BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 68, No. 4, 2020
DOI: 10.24425/bpasts.2020.134186

Calculations of energy savings using lighting control systems

A. WIŚNIEWSKI*

Warsaw University of Technology, Faculty of Electrical Engineering, Electrical Power Engineering Institute, Lighting Technology Division, Koszykowa 75, 00-662 Warsaw, Poland

Abstract. The development of technology and design of light management systems remains dynamic. Among all the benefits offered by these systems, the most valuable might definitely be the possibility of saving energy consumption. Knowing the value of energy savings is the key factor that users need to know before deciding to use a lighting management system (the type of light management system). For this purpose, it is useful to simulate the operation of the lighting control system, for example in the DIALux program. Such simulation helps evaluate potential savings in electricity consumption using the proposed lighting control system. In the DIALux program, it is possible to change the luminous flux value of luminaires. In such a case, it becomes possible to semi-simulate the light management system's operation as we don't receive actual information on reducing installed power of the lighting system during reduction of the luminous flux value of luminaires. This article shows what type of technical data are important to use for the DIALux program to properly and accurately simulate light management systems and to receive accurate data on energy saving. It also presents the results of photometrical and electric parameter measurements (Φ – luminous flux, P – power, PF – power factor, THDi – total harmonic distortion of current). The article discusses the power control characteristics obtained on the basis of these measurements and explores the source of differences between simulation of energy saving calculations and real measured energy savings. An existing lighting control system installed in an office reception area was used to compare calculations with the real value of energy consumption reduction. The impact of electronic power and control systems on electrical network parameters is also an important problem mentioned in this article. It also explores the effect of power regulation of LED luminaires and LED modules on the value of the power factor and total harmonic distortion (current) value (THDi).

Key words: light management system, LED lamps, LED modules, LED luminaires, lighting technology, interior lighting, energy efficiency.

1. Introduction

Currently, the use of lighting control systems is becoming more and more common as it provides many benefits for users. These benefits include saving electricity, lowering lighting maintenance costs, adjusting the illumination level to individual needs of employees and receiving feedback on the status of the lighting device (damaged luminaire, damaged ballast or light source). In general, different types of control systems (occupancy sensors, light sensors, time scheduling regulators etc.) lead to energy savings and improve the comfort of lighting use [1, 2]. In many cases in interior and exterior lighting systems the potential of energy saving [3–7] is one the most important benefits.

Generally, the largest savings in electricity consumption can be obtained by using daylight lighting systems. The users very often decide to use a lighting control system due to the possibility of reducing the lighting system maintenance costs. Accurate data allow users to make decisions about the type of control system to be installed. In order to calculate potential savings in using the lighting control system accurately, a lighting designer needs some important data about the control and controlled devices. For this purpose, measurements of basic electrical and photometric parameters of selected types of LED luminaires and LED modules are performed. These LED luminaires and LED modules with power regulation (luminous flux) are managed by the DALI signal.

This article is organized in the following manner.

- Chapter 2 presents the basic electric and photometric data of chosen LED luminaires and LED modules.
- Chapter 3 deals with the measured data of power control characteristics and the comparison between real power control and theoretical power control characteristics. In this presented research, the real power control characteristics were developed on the basis of measurements of power and luminous flux. The easy way to calculate savings in electricity consumption is to use theoretical control characteristics. However, this usually does not provide accurate data.
- Chapter 4 presents the comparison between real energy savings and energy savings calculated in the DIALux program. For this purpose, real measurements of electricity consumption in an office reception area were compared with the calculations made in the DIALux program. The theoretical control characteristics of tested luminaires were applied to calculate energy savings in the DIALux program.

The use of a lighting control system also has some disadvantages. LED luminaires and LED modules with the option of power control affect the power supply network parameters [8]. In many cases, the power control of LED luminaires often

*e-mail: andrzej.wisniewski@ien.pw.edu.pl

Manuscript submitted 2020-01-15, revised 2020-03-06, initially accepted for publication 2020-04-11, published in August 2020

causes a reduction in the power factor (PF) value and the introduction of harmonics. In this case, the cost of maintenance of a lighting system by means of using the lighting control system can be higher than theoretically assumed.

Higher harmonic value is the term used for current patterns with frequencies which exceed the basic frequencies and are superposed together, resulting in distortion of the original sinusoidal waveform. High total harmonic distortion (THD) value in the system causes lowering of the power factor, increasing peak currents and lowering efficiency [9, 10]. Non-linear loads constitute the main source of higher harmonic values in the system. Equipment such as electronic control gears for LED modules and LED luminaires and regulators constitutes a good example of non-linear loads.

Important problems caused by non-linear loads include:
- overheating resulting from increased current in the system,
- increased heating of the core caused by additional core loss in the motors,
- interference with communication transmission lines,
- disturbance of power-electric security system operation
- overload of capacitor batteries.

The LED modules and LED luminaires being tested constitute a non-linear load. The IEC 61000-3-1 [11], IEC 61000-3-2 [12] and IEC 61000-3-3 [13] standards determine the limit of total harmonic distortion (THD) values. This limit of THD values also applies to LED luminaires and LED modules.

