BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 69(3), 2021, Article number: e137194
DOI: 10.24425/bpasts.2021.137194

POWER SYSTEMS AND POWER ELECTRONICS

Active power losses and energy efficiency analysis of HPS lamps with electromagnetic control gear and electronic ballast under the sinusoidal and nonsinusoidal condition

Roman SIKORA*, Przemysław MARKIEWICZ, and Paweł RÓZGA

Lodz University of Technology, Institute of Electrical Power Engineering, ul. Stefanowskiego 18/22, 90-924 Lodz, Poland

Abstract. Outdoor lighting is an important element in creating an evening and nocturnal image of urban spaces. Properly designed and constructed lighting installations provide residents with comfort and security. One way to improve the energy efficiency of road lighting installation is to replace the electromagnetic control gear (ECG) with electronic ballasts (EB). The main purpose of this article is to provide an in-depth comparative analysis of the energy efficiency and performance of HPS lamps with ECG and EB. It will compare their performance under sinusoidal and nonsinusoidal voltage supply conditions for the four most commonly used HPS lamps of 70 W, 100 W, 150 W, and 250 W. The number of luminaires supplied from one circuit was determined based on the value of permissible active power losses. With the use of the DIALux program, projects of road lighting installation were developed. On this basis, energy performance indicators, electricity consumption, electricity costs, and CO_2 emissions were calculated for one-phase and three-phase installations. The obtained results indicate that an HPS lamp with EB is better than an HPS lamp with ECG in terms of energy quality, energy savings, and environmental impact. The results of this analysis are expected to assist in the choice of HPS lighting technology.

Key words: HPS lamp; electromagnetic control gear; electronic ballast; energy performance indicator; road lighting.

1. Introduction

Outdoor lighting, including road lighting, is an important element influencing the safety as well as the evening and nocturnal image of urban spaces. Safety is understood as road safety as well as public safety. Properly designed and constructed public lighting significantly reduces the risk of theft, vandalism, inappropriate behavior, and traffic accidents. It improves the safety and comfort of both pedestrians and road users [1–7]. Article [1] shows that driver activity should be considered in the determination of road visibility indicators. During the design stage, the influence of the environment, which determines the driver's concentration, should be considered. Outdoor lighting, and above all road lighting, should be designed in such a way to achieve its basic aims, i.e. to ensure safety and comfort of using urban space. The observed trend to reduce the electricity consumption of public lighting must not affect the main purpose of its use. The possibilities of improving energy efficiency in public lighting are widely described in the literature [8–20]. In [8] recommendations are presented to improve the quality of lighting while reducing electricity consumption.

Luminaires for high-pressure sodium (HPS) lamps have been used in outdoor lighting since the 1960s [21, 22]. Despite the technological progress observed in LED lighting and smart control systems, the luminaires for high-pressure sodium lamps are still in use. Moreover, they are used in new or modernized lighting installations. This is a consequence of the habits of investors and designers that have been established over the years, among other things. It also results from the advantages of these luminaires and their still very attractive price. The most important advantage of high-pressure sodium lamps is their high luminous efficacy within the range of 68–150 lm/W [21]. High-pressure sodium lamps require a suitable operating circuit to ensure proper operation. Usually, it is an ignitron and magnetic ballast. To initiate a discharge in the lamp, a high value of applied voltage is required. This task is performed by the ignitron. The main function of the ballast is to limit and stabilize the lamp current. The use of a magnetic ballast with a high inductance value makes the power factor of the luminaires small. To improve the power factor, the individual reactive power compensation is usually used in the form of a parallel-connected capacitor with an appropriately selected capacity.

In modern design solutions of luminaires for HPS lamps, electromagnetic control gear (ECG) is replaced by electronic ballasts (EB) [21–31]. Compared to ECG, electronic ballasts have many advantages. Changing the kind of ballast can affect the colorimetric parameters of the luminaire [27]. All components necessary for the proper operation of the lamp are placed in one housing. This ensures a high degree of IP protection, which determines the resistance to access its active parts and water penetration. Electronic ballasts also have higher efficiency and a power factor (often higher than 0.97). They also protect the lamp against the influence of the supply voltage changes. Electronic ballasts are equipped with soft-start systems to limit the start-up current for an optimal ignition cycle.

---

*e-mail: roman.sikora@p.lodz.pl

Manuscript submitted 2020-11-24, revised 2021-03-19, initially accepted for publication 2021-04-08, published in June 2021

From the point of view of improving energy efficiency, their most important advantage is the possibility of dimming. EB facilitates the integration of luminaires for an HPS lamp with smart lighting control systems. In addition to many unquestionable advantages, they also have disadvantages. At present, their most important disadvantages seem to be a high purchase cost and sensitivity to overvoltage [21–31].

In paper [21] the authors presented the results of a comparative analysis of high-pressure sodium lamps with ECG and electronic ballasts. Based on performed tests, it was found that EB causes smaller voltage drops. The conducted techno-economic analysis showed that, due to high prices and shorter lifetime of electronic ballasts, ECGs are still a better choice primarily from a financial point of view. In [24], the results of the performed tests are presented to compare the states of operation of a 250 W HPS lamp with magnetic and electronic ballast. The performance characteristics were obtained in both cases by direct measurements in two commercial installations. Both the heating cycle and the steady state of the lamp were examined. It was discovered that the lamp with the electronic ballast has practically better parameters than the same lamp with the magnetic ballast.

The literature describes many solutions to electronic ballast construction. The design of an electronic ballast with a bridge inverter is described in [23]. The proposed design solution facilitated a significant reduction in the higher harmonics generated to the mains. The use of electronic ballast with a ZigBee protocol-based communication system enables its remote control and diagnostics. Such a solution is presented in [24]. The results of electricity consumption and power measurements are also included. The results of studies in which 400 W HPS lamps were supplied with trapezoidal and rectangular voltage are presented in [32]. The results were compared with the case when the tested lamp was supplied with sinusoidal voltage. Moreover, the efficiency of this method of supplying HPS lamps has been estimated. In the literature, other construction solutions of electronic ballasts were described [25, 26, 32].

Since HPS luminaires for lamps with ECG are still in use, research is being conducted to develop an optimal method of power (luminous flux) regulation, i.e. reduction of electricity consumption [33, 34]. Paper [34] describes the use of a power reducer to reduce electricity consumption. The research was performed in the street lighting installation. Two methods were used to reduce the power. The first one is based on the regulation of the amplitude of the supply voltage and the second one uses an electronic circuit for a chopping wave shape. Energy savings of 25% and 30% were achieved for the transformer and electronic circuits, respectively. Paper [30] presents the results of tests made for lighting circuits with HPS lamps with a rated power of 70 W, 150 W, and 250 W. The research was done for the case when the lamps were supplied by both electromagnetic and electronic ballasts with a dimming function. The circuits have been tested at different power levels using the dimming for 220 V supply voltage. The results showed that the use of a central dimming system for large lighting systems with HPS lamps with ECG can be as energy efficient as HPS lamps with electronic ballasts. Similar studies have been described in [35] where the test results of model lighting circuits with a rated power of 50 W, 70 W, 100 W, 150 W, 250 W, and 400 W with magnetic ballasts have been presented. An electronic central controller was used to supply these circuits. Photometric, colorimetric and electrical parameters of the tested lamp circuits were measured. It was found that in the range of 180 V to 220 V voltages no influence of voltage values on colour temperature and luminous efficacy was observed. It has been observed that with the decrease of the value supply voltage the losses in the magnetic ballast decrease.

Moreover, research on the reliability of HPS lamps is still being continued. Article [36] presents the results of on/off tests, thermal tests, and EMC tests of HPS lamps. A method for determining the reliability of these lamps is also proposed. New mathematical models of HPS lamps are also being developed [37–39]. The literature also describes many results of comparative tests of HPS lamps with magnetic and electronic ballasts [24, 25, 29, 40].

The proper performance of any electrical device supplied from the mains depends on the electrical power quality (quality of the supply voltage). Electrical power quality parameters of lighting installations are described in many publications, e.g. [41–44]. In the standard [45], the permissible limits of the supply voltage parameters are specified. From the point of view of the proper performance of a luminaire, the most important indicators are the RMS value of the supply voltage and the voltage total harmonic distortion factor THD_V. For receivers supplied from the low voltage grid, such as outdoor lighting installations, the RMS value of the supply voltage every week, 95% of the 10-minute average RMS value of the supply voltage should be within the ±10% deviation range of the rated voltage. For a low voltage grid, the voltage *THD* factor, including harmonics up to 40, should not exceed 8%.

In practice, lighting installations are supplied from transformer substations also supplying other customers, such as residential buildings, commercial buildings, or small industrial plants. The power of the lighting installations in relation to the power of other supplied receivers from the transformer can amount to a few percent only. In this case, the quality of the supply voltage is determined by the 24-hour profile of the power received by other consumers. Since currently non-linear receivers generating disturbances to the mains are increasingly being used, an increase in the distortion of the mains voltage in low voltage networks is observed [41–44]. Non-linear receivers are also luminaires, including luminaires for HPS lamps with magnetic and electronic ballast [29, 37–39]. For non-linear loads, the level of the generated current harmonics can be influenced by the distortion of the supply voltage. In the literature, there are no results of studies aimed at investigating the influence of the level of voltage distortion on the photometric, colorimetric, and electrical parameters of HPS with ECG and electronic ballasts. This article aims to estimate how the level of voltage distortion affects the mentioned parameters.

An important but often neglected factor affecting energy efficiency is the problem of active power losses in lighting installations. The previous publications [46, 47] described it focusing only on lighting installations with LED luminaires.

Therefore, this article presents the calculation of active power losses in lighting systems with luminaires for HPS lamps with ECG and EB. The purpose of the calculations was to estimate the maximum number of light points so as not to exceed the assumed percentage of active power losses. The calculations were made for single-phase and three-phase installations and copper cables with cross-sections of 10 mm^2, 16 mm^2, and 25 mm^2 and for aluminum cables with cross-sections of 16 mm^2, 25 mm^2, and 35 mm^2. The calculation considers the influence of the current harmonics flow on the cable conductor resistance according to [48]. Four 70 W, 100 W, 150 W, and 250 W luminaires for HPS lamps were selected for the study. In the first stage, measurements were made for luminaires with magnetic ballasts. Subsequently, ECGs were replaced by electronic ballasts dedicated to these lamps. The research results presented in the article can be generalized assuming that in other construction solutions the physics of phenomena is similar. However, results for other ballast constructions and power supply conditions may be different.

The main aim of the article is to present the influence of the exchange of ECG on EB on several parameters considered in the assessment of the usefulness of the light source, such as the energy efficiency of the entire lighting installation, the costs of electricity consumption based on a given solution, the amount of greenhouse gas emissions, the quality of the electrical power and the active power losses in the power cable under sinusoidal and non-sinusoidal voltage supply. The multifaceted considerations also include the influence of harmonic current flow on the resistance value of the power cable as well as the active power losses. Moreover, the number of luminaires allowed for single-phase and three-phase installations made of aluminum-based and copper-based cables was determined for the most commonly used values of the cross-section in practice due to the permissible value of active power losses in the power cable. The results of this multi-criteria analysis, which have not been described in the literature so far in the form presented in the article, provide both practitioners and scientists working on the subject of lighting for utility purposes with valuable and significant data.

The article was organized as follows. Section 2 describes the experimental setup and test objects. Section 3.1 presents the results of measurements of electrical parameters and luminous flux. Based on the obtained results, the electrical parameters were additionally calculated according to the standard [49]. Section 3.2 presents the results of the analysis of the influence of active power losses on the permissible number of light points (with the assumed percentage of losses) in single-phase and three-phase installations. In Section 3.3, the calculation results of active power losses, energy performance indicators, energy, electricity costs, and CO$_2$ emission of road lighting installation were presented. Section 3.4 presents a discussion and selected conclusions, and Section 4 provides a summary.

2. Experimental setup

The main aim of the article is to compare the electrical and photometric (luminous flux) parameters of HPS lamps with magnetic and electronic ballasts supplied with sinusoidal and non-sinusoidal voltage. Four luminaires with 70 W, 100 W, 150 W, and 250 W, HPS lamps were selected as test subjects. A group of ballasts with a low degree of usage was selected for laboratory testing. Before measurements, each of them had been operating for at least 100 hours to stabilize their parameters.

In the first stage, the measurements of luminaires with a factory-mounted ECG were done. The ECGs were then replaced by electronic ballasts. The ballasts used in the study can control power (luminous flux). This function was not used. It was assumed that the lamps operate at full power resulting only from the power supply conditions. The test object was the entire luminaire, not just the ballast. A modern electronic ballast of a reputable manufacturer was chosen for testing. The tested ballast was equipped with a soft start, which limited the start-up current. According to the datasheet, the rated power in the normal duty cycle is equal to or lower than the rated power of the lamp. For the 70 W lamp, the luminaire power according to the technical data is also equal to 70 W. In the case of a 100 W lamp, the luminaire power is equal to 95 W. The luminaire power for the 150 W lamp is 140 W and for the 250 W lamp, it amounts to 225 W. The manufacturer states that these powers should be within ±5% for all copies. According to the ballast documentation, a PFC (power factor correction) system is included, which limits its negative impact on the mains. The electronic ballast supplies the luminaire with the voltage independently of the supply voltage.

As mentioned earlier, luminaires with ECG and electronic ballasts will require a sinusoidal and distorted supply voltage with a given spectrum of higher harmonics. The luminaires are powered by the AGILENT 6834B programmable power supply unit. The experimental setup used for the measurements is shown in Fig. 1. By using the software for programming the AGILENT 6834B power supply, five voltage signals with the following *THD* voltage are implemented: 1.80%, 2.50%, 5.00%, 7.50%, and sinusoidal (0%).

