Hydraulic Energy Storage of Wind Power Plants

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Abstract: The article discusses information on the need to accumulate energy from renewable sources to improve their efficiency, as well as some examples of the integration of systems for hydraulic energy storage and renewable sources, which ensure an increase in the reliability and volume of energy generation. The method for determining the parameters of the hydraulic energy storage system of a wind power plant, which is based on the balance of the daily load produced and spent on energy storage, is presented. This technique, with changing daily loads, makes it possible to determine the main parameters of the complex, including the volume of accumulated water, the coefficient of energy use of the wind power station. A functional diagram of the programmed control of the parameters of a pumped storage and wind power plant for the optimal use of the wind potential in hydraulic energy storage presented. Based on the results of calculations using the proposed method, the main parameters of the system based on a pumped storage and wind power plant with a capacity of 100 MW were determined, the efficiency of hydraulic energy storage was determined in comparison with lithium-ion batteries.

1 INTRODUCTION

Traditional centralized power systems have significant drawbacks, such as significant energy losses due to the remoteness of some consumers, insufficient flexibility of the production process caused by its low maneuverability, lack of proper regulation of consumption and energy tariffication. All these disadvantages ultimately lead to an increase in fuel consumption, the degree of CO_2 emissions and the cost of energy produced. In this regard, recently, localized power systems such as micro grid, smart grides, distributed generation clusters and virtual power plants are increasingly being used. Such systems can help solve very important problems, such as optimization, stabilization, flexibility of the power system, integration of renewable energy sources and "smart" control centers in the process of energy production and distribution [1,2,3]. Accumulation of an excess part of energy for use in peak hours is a necessary procedure for local power systems, for which electrochemical, regenerative - fuel and other energy storage devices are most often used.

Currently, the method of hydraulic energy storage has the best performance among storage devices and is considered as an effective direction for expanding the possibilities of using renewable energy sources, despite the fact that the decisive factors are the availability of sufficient natural resources, conditions for the construction of reservoirs and obtaining the necessary pressure [4,5].

The development of integration of systems for the use of wind power plants and hydraulic storage can lead to an increase in the share of wind energy on average up to 20% in the total energy consumption [6]. Investigating this issue depending on the power consumption, the author of [7] asserts that up to 80% of wind energy can be realized in power supply systems, provided that pumped storage is used. An increase in the utilization rate of wind energy is also observed with an increase in the duration of energy storage, so, for example, up to 90% of wind energy can be used to accumulate water in the upper reservoir for 1 ... 3 days [8].

In [9], an overview of the prospects for the development of hydraulic energy storage in the light of sustainable development was presented. According to this review, the most promising direction is the hybrid use of pumped storage power plants (PSP) of low power in a complex with wind and solar power

plants. This is confirmed by the results of the study, indicating an increase in the reliability and volume of energy generation by hybrid solar and wind power plants compared to their individual work [10].

The authors of [11, 12, 13] came to the conclusion that an integrated system for the use of wind energy and PSP under certain conditions is the most economically and technically competitive technology in different geographic latitudes.

In [14], the issues of large-scale integration of renewable energy sources with the use of pumped storage power plants into the Irish power system are considered on the example of the use of wind energy. The main key issues were considered: capital costs, optimal parameters and aspects of operation. The results of the study showed that the PSP allows increasing the efficiency of the use of renewable energy sources and reduces operating costs.

The integration of a PSP into a wind power plant system in Spain increases the profitability of this integrated system and minimizes wind energy losses [15].

The work [16,17,18] studied the possibility of maximum use of wind energy in combination with existing autonomous thermal power plants by using pumped storage power plants in the isolated energy system of the islands of Karpathos and Kasos, located in the Southeast Aegean Sea. The results of this study proved the economic feasibility of using low-power wind turbines to power pumping units of pumped storage power plants, even without taking into account the undoubted environmental benefits.

With the optimal integration of wind energy with a pumped storage power plant in lake Turkana (Kenya), the hydraulic energy storage of the wind turbine made it possible to reduce the energy deficit to 46%, which is equivalent to receiving an income of more than 10 thousand dollars per day [19].

2 METHODS AND MATERIALS

A schematic of a low-power PSP with a wind turbine is shown in Figure 1.

