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Selfoptimization local electric systems modes with renewable energy sources

***Abstract**. The article devoted creating optimal conditions for the integration of renewable energy source (RES) into electric grids, which were designed with power from centralized generation at large power plants. The possibility of simultaneous optimal functioning of electric grids and renewable energy sources is considered. The complex criterion of optimality is the economic mode of power sources, as well as the minimum losses of electricity during its transmission. To optimize the regimes of electricity grids with renewable energy sources, the principle of the least action is used. Optimal control of modes is carried out by the active-adaptive system.*

Streszczenie:** W artykule analizowano optymalne warunki integracji do systemu energetycznego źródła energii odnawialnej. Zaproponowano metode symulacji uwzględniając warunki ekonomiczne i minimum strat przesyłowych. Do optymalizacji wykorzystano aktywny system adaptacyjny.* ***Adaptacyjna optymalizacja systemu energetycznego z odnawialnym źródłem

Keywords: electric grid, local electric systems, renewable energy sources, automated system of optimal control, principle of least action.
Słowa kluczowe: lokalny system energetyczny, odnawialne źródło energii, optymalizacja

Introduction

Electric grids were functionally designed to transport and distribute electricity produced centrally at large power plants. With the development of non-traditional and renewable energy sources (RES), they acquire the features of a local electric system (LES). In this connection, new tasks arise: harmonization of load schedules of consumers and generation of RES with consideration of their dependence on meteorological parameters of the environment, optimal control of power flows in order to reduce the losses of electricity and improve its quality, ensuring the balance power reliability of the formed LES centralized and local generation, etc. Naturally, it is advisable to solve these problems with the use of modern Smart Grid technologies [1-3].

Among the tasks to be solved for switching to the electrical grids (EG) based on the concept of the Smart Grid, there are, among other things, tasks whose solution is intended to improve the power flow control system [4, 5]. To do this, it is necessary to ensure the technical condition and regulatory capabilities of the relevant equipment. This, first and foremost, concerns the actual renewable energy sources (RES) - wind and solar power stations (WEP and PV), small hydroelectric power plants (SHPP), cogeneration and biogas plants (CGU and BGU) [4, 5]. This also applies to transformers and autotransformers with tap regulators, for which modern operational diagnostic systems should be created, as well as improved conditions for their operation in order to optimally utilize their load capacity to control power surges between higher and lower voltage grids [6] .

At the same time it is necessary to improve the active-adaptive automatic control system (ACS) with power and voltage flows in electric grids of power systems, which allow to minimize power losses in them taking into account the technical state of electrical equipment of RES and the control effect of transformers with voltage and linear regulators [6].

It is possible to develop ASCs by power flows and voltages in the EG using the principle of least action (PLA) [7]. PLA in natural systems manifests itself in the form of a mechanism of selfoptimization, that is, the properties of systems and their parts self-adjust in such a way that it is ensured to increase their level with the transition to the most energy-efficient state. In this way, the most advantageous mode of operation is achieved. After deviating from the optimal state of functioning in the system, there occurs a counter, opposite directed action, that is, a counteraction that tries to bring the system back to its optimal state. Thus, for any system at any moment of its existence, the norm is a qualitative optimum whose depth is determined by the measure of the ideal of the system [7, 8].

The purpose of the article is to create conditions for the self-optimization of electric networks using Smart Grid technologies to reduce energy losses in them due to efficient use of renewable energy sources.

The task of optimization electrical grid modes with renewable energy sources

In connection with the growth of RES capacity in electric power systems (EPS), today the task of optimizing their regimes has become an urgent task in order to minimize deviations from the scheduled schedule for the next day and the announced system operator for the distribution of electricity [9]. For a separate power plant or a group of power plants using renewable energy sources, this task can be formulated as follows:

$$\int_{t_0}^{t_k} \frac{1}{2}\left[P_{RES}(t) - \sum_{i=1}^{n} P_i(t) \right]^2 dt \to \min, \quad (1)$$

where $P_{RES}(t)$ – an hourly schedule for generating RES for the next day is claimed, $\sum_{i=1}^{n} P_i(t)$ – total generation of n power stations with RES, connected to the balancing station bus.

