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Increasing the efficiency of hybrid photoelectric system equipped with a storage battery to meet the needs of local object with generation of electricity into grid

***Abstract**. The implementation of the electricity generation planned for the day ahead to the grid during peak hours based on the forecast of the generation of a photovoltaic battery is considered. The value of the energy capacity of the storage battery is substantiated with the reference of the initial degree of its charge and the limitation of the degree of discharge when the generation power in the evening peak is 37.5%, and in the morning peak up to 200% relatively to the load power. Simulation modeling showed the possibility of reducing the cost of paying for electricity consumed from the grid at one tariff rate from 1.3 times (in cloudy weather in winter) to 39 times (in summer).*

Streszczenie.** Rozważa się wprowadzenie do sieci zaplanowanej na następny dzień produkcji energii elektrycznej w godzinach szczytu na podstawie prognozy produkcji baterii fotowoltaicznej. Wartość pojemności energetycznej akumulatora uzasadniono odniesieniem do początkowego stopnia jego naładowania i ograniczenia stopnia rozładowania, gdy moc wytwarzania w szczycie wieczornym wynosi 37,5%, a w szczycie porannym do 200 % w stosunku do mocy obciążenia. Modelowanie symulacyjne wykazało możliwość obniżenia kosztów płacenia za energię elektryczną pobieraną z sieci przy jednej stawce taryfowej od 1,3-krotności (przy pochmurnej pogodzie zimą) do 39-krotnej (latem).* (Zwiększenie sprawności hybrydowego systemu fotoelektrycznego wyposażonego w akumulator na potrzeby lokalnego obiektu z wytworzeniem energii elektrycznej do sieci***)

Keywords: forecast of photovoltaic battery generation, setting the state of charge of the storage battery, reducing the cost of paying for electricity, simulation of energy processes in the daily cycle.
Słowa kluczowe. System fotowoltaiczny, magazynowanie energii

Introduction

"Small" energy at the level of local objects (LO) – small business facilities, household sector with distributed generation plays an important and growing role in the global production of electricity. Basically, these are hybrid photoelectric systems (PES) with connection to a distribution grid (DG). Moreover, recently, PES with energy storage systems have become widespread, which is aimed at solving the problem of the energy balance ensuring, since the time of the highest generation of electricity by PES does not coincide with the maximum of consumption. In this case, the following approaches are promising:

- to consume the energy generated by photovoltaic batteries (PV) for the LO's own needs [1, 2]. In this case, the storage battery (SB) ensures the redistribution of energy in time. With multi-zone tariffication of payment for electricity consumed from the DG, there is a possibility of redistribution between zones with different tariffs to reduce payment;
- the generation of surplus electricity planned for the day ahead to the DG during the hours of maximum (peak) consumption, along with the provision of the LO's own needs. This will help to ensure the balance of electricity in the power system and economic benefit to the consumers.

In PES with SB the „hybrid" inverters are used with connection to the grid, which are produced by many manufacturers, for example, ABB [3] at a power of up to 10 kVA with the possibility of combining three single-phase into a three-phase system 3 * 10 kVA. Inverters contain a set of equipment for PV and SB connecting. They have extensive control capabilities using operation priorities (from the grid, sun, SB) and control parameters via the Internet. Possibilities of energy management and redistribution according to the forecast and multi-zone tariffication are not used.

In [4], a PES with a SB with a "multi-converter" is presented, which has four converters with a common DC link for: PV, SB and supercapacitor, and grid inverter. The control system uses a proportional-integral (PI) voltage regulator in the DC link, which sets the SB and supercapacitor currents. The set of the maximum power of the PV is provided by the MPPT controller, but power regulation is not provided. The use "multi-converter" as a distributed energy unit in a collective system under the control of a centralized "smart" energy management system is considered.

A similar structure for PES with SB is given in [5]. The problem with combining several PES into an autonomous system is being solved when the grid is disconnected. The task of energy management is not considered.

