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IMPROVING A MODEL OF THE HYBRID PHOTOVOLTAIC SYSTEM WITH A STORAGE BATTERY FOR LOCAL OBJECT'S SELF-CONSUMPTION INVOLVING THE SETTING OF POWER CONSUMED FROM THE GRID

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The object of research is energy processes in a hybrid photovoltaic system with a storage battery for the needs of a local object involving the setting of power consumed from the network. The task addressed was to build a mathematical model of energy processes with the function of determining control parameters providing for the possibility of changing control scenarios. The mathematical model of the storage battery has been improved, taking into account the charge modes and discharge currents in terms of accuracy of reproduction of the manufacturer's specification not worse than 3 %. A structure of the model was proposed with separation of module, which defines control parameters, as well as the schedule of power setting for selected scenarios. A variable is introduced into the model description, which determines the specified power value and ensures the construction of SoC(t) schedule. An additional mode to increase the energy use of the photovoltaic battery and restrictions on the measured value of load power were taken into account. Modeling with a change in time scale was proposed: first, control parameters are determined, followed by modeling in the daily cycle. This eliminates the need for preliminary calculations before modeling and provides the ability to verify the determination of system parameters with subsequent adjustment. A procedure for determining control parameters with power setting and adjusting the model under different control scenarios has been devised. When using archival generation data for the location of the facility, this makes it possible at the design stage to choose an option for implementing the power supply system with the desired indicators. For specific uses, it has been shown that underestimating the power of a photovoltaic battery by only 9 % increases energy costs by 1.72–1.39 times. Overstating power by 16.7 % impairs usage by 13.7 % while reducing costs by 1.4 % to 2.5 %

Keywords: modular structure, SoC(t) schedule, power setting, control scenarios, daily simulation cycle

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1. Introduction

The current trend in the development of energy generation involving renewable energy sources (RES) is the localization of electricity use in the places of its generation. This, in particular, applies to RES power supply systems for local objects (LOs) in the private sector. Recently, hybrid photovoltaic systems (PVS) with energy storage and connection to the alternating current distribution grid (DG) have been widely used. Storage batteries (SBs) are commonly used as energy storage. This helps ensure the balance of electricity in the power system, and for the consumer – increasing the reliability of power supply. In this regard, the urgent issue is to achieve the maximum reduction in the cost of electricity consumed from the grid. To some extent, this is facilitated by the growth of electricity tariffs. But in general, the efficiency of using PVS with SBs is associated with the correct determination of parameters and management of energy processes in the system. This implies the existence of effective design methods and, in particular, mathematical models.

Therefore, the task to further improve the mathematical models of RES systems is relevant and important for the design of efficient power supply systems for a wide range of household and industrial consumers.

2. Literature review and problem statement

The mathematical model of PVS with SBs for the needs of LOs should solve certain problems at the design stage of the system. This concerns the definition of system parameters and control principles. First of all, the expected economic indicators are taken into account. For the initial assessment of the reduction in the cost of electricity consumed from the network, the model in [1] involves determining the coefficient of reduction of electricity costs. In work [2], the degree of energy savings consumed from the network is estimated. However, with regard to PVS for LO own needs, when the generation of excess energy into the grid is not used, these criteria do not take into account the use of the installed power of the photovoltaic cell (PV) P_{PVR}. That is why, in [3], the use of PV energy is additionally evaluated. In this case, as initial data for modeling, it is possible to use the data of the PV generation archive [4] for the location of PVS. To increase objectivity, in work [5], the distribution of average monthly values of PV generation by time intervals according to the daily load schedule is additionally taken into account. According to this, days with a generation schedule close to the average monthly time distribution are selected for modeling.

The implementation of the PVS model is associated with the use of certain management approaches, in particular, the application of scenarios. In [1], it is proposed to use a set of load scenarios with a maximum reduction in the cost of electricity consumed from the network, the choice of which is carried out according to the forecast of PV generation. This uses data from open web resources that provide a power forecast P_{PV} for a given location with a discreteness of 0.5 hours or less [6]. However, the load power of LO P_L varies according to the generation of PV, which is not always acceptable and limits use. In [7], multi-purpose optimization of the microgrid is performed using eight scenarios in the presence of renewable energy sources, but an additional diesel generator is involved. In [8], in the case of a load independent of the forecast, the use of scenarios is associated with the tariffication of payment, taking into account constant, night, half-peak, and peak tariffs. However, it is not shown how this is implemented in the model. In work [9], to evaluate the impact of electricity tariffs and energy management strategies, one additionally takes into account dynamic pricing, but this solution involves the use of electricity exchange with the grid.

The key in the model is the algorithm of energy redistribution in PVS, which is usually determined by the ratio of the current values P_{PV} and P_L, as well as the state of SB charge *SoC*. In [10], the rechargeable battery charge mode is considered at present and the discharge mode in the evening and at night. But this approach is appropriate only for specific uses. In work [11], it is implied to use an inertial storage with energy redistribution along with the rechargeable battery between drives. An important point is the use of excess PV energy in the absence of energy generation to the network. To do this, in work [12], upon reaching the charge state *SoC*, when the rechargeable battery enters the charge mode with a constant voltage, P_{PV} is adjusted while maintaining the rechargeable battery charge in accordance with the charging characteristics. This solution leads to incomplete use of PV energy but, in the absence of additional energy consumption, provides a balance of power of PVS. In work [8], the control with the setting of the value of power P_g consumed by LO from the network is considered. The P_g value is determined for the accepted schedule of LO load power $P_L(t)$ taking into account the data on the generation forecast of PV. This makes it possible to move away from comparing the current values of P_{PV} and P_L and equalize consumption from the network over time.

A common practice of modeling RES systems is to use the MATLAB software package. In the presence of semiconductor energy converters with a high modulation frequency to accelerate the simulation process in the cycle of 24 h, in [13, 14] vector modeling is used. Description of the implementation of the model is considered in [15] for single-phase power supply system. In this case, the model, as a whole, preserves the structure of the system, and modeling is carried out for the main harmonic. Energy converters are also excluded and the energy of PV and rechargeable battery to alternating current is converted. The solution using this approach for a hybrid three-phase system with RES for the region of Kazakhstan is considered in [16], for the V2G car-network system – in [17].

More expedient is the departure from the structure of the electrical circuit of the system to the direct study of energy processes at the level of active power [11]. The approach is based on the description of steady state taking into account the control algorithm. However, energy losses in energy converters are not taken into account, modeling is carried out according to the average monthly generation of PV. The focus is on the dynamics of the process of energy distribution between the rechargeable battery and the inertial storage. The exchange of PVS energy with the grid is also implied. The adopted approach to the use of the modular structure of the model looks promising. However, the function of determining control parameters by the possibility of changing control scenarios is not taken into account. A model in [5] is focused on the use of forecast data using archival data of PV generation. The regulation of P_{PV} to ensure power balance is taken into account, but the model description is constructed according to a specific algorithm. This requires appropriate modification of the model with a change in the algorithm.

One of the key elements of the PVS model is a rechargeable battery model. In [18], the use of a lead-acid battery is considered. The regulation cycle is limited with changes in *SoC* (30–90 %). The SB model uses linear interpolation to estimate the rechargeable battery voltage $U_B = f(SoC)$ during charging and discharging. In [19], a simplified rechargeable battery model is also considered. The model consists of a voltage source, which is characterized by an open circuit voltage OCV and internal resistance R_{int}.

