Determination of optimal parameters of pumping unit of pumped storage power plant operating using solar energy

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Abstract. This article provides information on the importance of hydroelectric power plants with a capacity of 0.1...10 MW in energy systems and their advantages. Based on published sources on this issue, the parameters of a small pumped storage power plant proposed by the hybrid renewable modular closed-loop scalable (h-mcs-PSH) and Shell Energy North America (SENA) with a corrugated steel upper and a floating membrane lower reservoir are analyzed and the effectiveness of their use, taking into account the conditions in the Republic of Uzbekistan, was noted. The graph analytical methodology for determining the optimal parameters and operating modes of pumping units based on the criteria of maximum use of photoelectric plant power and minimization of consumption energy in supplying pumping units of small-capacity hydroelectric power stations with solar panel electricity is presented. The results of calculations based on this methodology are given.

1 Introduction

Today, the scale of use of pumped storage power plants (PSP) in the world's energy systems exceeds 9000 GW·h, which is more than 90% of all energy storage systems [1]. The use of PSPs is now a developing field in the energy system of our republic; in this regard, it is planned to build two PSPs with a total capacity of 400 MW [2].

According to the conclusions of the International Forum on Pumped Storage Hydropower (IFPSH) held in November 2020 regarding the importance of PSPs in the energy system, "without adequate storage, there is a very real risk that electricity grids of the future will not be able to provide reliable power without recourse to high-carbon sources of back-up such as gas turbines" [3].

According to the conclusions of the above-mentioned working group of the forum, PSP is one of the main mechanisms for increasing the efficiency of energy systems.

According to experts engaged in research in this field, PSP is recognized as the most effective technology due to the improvement in technology, the ability to store a large amount of energy, and the low storage cost [4 - 8].

Most of the PSP in use today have a capacity of more than 100 MW and high thrust values, and many experts believe that small power and low thrust PSP are not profitable.

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But according to the results of some studies published in recent years, it has been proven that small power PSP can be effective for small power systems and microgrids [9,10].

A 100 kW pilot project of PSP known as h-mcs-PSH is being developed in the USA [9]. According to the project's authors, these PSPs' capacity can be 0.1...10 MW, and they use membrane polymer reservoirs for water storage. According to the authors of the project, PSP of this type have the following advantages:

According to the authors of the project, PSP of this type have the following advantages:

- construction is carried out in the minimum period and volumes;
- polymer tanks are made of durable, solid materials and require minimal maintenance;
- since the water circulates in a closed system, its volume of loss is minimal and does not require natural water sources;
- has almost no negative impact on the environment;
- service period is more than 20 years;
- renewable energy sources can be used to supply pumps with electricity;
- energy storage costs are cheap compared to lithium-ion batteries.

US company Shell Energy North America (SENA) proposed a small power PSP concept with the upper reservoir made of corrugated steel and the lower reservoir made of a membrane material floating on the surface of the water and called it a "hydro battery" called [10]. SENA's proposed Hydro Battery Pearl Hill project has a capacity of 5 MW in hydro turbine mode and 9 MW in pump mode. The upper reservoir is 300 feet in diameter, 20 feet high, and its surface is covered with a special floating coating to prevent evaporation.

Taking into account the shortage of water resources in the Republic of Uzbekistan and the lack of sufficient places on the surface of the earth to generate high pressures to reduce the costs and increase the reliability of energy supply to pumping stations that supply farms with water, agricultural products processing enterprises and other energy consumers, low-pressure small-capacity We believe that it is appropriate to use PSP [11,12,13]. When choosing sites for PSP, the conditions of formation of pressure and the geological conditions for ensuring the safety of structures should be considered [14,15].

In the above-mentioned h-mcs-PSH and Hydro Battery Pearl Hill projects, it was noted that using renewable energy sources, primarily solar and wind energy, reduces operating costs. The main part of the cost of energy storage in the upper basin is the cost of electricity used to supply the pumping units (PU) of the PSP, and therefore determining the optimal operating modes and parameters of the pumping units that ensure the minimum of these costs and the maximum use of solar or wind energy is considered an important task.

2 Methods

PU, which receives energy from photovoltaic plants (PVP), is used to pump the required volume of water to the upper water basin of PSP, and its operating mode and parameters must be adapted to the operating mode and parameters of PVP. Figure 1 shows the scheme of such a hybrid device.

