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CONTROL OF ELECTROMAGNETIC TRANSITION PROCESS IN THE SYSTEM FOR REGULATING THE OUTPUT PARAMETERS OF A SOLAR POWER PLANT IN THE CONDITIONS OF THE REPUBLIC OF TAJIKISTAN

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At present, as the demand for electricity increases in all sectors, there is an urgent need to introduce alternative renewable energy sources into modern energy systems. Renewable energy sources, which consist of solar (photovoltaic, PV), wind and hydro power, are key alternative sources of "green energy.’’ energies. Thanks to scientific and technological progress, the cost of photovoltaic solar radiation converters is constantly decreasing at a high rate, which makes it possible to build solar power plants of sufficiently large capacity. In the coming decades, solar energy will become an incentive for the economic development of countries that have the maximum "solar" resource. The Republic of Tajikistan is one of these countries with a high potential for solar energy.

The article presents an analysis of the resources and potential of solar energy in the Republic of Tajikistan. The study of electromagnetic transients in networks with photovoltaic solar power plants is performed. The main equations, simulation model and calculations of transients are presented, taking into account changes in voltage on DC buses. An algorithm for controlling the system of automatic control of output parameters is proposed. The analysis of dynamic and static modes in parallel operation of a solar power plant with the grid is carried out. A block diagram and computer model is constructed in the MATLAB package together with Simulink and Power System Blockset.

Keywords: solar energy, solar power plant, transients, computer mathematical model of a solar power plant.

УПРАВЛЕНИЕ ЭЛЕКТРОМАГНИТНЫМИ ПЕРЕХОДНЫМИ ПРОЦЕССАМИ В СИСТЕМЕ РЕГУЛИРОВАНИЯ ВЫХОДНЫХ ПАРАМЕТРОВ СОЛНЕЧНОЙ ЭЛЕКТРОСТАНЦИИ В УСЛОВИЯХ РЕСПУБЛИКИ ТАДЖИКИСТАН

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В настоящее время, по мере увеличения спроса на электроэнергию во всех секторах, существует острая необходимость во внедрении альтернативных возобновляемых источников энергии в современные энергосистемы. Возобновляемые источники энергии, которые состоят из солнечной (фотоэлектрической, PV), ветровой и гидроэнергии, являются ключевыми альтернативными источника ‘‘зеленой’’ энергии. Благодаря научно-техническому прогрессу стоимость фотоэлектрических преобразователей солнечной радиации неизменно снижается высокими темпами, что дает возможность строить солнечные электростанции достаточно большой мощности. В ближайшие десятилетия солнечная энергетика станет стимулом для экономического развития стран, которые обладают максимальным «солнечным» ресурсом. Республика Таджикистан является одной из таких стран, которая обладает высоким потенциалом солнечной энергии.

В статье представлен анализ ресурсы и потенциал солнечной энергии в условиях Республики Таджикистан. Выполнено исследование электромагнитных переходных процессов в сетях с фотоэлектрическими солнечными электростанциями. Представлены основные уравнения, имитационная модель и выполнены расчеты переходных процессов с учетом изменения напряжения на шинах постоянного тока. Предложен алгоритм управления системы автоматического регулирования выходных параметров. Проведен анализ динамических и статических режимов при параллельной работе солнечной электростанции с сетью. Построена структурная схема и компьютерная модель в пакете MATLAB совместно с Simulink и Power System Blockset.

Ключевые слова: солнечная энергия, солнечная электростанция, переходные процессы, компьютерная математическая модель солнечной электростанции.

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Introduction

Solar energetics is one of the most promising areas for the use of renewable and alternative energy sources on the planet. Its development is also associated with large-scale renewable energy support programs implemented in industrialized countries of Europe, the USA, China, and Japan. According to the reports of the International Sustainable Energy Network (INFORSE) REN21 for 2019, the growth dynamics of the installed capacity of solar energy reached 627 GW (Figure 1) [1]. Solar energetics grew intensively in 2007-2011; after that, the pace of the industry's development somewhat stabilized, but starting from 2013, it resumed its fast growth of 30% per annum.

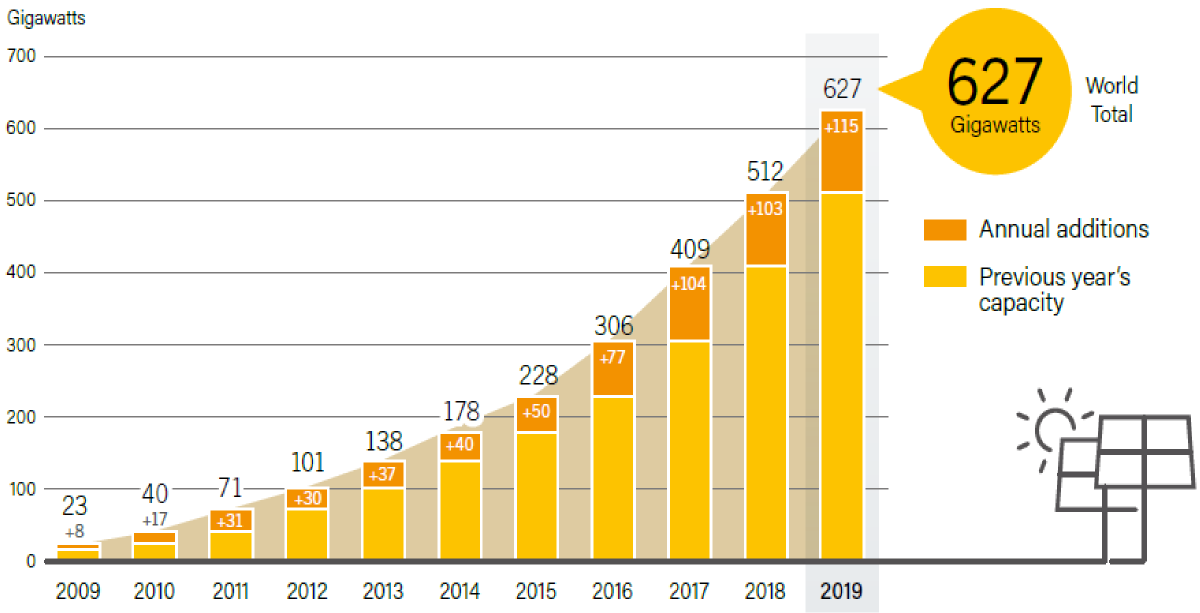

Fig. 1. Dynamics of growth of the cumulative volume of installed capacity of solar photovoltaic power plants.
Рис. 1. Динамика роста кумулятивного объема установленной мощности солнечных фотоэлектрических станций.