In [6], the dispatching of energy in hybrid PES with a SB system is considered. The problem of determining the optimal time for switching between SB, PV and DG based on the data on the history of LO consumption is solved. The amount of storage energy that is introduced during peak demand is optimized. The generation of excess energy to the DG is provided. SB charging from the grid is not provided.

Multifunctional inverters [7-11] have great opportunities for use in PES of LO, which also provide a power factor close to unity at the common point of connection to the grid. In this case, the use of SB is not considered. In [12], an option is considered with the use of SB and regulation of the PV generation power. At the same time, the limitation of the electricity generation to the grid is considered. The control of the degree of SB charge in the daily cycle of operation and the planning of generation to the grid is not provided.

The issues of increasing the efficiency of PES for LO are associated with the use of the prediction of the PV generation [13]. This makes it possible to plan the load, use various scenarios for the operation of the PES. Possibilities for forecasting the PV generation are provided by various web services, for example, [14]. In [15], an open web service is presented that provides consumers with access to forecasts for their location.

In [16], an energy management system for an autonomous microgrid with a PES and SB is presented. A predictive approach is used to set operation schedules. The goal is to minimize downtime in the microgrid, in particular through proactive load shedding. The system is not connected to a DG.

In [17], a simulation of a hybrid energy storage system for photovoltaic micro-grid systems connected to a grid of residential buildings is presented. The dynamic models of the SB and supercapacitor in Matlab are presented and the smoothing of load power fluctuations is investigated. There is no research on the management and redistribution of energy in the system.

In [18], PES with SB is considered to meet the own needs of a LO with multi-zone tariffication of payment for electricity consumed from the DG. The load scenario is set based on the forecast of PV generation. Simulation in the daily cycle of the object with an estimation of the cost of electricity consumed from the DG is used. Power generation to the DG is not considered. The load depends on the season and weather.

In [19], as applied to PES with SB to meet the LO's own needs, the use of the predicted SB charge degree according to the prediction of the PV generation to reduce energy consumption from the DG is considered. Power generation to the DG is not considered.

Thus, the issues of ensuring the planned for the day ahead uniform in time generation of electricity to the DG during peak hours (with the exclusion of generation at other times) require the additional study. At the same time, it is necessary to ensure the maximum reduction in the cost of paying for electricity consumed from the DG under condition that the power consumed by the load does not depend on weather conditions and the season of the year.

The aim and objectives of the study

The aim of this work is improving the management of the generation and redistribution of energy of PES with SB using a forecast to reduce the payment for electricity from the DG while meeting the needs of the LO and with the possibility of uniform generation to the DG during peak hours.

To accomplish the aim the following tasks have been set:

- to study the possibilities of implementing electricity generation to the DG during peak hours, along with ensuring the load of the LO. Generation is planned one day ahead in accordance with the forecast;
- to substantiate the parameters of the system and determine the dependencies for controlling the SB charge in accordance with the forecast of the PV generation;
- to formulate the principles of control of the PES converter unit;
- to carry out simulation modeling of energy processes in PES with the implementation of the proposed solutions for energy management with the real nature of the change in the PV generation according to the archive data.

The structure of hybrid photoelectric system

The structure of PES contains (Fig. 1) converter unit with PV and SB, to the outputs of which the LO load and through the contactor (K) DG are connected. Converter unit (CU) has the multifunctional grid inverter VSI with output filter, voltage PV (DC/DC1) and SB (DC/DC2) converters. DC/DC1 also has a switch for the measuring short-circuit current PV (I_{SCPV}) [20]. VSI, DC/DC1, DC/DC2 are controlled by a control unit (CU). DC/DC1 provides PV operation in maximum power mode with a reference from MPPT, or with PV power control with a reference from CU. For this, switch S is used. Parameters and operating modes are set by the program control unit (PCU). The connection to the website is carried out by the WiFi module (WFM). The automatic control system is made according to the well-known principles with a variable structure [20]. The automatic control system consists of three control channels with three proportional-integral (PI) voltage controllers VC, which ensure the stabilization the voltage U_d at the VSI input and which are used depending on the operating mode. In this case, VC_{PV} forms the reference of PV current I_{PV}, VC_g – grid current i_g, VC_B – the SB current I_B. The formation of VSI current i_C provides a current loop. The current reference i^1_C is possible from different sources: VC_g,, fixed value or VC_{uL}. VC_{uL} – PI-regulator of alternating voltage of the load u_L in the autonomous mode, when PES is disconnected from DG by the contactor K.