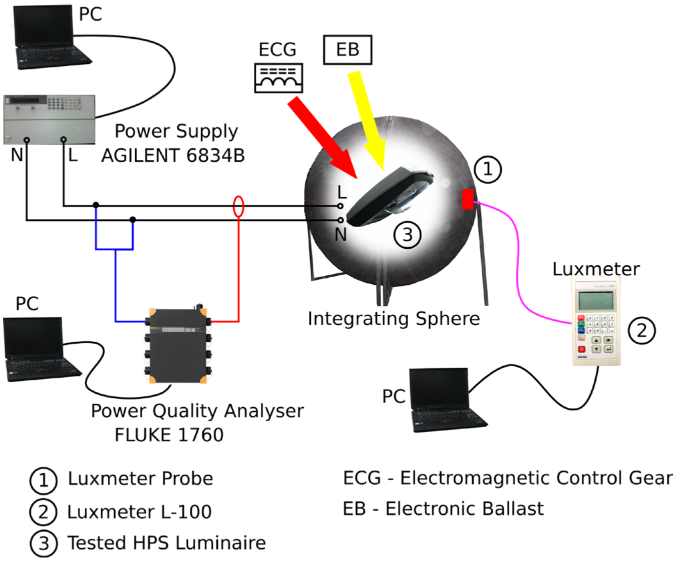

Fig. 1. Experimental setup for HPS luminaire with electromagnetic control gear and electronic ballast

The higher harmonic spectra of these voltages and their phase shift angles are shown in Figs. 2a and 2b (without sinusoidal voltage). In each case, the RMS value of the fundamental harmonic voltage was 230 V. The voltage signal of $THD_V = 1.80\%$ was obtained based on the measurement results made in the real outdoor lighting installation. The THD_V signals of 2.50%, 5.00%, and 7.50% are determined by proportionally increasing the harmonics for $THD_V = 1.80\%$.

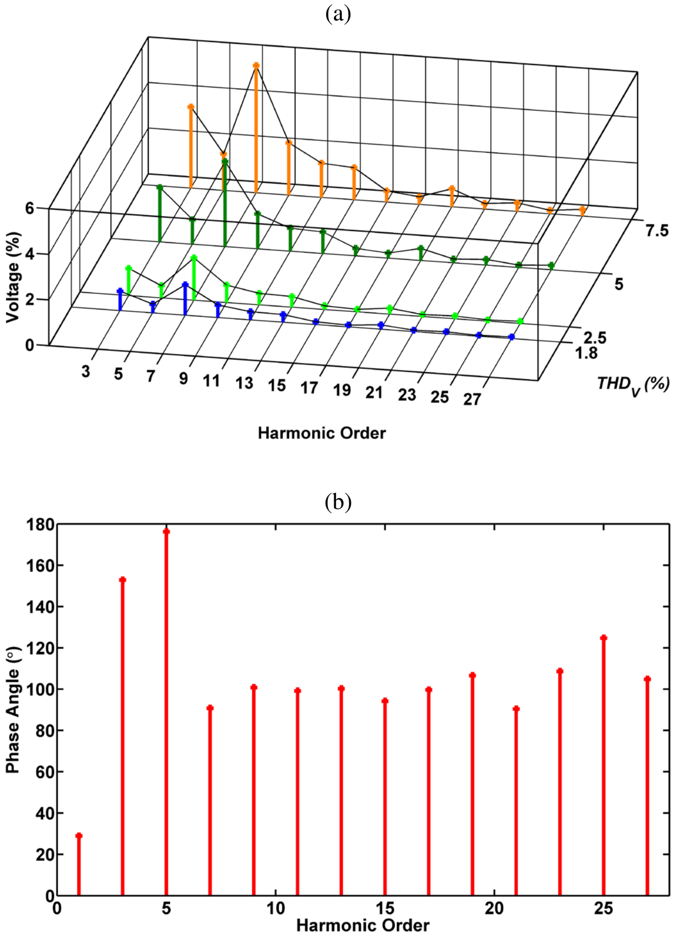

Fig. 2. Harmonics spectra of the supply voltage used during the measurements and their phase angle

The EN 50160 standard [45] specifies a permissible THD_V equal to 8% for LV distribution power grids. In real power grids, THD_V values are usually less than 8%. However, the THD_V value may be close to the permissible value. This situation should not be considered to be an emergency operating condition. The analysis was performed to verify the operation of luminaires for HPS lamps within the permissible range of changes in THD_V values. The analysis of the luminaire operation supplied with voltage exceeding 5% THD_V is interesting and not comprehensively described in the literature.

The measurements of electrical parameters were performed using the FLUKE 1760 power quality analyzer. The measurements of the luminous flux were taken in an integrating sphere. The luminous flux was measured with the lux meter L-100 marked as 2 in Fig. 1.

The measuring circuit shown in Fig. 1 facilitates the registration of the basic electrical parameters as well as the luminous flux. The purpose of the measurements was to measure electrical and photometric parameters in a steady state. In a steady state, the values of the measured quantities did not change noticeably. Therefore, the performed measurements did not require precise time synchronization.

3. Measurement and calculation results

3.1. Electrical parameters. In this section, the measurement results of the influence of voltage distortion on the electrical parameters of HPS lamps with ECG and EB are presented. The measurements were made in a steady state after the luminaires were lit for 1 hour. The average values over 1 minute of the measured parameters were used for further calculations.

The measured electrical parameters for the tested HPS lamp are presented in Table 1 for ECG and Table 3 for EB. After analyzing the measured current values of HPS lamps with ECG, it can be concluded that with the increase in the level of distortion in the supply voltage, its value significantly increases. For the 70 W lamp, the measured value of the current at sinusoidal voltage is 0.429A and for the THD_V voltage $= 7.50\%$, it is 0.650 A. Thus, the value of the current increased by 51.52%. For a 100 W lamp, these values amount to 0.579A and 0.820A respectively. For this luminaire, the value of the current increased the least, i.e. by 41.62%. For 150 W and 250 W lamps, the RMS value of the current increased by 55.34% and 54.73%.

The increase in the current value did not result in significant growth in the active or reactive power. Therefore, this phenomenon must be associated with an increase in the distorted power due to the flow of higher harmonic currents. Using the dependencies presented in the standard [49], the values of the distorted current I_H, distorted voltage V_H, harmonic active power P_H, apparent power for the fundamental harmonic S_1, non-fundamental S_N, and harmonic S_H can be calculated. Moreover, the values of the current distortion power D_I and voltage distortion power D_V were calculated. The calculation results are presented in Tables 2 and 4 for lamps with ECG and EB, respectively. Current distortion power D_I for a 70 W lamp with the ECG supplied with sinusoidal voltage is 21.771var and for $THD_V = 7.50\%$ is 114.496var. This power increased by 425.91%. For a 100 W lamp, current distortion power increased by 330.61%; for a 100 W lamp, the percentage increase is 570.52% and for a 250 W lamp, an increase of 451.63% was observed. An increase in the voltage distortion power is noticed as the voltage distortion level of the mains increases. The influence of the supply voltage distortion on the level of the higher current harmonics generated to the mains is illustrated by the changes in the THD_I coefficient. A change of the voltage distortion level from sinusoidal voltage to $THD_V = 7.5\%$ results in an increase in THD_I from 20.557% to 119.900% for a 70 W lamp. Similarly, the THD_I values for the other tested lamps increase, as shown in Fig. 3a. Using the Curve Fitting Toolbox, which is part of the MATLAB® program, an approximation function of the THD_I coefficient dependence in the function of THD_V was

Table 1
The measured values of the HPS lamp with ECG electrical parameters with a change in the distortion level of supply voltage

THD_V (%)	Lamp	V (V)	V_1 (V)	I (A)	I_1 (A)	THD_I (%)	P (W)	P_1 (W)	S (VA)	Q (var)	PF_D	PF_{DD}
0	70 W	229.950	229.950	0.429	0.418	20.557	96.915	95.915	98.660	1.884	0.999	0.978
	100 W	229.910	229.910	0.579	0.562	24.834	128.760	128.760	133.200	11.313	0.996	0.996
	150 W	229.880	229.880	0.730	0.719	18.106	163.440	163.470	167.910	23.971	0.989	0.973
	250 W	229.770	229.770	1.312	1.280	20.423	294.100	292.470	301.340	–19.348	–0.998	–0.976
1.80	70 W	229.930	229.890	0.445	0.419	35.495	96.168	96.322	102.250	0.341	0.999	0.941
	100 W	229.910	229.860	0.594	0.561	34.743	128.220	128.420	136.540	11.561	0.996	0.939
	150 W	229.880	229.840	0.763	0.719	35.637	163.290	163.520	175.490	24.202	0.989	0.930
	250 W	229.750	229.720	1.371	1.280	38.211	293.010	293.500	314.930	–18.589	–0.998	–0.930
2.50	70 W	229.940	229.860	0.460	0.419	44.744	96.188	96.397	105.670	–0.460	–0.999	–0.910
	100 W	229.900	229.830	0.609	0.560	42.447	127.950	128.210	139.920	11.849	0.996	0.914
	150 W	229.880	229.800	0.791	0.719	45.799	163.270	163.580	181.910	24.489	0.989	0.898
	250 W	229.770	229.660	1.417	1.279	47.708	292.430	293.080	325.520	–17.754	–0.998	–0.898
5.00	70 W	229.940	229.630	0.540	0.418	81.612	95.605	96.012	124.120	0.927	0.999	0.770
	100 W	229.900	229.590	0.694	0.558	74.115	126.970	127.460	159.580	13.480	0.994	0.796
	150 W	229.880	229.560	0.933	0.719	82.749	162.680	163.260	214.520	26.887	0.987	0.758
	250 W	229.770	229.430	1.668	1.271	85.018	289.960	291.090	383.290	–12.003	–0.999	–0.756
7.50	70 W	229.930	229.240	0.650	0.416	119.900	94.862	95.463	149.520	2.438	0.999	0.634
	100 W	229.890	229.190	0.820	0.565	108.940	125.860	126.550	188.590	16.019	0.992	0.667
	150 W	229.880	229.170	1.134	0.718	122.300	161.870	162.670	260.630	30.646	0.983	0.621
	250 W	229.780	229.030	2.030	1.263	125.740	287.430	288.930	466.340	–3.202	–0.999	–0.616

Table 2
The calculated values of the HPS lamp with ECG electrical parameters with a change in the distortion level of supply voltage

THD_V (%)	Lamp	V_H (V)	I_H (V)	P_H (W)	S_1 (VA)	S_N (VA)	S_H (VA)	D_I (var)	D_V (var)	$\tan\phi$
0	70 W	0.000	0.095	0.552	95.929	23.053	0.000	21.771	0.000	0.020
	100 W	0.000	0.140	–0.030	129.255	32.169	0.000	32.169	0.000	0.088
	150 W	0.000	0.130	–0.030	165.212	29.997	0.000	29.997	0.000	0.147
	250 W	0.000	0.287	1.630	294.037	66.956	0.000	65.954	0.000	0.066
1.80	70 W	4.289	0.149	–0.154	96.322	34.310	0.639	34.257	1.797	0.004
	100 W	4.795	0.195	–0.200	128.931	44.942	2.689	44.851	2.689	0.090
	150 W	4.288	0.256	–0.230	165.262	59.030	1.100	58.940	3.083	0.148
	250 W	4.793	0.489	–0.490	294.111	112.585	2.345	112.393	6.137	0.063
2.50	70 W	6.065	0.188	–0.209	96.399	43.275	1.139	43.185	2.544	0.005
	100 W	5.673	0.238	–0.260	128.739	54.806	1.350	54.697	3.178	0.093
	150 W	6.064	0.330	–0.310	165.323	75.900	1.999	75.748	4.363	0.150
	250 W	6.430	0.610	–0.650	293.666	140.416	3.923	140.121	8.222	0.061
5.00	70 W	11.936	0.341	–0.407	96.013	78.662	4.075	78.398	4.991	0.010
	100 W	11.935	0.413	–0.490	128.019	95.277	4.934	94.916	6.655	0.106
	150 W	12.125	0.595	–0.580	165.033	137.054	7.214	136.586	8.717	0.165
	250 W	12.495	1.081	–1.130	291.560	248.789	13.502	247.914	15.879	0.041
7.50	70 W	17.800	0.499	–0.601	95.467	115.080	8.890	114.496	7.413	0.028
	100 W	17.926	0.604	–0.690	127.134	139.302	10.835	138.523	9.944	0.127
	150 W	18.053	0.878	–0.800	164.457	202.173	15.845	201.135	12.955	0.189
	250 W	18.550	1.589	–1.500	289.288	365.765	29.468	363.823	23.431	0.011

Table 3
The measured values of the HPS lamp with EB electrical parameters with a change in the distortion level of supply voltage

