EXPERIMENTAL INVESTIGATION OF PQ IMPACT OF DIFFERENT LIGHTING SYSTEMS IN RAILWAY STATIONS

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New lighting technologies are very important for their overall efficiency in reducing the absorbed energy and the operating and maintenance costs. However, they can introduce Power Quality (PQ) problems such as harmonic distortions, losses on the grid and power factor. This paper presents the results of an experimental investigation on power and harmonic absorption of different outdoor lamps (LED and gas discharge lamps), supplied by different ballasts, used in a railway station. The PQ and harmonic analysis is based on the indexes reported in the IEEE Trial use standard definitions for measurement of electric power.

Keyword: Lighting System, Railway, Experimental measurements, Harmonics, Power Quality

1. Introduction

Even if nowadays lighting is quite efficient, in Europe it still absorbs the 14% of the total electric consumptions (19% worldwide).The 80% of this percentage is due to public lighting and the last 20% to private houses. This means that the corresponding CO_2 emissions are equal to about 600 millions of ton per year. It is then evident that lighting is a source to work on in order to perform energy saving and reduce the greenhouse gas emissions that lead to global climate change. These are therefore working priority items for the European Commission that expects to achieve a reduction of 20% before 2020 and 40% before 2030 with respect to 1990.

The need to reduce the energy consumptions and to extend the life of the lights, impacting on a less expensive maintenance, leaded to the development of more efficacious and long aged fluorescent lamps, such as the compact fluorescent lamp (CFL) [1]. Moreover, in recent times, Light Emitting Diode

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(LED) are more widely accepted than CFLs because of their lower power consumption and longer life.

This ongoing replacement has raised a concern of a possible adverse effect on the power grid as a resistive load is replaced with an electronic one [2], introducing Power Quality (PQ) problems such as harmonic distortions, losses on the grid and power factor. The study of the PQ issues related to the lighting equipment already started in ‘90s [3] and it is still an actual research topic worldwide [4]~~-[6]~~.

Many researches are focused on the PQ disturbances caused by CFLs and LEDs [5]-[7] and on the definition of indices for their measurement and analysis [8]. Less works relate to Gas Discharge Lamps (GDL), but also in this case their PQ impact can be considered important [9]-[13]. In this context, this work wants to give a contribute presenting an experimental analysis on power and harmonic absorption of different outdoor lamps used in a railway station. This paper overcomes the analysis conducted in [14]-[15], also based on the indexes reported in the IEEE Trial use standard definitions [16], because it doesn’t refer to single lamps supplied by their own power reactors but to a system of lamps with a common line to the connection to the electric box [17]-[18].

The railway field is a particular context because of the many sensitive devices to the harmonic components, such as the signalling system. It is therefore important well analyse the impact of new lamps in terms of PQ. In particular, the paper presents an experimental survey conducted in a railway station of the North of Italy on different lamp technologies (LED and GDL) and for different working conditions. The experimental data have been analysed following the IEEE standard requirements and PQ indices have been calculated and presented in Section 2. Section 3 describes the measurement survey and the monitoring equipment characteristics. Section 4 presents the results of the monitoring activity on different type of lamps with different power supply systems while Section 5 reports the analysis of the three-phase unbalanced system in which each phase supplies a different kind of lamp. Both Sections summarize the main results, pointing out power and harmonic absorptions. In Section 6 conclusions are reported.

2. Power Quality Analysis

A power quality analysis has been performed to compare the impact of different lamps. The indices chosen to evaluate the experimental data in term of power components are the ones reported in [15]. A deep analysis of these quantities is presented in the following in order to customize the general recommendation given in the standard to the specific research.