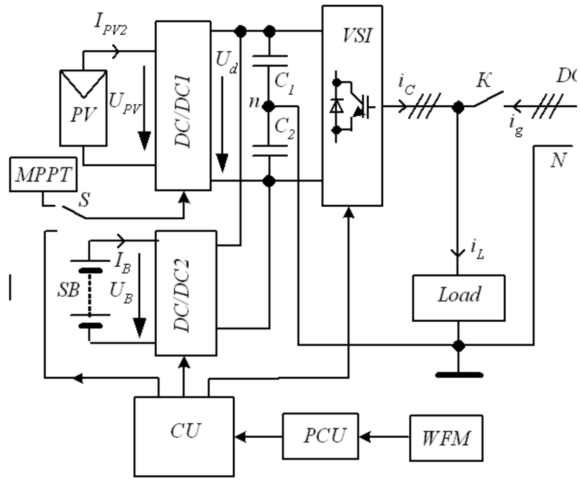

Fig.1. The structure of PES

The electricity generation to the distribution grid

Consider the possibilities of realizing PES control with load schedule in accordance with the distribution of peak tariffs with three-zone tariffication [21]. In this case, for the period late spring – summer – early autumn, we have the following intervals: day (half-peak) tariff (t_1=7.00, t_2=8.00), (t_3=11.00, t_5=20.00), (t_6=23.00, t_7=24.00); peak tariffs in the morning (t_2=8.00, t_3=11.00) and in the evening (t_5=20.00, t_6=23.00); night tariff (t_7=24.00, t_1=7.00). In the rest time of the year, zones with a reduction in the duration of daylight hours are shifted (t_2=8.00, t_3=10.00), (t_5=17.00, t_6=21.00). Let us introduce an additional point t_4=16.00 (in summer), after which, according to the archive data [22] for a clear day in July in Kyiv, the power of PV generation P_{PV} significantly decreases. In winter – t_4=14.00. Such peak load schedule is generally typical for residential consumers and facilities with a daily work schedule.

Meeting the needs of the LO along with the generation of energy to DG in peak hours is possible only due to the SB energy accumulated at night and daytime. In this case, we have two deep discharge cycles per day. It is preferable to use lithium batteries, for example, LiFePO4 [23], which, at degree of discharge DOD=50% provide 5000 discharge cycles (while maintaining a residual capacity of 80%). In this case, the life time is 5000/(365*2)=6.85 years. With DOD=80%, they provide 3000 discharge cycles and, accordingly, the life time of 4.1 years. For comparison, lead-acid deep discharge batteries of the OPzV12-100 type [24] at DOD=50% and maintaining a residual capacity of 60% provide 2500 discharge cycles (3.4 years). Due to the more complete use of energy with the same energy intensity $W_B=U_BC_B$ (U_B – SB voltage, C_B – capacity (Ah)), the lithium battery capacity is almost half as much. Accordingly, the SB charging time is reduced.

Assume that the load of LO does not depend on the season. In winter, the duration of the evening peak is 4 hours, in summer – 3 hours. With DOD = 80% in winter, the DOD value in summer is 60%. At the morning peak, take DOD=40%. Taking into account the losses in the PES energy converter (efficiency η_C) and in the SB (efficiency η_B), the energy supplied by the SB to the load is $W_{BL}=W_B\eta_C\eta_B$.

