The efficiency of combined electrothermal and electrochemical accumulation of electricity of a photovoltaic power plant

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***Abstract*— The relevance of the research is caused by the fact that renewable energy, in particular, photovoltaic generation is becoming essential support in the decentralized systems in Russia. However, the high cost of the power equipment of photovoltaic power plants is a deterrent to their wide practical application. This paper presents the method for reducing the cost of photovoltaic power plants by optimizing energy conversion processes in isolated power supply systems. The characteristics of equipment for photovoltaic generation and the subsequent conversion of parameters and power storage is an urgent task are presented.**

Keywords—distributed generation, photovoltaic systems, renewable energy, storage systems, thermal energy

I. Introduction

Currently, there is a problem of a significant discrepancy between daily insolation schedules and electricity consumption. To harmonize the energy balance of a stand-alone photovoltaic system, electrochemical batteries are widely used for that purpose. They are providing storage and exchange of electricity for the target of guaranteed power supply to consumers. Unfortunately, batteries have a limited operating lifetime, they are sensitive to operating temperature and have a high cost.

Typical stand-alone electrification examples are small villages and farm facilities. Among the electrical receivers of such consumers, a significant proportion is occupied by electric heaters. According to [1], the minimum daily consumption rate of hot water per human in a private house is 20~30 liters. Technological needs for milking one cow on dairy farms require an average of 24 to 28 liters of hot water per day [2].

For the consumers of the power supply under consideration, the accumulation of electricity of photovoltaic cells can be carried out not only in electrochemical batteries but also in water-heating installations. These installations will make it possible to reduce the cost of a photovoltaic power plant by reducing the capacity of batteries.

There are a large number of solar water heaters, characterized by simplicity of design and low cost. The specific cost of collectors of various designs differs by an order of magnitude. The simplest solar collectors cost from 2.3 thousand rubles/m2. Such collectors have an efficiency of about 19%. The most advanced evacuated tubular collectors cost already 25 thousand rubles/m2, which far exceeds the specific cost of photovoltaic panels. The efficiency of such collectors reaches 51~57% [3].

The level of insolation and weather conditions significantly affect the efficiency of solar collectors. Practically, in the conditions of central Russia, only seasonal use of solar water heating installations is possible from March to October with a probability of 70~80% of water heating up to 45~50 Celcius degrees [4]. The efficiency of photovoltaic conversion in a wide range of changes in insolation is almost unchanged, which expands the possibilities of photovoltaic power plants, including for hot water.

In this paper, the authors present investigations of exploring the possibility of reducing the cost of the system for accumulating electrical energy of a photovoltaic power plant through the use of combined electrochemical and electrothermal batteries.

II. Methods and Methodology

A. Object of the research

Potential objects of electrifications from power plants of renewable energy are the following: farms facilities, small agriculture enterprises, which are remote from centralized electrical network access. Typical examples are private houses, dairy farms, the power consumption of which includes a significant proportion of electric heaters.

B. The characteristics of the combined electricity storage

The authors show the characteristics of the combined electricity storage of a stand-alone photovoltaic power plant that supplies a private house. Energy needs at home can be evaluated as the sum of electricity consumption determined by social requires. They are the following: an average of 70 kWh per human per month [5], which is 2.3 kWh per day, or 7~9 kWh per family of 3~4 people including additional electricity consumption on hot water. Energy costs for heating water can be determined by the formula [6]:

$$P_t = m \cdot C_w \cdot (Q_2 - Q_1), \qquad (1)$$

where t – a time of heating water [s], P is the power of the heating element [kW], m is the mass of water [kg], C_w (4.2 kJ/kg·deg) – specific heat capacity of water, Q_2 and Q_1 – the final and initial temperature of the water.

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With an initial water temperature of 10 Celcius degrees, the daily energy demand of a water heater for heating 60~80 liters of water to 50 Celcius degrees will be about 10~13 kWh.

