Smart Grid Functioning of Solar Electric System Network Based on Complex Accumulation Control

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Abstract: Voltage maintenance in the distribution system takes place with the use of additional devices. The purpose of the work is to develop a Smart Grid functioning of the solar electric system network based on integrated storage control. Accumulator battery and thermoelectric accumulator as part of the solar electric system network acquire the additional status of voltage regulators in the distribution system. A comprehensive integrated system has been developed for supporting the functioning of the solar electric system network based on a prediction of changes in the battery capacity and power factor. Advanced decisions on change the capacity of the thermoelectric accumulator in redistributes the accumulated electrical energy. Changing the level of transmission of electric energy to the network make it possible to maintain voltage in the distribution system through maintaining the power factor of the network solar electric system. Continuous measurement of the voltage at the input to the hybrid inverter, the voltage at the output from the frequency converter and in the distribution system takes place. The change in the ratio of voltage at the output of the frequency converter and in the distribution system is evaluated. The peak load of the energy system is prevented, reducing the consumption of energy from the network to 14%.

Keywords: Solar energy, Smart grid, Accumulator battery, Thermoelectric accumulator, Power factor.

1. INTRODUCTION

The distributed generation of electricity using renewable sources requires intelligent systems for managing electricity flows and consumption. Smart Grid technoloies, demand management systems and energy storage are new components for the integration of distributed energy generation in the energy system.

In terms of connection to intelligent control systems, the author [1] proposes to predict voltage changes when easuring the temperature of the electrolyte in the volume of batteries. An energy saving technology has been developed for the operation of a storage battery; it does not allow overcharging, but it does not allow discharge based on the coordination ofelectrochemical and diffusion processes of discharge and charge. Integrated Smart Grid Systems of harmonization of production and consumption of electric power based on a prediction of changes in the battery capacity is developed [2]. Advanced decisions on the change in power transmission capacity have made it possible to regulate voltage in the distribution system by maintaining the power factor of the photoelectric charging station. Voltages at the input to the hybrid inverter and in the distribution system were measured to assess their ratio.

An urgent task regarding the further development of Smart Grid technologies is the maintenance of the power factor of the network solar electric system based on the integrated management of the accumulation of electric energy and heat. It is known that the thermoelectric accumulator is controlled according to the thermostat principle, that is, when the required temperature of the local heated water is established, the thermoelectric accumulator is disconnected from the power supply. Not using the change in the flow rate of local water during the charge period of the thermoelectric accumulator increases the charge period and leads to significant costs for the consumption of electrical energy. For the purpose of comprehensive management of the accumulation of electrical energy and heat, it is necessary to predict the change in the capacity of the battery. Adopting anticipatory decisions to change the power of the thermoelectric accumulator allows to maintain the voltage in the distribution system. The maintenance of the power factor of the grid solar electric system occurs when measuring the voltage at the input to the hybrid inverter, the voltage at the output of the frequency converter, and the frequency of the voltage when measuring the voltage in the distribution system. The change in the ratio of the voltage at the output of the frequency converter and the voltage in the distribution system is evaluated. Maintaining the power factor of the network solar electric system when making anticipatory decisions on changing the power of electric energy transmission to the network allows to prevent the peak load of the electric system when satisfying consumer requests.

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Optimization of distributed generation of electrical energy usually uses the improvement of intelligent control systems for both the production of electrical energy and consumption. Thus, work [3], which estimates energy losses to the photovoltaic module, is devoted to forecasting the efficiency of electric energy production. The estimate of the cost of energy based on the discounting method cannot be generalized. It is not possible to generalize and distribute the economic scheduling algorithm for minimizing the total costs of production [4], because it limits the balance of demand and the power of electric energy production. Work [5] is devoted to early forecasting of the efficiency of electric load, in which a neural model of planning and distribution of electric energy is proposed, but without coordination with production. The paper [6] presents the results of the implementation of the algorithm of stochastic optimization of distributed generation of electric energy using fuzzy logic. The relationship between the load of the electrical system and operating costs with the flexibility of managing distributed generation has been established. The limit level of electric power generation using the utility network as a virtual storage in order to maintain the flexibility of management is proposed. But the design and management strategy, on which the results presented in this work are calculated, do not allow to expand the level of distributed energy generation. Reconciliation of production and consumption of electrical energy presented in works [7, 8] requires uncertainty models, for example, using the Monte Carlo method [7], or genetic algorithm [8], which is based on deep learning for long-term memory. Therefore, for example, a blockchain-based data aggregation scheme for preserving privacy in smart networks is proposed [9]. Uncertainty can be prevented by using, for example, large-scale seasonal heat storage (ATES) [10] for intelligent management of distributed energy generation. However, the exchange of information between ATES systems regarding dynamic control does not establish a connection between the use of accumulation and the assessment of the power factor change.

The presented analysis of literature sources does not evaluate the support of the power factor in the distribution system regarding the connection of renewable energy sources. Management of the production and consumption of electrical energy usually takes place with the use of additional devices for voltage regulation in the distribution system and requires additional costs. The storage battery and the thermoelectric accumulator become elements of voltage regulation in the distribution system while ensuring comprehensive energy consumption and maintaining the power factor of the grid solar electric system.

Forecasting the change in battery capacity provides an opportunity to make anticipatory decisions on changing the capacity of the thermoelectric accumulator. There is a change in the number of rotations of the electric motor of the circulation pump in relation to the change in the flow rate and temperature of the heated water. Therefore, it is proposed to measure the voltage at the input to the hybrid inverter, the voltage at the output from the frequency converter, and the frequency of the voltage when measuring the voltage in the distribution system. The ratio of the voltage at the output of the frequency converter and the voltage in the distribution system is estimated. Making anticipatory decisions to change the power level of electric energy transmission to the network allows you to adjust the voltage in the distribution system to match energy production and consumption, preventing the peak load of the energy system. This substantiates the need for research in this direction.

