Operation of hydro and thermal power plants in a complex power system

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Abstract
This paper presents the methodology for power generation demand/supply planning in a complex electric power system. The model objective is to find an optimal power supply that meets the electricity demand, and takes into account the operating conditions of power generating stations. The model and the developed computer program are applied to the Macedonian Power System to provide a realistic application example. The results show the behavior of hydro and thermal power plants in dependence on their technical characteristics and electricity demand.

Keywords: hydrology, Hydro Power Plant (HPP), Thermal Power Plant (TPP), modeling, electricity, generation.

1. MODEL FOR OPERATION OF POWER PLANTS

This paper outlines the improvements of the original mathematical model [1, 3, 4]. The total interval of time under consideration (lasting \( T \)) is subdivided into several elementary subintervals (lasting \( dt \)). The optimization procedure can be applied to different time intervals in each specific application. The calculations can be performed on time intervals wider than 24 hours, such as: on monthly, weekly and daily basis. Also, the calculations can be performed with time subintervals down to 1 hour, or less, depending on the available data. The model includes energy balancing, the power balancing in each time interval, as well as water balancing for the hydro power plants and energy balancing for thermal power plants. Suppose the Generation System consists of \( K \) – Thermal Power Plants and \( M \) – Hydro Power Plants and \( N, V \) are the connected systems or import. The objective function is:

\[
\sum_{i=1}^{T} P_{i,j} \cdot \Delta t = W_j
\]

The model offers a high degree of flexibility, and can be applied in different situations because the optimization period can be conveniently subdivided into as small subintervals as desired. In order to achieve this flexibility, model improvements were introduced with respect to the terms covering the hydro power plants and the thermal power plants energy change representation.

The additional improved conditions for hydro power plants are the following:

a) HPP’s generated electricity managing expressed as:

\[
S_m \cdot \left( \sum_{i=1}^{T} \frac{W_{\text{out}}^{m,T_{mj}} - W_{\text{in}}^{m,T_{mj}}}{\Delta t} \right)^2 \cdot \Delta t
\]

where: \( W_{\text{in}}^{m,T_{mj}} = \sum_{i=1}^{T} P_{i,n} \cdot \Delta t \) is the inflow energy resulting from water inflow in a reservoir and \( W_{\text{out}}^{m,T_{mj}} = \sum_{i=1}^{T} P_{i,m} \cdot \Delta t \) is the generated energy resulting from water outflow. This is particularly important for regulating the discharge as well as water storage level in the reservoir.

b) HPP’s water spending control expressed as:

\[
\sum_{m,j=1}^{T_{mj}} \left( V_{\text{out}}^{m,T_{mj}} - V_{\text{in}}^{m,T_{mj}} \right)
\]

where: \( V_{\text{in}}^{m,T_{mj}} = \sum_{i=1}^{T_{mj}} Q_{i,m} \cdot \Delta t \) is the inflow water volume in the HPP “m” reservoir during the time period \( T_{mj} \) expressed using the inflow volumetric flow rate \( Q_{i,m} \) and

where: \( K_i(P_{i,j}) = P_{i,j} \cdot (A + B \cdot P_{i,j} + C \cdot P_{i,j}^2) \) \( i,k,n,v \)

The model also includes the following conditions:

- power balance for total load:

\[
\sum_{k=1}^{K} P_{k,j} + \sum_{n=1}^{N} P_{n,j} + \sum_{m=1}^{M} P_{m,j} = P_{i,j}
\]

- power balance for peak load:

\[
\sum_{m=1}^{M} P_{m,j} + \sum_{i=1}^{V} P_{i,j} = k_i \cdot P_{i,j}
\]
The outflow water volume in the HPP's "m" reservoir during the time period \( T_{mj} \) expressed using the discharge flow rate \( Q_{out}^{m} \). This condition is for the control of water outflow (HPP power generation control) during the time period \( T_{mj} \).

The additional improved conditions (5) and (6) are particularly important for the reservoirs with small water inventories compared to the water inflow during the analyzed period. This model feature helps to provide an appropriate treatment that is consistent with the reservoir water inventories (some reservoirs can be treated on yearly basis, whereas other reservoirs on seasonal, monthly, weekly, or daily basis).

