The principle of secondary hydraulic accumulation provided by pumped storage power plants is presently the only appropriate possibility for accumulating, on a large scale, surplus electrical energy produced by not regulating sources. Pumped storage power plants are regulating sources of electrical energy. In time of increasing electricity consumption these power plants generate required peak energy (on-peak power). When the electricity consumption decreases the pumped storage power plants use the surplus energy produced by not regulating energy sources (off-peak power) for pumping (the accumulation of energy in an upper reservoir). Due to their dynamic regulating abilities, pumped storage power plants provide additional support services for a power system. The operation of these facilities has to fulfill the requirements of the power system and simultaneously achieve an appropriate degree of economic effectiveness. Under the present conditions of the energy market, the operational effectiveness of these power plants is the crucial criterion for their versatility and further development.

In a power system, pumped storage power plants fulfill the requirements for the quantity and quality indicators of the electricity produced, and they increase the operational safety of the whole system. The functions of pumped storage power plants in a power system can be defined as static and dynamic. Static (planned) functions are defined as planned power generation and energy transfer. Dynamic (not planned) functions provide support services such as the regulation of frequency and power generation (primary, secondary, tertiary), power backup, compensation operation or “black start”. These functions are realized by power generation.

In the Slovak power system pumped storage power plants are important regulation elements. The total installed capacity of Slovak pumped storage power plants is 1046.4 MW, which is more than 40% of the installed capacity of all the Slovak hydropower plants and more than 10% of the total capacity of the Slovak power system. However, their share in the total production of electric power is only 0.75%. Every existing pumped storage power plant in Slovakia operates on a daily regulation cycle (Table 1). The planned development of the Slovak power system anticipates construction of several large pumped storage power plants (Ipeľ, Hrhov, Malá...

**ABSTRACT**

The operation of pumped storage power plants has to cover the power system’s requirements and achieve an appropriate degree of economic effectiveness. The methodology for optimizing the operation of such power plants described in this article is based on an economic evaluation of the operational effects of simulated operation scenarios. The optimal operation scenario is selected from the simulated scenarios as the best according to the economic effectiveness criterion.

**KEY WORDS**

- pumped storage powerplant,
- economic effectiveness,
- optimization
Vieska) due to the construction of planned nuclear power plants. These new classic types of pumped storage power plants should operate in weekly cycles. Their operation should be designed in a way that fulfils the technical requirements of the power system at the most effective level. That is the purpose of optimizing operations.

OPERATION OF CLASSIC PUMPED STORAGE POWER PLANT ON A WEEKLY CYCLE

The principle of classic pumped storage power plant operations is the cooperation between two reservoirs, where the volume and water level regime in the reservoirs is affected only by the actual performance of the power plant in the power system. Other factors and water losses can be ignored. Functions of pumped storage power plants in a power system are realized by producing or consuming electrical energy, which directly affects the regime in reservoirs. During on-peak power generation, water flows from an upper reservoir to a lower reservoir (the upper reservoir is emptying and the lower is filling). During off-peak power consumption, water flows from a lower reservoir to an upper reservoir (the lower reservoir is emptying and the upper is filling). Thus the pumped storage plant operation can be described by the volume equations of the reservoirs. The condition of the volume balance of the storage reservoirs in a regulation cycle has to be fulfilled.

The operating volume of a weekly cycle pumped storage power plant is as follows:

\[
V_o = 3600Q_t n_t t_p,5 - 3600Q_p n_p t_p, A = \text{[m}^3\text{]},
\]

where

- \(V_o\) - the operation volume \([\text{m}^3]\),
- \(Q_t\) - the turbine discharge \([\text{m}^3\text{s}^{-1}]\),
- \(n_t\) - the number of turbines,
- \(t_p\) - the daily duration of the power generating operation \([\text{hours}]\),
- \(Q_p\) - the pump discharge \([\text{m}^3\text{s}^{-1}]\),
- \(n_p\) - the number of pumps,
- \(t_p\) - the daily duration of the pumping operation \([\text{hours}]\),
- \(t_p\) - the duration of the pumping operation during the weekend \([\text{hours}]\).

The maximum operating volume \(V_o^{\text{max}}\) of the power plant should not exceed the maximum storage volume of the reservoirs and the maximum volume pumped during the weekend. In order to comply with these two conditions for the given daily duration of the power generating operation, the maximum daily duration of the power generating operation is defined by the following equations:

\[
t_{\text{reg},\text{A}} = \frac{V_{o}^{\text{max}} + 3600Q_p n_p t_p, A}{3600Q_t n_t,5} \text{[hours]} \tag{2}
\]

and

\[
t_{\text{reg},\text{P}} = \frac{3600Q_p n_p,48 + 3600Q_p n_p, t_p,5}{3600Q_t n_t,5} \text{[hours]} \tag{3}
\]

Table 1  Overview of existing pumped storage power plants in Slovakia (Sládek, V., 1996).

<table>
<thead>
<tr>
<th>Power plant</th>
<th>Year of construction</th>
<th>Number of units</th>
<th>Power generation</th>
<th>Power consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dolný Jelenec</td>
<td>1948</td>
<td>2</td>
<td>0.91 MW</td>
<td>0.92 MW</td>
</tr>
<tr>
<td>Dobšiná</td>
<td>1954</td>
<td>2</td>
<td>24 MW</td>
<td>18 MW</td>
</tr>
<tr>
<td>Mikšová II</td>
<td>1960-1965</td>
<td>1</td>
<td>2.38 MW</td>
<td>3.13 MW</td>
</tr>
<tr>
<td>Ružín</td>
<td>1972</td>
<td>2</td>
<td>60 MW</td>
<td>66 MW</td>
</tr>
<tr>
<td>Liptovská Mara</td>
<td>1975</td>
<td>2+2</td>
<td>198 MW</td>
<td>106 MW</td>
</tr>
<tr>
<td>Čierny Váh</td>
<td>1981</td>
<td>6</td>
<td>734.4 MW</td>
<td>600 MW</td>
</tr>
</tbody>
</table>
For the given power plant parameters, the lesser value of \( t_{\text{max,A}} \) and \( t_{\text{max,B}} \) is the maximum duration of the daily power generating operation. When the volume regime of the power plant reservoirs is determined, the power generation and consumption can be estimated. Technical aspects such as the duration of the on-peak generation, off-peak pumping, power generation and pumping capacity, etc., define the pumped storage plant’s operation.