The purpose of the work is to develop a Smart Grid technology for supporting the operation of a grid solar electric system based on integrated storage management. This will make it possible to maintain the voltage in the distribution system in relation to maintaining the power factor of the electrical system. The change in battery capacity is predicted in relation to the adoption of anticipatory decisions on the change in the capacity of the thermoelectric accumulator and the level of transmission of electrical energy to the network. To achieve the goal, the following tasks were set:

– to offer voltage support in the distribution system based on forecasting the change in the storage battery capacity regarding the adoption of anticipatory decisions on the change in the capacity of the thermoelectric accumulator and the level of transmission of electrical energy to the network to support the power factor of the network solar electric system. The voltage at the input to the hybrid inverter, the voltage at the output from the frequency converter and the voltage frequency when measuring the voltage in the distribution system are measured. The change in the ratio of the voltage at the output of the frequency converter and the voltage in the distribution system is evaluated.

– develop a structural diagram and perform complex mathematical modeling to obtain a reference estimate of the change in battery capacity, the power factor of the grid solar electric system;

– to propose taking anticipatory decisions on changing the power of the thermoelectric accumulator and the level of transmission of electrical energy to the network to maintain the voltage in the distribution system. For this purpose, develop a structural diagram and perform logical modeling to obtain a functional assessment of the change in battery capacity, the power factor of the grid solar electric system;

– develop a structural diagram and perform logical modeling regarding the acquisition of an integrated Smart Grid system for supporting the functioning of the grid solar electric system at the decision-making level;

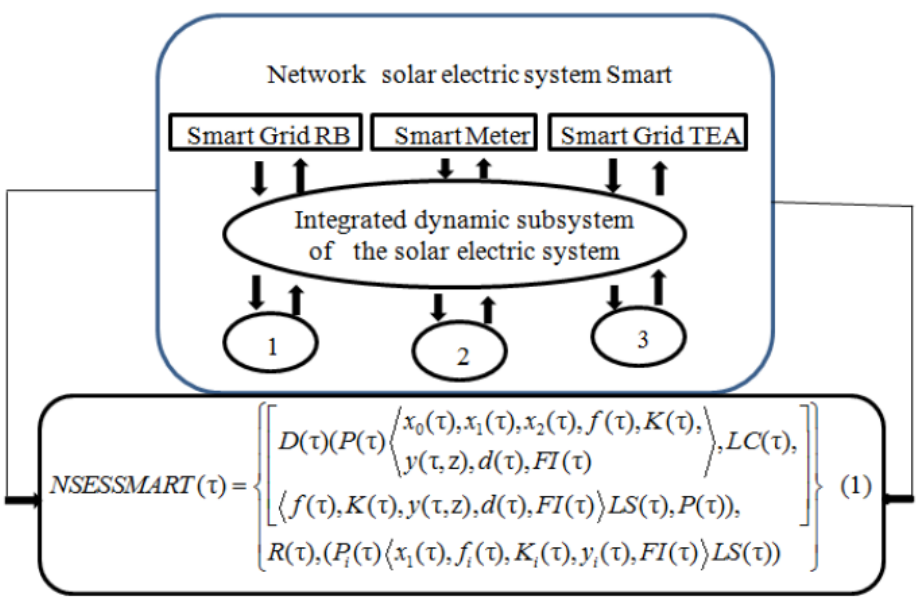
– ensure coordination of electric energy production and consumption based on forecasting changes in battery capacity, power factor of grid solar electric system in relation to voltage maintenance in the distribution system.

2. PROPOSED METHOD

2.1. Methodological and Mathematical Substantiation

Based on the methodological, mathematical, logical substantiation of the technological systems [11, 12] the architecture, mathematical substantiation of the architecture (1) are proposed (Figure **1**).

The mathematical substantiation of the architecture of the Network solar electric system Smart (1), (Figure **1**), based on the methodology of the mathematical description of dynamics of power systems, the method of the graph of cause-effect relations [11, 12] is proposed. Where *NSESSMART* (τ) – Smart grid solar electric system; *D*(τ) is an integrated dynamic subsystem (power grid, photovoltaic module, hybrid inverter, storage battery, two-way Smart Meter counter for changing the power level of electric energy transmission to the network; two-section storage tank, upper section of the two-section storage tank, frequency converter); *P*(τ)– properties of electrical system components; τ – time, s; *z* – coordinate of the length of the battery plates, m; *x(*τ) – impacts (change in solar radiation, change in consumption of electrical energy and heat); *f(*τ) – measured parameters (voltage at the input to the hybrid inverter, voltage at the output from the frequency converter, voltage frequency, voltage in the distribution system); *K*(τ) – coefficients of the mathematical description of the dynamics of the battery capacity change, the power factor of the network solar electric system; *y*(τ, *z*) – output parameters (battery capacity, power factor of the grid solar electric system); *d*(τ) – dynamic parameters of battery capacity change, power factor of the network solar electric system; *LC*(τ), *LS*(τ), R(τ) – logical relations in *D*(τ), *NSESSMART* (τ), respectively, *FI*(τ) –



$$NSESSMART(\tau)=\left\{\begin{matrix}\left[\begin{matrix}D(\tau)(P(\tau)\left\langle\begin{matrix}x_0(\tau),x_1(\tau),x_2(\tau),f(\tau),K(\tau),\\ y(\tau,z),d(\tau),FI(\tau)\end{matrix}\right\rangle,LC(\tau),\\ \langle f(\tau),K(\tau),y(\tau,z),d(\tau),FI(\tau)\rangle LS(\tau),P(\tau)),\end{matrix}\right]\\ R(\tau),(P_i(\tau)\langle x_1(\tau),f_i(\tau),K_i(\tau),y_i(\tau),FI(\tau)\rangle LS(\tau))\end{matrix}\right\} \quad (1)$$