### 2. APPLICATION ON MACEDONIAN POWER SYSTEM

The Macedonian Power System consists of hydro and thermal power plants. Each HPP (total 9) is represented by technical characteristics for hydraulic equipment: water reservoir, tunnel, penstock, turbine, water and power installed capacity. Another necessary information is the data for water natural inflows into water reservoirs. Table 1 gives the basic data for the existing hydro power plants in Macedonia (all are in operation except Sv. Petka with proposed installed capacity of 100 m3/s and reconstructed HPP Matka with installed capacity of 40 m3/s).

Dependence on hydraulic characteristics of the HPP, as well as their generating role in Macedonian electric system, the hydro power plants in Macedonia are divided into two groups:

1. **Storage HPPs**:
   1. derivation with large net height according to water discharge: Vrutok, Globocica
   2. with turbine house near dams, where water discharge has significant influence on water level variation large size: Kozjak, Tikves, Spilje
      small size Sv. Petka, Matka
2. run of river HPPs: Vrben, Raven

The two hydropower cascades in optimization process are also taken into account:

- cascade of the Treska river consists of: HPP Kozjak, HPP Sv. Petka, HPP Matka
- cascade of the river Crn Drim consists of: HPP Globocica, HPP Spilje

The basic data of the hydro power plants in Macedonia are given in Tab.1.

<table>
<thead>
<tr>
<th>HPP</th>
<th>No. Of units</th>
<th>( Q_{in}^{m} ) (m3/s)</th>
<th>( H_{geom} ) (m)</th>
<th>Net power (MW)</th>
<th>Reservoir ( 10^3 ) m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Globocica</td>
<td>2</td>
<td>54</td>
<td>110</td>
<td>42</td>
<td>15</td>
</tr>
<tr>
<td>2 Spilje</td>
<td>3</td>
<td>108</td>
<td>95</td>
<td>84</td>
<td>212</td>
</tr>
<tr>
<td>3 Tikves</td>
<td>4</td>
<td>144</td>
<td>100</td>
<td>116</td>
<td>272</td>
</tr>
<tr>
<td>4 Vrben</td>
<td>2</td>
<td>8</td>
<td>196</td>
<td>12.8</td>
<td>0</td>
</tr>
<tr>
<td>5 Vrutok</td>
<td>4</td>
<td>32</td>
<td>574</td>
<td>172</td>
<td>277</td>
</tr>
<tr>
<td>6 Raven</td>
<td>3</td>
<td>32</td>
<td>74</td>
<td>21.6</td>
<td>0</td>
</tr>
<tr>
<td>7 Kozjak</td>
<td>2</td>
<td>100</td>
<td>102</td>
<td>80</td>
<td>260</td>
</tr>
<tr>
<td>8 Sv.Petka</td>
<td>2</td>
<td>100</td>
<td>40</td>
<td>36.4</td>
<td>1</td>
</tr>
<tr>
<td>9 Matka</td>
<td>1</td>
<td>20</td>
<td>40</td>
<td>8.2</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>24</td>
<td></td>
<td>573</td>
<td>1038</td>
<td></td>
</tr>
</tbody>
</table>

*Tab.1 Basic data for the hydro power plants in Macedonia*

The thermal power plants in Macedonia are operating with maximum capacity according to the coal supply possibilities. The basic data for TPPs are given in Tab.2.

<table>
<thead>
<tr>
<th>TPP</th>
<th>Fuel</th>
<th>No. units</th>
<th>P_{min} (MW)</th>
<th>P_{max} (MW)</th>
<th>( W_{yearly} ) (GWh)</th>
<th>Planned outages (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bitola</td>
<td>Lignite</td>
<td>3</td>
<td>140</td>
<td>209</td>
<td>1400</td>
<td>45</td>
</tr>
<tr>
<td>Oslomej</td>
<td>Lignite</td>
<td>1</td>
<td>80</td>
<td>109</td>
<td>650</td>
<td>60</td>
</tr>
<tr>
<td>Negotino</td>
<td>Oil</td>
<td>1</td>
<td>140</td>
<td>198</td>
<td>1200</td>
<td>45</td>
</tr>
</tbody>
</table>

*Tab.2 Basic data for the thermal power plants in Macedonia*

The electricity demand is supposed to be 8000 GWh in a year with hourly distribution (8760 time subintervals). The analyses are given for the average hydrology where the water inflows are taken for 74% of hydrology according to statistical data.