The Republic of Tajikistan (RT) has colossal potential for almost all renewable energy sources (RES), including solar energy. With fair weather, the total amount of solar radiation in Tajikistan reaches 700-800 W / m2, or 7,500-8,000 MJ / m2 (Fig. 2). These parameters are much higher in the mountainous areas, especially in the Eastern Pamirs, where the population has a limited opportunity to use hydropower resources [2].

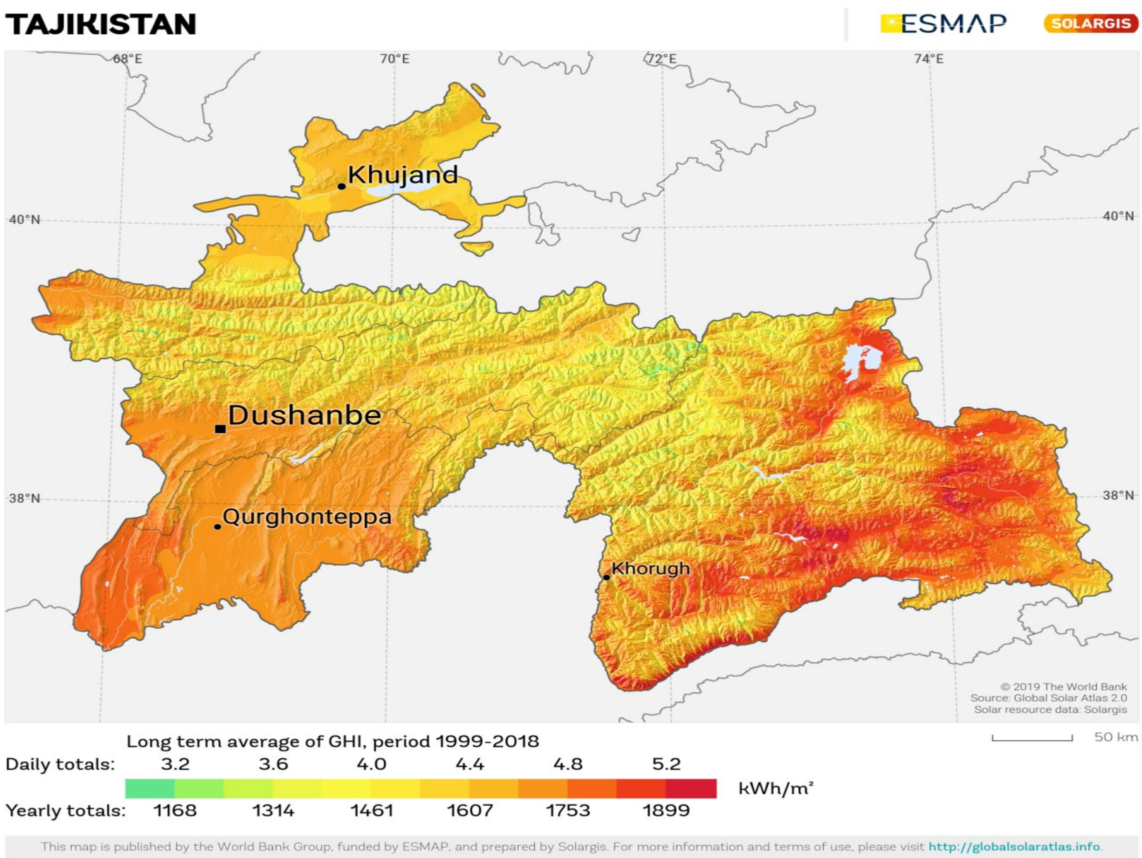

Fig. 2. The total direct solar radiation on the territory of Tajikistan.
Рис. 2. Суммарная прямая солнечня радиация на территории Таджикистана.

As the capacity of solar power plants (SPP) grows, the issue of parallel operation with the electric power system (PS) arises, since the use of storage batteries is not feasible for the high capacity power plants [3-4]. Under the parallel operation with the PS, the energy generated by the photovoltaic module in the form of direct current is converted into a three-phase alternating current and supplied to the external electrical network. The PS can receive the power generated by the SPP and compensate for its work in the absence of solar radiation. However, the parallel operation of solar power plants with a power system complicates their operation as a whole, as the power and voltage of the SPP depend on climatic factors, and vary depending on the weather conditions.

List of symbols	
PV	photovoltaic
RES	renewable energy sources
RT	Republic of Tajikistan
EPS	power system
SPP	solar power plants
ACS	automatic control system
PLL	phase locked loop
PWMU	pulse width modulation unit

Currently, two solar power plants with a total capacity of 160 kW are in use in the city of Dushanbe in parallel with an electric power system. They are:

1. SPP with a capacity of 120 kW in Dushanbe (38°58 'n 68°76' e) in the Central clinical hospital;
2. SPP with a capacity of 40 kW in Dushanbe (38°57 'n 68°79' e) in the Institute of Gynecology.