Figure 1: Network solar electric system Smart Grid: the architecture and mathematical description of architecture (1): RB – rechargeable battery; Smart Meter is a two-way counter of changes in the level of power transmission to the network; TEA – thermoelectric accumulator; 1 – the charging unit; 2 – the discharging unit; 3 – the unit of assessing the functional efficiency.

$$SFNSESSMART(\tau)=\left\{\begin{bmatrix}(D(\tau)(P(\tau),MM(z,\tau),AI(\tau),C(\tau),LC(\tau)\\ \langle x_0(\tau),x_1(\tau),x_2(\tau),f(\tau),K(\tau),y(\tau,z),d(\tau),FI(\tau)\rangle,\\ LMD(\tau),MD(\tau),NC(\tau),S(\tau),LS(\tau)\\ \langle f(\tau),K(\tau),y(\tau),d(\tau),FI(\tau)\rangle\\ P(\tau))),R(\tau),(P_i(\tau)\langle x_1(\tau),f_i(\tau),K_i(\tau),y_i(\tau)\rangle),\end{bmatrix}\right\} (2)$$

Figure 2: Network solar electric system Smart Grid: the architecture: Mathematical substantiation of maintenance of the operation (2).

functional resulting information. Indices: *i* – number of elements of the electrical system; 0, 1, 2 – initial stationary mode, external, internal nature of influences.

Based on the methodological, mathematical, logical substantiation of the technological systems [11, 12] the mathematical substantiation of maintenance of the operation (2) of the network solar electric system Smart Grid is proposed (Figure **2**).

The mathematical substantiation of maintenance of the operation of the network solar electric system Smart Grid (2), (Figure **2**), based on the methodology of the mathematical description of dynamics of power systems, the method of the graph of cause-effect relations [11, 12] is proposed. The basis of the proposed rationale is the mathematical description of the architecture of the network solar electric system Smart (1), (Figure **1**). Whear *SFNSESSMART*(τ) – Smart Grid support for the functioning of the network solar electric system; *D*(τ) – integrated dynamic subsystem (power grid, photovoltaic module, hybrid inverter, storage battery, two-way Smart Meter, two-section storage tank, upper section of two-section storage tank, frequency converter; *P*(τ) – properties of *SFNSESSMART* (τ) elements; *MM* (τ, *z*) – complex mathematical modeling of the dynamics of changes in battery capacity, the power of the upper section of the two-section storage tank, the power factor of the grid solar electric system; *sd*(τ) – the input data (the power of photoelectric module, the power of thermoelectric accumulator, the rechargeable battery and its type and capacity, the two-way Smart Meter counter and its type; *lp*(τ) – the boundary change in parameters (the voltage at the input to the hybrid inverter and at the output of the frequency converter, in the distribution system**;** *lf*(τ) – the levels of operation of the grid solar electric system**;** *fd* (τ) – the obtained parameters **(**mode parameters of the grid solar electric system)**;** *tf*(τ,*z*) – the transfer function of predicted parameters **–** in the battery capacity, power factor of the grid solar electric system**;** *AI(*τ, z) – reference information regarding the assessment of the change in the capacity of the storage battery, the power factor of the grid solar electric system, *C*(τ) – control of the operational capacity of the integrated dynamic subsystem, *MD*(τ) – making decisions on the change of the capacity of the upper section of the two-section tank - storage; *S*(τ) – identification of the state of the electrical system; *LC(*τ), *LMD*(τ), *LS*(τ) – logical relations in *C*(τ), *MD*(τ), *S*(τ), respectively; *FI*(τ) is functional resulting information; *NC*(τ) – new operating conditions as a result of decision-making; *x*(τ) – impacts (change in solar radiation, change in consumption of electrical energy and heat); *f*(τ) – measured parameters (voltage at the input to the hybrid inverter, voltage at the output from the frequency converter, voltage frequency, voltage in the distribution system); *K*(τ) – coefficients of the mathematical description of the dynamics of the battery capacity change, the power factor of the grid solar electric system); *y(*τ, *z*) – output parameters (battery capacity, power factor of grid solar electric system); *d*(τ) – dynamic parameters of battery capacity change, power factor of network solar electric system; *z* – coordinate of the length of the battery plates, m; τ – time, s. Indices: *i* – components of *SFNSESSMART* (τ) (charge block, discharge block, functional efficiency assessment block); 0, 1, 2 – initial mode, external, internal nature of influences.

Mathematical substantiation of the architecture of the network solar electric system Smart (1) and mathematical substantiation of maintenance of the operation of the the network solar electric system Smart Grid (2) (Figure **2**) make it possible to maintain the operation of the the network solar electric system Smart using the following actions:

– workability control (*C*(τ)) of the dynamic subsystem based on complex mathematical (*CMM*(τ, *z*)) and logical (*LC*(τ)) modeling regarding obtaining standard (*AI*(τ, *z*)) estimate of a change in the battery capacity, power factor of the the network solar electric system;

– workability control ($C(\tau)$) of the dynamic system based on complex mathematical ($CMM(\tau, z)$) and logical ($LC(\tau)$) modeling regarding the obtaining functional ($FI(\tau)$) estimate of a change in the battery capacity, power factor of the the network solar electric system;

– decision making ($MD(\tau)$) with the use of the functional resulting information ($FI(\tau)$), obtained based on logical modeling ($LMD(\tau)$); decision making to change the level of power transmission to the network to maintain the power factor of the the network solar electric system;

– identification ($S(\tau)$) of the new conditions of functioning of the the network solar electric system ($NC(\tau)$) based on logical modeling ($LS(\tau)$) as a part of the dynamic subsystem and confirmation of new operating conditions based on logical modeling ($R(\tau)$) from the units of the the solar electric system.

