1. Olexandr SHAVOLKIN[1], 2. Iryna SHVEDCHYKOVA[1], 3. Michal KOLCUN[2], 4. Dušan MEDVEĎ[2], 5. Svitlana DEMISHONKOVA[1]

Kyiv National University of Technologies and Design (1), Technical University of Kosice (2)
ORCID: 1. 0000-0003-3914-0812; 2. 0000-0003-3005-7385; 3. 0000-0002-8041-9076; 4. 0000-0002-8386-0000; 5. 0000-0001-5678-8114

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Implementation of planned power generation for a grid-tied photovoltaic system with a storage battery for self-consumption of local object

***Abstract**. The implementation of the planned power generation into the grid for a photovoltaic system with a battery is considered using the example of the accepted load schedule of a local object. Generation is carried out during peak hours at a constant power in time, taking into account the limit. The parameters are selected according to the average monthly generation of a photovoltaic battery for its location. Control with reference of active power uses a short-term forecast.*

Streszczenie.** Rozważono realizację planowanej generacji mocy do sieci dla systemu fotowoltaicznego z baterią na przykładzie przyjętego harmonogramu obciążenia obiektu lokalnego. Wytwarzanie odbywa się w godzinach szczytu ze stałą mocą w czasie, z uwzględnieniem limitu. Parametry dobierane są zgodnie ze średnią miesięczną generacją baterii fotowoltaicznej dla jej lokalizacji. Sterowanie w odniesieniu do mocy czynnej wykorzystuje prognozę krótkoterminową.* (Realizacja planowanej generacji mocy dla systemu fotowoltaicznego podłączonego do sieci z baterią akumulacyjną do własnego poboru lokalnego obiektu***)

Keywords: forecast of generation, planned power generation into the grid, peak hours, simulation in a daily cycle.
Słowa kluczowe: przewidywanie zapotrzebowania na energię, planowanie zapotrzebowania na energię.

Introduction

"Small" energy using renewable energy sources (RES) plays an important role in electricity production at the level of local objects (LO) (small business, agricultural objects, domestic sector, service) in different countries [1]. The numbering of such objects is constantly increasing. At the same time, the problem of ensuring the balance of energy is increasingly appeared associated with the fact that the time of the greatest generation does not match the maximum consumption. This has led to the emergence of new approaches, in particular, the localization of consumption at the place of generation, i.e., the use of RES for the own needs of LO [2, 3]. Hybrid photovoltaic systems (PVS) with connection to the distribution grid (DG) are widespread, which allows for an increase in the reliability of the power supply of LO. When using energy storage batteries (SB), the capabilities of the PVS are significantly expanded, but the additional investment must pay off. This is possible with lower energy costs. If there is an economic benefit to the consumer then the use of SB will help to ensure the balance of the energy in the system. Thus, there are topical issues of optimizing the parameters of the structure and improving energy management of PVS with SB to meet the needs of LO.

Literature review and problem statement

The issues of a planned power generation accordingly with a time-short forecast on the PVS level are no new. The use of the battery energy storage system (BESS) for the equalizing of generation in the time intervals at interaction with the system dispatcher is described in [4]. Achieving power generation, comparable to LO consumption from DG, requires a significant overestimation of the power of the photovoltaic battery (PV). In the real situation, the possibilities of the generation of surplus electricity to the grid are insignificant. Two main approaches can be distinguished in the implementation of PVS: using PV energy only for self-consumption; with the generation of surplus energy into the grid.

The paper [5] presents a comprehensive study of the technical and economic benefits that a typical residential prosumer may experience when investing in a solar system with a BESS. It is noted although the results demonstrate that the prosumer's self-consumption rate may increase up to 14% with the BESS coupling in the PV system, the investment proved to be economically unattractive in the current regulatory scenario and practically unfeasible in any of the proposed future scenarios. To make PV+BESS systems economically feasible, some business models are proposed and discussed, for example, providing subsidies for policymakers, financial agents, and battery manufacturers.

In [6] an overview of the effective parameters in the process of optimal planning of a solar photovoltaic system and a storage system (accumulators) for the residential sector connected to the grid are presented. The issues of dispatching, planning, and optimization of the size of the PV and SB are mentioned. At the same time, a PVS connected to the grid is considered, which provides load and can export additional power to the main grid. Issues of technical implementation are mainly declared.

The review publication [7] summarizes existing research on PV self-consumption and options to improve it. Two options for increasing own consumption are included, namely, energy storage and load management also called demand-side management (DSM). Generation issues in the grid are not considered.

In [8] the possibilities of the grid offloading from the effects of photovoltaic peak power through the use of battery storage systems are considered. It is shown that predictive storage management has a significantly higher potential for grid offload than a system that maximizes only native consumption, as it is commonly used today. Dumping stored energy into the grid is not considered.

In [9] the impact of SB use on-peak electricity demand in the household is considered. The peak shaving potential was further assessed under different control strategies of the batteries. Results show that the impact could be amplified to a decrease of 22% or 51% when the batteries are controlled by using heuristics or by assuming perfect foresight together with a power minimization algorithm, respectively. The findings of this paper emphasize the importance of collaboration between households and other stakeholders, such as distributed system operators and retailers in transitioning to a sustainable power system. The possibility of peak shaving demand by generating electricity for the grid is not considered.

The paper [10] explores and compares the storage potential of batteries with demand response strategies to reduce electricity payment in the residential sector in the context of the trend of PVS installation for own consumption. The advantages of storage and demand response are estimated using a linear programming algorithm. The electricity pricing scheme is a double tariff mode. Technical implementation issues are not considered.

The publication [11] confirms that the ratio of the installed peak power of photovoltaic systems to the useful capacity of the battery has a significant impact on its consumption, autonomy, and the economic efficiency of the entire system. The importance of taking into account the load profile when assessing economic expediency is substantiated. Technical and economic analysis is carried out without considering the technical implementation. In [12] the residential load with a TOU structure is considered. The expediency of using BESS with the Net-Metering scheme is substantiated. It is shown that the efficiency of SB use is tied to the operation schedule.

In the paper [13] a new algorithm for the energy management system of a photovoltaic grid-connected system, combined with a storage system is proposed. This algorithm can determine the most suitable (optimal) hours to switch between the battery, solar PVs, and principal grid based on historical consumption data and also determine the optimal amount of stored energy that be injected during the peak demand. At the same time, the generation of excess energy into DG is provided, and the battery charge is carried out from the PV during daylight hours. But the battery charge from the grid is not used at night, which limits the possibility of its use in the morning.

It is possible to note some contradictions in the approaches. Economic efficiency (for the owner) is increased by using the generation of surplus PV energy into the grid, which usually takes place during peak PV generation hours. On the other hand, the issues of offloading the grid from peak generation are solved. There is unanimity on the issue of peak demand. There is an interesting work [14], which assesses the possibility of mass use of battery technologies to manage peak demand in the UK. Taking into account the current cost of battery systems, this work deals with the rate of profit, which may be possible when buying electricity from the grid during periods of low demand and resale to peak demand in terms of the UK average household. The issues of tariffs, demand, and regulatory framework that must be created to make this possible are considered. Technical implementation is not considered.