THD_V (%)	Lamp	V (V)	V_1 (V)	I (A)	I_1 (A)	THD_I (%)	P (W)	P_1 (W)	S (VA)	Q (var)	PF_D	PF_{DD}
0	70 W	229.970	229.970	0.311	0.310	6.354	69.738	69.738	71.481	–14.977	–0.978	–0.976
	100 W	229.940	229.940	0.406	0.406	5.048	92.169	92.168	93.417	–14.402	–0.988	–0.987
	150 W	229.920	229.920	0.605	0.603	4.357	138.440	38.140	139.020	–11.133	–0.997	–0.996
	250 W	229.790	229.790	0.975	0.970	8.485	222.560	222.570	223.950	–11.391	–0.999	–0.994
1.80	70 W	229.940	229.900	0.311	0.310	7.397	69.684	69.666	71.478	–14.953	–0.978	–0.975
	100 W	229.400	229.900	0.406	0.406	5.945	92.136	92.109	93.414	–14.338	–0.988	–0.986
	150 W	229.910	229.880	0.604	0.604	4.849	138.380	138.320	138.980	–10.903	–0.997	–0.996
	250 W	229.780	229.750	0.974	0.970	8.159	222.500	222.560	223.900	–11.013	–0.999	–0.994
2.50	70 W	229.970	229.900	0.311	0.310	8.155	69.718	69.682	71.553	–14.962	–0.978	–0.974
	100 W	229.940	229.870	0.406	0.405	6.493	92.109	92.058	91.414	–14.345	–0.988	–0.986
	150 W	229.890	229.820	0.604	0.603	5.134	138.320	138.250	138.930	–10.961	–0.997	–0.996
	250 W	229.770	229.700	0.974	0.970	8.124	222.380	222.420	223.780	–10.845	–0.999	–0.994
5.00	70 W	229.960	229.680	0.312	0.310	11.414	69.700	69.549	71.678	–14.961	–0.979	–0.972
	100 W	229.950	229.670	0.407	0.405	9.053	92.095	91.890	93.522	–14.242	–0.988	–0.985
	150 W	229.900	229.610	0.605	0.603	6.780	138.310	130.040	138.970	–10.708	–0.997	–0.995
	250 W	229.780	229.490	0.974	0.969	8.335	222.360	222.200	223.800	–10.191	–0.999	–0.994
7.50	70 W	229.960	229.320	0.313	0.310	15.433	69.742	69.398	71.996	–14.370	–0.979	–0.969
	100 W	229.930	229.290	0.408	0.405	11.841	92.144	91.689	93.752	–14.156	–0.988	–0.983
	150 W	229.900	229.260	0.605	0.602	8.662	138.310	137.700	139.030	–10.381	–0.997	–0.995
	250 W	229.770	229.120	0.974	0.969	9.250	222.260	221.680	223.770	–9.341	–0.999	–0.993

Table 4
The calculated values of the HPS lamp with EB electrical parameters with a change in the distortion level of the supply voltage

THD_V (%)	Lamp	V_H (V)	I_H (V)	P_H (W)	S_1 (VA)	S_N (VA)	S_H (VA)	D_I (var)	D_V (var)	$\tan\phi$
0	70 W	0.000	0.020	0.000	71.327	4.691	0.000	4.691	0.000	0.215
	100 W	0.000	0.022	0.001	93.284	4.947	0.000	4.947	0.000	0.156
	150 W	0.000	0.040	0.300	138.576	9.111	0.000	9.111	0.000	0.080
	250 W	0.000	0.096	–0.010	222.864	22.084	0.000	22.084	0.000	0.051
1.80	70 W	0.018	0.024	0.018	71.260	5.595	0.101	5.434	1.329	0.215
	100 W	4.289	0.025	0.027	93.224	5.970	0.107	5.710	1.739	0.156
	150 W	3.714	0.030	0.030	138.783	7.319	0.113	6.966	2.242	0.079
	250 W	3.713	0.093	–0.060	222.844	21.722	0.346	21.419	3.601	0.049
2.50	70 W	5.674	0.026	0.036	71.285	6.185	0.146	5.927	1.759	0.215
	100 W	5.673	0.027	0.051	93.180	6.694	0.152	6.178	2.300	0.156
	150 W	5.673	0.032	0.070	138.692	8.083	0.181	7.320	3.423	0.079
	250 W	5.671	0.093	–0.040	222.696	21.971	0.525	21.265	5.498	0.049
5.00	70 W	11.345	0.036	0.151	71.120	8.927	0.405	8.187	3.513	0.210
	100 W	11.344	0.037	0.205	93.016	9.699	0.421	8.852	4.594	0.155
	150 W	11.544	0.042	0.270	138.471	11.821	0.480	9.541	6.962	0.077
	250 W	11.541	0.094	0.160	222.468	24.416	1.090	21.675	11.188	0.046
7.50	70 W	17.145	0.048	0.344	70.945	12.244	0.823	11.005	5.304	0.206
	100 W	17.144	0.048	0.455	92.830	13.127	0.831	11.112	6.941	0.154
	150 W	17.142	0.053	0.610	138.118	15.919	0.903	12.080	10.327	0.075
	250 W	17.271	0.102	0.580	221.919	28.783	1.761	23.357	16.728	0.042

determined. All tested luminaires, except for the luminaire for a 250 W HPS lamp, are inductive. The luminaire is capacitive because the capacitor that acts as a reactive power compensator has an oversized capacitance.

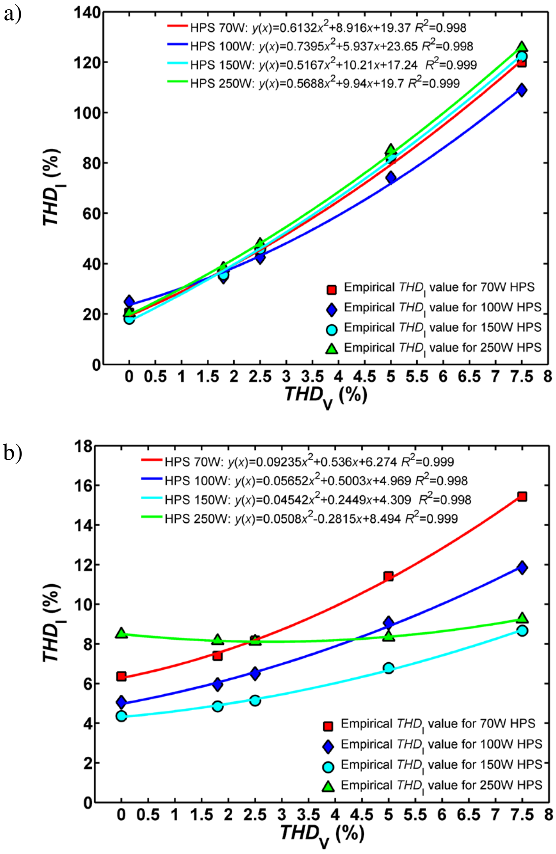

Fig. 3. The relationship between THD_I in a function of THD_V: (a) for HPS lamp with ECG, (b) for HPS lamp with EB

A luminaire equipped with electronic ballast is much less sensitive to the increase in the supply voltage distortion (Table 3). The active power and the current RMS value for each tested lamp practically do not change as the THD_V coefficient increases. The measurement results also confirmed the information concerning the power reduction of the luminaire provided by the manufacturer of the electronic ballast. For each value of the THD_V coefficient, the character of the circuit did not change, which in the whole range of tested changes in the THD_V coefficient was capacitive. After the replacement of the ECG with EB, the values of the generated higher current harmonics decreased significantly. This is illustrated by the THD_I values, which on average decreased more than three times when supplied with the sinusoidal voltage. Also, an increase in the supply voltage distortion in the case of an HPS lamp with EB leads to an increase in the THD_I value (Fig. 3b). For a 70 W lamp with EB, the THD_I increased by 142.89%. Compared to the lamp-ECG system, it is still a much smaller increase. For a 100 W lamp the THD_I value increased by 134.57% and for a 150 W lamp – by 90.81%. The smallest increase in the THD_I value was observed for a 250 W lamp. There was an increase of 9.02% only. Therefore, it can be concluded that in the case of EBs, their sensitivity to changes of the supply voltage distortion is lower than the ECG and depends on their design and operating principle. Also, for the EB-lamp system, the changes in the approximating functions THD_I in a function of THD_V have been determined (Fig. 3b). Despite the significant increase in THD_I observed with the increase in THD_V, its values did not exceed 16%. Even the largest current distortion of the EB lamp system with the largest supply voltage distortion is less than the smallest THD_I value of the ECG lamp system with the sinusoidal voltage supply.

3.2. The analysis of luminous flux and luminous efficiency.

From the operational point of view, it seems interesting to check whether the voltage distortion level affects the luminous flux value of HPS lamps with ECG and electronic ballasts (EB). For this purpose, the following quantity was measured. Based on the measurement results of electrical parameters and luminous flux, the luminous efficacy η was calculated. It was calculated as the quotient of the luminous flux Φ and the active power P (Eq. (1))

$$\eta = \frac{\Phi}{P} \quad \left(\frac{\mathrm{lm}}{\mathrm{W}}\right). \tag{1}$$

Table 5 shows the measured values of luminous flux and calculated luminous efficiency for the tested HPS lamps with ECG

Table 5
The summary of measured and calculated values of luminous flux and luminous efficiency of the HPS lamp with ECG and EB with a change in the supply voltage distortion level

THD_V (%)	Lamp	ECG		EB	
		Φ (lm)	η (lm/W)	Φ (lm)	η (lm/W)
0	70 W	7774.550	80.593	5311.289	76.161
	100 W	11727.535	91.102	7661.217	83.121
	150 W	15595.272	95.419	12340.326	89.138
	250 W	26838.235	91.255	21470.588	96.471
1.80	70 W	7740.600	80.490	5311.289	76.220
	100 W	11619.114	90.619	7661.217	83.151
	150 W	15595.272	95.507	12340.326	89.177
	250 W	26687.740	91.081	21470.588	96.497
2.50	70 W	7740.600	80.474	5311.289	76.182
	100 W	11601.044	90.669	7661.217	83.176
	150 W	15595.272	95.518	12340.326	89.216
	250 W	26587.410	90.919	21437.145	96.399
5.00	70 W	7672.700	80.254	5311.289	76.202
	100 W	11492.623	90.514	7661.217	83.188
	150 W	15595.272	95.865	12340.326	89.222
	250 W	26503.802	91.405	21453.866	96.483
7.50	70 W	7604.800	80.167	5311.289	76.156
	100 W	11348.061	90.164	7661.217	83.144
	150 W	15416.016	95.237	12340.326	89.222
	250 W	26252.978	91.337	21453.866	96.526

and EB. For lamps with ECG, an increase in the distortion level of the supply voltage does not change the luminous flux. For lamps operating with an electronic ballast, the luminous flux is lower than for the same lamp operating with an ECG. This is due to the assumed operating algorithm of the electronic ballast whose main aim is to reduce the active power received from the mains to achieve energy savings. For a 70 W HPS lamp with ECG, the luminous flux is 7774 lm and for the electronic ballast, it is reduced to 5311 lm. Thus, the reduction of the luminous flux resulting from using EB is 32%. In the case of a 250 W HPS lamp with ECG, the luminous flux is equal to 26838 lm and when using an electronic ballast, it reaches the value of 21470 lm. Changing the type of ballast results in a 20% reduction of the luminous flux.

3.3. The calculation of active power losses. Under the recommendations of the European Union and national legislation [50, 51], the energy efficiency of lighting installations, both indoor and outdoor, should be increased. For this purpose, the power consumption is usually limited (and if possible) with unchanged or even higher luminous flux values. Only the active power of the installation is used in the calculation of energy efficiency indicators (energy performance indicators). It is calculated as the sum of the active power of the light points and other devices necessary for the proper performance of the lighting installation. These calculations are usually done with the adoption of simplifications. One of them is to neglect active power losses. As it was proved in previous studies [46, 47], active power losses may exceed even 7% of the total power of luminaires for a single-phase installation. Therefore, reducing active power loss should be one of the objectives of modernization of lighting installations or a condition fulfilled by a new installation. There are no recommendations in the literature on permissible active power loss values for lighting installations. In the authors' opinion, the maximum value of active power losses that may be considered acceptable is no more than 5% of the installed power. In the case of luminaires with relatively small values of higher harmonics of the current generated to the mains, their influence on the value of the resistance of the cable can be neglected. However, with high harmonic values of the current flowing through the cable, this effect must be considered. Below, there are presented the relationships by which the resistance value of the power cable can be calculated for a given harmonic. The analysis focused only on cable lines because they are most commonly used in practice in the case of outdoor (road) lighting installations. In general, cable resistance is affected by three phenomena: skin effect, proximity, and metallic cable screen influence. The cable resistance for a given frequency (harmonic order) can be calculated from Eq. (2)

$$R_{\mathrm{AC}}(h) = R_{\mathrm{DC}}\left[1 + x_s(h) + x_p(h) + x_a(h)\right], \tag{2}$$

R_{DC} – DC conductor resistance (Ω); x_s – resistance increment caused by skin effect; x_p – resistance increment caused by proximity effect; x_a – resistance increment caused by the impact of the metallic cable screen.

Usually, the cables used in outdoor lighting installations have no metallic screen. Therefore, in dependence (2), the component x_a can be omitted (Eq. (3))

$$R_{\mathrm{AC}}(h) = R_{\mathrm{DC}}\left[1 + x_s(h) + x_p(h)\right]. \tag{3}$$

The literature describes many methods of determining the components x_s and x_p [48, 52–55]. In the calculations, the dependencies given in IEC-60287-1-1 will be used [48]. The value of the coefficient taking into account the skin effect is calculated from formula (4)

$$x_s(h) = \frac{y_s^4}{192 + 0.8 y_s^4}, \tag{4}$$

where

$$y_s^4 = \left(\frac{8\pi h f k_s}{R_{DC} 10^7}\right)^2, \tag{5}$$

f – mains rated frequency (Hz); h – harmonics order; k_s – correction coefficient depending on a cable conductor design.

The calculation assumes the value of the coefficient k_s for a single-strand cable equal to 1 and a multi-strand cable $k_s = 0.4$. The value of the coefficient taking into account the proximity effect according to IEC-60287-1-1 [48] is calculated using the relation (6)

$$x_p(h) = \frac{y_p^4}{192 + 0.8 y_p^4}\left(\frac{d}{D}\right)^2 \cdot \left[0.312\left(\frac{d}{D}\right)^2 + \frac{1.18}{\dfrac{y_p^4}{192 + 0.8 y_p^4} + 0.27}\right], \tag{6}$$

where

$$y_p^4 = \left(\frac{8\pi h f k_p}{R_{\mathrm{DC}} 10^7}\right)^2. \tag{7}$$

D – Distance between axes of conductors (m), d – conductor diameter (m).

