Вирішено задачу визначення вагових коефіцієнтів оптимальної системи автоматичного керування рівнем генерації електричної енергії відновлювальних джерел енергії в комбінованій електроенергетичній системі. Встановлено, що існуючі системи керування генерацією електроенергії відновлюваних джерел, що базуються на розв'язку задачі багатокритеріальної оптимізації, не враховують зміну з часом кількісного та якісного складу електроспоживачів.

Запропоновано для визначення вагових коефіцієнтів, що впливають на кінцевий розв'язок задачі багатокритеріальної оптимізації, використати математичний апарат нечіткої логіки. Це дозволило, на відміну від існуючих систем, в більш повній мірі врахувати зміну з часом кількісного та якісного складу електроспоживачів. Показано, що в якості вхідних параметрів нечіткої моделі найдоцільніше обрати значення коефіцієнту завантаження споживачів та коефіцієнту важливості навантаження, що враховує чутливість електроспоживачів до відхилень напруги.

Складено базу правил нечіткої системи визначення вагових коефіцієнтів, яка налічує 15 правил нечіткої продукції. В якості алгоритму нечіткого логічного виводу використано алгоритм Мамдані. Для визначення вхідних та вихідних лінгвістичних змінних використано трикутні і трапецієподібні функції приналежності. Дефазифікація вихідного параметру здійснювалась методом визначення центру ваги (центроїдним методом).

Проведено комп'ютерне імітаційне моделювання оптимальної системи автоматичного керування рівнем генерації електричної енергії відновлювальних джерел енергії з розробленим нечітким блоком визначення вагових коефіцієнтів. Аналіз результатів моделювання показав, що розроблена система автоматичного керування дозволяє підвищити рівень генерації електроенергії в мережу, порівняно з існуючими системами

Ключові слова: система автоматичного керування, відновлювані джерела енергії, розподільна електрична мережа, нечітка логіка

UDC 621.316.13
DOI: 10.15587/1729-4061.2020.193362

DETERMINING WEIGHT COEFFICIENTS FOR AN OPTIMAL SYSTEM OF CONTROL OVER ELECTRIC ENERGY GENERATION IN A COMBINED ELECTRIC POWER SYSTEM

P. Plieshkov
PhD, Professor, Head of Department*
E-mail: inbox@ets.kr.ua
V. Soldatenko
PhD, Lecturer*
E-mail: kirovograd41@gmail.com
V. Zinzura
PhD, Associate Professor*
E-mail: vasiliyzinzura@gmail.com
S. Plieshkov
PhD, Associate Professor
Department of Automation
of Production Processes**
*Department of Electrical Systems
and Energy Management**
**Central Ukrainian National Technical University
Universytetskyi ave., 8, Kropyvnytskyi,
Ukraine, 25006

Received date 19.12.2019
Accepted date 23.01.2020
Published date 28.02.2020

1. Introduction

The current stage of world energy generation development demonstrates tendencies towards a significant increase in the deployment of electric energy generating installations with renewable energy sources (RES). The most widely used are solar (SPP) and wind electric plants (WPP). In addition, enterprises in the agro-industrial sector exploit biogas power plants (BGP), operating on wastes of vegetable and animal origin. The main purpose of using these installations is to reduce payment for the consumed electricity at the expense of generating it onsite. In addition, electricity generation under a "green" tariff significantly shortens the payback period of RES-based installations.

A connection point of RES installations to an electrical distribution network (EDN) in most cases coincides with the point that connects an electric load. This leads to that under a mode of electric energy generation one observes excess values of the steady-state voltage deviation at a point that connects installations with RES to EDN [1].

Analysis of existing automated control systems (ACS) at RES-based installations has revealed that almost all ACS execute control laws aimed at limiting the level of electricity generation to a network depending on the fixed value of the voltage setpoint. The disadvantage of such an approach to automated control is a significant reduction in cash revenues from the sale of electricity under a "green" tariff. Therefore, it is a relevant task to improve ACS for installations with RES in order to maximize the level of generation of electrical energy while maintaining the normally permissible values of the steady-state voltage deviation in EDN.