Based on the above, this paper aims to develop a simulation model of an automatic control system (ACS) for regulating the output parameters of a solar power plant and to study the electromagnetic transient processes in the system for regulating the output parameters of the solar power plant under parallel operation with the electric network.

1. Relevance of the topic

To study the parallel operation of SPP with the network, we developed a simulation model in Simulink, based on the block diagram (Fig.3) and differential equations [4, 5, 6], which are describing electromagnetic processes in SPP.

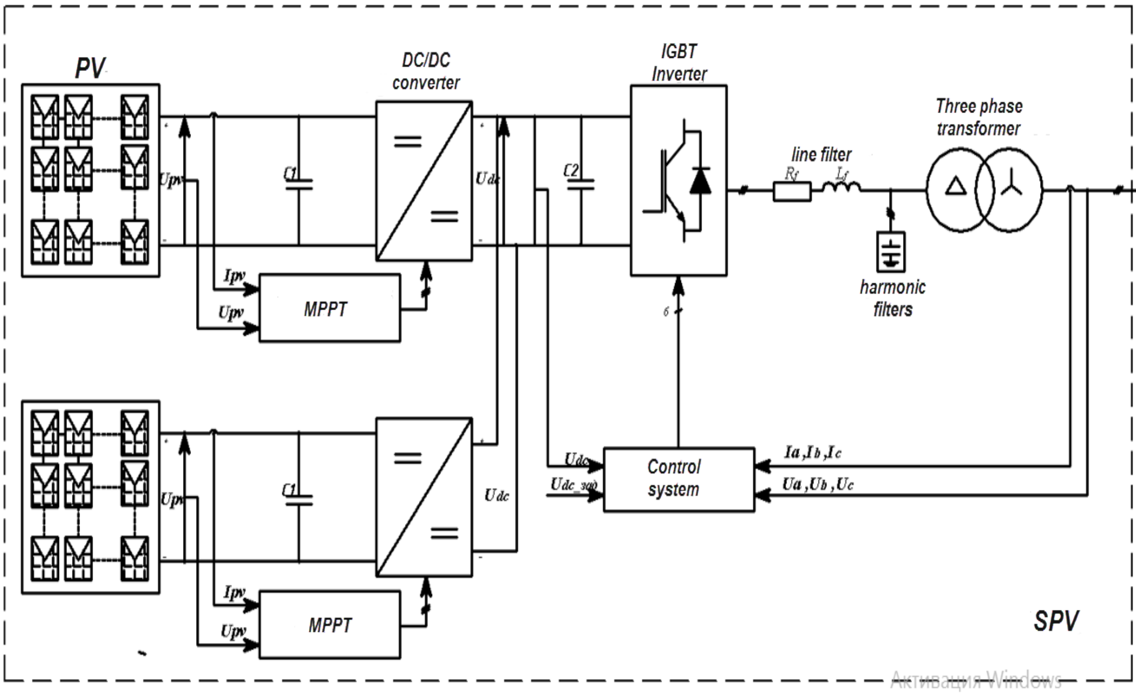

Fig. 3. General structural diagram of a solar power plant.
Рис. 3. Общая структурная схема солнечной электростанции.

The main components of an SPP are the voltage converters, (DC/DC Converter) that increase the voltage from 200 to 700 V; a three-phase inverter based on IGBT modules using a three-phase bridge scheme; and proportional-integrated current and voltage regulators. The opening and closing time of IGBT modules is several milliseconds, which makes it possible to effectively use the pulse width modulation principle to obtain sinusoidal voltages at the output of the inverter [4-5].

As part of the Converter, three-phase inverters perform the following major tasks:

- conversion of constant voltage into variable voltage from the frequencies of the power system;
- synchronization of the frequency of the voltage current with that of the PS;
- stabilization of the output voltage;
- limitation of the current during overloads and short circuits.

Converter units are a source of higher harmonics [5-6]. The commutation of thyristors and transistors distorts the shape of the curved currents and voltages in the adjacent AC network, which leads to the appearance of higher harmonics in the network. Higher harmonic filters are used to limit the circulation zones of higher harmonics outside the substations, to avoid the unfavorable impact of higher harmonic components of currents on the electrical equipment of adjacent systems, and to avoid radio interference in the communication lines.

2. Mathematical model

The study and analysis of transient processes in the control system of SPP output parameters during parallel operation with PS is based on the analysis of electromagnetic transient processes on the inverter. In the paper, the authors studied the equation that describes the electromagnetic processes, as well as the mathematical model of parallel operation of a solar power plant and a power system. The paper studies the automatic control system (ACS) of the output parameters of the SPP and the closed block diagram of parallel operation of the SPP and PS in more detail.

Currently, there are two main voltage inverter control systems [7]:

- vector control system based on linear regulators;
- vector control system based on hysteresis regulators.

Vector control systems are based on the model of a generalized vector on a complex plane, which is constructed by switching from a three-phase system to a two-phase coordinate system.

The mathematical model of the inverter in phase coordinates has the following disadvantages:

1. The difficulty of calculation of the electromagnetic processes in this model due to the load containing variable parameters, namely, the AC machines (asynchronous and synchronous), the model of which, as is known from the theory of electric machines, has periodically changing parameters (inductance of windings) even when the machines operate in steady mode [6].
2. A large number of differential equations, which complicates the calculation of electromagnetic transient processes.

These disadvantages of using natural coordinates for a given object can be eliminated completely or partially if we switch to the model of an inverter in an orthogonal (two-phase) coordinate system or, similarly, to the model of an inverter in the plane of a complex variable, the so-called model of an inverter for generalized vectors [7-8].