Figure 4 shows a view of a four-strand cable with the dimensions D and d marked. The correction coefficient depending on

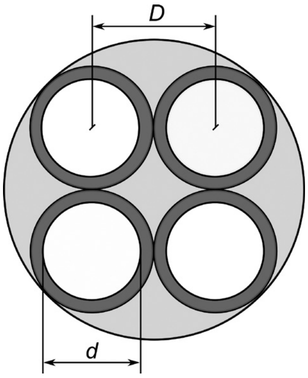

Fig. 4. A cross-section of a four-strand cable

the cable conductor design k_p is equal to 1 for a single-strand cable and 0.3 for a multi-strand cable.

For a three-phase installation, the active power losses in the cable can be calculated from relation (8) [56]

$$\Delta P_C^{3P} = 3R_{\mathrm{AC}}(h)\left[n^2\left(\frac{l_{01}+l}{l}\right) + \frac{n(n-1)(2n-1)}{2}\right]\sum_{h=1}^{\infty} {I_{\mathrm{Lum}_h}}^2. \tag{8}$$

Power losses in the neutral conductor of the power cable can be determined from Eq. (9) [56]. Losses in the neutral conductor are caused by the flow of higher zero-order harmonics and are a multiple of the number 3 ($h = 3, 9, 15, \ldots$)

$$\Delta P_N^{3P} = R_N(h)\left[9n^2 + \frac{l_{01}}{l} + \frac{n(3n-1)(6n-1)}{2}\right]\sum_{h=3}^{\infty} {I_{\mathrm{Lum}_h}}^2. \tag{9}$$

If the neutral conductor has the same cross-section, it is made from the same material and has the same length as the phase conductors, it can be assumed that $R_N(h) = R_{\mathrm{AC}}(h)$. The total active power losses in a power cable are equal to the sum of the power losses in phase and neutral conductors (equation 10)

$$\Delta P_T^{3P} = \Delta P_C^{3P} + \Delta P_N^{3P}\,. \tag{10}$$

For a single-phase installation, active power losses in the power cable are also total power losses. It can be calculated using the relationship (11) [56]

$$\Delta P_C^{1P} = 2R_{\mathrm{AC}}(h)\left[n^2\left(\frac{l_{01}}{l}\right) + \frac{n(n-1)(2n-1)}{6}\right]\sum_{h=1}^{\infty} {I_{\mathrm{Lum}_h}}^2. \tag{11}$$

Using the above dependencies, it is possible to determine the permissible number of the light points (luminaires) that can be supplied from one circuit and the active power losses will not exceed the assumed permissible value. The article presents the results of the calculations of the permissible number of light points due to the value of the assumed percentage losses of active power. The percentage of the active power losses is understood as the quotient of active power losses and total active power of luminaires. The installation of the road lighting was chosen as a sample test object. The calculations were made for five permissible values of active power losses in percentages: 1%, 2%, 3%, 4%, and 5%. In road lighting installations, both copper and aluminium strand cables are used. Therefore, calculations were made for cables with copper and aluminium strands. For cables with copper strands, the cross-sections of 10 mm^2, 16 mm^2, and 25 mm^2 have been selected; for cables with aluminium strands, the calculations have been made for the cross-sections of 16 mm^2, 25 mm^2, and 35 mm^2. Apparently, the calculations were made for all tested HPS lamps with both ECG and EB, and all analyzed distortion levels of the supply voltage. Single-phase and three-phase installations were analyzed, and the results of the calculations are presented in Tables 8–15.

To calculate the active power losses, it is necessary to know the length of the cable line between the poles. For this purpose, the lighting parameters on the road were calculated using DIALux. The lighting system parameters adopted for the calculation are presented in Table 6. For the 250 W lamp, a dual carriageway with four lanes was selected as a reference object. The arrangement of luminaires "Double row, opposing" was used. The calculation of the permissible number of poles (luminaires) due to the active power losses was made for a circuit located on one side of the road. For the other lamps, a "Single row, bottom" arrangement is used. The adopted assumptions concern the lighting installation for HPS lamps with ECG and EB. After the change of the ballast, neither the mounting of the luminaires nor the installation parameters were changed. These parameters were selected to meet the lighting requirements for the assumed road lighting classes. The calculation results of the lighting parameters on the road are presented in Table 7. The tested electronic ballast reduces the active power received from the mains. This was confirmed by the results of the tests described in Section 3.1. Unfortunately, the power reduction is also associated with a reduction in the luminous flux value (Section 3.2). This affects the lighting parameters on the road as illustrated by the calculation results in Table 7. The reduction of the luminous

Table 6
Parameters of road lighting installations

HPS Lamp	70 W	100 W	150 W	250 W
Arrangements	Single row, bottom			Double row, opposing
Pole distance (m)	25.00	28.00	25.00	33.00
Height (m)	8.00	9.00	10.50	10.30
Inclination (°)	0.00	5.00	6.00	1.00
Overhang (m)	–0.65	–0.65	–0.65	–0.15
Boom length (m)	0.50	0.50	1.00	0.00
Number of poles single-phase	22	19	16	10
Number of poles three-phase	48	42	36	21
Street length single-phase (m)	550	532	400	330
Street length single-phase (m)	1200	1176	900	693
Street width (m)	6 (2 lane)	7 (2 lane)	7 (2 lane)	7+7 (4 lane)
Maintenance factor	0.80			
Lighting class	M5	M5	M4	M1

Table 7
Results of photometric calculations

Luminaire		L_{avg} (cd·m^{-2})		U_0 (%)		U_l (%)		f_{TI} (%)		$\overline{E}$
		O1	O2	O1	O2	O1	O2	O1	O2	(lx)
70 W	ECG	0.64	0.67	0.41	0.39	0.54	0.55	3	2	13
	EB	0.51	0.54	0.41	0.39	0.54	0.55	3	2	10
100 W	ECG	0.75	0.80	0.41	0.39	0.59	0.65	4	2	14
	EB	0.54	0.58	0.41	0.39	0.59	0.65	4	2	10
150 W	ECG	1.08	1.16	0.42	0.40	0.74	0.67	4	3	19
	EB	0.76	0.82	0.42	0.40	0.74	0.67	4	2	13
250 W	ECG	2.47	2.54	0.77	0.72	0.80	0.88	7	8	39
		2.55	2.46	0.73	0.82	0.91	0.83	8	7	39
	EB	2.01	2.12	0.87	0.81	0.79	0.83	10	10	32
		2.13	2.00	0.81	0.86	0.87	0.76	10	10	32

Table 8
The permissible number of HPS lamps with EB for single-phase circuits for a copper cable cross-section

THD_V (%)	P_{Lamp}	Number of poles n														
		10 mm^2					16 mm^2					25 mm^2				
		1%	2%	3%	4%	5%	1%	2%	3%	4%	5%	1%	2%	3%	4%	5%
0	70 W	14	21	25	30	33	18	26	32	38	42	23	33	41	48	53
	100 W	12	17	21	24	27	15	22	27	31	35	19	27	34	39	44
	150 W	10	15	18	21	24	13	19	23	27	30	16	24	29	34	38
	250 W	6	10	12	14	16	8	12	15	18	20	11	16	20	23	26
1.80	70 W	14	21	25	30	33	18	26	32	38	42	23	33	41	48	53
	100 W	12	17	21	24	27	15	22	27	31	35	19	27	34	39	44
	150 W	10	15	18	21	24	13	19	23	27	30	16	24	29	34	38
	250 W	6	10	12	14	16	8	12	15	18	20	11	16	20	23	26
2.50	70 W	14	20	25	29	33	18	26	32	38	42	23	33	41	48	53
	100 W	12	17	21	24	27	15	22	27	31	35	19	27	34	39	44
	150 W	10	15	18	21	24	13	19	23	27	30	16	24	29	34	38
	250 W	6	10	12	14	16	8	12	15	18	20	11	16	20	23	26
5.00	70 W	14	20	25	29	33	18	26	32	37	42	23	33	41	47	53
	100 W	12	17	21	24	27	15	22	27	31	35	19	27	34	39	44
	150 W	10	15	18	21	24	13	19	23	27	30	16	24	29	34	38
	250 W	6	10	12	14	16	8	12	15	18	20	11	16	20	23	26
7.50	70 W	14	20	25	29	33	18	26	32	37	42	23	33	41	47	53
	100 W	11	17	21	24	27	15	22	27	31	35	19	27	34	39	44
	150 W	10	15	18	21	24	13	19	23	27	30	16	24	29	34	38
	250 W	6	10	12	14	16	8	12	15	18	20	11	16	20	23	26

flux mainly affects the value of luminance and illumination. For the road under consideration, the reduction of luminance did not cause negative effects, i.e. the reduction of luminance below the value allowed for a given road lighting class. Otherwise, the geometrical parameters of the lighting installation should be changed, for example, the pole distance, the height, the inclination, the overhang, and the boom length.

From the obtained results, it can be concluded that for HPS lamps with EB no effect of supply voltage distortion was observed on the permissible number of luminaires. This concerns both single-phase and three-phase installations with copper and aluminium cables. The increase in the permissible percentage of active power losses from 1% to 5% results in a more than 100% increase of the luminaires number that can be installed

Table 9
The permissible number of HPS lamps with EB for single-phase circuits for an aluminum cable cross-section

THD_V (%)	P_{Lamp}	Number of poles n														
		16 mm^2					25 mm^2					35 mm^2				
		1%	2%	3%	4%	5%	1%	2%	3%	4%	5%	1%	2%	3%	4%	5%
0	70 W	14	20	25	29	32	18	26	32	37	41	21	30	37	43	49
	100 W	11	16	20	24	27	15	21	26	30	34	17	25	31	36	40
	150 W	10	14	18	21	23	13	18	23	26	30	15	22	27	31	35
	250 W	6	9	12	14	15	8	12	15	18	20	10	14	18	21	24
1.80	70 W	14	20	25	29	32	18	26	32	37	41	21	30	37	43	49
	100 W	11	16	20	24	27	15	21	26	30	34	17	25	31	36	40
	150 W	10	14	18	21	23	13	18	23	26	30	15	22	27	31	35
	250 W	6	9	12	14	15	8	12	15	18	20	10	14	18	21	24
2.50	70 W	14	20	25	29	32	18	26	32	37	41	21	30	37	43	49
	100 W	11	16	20	24	27	15	21	26	30	34	17	25	31	36	40
	150 W	10	14	18	21	23	13	18	23	26	30	15	22	27	31	35
	250 W	6	9	12	14	15	8	12	15	18	20	10	14	18	21	24
5.00	70 W	14	20	25	29	32	18	26	32	37	41	21	30	37	43	49
	100 W	11	16	20	24	27	15	21	26	30	34	17	25	31	36	40
	150 W	10	14	18	21	23	13	18	23	26	30	15	22	27	31	35
	250 W	6	9	12	14	15	8	12	15	18	20	10	14	18	21	24
7.50	70 W	14	20	25	29	32	18	25	31	36	41	21	30	37	43	48
	100 W	11	16	20	24	27	15	21	26	30	34	17	25	31	36	40
	150 W	10	14	18	21	23	13	18	23	26	30	15	22	27	31	35
	250 W	6	9	12	14	15	8	12	15	18	20	10	14	18	21	24

Table 10
The permissible number of HPS lamps with ECG for single-phase circuits for a copper cable cross-section

THD_V (%)	P_{Lamp}	Number of poles n														
		10 mm^2					16 mm^2					25 mm^2				
		1%	2%	3%	4%	5%	1%	2%	3%	4%	5%	1%	2%	3%	4%	5%
0	70 W	12	17	22	25	28	15	22	28	32	36	20	28	35	41	45
	100 W	9	14	17	20	22	12	18	22	25	29	16	23	28	32	36
	150 W	9	13	16	19	21	11	17	21	24	27	15	21	26	31	34
	250 W	5	8	10	12	13	7	10	13	15	17	9	13	17	19	22
1.80	70 W	11	17	21	24	27	15	21	26	31	34	19	27	33	39	44
	100 W	9	13	17	19	22	12	17	21	25	28	15	22	27	31	35
	150 W	8	12	15	18	20	11	16	20	23	26	14	20	25	29	33
	250 W	5	8	10	11	13	7	10	12	14	16	9	13	16	19	21
2.50	70 W	11	16	20	23	26	14	21	26	30	34	18	26	33	38	43
	100 W	9	13	16	19	21	11	17	21	24	27	15	21	26	31	34
	150 W	8	12	15	17	19	10	15	19	22	25	13	20	24	28	32
	250 W	5	7	9	11	12	6	9	12	14	16	8	12	15	18	20
5.00	70 W	9	13	17	20	22	12	17	21	25	28	15	22	27	32	36
	100 W	8	11	14	16	18	10	14	18	21	24	13	18	23	27	30
	150 W	7	10	12	14	16	9	13	16	19	21	11	16	20	24	27
	250 W	4	6	8	9	10	5	8	10	12	13	7	10	13	15	17
7.50	70 W	7	11	14	16	18	10	14	17	20	23	12	18	22	26	29
	100 W	6	9	12	14	15	8	12	15	17	20	10	15	19	22	25
	150 W	5	8	10	12	13	7	10	13	15	17	9	13	16	19	22
	250 W	3	5	6	7	8	4	6	8	9	10	5	8	10	12	14

Table 11
The permissible number of HPS lamps with ECG for single-phase circuits for aluminum cable cross-section