**APPRAISAL OF THE EFFECTIVENESS OF PUMPED STORAGE POWER PLANT OPERATIONS**

An appraisal of the effectiveness of a pumped storage power plant’s operation is based on methods of assessing the effectiveness of the investment. The principle of the assessing is in a comparison of the capital expended (investment costs) to the gains brought by the investment. It is a balance of single-shot (investment) costs and annual gains in its economic life. Investment gains are defined as an increase in profits (taxed profits) and an increase in deductions. These two items together with some others create cash flow. Based on the cash flow methods of financial appraisal, the effectiveness of a given investment can be determined. The objectivity of the estimated costs and future income considerably affects the quality and accuracy of the results of the assessment.

For appraisals of pumped storage plant operations different operating scenarios, which result in different operating benefits, are used. The operating benefits are evaluated and assessed using the following methods based on cash flow estimation (Synk, M., et.al., 1996):  

- **Payback period (PBP)** – The period of time required for the return on an investment to “repay” the sum of the original investment.
- **Net Present Value (NVP)**- This method is one of the most accurate and reliable methods. It measures the excess or shortfall of cash flow in present value terms.

\[
NVP = \sum_{i=1}^{n} \frac{(CF_i - I)}{(1 + a)^i}
\]  

where  
- \( I \) - the investment,
- \( CF_i \) - the cash flow,
- \( a \) - the discount rate,
- \( i \) - the time of the cash flow,
- \( n \) - the total time of the project.

- **Rentability Index (RI)** It is suitable for a decision between different scenarios.

\[
RI = \frac{NPV}{I}
\]  

- **Internal Rate of Return (IRR)** This method gives the expected profitability of investments. The internal rate of return is defined as the discount rate, when the net present value equals the investment.

- **Benefit-Cost Balance (B)** It is an estimation of the annual balance between the costs and profits (benefits) of the investment. This method is suitable for existing projects.

\[
B = P - C
\]  

Where  
- \( B \) – the benefit – cost balance,
- \( P \) – the profits,
- \( C \) – the costs.

**OPTIMIZATION OF PUMPED STORAGE POWER PLANT OPERATIONS**

The optimal operation of a pumped storage power plant has to fulfil the requirements of the power system such as the duration of on-peak generation, the amount of power generated, the amount of power backup, the range of support services, etc. Concurrently, it has to provide the maximum economic effectiveness. For a given system’s requirements, the optimal operating scenario is the one that fulfils the needs of a power system at the best level of effectiveness. Based on the previous appraisal methods the optimization criterion can be defined as the following:

\[
\text{Min}(PBP) = \text{Max}(NVP) = \text{Max}(RI) = \text{Max}(IRR)
\]
The optimization process is based on a simulation model. The optimal operating scenario is selected from a group of simulated scenarios as the one that mostly fulfills the criterion. The basic scheme of this optimization methodology (Fig. 3) shows that the whole process consists of three basic steps. The first is the definition of the inputs such as an optimization criterion, the pumped storage power plant’s parameters, economic parameters and different operation scenarios based on the system’s requirements. The second step is the simulation and evaluation of scenarios in the simulation model. In the third step the optimal operation scenario is selected, according to the criterion of optimization. The reliability of the input data must be considered, especially since the economic parameters based on predictions are often a source of considerable inaccuracy.

**OPTIMIZATION OF OPERATION OF PUMPED STORAGE POWER PLANT IPEĽ**

The pumped storage power plant Ipeľ has been prepared for construction for more than 30 years as a weekly operation pumped storage project. It has been designed to utilize the maximum of the potential of the plant locality (Dušička, P., et al., 2005). Under the present conditions the concept of this power plant did not seem effective, due to the new economic conditions and power system requirements. The described methodology has been used to examine the possibilities of operating this plant under the present conditions.

Different operating scenarios have been simulated and evaluated under the present economic conditions. A comparison of the results of the simulated scenarios to the planned operating scenarios showed that the planned operation of this pumped-storage project is not effective and is unfeasible under the present conditions. It has also been proved that according to the effectiveness results of the planned operation of PPS Ipeľ under the present conditions, the whole project is unfeasible, and serious modifications to the planned operations but also to the entire plant concept must be made. However, the methodology has been used to determine the optimal operation for the present conditions. The operating effectiveness of the PSP Ipeľ has been increased by focusing the operation on providing support services to the...
power system. Further optimization showed that the power plant Ipeľ should be operated only as a large system backup to achieve maximum effectiveness.

CONCLUSIONS

The optimization of the operation of every system is an important issue for achieving its maximum effectiveness. Such an important source as a pumped storage power plant has to be operated effectively to ensure its versatility in the energy market. As the application of optimization methodology to the pumped storage power plant Ipeľ showed that, especially for new projects, it is necessary to operate at the best efficiency level to get a reasonable payback of the investment. In a larger scope it is not only the operation that can be optimized by new projects of pumped storage power plants, but also the whole power plant concept, which can be modified as an input to a simulation model.

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