UDC 621.316.7

https://doi.org/10.33271/nvngu/2021-1/111

Ya. V. Batsala,
orcid.org/0000-0003-4964-407X,
I. V. Hlad,
orcid.org/0000-0002-8247-655X,
I. I. Yaremak,
orcid.org/0000-0002-0698-0367,
O. I. Kiianiuk,
orcid.org/0000-0001-9959-5822

Ivano-Frankivsk National Technical University Oil and Gas, Ivano-Frankivsk, Ukraine, e-mail: batsala2012@gmail.com

MATHEMATICAL MODEL FOR FORECASTING THE PROCESS OF ELECTRIC POWER GENERATION BY PHOTOELECTRIC STATIONS

Purpose. Improving the efficiency of photovoltaic power plants in power systems by creating a model for forecasting the amount of electricity produced in the form of a harmonic function and determining the prospects for using the selected mathematical software to develop software applications.

Methodology. To determine the amount of electricity generated by photovoltaic plants per day and year, statistical methods are applied using the harmonic function which allows taking into account the main meteorological factors of power change of photomodules. A technique is proposed for taking into account the level of generation by photovoltaic stations to track changes in voltage levels in the connection nodes.

Findings. Mathematical models for forecasting the electricity generation of photovoltaic stations for different time ranges are built. The influence of weather factors, the length of daylight and the structure of the local generation system on the level of electricity generated by photovoltaic plants is investigated. Necessity is conditioned to use a harmonic function for forecasting the amount of electricity produced, which improves the efficiency of calculations for new and existing power plants.

Originality. The factors of the influence of daylight hours and cloudiness on the level of electricity generation by photovoltaic stations are taken into account, as well as meteorological data that make it possible to predict the value of the amount of electricity generated for a certain period of time. The dependences of the amount of generated electricity by photovoltaic stations are obtained in the form of a harmonious function with reference to a coefficient that takes into account the cloud level for predicting generation volumes.

Practical value. Created mathematical models of forecasting by means of harmonic function and analysis of voltage change in nodes of local networks allow increasing the efficiency of photovoltaic stations, simplify calculation of change of levels of voltages in a electric network, the forecasted values of the generated electric power on the “day ahead” system on the basis of duration of the light day, meteorological data and other external factors at commissioning of photovoltaic stations.

Keywords: *photovoltaic station, harmonic function, ARIMA model, energy efficiency, local generation*

Introduction. The paradigm shift in the energy sector of Ukraine and the world impugns current model of energy business through a gradual transition to renewable energy sources (RES). The large-scale challenges facing Ukraine’s energetics and economy have led to a crisis with electricity surpluses and the need to restructure the energy market. The universality of solar energy consists in the fact that by attracting investment we can get an energy source that does not require the presence of fields. This can lead to changes in the global world energy order, so for the energy sector of Ukraine it is important to attract promising technologies and models of industry development.

Increasing the share of photovoltaic power stations (PPS) in the power system leads to the construction of modern power supply systems, which with the help of intelligent monitoring and control functions will be able to provide the necessary mode parameters with appropriate power quality and electromagnetic compatibility. The growing branching of local networks with PPS, improper choice of electrical equipment and the lack of a clear strategy for connecting new power plants lead to the fact that the consumer’s electricity quality is deteriorating, and variability of weather factors affects the growth (decrease) of voltage levels regarding permissible values. Since according to current legislation, electricity producers will have to pay for the imbalance of produced and declared (forecasted) electricity when working in the market “day ahead”, the creation of an adequate mathematical model for forecasting electricity generation of PPS will allow responding to the changes in meteorological factors and getting a better productivity in compliance with existing standards.

Literature review. Methods for forecasting the expected power of PPS with taking into account meteorological factors (cloudiness, temperature, humidity, precipitation) are given in the works by Maurisio Soto, Xiao Qu, Rohini Kapoor, Travis Galoppo [1], Lezhnyuk P. D., Komar V. O., Kravchuk S. V., Bandura I. O. [2] and F. Mei, Y. Pan, K. Zhu and J. Zheng [3]. The peculiarities of the application of various methods are presented in the publication [4], and their choice depends on the time range and the possibility of using statistics, probabilistic weather forecasting (NWP), as well as satellite imaging.