### 3. OPERATION OF MACEDONIAN POWER PLANTS IN MACEDONIAN POWER SYSTEM

In order to have realistic picture for operating modes of hydro power plants, the time intervals of one hour in a year for the demand represent the seasonal as well as daily variations of the electricity needs. Based on statistical data for water inflows, and technical parameters for the reservoirs as well as for turbines and other hydraulic equipment in the HPP, the software tool gives the details about operating of each hydro power plant for each interval as the following: water discharge, water level in the reservoir, number of units engaged, and power output. The operating engagement of all thermal (lignite + oil) and hydro power plants with total electricity generation of 8000 GWh in a year is given in Fig.1.

The operating engagement of all hydro power plants with total electricity generation of 1473 GWh in a year is given in Fig.2.

In order to have a better picture of the operation of thermal and hydro power plants, Fig.3 and Fig.4 state the electrical generation for all power plants in the last 52nd week (winter) and 13th week (summer) of the year. It is noticed that HPP Vrutok as a derive HPP are works a short time in a day.
covering the high peaks, and the Kozjak, Tikves, Spilje and Globocica are in between Vrutok and run of river HPPs. The thermal power plants cover the base load.

The special operations of the cascade on Treska River (HPP Kozjak, Sv Petka and Matka) are given in Fig.7, 8 and Fig.9, respectively. HPP Kozjak has large water installed capacity according to water inflow, and its operation only a few hours a day. The gross head variation has a significant influence on electricity generation, so large discharging of the reservoir is not allowed.

HPP Tikves has very similar hydro technical parameters with HPP Kozjak and similar operating mode. HPP Globocica with Ohrid Lake as an accumulation has a role of derivation hydro power plant with large water inflow, which results in full capacity operation of 54 m3/s during the whole year (Fig.10). It means that the installed capacity can be extended for an additional unit.

HPP Spilje has double factor of installed capacity according to average inflow, and an additional unit will significantly improve the operation and reduce the spillways in wet years.
5. OPERATING LEVEL OF THE WATER RESERVOIRS

The levels of the water reservoirs follow the operation of the hydro power plants while taking into account water inflow through the year. Fig. 11 gives the annual changing of the water level in gross head for HPP Vrutok which is about 8 meters. The same for HPP Kozjak is given in Fig. 12.

![Fig.11 Annual gross head for HPP Vrutok](image)

![Fig.12 Annual gross head for HPP Kozjak](image)

Particularly interesting is the changing of water levels in the accumulations of HPP Sv Petka and HPP Matka with small water reservoirs of about 1 mill m³, according to water discharging from Kozjak. Fig. 13 gives the annual gross head of Sv Petka which has the variation from 37 to 40 m every day.

![Fig.13 Annual gross head for HPP Sv Petka](image)

The next Fig.14 and Fig.15 give the daily variation of water levels in the reservoirs for HPP Sv Petka and HPP Matka, respectively. The Fig.16 represents the cascade of the river Treska.

![Fig.14 Level of the reservoir Sv Petka](image)

![Fig.15 Level of the reservoir Matka](image)

CONCLUSIONS

The model for hourly operating mode in a year for electricity generation in a complex power system gives the real overall for each hydro power plant. In the test of Macedonian electric generation system, the hydro capacities are especially treated in order to find the optimal management of available water resources for electricity generation. HPP Vrutok and Globočica have relatively large reservoir capabilities (can save water during several years periods). The other HPPs, Kozjak, Tikves and Spilje, can save the water for less than a year, but on the other hand, the variation of the water level over 10 (m) will lead to significant energy losses. The model capabilities can be used to ensure an optimized energy generation in a power generation system, with an adequate energy supply that meets the projected energy demand for each time interval. The following points must be considered with the presented model, aimed at improving the operation of the power generation system:

- Defining power plant operation to meet the electricity demand in a given time interval;
Managing the water resources for energy purposes;
Influence of different hydrology in electricity generation for HPP;
Influence of disturbance of hourly electric demand for operation of HPP;
Determining the reservoir status of the existing storage HPP (water storage level during the period);
Defining the operation of existing HPP (number of units, output power, water discharge, water reservoir level, water for irrigation, etc);
Reducing the spillways in wet hydrology;
Identification for enlarging the installed power for HPP with new turbine units or with enlarging the water capacity of existing turbine units;
Special analysis for the hydraulic cascade of hydro power plants in order to find optimal operation according to water capacities and installed power.

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References

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