The SB models offered in MATLAB for use in the 24 h cycle [13–15] are based on the use of manufacturer characteristics. A procedure for calculating the parameters according to the charge characteristic – the dependence of voltage U_B on the degree of discharge *It* or $U_B(t)$ at fixed values of current *I*, which is given graphically, is described in [20]. The calculation of model parameters from many discretized points of the manufacturer curve is also considered in [21]. However, the dependence of the parameters defining the exponential zone on the discharge current *I* is not taken into account. An interesting model is proposed in [11], which takes into account the efficiency in determining *SoC*, but is based on experimental data. This makes it difficult to use. A common disadvantage of the above models is that the charging characteristic does not take into account changes in the charge mode (direct current/DC charge). Storage battery charge modes are taken into account in [5] but the voltage value is set tabularly for a fixed current value.

All this gives reason to assert that it is expedient to conduct a study on improving the mathematical model of energy processes in a hybrid PVS with SB for LO own needs. Management with the setting of power consumed from the network, according to the forecast of PV generation, looks promising, and provides targeted formation of the storage battery schedule *SoC*. This approach may be universal for use in different scenarios but is not well understood and needs to be improved. The development of the model is associated with the introduction of the function of determining control parameters involving the possibility of changing control scenarios. The energy intensity of SBs in PVS for own needs is large enough and ensures the redistribution of energy in the system. According to this, the storage battery model greatly affects the reliability of the simulation results. In addition, changes in the mode of operation are associated with a change in the storage battery charge mode. So, the question arises regarding the clarification and refinement of an SB model, which should reproduce the characteristics of the manufacturer. The same applies to the clarification of the general structure of the system model, taking into account changes in operating modes under different conditions. An important issue is determining control parameters that can be carried out directly in the process of modeling with scenario setting.

3. The aim and objectives of the study

The purpose of this work is to increase the reliability of the assessment of energy indicators with the possibility of refining the control mechanism of a hybrid PVS with SB involving the setting of consumed power in the simulation process.

To accomplish the aim, the following tasks have been set:

– to analyze the modes of PVS operation. To formalize the description of the model taking into account changes in operating modes and the introduction of a variable that will determine the value of power consumed from the network and ensures the construction of an $SoC(t)$ schedule;

– to increase the accuracy of reproduction by the SB mathematical model of the characteristics provided by the manufacturer, taking into account charge modes and discharge currents;

– to arrange the structure of the system model with the separation of the unchanged part from the implemented scenarios and the module that calculates the control parameters;

– to carry out modeling of the system under different management scenarios in the case of setting the generation of PV according to archival data for different seasons of the year.

4. The study materials and methods

The object of our research is energy processes in a hybrid PVS with a storage battery for the needs of a local object with the setting of power consumed from the network. As an initial provision, the improvement of the mechanism for forming the $SoC(t)$ schedule is adopted when managing with the setting of power consumption from the network to increase the degree of use of PV energy for consumption.

We studied ways to improve the model of a hybrid PVS with a storage battery on the basis of methods for analyzing electrical circuits. Clarification of the description of processes in the electrical circuits of PVSs was carried out for steady states under the condition of power balance in the case of controlling the active power consumed from the network. In this case, a variable has been introduced that determines the value of the power consumed from the network and ensures the construction of the $SoC(t)$ schedule. The use of a multifunctional grid inverter with maintaining close to 1 power factor at the point of connection to the network is considered. In this case, the analysis of energy processes was carried out at the level of active power. The influence of short-term transients during the change of operating modes on the overall energy indicators under the conditions of the daily cycle of the system was not taken into account. Energy losses in converters and batteries were taken into account through efficiency. Generation of excess electricity to the grid is not provided. When determining the operating modes, it was considered that the control system of the converter unit of the PVS was implemented according to the classical double-circuit structure with voltage stabilization at the input of the inverter. The power setting is provided through the amplitude of the current at the point of connection to the network. The changes made to the algorithm for changing operating modes and taking into account the measured power value are aimed at increasing the energy use of PV. When describing the discharge characteristics of SB, the change in the parameters determining the exponential region from the current value is taken into account. The corresponding dependences are obtained by analyzing the characteristics of the manufacturer, which are set graphically. The dependence of SB voltage on *SoC* during charging takes into account the change in the charging mode. In a charge zone with a given current value, the parameters of the equation are determined by the manufacturer's characteristic for a fixed charge current. In this case, the approximation takes into account the DOD (depth of discharge) depth limitation. The difference between the current value and the value set by the manufacturer is taken into account due to the voltage drop on the internal resistance of the storage battery. The dependence of the charge current on the *SoC* is given by limiting the current in relative (to capacitance) units according to the relevant manufacturer characteristics. For modeling, the MATLAB software package (USA) tested for this class of tasks using standard functions and blocks from its library was chosen. Determination of control parameters is carried out before the main simulation cycle in an accelerated time scale according to the generation of PV, which makes it possible to reproduce the operation of the control system according to the forecast. The load schedule was taken during the daily operation of LO in relation to the three-zone tariffication with peak hours in the morning and evening. The PV generation capacity was set according to archival data of the European geographic information system [4] for the PVS location.

5. Results of the study on improving the model of a hybrid photovoltaic system with a storage battery

5. 1. Analysis of the modes of operation of the photovoltaic system with the setting of the consumed power

The use of the structure of PVS with a converter unit (CU) based on a multifunctional grid inverter (GI) is considered [12]. The CU regulation system is dual-circuit with voltage stabilization U_d at the GI input [12]. This is carried out by the corresponding voltage controller (VC): current i_g consumed by LO from the grid, current of PV I_{PV}, storage battery current I_B. PV operates under a maximum power mode (MPPT) P_{PVM} or with regulation of generation power P_{PV} (I_{PV}). Stabilization U_d provides a balance of active power in the system. Since short-term transient regimes do not affect the daily energy balance, steady state of operation is considered. Electricity generation to the grid is not used.

The use of PVS with schedule $P_L(t)$ in relation to time to three-zone tariffication [22] is considered: peak in the morning (t_2, t_3) and evening (t_5, t_6), half-peak (day) load (t_3, t_5), (t_1, t_2), (t_6, t_7), night load (t_7, t_1). The additional point t_4 (changes from 16.00 in summer to 14.30 in winter) corresponds to the transition to a decrease in PV generation in the pre-evening. The $P_L(t)$ schedule corresponds to the maximum average value of P_L over time intervals.

To determine P_{PV} we use a procedure from [3]. The $P_L(t)$ schedule is recalculated to the base values, provided that the peak power P_L=200 W. The conversion factor of the installed power of PV to the value P_{PVR}=1 kW is determined with the maximum reduction in electricity consumption from the network W_g in the case of an average value generation of PV W_{PVAV} in summer:

$$m = \frac{W_{L25} + W_{L56} / \left(\eta_B \cdot \eta_C\right)^2}{W_{PV} \cdot \eta_C}, \tag{1}$$

where W_L is the energy consumed by the load, η_B and η_C – SB efficiency and energy conversion efficiency (voltage converter at the output of PV and GI).