Forecasting of the level of electricity generation of PPS depends on the forecast of meteorological data, and therefore it is advisable to use statistical methods for short-term forecasting based on time series using the Box-Jenkins methodology [5, 6]. This method is based on autocorrelation functions, consists of identification, evaluation and prediction. Since the generation process is a non-stationary process, it must be brought to a stationary one using the autoregressive integrated moving average (ARIMA) model [5]. With this model, the values of a certain process coordinate at a given point in time are set based on their previous values, using the moving average operator, the backward shift operator per unit of time B, the differential backward shift operator per unit of time ∇ and the integration operator S^d. A time-discrete random process is described using the following operators and equations

$$Z_t = \nabla^{-d} w_t = S^d w_t; \quad \nabla Z_t = Z_t - Z_{t-1};$$

$$Z_{t-1} = BZ_t; \quad \nabla = 1 - B.$$

In ARIMA models, each value of the series is linearly dependent on the previous values and the model error is a random component. For stationary series it is called "white noise". A number of assumptions have also been made that the factors that influenced the formation of meteorological factors will continue to operate.

Unsolved aspects of the problem. To achieve this goal it is necessary to develop a mathematical model for predicting electricity generation by photovoltaic plants based on statistics, daylight hours, and cloudiness using meteorological applications and determine the dependences of the amount of electricity generated in the form of harmonic functions and ARIMA model.

Results. Statistical data on the power generation process of PPS with single-crystal panels during 2014–2016 and 2019 were obtained using the program "Energycenter" of PJSC "Prykarpattiaoblenerho". For a larger sample, open resources of online monitoring of electricity generation of roof PPS with a capacity of 1.55 kW, installed in Tlumach, Ivano-Frankivsk region, were also used [7]. All statistic data are brought to a power of 1 kW.

As a result of mathematical processing of statistical data of the amount of electricity generated by PPS and the duration of daylight, the dependences which are described by a harmonic function were obtained. The amount of electricity generated by the PPS on any day of the year is determined by formula

$$W_{G_i} = W_{G0}\sin(\delta + \varphi) \pm k_1 W_{Ci} \pm \Delta W_{Ti},$$

where W_{G0} is the maximum value of the amount of electricity generated by the PPS per day according to statistics, kWh; δ is the coefficient of generation time, which characterizes the dependence of the increase in the duration of daylight on the amount of generated electricity of PPS and varies from 0° to 180° during the year; φ is the value that takes into account the beginning of the reference (the day of increasing of the duration of daylight); $k_1 = \dfrac{|T_c - T_i|}{T_c}$ is the coefficient that characterizes the level of cloudiness (a relative number of sunny hours) of a given day and depends on meteorological data; T_i is the number of absolutely clear hours of sunshine for the selected day of the year, h; T_c is the average number of sunny hours of a given day (month) according to statistical meteorological data, h; W_{Ci} is the average amount of electricity generated by PPS in a given day (month) according to statistical data, $\text{kW} \cdot \text{h}$; ΔW_{Ti} is deviation of the amount of generated electricity when changing temperature values, kWh.

We illustrate the plot of average values of the amount of generated electricity of PPS with a capacity of 1 kW and the curve of the harmonic function, which is brought to this power.

The abscissa represents both the days of the year and the coefficient of generation time δ (Fig. 1). The maximum duration of daylight in the city of Ivano-Frankivsk is observed in the period from 19 to 21 June (16 hours 12 minutes).

