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NATURAL-SIMULATION MODEL OF PHOTOVOLTAIC STATION GENERATION IN PROCESS OF ELECTRICITY BALANCING IN ELECTRICAL POWER SYSTEM

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Abstract. *The paper analyzes the methods of stabilizing generation schedules of photovoltaic stations (PV) in electric power systems (EPS) in the process of balancing electricity. Since PV is characterized by the instability of electricity production due to dependence on weather conditions, an automatic system for forecasting their generation schedules (ASFG) for the next day has been created to increase the energy efficiency of PV. The process of automating the prediction of the power stations as part of the balancing group of the power stations and the algorithm for adjusting the prediction of power plant generation are considered. The criterion for managing the forecasting process is the minimization of the difference between the values of forecasted and actual generation for the same period of time. Checking the performance and tuning of the ASFG PV in order to evaluate its functioning and the effectiveness of its application in the task of balancing the states of the EPS is possible only by means of simulation. It is shown that based on the nature of the process of forecasting the generation of PV using ASFG, it is advisable to use simulation modeling. Since the actual value of generation is constantly monitored during balancing using ASFG, it is possible to use these values during simulation and proceed to real-time simulation. In this case, modeling is considered as an experimental method of research, according to which it is not the object itself that is subjected to perturbations and research, but the software-implemented computer model of the object. The real-life simulation model of the operation of the PV makes it possible to more fully consider the various modes of their operation in the process of balancing the modes of the EPS as part of the balancing group and to more reasonably choose decisions regarding the participation of the PV in generation, taking into account weather conditions and the limitations of the system operators of transmission and distribution of electricity.*

Keywords: power system, photovoltaic stations, unstable generation, stabilization of generation schedules, natural-simulation modeling

NATURALNY MODEL SYMULACYJNY GENERACJI STACJI FOTOWOLTAICZNEJ W PROCESIE BILANSOWANIA ENERGII ELEKTRYCZNEJ W SYSTEMIE ELEKTROENERGETYCZNYM

Streszczenie*. W artykule przeanalizowano metody stabilizacji harmonogramów generacji stacji fotowoltaicznych (PV) w systemach elektroenergetycznych (EPS) w procesie bilansowania energii elektrycznej. Ponieważ PV charakteryzuje się niestabilnością produkcji energii elektrycznej ze względu na zależność od warunków atmosferycznych, w celu zwiększenia efektywności energetycznej PV stworzono automatyczny system prognozowania ich harmonogramów generacji (ASFG) na dzień następny. Rozpatrywany jest proces automatycznego kojarzenia predykcji elektrowni w ramach grupy bilansującej elektrownie oraz algorytm korygowania predykcji generacji elektrowni. Kryterium zarządzania procesem prognozowania jest minimalizacja różnicy pomiędzy wartościami generacji prognozowanej i rzeczywistej dla tego samego okresu czasu. Sprawdzenie działania i dostrojenie ASFG PV w celu oceny jego funkcjonowania i skuteczności zastosowania w zadaniu bilansowania stanów EPS jest możliwe tylko za pomocą symulacji. Wykazano, że na podstawie charakteru procesu prognozowania generacji PV z wykorzystaniem ASFG, wskazane jest zastosowanie modelowania symulacyjnego. Ponieważ podczas bilansowania z wykorzystaniem ASFG stale monitorowana jest rzeczywista wartość generacji, możliwe jest wykorzystanie tych wartości podczas symulacji i przejście do symulacji w czasie rzeczywistym. W tym przypadku modelowanie traktowane jest jako eksperymentalna metoda badań, zgodnie z którą perturbacjom i badaniom poddawany jest nie sam obiekt, ale zaimplementowany programowo komputerowy model obiektu. Model symulacyjny pracy PV w warunkach rzeczywistych umożliwia pełniejsze uwzględnienie różnych trybów ich pracy w procesie bilansowania trybów pracy EPS w ramach grupy bilansującej oraz bardziej racjonalny wybór decyzji dotyczących udziału PV w wytwarzaniu, z uwzględnieniem warunków pogodowych oraz ograniczeń operatorów systemu przesyłu i dystrybucji energii elektrycznej.*

