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Analysis of Problems of the Power System with a High Proportion of Solar Generation*

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The rapid development of solar energy has led to the creation of qualitatively new energy systems with a high share of solar generation. The behavior of systems of this kind in certain cases differs significantly from the behavior of traditional energy systems containing the predominant share of thermal power plants. Thus, a significant share of the generation of solar power plants as part of the power system, the lack of an adjustment range for reactive power and the generally accepted concept of modeling a solar power plant lead to the problem of introducing unnecessary restrictions to maintain the stability and reliability of the power system. At the same time, the problems of stability and reliability must be solved simultaneously with the problems of saving energy resources; this is precisely the problem of optimization. The balance between reliability and economy lies in meeting the required restrictions on the cross-sections of the power system.

The analysis made it possible to determine the priority directions in the study of the operation of solar power plants as part of a unified energy system. The calculation of the daily schedule of power generation for a set of SESs located in the same meteorological conditions for two seasons of the year has been performed. The real regulation range of reactive power was determined and the analysis of participation in the rating of stability and reliability of power systems was carried out. These results were obtained during the study of the power system of the Republic of Crimea and the city of Sevastopol.

One of the main conclusions of this paper is the lack of a general approach in the description of SES together with the control system in mathematical models for calculating steady-state and transient electric power modes. Given the growing trend towards digitalization, this issue is currently becoming more acute.

The conclusions made will allow us to set a vector for the development of the study of the issues of connecting the SES to the unified energy system.

Keywords: static stability, dynamic stability, severe short circuit, renewable energy, reactive power, daily generation schedule.

Introduction

Recently, solar power plants (SPP) have become widespread in the unified energy system of Russia [1]. The growth of the capacity generated by power plants based on renewable energy sources (RES) is caused by the latest trends in the development of the electric power industry in the country, fixed at the legislative level [2, 3]. Of course, this policy has a positive effect on the population, on the environmental aspect, but the growth of the installed capacity of RES has caused problems in the planning and management of the electric power sector power system mode [4].

The purpose of the work is to determine the real range of reactive power regulation at a set of solar power plants of the power system of the Republic of Crimea and the city of Sevastopol with the possibility of applying the results obtained to other power systems with a high proportion of installed SPP capacity.

Problem statement

An increase in the share of solar energy generation in the power system leads to an increase in the percentage of generated active power that cannot be accurately planned. This, in turn, leads to the need to take into account the emergency power imbalance caused by a decrease in the active capacity of solar power plants located in one power unit for 10 minutes due to changes in weather conditions associated with a decrease in solar activity (Requirements for ensuring the reliability of electric power systems, reliability and safety of electric power facilities and power receiving installations: order of the Ministry of Energy of Russia from 03.08.2018 № 630. Moscow, 2018. 16 page).

In addition, with the maximum generation of SPP in the 110 kV network, high voltage levels oc-

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cur in normal mode. However, in the post–emergency mode, when disconnecting stations, the opposite situation may arise, in which it is necessary to limit the permissible flow of active power in the cross section - in the aggregate of elements of one or more electrical connections, the simultaneous disconnection of which leads or does not lead to the separation of the power system into two isolated but working parts. At the same time, in the calculations of steady-state regimes, it is problematic to provide for the real value of energy generation, which imposes unnecessary restrictions on the management of the electric power regime.

Another important aspect of the operation of such stations in parallel with the power system is their impact on the stability of the power system. Firstly, a large proportion of SPP in combination with stations on traditional energy sources containing synchronous generators reduces the value of the equivalent moment of inertia of the power system. This factor in certain modes increases the likelihood of disruption of the dynamic stability of the power system.

Secondly, due to the lack of reactive power regulation on the part of the station, the limit of transmitted power in the connections of the power system is reduced, on which SPP have a great influence in terms of voltage regulation [5]. Such a problem leads to a decrease in static aperiodic stability in a power system with a high proportion of generation of solar power plants [6, 7].

The lack of regulation of the reactive power of solar power plants is a consequence of a purposeful narrowing of the range of cos φ changes. The purpose of such manipulation by the owner is to maximize the production of paid active power, as opposed to reactive. Expanding the range of reactive power regulation and proper adjustment of SPP regulators can increase the stability of the power system [8].