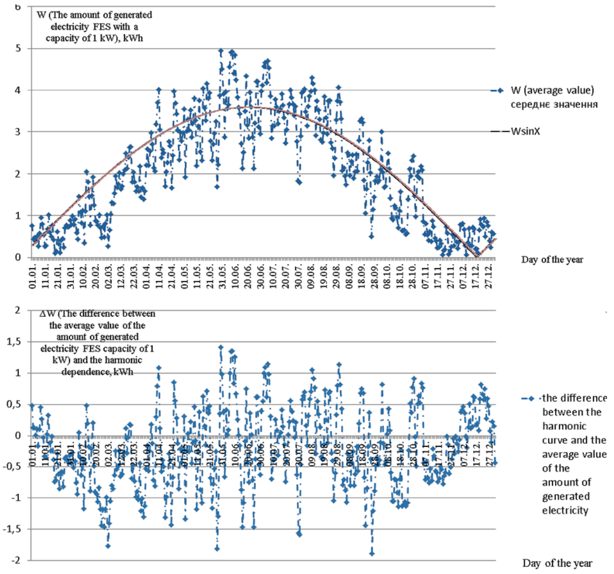

Fig. 1. Illustration of the deviation of the average values of the generated active electricity of PPS with a capacity of 1 kW from the harmonic function

Relative to the point with coordinates [July 20; $\delta = 90°$] a curve $f(x) = W_{G0}\sin\delta$ is drawn. The minimum duration of daylight 8 hours 14 minutes will be observed at the beginning and end of the year, namely on December 18–23, the increase in daylight begins again (Fig. 1).

The value of the amount of energy generated by the PPS every i^{th} day is described by equation in the period from January 1 to December 17,

$$W_{G_i} = W_{G_{\max}} \sin\left(\frac{y+8}{2}\right)^{\circ} \pm k_1 W_{Ci},$$

where y is the ordinal number of the day of the year, formula is used for the values of $y = 1 - 352$.

In the period from December 18 to December 31 we use equation

$$W_{G_i} = W_{G_{\max}} \sin\left(\frac{y-352}{2}\right)^{\circ} \pm k_1 W_{Ci},$$

accordingly we take ($y = 353 - 365$).

To verify the adequacy of the proposed mathematical model for forecasting the amount of generated electricity of PPS, meteorological data from the server Meteoblue [8] was used. This server contains information about weather conditions for the selected city for a period of 30 years, which allows us to get average temperatures and clear hours, to perform a comparative analysis of the accuracy of models on the following parameters: ambient temperature, precipitation, cloudiness, wind speed, and so on. Meteorological forecast statistics are generated using the information website [9].

The accuracy of PPS electricity generation forecasting models decreases with increasing of the time period for which the weather is forecasted. For the "day ahead" forecast for clear (cloudless) days, the accuracy of the model is 95 %, but for cloudy days it can be reduced to 50 % and depends on how accurately the information website [9] will indicate cloudiness and other parameters of a given day.

Figs. 2–4 show graphs of the dependence of the generated electricity of PPS W_G, kW during the day for April (Fig. 2), May (Fig. 3) and June (Fig. 4) 2020, as well as projected data according to the "day forward" forecast and according to the available values of meteorological data.

In April 2020 (Fig. 2), the weather was abnormally clear and warm, the average temperature increased by 2 °C, the

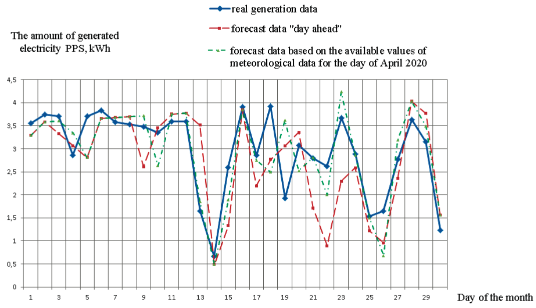

Fig. 2. Graphs of generated active electricity of PPS:
1 – real generation data; 2 – forecast data “day ahead”; 3 – forecast data based on the available values of meteorological data for the day of April 2020