The forward and reverse transition from a three-phase coordinate system to a two-phase rotating coordinate system is performed as follows, [5-6].

$$\begin{cases} f_d = \dfrac{2}{3}\left[f_a \cos\gamma + f_b \cos(\gamma - \dfrac{2\pi}{3}) + f_c \cos(\gamma + \dfrac{2\pi}{3}), \right] \\ f_q = \dfrac{2}{3}\left[f_a \sin\gamma + f_b \sin(\gamma - \dfrac{2\pi}{3}) + f_c \sin(\gamma + \dfrac{2\pi}{3}). \right] \end{cases}; \quad (1)$$

$$\begin{cases} f_A = f_d \cos\gamma + f_q \sin\gamma + f_0, \\ f_B = f_d \cos(\gamma - \dfrac{2\pi}{3}) + f_q \sin(\gamma - \dfrac{2\pi}{3}) + f_0 \\ f_C = f_d \cos(\gamma + \dfrac{2\pi}{3}) + f_q \sin(\gamma + \dfrac{2\pi}{3}) + f_0, \end{cases}; \quad (2)$$

where $f_0 = \dfrac{1}{3}(f_A + f_B + f_C)$ is the vector of the zero component.

The block diagram of the vector system of automatic control of the SPP output parameters is shown in figure 4.

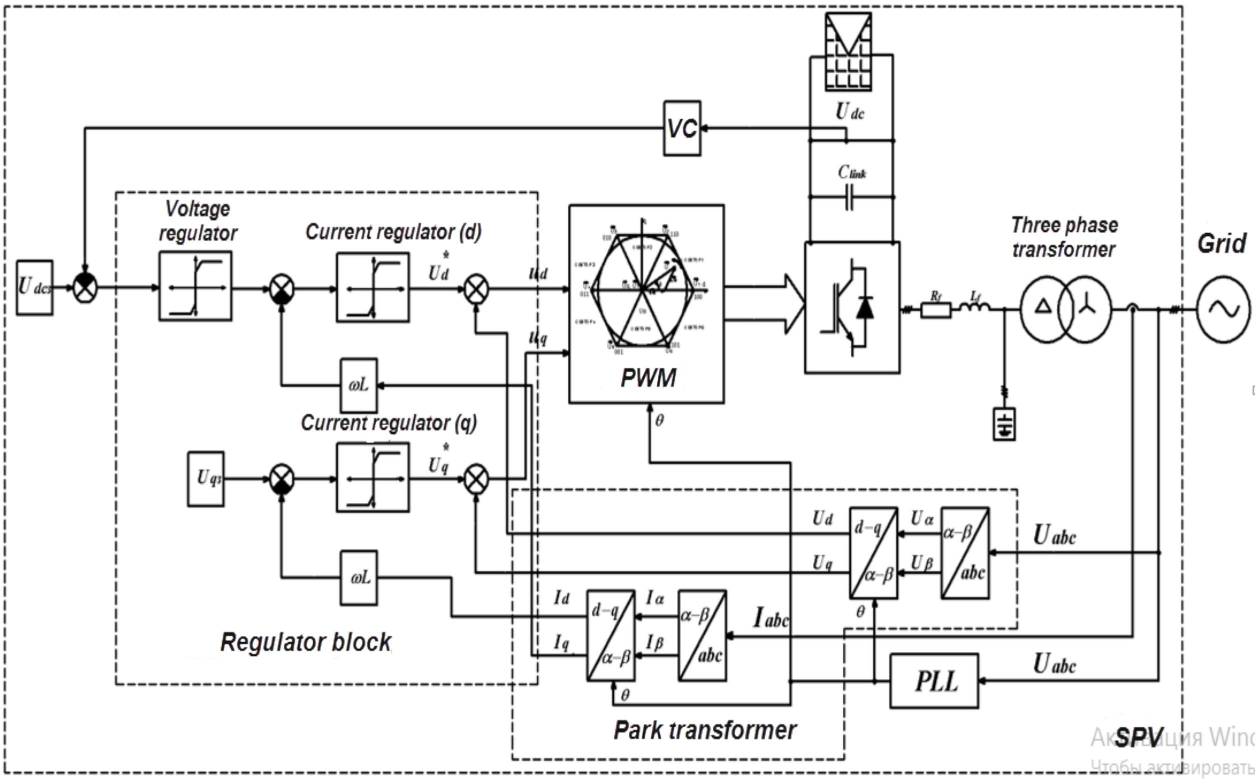

Fig. 4. Block diagram of the vector control system of the inverter.

Рис. 4. Структурная схема векторной системы управления инвертором.

The vector system of automatic control of SPP output parameters with linear regulators is based on the principle of subordinate control of coordinates. The automatic control system is a two-loop system, where the external loop is responsible for regulating the output voltage, and the internal loop is responsible for regulating the output current of the SPP. Control loops use projections of vectors on orthogonal axes that rotate with the network frequency.

The synchronization unit is a phase-locked frequency system (Phase Locked Loop(PLL))) [9-10] which calculates the network frequency f_c, obtained from the block of phase voltage sensors, and synchronizes the frequency, voltage, and angle with that of the power system. Today, the leading manufacturer of network inverters that implement *the PLL algorithm* is the *ABB* manufacturing company. According to *ABB*, these systems provide high-speed performance and frequency accuracy of 0.01% of the nominal value using direct-sequence phase voltage sensors. The block diagram of PLL that uses the synchronous reference Frame PLL method [11, 12, 13, 14, 15] is shown in figure 5.