The EN 50160 standard [14] specifies that for the lighting equipment the total harmonic distortion value (THDi) should not exceed 10%. THDi values between 10 and 50% may cause interference with other electrical devices.

In accordance with the requirements for magnetic and electronic ballasts (including LED drivers) included in the ANSI C82.11 standard [15], permitted total harmonic distortion (THDi) values cannot exceed 32% and permitted triples cannot exceed 30%. Therefore it can be assumed that all electronic LED drivers (ballasts) are rated less than 20%.

– Chapter 5 presents the results of power factor (PF) and total harmonic distortion of current (THDi) measurements of selected types of luminaires and LED modules as a function of power regulation via DALI signal.

2. Basic technical data of tested luminaires

Three types of LED luminaires and two types of LED modules were tested. Three samples for each type of LED luminaires and LED modules were used. All these luminaires were dedicated to indoor lighting. The average values of measured parameters for each chosen LED luminaire and LED module were analyzed.

The first type of luminaire was downlight LED 35 W, shown in Fig. 1. Basic technical data for downlight LED 35 W are presented in Table 1.

The second type of luminaire was a typical panel LED luminaire (600×600 mm), shown in Fig. 2. Basic technical data for the panel LED luminaire are presented in Table 2.

The third type of luminaire was a spot LED lamp, known generally as AR111, seen in Fig. 3. The power of this lamp was regulated by a phase control dimmer. Basic technical data for the S = spot LED lamp are shown in Table 3.

The tested LED COB 3000 (30.7 W) and LED COB 2000 (19.2 W) modules directly supplied 230 V mains voltage. These

Fig. 1 Tested downlight LED 35 W

Table 1
Basic technical data of downlight LED 35 W

Luminaire	P [W]	Φ [lm]	T_c [K]	CRI [–]	L_{70}/B_{50} [h]
Downlight LED 35	35	3325	4000	85	30 000

Fig. 2. Panel LED luminaire 33 W being tested

Table 2
Basic technical data of panel LED luminaire 33W

Luminaire	P [W]	Φ [lm]	T_c [K]	CRI [–]	L_{70}/B_{50} [h]
Panel LED luminaire 33 W	33	3100	4000	85	50 000

Fig. 3. Spot LED lamp 11.5 W being tested

Table 3
Basic technical data of spot LED lamp 11.5 W

Luminaire	P [W]	Φ [lm]	T_c [K]	CRI [–]	L_{70}/B_{50} [h]
Spot AR111	11.5	800	3000	85	40 000

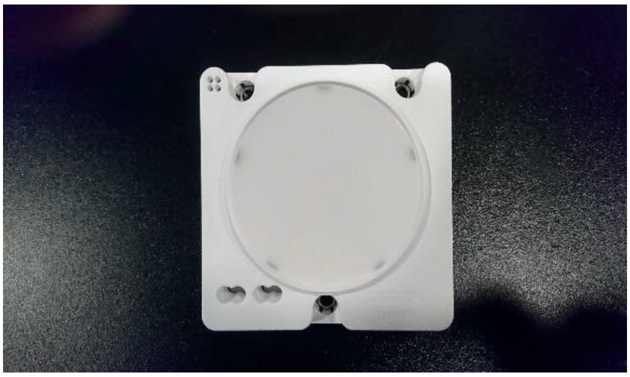

Fig. 4. LED modules COB being tested

Table 4
Basic technical data of LED modules COB 3000 and COB 2000

LED module COB	P [W]	Φ [lm]	T_c [K]	CRI [–]	L_{70}/B_{50} [h]
LED COB 3000	30.7	3000	4000	85	50 000
LED COB 2000	19.2	2000	4000	85	50 000

modules were regulated directly via DALI signal. The first and second type of LED modules construction is showed in Fig. 4 and basic technical data are presented in Table 4.

3. Measurements of power characteristics of luminaires and LED modules

The Ulbricht sphere with a diameter of 2 m was used to measure the luminous flux. A DPW 66202 power meter was used to measure power and network parameters (P, PF and THDi). The power analyzer provides measurement of basic electrical parameters with an accuracy of 2%. As for the operation of the lighting control system, we usually have the option of changing the luminous flux value of the luminaire when designing the lighting. A simple way to determine the power of a luminaire at a given luminous flux value is to assume the theoretical control characteristics. This characteristic allows us to determine the power of the luminaire at a given luminous flux. The assumption of proportional changes of power value in relation to the value of the luminous flux is the easiest way to calculate the luminaire's power. The accuracy of calculation of the measured power of the luminaire at a given luminous flux, using theoretical control characteristics, depends on the difference between the course of the measured and theoretical characteristics. The formula to calculate the difference between power value (ΔP) and the calculated theoretical value of power (P_t) and measured power (P_a) is presented in mathematical formula (1). The values of ΔP were calculated for the same values of luminous flux.

$$\Delta P = \frac{Pa - Pt}{Pt} \times 100\ [\%] \tag{1}$$

The changes of ΔP values in the function of power regulation for all measured LED luminaires and LED modules are also presented. Figure 5 presents the theoretical control characteristics adopted for a downlight LED 35 W luminaire. In order to determine the theoretical characteristic, the nominal power and nominal luminous flux of the luminaire are needed. The power and luminous flux rated values (35 W and 3325 lm) and the luminaire power value in the off state of the DALI system (standby mode, 0.2 W) were adopted to determine the theoretical characteristics for downlight LED 35 W. Figure 6 presents the measured power control characteristics for a downlight LED 35 W luminaire. The power differences (ΔP) between the measured and theoretical value of power in the function of power regulation for downlight LED 35 W are presented in Fig. 7.

