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AN ACCURATE MODEL OF LED LUMINAIRE USING MEASUREMENT RESULTS FOR ESTIMATION OF ELECTRICAL PARAMETERS BASED ON THE MULTIVARIABLE REGRESSION METHOD

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Abstract

Light sources and luminaires made in the LED technology are nowadays widely used in industry and at home. The use of these devices affects the operation of the power grid and energy efficiency. To estimate this impact, it is important to know the electrical parameters of light sources and luminaires, especially with the possibility of dimming. The article presents the results of measurements of electrical parameters as well as luminous flux of dimmable LED luminaires as a function of dimming and RMS supply voltage. On the basis of the performed measurements, a model of LED luminaire was developed for prediction of electrical parameters at set dimming values and RMS values of the supply voltage. The developed model of LED luminaire has 2 inputs and 26 outputs. This model is made based on 26 single models of electrical parameters, whose input signals are supply and control voltages. The linear regression method was used to develop the models. An example of the application of the developed model for the prediction of electrical parameters simulating the operation of an LED luminaire in an environment most similar to real working conditions is also presented.

Keywords: LED light source, LED luminaire, linear regression, electrical parameters measurement.

1. Introduction

Light sources and luminaires made in LED technology are nowadays widely used in industry and at home. Many studies conducted by several research groups and described in the literature are focused on various aspects of this technology. The research includes, among others, LED topology, LED drivers, analysis of electrical parameters (including electrical power quality) and photometric, colorimetric, durability and aging processes [1–7]. LED light sources and luminaires have many advantages in comparison with other light sources. Their most important advantages include: independence of the luminous flux value from environmental conditions, obtaining the rated luminous flux value almost immediately after switching on, reliability and ease of use of digital power control (luminous flux) [8–12].

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The LED light source (luminaire) is composed of two basic elements: the LED matrix and a SMPS (*Switch Mode Power Supply*) which also works as a driver. The power supply (controller) is equipped with analogue or digital inputs or has both these inputs. Nowadays, the lighting control systems applied can be generally divided into two groups. The first group includes the use in the luminaires of individual control gears equipped with astronomical clocks which automatically adjust the light duration to sunrises and sunsets. Usually, they realize specified lighting schedules. The use of additional sensors reacting to daylight, traffic intensity, *etc*. increases the functionality of the lighting system by dynamically reacting to changing conditions [13, 14]. Luminous flux (power) regulation can be realized within very wide limits, even in the range from 10% to 100% of the rated luminous flux value. The power supply operation with reduced power usually causes a change of its electrical parameters. As confirmed by research [15], the power factor value often decreases with a simultaneous increase in the level of generated current higher harmonics to the supply network. In the real distribution network, the voltage value changes constantly. As confirmed by previous researches, this influences the LED luminaires electrical parameters [15].

Knowledge about the changes of electrical parameters is important from both operational and economic point of view. At the stage of lighting design, to ensure adequate energy efficiency in accordance with EU directives and standards [16–21], energy efficiency indicators are calculated. The basic parameters used for this analysis are active power and illuminance or luminance. Illuminance and luminance depend on the value of the luminous flux emitted by the light source. Therefore, it is important to know the luminous flux dependence in dimming functions. As the dimming and RMS values of the supply voltage change, so does the reactive power value. These changes are non-linear, especially with small dimming [15].

In the case of LED light sources, reactive power is usually of capacitive character. Although many countries have not introduced fees for reactive energy consumed by lighting installations, its flow causes a number of negative effects. The most important of them is the increase in active power losses and RMS current values [22]. Not taking active power losses into account in energy efficiency analysis may cause that the actual energy consumed by lighting installations, and thus the fees for this energy, will be higher than assumed at the design stage. For this reason, it is also important to know the electrical parameters of light sources under given operating conditions.

The luminaire and the light source made in LED technology are *non-linear* receivers (NL) generating disturbances in the form of higher current harmonics to the mains. The literature describes a number of models of non-linear receivers, including light sources and LED luminaires [23–30]. These models are used to analyze their impact on the mains, current (including higher harmonics) and power flow. These models usually include simple AC/DC converters in variants with or without a PFC (*Power Factor Correction*) system. The load on the AC/DC converter is usually an RLC circuit or only the resistance. Another method used to develop the NL model is the use of neural networks. This method is most often used to estimate the higher current harmonics of an NL receiver. This method also has disadvantages, *e.g.*, there are many degrees of freedom: the choice of number of neurons, structure and type of neurons [31]. Besides, it is a very laborious and difficult method to implement. Non-linear receivers can also be modeled using regression models. Regression models are used to determine the dependence of given quantities as a function of the most important or required parameters, including LED light sources and lighting parameters [32–35]. The method using linear regression requires measurements of selected physical quantities in order to have an appropriate set of input data necessary to construct the model. In order to choose the right regression model, a number series of measurements must be taken. This allows to obtain proper knowledge about the properties and variability of a given quantity. One of the most frequently used methods is polynomial regression. Due to its

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advantages, this method is suitable for quickly developed models describing the dependence of a given quantity in function of required parameters. In the case of LED luminaires and LED light sources, it seems suitable for practical applications. The observed rapid development of LED technology in lighting is connected with the emergence of new design solutions. Developing models dedicated to given types of luminaires and light sources is very laborious and time consuming. This is not always justified because luminaire manufacturers make structural changes to their products. Thus, such an approach does not allow to model the devices with required accuracy.

It can therefore be concluded that there is a need to develop a model of a dimmable LED luminaire that does not require a great deal of work and modelling with an accuracy which is satisfactory from an engineering point of view. Methodology, development and validation of a dimmable LED luminaire model are presented in this article. The developed model enables prediction of the luminaire electrical parameters including higher harmonic currents. With the extent to which it predicts with the required accuracy the change of electrical parameters of the dimmable LED luminaire as a function of dimming and supply voltage, the model has not been previously described in the literature and contributes significantly to the existing knowledge.

2. Material and methods

2.1. Experimental setup

As a test object, a road LED luminaire with a rated power of 32 W was chosen. It was equipped with a power supply with an analogue control input made in the 1–10 V standard. The aim of the research was to determine the relationship between the electrical parameters and luminous flux of the luminaire as a function of supply voltage and dimming. Therefore, the RMS value of the V_S supply voltage was regulated in the range 230 V ± 10%, that is from 207 V to 253 V. This is the range of permissible voltage deviations in the low-voltage distribution network according to EN 50160 [32]. The luminaire was supplied with undistorted sinusoidal voltage with $THD_V = 0\%$. Only the RMS value of the voltage was changed during measurements. The measurements were made for supply voltages $V_S = [207\ 210\ 215\ 220\ 225\ 230\ 235\ 240\ 245\ 250\ 253]$ V. An Agilent 6834B power supply was used for this purpose. The dimming level is controlled by changing the V_C control voltage from 1 V to 10 V in 1 V steps. The source of DC control voltage was a laboratory power supply. Measurements of electrical parameters were made with the use of a FLUKE 1760 electrical power quality analyser. The luminous flux was measured in an integrating sphere using a L-100 luxmeter. The measurement results were stored in computer memory. Figure 1 shows the experimental setup. In this case, the DUT (Device Under Test) is the LED luminaire.