According to this scheme, the main energy producer is a wind power station (WPS), consisting of several wind turbine, which, in hours of minimum energy consumption, having excess power, supplies power to pumping units (PU) of a pumped storage power plant for accumulating water in the upper reservoir. During peak hours of energy consumption, when the power of the wind turbine is not sufficient, water from the upper reservoir is supplied to the

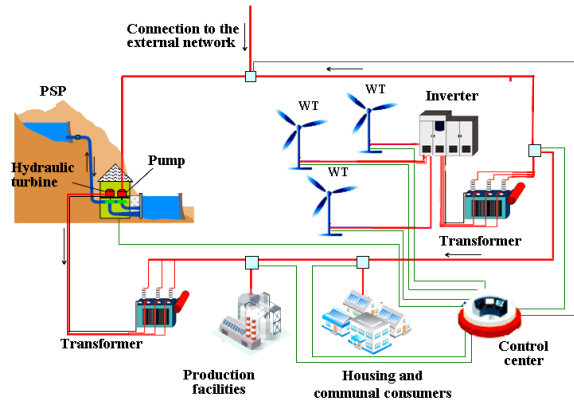hydro turbines to generate energy, and then to the lower reservoir.

Figure 1: Scheme of low power pumped storage power plant with wind farm.

With known values of the power of the wind flow, the installed power of the wind farm must be determined based on the values of the daily load schedule. Assuming that the energy generated by the wind turbines is used for two purposes: the main part of the energy is directed to the needs of the consumer, and the excess is used for storage, i.e. to power the PU. The average graphs of the daily load and energy of WPS with a maximum power of 100 MW are shown using the example shown in Figure 2.

For this example, the following expression is valid, which follows from the (1) for balancing the daily load and the generated energy.

$$E_{WPS} \cdot \eta_E = \int_0^T P(t)dt, \qquad (1)$$

where E_{WPS} – generated energy by WPS over time T; η_E – efficiency in the process of transferring energy to the consumer; $P(t)$ – load consumption values at points in time t. From here we can determine the average power of the WPS over time T (2):

$$N_{WWS\ av} = \frac{\int_0^T P(t)dt}{T \cdot \eta_E}. \qquad (2)$$

The installed capacity of a wind farm can be determined by the following (3):

$$N_{WPS} = N_{WT} \cdot n, \qquad (3)$$

where n – number of wind turbines.

Determination of the type, brand and number of installed wind turbines must be carried out on the basis of a feasibility study, taking into account local conditions on the basis of considering several options.
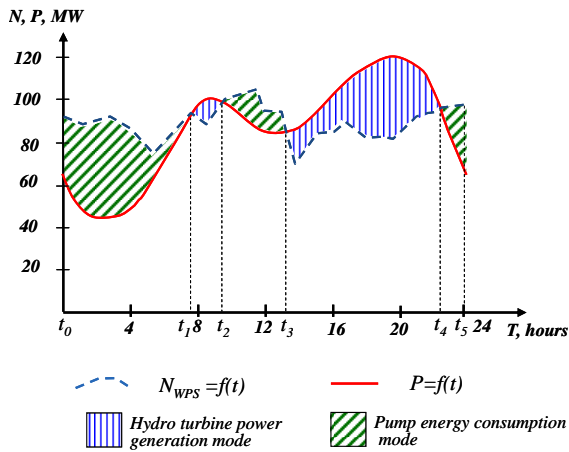
Figure 2: Schedule of the operating mode of a low-power PSP with a WPS.

All options must meet the condition specified in (1).

The obtained values of the power of the WPS N_{WPS}, depending on the time t, can be used to determine the mode of operation of the PSP with the WPS (see Figure 2 graph $N_{WPS}=f(T)$).

The condition for the energy balance of a PSP with a WPS in its pumping mode, i.e. when there is an excess of the generated energy over consumption, it is described by the following balance (4)

$$\sum_{i=1}^{n} N_{WPSi}t_i - \sum_{i=1}^{n} P_i \cdot T = \sum_{i=1}^{n} N_{Pi}t_i = E_P, \quad (4)$$

N_P, E_P - power and energy consumption in pumping mode.

From here we determine the maximum volume of the upper reservoir according to the well-known (5)

$$V_{max} = \frac{367 \cdot \eta_{pum}\left(\sum_{i=1}^{n} N_{WPSi}t_i - \sum_{i=1}^{n} P_i \cdot t_i\right)}{H_{Pi}}. \quad (5)$$

From (5) it can be seen that the volume of the reservoir V is determined in direct dependence on the amount of energy that must be accumulated, and in inverse dependence on the pressure H_P.

