OPTIMAL HYDRO-THERMAL COORDINATION WITH A MAXIMUM RES POWER UTILIZATION STRATEGY CONSTRAINTS MODEL

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Abstract: *This paper presents a formal and practical approach onto the short-term evaluation of the impact of the different RES power generation technologies. All these are considered stochastic and basically unreliable in the active power balance but they also seem to be an irreplaceable part of the electric power generation in the future. Here a generalized hydro-thermal coordination optimization model is presented aiming to help a day-ahead power balance impacts analysis and some further risk assessment to the EPS security and resilience.*

Keywords*: OPTIMIZATION MODELING, HYDRO-THERMAL COORDINATION, RES POWER GENERATION*

1. Introduction

The contemporary environmental requirements for the operation of the EPS lead to an increase in the installed nature-friendly renewable power resources (RES) production [1-5]. The model presented in this paper aims to assesses and evaluate the impact of increased RES generation in the EPS in a short-term power production planning when a certain strategy for max RES power production is aimed as well as evaluating on one side the different RES producers and on the other the implicit financial impact they introduce in the production power planning. A major feature of these plants is that the peaks of renewable production are often in periods of low system load, which in turn affects the overall management of the EPS. In such periods it might be necessary to reject part of the renewable production. The another purpose of the planning optimization model is to reduce the amount of unused renewable energy [3] by optimizing the combined operation of the thermal power plants and the PHPS storage capacities and to achieve minimum values for the costs of the production activity. The model is constructed for the general case of an EPS with generally nonlinear thermal, HPS and PHPS.

The production of HPPs is determined by the available inlet water quantities. If there is a possibility of accumulation (sufficient useful volume of the tank), the HPP can produce energy when needed (under the circumstances of energy shortages). In many countries worldwide, at a peak load periods, HPPs are mainly used as peak, regulating and reserving capacities. Pumped storage power plants (PSPP) posses the potential to accumulate the processed water quantities (presence of a lower reservoir) and are used for balancing loads, being practically the most flexible and multifunctional elements of the EPS. In the peak load periods PHPSs operate in generator (turbine) mode, and in low load periods and in the inability to reduce the power output of other generating units, they operate in pumping mode by pumping water from the bottom into the upper tank as controllable loads. In addition to importing the requested extra load into the system, they accumulate part of the surplus electricity, which is later attributed to the peak periods at a higher price. This reversible cycle (turbine-pump, load-generator) helps to prevent frequent and multiple stops and starts of thermal units or prevents changes in the output levels of the nuclear and thermal generators [6-11].

The criterion for the efficient operation of PHPP is the financial income from the plant's operation that is generally determined by the difference between the sold electricity production and the purchased electricity consumed in the operation of the pumps [5,12]. From an economic point of view the accumulation process is a "*cost with recovery in the future*". If the accumulated energy is not sold in the future periods at better prices (this condition guarantees a positive revenue), these costs will also include the cost of the lost economic benefits as the unit was idle and waited for the corresponding economically advantageous period. Thus the energy accumulation may prove itself technically necessary from the point of view of the EPS but economically unprofitable for the PHPS owner. Sometimes it may be necessary to release water from the above reservoir (primal energy resource waste) to turn on the load in future period according the major EPS balance requirements, and in this case there must be a mechanism to stimulate the PHPS owner. Energy storage is economically justified when the cost of the electricity used by the pumps is less than the electricity generated and sold, taking into account the accumulation-production cycle losses.

The system load changes with daily, weekly and seasonal patterns and these changes lead to the respective changes of the generating plants power outputs. When PHPPs are available system operators accumulate cheaper energy produced during low load periods and inject it into the grid during peak periods when the process is cost-effective. Where there is an opportunity to accumulate energy (large dams are built), the power injections may be postponed, having in mind that this is not a "surplus" energy storage but it can later participate in energy production or balance market. Power plant using RES (exception of HPPs of stored water) generally are considered as incapable of storing their primal energy source [13] (water, solar radiation, etc.) and when aiming to use the whole availability of these stochastic RES power plants they usually increase the EPS balance problems [5,12,14].

