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Method of Calculating Power Capacity of Solar Power Plants

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ABSTRACT:In this article the method of calculation of the power of autonomous solar power station and its elements allowing to consider a change of loading during the day is developed, it is thereby correct to determine the necessary power of the battery and to exclude unreasonable excess of the power of elements of power plant and cost of the autonomous solar power station.

KEYWORDS: autonomous, autonomous solar power station, DC pulse converter, inverter, solar module, solar power station, voltage.

I. INTRODUCTION

Solar power generation is now practised almost worldwide, and the use of solar panels is constantly increasing.Many factors contribute to this, the most important of which is the recent use of alternative (renewable) energy sources, the depletion of the Earth's natural energy resources and the negative impact of traditional energy sources on the environment [1].

Solar power plants are constantly improving.Today, they can be used together with a central power supply or as an additional power supply that works completely autonomously.Solar power plants that are not connected to industrial power grids, i.e. autonomous solar power plants (ASE) designed to power small country houses, cottages, sports grounds, farm fields, call centres, etc. Consumers away from electrical networks, electricity usually requires large financial and labour costs.

The autonomous solar power plant (ASE) has a stabilized and unstable output voltage.Functional diagrams of autonomous solar power plants: solar panels that convert sunlight into electricity; a pulse converter converting a direct voltage to an alternating voltage; storage batteries for energy storage; consists of control devices for charging and discharging control.To design autonomous solar power plants, it is necessary to determine the rated power of solar modules, their number, the capacity of storage batteries, inverter and charge-discharge control devices. [1]

In this case, the following data are required to calculate the capacity of the solar power plant: location area; the total area of the house; the number of rooms; used electrical equipment; availability of heating and hot water supply; total maximum capacity of all electrical equipment; approximate operating time of each energy consumer.These issues are not fully covered in the existing literature, therefore, the development of a methodology for calculating the capacity of autonomous solar power plants and its elements is an urgent task.

II. MATERIALS AND METHODS

The purpose of this study is to develop a methodology for calculating the capacity of autonomous solar power plants, divided into several main stages for ease of representation. Consider in more detail the proposed step calculation method.

A. Step 1. Calculation of the output power of an autonomous solar power plant. When designing an autonomous solar power plant, it is necessary to first compile a list of all electricity consumers, find out their power consumption, voltage and add them to the list (Table 1).

If different power types and voltages are specified in the client list, their power should be recalculated on the main ASP power bus.Then the power of the individual loads on the main power bus is recalculated according to the following formula:

$$P_{oc}, i = P_{н,i}\eta_i; \qquad (1)$$

Here

$P_{H,i}$- is consumer power;

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P_{oc} - i is the capacity of the *i* - th consumer, converted to the main capacity of the Autonomous Solar Power Plant (ASP);

η_i The efficiency of the *i*-th autonomous voltage inverter (in Table 1, the efficiency of AIN and IPPN is accepted as 0.8).

If the DC consumer is connected directly to the main power supply or operates from a separate voltage of the battery, the voltage of the battery will be less than (No. 6, Table 1), then in the conversion formula (1), the efficiency is taken equally.[2]Then we need to calculate how much time a particular appliance consumes during the day and how much time the appliance consumes, determine the daily electricity demand, and write this information into the appropriate columns in the table.This creates a table of total energy consumption per day.A solar power plant can use a large amount of electrical equipment if their power consumption does not exceed the power generation at ASP. The list of electricity consumers includes permanent or temporary workloads (rarely, very rarely).

Table 1. Total daily energy consumption.

№	Consumers	Voltage U, Power (watts)	Power on the main bus, W.	Working hours hours / day	Energy consumption W * hours / day
1	Electrickettle	220 V, 1000 Vt	1250	0.25	312.5
2	Refrigerator	220V, 1200 Vt	1500	12	18000
3	Conditioners	220V 1000 Vt	1200	6	7200
4	Electricstove	220V, 1500 Vt	1800	0.25	450
5	TV set	220 V 80 Vt	80	6	480
6	Roomlighting(4 rooms)	220 V, 60Vt	60	6	360
7	Kitchenandshowerlighting	220V, 30 Vt	30	4	120
8	Other types of consumers (charger vacuum cleaner, etc.)	220 V, 30 Vt	30	2	60
	Total		5950		26982.5

In turn, periodic workloads are divided into stable and floating interval workloads (e.g. refrigerator No. 2, Table 1).Ignoring these factors can lead to an unreasonable increase in production capacity and an increase in the cost of an autonomous solar power plant.Therefore, it is necessary to correctly determine the output power of an autonomous solar power plant.To reduce the cost of ASP, it is necessary to create a schedule of daily load change, that is, a schedule of dependence on the total load capacity of consumers who work from time to time or during the day.In this case, it is necessary to avoid the simultaneous operation of a large or large number of low power consumers and distribute the loads during the connection so that the output power of ASP is minimal.For example, assume that the microwave is switched on only after the electric kettle is turned off (No. 1 and No. 2, Table 1).

