Power Quality Assessment of Indoor LED Luminaires

Ramazan Ayaz
Electrical Engineering Dept.
Yildiz Technical University
Istanbul, Turkey
ayaz@yildiz.edu.tr

Kadir Dogansahin
Electrical&Electronics Engineering Dept.
Artvin Coruh University
Artvin, Turkey
dogansahin@artvin.edu.tr

Altug Bozkurt
Electrical Engineering Dept.
Yildiz Technical University
Istanbul, Turkey
abozkurt@yildiz.edu.tr

Bedri Kekezoglu
Electrical Engineering Dept.
Yildiz Technical University
Istanbul, Turkey
bkekez@yildiz.edu.tr

***Abstract*—Due to the fact that it is a semiconductor based lighting equipment, the LEDs have important effects on the power quality. In the ever-expanding lighting industry, the use of LED equipment is increasing day by day. Therefore, it is very important to analyze and interpret the effects of LEDs on the grid. In this study, power quality measurements of 4 different commercial LED luminaires have been realized and the results obtained have been interpreted. According to the measurements, it is found that the power factor values are acceptable for the luminaries when they are completely on. However, when the luminaries are dimmed, it has been observed that the power factor decreased and the current harmonics exceeded the limit values determined by the related standards. On the other hand, it is seen that all the luminaires provide flicker boundaries. As a result of the study, it has been concluded that the effects of dimmable equipment on power quality should be analyzed in more detail.**

Keywords—LED lamps, power quality, harmonics, flicker, power factor

I. Introduction

A. Motivation

Lighting has become one of the most basic needs of human being nowadays. The energy used for lighting corresponds to nearly 20% of the global electricity consumption and 5% of CO_2 emission [1]. Increasing efficiency in lighting systems provides significant environmental and economic returns.

Recently, many studies have been realized about the effects of lighting on human health and quite striking results have been achieved [2], [3]. Therefore, the suitability to intended use and the comfortability providing to the user has become an important issue, in addition to efficiency. Considering all these requirements, economic and quality lighting solutions have become an important research area.

Lighting technologies are developed constantly in parallel with the current needs and trends. LED lighting is one of the technologies developed in response to the needs mentioned above with their high efficacy factor, color rendering index and correlated color temperature range [4].

A LED, as the basic structure, is composed of a diode emits light with a current flows through. According to the characteristics of the semiconductor material in the LED structure, the wavelength of the light emitted to the environment differs. Similarly, the electrical magnitudes are determined in the light of electrical characteristics of the semiconductor material. LEDs need constant and direct current supply. In power systems, LEDs are applied with an auxiliary system that converts AC to DC and drives appropriate current. These auxiliary systems mainly consists of an EMI filter at the input, a rectifier bridge and a DC-DC converter circuit. Buck, boost, flyback and resonance converters are common for the LEDs.

Since LEDs intrinsically operate with direct current, they cannot be used in the systems with alternative current, without drivers comprised of power electronics. Power electronics are nonlinear components and cause harmonics in power systems. In this respect, a reciprocal interaction between the power system and the LEDs in terms of power quality can be mentioned. As a load, LEDs have disturbing effects on the power system in terms of power quality. This effect is quite remarkable considering the wide range of usage area of LEDs and their quantitative potential in power systems. On the other hand, LEDs as a lighting element may experience deterioration in lighting quality due to disturbances in the power system. Any information about the effects of LEDs on the power system and the effects of instabilities in the power system on the lighting quality of the LEDs contribute to understand the future problems and the potential solutions that can be experienced.

B. Literature

LED lighting has been widely investigated in the literature, in many aspects. Since this study is focused on the power quality of LED lighting, the literature shared in this section is limited only within this scope. The majority of the studies has been performed by the power quality measurements taken from experimental setups to prove the effects of LED systems on power quality. In some of these studies, the scope has been kept wide by involving many power quality subject together [5]–[7], and in some of them the power quality assessments have been made on a single subject such as harmonics [8], [9], power factor or power losses [10].