So, we take the value of the installed power $P_{PV}=mP_{PVR}$.

As a basis, we take control scenarios taking into account tariffs given in [8]. At two tariffs, it is appropriate [8] to use the same scenario as for three tariffs (3T) with the exclusion of consumption from the network during peak times. At one tariff, the scenario with an equalization of daily consumption 1T and a decrease in consumption during peak times 1T1. The setting of the value P_g at time intervals is determined subject to the construction of the desired $SoC(t)$ schedule.

Storage battery energy capacity $W_B=U_B\cdot C_B$ (U_B and C_B – voltage and capacity (A·h) of SB) is determined provided that the LO load is powered, excluding electricity consumption from the grid at the evening peak (t_5, t_6) according to $W_{PV56}\to 0$ (scenario 3T):

$$W_B = \frac{W_{L56}}{0.01\Delta Q_{56}^{*} \cdot \eta_C \cdot \eta_B}, \tag{2}$$

where $\Delta Q_{56}^{*} = \left(\Delta Q_6^{*} - \Delta Q_5^{*}\right)$ is the degree of storage battery discharge on the interval (t_5, t_6), $Q^*=Q/Q_R$ – degree of SB charge, Q_R corresponds to 100 % of the storage battery charge according to capacity C_B.

We take the duration of the evening peak (winter and autumn) to 4 hours and $\Delta Q_{56}^{*} \le 80\,\%$ (when using a LIFEPO4 storage battery, we limit DOD≤80 %). The maximum value of Q^* for scenario 3T corresponds to $\Delta Q_4^{*} \to 100\,\%$. We take the final value of W_B with a margin of 5 %, which takes into account the SB discharge on the interval (t_4, t_5).

Maintaining a given value of P_g is achieved according to the value of the amplitude of the current I_{gm}^{1}, which is the task for the current regulation circuit of the grid inverter [12]. With a power factor close to 1 the value $P_g = U \cdot I_{gm} / \sqrt{2}$ (single-phase version) or $P_g = 3U_\Phi \cdot I_{gm} / \sqrt{2}$ (three-phase version, U_Φ – phase voltage of the network). In terms of time intervals, we have:

– interval (t_2, t_3). Given $P_{gR23}\left(I_{gm}^{1}\right)$, PV operates under a maximum power mode (MRRT) $P_{PV}=P_{PVM}$. The SB current I_B is set by the voltage controller VC I_B, which keeps the voltage U_d at the input of the inverter constant while maintaining the power balance in the system. Given this:

$$I_B = \frac{{}_{PV} \cdot \eta_C + P_g - P_L}{U_B};$$

– interval (t_3, t_5). Given by $P_{gR35}\left(I_{gm}^{1}\right)$, $P_{PV}=P_{PVM}$ (MPPT). The SB current I_B is set by VC I_B. Upon reaching $Q^* \ge Q_d^*$ (Q_d^* corresponds to the transition to the storage battery charge according to U_B=const), the current I_B decreases and becomes uncontrolled VC I_B. This leads to an imbalance of power – the storage battery is not able to accept excess energy of PV. The controllers are switched and the controller VC I_{PV} works, which regulates the power of PV $P_{PV}\cdot\eta_C=P_L+P_B-P_g$. With this, the current I_B is determined by the characteristic of the storage battery. With a decrease in P_{PV}, the reverse – switching of controllers is carried out. According to $Q^* \ge Q_d^*$ and $P_L\approx P_g$, a possible situation is when $P_{PVM}\cdot\eta_C>(P_B+P_C)$ and $P_{PVM}\cdot\eta_C>P_L$. According to $P_C\to 0$, regulation P_{PV} will lead to incomplete use of the energy of PV with consumption $P_L\approx P_g$. In this case, it is advisable to use PHI_g, which will reduce $P_{gR}=P_g$ when the PV works at P_{PVM}. To exclude the situation when $P_C=(P_L-P_g)<0$, the measurement P_L is used and, under the condition $P_C<0$, $P_{gR}=P_g=P_L$ is set;

– interval (t_5, t_6). During evening peak hours, the power issued by the inverter is $P_{C56}=P_{L56}-P_{g56}$. With this, the discharge current $I_{B56}=P_{C56}/U_{BAV}$.

In the case of full compensation of consumption from the network ($W_{g56}=P_{g56}\cdot t=0$) $P_{C56}=P_L$ and $I_{B56}=P_L/U_B$. Storage battery discharge is carried out until reaching Q_6^*;

– interval (t_6, t_2). When using the night SB charge from the grid to the value Q_{2R}^* according to the forecast of PV generation the next day:

$$I_{B62R} = \frac{0.01C_B\left(Q_{2R}^{*} - Q_6^{*}\right)}{\left(t_2 - t_6\right)}. \tag{3}$$

In the period spring – summer, the generation of PV is possible before the beginning of the morning peak. In this case, the system has certain features: PV operates under MRRT mode; the storage battery charge current value is set by I_{B62R}; the current controller of the grid I_g sets the power consumed from the network P_g. SB current value:

$$I_{BPV} = \begin{cases} \dfrac{P_{PVM} \cdot \eta_C - P_L}{U_B}, \text{ if } P_{PVM} \cdot \eta_C > \left(P_L + P_B\right), \\ I_{B62R}, \text{ if } P_{PVM} \cdot \eta_C \le \left(P_L + P_B\right). \end{cases} \tag{4}$$

In this case, if the generation power of PV is $P_{PVM}\cdot\eta_C\ge$ $\ge(P_L+P_B)$, P_g=0 is set, and the SB current is set by the controller.

5. 2. Formalization of the description of energy processes in the photovoltaic system

The time is set by variables t_{23}, t_{34}, t_{45}, t_{56}, t_{62}, taking values 1 at appropriate time intervals. Auxiliary variables are also used:

$$q = \begin{cases} 1, \text{ if } Q^* \ge Q_d^*, \\ 0, \text{ if } Q^* < Q_d^*, \end{cases}$$

$$pv = \begin{cases} 1, \text{ if } P_{PVM} \cdot \eta_C \ge P_L, \\ 0, \text{ if } P_{PVM} \cdot \eta_C < P_L, \end{cases}$$

$$n = \begin{cases} 1, \text{if } P_{PVM} \cdot \eta_C \ge \left(P_L + P_B\right), \\ 0, \text{if } P_{PVM} \cdot \eta_C < \left(P_L + P_B\right), \end{cases} \tag{5}$$

$$b = \begin{cases} 1, \text{if } P_{PVM} \cdot \eta_C \ge \left(P_C + P_B\right), \\ 0, \text{if } P_{PVM} \cdot \eta_C < \left(P_C + P_B\right), \end{cases}$$

$$c = \begin{cases} 1, \text{if } P_C \ge 0, \\ 0, \text{if } P_C < 0. \end{cases}$$

Current generation of PV taking into account regulation:

$$P_{PV}\cdot\eta_C = P_{PVM}\cdot\eta_C\cdot\left(\bar{q}\vee\overline{pv}\vee q\wedge pv\wedge b\right)+ \\ +\left(P_C+P_B\right)q\cdot pv\cdot t_{26}\cdot\bar{b}, \quad (6)$$

where $P_B=U_BI_B$.