With the increase of the share of renewable wind and solar generally uncontrollable stochastic power plants, PHPPs become an indispensable element in the EPS operation that assures the balance as a buffer to reconcile the specifics of the renewable generation and consumer load schedules[15-18]. This is extremely important most of the contemporary EPS as optimization of the coordinated work of the three different generating types are involved in order to minimize the total operation costs in the EPS and preserve the active power balance. The model presented in this paper aims to optimally model the functioning and operation of HPPs and PHPPs as an active power balance tool in order to minimize the total EPS costs with different origin of the RES power production and also with the respective attention to the specifics of the different hydro-power plants under consideration, generally at limited water availability circumstances.

Hydro-power generation is known for many ears and the HPPs have a considerably long exploitation period, some of them more than 50 years. So hydro-power plants are build in different moments and in different terrain thus leading to different efficiency of each plant. Many power plants also struggle from limited water quantities or tank volumes that further limit their operation. In some terrains the processed primal water resource of a HPS may be used again by another HPS that is below the first one, making a hydro-power cascade and thus optimizing the utilization of the limited water resource. Cascades lead to other problems in the optimization modeling.

The importance of energy storage increases with the increased RES power generation penetration [16,17,19]. Energy storage is applied for smoothing short-term fluctuations in the power generation of wind and solar plants due to wind gusts or clouds, for electric power source for longer periods of RES generation intersections (at night or when it is windless), as a back-up power source, for example a in case of a main network failure, or as a main or auxiliary energy source of for vehicles, etc. So depending on their purpose, the energy storages are considered system-general, in the distribution network or local [17]. The former are a tool of the Electricity System Operator for tertiary frequency control and cross-border exchanges. They are powerful facilities, predominantly connected to the power transmission network of hydro-power stations, with the possibility of storing water in an upper tank. The second is a device whose capacity is proportional to the load of a distribution line. These are installed in distribution substations or transformer stations. The third ones are in scale with the load of an individual consumer who needs to be fed when the primary source drops out. They are installed in the user's property.

When combining conventional thermal power generation and water a separate class of EPS optimization problems emerge - those of optimal hydro-thermal coordination. [5,7,9,19-21].

The hydro-thermal optimal coordination model presented here is a high-dimensional non-linear mixed-integer model because of the presence of reversible accumulation-generation power plants. HPPs with their responsiveness to meet load changes and speed are the top balance and peak sources for most EPS. Taking into account the fact that the costs of the water as a primary energy resource is practically inconsistent with those of conventional thermal power plants, HPPs have a significant impact on the total EPS operating and production costs, usually in the direction of their reduction [1,20-22].

2. Model Formulation

The presentation here models the formation of an optimal strategy for combined thermal and hydro power generation when a significant power is injected in inappropriate moments from renewable power generators. Active power balance should be satisfied at any moment and the possible alternative for renewable power generation rejection has to be properly presented and evaluated. No start or stop of a thermal unit is allowed in the optimization horizon so if the max RES power utilization strategy is adopted optimal operation plan for systems controllable loads (pumps) has to be elaborated thus leading total costs reduction, peak shaving and steady thermal power operation. In the model formulation a certain nomenclature is used and it is given below.

FORECASTED VALUES USED IN THE MODEL:

D_j - load forecast

P_{Wj} and P_{Sj} - forecasts for the wind and solar production

$P_{Resj} = P_{Wj} + P_{Sj}$ - expected summary renewable production

$L_{Res,j}$ - resulting load in a time interval j

NOMENCLATURE FOR THE THERMAL GENERATION UNITS

i – thermal unit,

c_i - price for fuel for 1 MWh for a thermal init i

P_{ij}, P_{imin}, and P_{imax} – power output level, minimal and maximal admissible values of the thermal unit's i operational range in MWh i in a unit interval j