Besides, various studies has been conducted in order to examine the flicker, which is an event experienced in lighting systems as a result of power quality problems, on the point of LEDs. In [11], [12], the contribution of the LEDs to the flicker event has been analyzed. In [13], classification of the LEDs have been examined according to the flicker efficiency. Moreover, there are studies that performed on creating a suitable model for LEDs according to their behavior in systems in terms of power quality [14].

By the increasing use of LED systems, the comparison of the performances of different types of lighting equipment in terms of power quality has become a matter of curiosity [15], [16]. Especially, numerous studies on the comparison of CFL and LED technologies can be found in the literature [17], [18]. Studies investigating the use of CFLs and LEDs together are also frequently encountered [19].

On the other hand, there is a part in the literature involving the studies on the solutions about preventing power quality problems caused by LEDs [20], [21].

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C. Contribution and Organization of the Paper

In this study, four different commercially available LED fixtures are evaluated in terms of power quality. The results have been examined in a comparative manner and interpreted in the light of standards.

Contributions of the study to the literature:

- The measured power quality indices over the nominal and dimmed values of different types of commercially available LED fixtures are compared and the results are interpreted.
- The effects of different lighting intensities, power levels and color temperatures on the power quality parameters are determined and compared.
- The results are given in detail. A reference can be made to provide an idea for the studies to be carried out on the disruptive effects of LEDs on the power system.

In the second section of the paper brief information are given regarding power quality parameters and indices. Details about the measurement setup and the LED fixtures are given in the third section. The obtained results and their interpretations are shared in the fourth section of the study. The study is concluded by the fifth section with referring the remarkable findings obtained through the study.

II. Power Quality Parameters and Indices

A. Harmonics

Harmonics are one of the most important power quality parameters. As with the definition given in IEEE 519, harmonic is a component of order greater than one of the Fourier series of a periodic quantity [21]. Following recent developments in semiconductor technologies, the application field and usage of power electronics systems has become more widespread. Therefore the penetration of the nonlinear loads increased within the power systems.

Harmonic distortion must be limited within a certain level, otherwise it may cause various problems in the systems. For this reason, several indices and criteria have been determined. One of these indices is Total Harmonic Distortion (THD), which is a ratio of the components in a signal to the fundamental component of the signal. Another important harmonic index applied in harmonic analysis is total demand distortion (TDD) [21]. Mathematical definitions of THD and TDD are given in (1) and (2), respectively.

$$THD = \sqrt{\sum_{n=2}^{n}\left(\frac{V_n}{V_1}\right)^2} \tag{1}$$

$$TDD = \sqrt{\sum_{n=2}^{n}\left(\frac{I_n}{I_{max}}\right)^2} \tag{2}$$

where, V and I denotes rms values of voltage and current, respectively. The subscript n indicates the order of the component. I_{max}, is the maximum current of fundamental component measured at the point of common coupling.

In power systems voltage values are defined over certain levels. Therefore, it is more appropriate to use THD for the evaluation of voltage distortion. However, current is special to the load and applying THD in current evaluation may be misleading for the loads at low power. IEEE 519 is a well-documented guide for the necessary recommendations and further details [21].

B. Flicker

Flicker is the variation of light intensity within the human eye perception limits [22]. The reason of flicker is the voltage fluctuations at the point of connection. In a 50 Hz power system, voltage alternates between positive and negative cycles 50 times in a second, but the visual impact of this fluctuation is out of human eye perception. The voltage may sag or swell for a longer period than tens of cycles, caused by disturbances in power systems. In this case, the light intensity may decrease or increase for a while or it is also possible to fluctuate. A number of studies have been carried out to investigate the effect of flicker on human health and it is understood that flicker impairs vision process and brain reactions [2], [3].