The total daily power consumption of the house for the considered example will be:

$$W = W_e + W_{wh} = 17\sim20\ kWh, \tag{2}$$

where W_e – is the electricity consumed by electrical loads, W_{wh} – the electric power consumed by the water heater.

This amount of electricity must be generated daily by a photovoltaic power plant, and the necessary amount of this energy must be supplied to the electric receivers through the storage systems.

A typical graph of the daily summer consumption of a rural home is shown in Fig. 1 [7,8] together with a photovoltaic generation schedule.

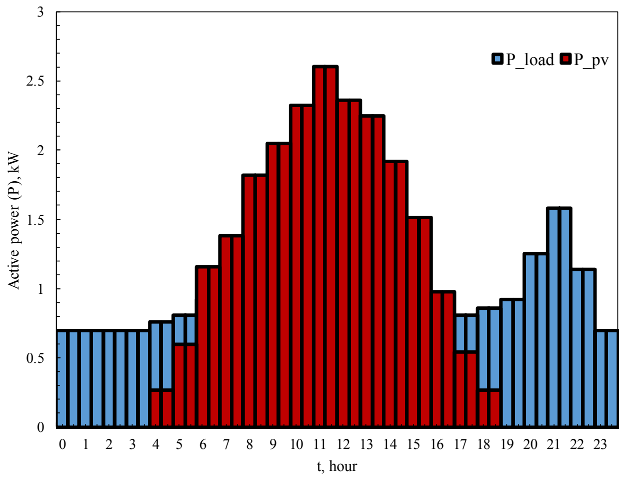

Fig. 1. Daily dependencies of the generation of a photovoltaic plant in Russia and the total load of a rural house

Electricity consumption for water heater of accumulative type can be assumed uniform throughout the day. The average power consumption of the water heater, with a daily energy consumption of 11.5 kWh, will be 0.48 kW. Maximum total power required 1.58 kW. The average power of night load is 0.9 kW (at 21:00 p.m.), daytime – 0.84 kW (at 15:00 p.m.).

The nominal power density of a photovoltaic solar battery is determined by the formula:

$$P_{sb} = P_i \cdot K = 180\ W/m2, \tag{3}$$

where P_i – is a benchmark of insolation (1000 W/m2), K – is the efficiency of monocrystalline silicon panels (18%).

The maximum power density of the solar battery at a latitude of 50 degrees, for example, the village of Kosh-Agach of the Altai Region, taking into account the maximum summer insolation of 750 W/m2 [8], will be 135 W/m2. The average specific capacitance of a solar battery per day in these conditions will be determined through the operating load factor of the daily insolation schedule [9] as:

$$P_{avg} = P_{sb} \cdot K_l = 68.4\ W/m2, \tag{4}$$

where K_l (0.38) – the operating load factor for the daily insolation schedule in the area of the village of Kosh-Agach. The specific daily energy of the photovoltaic power plant will be 1.23 kWh (W_{spec}).

The area of the solar battery is determined by the ratio of the required daily energy of the load and the specific daily capacitance of the photovoltaic conversion:

$$S_{sb} = W / W_{spec} = 16.3\ m3 \tag{5}$$

To design a photovoltaic power plant, single-crystal panels can be chosen, such as, for example, type HH-MONO-200 W. The nominal voltage and current of this panel are 36.5 V and 5.5 A, respectively. To generate the required amount of electricity should be used not less than N panels:

$$N = S_{sb} / S_p = 13 \tag{6}$$

Taking into account the efficiency of the batteries as 0.8, we take $N = 16$. The average daily power generation of a photovoltaic power plant will be $P_s = 1\ kW$, respectively, the daily energy is 24 kWh. The maximum noon power of photovoltaic generation is determined taking into account the specific capacitance of the daily insolation graph K_l at the considered latitude [9], as the following:

$$P_{max} = P_s / K_l = 2.6\ kW \tag{7}$$

Graphs of the total daily power consumption and generation of photovoltaic power plants for the considered example are shown in Fig.1. According to the nature of the distribution of these quantities during the day, there is a noticeable discrepancy between the maximum of insolation and maximum loads. To eliminate this contradiction, it is necessary to use the energy storage.