In particular, with regards to the single phase case, the *RMS* values of voltage and current are decomposed, respectively, as:

$$V^2 = V_1^2 + V_H^2 \quad (1)$$

$$I^2 = I_1^2 + I_H^2 \quad (2)$$

where the subscript 1 refers to the fundamental harmonic and the subscript *H* refers to all the other the harmonics. The total harmonic distortion, or *THD*, of a signal is a dimensionless index of the harmonic distortion present and it is defined, for current and voltage respectively, as:

$$THD_V = V_H / V_1 \quad (3)$$

$$THD_I = I_H / I_1 \quad (4)$$

Starting from (1) and (2), the apparent power is decomposed into fundamental apparent power S_1, current distortion power D_I, voltage distortion power D_V and harmonic apparent power S_H as indicated in [17]. In particular:

$$S_1 = V_1 \cdot I_1 = \sqrt{P_1^2 + Q_1^2} \quad (5)$$

$$D_I = V_1 \cdot I_H,\ D_V = V_H \cdot I_1,\ S_H = V_H \cdot I_H \quad (6)$$

$$S_N^2 = D_I^2 + D_V^2 + S_H^2 \quad (7)$$

Fundamental apparent power accounts the power quantities related to the voltage and current fundamental harmonic and is composed by the fundamental active and reactive power. Current distortion power is related to the product of the voltage fundamental harmonic with all the current harmonic components. Similarly, voltage distortion power is related to the product of the current fundamental harmonic with all the voltage harmonic components.

The ratio between the non-fundamental apparent power S_N and S_1 is an important index in term of harmonic pollution. With regard to energy conversion, the active power *P* is defined as the mean value over a period of the instantaneous power p(t). The fundamental active power P_1, defined in (5), is given by:

$$P_1 = V_1 \cdot I_1 \cdot \cos\varphi_1 \quad (8)$$

Finally, the power factor is defined as:

$$PF = P / S \quad (9)$$

PF represents the ratio of the average power converted by the device *P* and the maximum average power that may be converted *S* considering the same *RMS* values of voltage and current. In this context, *PF* can be considered as an indicator of the quality in the energy conversion [12]. The efficiency of the device is instead the ratio between the output and input power of the device and it is a measure of the power losses into the device.

Considering a four wires three phase system, the *RMS* values of effective voltage and current they can be broken up into two terms that represent the *RMS* value of the first harmonic of the effective voltage V_{e1} and of the current I_{e1}, and their total harmonic content V_{eH} and I_{eH}:

$$V_e^2 = V_{e1}^2 + V_{eH}^2 = \frac{1}{18}\left(3\cdot\left(V_a^2 + V_b^2 + V_c^2\right) + V_{ab}^2 + V_{bc}^2 + V_{ca}^2\right) \tag{10}$$

$$I_e^2 = I_{e1}^2 + I_{eH}^2 = \left(I_a^2 + I_b^2 + I_c^2 + I_n^2\right)\Big/3 \tag{11}$$

Consequently, the equivalent total harmonic distortion for three-phase voltage and current, is:

$$THD_{eV} = V_{eH} / V_{e1} \tag{12}$$

$$THD_{eI} = I_{eH} / I_{e1} \tag{13}$$

Following the same procedure for single-phase systems, the effective apparent power S_e is broken up into fundamental effective apparent power S_{e1} and non-fundamental apparent power S_{eN}. S_{eN} is further broken up into effective current distortion power D_{eI}, effective voltage distortion power D_{eV}, and effective harmonic apparent power S_{eH} as:

$$S_e = 3V_e \cdot I_e \tag{14}$$

$$S_{eN}^2 = S_e^2 - S_{e1}^2 = D_{eI}^2 + D_{eV}^2 + S_{eH}^2 = \left(3V_{e1}\cdot I_{eH}\right)^2 + \left(3V_{eH}\cdot I_{e1}\right)^2 + \left(3V_{eH}\cdot I_{eH}\right)^2 \tag{15}$$

$$S_{e1} = 3V_{e1} \cdot I_{e1} \tag{16}$$

In three phase systems, the fundamental active and reactive powers are the one referred to the positive-sequence quantities. As a consequence, fundamental effective apparent power is decomposed into fundamental positive-sequence apparent power S_1^+ and fundamental unbalanced power S_{U1}:

$$S_1^+ = \sqrt{\left(P_1^+\right)^2 + \left(Q_1^+\right)^2} = \sqrt{\left(3V_1^+ \cdot I_1^+ \cdot \cos\varphi_1^+\right)^2 + \left(3V_1^+ \cdot I_1^+ \cdot \sin\varphi_1^+\right)^2} \tag{17}$$

$$S_{U1} = \sqrt{\left(S_{e1}\right)^2 - \left(S_1^+\right)^2} \tag{18}$$

The ratio S_{U1} over S_1^+ represents an index to determine the load unbalance. The ratio S_{eN} over S_{e1} is an important index to identify the harmonic pollution.

The fundamental positive-sequence power factor is defined as:

$$PF_1^+ = P_1^+ / S_1^+ \tag{19}$$

The power factor, that represents the percentage of the active power over the effective sizing power, is defined as:

$$PF = P / S_e \tag{20}$$

3. Monitoring Equipment Characteristics

A network analyzer and a 4-channel oscilloscope are used as monitoring system for the measurement campaign. The network analyzer was connected at the beginning of the three phase line in the main distribution electric box and it allowed the simultaneous recording of all the electrical quantities for a four-wire three phase system. The oscilloscope was connected at the end of the line 1 and it measured the line voltage and current simultaneously with the network analyzer.

The network analyzer recorded, for each test, the waveforms of line to neutral voltages, line currents, neutral current. The sampling rate for each waveforms was 256 samples/cycle (referred to the European frequency of 50 Hz). The measurement of the voltages did not require any transducers, while the currents was measured through current clamps whose bandwidth is from 40 Hz to 3 kHz and their scale is 5A. The neutral current was measured by using an active DC/AC current clamp whose scale is 10A.

The oscilloscope provides, for each test, the waveforms of the line to neutral voltage and the line current absorbed by the last load. The sampling rate for each waveforms is 100 kS/s. In order to reduce the noise, 5 cycles are sampled and the average period is calculated. Line to neutral voltage is measured through a differential voltage divider, while neutral to ground voltage is measured by a 10x attenuated probe. Line current is through current DC/AC clamps with 100mV/A ratio and bandwidth up to 30 kHz.

Network analyzer and oscilloscope are not automatically synchronized by a common clock signal, however voltage and current waveforms are quite stable and manual synchronization can be acceptable. The aim of this measurements campaign is the harmonic analysis up to 2 kHz presented in the following.

4. Single Phase Lamps Monitoring Survey

The survey deals with some different types of outdoor lamps, two type of LEDs and GDL, supplied with different electronic ballasts. In particular, the monitoring activities have been performed on:

1. The first lighting system (LED 1) is composed by 14 LED bars each one with a rated power of 35W supplied by three electronic system.
2. The second lighting system (GDL) is composed by 5 GDL each one with a rated power of 70W supplied by 5 electronic systems, and 10 traditional lamps each one with a rated power of 20W.
3. The third lighting system (LED 2) is composed by 8 pole-mounted LED lamps each one with a rated power of 75W and 2 pole-mounted LED lamps each one with a rated power of 100W supplied by electronic systems.

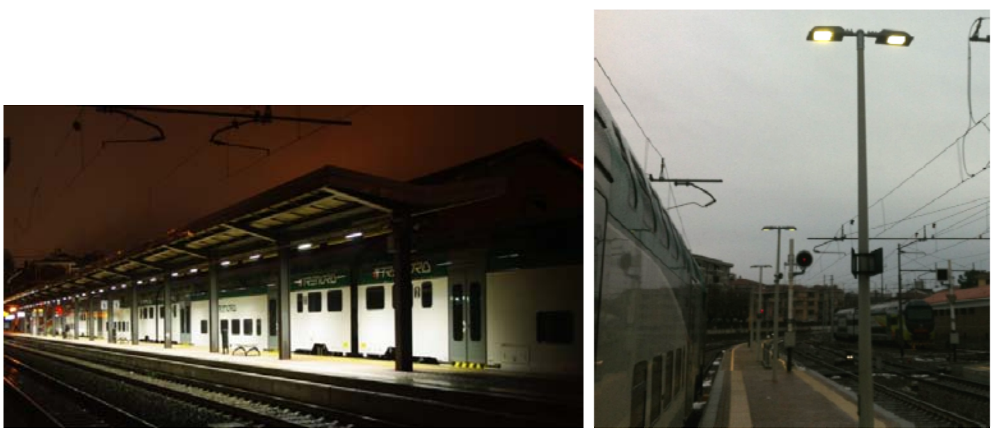
In case of LED lamp the flux intensity is regulated acting on the duty cycle to obtain 5 different dimming rates starting from 0% to 100% (full power). In the following it is reported a detailed analysis of the measurements performed on these three different lighting systems.