The declared $P_{RES}(t)$ generation schedule is generated in such a way as to ensure the maximum revenue from sales of RES in the "green" tariff:

$$\sum_{i=1}^{n} \int_{t_0}^{t_k} z_i P_i(t) dt \to \max, \quad (2)$$

where z_i - "green tariff" for the released electricity and the first power plant with RES.

The tasks of both (1) and (2) are solved on condition of balance on the tires of the balancing group of power sources and load (see Fig. 1):

$$P_{CPS}(t) + \sum_{i=1}^{n} P_{RES_i}(t) - \sum_{j=1}^{m} P_{TS_j}(t) - \Delta P(t) \pm P_{storage}(t) = 0, \quad (3)$$

where $P_{CPS}(t)$ – power transferred to electric grid from centralized sources of electricity, $P_{TS_j}(t)$ – load of transformer substations, m - the number of TS, $\Delta P(t)$ –

technological losses of electricity (TLE) in the electric network, $P_{storage}(t)$ – power that is generated or consumed by energy storage, $P_{RES}(t)$ – total power generation of renewable energy sources.

At the same time, the announced schedule for generating $P_{RES}(t)$ and generating the remaining sources of active and reactive electricity is planned in such a way that power flows provide the minimum power losses in the power grid.

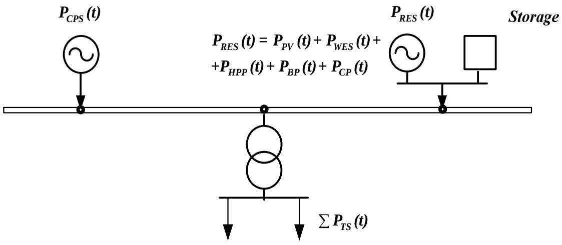

Fig. 1. Power supply balance in the electric grid

The peculiarity of the generation schedule of $P_{RES}(t)$ is dependence on weather conditions of the environment and its accuracy is largely determined by the forecast data of meteorological parameters (temperature, direction and wind power, solar radiation, cloudiness). This is a separate task and, to some extent, it is solved in [10, 11]. The declared generation schedule of $P_{RES}(t)$ and the generation of the remaining sources of active and reactive electricity is planned in such a way that power flows in the electrical network provide minimal energy losses in it. For the practical implementation of optimal power flows, an appropriate automatic control system is being built.

Active-adaptive control of power powers in electrical network

Adaptive Automatic Control Systems (ACSs) allow the management of technological processes in conditions of incomplete or imperfect current information regarding the characteristics of the control object and the environmental impacts that are characteristic of RES, especially if management is to be carried out in real time. The most well-known direction of the deterministic functional-adaptive, self-regulated control systems is control with a reference model [12]. The scheme of such an adaptive system with the reference model is shown in Fig. 2
The operation of local ACSs is subject to the centralized automated control system and is implemented by law [13]:

$$\mathbf{u}(t) = -\pi\,\mathbf{y}(t),$$

where $\mathbf{u}$ – vector of control effects; $\mathbf{y}$ – vector of observation; π – the matrix of coefficients of proportionality, having the physical content of the similarity criteria.

In this scheme, the reference model is part of the control system, and the coordination of centralized and decentralized control is carried out through a control adjustment block that links the external and internal (main) control loops. The main circuit is formed by the object of control and the system of local control. For example, for an SHPP case, an integrated power regulator is used which affects the angle of opening of the guiding apparatus of a separate block. For the PV the influence is carried out on the angle of opening of the inverter thyristors. The parameters of the regulator are adjusted by the external control circuit so as to minimize inconsistency between the output of the reference model of centralized control and the output of a controlled process, which is controlled by the corresponding feedback. At different stages of Smart Grid implementation, the reference model of the control system performs various functions.