In order to measure the flicker severity, two flicker indices have been designated by taking into account voltage light interaction of incandescent bulbs. One of the indices is the short-term flicker (P_{ST}), which is based on voltage monitoring for 10 minutes and defined over time of certain threshold values. The other one is the long term flicker (P_{LT}) indices, which is based on an hour voltage measurement [23]. Mathematical expression of long term flicker is given in (3).

$$P_{LT} = \sqrt[3]{\frac{\sum_{i=1}^{N} P_{STi}^3}{N}} \tag{3}$$

The equation for P_{LT} is given simply. However, the definition of P_{ST} is much more than an equation, for detailed information IEC 61000 can be referred [23].

C. Power Factor

Power factor is the ratio of the power that is utilized by the load, to the power provided in a cycle. In sinusoidal systems with linear loads, there are only fundamental components and it is easy to determine the power factor. However, there are more components other than fundamentals in nonsinusoidal systems and these components cause additional loading on the system. For this reason there are two different expressions for power factor. One of them is addressed with the name of power factor and it corresponds to value that is obtained by taking into account only the fundamental components. The other one is known as the true power factor (4) and it takes into account all components.

$$S = V_1 I_1$$
$$P = V_1 I_1 \cos(\varphi)$$
$$PF = P/S$$
$$PF_{true} = \frac{P}{S\left(\sqrt{1+\left(\frac{THD_V}{100}\right)^2}\right)\left(\sqrt{1+\left(\frac{THD_I}{100}\right)^2}\right)} \tag{4}$$

III. Measurement Setup and Lighting Luminaires

A. Details of Lighting Luminaires

The measurements of four different commercial 60 × 60 LED indoor lighting luminaires were performed in this study. The characteristic values of tested luminaires were determined by the measurements. The photometric and electrical measurements of the luminaires were carried out in Yildiz Technical University Lighting Laboratory. While the luminous flux and efficacy of the luminaires were determined with the measurement using goniophotometer, the correlated color temperature (CCT) and color rendering index (CRI) of the luminaires were measured with the Ulbricht sphere which has 2 m diameter. The luminaires were tested without seasoning. It should be noted that, the light output of some LEDs can increase slightly during the first 1000 h of operation, but many LED sources do not exhibit similar behavior [24]. All photometric measurements were initiated after the luminaires became stable. The goniophotometer and sphere photometric measurement systems are shown in Figs. 1 and 2, respectively. The temperature and humidity of the laboratory were maintained at 25 ± 1 °C and 65%, respectively, with the help of an air condition unit. The test distance of goniophometer was 13.64 meters.

Fig. 1. Goniophotometer measurement system.

Fig. 2. Ulbricht sphere measurement system.

The obtained photometric and electrical values for the tested luminaires are presented in Table I and Table II, respectively. The photometric and electrical values were measured at 220V test voltage.

TABLE I. ELECTRICAL PARAMETERS OF LUMINAIRES

Manufacturer	Current (A)	Power (W)	Power Factor
A	0.1643	34.53	0.9593
B	0.1576	33.53	0.9666
C	0.2218	47.86	0.9804
D	0.1480	31.40	0.9637

TABLE II. PHOTOMETRIC PARAMETERS OF LUMINAIRES

Manufacturer	Luminous Efficacy (lm/W)	Luminous Flux (lm)	Color Rendering Index (Ra)	Correlated Color Temperature (K)
A	111.47	3849.58	84.1	3996
B	75.29	2524.7	85.5	6420
C	107.83	5160.84	85.0	3927
D	74.67	2344.46	82.8	3876

It has been seen that the C luminaire has the highest nominal power with 47.86 W and the highest power factor with 0.9804. When the photometric measurements are considered, it is seen that the efficacy of B and D luminaires are approximately 75 lm/W and the efficacy of A and C luminaires are approximately 110 lm/W. The highest luminous efficacy was found in the A luminaire with 111.47 lm/W. In color temperature, the A, C, and D luminaires have natural white light but the B luminaire has a cold white light. The CRI of all luminaires were more than 80.