But because the PVP energy is changing rapidly, the parameters of the pumps are also changing rapidly. In such cases, the procedure for determining the operating mode of the PU can be given as follows.

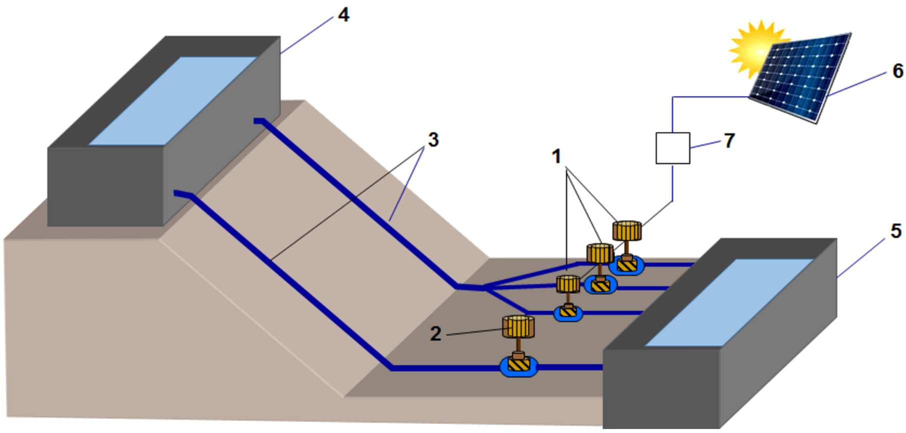


Fig. 1. Small power PSP scheme: 1 is pumps; 2 is hydro turbine; 3 is pressure pipes; 4 is upper water reservoir; 5 is lower water reservoir; 6 is photovoltaic plant; 7 is energy transfer blog.

To ensure the optimal ratio of PVP and PU, at the given time of day $T=t_2 - t_1$, the such operating mode of PU (number of pumps working at the same time, their capacity, water supply efficiency, u.w.c., PU water supply efficiency, power, consumption the amount of electricity produced) should be found, in which, taking into account the given restrictions, the maximum use of the electricity generated by PVP should be ensured, that is, the following requirement should be met.

$$\int_{t_1}^{t_2} N_{PU}(t)dt \approx \int_{t_1}^{t_2} N_{PV}(t)dt \qquad (1)$$

Pump pressure and water supply efficiency are the main energy parameters that determine the efficiency of PU in PSP.

The main condition for the optimal operation of the PU is to pump water from the lower reservoir to the upper reservoir with the help of pumps during the period of active solar radiation t_2 - t_1, the volume of water required for accumulating the specified energy in the selected energy system, that is, meeting the following requirement need

$$Э_{PU}(T) = \int_{t_1}^{t_2} N_{PU}(t)dt = 9{,}81\int_{t_1}^{t_2} Q_{PU}(t)H(t)\eta_{PU}^{-1}(t)dt \Rightarrow \min \qquad (2)$$

where $Э_{PU}(t)$, $N_{PU}(t)$, $Q_{PU}(t)$, $H(t)$, $\eta_{PU}(t)$ are, respectively, the amount of electric energy consumption, power, water supply efficiency, efficiency and useful work coefficient of PU during operation time t.

Therefore, according to (1), for the consumption of electric energy to be minimal, it is necessary to choose such an operation mode of the PU so that at the appropriate values of the water supply efficiency and pressure, the device's useful work coefficient is at maximum values.

Requirements (1) and (2) above must be met subject to the following conditions and restrictions

According to the upper reservoir volume:

$$V = \sum_{i=1}^{T} Q_i \cdot t_i \qquad (3)$$

where Q_i is the values of water consumption driven by the pumps to the pressure pipe, and i is time excesses

According to the constraint of head values:

$$H_{min} \leq H \leq H_{max} \quad (4)$$

The volume of the upper water reservoir is determined by the following relationship in the average values of η_{pu} and H according to the requirements for the electric energy that needs to be accumulated in the PSP.

$$V = 367 \cdot Э \cdot \eta_{pu} \cdot H^{-1} \quad (5)$$

We can determine the change of PU pressure based on the following equation of the pipe system head characteristic

$$H_{pipi} = H_G + K \cdot Q_i^2 \quad (6)$$

where H_G is the geometric head value, K is the coefficient of hydraulic resistance of the piping system.