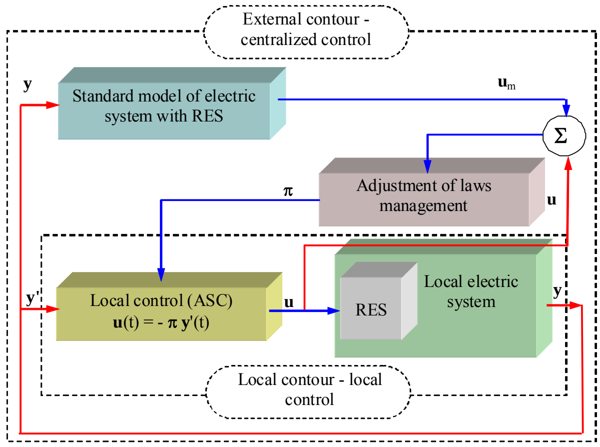

Fig. 2. Adaptive control system with the reference model

With it, the operational staff not only detects and corrects the adjustment parameters of the SAC, but also reproduces the predicted states of RES, evaluates the effects of management influences, including automatic ones. After the final implementation of the management system and the transition to the Supervisory Control level, the reference model becomes the main element of self-adjustment of the centralized control system and self-analysis of the SAC.

The effectiveness of an adaptive approach depends on the ratio of the frequency of receiving feedback and the rate of changes occurring in the control object. The stability of the object improves the efficiency of the adaptation process. The main difficulty of using self-regulated control systems is the need for a large amount of computations and, accordingly, a significant time to identify the model of the local system and to determine the control vector. However, in the case of prior identification using similarity theory methods, this disadvantage is not decisive for the construction of a local RES system [13, 14]. The use of this approach makes it possible to use as the governing laws a stable relationship between the parameters of the EG mode, obtained by means of the theory of similarity [14]. They allow you to move away from centralized management and more efficiently and locally use control over local settings.

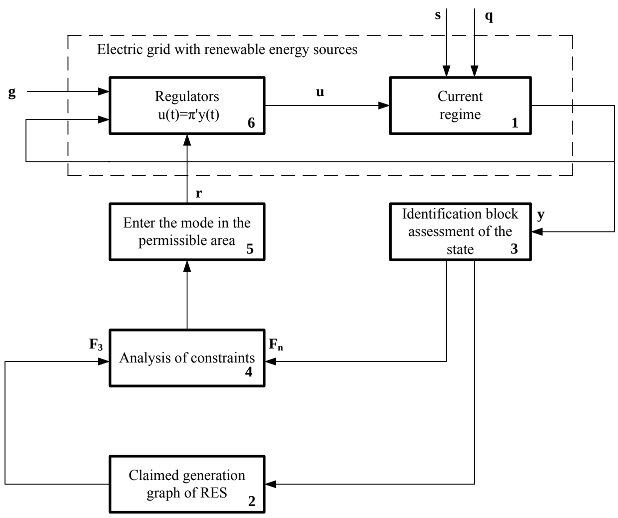

Fig. 3. Adaptive system of optimal control of the normal LES regime

Thus, for the realization of the tasks of operative and automatic control of the normal modes of RES in the local power system it is possible to use an adaptive control system for regulating devices. The efficiency of the adaptive approach is increased by separating the function of control of the modes of RES - centralized formation of the laws of management of complete mathematical models of the electrical system and RES and decentralized implementation of these laws in the local control and management systems of individual RES and their groups by local information.

In fig. 3 presents the system of optimal control of the normal LES regime, which is adapted to the features of the functioning of the RES. It takes into account the current technical state of the control devices, which may vary depending on meteorological conditions and the nature of the load. The LES economic regime is used as a reference model, implementation of which ensures minimal losses of electricity during its transmission and distribution. In this system of optimal control, the LES system and regulators form the main circuit of the automatic control system.

In EG mode, perturbations are continuously in the form of load changes **s** and parametric disturbances - the deviation of the EG parameters from their values **q** in the declared mode. The value of the defining parameters **y'**, the composition of which is determined from the results of the analysis on the sensitivity of the optimality criterion F to the control parameters **u**, is given to the input of the regulators, which, in accordance with the given laws of control, the EG mode is contained in the permissible optimality domain. Through the regulators, the control influences **g** are carried out, which are determined as the result of the most favorable distribution of the load between the power sources in the EG (see Figure 3), or, if necessary, directly carried out by operational personnel. The contour of adaptation (blocks 2-5) controls the coefficients of the regulators. The process of adaptation depends, as a rule, on the vectors of influences **g**, **s** and on the parametric perturbations **q** caused by the change of meteorological parameters. In block 3 from the Operational-Information Complex database (OIC), information is received to determine the current F_c and the declared F_f values of generation of RES in the electrical grid. Block 2 is a model for determining the hourly schedule for generation of RES according to forecast data of meteorological parameters for the next day [11]. In block 4 conditions are checked:

$$\Delta F = \left|F_c - F_f\right| \le \xi_F,$$

where ξ_F - permissible deviation of current values of generation of RES from their declared values.