The volume of water in the upper and lower reservoirs during the day will be variable, and depends on the operating time of the PSP in turbine and pumping modes. To assess changes in water volumes, graphs $W_{lev} = f(V)$ are used, characterizing the dependence of the water level W_{lev} in reservoirs on their volumes V.

The excess capacity of the PSP $N_P = N_{WPS} - P$ must be used to power the PSP pumping the volume of water ΔV_H into the upper reservoir, for example,

according to the graph in Figure 2 during the time from t_0 to t_1, t_2 to t_3 and from t_4 to t_5.

When there is not enough WPP power to cover the daily load schedule, the lack of power $N_H = P - N_{WPS}$ is compensated by transferring the PSP to the mode of power generation with water supply to the hydro turbines, which will generate the missing electricity. For example, according to the schedule in Figure 2 during the time from t_1 to t_2 and t_3 to t_4. It is convenient to present the calculation results in tabular form (Table 1).

The amount of electricity is determined by discrete summation of the products $N \cdot \Delta t$ in fixed time intervals, for example, for the period t_{0-1}

$$E_{P(0-1)} = \sum_{i=1}^{n} N_{Pi} \cdot \Delta t_i,$$

and for the period t_{1-2}

$$E_{H(1-2)} = \sum_{i=1}^{n} N_{Hi} \cdot \Delta t_i$$

The volume of water supplied by the PU to the upper reservoir in the first period of operation an be determined as follows (6)

$$\Delta V_{P(0-1)} = \frac{367 \cdot E_{P'(0-1)} \cdot \eta_{pum}}{H_{P(0-1)}}, \quad (6)$$

where $H_{P(0-1)}$, η_{pum} – head and efficiency of pumped storage power plant in pumping mode.

With the alternating supply and withdrawal of water from reservoirs, the water level in them changes and, therefore, the pressure values of the PSP will be different and they are determined by the following relationship (7) [20],

$$H_{Hi,Pi} = H_{Hi,Pi}^{G} \pm \Delta H_i, \quad (7)$$

where ΔH_i is the pressure loss in the water conduits, which depend on the flow rate of the pump or turbine Q and can be calculated using well-known hydraulic calculation methods. In the above formula, the (+) sign corresponds to the pumping mode, and the (-) sign to the turbine mode, H^G – geometric head.

When the time of energy insufficiency of the WPP t_{1-2} comes, the HP will be stopped and the hydro power plants (HPP) will be put into operation with the supply of a volume of water $\Delta V_{H(1-2)}$ (8) (Figure 2 and Table 1).

$$\Delta V_{H(1-2)} = \frac{367 \cdot E_{H(1-2)}}{H_{H(1-2)} \cdot \eta_{tur}}, \quad (8)$$

$H_{H(1-2)}$, η_{tur} – head and efficiency of pumped storage power plant in turbine mode.

Table 1: Determination of the capacity of the PSP.

Time of day	Daily load of electric power P, kW	WPS power N_{WPS}, kW	Pumping power regime, N_P, kW	Turbine power, N_H, kW	The amount of electricity in pumping mode, E_P, kW/h	The amount of electricity in turbine mode, E_H, kWh	Volume water supply upper reservoir, V_P, m^3	Volume water supply lower reservoir, V_H, m^3
t_{0-1}	$P_{i\,(0-1)}$	$N_{WPS\,i\,(0-1)}$	$N_{P\,i\,(0-1)}$	-	$E_{P(0-1)}$	-	$\Delta V_{P(0-1)}$	-
t_{1-2}	$P_{i\,(1-2)}$	$N_{WPS\,i(1-2)}$	-	$N_{Hi(1-2)}$	-	$E_{H(1-2)}$	-	$\Delta V_{H(1-2)}$
t_{2-3}	$P_{i\,(2-3)}$	$N_{WPS\,i(2-3)}$	$N_{P\,i\,(2-3)}$	-	$E_{P(2-3)}$	-	$\Delta V_{P(2-3)}$	-
t_{3-4}	$P_{i\,(3-4)}$	$N_{WPS\,i(3-4)}$	-	$N_{H\,i(3-4)}$	-	$E_{H(3-4)}$	-	$\Delta V_{H(3-4)}$
t_{4-5}	$P_{i\,(4-5)}$	$N_{WPS\,i(4-T)}$	$N_{P\,i(4-T)}$	-	$E_{P(4-5)}$	-	$\Delta V_{P(4-5)}$	-

The volume of water in reservoirs corresponding to the operating mode of the PSP and WPP, shown in Figure 2 can be determined by the maximum value of ΔV_H or ΔV_P according to Table 1.

