ELECTRIC POWER SYSTEMS MODELING AND EDUCATION: HYDRO POWER STATIONS MODELING FRAMEWORK

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Abstract: *In this paper we try to bring a modeling framework in optimization problems for hydro-thermal coordination problems solved in electric power systems. There are certain specifics when dealing with hydro power plants and the reservoirs they are fed from. In many cases these water reservoirs are connected and this involves additional complications in optimization models building. We give guidelines for model size reduction and awareness. This framework is suitable for practitioners willing to be aware of hydro-power modeling and optimization but having no previous mathematical optimization training and experience.*

Keywords: HYDRO-THERMAL COORDINATION, WATER RESERVOIRS MODELING TECHNIQUES

1. Introduction

The unit commitment problem is the procedure for defining the optimal engagement of the units and a plan for optimal operation of the plants in an Electric Power System (EPS). The solution of this problem involves two things: the determination of the operating and reserved units and the output power of each operating unit (an economic dispatch)[1]. The cost function represents in most of the cases a striving to minimize the total operating and production costs while strictly respecting the balance between consumption and production, the reliability and security requirements, according to the constraints arising from the generating units themselves. Due to the nature of the different power stations, often the optimization problems involving the operation of both hydro-power and thermal power plants are subjected to a separate class of problems solved in EPS, called *optimal hydro-thermal coordination*.

2. The HPS and PHPS

Hydro power stations (HPS) use water as a primal source to produce electric power. The cost of water is negligible smaller related to the price for fuels used by the conventional thermal power plants. Water, however, is also a limited resource meaning that the available quantities for the individual planning periods must be used wisely. HPS are the most widely used plants for electricity generation from renewable energy sources, accounting for 16% of global electricity production by 2010, and is projected to grow by an average of 3.2% annually over the next 25 years [2,3]. HPS are used in over 150 countries where China leads with 721 TWh in 2010. There are four HPS with a capacity over 10 GW worldwide.

Since the output level of a hydropower plant depends on the water supply and head, the costs curves are nonlinear as well as in the conventional thermal power stations. The advantages that the HPP provide for the balance of the EPS are not limited only to the possibility of rapid change of their working outputs and fast automated start and stop. Although this flexibility is the main factor determining HPS as peak power plants. HPS also have very low operational (production-dependent) costs, as there are virtually no costs of purchasing and supplying fuel, and the aforementioned operating costs are related to the cost of providing ancillary services, operating and maintenance. Fixed costs, however, include the return of investments for construction and modernization, depreciation of facilities, insurance, etc. Sometimes such fixed costs might be significant, especially for brand new installations. HPS have a very long life cycle and do not require large operating labor costs as HPS are operated automatically. Water dams on the other hand are multifunctional facilities, which are used for the drinking water and domestic water supply purposes, irrigation, industrial water supply, fish-breeding, aquaculture, etc. besides for electricity production purposes (according to most legislations electricity production is of lowest priority among other water purposes). Regarding construction costs, for a hydropower plant the building of the water collection system and its derivative is more expensive than the actual construction and installation of the water turbines. In fact, all deficiencies of HPS are mainly related to water collection and accumulation installments, not to the installed electricity generation apparel. Among the disadvantages the following are often stated: ecosystems damages, habitat fragmentation, land losses in the construction process of large reservoirs, congestion of large areas of land, forests and territories with rich soils, need for relocation of people, reorganization of road infrastructure, flows reduction, methane emissions of rotting organisms and flows risks. Since there is no fossil fuel combustion HPS are considered with no direct carbon dioxide production, except the relatively small quantities produced the construction phase. However, these quantities remain negligible compared to thermal plants.

The electricity production of HPS is determined by the available inlet water quantities. If there is a possibility of accumulation (sufficient useful volume of the water tank), the HPS can produce enough power when needed (under circumstances of electric power shortage). In Bulgaria HPS are mainly used as peak, balance and also accumulation capacities. Pump-storage hydropower plants (PHPS) are capable to accumulate the processed by a water turbine quantities (in the presence of a lower reservoir) and are used for balancing loads, being practically the most flexible and multifunctional elements of the EPS. During high load periods, PHPS operate as generators producing the famine power for the system's balance. During low load periods when the reduction of the power outputs of other generating units is practically impossible, PHPS operate in pumping mode like controllable loads by feeding the excess power to the pumps draining water from the lower into the upper reservoir. In addition to importing the required extra load into the system, they accumulate part of the surplus electricity, which can be later injected during the peak periods at a higher price. This reversible cycle (turbine-pump, load-generator) helps preventing frequent start-stop and the needs for frequent changes in the working levels of nuclear and thermal units.