The issue of implementing the generation of electricity to the grid during peak load hours in the morning and evening using the PV generation forecast is considered in [15]. But generation is somewhat declared – guaranteed values of generation power are not defined. The power limit on consumption and, respectively, on the power generation into the grid is not taken into account. There is an overestimation of the battery capacity, which will lead to an overestimation of the consumption of the battery charge at night. The tasks of reducing consumption from the grid in the daytime are solved. A similar solution is discussed in [16]. An assessment of the efficiency in both works is given for several selected days in summer and winter. It makes it impossible to get a holistic view of the cost reduction during the year.

Much attention is paid to the optimal choice of the ratio of the PV and battery size. Although the estimations are different. So, in [9] the optimal storage sizes in the range of 0.5–9 kWh for the system for self-consumption are proposed. The work [7] shows that it is possible to increase the relative self-consumption by 13–24% points with a battery storage capacity of 0.5–1 kW h per installed kW PV power. In [16] and [15] SB capacity, respectively, 1.55 kW h and 1.66 kWh per installed kW of PV power.

Wide opportunities for the implementation of solar power plants are provided by the electrotechnical market, where there is a big choice of hybrid inverters, which contain the entire set of equipment for PV and SB connecting. Such inverters provide several functions using the priorities of operation (from the grid, sun, battery) and control of parameters via the Internet, including the generation of surplus electricity into the grid with the possibility of restriction. But generation is possible in the presence of surplus electricity. The possibilities of control and redistribution of energy according to the forecast are not used.

A multifunctional grid inverter is promising for use in PVS [17-21]. In addition to providing a power factor close to a unit, the multifunctional grid inverter allows direct control of current (power) at a common coupling point to the grid. That is, it is possible to set the value of the power consumed or generated in the grid. In the three-phase version, it is possible to equalize the consumption by phases at the common coupling point to the grid at an unbalanced load [19, 21].

Implementation of most decisions to improve the efficiency of LO PVS is based on the use of a short-term PV generation forecast [22, 23]. This allows planning the load, to use various scenarios for the operation of the PVS. PV generation forecast data according to the location of LO with different discreteness provide various web services, such as [24, 25].

Experimental research of PVS operation in different seasons of the year requires a lot of time and material costs. Therefore, mathematical modeling is usually used as a tool for assessing the effectiveness of systems. In [26, 27] simulation of a hybrid energy storage system for photovoltaic microgrid systems connected to a grid of residential buildings is presented. Dynamic models of SB and supercapacitor in MATLAB are presented, and the smoothing of load power fluctuations is investigated. There is no research on the control and redistribution of energy in the system. In [16, 17, 23, 28] to assess the effectiveness of PVS with batteries, modeling of energy processes in the daily cycle according to the data of the archive [29] is considered. As a simplified criterion, the ratio of energy consumed by the load and energy consumed from the grid is chosen. Estimation is performed for several days, which does not allow us to give an integral assessment for the year.

The issues of implementation of PVS with SB, which combines the functions of providing its own needs of LO with the planned generation for the day ahead during peak load hours, are not well studied. This concerns the justification for the choice of system parameters taking into account the real meteorological conditions during the year and the possibilities of guaranteed generation of electricity to the grid. In this case, the use of statistical data on the PV generation for a specific location of PVS is useful. Implementation of efficient use of SB in the system with the formation of state degree charge graph on the base of a short-term PV generation forecast involves the improvement of principles of control of the PVS converter unit using the capabilities of a multifunctional grid inverter.

At the same time, it is necessary to take into account the possibility of reducing the PV power, the impact of the load value, and use in conditions of different tariffing of payment for electricity consumed from the grid.

The purpose of the article is improvement the implementation of principles of a planned power generation into the grid during peak load hours for a hybrid PVS with an SB used for the needs of the LO, while the value of generated power is constant in time, taking into account the limitations on consumption from the grid.

The main tasks are defined:

- to study the possibilities of ensuring a planned power generation to the grid during peak hours and justify the choice of system parameters for the adopted load schedule of LO taking into account the data of the monthly average PV generation for the coordinates of LO;
- to develop the principles of formation of a given graph of the SB state of charge using a short-term PV generation forecast;
- to develop the principles of realization of the converter unit control systems of PVS;
- to carry out the modeling of energy processes in the daily cycle with an assessment of the possibilities of reducing the cost of paying for electricity during the year.

Research Results

Consider the well-known structure of PVS with SB [20, 21] when using in a converter unit (CU): three-phase multifunctional grid inverter; DC/DC converter for PV with MPPT function and switching to direct reference PV current (I^1_{PV}) to regulate generation; DC/DC converter with bilateral conductivity for SB. The control system of CU for PVS is also implemented according to the principles presented in [20] with the program control unit (PCU) and with a Wi-Fi module for connection with web resource of PV generation forecast. PCU carries out the processing of forecast data, and calculation of reference parameters by time intervals and sensor signals, it also controls the switching of modes. The control system uses three controllers to stabilize the voltage U_d at the inverter input: VCI_B – reference of SB current (I^1_B); VC_{PV} – reference of PV current (I^1_{PV}); VCI_g – reference of grid current (I^1_{gm}). Stabilization U_d is needed to ensure the balance of power in the system. In this case, referencing the current is possible either by a regulator or by using the appropriate constant. The value of the constant for the amplitude of the grid current I^1_{gmREF} is determined by the calculated power value, consumed (generated) from the grid P_g. In any of the modes, the value of one of the currents is set by the regulator, for the others - by a given constant (for PV by MPPT controller).

Consider PVS functioning for daily load schedule, typical for LO domestic and non-household purposes for one-shift work. We accept the distribution of time zones, usually used in three-zone tariffication [24, 29]. We will also introduce an additional time point t_4, when there is a decrease in PV generation in the evening. The corresponding intervals are given in Fig. 1.

We proceed from the rated PV power P_{PVR}=1 kW. The final calculation of the PV power is carried out following the required load power. Calculation of SB energy capacity $W_B=U_BC_B$ (Wh, U_B, and C_B – voltage, and capacitance of SB (Ah)), is carried out from the conditions of sufficiency:

- for compensation a consumption by LO load during peak load hours and ensuring guaranteed generation into the grid;
- for ensuring 100% SB charge at night, taking into account the night load of the LO within the limit P_{LIM} per consumption from the grid at the maximum value of deep discharge (DOD).

For a specific location point of PVS, there is information available on the average monthly generation W_{PVAV} for given PV power [28]. For example, for Kyiv (Ukraine) on a clear day of summer, total PV generation energy with P_{PVR}=1 kW is W_{PV}≈6000 Wh, and the average value of the power generated per day, $P_{PVAV}=W_{PV}/12$=500 W. According to [28] in July for Kyiv, the value of the average monthly daily generation (Table 1) is W_{PVAVD}=4380 Wh, and in winter – W_{PVAVD} from 910 Wh to 1810 Wh. This should be taken into account to achieve a real reduction in the cost of electricity consumption from the grid.

Similar data are given in Table 1 for the city of Košice (Slovak republic) - W_{PVAVD1}. In general, there is approximately similar. In Table 1 the estimated data on the average monthly daily PV generation W^*_{PVAVD} are presented, also for specified time intervals W^*_{PV23}, W^*_{PV34}, W^*_{PV45} from 2012 to 2016 (Kyiv).

In Table 1 data for selected days (for research), when the generation is close to the monthly average (numerator) for the specified intervals, are also presented.