SB current:

$$I_B = I_{B62}+\left(\bar{q}\vee q\wedge\overline{pv}\right)\cdot t_{25}\cdot\frac{P_{PV}\cdot\eta_C-P_C}{U_B}+ \\ +\frac{P_{PVM}\cdot\eta_C-P_C}{U_B}\cdot q\cdot pv\cdot t_{25}-t_{56}\frac{P_{C56}}{U_B}, \quad (7)$$

where $I_{B62}=I_{B62R}\cdot t_{62}\cdot\bar{n}+t_{62}\cdot I_{BPV}\cdot n.$

The value of the power given by the inverter:

$$P_C=\left(P_L\cdot t_{62}+\left(P_L-P_{gR}\right)\cdot t_{25}+P_{C56}\cdot t_{56}\right)c, \quad (8)$$

where $P_{gR}\le P_L(t)$ is the variable that sets the power value:

$$P_{gR}=P_{gR}\cdot c\left(\overline{q\wedge pv\wedge b}\right)+ \\ +\left(P_L+P_B-P_{PVM}\cdot\eta_C\right)q\cdot pv\cdot b+P_L\cdot\bar{c}. \quad (9)$$

Power consumed from the network:

$$P_g=\left(P_L-P_C\right)\cdot t_{56}+\left(P_L+P_B-P_{PVM}\cdot\eta_C\right)\cdot t_{62}+P_{gR}\cdot t_{25}. \quad (10)$$

The evaluation module determines the value of the coefficient of reduction of costs for electricity consumed by LO b_E (b_{E1}, b_{E2}, b_{E3} are the values, respectively, for one, two, three rates):

$$b_E=\frac{C_L}{C_g},$$

where C_L and C_g is the cost of electricity consumed, respectively, by the load of LO and from the network:

$$C_L=T_n\cdot 0.001\int\left(P_L\cdot t_{62}\right)\cdot dt+ \\ +T_d\cdot 0.001\int\left(P_L\cdot t_{25}\right)\cdot dt+T_P\cdot 0.001\int\left(P_L\cdot\left(t_{23}+t_{56}\right)\right)\cdot dt,$$

$$C_g=T_n\cdot 0.001\int\left(P_g\cdot t_{62}\right)\cdot dt+ \\ +T_d\cdot 0.001\int\left(P_g\cdot t_{25}\right)\cdot dt+T_P\cdot 0.001\int\left(P_g\cdot\left(t_{23}+t_{56}\right)\right)\cdot dt,$$

where T_n, T_d, T_P – relative values of tariff rates (at one rate $T_n=T_d=T_P=1$, at two $T_d=T_P=1$, $T_n=0.5$, at three $T_d=1$, $T_P=1.5$, $T_n=0.4$).

The energy utilization factor of PV is defined as the ratio of the total energy of PV taking into account the regulation W_{PV} to the value under the maximum power mode $k_{PV}=W_{PV}/W_{PVM}$.

The SB model is performed according to catalog data, charging ($U_{Brch}(t)$) at different values of the discharge current $I_{Brch}=(0.1, ..., 2)$ C_B and charging ($U_{Bch}(Q^*)$ and $I_{Bch}(Q^*)$) $I_{Bch}(Q^*)$) characteristics that are specified graphically [23]. The use of LIFEPO4 SB with a voltage of 12.8 V and $C_B=32, ..., 150$ Ah is considered [23], whose internal resistance $R_{int}\le 40, ..., 25$ mΩ, for which the charge/discharge characteristics are identical.

To describe the discharge characteristic at constant value I_{Brch} we used expression from work [20], which is reduced to the form:

$$U_{Brch}=E_0-\frac{K\cdot Q_R^*}{Q_R^*-\Delta Q^*}\Delta Q^*+A\cdot\exp\left(-B\cdot\Delta Q^*\right), \quad (11)$$

where E_0 is the constant voltage of SB (V); K – coefficient proportional to the polarization voltage, A – voltage drop in the exponential zone (V); B – inverse of capacitance at the end of the exponential zone $(A\cdot h)^{-1}$, Q_R corresponds to the nominal capacitance C_B (Ahour), $\Delta Q^*=I_{Brch}\cdot t_{rch}=100-Q^*$ (Q^* – current value).

Q^* value considering initial value Q_0^*:

$$Q^*=\left(Q_0^*+\int I_B dt\right)/C_B. \quad (12)$$

The procedure for determining parameters used in (11) according to $U_{Brch}(t)$ is given in [20], in particular it concerns K. The value of K practically does not depend on the discharge current of the storage battery. But the values of A and B vary significantly. The corresponding dependences $A=f(I)$ and $B=f(I)$ for two current variation intervals $I_B\le 0.5C_B$ and $I_B>0.5C_B$ are obtained:

$$A=\begin{cases}1.394I_{Brch}+0.587, \text{ if } I_{Brch}\le 0.5C_B,\\ 0.42I^2_{Brch}+0.45I_{Brch}+1.4, \text{ if } 0.5C_B<I_{Brch}\le 2C_B,\end{cases} \quad (13)$$

$$B=\begin{cases}13.75I^2_{Brch}-10.125I_{Brch}+1.875, \text{ if } I_{Brch}\le 0.5C_B,\\ -0.03I_{Brch}+0.26, \text{ if } 0.5C_B<I_{Brch}\le 2C_B.\end{cases} \quad (14)$$

The charging characteristics have two sections: a charge with direct current at $Q^*=\left(0,...,Q_d^*\right)$, when the current can be any within the maximum value (limit to the value C_B) and a charge with a constant voltage at $Q^*\ge Q_d^*$.

The charging characteristic $I_{Bch}(Q^*)$ is given by limiting the charge current value from above:

$$\lim I_{Bch}=\begin{cases}f\left(Q^*\right), \text{ if } Q^*\ge Q_d^*,\\ \le C_B, \text{ if } Q^*<Q_d^*,\end{cases} \quad (15)$$

where $f(Q^*)$ is the dependence given in tabular form according to schedule in [23] for the interval $\left(Q_d^*, 100\,\%\right)$.

The dependence $U_{BCh}=f(Q^*)$ is also specified for two intervals. For $UQ^*\ge Q_d^*$ U_{BCh}=const=14.6. For $Q^*=0,...,Q_d^*$ the manufacturer sets two characteristics at the initial charge stage $Q_0=0$ % and $Q_0=40$ % at the charge current $I_{Bch}=0.5C$. The characteristic has an initial section when the starting point is determined by the discharge curve with the subsequent exit to the linear section, then to the exponential section. The corresponding dependence can be expressed as:

$$U_{Bch}=U_R+K_C\frac{Q_R^*}{Q_R^*+Q^*}Q^*+A_Ce^{-B_C\left(Q_d^*-Q^*\right)}, \quad (16)$$

where the $U_R<U_{BQGIN}$, A_C and B_C values determine the exponential zone of discharge, U_{BQGIN} corresponds to the minimum degree of discharge Q_{GIN}.

The calculation is carried out according to the charge curve at $Q_0^*=0\,\%$. Thus, for $Q_{MIN}^*=10\,\%$ (DOD=90 %), U_{BQGIN}=13 V. For U_R=12.8, the value K_C=0.024, A_C=0.7, B_C=0.5. For comparison, in the case of a discharge characteristic at $I_{Bc}=0.5C_B\cdot K=0.15$, $A=1.275$, $B=0.25$.