If the last condition is fulfilled, then this means that the EG mode is balanced and is within the permissible range and no control actions are required. Otherwise, the input to block 5 is transmitted ΔF and changes are made in the control laws r that change the power of the PES from the power unit, as well as, if possible and necessary, the change in the generation of RES. As a result of these actions, ΔF is reduced to ξ_F.

Current regime in the adaptive system of optimal control of the normal mode of EG should match the scheduled regime for the next day. In fig. 4 shows the functional scheme of the distributed computing complex for optimizing the operation of power sources (OOPS) in the power grid in the process pace [15], adapted to electric networks with RES. It is implemented in the TRACE MODE computing environment. Its composition is as follows.

The computer system of the most advantageous distribution of the load between the sources of electricity is part of the automated control system of the EG. It is connected to the database (DB) of the operational information complex (OIC), from where the information on the load of the system's nodes enters the EG model. Electric power sources in the computer system are modeled by their characteristics of economic resistance (HSE). The working part of the characteristic, which is determined by the control range of the station $P_{min} \le P \le P_{max}$, is allocated to the heights of each source. Characteristics of the sources can change in time t. Decisions on their optimal load are taken taking into account the transit flows between the networks of higher and lower voltage, which affect the transmission capacity of the transmission lines and loss of power in them. The power flows are redistributed between the networks of higher and lower voltage by changing the coefficients of the transformers of communication. The results of the optimal distribution of the load between the power sources g are transmitted to the main circuit of the automatic control system EG and b in the data bank for generalization.

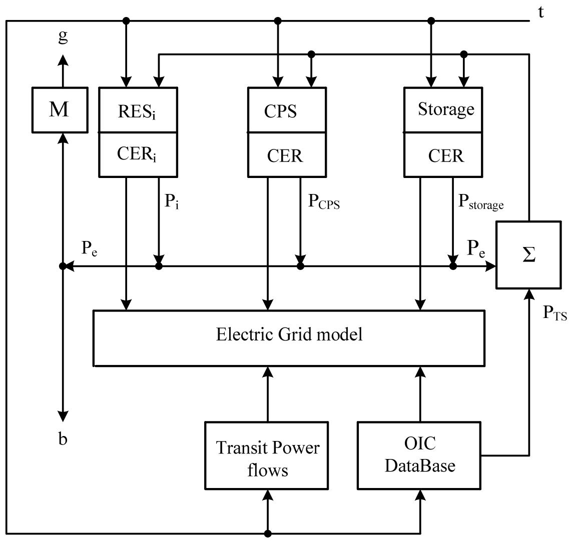

Fig. 4. Functional scheme of the most advantageous distribution of load between power plants

The functioning of the computing complex for optimizing the operation of power sources in the EG in the process of the process is as follows. The process consists of two stages. First, according to the actual data from the OIC, the optimal EG regime is determined and the most advantageous load of the electricity sources is determined. The calculation model (R-scheme) of the system and the characteristics of the economic resistance of the sources with a dedicated regulatory range are entered into the ORDES. The optimal power sources of electric power are set. Transit flows are taken into account, as they are reflected in the database of real OIC data, which determines the optimal EG mode. When changing the load in EG there is the most advantageous redistribution of power according to the CEO between sources of electricity.

Mathematical model of optimization of EG modalities using PLA

In the LES as well as in the EU, two scenarios for the optimization of normal regimes are possible: separate optimization, separately for active and reactive power, and complex optimization, both for active and reactive power [16]. When optimizing for active power the optimality criterion is the cost of electricity generation by power plants, optimization of the regime for reactive power and voltage is carried out according to the optimality criterion - the minimum of electric power losses in electric networks during its transportation, the optimality criterion at the complex optimization is the expenses for electricity production by power stations from taking into account the minimum amount of electricity losses during its transmission and distribution. Practical implementation of separate optimization is carried out in the following way. First, the most advantageous distribution of load between the power plants is calculated, and then, when the active capacities of the stations are fixed, the mode of electric networks is optimized for reactive power and voltage. It is this approach that corresponds to the optimization of LES regimes, when the sources of electricity and electricity networks are different property and, accordingly, the criteria for their optimality are different.