Słowa kluczowe: system elektroenergetyczny, stacje fotoelektryczne, niestabilność generowania, stabilizacja wykresów generowania, modelowanie makietowo-imitacyjne

Introduction

Despite the benefits of photovoltaic stations (PV), they have a number of problems when using them in electric power systems (EPS). One of them is their unstable generation during the day due to dependence on natural conditions. This is especially evident when their electricity generation begins to significantly affect the electricity balancing process in the EPS. This occurs when the relative part of PV in the EPS reaches a value that is commensurate with and greater than the reserves of maneuvering power in the EPS. As a rule, this happens when the capacity of renewable energy sources (RES) in the EPS reaches 20% or more [1, 8]. With the development of solar and wind power stations, in order to be able to regulate the frequency and voltage in the EPS and ensure the stability of the energy system, it is necessary to increase the reserve of maneuvering power in it or to use means to compensate for the unstable generation of the PV [2, 24]. In essence, this is also capacity reservation, but with the use of the PV itself. Since PV can work in the modes of surplus or deficit of electricity in the EPS, they must be provided with means of energy storage and its conversion into electricity if necessary. These can be, for example, electrochemical electricity storage system, hydrogen technologies, hydraulic storage stations [3, 23]. Other methods can be used to coordinate unsustainable power generation with the EPS tasks in the process of power and electricity balancing: biogas technologies, changing electricity consumption schedules by consumers in accordance with power generation schedules, etc. [9, 12].

The task of achieving the minimum difference between the actual schedule of generation by EPS stations and the declared (forecast) for a certain period of time is common to all means of reserving the instability of PV generation and methods of agreeing schedules of electricity generation and consumption in the EPS. The declared electricity generation schedule in the EPS is formed on the basis of the forecasted consumption schedule for the same time period. As a rule, in operational tasks, this period of time is the next day. Accordingly, for PV, the task is set in such a way that it is necessary to forecast their hourly generation schedule for the next day, depending on weather conditions and their technical condition [10, 17].

1. Formulation of the task for the formation of a natural-simulation model of generation of PV in the process of balancing electricity in the EPS

The EPS is considered, which includes nuclear, thermal and large hydroelectric power stations (NPS, TPS, HPS), as well as power stations that use renewable energy sources, in particular PV. To ensure stability in periods of maximum (minimum) consumption or limited throughput of the centralized power supply system, the optimization of PV modes is relevant. In order to minimize deviations from the centrally set schedule of aggregate generation of the PV under the established restrictions on primary energy resources, the task is formulated as follows [11]:

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

taking into account the balance limit:

$$P_{CPS}(t) + \sum_{i=1}^{n} P_i(t) - P_{load}(t) - \Delta P(t) = 0 \qquad (2)$$

where $P_{PV}(t)$ – the predicted total schedule of PV generation in the balancing group; $P_i(t)$ – actual generation of all n PV of the balancing group; P_{CPS} – centralized power supply from TPS, NPS, HPS; $P_{load}(t)$ – total load of electricity consumers; $\Delta P(t)$ – power losses in electrical grids.

Task (1), as a rule, should be considered as a whole for the EPS. Another option is when for simpler and more accurate control of generation of PV stations in the EPS, several balancing groups of PV stations are allocated. In each balancing group, an automated system of commercial electricity accounting (ASCEA) is installed for each PV and forecasting of the hourly schedule of electricity generation for the next day is carried out [13]. That is, for each i-th PV, the actual and forecasted electricity generation values for a given time period are known. Therefore, in accordance with problem (1), for each i-th PV, the problem of achieving a certain accuracy between the predicted and actual electricity generation for a certain time, for example, one hour, is formulated:

$$\delta_i = \frac{w_i^P - w_i^A}{w_i^A} \le \delta_{per} \qquad (3)$$

where w_i^P, w_i^A – predicted and actual values of electricity generation of the i-th PV for the same time; δ_i, δ_{per} – current and permissible value of errors (the margin of error is often set at 0.05).