Expression (16) corresponds to the current $I_{Bch}=0.5C_B$. In general:

$$U_{Bch} = U_R + K_C \frac{Q_R^*}{Q_R^* + Q^*} Q^* + + A_C e^{-B_C\left(Q_d^* - Q^*\right)} + R_{int}\left(I_{Bch} - 0.5C\right), \qquad (17)$$

where R_{int} is the internal resistance of SB.

Expression (17) takes into account the change in the voltage drop by R_{int} during SB charging depending on the current.

5. 3. Construction of the structure for a photovoltaic system model

The general structure of the model (Fig. 1) is composed of the following modules: generation (GM), load (LM), SB (SBB), control and calculation (CCM), evaluation (EM). This part of the model is unchanged. The task calculation module (TCM), which operates on an accelerated time scale, is separated. The load power $P_L(t)$ is set tabularly. In GM, archival data is set to $P_{PVM}(t)$. The control and calculation module is made according to (3) to (10).

The structure of SB model, built according to (11) to (17), is shown in Fig. 2.

TCM calculates the parameters according to the forecast for the current day. According to the initial data $P_L(t)$, $mP_{PVM}(t)$ (according to archival data) and Q_6^* the calculation of $Q_{2R}^*(t)$, $P_{gR}(t)$, I_{B62}, is carried out, Q_{00}^* is the degree of storage battery charge at 00.00 (beginning of the day) for all scenarios. To exclude the reconfiguration of tariff zones, 3 models are provided for summer, spring-autumn, and winter seasons. According to this, the simulation is carried out in two stages for preliminary (accelerated) calculation of parameters, continuation of calculation in the daily cycle. The introduction of TCM makes it possible to simulate the operation of the PVS control system and provides for the possibility of developing a control algorithm without changing the main part of the model.

The calculation of control parameters in TCM is carried out according to the algorithm in Fig. 3. The corresponding functions of the blocks are given below.

Block 2. The value of the PV energy and load at given time intervals is determined, for example, for (t_2, t_3) as:

$$W_{PV23} = \int \left(P_{PVM} \cdot t_{23}\right) \cdot \mathrm{d}t, \; W_{L23} = \int \left(P_L \cdot t_{23}\right) \cdot \mathrm{d}t.$$

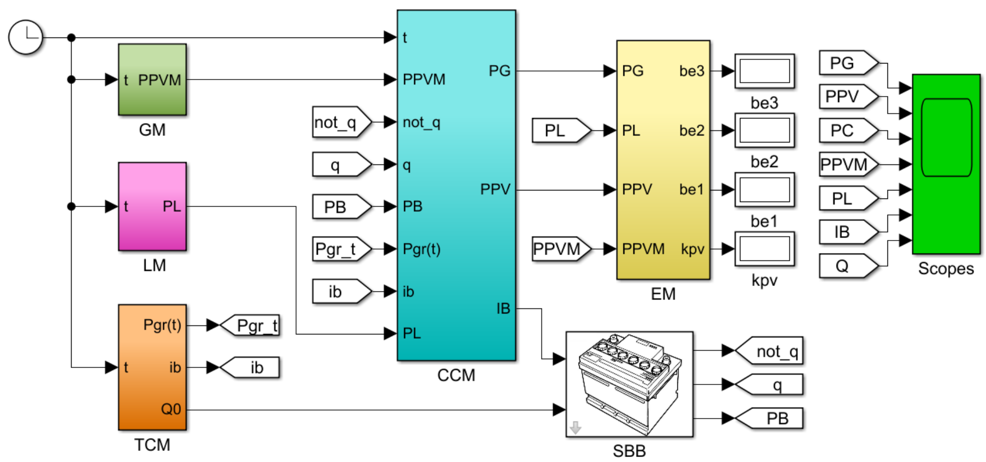

Fig. 1. General structure of the model

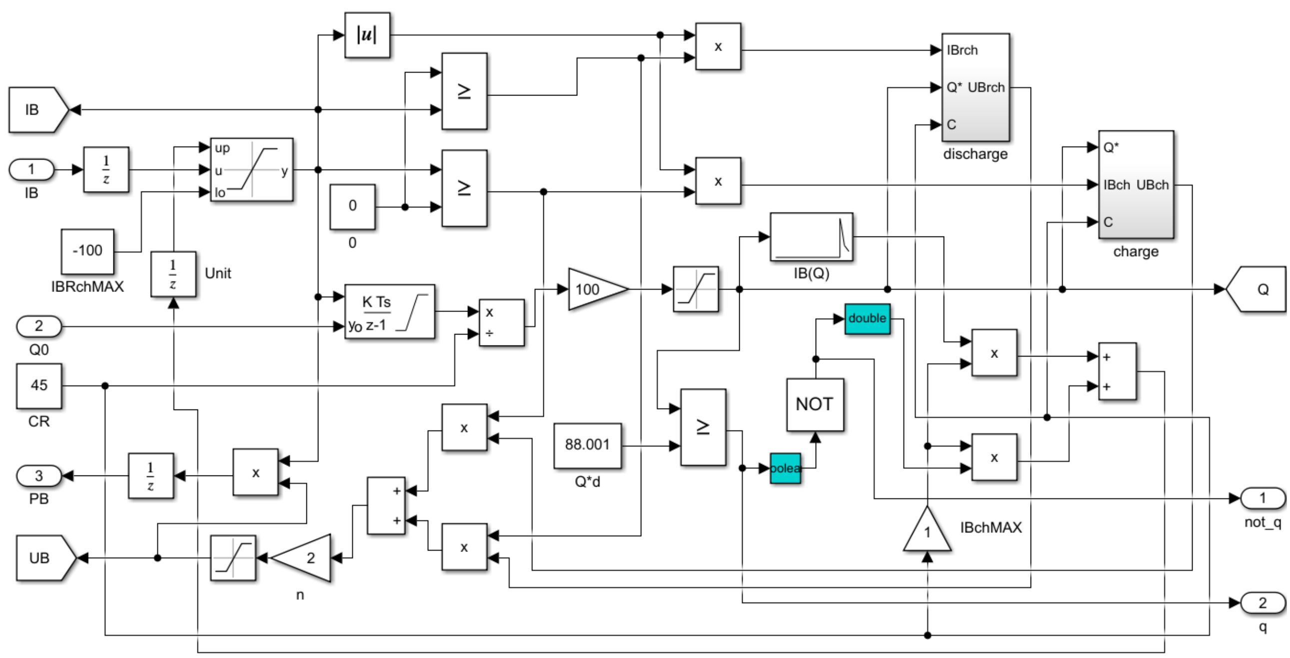

Fig. 2. Storage battery model structure

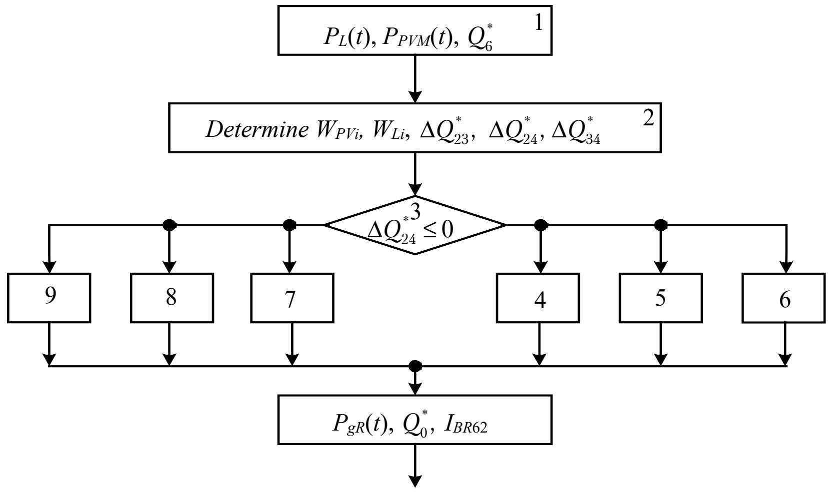

Fig. 3. Algorithm for calculating control parameters

For other intervals, the calculation is performed similarly. ΔQ_{24}^* on the interval (t_2, t_4):