An urgent problem in calculating the steady-state and transient modes of the power system is the lack of a verified SPP model in software complexes. The model, detailed with the necessary accuracy, would allow taking into account the reaction of the station in the power system to the weighting trajectory required for calculating static stability, as well as to severe short circuits necessary for calculating dynamic stability. The severity of short circuits in this case is determined by their type (single-phase, two-phase, three-phase), the time of current flow and the magnitude of the transient resistance at the point of closure.

Calculation of the real range of regulation of reactive power of solar power plants

In the power system of the Republic of Crimea and the city of Sevastopol, the total installed capacity of solar power plants reaches about 300 MW. The largest SPP on the Crimean peninsula are: “Perovo” (106 MW), “Okhotnikovo” (80 MW), “Nikolaevka” (70 MW), which can also be called one of the largest in Russia [9]. Another feature of the solar power plants of the Crimean Peninsula is their location in close proximity to each other, both geographically and as part of the power system. All power plants are located within a radius of 23 km in the western part of the peninsula. Thus, the studies conducted for a group of power plants will be fair, since all power plants are in the same meteorological conditions.

However, achieving the value of the generation of the installed power of the SPP even at noon is impossible due to many factors [10]. The main limiting factors for generating the maximum power of the station are: illumination, cloud cover and daylight duration [11-13]. Such meteorological factors are typical for certain seasons of the year [14, 15].

To determine the real range of reactive power regulation in the course of the study, a sample of the values of the generation of active power of the power system during the day according to characteristic seasons was made. The results obtained are presented in the form of graphs of suexact generation.

To determine the total average daily generation schedules of the SPP of the power system, data for 2020 were taken with an interval of 30 minutes. Based on this, a generation profile was obtained based on the average half-hour values for each month of the year. As a result, two most contrasting generation profiles were identified for the winter and summer seasons; this separation is due to meteorological factors characteristic of the energy system of the Crimean Peninsula.

Figure 1 shows graphs of the total generation of SPP in the summer and winter seasons. The main differences are in the magnitude of the generation of active power and the duration of daylight.

The daily schedule of solar power generation in the summer season of the power system of the Republic of Crimea and the city of Sevastopol is typical for eight months of the year – from March to October. The winter season is typical for four months – from November to February – as for the months of the cloudiest, with a short light day. This separation by seasons is typical for the solar generation of the Crimean Peninsula.