In order to control the value of the error δ_i, it is necessary to simulate two graphs: the predicted and the actual generation of the PV. The error δ_i as the difference between these graphs should be in the permissible zone or approaching it (see Fig. 1). The following implementations of this task are possible: 1) the actual schedule is what it is, and the predicted schedule is adjusted every hour or every 15–20 minutes; 2) the predicted schedule is as it is, and the actual one is adjusted to the predicted one, more precisely, it is entered into the permissible zone. True, in the last option, electricity generation and, accordingly, profit decreases. It is decided what is better: whether to lose electricity generation, or to reduce sanctioning fines for deviations from the permissible zone? A third option is also possible, when the predicted schedule is simultaneously adjusted and the actual generation is changed to enter the permissible zone or approach it.

The goal of the article is to develop a natural-simulation model for researching the processes of short-term forecasting and operational management of the generation of PV stations in the EPS mode balancing system using SMART Grid technologies.

2. Automation of the PV forecasting process as part of the balancing group

In order to build an effective algorithm for forecasting the schedule of electricity generation by photovoltaic stations (Fig. 2) and its successful automation, it is necessary to have a suitable array of output data and software. The first step is the formation of a mathematical model of the PV itself. For this, it is necessary to have information with the characteristics of PV modules, which are written in the passport data. The determining information is: the orientation of the modules relative to the South, the angle of their inclination, the type of module, the number of elements of the photovoltaic module, the no-load voltage, the short-circuit current, etc. The configuration of the electrical circuit of the PV consists of information on the number of modules in the string, the number of strings per inverter, the number of inverters and the number of transformer substations.

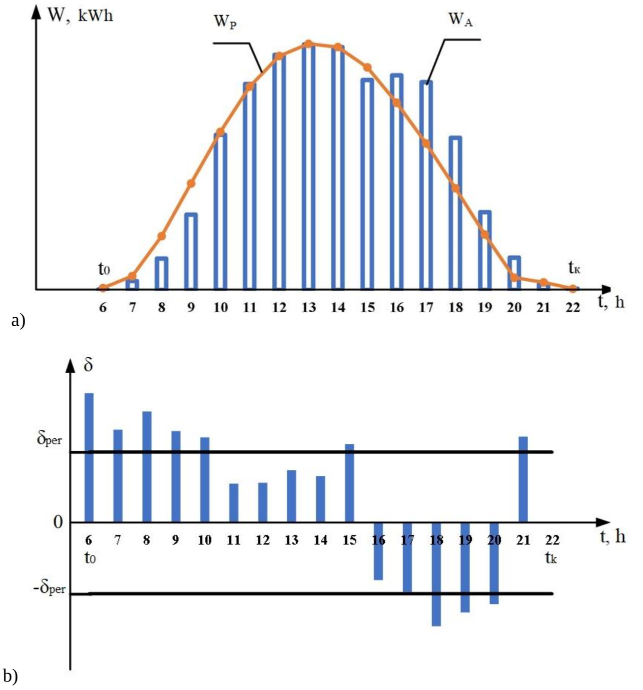

Fig. 1. Schedule of the actual and forecasted generation of PV (a) and, accordingly, forecasting errors (b)