B. Power Quality Measurement Setup

The power quality measurements of four different LED luminaires were carried out using FLUKE 435-II quality analyzer in this study. The voltage, current, power and power factor changes, harmonic values and flicker levels of luminaires were recorded at 3 s intervals during measurement. The power quality measurement setup is shown in Fig. 3.

Fig. 3. Power quality measurement setup.

IV. RESULTS AND DISCUSSION

Power factor, harmonic and flicker measurements has been realized on 4 different commercially available LED luminaries taken into consideration in the study. The measurement results are presented below with their interpretations.

A. Power and Power Factor

The active power, apparent power and power factor measurements for all luminaires are plotted in Fig. 4.

As a result of the measurements, power factor values were found to be above 0.95. It was observed that the power factor values of the all products other than the one that belongs to manufacturer A, remained constant during the measurement. The product that belongs to the manufacturer A is in oscillation between the 0.95–0.96 values.

The values obtained as a result of the power factor measurements performed at different luminous flux values on the dimmable products of the manufacturer C and D are shown in Fig. 5 and Fig. 6, respectively.

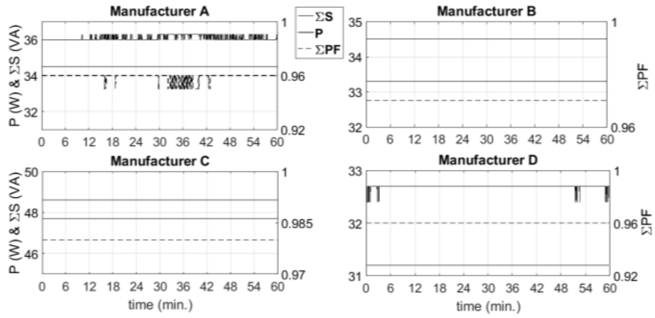

Fig. 4. Power factor variation of the luminaires.

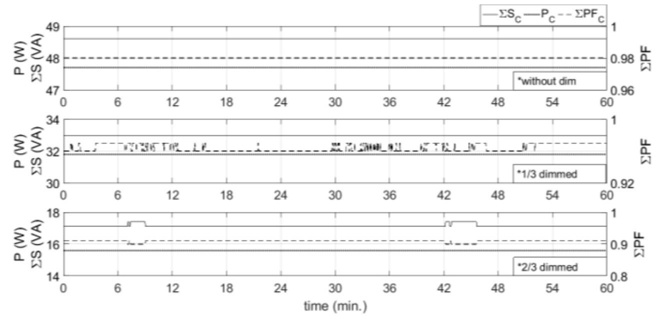

Fig. 5. Power factor variation at different luminous flux for the luminaire belongs to manufacturer C.

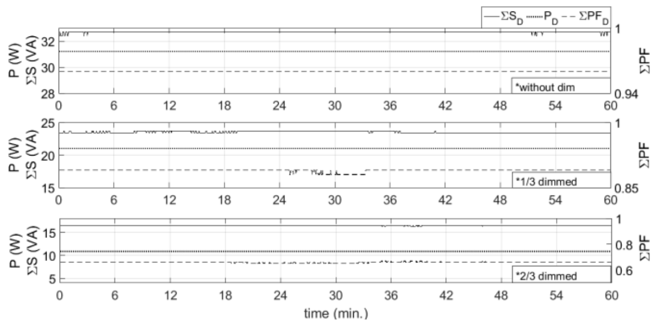

Fig. 6. Power factor variation at different luminous flux for the luminaire belongs to manufacturer D.

Table III shows the power factor values obtained for different light fluxes. When the values are examined, it is understood that the power factor value decreases due to the decrease in light flux. In other words, in the case of dim lighting, the power factor value is also decrease in value. When the measurement results for both armature are evaluated, it is figured that the power factor decrease is much more dramatically in the product of manufacturer D than that of manufacturer C.

