1. Marek PAVLÍK[1], 2. Ján ZBOJOVSKÝ[2]

Technical university of Kosice (1), Technical university of Kosice (2)
ORCID: 1. 0000-0002-8375-2819; 2. 0000-0003-4383-3996

doi:10.15199/48.2022.01.44

Determination of effect of photovoltaic cells defect on electricity produce by use mathematical model

***Abstract**. The paper describes a replacement model of a photovoltaic cell as well as its parts. The replacement model of the photovoltaic (PV) cell also consists of a series R_S and a parallel R_P resistor. The effect of changing these resistances is describe in this paper. Changes in the resistances R_P and R_S affect the shape of the VA characteristic as well as the MPP point. Because the shape of the VA characteristic and the MPP point change, the total power of the PV cell as well as its produced electric energy also changes. The ideal photovoltaic cell should have the lowest possible value of the series resistance R_S and, conversely, the highest possible value of the parallel resistance R_P. However, in practice, this is not possible and therefore we focused on how the change of these parameters affects the power and the production of the photovoltaic cell.*

Streszczenie.** W artykule opisano model zastępczy ogniwa fotowoltaicznego oraz jego części. Model zastępczy ogniwa fotowoltaicznego składa się również z szeregowego R_S i równoległego rezystora R_P. Efekt zmiany tych oporów jest opisany w tym artykule. Zmiany rezystancji R_P i R_S wpływają na kształt charakterystyki VA oraz punkt MPP. Ponieważ zmienia się kształt charakterystyki VA i punkt MPP, zmienia się również całkowita moc ogniwa fotowoltaicznego oraz wytwarzana przez niego energia elektryczna. Idealne ogniwo fotowoltaiczne powinno mieć najniższą możliwą wartość rezystancji szeregowej R_S i odwrotnie, najwyższą możliwą wartość rezystancji równoległej R_P. Jednak w praktyce nie jest to możliwe i dlatego skupiliśmy się na tym, jak zmiana tych parametrów wpływa na moc i produkcję ogniwa fotowoltaicznego. (**Wyznaczanie wpływu defektu ogniw fotowoltaicznych na produkowaną energię elektryczną z wykorzystaniem modelu matematycznego)

Keywords: photovoltaic cell, defect of photovoltaic cell, maximum power point.
Słowa kluczowe: ogniwo fotowoltaiczne, wada ogniwa fotowoltaicznego, maksymalny punkt mocy.

Introduction

Photovoltaic cells have many applications. The individual cells are used to power small devices, such as electronic calculators. Photovoltaic arrays generate electricity from a renewable energy source (solar), which is especially useful in situations where it is impossible to obtain electricity from the grid, remote power grids, orbiting satellites and space probes, radiotelephones and water pump applications. Nevertheless, photovoltaics is becoming more and more widespread even in conventional electrical systems [1] [2] [3] [4].

Photovoltaic cells (like other sources of electricity) are connected to batteries in order to achieve a higher nominal voltage and current. Due to the variable lighting and thus the variable output parameters (power, current, voltage), the output of the photovoltaic batteries is modified (eg for connection to the mains) by connected power electronics, which often also include accumulators [4] [5] [6] [7].

The efficiency of the conversion of (potentially incident) light into a photovoltaic cell into electrical energy is the most important parameter of the cell. Several parameters affect the overall efficiency: [3] [8] [9] [10]

- surface cleanliness
- reflections on the surface
  - o angle of impact - the use of rotation increases the price, reduces reliability and it is necessary to consider whether the energy gain equals the power input of the rotation system.
  - o surface reflectivity - due to the large difference in refractive indices at the air / semiconductor interface, it is necessary to use an adaptive (anti-reflective) layer (or system of layers)
- narrow absorption region - charge carriers generated outside the spatial charge region of the pn-junction are not separated, recombine, and do not contribute to the resulting current. Therefore, it is important that the pn-transition be located as close to the surface as possible and that it be as wide as possible.
- absorption spectrum - in semiconductors it is relatively narrow, i. j. part of the incident photons passes through the semiconductor and part is absorbed but only part of their energy is used to generate the electron-hole pair, the rest is converted to heat, the other part is converted only to heat. To increase efficiency, a set of layers of different composite semiconductors (with different bandwidths and thus) with several pn transitions above each other is used [3] [7] [11] [12].
- recombination of photogenerated carriers - pure monocrystalline semiconductors must be used for reduction
- series resistance (causes ohmic losses)
  - o semiconductor - photogenerated carriers pass through the P and N layer of the semiconductor to the contacts on the surface, therefore the high conductivity of the substrate is important
  - o contacts - transparent upper contacts (apart from the higher price) have a significant series resistance (and also a considerable reflectivity), therefore, despite the loss of part of the surface, opaque ridge contacts are used.