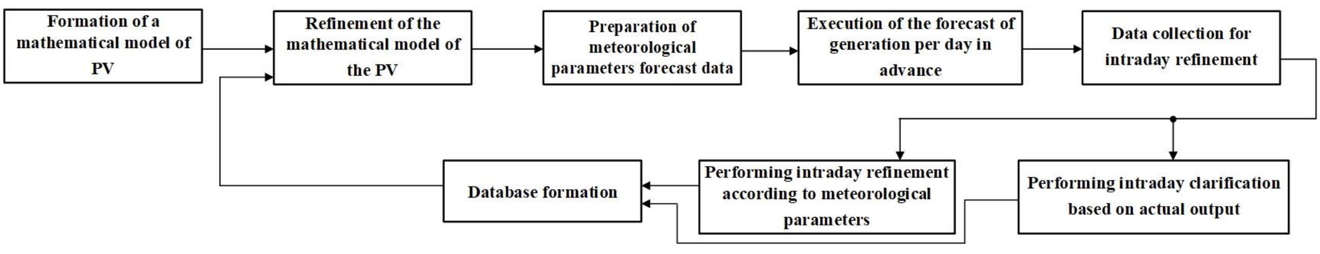

Fig. 2. Structural diagram of the automation of the PV forecasting process as part of the balancing group

Since the operating conditions of PV are constantly changing, their mathematical model is constantly refined. A parameter database (DB) is being created to automate the process of refining the PV generation prediction model. Usually, MySQL is used, so it slows down its work when it is significantly filled. The necessary meteorological parameters from various services are collected in the database. There are quite a lot of such services on the market, all of them allow you to organize API communication, which allows you to automate the data collection process, in addition, there are a significant number of libraries in C#, Python, etc., which implement such communication.

After making a forecast for one-day ahead, no company that provides such services can guarantee sufficient accuracy, so it is necessary to use the possibility of intraday correction. In different countries, the market accepts the results of this adjustment with different discreteness. As a rule, this time is from 15 minutes to 2 hours. Obviously, the smaller this interval, the better results can be obtained. Intraday adjustments can be made in two ways: recalculating the generation schedule based on refined meteorological parameters or based on the results of monitoring the current production of electric energy by the PV.

The first algorithm requires the use of weather services that adjust their forecasts during the current day. The second requires the use of telemetry, which can provide polling almost every minute, or ASCEA, which usually operates with greater discreteness.

After correction, the results are sent to the operator of the balancing group.

All data on meteorological parameters, production forecast and the actual value of the produced energy are also entered in the database for further correction of the mathematical model of the power station. Such correction is carried out during the first month of provision of forecast services and then provided as needed to take into account seasonal changes and degradation processes in the equipment of the PV.

3. Automation of the PV forecasting process as part of the balancing group

The logical scheme for calculating the adjusted value of the hourly forecast of PV generation for the next hour of the current day is as follows. Hour i is determined, from which i_b starts and ends i_e of PV electricity generation, where i is the current value of the hour number.

Further:

- $i = i_b$, the prediction error for the i-th hour is determined $\delta_i = \frac{w_i^P - w_i^A}{w_i^A}$;
- $i = i+1$, the prediction error for the i+1st hour is determined $\delta_{i+1} = \frac{w_{i+1}^P - w_{i+1}^A}{w_{i+1}^A}$.

If $\delta_{i+1} \succ 0$, then:

if $\delta_{i+1} \le \delta_{per}$, then k = 1 $w_{i+1}^P = k\, w_{i+1}^P$ (That is, the forecast remains the same, in the permissible area);

if $\delta_{i+1} \le \delta_i$, then we go to the beginning of the cycle i = i+1 ("Prediction" is getting closer to "fact");

if $\delta_{i+1} \succ \delta_i$ ("Forecast" differs from "fact") and $\delta_{i+1} \succ \delta_{per}$, then $k = 1 - \delta_i$ and $w_{i+1}^P = k\, w_{i+1}^P$ and go to the beginning of the cycle i = i+1.

