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Original Research Article

Water storage as energy storage in green power system

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ABSTRACT

The paper presents a conceptual explanation of how to couple hydroelectric systems with other renewable sources. Recent energy policies have been planning for a bigger share of renewable energy sources in energy supply. However, inherent characteristics of renewable energy sources – based electricity generation systems are intermittency and non-controllability. That is why electric energy storage has the key role in a more productive use of these energy sources. Numerous energy storage technologies are known today, but none of the present-day technologies could in terms of ratings be compared to water storage. It has been demonstrated here that water storage is able to reduce volatility and increase reliability and stability of green electric energy. Furthermore, the paper analyses the use of water storage as energy storage in the future green energy power system and presents the basic concepts and characteristics of renewable energy conversion into hydroelectric energy. The results highlight that water storage has been important in the production of electric energy, and it is expected to remain so in the future.

1. Introduction

In view of climate changes due to human activities [1], recent energy policies have been planning for a bigger share of renewable energy sources (RES) in energy supply, from 20% in 2020 [2], up to 80% in 2040 [3]. These scenarios foresee the use of renewable energy sources in order to enable a continuous supply of energy (RES-C, which includes geothermal, biomass energy, hydro energy, etc.), as well as those that provide intermittent supply (RES-I, which includes wind (W), photovoltaic (PV) and solar thermal (ST)). The latest ambitions are complete replacement of conventional energy sources with renewable sources [4].

Since electric power systems (EPS) will in the future be significantly based on RES-I (EREC; 22% W, 25% PV and 2% ST), it is obvious that the purpose of energy storage is more important than in classical EPS, since most of the green energy production will be intermittent and unbalanced with energy demand [5]. There are also other solutions which primarily provide transport of high power energy over long distances through power grids [6]. However, these solutions are insufficient because they solve the current use of available energy, but not the problem of long-term security of energy supply when the RES-I of high power do not produce energy. Energy storage will obviously have a significant role in the realization of sustainable energy supply. Higher share of RES-I in EPS results in higher needs for electric energy storage (EES) [7].

For now, the only energy storage technology for large-scale applications is water storage, or (i) storage of hydroelectric plant; and (ii) pump storage hydroelectric plant (PSH) [8–10]. Pumped hydroelectric systems account for 99% of the worldwide storage capacity, or about 172,000 MW [11]. Other possible large storage technologies include: compressed air, double layer capacitors, flywheels, and lead acid, lithium-ion, sodium-sulphur, nickel–cadmium, nickel-metal hydride, vanadium redox and zinc-bromide batteries. The analysis of the characteristics of water storage as energy storage in such future EPS is the scope of this paper.

Water storage has always been important in the production of electric energy and most probably will be in future energy power systems. It can help stabilize regional electricity grid systems, storing and regulating capacity and load following, and reduce costs through coordination with thermal plants. There are two main objectives in the construction of water storage in hydro energy production:

- A more thorough and complete exploitation of water resources in accordance with environmental and water management constraints;
- Regulation of electric energy production in accordance with the needs of the electric power system (EPS).

Complete exploitation means maximum regulation of natural flow of water for the purpose of higher annual energy production. In practical realization this objective is reduced to exploitation of water resources in accordance with environmental, technical and economic constraints. Today technical constraints and funding aren't a significant obstacle in the construction of hydropower

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plants, because hydro energy is the most cost effective. However, environmental constraints are most important, especially in developed countries [12,13].

Hydropower is a widely-used renewable source of energy and plays a major role in reducing the emission of greenhouse gasses. However, the construction of dams has negative impacts, including displacement of local population and ecosystem degradation (biodiversity and wetland losses, proliferation of invasive species). In addition, some reservoirs rich in organic matter (eutrophic) are significant emitters of CO_2 and methane [14,15]. Because of that many NGOs remain critical and cautious of hydropower. They express serious concern about risk and difficulties of hydropower and maintain strong commitments to stringent guidelines.

The second objective is the construction of storage is the *regulation of electric energy production* in line with monthly, weekly, daily needs. The role of water storages in firm energy production is very important, especially for daily peak load and intermediate load levelling. The changes of energy load in EPS are large and relatively quick and are most successfully satisfied by operation of storage of high power hydroelectric power plants.

HE and PSH storages can be designed to operate on either daily/weekly cycle or seasonal cycle. For equalization of daily energy needs, as opposed to total water exploitation or seasonal balancing, storages of significantly smaller capacity are required. This means that the environmental, technical and financial constraints are less important. In the case of PSH, negative impacts are very small, because the same water circulates within the system, between lower and upper pool. Because of all this, PSH are very desirable sources of green energy and are traditionally used as a solution for balancing production and consumption of high power energy [7,16]. That is why water storages will also be necessary in the future green energy power systems.

