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Investigation of Existence of Steady States of a Solar Power Plant Operating in the Distribution Network of an Electric Power System*

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The paper presents the results of studies of the steady-state operating modes of solar photovoltaic stations. Using the data obtained, it is possible to significantly increase the efficiency of using solar power generating plants and significantly increase the service life of additional equipment.

The relevance of this study is due to the increasing demand for low-power electric power systems, as well as for renewable energy technologies. For the research, materials were taken from relevant international departments and agencies, the Ministry of Energy of the Russian Federation. In addition, the sources of data are publications and studies of Russian and foreign scientists on the issues under study.

The Federal Law No. 35-FZ "On Electricity", adopted in December 2019 by the State Duma of the Russian Federation, introduces such a concept as "Micro-generation facility", thereby simplifying the possibility of installing, connecting to the general network of an electrical system, for example, a small solar power plant (SPP) consumer.

Small-scale electric power industry at this stage of its life is an energy-efficient tool in the restructuring of the energy sector of the Russian Federation, contributing to the abandonment of the traditional centralized system based on the use of large sources of electric power production, and the transition to alternative methods of generating electricity based on the use of energy sources, updated for specific natural conditions and requests of potential consumers.

Reducing pollutants and emissions that are harmful to human health can reduce the level of the existing burden on the country's economy and give an impetus to the development of its potential due to the freed up resources. reduce the burden on the economy, thereby freeing up resources for its growth.

Of course, the transition from traditional economic models to the model of "green growth" can be realized only if significant efforts are made to expand international cooperation in this area. At the same time, there is a need for consistent implementation of events at various levels on the part of all states, as well as maintaining the chosen political course for many years.

Keywords: solar power plant (SES), steady state SES, energy generation, statistical stability, small generation, wind turbines.

Introduction

The object of microgeneration (small generation) are devices for the production of electrical energy, owned by the right of ownership or other legal grounds to the consumer (individual or organization). Such devices can be generating capacities based on renewable energy sources (RES) (solar batteries, wind turbines, tidal / wave power plants, etc.), for example, solar power plants (SPP) based on photovoltaic modules (Fig. 1) [1].

Technological connection of microgeneration facilities should provide for their connection to the networks of the last resort supplier at a voltage of up to 1000 V and ensuring the technical limitation of the output of electrical energy to the network with a maximum power not exceeding the maximum power of the receiving devices of the consumer of electrical energy, which belong on the right of ownership or other legal grounds to microgeneration facilities, and the component is not more than 15 kW [2].

The requirement for connecting the solar power plant to the network consists in the flow of current through the power line from it to the network, synchronized in frequency and phase, while the voltage of the solar power plant inverter should be slightly higher than the voltage in the network [3].

If the task of introducing a solar power plant is to sell electricity to the grid at a "green" tariff and earn money, then the network inverter must be selected according to the following parameters:

- the inverter power is not more than the permitted power (can be increased up to 30 kW);

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- the electricity consumed by the load of the owner of the solar power plant should not be more than that generated by solar panels and supplied by the grid inverter;
- the grid inverter must be certified;
- the network inverter must be mounted by an organization that has a license for the construction of objects of the 4th and 5th category of complexity.

At the international conference Energy Transition Dialogue dedicated to the global transition to renewable energy, which was held in Berlin in April 2020, the International Renewable Energy Agency (IRENA) made a presentation "Transforming the global energy system. Roadmap to 2050". According to them, in 30 years the share of green electricity, produced mainly by the sun and wind, can be increased to 86 % [4].