Measurements of luminaire parameters were performed according to the recommendations of standards [36-38]. Before measurements, the luminaire had been operated for a minimum of 100 hours. After the luminaire was switched on according to the recommendation of the standard [38], the luminous flux and active power of the luminaire were measured, so that it could be assumed that the thermal conditions of the luminaire were stabilized and the values of the luminous flux and power change only within the acceptable range of 0.5%. For each measurement point, the same procedure was performed. The measured values of photometric and electrical parameters of the luminaire were additionally averaged over 1 minute. Since the purpose of the measurements was to record the steady-state values of these parameters, this approach is reasonable.

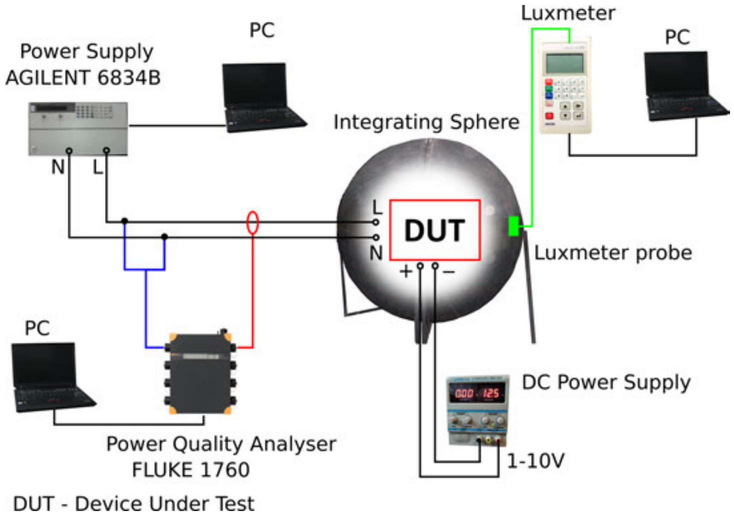

Fig. 1. Experimental setup.

2.2. Measurement results

From the measurements performed the following relationships were noticed. Active power P of the luminaire (Fig. 2a) in the range of V_C control voltage from 1V to 8 V is linear. In the range of V_C voltages from 8 V to 10 V, it can be assumed that the luminaire works at full power. The value of the luminaire's active power practically does not depend on the value of the supply voltage within the considered limits of its changes. The value of reactive power Q (Fig. 2b) increases with the value of the V_S supply voltage. It reaches a maximum value (20 var) for $V_C = 3$ V and $V_S = 245$ V. With a constant value of active power as a function of the supply voltage and a simultaneous increase in the reactive power, this is the reason for the deterioration of the luminaire power factor. In turn, the current RMS value I (Fig. 2c) increases linearly with dimming (for V_C from 1 V to 8 V) and depends slightly on the supply voltage. The current dependence of the luminaire on the control and supply voltage is similar to that of the active power. Analysing the current total harmonic distortion THD_I, it can be noticed that the relationship between THD_I as a function of the V_S supply voltage and the V_C control voltage (Fig. 2d) shows two different change areas. For control voltages greater than 5 V, the current THD_I value varies within small limits. In the control voltage range from 5 V to 1 V the THD_I factor shows a strong upward trend. The maximum THD_I value is 44.59% for $V_C = 1$ V and $V_S = 235$ V. Referring to supply conditions for $V_C = 10$ V and $V_S = 230$ V, the THD_I value has more than tripled. Such a large increase in the current higher harmonics generated to the mains can cause many negative phenomena.

The luminous flux change of the tested luminaire as a function of V_C control voltage and V_S supply voltage is shown in Fig. 2e. In the range of control voltages from 1 V to 8 V the luminous flux value increases linearly until the maximum value is reached. For $V_C \geq 8$ V, the luminous flux value does not change. As in the case of active power, no dependence of the luminous flux on the supply voltage has been observed. Table 1 summarises the results of scaling the luminous flux Φ and power P as a function of control voltage V_C and for $V_S = 230$ V ($THD_V = 0\%$). It can be observed that 1V of control voltage V_C corresponds to 19.32% of the rated power and 14.35% of the luminous flux (Fig. 3). This is the lower regulation limit.