$$\Delta Q_{24}^* = \frac{W_{PV24} \cdot \eta_C - W_{L24}}{0.01 W_B \eta_C \eta_B}.$$

Block 4 corresponds to the implementation of scenario 3T. If $\Delta Q_{24}^* \leq 0$ you set the value:

$\Delta Q_{2R}^* = 100\,\%$, $P_{g23} = P_{g56} = 0$, $P_{C56} = P_{L56}$,

$$P_{g34} = \frac{\Delta W_{B34} + W_{L34} - W_{PV34} \cdot \eta_C}{(t_4 - t_3)},$$

$$P_{g34} = \frac{\left|W_{PV23} \cdot \eta_C - W_{L23}\right| / (\eta_C \cdot \eta_B)^2 + W_{L34} - W_{PV34} \cdot \eta_C}{(t_4 - t_3)},$$

where $\Delta W_{B34} = 0.01 \Delta Q_{34}^* W_B / \eta_C \eta_B$ is the energy consumed to charge SB,

$$\Delta Q_{34}^* = \left|\Delta Q_{23}^*\right|, \quad \Delta Q_{23}^* = \frac{W_{PV23} \cdot \eta_C - W_{L23}}{0.01 W_B \eta_C \eta_B}.$$

At $\Delta Q_{24}^* = 0$ value $P_{g34} = 0$.
Value P_{g45}:

$$P_{g45} = \frac{W_{L45} - W_{PV45} \cdot \eta_C - \Delta W_{B45}}{(t_5 - t_4)} \geq 0,$$

where $\Delta W_{B45} = 0.01 \Delta Q_{45}^* W_B \cdot \eta_C \cdot \eta_B = 0$ is the energy that can SB give at $\Delta Q_{45}^* = (Q_5^* - 100)$.

The ΔQ_5^* value in the case of $Q_6^* = Q_{MIN}^* = 20\,\%$ in summer is $Q_5^* \geq 77\%$, in winter $Q_5^* \geq 96\,\%$ according to the duration of the evening peak three hours in summer $(\Delta Q_{56}^* = 60 / 1.05 = 57.1\%)$ and 4 hours in winter and in the spring-autumn period $(\Delta Q_{56}^* = 80 / 1.05 = 76.2\,\%)$.

The value of the SB charge current I_{B62R} is determined according to (3). Value Q_0^* at the beginning of calculation (days) $Q_{00}^* = Q_6^* + I_{B62R}(24 - t_6)$.

Block 5 corresponds to the implementation of scenario 1T1 with equalization of consumption at the interval (t_2, t_5) and maintaining consumption in the evening peak at a given level P_{g56}^1. The energy that the storage battery gives off in the evening peak, taking into account P_{g56}^1 is $\Delta W_{B56} = W_{L56} - W_{g56}^1$, respectively,

$$\Delta Q_{56}^* = \frac{\Delta W_{B56}}{0.01 W_B \cdot \eta_C \cdot \eta_B}.$$

Values $Q_5^* = (Q_6^* + \Delta Q_{56}^*) \leq 96\,\%$, $Q_{2R}^* = Q_6^* = (96 - \Delta Q_{56}^*)$. Energy for SB charge during day $\Delta W_{B25} = \Delta W_{B56}/(\eta_C \cdot \eta_B)^2$. The value P_{g25}:

$$P_{g25} = \frac{W_{L25} + (W_{L56} - W_{g56}^1) / (\eta_C \cdot \eta_B)^2 - W_{PV25} \cdot \eta_C}{(t_5 - t_2)}.$$

The value of the SB charge current $I_{B62R} = 0$. Value $Q_{00}^* = Q_6^*$. In general, the Q_6^* value is determined at the beginning of the evening peak according to the forecast for the next day $Q_6^* = Q_{2R+1}^*$. With this, it may be less than Q_{2R}^*, which will lead to an additional discharge of SB in the interval (t_5, t_6) with a decrease in consumption.

Block 6 corresponds to the implementation of scenario 1T. With this, we have equalization of consumption from the network during the daytime. This scenario can be considered as 1T1 at $P_{g56}^1 = P_{g25}$. The calculation is carried out similarly. P_g value:

$$P_{g26} = \frac{W_{L25} + W_{L56} / (\eta_C \cdot \eta_B)^2 - W_{PV26} \cdot \eta_C}{(t_5 - t_2) + (t_6 - t_5) / (\eta_C \cdot \eta_B)^2}.$$

Value $Q_{2R}^* = Q_6^* = 95 - \Delta Q_{56}^*$:

$$\Delta Q_{56}^* = \frac{W_{L56} - P_{g56} \cdot (t_6 - t_5)}{0.01 W_B \cdot \eta_C \cdot \eta_B}.$$

The value of the SB charge current $I_{B62R} = 0$. Value $Q_{00}^* = Q_6^*$.

Block 7 corresponds to the implementation of scenario 3T at $\Delta Q_{24}^* > 0$, $P_{g34} = 0$, and the Q_{2R}^* value should be reduced according to the condition $Q_{2R}^* = (100 - \Delta Q_{24}^*) \geq (Q_{MIN}^* + \Delta Q_{23}^*)$ (Q_{MIN}^* – minimum degree of charge, 20 %). The P_{g45} value is calculated.

Block 8 corresponds to the implementation of scenario 1T1. The energy that the storage battery gives off in the evening peak, taking into account $\Delta Q_{24}^* > 0$, $\Delta W_{B56}^1 = 0.01(\Delta Q_{56}^* + \Delta Q_{24}^*) W_B \cdot \eta_C \cdot \eta_B$, at this value ΔQ_{56}^* and ΔW_{B56} corresponds to a given limit P_{g56}^1 (block 5). Value $Q_{2R}^* = Q_6^* = (100 - \Delta Q_{56}^* - \Delta Q_{24}^*)$. The energy for SB charge during the day remains unchanged $\Delta W_{B25} = \Delta W_{B56}/\eta_C \cdot \eta_B$.

Value P_g:

$$P_{g25} = \frac{W_{L25} + \Delta W_{56} / \eta_C \cdot \eta_B - W_{PV25} \cdot \eta_C}{(t_5 - t_2)},$$

$$P_{g56} = \frac{W_{L56} - \Delta W^1{}_{56}}{(t_6 - t_5)}.$$

Block 9 corresponds to the implementation of scenario 1T. The calculation is similar to block 6.

