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Impact of Dimming LED Street Luminaires on Power Quality

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Abstract— **More and more street lighting deployments use LED technology as a light source. Unfortunately, the new technology also brings some challenges with it that remain unnoticed until installed at scale. This article presents issues related to capacitive reactive power consumed by LED luminaires. The problem is even more profound if the luminaire is dimmed, because it consumes capacitive reactive power, which is very undesirable in the power system. Countermeasures in terms of reactive power compensation for a luminaire working with variable power and their effects are also presented. The article also contains the results of the harmonic analysis of the LED luminaires current for full power and dimmed operation.**

***Keywords*—capacitive reactive power, current characteristics, LED luminaires power quality, LED street lighting, reactive power compensation, voltage characteristics**

I. INTRODUCTION

STREET lighting generates a significant cost of maintaining road infrastructure in cities [1]. The development of luminaires using LED (light-emitting diode) technology has enabled the replacement of traditional light sources with luminaires that consume significantly less energy [2, 3, 4]. There are some undeniable advantages of this type of light sources such as: compact design, long service life of LED luminaire and above all low energy consumption [5]. It is also important that light should not be excessive and should be properly directed [6] which could be achieved in LED fixture. However, there are also drawbacks, mainly related to the impact on the power quality. The major issue is the problem of capacitive reactive power consumption and distortion of the current consumed by the luminaire [7,8,9].

The main goal of this research was to determine the maximum value and variations in capacitive reactive power consumed by luminaires depending on their power setting. The secondary objective was to investigate reactive power compensation taking into ac-count broad range of dimming. This article is an extended version of a paper [10] presented at the EPQU conference and includes additionally the results of analysis of the power quality consumed by LED luminaires.

The experiments regard measurements taken for two luminaires from different vendors, designated hereinafter A and B. Both luminaires are equipped with light emitting diodes and electronic power drivers. Their parameters are in the Table 1. The measurements were taken after the luminaires reached a stable temperature.

TABLE I
LAMP PARAMETERS

	Rated power	Light output
Luminaire A	196 W	18100 lm
Luminaire B	198 W	22900 lm

Most of LED luminaires being currently used in street lighting have the ability to smoothly control the luminous flux. The main purpose of this ability is to adjust the luminous flux to match it with actual needs and conserve electricity. The power of individual luminaire is controlled by electronic drivers supplying individual chains of LEDs. Different types of drivers may be used, depending on the manufacturer of the luminaire. There is no standard in this regard.

To improve the quality of current consumed by the luminaire a common feature of LED drivers, especially those of high-power lighting, is the use of a filter [11]. It needs to be stretched that the operating parameters of the LED driver, such as absorbed current and power factor, are provided by the manufacturer for the nominal load only. It is when the luminaire works at the maximum rated luminous flux with no dimming. In the case of tested luminaires, the value of the declared power factor was above 0.9. It is expected that it would decrease when the luminaire is dimmed. In such a case the luminaire would work with limited power simultaneously having a negative effect on the power quality in the grid. The spec sheets share by the manufacturers of LED luminaires contain information about PF at maximum load only. What is more, unauthorized information and our research indicates that the same luminaire types (same official specs) might have different power drivers with different PF characteristics.

II. ANALYSIS OF REACTIVE POWER AND POWER FACTOR OF LED LUMINAIRES

In order to determine the power factor of luminaire, a series of measurements of luminaire voltage and current was carried out for various values of dimming. The recording has been made at a frequency of 30 kHz. The data was delivered by a PC-connected data acquisition card that sampled both voltage and current. Figure 1 shows a laboratory measuring stand. The voltage and current supplying the luminaire were converted into measured signals with use of hallotron converters. Based on recorded for 1s waveforms of voltage and current, the RMS values was calculated according to the definitions (1), (2):

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$$U=\sqrt{\frac{1}{T}\int_0^T u^2(t)dt} \tag{1}$$

$$I=\sqrt{\frac{1}{T}\int_0^T i^2(t)dt} \tag{2}$$

Figure 2 shows an example of the voltage and current waveform of luminaire A operating at full power which corresponds with 0% dimming.