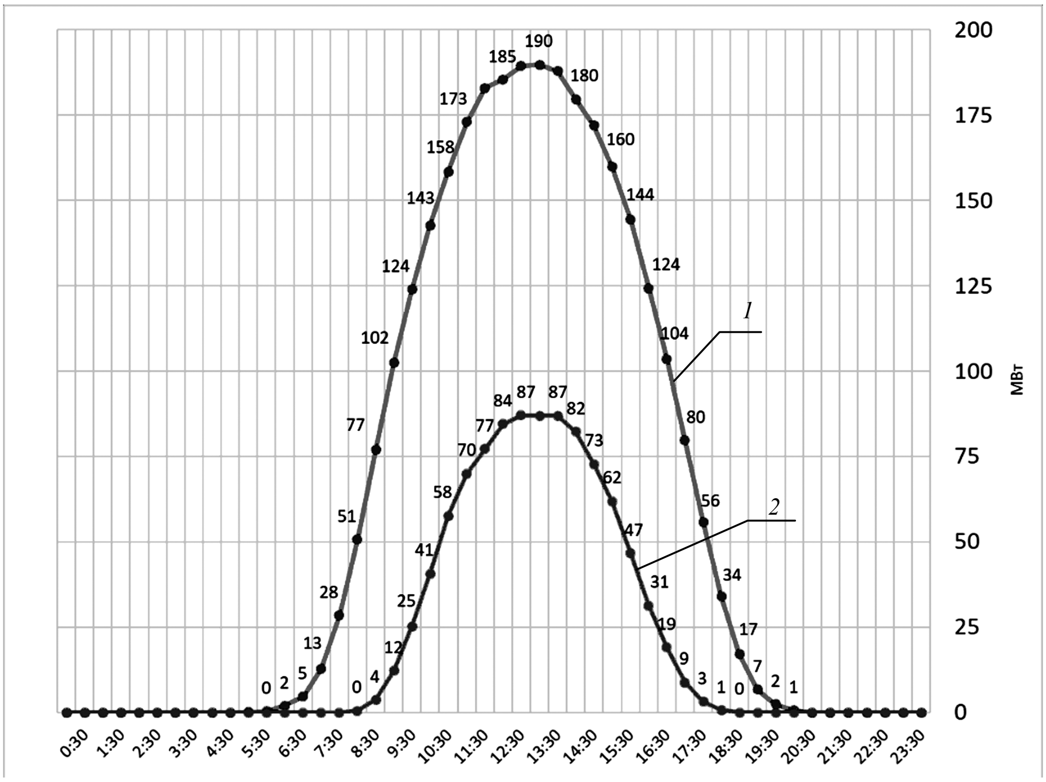

Fig. 1. Diagrams of daily generation of SPP for typical seasons of the year: *1* - summer season; *2* - winter season

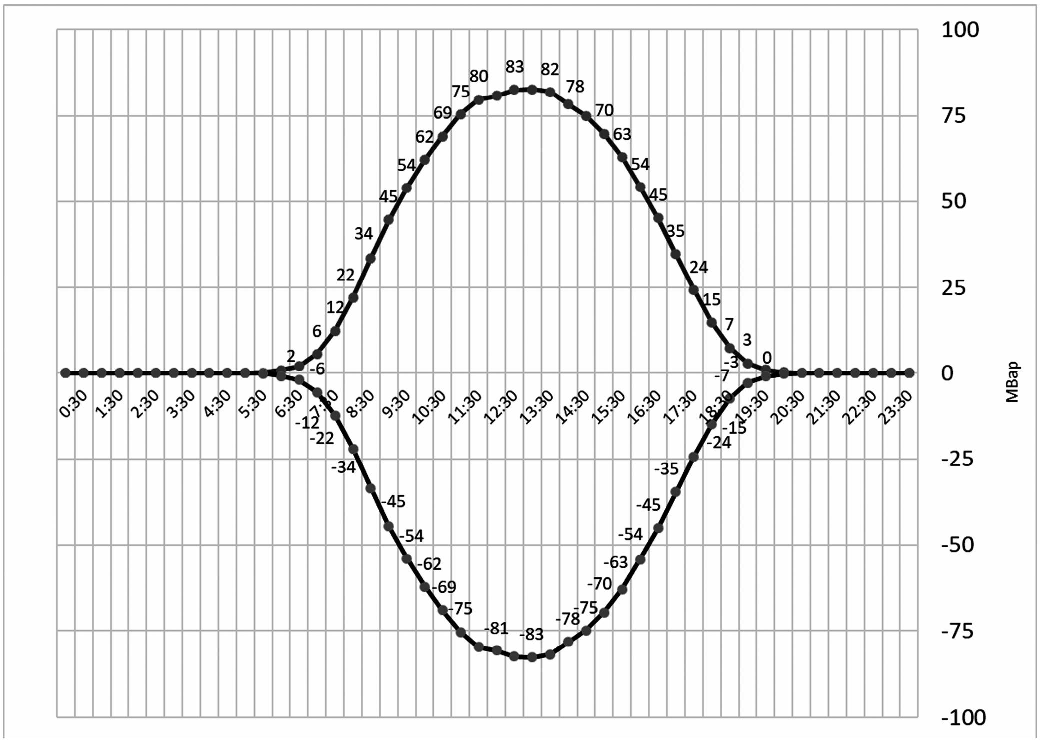

Fig. 2. The total adjustment range of reactive power of the SPP of the power system of Crimea in the summer season (upper and lower limit)

Based on the results of calculations of the graphs of the total generation of the active power of the SPP, the graphs of the upper and lower limits of the adjustment range of the reactive power of the power system are determined, respectively, in Figures 2 and 3. The extreme limits of the range are calculated taking into account the nominal parameters of the inverters used at the stations. For example, the nominal data of the Protect PV.250 inverter is taken as the most widespread in the solar power plants of the Crimean power system. The manufacturer of the inverter declared cos φ equal to the range of values from -0.9...1 to +0.9 (Fig. 4).