Figure. 6 presents the measured and theoretical power regulation characteristics. The calculated ΔP values (characteristic ΔP in the function of the power value) for downlight LED

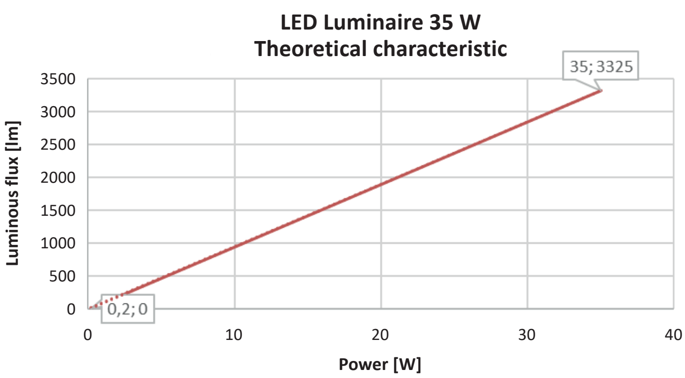

Fig. 5. Theoretical characteristic of power regulation for downlight LED 35 W luminaire

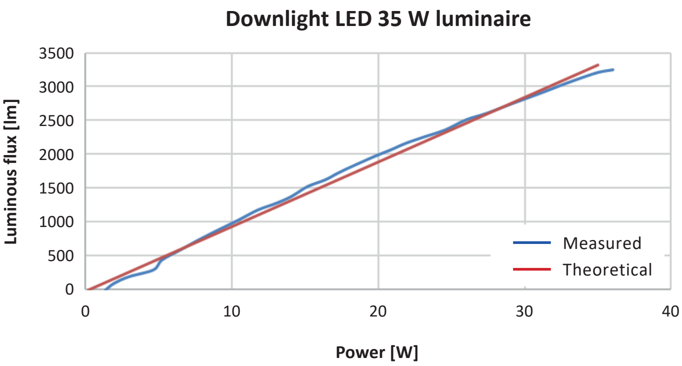

Fig. 6. Measured and theoretical characteristic of power regulation for downlight LED 35 W luminaire

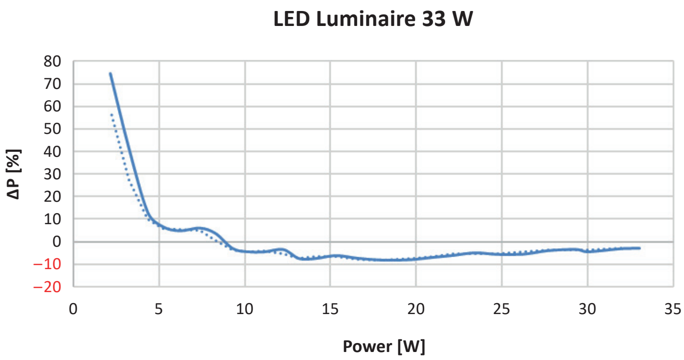

Fig. 9. ΔP changes in function of LED luminaire 33 W power value

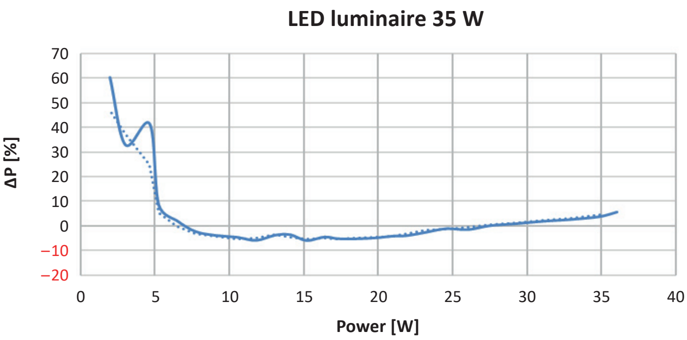

Fig. 7. ΔP changes in function of LED luminaire 35 W power value

35 W show that the ΔP value increases significantly when the power of luminaires is reduced below 5 W. The ΔP value increases significantly below 14% of the power control range.

The maximum of ΔP increases to over 60% when luminaire power value is lower than 2 W. Figure 8 presents the measured and theoretical power control characteristics for a panel LED luminaire 33 W.

The power differences (ΔP) between measured and theoretical value of power in the function of power regulation for downlight LED 33 W are presented in Fig. 9. The calculated ΔP values (characteristic ΔP in the function of the power value) for LED luminaire 33 W show that the ΔP value increases significantly when the power of luminaires is reduced below 4 W. The ΔP value increases significantly below 12% of the power control range. The maximum of ΔP increases to over 70% when luminaire power value is lower than 2 W.

Figure 10 presents the measured and theoretical control characteristics for a spot LED lamp 11.5 W.