3. MAINTAINING THE VOLTAGE WITHIN THE DISTRIBUTION SYSTEM BASED ON A PREDICTION OF CHANGES IN THE BATTERY CAPACITY

According to formulas (1), (2) (Figures **1**, **2**) it is proposed to forecast changes in the capacity of the battery, the power factor of the grid solar electric system. The voltage at the input to the hybrid inverter, the voltage at the output from the frequency converter and the voltage frequency when measuring the voltage in the distribution system are measured. The change in the ratio of voltage at the output of the frequency converter and voltage in the distribution system was evaluated. Transfer functions by channels: "battery capacity - voltage at the output of the frequency converter", "power factor of the network solar electric system - voltage in the distribution system" are presented as follows:

$$W_{CE-U_2} = \frac{K_{ce}K}{\left(T_e S+1\right)\beta - 1}\left(1-e^{-\gamma\xi}\right), \tag{3}$$

$$W_{pf-U_3} = \frac{K_{pf}K}{\left(T_e S+1\right)\beta - 1}\left(1-e^{-\gamma\xi}\right), \tag{4}$$

where $K_{ce} = \frac{I_1U_1}{\left(U_2-U_3\right)}$; $K_{pf} = \frac{I_1U_1 - I_2\left(U_2-U_3\right)}{N}$;

$$K = \frac{m\left(\theta_0-\sigma_0\right)}{G_{e0}};\ L = \frac{G_e\,C_e}{\alpha_0 h_0};\ T_e = \frac{g_e\,C_e}{\alpha_0 h_0};$$

$$\beta = T_m S + \varepsilon + 1;\ T_m = \frac{g_m C_m}{\alpha_0 h_0};\ \varepsilon = \left(1-L\right);\quad \gamma = \frac{\left(T_e S+1\right)\beta\text{-}1}{\beta};$$

$$\xi = \frac{z}{L},$$

where CE is the battery capacity, Ah; PF is the power factor of the network solar electric system; I_1, I_2 – currents at the input to the hybrid inverter, at the output of the frequency converter, respectively, A; U_1, U_2, U_3 – voltage at the input to the hybrid inverter, at the output from the frequency converter, in the distribution system, respectively, V; N is the power of the network solar electric system, kW; C – specific heat capacity, kJ/(kg·K); α – heat transfer coefficient, kW/(m^2·K); G – substance consumption, kg/s; g – specific mass of substance, kg/m; h – specific surface, m^2/m; σ, θ – the temperature of the electrolyte at the outlet of the battery, the separating wall, respectively, K; z – coordinate of the length of the battery plates, m; T_e, T_m are time constants characterizing the thermal accumulative capacity of the electrolyte, metal, respectively, s; m is an indicator of the dependence of the heat transfer coefficient on the consumption; ι – time, s; S is the Laplace transform parameter; S=ωj; ω – frequency, 1/s. Indices: 0 – initial stationary mode; ce – capacity; e – electrolyte; m is a metal wall.

A real part of the transfer functions are separated:

$$O\left(\omega\right) = \frac{\left(L_1A_1\right)+\left(M_1B_1\right)\left(1-L\right)}{\left(A_1^2+B_1^2\right)}. \tag{5}$$

The K factor includes the temperature of the separating wall θ:

$$\theta = \left(\alpha_e\left(\sigma_1+\sigma_2\right)/2\right)+\left(A\left(t_1+t_2\right)/2\right)/\left(\alpha_e + A\right), \tag{6}$$

where σ_1, σ_2 are the temperature of electrolyte at the inlet and outlet of the battery, K, respectively; t_1, t_2 are the temperature of electrolyte in pores of the plates and above the plates at the battery inlet and outlet, respectively, K; α is the heat transfer factor, kW/(m^2·K). Indice: e – electrolyte.

$$A = 1/\left(\delta_m/\lambda_m + 1/\alpha\right), \tag{7}$$

where δ is the battery plate wall thickness, m; λ is the thermal conductivity of metal of the battery plate, kW/(m·K). Indice: m is the metal wall of the battery plate.

To use the real part $O(\omega)$, the following factors were obtained:

$$A_1 = \varepsilon - T_e T_m \omega^2; \tag{8}$$

$$A_2 = \varepsilon + 1; \tag{9}$$

$$B_1 = T_e \varepsilon \omega + T_e \omega + T_m \omega; \tag{10}$$

$$B_2 = T_m \omega; \tag{11}$$

$$C_1 = \frac{A_1 A_2 + B_1 B_2}{A_2^2 + B_2^2}; \tag{12}$$

$$D_1 = \frac{A_2 B_1 - A_1 B_2}{A_2^2 + B_2^2}; \tag{13}$$

$$L_1 = 1 - e^{-\zeta C_1} \cos\left(-\xi D_1\right); \tag{14}$$

$$M_1 = -e^{-\zeta C_1} \sin\left(-\xi D_1\right). \tag{15}$$

The transfer functions (3), (4) which was obtained based on the use of the operator method of solving the system of nonlinear differential equations, includes the Laplace transform parameter – S (S = ωj), where ω is the frequency, 1/s. To switch from the frequency area to the time area, a real part (5), obtained as a result of the mathematical treatment of transfer functions, was separated. It is this part that is included in the integrals (16), (17) which makes it possible to obtain dynamic characteristics of a change the battery capacity, power factor of the network solar electric system using the inverse Fourier transform:

$$CE\left(\tau\right) = \frac{1}{2\pi} \int_0^\infty K_{ce} KO\left(\omega\right) \sin\left(\tau\omega/\omega\right) d\omega, \tag{16}$$

$$PF\left(\tau\right) = \frac{1}{2\pi} \int_0^\infty K_{pf} KO\left(\omega\right) \sin\left(\tau\omega/\omega\right) d\omega, \tag{17}$$

where *CE* is the battery capacity, Ah; *PF* is the power factor of the network solar electric system.

According to formulas (1) – (4) and the proposed block diagram (Figure **3**), the results of reference information obtained on the basis of complex mathematical modeling of the network solar electric system Smart Grid is presented (Tables **1-3**).