TABLE III. POWER FACTOR VALUES FOR DIFFERENT LUMINOUS FLUX

Luminous Flux	Man. C	Man. D
3/3	0.9804	0.9637
2/3	0.9639	0.8891
1/3	0.9091	0.6586

B. Harmonics

In the measurements performed in the study, voltage and current harmonics from the terminals of the luminaires have been taken into consideration separately. In the evaluation of voltage harmonics, THD index and in the evaluation of current harmonics, TDD index has been taken into account.

a) Voltage harmonics

The 1-hour THD variations of the luminaires are given in Fig. 7. It is observed that the effects of the luminaires, in terms of voltage harmonics, are quite limited on the point of connection. Considering the IEEE 519-2014 standard, it can be seen that the THD values remained within the limits.

Fig. 8 and Fig. 9 illustrates the variation of the THD values for different luminous flux values belongs to the luminaires of manufacturer C and D, respectively. It is observed that the THD values decreased due to the decrease in the power value taken in the dimmed conditions.

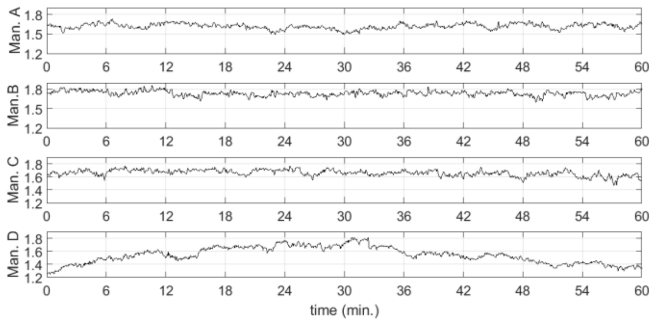

Fig. 7. THD variation of the luminaires.

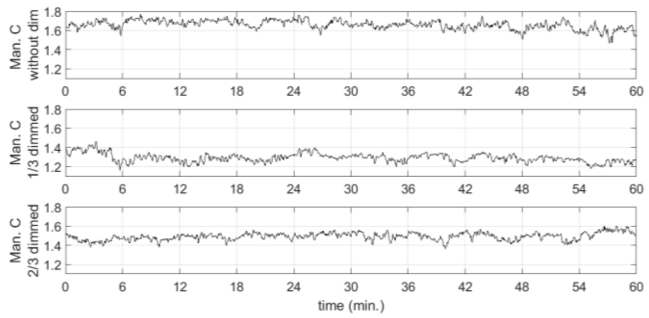

Fig. 8. THD variation at different luminous flux for the luminaire belongs to manufacturer C.

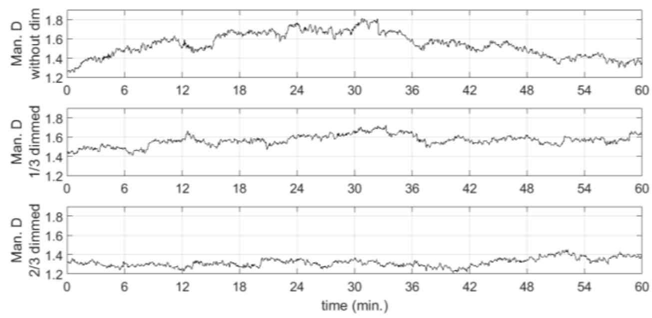

Fig. 9. THD variation at different luminous flux for the luminaire belongs to manufacturer D.

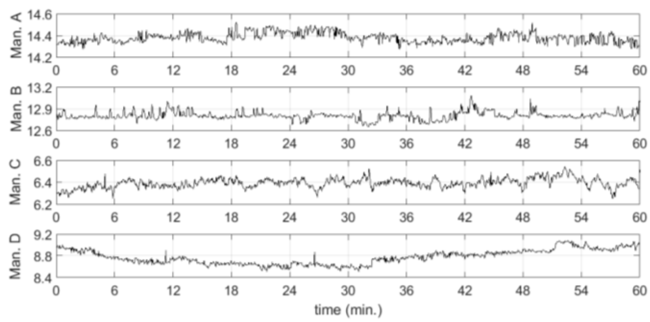

Fig. 10. TDD variation of the luminaires.

b) Current harmonics

TDD variations of the luminaires are given in Fig. 10. Table IV shows the minimum, maximum and average TDD values calculated over 1-hour measurements of the luminaires examined within the scope of the study. When the measurement results are evaluated, it can be observed that the product which is belongs to the manufacturer C has the lowest harmonic deterioration, whereas the highest value is experienced in the luminaire that of manufacturer A.