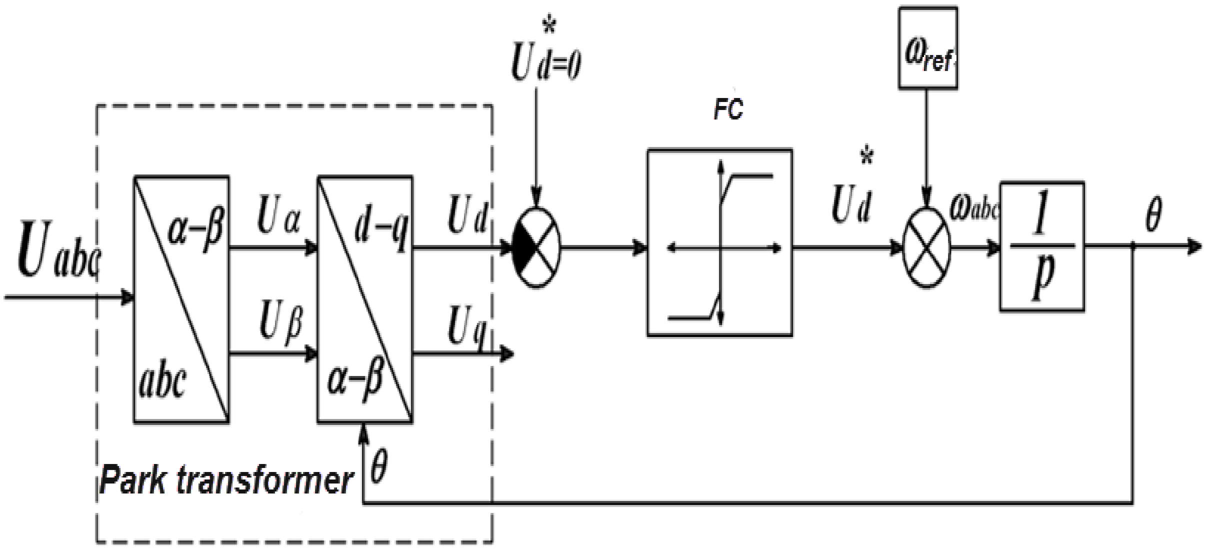

Fig. 5. Block diagram of the automatic phase frequency adjustment.

Рис. 5. Структурная схема фазовой автоподстройки частоты.

3. Simulation of electromagnetic transient processes in the control system of the output parameters of a solar power plant

A simulation model of the ACS of the output parameters of the SPP in parallel operation with the power system developed based on the MatLab / Simulink software package [16, 17] is shown in Figure 6.

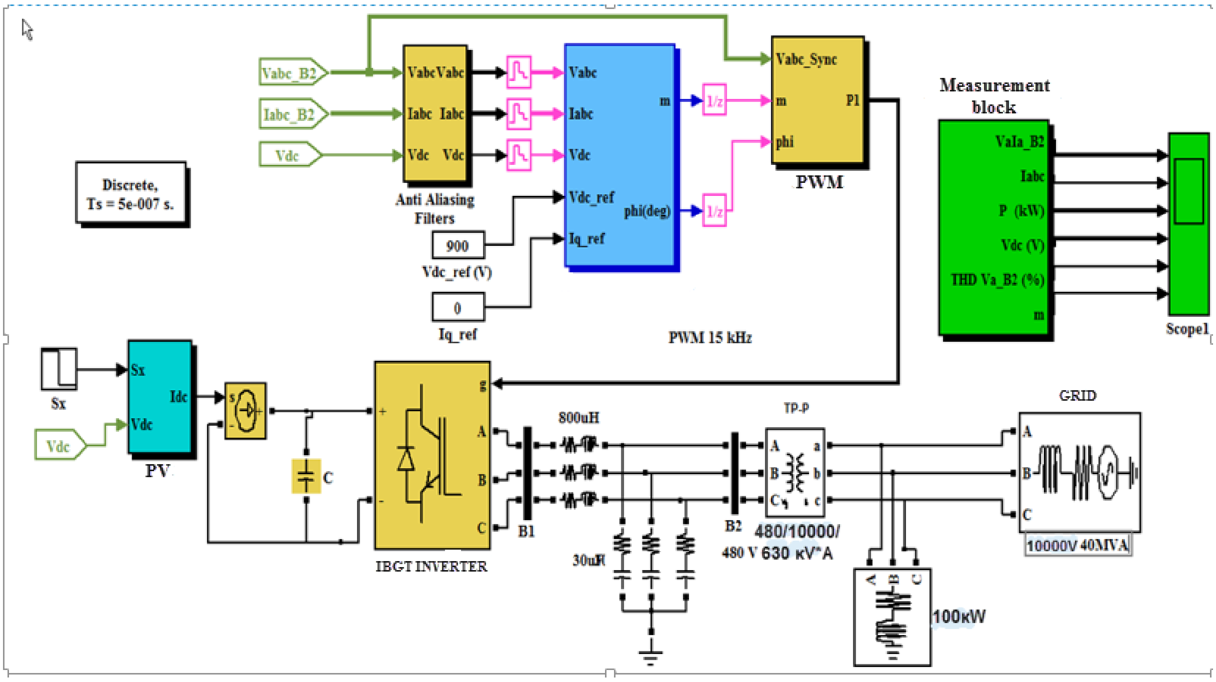

Fig. 6. Simulation computer model of the automatic control system in Matlab / Simulink.
Рис. 6. Имитационная компьютерная модель системы автоматического регулирования в Matlab/Simulink.

The main components of the model are SPP, IGBT inverter, regulator block, Pulse Width Modulation Unit (PWMU), step-up transformer, measuring block, and PS. The study of electromagnetic transient processes in parallel operation of SPP and PS was carried out taking into account the optimized structure of control loops. The parameters of the electric power system used in the study are summarized in table 1.

Table 1

The parameters of the power system.

Таблица 1

Параметры электроэнергетической системы

Solar power plant capacity	P_{SPP}, kW	120
DC bus voltage	U_{dc}, V	260
Inverter output filter parameters	R_f, [Ohm]	0.004
	L_f, [Gn]	$800 * 10^{-6}$
Reactive power filter	C, F	$30 * 10^{-6}$
Three-phase step-up transformer:	U_{nn} / U_{ext}, [V] [kVA]	480/10000
	S_n, [kVA]	630
PS parameters	S_n, [MVA]	40
	U_n, [B]	10000
Natural angular frequency	ω_0, rad / sec	314
Attenuation coefficient	ξ, o.e.	0.707

Figure 7 shows the calculation results of the transient process of the change in SPP parameters when the solar radiation level decreases from 1000 W /m^2 to 500 W/m^2.