Average value of load power P_L in the evening peak is

$$P_{L56}=\frac{0.01\cdot DOD\cdot W_{BL}}{(t_6-t_5)}.$$

Energy W_{PVC}, produced by PV with rate power P_{PVR}=1kW in clear day of July for Kyiv is W_{PVC}≈6 kWh. Accordingly, the average value P_{PVAV} for day (12 hours) will be P_{PVAV}=500 W. To ensure the efficiency of PES in cloudy weather, PV power is accepted with a margin. Consider a variant with an average value of the load power $P_L=P_{L56}=(0.5\div0.6)P_{PVAV}$. At η_C=0.94, η_B=0.96 there is W_B=1551 Wh (at U_B=25.6 V, C_B value is C_B=60 Ah). The SB discharge current I_B during the evening peak hours corresponds to the standard value $I_{BR}\leq0.2C_B$.

In this case, at P_{L56}=275 W, it is possible to set the LO consumption at the level of P_{L1}=200 W. Then, generation is possible at P_{g2}=75 W, which will be P^*_{g2}=37.5% to P_{L1} ($P^*_{g2}=P_{g2}/P_{L1}$). The energy generated to DG for the morning peak is determined taking into account the total PV generation and the generation W_{PV23} during these hours. This data can be obtained from the P_{PV} forecast for the day ahead.

Restrictions associated with ensuring gentle operating conditions of the SB according to the DOD values (degree of charge to the nominal Q_R $Q^*=100Q/Q_R$, $Q=Q_S+\int I^*_B\cdot dt$, $I^*_B=I_B\eta_B$ – SB charging current and $I^*_B=I_B/\eta_B$ – SB discharging current, Q_S – initial value): for time t_2 $DOD_2\leq20\%$ ($Q^*_2\geq80\%$), for time t_3 $DOD_3\leq40\%$ ($Q^*_3\geq60\%$), for time t_6 in summer $DOD_6\leq60\%$ ($Q^*_6\geq40\%$) and in winter $DOD_6\leq80\%$ ($Q^*_6\geq20\%$).

Possibilities of reducing the consumption of electricity from DG. To reduce the cost of paying for electricity at the day rate, the SB charge is not use at the intervals (t_1, t_2) and (t_6, t_7) when connected to the DG.

Electricity consumption from grid in order to charge SB in night time

$$W_{B71}=0.01\frac{\Delta Q^*_{71}W_B}{\eta_C\eta_B}, \qquad (1)$$

where $\Delta Q^*_{71}=\Delta Q^*_{62}=Q^*_6-Q^*_2$.

Possibilities to reduce costs at night are limited to $DOD_2\leq20\%$ ($Q^*_2\geq80\%$).

The minimum energy consumption from grid for SB charging in the intervals (t_4, t_5) occurs if by the time t_4 $Q^*_4\rightarrow100\%$. This is possible if at the interval (t_3, t_4) W_{PV34} is sufficient to provide the LO load and charge the SB

$$0.01\Delta Q^*_{34}W_B\leq\eta_C\eta_B(W_{PV34}\eta_C-W_{L34}). \qquad (2)$$

With taking into account $Q^*_3\geq60\%$ – $\Delta Q^*_{34}\leq40\%$.

Value $Q^*_2=(Q^*_3+\Delta Q^*_{23})\geq80\%$, where

$$\Delta Q^*_{23}=100\frac{(t_3-t_2)(P_{L1}+P_{g1})-W_{PV23}\eta_C}{W_{BL}}. \qquad (3)$$

In (3), the same average load P_{L1} was taken as in the evening peak. Taking into account the adopted PV power margin, condition (2) is fulfilled for the total generation $W_{PV}\geq(0.5\text{-}0.6)W_{PVC}$.

When (2) is fulfilled, there are possible "gaps" in the PV generation $P_{PV}(t)$, when $P_{PV}\eta_C\leq P_L$ and the mode of operation of the PES changes with the transition to the consumption of the missing energy from the DG. In this case, in order to reduce the consumption from the grid, the SB charging current should be set I_B=0.