It can be seen from the graphs of Figures 2 and 3 that the range of reactive power regulation of more than ± 20 MVar is provided in the summer season for about 11 hours, and in winter - up to 4 hours during the day. In addition, for the summer season, a control range of more than ± 70 MVar is provided for 4 hours a day. Such values in the regulation of reactive power are comparable to the generation of a battery of static capacitors and the consumption of a shunt reactor, or with the adjustment range of a modern thermal power plant up to 150 MW.

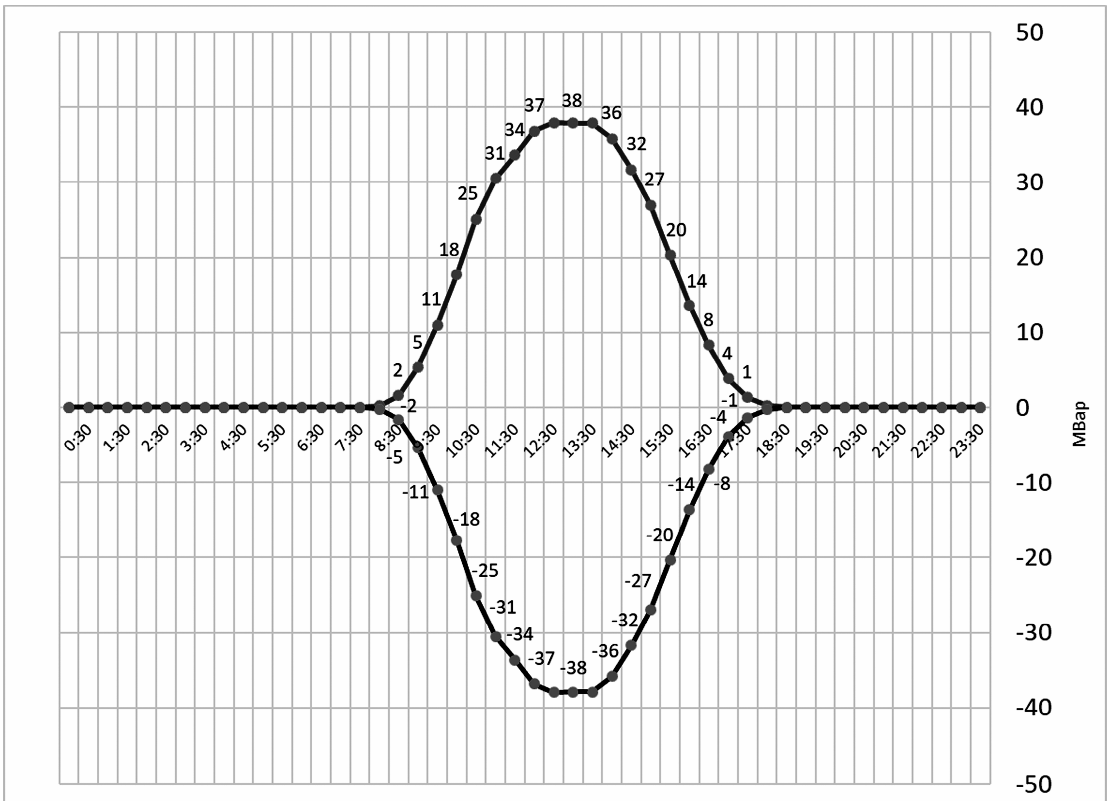

Fig. 3. The total adjustment range of reactive power of the SPP of the power system of Crimea in the winter season (upper and lower limits)