It is also necessary to connect consumers to one autonomous inverter with one outlet to ensure uninterrupted connection and reduce the cost of ASP.[3]When planning a load change, it is not possible to define a load change interval with a floating operating interval (Refrigerator, Table 1).

Therefore, by simplifying the load change schedule, we assume that such loads work continuously.Based on the above, a daily load change schedule is generated.The total load capacity for the selected time interval is calculated using the following formula.

$$P_{H,j} = \sum_{i=l}^{N} P_{oc,i}; \qquad (2)$$

here$_{H,j}$ - i is the number of consumers connected to the network during the time interval.

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Table 2. Variation of daily loads.

№	Electrickettle Refrigerator	Consumption power over time, W.												
		C 700 до 705	C 705 до 710	C 710 до 800	C 800 до 1200	C 1200 до 1205	C 1205 до 1210	C 1210 до 1400	C 1400 до 1700	C 1700 до 1705	C 1705 до 1710	C 1710 до 1900	C 1900 до 2300	C 2300 до 700
1	Conditioners	1250				1250				1250				
2	Electricstove	1500				1500			1500	1500				1500
3	TV set	1000				1000			1000	1000				1000
4	Roomlighting(4 rooms)		1800				1800				1800			
5	Kitchenandshow erlighting												80	
6	Other types of consumers (charger vacuum cleaner, etc.)												60	
7	Total	30				30							30	
8	Electrickettle	30				30						30		
	Refrigerator	3810	4360	2500	2500	2560	4360	2560	2500	3750	4300	2500	2700	2500

Refrigerators, pumps, electric reels and several other electrical appliances at start-up consume 5-6 times more power than the "passport." If there are too many such consumers with such a high volume of electricity, this will lead to an increase in production capacity and the cost of an autonomous solar power plant. In this case, it is recommended to eliminate the simultaneous introduction of such electrical equipment and implement initial power consumption from batteries.[4]

During the day, the solar panel charges the battery and provides power to consumers.

We take into account the time of day: $\Delta t_{dv} = 14\ hours$ in summer (from 600 to 2000), $\Delta t_{dv} = 8$ hours (from 800 to 1600) in winter.

The output power of an autonomous solar power plant is then determined by the maximum load capacity for the summer day interval according to the following formula.

$$P_H = max\left\{P_{H,j}\right\},\ \forall\ j \grave{o} 1, M \quad ; \qquad (3)$$

where M is the number of time slots included in the summer day interval.

According to Table 2, the output power of the autonomous solar power plant is Pn = 4360 W, which is used to calculate the power of the ASP solar cell.

The above-mentioned ASP power output calculation technique takes into account the change in load power over time and is the norm. In a particular case, the load of the ASP does not change, i.e. constantly. Such consumers include cell sites, power supply systems for power plants and substations, traffic lights, etc.

In this case, the output power of the autonomous solar power plant should correspond to the full load power.

B. Stage 2. Calculation of the capacity of an autonomous solar power plant (ASP). At night, the energy stored in the battery of an autonomous solar power plant is consumed by the load. The energy of the battery (energy density) depends on its capacity with a nominal voltage. The capacity indicates the potential of the battery, which means that if it is fully charged, it can be charged for some time. Battery capacity is measured in ampere-hours. When you discharge the battery, the voltage and power consumption of the battery decreases. The ACE battery capacity is defined as the energy consumption time ΔC, defined as $\Delta t_{нв}$.

$$\Delta C = \frac{P_H}{U_H}\Delta t_{нв} = \frac{P_H}{U_H}\left(24 - \Delta t_{дв}\right); \quad (4)$$

here: P_H-rated lifting capacity;
U_H-rated load voltage;
$\Delta t_{нв}$-диапазон night time of day (in summer $\Delta t_{нв}$= 10 hours, in winter - $\Delta t_{нв}$= 16 hours);
$\Delta t_{дв}$ is the daily time interval.
Deep discharge can damage the battery.Therefore, battery manufacturers set the final discharge voltage, after which the battery will need to be turned off and recharged.The battery should never be discharged by more than 70-80% for long service life.
The battery discharge rate of an autonomous solar power plant.