Table 1. Average PV generation during the year

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
W_{PVAVD1} [kWh]	1.272	2.053	2.811	3.799	3.76	3.914	4.073	3.84	3.434	2.6	1.418	1.25
W_{PVAVD} [kWh]	1.17	1.81	2.87	3.88	4.27	4.43	4.38	4.24	3.85	2.57	1.14	0.91
$W^*_{P\{VCPD}$ [kWh]	0.98	1.81	2.83	3.83	4.26	4.48	4.37	4.16	3.52	2.49	0.96	1.03
W^*_{PV23} [kWh]	$\frac{0.144}{0.166}$	$\frac{0.31}{0.36}$	$\frac{0.5}{0.55}$	$\frac{0.62}{0.52}$	$\frac{1.06}{1.15}$	$\frac{1.26}{1.17}$	$\frac{1.17}{1.13}$	$\frac{0.581}{1.08}$	$\frac{0.41}{0.56}$	$\frac{0.34}{0.33}$	$\frac{0.225}{0.22}$	$\frac{0.166}{0.21}$
W^*_{PV34} [kWh]	$\frac{0.643}{0.78}$	$\frac{1.31}{1.36}$	$\frac{1.83}{1.84}$	$\frac{2.09}{2.38}$	$\frac{2.43}{2.43}$	$\frac{2.51}{2.27}$	$\frac{2.46}{2.5}$	$\frac{2.78}{2.45}$	$\frac{2.25}{2.27}$	$\frac{1.95}{1.74}$	$\frac{0.535}{0.69}$	$\frac{0.806}{0.8}$
W^*_{PV45} [kWh]	$\frac{0.061}{0.038}$	$\frac{0.16}{0.083}$	$\frac{0.22}{0.32}$	$\frac{0.79}{0.84}$	$\frac{0.539}{0.53}$	$\frac{0.62}{0.63}$	$\frac{0.57}{0.61}$	$\frac{0.66}{0.53}$	$\frac{0.65}{0.72}$	$\frac{0.148}{0.39}$	$\frac{0.036}{0.03}$	$\frac{0.03}{0.021}$
$W_{PV23MIN}$ [kWh]	7	15	25	35	120	115	78	80	30	9	11	7

The choice of the average value of the load power of LO P_L is possible by PV generation W^*_{PVAVD} in March and October. Then most of the year (8 months) average monthly PV generation will be higher than these values. Accept the base value W_{PVB}≈2500 Wh and, respectively, the value P_{PVAV}=208.3 W. Taking into account the efficiency of the converter (accept η_C=0.94) we get P_{AV}=195.6 W. As an example, we consider the following schedule of load: for the evening (t_5, t_6) and morning (t_2, t_3) peaks of load accept $P_{L23}=P_{L56}=P_L$=200 W, for intervals (t_3, t_4) and (t_4, t_5) – $P_{L34}=0.9P_L$ and $P_{L45}=0.8$ P_L. The value of the limit on consumption from the grid is accepted with a margin of 25% P_{LIM}=250 W. Energy supplied by the SB to the load and grid (interval (t_5, t_6)):

(1) $\left(W_L + W_{g2}\right) = \Delta W_B = 0.01\Delta Q^*_{RC}\, W_B \eta_B \eta_C,$

where $W_L=P_L \cdot t_{RC}$, $W_{g2}=P_{g2} \cdot t_{RC}$, P_{g2} – generation power into the grid during evening load peak, η_B – efficiency of SB, ΔQ^*_{RC} –SB DOD, $Q^*=100Q/Q_R$ – state of charge (SOC) of SB in %, $Q=\int I_B dt$ – SB charge, Q_R – corresponds to full charge (100%), t_{RC} – time of discharge (duration of evening peak).

The maximum value of energy, consumed from the grid at night charge, is up to 100%:

(2) $\Delta W_B = 0.01\Delta Q^*_{Ch}\, W_B / (\eta_B \eta_C) \leq \left(P_{LIM} - P_{Ln}\right) t_{Ch},$

where P_{Ln} – average value of night load power of LO, ΔQ^*_{Ch} – SOC of SB, t_{Ch} – time of the charge.

We consider the LO with a daytime mode of operation and a predominance of daily load. Accept P_{Ln}≤120 W ($0.6P_L$), values are $\Delta Q^*_{Ch}=\Delta Q^*_{RC}$=80%, η_B=0.96. Then according to (1) and (2) can be accepted W_B=1126 Wh (for example, C_B=44 Ah at U_B=25.6 V) with charge duration t_{Ch}≤8h, which usually corresponds to dual-zone tariffing (night tariff from 23.00 to 7.00). In this case, the value of the power given by the SB at t_{RC}=3h in summer will be 277 W, i.e. it is possible to accept the guaranteed value of the generation power P_{g2g}=77 W. At t_{RC}=4 h (winter) get 208 W, i.e. P_{g2}=8 W, which doesn't make sense. Possible option for wintertime – reduces the generation time in the evening to 3 h at P_{g2g}=50 W and reduces load consumption during the remaining peak hour to nighttime load level (P_{L56} - ΔP_L) =P_{Ln} (ΔP_L=80 W).

In this case, we have a ratio P_{PVR}/P_L=5:1 (P_{PVR}=1 kW to P_L=200 W). With a total load of LO, for example, P_{LC}=10 kW it's necessary $P_{PVRC}=50P_{PVR}$ =50 kW and $W_{BC}=50W_B$. The base value of W_{PVB} can be taken from the average monthly value for the year. Then, with the same P_{LC} and W_{BC}, the value of the total PV power P_{PVRC} can be reduced to 0.8-0.85, which will lead to an increase in consumption from the grid, especially when W_{PV}≤W_{PVB}.

Guaranteed generation during the morning peak hours during winter-spring - autumn with duration (t_3 - t_2) =2 h is possible even in the absence of PV generation. At values, Q^*_2=100% and Q^*_3=40% value is P_{g1g}=110 W. In summer should be taken into account the value W_{PV23}. By Table 1 minimum value is W_{PV23MN}=78 Wh, with Q^*_3=40% providing a value of P_{g1g}=30 W. With an average value of W_{PV23} in summer is above 581 Wh. This is an exception to the rule. Therefore, we accept the same value. P_{g1g}=110 W when increasing the depth of discharge to 80%, if $W_{PV23}=W_{PV23MN}$.

The effective functioning of PVS is associated with the rational use of SB energy. This involves the formation of a schedule $Q^*(t)$ (*SOC(t)*) by intervals of work, taking into account the data of the short-term forecast of PV generation. The use of generation into the grid during peak hours implies a fairly deep discharge of the SB twice a day, therefore, the use of a lithium-ion battery is being considered. It is envisaged:

- ensuring the value $Q^*_4 \rightarrow (Q^*_{4MIN} \div 100\%)$. For lithium-ion SB [30] value $Q^*_{4MIN}=Q^*_d$≥90%, upon reaching which charge is carried out at a constant voltage and charge current determined by the charging characteristic $I_B=I_B(Q)$. In this case, the value I_B significantly reduces, and the energy, stored in the SB, is also reduced;
- possibility of full charge up to 100% on the interval (t_4, t_5). Limitation on the level $Q^*_{4MIN}=Q^*_d$, when charge current of SB significantly reduces, allows to reduce power, SB consumed at the interval (t_4, t_5);
- elimination of SB discharge at the interval (t_3, t_4);
- using the reference value for estimated active power P_{gREF}, which is consumed from the grid, to control the inverter. This allows you to equalize in time and limit the value of power, consumed from the grid, with a small PV generation, when most of the time $P_{PV} \cdot \eta_C < P_L$.