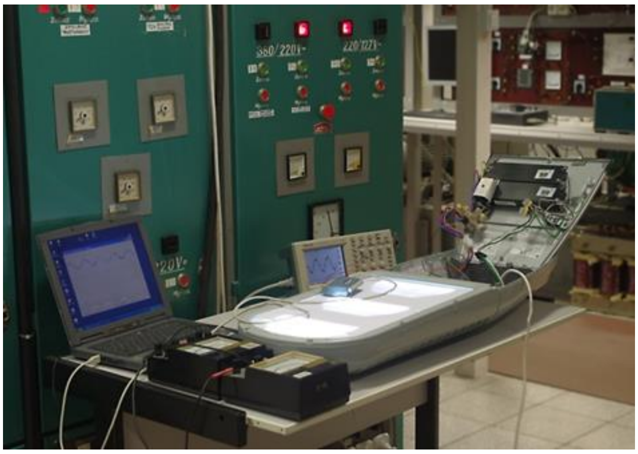

Fig. 1. Measurement of LED luminaires in the laboratory

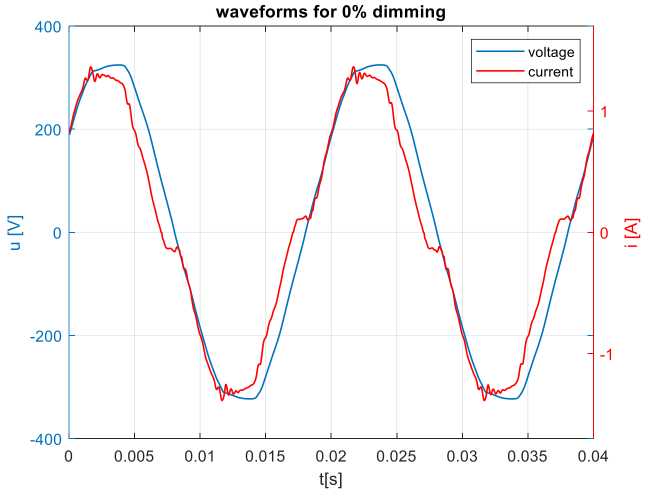

Fig. 2. Voltage and current waveform of luminaire A at full power

The dimming of luminaires was controlled by the LED driver through the voltage signal in the range of 0-10V, where 0V - 100% dimming, 10V - 0% dimming.

The active power was calculated according to the definition (3):

$$P=\frac{1}{T}\int_0^T u(t)i(t)dt \tag{3}$$

For sinusoidal waveforms of voltage and current, the power equation is met:

$$S^2=P^2+Q^2 \tag{4}$$

Based on it, the reactive power consumed by the receiver is as follows:

$$Q=\sqrt{S^2-P^2} \tag{5}$$

while the power factor is defined as:

$$\cos\varphi=\frac{P}{S} \tag{6}$$

The results of active power (P), apparent power (S), reactive power (Q) and power factor (cos φ) based on the above equations are presented in Fig. 3 and 4.