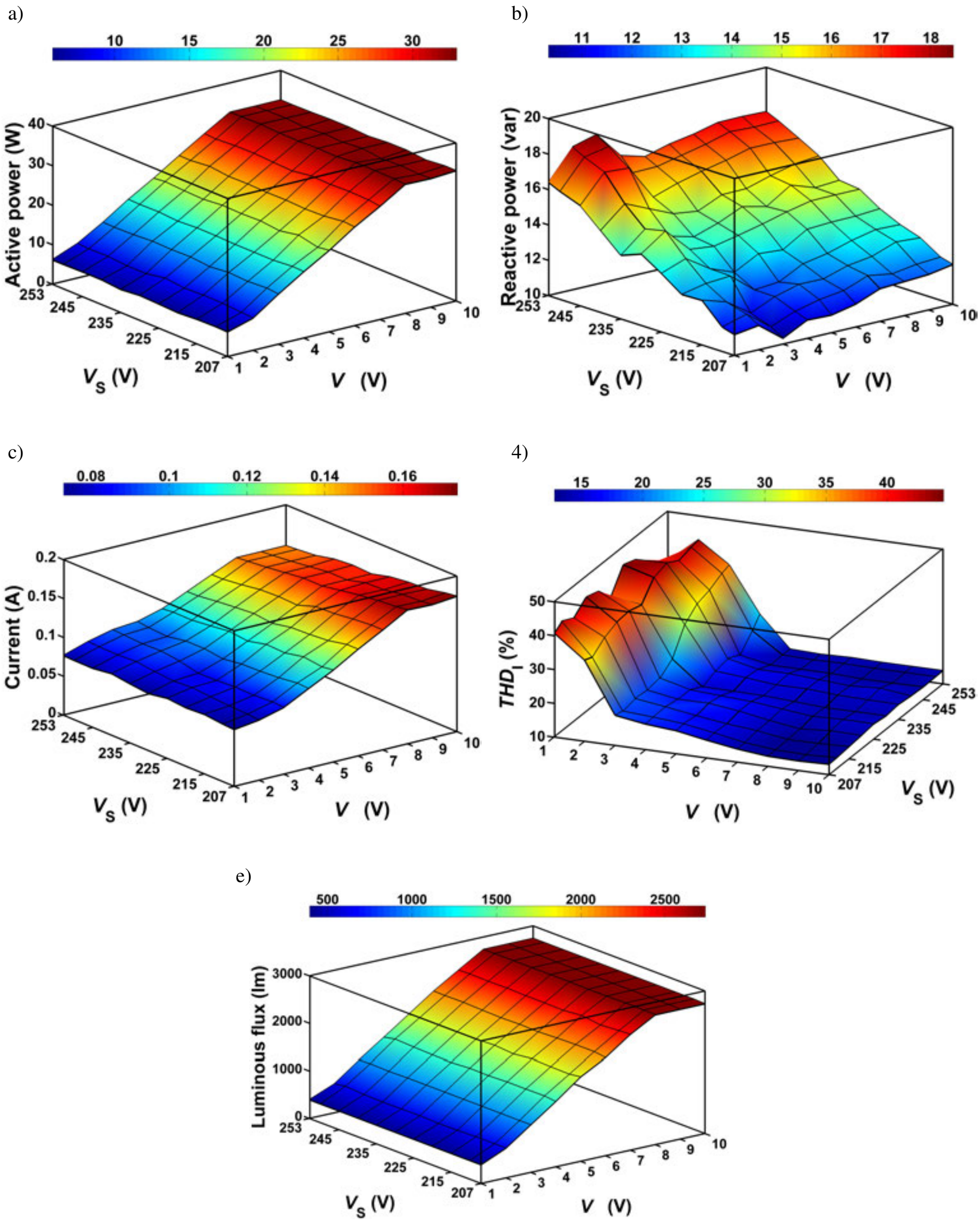

Fig. 2. Relationship between: a) luminaire active power P; b) luminaire reactive power Q; c) luminaire current I; d) current THD_I factor; e) luminaire luminous flux Φ as a function of V_S supply voltage and V_C control voltage.

The LED luminaire, due to the design and operating principle of the switching mode power supply (SMPS) and the LED matrix, is a nonlinear receiver. A nonlinear receiver generates higher harmonic currents to the mains, which can cause many negative phenomena. The flow

Table 1. Scaling of luminaire luminous flux Φ and active power P as a function of control voltage V_C for V_S = 230 V.

V_C [V]	Φ [lm]	Φ [%]	P [W]	P [%]
1	393	14.35	6.28	19.32
2	621	22.68	9.05	27.85
3	1001	36.59	12.84	39.54
4	1388	50.72	16.62	51.18
5	1747	63.84	20.68	63.65
6	2072	75.72	24.48	75.36
7	2409	88.04	28.36	87.29
8	2736	100.00	32.48	100.00
9	2736	100.00	32.48	100.00
10	2736	100.00	32.48	100.00

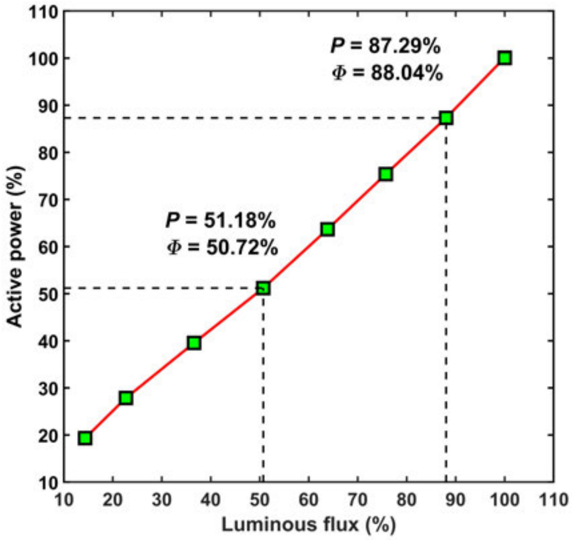

Fig. 3. Relationship of the luminaire active power P as a function of the luminous flux Φ.

of higher harmonic currents through the power cable causes an increase in active power losses, which deteriorates the energy efficiency of the lighting installation. Therefore, knowing the higher harmonics of the current is important. This knowledge can be used both to estimate power losses and to compensate for higher current harmonics. The FLUKE 1760 Power Quality Analyzer used by us allows the measurement of current harmonics up to and including the 50th harmonic. Only odd harmonics up to the 40th harmonic were analyzed. Figures 4a to 4d show the measured RMS values of selected current harmonics of the luminaire as a function of changes in supply voltage V_S and control voltage V_C.

The value of the first harmonic of the current does not depend on changes of the supply voltage RMS value and decreases with reduction of the control voltage value V_C. The characteristic of