2. Literature review and problem statement

Paper [2] proposed an ACS of operation mode for an integrated electric energy system (IEES), which includes the solar and wind power plants. In a given IEE a photovoltaic battery and a wind turbine are the main energy sources that cover the controlled and uncontrolled load. A lead-acid battery is used to compensate for power fluctuations (excess or shortage) and to implement a general power management strategy. ACS productivity is estimated during actual operation of the power system: data from various subsystems are recorded and analyzed with the help of data collection units and used for daily forecasting of electricity consumption. The disadvantage of the ACS proposed in [2] is the need to use a lead-acid battery, as well as disregard of the impact of electricity generation to a network at the level of steady-state voltage deviation.

Work [3] proposed an ACS of IEES operation mode, which is based on a proportional-integral law for controlling voltage and network frequency values. In this case, the optimum values for PI-controller parameters are determined in real time by using the Grasshopper Optimization Algorithm. This approach ensures improved dynamic characteristics of ACS under conditions of alternating load. Paper [4] describes a similar approach to the automated control over IEES operating mode, but the Salp Swarm Optimization Algorithm is used to optimize PI-controller parameters. In work [5], in order to optimize the PI-controller parameters, which ensures the stabilization of the steady deviation of voltage and frequency in IEES, it is proposed to use the Pareto-based Big Bang-Big Crunch algorithm, based on the ideas from methods of multi-criteria optimization. The common drawback of ACSs, described in [3–5], is the disregard of the influence of electricity generation to an electrical network on the value for the steady-state voltage deviation at the point that connects installations to RES.

Article [6] described a microprocessor ACS of IEES operating mode, which includes its own system of distribution, control, and monitoring of consumed and RES-generated energy. The algorithm of a given ACS implies RES connection to an electric network only if the power consumption from the electric network exceeds the predefined limit. An ACS described in [6] almost does not allow the occurrence of excess values of the steady-state voltage deviation by generating electricity from RES to the network. However, the implementation of this approach to automated control significantly reduces profit from generating electricity to a network under a “green” tariff.

Paper [7] proposed an optimum control system of IEES mode, which ensures normal permissible levels of voltage deviation and minimization of power losses within an electrical distribution network. However, the ACS described in [7] considers only seasonal changes in power flows from renewable energy sources and does not take into consideration a time-dependent change in the quantitative and qualitative composition of electric consumers over 24 hours, which, under certain conditions, can lead to the excess values of steady-state voltage deviation.

Work [8] proposed an approach to the automated control over the level of active power generation by installations with RES, which considers the level of the steady-state voltage deviation at the electric consumers’ buses. Underlying the ACS of the level of active power generation, reported in [8], is an algorithm that is based on the solutions to a multi-criteria optimization problem. However, the disadvantage of this approach is, first of all, the lack of substantiation of the choice of weight coefficients, whose values affect both deriving the final solution to the specified problem (optimum control vector) and the effectiveness of ACS operation in general. Given this, there is a need to undertake a more detailed research in this area.

3. The aim and objectives of the study

The aim of this study is to devise a technique to determine the weight coefficients for a system of control over the operational mode of renewable energy sources, which takes into consideration a time-dependent change in the quantitative and qualitative composition of electric consumers.

To accomplish the aim, the following tasks have been set:

– to construct an algorithm for determining the weight coefficients for the final solution to the problem on optimum control over power generation by RES in IEES;

– to develop a computer simulation model of the ACS of the level of electricity generation by plants with RES and, by using it, to determine a possible effect from the application of a given ACS.

4. Studying the system of automated control over electricity generation by renewable sources within an integrated electricity power system

4. 1. Construction of an algorithm for determining weight coefficients in a system of automated control over electricity generation by renewable sources

One of the ways to improve the operational efficiency of IEES with RES, namely to increase the level of electricity generation by RES at a negligible deterioration in the quality of electricity, is to improve their ACSs.