The reference value of the state of charge Q^*_2 at the beginning of the day and clarification of the generation power value into the grid P_{g1} is defined according to the PV generation forecast for the next day. Taking into account DOD_6=80% (Q^*_6=20%) value DOD_3 should be limited, for example, to 60% and, accordingly, Q^*_{3L}≥40%. Minimum W_{O23} and maximum W_{O23M} values of energy transmitted into the grid and load at the interval (t_2, t_3):

$$W_{O23} = \left(P_{g1g} + P_{L23}\right)\left(t_3 - t_2\right), W_{O23M} = \left(P_{LIM} + P_{L23}\right)\left(t_3 - t_2\right).$$

Respectively, minimum ΔQ^*_{23MIN} and maximum value ΔQ^*_{23MAX}:

$$\Delta Q^*_{23MIN} = \frac{W_{O23} - W_{PV23}\eta_C}{0.01W_B \eta_C \eta_B}, \Delta Q^*_{23MAX} = \frac{W_{O23M} - W_{PV23}\eta_C}{0.01W_B \eta_C \eta_B}.$$

At $W_{PV23} \cdot \eta_C \geq W_{O23}$ (approximately corresponds to the average monthly generation in the spring-autumn period) value ΔQ^*_{23MIN}≤0 (SB charge), respectively, Q^*_{3MAX}= (Q^*_2 - ΔQ^*_{23MIN})≥Q^*_2 and Q^*_{3MIN}=(Q^*_2-ΔQ^*_{23MAX}). Accept the value $Q^*_2=Q^*_{3L}+\Delta Q^*_{23MAX}$.

For values $W_{PV23} \cdot \eta_C < W_{O23}$ (SB discharge) we accept $Q^*_2=Q^*_{3L}+\Delta Q^*_{23MAX}$≤100% and there are two values Q^*_{3MIN}=(Q^*_2 - ΔQ^*_{23MAX}) and Q^*_{3MAX}=(Q^*_2 - ΔQ^*_{23MIN}). If Q^*_{3MIN}≤Q^*_{3L}, then accept the minimum value Q^*_{3L}. So, for possible values Q^*_3 there is the condition:

(3) $$Q^*_{3MAX} \geq Q^*_3 \geq Q^*_{3MIN},$$

Options for implementing the schedule $Q^*(t)$ depending on the PV generation at $W_{PV23} \cdot \eta_C < W_{O23}$ are shown in Fig.1. So, with high generation W_{PV34} it is possible to charge the battery at the interval (t_3, t_4) from Q^*_{3L} to Q^*_4=100% (curves 2 and 3) or Q^*_{4MIN}. In case 1, when Q^*_2=100%, W_{PV34} is enough for SB charge to Q^*_4=100%, and in the case of 4 - only up to Q^*_{4MIN}. At the same time, energy from the grid is not consumed. With a lower value, W_{PV34} PV energy is no longer enough, and the missing part of the energy to charge the SB is consumed from the grid.

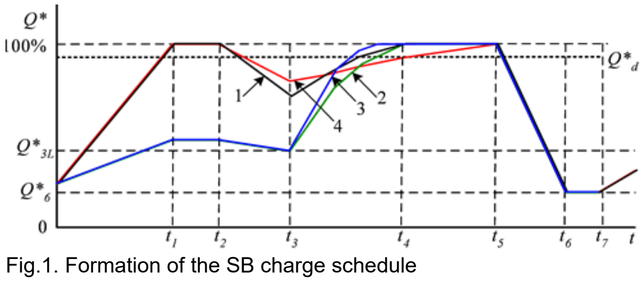

Fig.1. Formation of the SB charge schedule

Energy balance at the interval (t_3, t_4) – $W_{L34}+\Delta W_{B34}$ - $W_{PV34} \cdot \eta_C$ - W_{g34}=0, where $W_{g34}=P_{g34}(t_4-t_3)$ – energy, consumed from the grid, $\Delta W_{B34}=0.01\Delta Q^*_{34}W_B/(\eta_C \cdot \eta_B)$ – energy for SB charging.

Accordingly, reference the value of the active power, consumed from the grid P^1_{g34}:

(4) $$P^1_{g34} = \frac{W_{L34} + 0.01\Delta Q^*_{34}\, W_B / \eta_C \eta_B - W_{PV34}\eta_C}{(t_4 - t_3)}.$$

The following options are possible:

(5) $$P^1_{g34}=\begin{cases}0, & if \quad W^1_{PV34}\eta_C \ge W_1 = P_{L34}(t_4-t_3)+0.01(Q*_{4MIN}-Q*_{3MAX})W_B/\eta_C\eta_B,\\ \dfrac{W_1-W_{PV34}\eta_C}{(t_4-t_3)}, & if \quad W_1 > W_{PV34}\eta_C > W_2 = 0.01(100-Q*_{3MIN})W_B/\eta_C\eta_B,\\ P_{L34}, & if \quad W_2 \ge W_{PV34}\eta_C \ge W_3 = 0.01(Q*_{4MIN}-Q*_{3MAX})W_B/\eta_C\eta_B,\\ (P_{L34}+\dfrac{(W_3-W_{PV34}\eta_C)}{(t_4-t_3)}) \le P_{LIM}, & if \quad W_{PV34}\eta_C < W_3.\end{cases}$$

Consider the option when PV energy $W_{PV34}\cdot\eta_C$ sufficiently and P^1_{g34}=0. Increment value $\Delta Q*_{34}$ is:

(6) $$\Delta Q*_{34}=\frac{W_{PV34}\eta_C-P_{L34}(t_4-t_3)}{0.01W_B/\eta_C\eta_B}.$$

Value $Q*_3=Q*_4 - \Delta Q*_{34}$.

If the resulting value $Q*_3$ corresponds to the condition (3), then by $\Delta Q*_{23MAX}$, $Q*_2$ and $\Delta Q*_{23}=(Q*_2 - Q*_3)$ are determined and the value P_{g1} is clarified as:

(7) $$P_{g1}=\frac{W_{PV23}\eta_C+0.01\Delta Q*_{23}W_B\eta_C\eta_B}{(t_3-t_2)}-P_{L23}.$$

If derived from (6) value $Q*_3$ does not correspond to the condition (3) and $Q*_3<Q*_{3MIN}$, then we accept $Q*_3=Q*_{3L}$ and recalculate $Q*_2=Q*_{3L}+\Delta Q*_{23MAX}$ ($P_{g1}=P_{LIM}$). A case when PV energy is not sufficiently $W_{PV34}\cdot\eta_C\le W_2$ и $P^1_{g34}=P_{L34}$.

We define the value $\Delta Q*_{34}$ and $Q*_3$, in which PV energy is sufficient only for SB charge, i.e. $\Delta W_{B34}=W_{PV34}\eta_C$:

(8) $$\Delta Q*_{34}=\frac{W_{PV34}\eta_C}{0.01W_B/\eta_C\eta_B}.$$

If $Q*_3$ corresponds the condition (3), then clarify the value P_{g1} by (7).

If $Q*_3$ does not correspond to condition (3) and exceeds $Q*_{3MAX}$, then we accept $Q*_3=Q*_{3MAX}$, $P_{1g}=P_{g1g}$. In this case, the full charge of the SB ends at the interval (t_4, t_5).