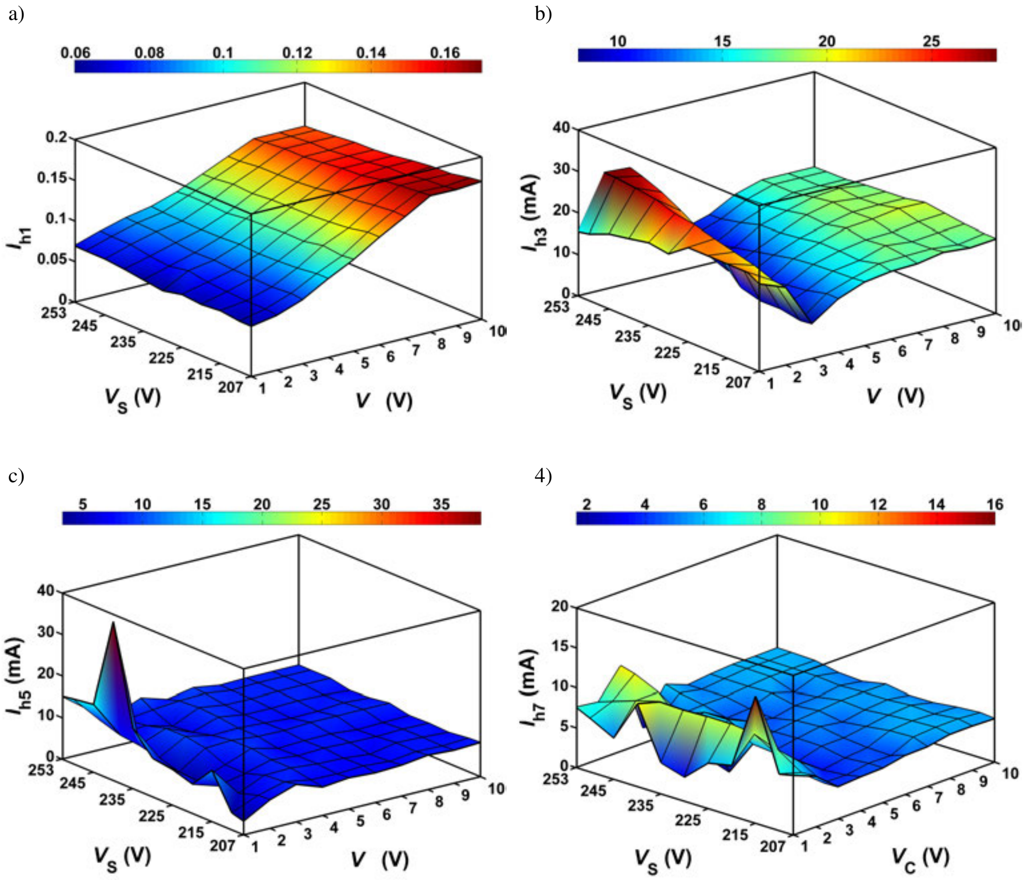

Fig. 4. a) Dependence of the first current harmonic I_{h1} of the luminaire as a function of supply voltage V_S and control voltage V_C; b) Dependence of the third current harmonic I_{h3} of the luminaire as a function of supply voltage V_S and control voltage V_C; c) Dependence of the fifth current harmonic I_{h5} of the luminaire as a function of supply voltage V_S and control voltage V_C; d) Dependence of the seventh current harmonic I_{h7} of the luminaire as a function of supply voltage V_S and control voltage V_C.

these changes is evidently linear. Observing the measured values of the current higher harmonics, there can be noticed an area where changes in the supply voltage V_S and the control voltage V_C do not significantly affect the value of a given harmonic. This is the area of change of *t* control voltage V_C in the range of 3 to 10 V. For a control voltage V_C of less than 3 V, a significant increase in current higher harmonic can be observed, which may be a symptom of unstable operation. In order to better illustrate the dependence of the luminaire current distortion as a function of the supply and control voltages, instantaneous waveforms of the luminaire current are presented in Figs. 5a to 5i. Instantaneous current waveforms are included for supply voltages of 207 V, 230 V and 253 V and control voltages of 1 V, 5 V and 10 V. Analyzing the presented instantaneous current waveforms, it can be stated that the current distortion level for V_C = 1 V is higher than for V_C = 5 V and V_C = 10 V. The percentages of higher harmonics related to the fundamental harmonic are greater for V_C = 1 V than for the other two cases.

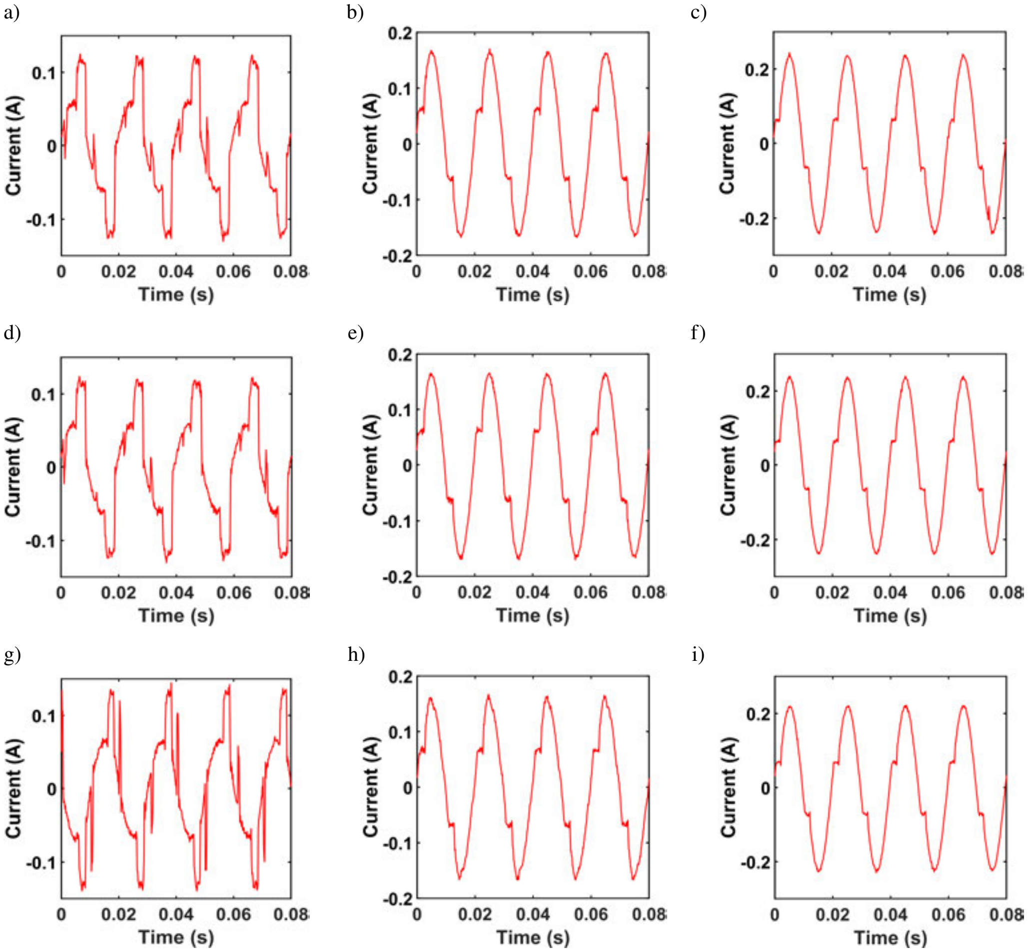

Fig. 5. Instantaneous current waveforms for: a) V_S = 207 V and V_C = 1 V, b) V_S = 207 V and V_C = 5 V, c) V_S = 207 V and V_C = 10 V, d) V_S = 230 V and V_C = 1 V, e) V_S = 230 V and V_C = 5 V, f) V_S = 230 V and V_C = 10 V, g) V_S = 253 V and V_C = 1 V, h) V_S = 253 V and V_C = 5 V, i) V_S = 253 V and V_C = 10 V.

2.3. Multivariable Polynomial Fit of Electrical Parameters of an LED luminaire

It was proved in the previous section that the electrical parameters of an LED light source (luminaire) depend on two variables: V_C control voltage and V_S supply voltage. Therefore, the output quantity of the model must be a function of these two quantities. Thus, it is possible to determine the approximation function $f(x)$ of the two variables describing the relationship between the individual electrical parameters of a luminaire:

$$y = f(x) + \varepsilon, \tag{1}$$

where $x = [V_C,\ V_S]^T$.