As shown in [8], a problem on the simultaneous maximization of the level of electric power generation by plants with RES and the minimization of losses from excess values of steady-state voltage deviation should be interpreted as the problem of multi-criteria optimization [8, 9]:

$$\begin{cases} Q_1\left(P_{\text{gen}}\right) = -\text{INC}\left(P_{\text{gen}}\right) \to \min; \\ Q_2\left(P_{\text{gen}}\right) = \text{LOS}_{\Delta U}\left(P_{\text{gen}}\right) \to \min; \\ P_{\text{gen}} \in \left[P_{\min} \ldots P_{\max}\right], \end{cases} \tag{1}$$

where Q_1, Q_2 are the optimization criteria; P_{gen} is the power generated by installations with RES to a power grid; $[P_{\min} \ldots P_{\max}]$ is the range of permissible values for P_{gen}; $\text{INC}(P_{\text{gen}})$ is the income from generating electric power by installations with RES under a “green” tariff; $\text{LOS}_{\Delta U}(P_{\text{gen}})$ are the economic losses from excess values of steady-state voltage deviation at the clamps of electric consumers:

$$\text{LOS}_{\Delta U}\left(P_{\text{gen}}\right) = a_1\left(\Delta U\left(P_{\text{gen}}\right) + a_2\right)^2 \frac{S_{\text{load}}}{S_{\text{load max}}}, \tag{2}$$

where $\Delta U\left(P_{\text{gen}}\right)$ is the value of a steady-state voltage deviation at the clamps of electric consumers; a_1, a_2 are the constant coefficients, determined by the qualitative composition of electric consumers; S_{load} is the current value of a load full power; $S_{\text{load max}}$ is the maximum value of a load full power.

As shown by works [8, 9], it is advisable, for finding solutions to the problem of multicriterial optimization in form (1), to apply a method of approximation to the utopian point in a criteria space, which is implemented in 2 stages:

Stage 1. The result of minimization of each criteria (1) is the derived coordinates for an utopian point $Q_{ut}=(Q_{ut1}, Q_{ut2})$ within the optimization criteria space $Q\subset\mathbb{R}^2$.

Stage 2. By solving a series of problems on minimizing distance ρ from the utopian point to the Pareto-optimal set of solutions in the criteria space one finds the coordinates for a solution to the problem of multicriterial optimization P_{gen}^{opt} within a control space $P^{opt}\subset\mathbb{R}^1$.

An expression for finding the final solution to problem (1) for the case of minimizing the Chebyshev distance takes the form:

$$\begin{cases} F\left(P_{gen}\right)=\max\begin{Bmatrix} k_1\left[Q_1\left(P_{gen}\right)-Q_{ut1}\right], \\ k_2\left[Q_2\left(P_{gen}\right)-Q_{ut2}\right] \end{Bmatrix}\to\min; \\ P_{gen}\in\left[P_{\min}\dots_{\max}\right], \end{cases} \tag{3}$$

where k_1 and k_2 are the weight coefficients that account for the relative importance of each criteria; the following ratio holds for the case of criteria normalization in expression (3):

$$k_1+k_2=1. \tag{4}$$

Paper [8] notes that the values of weight coefficients k_1 and k_2 are permanent and are chosen during operation depending on the power of RES installations and the quantitative and qualitative composition of load. However, such an approach to the choice of weight coefficients k_1 and a k_2 is not the most appropriate, as it does not take into consideration a change in the quantitative and qualitative composition of load. In addition, expression (2) holds only for the case when the largest specific share of load is produced by asynchronous motors. If load includes powerful consumers of other types, there are difficulties in determining constant coefficients a_1, a_2.

Promising in an approach whereby values for weight coefficients k_1 and k_2 should be determined in real time depending on the quantitative and qualitative composition of equipment.

Given the relatively large number of factors that influence the value for these weight coefficients, construction of a traditional mathematical model, which would have a sufficient level of accuracy in describing their relationship with values for the qualitative and quantitative composition of electrical equipment, is almost impossible. Therefore, to solve a given problem, the most appropriate approach is based on the use of a mathematical apparatus of fuzzy logic [10].

To build such a fuzzy model, first of all, it is necessary to determine the quantities that most significantly affect the value of weight coefficients k_1 and k_2. In this case, based on expression (4), it is possible to confine ourselves to finding a value for only one weight coefficient (for example, k_2).

The input parameters for a fuzzy model are:

– a loading coefficient k_z of electric energy consumers, which makes it possible to consider the share of consumers of electric energy that are currently connected to the grid;

– a loading importance coefficient k_{imp}, taking into consideration the sensitivity of equipment of consumers of electrical energy to the excess values for a steady-state voltage deviation.