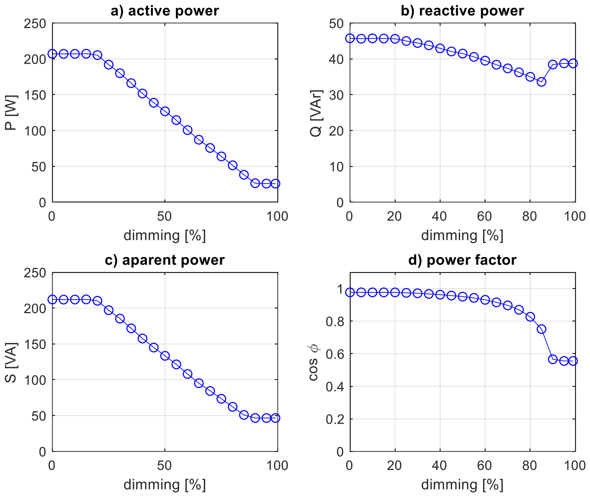

Fig. 3. Calculation results for luminaire A

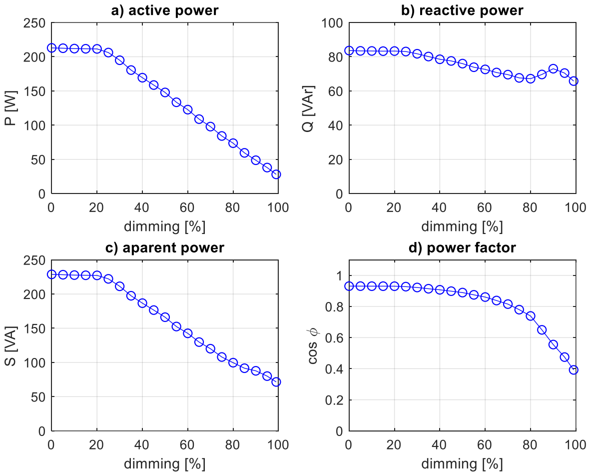

Fig. 4. Calculation results for luminaire B

Luminaire characteristics presented in Fig. 3 and 4 show almost linear relation-ship between active and apparent power and the control signal in both cases, which is in line with expectations. Reactive power changes in both cases: for luminaire A in the range of about 10 Var, for luminaire B in the range of about 15 Var. The power factor cos φ, in the case of the first luminaire in the range from 100 to 30 % of luminous flux, maintains a value above 0.9, while for lower luminous flux values it falls significantly below this value. For the second luminaire, the power factor drops below 0.9 already for the luminous flux below 60%.

The method of calculating reactive power and the power factor used for the calculations presented above is used in many measuring devices and electric energy meters. It should be noted, however, that while the active and apparent power, and therefore also the power factor calculated on their basis can be calculated in this way, reactive power may be wrong. Formula 5 does not consider the distortion factor, so in the case of LED luminaires distorted currents, the results of reactive power shown in Fig. 3 and 4 are in-correct. [12 ,13]

In order to correctly determine the reactive power value, C. J. Budeanu [14] definition was used:

$$Q_B = \sum_{h=1}^{\infty} U_h I_h \sin \varphi_h \tag{7}$$

Although the Budeanu definition of reactive power was removed to the IEEE 1495 standards in 2010, newer research works [15] show that it can be successfully applied in certain cases. According to this definition, the reactive power consumed by the receiver is equal to the sum of the reactive power of individual voltage and current harmonics. The IEC 61000-3-2 [16] standard specifies the permissible level of individual voltage harmonics during measurements. In the case of measurements carried out in laboratory conditions, the values of all harmonics fell within the specified limits, therefore the influence of voltage distortion was neglected. The effect of supplying the luminaire with distorted voltage was beyond the scope of research. Due to the above, it was assumed that reactive power depends only on the first harmonic of voltage and current for further calculations.

Considering that reactive power differs from the value calculated from the power equation (5), the more reliable power factor is tg φ calculated as the ratio:

$$tg\varphi = \frac{Q}{P} \tag{8}$$

It is also an indicator, defined in the electricity supply contract by the grid operator, which considers the reactive power that the receiver loads the network. The power factor calculated according to (8) also takes into account whether the reactive power consumed by the receiver is inductive or capacitive, which is essential from the point of view of the grid operator. Capacitive reactive power can cause an increase in voltage at the consumer endpoint, which is particularly undesirable. In a typical electricity supply contract, the power factor limit value tg φ is 0,4 [17].

The results of calculations using the relationships (7) and (8), considering the first harmonics of voltage and current, are shown in Fig. 5 and 6.