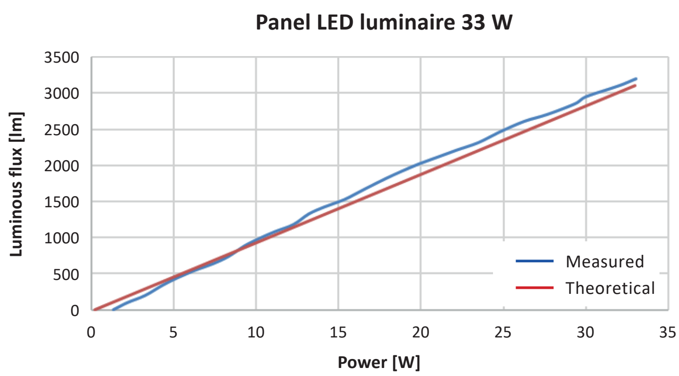

Fig. 8. Measured and theoretical characteristic of regulation for panel LED luminaire 33 W

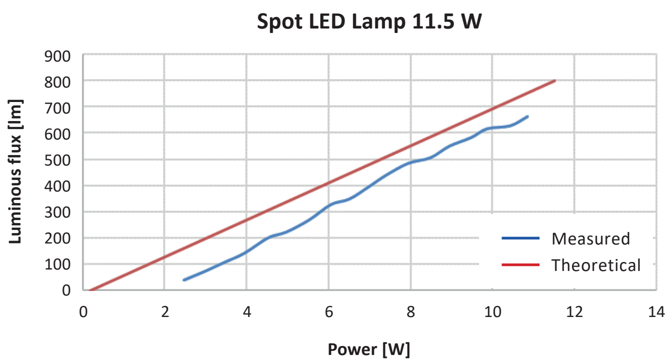

Fig. 10. Measured and theoretical characteristic of regulation for LED luminaire power 11.5 W

The power differences (ΔP) between measured and theoretical value of power in the function of power regulation for LED luminaire 11.5 W are presented in Fig. 11.

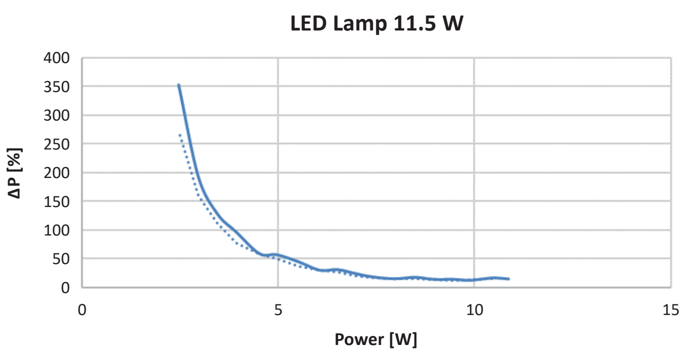

Fig. 11. ΔP changes in function of LED luminaire 11.5 W power value

The calculated ΔP values (characteristic ΔP in the function of the power value) for LED luminaire 11.5 W show that the ΔP value increases significantly when the power of luminaires is reduced below 5 W. The ΔP value increases significantly below 43% of the power control range. The maximum of ΔP increases to over 120% when the luminaire power value is lower than 3 W. This lamp is supplied by the phase cut dimmer with potential regulation via DALI signal. The phase cut dimmer significantly reduced the power and values of the luminous flux emitted by the spot LED lamp 11.5 W in relation to the rated values. The work of the phase control dimmer has the biggest impact on the differences between measured and theoretical power control characteristics of spot LED lamps 11.5 W.

Figure 12 presents the measured and theoretical control characteristics for a LED module COB 3000 (30.7 W).

The power differences (ΔP) between measured and theoretical value of power in the function of power regulation for LED module COB 3000 W are presented in Fig. 13.

The calculated ΔP values (characteristic ΔP in the function of the power value) for LED module COB 3000 show that the ΔP value increases significantly when the power of the LED module is reduced below 3 W. The ΔP value increases significantly below 10% of the power control range. The maximum of ΔP increases to over 69% when the luminaire power value is lower than 1 W. Figure 14 presents the measured and theoretical control characteristics for a LED module COB 2000 (19.2 W). The power differences (ΔP) between measured and theoretical value of power in the function of power regulation for LED module COB 2000 W are presented in Fig. 15. The calculated ΔP values (characteristic ΔP in the function of the power value) for LED module COB 2000 show that the ΔP value increases significantly when the power of the LED module is reduced below 3 W.