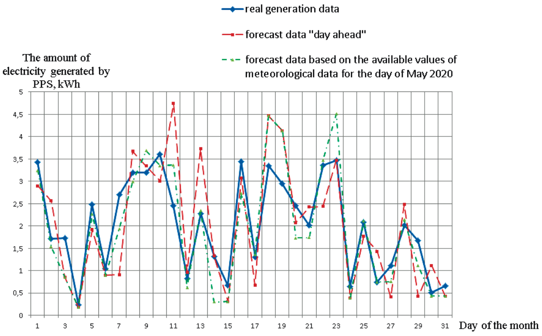

Fig. 3. Graphs of PPS electricity generation and projected generation values during the day of May 2020

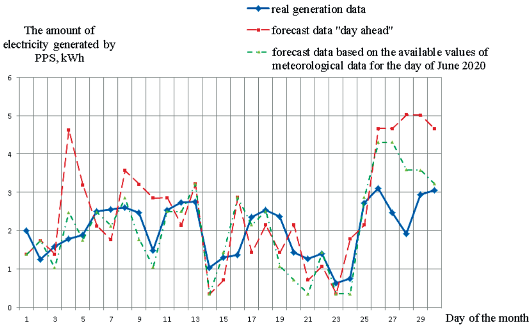

Fig. 4. Graphs of PPS electricity generation and projected generation values during the day of June 2020

amount of precipitation decreased by 2 times, the electricity generation of PPS increased respectively by 27 %.

On the contrary, May and June 2020 were the coldest months in Prykarpattia region, according to the observations of weather forecasters for the last 16 years. Due to the increase in the number of cloudy days and precipitation, the average number of hours of sunshine decreased significantly, as did the amount of electricity generated by PPS (decreased by 16 and 18 % relatively to the average values).

The synthesis of statistical data for PPS with a capacity of 1 kW for daily generation of each month of the year in terms of half-hour intervals is illustrated in Fig. 5.

The obtained array of statistical data in sections of day and month is necessary for modeling and forecasting the generation of PPS during a given day and balancing the modes of local electrical networks with storage and in Solar Storage systems [10, 11].

The search of instantaneous values of current and voltage, and accordingly the power of PPS also depends on the ambient temperature T_i, the actual temperature on the sensor of the photomodule T_{PV}, and the magnitude of solar insolation E_β and is calculated by direct use of information about weather or is determined by formulas

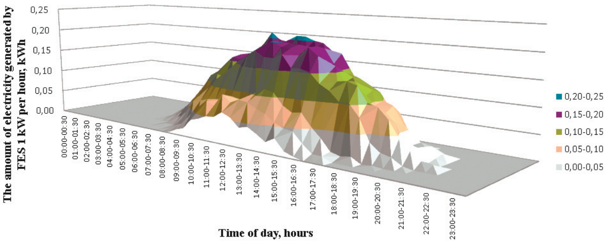

Fig. 5. Graph of the dependence of the amount of electricity generated by PPS with a capacity of 1 kW on the month and time of a day

$$P_{PV} = N \cdot FF \cdot U_{PV} I_{PV};$$

$$FF = \frac{U_{MPP} I_{MPP}}{U_X I_K}; \tag{1}$$

$$I_{PV} = \frac{I_\beta}{I_K}\left(I_K + k_i(T_0 - 25)\right);$$

$$I_\beta = (E,T) = \frac{E_\beta}{E_N} \cdot I_K + k_I(T_i - T_{PV});$$

$$U_{PV} = U_X - k_U\left(T_i + E_\beta \frac{(T_0 - 20)}{800}\right),$$

where N is the number of photomodules; FF is the coefficient (full factor); U_{MPP} is voltage when searching for maximum power (MPPT – Maximum power point tracker); I_{MPP} is current of MPPT; $\frac{E_\beta}{E_N}$ is the ratio of the actual value of solar insolation to the normalized value of solar insolation; I_β is current at a given solar insolation, A; T_0 is the temperature on the sensor of the photomodule at an ambient temperature of 20 °C, solar insolation of 800 W/m^2 and wind speed of 1 m/s; T_{PV} is the temperature on the surface of the photomodule, °C; I_K is short circuit current; U_X is idle voltage; k_i is the current-temperature coefficient, A/°C; k_U is the voltage-temperature coefficient V/°C.