The results of reactive power calculations according to (7) in both cases gave results 10-15% lower than in the case of the power equation (5). Moreover, the reactive power has a negative sign, which indicates that it is capacitive. The value of the power factor tgφ goes below 0.4 for luminous flux less than 35% for luminaire A, and less than 70% for luminaire B. It indicates that the luminaire B introduces more distortion while being dimmed.

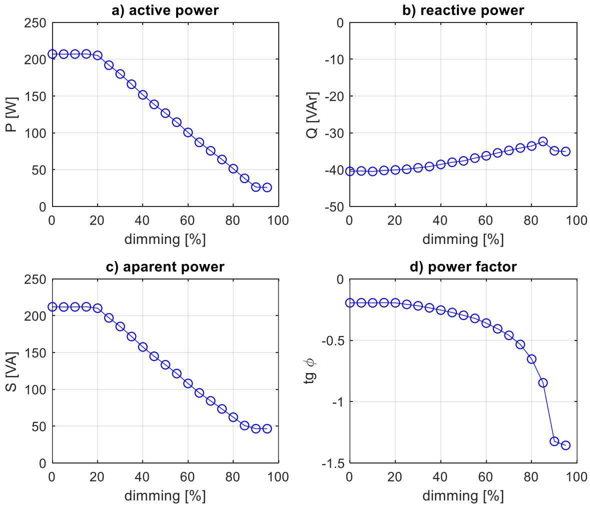

Fig. 5. The calculation results according to Budeanu definition for the luminaire A

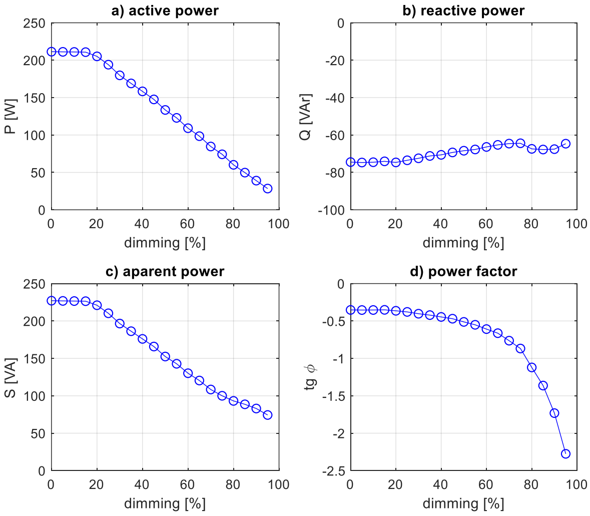

Fig. 6. The calculation results according to Budeanu definition for the luminaire B

III. CAPACITIVE REACTIVE POWER COMPENSATION

Theoretically the simplest way of reactive power compensation is to use a choke. Its inductance is calculated from generally known formulas. First, the capacitive reactance is calculated assuming that the capacitive reactive power is equal to 40.45 Var (9):

$$Q = \frac{U^2}{X_C} \Rightarrow X_C = \frac{U^2}{Q} = 1361\Omega \tag{9}$$

Then inductance can be calculated using formula (10)

$$L = \frac{X_L}{\omega} = 4{,}33H \tag{10}$$

To confirm the correctness of the calculations, simulations were performed, and their results are presented in Fig. 7.

As shown in Fig. 7 and 8, tg φ in the entire operating range is positive and is lower then 0.4. When the luminous flux is above 50%, tg φ does not even exceed 0.05.

The choke, which is simple in construction, is not a very cheap element, however. The weight of such a choke varies within 1 kg and the power loss can be estimated at several watts.

These values must be taken into account when making a decision about reactive power compensation.