If $\delta_{i+1} \prec 0$, then:

if $\delta_{i+1} \ge -\delta_{per}$, then k = 1 $w_{i+1}^P = k\, w_{i+1}^P$ (That is, the forecast remains the same, in the permissible area!);

if $\delta_{i+1} \succ \delta_i$, then we go to the beginning of the cycle i = i+1 ("Prediction" is getting closer to "fact");

if $\delta_{i+1} \prec \delta_i$ ("Forecast" differs from "fact") and $\delta_{i+1} \prec -\delta_{per}$, then $k = 1 - \delta_i$ and $w_{i+1}^P = k\, w_{i+1}^P$ and go to the beginning of the cycle i = i+1.

In Fig. 3 shows the algorithm of the hourly adjustment program for forecasting the electricity generation of the PV, and Fig. 4 shows an example of the result of an hourly prediction of the generation of the PV using the forecast correction program with error compensation δ_i,.

As can be seen, the forecasting error of PV electricity generation per day decreased from 15.6% to 4.7%. That is, the algorithm with compensation of hourly errors in forecasting the generation of PV gives a satisfactory result.

It can be used along with the adjustment of PV generation based on hourly refinement of daily meteorological parameters.

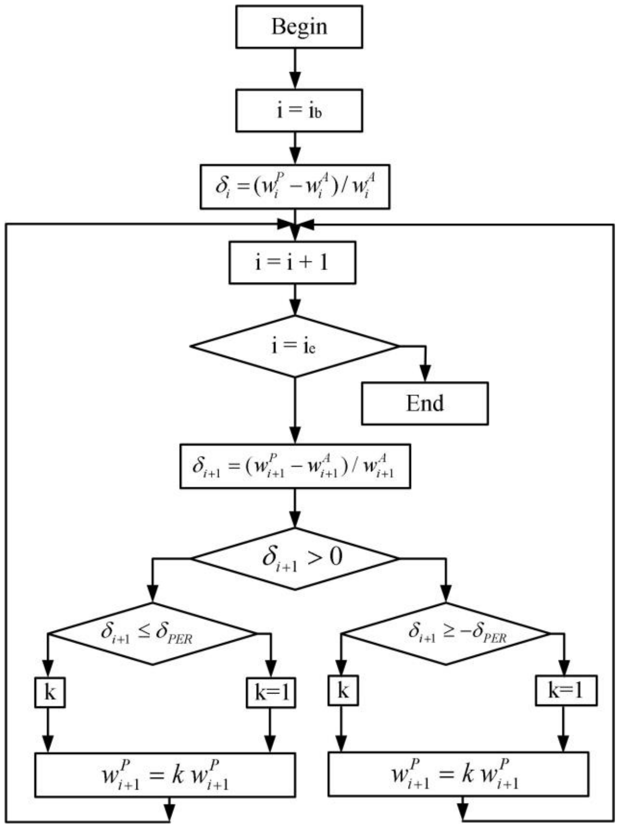

Fig. 3. Algorithm of the program for hourly adjustment of forecasting of electricity generation of PV

4. Natural-simulation modeling of PV generation in the process of balancing EPS modes

The process of automating the forecasting of the power station generation schedules and their current adjustment in accordance with changes in operating conditions, primarily weather conditions, is an important element of the successful balancing of the state of the power station.

As in all dynamic processes related to electric power systems, and in our case, a feature is the impossibility of studying them in different modes directly on the object [7, 21].

Therefore, checking the performance and setting of the automatic generation forecasting system (AGFS) of the PV in order to evaluate its functioning and the effectiveness of its application in the task of balancing the modes of the EPS is possible only by means of simulation.

Based on the nature of the AGFS process, it is advisable to use simulation modelling.