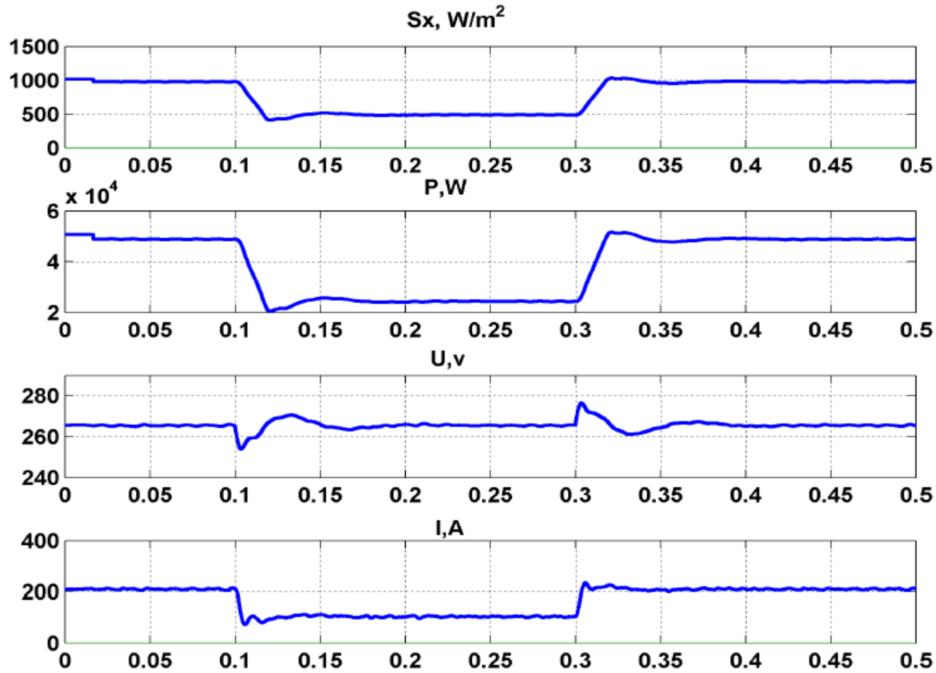

Fig. 7. Transient processes of changes in the SPP parameters on the DC side when the level of solar radiation changes.
Рис. 7. Переходный процессы изменения параметров СЭС на стороне постоянного тока при изменении уровня солнечной инсоляции.

One can see that when the level of solar radiation decreases, at the initial moment of the transient process (*t=0.1*c), the voltage on the direct current bus U_{dc} decreases, and after that restores its initial value of 263V. This can be explained by the fact that when the level of solar radiation decreases, the electric photocurrent of the solar panel decreases, resulting in the decrease of the voltage, current, and output power of the solar power plant. Since the SPP operates in the maximum power retrieval mode, at that moment, the voltage regulator comes into action and increases the voltage on the DC bus, thus compensating for the dynamic voltage drop.

Figure 8 shows the calculation results of the transient process of the SPP parameters' changes on the AC side. Analysis of the figure shows that the system of automatic voltage regulation on the DC bus provides stabilization of the output voltage of the inverter and the SPP, thereby protecting the PS from frequent overvoltages when working in parallel with the power system.

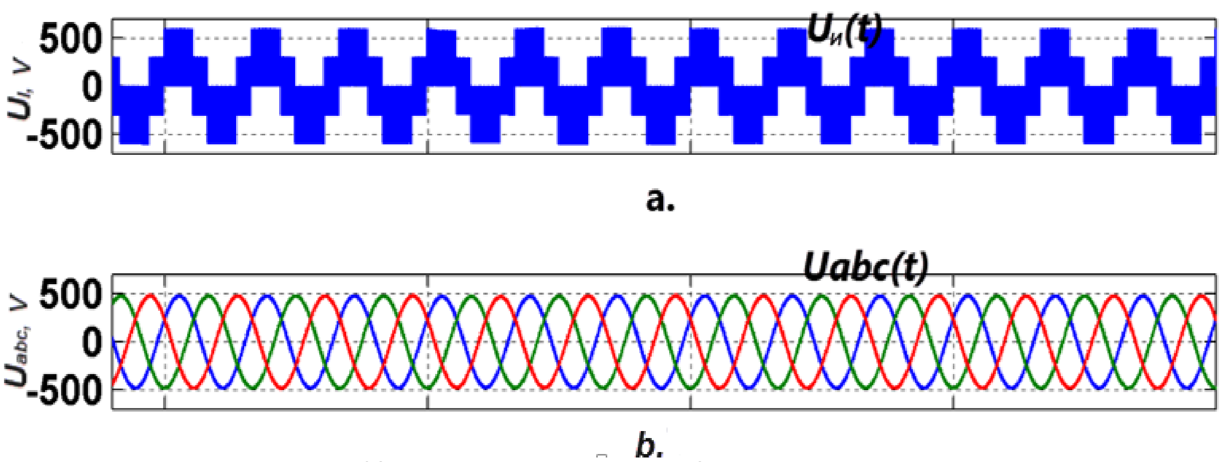

Fig. 8. Transient processes of SPP parameter changes on the AC side when the solar radiation level changes: a – output voltage of the inverter, b-voltage after the filter.
Рис. 8. Переходный процесс изменения параметров СЭС на стороне переменного тока при изменении уровня солнечной инсоляции: а – выходное напряжение инвертора, б – напряжение после фильтра.