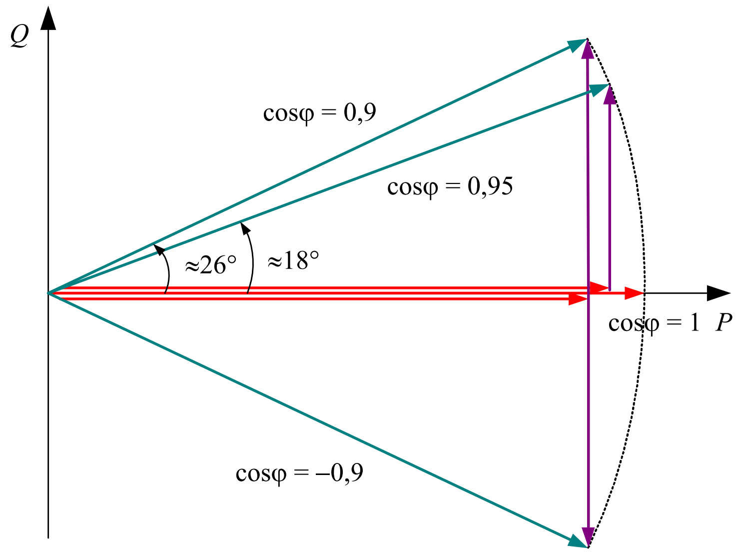

Fig. 4. Vector diagram of power the SPP

Analysis of the impact of solar power plants on the stability of the energy system

It is not beneficial for the owner to participate in regulating the voltage of solar power plants, since when the generating equipment is loaded by reactive power, it is unloaded by active power, for which the owner receives payment. This situation is clearly shown in the vector diagram (Fig. 4).

The owner of the SPP deliberately reduces the value of cos φ to one in order to obtain the maximum generation of active power equal to the full power of the station:

$$S_{SPP} = P_{SPP} \cdot \cos\varphi,$$

where S_{SPP} is the total total power generated by the station; P_{SPP} is the generated total active power of the station.

In this case, the station is not involved in voltage regulation. However, as mentioned above, voltage regulation plays an important role in ensuring the stability of the power system.

For example, let's consider the effect of regulating the reactive power of solar power plants in the summer season in an excess energy district (Fig. 5). In this example, the generation of an excess energy district consists of solar (SPP) and thermal (TPP) power plants, and the section connecting the energy district with the unified energy system (UES) is complete.

In such a situation, it is quite possible to violate dynamic stability with a normative disturbance in a normal or repair scheme. As a result, it is necessary to regulate the flow in the cross section by limiting the generation of thermal power plants to prevent the possible consequences of a severe short circuit [16].