The sign (–) in equation (1) is used provided that $T_i < T_c$, the sign (+) for values $T_i > T_n$.

To build an autoregressive model, the graph of total average values of PPS electricity generation during the month in the context of half-hour intervals, which reflects a non-stationary discrete random generation process, is converted into a “stationary” one. For this purpose, the first difference of the adjacent values of the lattice function is determined. It is assumed that the generation process is constant and the daily schedule of generated electricity of PPS is presented in the form of a lattice function. The conversion of the graph for May 2020 is illustrated in Fig. 6.

ADF test (advanced Dickie Fuller test) is used to check the stationarity of a series.

To illustrate the finding, the forecast model in the form of autoregression Z_t for May 2020 is presented with the identified parameters

$$\sigma_\varepsilon = \sqrt{\sigma_\varepsilon^2} = 0.04; \quad \text{m} = 0.0016;$$

$$z_t = -1.071 z_{t-1} - 0.326 \varphi_2 z_{t-2} + \xi_t.$$

The disadvantage of the ARIMA model is its complexity, the need to bring the series to a stationary series, cumbersome adequacy checks, so it is proposed to use a predictive model using the harmonic function and coefficient of cloudiness.

To confirm the possibility of using a selected mathematical model, the reliability of the model is determined by formula

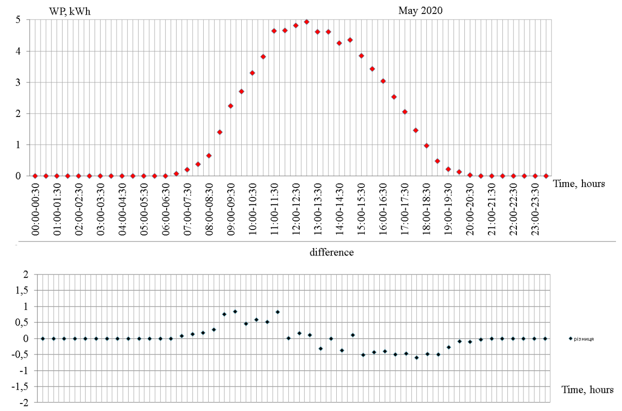

Fig. 6. Construction of autoregressive model

$$R = 1 - \frac{\sum (W_M - W_R)^2}{\sum (W_M^2) - \frac{1}{n}\sum (W_M)^2} = 0.99,$$

where W_M is the value obtained using the model; W_R is the real value of the amount of generated electricity of PPS.

According to the obtained characteristics of PPS electricity generation, it is possible to obtain the probability of compliance of the consumer load schedule with the renewable energy sources (RES) generation schedule, as well as to prevent disconnection of PPS by voltage regulation in case of noncompliance with normalized values of electricity quality and PPS inverter modes.

Since the inverter is disconnected if the voltage in the local network does not match the specified range of it, applying the technology of voltage adjustment using battery stations and automatic voltage regulation of the transformer, we get higher efficiency of the inverter and higher profitability of PPS. To balance the load graph, it is necessary to use more accurate data from local weather stations, but their efficiency due to the high cost may be unreasonable for local power plants. More promising is the use of "PPS-storage" models for load balancing. Using equipment and software is expediently used for a large number of powerful photovoltaic stations (more than 1 MW), with the help of control centers it is possible to create the correlation generating power received according to changes. Commercial products offer forecast updates from 3 to 15 hours in 15 minutes. Forecasting errors can lead to loss of profit, and the dynamic lag of changes in meteorological factors is more effective.

Using forecast models for photovoltaic systems with battery or supercapacitor [12] with single-phase PPS to load balancing will reduce asymmetry in local networks, and shifting the time of consumption of accumulated load will reduce its peaks. The setting of the battery charging process and its time should be related to the limitation of electricity generation during peak hours, but it is necessary to take into account the weather forecast, as it is not always possible to combine it in high clouds.

Using the Matlab Simulink environment and the model of the local network with PPS using the forecast model (Fig. 7), the voltage levels at the output of the inverters and in the network were obtained. It should be noted that intelligent voltage regulation in local networks is a promising area of development of electric power industry.