With the limiting value ΔQ^*_{23}=40% (Q^*_2=100%, Q^*_3=60%) and the absence of PV generation W_{PV23}=0, the SB energy in the summer in the morning peak is not enough to meet the needs of the LO without being consumed from the grid. To exclude this, the minimum value

$$W_{PV23\min}=\frac{(t_3-t_2)P_L-0.01\Delta Q^*_{23}W_{BL}}{\eta_C}.$$

With significant nighttime consumption for SB charging, small generation into the grid during the morning peak practically makes no sense. We accept the minimum value $P_{g1}=P_{g2}$, which corresponds to

$$W_{PV23\min g}=\frac{(t_3-t_2)(P_{g2}+P_L)-0.01\Delta Q^*_{23}W_{BL}}{\eta_C}.$$

For the accepted parameters – $W_{PV23ming}$=282.4 Wh. If $W_{PV23}<W_{PV23ming}$ we accept P_{g1}=0 and value Q^*_2

$$Q^*_2=Q^*_3+100\frac{(t_3-t_2)P_{L1}-W_{PV23}\eta_C}{W_{BL}}.$$

We assume that the payment for electricity consumed from the DG and payment for generation to the DG is carried out at the same tariff rate with its value equal to 1. That is, we pass to the comparison of energy. Energy consumed from the DG in the interval (t_7, t_3) $W_{73}=W_{B71}-W_{g23}$ (value W_{B71} is determined by (1), $W_{g23}=(t_3-t_2)P_{g1}$). The minimum W_{B71} value is at Q^*_2=80%. The value W_{73}=0 corresponds to $W_{g23}=W_{B71}$=687 Wh at P_{g10}=229 W and W_{PV230}=1071 Wh. In this case, the generation to the DG compensates the night consumption for the SB charge.

For simplicity, we take for the interval of values $W_{PV23ming}\leq W_{PV23}\leq W_{PV230}$ the linear law of reference $Q^*_2(W_{PV23})$ from Q^*_2=100% to Q^*_2=80%. According to the archived data for Kyiv in May-September 2015, only for five days (September), the value $W_{PV23}\leq W_{PV23min}$ and changed to $W_{PV23max}$=1400 Wh. In this case, $W_{g23}>W_{73}$, which allows to vary with the value of Q^*_2. Generation power to the grid

$$P_{g1}=\frac{W_{PV23}\eta_C-(t_3-t_2)P_L+0.01\Delta Q^*_{23}W_{BL}}{(t_3-t_2)}.$$

At the values Q^*_2=80%, Q^*_3=60% there is a power P_{g1}=332 W ($P^*_{g1}=P_{g1}/P_L$=166%). A similar result will be at Q^*_2=90%, Q^*_3=70%, while there is a positive decrease in the degree of SB discharge.

The planning of the Q^*_2 value is carried out according to the forecast for the next day, the P_{g1} value is determined from the forecast at the time t_2. Condition (2) is checked at the time t_3 taking into account the current forecast and the actual value Q^*_3.

The operation modes of system of automatic control of PES

The operation modes of system of automatic control of PES are connected to the different tariff zones in daily cycle (Table 1). Table 1 shows the ratios characterizing the operating modes and controllers used in each zone. In this case, I^1_B is the reference value of the SB current, I_B is the actual value taking into account the charging characteristic of the battery [23] $I_B(Q^*)$, which decreases with increasing Q^* and at Q^*=100%, $I_B=0.02C_B$. P_{PV} and P_{PVF} –respectively, the possible at a given time value of the maximum PV power and the actual value taking into account the regulation. On the interval (t_3 - t_5), when LO is working with the grid, an additional variable gm1 is used, which corresponds to condition (2).

In the emergency autonomous mode, when the grid is disconnected, the load voltage controller VC_{uL} is used, which sets the VSI current. The stabilization of U_d is provided by the controller VC_{PV}, which changes the I_{PV} current and regulates P_{PV}. SB current is setting $I^1_B=(P_{PVF}\eta_C - P_L)/U_B$.