If $W_1>W_{PV34}\cdot\eta_C>W_2$ then value $Q*_3=Q*_{3MAX}$ at $P_{1g}=P_{g1g}$. In this case, the value P^1_{g34} is minimum and it's determined by (4).

Analysis of Table 1 data shows that when PV generation is at the middle level and above, it becomes possible to increase the duration of generation P_{g1} in the morning peak in spring from 8.00 to 11.00, and in summer from 8.00 to12.00.

Modes of operation and the main ratios are given in Table 2. This takes into account that when $Q*\ge Q*_d$ charge current is determined by the charging characteristic $I_B=I_B(Q)$. In this case, using VCI_B is senseless.

During morning peak hours (mode *mp*) is set $I^1_{1gmREF}\le 0$, corresponding to the value of the generated power into the grid $P_{1gREF}\ge 0$ ($P_{1gREF}=3U_{gph}I_{1gm}/\sqrt{2}$, U_{gph} and I_{1gm} - respectively, voltage (phase to neutral) and grid phase current). Current processing I^1_{1gmREF} is carried out by the inverter current control circuit taking into account the load current [19, 20]. Herewith $P_g=P_{1gREF}$. PV generation power is set by MPPT. Reference of SB current is formed by a voltage controller $VCI_B\rightarrow I^1_B$. A similar implementation is during evening peak hours (mode *ep*).

At intervals (t_3, t_4) difference mode *gm1* in that, what is set $P_g=P_{gREF}=P_{g34}\le 0$ (energy consumption from the grid). Mode *gm2* takes place provided conditions $P_{PV}\eta_C$-P_L-$P_{gREF}\le 0$. How the analysis shows, that this situation is possible when $P_{gREF}=P_{g34}=0$. In this case, the charge current is 0, and VCI_g sets the consumption from the grid to ensure a balance of power. In mode *gm*3, when the value $Q*>Q*_d$, the balance of powers provides VC_{PV}, which reduces the power of PV (P_{PVF} – actual PV generation power with taking into account the regulation).

At interval (t_4, t_5) at $Q*>Q*_d$ a voltage controller VCI_g is used, which provides power balance and regulates power consumption from the grid (mode *gm4*).

Switching from mode *mp* to *gm1* is carried out by time (t_3) by modifying the reference P_{1gREF}. Switch modes *gm1*, *gm2,* and *gm3* are carried out by two conditions, which are intended to eliminate the influence of transient processes. So, a switch from mode *gm1* to *gm2* takes place, for example, with the "failure" of PV generation. In this case, the SB current is set by the voltage controller VCI_B and is limited to the value $I^1_B\ge 0$ (is reduced to 0), which leads to a decrease $U_d<U^1_d$ (second condition). After switching VCI_g current I^1_{gm} increases (energy consumption from the grid is growing, compensating for the reduction P_{PV}), and the voltage is restored at a predetermined level $U_d=U^1_d$. With an increase in PV generation current I^1_{gm} decreases to I^1_{gmREF}, which leads to an increase in $U_d>U^1_d$ (second condition) and switching VCI_B. Switching of other operating modes is carried out in time.

Modeling the energy processes in the daily cycle

A simulation of energy processes in the system at the level of active power was performed for the daily cycle of operation (Table 2) using MATLAB. Transient processes were not taken into account when changing operating modes, losses in converters and SB were accounted for through efficiency. Approaches were used and discussed in [15, 16, 23, 28]. To set the PV generation in different seasons of the year, archival data were used [29] with the selection of days, when the generation is close to the average monthly values (Table 1).

To set intervals of operation (Table 2) variables are introduced t_{12}, t_{23}, … t_{71} (for winter, spring, and autumn according to Table 2 instead of t_{56} two variables t_{E1} and t_{E2} are used), which take a value of 1 at the appropriate time interval.

Variables are also introduced:

$$pv=\begin{cases}1, \text{if } (P_{PV}\eta_C-P_L-t_{34}\cdot P_g)>0\\ 0, \text{if } (P_{PV}\eta_C-P_L-t_{34}\cdot P_g)\le 0\end{cases},$$

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

Load power $P_L(t)$ and PV generation PV(t) (P_{PVM} corresponds to the maximum power mode) are set in tabular form. The actual current value of PV generation power $P_{PVF}(t)$ taking into account the regulation:

$$P_{PVF}\eta_C=P_{PVM}\cdot\eta_C\cdot(t_{23}+t_{34}\cdot\overline{q}+t_{45}\cdot q\cdot\overline{pv})+$$
$$+(P_L-P_g+P_B)(q\cdot t_{34}+q\cdot pv\cdot t_{45}).$$

Table 2. Operation modes of the PVS with SB

Modes of operation and the main ratios					
Interval	Load morning peak (peak tariff) (t_2, t_3) (8.00, 11.00) summer; (8.00, 10.00) autumn, winter, spring	Daytime load (daytime tariff) (t_3, t_4) and (t_4, t_5) (11.00, 16.00) (16.00, 20.00) summer; (10.00, 14.30) (14.30, 17.00) winter; (10.00, 15.00) (15.00, 18.00) spring-autumn			
Mode	*mp*	*gm1*	*gm2*	*gm3*	*gm4(t_4, t_5)*
Reference I^1_{gm}	$P_g=P_{1gREF}=$ $=3U_{gph}I_{1gm}/\sqrt{2}\geq 0$ $P_{1gREF}\rightarrow I^1_{1gmREF}\leq 0$	$P_g=P_{gREF}=P_{g34}\leq 0$, $P_{gREF}\rightarrow I^1_{gmREF}\geq 0$	$\mathbf{VCI_g}\rightarrow I^1_{gm}\geq 0$ $P_g=P_{PV}\eta_C - P_L$	$P_g=P_{gREF}\leq 0$, $P_{gREF}=P_{g34}$ (t_3, t_4), $P_{gREF}=0$ (t_4, t_5), $P_{gREF}\rightarrow I^1_{gmREF}\geq 0$	$\mathbf{VCI_g}\rightarrow I^1_{gm}\geq 0$ $P_g=P_{PV}\eta_C - P_L - P_B$
Reference I^1_{PV}	MPPT	MPPT	MPPT	$\mathbf{VC_{PV}}\rightarrow I^1_{PV}\rightarrow P_{PVF}$ $P_{PVF}\eta_C=P_L - P_g+P_B$	MPPT
Reference I^1_B	$\mathbf{VCI_B}\rightarrow I^1_B$ $I_B=(P_{PV}\eta_C - P_L - P_{1g})/U_B$	$\mathbf{VCI_B}\rightarrow I^1_B>0$ $I_B=(P_{PV}\eta_C - P_L - P_g)/U_B$	$I^1_{BREF}=0$, *if* $P_{PV}\eta_C - P_L\leq 0$	$I^1_{BREF}>I_B(Q)$, $I_B=I_B(Q)$	$I^1_{BREF}>I_B(Q)$ $I_B=I_B(Q)$, $P_B=I_BU_B$
SOC	$Q^*_2\rightarrow Q^*_3$	$Q^*\leq Q^*_d$	$Q^*=const$	$Q^*>Q^*_d$	$Q^*>Q^*_d$
Modes of operation and the main ratios					
Interval	Daytime tariff (t_1, t_2) (7.00, 8.00) summer; (6.00, 8.00) autumn, winter, spring	Load evening peak (peak tariff) (t_5, t_6) (20.00, 23.00) summer; (t_{E1}) (17.00, 20.00) winter; (18.00 – 21.00) autumn, spring	Load evening peak (peak tariff) (t_{E2}) (20.00, 21.00) winter; (21.00 – 22.00) spring-autumn	Daytime tariff (t_6, t_7) (23.00, 24.00) summer; (21.00, 23.00) winter; (22.00, 23.00) autumn, spring	Night tariff (t_7, t_1) (24.00, 7.00) summer; (23.00, 6.00) autumn, winter, spring
Mode	*d1*	*ep*	*ep1*	*d2*	*n*
Reference I^1_{gm}	$P_g= P_L$ $P_L\rightarrow I^1_{1gm}\geq 0$	$P_g=P_{2gREF}=3U_{gph}I_{2gm}/\sqrt{2}\geq 0$ $P_{2gREF}\rightarrow I^1_{1gm}\leq 0$	$P_g=P_L - \Delta P_L\rightarrow$ $I^1_{gm}\geq 0$	$VC_{Ig}\rightarrow I^1_{gm}\geq 0$ $P_g=P_L$	$VC_{Ig}\rightarrow I^1_{gm}\geq 0$ $P_g=P_L+P_B$
Reference I^1_{PV}	MPPT	MPPT	-	-	-
Reference I^1_B	$VC_B\rightarrow I^1_B$ $I_B=P_{PV}\eta_C/U_B$	$VC_B\rightarrow I^1_B$ $I_B=P_L/U_B$	$VC_B\rightarrow I^1_B$ $I_B=(P_L-P_g)/U_B$	$I^1_{BREF}=0$	$I_{BREF}=$ $=(P_{LIM} - P_L)/U_B$
SOC	$Q^*_1\rightarrow Q^*_2$	$Q^*\downarrow$	$Q^*\rightarrow Q^*_6\geq 20\%$	$Q^*=const= Q^*_6$	$Q^*_6\rightarrow Q^*_1$