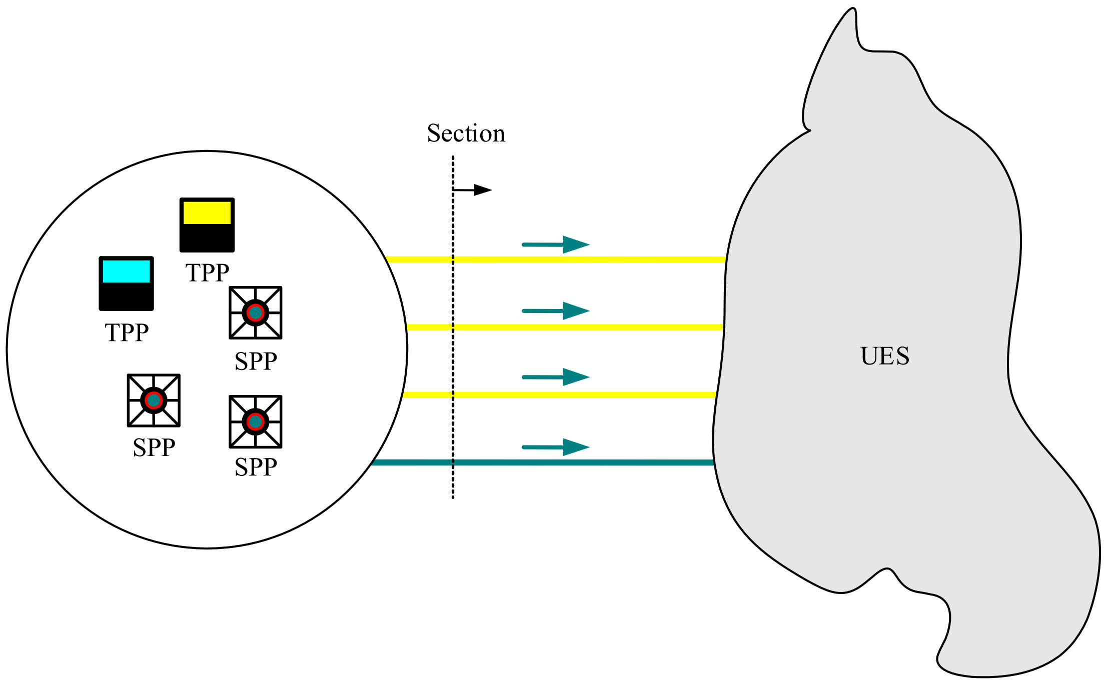

Fig. 5. The simplest scheme of operation of a redundant area in the UES

However, using the full range of SPP in terms of reactive power regulation, we can dampen disturbances occurring in the power system. For a detailed consideration of the operation of the regulation of a solar power plant, let us turn to the angular characteristic of the transmitted power shown in Figure 6 and determined by the formula

$$P_c = \frac{U_1 U_2}{Z_c}\sin\delta,$$

where P_c – active power transmitted across the cross section (see Fig. 5); U_1, U_2 – stresses at the ends of the section; Z_c – the total resistance of the lines included in the section; δ - the angle between the stress vectors at the ends of the section.

As can be seen from Figure 6, in the event of a severe short circuit close to the cross section, as well as with the operating mode of the energy district, the instantaneous reaction of the regulators of the solar power plant will reduce the acceleration pad and increase the braking pad due to unloading by active power and additional loading by reactive power. Such operation of the SPP will reduce the excess power in the power district, thereby preventing the rotors of the TPP generators from accelerating during the short-circuit current flow, and will also increase the limit of transmitted power in pre-emergency and post-emergency modes by increasing the voltage in the network.

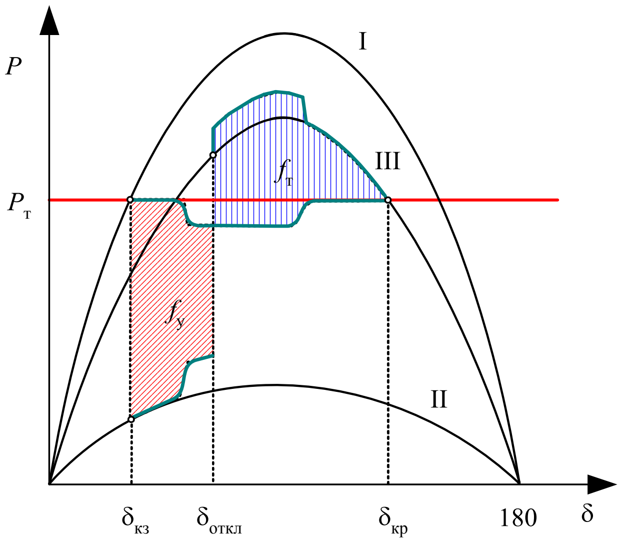

Fig. 6. Angular characteristic of the transmitted power while maintaining the remote control: I - characteristic of the transmitted power limit in the pre-emergency mode, II - during a short circuit, III - after disconnecting the damaged network element; $\delta_{кз}$ - angle at which a short circuit occurred (equilibrium point); $\delta_{откл}$ - the angle at which the network element was disconnected, $\delta_{кр}$ - the angle above which the stability of the connection is violated; f_y - acceleration area, $f_т$ - braking area; $P_т$ - active power generated at power plants of the energy district

Conclusions

Studies of the electric power system with a high proportion of solar generation have been carried out, the definition of the real range of reactive power regulation on the set of SPP of the power system of the Republic of Crimea and the city of Sevastopol has been given. The research allows us to draw the following conclusions.

The expansion of the range of regulation of the reactive power of the SPP will improve the quality of electricity in terms of voltage requirements, as well as provide damping of disturbances arising in the power system. Such operation of solar power plants will favorably affect the stability and reliability of the electric power system as a whole.

One of the main technical problems voiced in this paper remains the absence of any general approach to modeling and accounting of SPP control systems in computational models. Creation of a detailed verified model of the power system containing a set of high-power solar power plants for calculations of steady-state and transient modes is possible on the basis of existing software complexes RastrWin3 and RUStab.