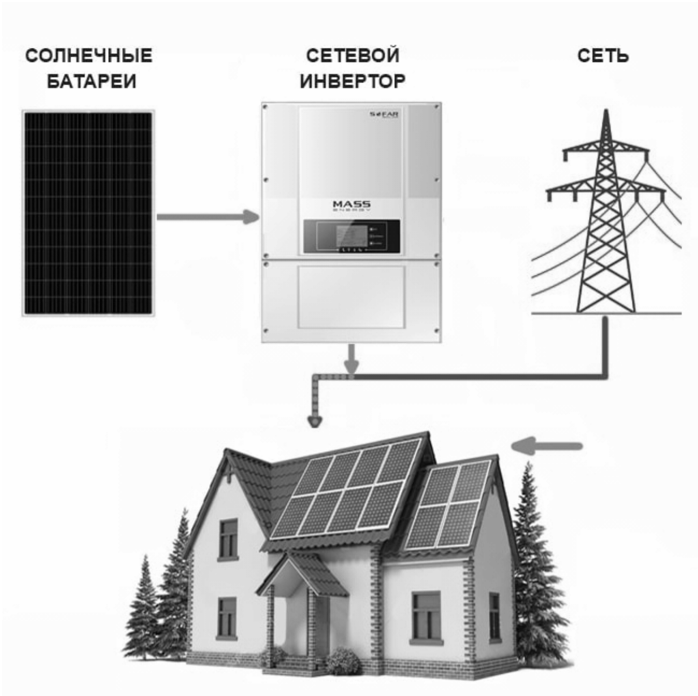

Fig. 1. SPP with a gridin verter as a microgeneration object

In addition to RES, the most common distributed energy generation technologies in the world practice are natural gas-based technologies, more maneuverable GTPs and CCGTs, etc.

Distributed generation mainly includes low power sources, such as wind power plants with a capacity of up to 500 kW, solar power plants up to 1 MW, gas turbine power plants up to 250 kW [5].

The power limits for distributed generation sources, as defined by the European Union Dynamical Exascale Entry Platform (EU-DEEP), are as follows: wind farms - 6 MW; solar stations - 5 MW; thermal power plants (steam, gas turbines, reciprocating engines) - up to 10 MW, micro-turbines - up to 500 kW [6].

The transition of the energy system to a new level leads to sustainable territorial development, energy security, and also allows solving global environmental problems, which many states are aiming at, and are implementing various programs for the development of small generation

Among the measures taken by the states to support the development of distributed generation, it is worth noting tax incentives, the formation of various funds, through which the relevant research and development work and project activities are financed, the approval of the volume of electrical energy that should be generated on RES, etc. [7].

Distributed generation introduces large changes in the network configuration and modes, as a result, the requirements for traditional protection and the control system have to be adjusted and rebuilt. As of today, the standards for connecting distributed generation to the power supply system are mostly based on the principle that distributed generation should not affect the normal execution of protection actions and system control. But this option cannot be used when the share of distributed generation is more than 15% of the total installed capacity, which has a significant impact on the operating modes of the power system with various fluctuations [8].

Distributed generation is a practically rational option for ensuring the reliability of power supply in areas of centralized energy. The main means of increasing reliability is structural redundancy [9]. A backup power plant or a backup electrical unit in a local area requiring increased reliability can easily solve this problem.

Electric energy produced at microgeneration facilities and not consumed by their owners and other legal owners in order to meet their own household and (or) production needs, is sold on retail markets in the manner established by the basic provisions for the functioning of retail markets [10].

The sale by individuals of electrical energy produced at microgeneration facilities is not an entrepreneurial activity.

The conclusion of a contract for the sale and purchase of electric energy produced at microgeneration facilities located in the area of activity of the guaranteeing supplier with the owner or other legal owner of microgeneration facilities who applied to the guaranteeing supplier is mandatory for the guaranteeing supplier [11] .

Accounting for consumed and released electricity between the SES and the grid organization can be controlled, for example, by a multifunctional bidirectional meter PSC-4TM.05MD.21 [12].

A supplier of last resort, operating in the price and non-price zones of the wholesale market, purchases on retail markets from the owners and other legal owners of microgeneration facilities electric energy produced at microgeneration facilities at prices not exceeding the prices for purchased in the wholesale market by guaranteeing suppliers of electric energy and power [13].