The overall efficiency of the entire photovoltaic system is compounded by losses in the connections between the cells, the efficiency of the power electronics (inverter) or the efficiency of energy storage and recovery in the batteries. Since the illuminated part of the cell also performs the function of contact and dissipates the produced current, it is important that it puts as little resistance as possible and thus that it dissipates the obtained energy with the least possible losses [10] [13] [14].

Photovoltaics cell parameters

This section will describe the basic parameters determining the quality of a photovoltaic cell. These parameters will be further monitored in the part of photovoltaic panel defect modelling [3] [15] [16].

Open-circuit voltage U_{OC}

Open-circuit voltage U_{OC} This is the maximum value of the voltage at the output terminals of the PV cell at zero current, without a connected load at a given temperature and light intensity. The U_{OC} value ranges from tens to hundreds of Volts [3] [17].

Short circuit current I_{SC}

This is the maximum value of the current at a given lighting and at zero cell voltage. It is thus equal to the current generated by the light I_{SC}=I_L, assuming that the resistance RS is zero. The magnitude of the short-circuit current depends on the intensity of illumination, spectral sensitivity, irradiated area and temperature and varies in the order of units up to tens of A [3] [18] [19].

Maximum power P_{MPP}

The main unit is Wp (Watt Peak – top performance). This is the maximum power that the panel is able to deliver under STC conditions. The value of the maximum power is given by the relation:[3] [7] [20]

$$P_{MPP} = U_{MPP} * I_{MPP} \quad (1)$$

where the voltage U_{MPP} is at the point of maximum power of the panel and where the jet I_{MPP} is at the point of maximum power of the panel.

Effectiveness η

The efficiency of a photovoltaic panel is determine by the properties of the materials from which the panel and the photovoltaic cell w made. The material affects the spectral sensitivity of the cell to incident radiation, which means that the panel cell uses energy of different wavelengths with different efficiencies. The efficiency of a photovoltaic panel cell can be define by the formula:[3] [21] [22]

$$\eta_{ef} = \frac{P_{MPP}}{P_{rad}} = \frac{P_{MPP}}{E * A_c} \quad (2)$$

where P_{rad} is the power of the incident radiation, E is the light intensity under standardized test conditions, A_C is the area of the photovoltaic cell.

Fill Factor FF

It depends on the quality of the contacts, the morphology of the material and the resistance of the active semiconductor layer. In translation, we know it as the load factor, and the higher this value, the more power the PV cell is able to deliver to the load. The average value for amorphous cells is around 0.6. Fill Factor is based on the relationship:[3] [23]

$$FF = \frac{P_{MPP}}{I_{SC} * U_{OC}} = \frac{U_{MPP} * I_{MPP}}{I_{SC} * U_{OC}} \quad (3)$$

Series resistance R_S

It is an indicator of the quality of a PV cell. It is a parasitic resistance that is derived from the total resistance of the semiconductor material, the resistance of contacts and connections. A good cell should have the lowest R_S value, because its high value causes a voltage drop at the panel terminals [3] [7].

Parallel resistance R_P

In most cases, it is caused by extensive defects. Too low an R_P value indicates a poor PV cell that behaves almost like a short circuit. The resistance value should be as high as possible [3] [7].

Mathematical model of a photovoltaics

The P-N junction is a semiconductor diode. Depending on the polarity of the externally connected DC voltage, current (direct direction) or no current (closing direction) flows through the diode. The magnitude of the current at the P-N junction is given by the U-I characteristic given by the Shockley equation: [3] [7] [19]

$$I_D = I_S \left(exp\left[\frac{qU_D}{kT} - 1\right]\right) \quad (4)$$

where I_D is the current on the diode, I_S is the saturation current, U_D is the voltage on the diode, q (= 1.6 × 10-19 C) is the electron charge, k (= 1.38 × 10-23 J/K) is the Boltzmann constant and T is thermodynamic temperature at which the diode operates. The replacement scheme of the photovoltaic cell is based on the principle of the Shockley equation and is shown in Fig.1. The given scheme consists of a current source, an ideal diode, a parallel resistor R_{SH} expressing the stray current and a series resistor R_S, which represents the internal resistance [3] [19].