Further elaboration of the conclusions obtained will allow to reduce the restrictions in the controlled sections of the power system (to maintain a balance between economy and reliability), and in the future, in conjunction with the monitoring system of the stability margin, to bring the management of the power system to a qualitatively new level.

References

1. Yakimovich B.A., Kuvshinov V.V. [The sixth technological order, use of thermoelectric photovoltaic systems in the communal sector of the Crimea]. *Sotsial'no-ekonomicheskoe upravlenie: teoriya i praktika*, 2017, no. 2, pp. 109-111 (in Russ.).

2. Belokrylova E.A., Kologermanskaya E.M. [Modern political and legal aspects of the development of renewable energy sources in the Russian Federation]. *Vestnik Udmurtskog ouniversiteta*, *Economics and Law,* 2017, vol. 27, no. 2, pp. 85-93 (in Russ.).

3. Rybkina Ya. A. [Legal nature of the selection of renewable energy projects and the application of antitrust laws to the procedure for selecting renewable energy projects]. *Pravovoi energeticheskii forum*, 2018, no. 4, pp. 38-45 (in Russ.).

4. Guriev V.V., Kuvshinov V.V. [Optimization of methods for predicting the generated power of solar power plants in the power system of the Republic of Crimea and the city of Sevastopol]. *Ekologicheskaya, promyshlennaya i energeticheskaya bezopasnost' – 2018 : sb. statei po materialam mezhdunarodnoi nauchno-prakticheskoi konferentsii (Sevastopol', 24-27 sentyabrya 2018 g.)*. [Ecological, industrial and energy safety - 2018: collection of articles. articles based on the materials of the international scientific and practical conference (Sevastopol, September 24-27, 2018)]. Sevastopol, SevGU, 2018, pp. 325-327 (in Russ.).

5. Kramskoy Y.G. Integration of renewable energy sources into electrical networks using power electronics. *Energiya edinoi seti*, 2017, no. 1, pp. 55-69 (in Russ.).

6. Sharifov B.N. [Electromagnetic transients in the control system of the output parameters of a solar power plant]. *Politekhnicheskii vestnik, Inzhenernye issledovaniya*, 2019, no. 4, pp. 26-32 (in Russ.).

7. Al Bairmani A.G., Kuvshinov V.V., Yakimovich B.A. [Mathematical model for optimizing the operating mode of the power system of the Republic of Crimea and the city of Sevastopol]. *Nauchnaya initsiativa inostrannykh studentov i aspirantov rossiiskikh vuzov : sb. dokladov 9-i Vseros. nauch.-prakt. konf.* [Scientific initiative of foreign students and postgraduates of Russian universities: Collection of reports of the 9th All-Russian Scientific and Practical Conference]. Tomsk : Tomsk Polytechnic University, 2019, pp. 66-73 (in Russ.).

8. Ismagilov F.R., Sharifov B.N., Gzysin B.M., Teregulov T.R., Babkina N.L. [Investigation of parallel operation of a solar power plant with a grid]. *Vestnik Ufimskogo gos. aviatsionnogo tekhn. un-ta*, 2016, vol. 20, no. 4, pp. 71-79 (in Russ.).

9. Guriev V.V., Kuvshinov V.V., Yakimovich B.A. [Prospects for the development of renewable energy

sources on the territory of the Crimean peninsula]. *Vestnik IzhGTU imeni M.T. Kalashnikova*, 2019, vol. 22, no. 4, pp. 116-123 (in Russ.).

10. Dzhumaev A.Ya. [Analysis of the effect of temperature on the operating mode of a photovoltaic solar station]. *Cb. statei XLVI Mezhdunar. nauch.-prakt. konf. „Tekhnicheskie nauki - ot teorii k praktike" (Novosibirsk, 27 maya 2015 g.)* [XLVI International scientific-practical conf. "Engineering - from theory to practice" (Novosibirsk, May 27, 2015)], no. 5, pp. 33-40. Novosibirsk, SibAK Publ, 2015 (in Russ.).

11. Guriev V.V. [Improvement of prediction methods generating power of solar power stations in the energy system of the Republic of Crimea and the city of Sevastopol]. *Nauchnye gorizonty*, 2017, no. 4, pp. 63-73 (in Russ.).