Power, consumed from the grid in the summer, is:

$$P_g = -t_{12}P_L + t_{23}P_{1g} - t_{34}P_{g34}pv - t_{34}(P_L - P_{PVM}\eta_C)\overline{pv} -$$
$$- t_{45}\cdot P_{g45}\cdot \bar{q} - t_{45}(P_L + P_B - P_{PVM}\cdot \eta_C)\overline{pv} +$$
$$+ t_{56}\cdot P_{2g} - t_{67}P_L - t_{71}(P_L + P_B).$$

In autumn-winter time the term $t_{56}P_{2g}$ changes on $(+t_{E1}P_{2g} - t_{E2}(P_L - \Delta P_L)$.

SB current for summertime is:

$$I_B = (t_{23} + t_{35}\cdot pv\cdot \bar{q})\frac{P_{PV}\eta_C - P_L - P_g}{U_B} +$$
$$+ I_B(Q^*)\cdot t_{35}\cdot q + t_{12}\frac{P_{PV}\eta_C}{U_B} +$$
$$+ t_{56}(\frac{P_L + P_{2g}}{U_B}) + t_{71}\frac{P_{LIM} - P_L}{U_B}.$$

In autumn-winter-spring time the term $\frac{P_L + P_{2g}}{U_B}t_{56}$ changes on $\frac{P_L + P_{2g}}{U_B}t_{E1} + \frac{P_L - P_g}{U_B}t_{E2}$.

The SB model is made according to the datasheet, which is given by the manufacturer [30]: characteristics of charge $I_B(Q^*)$, $U_B(Q^*)_C$ at $I_B\geq 0$, and discharge $U_B(Q^*)_R$ at $I_B<0$.

In this case, the charge current is:

$$I_B = \begin{cases} I_B, \text{ if } Q^* < Q^*_d \\ I_B(Q^*), \text{ if } Q^* \geq Q^*_d \end{cases}.$$

Value Q is defined by SB current $Q = Q_0 + \int I^1_B dt$, Q_0 – initial value, $I^1_B=I_B\eta_B$, if $I_B>0$ (SB charge), and $I^1_B=I_B/\eta_B$, if $I_B<0$ (SB discharge).

The model also contains a module for estimating the cost of electricity consumed from the grid. The use of one and two tariffs is considered: daytime T_d=1 and night T_n=0.5. Cost reduction coefficient is used [22, 27] $k_E=W^*_{LS}/W^*_{gS}$, where W^*_{LS} – the relative cost of the total electricity consumed by the LO load per day, W^*_{gS} – the relative cost of electricity consumed by LO from the grid:

$$W^*_{LS} = 0.001T_n\int P_L t_{71}dt +$$
$$+0.001T_d\int (P_L(t_{12} + t_{23} + t_{35} + t_{56} + t_{67}))dt,$$
$$W^*_{gS} = 0.001T_n\int P_g t_{71}dt +$$
$$+0.001T_d\int (P_g(t_{12} + t_{23} + t_{35} + t_{56} + t_{67}))dt.$$

Choosing a ratio of W_B and P_L at P_{PVR}=1 kW is essential in the design of PVS. So, the proposed ratio for LO with a power of 10 kW (50P_L) will need PV with power 50P_{PVR}=50 kW at the energy capacity of the SB 50W_B. If accept, for example, 1.25W_B and 1.25P_L, then the same energy capacity of the SB 50W_B and PV power will be a quarter less (40 kW). Respectively, the cost of PVS is reduced.

Therefore, when simulation, there is a need to compare the achieved indicators.

Results of simulation modeling

Consider the functioning of the PVS under two variants of the night load schedule of LO:

- variant a) P_{71}=40 W (0.2P_L), P_{12}=60 W (0.3P_L), P_{67}=60 W (0.3P_L);
- variant b) P_{71}=83 W (0.33P_L), P_{12}=110 W (0.55P_L), P_{67}=110 W (0.55P_L), winter-spring $P_{71}=P_{12}=P_{67}$=120 W (0.6P_L).

We proceed from the fact that the load schedule sets the maximum average load value at time intervals. That is, the most intense mode of operation is considered. In this case, does not take into account the reduction of the load at lunchtime and during any technological pauses. Oscillograms P_L, P_g, P_{PV}, P_{PVF}, I_B, Q^* for a May Day with a variable relative to the accepted schedule $P_L(t)$ load of LO are presented in Fig.2, a (k_{E1}=23.46, W_{gS}=135 Wh, W_{LS}=3137 Wh), when the load of the LO schedule matches $P_L(t)$ – in Fig.2, b (k_{E1}=23.6, W_{gS}=134 Wh, W_{LS}=3140 Wh).

a) b)