The results of experimental studies of the operation of SPP with a capacity of 120 kW are shown in figures 9 and 10. Figure 9 shows a diagram of changes in the level of solar radiation, ambient temperature, and electrical power generation of a solar power plant. Analysis of the diagram shows that with an average daily value of the solar radiation level of 5.1 kWh/m^2, the SPP electric power generation is 132.9 kWh. Also, the diagram shows the non-linear nature of changes in the level of solar radiation (red line), which proportionally affects the output power and voltage of the SPP.

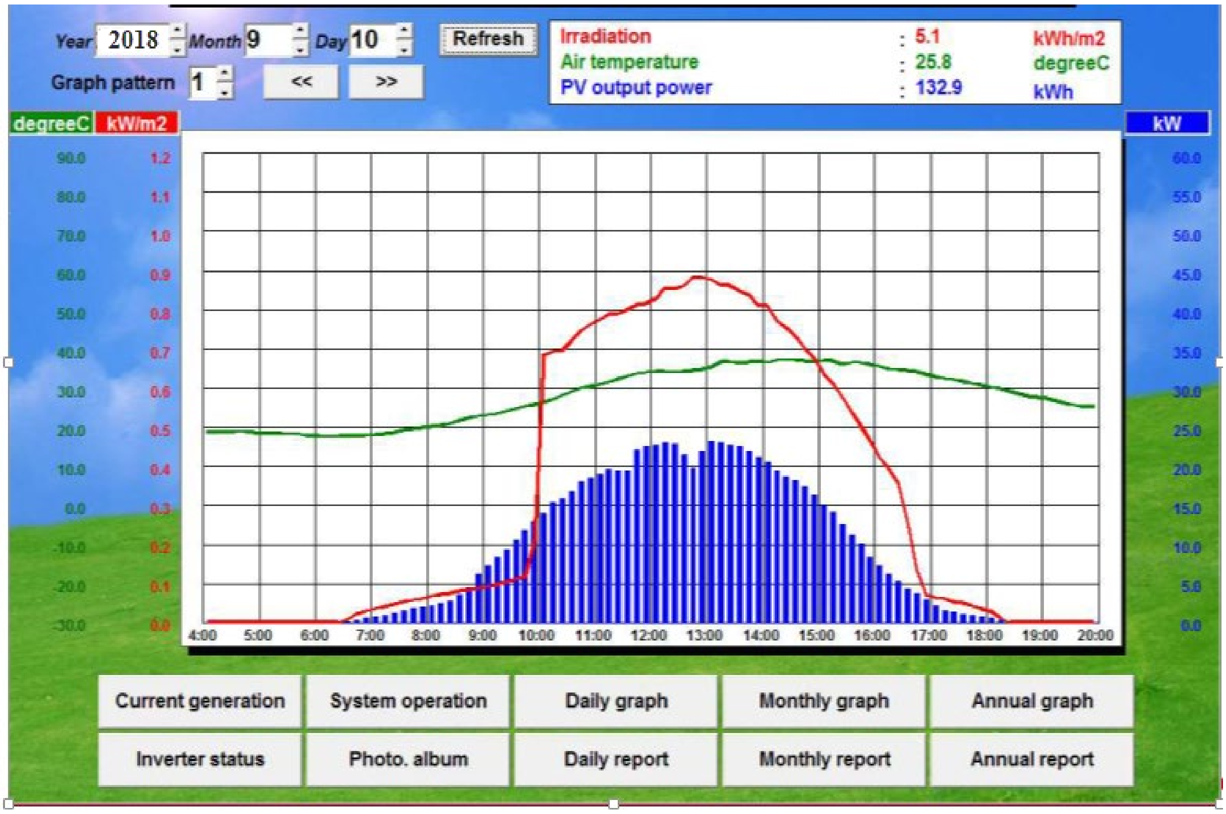

Fig. 9. Average daily power generation of a solar power plant with a capacity of 120 kW.
Рис. 9. Среднедневная выработка электроэнергии СЭС мощностью 120 кВт.

Despite the non-linearity of changes in the solar radiation level, the control system with a proportional-integral voltage regulator provides for stabilization of the SPP output voltage over the entire range of changes in the solar radiation level (Figure 10).

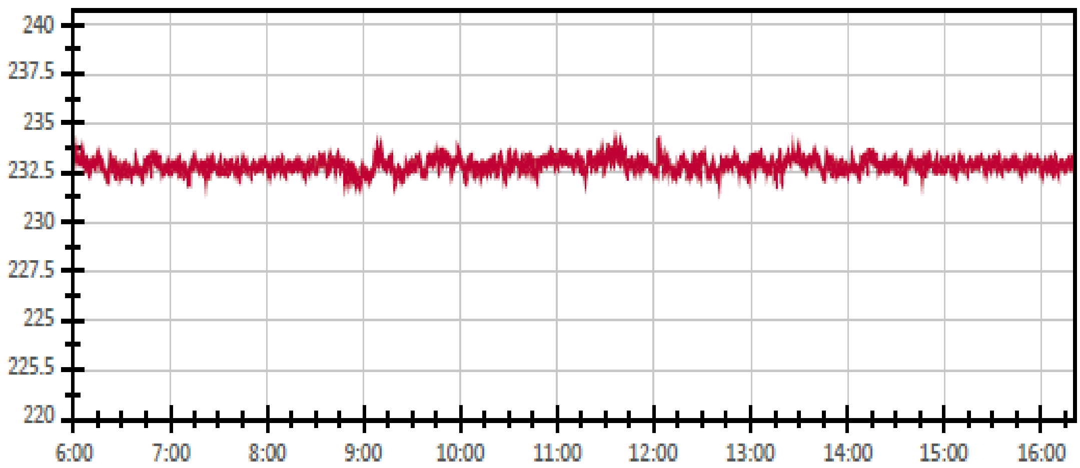

Fig. 10. Output voltage of the power plant on the DC bus.
Рис. 10. Выходное напряжение электростанции на шине постоянного тока.