Time constants and the coefficients that are components of mathematical models of dynamics (3), (4) presented in Table **3** were obtained based on the

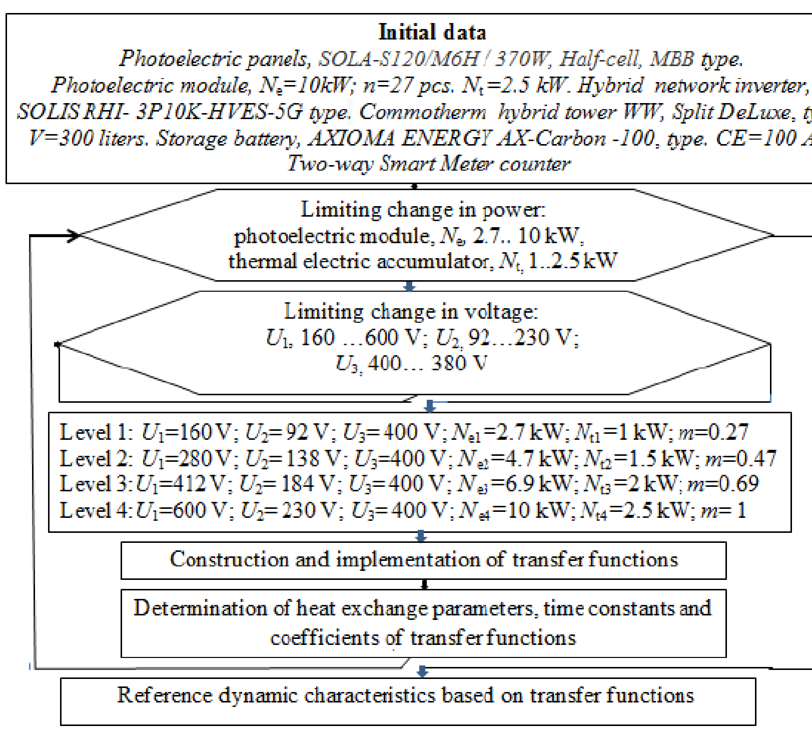


Figure 3: Block diagram of comprehensive mathematical modeling of the network solar electric system: N_e, N_t – the power of photoelectric module and thermoelectric accumulator, respectively, kW; *CE*– battery capacity, Ah; U_1, U_2, U_3– voltage at the input to the hybrid inverter and at the output of the frequency converter, in the distribution system, respectively, V; *n* – the number of photoelectric panels; *m* – the power level of the network solar electric system.

Table 1: Mode Parameters of the Network Solar Electric System

Levels of Operation	N_e, kW	N_t, kW	t, °C	G, kg/s	τ, hours	U_1, V	U_2, V	U_3, V	m
first level	2.7	1	40	0.007	2	160	92	400	0.27
second level	4.7	1,5	45	0.009	0.21	280	138	400	0.47
third level	6.9	2	50	0.011	0.12	412	184	400	0.69
fourth	10	2,5	55	0.012	0.077	600	230	400	1

Note: N_e – the power of network solar electric system, kW; N_t – the power of thermoelectric accumulator, kW; t – local water temperature, °C; G – consumption of local water, kg/s; τ – charging time of the thermoelectric accumulator, hours; U_1, U_2, U_3 – voltage at the input to the hybrid inverter and at the output of the frequency converter, in the distribution system, respectively, V; m – the power level of the network solar electric system.

Table 2: Heat Exchange Parameters of the Battery

Operation levels	Параметр		
	α_1, W/(m^2·K)	α_2, W/(m^2·K)	k, W/(m^2·K)
Charge, discharge	8.176	8.152	2.43

Note: α_1 – coefficient of heat transfer from the electrolyte to a wall of the battery plate when charged, W/(m^2·K); α_2 – coefficient of heat transfer from the wall of the battery plate to the electrolyte when discharged, W/(m^2·K); k – coefficient of heat exchange, W/(m^2·K).

Table 3: Time constants and coefficients of mathematical models of dynamics of the network solar electric system

Peration Levels	T_e, , s	T_m, , s	ε	ζ	L, m
Charge	3395	11378	0.997	0.227	1.6
Discharge	3405	11411	0.997	0.227	1.6

parameters of heat exchange for charge and discharge of the battery presented in Tables **1**, **2**.

Based on the proposed mathematical substantiation Smart Grid maintenance of functioning of the network solar electric system (1) to (4) the block diagram for the control of serviceability of the network solar electric system (Figure **4**) is developed.

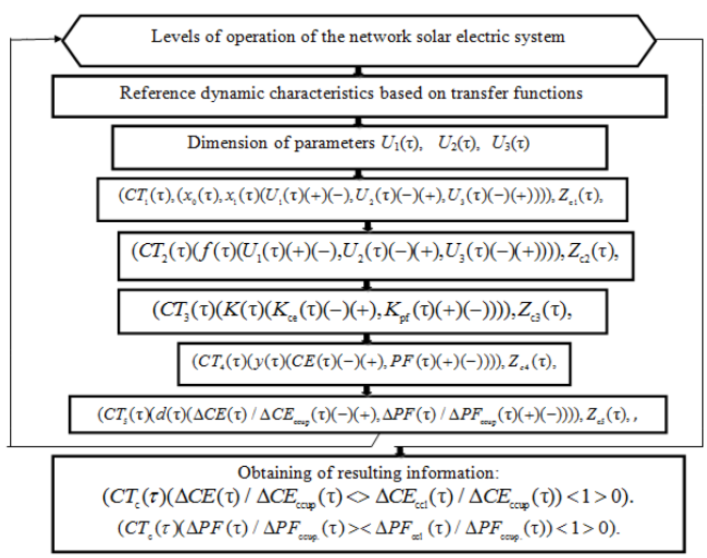


Figure 4: Block diagram of the network solar electric system functioning control: U_1, U_2, U_3 – voltage at the input to the hybrid inverter and at the output of the frequency converter, in the distribution system, respectively, V; CE – battery capacity, Ah; KF – power factor of the network solar electric system; CT – event control; Z – logical relations; d – dynamic parameters; x – effects; f – parameters measured; y – parameters predicted; K – coefficients of mathematical description; ι – time. Indices: c – control of operability; ccup– constant calculated value of the parameter of upper level of operation; ccl – constant calculated value of the parameter of level of operation; 0, 1, 2 – initial stationary mode, external, internal influences; 3 – coefficients of dynamics equations; 4 – significant predicted parameters; 5 – dynamic parameters.