The operation of PHPS is effective if the income of the operation of the plant is positive. This income is mainly determined by the difference between the sold electricity that is produced and the purchased electricity that is consumed by the pumps [4]. From a financial point of view, the accumulation process is an expense with a future return. If the accumulated energy is not realized in the future at better prices (this condition guarantees a positive revenue), these costs will also include the costs of lost financial benefits as the unit was idle and waited for the respective better financial period. Thus, in the end, the electric power accumulation may prove technically necessary and even crucial from the point of view of the EPS balance but economically unprofitable for the PHPS owner. Sometimes some water wastes from the upper reservoir might be required in order to provide for further load leveling. Energy storage is economically justified when the cost of the electricity used by the pumps is lower than the electricity generated and sold, taking into account the accumulation-generation cycle losses. System load demonstrates daily, weekly and seasonal changes that have to be followed by the power plants. A system operator having a PHPS accumulate the cheaper energy produced during low load periods and deliver it to the grid during the peak periods when the process is cost-effective. If there is an opportunity to accumulate energy (large dams are built), generation may be postponed. This is not a "*surplus*" energy storage. This power can be used in the balancing market later. Power plants using renewables (except HPS of stored water) can not generally accumulate their primary source and by using their current availability they usually increase the EPS balancing problems [5-7].

With the increase in penetration of power stations using renewable power sources as wind and sun (also considered as stochastic power plants), PHPS become an indispensable element in the balance management of EPS, that present a buffer to reconcile the inconsistency of the renewable generation and load curves. In this paper, some attention is paid to the operation optimization of HPP and PHPS as balancing capacities and a means of minimizing total costs in the EPS[8-14].

3. Modelling interconnected HPS and PHPS

The modeling of the operation of the HPS and PHPS requires modeling of the plant's curve and associated water volumes. Some HPS operate in a cascade mode, i.e. their work is interconnected (consecutive and dependent) within a given terrain. So despite that the cost of the primary energy carrier for HPS is negligible, it is also necessary to model the "*stock*" of water availability. Water reservoirs may be of a complex purpose or electricity production only. The water reservoirs also imply a certain cycles for the water levels management (daily, seasonal, yearly) associated with the so-called water allowances. The inclusion of HPS and PHPS in the EPS optimization leads to two events: HPS allow for *peak shaving* to be adjusted, but also lead to the addition of additional constraints and variables for modeling the work of water power plants. The curve of water waste for a HPS is a function of the water quantity Q fed to the turbine: $P_{k,j} = f(Q)$.

Nomenclature for HPS and PHPS:

r - reservoirs

k - power stations (HPS and PHPS)

$V^{\min}_{r,Usable}, V^{\max}_{r,Usable}$ - minimal and maximal usable water reservoir r volume

$V_{r,j}$ - water reservoir r volume at the end of the time interval j

$F_{r,j}$ - water flow in r during a unit interval j

$R_{r,j}$ - unprocessed water from r in a unit interval j. Unprocesses water quantity includes controllable water release as well as uncontrollable losses such as evaporation.

$P_{Pk,j}$ - power used by the pumps of k in a unit interval j

$P_{Hk,j}$ - power produced by the turbines of k in j

$P^{\min}{}_{P,k}$, $P^{\max}{}_{P,k}$ - minimal and maximal pump capacity of k

$P^{\min}{}_{H,k}$, $P^{\max}{}_{H,k}$ - minimal and maximal generating capacity of plant k

φ_{Hk} и φ_{Pk} - water consumption (m^3/MWh) for plant k in both generation and accumulation mode

$w_{k,j}$ - artificial binary variable for the operation mode of a PHPS k. $w_{k,j} = 1$ if the mode is pumping in j

The operational curve of a HPS with neglecting the water head may be expressed via the following linear functions:

$Q_{Hk,j} = \varphi_{Hk} P_{Hk,j}$ (1) - processed water quantity by the turbines of plant k in a unit interval j

$Q_{Pk,j} = \varphi_{Pk} P_{Pk,j}$ (2) - processed water quantity by the pumps of plant k in a unit interval j

The output level of all units / plants must be within the technological limits:

$$P^{\min}{}_{H,k} \le P_{Hk,j} \le P^{\max}{}_{H,k} \quad \text{and} \quad P^{\min}{}_{P,k} \le P_{Pk,j} \le P^{\max}{}_{P,k} \qquad (3)$$

When modeling the PHPS operation, it is necessary to introduce restrictions for non-simultaneous operation of pumping and production capacities for each PSHP in a single interval:

$$P_{Pk,j} - w_{k,j} P^{\max}_{Pk} \le 0 \ \text{and}\ P_{Hk,j} - \left(1 - w_{k,j}\right) P^{\max}_{Hk} \le 0 \qquad (4)$$

The volume of each reservoir in every unit interval must be within the actual water level limits:

$$V^{\min}{}_{r,Usable} \le V_{r,j} \le V^{\max}{}_{r,Usable} \qquad (5)$$

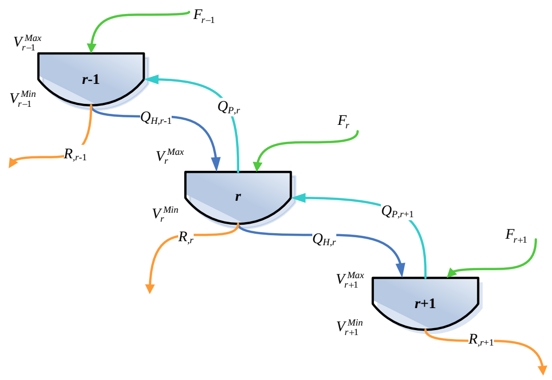
Values for the first (j=1) and last interval (j=$j_{\max}$) might be provided for the water level maintenance cycle:

$$V_{r,j=1} = V_{r,1} \quad \text{and} \quad V_{r,j=j\max} = V_{r,N} \qquad (6)$$