The conditions for optimal distribution of the load between sources of electricity can be obtained using the principle of least action (PLA) according to the method described in [15]. At this time interval, the load schedule for generating electricity sources is assumed to be constant. Unchanged is also z - the cost of electricity is RE. Under these conditions you can write down

(4) $$f = V_i \Delta t c = z_i P_i \Delta t \ ,$$

where *c* - the cost of 1 kW h of electricity loss, V_i - the loss of active power on the R_{ei} element from power overflows with RES in EG P_i. Taking into account that:

$$V_i = \frac{P_i^2}{U_i^2} R_{ei} \ ,$$

the expression (4) will be rewritten

$$f = \frac{P_i^2}{U_i^2} R_{ei} \Delta t c = z_i P_i \Delta t \ ,$$

From the last expression we obtain a formula for calculating the values of economic active resistance, which hold RES:

(5) $$R_{ei} = \frac{U_i^2 z_i}{P_i \ c} \ ,$$

Taking into account the changes in the economic active resistance in time, depending on the power, determined by the CER. Similarly, the value of the economic resistance and the CER, which is located centralized power:

(6) $$R_{ei \ CPS} = \frac{U_{CPS}^2 h(t)}{P_{CPS} c} \ ,$$

where *h(t)* - the cost of electricity from the electric power system (EPS) at the multi-level tariff. If the timing of the generation of RES does not coincide with the declared graph with the permissible error, then *h(t)* increases to the value of the paid service for using the power reserve from the EPS.

Another variant of the application of the generated schedule of generation of RES with the given accuracy is the use of electric power storage in the electrical grid. There are two possible options here. The first one, when power storage units are installed directly on RES, and the cost of their electricity/charge is included as part of the z_i tariff. Another option when the power storage is a separate object for group balancing of the EG mode. In this case, the balancing unit of the system is likely to buy an excess electricity at the z_i rate, and sell insufficient to execute the generated generation schedule at a price of $d (d > z_i)$. Accordingly, the economic active resistance that the group drive is connected to will be defined as:

(7) $$R_{e\,storage} = \frac{U_i^2 z_i}{P_{i\,storage} c} \text{ або } R_{e\,storage} = \frac{U_i^2 d}{P_{i\,storage} c} \ ,$$

Similarly, economic active supports for reactive power sources can be obtained. We will assume that the active power is given and unchanged. Then losses depend only on reactive power. The task of optimizing the regime of LES by reactive power and voltage is recorded as a task to minimize the loss of active power [16]:

(8) $$V_Q = f(Q, U) \rightarrow \min$$

under the condition of the balance of reactive power in the system

(9) $$G = \sum_{i=1}^{l} Q_i(t) - \sum Q_i \ (t) - \Delta Q(t) = 0 \ ,$$

where $\sum_{i=1}^{l} Q_i(t)$ – total generation by sources of reactive power Q_i, *l* – number of sources of reactive power (DFP), $\sum Q_i$ – total load, the value of which is constant, ΔQ – loss of reactive power in system elements.

The costs of electric power losses caused by reactive power flows in a system with a resistance to Re for a time interval *Δt* are defined as

(10) $$Ç_{Qi} = V_{Qi} \ \Delta t \ c = \frac{Q_i^2}{U_i^2} R_{ei} \ \Delta t \ c \ .$$

Electricity to cover these losses is produced at power stations. Costs for its production are determined by:

(11) $$Ç_{Qi} = P_i \ \Delta t \ \beta_i \ ,$$

Electricity to cover these losses is produced at power stations. Costs for its production are determined by: $\beta_i = h$; if the source is RES, then $\beta_i = z_i$).