The work of a thermal unit i is the function $f(P_{ij})$ and the total costs for its operation for the whole planning horizon is $\Sigma c_i f(P_{ij})$

NOMENCLATURE FOR THE HPS AND PHPS:

r - reservoirs

k - power stations (HPS and PHPS)

m_k - available number of pumps in a k-th PHPS with similar operation values, that in the fixed level of the pump $P^F_{P,mk}$

$V^{\min}_{r,Usable}, V^{\max}_{r,Usable}$ - 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. Unprocessed 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

$P_{Pmk,j}$ - power used by the pump m_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

$P^F_{P,mk}$ - available (fixed) pump level of a pump m_k

$0 \le n_{k,j} \le m_k$ and integer is the number of pumps working in j

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

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

η_k - efficiency coefficient for a PHPS plant k

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

$w_{mk,j}$ - artificial binary variable for the operation mode of a pump m_k. $w_{mk,j} = 1$ if pump m_k is working at a fixed level P^F_{Pmk} in j

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

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

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

c_{Hk} and c_{Pk} - costs for the operation of hydro plants may be introduced in the model. These costs might include a complex structure like constant and variable components. In the current model formulation operation costs of hydro power plants are neglected

δ_i - permissible change of the output generation of a thermal unit i between two successive time intervals

α_j and β_j - rejection of renewable power for a time interval j, $0 \le \alpha_j \le 1$ and $0 \le \beta_j \le 1$

The model aims to minimize the total operation costs in a short-term (day-ahead) interval of an EPS consisting of continuously operating i thermal units (within their operation range [P_{imin}, P_{imax}]), renewable stochastic generation form wind and solar power plants and k PHPS as peak generators with a strategy of maximum RES penetration.

$$\min_P J = c_i \sum_{ij} f(P_{ij}) \tag{1}$$

The balance constraint (2) will guarantee that the total production of both controllable and uncontrollable units and loads will equal the load forecasts for each time interval in the planning horizon:

$$\sum_j P_{ij} + \sum_j P_{H,kj} - \sum_j P_{P,kj} = L_{Res,j} \text{ for each } j \tag{2}$$

The right-hand side of the balance constraint is the resulting load the has to be covered form the working controllable generation units:

$$L_{Res,j} = D_j - (1-\alpha_j)P_{W,j} - (1-\beta_j)P_{S,j} \quad (3)$$

It is clear that in some periods with peak RES production the resulting load will be less than the total minimum of operating thermal plants. In these periods excess renewable power should be rejected in order to sustain the power balance or this excess power has to be accumulated for further periods.

In order to avoid the modeling of the water balance constraints which is redundant and exhaustive for a short-term optimal coordination problem a single efficiency constraint for each PHPS k may be introduced.

$$\eta_k \sum_j P_{P,k} = \sum_j P_{H,k} \quad \text{for each } k \quad (4)$$

Water balance constraints (5) have to be formulated if not all hydro units are reversible of if a PHPS and a HPS use same water reservoirs. Further reduction of the number of the water balance constraints in achieved by formulating such constraints for those r that limit the hydro units operation in the given horizon (i.e. the limiting reservoir that is the smaller one). (5) is a general form of a water balance constraint for each reservoir r with modeling the work of all interconnected to r generators a pumps (feed-in and feed-out) as well as controllable and non-controllable inflows and outflows:

$$\begin{aligned} V_j = V_{j-1} &- \sum_{k\in\Gamma from} \varphi_{Hkj} P_{Hkj} + \sum_{k\in\Pi in} \varphi_{Pkj} P_{Pkj} + \\ &+ \sum_{k\in\Pi from} \varphi_{Hkj} P_{Hkj} - \sum_{k\in\Gamma in} \varphi_{Pkj} P_{Pkj} + Q_{Rj} + \\ &+ \sum_{q\in In} L_{R,qj} - L_{Rj} - R_{Rj} \end{aligned} \quad (5)$$

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.

