The role of pumped storage power plants in the power system operation

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***Abstract*–The paper discusses the function of pumped storage power plants in the power system as an accumulator of alternating-current power, a source and also an electric appliance which does not produce electricity by conversion from other forms of primary energy, e.g., conversion from chemical energy of fuel, but only shifts this electricity in time from periods of surplus to periods of deficiency during the re-pumping cycle.**

After evaluation of the usefulness of services provided by pumped storage power plants to maintain the balance of output of the Czech power system in real time, we propose an efficient way to increase the installed pumped storage power plants capacity by utilizing a flooded strip mine after mining termination as part of the landscape reclamation in North Bohemia.

Keywords–pumped storage power plant; flooded quarry; reclamation after maining; wind turbines; accumulator of energy

I. Introduction

In the last decade, we have been witnessing in Central Europe a rapid increase in the installed capacity of intermittent power sources using renewable energy sources (hereinafter, RES) such as the sun and, more importantly, wind, which has been increasing the requirements on the transmission capabilities of power lines and the quantity and quality of support services purchased by power transmission systems. Pumped storage power plants (PSP) have been a traditional and efficient way of accumulating electricity. The problem with them is that suitable locations for their construction are in mountains and usually inside protected landscape areas. That comes up against opposition by environmentalists, conservationists and local population interest groups [3,5]. This opposition can be minimised by utilising the site of a depleted coal mine for the construction and operation of a PSP, which is also the main advantage of the proposed design in addition to the high capacity and power output of this PSP.

II. Classification of Power Plants Based on Their Function in the Power System

In terms of their ability to adjust the grid frequency, i.e., ability to adjust the power output supplied to the system upon the controller's instruction, power sources within the power system (PS) can be divided into two large categories:

1. manageable by the control centre, referred to as **system's**;
2. other (small), which are **dependent** on the network frequency, run synchronously with it and are not managed by the control centre.

Besides, they can be distinguished according to the type of load for which they are intended:

1. system's (manageable by the control centre for frequency adjustment):
   a) primary (nuclear power plants – NPP, run-of-the river hydropower plants – ROR)
   b) semi-peak (condensing coal plants – COP, combined-cycle plants – CCP)
   c) peak (gas turbines – GT, storage hydropower – STH)
   d) **accumulators** (PSP)

2. dependent:
   a) manageable – at least partly (factory power plants, heating plants, combined heat and power plants with piston engines or microturbines, small hydropower plants – SHP, etc.)
   b) intermittent – unadjustable, can only be switched off (wind – WPP, photovoltaic – PVP).

Generally speaking, systemic power plants intended to cover the **base** load are more capital-intensive; thus, they tend to have higher fixed costs but lower variable costs. The opposite applies to power sources intended to cover peak loads. PSP can also be viewed as peak power sources, as they are used to cover peak loads and their "fuel" is electricity consumed in periods of low loads for the re-pumping. However, their function as an **electricity accumulator** has come to the fore in recent times much more than previously, because as the share of intermittent power plants using RES to supply electricity increases, there is more demand (and appreciation) for their ability to **quickly pump surplus power out of the system** at any given time during low demand rather than just supply it in periods of peak loads. PSP therefore deserve to be regarded as a special type of power plant in terms of their function in the PS because, unlike conventional peak power sources, which flexibly supply electricity at times of power shortage by means of conversion from other primary

978-1-5090-0908-4/16/$31.00 ©2016 IEEE

forms of energy, the typical feature of PSP is that, like accumulators, they are not capable of supplying electricity by converting a primary form of energy other than electricity again (neglecting their natural inflow). Electricity is **only shifted in time** by means of them. PSP shift electricity from periods of surplus to periods of deficiency within their re-pumping period. The length of that period is derived from the ratio of the nominal power output of their turbines and generators (or pumps and motors, respectively) to their capacity, i.e., the maximum quantity of energy accumulated. Typically, they are operated in a daily cycle, although in the case of the PSP in the depleted strip mine the storage capacity would be so enormous that it would even allow a weekly re-pumping cycle.

III. PSP in the Czech PS

According to the statistical data drawn from [1], the utilisation of the installed PSP capacity in the Czech Republic (CR) has been steadily increasing since 2008 (see Table 1). That said, the installed capacity was at a steady rate of 1146.5 MW from the commissioning of the Dlouhé Stráně PSP in 1996 until 2014, when the renovation of the machinery set at the Dalešice PSP resulted in a capacity increase to the current total of 1171.5 MW.