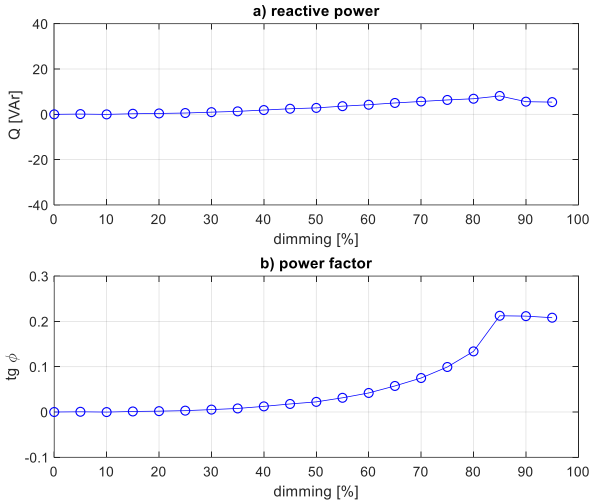

Fig. 7. Reactive power and tgφ of luminaire A after compensation

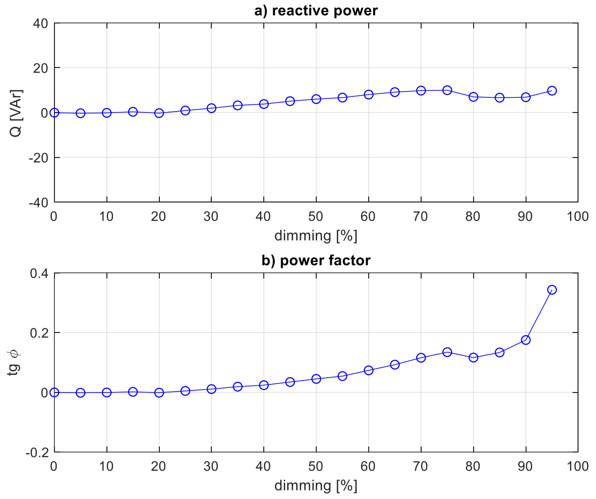

Fig. 8. Reactive power and tg φ of luminaire B after compensation

IV. ANALYSIS OF LUMINAIRE POWER QUALITY

Power electronic systems used in LED lamp drivers consume a significantly distorted pulse shaped current. In order to improve the quality of energy, drivers use filters that adjust the shape of the consumed current, which brings it closer to a sinusoid. The measurements show that the current distortion, measured with the THD coefficient, changes with the dimming at which the lamp works. The THD factor is calculated according to the formula [16]:

$$THD = \sqrt{\sum_{h=2}^{40} \left(\frac{I_h}{I_1} \right)^2} \tag{11}$$

where: I_1– RMS value of the fundamental component of the current,
I_h– RMS value of the kth current harmonic.

The lowest level of distortion occurs when working with full power, while with increasing power limitation (dimming) the current THD factor increases. In large cities, street lighting is an important part of energy receivers, therefore the distortion of consumed current by the luminaires may affect the quality of the voltage in the power grid. In the case of the performed measurements, the network voltage distortion THD equals 2.5%.

According to the standards [18], the permissible voltage deformation limit is 5%. The current distortion for the lamp operating at full power was 13% and it increased with dimming. Thus, with a large number of receivers consuming such a distorted current, the quality of the voltage in the network also deteriorates and the 5% THD limit may be exceeded.

Fig. 9-12 show the measurement results for luminaire A. While Fig. 9-10 present the voltage and current waveforms and their harmonics for 50% dimming, Fig. 11-12 show it for full power operation. Fig. 13-16 show the same waveform and harmonics for luminaire B. Choosing the 50% dimming follows a typical street lighting application where such a level is rarely crossed. Typical dimming ranges from 0% to 50% which reflects 100% to 50% power setting. In the Fig. 10, 12, 14, 16, marked the limits for individual harmonics calculated according to standard IEC 61000-3-2 [16].