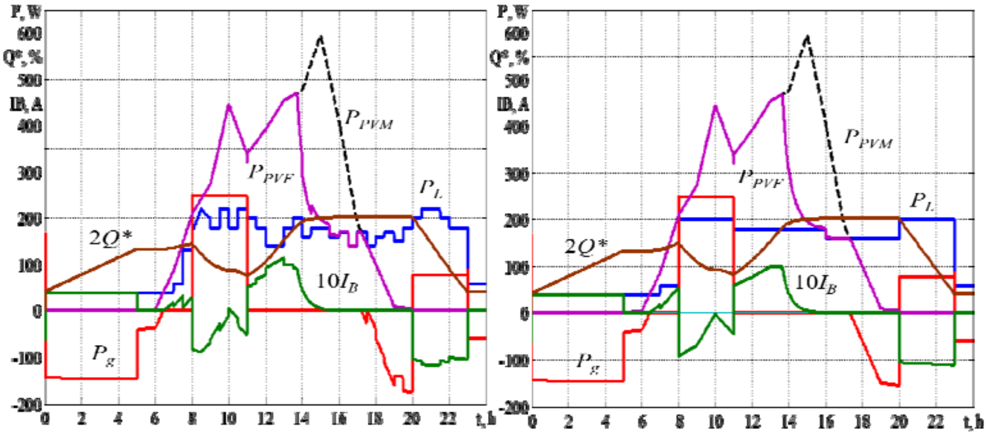

Fig. 2. Oscillograms of the daily cycle of operation for a May Day: a) load is variable relative to the accepted schedule $P_L(t)$; b) load corresponds to the accepted schedule $P_L(t)$

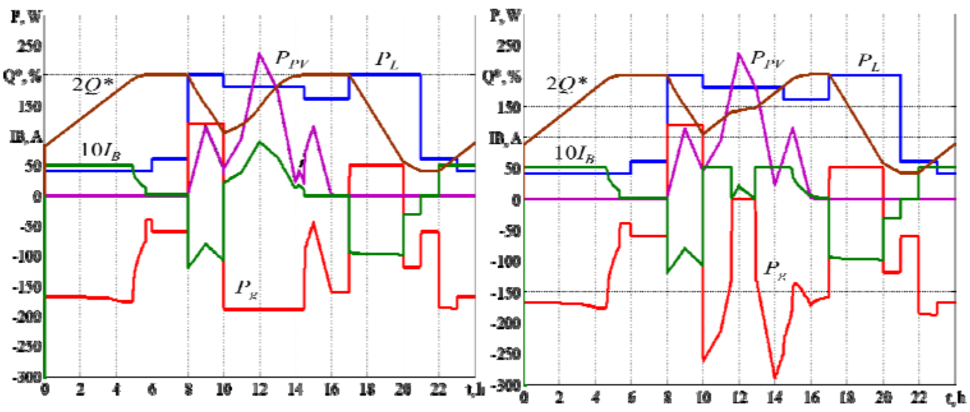

Fig.3. Oscillograms of the daily cycle of operation for a January day: a) with reference P_{g34}; b) with reference the operating mode by ratio $P_{PV}\eta_C$ and P_L

Oscillograms P_L, P_g, P_{PV}, P_{PVF}, I_B, Q^* for a January day are shown in Fig. 3, a when reference a calculated value P_{g34}, and in Fig.3.b, when with insufficient value $P_{PV}\eta_C<P_L$ SB charge is carried out due to the consumption of energy from the grid. Fig.3, a shows equalization of the power, consumed from the grid at the interval (t_3, t_4) without exceeding the power limit.

Oscillograms P_L, P_g, P_{PV}, P_{PVF}, I_B, Q^* for an April day with an extended duration of generation in the morning (from 8.00 to 11.00) are presented in Fig.4.

Values P_{1g}, P_{2g}, W^*_{gS}, W^*_{LS} for selected days are given in Table 3 at one and two rates of payment for variants a and a1 (with an increased duration of generation to the grid in the summer from 8.00 to 12.00 and in the period spring - autumn from 8.00 to 11.00). Sign (-) for W^*_{gS} indicates that taking into account the payment tariff, the electricity supplier must pay.

Value k_E for the year was defined as $k_{EY}=W_{LY}/W_{gY}$, where $W_{LY}=\sum_1^{12} W_{Li}$ and $W_{gY}=\sum_1^{12} W_{gi}$ - values of energy for the year, a W_{Li} и W_{gi} - values of energy for the month. Values k_{EY} are obtained by the average monthly generation and there are evaluative to compare the considered options for selecting parameters under the same weather conditions.

When PV generation is below the monthly average, consumption from the grid increases. The more difficult question is how the consumption from the grid will change when the PV generation is above the average in conditions of restrictions on the generated power to the grid and the limitation of PV generation when the SB is charged. Thus, there are grounds for confirming the possibility of reducing consumption. So, for the average day of July with W_{PV}=0.728W_{PVM} and one tariff rate value W^*_{gS}=19 Wh (consumption). For a clear day with W_{PVM}=6000 Wh, W^*_{gS}=-194 Wh, at an intermediate generation value (0.9W_{PVM}) W^*_{gS}=-110 Wh. Reducing consumption is achieved by reducing Q^*_2 and, respectively, night consumption per SB charge, as well as increasing PV generation in the morning before 8.00 and in the pre-evening time. Biggest opportunities for reducing consumption take place during the winter-spring-autumn period. So, for a December day with a total generation of 1716 Wh we have k_{E1}=1.926, k_{E2}=2.825 at P_{1g}=240 W, in comparison with the day chosen for the average monthly generation, when P_{1g}=170 W, k_{E1}=1.303, k_{E2}=1.644.

General values of k_{EY1} (one tariff rate) and k_{EY2} (two tariff rates) for variants a) and b) are presented in Table 4.

Discussion of the research results on the improvement of PVS with SBs using the planned power generation into the grid during peak load hours

An additional reduction in the cost of paying for electricity consumed by the LO from the DG, when using the planned generation of electricity to the grid, can be achieved by:

- improving the mechanism of redistribution of energy not used at night and PV energy with the formation of an SB schedule *SOC(t)*;
- formation *SOC(t)* by regulating the active power consumed from the grid, by the short-term forecast of PV generation and if the SB discharge is excluded in the period between peak loads;
- ensuring guaranteed generation to the grid during peak hours. It is possible to increase the power of generation to a value equal to the limit on consumption from the grid in the morning hours by the forecast of PV generation. In the period of spring-summer-autumn, it is possible to increase the duration of generation in the morning.

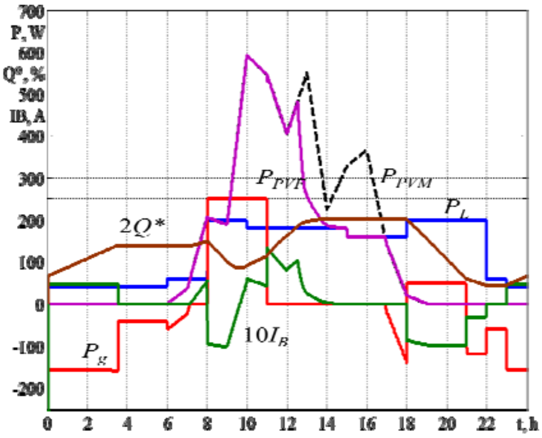

Fig.4. Oscillograms of the daily cycle of operation for April day

Implementation of the planned guaranteed generation to the grid during peak load hours at constant in time power simplifies the relationship with the electricity supplier and contributes to the balance of power in the power system

This article is the development of work [14] and [15], where increasing the efficiency of hybrid PVS with SBs for the needs of LO when using the power generation to the grid during peak load hours was considered.