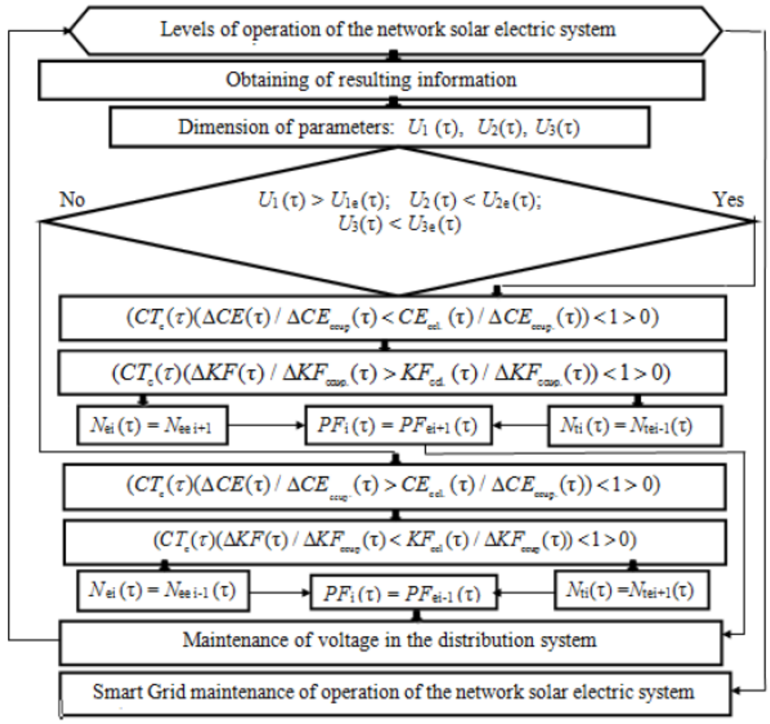


Figure 5: Block diagram of maintenance of operation of the network solar electric system: U_1, U_2, U_3 – voltage at the input to the hybrid inverter and at the output of the frequency converter, in the distribution system, respectively, V; *CE* – battery capacity, Ah; *KF* – power factor of the network solar electric system; N_e, N_t – the power of photoelectric module and thermoelectric accumulator, respectively, kW; ι – time, s. Indices: *i* – number of operation levels; e – the reference value of the parameter; ccup– constant calculated value of the parameter of upper level of operation; ccl – constant calculated value of the parameter of level of operation.

Control of workability of the network solar electric system (Figure **4**) enables obtaining the resulting information for on advance decision-making about the maintenance of the voltage in the distribution system. Based on the proposed mathematical substantiation Smart Grid (1) to (4) the block diagram of maintenance of operation of the network solar electric system (Figure **5**) is developed.

Voltage maintenance in the distribution system (Figure **5**) makes it possible to ensure the operation of the network solar electric system.

4. RESULTS AND DISCUSSION

4.1. Smart Grid System of Maintaining the Operation of the Network Solar Electric System at the Decision-making Level

A comprehensive integrated system has been developed (Table **4**) for maintaining the operation of the network solar electric system based on a prediction of changes in the battery capacity and power factor of the network solar electric system. Advanced decisions on change the capacity of the thermo-electric accumulatorin redistributes the accumulated electrical energy. Changing the level of transmission of electric energy to the network make it possible to maintain voltage in the distribution system through maintaining the power factor of the network solar electric system. Continuous measurement of the voltage at the input to the hybrid inverter, the voltage at the output from the frequency converter and in the distribution system takes place. The change in the ratio of voltage at the output of the frequency converter and voltage in the distribution system is evaluated.

The integrated Smart Grid system of maintenance of operation of the network solar electric system (Table **4**) provides an opportunity to coordinate electric power production and consumption.

4.2. Coordination of Electric Power Production and Consumption Based on Accumulation Control

The battery capacity at a specified time point was determined as follows:

Table 4: Integrated System for Supporting the Functioning of the Network Solar Electric System