The parameters are calculated at the beginning of modeling on an accelerated time scale ($t \cdot 10000$) relative to the main daily cycle ($t \cdot 100$). Value $P_{gR}(t) = P_{g23} \cdot t_{23} + P_{g34} \cdot t_{34} + P_{g45} \cdot t_{45} + P_{g56} \cdot t_{56}$.

5. 4. Simulation results of energy processes in the photovoltaic system

The modeling of PVS with the setting of generating PV at P_{PVR}=1 kW according to archival data is considered [4]. The load schedule with the maximum average load values relative to the peak load ($P_L = P_{LIM}$=200 W) is adopted: P_{L23}=0.95, P_{L34}=0.75, P_{L451}=0.6, P_{L452}=0.8, P_{L56}=1, summer P_{L71}=0.2, P_{L12}=0.4, P_{L67}=0.4, winter P_{L62}=0.3. At the interval (t_4, t_5), an additional degree is introduced one hour before the evening peak P_{L452}. The operation of PVS without generation in DG under different weather conditions at W_B=1152 Wh is considered.

Fig. 4, *a* shows the waveforms of work at the accepted schedule $P_L(t)$ for scenario 3T at values b_{E3}=2.174, b_{E2}=1.673, b_{E1}=1.312, k_{PV}=0.999. Daily generation at P_{PVR}=1 kW is W_{PV}=1416 W·h, m=0.6. In the case of changing $P_L(t)$ at intervals within the average value for the same generation of PV (Fig. 4, *b*) b_{E3}=2.213, b_{E2}=1.701, b_{E1}=1.329, k_{PV}=1. Consequently, the indicators have not changed much – in this case, for b_E we have an improvement of 1.3–1.8 %. The dependence $Q^*(t)$ corresponds to that accepted for the calculation and also practically did not change.

We have similar results for other scenarios. Fig. 4 shows the waveforms for scenario 1T at b_{E3}=1.194, b_{E2}=1.156, b_{E1}=1.146, k_{PV}=1 (Fig. 4, *c*) and with load change b_{E1}=1.207, b_{E2}=1.17, b_{E3}=1.161, k_{PV}=1 (Fig. 4, *d*).

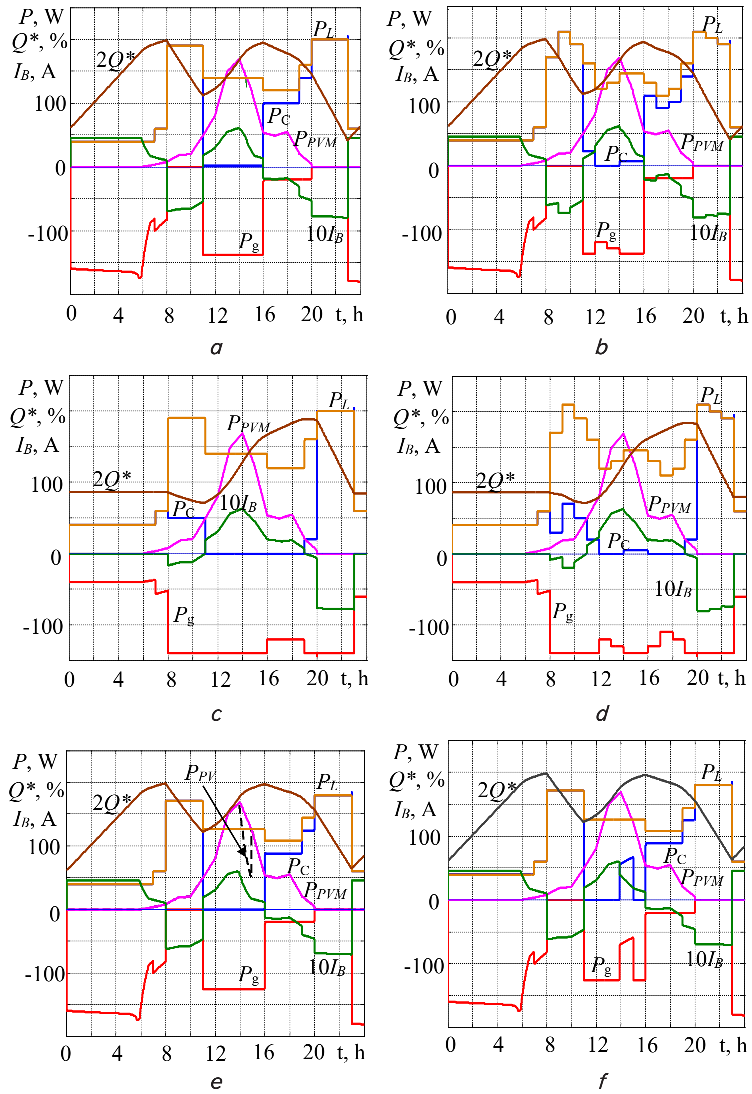

Fig. 4. Oscillograms P_{PVM}, P_{PV}, P_L, P_g, P_C, I_B: *a* – scenario 3T at accepted $P_L(t)$; *b* – scenario 3T $P_L(t)$ with maintaining the average value at intervals; *c* – scenario 1T at accepted $P_L(t)$; *d* – scenario 1T $P_L(t)$ changes while maintaining the average value at intervals; *e* – scenario 3T $P_L(t)$ – 0.9 of the accepted value; *f* – scenario 3T $P_L(t)$ – 0.9 of the accepted value in case of changing the algorithm

Regarding the choice of the PV power value, modeling is advisable for the conditions of average monthly generation. The values of b_E and k_{PV} for scenario 3T at different values of m are shown in Table 1 with the same schedule of $P_L(t)$ and $P_{PVM}(t)$ for the day of June with a generation close to the monthly average (W_{PV}=4416 W·h). The value m=0.6 corresponds to the calculation using (1). Overestimation of P_{PV} by 16.7 % (0.7/0.6) leads to an increase in b_E by only 1.4–2.5 % with a decrease in k_{PV} by 13.7 %. At the same time, a decrease in P_{PV} by only 9.09 % (0.6/0.55) improves k_{PV} by 1.4 %, while a decrease in b_E by a factor of 1.72–1.39.

Fig. 4, *d* shows the waveforms of work at $0.9P_L(t)$ for the same conditions as in Fig. 4, *a*, at values b_{E3}=2.054, b_{E2}=1.581, b_{E1}=1.234, k_{PV}=0.938. Consequently, we have a deterioration in the use of PV and a decrease in b_E. In the case of changing the algorithm with regulation P_{g34} (Fig. 4, *e*) under the same conditions we have b_{E3}=2.156, b_{E2}=1.654, b_{E1}=1.275, k_{PV}=1. So, we have an increase in k_{PV} by 6.6 %, and b_E by 3.3–5 %.