4.1. Experimental survey results on LED System 1

The first experimental survey was related to the voltage and current measurements of a row of 14 bar led lamps supplied by three electronic ballasts with a dimmable drive for the control of the operating status. These lamps are placed under the platform roof of the station as depicted in Fig. 1a.

Voltages and currents are recorded at the beginning of the supply line for different dimming rate. In particular, in Fig. 3 are shown the line voltage and the absorbed current for dimming rated of 50% and 100% (full power) respectively.

As it is possible to see, the voltage is quite sinusoidal (the THDV is about 1.7%) since it has been recorded near the main electric box, that is a point with high short circuit level. Although the current waveform appears distorted, the harmonic content is not very high especially with high load factor as depicted in Fig. 2. In fact, the total harmonic distortion of the current is about 16% at full power. In this condition, the THD_V reaches its maximum value of 1.9%. As a consequence, the *PF* is high (Table 1), but it decreases as load factor decreases.



(a) (b)

Fig. 1. (a) System LED 1 and (b) System LED 2

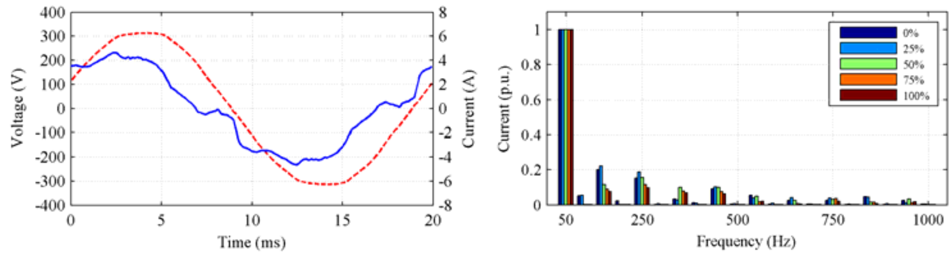


Fig. 2. Voltage and current waveform absorption at 100% (full power) and harmonic contents of current for the LED System 1 with different load factor

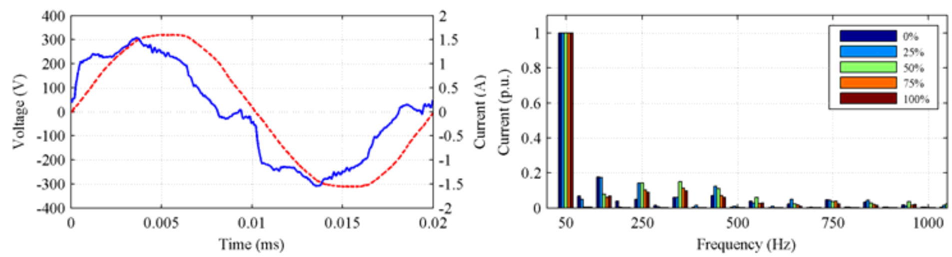


Fig. 3. Voltage and current waveform and harmonic contents of current for the last load of LED System 1 with different dimming rates

At the end of the line the same measurements are performed by using the oscilloscope. As shown in Fig. 3 the current waveform absorbed by the last load appears distorted as the current measured at the beginning of the line in all the cases. The THD_I measured in correspondence of the last ballast at full power is 17%, and it varies with load factor as those one measured at the beginning of the line. Instead the voltage remains quite sinusoidal: its THD_V is equal to 3.3%. The voltage drops along the line and between loads are very small, therefore the voltage applied to each load is about the same and, since the devices are identical, the current waveforms that characterize each load are quite the same.