THD_V (%)	P_{Lamp}	Number of poles n														
		16 mm^2					25 mm^2					35 mm^2				
		1%	2%	3%	4%	5%	1%	2%	3%	4%	5%	1%	2%	3%	4%	5%
0	70 W	12	17	21	25	28	15	22	27	31	35	18	26	32	37	41
	100 W	9	13	17	19	22	12	17	21	25	28	14	21	25	30	33
	150 W	9	13	16	18	21	11	16	20	24	26	13	19	24	28	31
	250 W	5	8	10	12	13	7	10	13	15	17	8	12	15	18	20
1.80	70 W	11	16	20	23	26	14	21	26	30	34	17	25	31	35	40
	100 W	9	13	16	19	21	11	17	21	24	27	14	20	25	29	32
	150 W	8	12	15	18	20	11	15	19	22	25	13	18	23	27	30
	250 W	5	7	9	11	12	6	10	12	14	16	8	12	14	17	19
2.50	70 W	11	16	20	23	26	14	20	25	29	33	17	24	30	35	39
	100 W	9	13	16	18	21	11	16	20	24	27	13	19	24	28	31
	150 W	8	12	14	17	19	10	15	19	22	24	12	18	22	26	29
	250 W	5	7	9	11	12	6	9	12	14	15	7	11	14	16	18
5.00	70 W	9	13	16	19	21	12	17	21	24	27	14	20	25	29	32
	100 W	7	11	14	16	18	10	14	18	20	23	12	17	21	24	27
	150 W	6	10	12	14	16	8	12	15	18	20	10	15	18	21	24
	250 W	4	6	7	8	10	5	8	10	11	13	6	9	12	14	15
7.50	70 W	7	11	13	16	18	9	14	17	20	22	11	16	20	24	27
	100 W	6	9	11	13	15	8	12	15	17	19	9	14	17	20	23
	150 W	5	8	10	11	13	7	10	12	15	16	8	12	15	17	20
	250 W	3	5	6	7	8	4	6	8	9	10	5	7	9	11	12

Table 12
The permissible number of HPS lamps with EB for three-phase circuits for copper cable cross-section

THD_V (%)	P_{Lamp}	Number of poles n														
		10 mm^2					16 mm^2					25 mm^2				
		1%	2%	3%	4%	5%	1%	2%	3%	4%	5%	1%	2%	3%	4%	5%
0	70 W	36	51	63	72	81	45	66	81	93	105	57	81	102	117	132
	100 W	30	42	51	60	69	36	54	66	78	87	48	69	84	96	108
	150 W	24	36	45	51	60	33	45	57	66	75	42	60	72	84	93
	250 W	15	24	30	36	39	21	30	39	45	51	27	39	48	57	63
1.80	70 W	36	51	63	72	81	45	66	81	39	102	57	81	102	117	132
	100 W	30	42	51	60	66	36	54	66	75	87	48	69	84	96	108
	150 W	24	36	45	51	60	33	45	57	66	75	42	60	72	84	93
	250 W	15	24	30	36	39	21	30	39	45	51	27	39	48	57	63
2.50	70 W	36	51	63	72	81	45	63	78	39	102	57	81	102	117	129
	100 W	30	42	51	60	66	36	54	66	75	87	48	69	84	96	108
	150 W	24	36	45	51	60	33	45	57	66	75	42	60	72	84	93
	250 W	15	24	30	36	39	21	30	39	45	51	27	39	48	57	63
5.00	70 W	36	51	63	72	81	45	63	78	39	102	57	81	99	117	129
	100 W	30	42	51	60	66	36	54	66	75	84	48	66	84	96	108
	150 W	24	36	45	51	57	33	45	57	66	75	42	60	72	84	93
	250 W	15	24	30	36	39	21	30	39	45	51	27	39	48	57	63
7.50	70 W	36	51	63	72	81	45	63	78	90	102	57	81	99	117	129
	100 W	30	42	51	60	66	36	54	66	75	84	48	66	84	96	108
	150 W	24	36	45	51	57	33	45	57	66	75	42	60	72	84	93
	250 W	15	24	30	36	39	21	30	39	45	51	27	39	48	57	63

Table 13
The permissible number of HPS lamps with EB for three-phase circuits for an aluminum cable cross-section

THD_V (%)	P_{Lamp}	Number of poles n														
		16 mm^2					25 mm^2					35 mm^2				
		1%	2%	3%	4%	5%	1%	2%	3%	4%	5%	1%	2%	3%	4%	5%
0	70 W	33	51	60	72	81	45	63	78	90	102	51	75	93	108	120
	100 W	27	42	51	60	66	36	51	66	75	84	42	63	75	87	99
	150 W	24	36	45	51	57	33	45	57	66	72	36	54	66	78	87
	250 W	15	24	30	33	39	21	30	36	45	48	24	36	45	51	57
1.80	70 W	33	51	60	72	81	45	63	78	90	102	51	75	93	108	120
	100 W	27	42	51	60	66	36	51	63	75	84	42	63	75	87	99
	150 W	24	36	45	51	57	33	45	57	66	72	36	54	66	78	87
	250 W	15	24	30	33	39	21	30	36	45	48	24	36	45	51	57
2.50	70 W	33	51	60	72	81	45	63	78	90	102	51	75	93	105	120
	100 W	27	42	51	60	66	36	51	63	75	84	42	63	75	87	99
	150 W	24	36	45	51	57	33	45	57	66	72	36	54	66	78	87
	250 W	15	24	30	33	39	21	30	36	45	48	24	36	45	51	57
5.00	70 W	33	48	60	72	7	45	63	78	90	102	51	75	90	105	120
	100 W	27	42	51	60	66	36	51	63	75	84	42	63	75	87	99
	150 W	24	36	45	51	57	33	45	57	66	72	36	54	66	78	87
	250 W	15	24	30	33	39	21	30	36	45	48	24	36	45	51	57
7.50	70 W	33	48	60	69	78	45	63	78	90	99	51	75	90	105	120
	100 W	27	42	51	57	66	36	51	63	75	84	42	60	75	87	99
	150 W	24	36	45	51	57	33	45	57	66	72	36	54	66	75	87
	250 W	15	24	30	33	39	21	30	36	45	48	24	36	45	51	57

Table 14
The permissible number of HPS lamps with ECG for three-phase circuits for a copper cable cross-section

THD_V (%)	P_{Lamp}	Number of poles n														
		10 mm^2					16 mm^2					25 mm^2				
		1%	2%	3%	4%	5%	1%	2%	3%	4%	5%	1%	2%	3%	4%	5%
0	70 W	27	42	51	60	66	36	51	66	75	84	45	66	81	96	105
	100 W	21	33	39	45	51	27	42	51	57	66	36	51	63	75	84
	150 W	21	30	39	45	51	27	39	48	57	63	36	51	63	72	81
	250 W	12	18	24	27	33	18	24	30	36	42	21	33	39	45	51
1.80	70 W	27	39	48	57	63	33	51	60	72	81	45	63	78	90	102
	100 W	21	30	39	45	51	27	39	48	57	63	36	51	63	72	81
	150 W	21	30	36	42	48	27	36	45	54	60	33	48	60	69	78
	250 W	12	18	21	27	30	15	24	30	33	39	21	30	36	42	48
2.50	70 W	27	39	45	54	60	33	48	60	69	78	42	60	75	87	99
	100 W	21	30	36	42	48	27	39	48	54	63	33	48	60	69	78
	150 W	18	27	33	39	45	24	36	45	51	57	30	45	57	66	72
	250 W	12	18	21	24	27	15	21	27	33	36	18	27	36	42	45
5.00	70 W	21	30	36	42	48	27	39	48	54	60	33	48	60	69	78
	100 W	18	24	30	36	42	21	33	39	45	51	27	42	51	60	66
	150 W	15	21	27	33	36	18	27	36	42	45	24	36	45	51	57
	250 W	9	12	18	21	24	12	18	21	27	30	15	24	27	33	36
7.50	70 W	15	24	30	33	39	21	30	36	42	48	27	39	48	54	63
	100 W	12	21	24	30	33	18	27	33	36	42	24	33	42	48	54
	150 W	12	18	21	24	27	15	21	27	33	36	18	27	36	39	45
	250 W	6	9	12	15	18	9	12	18	21	21	12	18	21	24	30

Table 15
The permissible number of HPS lamps with ECG for three-phase circuits for an aluminum cable cross-section

THD_V (%)	P_{Lamp}	Number of poles n														
		16 mm^2					25 mm^2					35 mm^2				
		1%	2%	3%	4%	5%	1%	2%	3%	4%	5%	1%	2%	3%	4%	5%
0	70 W	27	39	51	57	66	36	51	63	72	81	42	60	75	87	96
	100 W	21	30	39	45	51	27	39	48	57	63	33	48	57	69	75
	150 W	21	30	39	45	48	27	39	48	57	63	33	45	57	66	75
	250 W	12	18	24	27	30	15	24	30	36	39	21	30	36	42	48
1.80	70 W	27	39	48	54	60	33	48	60	69	78	39	57	72	81	93
	100 W	21	30	36	45	48	27	39	48	57	63	33	45	57	66	75
	150 W	18	27	36	42	45	24	36	45	54	60	30	42	54	63	69
	250 W	12	18	21	27	30	15	24	27	33	36	21	27	33	39	45
2.50	70 W	24	36	45	54	60	33	48	57	66	75	39	57	69	78	90
	100 W	21	30	36	42	48	27	36	45	54	60	30	45	54	63	72
	150 W	18	27	33	39	45	24	36	42	51	57	27	42	52	60	66
	250 W	12	18	21	24	27	15	21	27	33	36	18	27	33	39	42
5.00	70 W	21	30	36	42	48	27	36	45	54	60	30	45	54	63	72
	100 W	15	24	30	36	39	21	30	39	45	51	27	36	45	54	60
	150 W	15	21	27	30	36	18	27	33	39	45	21	33	42	48	54
	250 W	9	12	15	18	21	12	18	21	24	27	15	21	27	30	33
7.50	70 W	15	24	27	33	36	21	30	36	42	48	24	36	42	51	57
	100 W	12	18	24	27	33	18	24	30	36	42	21	30	36	42	48
	150 W	12	15	21	24	27	15	21	27	30	36	18	24	30	36	42
	250 W	6	9	12	15	18	9	12	15	18	21	12	15	21	24	27

on one single-phase and three-phase circuit. For a single-phase installation, the smallest increase in the permissible number of lamps was found for lamps of 100 W with EB and a circuit made with a 10 mm^2 copper cable. The increase was 125%, i.e. the number of luminaires can be increased from 12 to 27 units. The highest increase in the permissible number of lamps was observed for a 250 W lamp with EB also for a circuit made with a 10 mm^2 copper cable. The number of luminaires can be increased from 6 to 16, an increase of 167%. In a three-phase installation, increasing the permissible percentage of active power losses (from 1% to 5%) also increases the permissible number of lamps supplied from one circuit. The largest increases in the lamp number that can be supplied from one circuit were found for 250 W lamps with EB and circuits made with 10 mm^2 copper cable and 16 mm^2 aluminium cable. In these cases, the number of lamps can be increased from 15 to 39 (160% increase).

In the case of HPS lamps with ECG, the influence of the distortion level of the supply voltage on the permissible number of lamps can be observed. For permissible active power losses equal to 1% in a single-phase circuit and with an increase of THD_V from 0 to 7.50%, the number of luminaires that can be supplied from a single circuit has decreased on average by 39%. Considering the variant where the permissible active power loss is 5%, the number of luminaires decreased on average by 36%. The greatest decrease in the permissible number of HPS lamps with ECG was found for a 250 W lamp, with the permissible active power losses equal to 1% and a copper cable of 25 mm^2 cross-section. The number of lamps has been reduced by 44% from 9 to 4. The smallest reduction in the lamp number caused by an increase in THD_V occurred for a 100 W lamp, with the permissible power losses value equal to 5% and an aluminium cable with a cross-section of 35 mm^2. The number of lamps has decreased from 33 for $THD_V = 0\%$ to 23 for $THD_V = 7.50\%$. This is a 30% reduction. By increasing the permissible value of power losses, the permissible number of lamps (luminaires) increases. In the case of 250 W luminaire with ECG and single-phase circuit, the largest increase in the lamp number occurred for 25 mm^2 copper cable and reached 180%. The number of lamps has increased from 5 to 14. The smallest increase in the permissible lamp number was observed in several cases: for 100 W lamp with ECG $THD_V = 5\%$ and 10 mm^2 copper cable and $THD_V = 0\%$ and 25 mm^2 copper cable, 70 W and $THD_V = 0\%$, 5.00% lamps and 25 mm^2 copper and aluminium cables, respectively. The percentage increased to 125%.

In a three-phase circuit, as one might expect, it is possible to supply a much larger number of lamps from one circuit. For a copper cable with a cross-section of 25 mm^2 and a sinusoidal voltage supply, the maximum number of lamps that can be supplied from one circuit at the active power losses of 5% is 105 (for a single-phase installation it is 45 lamps). Analyzing the obtained results for a 250 W lamp with ECG (three-phase circuit), it can be concluded that for this circuit the greatest reduction in the lamp number due to an increase in THD_V occurred.

Increasing THD_V from 0 to 7.50% caused a reduction in the lamp number by up to 50%. This decrease was observed for a copper cable with a cross-section of 10 mm^2 and 16 mm^2, aluminium cable 16 mm^2, and the permissible value of active power loss of 1%. The smallest reduction in the lamp number, only by 33%, was found for 100 W luminaire, 16 mm^2 copper cables, and 25 mm^2 for the permissible active power losses of 1%, and 25 mm^2 aluminium cable for the permissible active power losses of 1% and 5%. To conclude, it can be stated that on average for all tested cases of HPS lamps with ECG, there was an increase in THD_V results with a 42% decrease in the permissible lamp number. The biggest and the smallest increase in the permissible lamp numbers supplied from one circuit occurred for a 250 W lamp with an increase in the permissible active power losses from 1% to 5%. For $THD_V = 7.50\%$, the number of lamps has increased from 6 to 18, an increase of 200%. Such a case occurred for copper and aluminium cables of 10 mm^2 and 16 mm^2 cross-section, respectively. The smallest increase in the number of luminaires was observed for $THD_V = 7.50\%$ and 35 mm^2 aluminium cable. It amounted to 114% only.