Table 1

System performance at different values of m

m	P_{g34}, W	b_{E3}	b_{E2}	b_{E1}	k_{PV}
0.55	30	8.77	6.71	5.141	0.987
0.6	0	15.06	10.93	7.156	0.973
0.7	0	15.44	11.18	7.26	0.856

If we define P_g at 0.9 $P_L(t)$ under the same conditions of schedule construction $Q^*(t)$, we have b_{E3}=2.404, b_{E2}=1.828, b_{E1}=1.371, k_{PV}=1. Increase in load above the accepted $P_L(t)$ was not considered because $P_L(t)$ corresponds to the maximum value. We have a similar picture in the case of PV generation above the forecast. In the case of generation of PV below the forecast at the accepted $P_L(t)$, the construction of $Q^*(t)$ is not provided and the Q^*_4 value is less than the required one. This leads to an increase in P_{g56} since the SB discharge will stop before the end of the evening peak upon reaching the value of Q^*_{6MIN}.

6. Discussion of results of improving the mathematical model of the photovoltaic system for the own needs of the local object

Improvement of the mathematical model of PVS with SB for own needs of LO with regulation of power consumed from the network is achieved through:

– ensuring compliance of the charging and discharge characteristics of the storage battery with the characteristics of the manufacturer [23]. This is achieved by determining the dependence of parameters A (13) and B (14), which characterize the exponential zone of the discharge characteristic $U_{Brch}(I_B)$ on t discharge current. When reproducing the charge characteristic $U_{Bch}(Q^*)$ and $I_B(Q^*)$, the change in charge mode at $Q^*>Q^*_d$ (15) and the internal resistance of SB (17) are taken into account;

– introducing of the task calculation module (Fig. 1), which calculates the control parameters on an accelerated time scale before the beginning of the main modeling cycle. Given this, the calculation is carried out for a certain set of scenarios (Fig. 3);

– introducing of the independent variable $P_{gR}(t)$ (9), which is specified by the module of task construction or manually, if necessary, during the programmed stop of the modeling process;

– introducing of estimation of the degree of energy use of PV k_{PV} (Fig. 1);

– clarification of expressions for power (P_{PV} (6), P_C (8), P_g (10)) and SB current (7) taking into account changes in operating modes and changes made to the control algorithm. In particular, this concerns the interval (t_3, t_5) at $Q^*\geq Q^*_d$ and $P_L\approx P_g$, when the regulation P_{PV} is excluded (Fig. 4, *d*, *e*) and excluding the situation when $P_C=(P_L-P_g)<0$;

– determination of the added power of the inverter P_{C56} during the evening peak load hours, taking into account P_{gR} ($P_{C56}=P_{L56}-P_{g56}$), which makes it possible to consider different scenarios for the operation of PVS at different tariffs for electricity consumed from the grid.

This paper is continuation of work [3], which considers PVS control with regulation of power consumed from the network, with a description of the mathematical model of energy processes. The emphasis of the current work is on the choice of PVS parameters under the condition of maximum use of PV energy with a decrease in energy consumption from the network. Control with P_g setting is considered as the possibility of equalizing $P_g(t)$ and reducing consumption, in particular during evening peak hours. The degree of PV energy use has not been assessed.

The mathematical model built provides such additional features as the estimation of PV energy use and comparison of indicators under different control scenarios. The peculiarity of the proposed model, along with clarification of the description of the system elements, is the introduction of TCM (Fig. 1), which according to the schedule of PV power and load determines the $P_{gR}(t)$ schedule. In addition, two modes are used: the calculation of parameters with acceleration of time and the main daily cycle of work. In [3], calculations of control parameters were carried out manually, which complicates the change of the scenario, the installed capacity of the PV and the energy intensity of the storage battery. Modular model structure considered in [11] also does not imply a module for task setting. TCM actually performs the function of a PVS control system. The calculation is subject to the construction of $SoC(t)$ schedule under the appropriate control scenario. This provides an opportunity to select (specify) the value of the installed capacity of PV and the energy capacity of SB for a given LO load schedule (Table 1). Certain changes relate to the algorithm for the implementation of work at values $Q^*>Q^*_d$ and the use of the measured P_L value, which contributes to the improvement of performance and ensures functioning with a decrease in P_L. Regarding the SB model compared to [3], the description of the discharge and charge characteristics has been clarified.

There are certain restrictions on the use of our study results:

– control scenarios relate to an object with the main electricity consumption in the daytime, when at night it is possible to charge the SB without exceeding the consumption limit;

– control scenarios and $SoC(t)$ schedule are tied to fixed tariff zones of payment for electricity.

The disadvantage of the considered control algorithm is the deterioration of indicators (decrease in b_{E3} and k_{PV}) in the case of deviation of the load from the accepted $P_L(t)$ schedule and generation of PV from the value according to the forecast. This is due to the fact that the construction of a given $SoC(t)$ schedule is not ensured.

At the same time, the presence of variable P_{gR}, which is a control parameter, allows for the corresponding correction of the $SoC(t)$ schedule at the deviation of the measured and specified values of *SoC*. Consequently, the further advancement of the work is to improve the PVS power control system and, accordingly, the task construction module with correction of the power consumed from the network.

7. Conclusions

1. Clarification of the model description concerns:

– the introducing of independent variable $P_{gR}(t)$, which is specified by TCM;

– the introducing of an assessment of the degree of energy use of PV with a direct determination of the energy generated and used for consumption;

– taking into account changes in operating modes;

– determining P_C during evening peak load hours, taking into account P_{gR}, which makes it possible to consider different scenarios for the operation of PVS at different tariffs for electricity consumed from the grid.

2. Improving the accuracy of reproduction of the charge characteristics ($U_{Bch}(Q)$ and $I_B(Q)$) and discharge ($U_{Brch}(I_B)$) of SB, which are provided by the manufacturer in graphical form, is achieved in the mathematical SB model by:

– taking into account the dependence of the parameters characterizing the exponential zone of the discharge characteristic $U_{Brch}(I_B)$ on discharge current;

– separate description of the charge characteristic $U_{Bch}(Q)$ and $I_B(Q)$ for charge modes with a given current and at a constant voltage.

Given this, the difference in the estimated data on the characteristics by the manufacturer does not exceed 3 %.

3. The layout of the model structure from the following modules has been substantiated: generation, load, SB, control and calculation, evaluation. This part of the model provides simulation in the daily cycle and is unchanged from the

algorithm and control scenario. The module of task construction, which calculates control parameters on an accelerated time scale before the beginning of the main simulation cycle, is separated. The calculation is carried out for a specific set of scenarios. This structure is flexible enough to change scenarios and further improve control with adjustment of the value of power consumed from the network.

4. The simulation results confirm:

– correctness of determination of control parameters regarding the construction of a given $Q(t)$ schedule under accepted control scenarios for different conditions and load schedules. In this case, the average power value at time intervals is decisive;

– the possibility of selecting (specifying) the value of the installed capacity of PV P_{PVR}. Thus, in the specific case, for the adopted $P_L(t)$ schedule, the correctness of choosing the value of the conversion factor $m=0.6$ is confirmed. Overestimation of P_{PV} by 16.7 % (0.7/0.6) leads to an increase in b_E by only 1.4–2.5 % with a decrease in k_{PV} by 13.7 %. At the same time, a decrease in P_{PV} by only 9.09 % (0.6/0.55) improves k_{PV} by 1.4 % with a decrease in b_E by a factor of 1.72–1.39;

– the possibility due to changes made to the algorithm for preserving (improving) indicators under real conditions, when the load is less than the accepted value, and generation differs from the forecast. Further improvement of indicators under actual conditions is possible in the case of correction of power setting, provided that the $Q(t)$ schedule is maintained.

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Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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