Simulation of energy processes

Simulation of energy processes was carried out in Matlab in the daily cycle of operation in accordance with the archived data of PV generation with P_{PVR}=1 kW [22]. The influence of transient processes, the duration of which is short, was not taken into account. Also, only the first harmonic was taken into account, energy losses from higher harmonics are taken into account in the efficiency. Average value of the load over the work intervals: P_{71}=75 W (P^*_{71}=0.375), P_{12}=110 W (P^*_{12}=0.55), P_{23}=200 W (P^*_{23}=1), P_{34}=200 W (P^*_{34}=1), P_{45}=170 W (P^*_{45}=0.85), P_{56}=200 W (P^*_{56}=1), P_{67}=110 W (P^*_{67}=0.55). The model uses the calculated ratios given in Table 1.

To assess the reduction in the cost of paying for electricity consumed from the grid, the coefficient [19] $k_E=C_1/C_2$ is used (C_1 is the cost of electricity consumed by the load of LO, C_2 is the cost of electricity consumed from the DG). It is assumed that payment for electricity transmitted to the DG is carried out by the energy supplier at the same tariff as consumption.

When assessing the cost of electricity consumed from the DG, the use of the following was considered: a single tariff rate $T_d=T_P=T_n$=1 (T_d – daytime, T_P – peak, T_n – nighttime tariffs), k_{E1} value; two tariff rates T_n/T_d=0.5, $T_d=T_P$=1, k_{E21} value; three tariff rates T_d=1, T_n=0.4, T_P=1.5, k_{E31} value [21]. The cost of electricity consumed by the LO's load was estimated at one tariff.

The simulation results for days with different PV generation are shown in Table 2. The + sign in Table 2 means that the electricity supplier is the debtor.

Table 1. The operation modes in daily cycle

Time interval	($t_1 - t_2$), ($t_6 - t_7$)	($t_2 - t_3$), ($t_5 - t_6$)	($t_3 - t_5$)			($t_7 - t_1$)
Mode	GMd	GMg	GM0	GM		GMn
Variable	*gd*=1	*g*=1	*am*=1	*gm*=1	gm_1=1 ($t_3 - t_4$)	*gn*=1
Condition	$P_{PV}\eta_C<P_L$	$P_{PV}\eta_C+P_B\eta_C\eta_B\geq P_L$	$P_{PV}\eta_C\geq P_L$	$P_{PV}\eta_C<P_L$	$P_{PV}\eta_C<P_L$	
PV and SB powers	$P_{PVF}=P_{PV}$ $P_B=0$	$P_{PVF}=P_{PV}$ $P_B=I_B\cdot U_B$	$P_{PVF}=P_L+P_B\eta_C$ $P_B=I_B\cdot U_B$	$P_{PVF}=P_{PV}$ $P_B=I_B\cdot U_B$	$P_{PVF}=P_{PV}$ $P_B=0$	$P_{PV}=0$ $P_B=I_B\cdot U_B$
Reference of grid current (controller)	I_g (VCg)	$I_g(P_g)=const\geq0$	$I_g=const=0$	I_g (VCg)	I_g (VCg)	I_g (VCg)
Reference of PV current (controller)	I_{PV} (MPPT)	I_{PV} (MPPT)	I_{PV} (VC_{PV})	I_{PV} (MPPT)	I_{PV} (MPPT)	$I_{PV}=0$
Reference of SB current (controller)	$I^1_B=0$	$I^1_B=(P_{PV}\eta_C-(P_L+P_g))/U_B$ (VC_B)	$I^1_B=(P_{PVF}\eta_C-P_L)/U_B$	$I^1_B=0.2C_B$	$I^1_B=0$	$I^1_B=0.1C_B$
P_g	$P_g=P_{PV}\eta_C-P_L$	$P_g\geq0$	$P_g=0$	$P_g=P_{PV}\eta_C-P_B/\eta_C-P_L$	$P_g=P_{PV}\eta_C-P_L$	$-P_g=P_{Ln}+P_B/\eta_C$