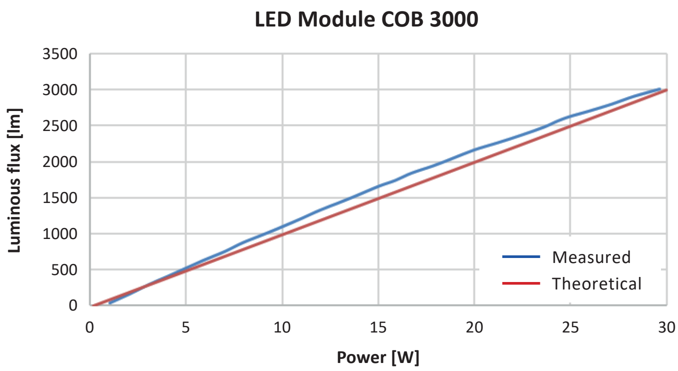

Fig. 12. Measured and theoretical characteristic of regulation for LED COB 3000

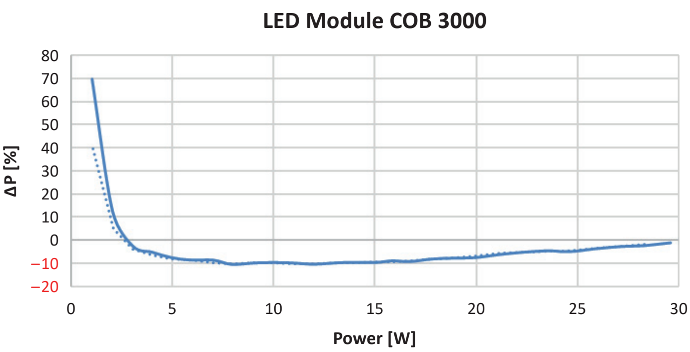

Fig. 13. ΔP changes in function of LED module COB 3000 power value

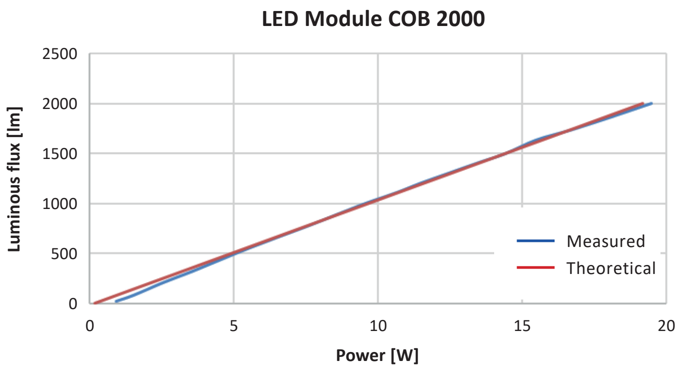

Fig. 14. Measured and theoretical characteristic of regulation for LED COB 2000

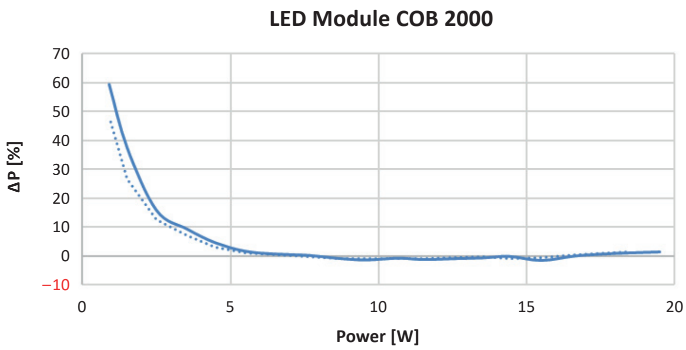

Fig. 15. ΔP changes in function of LED module COB 2000 power value

The ΔP value increases significantly below 16% of the power control range. The maximum of ΔP increases to over 59% when the luminaire power value is lower than 1 W. Table 5 presents the maximum of power calculations differences ΔP

Table 5
Maximum value of differences between measured and theoretical power calculation of LED luminaires and LED modules at a given luminous flux value

Type of luminaire	Power reduction [W]	ΔP maximum [%]
Downlight LED 35 W	2.0	60
Panel LED luminaire 33 W	2.2	74
Spot LED lamp 11.5 W	2.4	352
LED module COB 3000	1.0	70
LED module COB 2000	0.9	59

between measured and theoretical power characteristics calculation of LED luminaires and LED modules at a given luminous flux value.

The presented characteristics of power control for selected types of LED luminaires and LED modules indicate that the use of theoretical control characteristics for calculations may introduce large errors in the calculation of LED luminaire and LED module power at a given luminous flux. Presented characteristics indicated that the ΔP values increase significantly between 10% and 43% of the power control range. Therefore, it is recommended to use the measured power control characteristics to calculate the power of luminaires and LED modules at a given luminous flux accurately.

Fig. 17. Picture of the reception area

4. Calculation of energy saving

For the analysis intended to this article, I have chosen a reception area that actually exists. The aim of this analysis was to compare the results of real power of the lighting device with the power calculation results obtained by means of simulation in the DIALux program. The DIALux software is a verified tool [16] applied for analysis of electric lighting in interiors, e.g. [17, 18], and according to CIE publication 171:2006. This reception lighting control system reduces the power (luminous flux) of the luminaires at a pre-programmed time and these luminaires work at full power during the office working time. However, during night time the power (luminous flux) of luminaires is reduced.