The model has practical value because it takes into account a number of historical meteorological data, cloudiness, and duration of daylight and, therefore, is suitable for practical engineering applications. In addition to the intensity of solar insolation and temperature, other factors related to changes in network parameters are estimated, but they are excluded from the model in order to simplify and reduce the number of calculations and increase efficiency.

Since the quality of electricity [12] affects the performance of electrical equipment and electromagnetic compatibility, the detection of network modes with unacceptable parameters and indicators of electricity quality will lead to more efficient operation and increased productivity. The use of the programming environment of virtual devices LabView [13] allows us to combine experimentally obtained parameters in real time of the model with a predictive model.

Conclusions. With the help of the developed mathematical model for forecasting the process of electricity generation by photovoltaic stations, the dependences of the generated electricity on the duration of daylight and meteorological factors were determined by the calculation-experimental method.

It is established that the accuracy of the mathematical model of forecasting the process of generating electricity of PPS increases with an increasing number of sunny hours during the day and the accuracy of weather forecasts.

The obtained results can be used for software applications for forecasting the amount of generated electricity of PPS.

References.

1. Maurisio Soto, Xiao Qu, Rohini Kapoor, & Travis Galoppo (2019). Applying Data Science to Improve Solar Power Production and Reliability. *INFORMS Workshop on Data Science,*

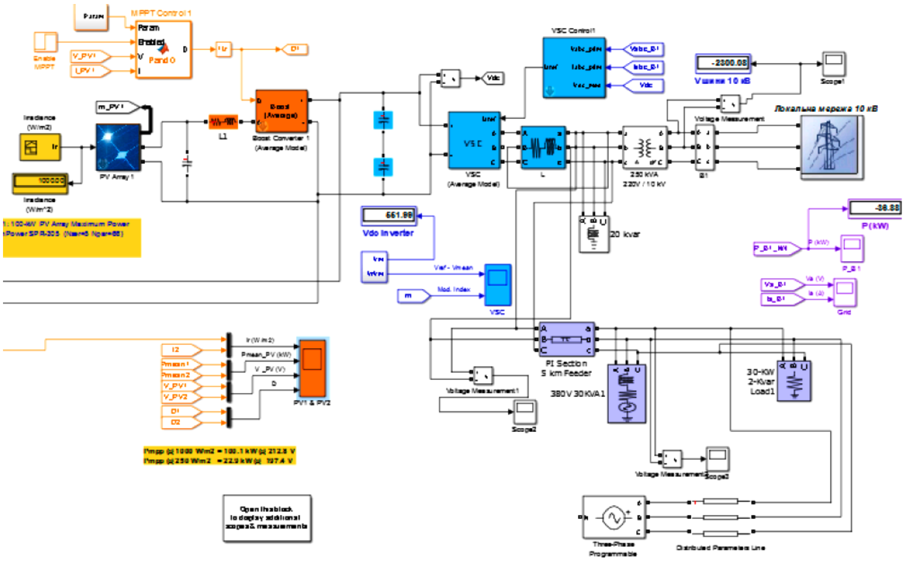

Fig. 7. Fragment of the model in Matlab Simulink to determine the network voltage levels

1-12. Retrieved from https://www.cs.cmu.edu/~msotogon/Papers/ApplyingDataScience2019.pdf.

2. Lezhniuk, P. D., Komar, V. O., Kravchuk, S. V., & Didichenko, Ye. S. (2017). Analysis of meteorological parameters for hourly forecasting of electricity generation by photovoltaic power plants for the day ahead. *Enerhetyka ta kompiuterno-intehrovani tekhnolohii v APK, 1*(6), 27-31. Retrieved from http://dspace.khntusg.com.ua/bitstream/123456789/2183/1/8.pdf.

3. Mei, F., Pan, Y., Zhu, K., & Zheng, J. (2018). A hybrid online forecasting model for ultrashort-term photovoltaic power generation", *Sustainability, 10*(3), 820. https://doi.org/10.3390/su10030820.