Table 2. k_e values for the different tariff zones

W_{PVP}, kWh	k_{E1}	k_{E21}	k_{E31}	Q^*_2 (DOD), %	Q^*_3 (DOD), %	Q^*_7 (DOD), %	$\frac{P_{g1}}{P_L}$, %	$\frac{P_{g2}}{P_L}$, %
				July				
6	39.6	+	+	85 (15)	60 (40)	40 (60)	195	37.5
4.756	8.64	+	+	90 (10)	60 (40)	40 (60)	170	37.5
3.367	5.11	22.63	+	80 (20)	60 (40)	40 (60)	160	37.5
2.856	3.1	6.31	24.5	85 (15)	62 (38)	40 (60)	65	37.5
2.83	2.7	5.1	10.6	90 (10)	60 (40)	40 (60)	42.5	37.5
1.951	1.87	2.7	3.97	85 (15)	60 (40)	40 (60)	65	37.5
1.32	1.47	2.07	2.42	100 (0)	60 (40)	40 (60)	0	37.5
6	12.6	+	+	88 (12)	70 (30)	40 (60)	170	37.5
4.756	5.9	+	+	95 (5)	70 (30)	40 (60)	150	37.5
3.367	5.05	29.2	+	86 (14)	70 (30)	40 (60)	150	37.5
				December				
1.716	1.69	2.71	4.2	90 (10)	60 (40)	20 (80)	75	37.5
1.716	1.71	2.62	3.34	80(20)	72 (28)	20 (80)	0	37.5
1.716	1.49	2.14	2.34	80 (20)	72 (28)	42 (58)	0	0
0.75	1.3	1.9	2.54	100 (0)	60 (40)	20 (80)	70	37.5
0.75	1.31	1.86	2.12	90 (10)	70 (30)	20 (80)	0	37.5
0.75	1.18	1.6	1.73	90 (10)	70 (30)	42 (58)	0	0

In winter, at low values of W_{PV}, when k_{E1} is close to 1, for example, at W_{PV}=0.75 kWh, it may be expedient to use the option without generation to the grid (Table 2). This allows to reduce the degree of SB discharge.

The oscillograms of the daily operation cycle at W_{PV}=2.856 kWh (07.20.15) are shown in Fig. 2, a. At noon there is a "gaps" of the PV generation with switching to work with the grid. In this case, the SB charge Q^*_2=85%, Q^*_3=62%, Q^*_6=40%, P_{g1}=130 W, P_{g2}=75 W, k_{E1}=2.72, k_{E21}=4.93, k_{E31}=11.78. At the same time, the power consumed from DG to charge the SB is quite large, and the energy of the PV W_{PV} in the interval 14.00 -16.00 is also not fully used (dotted line in Fig. 2, a). The exclusion of the SB charge (Fig. 2, b) in case of a "gaps " of the PV generation allows to reduce the consumption from the DG with a more complete use of W_{PV34} energy. Under equal conditions, k_{E1}=3.1 (an increase of 13%), k_{E21}=6.31 (an increase of 27.7%), k_{E31}=24.5 (an increase of 208%). The oscillograms for a day of December are shown in Fig. 3.