When determining the range of change of Q_i, it is necessary to determine the values of Q_{min} and Q_{max} based on their average value $Q_{av} = V/T$ and select the number of pumps. The values of Q_{min} and Q_{max} and H_{min} and H_{max} are the basis for choosing the brand of pumps.

We believe that it is appropriate to demonstrate the steps to fulfill the requirements (1) and (2) and to determine the value of $Э_{PU}(t)$ in a graphical way of determining the pump parameters.

The connection diagram of the pumps with the pressure pipeline is shown in Fig. 1; the number of pumps is three.

In this case, the number of pumps working simultaneously as the common pressure pipe can be in the following order.

1. Pump 1 works alone.
2. Pump 2 works alone.
3. Pump 3 works alone.
4. Pumps 1 and 2 work together.
5. Pumps 1 and 3 work together.
6. Pumps 2 and 3 work together.
7. Pumps 1, 2 and 3 work together.

In these options, the operation mode of the pumps is represented by the graphs shown in Fig. 2. In the graphs, the operating modes of the pumps are defined by operating points A_1, A_2,.... A_{1+2+3}, at each point, the corresponding values of Q, H, η, and H can be determined in the graph.

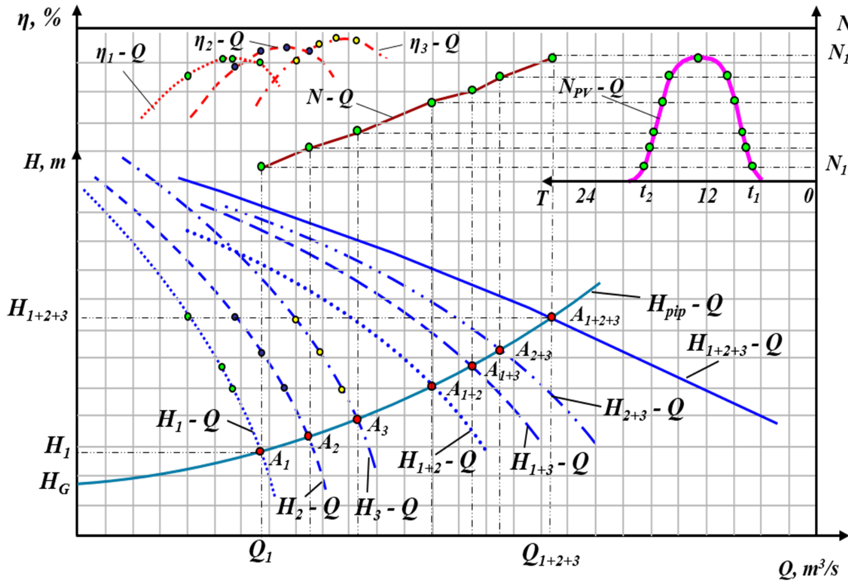


Fig. 2. Graphs of operating modes of three pumps connected in parallel: $H_{1,2,3} – Q$ - 1,2 and 3 - head characteristics of pumps; $H_{1+2,1+3,2+3,1+2+3} – Q$ - head characteristics of pumps in parallel operation; $\eta_{1,2,3} – Q$ – efficiency of pumps characteristics; $N – Q$ – characteristics of pump power, $N_{PV} – Q$ – power characteristic of PVP.

Determining the power values corresponding to each operating mode, i.e., operating points of pumps operating in parallel is carried out as follows

$$N_{PUi} = 9.81 \cdot H_i \cdot Q_{PUi} / \eta_{tot\, i} \tag{7}$$

where η_{tot} is the total useful work coefficient of pumps working in parallel. This value can be determined as follows, for example, for point A_{1+2+3}

$$\eta_{tot} = \frac{Q_{1+2+3} \cdot \eta_1 \cdot \eta_2 \cdot \eta_3}{Q'_1 \cdot \eta_2 \cdot \eta_3 + Q'_2 \cdot \eta_1 \cdot \eta_3 + Q'_3 \cdot \eta_1 \cdot \eta_2} \tag{8}$$

where Q'_1, Q'_2, Q'_3 are the values determined from the graph in parallel operation of the pumps, η_1, η_2, η_3 are the values obtained from the η-Q graph of the pumps.