Figure 16 presents the reception model made using the DIALux program and Fig. 17 shows pictures of the reception area. In this reception, the measurements of illumination levels in points were made and the average value of illuminance was calculated. Measurements were made using an LS100 luxmeter to ensure accurate measurements of illumination level according to class A (CIE, DIN 5032–7), i.e. spectral matching f1 $\leq$ 2% and directional matching f2 $\leq$ 1.5%, with total error $\leq$ 2.5%. The measurements were made for two options – the full and reduced power. The comparison was conducted in such a way that the luminous flux of the luminaires was changed in the DIALux program to obtain the same real (measured) average illumination values. Two lighting levels were simulated at full and reduced power (night time). In order to calculate the power reduction, the theoretical characteristics of power regulation were adopted. Table 6 presents the comparison of the average illumination levels obtained from the DIALux program and the real values obtained from the measurements. The comparison is also made of the measured values of the real power installed with the power calculated in the DIALux program on the basis of the theoretical characteristics of power regulation. The differences values of 3.5% (full power) and 3.4% (reduced power) between the measured average level of illuminance and the average calculated illuminance level (in DIALux program) confirm good simulation of the lighting system. The difference of 8.5% between the measured maximum power of the lighting system and the calculated maximum power in the DIALux program confirm the good simulation power value of the lighting system in the reception room. The big difference (194.2%) between the minimum measured power and the minimum calculated power (adopting the theoretical power characteristic) causes a substantial power calculation error.

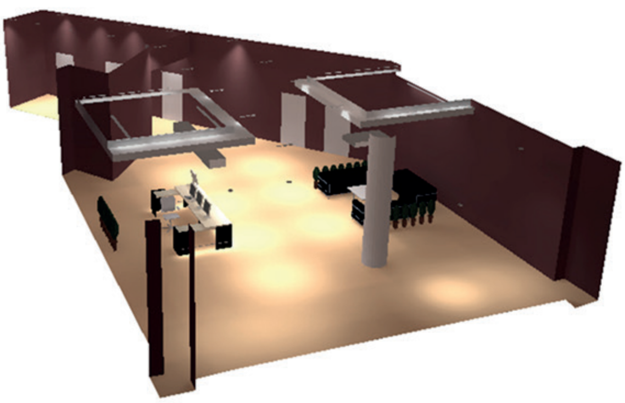

Fig. 16. Reception model in DIALux program

Table 6
Comparison of average illuminance levels for the reception

Reception area			
Average illuminance	**Measurement Em [lx]**	**DIALux Em [lx]**	**Difference [%]**
Full power	843	814	3.4
Reduction power	198	205	3.5
Installed Power	**Measurement P [W]**	**DIALux P [W]**	**Difference [%]**
Full power	1547	1679	8.5
Reduction power	154	453	194.2

In this analyzed case of the reception area, adoption of the measured power control characteristics is recommended. In the reception are being discussed it was not possible to take measurements of the basic electrical and light parameters of the luminaires used and to receive the measured characteristic of power regulation.

5. Impact of power regulation of LED luminaires on the power network

Furthermore, usage of the lighting control system is really beneficial. There are many benefits of using the lighting control system. Special attention should be paid to the effect of power regulation of LED luminaires and LED modules on the power network parameters. LED lamps also have a significant impact on network parameters [19]. The introduction of harmonic values and lowering the value of the power factor when reducing the power (luminous flux) of the luminaires need to be particularly taken into consideration. Figure 18 shows the graph of THDi value changes in the function of power of the downlight LED 35 W luminaire and panel LED luminaire 33 W, regulated by the DALI signal.

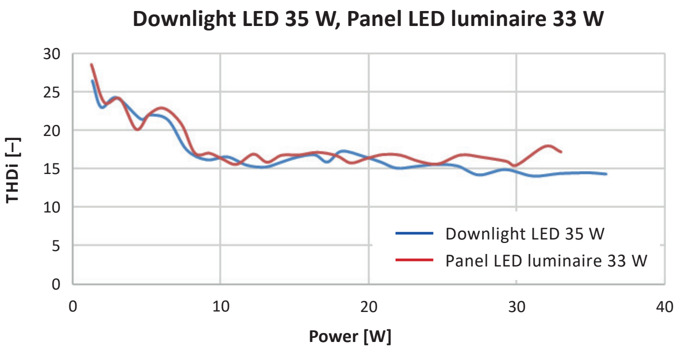

Fig. 18. Changes of THDi values in function of power for downlight LED 35 W and panel LED luminaire 33 W

Measurements of THDi values for downlight LED 35 W and panel LED luminaire 33 W show that the value of THDi increases significantly when the power of luminaires is reduced below 9 W. Figure 19 shows the graph of THDi value changes in the function of power of the luminaire spot LED lamp 11.5 W, supplied by the phase cut dimmer regulated by the DALI signal.

Measurements of the THDi value for the spot LED lamp 11.5 W show that the value of THDi is higher than THDi for downlight LED 35 W luminaires and panel LED luminaires 33 W. In this case the construction of the phase cut dimmer is the source of the high THDi value. Figure 20 shows the graph of THDi value changes in the function of power of the LED module power (COB 3000 and COB 2000), regulated by the DALI signal.