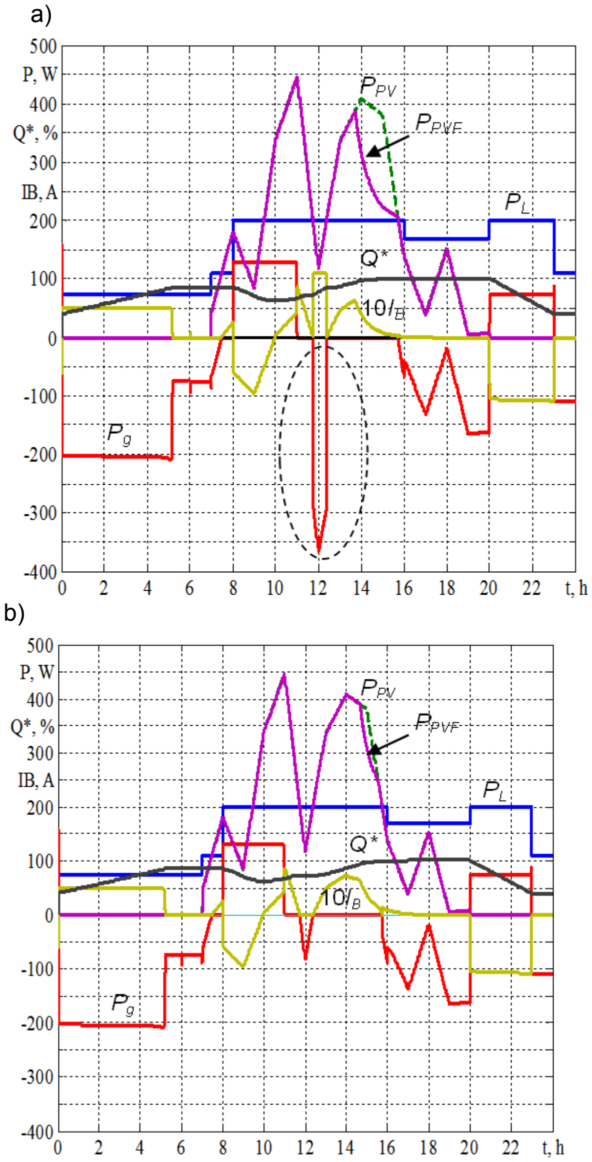

Fig.2. Oscillograms of daily cycle operation at W_{PV}=2.856 kWh

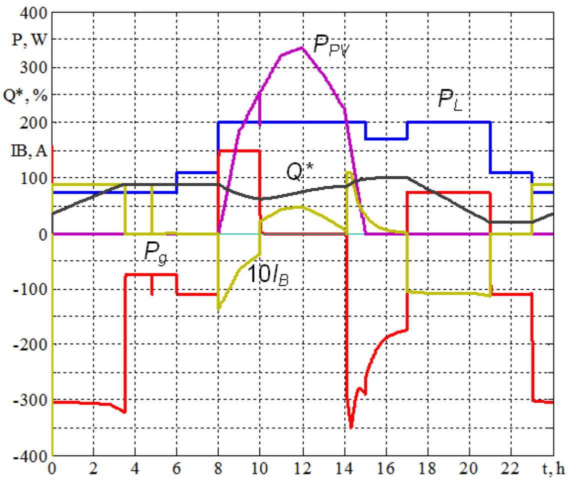

Fig.3. Oscillograms of daily cycle operation in December at W_{PV}=1.716 kWh

Conclusions

The possibility of meeting the needs of the LO along with the planned one day ahead of energy generation to the grid during peak hours has been substantiated. In this case, the degree of SB charge by the beginning of generation is set based on the data of the forecast of the PV generation for the next day.

The generation power during the morning peak and the SB charging mode are accepted according to the current forecast, taking into account the actual SB charge. The results of simulation modeling of energy processes in PES confirm the effectiveness of the proposed solutions. With the accepted ratios of the PV rated power, the SB energy intensity and the load power, the reduction in the cost of paying for electricity from the grid for one tariff rate is from 1.3 to 39.6 times.

The highest efficiency is achieved when the PV power which is generated is above 0.5 of the maximum on a clear summer day, which corresponds to the accepted overestimation of the PV power. In this case, it is also possible to reduce the degree of SB discharge. In this case reduction of the cost at single tariff zone is from 5 times and higher, and when using multi-zone tariffication, energy supplier is required to pay to consumers for the electricity. The generation power in the evening peak is constant and amounts to 37.5% of the load power; in the morning peak, an increase of up to 195% is possible. The ability to generate in the DG during peak hours allows to reduce costs even with low PV generation. Thus, at one tariff rate in winter at W_{PV}=0.75 kWh, costs are reduced by 1.3 times, at two rates by 1.9 times. At the same time, the situation is ambiguous, since the exclusion of generation in winter allows reducing DOD and extending the SB life. The development of research is associated with further optimization of the reference of the degree of SB charge and the use of the recommended load schedule.

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