The rows of Table 1 identified by LED 1 show the results of the power quality analysis reported in Section 2 for the measurement at the beginning of the line. Table 2 shows the results of the power quality analysis for the measurement in correspondence of the last load of the same line.

Table 1

Power Quality Analysis of the measurements results obtained by LED system 1, GAS-discharge lamps, and the LED system 2

	Load factor	THD_V	THD_I	Apparent Power S (VA)	Active Power decomposition			Apparent Power Decomposition			$\cos\varphi_1$	PF	S_N/S_1
					P (W)	P_1 (W)	P_H (W)	S_1 (VA)	S_N (VA)	S_H (VA)			
LED 1	0%	1.7%	29.6%	163.15	83.87	84.25	-0.385	156.40	46.43	0.782	0.539	0.514	0.297
	25%	1.9%	33.1%	291.29	208.03	208.86	-0.831	276.45	91.76	1.698	0.755	0.714	0.332
	50%	1.9%	25.5%	456.13	356.07	357.10	-1.032	441.87	113.14	2.147	0.808	0.781	0.256

	75%	2.0%	18.9%	578.23	478.29	479.32	-1.028	568.03	108.10	2.121	0.844	0.827	0.190
	100%	1.9%	16.0%	692.92	608.63	609.60	-0.970	684.05	110.53	2.045	0.891	0.878	0.162
GDL	-	1.9%	25.3%	762.79	619.77	618.53	1.233	739.43	187.33	3.588	0.836	0.812	0.255
LED 2	0%	1.8%	87.0%	289.98	143.79	146.43	-2.643	218.74	190.38	3.455	0.669	0.496	0.870
	25%	1.8%	110.2%	474.49	273.69	278.13	-4.446	318.74	351.49	6.384	0.873	0.577	1.103
	50%	2.1%	109.3%	688.95	429.81	437.36	-7.554	464.88	508.46	10.43	0.941	0.624	1.095
	75%	2.1%	106.6%	894.31	580.91	590.80	-9.896	611.68	652.41	14.01	0.966	0.650	1.066
	100%	2.2%	103.4%	1122.99	750.43	763.27	-12.84	780.37	807.54	17.87	0.978	0.668	1.035

Table 2

Power Quality Analysis of the measurements results on the last load of LED system 1 and of of the single pole-mounted LED lamp tested in the PQ Lab.

	Load factor	THD_V	THD_I	Apparent Power S (VA)	Active Power decomposition			Apparent Power Decomposition			$\cos\varphi_1$	PF	S_N/S_1
					P (W)	P_1 (W)	P_H (W)	S_1 (VA)	S_N (VA)	S_H (VA)			
LED 1 Last laod	0%	3.2%	42.68	42.68	15.04	15.12	-0.07	41.43	10.26	0.32	0.365	0.352	0.248
	25%	3.3%	89.60	89.60	59.23	59.38	-0.15	85.84	25.71	0.85	0.692	0.661	0.300
	50%	3.3%	141.65	141.65	105.10	105.59	-0.49	136.38	38.27	1.25	0.774	0.742	0.281
	75%	3.3%	183.21	183.21	146.92	147.25	-0.33	179.75	35.41	1.15	0.819	0.802	0.197
	100%	3.3%	221.53	221.53	191.19	191.60	-0.41	218.27	37.85	1.24	0.878	0.863	0.173
LED 2	100%	2.2 %	164.2%	154.3	77.7	79.1	-1.4	80.2	131.8	2.9	0.986	0.503	1.643

Comparing these results, it is possible to note that the behavior of the total lighting system 1 is quite better than those one of the single ballast. This is mainly due to some harmonic current compensations among the various load. In any case, the effects of these harmonics do not have a great impact on the voltage quality as the THD_V remains lower the allowed limits indicated by the EN50160 standard.