If we divide the cost, for example, of a network solar power plant with a capacity of 20 kW, by its daily output, multiplied by the approximate price of electricity on the wholesale market, then the payback period of the solar power plant will be about 15 years. Such a period is comparable with the service life of solar panels and is almost twice as long as the service life of a network inverter [14]. Therefore, it is not profitable to buy solar power plants as a microgeneration facility in order to receive profit from the sale of electricity in the absence of a feed-in tariff. Also, it will not be possible to use the network as a huge external battery, where you can store the excess generated electricity, since the consumer has a bidirectional meter that separately counts the amount of electricity supplied to the network and the amount of electricity received from the network [15].

When calculating at the end of the month, a balance is drawn up, and if the SPP generated more electricity than its owner consumed, he is paid the difference calculated at wholesale market prices. If he generated less electricity at the solar power plant than he consumed, then he pays the difference at the retail price [16].

Purpose of the study – development of a method for analyzing the static stability of steady state operation modes of a network SES based on the Jacobian of the steady state equations and constructing allowable areas in the space of voltages and powers, which can be applied to a SES of arbitrary power.

To solve the proposed goals, the following research tasks were set:

– carrying out theoretical studies to determine the modes of generation of electrical energy by SPP in parallel operation with the network;

- solution of mathematical equations used in modeling the operation of a solar power plant operating in conjunction with a common power system;

- determination of the areas of permissible values for the steady-state operating modes of the solar power plant.

The established mode of operation of the solar power plant together with the electrical system network

Let's consider the steady-state operation of the solar power plant together with the network of the electrical system (Fig. 2). The steady-state mode must satisfy not only the technical restrictions on the voltage level of the SES ($1.1U_n \geq U_1 \geq 0{,}9U_n$) and the long-term permissible current in the power line connecting the SES to the network, but also be statically stable [17].

The steady state equations for the system shown in fig. 3, represent the power balance equations in node 1 of the SES, i.e., the total generation power of the SES (usually taken as negative) must be completely transmitted via power lines to the network or consumed by the load of the node:

$$-\dot{S}_1 = \sqrt{3}\,\dot{U}_1 \overset{*}{I}, \qquad (1)$$

where $-\dot{S}_1$ – total generation capacity of solar power plant; $\dot{U}_1$ – complex voltage of the SES grid inverter; $\overset{*}{I}$ – conjugated complex of current flowing from the solar power plant to the network or from the network to the node via power lines.

For further analysis, it is convenient to represent in equation (1) the total power complex in algebraic form, and the voltage complex in trigonometric form:

$$-\left(P_1 + jQ_1\right) = \sqrt{3}\left(U_1 \cos\delta_1 + jU_1 \sin\delta_1\right). \qquad (2)$$

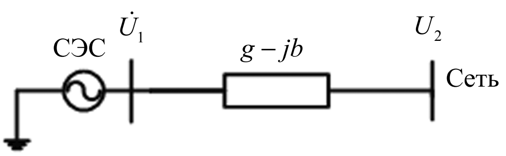

Fig. 2. Scheme of power output of SPP to the general distribution network of the electrical system

The mains voltage U_2 is taken as basic and real ($\delta_2 = 0$), and the current complex in the power line is determined by Ohm's law:

$$\dot{I} = \left(-U_2\right)\left(g - jb\right). \quad (3)$$

The active g and reactive b conductivity of the power transmission line can be determined by the corresponding active r_0 and reactive x_0 linear resistances of the wire connecting the SES to the network, and its length L:

$$\begin{Bmatrix} g = \dfrac{r_0}{L\left(r_0^2 + x_0^2\right)} \\ b = \dfrac{x_0}{L\left(r_0^2 + x_0^2\right)} \end{Bmatrix}. \quad (4)$$

From (1) it is possible to determine the current complex in the power transmission line if we divide the conjugate complex of total power by the conjugate complex of voltage

$$\dot{I} = \frac{-\overset{*}{S}_1}{\sqrt{3}\overset{*}{U}_1}. \quad (5)$$

Substituting the resulting expression for the current into equation (3) and replacing the phase voltages with linear ones, we obtain a complex equation that describes the steady state in the electrical network shown in Figure 3:

$$-\overset{*}{S}_1 = \overset{*}{U}_1\left(\dot{U}_1 - U_2\right)\left(g - jb\right). \quad (6)$$