Variable ε is a random variable that describes the distribution of measurement data. Using experimental data, function $f(x)$ can be approximated by adjusting the regression model. To appropriately determine the properties of a random variable, a series of experiments must be performed for each input variable. This makes it significantly easier to create the best regression model. In practice, it is often difficult, labour-intensive and costly to obtain large numbers of measurement data. Therefore, if possible, change areas for input variables should be specified. In the case under consideration, the change range of control voltage from 1 V to 10 V can be very precisely defined. This is due to the design of the power supply used to supply the LED matrix. The change range of the supply voltage was assumed to be from 207 V to 253 V which corresponds to 230 V ± 10%. For the tested unit of the LED luminaire, high repeatability of obtained measurement results was observed.

The approximation polynomial $p(V_C,\ V_S)$ for input variables V_C and V_S is described by a relationship:

$$p(V_C, V_S) = \sum_{i=0}^{n} \sum_{j=0}^{m} a_{ij} V_C^i V_S^j\,, \tag{2}$$

where the coefficients a_{ij} are polynomial parameters.

Approximate polynomials have been determined for such electrical parameters as active power P, reactive power Q, current RMS value I and THD_I factor. Knowing the values of active and reactive power, power factor $\cos\varphi$ and $\tan\varphi$ can be calculated. Knowing the values of these coefficients is important for reactive power management (selection of the compensator) and forecasting the costs of active and reactive energy. The approximation of the current RMS value can be used to calculate the power losses in the elements of the supplying network. The approximation polynomials describing the dependence of active power, reactive power and RMS value of current on V_C and V_S voltage are shown in (3), (4) and (5) respectively.

$$P\,(V_C, V_S) = \sum_{i=0}^{n} \sum_{j=0}^{m} a_{ij} V_C^i V_S^j\,, \tag{3}$$

$$I\,(V_C, V_S) = \sum_{i=0}^{m} \sum_{j=0}^{m} b_{ij} V_C^i V_S^j\,, \tag{4}$$

$$Q\,(V_C, V_S) = \sum_{i=0}^{m} \sum_{j=0}^{m} c_{ij} V_C^i V_S^j\,. \tag{5}$$

The coefficients of the polynomials a_{ij}, b_{ij} and c_{ij} in (3), (4) and (5) can be written in the matrix form as **A**, **B** and **C**:

$$\mathbf{A} = \begin{bmatrix} a_{00} & a_{01} \\ a_{10} & a_{11} \\ a_{20} & a_{21} \\ a_{30} & a_{31} \\ a_{40} & 0 \end{bmatrix}_{n\times m}, \qquad \mathbf{B} = \begin{bmatrix} b_{00} & b_{01} & b_{02} & b_{03} & b_{04} & b_{05} \\ b_{10} & b_{11} & b_{12} & b_{13} & b_{14} & 0 \\ b_{20} & b_{21} & b_{22} & b_{23} & 0 & 0 \\ b_{30} & b_{31} & b_{32} & 0 & 0 & 0 \\ b_{40} & b_{41} & 0 & 0 & 0 & 0 \\ b_{50} & 0 & 0 & 0 & 0 & 0 \end{bmatrix}_{m\times m},$$
$$\mathbf{C} = \begin{bmatrix} c_{00} & c_{01} & c_{02} & c_{03} & c_{04} & c_{05} \\ c_{10} & c_{11} & c_{12} & c_{13} & c_{14} & 0 \\ c_{20} & c_{21} & c_{22} & c_{23} & 0 & 0 \\ c_{30} & c_{31} & c_{32} & 0 & 0 & 0 \\ c_{40} & c_{41} & 0 & 0 & 0 & 0 \\ c_{50} & 0 & 0 & 0 & 0 & 0 \end{bmatrix}_{m\times m}. \tag{6}$$

In order to validate the model, error values were determined at calculation points. The value of the relative error was calculated using the equation below.

$$\Delta X = \frac{X_{\text{measurement}} - X_{\text{Model}}}{X_{\text{measurement}}} \cdot 100\%, \tag{7}$$

where:

X_{Model} – value calculated using the model,
$X_{\text{Measurement}}$ – measured value.

The error values defined in (7) are shown in Figs. 6a, 6b and 6c for active power P, reactive power Q and RMS value of current I, respectively. For the approximation polynomial determined for active power P, the biggest error occurred for control voltage V_C =1V and V_S =207V and amounts to 9.23%. The maximum fitting error for reactive power is 5.24% for V_C = 3 V and V_S = 215 V. For luminaire current, the maximum error value is 3.45% for V_C = 4 V and V_S = 245 V.

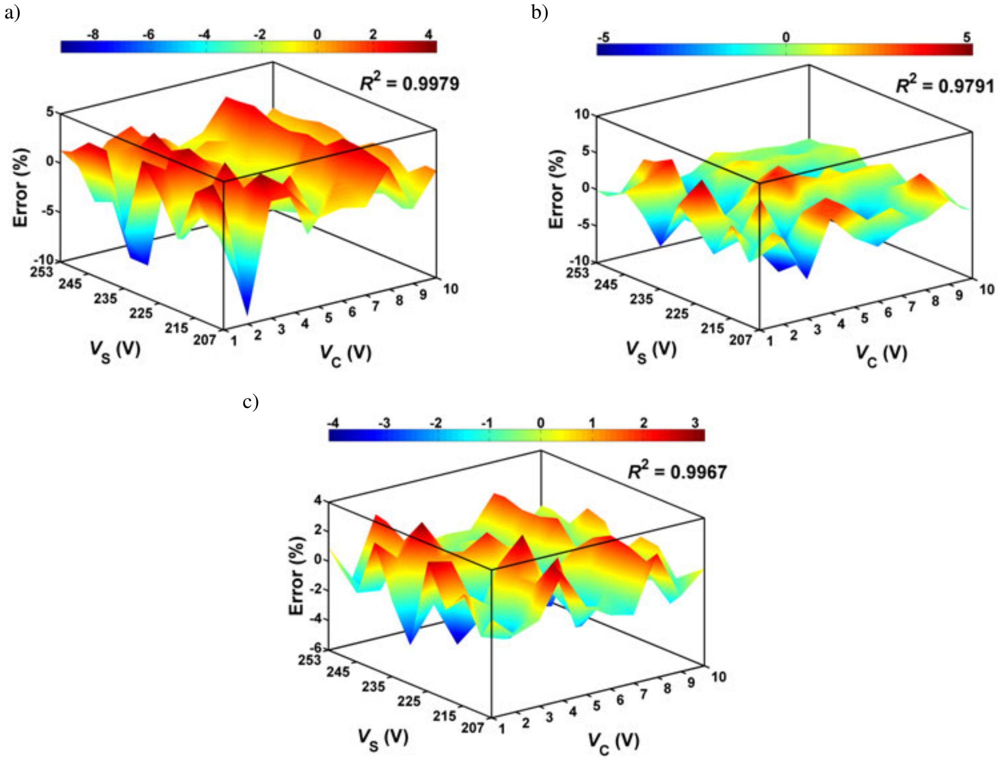

Fig. 6. a) Approximate polynomial error plot for $P(V_S, V_C)$. b) Approximate polynomial error plot for $Q(V_S, V_C)$. c) Approximate polynomial error plot for $I(V_S, V_C)$.