3.4. Case study: calculation of active power losses, energy performance indicators, energy, electricity costs, and CO$_2$ emission of road lighting installation. To fully compare the road lighting installations with luminaires for HPS lamps with ECG and EB, the energy performance indicators according to EN 13201-5 [57], the electricity consumption costs, and CO$_2$ emissions must be additionally calculated. The calculation of energy performance indicators: the power density indicator (PDI) D_P and the annual electricity consumption indicator (AECI) D_E shall be made for the installation to be lit in a given area. The calculation of these indicators also requires knowledge of the horizontal average illuminance of the road. The illumination value can be calculated, for example, by using DIALux at the design calculation stage. The calculation of the active power losses requires, as written before, knowledge about the length, the cross-section, and the material of the cable. In the analyzed case it has been assumed that the road lighting installation is made with an aluminium cable with a cross-section of 25 mm^2. This assumption applies to both single-phase and three-phase installations. It was assumed that the active power losses in the most unfavorable case (i.e. for $THD_V = 7.50\%$ and lamps with ECG) cannot exceed 5%. The values of the permissible number of luminaires (lamps) for the adopted assumption were read in Tables 10 and 14. For a single-phase installation, the following number of luminaires was assumed: 70 W – 22 luminaires, 100 W – 19 luminaires, 150 W – 16 luminaires, and 250 W – 10 luminaires. For a three-phase installation, these are the following values: 70 W – 48 luminaires, 100 W – 42 luminaires, 150 W – 36 luminaires, 250 W – 21 luminaires. Table 6 lists the parameters of the lighting installations under consideration, including the number of luminaires and areas to be lit. Table 7 shows the average illuminance values used to calculate energy performance indicators calculated in the DIALux program. For installations with 250 W lamps, only one carriageway was analyzed. The results of the calculations are presented in Tables 16–19.

Energy performance indicators are calculated only based on the active power of the road lighting installation. It is calculated as the sum of the active power of luminaires and the sum of the power of the other devices necessary for the operation of the installation. During the calculations, it was assumed that the power of the lighting system is equal to the sum of the luminaire power. The power of other devices related to the operation of the road lighting installation under consideration was omitted. The calculation of the AECI also requires the knowledge of the illumination time. The calculations assume an annual illumination time equal to 3950 h. It is a calculated average annual time of illumination based on the astronomical calendar taking into account the hours of sunrises and sunsets for the geographical location of Poland. The active energy price of 0.1194 € for 1 kWh was adopted for the calculation. This is the average price for customers non-residential in the EU based on [58]. In Poland, the guidelines contained in [59] are used to calculate CO$_2$ emissions. The generation of 1 kWh of energy is accompanied by the emission of 0.781 kg of CO$_2$. This value of 1 kWh per kg of CO$_2$ has been assumed in the calculation. The calculated costs of electricity consumption for a road lighting installation with HPS lamps with EB and ECG are shown in Tables 17 and 19, respectively. In addition, the aforementioned tables show the calculated values of CO$_2$ emitted to the atmosphere.

Analyzing the obtained results, it can be observed that an installation with HPS lamps equipped with electronic ballasts is less sensitive to the supply voltage distortion changing within the assumed range than the installation with HPS lamps equipped with ECG. For a single-phase installation with 70 W lamps with ECG, the active power losses are equal to 42 W for the sinusoidal voltage supply. If the lighting installation is supplied by non-sinusoidal voltage, active power losses increase to 96 W. Thus, in this case, the active power losses are comparable to the power of a single luminaire. An increase in the supply voltage distortion level results in an unnecessary increase in electricity consumption of 216 kWh/year. This generates the annual costs of 25 € and produces 168 kg of CO$_2$ emissions in the atmosphere. For a single-phase installation equipped with luminaires for 250 W HPS lamps with ECG, the active power losses equal 52 W for the supply of sinusoidal voltage and increase to 126 W for the variant with $THD_V = 7.50\%$. Changing the power supply conditions causes the power losses to more than double only due to the supply voltage distortion. In the cost of electricity consumption, there is an additional unjustified cost of 32 € and an additional 248 kg of CO$_2$ emitted into the atmosphere. The level of the supply voltage distortion slightly affects the PDI and AECI energy performance indicators. A slight increase in the value of these indicators can be observed as the supply voltage distortion level increases. It should be remembered here that their value per unit of area to be lit is determined. For a single-phase installation with HPS 70 W lamps equipped with EB, the active power losses are 21.98 W for sinusoidal voltage supply and increase slightly to 22.30 W (for $THD_V = 7.50\%$). Such a slight difference between these values increases the electricity consumption of only 1.24 kWh. The difference between the

Table 16
Installed power, active power losses, and energy performance indicators for a single-phase installation

THD_V (%)	Lamp	$P^{1P(\mathrm{EB})_I}$ (W)	$\Delta P^{1P(\mathrm{EB})_T}$ (W)	$P^{1P(\mathrm{ECG})_I}$ (W)	$\Delta P^{1P(\mathrm{ECG})_T}$ (W)	$D^{1P(\mathrm{EB})_P}$ ($\mathrm{W \cdot lx^{-1} \cdot m^{-2}}$)	$D^{1P(\mathrm{EB})_{P(\Delta P)}}$ ($\mathrm{W \cdot lx^{-1} \cdot m^{-2}}$)	$D^{1P(\mathrm{ECG})_P}$ ($\mathrm{W \cdot lx^{-1} \cdot m^{-2}}$)	$D^{1P(\mathrm{ECG})_{P(\Delta P)}}$ ($\mathrm{W \cdot lx^{-1} \cdot m^{-2}}$)	$D^{1P(\mathrm{EB})_E}$ ($\mathrm{W \cdot lx^{-1} \cdot m^{-2}}$)	$D^{1P(\mathrm{EB})_{E(\Delta P)}}$ ($\mathrm{W \cdot lx^{-1} \cdot m^{-2}}$)	$D^{1P(\mathrm{ECG})_E}$ ($\mathrm{W \cdot lx^{-1} \cdot m^{-2}}$)	$D^{1P(\mathrm{ECG})_{E(\Delta P)}}$ ($\mathrm{W \cdot lx^{-1} \cdot m^{-2}}$)	$E^{1P(\mathrm{EB})_I}$ (kWh)	$\Delta E^{1P(\mathrm{EB})_T}$ (kWh)	$E^{1P(\mathrm{ECG})_I}$ (kWh)	$\Delta E^{1P(\mathrm{ECG})_T}$ (kWh)
0	70 W	1534.24	21.98	2122.27	41.54	39.85	40.42	55.12	56.20	1.57	1.60	2.18	2.22	6060.23	86.84	8382.98	164.10
	100 W	1751.21	27.38	2445.87	55.70	47.03	47.76	46.91	47.98	1.86	1.89	2.59	2.65	6917.28	108.16	9661.19	220.00
	150 W	2215.04	32.74	2615.04	47.88	60.85	61.75	49.15	50.05	3.12	3.17	3.69	3.76	8749.41	129.31	10329.41	189.13
	250 W	2225.60	28.89	2941.00	52.30	30.11	30.50	32.65	33.23	3.81	3.86	5.03	5.12	8791.12	114.11	11616.95	206.57
1.80	70 W	1533.05	21.99	2115.70	44.99	39.82	40.39	54.95	56.12	1.57	1.60	2.17	2.22	6055.54	86.85	8357.00	177.71
	100 W	1750.58	27.38	2436.18	58.50	47.01	47.74	46.73	47.85	1.86	1.89	2.58	2.65	6914.81	108.16	9622.91	231.09
	150 W	2214.08	32.79	2612.64	52.27	60.83	61.73	49.11	50.09	3.12	3.17	3.69	3.76	8745.62	129.52	10319.93	206.47
	250 W	2225.00	28.88	2930.10	57.24	30.10	30.49	32.52	33.16	3.80	3.85	5.01	5.11	8788.75	114.07	11573.90	226.12
2.50	70 W	1533.80	22.03	2116.14	47.01	39.84	40.41	54.96	56.19	1.57	1.60	2.17	2.22	6058.49	87.01	8358.74	185.69
	100 W	1750.07	27.38	2431.05	61.44	46.99	47.73	46.63	47.81	1.86	1.89	2.58	2.64	6912.78	108.16	9602.65	242.68
	150 W	2213.12	32.77	2612.32	56.17	60.80	61.70	49.10	50.16	3.12	3.17	3.69	3.76	8741.82	129.45	10318.66	221.88
	250 W	2223.80	28.85	2924.30	61.18	30.10	30.49	32.52	33.16	3.80	3.85	5.01	5.11	8784.01	113.96	11550.99	241.66
5.00	70 W	1533.40	22.11	2103.31	66.30	39.83	40.40	54.63	56.35	1.57	1.60	2.16	2.23	6056.93	87.32	8308.07	261.89
	100 W	1749.81	27.44	2412.43	79.94	46.99	47.72	46.27	47.81	1.86	1.89	2.56	2.64	6911.73	108.39	9529.10	315.74
	150 W	2212.96	32.79	2602.88	78.13	60.80	61.70	48.93	50.39	3.12	3.17	3.67	3.78	8741.19	129.53	10281.38	308.62
	250 W	2223.60	28.85	2899.60	84.82	30.08	30.47	32.19	33.13	3.80	3.85	4.96	5.10	8783.22	113.98	11453.42	335.02
7.50	70 W	1534.32	22.30	2086.96	96.25	39.85	40.43	54.21	56.71	1.57	1.60	2.14	2.24	6060.58	88.08	8243.51	380.18
	100 W	1750.74	27.58	2391.34	111.66	47.01	47.75	45.87	48.01	1.86	1.89	2.54	2.65	6915.41	108.94	9445.79	441.08
	150 W	2212.96	32.82	2589.92	115.34	60.80	61.70	48.68	50.85	3.12	3.17	3.65	3.82	8741.19	129.63	10230.18	455.59
	250 W	2222.60	28.85	2874.30	125.55	30.07	30.46	31.90	33.30	3.80	3.85	4.91	5.13	8779.27	113.96	11353.49	495.91

Table 17

Annual costs and CO_2 emissions for a single-phase installation

THD_V (%)	Lamp	$C^{1P(\text{EB})_I}$ (EUR)	$\Delta C^{1P(\text{EB})_T}$ (EUR)	$C^{1P(\text{ECG}_I}$ (EUR)	$\Delta C^{1P(\text{ECG}_T}$ (EUR)	$C^{1P(\text{EB})_{I(\Delta P)}}$ (EUR)	$C^{1P(\text{ECG}_{I(\Delta P)}}$ (EUR)	$CO_2{}^{1P(\text{EB})_I}$ (kg)	$CO_2{}^{1P(\text{EB})_{\Delta P}}$ (kg)	$CO_2{}^{1P(\text{ECG}_I}$ (kg)	$CO_2{}^{1P(\text{ECG}_{\Delta P}}$ (kg)	$CO_2{}^{1P(\text{EB})_{I(\Delta P)}}$ (kg)	$CO_2{}^{1P(\text{ECG}_{I(\Delta P)}}$ (kg)
0	70 W	723.59	10.37	1000.93	19.59	733.96	1020.52	4733.04	67.82	6547.11	128.16	4800.86	6675.27
	100 W	825.92	12.91	1153.55	26.27	838.84	1179.81	5402.40	84.48	7545.39	171.82	5486.87	7717.21
	150 W	1044.68	15.44	1233.33	22.58	1060.12	1255.91	6833.29	100.99	8067.27	147.71	6934.28	8214.98
	250 W	1049.66	13.63	1387.06	24.66	1063.28	1411.73	6865.86	89.12	9072.84	161.33	6954.99	9234.17
1.80	70 W	723.03	10.37	997.83	21.22	733.40	1019.04	4729.38	67.83	6526.82	138.79	4797.20	6665.60
	100 W	825.63	12.91	1148.98	27.59	838.54	1176.57	5400.46	84.48	7515.49	180.48	5484.94	7695.97
	150 W	1044.23	15.46	1232.20	24.65	1059.69	1256.85	6830.33	101.15	8059.86	161.25	6931.48	8221.12
	250 W	1049.38	13.62	1381.92	27.00	1063.00	1408.92	6864.01	89.09	9039.21	176.60	6953.10	9215.81
2.50	70 W	723.38	10.39	998.03	22.17	733.77	1020.20	4731.68	67.96	6528.17	145.03	4799.64	6673.20
	100 W	825.39	12.91	1146.56	28.98	838.30	1175.53	5398.88	84.47	7499.67	189.53	5483.36	7689.20
	150 W	1043.77	15.46	1232.05	26.49	1059.23	1258.54	6827.36	101.10	8058.88	173.29	6928.46	8232.16
	250 W	1048.81	13.61	1379.19	28.85	1062.42	1408.04	6860.31	89.00	9021.32	188.74	6949.32	9210.06
5.00	70 W	723.20	10.43	991.98	31.27	733.62	1023.25	4730.46	68.20	6488.61	204.54	4798.66	6693.14
	100 W	825.26	12.94	1137.77	37.70	838.20	825.26	5398.06	84.66	7442.23	246.60	5482.72	7688.82
	150 W	1043.70	15.47	1227.60	36.85	1059.16	1264.45	6826.87	101.16	8029.75	241.03	6928.03	8270.78
	250 W	1048.72	13.61	1367.54	40.00	1062.33	1407.54	6859.69	89.02	8945.12	261.65	6948.71	9206.77
7.50	70 W	723.63	10.52	984.27	45.39	734.15	1029.67	4733.31	68.79	6438.18	296.92	4802.10	6735.10
	100 W	825.70	13.01	1127.83	52.66	838.71	825.70	5400.93	85.08	7377.16	344.48	5486.02	7721.65
	150 W	1043.70	15.48	1221.48	54.40	1059.18	1275.88	6826.87	101.24	7989.77	355.81	6928.11	8345.59
	250 W	1048.24	13.61	1355.61	59.21	1061.85	1414.82	6856.61	89.00	8867.07	387.30	6945.61	9254.38