From (10) and (11) we have that the economic resistance, the cost of electricity losses which is equivalent to the costs of its production at the station, is calculated by the formula:

(12) $$R_{ei} = \frac{P_j \ U_i^2 \ \beta_j}{Q_i^2 \ c} \ .$$

The task of optimizing the regime of LES power by reactive power is formulated as follows:

(13) $$V_{Q\Sigma} = \sum_{i=1}^{v} 3 R_{ei} I_i^2 \rightarrow \min$$

under conditions of balance of reactive power in the LES (9). In (13) v - the number of branches in the LES.

We write the Lagrange function for the problem (14) - (9):

$$L = \sum_{i=1}^{v} 3 R_{ei} I_i^2 + \lambda \left(\sum_{i=1}^{l} Q_i - \sum Q_i \ - \Delta\text{Q} \right) .$$

After substituting in the last expression the values of economic resistances in accordance with (12) and taking into account that in (12) $P_j = V_{Qi}$, we obtain the Lagrange function in the form:

$$L = \sum_{i=1}^{v} \frac{V_{Qi} \beta}{c} + \lambda \left(\sum_{i=1}^{l} Q_i - \sum Q_i \ - \Delta\text{Q} \right) .$$

Under conditions $\partial L / \partial Q_i = 0, i = \overline{1, l}$ we obtain the criterion for optimal loading of reactive power sources:

(14) $$\frac{\partial V_Q / \partial Q_i}{1 - \partial \Delta Q / \partial Q_i} \frac{\beta}{c} = idem \ .$$

The criterion for optimal loading of the sources of reactive power (SRP) (14) is obtained provided that the cost of the electricity generated at the power stations, which goes to cover losses in the EPS, β and the cost of electricity losses in the system are constant at time interval Δt, that is, β/c = const. Under these conditions, the actions according to the optimality criteria (14) do not differ from [16]. Thus, the problem of optimal load distribution between sources of reactive power can be reduced to the calculation of the established regime of EPS with a sub-R-scheme in which the DPF are nonlinear economic supports.

After placing the sources of electric energy in the calculated supports, as shown in Fig. 5, it is possible to replace the definition of the minimum of total expenses for electricity production by calculating the economic regime of the electric network with RES in accordance with the sub-scheme, composed only of the active resistance of the elements of the EG and the economic resistance of the links with the sources of energy.

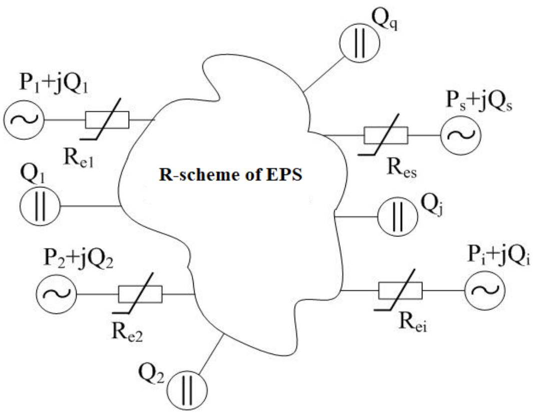

Fig. 5. The circuit diagram of the electric network with economic supports

The task of optimizing the modes of the electrical network in the EPS is formulated:

(15) $$\min\left\{V = \sum_{i=1}^{s} \frac{P_i^2 + Q_i^2}{U_i^2} R_{ei}\right\}$$

provided the balance of active and reactive power in the form (3) and (9).

Conclusion

The process of optimizing modes of electric networks with RES can be carried out using the principle of least action. In this case, the sources of active and reactive power in the calculation model appear to be economic resistance. The values of these active resistances, which simulate the cost of generating power, are determined in accordance with the chosen optimality criterion for the modes of electric networks and depending on the price indicators that may change. Determination of the optimal generation of electric power sources of the electric network (external and internal) is reduced to the calculation of the established mode of the electrical network by its sub-R-scheme. The implementation of such a regime ensures not only the economic mode of the electricity sources, but also minimizes electricity losses during its transmission.

Adaptive control system of the normal mode of the electric network with RES, where as the reference model uses the model of its economic regime, allows to realize the task of approximation of the current regime to economic, taking into account restrictions. As the source information, the OIC database is used, which ensures the adequacy of the optimization results. The proposed scheme of a distributed computing complex for optimizing the operation of the electric network with RES in the process pace that is implemented in the TRACE MODE computing environment. The computer system of the most advantageous distribution of the load between the sources of active and reactive power in the electrical network is part of its automated control system.