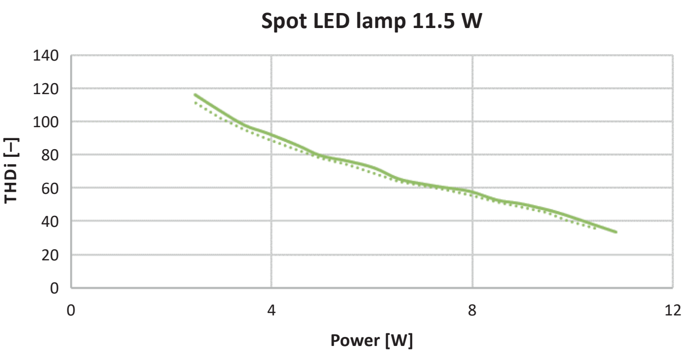

Fig. 19. Changes of THDi in function of power for spot LED lamp 11.5 W

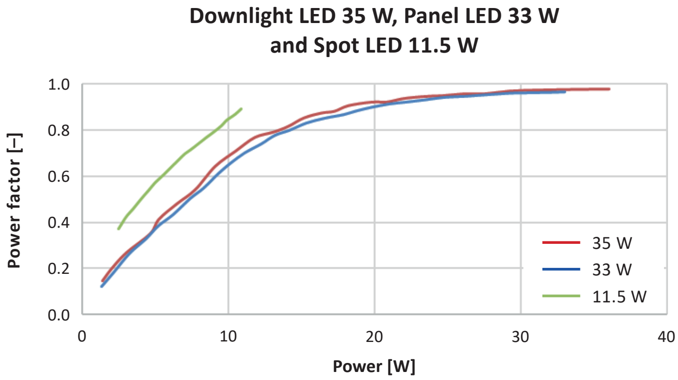

Fig. 20. Changes of PF in function of power for luminaires 35 W, 33 W and 11.5 W

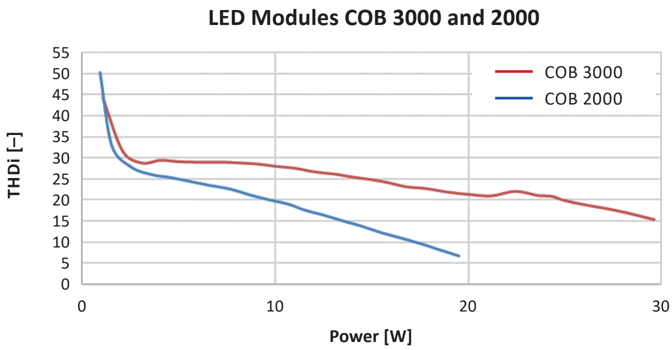

Fig. 21. THDi changes in function of the LED modules power, regulated by the DALI signal

Measurements of the THDi value for LED modules (COB 3000 and 2000) show that the value of THDi increases significantly when the power of LED modules is reduced below 3 W.

The measurement results (showed in Fig. 18. and Fig. 19.) indicate that the harmonic content (THDi) increases during the reduction of the power of the luminaires being tested. This phenomenon should be taken under consideration when it comes to designing lighting control systems. In the case of a spot LED lamp 11.5 W, the values of THDi are much higher than the THDi for luminaires of 35 W and 33 W in power. These big differences in THDi values are caused by the different regulation systems applied. Power reduction in downlight LED 35 W and panel LED luminaire 33 W is realized by PWM, and in luminaire spot LED lamp 11.5 W the phase cut control dimmer is used.

The reduced value of the power factor results in increased reactive power consumption, which is more expensive than active power. Figure 20 presents changes in the power factor value as the function of the power of luminaires: panel LED 33, downlight LED 35 W and spot LED lamp 11.5 W. The results of power factor measurements as a function of power changes of the luminaires indicate large changes in its value. At maximum power, the power factor is relatively high (PF > 0.9). By reducing the power, its value decreases to PF = 0.12 for the panel LED luminaire 33 W, while PF = 0.15 for downlight LED 35 W luminaire and PF = 0.38 for spot LED lamp 11.5 W. The value of power factor LED luminaires (downlight LED 35 W and panel LED 33 W) is reduced significantly when the power of luminaires is reduced below 10 W. The value of power factor of the spot LED lamp 11.5 W decreases with the power reduction and its value drops below 0.5 at the power value of 4.0 W. Figure 22 presents changes in the power factor value as the function of the power of LED modules COB 3000 and COB 2000.

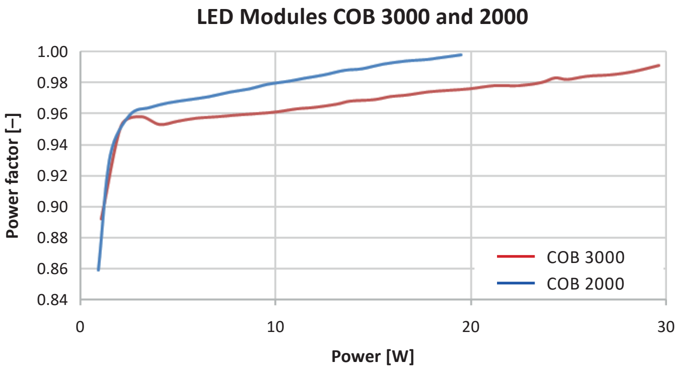

Fig. 22. Changes of PF in function of power for LED modules COB 3000 and 2000

The value of power factor LED modules (COB 3000 and COB 2000) is reduced significantly when the power of modules is reduced below 2.5 W.