Table 18

Installed power, active power losses, and energy performance indicators for a three-phase installation

THD_V (%)	Lamp	$P^{3P(\text{EB})_I}$ (W)	$\Delta P^{3P(\text{EB})_T}$ (W)	$P^{3P(\text{ECG})_I}$ (W)	$\Delta P^{3P(\text{ECG})_T}$ (W)	$D^{3P(\text{EB})_P}$ ($\text{W}\cdot\text{lx}^{-1}\cdot\text{m}^{-2}$)	$D^{3P(\text{EB})_{P(\Delta P)}}$ ($\text{W}\cdot\text{lx}^{-1}\cdot\text{m}^{-2}$)	$D^{3P(\text{ECG})_P}$ ($\text{W}\cdot\text{lx}^{-1}\cdot\text{m}^{-2}$)	$D^{3P(\text{ECG})_{P(\Delta P)}}$ ($\text{W}\cdot\text{lx}^{-1}\cdot\text{m}^{-2}$)	$D^{3P(\text{EB})_E}$ ($\text{W}\cdot\text{lx}^{-1}\cdot\text{m}^{-2}$)	$D^{3P(\text{EB})_{E(\Delta P)}}$ ($\text{W}\cdot\text{lx}^{-1}\cdot\text{m}^{-2}$)	$D^{3P(\text{ECG})_E}$ ($\text{W}\cdot\text{lx}^{-1}\cdot\text{m}^{-2}$)	$D^{3P(\text{ECG})_{E(\Delta P)}}$ ($\text{W}\cdot\text{lx}^{-1}\cdot\text{m}^{-2}$)	$E^{3P(\text{EB})_I}$ (kWh)	$\Delta E^{3P(\text{EB})_T}$ (kWh)	$E^{3P(\text{ECG})_I}$ (kWh)	$\Delta E^{3P(\text{ECG})_T}$ (kWh)
0	70 W	3347.42	37.12	4630.42	77.23	39.85	40.29	42.40	56.04	1.57	1.59	2.18	2.21	13222.32	146.62	18290.14	305.05
	100 W	3871.10	47.67	5406.66	112.24	47.03	47.60	46.91	47.89	1.86	1.88	2.59	2.65	15290.84	188.28	21356.31	443.34
	150 W	4983.84	59.55	5883.84	94.18	60.85	61.58	49.15	49.94	3.12	3.16	3.69	3.75	19686.17	235.21	23241.17	372.00
	250 W	4673.76	42.47	6176.10	83.66	30.11	30.38	32.65	33.09	3.81	3.84	5.03	5.10	18461.35	167.74	24395.60	330.46
1.80	70 W	3344.83	37.20	4616.06	85.10	39.82	40.26	42.27	55.97	1.57	1.59	2.17	2.21	13212.09	146.93	18233.45	336.13
	100 W	3869.71	47.74	5385.24	117.53	47.01	47.59	46.73	47.75	1.86	1.88	2.58	2.64	15285.36	188.59	21271.70	464.24
	150 W	4981.68	59.70	5878.44	105.47	60.83	61.56	49.11	49.99	3.12	3.16	3.69	3.75	19677.64	235.82	23219.84	416.61
	250 W	4672.50	42.45	6153.21	93.69	30.10	30.37	32.52	33.02	3.80	3.84	5.01	5.09	18456.38	167.66	24305.18	370.08
2.50	70 W	3346.46	37.32	4617.02	90.92	39.84	40.28	42.28	56.05	1.57	1.59	2.17	2.21	13218.53	147.40	18237.24	359.12
	100 W	3868.58	47.78	5373.90	124.83	46.99	47.57	46.63	47.71	1.86	1.88	2.58	2.64	15280.88	188.75	21226.91	493.07
	150 W	4979.52	59.70	5877.72	116.35	60.80	61.53	49.10	50.08	3.12	3.16	3.69	3.76	19669.10	235.81	23216.99	459.58
	250 W	4669.98	42.41	6141.03	101.98	30.08	30.36	32.46	33.00	3.80	3.84	5.00	5.08	18446.42	167.53	24257.07	402.81
5.00	70 W	3345.60	37.69	4589.04	140.43	39.83	40.28	42.02	56.30	1.57	1.59	2.16	2.22	13215.12	148.87	18126.71	554.70
	100 W	3867.99	48.08	5332.74	173.47	46.99	47.57	46.27	47.78	1.86	1.88	2.56	2.64	15278.56	189.92	21064.32	685.20
	150 W	4979.16	59.89	5856.48	178.64	60.80	61.53	48.93	50.42	3.12	3.16	3.67	3.78	19667.68	236.58	23133.10	705.61
	250 W	4669.56	42.45	6089.16	154.32	30.08	30.35	32.19	33.00	3.80	3.84	4.96	5.08	18444.76	167.67	24052.18	609.58
7.50	70 W	3347.62	38.36	4553.38	219.64	39.85	40.31	41.70	56.82	1.57	1.59	2.14	2.24	13223.08	151.50	17985.84	867.59
	100 W	3870.05	48.55	5286.12	259.45	47.01	47.60	45.87	48.12	1.86	1.88	2.54	2.66	15286.69	191.77	20880.17	1024.83
	150 W	4979.16	60.15	5827.32	286.73	60.80	61.53	48.68	51.08	3.12	3.16	3.65	3.83	19667.68	237.58	23017.91	1132.57
	250 W	4667.46	42.54	6036.03	246.81	30.07	30.34	31.90	33.21	3.80	3.84	4.91	5.12	18436.47	168.02	23842.32	974.89

Table 19

Annual costs and CO_2 emissions for a three-phase installation

THD_V	Lamp	$C^{3P(\mathrm{EB})_I}$ (EUR)	$\Delta C^{3P(\mathrm{EB})_T}$ (EUR)	$C^{3P(\mathrm{ECG})_I}$ (EUR)	$\Delta C^{3P(\mathrm{ECG})_T}$ (EUR)	$C^{3P(\mathrm{EB})_{I(\Delta P)}}$ (EUR)	$C^{3P(\mathrm{ECG})_{I(\Delta P)}}$ (EUR)	$\mathrm{CO_2}^{3P(\mathrm{EB})_I}$ (EUR)	$\mathrm{CO_2}^{3P(\mathrm{EB})_{\Delta P}}$ (EUR)	$\mathrm{CO_2}^{3P(\mathrm{ECG})_I}$ (EUR)	$\mathrm{CO_2}^{3P(\mathrm{ECG})_{\Delta P}}$ (EUR)	$\mathrm{CO_2}^{3P(\mathrm{EB})_{I(\Delta P)}}$ (EUR)	$\mathrm{CO_2}^{3P(\mathrm{ECG})_{I(\Delta P)}}$ (EUR)
0	70 W	1578.75	17.51	2183.84	36.42	1596.25	2220.27	16929.99	187.73	23418.88	390.59	17117.73	23809.47
	100 W	1825.73	22.48	2549.94	52.94	1848.21	2602.88	19578.54	241.07	27344.82	567.66	19819.61	27912.48
	150 W	2350.53	28.08	2775.00	44.42	2378.61	2819.41	25206.36	301.16	29758.22	476.31	25507.53	30234.53
	250 W	2204.29	20.03	2912.83	39.46	2224.31	2952.29	23638.09	214.77	31236.36	423.13	23852.87	31659.49
1.80	70 W	1577.52	17.54	2177.07	40.13	1595.07	2217.21	16916.88	188.13	23346.29	430.39	17105.01	23776.68
	100 W	1825.07	22.52	2539.84	55.43	1847.59	2595.27	19571.53	241.48	27236.49	594.42	19813.00	27830.91
	150 W	2349.51	28.16	2772.45	49.74	2377.67	2822.19	25195.44	301.95	29730.91	533.43	25497.38	30264.33
	250 W	2203.69	20.02	2902.04	44.19	2223.71	2946.23	23631.72	214.68	31120.59	473.85	23846.40	31594.44
2.50	70 W	1578.29	17.60	2177.53	42.88	1595.89	2220.41	16925.14	188.73	23351.15	459.83	17113.87	23810.97
	100 W	1824.54	22.54	2534.49	58.87	1847.07	2593.37	19565.79	241.67	27179.14	631.33	19807.46	27810.47
	150 W	2348.49	28.16	2772.11	54.87	2376.65	2826.98	25184.51	301.93	29727.27	588.45	25486.44	30315.71
	250 W	2202.50	20.00	2896.29	48.10	2222.51	2944.39	23618.98	214.51	31058.99	515.76	23833.48	31574.75
5.00	70 W	1577.89	17.77	2164.33	66.23	1595.66	2230.56	16920.77	190.61	23209.61	710.25	17111.38	23919.86
	100 W	1824.26	22.68	2515.08	81.81	1846.94	2596.89	19562.82	243.18	26970.96	877.34	19806.00	27848.30
	150 W	2348.32	28.25	2762.09	84.25	2376.57	2846.34	25182.69	302.92	29619.84	903.47	25485.61	30523.31
	250 W	2202.30	20.02	2871.83	72.78	2222.32	2944.61	23616.85	214.69	30796.65	780.52	23831.54	31577.16
7.50	70 W	1578.84	18.09	2147.51	103.59	1596.93	2251.10	16930.96	193.99	23029.24	1110.87	17124.95	24140.11
	100 W	1825.23	22.90	2493.09	122.36	1848.13	2615.46	19573.23	245.54	26735.18	1312.20	19818.77	28047.38
	150 W	2348.32	28.37	2748.34	135.23	2376.69	2883.57	25182.69	304.20	29472.36	1450.15	25486.89	30922.51
	250 W	2201.31	20.06	2846.77	116.40	2221.38	2963.17	23606.23	215.13	30527.94	1248.25	23821.36	31776.19

electricity costs is therefore small. Immunity against the supply voltage distortion of electronic ballasts is their undoubted advantage over ECG.

For example, for a three-phase installation equipped with 70 W HPS lamps with ECG, the active power losses are equal to 77.23 W for the sinusoidal voltage supply and increase to 219.64 W for the $THD_V = 7.50\%$ supply voltage. The increase of power losses resulting from the change in power supply conditions is more than triple. When comparing the results obtained for single-phase and three-phase installations, it is important to remember the assumptions made and the different number of light points (luminaires) in both cases. An increase in the voltage distortion level causes an unjustified increase in the annual electricity consumption by 562 kWh. This situation consequently increases the cost of electricity consumption by 68 € and has the unwanted environmental effect of 720 kg of CO_2 emissions. When the magnetic ballast is replaced by electronic ballast, the active power losses are 37.12 W (for $THD_V = 0\%$) and increase to 38.36 W ($THD_V = 7.50\%$) only. It can be stated that even in this case the voltage distortion does not affect the value of active power losses.

For a three-phase installation equipped with 250 W lamps with ECG, the estimated active power losses are 84 W when supplied with sinusoidal voltage and increase up to 247 W. This is the reason for the electricity consumption increase of 289 kWh/year. The additional costs of electricity consumption and the adverse environmental effects are a consequence of this. The increase of the active power losses resulting from the change of the supply voltage distortion level is compared to the power of a single luminaire. With a distorted supply voltage, the installation generates such costs and environmental effects as if it were equipped with an additional lighting point. As for the 70 W lamp, it is worth using electronic ballasts instead of ECG in terms of costs and environmental impact.

4. Conclusion

The article aimed to compare the energy efficiency of lighting installation with HPS lamps equipped with electromagnetic control gear and electronic ballasts supplied with sinusoidal and non-sinusoidal voltage. Replacing ECG with EB should improve the lighting quality, the energy efficiency, reduce the electricity costs and greenhouse gas emissions. However, when exchanging ECGs for EB on a one-to-one basis, several important aspects need to be taken into account. The new technology should meet or exceed the performance of the existing technology, including the lighting quality, and reduce the power and costs.

The article presents the results of the performance comparison of HPS lamps with electromagnetic control gear and electronic ballasts under the sinusoidal and the non-sinusoidal supply condition. The electrical, photometric, and colorimetric parameters of HPS lamps with power ratings of 70 W, 100 W, 150 W, and 250 W were measured and analyzed.

To accurately analyse the influence of the distortion supply voltage on electrical parameters, additional parameters have been calculated following the relations presented in the IEEE Std. 1459-2010. Moreover, the permissible number of luminaires for single-phase and three-phase installations made from aluminium and copper cables for the most frequently used in practice cross-sectional values were calculated due to the permissible value of active power losses in the power cable. The calculations consider the influence of harmonic currents flow on the value of power cable resistance and active power losses. The calculations of energy performance indicators, electricity consumption and costs, and CO_2 emissions were also made for exemplary road lighting installations.

These calculations were made for a single-phase and three-phase installation with an assumed number of luminaires for all analyzed distortion levels of the supply voltage. There is no such comprehensive analysis of HPS lamps with ECG and EB made for different power supply conditions found in the literature. The presented results and method of calculations can be useful in the technical and economic analysis of the advisability of exchanging ECGs and replacing their EB.