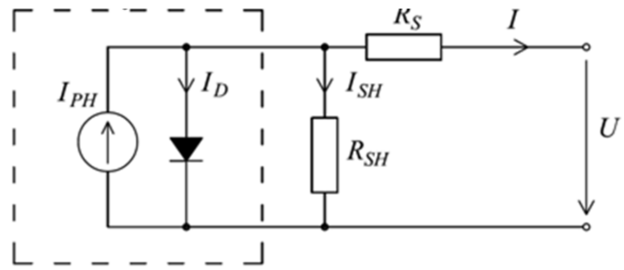

Fig.1. Fig. 1. The replacement scheme of the photovoltaic cell[3]

The volt-ampere characteristic (U-I) is given by the equation:[3] [19]

$$I = I_{PH} - I_S \left(exp\left[\frac{q(U+IR_S)}{kTA}\right] - 1\right) - \frac{(U - IR_S)}{R_{SH}} \quad (5)$$

where I_{PH} is the light generated current or photocurrent, U is the output voltage of the solar cell, A is the ideal factor. The photocurrent largely depends on the intensity of the radiation and on the temperature at which the solar cell operates and is given by the relationship: [3] [19]

$$I_{PH} = \lambda(I_{SC} + K_I(T - T_r)) \quad (6)$$

where I_{SC} is the short-circuit current of the photovoltaic cell at 25 °C and λ = 1 kW/m2, K_I is the short-circuit cell temperature coefficient, T_r is the reference cell temperature and λ is the radiation intensity in kW/m2. The saturation current of a photovoltaic cell varies depending on the temperature and is described as follows: [3] [19]

$$I_S = I_{RS} \left(\frac{T}{T_r}\right)^3 exp\left[qE_G \frac{(1/T_r - 1/T)}{KA}\right] \quad (7)$$

where I_{RS} is the final saturation current depending on the reference temperature and solar radiation, E_G is the band gap energy of the semiconductor used in the cell. The ideality factor A depends on the production technology of the photovoltaic cells used. The dependence of the final saturation current on the reference temperature is expressed by the relation: [3]

$$I_{RS} = \frac{I_{SC}}{exp\left[\frac{qU_{OC}}{kAT}\right] - 1} \quad (8)$$

where U_{OC} is the short-circuit voltage of the photovoltaic cell at the reference temperature. Another more accurate model that can be used to describe a PV cell is the double exponential model. This type is derived from the physical behavior of a cell made of poly-crystalline silicon. This model consists of a light-affected current source, two diodes, a series resistor and a parallel resistor. However, due to the implicit and nonlinear nature of this model, it is difficult to define the parameters of the V-A characteristic of the model, and therefore this model is not yet widely applied in practical simulations. Approximate models of a photovoltaic cell with suitable complexity can be further derived by neglecting the parallel resistance and described by: [3]

$$I = I_{PH} - I_S \left(exp\left[\frac{q(U+IR_S)}{kTA} - 1\right]\right) \quad (9)$$

For an ideal photovoltaic cell, there are no serial or parallel losses and therefore there is no voltage drop to ground, which means R_S = 0Ω and R_{SH} = ∞Ω. The replacement circuit describing such a cell can be further simplified by redefining the relationship: [3]

$$I = I_{PH} - I_S\left(exp\left[\frac{qU}{kTA}\right] - 1\right) \quad (10)$$

External conditions such as the temperature of the solar cell or the intensity of the incident light have a significant effect on the shape of the VACH. Also, its shape is also affected by the internal properties of the cell (cell structure), such as the series resistance R_S, which is required to have the lowest possible value, and the leakage resistance R_{SH}, which is to reach a high value. The point on the VACH at which the solar cell reaches maximum power is called the Maximum power point. The voltage and current values in this case will be indicated in Fig. 2 as U_m respectively I_m. In the idle and short circuit state, no power is produced by the cell [3] [19].