Conclusion

1. The paper presents a universal mathematical model that describes the possibility of parallel operation of a solar power plant and the power system with regard to both the steady-state and transient modes, and that provides for correct evaluation of the system's operation in normal and emergency modes.

2. The paper proposes an algorithm for controlling the automatic control system of the output parameters of a solar power plant in parallel operation with the power system. The algorithm is based on the principle of subordinate control of coordinates. In this case, the outer loop serves to regulate and stabilize the voltage, and the inner control loop ensures the stabilization of the output current of the power plant.

3. The program modeling of the electromagnetic transient processes with the output parameters of solar power plants in parallel operation with the power system has been carried in the MatLab / Simulink and Power System Blockset software environment, which allows simulating the parallel operation of stations and power systems.

4. It is shown that in the presence of current and voltage regulators in the control system, electromagnetic transient processes demonstrate high reliability and performance speed during operation under both normal and emergency conditions.

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References

1. Renewables 2020, Global Status Report/ REN 21 Paris-2020.Official website of NP "Russian solar energy Association". URL. http: / /pvrussia.ru (accessed 17.09.2016).

2. Safaraliev, M.K., Odinaev, I.N., Ahyoev, J.S., Rasulzoda, K.N., and Otashbekov, R.A. Energy Potential Estimation of the Region's Solar Radiation Using a Solar Tracker. Appl. Sol. Energy 56, 270–275 (2020).

3. Ismagilov F. R., Sharifov B. N., Gaisin N. B. M., Teregulov T. R., Babkina N. L. Investigation of parallel operation of a solar power plant with a grid. /Journal Ufa aviation state technical university, 2016, no. 4 (74), pp. 71-79.

4. Kryuchkov I. P., Starshinov V. A., Gusev Yu. P., Piratorov M. V. perekhodnye protsessy V elektroenergeticheskikh sistemakh: [Transient processes in electric power systems: a textbook for universities].

5. Zinov'ev S. G. silovaya Elektronika: uchebnoe posobie dlya bakalavrov [Power electronics: a textbook for bachelors].

6. Schreiner R. T. Mathematical modeling of AC electric drives with semiconductor frequency converters. Yekaterinburg: Ural BRANCH of the Russian Academy of Sciences, 2000, 654 p.

7. Malek Hadi. Control of Grid-Connected Photovoltaic Systems Using Fractional Order Operator // All Graduate Theses and Dissertations 2014, paper 2157.

8. P. Rodriguez, R. Teodorescu, I. Candela, A.V. Timbus, M. Liserre, F. Blaabjerg, New positive-sequence voltage detector for grid synchronization of power converters under faulty grid conditions // Power Electronics Specialists Conference PESC 06. 37th IEEE. 1–7, 18th June, 2006.

9. N.F. Guerrero-Rodríguez, L.C. Herrero-de Lucas. Performance study of a synchronization algorithm for a 3-phase photovoltaic grid-connected system under harmonic distortions and unbalances. // Electric Power Systems Research 2014, №116, pp 252–265.

10. P. Rodriguez, A. Luna, M. Ciobotaru, R. Teodorescu, F. Blaabjerg, Multiresonant frequency-locked loop for grid synchronization of power converters under distorted grid conditions // IEEE Trans. Ind. Electron, 2011. - No. 58, pp. 127-138.

11. Klyuchev V. I. Teoriya elektroprivoda: uchebnoe posobie dlya vuzov [Theory of electric drive: a textbook for universities].

12. Curev P. Y. Development of systems of vector control of asynchronous drive on the base of specialized signal microcontrollers: Dis. Cand. tech.nauk: 05.09.03, Moscow, 2002, 256 p.

13. Ilinsky N. F., Kozachenko V. F. obshchiy Kurs elektroprivoda [General course of electric drive]. Moscow: Energoatomizdat, 1992, 544 p.

14. F. Ruz, A.B. Rey-Boué, J.M. Torrelo, A. Nieto, F.J. Canovas, Real time test benchmark design for photovoltaic grid-connected control systems, // Electric Power System. Research, 2011, No. 81, pp. 907-914.

15. Popov E. P. Teoriya lineynykh sistem avtomaticheskogo regulirovaniya I upravleniya [Theory of linear systems of automatic regulation and control].- 2nd ed., reprint. and add. - Moscow: Nauka. Chief editor of Phys. - math. lit, 1989, 304 p.

16. Herman-Galkin S. G. Computer modeling of semiconductor systems: a textbook: SPb KORONA-Print, 2001, 320 p.

17. Matlab/Simulink the MathWorks Inc. URL. http://www.mathworks.com.

18. Sridhar, V.; Umashankar, S. A comprehensive review on CHB MLI based PV inverter and feasibility study of CHB MLI based PV-STATCOM. Renew. Sustain. Energy Rev. 2017, 78, 138–156.

19. Chen, L.; Chen, H.; Li, Y.; Li, G.; Yang, J.; Liu, X.; Xu, Y.; Ren, L.; Tang, Y. SMES-Battery Energy Storage System for the Stabilization of a Photovoltaic-Based Microgrid. IEEE Trans. Appl. Supercond. 2018, 28, 1–7.

20. Olaszi, B.D.; Ladanyi, J. Comparison of different discharge strategies of grid-connected residential PV systems with energy storage in perspective of optimal battery energy storage system sizing. Renew. Sustain. Energy Rev. 2017, 75, 710–718.

21. Vavilapalli, S.; Padmanaban, S.; Subramaniam, U.; Mihet-Popa, L. Power Balancing Control for Grid Energy Storage System in Photovoltaic Applications—Real Time Digital Simulation Implementation. Energies 2017, 10, 928.

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