The research results can be summarised as follows. Luminaires equipped with magnetic ballasts for sodium lamps are sensitive to the quality of the supply voltage. An increase in the voltage distortion level causes an increase in the active power losses and energy losses in a lighting installation equipped with such luminaires. Luminaires equipped with electronic ballasts as opposed to luminaires with magnetic ballasts are practically immune to the electrical power quality. The decision to modernize the road lighting installation by replacing ballasts should be preceded by a thorough technical and economic analysis and in particular, by a comparison of investment and operating costs of both solutions.

In the case of magnetic ballasts, the results obtained are representative of other ballasts of this type available on the market. For electronic ballasts, the situation is slightly more complicated. Unlike their magnetic counterparts, they can differ in design, although the principle of operation remains the same. In their case, as in the case of LED power supplies, the generalization of results may apply to devices of similar design. Devices of similar construction will have a similar effect on the supply network, although the spectrum of higher harmonics may be different. However, there may be non-standard solutions, which should be considered individually.

REFERENCES

[1] A. Mayeur, R. Bremond, and J.M.Ch. Bastien, “The effect of the driving activity on target detection as a function of the visibility level: implications for road lighting”, *Transp. Res.* 13(2), 115–128 (2010).
[2] Ch. Boomsma and L. Steg, “The effect of information and values on acceptability of reduced street lighting“, *J. Environ. Psychol.* 39, 22–31 (2014).
[3] A. Pena-Garcia, A. Hurtado, and M.C. Aguilar-Luzon, “Impact of public lighting on pedestrians’ perception of safety and well-being”, *Saf. Sci.* 78, 142–148 (2015).
[4] J.D. Bullough, E.T. Donnell, and M.S. Rea, “To illuminate or not to illuminate: roadway lighting as it affects traffic safety at intersections”, *Accid. Anal. Prev.* 53, 65–77 (2013).

[5] A. Jafari-Anarkooli and M. Hadji Hosseinlou, “Analysis of the injury severity of crashes by considering different lighting conditions on two-lane rural roads”, *J. Saf. Res.* 56, 57–65 (2016).

[6] M. Jackett and W. Frith, “Quantifying the impact of road lighting on road safety-a New Zealand study”, *IATSS Res.* 36, 139–145 (2013).

[7] K. Kircher and Ch. Ahlstrom, “The impact of tunnel design and lighting on the performance of attentive and visually distracted drivers”, *Accid. Anal. Prev.* 47, 153–161 (2012).

[8] M. Kostic and L. Djokic, “Recommendation for energy efficient and visually acceptable street lighting”, *Energy* 34, 1565–1572 (2009).

[9] D. Campisi, S. Gitto, and D. Morea, “Economic feasibility of energy improvements in street lighting systems in Rome”, *J. Clean. Prod.* 175, 190–198 (2018).

[10] S. Yoomak and A. Ngaopitakkul, “Optimisation of quality and energy efficiency of LED luminaires in roadway lighting systems on different road surfaces”, *Sustain. Cities Soc.* 38, 333–347 (2018).

[11] F. Lecce, G. Salvadoni, and M. Rocca, “Critical analysis of the energy performance indicators for road lighting systems in historical towns of central Italy”, *Energy* 138, 616–628 (2017).

[12] M. Beccali, M. Bonomolo, F. Leccese, D. Lista,, and G. Salvadoni, “On the impact of safety requirements , energy prices and investment costs in street lighting refurbishment design”, *Energy* 165, 739–759 (2018).

[13] P. Pracki, A. Wiśniewski, D. Czyżewski, R. Krupiński, K. Skarżyński, M. Wesołowski, and A. Czaplicki, “Strategies influencing energy efficiency of lighting solutions”, *Bull. Pol. Acad. Sci. Tech. Sci.* 68(4), 711–719 (2020).

[14] P.R. Boyce, S. Fotios, and M. Richards, “Road lighting and energy savings”, *Lighting Res. Technol*. 41, 245–260 (2009).

[15] C.C.M. Kyba, A. Hänel, and F. Hölker, “Redefining efficiency for outdoor lighting”, *Energy Environ. Sci*. 7, 1806–1814 (2014).

[16] M. Beccali, M. Bonomolo, G. Ciulla, A. Galatioto, and V. Lo Brano, “Improvement of energy efficiency and quality of street light-ing in South Italy as an action of Sustainable Energy Action Plans. The case study of Comiso (RG)”, *Energy* 92(3), 394–408 (2015).

[17] A. Wiśniewski, “Calculations of energy savings using lighting control systems ”, *Bull. Pol. Acad. Sci. Tech. Sci.* 68(4), 809–817 (2020).

[18] M. IndraalIrsyad and N. Rabindra, “A survey based approach to estimating the benefits of energy efficiency improvements in street lighting systems in Indonesia”, *Renew. Sust. Energ. Rev.* 58, 1569–1577 (2016).

[19] S. Pizzuti, M. Annunziato, and F. Moretti, “Smart street lighting management”, *Energy Effic.* 6, 607–616 (2013).

[20] D. Radulovic, S. Skok, and V. Kirincic, “Energy Effic. public lighting management in the cities”, *Energy* 36, 1908–1915 (2011).

[21] A. Djuretic and M. Kostic, “Comparison of electronic and conventional ballasts used in roadway lighting”, *Light. Res. Technol.* 46, 407–420 (2014).

[22] S. Yoomak, Ch. Jettansen, and S. Ngaopitakkul Bunjongjit, “Comparative study of lighting quality and power quality for LED and HPS luminaires in a roadway lighting system”, *Energy Build.* 159, 542–557 (2018).

[23] M.H. Omar, H. Abdul Rahman, M.S. Majid, M.Y. Hassan, and N. Rosmin, “The reduction of total harmonic distortion and electromagnetic interference in high pressure sodium street lighting using single stage electronic ballast”, *IEEE International Power Engineering and Optimization Conference (PEOCO)* 2012, pp. 230–235.

[24] A.A. Mansour and O.A. Arafa, “Comparative study of 250 W high pressure sodium lamp operating from both conventional and electronic ballast”, *J. Electr. Syst. Inf. Technol*. 1, 234–254 (2014).

[25] W. Nsibi, M. Nehdi, A.J. Chammam, A. Sellami, and G. Zissis, “Dimmable electronic ballast for HPS lamp operating in LF”, *7th International Renewable Energy Congress (IREC)*, Hammamet, Tunisia, 2016, pp. 1–4.

[26] M.N. Nehdi, W. Nsibi, A. Chammam, A. Sellami, and G. Zissis, “Frequency dimmable electronic ballast for a 250W HPS lamp”, *7th International Renewable Energy Congress (IREC)*, Hammamet, 2016, pp. 1–3.

[27] R. Sikora and P. Markiewicz, “Assessment of Colorimetric Parameters for HPS Lamp with Electromagnetic Control Gear and Electronic Ballast”, *Energies*, 13(11), 2909 (2020), doi: 10.3390/en13112909.

[28] F.B. dos Reis, J. Cesar Marques de Lima, and F.S. dos Reis, “Development of a flexible public lighting system”, *39th Annual Conference of the Industrial Electronics Society (IECON)*, 2013, pp. 6046–6051.

[29] A. Gil-De-Castro, A. Moreno-Munoz, and J.J.G. De La Rosa, “Comparative study of electromagnetic and electronic ballasts – an assessment on harmonic emission”, *Electr. Rev.-Prz. Elektrotechniczny* 88(2), 288–294 (2012).

[30] H. Shu-Hung Chung, N.M. Ho, W. Yan, P. Wai Tam, and S.Y. Hui, “Comparison of Dimmable Electromagnetic and Electronic Ballast Systems—An Assessmenton Energy Effic. and Lifetime”, *IEEE Trans. Ind. Electron.* 54, 3145–3154 (2007).

[31] M.H. Omar, H.A. Rahman, M.S. Majid, N. Rosmin, M.Y. Hassan, and W.Z. Wan Omar, “Design and simulation of electronic ballast performance for high pressure sodium street lighting”, *Light. Res. Technol.* 45, 729–739 (2013).

[32] S. Hossein-Hosseini, M. Sabahi, and A. Yazdanpanah-Goharrizi, “An improved topology of electronic ballast with wide dimming range,PFC and low switching losses using PWM-controlled soft-switching inwerter”, *Electr. Power Syst. Res*. 78, 975–984 (2008).

[33] A. Burgio and D. Menniti, “A novel technique for energy savings by dimming high pressure sodium lamps mounted with magnetic ballasts using a centralized system”, *Electr. Power Syst. Res*. 96, 16–22 (2013).

[34] K. Hyodhyad and K. Supanaroj, “Energy saving project for street lighting of Provincial Electricity Authority (PEA)”, *2nd Joint International Conference on Sustainable Energy and Environment (SEE2006),* 2006, pp. 1–6.

[35] W. Yan, S.Y.R. Hui, and S.H. Chung, “Energy saving of large-scale high-intensity -discharge lamp lighting networks using a central reactive power control system”, *IEEE Trans. Ind. Electron.* 50, 3069–3078 (2009).

[36] M. Catelani and L. Ciani, “Experimental tests and reliability assessment of electronic ballast system”, *Microelectron. Reliab.* 52, 1833–1836 (2012).

[37] J. Molina, L. Sainz, J.J. Mesas, and J.G. Bergas, “Model of discharge lamps with magnetic ballast”, *Electr. Power Syst. Res.* 95, 112–120 (2013).

[38] C.B. Viejo, J.C.A. Anton, A. Robles, F.F. Martin, J.C. Viera, S. Bhosle, and G. Zissis, “Comparison between different discharge lamp models based on lamp dynamic conductance”, *IEEE Trans. Ind. Electron.* 47, 1983–1991 (2011).

[39] J. Mesasa, L. Sainza, and A. Ferrerb, “Deterministic and stochastic assessment of the harmonic currents consumed by discharge lamps”, *Electr. Power Syst. Res.* 81, 10–18 (2011).

[40] I. Azcarate, J.J. Gutierrez, A. Lazkano, P. Saiz, K. Redondo, and L.A. Leturiondo, "Experimental study of the response of efficient lighting technologies to complex voltage fluctuations", *Electr. Power Energy Syst.* 63, 499–506 (2014).

[41] A. Dolara, R. Faranda, S. Guzzetti, and S. Leva, "Power Quality in Public Lighting Systems", *Proceedings of the 14th International Conference on Harmonics and Quality of Power*, Bergamo, Italy, 2010, pp. 1–7.

[42] A. Gil de Castro, M.A. Moreno, L.V. Pallarés, and A.A. Pérez, "Harmonic Effect in Street Lighting", *Proceedings of the 7th International Conference-Workshop Compatibility and Power Electronics (CPE)*, Tallinn, Estonia, 2011, pp. 16–21.

[43] M.J.H. Orzáez, Róchaz J. Sola, and A. Gago-Calderon, "Electrical consequences of large-scale replacement of metal-halide by LED luminaires", *Light. Res. Technol*. 50, 282–293 (2016).

[44] M.H.J. Bollen, S.K. Rönnberg, E.O.A. Larsson, M. Wahlberg, and C.M. Lundmark, "Harmonic Emission from Installations with Energy-Efficient Lighting", *Proceedings of the 11th International Conference on Electrical Power Quality and Utilisation*, Lisbon, Portugal, 2011, pp. 1–6.

[45] EN 50160:2007 "Voltage Characteristics of Electricity Supplied by Public Distribution Systems", European Union: Brussels, Belgium, (2007).

[46] R. Sikora, P. Markiewicz, and W. Pabjańczyk, "Computing Active Power Losses Using a Mathematical Model of a Regulated Street Luminaire", *Energies* 11, 1386–1406 (2018).

[47] R. Sikora, P. Markiewicz, and W. Pabjańczyk, "The Active Power Losses in the Road Lighting Installation with Dimmable LED Luminaires", *Sustainability*10, 4742–4760 (2018).

[48] IEC 60287-1-1, Electric Cables – Calculation of current rating – calculation of losses – Section 1: General, (2006).

[49] IEEE Std. 1459-2010. Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions, (2010).

[50] Ustawa z dnia 20 maja 2016 r. o efektywności energetycznej, Dz.U. 2016 poz. 831.

[51] The Energy Effic. Directive (2012/27/EU).

[52] R.C. Degeneff, T.M. Halleran, T.M. McKernan, and J.A. Palmer, "Pipe – type cable ampacities in the presence of Harmonics", *IEEE Trans. Power Deliv.* 8, 1689 –1695 (1993).

[53] C. Demoulias, D.P. Labridis, P.S. Dokopoulos, and K. Gouramanis, "Ampacity of Low-Voltage Power Cables Under Nonsinusoidal Currents", *IEEE Trans. Power Deliv.* 22, 584–594 (2007).

[54] J.J. Desmet, G. Vanalme, R. Belmans, and D. Van Dommelen, "Simulation of losses in LV cables due to nonlinear loads", *2008 IEEE Power Electronics Specialists Conference,* Rhodes, Greece, 2008, pp. 785–790.

[55] A. Hiranandani, "Calculation of cable ampacities including the effects of harmonics", *IEEE Industry Applications Magazine* 4, 42–51 (1998).

[56] Z. Gabryjelski and Z. Kowalski, *Sieci i urządzenia oświetleniowe. Zagadnienie wybrane*, Wydawnictwo Politechniki Łódzkiej, Łódź, 1997.

[57] EN 13201-5:2015. Light and lighting. Road lighting – Part 5: Energy performance indicators.

[58] "Electricity price statistics". [Online] Available: https://ec.europa.eu/eurostat/statistics-explained/pdfscache/45239.pdf.

[59] Krajowy Ośrodek Bilansowania i Zarządzania Emisjami, "Wskaźniki emisyjności CO_2, SO_2, NO_x, CO i pyłu całkowitego dla energii elektrycznej". [Online] Available: http://www.kobize.pl/ [in Polish].