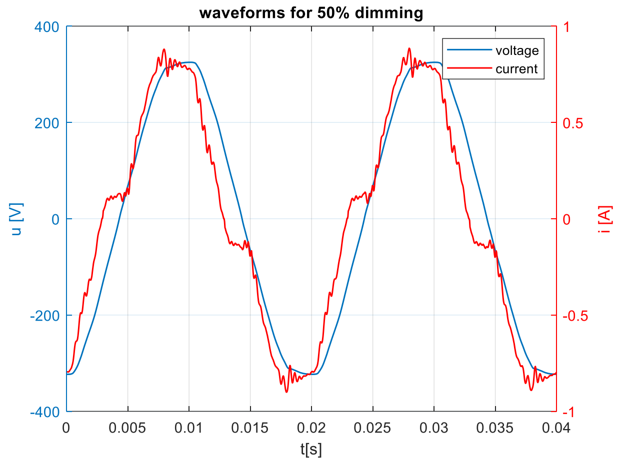

Fig. 9. Voltage and current waveforms for 50% dimming of luminaire A

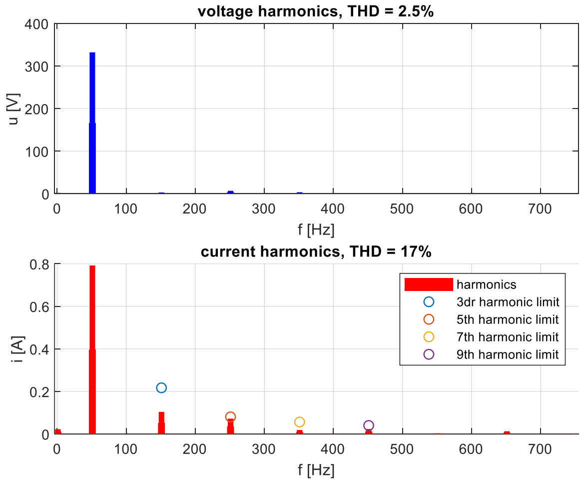

Fig. 10. Voltage and current harmonics for 50% dimming of luminaire A

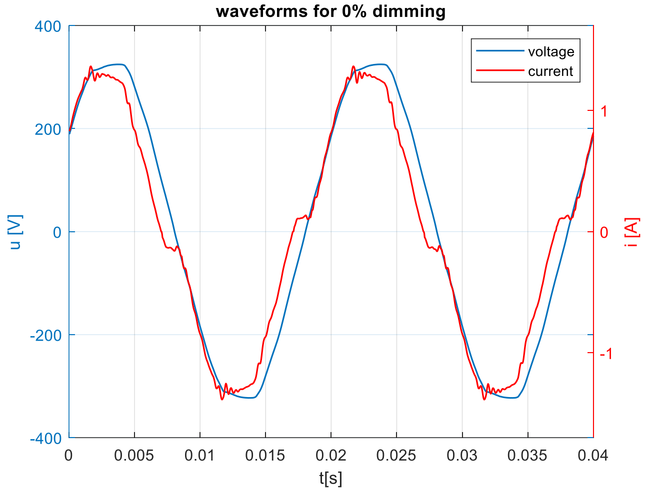

Fig. 11. Voltage and current waveforms for 100% power of luminaire A

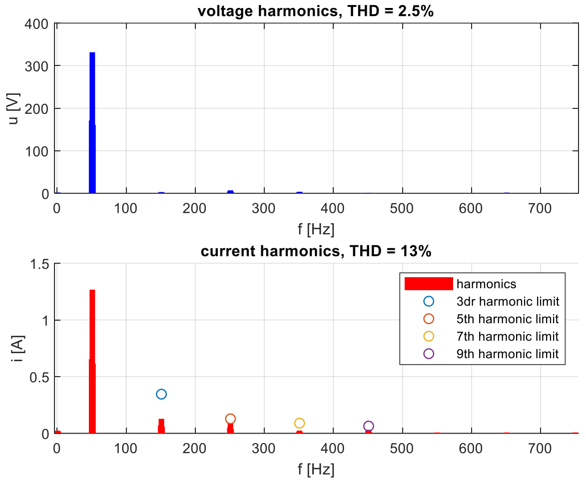

Fig. 12. Voltage and current harmonics for 100% power of luminaire A

As can be seen in Fig. 10 and 12, when the lamp power is changed from 50% to 100%, the current distortion of the luminaire decreases from 17 to 13% THD with the same voltage distortion.