Time, τ, 10^3 s	Change in Parameters	$\Delta CE(\tau)/\Delta CE_1(\tau)$	$CE(\tau)$, Ah	$\Delta PF(\tau)/\Delta PF(\tau)_1$	$PF(\tau)$
0	Charge – discharge U_1=160 V; U_2=230 V;U_3=400 V; m=0.27	0.2667	100	0.3382	0.7153
3	Charge – discharge U_1=184 V; U_2=230 V; U_3=395 V; m=0.31	0.3160	98.77	0.3641	0.7257
6	Charge – discharge U_1=208 V; U_2=230 V; U_3=390 V; m=0.35	0.3683	97.46	0.3892	0.7357
9	Charge – discharge U_1=232 V; U_2=230 V; U_3=385 V; m=0.39	0.4240	96.07	0.4159	0.7464
12	Charge – discharge U_1=256 V; U_2=230 V; U_3=380 V; m=0.43	0.4835	94.58	0.4418	0.7568
15	Decision–making m=0.47; U_1=280 V; U_2=184 V; U_3=400 V	0.3673	97.48	0.5255	0.7903
18	Charge – discharge U_1=304 V; U_2=184 V; U_3=395 V; =0.51	0.4082	96.46	0.5432	0.7974
21	Charge – discharge U_1=328 V; U_2=184 V; U_3=390 V; m=0.55	0.4511	95.39	0.5773	0.8110
24	Charge – discharge U_1=352 V; U_2=184 V; U_3=385 V; m=0.59	0.4982	94.22	0.6032	0.8214
27	Charge – discharge U_1=376 V U_2=184 V; U_2=380 V; m=0.63	0.5435	93.09	0.6291	0.8318
30	Decision–making m=0.67; U_1=400 V; U_2=138 V; U_3=400 V	0.4320	95.88	0.7128	0.8653
33	Charge – discharge U_1=424 V; U_2=138 V; U_3=395 V; m=0.71	0.4674	93.23	0.7387	0.8757
36	Charge – discharge U_1=448 V; U_2=138 V; U_2=390 V; m=0.75	0.5037	92.33	0.7646	0.8861
39	Charge – discharge U_1=472 V; U_2=138 V; U_3=385 V; m=0.79	0.5414	91.39	0.7905	0.8965
42	Charge – discharge U_1=496 V; U_2=138 V; U_3=380 V; m=0.83	0.5807	90.41	0.8164	0.9069
45	Decision–making m=0.87; U_1=520 V; U_2=92 V; U_3=400 V	0.4783	92.97	0.9	0.9403
48	Charge – discharge U_1=544 V; U_2=92 V; U_3=395 V; m=0,91	0.5087	92.21	0.9260	0.9507
51	Charge – discharge U_1=568 V; U_2=92 V; BU_3=390 V; m=0.95	0.5400	91.43	0.9519	0.9611
54	Charge – discharge U_1=594 V; U_2=92 V; U_3=385 V; m=0,99	0.5744	90.57	0.9803	0.9725
55	Decision–making m=1; U_1=600 V;U_3=400 V	0.4250	94.30	1.0749	1.0103

Note: U_1, U_2, U_3 – voltage at the input to the hybrid inverter and at the output of the frequency converter, in the distribution system, respectively, V; N_e – the power of network solar electric system, kW; N_t – the power of thermoelectric accumulator, kW; m – the power level of the network solar electric system; CE – battery capacity, Ah; KF – power factor of the network solar electric system; ι – time, s. Indice: 1 – constant calculated value of the parameter of upper level of operation.

$$CE_{i+1}(\tau) = CE_i - + \begin{pmatrix} \Delta CF_{i+1}(\tau)/\Delta CE_1(\tau) - \\ -\Delta CE_i(\tau)/\Delta CE_1(\tau) \end{pmatrix} (CE_2 - CE_1), \quad (18)$$

where CE – the battery capacity, Ah; CE_1, CE_2 – initial and final values of the battery capacity, Ah; τ – time, s. Indices: 1 – constant calculated value of the parameter of upper level of operation; i – the number of levels of operation of the network solar electric system.

The power factor of the network solar electric system at the set time is determined as follows:

$$PF_{i+1}(\tau) = PF_i + \left(\begin{array}{l} \Delta PF_{i+1}(\tau)/\Delta PF_1(\tau) - \\ -\Delta PF_i(\tau)/\Delta PF_1(\tau) \end{array} \right)(PF_2 - PF_1), \quad (19)$$

where *PF* – power factor of the network solar electric system; PF_1, PF_2 – initial and final values of the power factor; τ – time, s. Indices: 1– constant calculated value of the parameter of the upper level of operation; *i* – the number of levels of operation of the network solar electric system.

For example, in a period of $15 \cdot 10^3$ s (4.17 hrs) the battery capacity was predicted to increase to the level of 97.48 Ah with voltage growth at the input to the hybrid inverter at the level of 280 V. Value of the battery capacity was determined using the formula (18) as follows (Table **4**, Figure **6**):

97.48 Ah =94.58+(0.4835–0.3673)(100–75).

In this period of time, it is necessary to make a preliminary decision to reduce the power of the thermoelectric accumulator to the level of 2 kW and increase the level of power of transmission of electrical energy to the network from 0.43 to 0.47. The voltage level in the distribution system is set at the level of 400 V and the power factor of the grid solar electric system at the level of 0.7903.

The value of the power factor in this period of time using formula (19) is determined as follows (Table **4**, Figure **7**):

0.7903=0.7568+(0.5255–0.4418)(0.98–0.58).

Performing such actions will enable maintenance of voltage in the distribution system to coordinate the production and consumption of electric power.

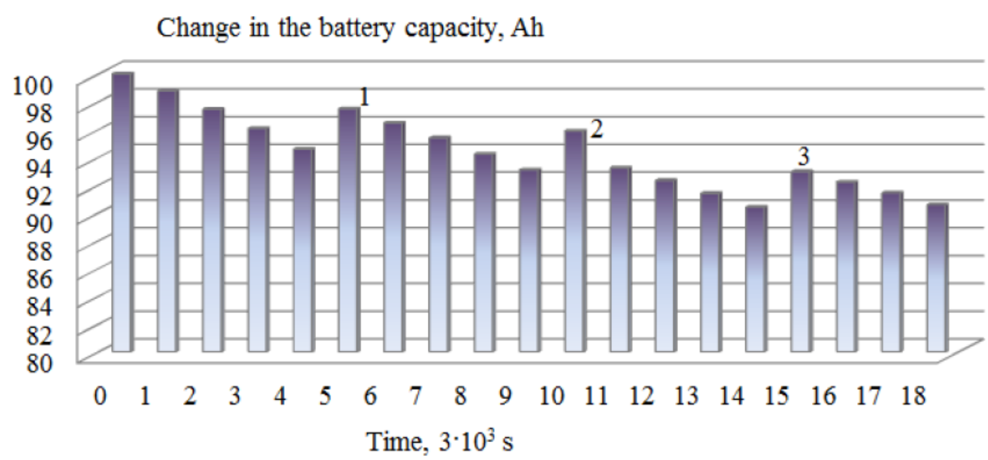


Figure 6: Maintenance of change in the battery capacity. 1, 2, 3 are the decisions were made to change the level of power of thermoelectric accumulator.