III. Research Results

Universal storage of electricity is an electrochemical battery. The daily energy balance of power consumption of a photovoltaic power supply system of a house with a battery storage for the example in question can be obtained by the following formula:

$$(P_{si} - P_{ei} - P_{hwi} + P_{ai}) \cdot t_i = min + P_{ai}, \tag{8}$$

where P_{si}, P_{ei}, P_{hwi}, P_{ai} – is, respectively, the power of photovoltaic generation, electricity consumption, electricity consumption for hot water supply, charge or discharge of a battery in the *i-th* time interval, taken to be as 1 hour.

An optimum energy balance, taking into account the discreteness of the equipment, will correspond to a small excess of photovoltaic generation (8), which will be unclaimed from the moment the batteries are fully charged. For the considered example, using the data of table 1, the authors found that the energy of charging batteries during the day is 11.75 kWh. The discharge energy is 9.95 kWh.

TABLE I. Aggregated Data of Calculations

t, hour	Power balance parameters		
	P_s, kW	P_e, kW	P_{sb}, kW
1	0	0.7	-0.7
2	0	0.7	-0.7
3	0	0.7	-0.7
4	0	0.7	-0.7
5	0.27	0.76	-0.49
6	0.6	0.81	-0.21
7	1.16	0.92	-0.24
8	1.38	0.97	0.41
9	1.82	0.92	0.9
10	2.05	0.81	1.24

t, hour	Power balance parameters		
	P_s, *kW*	P_e, *kW*	P_{sb}, *kW*
11	2.32	0.81	2.22
12	2.6	0.81	1.79
13	2.36	0.86	1.5
14	2.25	0.81	1.44
15	1.92	0.81	1.11
16	1.51	0.81	0.7
17	0.98	0.81	0.17
18	0.54	0.81	-0.27
19	0.27	0.86	-0.59
20	0	0.92	-0.92
21	0	1.25	-1.25
22	0	1.58	-1.58
23	0	1.14	-1.14
24	0	0.7	-0.7

Thus, the daily exchange rate of electricity will be 10 kWh. Taking into account the permissible (for reasons of service life of batteries), the discharge depth of 50% relative to the nominal capacity of the battery energy reserve will be 20 kWh. A sequence diagram of the battery's energy reserve is shown in Fig.2. *Curve 1* shows the change in charge per day, starting with the original 100% charge. *Curve 2* corresponds to the established periodic daily operation mode of the storage device.

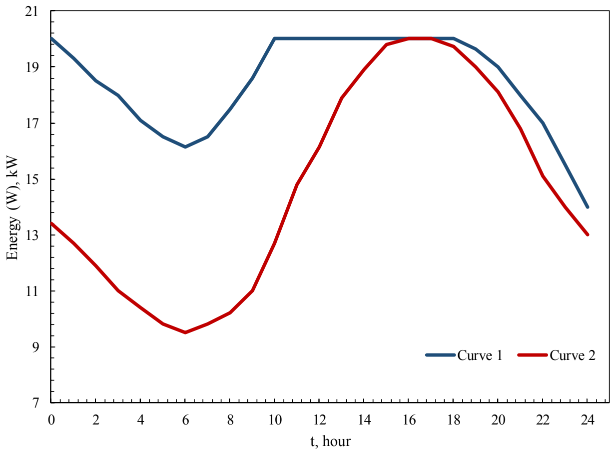

Fig. 2. The cyclogram of the battery power reserve.

The cost of a rechargeable battery, with a unit cost of lead-acid batteries of 0.06 \$/Wh [10], is \$ 1200.

Another variant of the power supply system with the release of hot water supply and accumulation of the necessary electric power for this purpose as a supply of hot water in a thermally insulated tank will reduce the capacity of electrochemical batteries by the amount of energy required for hot water supply at home. For this example, this value will be 11.5 kWh. The condition for this is to heat the daily volume of water to the required temperature during the active operation of the photovoltaic converters with a sufficient level of insolation. For this example, this time from 8 to 16 hours. During this time, a 1.5 kW electric water heater will provide the necessary heating of water with a power consumption of about 12 kWh.