The output parameter for a fuzzy model is a weight coefficient k_2, which takes into consideration the relative importance of criterion Q_2 in optimization problem (1).

Table 1 shows the input and output parameters for a fuzzy model, as well as the ranges of change in their values.

Table 1

Values of the input and output parameters for a fuzzy model

No. of entry	Parameters	Parameter title	Change range	Terms
Model's input parameters				
1	k_z	Loading coefficient	0...1	very low (VL), low (L), medium (M), high (H), very high (VH)
2	k_{imp}	Loading weight coefficient	0...1	low (L), medium (M), high (H)
Model's output parameter				
1	k_2	Weight coefficient k_2	0...1	very low (VL), low (L), medium (M), high (H), very high (VH)

Flowchart of a fuzzy unit for determining the weight coefficient k_2 is shown in Fig. 1.

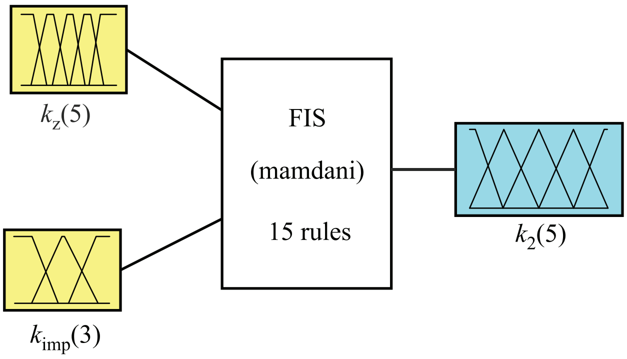

Fig. 1. Flowchart of a fuzzy unit for determining the weight coefficient k_2

Given the number of input and output variables, as well as the number of terms in each membership function, we compiled a fuzzy knowledge base, given in the form of Table 2.

To solve the set task, a chosen fuzzy algorithm was the Mamdani algorithm. This choice is due to that a given algorithm is the simplest one in terms of programming, and is characterized by simplicity and clarity of all its components.

When constructing a fuzzy model, we used membership functions of two types: triangular and trapezoidal. Graphical representation of the specified membership functions, as well as their numerical characteristics, are shown in Fig. 2–4.

Based on the constructed expert knowledge base, as well as the selected types of membership functions, we built fuzzy logic equations that take the following form:

$$\begin{aligned}&\mu^{VL}\left(k_2\right)=\left(\mu^{VL}\left(k_z\right)\cdot\mu^{L}\left(k_{imp}\right)\right)\vee\\&\vee\left(\mu^{VL}\left(k_z\right)\mu^{M}\left(k_{imp}\right)\right).\end{aligned} \tag{5}$$

$$\mu^{L}(k_2)=\left(\mu^{VL}(k_z)\cdot\mu^{H}(k_{\text{imp}})\right)\vee$$
$$\vee\left(\mu^{L}(k_z)\cdot\mu^{L}(k_{\text{imp}})\right)\vee\left(\mu^{L}(k_z)\cdot\mu^{M}(k_{\text{imp}})\right). \quad (6)$$

$$\mu^{M}(k_2)=\left(\mu^{L}(k_z)\cdot\mu^{H}(k_{\text{imp}})\right)\vee$$
$$\vee\left(\mu^{M}(k_z)\cdot\mu^{L}(k_{\text{imp}})\right)\vee\left(\mu^{M}(k_z)\cdot\mu^{M}(k_{\text{imp}})\right). \quad (7)$$

$$\mu^{H}(k_2)=\left(\mu^{M}(k_z)\cdot\mu^{H}(k_{\text{imp}})\right)\vee\left(\mu^{H}(k_z)\cdot\mu^{L}(k_{\text{imp}})\right)\vee$$
$$\vee\left(\mu^{H}(k_z)\cdot\mu^{M}(k_{\text{imp}})\right)\vee\left(\mu^{VH}(k_z)\cdot\mu^{L}(k_{\text{imp}})\right). \quad (8)$$

$$\mu^{VH}(k_2)=\left(\mu^{H}(k_z)\cdot\mu^{H}(k_{\text{imp}})\right)\vee$$
$$\vee\left(\mu^{VH}(k_z)\cdot\mu^{M}(k_{\text{imp}})\right)\vee\left(\mu^{VH}(k_z)\cdot\mu^{H}(k_{\text{imp}})\right). \quad (9)$$