TABLE IV. TDD VALUES OF THE LUMINAIRES

Manufacturer	Minimum TDD	Average TDD	Maximum TDD
A	14.273	14.3791	14.5199
B	12.6471	12.8041	13.0805
C	6.2517	6.3923	6.5456
D	8.5094	8.7742	9.0825

TDD index is recommended to be used in the evaluation of current harmonics by IEEE 519-2014 standard. According to the standard, the limit values for TDD and odd harmonics are expressed depending on the short circuit power at the point of common coupling to which the load is connected. When the values given in Table IV are examined, it can be deduced that significant harmonic problems can be experienced especially when the luminaires of manufacturers A and B are used in a weak connection point.

The histograms generated with the percentages of current harmonics obtained over the value of the fundamental component is shown in Fig. 11. When the histograms are examined, it is seen that the 3rd degree harmonic component becomes more dominant and all components up to the 30th harmonic component show activity.

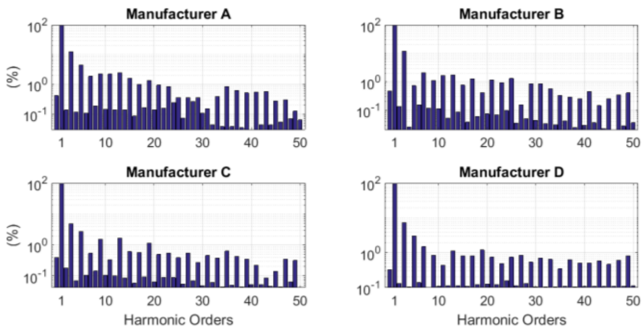

Fig. 11. Histogram of current harmonics for the luminaires.

Asymmetric current and voltage waveforms produced by the half-wave rectifier and half-controlled converters cause even harmonics. The even harmonics are less in the D luminaire compared to the A, B and C luminaires. This difference may cause from the difference in driver structures of the luminaires. These harmonics can cause losses in the power system and cause excessive current to flow from the neutral line.

Figs. 12 and 13 show the variation of current harmonic deterioration in terms of TDD at different luminous flux levels of luminaires of manufacturers C and D, respectively. Table V shows the average TDD values for different luminous flux levels.

When Table V is examined, it is seen that there is a significant increase in the TDD values with the decrease of the luminous flux value in both luminaires. Especially in low luminous flux values, the TDD value reaches very high levels such that for both luminaires this value has exceeded 10%.

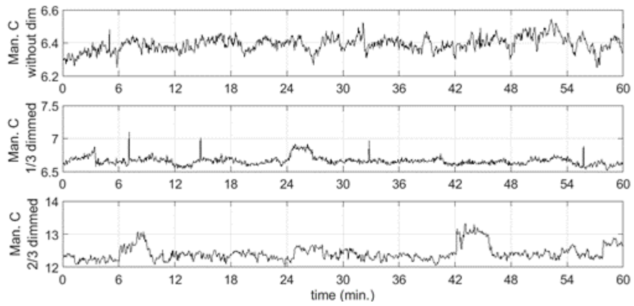

Fig. 12. TDD variation at different luminous flux for the luminaire belongs to manufacturer C.