4.2. Experimental survey of Gas-Discharge lamp

The second experimental survey was related to gas-discharge lamps, in particular 5 floodlight lamps of 70 W each and 10 conventional lamps of 20 W each. Every lamp is equipped with electronic ballast without dimming system.

As it is possible to note in Fig. 4, the current is quite triangular with a moderate harmonic content that does not significantly increase the THD_V. Instead, the power factor can be considered quite high as reported in Table 1. Compared to the previous case, two main differences can be identified. The first one regard the power factor that is greater for the first case (LED 1) than for the second (GDL), even if the total power factor is similar. This is due to fact that displacement factor $\cos\varphi_1$ is higher, so the ballast absorbs less reactive power, and the harmonic content, identified with the index S_N/S_1, is lower. The second difference is related to the efficiency of the ballasts, that is about 81% for the LED 1 and 89% for the GDL, even if the overall efficiency of the lighting system is much greater for the

LED 1. The row of Table 1 identified by GDL shows the results of the power quality analysis presented in Section 2 for this experimental survey.

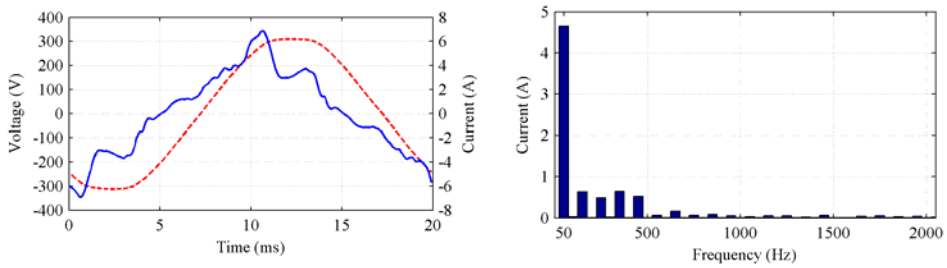


Fig. 4. Voltage and current waveform, and current harmonic contents of the Gas-Discharge lamp System

4.3. Experimental survey results of LED System 2

The last survey regarded the voltage and current measurements in the line that supplies the pole-mounted LED lamps placed in the station platform as reported in Fig. 2b. These lighting system consists in 8 lamps of 75 W each plus 2 lamps of 100 W each, supplied by electronic ballasts. Therefore, this survey has been carried out for different dimming rates.

These ballasts are characterized by pulse-shaped current absorptions typical of rectifiers based on diode bridge plus bulk capacitor in the DC section as input stage (see fig. 5). In fact, the amplitude of the pulses is proportional to the absorbed power. Due to this particular current waveform, the harmonic content is much higher than the previous cases as reported in Fig. 2. Indeed, the THD_I reaches 103% at full power that increases the THD_V till 2.2%.

The same lamp typology has been previously tested at the Politecnico di Milano in full power condition. The result of the harmonic content analysis is reported in Fig. 5. The trend of harmonic content is the same, but the amplitude of each harmonic is quite different. In fact, for the infield installation it is possible to identify a bigger attenuation than in the laboratory case of the current harmonic components. This is mainly due to the effect of the harmonic compensation between the various ballast as previously seen in LED 1.

The rows of Table 1 identified by LED 2 show the results of the power quality analysis for this experimental. Table 2, last row, shows the results of the power quality analysis for the measurement carried up on the same lamp at the Politecnico di Milano in full power condition.