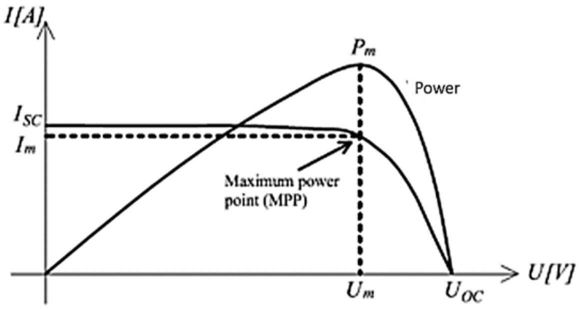

Fig.2. U – I and U – P characteristics of the photovoltaic cell[3]

Modelling of photovoltaics cells defect

As mentioned earlier, for an ideal photovoltaic cell, there are no serial or parallel losses, which means R_S = 0Ω and R_{SH} = ∞Ω. In this part of modelling, we will focus on the effect of changing the series and parallel resistance of a photovoltaic cell. The scheme of photovoltaic cell consists of a current source, an ideal diode, a parallel resistor R_{SH} expressing the stray current and a series resistor R_S, which represents the internal resistance. The internal resistance changes over time, which can be cause by imperfect connections.

a) Defect caused by a change in the R_S series resistance

The R_S series resistance in the replacement photovoltaic cell model represents panel losses. These losses represent the resistance of the material, contacts, cables and connections. This resistance changes during operation. Changes in R_S resistance are cause by aging of the material. In addition, the resistance changes with changing temperature. Several simulations of the series resistance change in the surrogate model were perform. In the simulations, the values of the series resistance were set to 0.1 0.15 0.3 0.6 and 1 Ω. If we compare the results of the simulation with the ideal V-A characteristic of the photovoltaic cell shown in Fig.2, it is possible to state:

a) With increasing value of series resistance the V-A characteristic deforms.

b) Increasing the series resistance will cause the MPP point to shift to the left. This shift will cause a significant reduction in current and thus a reduction in electricity production

c) Increasing the R_S don´t change the maximum voltage value.

For comparison, with an R_S resistance of 0.1 Ω, the current at the MPP point is approximately 0.65 A. When the R_S resistance increases to 0.6 Ω, the current at the MPP point is 0.18 A.

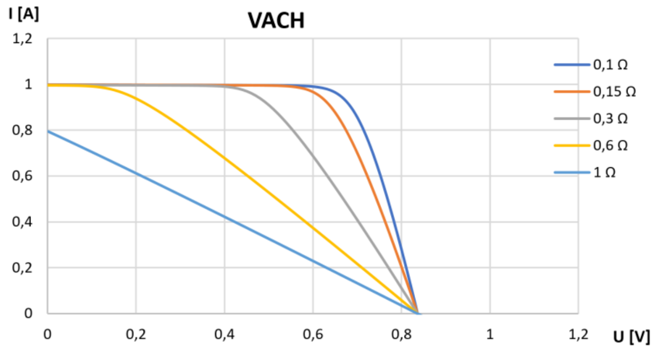

Fig.3. V-A characteristics of the photovoltaic cell - RS series resistance change

b) Defect caused by a change in the R_P parallel resistance

Several simulations of the change in parallel resistance in the surrogate model were perform. During the simulations, the values of the parallel resistance were set to 1 3 5 10 and 150 Ω. If we compare the results of the simulation with the ideal V-A characteristic of the photovoltaic cell shown in Fig. 2, it can be state:

a) If the value of the parallel resistance R_P decreases, the maximum current decreases. The maximum voltage is also reduce. A reduction in the maximum current and voltage will cause a decrease in the power of the photovoltaic cell and thus a decrease in the electricity produced.

b) Changing the value of the parallel resistance R_P distorts the V-A characteristic.

c) Changing the value of the parallel resistance will change the MPP point.

d) Decrease in the value of the parallel resistance will cause a more significant drop in voltage than current.

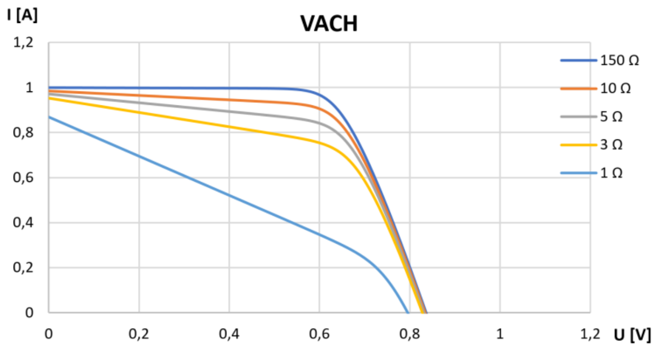

Fig.4. V-A characteristics of the photovoltaic cell - Change of parallel resistance of RP

Conclusion and discussion

This paper deals with the investigation of defects on a photovoltaic cell. Each defect can affect the performance of the photovoltaic cell as well as the panel. The decrease in power affects the overall production of electricity. The article describes a replacement model of a photovoltaic cell in which there is a series and parallel resistance. These two parameters affect the power and production of electricity. In addition to these parameters, the intensity of solar radiation and the temperature of the photovoltaic panel also affect the overall output and production of electricity.