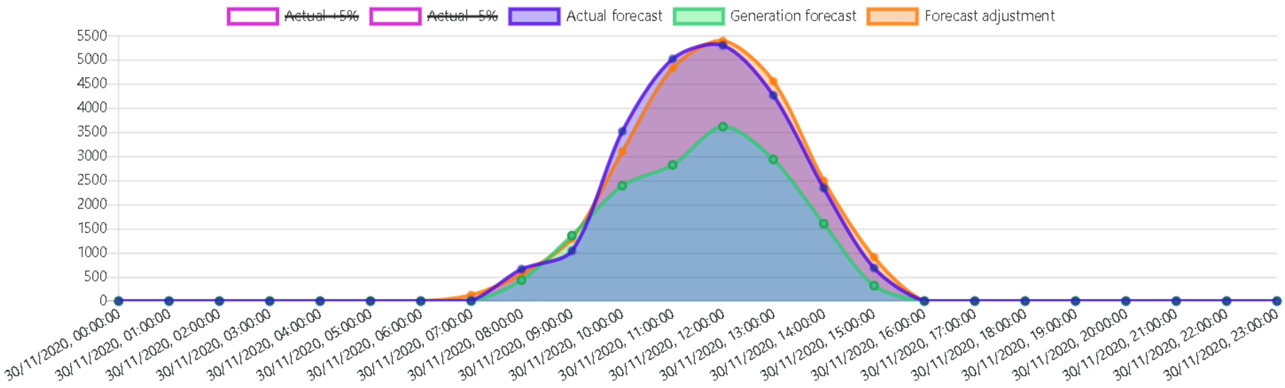

Fig. 4. Correction of PV generation forecasting based on the results of error control

Because during balancing using AGFS, the actual value of generation is constantly monitored w_i^A, then it is possible to use these values during simulation. Such a model can be classified as natural-simulation [7, 22]. The method of nature-simulation modeling is considered as an experimental method of research, according to which the object itself is subjected to disturbance and research, but the simulation model of the object implemented on a computer.

In Fig. 5 shows the structure of the nature-simulation model (NSM) of checking and adjusting the AGFS PV.

It contains a functional model of the object (FMO), which together with the AGFS PV forms a closed system. This allows for a fairly accurate modeling of the control object to achieve the maximum probability of testing the AGFS PV, since the test system can reproduce an arbitrary mode of the object in the permissible area of existence. Along with the benefits, it is necessary to note a certain complexity in the implementation of the structure, which is primarily reflected in the need for not only informational, but also physical compatibility of the model and AGFS. The assessment of the correct functioning of the AGFS in this structure is provided by comparing the outputs of the AGFS with the control data of the modes of the real object.

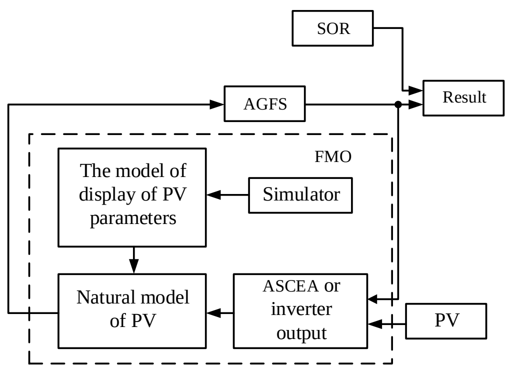

Fig. 5. The structure of the natural-simulation system of AGFS testing

The key link in the organization of the NSM test system is the construction of the simulator, which is part of the FMO.

The simulator is designed to reproduce a certain number of modes of the object. The regime of PV [14, 15] is an admissible set of its states and processes of its change. During the transition from one state to another, the current mode indicators (mode parameters) change, which occurs under the influence of external disturbances (changes in loads) or control signals to change the actual generation of the power stations.

When creating and testing a control system based on simulation, the continuous operation of the PV is replaced by a set of characteristic modes. The correct implementation of this principle ensures the necessary reliability of the process of checking control devices. Correctness in this case implies the appropriate choice of modes and their number, a set of parameters and the accuracy of their measurement by means of the automatic system of commercial electricity accounting (ASCEA). When introducing signals simulating the parameters of the PV modes into the control system, system operator restrictions (SOR) of the EPS are taken into account. First of all, this is the mode of the EPS in relation to the deficit or surplus in the electricity balance.