The following constraints model the physics of the accumulation-generation cycle, namely that no pumping and generation are possible simultaneously in a single time interval j:

$$P_{P,kj} - v_{kj} P^{\max}_{P,k} \le 0 \quad (6)$$

$$P_{Hk} - (1-v_{kj}) P^{\max}_{H,k} \le 0 \quad (7)$$

Constraint (6) implies that the summary of the pumps is a controllable load whose power can be linearly controlled in a certain interval. Most pumps are considered controllable loads with a fixed power consumption. In order to model such particularity the following changes in the model may be introduced:

If using the number of pumps as groups (8) should be added:

$$P_{Pk,j} - \sum_{mk} n_{k,j} P^{F}_{P,mk} = 0 \quad (8)$$

If using a respective modeling for each pump with a fixed level (6) will change because the summary pump consumption is determined by the work of each pump, i.e. $P_{P,kj} = \sum_{mk} P_{P,mkj}$ thus becoming (9) and adding (10) to keep each pump in the allowed power level (one of 0 and $P^F{}_{P,mk}$):

$$\sum_{mk} P_{P,mkj} - v_{kj} P^{\max}_{P,k} \le 0 \quad (9)$$

$$P_{P,mkj} - w_{mk,j} P^{F}_{P,mk} = 0 \quad (10)$$

Ramp-up and ramp-down constraints for the thermal units:

$$\left|\Delta P_{ij}\right| \le \delta_i \rightarrow \begin{cases} P_{ij} - P_{ij-1} \le \delta_i \\ P_{ij} - P_{ij-1} \ge -\delta_i \end{cases} \text{for each } i \text{ and } j \quad (11)$$

If the duration of a unit time interval is greater that 30 minutes the ramp up and down constraints might be neglected, because most of the large thermal units can reach maximal operating value within 30 minutes.

Operation range for the thermal units is modeled with simple bonds:

$$P_{i\min} \le P_{ij} \le P_{i\max} \quad (12)$$

The following simple bounds for the water reservoirs and the controllable outflows are introduced if water balance constraints (5) are implied in the model. The volume of each reservoir in every unit interval must be within the actual water level limits:

$$V^{\min}{}_{r,Usable} \le V_{r,j} \le V^{\max}{}_{r,Usable} \quad (13)$$

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

$$V_{r,j=1} = V_{r,1} \quad \text{and} \quad V_{r,j=j\max} = V_{r,N} \quad (14)$$

Thus this model allows for the analysis of the impact of different RES production in a short-term power balance as well as presenting in an appropriate way the specifics of hydro-power plant under consideration.

3. Conclusion

A model for optimized combined operation of thermal, PHPP and RES is formulated for short-term planning in the absence of the possibility of starting and stopping of the thermal generating units, resulting in a uniform operation of the base thermal plants and realization of the ideas of Energy Demand Management. The introduction of price indicators for the operation of storage capacities is justified from the point of view of the development and maintenance of these facilities, thus modifying investments in improving the installed facilities or their investments return policies. Differences in PHPSs may be modeled appropriately as general constraints using the efficiency coefficient for each storage plant or using water balance equations that allow for the estimation of natural resources in periods of high water and drought, as well as the quantitative and cost recovery of unprocessed water. Further the problem with the fixed operation level of pumps is discussed and appropriately solved in the model. It is built on a strategy for maximum production and utilization of RES energy, which is in line with environmental requirements as 100% RES power utilization, reduces the negative environmental impact of the thermal power plants. These models are especially useful in the case of generating power from renewable energy sources, which have a random nature of the generated electric power (wind turbines and photovoltaic power plants) and large amplitudes in the load schedules. In these cases, the optimal coordinated of conventional thermal power plants and storage capacities allows for an increase in the share of renewable production and hence the ecological operation of base power plants at small deviations. Without manageable loads and peak power, the balance of the EPS will be severely hampered. The approach of this model formulation to the different renewable stochastic resources allows for a deep analysis of the impact of the different RES production strategies and production/energy market penetration as well as it is a useful tool for the EPS optimization and development problems.

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