Having performed the multiplication on the right side of equation (6), we obtain the following algebraic expression:

$$-\left(P_1 - jQ_1\right) = U_1^2 g - jU_1^2 b - U_1 U_2 g\cos\delta_1 +$$
$$+ jU_1 U_2 b\cos\delta_1 + jU_1 U_2 g\sin\delta_1 + U_1 U_2 b\sin\delta_1. \quad (7)$$

Complex equation (7) can be reduced to two real equations that determine the balance in the network of active and reactive power, and is represented by the following equations:

$$P_1 + U_1^2 g - U_1 U_2 g\cos\delta_1 + U_1 U_2 b\sin\delta_1 = W_a; \quad (8)$$

$$-Q_1 - U_1^2 b + U_1 U_2 b\cos\delta_1 + U_1 U_2 g\sin\delta_1 = W_r. \quad (9)$$

In equations (8) and (9) W_a and W_r unbalances, respectively, active and reactive power in the PSS node, which are implicit functions of the variables U_1, δ_1, P_1, Q_1 and U_2, in the steady state should be equal to zero.

In turn, the variables U_1, δ_1 will be dependent on P_1, Q_1 and U_2. Based on the work carried out in this direction, including by other authors, we draw a logical conclusion that it is possible to judge the static stability of the mode of an electrical system by the Jacobian of the equations of the steady state, which coincides with the free term of the characteristic equation of small oscillations.

Jacobian of equations steady state

Consider the Jacobian of the steady state equations (8), (9), which can characterize the stability of the SES operation as part of the electrical system:

$$\det = \begin{bmatrix} \dfrac{\partial W_a}{\partial \delta_1} & \dfrac{\partial W_a}{\partial U_1} \\ \dfrac{\partial W_r}{\partial \delta_1} & \dfrac{\partial W_r}{\partial U_1} \end{bmatrix} = \frac{\partial W_a}{\partial \delta_1}\frac{\partial W_r}{\partial U_1} - \frac{\partial W_r}{\partial \delta_1}\frac{\partial W_a}{\partial U_1}. \quad (10)$$

Here $\dfrac{\partial W_a}{\partial \delta_1}, \dfrac{\partial W_r}{\partial \delta_1}, \dfrac{\partial W_a}{\partial U_1}, \dfrac{\partial W_r}{\partial U_1}$ – respectively, the partial derivatives of the unbalances of active and reactive power in the SES node in terms of angle and voltage modulus.

When performing calculations of derivatives, as well as when performing arithmetic operations according to formula (10), we obtain the following fairly simple expression for the Jacobian:

$$\det = U_1 U_2\left(g^2 + b^2\right)\left(U_2 - 2U_1\cos\delta_1\right). \quad (11)$$

Equation (11) makes it possible to determine the boundary of the limiting static stability of the established modes of operation of the solar power plant, at which det becomes equal to zero.

Taking into account the fact that none of the above parameters – U_1, U_2 and $(g^2 + b^2)$ – can be equal to zero in really existing modes, equation (11) can be written as

$$U_1 = \frac{U_2}{2\cos\delta_1}. \quad (12)$$

Using equation (12), which determines the limiting state of the steady state equations, we will consider the operation of a solar power plant connected to a 0.4 kV electrical system network by an overhead power line with a SIP 2a 4×16 mm^2 wire.

The voltage established at the point of connection of the solar power plant to the network U_2 will be considered equal to U_n = 0.4 kV.

Linear parameters of the power line wire from (8): r_0 = 1.91 Ohm/km; x_0 = 0.0865 Ohm/km. We take the length of the power line equal to 50 m.

Calculated according to the indicated equation (4), the active and reactive components of the conductivity of the power transmission line, respectively:

g = 10.45 cm;

b = 0.47 cm.

Figure 3 shows a curve for the specified parameters of the network and power transmission lines, constructed according to the data obtained from the calculation according to formula (12), on which the Jacobian of equations (8), (9) vanishes.