4. Tuohy, A., Zack, J., Haupt, S. E., Sharp, J., Ahlstrom, M., Dise, S., ..., & Collier, C. (2015). Solar Forecasting: Methods, Challenges, and Performance. *IEEE Power and Energy Magazine*, *13*(6), 50-59. https://doi.org/10.1109/MPE.2015.2461351.

5. Demchyk, Ya. M., & Rozen, V. P. (2019). Estimation of error of forecast models and forecasts of consumed electricity at energy market facilities. *Power Engineering: economics, technique, ecology*, (4), 69-78. https://doi.org/10.20535/1813-5420.4.2019.200489.

6. Dzendzeliuk, O., Kostiv, L., & Rabyk, V. (2013). Developing ARIMA time series models for forecasting meteorological data in a programing language R. *Electronics and information technologies*, *3*, 211-219.

7. *Sunny Portal. PV System Data* (n.d.). Retrieved from https://www.sunnyportal.com/Templates/PublicPage.aspx?page=0fa455f6-64b8-4475-b66e-b01cb5a0836d.

8. *Meteoblue delivers local weather information* (n.d.). Retrieved from https://www.meteoblue.com/.

9. WetterRadar & Warnungen. Wetter Online Meteorologische Dienstleistungen GmbH. Retrieved from https://www.weatherandradar.com/apps/.

10. Lezhniuk, P. D., Komar, V. O., & Kravchuk, S. V. (2016). Estimation of probabilistic characteristics of solar power plant generation in the problem of intellectualization of local electrical systems. *Visnyk NTU "KhPI"*, (18), 92-100.

11. Lezhniuk, P. D., Komar, V. O., Kravchuk, S. V., & Bandura, I. O. (2019). Photovoltaic stations with storage as an element of balancing mode in the local power system. *Naukovi notatky. Lutsk*, (65), 129-136. Retrieved from http://notatki.com.ua.

12. Javed, K., Ashfaq, H., Singh, R., Hussain, S. S., & Ustun, T. S. (2019). Design and Performance Analysis of a Stand-alonePV System with Hybrid Energy Storage for Rural India. *Electronics, 8*(952), 16. https://doi.org/10.3390/electronics8090952.

13. Hlad, I. V., & Batsala, Ya. V. (2017). Influence of solar power plants on low-voltage distribution networks. *Enerhetyka. Ekonomika, tekhnolohii*, (3), 119-123. https://doi.org/10.20535/1813-5420.3.2017.117378.

14. Fedoriv, M. Y. (2017). Increasing reliability and energy efficiency of electric driven boring units. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (2), 93-98.

15. Weniger, J., Bergner, J., & Quaschning, V. (2014). Integration of PV Power and Load Forecasts into the Operation of Residential PV Battery Systems. *Conference 4th Solar Integration Workshop at Berlin*, 1-9. https://doi.org/10.13140/2.1.3048.9283.

Математична модель прогнозування процесу генерування електроенергії фотоелектричними станціями

Я. В. Бацала, І. В. Гладь, І. І. Яремак, О. І. Кіянюк

Івано-Франківський національний технічний університет нафти і газу, м. Івано-Франківськ, Україна, e-mail: batsala2012@gmail.com

Мета. Підвищення економічності роботи фотоелектричних станцій в енергетичних системах шляхом створення моделі прогнозування кількості виробленої електроенергії у вигляді гармонічної функції та визначення перспектив щодо використання обраного математичного забезпечення для розробки програмних додатків.

Методика. Для визначення кількості згенерованої електроенергії фотоелектричними станціями за добу та рік використано статистичні методи із застосуванням гармонічної функції змінної часу, що дозволяє врахувати основні метеорологічні чинники зміни потужності фотомодулів. Запропонована методика врахування впливу генерування електроенергії фотоелектричними станціями на параметри електричної мережі придатна для відстеження зміни рівнів напруг у вузлах приєднання.