Table 2

Fuzzy knowledge base of the model for determining the weight k_2

No. of entry	Input variables		Output variable
	k_z	k_{imp}	k_2
1	VL	L	VL
2	VL	M	VL
3	VL	H	L
4	L	L	L
5	L	M	L
6	L	H	M
7	M	L	M
8	M	M	M
9	M	H	H
10	H	L	H
11	H	M	H
12	H	H	VH
13	VH	L	H
14	VH	M	VH
15	VH	H	VH

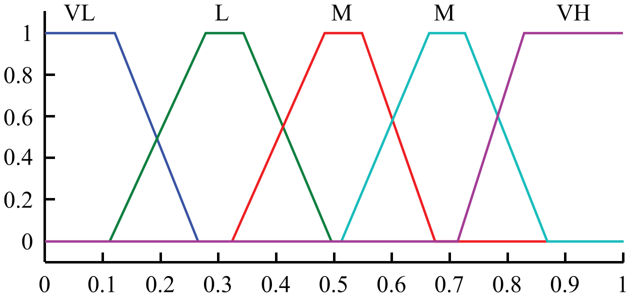

Fig. 2. Fuzzy values of input variable k_z

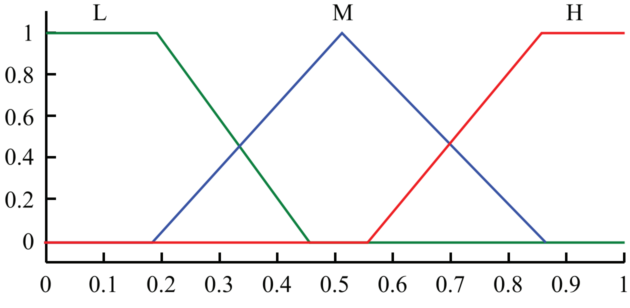

Fig. 3. Fuzzy values of input variable k_{imp}

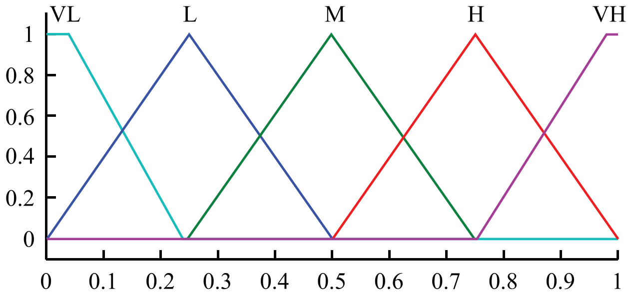

Fig. 4. Fuzzy values of output variable k_2

The results from our simulation have demonstrated that it is expedient, in order to defuzzify the output parameter, to use the method of determining the center of gravity (centroid method).

Graphical dependence, which reflects a change in the output parameter on the input ones, is shown in Fig. 5 in the form of a three-dimensional response surface.

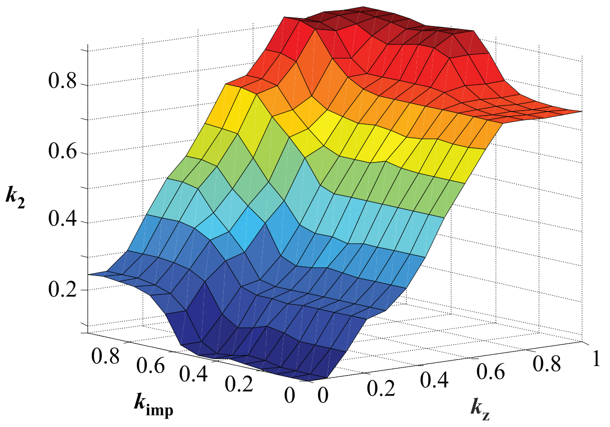

Fig. 5. Chart of surface $k_2=f(k_z, k_{\text{imp}})$

As one can see from Fig. 5, a given surface demonstrates a rather "smooth" character, that is, there are no drastic changes in the values of the output value at a small change in any of the input quantities. This indicates a rather low sensitivity of the output parameter relative to the input ones, which positively influences the robustness of ACS operation in general.