2. Water storage and renewable energy production

2.1 Coupling of hydropower system and other renewable sources

The use of water storage as electric energy storage means that it is necessary to apply the concept of power plant which is functionally similar to the work of PSH. There are two basic types of pumped-storage plants:

- Pure (or off-stream) pump-storage plant, which relies entirely on water that has been pumped into an upper reservoir as its source of energy;
- Combined pump-storage plant, which uses a combination of pumped water and natural streamflow to produce energy (pump-back plant).

PSH are built of low-cost materials, available in many areas, like concrete, various earth material, rock, and water. The lifetime of such systems and materials is more than 40 years. PSH has high round-trip efficiency (about 75%) and small maintenance costs. It is a simple system which can be easily constructed without traditional technology. Suitable geographical condition is a prerequisite for development. The main variables of the plant are water volume pumped with pumps V_{PS} (m^3) of the upper storage and head drop of the plant H_{nT} (m) which determines the potential capacity:

The stored energy of water in the storage E_{HE} (kW h) is:

$$E_{HE} = V_{PS} \cdot E_{sp} \quad (\text{kWh}) \tag{1}$$

where specific production of electric energy (E_{sp}) is:

$$E_{sp} = \frac{E_{HE}}{V} = \frac{H_{nT}}{367} \cdot \eta_{HE} \quad (\text{kWh m}^{-3}) \tag{2}$$

and specific power (P_{sp}) is:

$$P_{sp} = 9.81 \cdot H_{nT} \cdot \eta_{HE} \quad (\text{kW/m}^3/s) \tag{3}$$

η_{HE} is the overall efficiency of HE, i.e. turbine and generator (0.75–0.92) [17].

The PSH usually depend exclusively on pumped water as their source of energy. Relatively low-cost electric energy, usually from coal-fired steam plants, is used to pump water into the upper storage reservoir during periods of low power demand (nights and weekends).

In combination with RES, PSH can basically be used in two ways (Fig. 1):

(i) Type I, directly on production line of RES or in serial connection with EPS (RES-PSH-EPS); and
(ii) Type II, indirectly by direct connection with EPS as today do classical PSH, (RES-EPS-PSH-EPS).

In the case of type I, energy can be produced continuously, according to the EPS needs, as in the case of conventional hydroelectric plants, while in the case of type II, PSH in principle serves to meet daily peak energy consumption in EPS, as in the case of classical PSH. Type II and type I also serve as a backup system in case of outage or insufficient power of RES-I. Since RES-I produces energy of various power during the year, with occasional longer or shorter breaks, i.e. daily in case of solar energy, it is obvious that in the future green EPS must use both solutions (Type I and II) in order to achieve system stability.

The Type I and II concepts can be applied in combination with off-stream pump-storage plant and combined pump-storage plant. For the purpose of reliable and fully manageable work of integrated concept of RES-I-PSH type I, as well as type II, it must be developed as a conventional HE plant where the inflow of water into storage is independent of outflow. This means that the PSH concept must have two pipelines, one for water supply to the upper storage and the other for water supply to the HE turbines. This type of integration of RES-I and PSH enables seasonal, weekly and daily balancing of energy production from RES-I and demand, i.e. energy production in accordance with the needs of the EPS. The solution with two pipelines is necessary because in the future green power system, RES-I energy production is not fully controlled and predictable and therefore the pump-turbine unit operation cannot be satisfactorily planned. Namely, the power plant works under operation rule "must run".

Therefore, two pipelines in the PSH concept enable:

1. A more complete exploitation of the subject RES-I resources;
2. Regulation of electric energy production in accordance with the needs of the EPS.

In the first case, storage harvests available electric energy (man-made water resources) directly from RES-I or indirectly from EPS, in order to maximize hydroelectric energy production as a reliable and fully controlled renewable energy resource.

In the second case, man-made water resources are used for firm energy production; peak daily energy sheaving and levelling, weekly or seasonal load balancing between energy production and energy demand.

It can be concluded that in the future green EPS water storage as energy storage *serves the same objectives as in natural flow of water*.

Thus, the difference that occurs between the current and future use of water storages is only in the features of "*water resources*" used for hydroelectric energy production. In case of classical hydro plants the total amount of water available for power generation at a given site is fixed by local hydrology conditions. In some cases the increasing plant size may increase the percentage of the potential energy that is utilized, but it cannot increase the total supply.