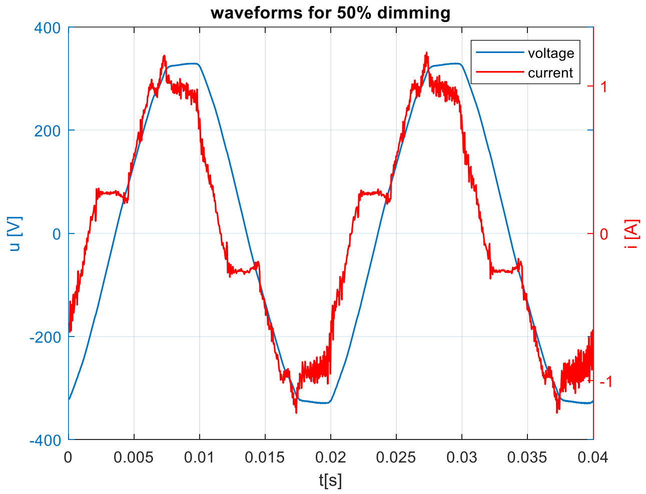

Fig. 13. Voltage and current waveforms for 50% dimming of luminaire B

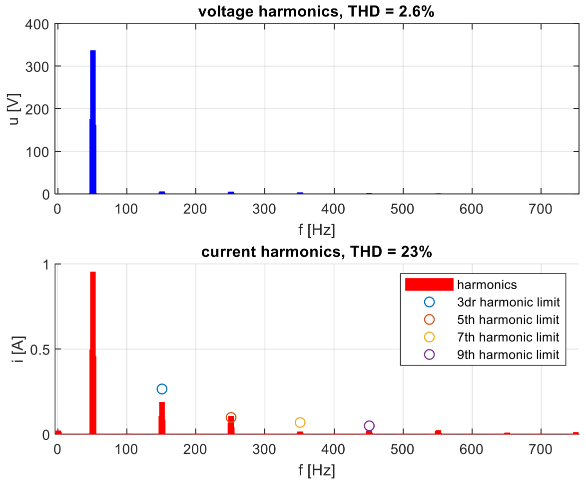

Fig. 14. Voltage and current harmonics for 50% dimming of luminaire B

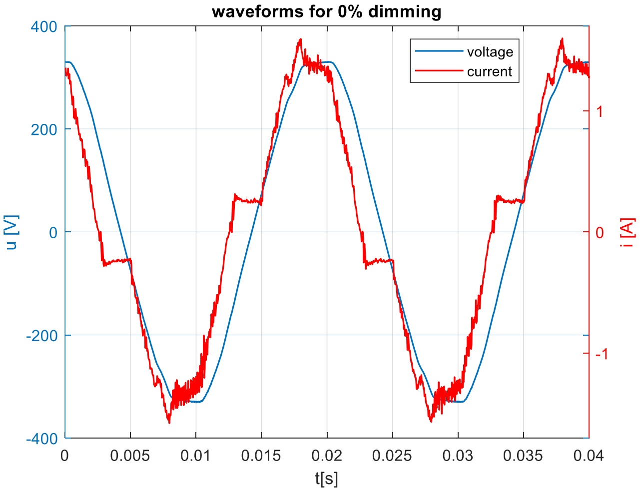

Fig. 15. Voltage and current waveforms for 100% power of luminaire B

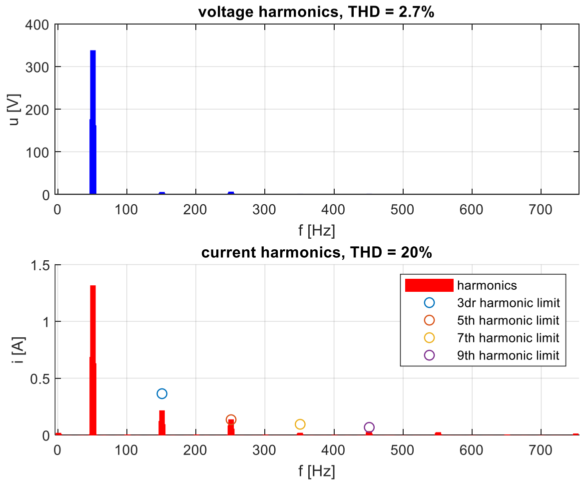

Fig. 16. Voltage and current harmonics for 100% power of luminaire B

In the case of luminaire B, the change in lamp power from 100% to 50% changes the current THD from 20% to 25%. It is worth noting that for both luminaires the greatest share of higher harmonics has 3rd and 5th in the consumed current. The effects of current distortion will therefore add up even when using different types of luminaires.

V. COMPENSATION PROBLEM IN COMPLEX STREET LIGHTING SYSTEMS

Compensating the capacitive reactive power of a single luminaire is a simple task that does not require advanced control systems. This method of compensation, however, is inconvenient to use, due to the need to install the compensation chokes separately in each luminaire. A much more effective method is to compensate for the entire chain of lamps illuminating one street or a lighting system that enlightens several streets supply from the same switchgear. An example of a layout of several streets whose lighting is supplied from the same switchgear is shown in Fig. 17. Individual lamp chains are marked with C_1-C_4 symbols.

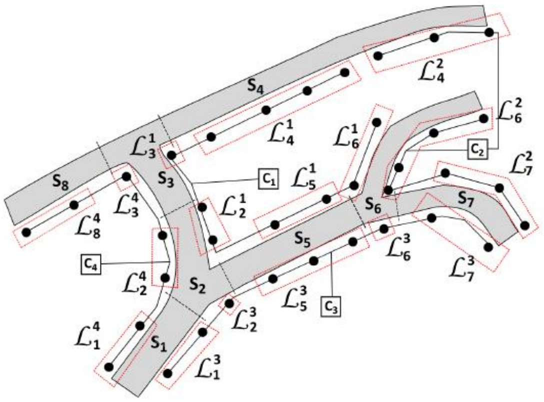

Fig. 17. An exemplary diagram of a street lighting system

In this case, however, there is the problem of selecting and controlling the reactive power of the compensator. Street lighting works with variable intensity, moreover, some sectors may be temporarily turned off. In such a case, controlling the compensation system requires the use of advanced control systems which based on the data on the number of working lamps and individual dimming select the appropriate value of the compensator reactive power, for example [19].

VI. CONCLUSIONS

The research shows that using lighting based on LED luminaires can pose energy quality issues if the luminaires are dimmed. On the other hand, dimming is essential in aspect of power saving and ecology issues [6].

In such a case there is a problem of capacitive reactive power. The value of capacitive reactive power varies depending on the luminaire dimming. Capacitive reactive power is undesired from the grid operator point of view. The main reason is that it leads to uncontrolled voltage spikes in the network. Capacitive reactive power can be fully compensated though, by using an induction compensator with a proper setting attuned for a particular type of LED luminaire. For correctly selected choke inductance the power factor tgφ should not exceed 0.4 (inductive), even for maximum dimming of the luminaire which is at the level permitted by the grid operator.

Furthermore, it is not only a problem of the reactive power but also voltage and current distortions. They could significantly impact grid operations and metering, especially when luminaires are dimmed to reduce energy consumption. This issue is subject to further research.

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