4. 2. Computer simulation of ACS of electrical energy generation by renewable sources

To study the operation modes of ACS of the generation of electric energy by installations with RES, which includes a fuzzy unit for determining weight coefficients k_1, k_2, we designed its computer simulation model, whose generalized structural scheme is shown in Fig. 6.

Designations in Fig. 6: "Voltage U1" – unit for simulating the magnitude of voltage by EDN; "Load" – unit for modelling the load of consumers; «RES» – unit for modeling the operation of RES installations; «EDN» – unit for modeling the operational mode of EDN; «CU» – unit for modeling the operation of RES controller of electricity generation; «Wh_gen_meter» – unit for calculating generated electrical energy; «V_calc» – unit for calculating voltage deviation at the consumers' buses; «RMS» – unit for calculating the current value of voltage at the consumers' buses.

A structural scheme of unit CU, which implements a fuzzy algorithm for determining the weight coefficient k_2, is shown in Fig. 7.

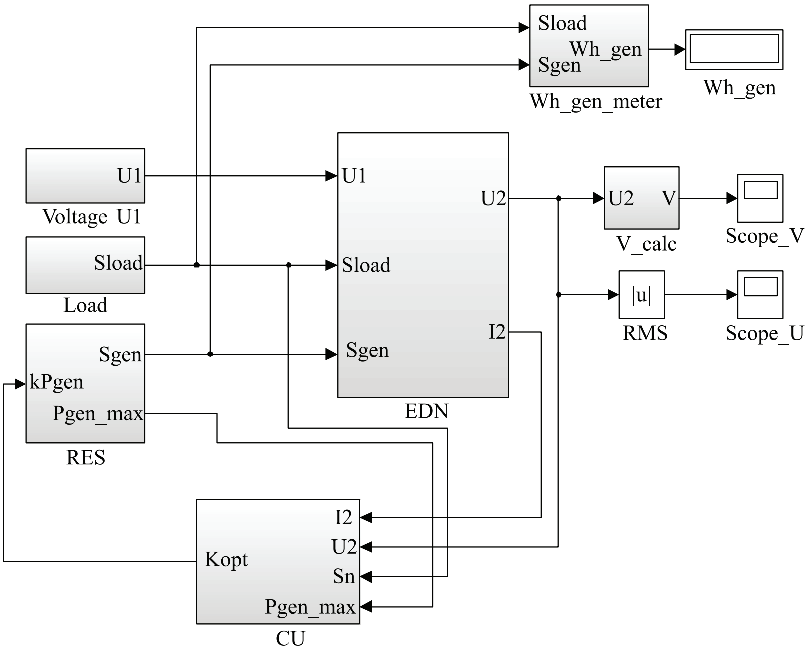

Fig. 6. Generalized computer simulation model of ACS of the generation of electric energy by RES within IEES

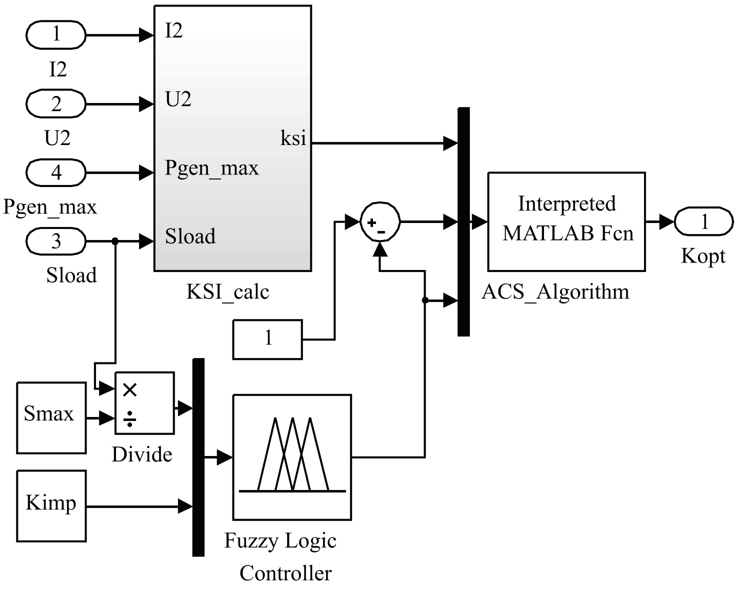

Fig. 7. Structural scheme of CU controller unit

Designations in Fig. 7: «KSI_calc» – unit for determining a vector of setting parameters; «ACS_Algorithm» – unit for determining a vector of optimum control $\mathbf{K}^{\mathrm{opt}}$; “fuzzy Logic Controller” – unit that implements the constructed fuzzy algorithm for determining the weight coefficient k_2.