12. Kakushina E.G., Yakimovich B.A., Kuvshinov V.V., Kuznetsov P.N., Solomennikova S.I. [Technical and economic aspects of the development of autonomous solar energy systems]. *Energeticheskie ustanovki i tekhnologii*, 2018, vol. 4, no. 4, p. 55-60 (in Russ.).

13. Morozov I.A., Tykvinsky A.M. [Influence of illumination on the output power of the solar module. Cybernetics of energy systems]. *Cb. materialov XXXVIII sessii Vseros. nauch. seminara "Diagnostika energooborudovaniya" (Novocherkassk, 17–19 oktyabrya 2016 g.)*. [Proc. XXXVIII session of the All-Russian scientific seminar on the topic "Diagnostics of power equipment", Novocherkassk, October 17-19, 2016]. Novocherkassk, Yuzhno-Rossiiskii gos. politekh. un-t (NPI) imeni M.I. Platova, 2016 (in Russ.).

14. Morozova N.V., Kuvshinov V.V. [Possibilities of increasing the power characteristics of solar installations for use in the power industry of the Crimea]. Moscow, Sputnik+ Publ., 2017, 174 p. (in Russ.).

15. Tukfatullin O.F. [Selection of the optimal angle of inclination of photovoltaic panels with one-position fixation of stationary photovoltaic systems, depending on the geographical latitude and insolation throughout the year]. *Geliotekhnika*, 2016, no. 4, pp. 17-20 (in Russ.).

16. Nikiforov I.S., Khatunitskiy V.V. [Optimization of the reactive power mode to increase the dynamic stability of the Pskov SDPP]. *Elektroenergetika glazami molodezhi : tr. VI Mezhdunar. nauch.-tekhn. konf. (Ivanovo, 9-13 noyabrya 2015 g.)* [Electric power industry through the eyes of youth: Proc. of the VI International Scientific and Technical Conference, (November 9-13, 2015)]. Ivanovo, Ivanovskii gos. energeticheskii un-t im. V. I. Lenina, 2015, vol. 1, 628 p. (in Russ.).

Анализ проблем энергосистемы с высокой долей солнечной генерации

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Стремительное развитие солнечной энергетики привело к созданию качественно новых энергосистем с высокой долей солнечной генерации. Поведение систем подобного рода в определенных случаях существенно отличается от поведения традиционных энергетических систем, содержащих преимущественную долю тепловых электростанций. Так, значительная доля генерации солнечных электростанций (СЭС) в составе энергосистемы, отсутствие регулировочного диапазона реактивной мощности и общепринятой концепции моделирования солнечной электрической станции приводят к проблеме ввода излишних ограничений для сохранения устойчивости и надежности энергосистемы. Вместе с тем задачи устойчивости и надежности необходимо решать одновременно с задачами экономии энергоресурсов – именно в этом заключается проблема оптимизации. Баланс между надежностью и экономией заключается в соблюдении требуемых ограничений по сечениям энергосистемы.

Проделанный анализ позволил определить приоритетные направления в исследовании работы солнечных электростанций в составе единой энергосистемы. Произведен расчет суточного графика генерации активной мощности для совокупности солнечных электростанций, находящихся в одинаковых метеорологических условиях, для двух характерных сезонов года (зимний и летний). Определен реальный регулировочный диапазон реактивной мощности и проведен анализ участия СЭС в обеспечении устойчивости и надежности энергосистемы. Данные результаты получены в ходе исследования энергосистемы Республики Крым и города Севастополя.

Одним из главных выводов данной статьи является отсутствие общего подхода в описании СЭС совместно с системой регулирования в математических моделях для расчета установившихся и переходных электроэнергетических режимов. С учетом нарастающей тенденции цифровизации в настоящее время данный вопрос встает более остро. Сделанные выводы позволят задать вектор развития проработки вопросов присоединения солнечных электростанций к единой энергетической системе.

Ключевые слова: статическая устойчивость, динамическая устойчивость, тяжелое короткое замыкание, возобновляемые источники энергии, реактивная мощность, суточный график генерации.

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