The water flow rate of the PSP in turbine and pumping modes Q_H and Q_P at fixed times t_i can be determined based on the values of powers and heads according to the following formulas.

$$Q_{Hi} = \frac{N_{Hi}}{9,81 \cdot \eta_{tur} \cdot H_{Hi}} \,,$$

$$Q_{Pi} = \frac{N_{Pi} \cdot \eta_{pum}}{9,81 \cdot H_{Pi}} \qquad (9)$$

One of the specific energy indicators is the utilization rate of the generated and consumed energy, calculated according to the following relationship.

$$K_t = (E_{WPS} - E_P + E_H) / E_{WPS} \qquad (10)$$

Thus, we can summarize that the above method allows you to determine the parameters of the pumped storage power plant, the maximum corresponding to the capacity of the wind farm and the daily electrical load.

For this complex, a functional diagram of the execution of operations for the programmed control of the parameters of PSP and WPP has been developed (Figure 3).

At the first stage of the complex functioning, in order to resolve the issue of "accumulate or generate energy", the power value of the N_{WPS} at time t compared with the corresponding power of the daily load schedule P, because of which one of three possible operations performed.

a) $N_{WPS} = P$, at the same time, the PSP does not work, the loads are covered by the energy of the WPS.

b) in the case of $N_{WPS} > P$, an excess of energy is observed, which must be directed to feed the PU in order to accumulate water in the upper reservoir.

c) the state of the $N_{WPS} < P$ shows the lack of generated energy, which precedes the start of the power plant with water supply from the upper reservoir.

Thus, the main task of the first stage is to determine the time and conditions for the start-ups of the HPP and PU according to the parameters of the N_{WPS} and P.

The second stage begins with the start-up of the PU with a full or almost full volume of water in the lower reservoir. During the operation of the pumps, it is necessary to control the water level in the lower reservoir and the power of the pump in order to perform the following operations:

- when the water level drops to the level of the dead volume, the PU is switched off;
- if N_P does not correspond to the P_H value, which is characterized as the difference in the capacities of the $P_H = N_{WPS} - P$ (excess power of the WPP, directed to power the PU), an operation is performed to increase or decrease the flow rate of water supplied to the PU in order to achieve the correspondence $N_P = P_P$.

At the third stage, when $N_{WPS} < P$, in order to replenish the missing part of the load, the hydro power plant is launched. During the period of operation of the HPP, N_H is regularly measured and it is compared with the value of P_H, which characterizes the difference $P_H = P - N_{WPS}$. If these values are equal, this means that the power of the power plant is sufficient to cover the load curve and the position of the water level in the upper reservoir is checked, i.e.
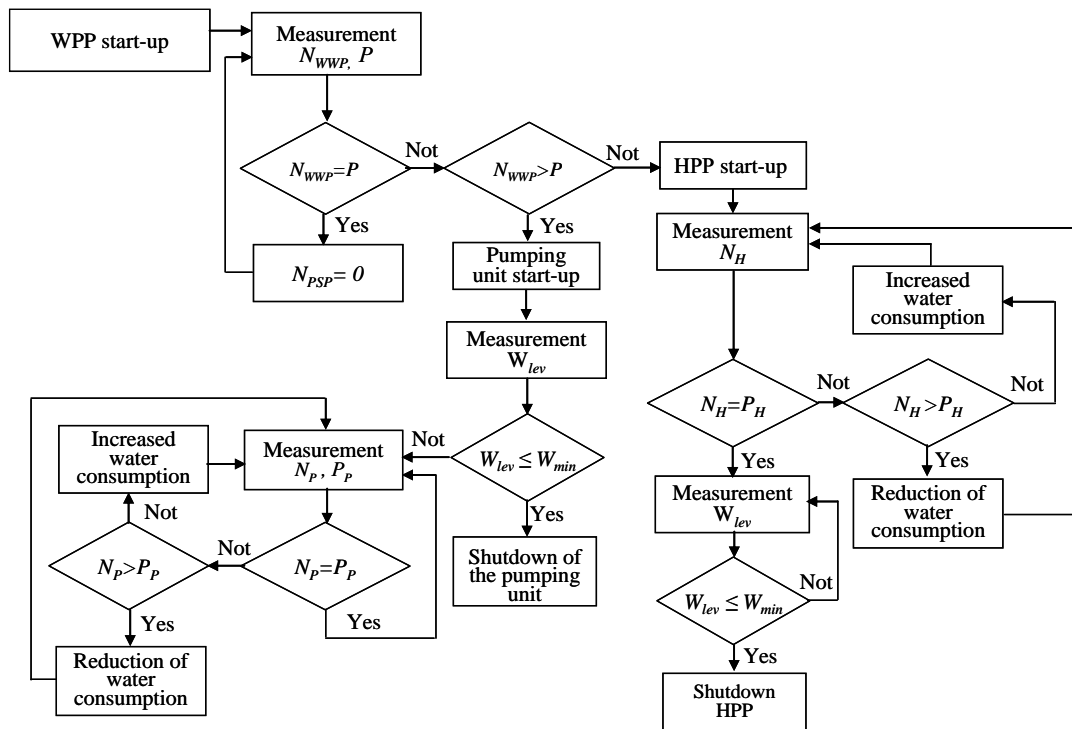
Figure: 3. Functional diagram of PSP with WPS.