The mathematical formulation of the task of organizing the FMO simulator can be formulated as follows. Dependency given (function):

$$y = f(t), \tag{4}$$

where f and, accordingly, y is an n-dimensional vector in the general case, $f = [f_1, f_2, \ldots, f_n]^T$; independent variable t, which is the time specified on some finite interval $t \in [t_0, t_k]$. The process of reproducing function (4) is organized subject to certain conditions: the necessary modeling accuracy must be ensured, given, for example, in the form of a value

$$\varepsilon = \left|\max y(t) - \bar{y}(t)\right|, \quad t_0 \le t \le t_k \tag{5}$$

that is, in the form of the maximum permissible difference between the reproduced process y(t) and its machine model; the system for entering function (4) into the model should have the properties of flexible control (stop, repeat, change modes, etc.) to ensure the effectiveness of the test system as a whole; the reproduction process must be controlled to ensure the reliability and validity of the exam results.

Experiments can be carried out both according to a previously prepared plan and sequentially, the purpose of a new experiment is established based on the analysis of the results of the previous one. In the case of implementing the simulator on a computer, not only the actual simulator program is created, but also the experiment management program, which leads to the fact that: the state of the simulator does not change after conducting the next experiment and the next experiment is conducted; after each experiment, the simulator returns to the initial state common to all experiments; the results of the experiment lead to a change in the imitator, that is, the model [4].

The PV functional model has the same transforming properties as the modeled object itself. FMO PV is built with a defined set of structures and is described in the form of an equation

$$\mathbf{Y} = F(\mathbf{y}, \mathbf{x}, \mathbf{u}, t) \tag{6}$$

where **y** – n-dimensional vector of initial coordinates $y_i(t)$, $i = \overline{1, n}$; **x** – r-dimensional vector of disturbing influences $i = \overline{1, r}$; **u** – m-dimensional vector of controlling influences $u_i(t)$, $i = \overline{1, m}$; the ranges of variable values are known: $y \in V$, $x \in X$, $u \in U$.

An important condition determining the field of application of the model is the requirement that the input and output variables of the model are natural. If there are requirements for naturalness of variables, the model is based on the following principles [5, 16]. As three main, functionally independent interdependent parts, the system contains a reference model of the reproduced object (reproduced image), fixed in the form of an information carrier, a controlled carrier of real variables (real model) and a control system (control device). The functioning of the modeling system is organized by the control system, which provides control of the input variables of the real model in such a way that its output variables change according to the law set by the reference model, that is, the nature model monitors the behavior of the reference model.

The reference model is the carrier of the image of the modeled object. It is implemented by dependencies that record the capacity of the certified generation of the PV or the calculated generation according to the reference model is the carrier of the image of the modeled object. It is implemented by dependencies that record the capacity of the certified generation of the PV or the calculated generation according to the volt-ampere characteristics (VAC) taken during the commissioning of the PV. In all cases, the reference model is described by the given equation (6) or solves it. The variables reproduced by the reference model differ from real processes by scale factors. The time scale of the output signals is equal to one, since real control signals must be received at the input of the natural model in the simulation system.

Since the natural model must satisfy the requirements for the full-scaleness of its initial characteristics [5, 6], its internal properties must satisfy the controllability conditions. This is achieved by ASCEA or parameters transmitted directly from the output of PV inverters. In the latter case, additional equipment is required, but it is possible to control the ASCEA errors, which are introduced into the results of the actual electricity generation of the PV. If a natural model is selected, then its equation is known and has the form

$$\mathbf{Z} = \Phi(\mathbf{z}, \mathbf{v}, \mathbf{x}, t) \quad (7)$$

where $\mathbf{z} \in \mathbf{Z}$ – coordinates of the mode, i.e. modeling variables of the system; $\mathbf{v} \in \mathbf{V}$ – control variables; $\mathbf{x} \in \mathbf{X}$ – natural external influences (the same variables that enter the equation of the modeled object, since the object and the model are designed to work in the same external environment).