A common problem is the need to somewhat overestimate the PV power about the load power of the LO, which is necessary for use in conditions of low PV generation. A feature of the proposed solutions is a change in the approach to the formation of SB *SOC(t)*, when, between peak hours, the value of the active power consumed from the grid is regulated, with an SB discharge exception. The energy capacity of SB is reduced. Calculated average monthly values of PV generation at given time intervals are used according to archival data [28] for a given location of the PVS for justifying the possibility of providing guaranteed generation to the grid and for assessing the reduction in energy costs. This allows for assessment during the year. Also, the possibility of reducing the PV power and the influence of night load on the indicators were assessed. There are certain limitations regarding the use of work results:

- an object with the main load in the daytime in the presence of peak loads in the morning and evening hours is considered when it is possible to charge the SB at night within the limit on consumption from the grid;
- calculated data of average monthly PV generation on archive data for specific coordinates of LO were used [29]. Processing a large amount of data is quite laborious;
- an annual assessment of efficiency is somewhat simplified and was performed according to monthly averages;
- modeling is based on the fact that the real PV generation corresponds to the forecast and does not change during the day, and the average value of the LO load corresponds to the calculated (maximum) values.

The development of this work is connected with the development of software for processing archival data with the formation of parameters and recommendations for a specific LO and a given load schedule.

Table 3. Indicators of PVS operation

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
					One tariff rate – variant a							
P_{1g}, W	120	240	250	250	250	250	250	160	250	250	120	170
P_{2g}, W	50	50	50	50	77	77	77	77	50	50	50	50
W^*_g, Wh	2353	1453	954	504	134	210	19	748	728	1176	2392	2249
W^*_L, Wh	2930	2930	3040	3040	3140	3140	3140	3140	3040	3040	2930	2930
					One tariff rate – variant a1							
P_{1g}, W	120	240	250	250	250	250	250	160	250	250	120	170
P_{2g}, W	50	50	50	50	77	77	77	77	50	50	50	50
W^*_{gS}, Wh	2353	1453	775	254	-58	-40	-219	588	474	974	2392	2249
W^*_{LS}, Wh	2930	2930	3040	3040	3140	3140	3140	3140	3040	3040	2930	2930
					Two tariff rates – variant a							
P_{1g}, W	120	240	250	250	250	250	250	160	250	250	120	170
P_{2g}, W	50	50	50	50	77	77	77	77	50	50	50	50
W^*_{gS}, Wh	1802	902	438	79	-255	-213	-341	205	198	600	1841	1698
W^*_{LS}, Wh	2790	2790	2900	2900	3000	3000	3000	3000	2900	2900	2790	2790
					Two tariff rates – variant a1							
P_{1g}, W	120	240	250	250	250	250	250	160	250	250	120	170
P_{2g}, W	50	50	50	50	75	75	75	75	50	50	50	50
W^*_{gS}, Wh	1802	902	234	-171	-476	-463	-585	45	-54	375	1841	1698
W^*_{LS}, Wh	2790	2790	2900	2900	3000	3000	3000	3000	2900	2900	2790	2790

Table 4. Comparison of indicators of PVS operation

k_{EY}	P_{PVR}=1000 W		P_{PVR}=800 W		P_{PVR}=1000 W
	Variant a	Variant a1	Variant a	Variant a1	Variant b
k_{EY1}	2.82	3.255	2.383	2.59	2.27
k_{EY2}	5	6.75	3.82	4.47	3.34

Conclusions

The possibility of ensuring a guaranteed year-round planned generation of electricity to the grid during peak hours with the LO load schedule, which is unchanged during the year, and the specified limit is shown. In this case, the calculated values of the average monthly PV generation for the accepted LO load schedule, which were obtained from archival data for 5 years for the LO coordinates, were used. The value of the power generation in time in these hours is constant and is limited by the value of the limit set on consumption for LO. At the same time, generation in the morning peak in summer is carried out 3 hours, in the period autumn-winter-spring - 2 hours. The power of generation into the grid is determined taking into account the ensuring of the required schedule of *SOC(t)* for SB. In the evening peak, the generation power is fixed with a duration of 3 hours. It also takes into account the ensuring of charge at night within the limit on consumption, taking into account the night load of LO. The duration of generation in the morning can increase to 4 hours in summer and up to 3 hours in spring and autumn.

Formation of dependency SOC(t) for SB with the achievement of the required values Q^* at the boundaries of the specified time intervals of the load graph is carried out by regulating the active power, consumed from the grid, using the PV generation forecast when taking into account the charging characteristic $I_B(Q^*)$ of SB. At the same time, the possible value of the generation power into the grid is taken into account and specified ranging from guaranteed to maximum values. This provides a limitation of DOD≤80% and reduces the consumption of electricity from the grid in the pre-evening time.

The control of the PVS is carried out with the regulation of the active power at the common coupling point of the LO to the grid by the time intervals of the load schedule. During peak hours, the mode of generating a given power value into the grid is implemented. In the daytime, the power consumed from the grid is regulated taking into account the charging characteristics $I_B(Q^*)$ of SB when an SB discharge is excluded. Changes in the structure of the control system by the PVS converter unit are carried out at intervals of time, and in the interval - when two conditions are fulfilled to eliminate the impact of transients. Power regulation also helps to equalize consumption within the limit.

Simulation of energy processes in the daily cycle confirms the possibility of implementing the planned generation of electricity to the grid throughout the year. With the average monthly PV generation, the value of generating power for most of the year is close to the established limit. In the absence of a "green" tariff, a real reduction in the cost of paying for electricity due to the generation of electricity into the DG is possible if there is a night tariff and an increase in the duration of generation to the grid in the morning. With the accepted load schedule and LO coordinates is a possible decrease during the year by 6.75 times, whereas at one rate the reduction is only 3.255 times. When evaluating PVS efficiency, the night load of the LO should also be taken into account, and even if there is a night tariff, an increase in the night load leads, all other things being equal, to the decreasing k_{EY2} from 5 to 3.34. Accepted load power ratio, the energy capacity of SB, and installed PV power are characterized by some overestimation of the PV power. There are options with a decrease in the installed PV power, but the degree of reduction in electricity costs is less. So, with a decrease in the installed PV power by a quarter, the value k_{EY1} decreases from 3.255 to 2.59, and k_{EY2} - from 6.75 to 4.47.

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Authors: Prof. DSc (Engineering) Olexandr Shavolkin, Kyiv National University of Technologies and Design, Department of Computer Engineering and Electromechanics, NemirovichaDanchenka str. 2, 01011 Kyiv, Ukraine, E-mail: shavolkin@gmail.com. Prof. DSc (Engineering) Iryna Shvedchykova, Kyiv National University of Technologies and Design, Department of Computer Engineering and Electromechanics, Nemirovicha-Danchenka str. 2, 01011 Kyiv, Ukraine, E-mail: shvedchykova.io@knutd.edu.ua. Dr.h.c. prof. Ing. Michal Kolcun, PhD, Technical University of Kosice, Faculty of Electrical Engineering and Informatics, Letná 9, 04200 Košice, Slovakia, E-mail: Michal.Kolcun@tuke.sk. *Doc. Ing. Dušan Medveď, PhD, Technical University of Kosice, Faculty of Electrical Engineering and Informatics, Letná 9, 04200 Košice, Slovakia, E-mail: Dusan.Medved@tuke.sk. Docent, CSc (Engineering) Svitlana Demishonkova, Kyiv National University of Technologies and Design, Department of Computer Engineering and Electromechanics, Nemirovicha-Danchenka str. 2, 01011 Kyiv, E-mail: demishonkova.sa@knutd.com.ua.*

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