The area D_x, which is shown in the same figure, corresponds to statically aperiodically stable operating modes of the solar power plant, in this area det > 0.

Outside this area, the established mode of operation of the solar power plant will be unstable, and its implementation is impossible. According to the data obtained, at $\delta_1 > 0$, the SES generates power to the network, at $\delta_1 < 0$ the SES switches to the mode of power consumption from the network.

If the curve det = 0 in the space $U_1 - \delta_1$ using equations (8), (9) is mapped into the space of active and reactive powers of the solar power plant, then we get the region of existence of steady-state modes D_y. The image of this area is shown in Figure 4.

For any power that belongs to D_y, there is a steady state, which can be represented in the coordinates $U_1 - \delta_1$.

It should be noted that for P_1 and Q_1 outside D_y, there are no steady-state SES modes. Within the area of stable modes D_x (Fig. 3), the area of steady state modes of the solar power plant, admissible according to the voltage level U_1 – D_{xd}, in which the steady state modes of the solar power plant will be stable and permissible, is highlighted.

In order for U_1 and δ_1 to be in the allowable region D_{xd} in the steady state, this region must be mapped into the space $P_1 - Q_1$.

Figure 5 shows the obtained area D_{sp} of acceptable values P_1 and Q_1, when set at the SPP, technical restrictions on the voltage level U_1 will be met.

As can be seen from Figure 5, in the area of micro-generation of active power or its consumption from the network (–0.1 MW < P_1 < 0.1 MW), the steady-state modes of the SES are completely within the allowable area D_{sp}.

However, for each value of P_1 and Q_1, even from D_{sp} in the space $U_1 - \delta_1$, there are 2 steady-state modes, one of which, belonging to D_{xd}, will be statically stable, and outside the D_x region it will be statically unstable.

Therefore, setting P_1 and Q_1 from D_{sp} is a necessary but not sufficient condition for the steady state mode of the SES to have static stability.

To ensure the static stability of the steady state mode of the solar power plant, it is necessary to control both the voltage module of the station and the angle of this voltage relative to the voltage U_2. In the range of permissible U_1 values, this angle should not exceed ± 63° for $U_1 = 1.1U_n$ and ± 56.3° for $U_1 = 0.9U_n$.

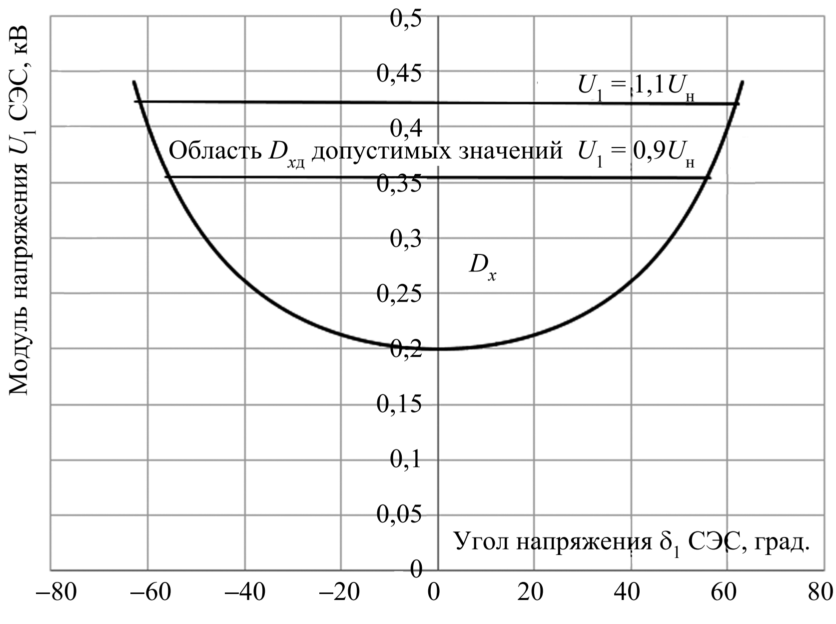

Fig. 3. Boundary of the Jacobian (det) equal to zero of the equations of steady state SPP regimes in coordinates U_1 and δ_1