6. Conclusions

Undoubtedly, the use of lighting control systems contributes to savings in electricity consumption and reduction of cost maintenance of a lighting system as compared to a traditional lighting system. Before deciding to install a lighting management system, it is important for the user to know what the value of the saving energy will be. The exact calculation of power reduction and thus the determination of savings in lighting operation depends on the available data on the lighting control system being used. The accurate calculation of energy consumption savings using a lighting control system will certainly influence the user's rational decision.

This paper presents the differences between a calculated (simulated in DIALux program) power reduction of a lighting management system and a real power reduction. The adoption of theoretical power control characteristics of LED luminaires and LED modules leads to calculation mistakes of potential energy savings. The DIALux program should serve as a useful tool for accurate calculations of power reduction using lighting control systems when the real power control characteristics were adopted. When DIALux is used to the simulate the power reduction of the lighting system using the light management system, real control characteristics are recommended.

This article proves that the application of real power control characteristics as compared to the theoretical ones results in greater accuracy of simulated calculations of energy savings using lighting control systems.

Using a lighting control system has the vast advantage of reducing active power. However, special attention should be paid to the negative influence of power control systems on electrical system parameters such as the value of the power factor and the value of current harmonics (THDi) in the function of power regulation of LED luminaires and LED modules.

References

[1] M.A. ul Haq et al., "A review on lighting control technologies in commercial buildings, their performance and affecting factors," *Renewable and Sustainable Energy Reviews* 33, 268–279, (2014), doi: 10.1016/j.rser.2014.01.090.

[2] E. Shen, J. Hu, and M. Patel, "Energy and visual comfort analysis of lighting and daylight control strategies," *Building and Environment*, 78, 155–170 (2014), doi: 10.1016/j.buildenv.2014.04.028.

[3] B. Roisin, M. Bodart, A. Deneyer, and P. D'Herdt, "Lighting energy savings in offices using different control systems and their real consumption", *Energy Build*. 40, 514–523 (2008).

[4] L. Xu, Y. Pan, Y. Yao, D. Cai, Z. Huang, and N. Linder, "Lighting energy efficiency in offices under different control strategies," *Energy Build.* 138, 127–139 (2017), doi: 10.1016/j.enbuild.2016.12.006.

[5] P.K. Soori and M. Vishwas, "Lighting control strategy for energy efficient office lighting system design," *Energy Build*. 66, 329–337 (2013), doi: 10.1016/j.enbuild.2013.07.039.

[6] A. Pandharipande and D. Caicedo, "Daylight integrated illumination control of LED systems based on enhanced presence sensing", *Energy Build*. 49, 944–950 (2011).

[7] S. Zalewski and P. Pracki, "Concept and implementation of adaptive road lighting concurrent with vehicles", *Bull. Pol. Ac.: Tech.* 67(6), 1117–1124 (2019).

[8] A. Djuretic, V. Skerovic, N. Arsic, and M. Kostic, "Luminous flux to input power ratio, power factor and harmonics when dimming high-pressure sodium and LED luminaires used in road lighting," *Light. Res. Technol.* 51, 304–323 (2019). doi: 10.1177/1477153518777272.

[9] VALO Information, "Total Harmonic Distortion in LED Lighting", VALO. [Online]. Available: www.i-valo.com/assets/files/2016/03/Total-Harmonic-Distortion-THD.pdf [Accessed: Aug. 31, 2018].

[10] M.H. Pourarab, N. Nakhodchi, and M. Monfared, "Harmonic analysis of led street lighting according to IEC61000-3-2; a case study", 23rd International Conference on Electricity Distribution. Lyon, France, p. 1483, 2015

[11] Standard IEC 61000-3-1, Electromagnetic Compatibility (EMC) – Part 3–1: Limits – Overview of emission standards and guides. Technical Report.

[12] Standard IEC 61000-3-2, Electromagnetic compatibility (EMC) – Part 3–2: Limits – Limits for harmonic current emissions (equipment input current ≤ 16 A per phase).

[13] Standard IEC 61000-3-3, Electromagnetic compatibility (EMC) – Part 3–3: Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current <= 16 A per phase and not subject to conditional connection.

[14] Standard EN 50160. Voltage Characteristics in. Public Distribution Systems. Voltage Disturbances. 2010.

[15] American National Standard for Lamp Ballasts—High Frequency Fluorescent Lamp Ballasts ANSI C82.11–2017.

[16] R.A. Mangkuto, "Validation of DIALux 4.12 and DIALux evo 4.1 against the Analytical Test Cases of CIE 171:2006", *Leukos* 12(3), 139–150 (2016)

[17] G. Lowry, "Energy saving claims for lighting controls in commercial buildings", *Energy Build.* 133, 489–497 (2016)

[18] A. de Vries, J.L. Souman, B. de Ruyter, I. Heynderickx, and Y.A.W. de Kort, "Lighting up the office: The effect of wall luminance on room appraisal, office workers' performance, and subjective alertness", *Build. Environ.* 142, 534–543 (2018)

[19] P. Tabaka and P. Rózga, "Assessment of methods of marking LED sources with the power of equivalent light bulb", *Bull. Pol. Ac.: Tech.* 65(6), 883–890 (2017), doi: 10.1515/bpasts-2017-0095.