Based on the calculated N_{PU} values, the N_{PU}-Q graph and the N_{PU}-t graph of the energy power that the PVP should provide to the pumping device corresponding to the intervals t_1 and t_2 of the day are constructed (Fig. 2), and the amounts of electricity consumed by the PU and produced by the PVP are determined

$$Э_{PU} = \sum_{i=1}^{T} N_{PUi} \cdot t_i ; \qquad Э_{PV} = \sum_{i=1}^{T} N_{PVi} \cdot t_i \tag{9}$$

where t_i is the time intervals of solar radiation in hours.

According to the results of calculations (1), we determine the coefficient of use of PU from PVP energy to evaluate the fulfillment of the requirement

$$K_i = Э_{PUi} / Э_{PVi} \quad (10)$$

Alternatively, the fulfillment of condition (3) should be checked in the following manner

$$V = Q_1 \cdot t_1 + Q_2 \cdot t_2 + Q_3 \cdot t_3 + Q_{1+2} \cdot t_{1+2} + Q_{1+3} \cdot t_{1+3} + Q_{2+3} \cdot t_{2+3} + Q_{1+2+3} \cdot t_{1+2+3}$$

In this way, the optimal option of pump device parameters and operating mode is determined among all the options included in the calculations based on the requirements and conditions (1), (2), (3), and (4) according to the methodology presented above. The sequence and order of calculations are described in the block diagram presented in Figure 3.

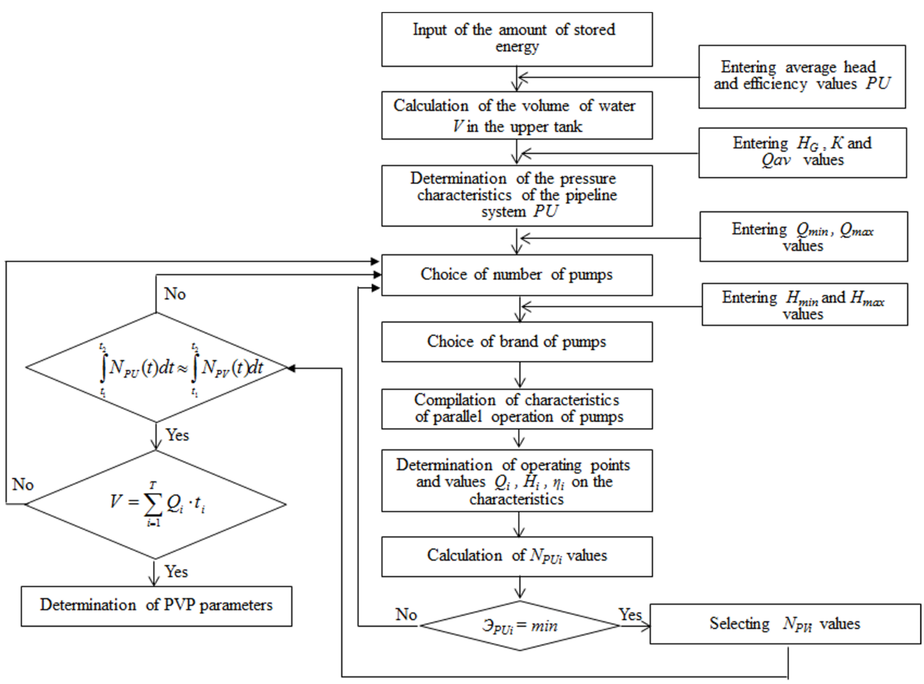


Fig. 3. Block diagram of the method of determining the parameters of the pump and photoelectric device

3 Results and discussion

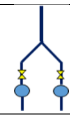
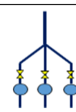
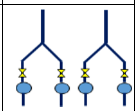
As an example of the methodology presented above, we present the results of calculations of the working mode and parameters of the PU according to four options.

To accumulate 2600 kW·h of electric energy in the power system, it is required to collect the required amount of water in the upper reservoir with the help of PU. It is envisaged that the pumps will be supplied with electricity using the PVP. If the average pressure of the pump is 25 meters and efficiency, if we take it equal to 0.8, the volume of water needed per day is equal to 33000 m3 according to (5).