Using the devised model, we performed computer simulation with the results shown in the form of charts in Fig. 8, 9.

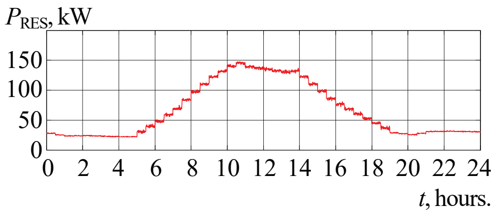

Fig. 8. Daily schedule of active power generation by installations with RES

Table 3 gives results from processing data on computer simulation of the devised ACS, as well as the control system that was taken as a base for comparison and was described in [8].

Table 3

Results from processing data on computer simulation of operation of the base and devised ACS of active power generation

No. of entry	Indicator	Base ACS	Devised ACS
1	Electric energy generated to a power grid W_{gen}, kWh	181.16	188.3
2	Electric energy generated by SPP W_{SPP}, kWh	1,004	1,048.5
3	Electric energy generated by WPP W_{WPP}, kWh	83.72	85.78
4	Electric energy generated by BGP W_{BGP}, kWh	503.3	518.16
5	Electric energy generated by RES W_{RES}, kWh	1,591.02	1,652.44
6	Integrated probability of a voltage deviation ΔU entering the range of permissible values, $P[-5<\Delta U<5]$, r. u.	0.950	0.964

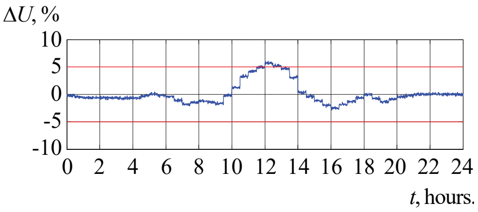

Fig. 9. Daily schedule of change in the value of a steady-state voltage deviation at the point where electricity consumers are connected

As shown by Table 3, when using the devised ACS of electricity generation by power plants with RES employing a fuzzy algorithm for determining coefficients k_1, k_2, one observes an increase in the electricity generation by RES installations by 3.9 %. At the same time, both the base and devised ACSs execute control providing for normally permissible values for a steady-state voltage deviation.

6. Discussion of results of studying the process of automated control over electricity generation by renewable sources

The findings from our research demonstrate that the use of a fuzzy model based on the Mamdani algorithm to determine weight coefficients k_1, k_2 improves the operational efficiency of ACS of electricity generation by RES within IEES by taking into consideration the impact of a time-dependent change in the quantitative and qualitative composition of electrical consumers.

As shown by the results from computer simulation, when applying ACS with a fuzzy algorithm for determining k_1, k_2, $K1$, one observes an increase in the electricity generation by RES (by 3.9 %) compared to the base ACS [8]. In addition, for the case of the devised ACS, the value of the integrated probability ΔU entering the range of normal allowable values is 1.45 % higher than that for the base ACS. Such results are explained, first of all, by imperfection of the approach, described in [8], to determining weight coefficients that affect the final solution to the problem on the optimal control over IEES operation mode.

It should be noted that the scope of application of the developed ACS of electricity generation by RES is limited to electrical networks whose rated voltage is 0.4 kV, which have a relatively low throughput capacity.

A disadvantage of the proposed approach to automated control is a certain complexity in constructing an expert knowledge base. More promising might be to use, in order to determine weight coefficients k_1, k_2, more advanced artificial intelligence algorithms (for example, neural-fuzzy networks). However, such an approach requires a sufficiently large volume of statistical information about the parameters of operating mode of IEES with RES, which greatly complicates its implementation.

The above results of our study are advancement of the approach, proposed in work [8], to constructing ACS of electricity generation by RES within IEES. Further research is planned in the field of devising similar ACSs for branched electrical distribution networks, as well as for other variants of IEES configuration.