2.4. Cubic Spline Interpolation of harmonic currents

The calculation of power losses requires knowledge about current harmonics. In order to analyse disturbances generated to the mains supply in the form of higher harmonics, information on the higher harmonic currents is also required. Therefore, the developed model enables pre-

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diction of RMS values of higher harmonic currents. The input signals of the model are control voltage V_C and the RMS value of supply voltage V_S. Output signals are RMS values of higher harmonic currents. The RMS values of harmonic currents are determined using calculated real and imaginary harmonic parts up to and including the 39th, including the basic harmonic. This consideration is limited to odd harmonics only.

The use of the approximation polynomial method to determine the model did not bring the expected results. The fitting accuracy was less than the permitted value, *i.e.*, the condition R^2 >0.95 was not met. Therefore, the matching method using Cubic Spline Interpolation was used to determine the models of real and imaginary parts of the harmonic currents (8). In the case of the Cubic Spline Interpolation, the value of R^2 at the measurement points is equal to 1. This is due to the properties of this method. For this reason, the error analysis for this method is not included in the article. The matrix notation of cubic spline interpolation is (9):

$$\begin{bmatrix} x(u) \; y(u) \; z(u) \end{bmatrix} = \begin{bmatrix} u^3 \; u^2 \; u \; ^1 \end{bmatrix} \begin{bmatrix} a_x & a_y & a_z \\ b_x & b_y & b_z \\ c_x & c_y & c_z \\ d_x & d_y & d_z \end{bmatrix}, \tag{8}$$

$$\mathbf{P} = \mathbf{U}\,\mathbf{A}. \tag{9}$$

The application of this method made it possible to predict the RMS values of higher current harmonics with accuracy sufficient from a practical point of view. Due to the high nonlinearity of THD_I, this method was also used to develop the $THD_I(V_C, V_S)$ model.

3. Model development of LED luminaire electrical parameters

The development of a model of an LED luminaire based on the linear regression method requires performing measurements of the DUT (Device Under Test) parameters. To achieve a sufficiently accurate approximation function, a series of experiments is required for each input variable. To create the model, data that have already been statistically processed should be selected. For this reason, the first stage of model creation is to perform experimental measurements of selected parameters of the analysed object. On the basis of the measurement results obtained, which have been mathematically processed earlier, multi-variable models are created. In the first step, a polynomial of the order of 1 is taken as an approximation function. In case the required fitting accuracy ($R^2 > 0.95$) is not achieved, the polynomial order and check the error value should be increased again. A mean square error can be used to determine the fitting accuracy of the models. If the polynomial order increase does not bring the expected results, the regression method should be changed *e.g.*, to cubic spline interpolation or the analysed range of parameter changes should be divided into 2 or more intervals. After creating models of individual parameters, a matrix of models is generated which are used at a later stage to predict the parameters at the present input values. In the case of luminaires, a frequently set parameter is the luminous flux or active power. In the case under consideration, the luminous flux Φ is assumed to be the input quantity. Since the input values of the electrical parameters models of the are the RMS value of supply voltage V_S and value V_C, it is necessary to develop a model describing the relationship between changes of control voltage V_C in function of luminous flux Φ. In this case also, the measure of model accuracy is a value of the mean square error not less than 0.95.

Having arrived at the model matrix and the $V_C = f(\Phi)$ model, it is possible to perform prediction of electrical parameters of the tested object in the given conditions – RMS values of supply voltage and luminous flux Φ. The algorithm of the luminaire model development process and prediction of its electrical parameters is presented in Fig. 7.

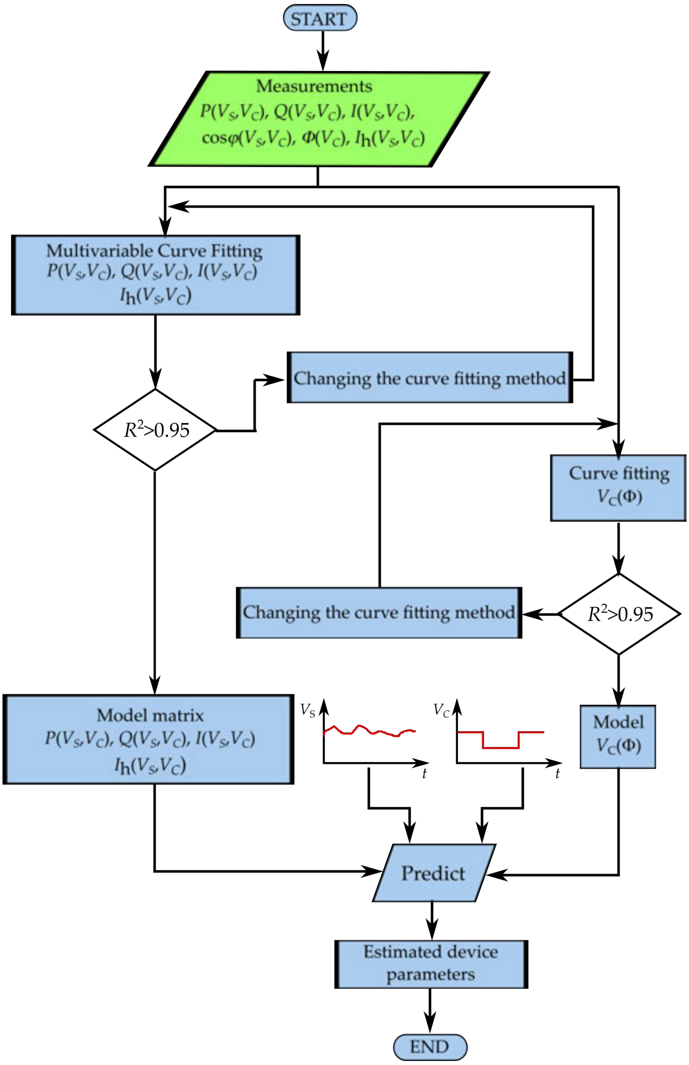

Fig. 7. Algorithm for model development and prediction of parameters of an LED luminaire.