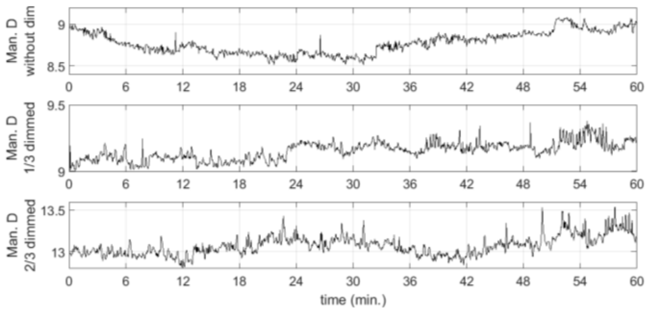

Fig. 13. TDD variation at different luminous flux for the luminaire belongs to manufacturer D.

TABLE V. TDD VALUES FOR DIFFERENT LUMINOUS FLUX

Işık Akısı	Man. C	Man. D
3/3	6.3923	8.7742
2/3	6.6599	9.1523
1/3	12.4202	13.0759

Figs. 14 and 15 show the histograms for the current harmonics at different luminous flux levels of the luminaries of the manufacturers C and D, respectively.

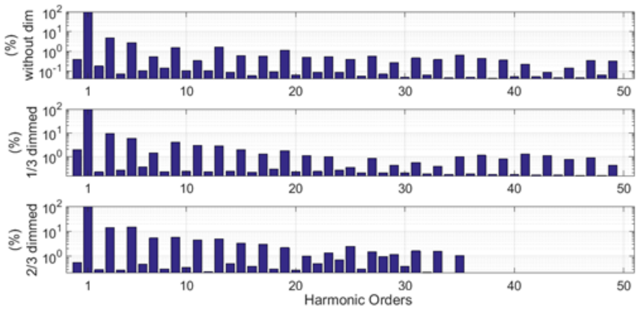

Fig. 14. Histogram of current harmonics at different luminous flux for the luminaire belongs to manufacturer C.

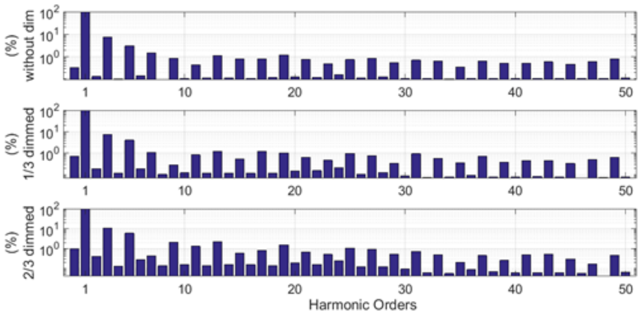

Fig. 15. Histogram of current harmonics at different luminous flux for the luminaire belongs to manufacturer D.

C. Flicker

The variation of the short-term flicker severity values during the 1-hour measurements of the LED luminaires are shown in Figs. 16, 17, and 18. The values for the long-term flicker severity obtained from the short-term flicker values are presented in Table VI.

According to EN 50160, the P_{LT} value should be less than 1 for at least 95% of the measurement time. When the values given in the Table VI are examined, it is seen that all luminaires meet the relevant limit.

Variations of the short-term flicker severity index obtained from measurements realized with different luminous flux levels on the LED luminaires belonging to manufacturer C and D are plotted in Fig. 17 and Fig. 18, respectively. Long-term flicker severity indices obtained for both products are listed in Table VII.

When the measurements performed with different light fluxes are evaluated, it is observed that the flicker variable increases as the luminous flux decreases for both luminaires.

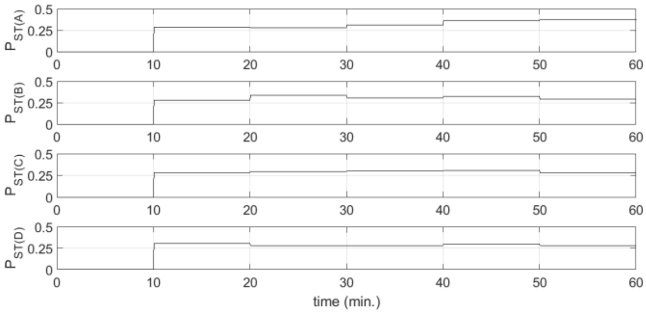

Fig. 16. Variation of short term flicker.