7. Conclusions

1. Our analysis has revealed that in order to improve the operational efficiency of ACS of power generation by installations with RES, which is based on the solution to the problem of multi-criteria optimization by the method of approximation to utopian point, it is necessary to apply an adaptive algorithm for determining weight coefficients k_1, k_2, which influence values of the optimal control vector. Application of the devised fuzzy model for determining weight coefficients k_1, k_2, which is based on the algorithm of fuzzy derivation by Mamdani, makes it possible to improve the operational efficiency of ACS of electricity generation by plants with RES, compared with existing systems, by taking into consideration a time-dependent change in the quantitative and qualitative composition of electricity consumers.

2. Results from computer simulation of operation of ACS of the level of power generation by installations with RES have confirmed correctness of theoretical studies. Thus, when applying ACS with the designed fuzzy unit for determining weight coefficients k_1, k_2, there is an increase in the electricity generation by plants with RES by 3.9 % compared to existing model. In this case, levels of a steady-state voltage deviation at the clamps of electricity consumers remain within the range of normal permissible values.

References

1. Kyrylenko, O. V., Pavlovskyi, V. V., Lukianenko, L. M., Zommer, A. E. (2011). Analiz vplyvu pryiednannia vidnovliuvanykh dzherel elektroenerhiyi na rivni napruhy elektrychnykh merezh. Tekhnichna elektrodynamika. Tem. vypusk «Sylova elektronika ta enerhoefektyvnist», 2, 44–49.
2. Kosmadakis, I., Elmasides, C. (2019). Towards performance enhancement of hybrid power supply systems based on renewable energy sources. Energy Procedia, 157, 977–991. doi: https://doi.org/10.1016/j.egypro.2018.11.265
3. Jumani, T. A., Mustafa, M. W., Rasid, M. M., Mirjat, N. H., Leghari, Z. H., Saeed, M. S. (2018). Optimal Voltage and Frequency Control of an Islanded Microgrid using Grasshopper Optimization Algorithm. Energies, 11 (11), 3191. doi: https://doi.org/10.3390/en11113191
4. Jumani, T., Mustafa, M., Md. Rasid, M., Anjum, W., Ayub, S. (2019). Salp Swarm Optimization Algorithm-Based Controller for Dynamic Response and Power Quality Enhancement of an Islanded Microgrid. Processes, 7 (11), 840. doi: https://doi.org/10.3390/pr7110840
5. Moarref, A. E., Sedighizadeh, M., Esmaili, M. (2016). Multi-objective voltage and frequency regulation in autonomous microgrids using Pareto-based Big Bang-Big Crunch algorithm. Control Engineering Practice, 55, 56–68. doi: https://doi.org/10.1016/j.conengprac.2016.06.011
6. Ghodki, M. K. (2013). Microcontroller and solar power based electrical energy management system for renewable energy applications. International Journal of Electrical Power & Energy Systems, 44 (1), 852–860. doi: https://doi.org/10.1016/j.ijepes.2012.08.041
7. Senthil kumar, J., Charles Raja, S., Srinivasan, D., Venkatesh, P. (2017). Hybrid renewable energy-based distribution system for seasonal load variations. International Journal of Energy Research, 42 (3), 1066–1087. doi: https://doi.org/10.1002/er.3902
8. Pleshkov, P. G., Garasova, N. Y., Soldatenko, V. P. (2018). Optimal control of the work of the hybrid electric energy system with renevable sources of energy. Bulletin of NTU “KhPI”. Series: Problems of Electrical Machines and Apparatus Perfection. The Theory and Practice, 32 (1308), 64–70. doi: https://doi.org/10.20998/2079-3944.2018.32.12
9. Plieshkov, P. H., Zinzura, V. V., Plieshkov, S. P. (2019). Automatic control of electrical distribution network mode with the voltage unbalance. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 3, 83–91. doi: https://doi.org/10.29202/nvngu/2019-3/10
10. Hrabko, V. V., Balzan, I. V. (2012). Vyznachennia koefitsienta vplyvu transformatora nyzhnoho rivnia v zadachi rehuliuvannia napruhy za dopomohoiu transformatora z prystroiem rehuliuvannia pid navantazhenniam. Elektromekhanichni i enerhozberihaiuchi systemy, 3, 508–511.