The paper presents changes in the photovoltaic cell model, which represent defects on the photovoltaic cell. In the simulation, first the series resistance and then the parallel resistance were changed. In the simulations, the values of the series resistance were set to 0.1 0.15 0.3 0.6 and 1 Ω. The results lead to the conclusions described in

Part IV modelling of photovoltaics cells defect.

In the second part of the simulation, the influence of parallel resistance on power and electricity production was solve. The conclusions are also describe in Part IV Modelling of photovoltaics cells defect.

The simulation shows that changing both the series resistance and the parallel resistance affects the V-A characteristic of the photovoltaic cell. As mentioned above, the ideal photovoltaic cell should have the lowest possible value of the series resistance R_S and, conversely, the highest possible value of the parallel resistance R_P.

This work was supported by project: FEI-2021-74, Research of the influence of selected building materials and elements in order to evaluate their interaction with high-frequency electromagnetic radiation.

***Authors**: Ing.Marek Pavlík, PhD., Department of Electric Power Engineering, Faculty of Electrical Engineering and Informatics, Technical university of Kosice, E-mail: marek.pavlik@tuke.sk*
Ing. Ján ZBojovský, PhD. Department of Electric Power Engineering, Faculty of Electrical Engineering and Informatics, Technical university of Kosice, E-mail: jan.zbojovsky@tuke.sk