Результати. Побудовані математичні моделі прогнозування виробітку електроенергії фотоелектричними станціями для різних часових діапазонів. Досліджено вплив погодних чинників, тривалості світлового дня та структури системи локальної генерації на кількість згенерованої електроенергії фотоелектричними станціями. Обумовлена необхідність використання гармонічної функції для прогнозування кількості виробленої електроенергії, що покращує ефективність розрахунків для нових і вже існуючих електростанцій.

Наукова новизна.Ураховані фактори впливу тривалості світлового дня й рівня хмарності на рівень генерування електроенергії фотоелектричними станціями, а також метеорологічні дані, що дають змогу спрогнозувати значення кількості згенерованої електроенергії для визначеного проміжку часу. Отримані залежності кількості згенерованої електроенергії фотоелектричними станціями у вигляді гармонічної функції з урахуванням коефіцієнта, що враховує рівень хмарності для прогнозування обсягів генерування.

Практична значимість. Створені математичні моделі прогнозування за допомогою гармонічної функції та аналізу зміни напруг у вузлах локальних мереж дозволяють підвищити ефективність фотоелектричних станцій, спрощують розрахунок зміни рівнів напруг у мережі та прогнозованих значень згенерованої електроенергії за системою «доба наперед» на основі тривалості світлового дня, метеорологічних даних та інших зовнішніх чинників при введенні фотоелектричних станцій в експлуатацію та при їх роботі в енергосистемі.

Ключові слова: *фотоелектрична станція, гармонічна функція, ARIMA модель, енергоефективність, локальна генерація*

Математическая модель прогнозирования процесса генерирования электроэнергии фотоэлектрическими станциями

Я. В. Бацала, И. В. Гладь, И. И. Яремак, А. И. Киянюк

Ивано-Франковский национальный технический университет нефти и газа, г. Ивано-Франковск, Украина, e-mail: batsala2012@gmail.com

Цель. Повышение эффективности работы фотоэлектрических станций в энергетических системах путем создания модели прогнозирования количества произведенной электроэнергии в виде гармоничной функции и определение перспектив по использованию избранного математического обеспечения для разработки приложений.

Методика. Для определения количества сгенерированной электроэнергии фотоэлектрическими станциями в сутки и год используются статистические методы с применением гармоничной функции, которая позволяет учесть основные метеорологические факторы изменения мощности фотомодулей. Предложенная методика для учета уровня генерирования фотоэлектрическими станциями пригодна для отслеживания изменения уровней напряжений в узлах присоединения.

Результаты. Построены математические модели прогнозирования выработки электроэнергии фотоэлектрическими станциями для различных временных диапазонов. Исследовано влияние погодных факторов, продолжительности светового дня и структуры системы локальной генерации на количество сгенерированной электроэнергии фотоэлектрическими станций. Обусловлена необходимость использования гармоничной функции для прогнозирования количества произведенной электроэнергии, что улучшает эффективность расчетов для новых и уже существующих электростанций.

Научная новизна. Учтены факторы влияния продолжительности светового дня и уровня облачности на уровень генерирования электроэнергии фотоэлектрическими станциями, а также метеорологические данные, которые позволяют спрогнозировать значение количества сгенерированной электроэнергии для определенного промежутка времени. Получены зависимости количества сгенерированной электроэнергии фотоэлектрическими станциями в виде гармоничной функции с учетом коэффициента, который учитывает уровень облачности для прогнозирования объемов генерации.

Практическая значимость. Созданные математические модели прогнозирования с помощью гармоничной функции и анализа изменения напряжений в узлах локальных сетей позволяют повысить эффективность фотоэлектрических станций, упрощают расчет изменения уровней напряжений в сети, прогнозируемых значений сгенерированной электроэнергии по системе «на сутки вперед» на основе продолжительности светового дня, метеорологических данных и других внешних факторов при введении фотоэлектрических станций в эксплуатацию и работе в энергосистеме.

Ключевые слова: *фотоэлектрическая станция, гармоническая функция, ARIMA модель, энергоэффективность, локальная генерация*

Recommended for publication by V.S. Kostyshyn, Doctor of Technical Sciences. The manuscript was submitted 17.07.20.