$$S_p = \frac{C_H - C_{min}}{C_H}100\% = \frac{\Delta C}{C_H}100\%; \quad (5)$$

(5) Given the capacity C_H (4), we obtain an expression to determine the required capacity of the ASP battery as follows.

$$C_H = \frac{100}{S_p}\frac{P_H}{U_H}\Delta t_{HB}; \quad (6)$$

Equation (6) simplifies the calculation of the required capacity of the ASP battery under constant load. The most difficult process for ASP batteries is wintertime, so in the calculations, according to formula (6), we take $t_{нв}$ = 16 hours and assume that the discharge rate of the battery S_p = 70%. The higher the output voltage of the ASE, the lower the battery capacity, discharge current $I_r = P_r/U_n$ and its cost. In the case of lead-acid batteries for stationary (industrial), the maximum discharge current is equal to the battery capacity from 5 to 25 in digital amps. The lower the ASP current, the lower the ohmic power loss, the higher the efficiency and therefore lower the cost of a solar power plant. It is therefore advantageous to have high voltage electrical systems. Also, the higher the capacity of the power plant, the more useful it is in a high-voltage system compared to a low-voltage one.
In the past, almost all photovoltaic systems used 12V DC, so 12V devices powered directly by batteries were widely used. With the advent of efficient and reliable inverters, 24, 48 V and higher voltages are increasingly used in ASP. Thus, autonomous solar power plants that produce and consume less than 1000-1500 watts per day in combination with a voltage of 12 volts produce ASP of 1000-3000 watts per day and typically use 24 volts. The voltage in the system is a very important factor affecting the parameters of the inverter, control, charger and conductor. Once you buy these components, they will be difficult to replace. Some components of the system, such as photovoltaic modules, can be switched to a voltage above 12 V, while others - inverters, conductors and control equipment - are designed for a certain voltage and can only work in it. The Sn ASP battery is connected in series and parallel with a separate series of small storage batteries.[5] The series connection of these batteries is used to increase the voltage, in which case the capacity of the battery corresponds to the capacity of the individual battery. The rechargeable battery resulting from the parallel connection has the same voltage as the single rechargeable battery, and the capacity of such rechargeable battery is equal to the sum of the capacities of the single rechargeable batteries included therein. The battery power consumption of an autonomous solar power plant is calculated as follows.

$$W = C_н U_н; \quad (7)$$

The number of batteries connected in series in the system

$$n = U_н / U_{ab}; \quad (8)$$

here,
U_{ab} - the voltage of a single battery.
ASP the number of parallel branches in the battery

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$$m = C_н / C_{ab};\qquad (9)$$

here,
C_{ab} -capacity of a single battery.
Then the total number of individual batteries in the ASP battery

$$N = nm;\qquad (10)$$

Substituting equations (6) to (9) in (10), we determine the total number of individual batteries included in the ASP batteries in the following ratio:

$$N = \frac{100 P_H}{S_p W_{ab}} \Delta t_{HB};\qquad (11)$$

here $W_{ab} = C_{ab}U_{ab}$ - power consumption of a single battery. The higher the power density or capacity at the specified battery voltage, the fewer batteries are required in the ASP battery. By selecting the battery with the power given by equations (6) and (9), we generate an expression to determine the battery voltage ASP as follows:

$$U_H = \frac{100}{S_p} \frac{P_H}{mC_{ab}} \Delta t_{HB};\qquad (12)$$

In general, the ASP load is unstable, that is, it will change over time.According to Table 2, the load change can be close to the graphics shown in the figure at night (16^{00} to 8^{00} per hour). Figure 1.

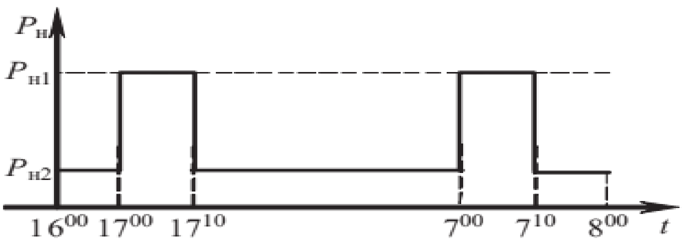

Figure 1. Simplified schedule for changing downloads.