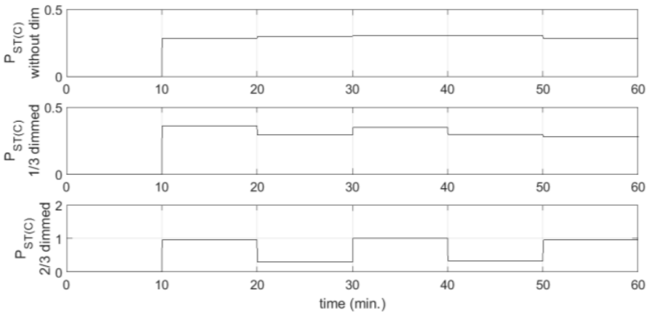

Fig. 17. Short term flicker for the luminaire belongs to manufacturer C.

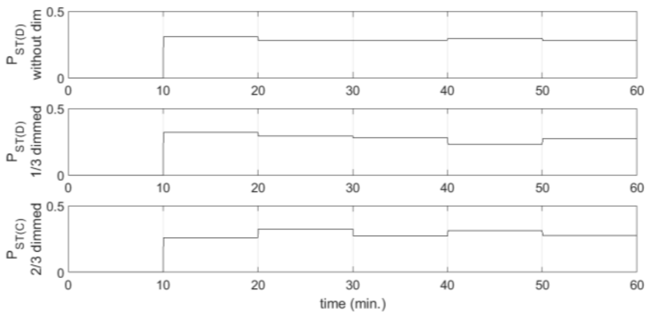

Fig. 18. Short term flicker for the luminaire belongs to manufacturer D.

TABLE VI. VALUES OF LONG TERM FLICKER

Manufacturer	P_{LT}
A	0.317
B	0.307
C	0.297
D	0.304

TABLE VII. LONG TERM FLICKER AT DIFFERENT LUMINOUS FLUX

Luminous Flux	Man. C	Man. D
3/3	0.297	0.304
2/3	0.320	0.281
1/3	0.311	0.280

V. CONSLUSION

Today, numerous equipment are available for being used in lighting purposes. LED lighting equipment takes an important place in the sector by means of their high efficacy factor aspect. Analysis of the power quality impacts of LED luminaires on the power systems has also become a necessity with their increasing utilization rates.

In the study, power quality measurements have been realized for 4 different commercially available LED luminaires. Firstly, the characteristic values of the luminaires have been determined by the measurements performed and then their impacts on the power quality have been examined.

As a result of the measurements, it is seen that all luminaires have greater power factor than 0.95 at their complete luminous flux level. On the other hand, it has been observed that the power factor values decreased by the reduction of the luminous flux. It is seen that the voltage harmonics are below the THD limits and the THD values are decreased by dimming the luminaires due to the decreasing power.

It has been observed that the luminaires have very high values in terms of current harmonics. While the highest deterioration is seen in the luminaires of manufacturer A with a value of 14.37915%, the lowest deterioration is occurred on the luminaire that of manufacturer C, with 6.3923%. According to the results, as the luminous flux decreases, the TDD value increases. Moreover, the 3rd component is the dominant current harmonic for all the cases.

It has been observed that the flicker values obtained for each measurement performed provide the relevant limits. On the other hand, it has been observed that the flicker value increased when the light flux decreased.

As a result of all the evaluations:

- The LEDs in close electrical and light features may have different harmonic characteristics,
- Power quality parameters get worse when the LEDs are dimmed,
- The LEDs are far from jeopardizing power quality when they are considered individually. However, they may become a threat in large groups.

By the considering power quality parameters, the studies performed on the use of LEDs of different manufacturers and in different technologies may bring significant contribution to the literature.

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