According to the principle of replacing the object with a model, equations (6) and (7) do not coincide, i.e. $F \neq \Phi$, and, in addition, the scopes of the variables included in these equations do not coincide, and the dimensions of the vectors **y** and **z** may also not coincide. Therefore, in the general case, it is impossible to ensure a full reproduction in the model of all modes of operation of the modeled object [18, 19, 20].

The control system is built on the basis of known control principles. The choice of the method of synthesis of the control system and its structure is determined by similarity criteria [21].

Restrictions on the ratio between the simulated variables y_i coming from the reference model and the modeling variables z_i reproduced by the natural model are accepted as similarity criteria. The determining criteria of similarity are the functionals of the modeling error $\varepsilon = y - z$.

Different structures of modeling systems can be obtained depending on the type of given equations of the reference model, the adopted control method (by disturbance, by deviation, program method), type of control law. We will consider the organization of some structures of modeling systems using the example of a linear object described by a linear, in general, matrix equation of the form

$$\mathbf{Y} = \mathbf{F}\mathbf{y} + \mathbf{u} \quad (8)$$

where is the vector of initial coordinates is **y** and the vector of input influences **u**, having the same dimension n; **F** is a matrix of operators of dimension $n \times n$.

The structure of the modeling system implementing the functional model of the object is described by the equation

$$\mathbf{Z} = \mathbf{\Phi}\mathbf{z} + \mathbf{v} \quad (9)$$

where the components **z**, **v** and **F** are analogous to the components of equation (7) and have the same dimension.

The similarity of the model and the object is ensured by the input into the modeling system of the control signal **u** with the condition

$$\mathbf{Z} = \mathbf{Y} \quad (10)$$

Since condition (10) is equivalent to equality

$$\mathbf{F}\mathbf{y} + \mathbf{u} = \mathbf{\Phi}\mathbf{z} + \mathbf{v} \quad (11)$$

and this control leads to the observation of coordinates **z** by the ratio of variables **y**.

Management is carried out using regional dispatch centers, which are coordinated by operators of the transmission and distribution system. The control criterion is the achievement of a stable balance of electricity in the system with the optimal composition of available means. One of the necessary methods of balancing is the limitation of RES generation in order to maintain the frequency and voltage within acceptable limits. In natural-simulation modeling, a complex system of balancing groups of PV can be divided into subsystems. In this case, a simulation model is developed for individual subsystems, other subsystems are not simulated and a natural experiment is carried out for them.

A subsystem can be a separate PV or a group of PV united by some feature (for example, territorially, when a group of PV is characterized by the same meteorological parameters). At the same time, appropriate AGFS with their own databases are used, which does not require any additional costs for information support of natural-simulation modeling.

5. Conclusions

The application of the developed natural-simulation model of the process of assessing the compliance of the predict and the actual generation of the PV makes it possible to assess in real time the consequences of non-fulfillment of the power balance by individual balancing groups. This is taken into account for the improvement of the existing operational and information complex of PV with means of compensation for the instability of their generation. As a result, the efficiency of the functioning of distribution electric grids increases, operational management of distributed generation operating modes based on SMART Grid principles is improved, and power quality indicators are improved.

As a result of research and consistent implementation of natural-simulation modeling to improve the automatic forecasting system of PV generation during short-term forecasting and operational management of PV generation in the EPS mode balancing system, regulation accuracy increases. This approach to reducing the error of compensating the instability of generation of power stations creates favorable conditions for their wider and effective use in the EPS. A technical possibility is provided for increasing the volume of PV generation in electric power systems in accordance with the values declared by investors and the technical conditions issued for them to connect to electric grids.

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