To simplify the table, two values of P_{n1} = 4360 W and P_{n2} = 2700 W is provided for the load in five-time intervals. By combining the time intervals shown in the graph (Figure 1) with the same load values, we obtain a two-step load change graph (Figure 2, a). For loads defined as timeslots $\Delta t_1$and Δt_2, the sum of timeslots P_{n1} and P_{n2} is Δt_1= 1/3 hours and Δt_2= 15 * 2/3 hours, respectively.

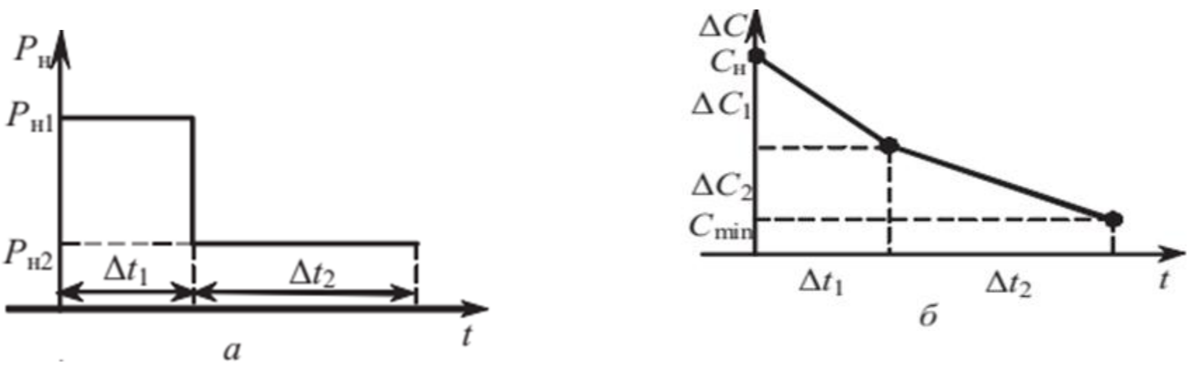

Figure. **2**. Schedule of change of load (a) and battery capacity (b).
The battery capacity graph of an autonomous solar power plant with a two-stage load is shown in Figure 2b.The battery charge rate for the first time interval is determined as follows.

$$\Delta C_1 = \frac{P_{H1}}{U_н} \Delta t_1; \quad (13)$$

And in the second interval

$$\Delta C_2 = \frac{P_{H2}}{U_н} \Delta t_2 \quad (14)$$

If $\Delta C = \Delta C_1 + \Delta C_2$, from (5), (13) and (14) we get an expression to determine the required power of an autonomous solar power plant.

$$C_н = \frac{100}{S_p U_н} (P_{н1} \Delta t_1 + P_{н2} \Delta t_2) \quad (15)$$

The calculation according to equation (15) gives the desired performance with exceptional accuracy. Changes in the night load schedule should be taken into account as accurately as possible to determine the required capacity.

C. Step 3. Calculate the charging power of the ASP. Charging the battery is the process of discharging the battery back: the battery is charged from an external current source or energy from the solar panel during charging.Full charging requires a charge equal to the battery capacity.In practice, when using batteries, as a rule, one of two methods of charging the battery is used: direct current charge or constant voltage charge.Both methods affect battery capacity equally.DC charge is generated by a current of 10% of nominal capacity in 20-hour discharge mode.For most lead-acid batteries, this current state is taken into account.The maximum value of the charging current is from 0.2 to 0.3 of the battery capacity.The regulator is required to maintain DC during the entire charging process.Disadvantages of this charging method are the need for constant monitoring and control of the charging current.[6]To increase the battery charge, it is recommended to gradually reduce the current as of the charging voltage increases. As the battery is charged, the temperature of the electrolyte increases, so its value must be controlled, especially until the end of charging. If the electrolyte density at the end of the charge is different from normal, in cases where the density is higher than normal, distilled water is added or when it is lower than normal, a sulfuric acid solution with a density of 1.4 g/sm^3 is added. need to be adjusted. To fully charge batteries in a short time, the accelerated charging method is used, which includes charging in two stages. In the first stage, charging is performed with the direct current until a voltage of 14.5 V is generated, in the second stage - with a constant voltage of 13.8 V. This fast charging method is sometimes called the I-U (current-voltage) charging method. This method allows the lead battery to be fully charged in about six hours with an initial charge current of 20%. Fast charging is more often used when batteries operate in cyclic mode, that is, in ASP. Based on the above, to charge the battery at 12 V (U_{ab} = 12 V), the maximum charging current, charge = 0.2 Kl/1 hour, and the maximum output voltage of the charger U_{max}, charge = 16.5 V. As a rule, the battery of an autonomous solar power plant consists of one battery connected by a series N. In this case, the output power of the charger is as follows:

$$P зу = nI_{max,char} U_{max,char} = 1,375 nI_{max,char} U_{ab} \quad (16)$$

Sequential charging of lead-acid accumulators is dangerous.When serially connected accumulators of different capacities are charged, their parameters (energy density, voltage) become more and more different.Therefore, in practice, the charging of individual batteries is widely used.N times less energy is required than n chargers from a single battery charge.

D. Step 4. Calculate the power of the ASP main bus. All consumers of energy and battery charge of an autonomous solar power plant receive power from the main bus.To correctly select the section of the main tyre and determine the strength of the ASP solar panels, you need to know the cross-country capacity of the main tyre.The capacity of the ASP main bus is defined as the sum of the load and battery capacity:

$$P_{ош} = P_н + P_{зу} / \eta_2 \quad (17)$$

where P_H - armament lifting capacity; P_{zu} - ASP charger power; η_2 - ASP charger efficiency.

E. Step 5. Calculate the power of ASP solar panels. Calculating the power of solar panels is necessary for their correct selection and providing an autonomous solar power plant with the necessary amount of electricity.The required power is determined by the ratio of the required solar energy.

$$P_{сб} = P_{ош} / \eta_1 = P_н / \eta_1 + P_{зу} / \eta_1 \eta_2 \quad (18)$$

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where η_1 is the efficiency of the low-voltage pulse converter. The amount of electricity produced by the solar cell depends on weather conditions. To take this factor into account, it is necessary to determine the solar energy that can be indicated in a particular area. Usually, this information can be obtained from a local supplier of solar panels or at a weather station. Two factors must be taken into account: average annual solar radiation, as well as its average monthly value under the worst weather conditions.[7] Using the first factor, the photovoltaic system can be calculated according to the average annual solar radiation, i.e. in some months, the energy will be more than required, in others - less. When choosing the second factor, if you exclude very long periods of weather, there will always be enough energy to satisfy at least the need. Now we can calculate the rated power of the photoelectric module. Taking the value of solar radiation for the period of interest from the tables and dividing it into 1000, we will get the so-called peak hours, i.e. in normal times, the sun shines as if with an intensity of 1000 W/m^2. In the selected period, the power module Rw generates the following amount of power:

$$W = kEPw/1000 \qquad (19)$$

where E is the insulation value for the selected period; k is a coefficient of 0.5 and 0.7, respectively, in summer and winter.Corrects the loss of capacity of solar panels when heated in the sun, and also takes into account the inclination of rays on the surface of modules during the day.The difference in its importance in winter and summer is associated with less heating of the elements in winter.

F. Step 6. Calculate ASP performance. The efficiency of an autonomous solar power plant is determined by the ratio of useful power to total power.

$$\eta = \frac{P_н}{P_{сб}} = \frac{P_н \eta_1 \eta_2}{P_н \eta_2 + P_{zu}} \qquad (20)$$

G. Step 7. Selection of autonomous ASP voltage inverters. When selecting an inverter, it is necessary to calculate the total load of devices connected to the inverter and increase the received power by at least 30%.The inverter selected at this power allows you to start electrical equipment, such as a compressor cooler, pump, etc., where the starting power is 3-4 times higher than the nominal.In this case, the self-contained voltage inverter supplies current to the electric kettle and the electric plate from one outlet in series. Also, the electric stove has more power than the electric kettle. Therefore, the inverter power is 2340 W and is determined by increasing the power of the electric plate by 30%, which is converted to the main consumer.

III. CONCLUSION

1. A method for calculating the capacity of an autonomous solar power plant and its elements has been developed, which allows taking into account the change in load during the day.
2. Taking into account the change in the load schedule at night allows you to accurately determine the required battery capacity.
3. The expression for determining the required battery capacity of an autonomous solar power plant can be easily generalized to any changes in the load table steps.
4. The developed method of calculating the capacity of autonomous solar power plants prevents an unreasonable increase in the capacity of power plant elements and an increase in the cost of an autonomous solar power plant.

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