TABLE I. Trend of utilisation of inst. PSP capacity in CR [1]

Year	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*
Generation (GWh)	362	563	602	711	733	905	1 052	1 275
Consumption for pumping (GWh)	477	747	795	944	982	1 217	1 363	1 514
Time of utilisation of inst. capacity (hrs/year)	732	1 143	1 218	1 444	1 496	1 851	2 061	2 380

The quantity of electricity "re-pumped" using PSP has been increasing along with the growing generation from intermittent power sources in Central Europe, primarily in neighbouring Germany, as their operation is capable of levelling out even short-term oscillations within several hours. Often it is the case that a PSP runs in the pump mode for an hour during the day and switches to the turbine mode the next hour, to again shift to the pump mode an hour later. The mode switching therefore occurs several times a day, not like in the past without intermittent sources, when pumping was done at night and then the turbine mode was switched on for the morning peak and then again only for the afternoon peak in the PS consumption following a possible midday pumping period.

It follows from the above that it would be very wise to increase the installed PSP capacity in the country's system and, together with a higher transmission capability of the cross-border power lines to Germany, offer the services of the Czech Republic's PSP to German electricity traders and/or transmission system operators for a payment. The payment would have to be at a rate such that would make the new PSP profitable. However, it should certainly not exceed the opportunity costs of forced switching off of wind turbine power plants, i.e., not taking the opportunity to store electricity not needed at the moment for later meaningful use. The determining of these opportunity costs could be the subject of further research.

IV. Value of services provided by PSP

Services provided by PSP to the network can essentially be divided into two categories:

1. static, attractive (valuable) for electricity traders; and
2. dynamic, attractive for centralised network dispatching in real time.

Both the categories of services are aimed at minimising the difference between planned and actual rates of supply and demand at any time during PS operation.

The value of the static service depends on the business margin, i.e., differences between electricity prices during peak and low loads, i.e., hours of high demand, when the price per MWh tends to be higher than in hours of low demand, when electricity is traded at lower prices. Power electricity prices on the market have been decreasing in recent years precisely thanks to the inflow of electricity from subsidised RES, which generate at short-term marginal costs near zero, thus pushing conventional power plants out of the market; the latter are forced to reduce their bidding price for electricity generated to stay on the market.

PSP may admittedly benefit from moments when electricity is sold at a negative price, which will increase in future, but it is still obvious that PSP will not pay back for themselves by static services thanks to decreasing power electricity prices, thus decreasing the average business margin, and that the price of dynamic services that they provide, i.e., support services sold to the transmission system, is much more important for their economy. Solving unplanned surplus of transmitted power output is currently more frequent and serious an issue than solving its deficiency, because the country's transmission system has long been overloaded by overflows from wind turbine plants from North Germany. A convenient placement of a new PSP with a high power output and accumulation capacity in North Bohemia with a connection to the Hradec substation, where the line from Röhsdorf, Germany, also terminates, would enable elimination of sudden inflows of power from German wind by pumping water into the upper reservoir for later use. However, this would require implementing in the international trade a payment for such a service provided by the Czech Transmit System Operator (TOS) – "ČEPS" to German's TOS "50Hz" or a direct purchase order for services from the German side to the Czech operator of the assumed PSP.

V. Proposed design of PSP

Imagine the dimensions of the roughly rectangular pit of the depleted strip mine [9]:

1. 4 km long,
2. 2 km wide,
3. 150 m deep, being the dam height too

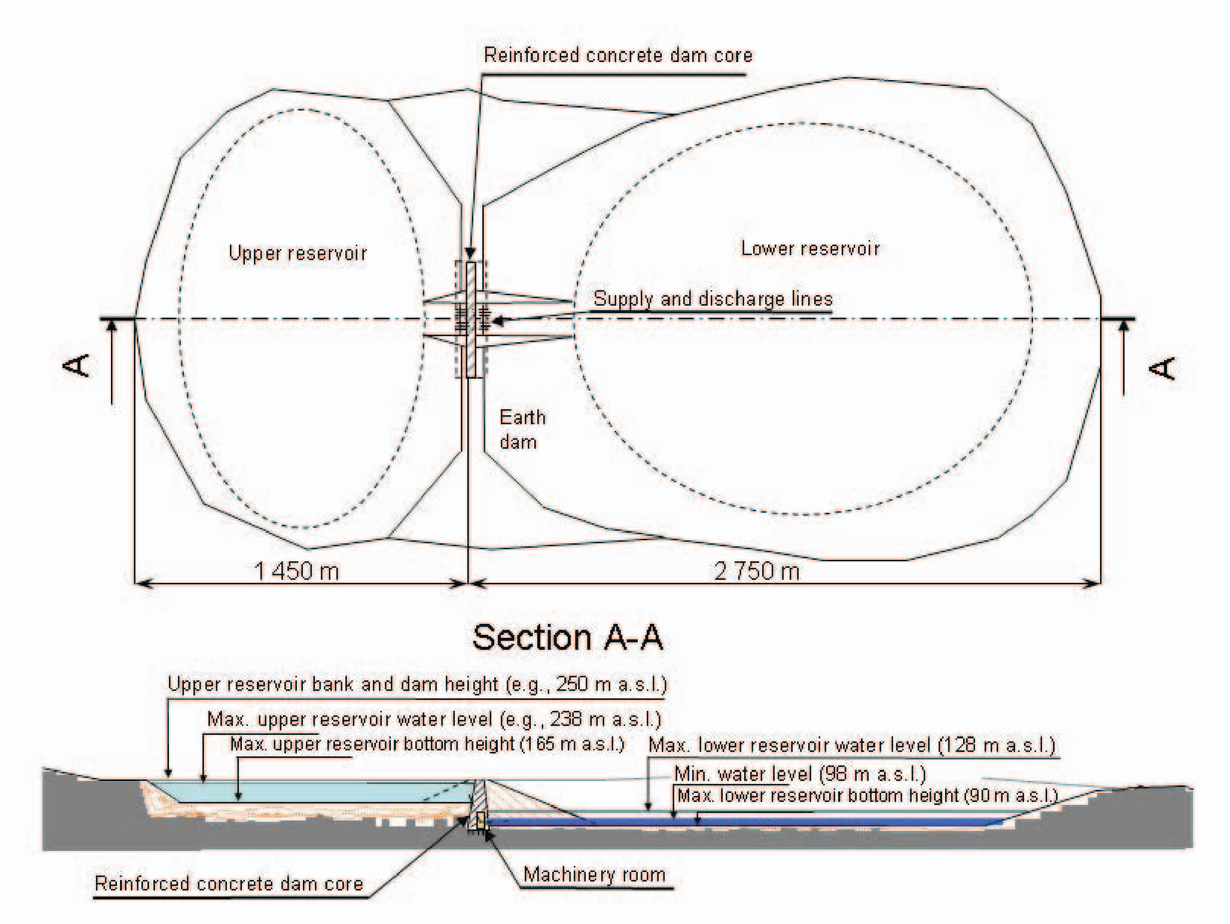

Fig. 1. Proposed PSP design in depleted lignite strip mine.

In contrast with proposal in [7] where is "upper" reservoir proposed out of mineshaft and this would be used like down reservoir, we propose directly damming mining pit.

It would be convenient that the upper reservoir could be formed already during the coal mining process using removed overburden in the oldest part of the mine pit (in terms of mining progress), where the overburden is being tipped anyway (internal depot). This part could be approximately one third of the total planned length of the depleted pit. It would be advisable to reinforce and seal the bottom and the walls using a stabiliser and power gypsum, the latter being a construction material convenient for land reclamation purposes and produced by coal power plants in abundant quantities. An important rule would be to achieve a maximum gradient of the banks at 30 ° from the horizontal plane so that instability of the modelled slopes could not be a risk in any place. In fact, if surplus material exists, it would not be out of the question to raise the banks of the upper reservoir in relation to the surrounding terrain so that its capacity (volume and head) is as large as possible.

The bottom of the upper reservoir could be raised as needed in relation to the lower reservoir with a backfill to prevent the need for as much water for filling it, but that would depend on the amount of the removed overburden. If overburden is lacking, the bottom of the upper reservoir could be lower down, but more water would be needed to fill the reservoir. This water would remain constantly at the bottom of the upper reservoir and would not be engaged in the re-pumping cycle. Nevertheless, it would increase the store of water in the landscape for incidences of prolonged drought. The water supply for the first filling would be carried from the river "Ohře" and "Bílina", respectively, from "Podkrušnohorský" canal (drain) [4] that connects the both rivers and collect water from mountain "Krušné hory". To complement evaporation would be enough water from the springs flowing into the lower reservoir, which now in mining time has to pump up into the drain.

It is important to achieve a certain thickness of the stabiliser-reinforced bottom at the centre of the strip mine for the foundations of the concrete portion of the dam, in which the machinery room would be installed. This reinforced concrete portion would be inserted in an adequately sized earth dam, which would also support it. On the surface, it would be reinforced with a thick surface layer of stabiliser, which would be of a water-resistant composition, and resistant to pressure similar to lean concrete.

Figure 1 outlines the floor plan and section view of the formed pit to be used for the PSP operation purposes. The original rectangular shape of the mine pit would be altered to a figure-eight shape. The pit is narrowed down with an earth dam at approximately one third of its length to minimise the length of the concrete dam core resting on the embankments.

The advantage of this layout is the very short supply lines to the reversible turbines linking the upper and lower reservoirs, which leads to a significant reduction in the energy loss due to friction and turbulence of water in the pipelines during both pumping and turbine operation compared to the conventional layout in mountains, where the supply lines are relatively long. Therefore, the overall efficiency of the re-pumping cycle can be expected to be no lower than 75%.