The developed LED luminaire model has 2 inputs and 26 outputs. A diagram of the model is shown in Fig. 8. The model inputs are the luminous flux and the RMS value of the supply voltage. In lighting control systems, the set point value is primarily the luminous flux value. The lighting parameters and electrical parameters of luminaires included in the lighting installation are changed by setting a specific value of the luminous flux. For this reason, it has been decided that the input quantities will be the luminous flux. The output quantities are active power, reactive power, current RMS value, cos φ, tan φ, THD_I factor and RMS values of current odd higher harmonics up to the 40th harmonic (including the first harmonic). The power factors values were calculated considering the active and reactive power.

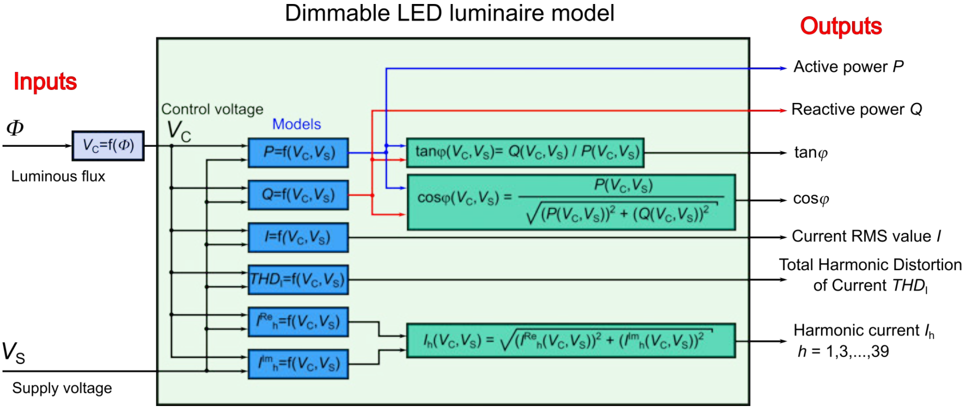

Fig. 8. LED luminaire model (MIMO system).

All the approximating polynomials of the electrical parameters are a function of the control and supply voltage. For this reason, it is necessary to determine the polynomial approximating control voltage as a function of the luminous flux. Based on the measurements performed, it was assumed that the value of the luminous flux does not depend on the supply voltage (Fig. 6).

The approximating function showing the relationship $V_C = f(\Phi)$ is described by formula (10). This function has been determined for a supply voltage equal to 230 V. In the case of the full luminous flux (without dimming), the control voltage was assumed to be 10 V. The control voltage for the luminous flux values in the range 392 lm $\leq \Phi <$ 2736 lm is calculated by using the linear approximating function (10), as shown in Fig. 9.

$$V_C(\Phi) = \begin{cases} 10 & \text{for } \ \Phi = 2736 \text{ lm} \\ 0.029 \cdot \Phi + 0.01796 & \text{for } \ 392 \text{ lm} \leq \Phi < 2736 \text{ lm} \end{cases} \tag{10}$$

The mean square error R^2 obtained for this fitting is 0.9982.

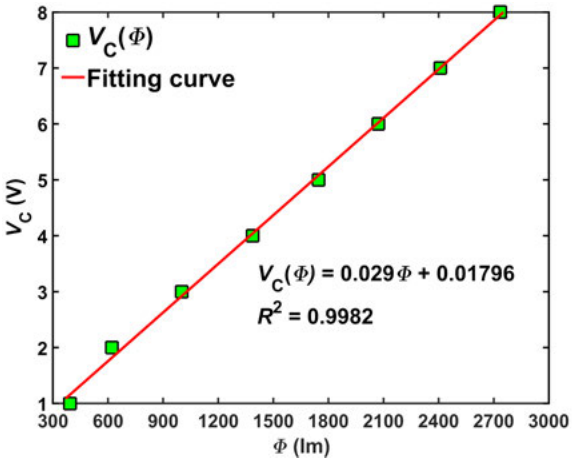

Fig. 9. Plot of the $V_C(\Phi)$ dependence approximating function.

4. Example of using the LED luminaire model to predict its electrical parameters under varying power supply conditions

The previous sections have described the development of a luminaire model using the linear regression method. Using the developed model, it is possible to easily make predictions of the luminaire electrical parameters with a wide range of changes in its operating conditions, especially the RMS value of the supply voltage. The usefulness of the developed model is demonstrated using the following example.

Prediction of electrical parameters of the considered luminaire was made with the following assumptions: the calculations were made for the adopted daily lighting schedule. and the luminaire operates with the rated luminous flux from 4 p.m. to 11 p.m. and from 5 a.m. to 7 a.m. in accordance with the established lighting schedule. Also, during the night hours from 23 p.m. to 5 a.m. it is dimmed to 50% of its rated flux. To model the changing process of the supply voltage RMS value, the results of the measurements taken from a real road lighting installation in one of the Polish cities were used. The results of these measurements are the input values of the luminaire model.

Analysing changes in the RMS value of the supply voltage (obtained through the measurements), it can be observed a constant increase in its value between 4 pm and 10 pm from about 240 V to 245 V. Between 10 pm and 11 pm, the voltage drops to about 240 V. From 11 p.m. to 2 a.m. a continuous increase in the supply voltage to 245 V is observed. During the period from 2 a.m. to 7 a.m. the supply voltage decreases slowly to about 237 V. In the road lighting installation, at which the measurements were performed, the value of the supply voltage was higher than the rated phase voltage of 230 V during the whole measurement period. Using the developed model for the adopted lighting schedule of light duration and changes of the supply voltage RMS value, the electrical parameters of the considered luminaire were predicted over the whole period of time when the light was on. The calculations results are shown in Figs. 10 to 17.

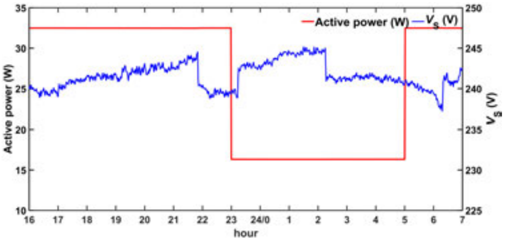

Fig. 10. Active power P for the assumed lighting schedule and supply voltage RMS value

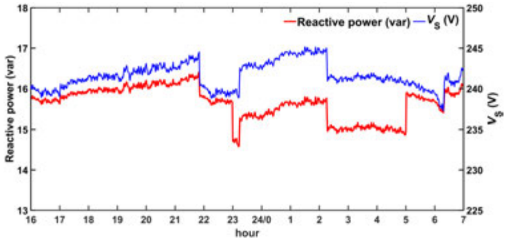

Fig. 11. Reactive power Q for the assumed lighting schedule and supply voltage RMS value.