$W_{lev} \leq W_{min}$. If the water level drops below W_{min}, the power plant is turned off and the pumped storage power plant switches to pumping mode. In case of non-compliance of $N_H \neq P_H$, a command is given to increase or decrease the flow rate of water supplied to the power plant to achieve the balance $N_H = P_H$.

3 RESULTS AND DISCUSSION

Consider a certain local power system with a daily demand from 800 to 1050 MW·h based on a wind farm, generating 850÷1100 MW×h of electricity per day, the schedules of $N_{WPS} = f(T)$ and $P = f(T)$ of which are shown in Figure 2. Based on the results of calculations performed using the characteristic graphs $N_{WPS} = f(T)$ and $P = f(T)$, the following indicators were obtained:
1) The amount of accumulated energy is $E_P = 110÷150$ MW·h, and the generated energy $E_H = 76÷104$ MW×h.
2) Reservoir volume V=8 000 000÷10 230 000 m3
3) Installed capacity of WPP $N_{WPS} = 100$ MW
4) Installed capacity of PU and HPP $N_P = 55$ MW, $N_H = 35$ MW
5) The average operating time of the PU is 12.5 hours, and the HPP – 11,5 hours.
6) Average head $H_P = 40,0$ m, $H_H = 38,5$ m.

The calculation results show that the amount of accumulated energy is 13,0 ÷13,6 % of the generated, for which it is necessary to build a 55 MW PSP with two reservoirs with volumes of 8,0 ÷10,23 million m³. The energy utilization factor of the WPS is 0,91 ÷0,96, which is one of the highest indicators for this type of power plant [7].

In order to answer the question of how economically beneficial it is, we compare the costs of hydraulic energy storage with the costs of its storage by lithium-ion batteries, which are one of the most common storage devices in 2021. According to the financial consulting company Lazard, given in [21], the LCOS of lithium-ion batteries of the LIP type with a capacity of 100 MW is 146... MWh. These costs take into account the cost of storing power for 4 hours for lithium-ion batteries, and for 10 hours for a pumped storage power plant. In addition, it should be noted that the average lifetime of lithium-ion batteries is 10 years, and PSP is 40 years, and in this regard, these plants have advantages despite high capital costs (capital costs of PSP 2623 $ / kW, Li-ion batteries - 1541 $/kW for the same power [22]). If we take into account the difference in the LCOS values of both installations (for example, with their difference of 65 $/MWh), the economic effect from the use of PSP in the considered energy system compared to lithium-ion batteries is $7150÷9750 per day.

4 CONCLUSIONS

The paper has accomplished the following:
1) A method has been developed for determining the parameters of the PSP and WPP complex, based on ensuring the balance of generated, consumed and accumulated energy in the power system.
2) A functional diagram of the programmed control of the parameters of pumped storage power plants and wind power plants has been developed, which makes it possible to achieve optimal use of the wind potential by hydraulic energy storage.
3) The results of comparative calculations of the costs of energy storage have shown the economic efficiency of PSPP in comparison with lithium-ion batteries, estimated at $7150÷9750 per day.

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