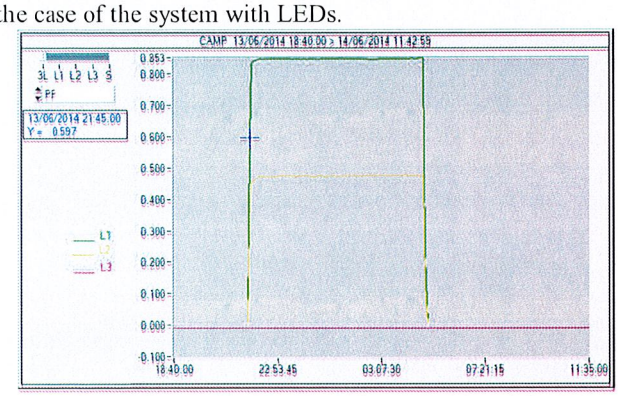


Figure 12. The power factor in the lighting system of the town *B* (sodium-vapor lumps)

Comparing the voltage values, minimum and maximum in (Fig. 8) with those mentioned in ANRE-28-2007 we conclude that the voltage level and its variations fall within the rules prescribed in Article 19, Table 1. Monitored values of *THD*'s (Fig. 9), with the highest value of 1,8%, on *S* phase, is under the limit of 8% mentioned in Article 22. of the same STAS.

Average power factor calculated [6] from the data presented in the graph in (Fig. 12), it is around 0,65, which is not supported by the norms.

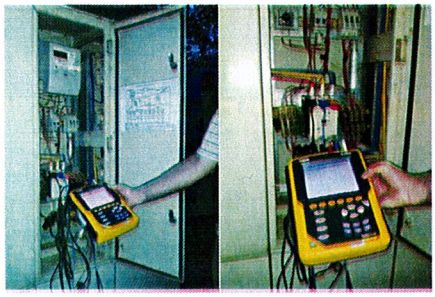


Figure 12. Measurements in city *B*

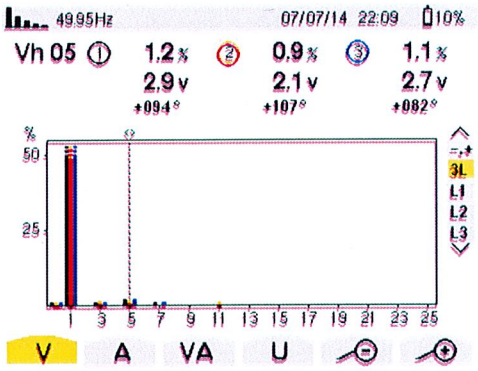


Figure 13. The voltage waveform spectrum

In (Fig. 13) is shown the voltage waveform spectrum as was found in the lighting system that uses conventional light sources (city *B*). The most prominent voltage harmonic is that of the rank 5, for the phase *R* has the value 1,2%, 0,9% for *S* phase and for *T* is 1,1%.

All values are well below the maximum 8% stipulated by Order 28-2007.

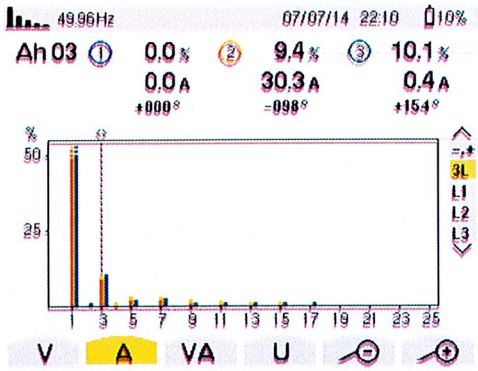


Figure 14. The current waveform spectrum

In the (Fig. 14) can be observed that the most important current harmonic is that of the rank 3 having the *R* phase 0% (free phase), 9.4% for the *S* phase and 10.1% fot *T* phase.