To calculate the capital costs for PVP, we use data from the International Renewable Energy Agency for the year 2021, and according to them, the cost of solar panels is 857 $/kW [16].

The results of the calculations are presented in Table 1. According to these results, Option 3 is the most appropriate, as it has the highest solar energy utilization factor, the lowest PVP capital costs, and close to the lowest electricity consumption.

Table 1. Results of calculation of PVP and PU parameters

Parameters \ Options	Option 1	Option 2	Option 3	Option 4
Number of pumps	1	2	3	4
Pump pipe diagram				
Brand of pumps	D6300-27	D3200-33 D3200-33	D2000-21 D2500-62 D2500-62a	D1600-90 D2000-21
Head, m	20-29	21-30	22-26	20-28
Pumps maximum useful efficiency	0.89	0.87	0.86 0.87	0.80 0.86
Total water delivery efficiency of the pumps, m^3/s	1.1…1.5	1.2…1.6	1.15…1.7	1.1…1.6
The maximum capacity of the pumping unit, kW	580	560	400	540
Amount of electrical energy consumption of the pumping unit, kW·h	2625	2700	2650	2780
Operating time of the pumping unit, hours	4.6	4.9	9.0	5.2
The maximum power of the photoelectric device, kW	600	600	400	550
Electricity produced by the photoelectric device, kW	3860	3860	2972	3350
Coefficient of use of the pumping device from the photovoltaic plant energy	0.68	0.70	0.89	0.83
Capital costs for a photovoltaic plant, dollars	514200	514200	342800	471350

Economic indicators of small power PSP were analyzed in [9,17,18]. For example, the initial capital costs for PSP with a capacity of 10 MW are almost 1.36 times greater than the costs of lithium-ion batteries of such capacity, and the levelized cost of storage (LCOS) is slightly cheaper ($221/MW·h 238 $/MW ·hours) is shown. But taking into account the half-life of lithium-ion batteries (10 years) compared to PSP, the capital costs for lithium-ion batteries double over 20 years and increase by 1.47 times compared to PSP. In addition, the fact that the storage duration of lithium-ion batteries is 4 hours, 8...10 hours for PSP, once again shows their advantage. Based on the following analysis, it can be shown that this hybrid system is economically efficient because electricity tariffs are relatively cheap compared to the tariff of thermal power plants(TPP), despite the high initial capital costs for the use of solar energy for small-power PSP.

Currently, the price of electricity from TPP has risen to relatively high levels due to the increase in fuel prices; for example, in 2022, it will reach 330 euros/MWh in Europe, 120 euros/MWh in Japan and Korea, and 91 dollars/MWh in the USA [19]. According to the information from the International Agency for Renewable Energy Sources, the average price of solar energy in the world in 2021 is $48/MWh [17]. The cost of energy from solar power plants in the Republic of Uzbekistan is announced at $26.79/MWh (Masdar Clean Energy company) and $42.73/MWh (Total Eren company) [20].

Suppose we accept the average price of electric energy from thermal power plants as 180 $/MWh and the price of solar energy as 48 $/MWh. In that case, the difference in the price of supplying the pumping equipment of PSP with electric energy from the PVP is 132 $/MWh. This difference allows to cover the capital costs spent on the construction of the power plant in a short period and to increase the efficiency of the PSP.

4 Conclusions

1. Currently, based on the analysis of the technical and economic parameters of small-power PSPs, scientific-research work has been carried out to determine their efficiency; PSPs with a power of 0.1...10 MW, pump devices supplied by solar or wind energy provide consumers in the Republic of Uzbekistan with reliable, cheap, «green" energy can be one of the most effective directions.

2. A graph analytical method for determining the parameters and operating mode of pump units in small-power PSPs based on the requirements of maximum use of solar energy and minimization of energy consumption was proposed.

3. With the help of the proposed methodology, it was determined that it is possible to ensure the maximum level of use of the energy of the photovoltaic device based on the correct selection of pump parameters and operating modes. As a result of this, economic efficiency can be achieved. For example, to accumulate the water volume of 33000 m3 in the upper water reservoir, which is necessary for the accumulation of 2600 kWh of electricity, in the most economically convenient option, the maximum power of the solar power plant is 400 kW, and in this case, the solar energy utilization coefficient of the solar power plant is equal to the highest 0.89, and minimum capital costs are achieved.

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