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REFERENCES

[1] Kobets B. B., Volkova I.O. Innovative development of electric power industry based on the concept of Smart Grid. - Moscow: IAC Energiya, 2010. - 208 p.

[2] S. M. Canevese, A. Iaria and M. R. Rapizza, "Optimal Automatic Parameter Tuning for Innovative Grid Frequency Regulation Functions," 2018 AEIT International Annual Conference, Bari, Italy, 2018, pp. 1-6.do: 10.23919 / AEIT.2018.8577445

[3] Feynman P. Quantum Electrodynamics. - 1962. Addison Wesley. ISBN 978-0-8053-2501-0.

[4] Intelligent Electric Networks: Elements and Modes / Ed. O.V. Kyrylenko - K .: Institute of Electrodynamics of NAS of Ukraine, 2016. - 400 p.

[5] M.A. Zehir et al., "Managing Inverter-Based Distributed Energy Resources for Providing Voltage Regulatory Support in Icelandic Operation of Low Voltage Networks," 2018 53rd International University Power Engineering Conference (UPEC), Glasgow, 2018, pp. 1-5. doi: 10.1109/ UPEC.2018.8541988

[6] P.D Lezhniuk,. and I.O Hunko,. and S.V. Kravchuk, and P, Komada,. and K, Gromaszek,. and A, Mussabekova,. and N. Askarova, and A, Arman. “The influence of distributed power sources on active power loss in the microgrid”, Przeglad Elektrotechniczny,2017,No.93,,p.107-112 doi10.15199/48.2017. 03.25.

[7] I. P. Krasnov, "On principle of the least action in classical electrodynamics," 2017 Progress In Electromagnetics Research Symposium - Spring (PIERS), St. Petersburg, 2017, pp.3532-3538. doi: 10.1109/PIERS.2017.8262371

[8] Chaban A. Mathematical modeling of oscillatory processes in electromechanical systems: Monograph. - Lviv: Taras Soroka Publishing House, 2007. - 312 p.

[9] The Law of Ukraine "On the Electricity Market" dated April 13, 2017, No. 2019-VIII. Access mode: http: //zakon5.rada.gov.ua/laws/show/2019

[10] J. G. D. SF Junior, Y. Nishitsuji, Y. Udagawa, T. Oozeki and K. Ogimoto, "Improving Regional PV Power Curtailment with Better Day-ahead PV Forecasts: An Evaluation of 3 Forecasts," 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC), Waikoloa Village, HI, 2018, pp. 2299-2304. do: 10.1109 / PVSC.2018.8548285

[11] P. Lezhnyuk, V. Komar, S. Kravchuk, V. Lesko, V. Netrebskiy, "Meteorological Parameters Analysis for the Hourly Forecast of Electricity Generation by Photovoltaic Power Station on the Day Ahead", 2018 IEEE 3rd International Conference on Intelligent Energy and Power Systems (IEPS), Kharkiv, Ukraine, 2018, pp. 235-238. DOI: 10.1109 / IEPS.2018.8559598.

[12] Manual on the theory of automatic control, Ed. A.A Krasovskogo. -M .: Science. - 1987 - 712 p.

[13] Lezhnyuk P.D., Kulyk V.V., Obolonskiy D.I. Design and indemnification of the influence of heterogeneity of electric networks on the economy of their modes // Elektrichestvo. - 2007. - No. 11. - PP. 2-8. (Rus.)

[14] Venikov V.A Theory of similarity and modeling. -M .: Higher school, 1976. - 479 p.

[15] Lezhnyuk P.D., Kulyk V.V, Netrebsky V.V., Teptya V.V. Principle of the least action in electrical engineering and power engineering: Monograph. - Vinnitsa: VNTU, 2014 - 212 p.

[16] Methods for Optimization of Power Systems Modes / V. M. Hornshtejn, B. P. Miroshnichenko, A. V. Ponomarev et al. - Moscow: Energoizdat, 1981. - 336 pp.