The price of accumulative electric water heaters with a volume of 100 liters for most manufacturers ranges from \$ 120 to \$ 220 [11].

In this case, to provide electricity for electrical loads will require batteries capable of exchanging energy in the amount of 3.5~4.5 kWh per day. The total capacity of electrochemical batteries of a photovoltaic power plant will decrease to 7~9 kWh. The cost of storage devices will be \$ 420~530. The rechargeable batteries will be charged from 6 to 18 hours, consuming the charging power in accordance with the current energy balance of the stand-alone photovoltaic power plant.

The cost of a combined solar energy storage system will not exceed \$ 750, which is almost 2 times cheaper than electrochemical storage for this example. Fig. 3 shows a block diagram of a photovoltaic power plant with a combined storage of solar energy.

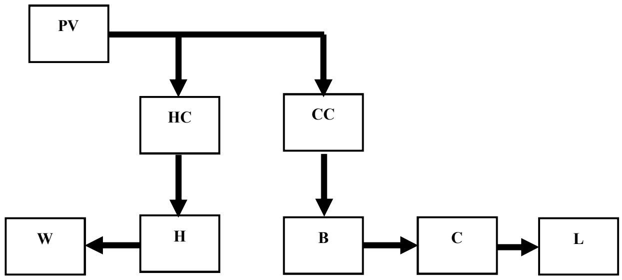

Fig. 3. Block diagram of a photovoltaic power plant with a combined accumulation of solar energy

The electricity from the photovoltaic panels (PV) is fed to the intelligent controllers: the charge (CC) of the battery (B) and the power to the water heater (HC). Battery energy through an autonomous inverter (C) feeds electrical loads (L). A water heater (H) receives electricity from photovoltaic panels that are not currently required by the storage battery. The water heater of the accumulative principle of action ensures the accumulation of solar energy during periods of maximum insolation into the thermal energy of water and ensures its storage during the day due to thermal insulation. When the water heater is on, the power of the photovoltaic power plant exceeds the electric consumption of the water heater – 1.5 kW.

Ensuring the maximum use of insolation is achieved by using MPPT technologies (Maximum Power Point Tracking) in the design of the considered controllers. These intelligent technologies ensure the operation of panels in the mode of generating maximum power corresponding to the current level of insolation.

The algorithm of the functioning of the circuit shown in Fig. 3 can be formulated as the following conditions:

a) With a high level of insolation, exceeding the optimal charge energy of electrochemical batteries, solar energy is converted into electricity and is distributed to the battery charge and water heating in the water heater. At the same time, the electric energy of a photovoltaic power plant is accumulated in electrochemical batteries and in the form of thermal energy of heated water. With charged batteries the energy is spent on water heating.

b) With an insufficient level of insolation, the electrical energy of the panels is directed only to the charge of the batteries.

c) In the absence of insolation, electrical and thermal characteristics are fed from the corresponding batteries of electrical and thermal energy.

IV. Conclusion

A. The reduction of energy intensity

The use of combined solar energy storage systems with electrochemical and heat accumulators in stand-alone photovoltaic power plants makes it possible to reduce the energy intensity of electrochemical accumulators by the amount of energy consumption for thermal characteristic.

B. The efficiency growth

The efficiency of direct conversion of photoelectricity into heat is significantly higher that its conversion through an intermediate in the form of an electrochemical battery.

C. The reduction of unitary cost

The unitary cost of the thermal accumulator is several times less than the electrochemical one. The work shows almost a double reduction in the cost of a combined solar energy storage system of a photovoltaic power plant for a private house.

D. The reduction of installed power of inverter

It is advisable to supply the electric water heater with DC from photovoltaic panels, which makes it possible to reduce the installed power of the inverter to a value determined by the peak value of electrical loads of AC. Considering the lower cost of the water heater controller compared to the inverter, it also reduces the cost of this photovoltaic power plant.

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