Analysing the spectrum of higher harmonics of the current (Fig. 17), it can be observed that the percentage value of the third harmonic related to the fundamental harmonic practically does not change after switching to the operation state with 50% dimming. The percentage value of the fifth harmonic related to the fundamental harmonic at 100% dimming is 5.08%, and reducing the power (luminous flux) of the luminaire increased this value to 7.15%. For the seventh harmonic, changing the dimming from 100% to 50% causes its percentage value to increase almost twice. For 100% dimming it is 3.42% and for 50% dimming it is 6.45%. For harmonics 13, 15 and 17, the increase in the percentages of higher harmonics referred to the fundamental harmonic is more than double. The value of the eleventh harmonic value practically does not change when changing the level of dimming.

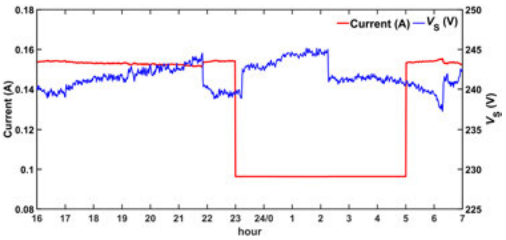

Fig. 12. Current I for the assumed lighting schedule and supply voltage RMS value.

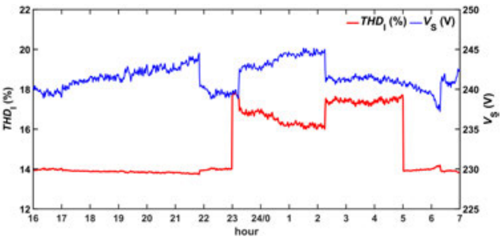

Fig. 13. THD_I factor for the assumed lighting schedule and supply voltage RMS value.

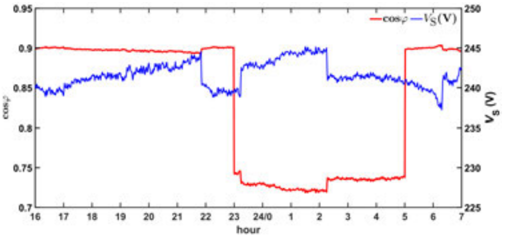

Fig. 14. Power factor cos φ for the assumed lighting schedule and supply voltage RMS value.

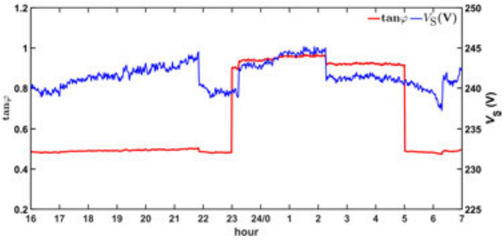

Fig. 15. Power factor tan φ for the assumed lighting schedule and supply voltage RMS value.

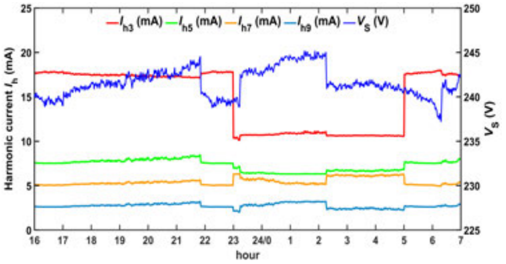

Fig. 16. Selected odd current higher harmonics for the assumed lighting schedule and supply voltage RMS value.

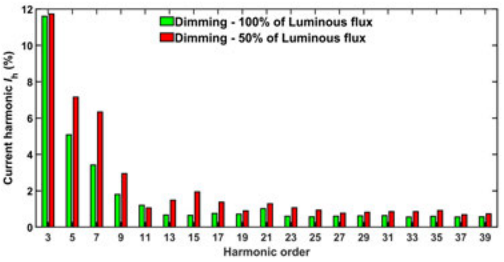

Fig. 17. Spectrum of current higher harmonics for 100% and 50% of dimming reference to fundamental harmonics.

5. Conclusions

The paper presents a mathematical model of a dimmable luminaire built on the basis of the regression method. It has two inputs *i.e.*, the RMS value of supply voltage V_S and the control level determined by control voltage V_C. The output values are the electrical parameters of the luminaire such as active power P, reactive power Q, supply current I and $\cos\varphi$, $\tan\varphi$, THD_I and odd higher harmonics up to the 40th. In practical solutions, the value of the luminous flux is the set-point. Therefore, a function has been determined which approximates the relationship between voltage V_C as a function of the luminous flux.

Having such a model at the design or operation stage, it is possible to optimise the control algorithm, which is most often the lighting schedule. Optimisation is carried out primarily in terms of energy efficiency, *i.e.*, reduction of active power. This optimisation does not always take into account the problem of reactive power and the impact of higher current harmonics. With the help of the developed model, it is possible to quickly predict the selected electrical parameters of the luminaire in given operating conditions.

Energy efficiency assessment shall normally be carried out for the rated supply voltage and the impact of its changes shall not be taken into account. However, in real distribution grids, the value of the supply voltage varies within quite wide limits. Using the developed model, it is possible to calculate the parameters of the LED luminaire for a given value of supply voltage. This will make it possible to define the limits of the changes and to accurately determine, above all, the consumption of active and reactive energy. This could result in significant savings of electricity consumption costs.

The mathematical model of the luminaire has been created using available tools in MATLAB environment. It is assumed that the model should be as simple as possible and should represent the real object with assumed accuracy. The assumption of the mean-square error value of less than 5% makes it unnecessary to use more advanced mathematical tools to achieve the assumed goal, *e.g.*, Hermite interpolation polynomial.

The advantage of the developed model is its low labour intensity and high accuracy. To develop a model, it is enough to have the results of measurements of the selected quantities. The second advantage is that such a model can be developed for practically any non-linear receiver.

In future research, it is planned to perform power quality measurements in a real road lighting installation. Based on these measurements, a comprehensive validation of the accuracy of the developed model will be performed. Measurements in real road lighting installations are in many cases difficult to perform. The first reason is to obtain permission from the owner of the road lighting installation to make measurements and publish the results. Although the installation of power quality analysers does not require much intervention in the lighting installation, there is always the risk of an emergency situation. Measurements should be made at night, due to load on the transformer being different than during the day, which affects the voltage values in the distribution power grid. The occurrence of a malfunction may result in the shutdown of road lighting which will reduce traffic safety. Another reason for the difficulty in making measurements is their physical realization. The power quality analyser shall be connected to the pole panel board so that the parameters of a single luminaire can be measured. Due to the dimensions of power quality analysers, it is not practically possible to place them in a pole socket. Since the measurement will last for many hours (*e.g.*, from 5 to even 16 hours), the power quality analyser should be protected from the influence of atmospheric conditions, which may additionally influence on the measurement accuracy.

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