General form of the water balance constraints:

$$V_{r,j} = V_{r,j-1} + \left(\begin{array}{l} -\sum_{m\in\Gamma from} \varphi_{Hm} P_{Hm,j} + \sum_{n\in\Gamma in} \varphi_{Hn} P_{Hn,j} - \\ -\sum_{q\in\Pi from} \varphi_{Pq} P_{Pq,j} + \sum_{s\in\Pi in} \varphi_{Ps} P_{Ps,j} \end{array} \right) + \\ + F_{r,j} - R_{r,j} + \sum_{\rho\in in} R_{\rho,j} \qquad (7)$$

, where Γ*from* and Π*from* are the sets ot plants (with their pumps and turbines)that drain water from r during j. Γ*in* and Π*in* are the sets of plants that feed in water in r during j. So $\sum_{\rho\in in} R_{\rho,j}$ is the sum of controlled water wastes associated with the current reservoir r (both in and out) (see figure below).



In a short-term planning (day, week) of HPS and PSHP operation, water balance equations bring more security than complexity in the model, whereas in a medium-term planning (e.g. a year) the modeling of cascade-connected water reservoirs with complex purposes will increase complexity of the model and its size. Different purposes and usage of water volumes may be modeled with so-called quotas. When a large dams with yearly or seasonal water level management is available, a long-term strategy for the possible use of water needs to be applied.

Water balance constraints are build for each interval and each reservoir, i.e. their number depends on the number of unit intervals in the planning horizon. The cycle mater management implies the existence of a certain relationship between the functional dependencies at the beginning and end of the planning horizon. In other words, if modeling of water volumes is performed for a period of one year and the single interval's duration is 1 hour, for each reservoir, 365x24 or a total of 8 760 variables have to be introduced as well as 8 760 of water balance equations, and the constraints (6) must be respected for each equalization cycle.

For large reservoirs with annual management cycle this complication can be avoided by using long-term quotas i.e. by adding availability of water quantities by months, seasons, and even annually. This will result in the introduction of significantly fewer constraints. In the case of cascade-coupled different water volumes, the constraints of the upper and lower reservoirs (8) will keep the levels of the large tanks within their respective limits.

$$Q_r^z \le Q_r^{z-1} + F_r^z + (1/z)V_r^{\max} - \\ -\sum_{k,j} Q_{Hk,j}^r + \sum_{k,j} Q_{Hk,j}^{r-1} + \sum_{k,j} Q_{Pk,j}^{r+1} - \sum_{k,j} Q_{Pk,j}^{r-1} \quad (8)$$

, where Q_r^z is the water volume in m^3 in reservoir *r* at the end of sub-period *z*, F_r^z is the flow in the reservoir during the sub-period and $F_r^z + (1/z)V_r^{\max}$ models the available water quantities for the whole sub-period.

The expression $-\sum_{k,j} Q_{Hk,j}^r + \sum_{k,j} Q_{Hk,j}^{r-1} + \sum_{k,j} Q_{Pk,j}^{r+1} - \sum_{k,j} Q_{Pk,j}^{r-1}$ models the operation of the pumps and turbines fed by and feeding in the reservoir *r* using the respective processed water quantities for the whole sub-period *z*. Thus, if a one-year horizon is considered for 1 hour single interval duration and seasonal plant operation is modeled, the water balance constraints for a reservoir *r* are reduced to four from the value 8 760. If an annual quota is used and seasonal interconnectivity is not required (or they are reported with similar indicators in terms of inflows, outflows and maximum volume), the constraint (8) will be only one. Thus, in an optimization problem for an optimal hydro-thermal coordination in which several cascades are modeled and the included water reservoirs are of a different purpose, volume, and management cycle it is possible to model the work of all hydro-power plants in the medium-term planning horizon and this is done without the addition of redundant complexity in the model only by using the appropriate generalization technique. Small reservoirs in the cascades are modeled by water balance equations of type (6) and (7), and the larger ones - with inequalities of the type (8).

4. Conclusion

The general idea of linear programming modelling of hydro-power plants is given including both turbines and pumps (if available), the importance of pump- hydro stations in power balance as well as the specific constraints deriving from the nature of hydro-power generation. Interconnected water reservoirs bring additional complexity and specifics in the optimization modelling. This modelling framework may be used for HPS forecasting, ED or in combination with the thermal framework for optimal coordinated work in an EPS with HPS integration. When the hydro-thermal coordination involves the optimization of PHPS a mixed-integer programming model is required. Some generalisation techniques are proposed for model size reduction that may be handy in many cases of optimization modelling.

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