The theoretical accumulation capacity of the PSP is derived from the usable capacity of the upper reservoir, which in this case is more than 110 million m^3 with a median hydraulic head of approx. 90 metres. With an 89% efficiency in the turbine mode, this results in the maximum amount of energy that the PSP could supply in the turbine mode per re-pumping cycle:

$$W_t = h_s \varsigma g V \eta_c = 91 \cdot 1000 \cdot 9.81 \cdot 110 \cdot 10^6 \cdot 0.89 \cdot 10^{-12} \cong 24 \text{GWh} \quad (1)$$

where

- W_t energy supplied by PSP in turbine mode per cycle (GWh)
- h_s median hydraulic head (m)
- ς water density (kg/m^3)
- g acceleration due to gravity (m/s^2)
- V usable capacity of upper reservoir (m^3)
- η_t efficiency in turbine mode

This is eight times more than the country's largest existing PSP in at Dlouhé Stráně [2,3]! Conversely, the filling of the upper reservoir from the minimum to the full condition would consume about the following amount with a pumping efficiency of about 85 %:

$$W_c = \frac{h_s \cdot \varsigma \cdot g \cdot V}{\eta_c} \cong 116 \text{ TJ} \cong 32 \text{ GWh} \quad (2)$$

This result in the overall efficiency of the re-pumping cycle is approximately 0.76. Since the Czech Republic generates about 220 GWh of electricity a day (exclusive of own consumption), it can be concluded that this new PSP would be able to accumulate almost one eighth of the daily production of the CR's PS [1].

VI. Conclusion – Economic Efficiency of the Plan

The advantage of this proposal is the possibility to distribute the construction works over a longer time period and, more importantly, that the works connected to the formation of the upper reservoir will merge with standard land reclamation, which will have to be carried out anyway. Thus, the expenditures on this part of the construction of the structural part of the future PSP can be **regarded not as capital investment costs of PSP construction**, but as expenditures on land reclamation of the strip mine after the coal seam is depleted. The estimated total investment costs of the construction part is thus only somewhere in the region of CZK 10 billion.

The expenditures on process equipment acquisition depend on the installed capacity of the machinery set. Assuming the nominal investment costs of equipment at CZK 10 thousand per kW and 6 units with 300 MW each in the turbine mode allowing a slight speed increase (by about 10% compared to synchronous) in the pumping mode [6,8], thus achieving a power input of about 390 MW for the pumping to accelerate the depletion of surplus power in the PS, the total capital investment costs of process equipment would be CZK 18 billion.

The total direct capital investment costs can thus be estimated at CZK 28 billion, which is very little compared to selected mountain sites in the CR as a consequence of the reservoir capacity that is an order of magnitude greater. For instance, the Šumný Důl site would cost CZK 27 billion according to [3], with an installed capacity of 880 MW and a power capacity of 5.3 GWh per re-pumping cycle, which is relatively more costly. The operating costs can be estimated at approx. 0.5% of the capital investment costs, i.e., less than CZK 150 million.

To achieve a Internal Rate of Return at *IRR* = 6 % with a 35 years of service life, it is necessary that the annual revenue from services provided be around CZK 2 billion. The efficiency of the static PSP services depends on the difference in power electricity prices in the different time periods. The ratio of the selling to the purchasing price of electricity has to be at least equal to the inverse value of the re-pumping cycle efficiency, i.e., the so-called re-pumping coefficient:

$$k_c = \frac{1}{\eta_c} = \frac{1}{0.76} = 1.3 \quad (3)$$

The achievement of the required rate of return on the invested capital requires a higher ratio, which need not necessarily be guaranteed. Therefore, revenues from the dynamic services are more important, i.e., revenues from support services to the power transmission system. The required daily revenue from sales of the "MZ±5" service is approx. CZK 5 million, translating to at least CZK 96 per MW per hour of stand-by.

The standard prices currently attained for this service are usually several times higher, which is why selling this service by Czech Transmit System Operator "ČEPS" could attain relatively high revenue and the simple payback time on the PSP investment could be even shorter than 5 years. Naturally, the supply of support services from this PSP would certainly push down their price over time, but its very low operating costs would certainly guarantee a high cash flow for its owner and, alongside the other PSP, it would represent a certainty for centralised control of the Czech power system in an uncertain future full of intermittent power sources in Europe. To guarantee annual revenues at the necessary rate, it would be enough to sell support services, which would be of advantage to the operator because it would mean revenue without standard wear of the PSP machinery due to performing everyday static services.

Besides the importance of this project for the energy sector, it would be no less important for water management. The PSP would have a vacant (retention) volume of 220 million m^3 in its lower reservoir, which is a volume that could handle even large-scale floods assuming a sufficient feed capacity.

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