REFERENCES

[1] T. Wu, W. Liu, C. Moo, H. Cheng and Y. Chang, "An electric circuit model of photovoltaic panel with power electronic converter," 2016 IEEE 17th Workshop on Control and Modeling for Power Electronics (COMPEL), 2016, pp. 1-6, doi: 10.1109/COMPEL.2016.7556672.
[2] J. Zhang, Y. Liu, K. Ding, L. Feng, F. U. Hamelmann and X. Chen, "Model Parameter Analysis of Cracked Photovoltaic Module under Outdoor Conditions," 2020 47th IEEE Photovoltaic Specialists Conference (PVSC), 2020, pp. 2509-2512, doi: 10.1109/PVSC45281.2020.9300720.
[3] A. Beláň, "Model fotovoltického článku," Posterus, Vol.6, No. 10, ISSN: 1338-0087.
[4] J. Molnár, et al., "Weather Station IoT Educational Model Using Cloud Services," J. Univers. Comput. Sci., 2020, 26.11: 1495-1512.
[5] T. Vince, et al., "IoT Implementation in Remote Measuring Laboratory VMLab Analyses," J. Univers. Comput. Sci., 2020, 26.11: 1402-1421.
[6] S. Chtita, Y. Chaibi, A. Derouich and J. Belkadid, "Modeling and Simulation of a Photovoltaic Panel Based on a Triple Junction Cells for a Nanosatellite," 2018 International Symposium on Advanced Electrical and Communication Technologies (ISAECT), 2018, pp. 1-6, doi: 10.1109/ISAECT.2018.8618840.
[7] M. Bereš, et al., "Efficiency Enhancement of Non-Isolated DC-DC Interleaved Buck Converter for Renewable Energy Sources," Energies, 2021, 14.14: 4127. https://doi.org/10.3390/en14144127.
[8] W. Hayder, A. Abid and M. Ben Hamed, "Modeling of a photovoltaic cell based on recurrent neural networks," 2017 International Conference on Green Energy Conversion Systems (GECS), 2017, pp. 1-5, doi: 10.1109/GECS.2017.8066271.
[9] S. Bucko, et al., "Modulation of Staphylococcus Aureus Biofilm by Elecromagnetic Radiation," 2020. In: The journal of microbiology, biotechnology and food sciences. - Nitra (Slovensko) : Fakulta biotechnológie a potravinárstva, 2011 Roč. 9, č. 5 (2020), 1020-1022 [online]. - ISSN 1338-5178
[10] N. Das, A. Al Ghadeer and S. Islam, "Modelling and analysis of multi-junction solar cells to improve the conversion efficiency of photovoltaic systems," 2014 Australasian Universities Power Engineering Conference (AUPEC), 2014, pp. 1-5, doi: 10.1109/AUPEC.2014.6966482.
[11] J. Zbojovský, A. Mészáros, P. Kurimský, "Modelling the high frequency electromagnetic field propagation through the polystyrene, 2015," In: Elektroenergetika 2015. - Košice : TU, 2015 S. 556-559, ISBN 978-80-553-2187-5.
[12] A. H. Hasani, S. F. Abdullah, A. W. Mahmood Zuhdi, M. S. Bahrudin, F. Za'abar and M. N. Harif, "Modelling and Simulation of Photovoltaic Solar Cell using Silvaco TCAD and Matlab Software," 2018 IEEE International Conference on Semiconductor Electronics (ICSE), 2018, pp. 214-217, doi: 10.1109/SMELEC.2018.8481307.
[13] M. Bereš, D. Schweiner, I. Kováčová and A. Kalinov, "Current ripple comparison of multi and single phase Buck-boost converters," 2017 International Conference on Modern Electrical and Energy Systems (MEES), 2017, pp. 260-263, doi: 10.1109/MEES.2017.8248905.
[14] J. Dudas, M. Guzan, S. Gabani, et al., "Electric charge transport anomalies in holmium and thulium thin films at low temperatures," In: Czechoslovak Journal of Physics. Vol. 54, suppl. D (2004), p. D253-D256. - ISSN 0011-4626.
[15] A. Zielińska, M. Skowron and A. Bień, "Modelling of photovoltaic cells in variable conditions of temperature and intensity of solar insolation as a method of mapping the operation of the installation in real conditions," 2018 International Interdisciplinary PhD Workshop (IIPhDW), 2018, pp. 200-204, doi: 10.1109/IIPHDW.2018.8388357.
[16] M. Ivančák et al., "Modelling microgrid as the basis for creating a smart grid model," In: Przegląd Elektrotechniczny. Warsaw: Stowarzyszenie Elektrykow Polskich, 1919 Vol.95, No. 8 (2019), pp. 41-43 [print]. ISSN 0033-2097. Doi:10.15199/48.2019.08.11.
[17] P. Jacko, D. Kováč, R. Bučko, T. Vince and O. Kravets, "The parallel data processing by nucleo board with STM32 microcontrollers," 2017 International Conference on Modern Electrical and Energy Systems (MEES), 2017, pp. 264-267, doi: 10.1109/MEES.2017.8248906.
[18] Medveď, D., "Temperature field distribution analysis of electrical contacts for high-current equipment," In: Proceedings of the IEEE 2nd International Conference and Workshop in Óbuda on Electrical and Power Engineering. New York (USA): Institute of Electrical and Electronics Engineers, pp. 137-141 [online]. ISBN 978-1-7281-4358-3. Doi: 10.1109/CANDO-EPE47959.2019.9110966.
[19] D. Medveď et al., "Reducing the impact of transient phenomena of arc furnace on power network operation," In: EPE 2019 : Proceedings of the 20th International Scientific Conference on Electric Power Engineering. Ostrava: VŠB – Technická univerzita Ostrava, pp. 1-5 [USB-key]. ISBN 978-1-7281-1333-3. Doi: 10.1109/EPE.2019.8778130.
[20] S. Tumański, "Modern magnetic field sensors – a review," *Przegląd Elektrotechniczny*, Vol. 2013, No. 10, pp. 1-12, ISSN 0033-2097
[21] AJ. Drzymala, E. Korzeniewska," Profitability of solar photovoltaic investment in the light of the new act on renewable energy in Poland," *Przegląd Elektrotechniczny*, Vol. 2020, No. 96, pp. 210-213, ISSN 0033-2097, DOI 10.15199/48.2020.01.47.
[22] L. Topolski et al., " Limitation of voltage swells and unbalance caused by single-phase photovoltaic microinstallations using a series automatic voltage regulator in a low-voltage network," *Przegląd Elektrotechniczny*, Vol. 2020, No. 96, pp. 37-41, ISSN 0033-2097, DOI 10.15199/48.2020.03.10.
[23] K. Necka et al., " Characteristics of the electrical energy quality in a municipal service facility cooperating with photovoltaic microinstallation," *Przegląd Elektrotechniczny*, Vol. 2020, No. 96, pp. 56-591, ISSN 0033-2097, DOI 10.15199/48.2020.02.12.