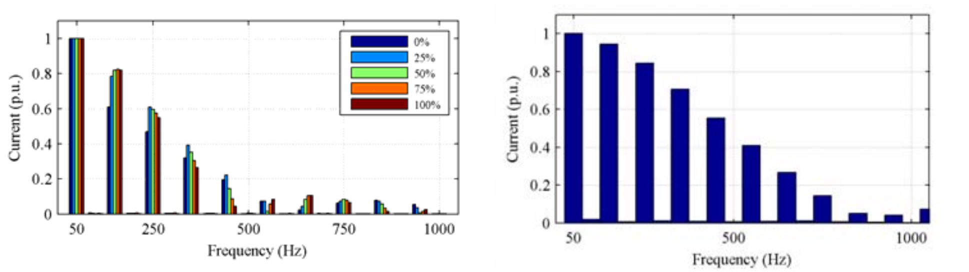


Fig. 5. Harmonic contents of current with different dimmer working condition of the LED System 2 and harmonic contents of current for one LED lamp of System 2 measured in Lab at full power

5. Three Phase System

In this case, the survey deals with the whole lighting system of the station platforms, that include the same types of outdoor lamps analyzed in the previous section supplied at the same time. These lamps are supplied by a four wire three phase line in the following configuration:

- line 1 supplies the system LED 1, that light the platform 1;
- line 2 supplies a load similar to those of line 1 that light the platform 2, but in this case the pole-mounted lamps have a rated power of 70 W with their own ballasts of 100 W each.
- line 3 supplies the systems GDL analyzed in Section 4.2.

The monitoring activities have been performed considering the following two cases:

- Case A: line 1 and line 2 are switch on, while line 3 is switch off.
- Case B: all lines are switch on.

In any cases, LED lamps worked at their full power.

5.1. Two-phase load

This case represents a non-sinusoidal and unbalanced system that supply same lamps technology. Voltages and currents recorded at the beginning of the three-phase line are shown in Fig. 6.

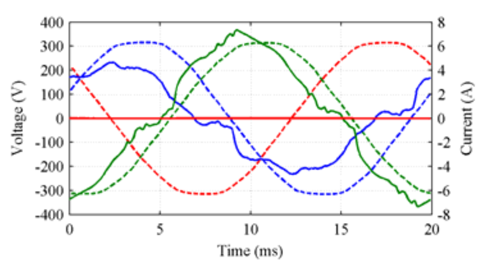


Fig. 6. Voltage (dotted) and current (continuous) waveform measured in case A; blue, green and red represent line 1, 2 and 3 respectively

The resulting neutral current and its spectra at the electric box are shown in Fig. 7.

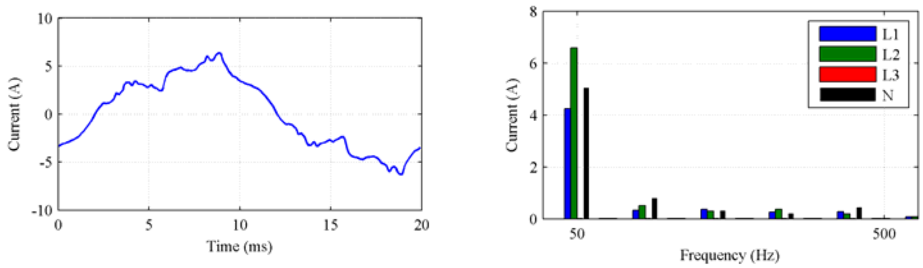


Fig. 7. Neutral current waveform and harmonic contents of line and neutral currents in case A

Table 3

Power Quality Analysis of the measurements results obtained by Three-Phase System

	THD_{Ve}	THD_{Ie}	Apparent Power S_e (VA)	Active Power decomposition			Apparent Power Decomposition					PF	PF_{1+}	S_{eN}/Se_1	S_{U1}/S_{1+}
				P (W)	P_{1+} (W)	P_H (W)	S_{e1} (VA)	S_{1+} (VA)	S_{U1} (VA)	S_{eN} (VA)	S_{eH} (VA)				
A	2%	15%	2640.68	1613.81	1614.96	-2.09	2609.32	1742.29	3137.53	405.74	2.23	134.45	14.45	0.79	0.611
B	2%	27%	2700.3	2226.1	2231.9	-1.40	2603.8	2446.6	3572.9	715.59	3.76	0.82	0.91	0.27	1.46