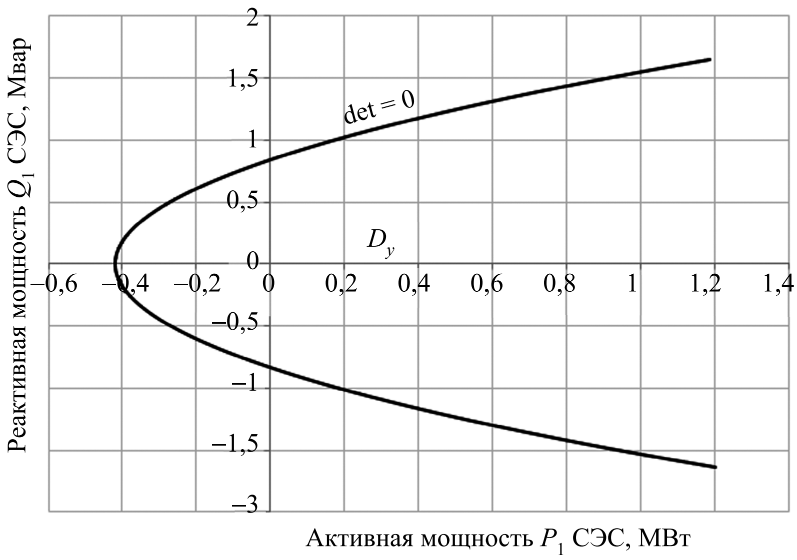

Fig. 4. The region of existence of steady-state SPP regimes D_y in coordinates of generation of its active P_1 and reactive Q_1 power

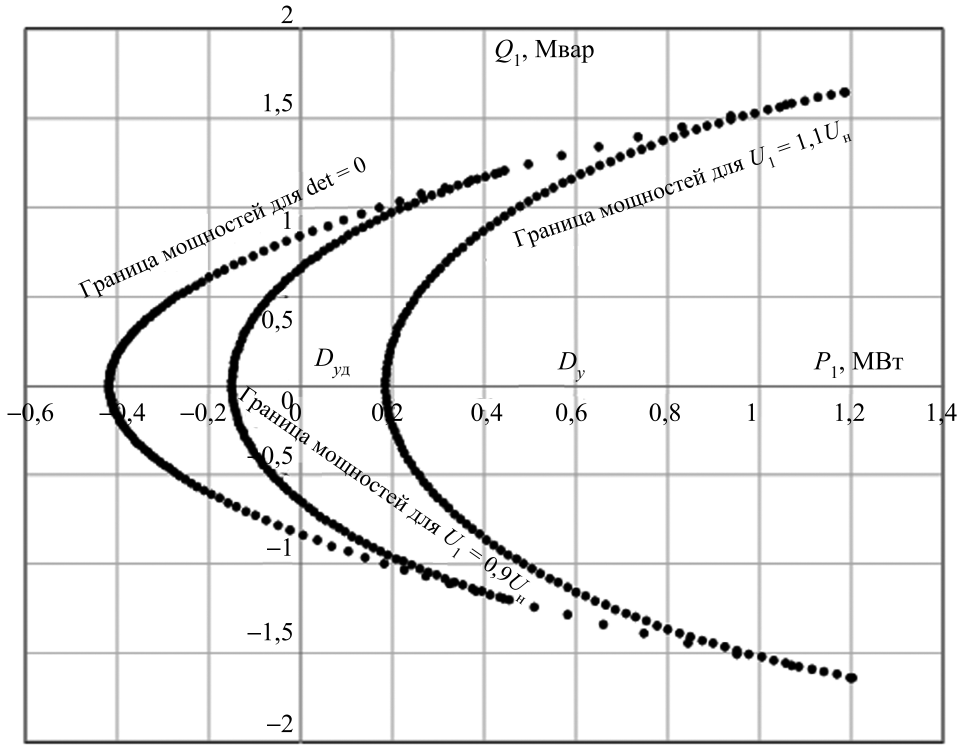

Fig. 5. The area of admissible values of P_1 and Q_1 SPP (D_{ya}) inside the area of existence of steady-state modes D_y, at which the voltage U_1 is in the range (0.9…1.1) U_v

During the operation of the SES as part of an electrical system, a violation of the static stability of its steady-state modes can occur, for example, with a sudden increase in the voltage of the U_2 network caused by switching switching or atmospheric phenomena, since 0.4 kV networks are often installed on the same supports with 10 kV networks[18].