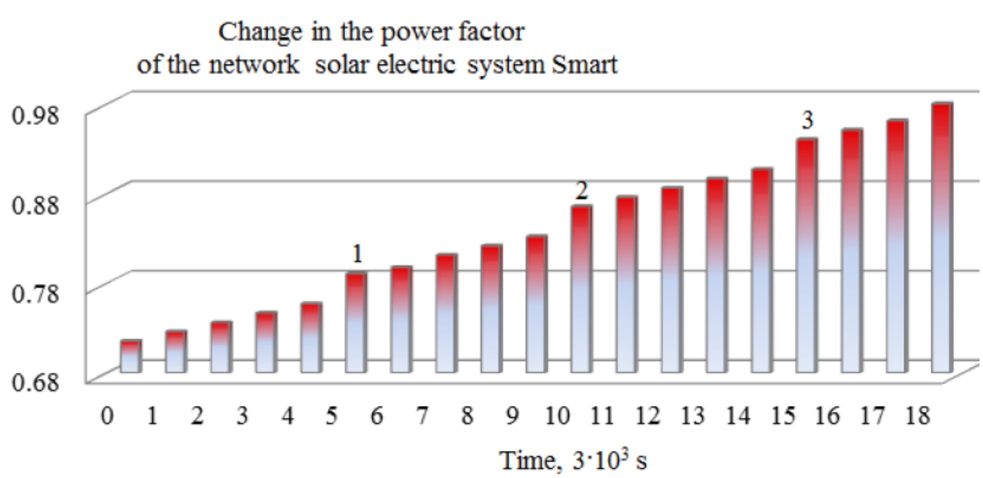


Figure 7: Maintenance of change in the power factor. 1, 2, 3 are the decisions were made to change the level of power of thermoelectric accumulator and transmission of electrical energy to the grid.

5. CONCLUSIONS

1. It is proposed to support the voltage in the distribution system on the basis of forecasting the change in the capacity of the storage battery in order to make anticipatory decisions on the change in the power of the thermoelectric accumulator, in relation to the support of the power factor of the network solar electric system. There is an assessment of the change in the ratio of the voltage at the output of the frequency converter and the voltage in the distribution system, which are measured when measuring the voltage at the input of the hybrid inverter. Thus, when the charging voltage at the input of the hybrid inverter changes from 160 V to 600 V and the battery discharge reaches 10% from 100 A·hours to 90.57 A·hours, anticipatory decisions are made to reduce the power of the thermoelectric accumulator from 2.5 kW to 1 kW and an increase in the power level of electric energy transmission to the network from 0.27 to 1. This allows maintaining the voltage in the distribution system by increasing the power factor of the the network solar electric system to 30% from 0.71 to 0.97.

2. A structural diagram was developed and complex mathematical modeling was performed to obtain a reference estimate of the change in battery capacity, the power factor of the the network solar electric system. The unifying element of the mathematical modeling of the dynamics is the estimation of the ratio of the voltage at the output of the frequency converter and the voltage in the distribution system, which are measured. The parameters of heat exchange in the storage battery, time constants and coefficients of mathematical models of dynamics for the established levels of functioning have been determined. Reference dynamic estimates of the change in battery capacity were obtained: 100 A·hour, 97.48 A·hour, 95.88 A·hour 92.97 A·hour and the power factor of the the network solar electric system: 0.7153, 0.7903, 0, 8653, 0.9725 according to the established levels of functioning.

3. It is proposed to make anticipatory decisions on changing the power level of the thermoelectric accumulator and the transmission of electrical energy to the network in order to maintain the voltage in the distribution system. A structural diagram has been developed and a logical modeling of the monitoring of the efficiency of the the network solar electric system has been carried out, which takes place according to the principle of cause-and-effect relationships. The logic unit has components that evaluate the voltage change in the range of 160-600 V at the input to the hybrid inverter and the voltage in the distribution system in the range of 400-380 V, which are measured. According to the structural diagram, the temperature change of the battery plate wall, the coefficients of mathematical models of dynamics, *K*ce, *K*pf, the battery capacity, and the power factor of the the network solar electric system are evaluated. The dynamic parameters of the battery capacity from 100 A·hours to 90.57 A·hours, the power factor of the the network solar electric system from 0.7153 to 0.9725 were estimated. In the resulting performance monitoring unit, a functional assessment of the change in battery capacity and the power factor of the the network solar electric system was obtained.

4. An integrated Smart Grid system for supporting the operation of the the network solar electric system was developed based on the developed logical modeling structural scheme. The power factor support of 0.71 to 0.97 is based on the comparison of the measured voltages at the input to the hybrid inverter, at the output of the frequency converter and in the distribution system with the reference values. The reference values of the voltage at the input to the hybrid inverter are 160 V, 280 V, 412 V, 600 V, the voltage at the output of the frequency converter is 92 V, 138 V, 184 V, 230 V according to the established levels of operation. The reference voltage value in the distribution system is 400 V with a functional change in the range of 400–380 V.

5. Coordination of electricity production and consumption is ensured on the basis of forecasting the change in battery capacity, the power factor of the the network solar electric system. Taking anticipatory decisions to change the power of the thermoelectric accumulator in relation to the change in the level of transmission of electrical energy to the network allows you to adjust the voltage in the distribution system. Supporting the functioning of the network solar electric system using the developed Smart Grid technology allows you to prevent the peak load of the energy system, reducing the consumption of electrical energy from the network and the payback period up to 14% while increasing the monetary profit to €2198/year under the "green tariff". Taking proactive decisions allows you to increase the power factor of the network solar electric system up to 30%.

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