Due to the load unbalance, the fundamental of the neutral current is very high (I_{N1}=3.58 A). The harmonic content and the THD_I for the current in line 1 is 15.4% and it is quite similar to those obtained in Section 4.1, while the THD_I for the current in line 2 it is lower and equal to 11.2%. Despite the same lamp technology, ballasts connected to phase 2 are characterized by a lower non-sinusoidal absorption manly due to their different rated power. The effective neutral current is 3.66 A and its THD_I is 20.8%. The harmonic content of neutral current it is mainly due to the in phase sum of the line 3rd harmonic currents and their odd multiples. The row of Table 3 identified by A shows the results of the power quality analysis for this experimental survey.

5.2. Three-phase Load

This case represents a non-sinusoidal and unbalanced system that supply lamps with two different technologies. Voltages and currents recorded at the beginning of the three-phase line are shown in Fig. 8, while the resulting neutral current and its spectra at the electric box are shown in Fig. 9.

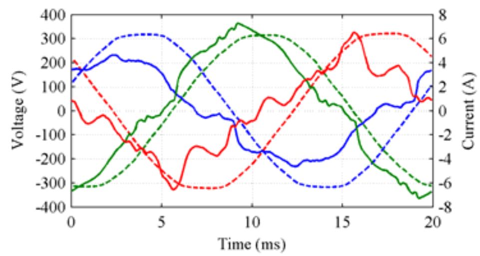


Fig. 8. Voltage and current waveforms at full power of dimmer in case B in steady state condition

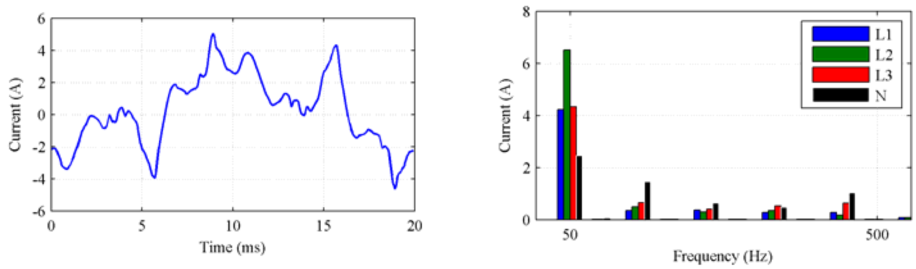


Fig. 9. Neutral current waveform and harmonic contents of line and neutral currents in case B

Due to the load unbalance, the fundamental of the neutral current is nonzero, but it is about half than in Case A (I_{N1}=1.74 A). The harmonic content and the THD_I for the currents in lines 1 and 2 are very similar to those obtained in two-phase load (THD_{I1}=15.7%, THD_{I2}=11.2%,), while for the line current in phase 3 it is higher and equal to 27.1%. The effective neutral current decreases until 2.25 A, but its THD_I grows up to 81.7%, highlighting a high level of distortion.

6. Conclusion

In this paper, a measurement campaign, carried out in a railway station, has been analyzed and commented in order to identify the behaviour of new lighting systems based on LED lamps. In particular, the recorded measurements have been analyzed to find the harmonic content in different working condition of voltage and current.

The obtained results show that the harmonic current content is not related to the lamp typologies, but to their supply ballasts, even if the efficiency of the lighting system, in terms of energy consumption and operating and maintenance costs, is more favourable for LED systems.

In unbalance three-phase systems, as the one here analyzed, LED lamps do not cause a particular voltage quality decay. In fact, even if they can absorb very distorted currents depending on their ballast typology, they absorb small power due to their high efficiency, therefore the voltage drop along the low-voltage feeders is moderate. However, particular care has to be taken in neutral current, because it can have a greater harmonic content mainly due to 3rd harmonic summation. Furthermore the measurements conducted on the lamps installed on the station platform show a lower total harmonic distortion than those carried out on the same lamp in the laboratory.

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