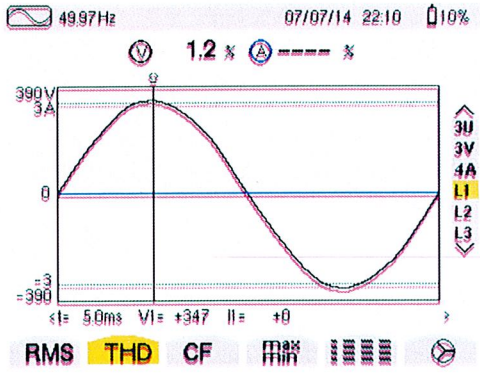


Figure 15. The voltage and current waveform for *R* phase

In (Fig. 15) we see that the *R* phase current is 0 (free phase).

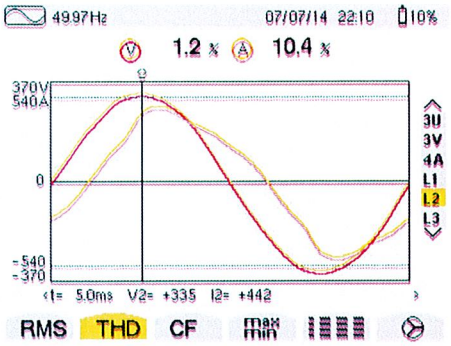


Figure 16. The voltage and current waveform for the *S* phase

It can be seen (Fig. 16), the strong phase shift between voltage and current and that the ripple current is more distorted than that of the voltage (red). The *THD* (V and I) 1,2% and 10,4% fall in standards mention.

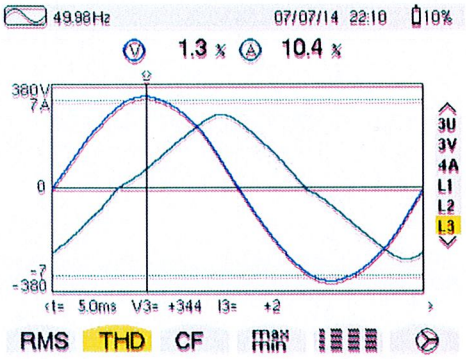


Figure 17.The voltage and current waveform for the *T* phase

From (Fig. 11, 16 and 17) we see that if we have an equal load of the phases *S* and *T*, the distortions of the current waveform are also identical.

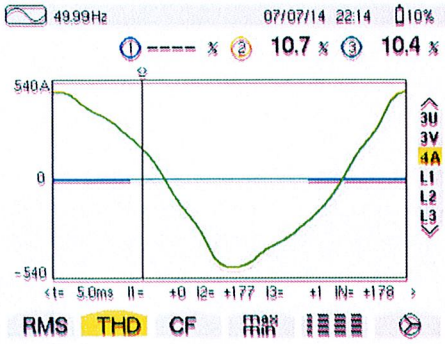


Figure18. The *THD* (I) values for all three currents

C. Illumination

The table below shows the comparative average illuminations found in four cities with different lightning systems (different light sources). We arrived [7] at these results, shown in Table 1, after we measure the illumination in the street for about 700 poles (24 km) in about 2100 points.

TABLE 1. AVBRAGE ILUMINATION

No.	City	Average illumination	Light sources	Street type	Illumination STAS SR 13433
1	A	15,62 [lx]	LED	M4	10 (lx)
2	B	14 [lx]	HPSL	M4	10 (lx)
3	C	23,6 [lx]	HPSL	M4	10 (lx)
4	D	2,1 [lx]	HPSL	M4	10 (lx)

As observed in the Table 1, the average illumination is approximately equal in the first three cities. The difference of 8 [lx], between the average illumination of the town *B* and city *C* (cities that were analyzed in terms of power quality) is explained by mentioning that in the second case the measurements were performed over a period of winter when the light reflection factor is slightly higher.

In the city *A* (illuminate LED), the quality analysis was done in an electric panel that feed 92 luminaires equipped with LEDs sources (72 of 150 [W], 14 of 51 [W] and 6 of 76 [W]) with an input power of approximately 12 [KW]. The total street length covered by these luminaires is 3,68 [km].

In town *B* (conventional lighting sources), the electric panel monitored feed 52 luminaires fitted with sodium vapor light with power of 250 [W] (a load of 13 [KW]). Considering the distance between poles 40 [m] we can say that the total length of the streets covered is 2,08 [km].