Also, a short-term decrease in U_1, caused, for example, by the start of a powerful motor in the SES node, or a failure in the operation of the SES grid inverter, which led to the output of δ_1 beyond the above limits, can lead to the output of the parameters of the steady state mode from the static stability region [19].

Using the data obtained, it is possible to significantly increase the efficiency of the generation of electrical energy by a solar station. The use of the most rational modes of operation of SES can significantly increase the service life of auxiliary equipment and reliability of operation [20].

Findings

1. The proposed method for analyzing the static stability of steady-state operating modes of a network SES based on the Jacobian of steady state equations and constructing allowable areas in the space of voltages and powers can be applied to SES of arbitrary power.

2. In the process of setting up devices for monitoring the electrical parameters of the solar power plant, one should take into account the restrictions not only on the modules, but also on the voltage angles of the station.

3. Overvoltage in the network, a decrease in the voltage module in the SES node, caused, for example, by the start of a powerful electric motor, as well as failures in the operation of the station's network inverter, can lead to the transition of the steady state to a statically unstable region.

4. The results of the study showed the feasibility and accuracy of the proposed method in an incomplete case study. The performed calculations prove the indisputability of the fact of the significant contribution of this article to research on the subject of microgeneration.

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Исследование установившихся режимов солнечной электростанции, работающей в распределительной сети электроэнергетической системы

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Приведены результаты исследований установившихся режимов работы солнечных фотоэлектрических станций. При использовании полученных данных возможно значительно поднять эффективность использования солнечных электрогенерирующих установок и значительно увеличить срок службы дополнительного оборудования.

Актуальность данного исследования обусловлена увеличивающимся спросом на электроэнергетические системы малой мощности, а также на технологии возобновляемой энергетики. Для проведения исследований были взяты материалы профильных международных ведомств и агентств, Министерства энергетики Российской Федерации. Кроме того, источниками данных являются публикации и исследования российских и зарубежных ученых по исследуемой проблематике.

Принятый в декабре 2019 г. Государственной думой РФ Федеральный закон № 35-ФЗ «Об электроэнергетике» вводит понятие «объект микрогенерации», тем самым упрощая возможность установки, подключения к общей сети электрической системы, например, небольшой солнечной электростанции потребителя.

Малая электроэнергетика на данном жизненном этапе – энергетически эффективный инструмент в переформировании энергетики Российской Федерации, способствующий отказу от традиционной централизованной системы, основанной на применении крупных источников электроэнергетического производства, и переходу на альтернативные способы получения электроэнергии, основанных на использовании источников энергии, актуализированных под конкретные природные условия и запросы потенциальных потребителей.

Уменьшение загрязняющих и являющихся вредными для здоровья человека выбросов позволяет снизить уровень сложившейся нагрузки на экономику страны и дать толчок для развития ее потенциала за счет высвободившихся ресурсов, уменьшить нагрузку на экономику, тем самым определяя ресурсы для ее роста.

Безусловно, переход от традиционных экономических моделей к модели зеленого роста может быть реализован только в случае приложения существенных усилий, направленных на расширение международного сотрудничества в этой области. Одновременно с этим возникает необходимость в последовательном проведении мероприятий различного уровня со стороны всех государств, а также поддержание выбранного политического курса на протяжении многих лет.

Ключевые слова: солнечная электростанция (СЭС), установившийся режим СЭС, генерация энергии, статистическая устойчивость, малая генерация, ветротурбины.

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