Since the streets were nearly identical at the illumination level and since they have similar geometry we can define an efficiency ratio EF = (power consumption) / (street length) as follows:

-case *A*:

$$EF = \frac{12000[\mathrm{W}]}{3680[\mathrm{m}]} = 3{,}26\ \left[\frac{\mathrm{W}}{\mathrm{m}}\right];$$

-case *C*:

$$EF = \frac{13000[\mathrm{W}]}{2080[\mathrm{m}]} = 6{,}25\ \left[\frac{\mathrm{W}}{\mathrm{m}}\right];$$

Analyzing reports of *EF* it can be said that in terms of energy economy, in city *A* is achieve a minimum of 50% reduction in energy consumption for the same illumination level as in case *C*. This implies a halving of electricity costs. The actual data recorded by the electric meter of the circuit analyzed in the city, is illustrated in (Fig.19) (the power consumption for the last two years). It can be identified that during winter, the consumption is higher. Until mid-2013 public lighting in the city was done with classical sources. You may notice the changes in terms of consumption after replacing the traditional lumps with LED sources. If we consider the

winter 18.10.2012-6.04.2013 and 1.10.2013-2.03.2014 we can see the bellow a saving of around 50% in energy consumption (the peak around the date of 26.01.2013 disappears).

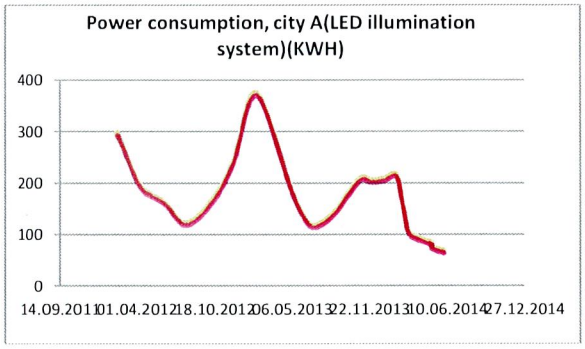


Figure 19. Average power consumption (daily)

IV. CONCLUSION

The parameters that describe the quality of current and voltage waveforms of the two lighting systems monitored, are shown in the following table:

TABLE 2. MEASUREMENT RESULTS

No.	Parameter	City A	City C	STAS
1	Vrms (min)	227 [V]	235 [V]	211,6[V]
2	Vrms (max)	237 [V]	248 [V]	248,4[V]
3	THD (V)	2,4%	1,8%	8%
4	THD (I)	40,7%	14,3%	-
	Power factor	0,94	0,65	0,92
5	Harmonic (V) rank. 3	1,4%	0,6%	5%
6	Harmonic (V) rank. 5	0,5%	1,1%	6%
7	Harmonic (V) rank. 7	1,3%	0,4%	5%
8	Harmonic (V) rank. 9	1%	0%	1,5%
9	Harmonic (I) rank. 3	30%	10%	-
10	Harmonic (I) rank. 5	17,3%	3%	-
11	Harmonic (I) rank. 7	11,6%	4,1%	-
12	Harmonic (I) rank. 9	13%	3%	-

Analyzing the results of centralized measurements in the table above, we can state the following conclusions:

a) a higher *THD* (V) and *THD* (I) in the case of lighting systems with LEDs. This means that the waveform of the voltage and current is more distorted in the first case (the city A).

b) The *THD* for voltage and current waveforms, in the case of LEDs, increases with the reduction of the lump luminosity.

c) a much lower power factor, of 0,65 in the clasical system, versus a 0,95 in town A (LED sources). After analyzing both real and circuit simulations in the laboratory, we conclude that the low PF is imposed because of the classic electromagnetic ballast used in the circuits.

d) current and voltage harmonics fall below permissible limits by ANRE Order 28-2007 in both cases.

d) Looking at the overall results, we note gratifying that the lighting systems analyzed are situated in the frame of power quality standards mentioned, except the power factor of 0,65 in town *C* (Fig. 12) and the unbalance load phases in both cases (Fig. 5 and 11).

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