Peter Šulek, Peter Dušička

Mathematical Model of the Váh Cascade

The optimal operation of an electrical power supply subsystem results from respect for the effectiveness criterion for the control of an industrial enterprise. It is essential for the operation of the SE-VET – a significant hydro-energy system. The fundamental principle of this operation is the potential hydropower utilization of water courses of the SE-VET in addition to planning the control of SE system.

Key words: ELECTRICAL SUPPLY SYSTEM, OPTIMAL OPERATION, HYDROPOWER PLANT, OPTIMIZATION CRITERION, OPTIMAL PROGRAMMING, SIMULATION MODEL.

I. INTRODUCTION

The preparation of Principally, efficient management of the subsystems of the electrical system (ES) must be based on respecting the fundamental criterion of efficient ES management. This is also the governing principle of managing the important hydroelectric system within the national utility company Slovenské elektrárne (SE, a.s). – hydro power plant Váh Cascade (Fig. 1). The core management criterion for this subsystem is the cost-effective use of the hydropotential of SE's water sources to cover the requirements of Daily Load Chart in respect to preparing the operation of SE‘s sources, while faciliating all marginal water management and energy conditions.

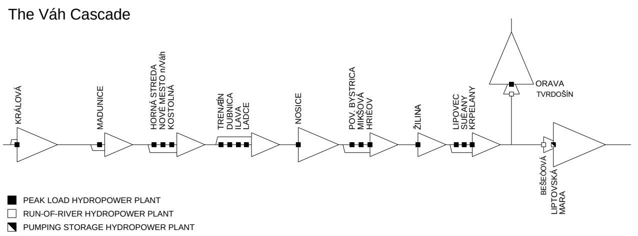


Figure 1. Scheme of the Váh Cascade.

The preparation of hydropower plant (HPP) operation seeks to ensure reliable and efficient operation of the hydroelectric system. Planning and preparation of operation within the Dispatching Management System of the Vodné elektrárne Trenčín utility company (VET) is defined as „computations and modelling of hydro plant operation based on the input of coordinating signals from higher management level in intervals (year, month, day) and respecting the ES hydraulic conditions and requirements to efficiently use the hydroelectric potential“. One of the important elements in the HPPs pre-operation process is the computations and operation modelling using the hydromodel of the Váh cascade („Hydro-Model“). The Hydromodel represents the programatic model for a cost-effective use of the HPPs Váh Cascade hydropotential in covering the Daily Load Chart requirements in respect to pre-operation of other SE, a.s sources (hydro-thermal coordination).

The Hydro-Model‘s algorithms are programmed and tuned in the ADA95 program language environment, and are currently implemented by means of external DLL library into the complex IT environment supporting the pre-operation process of HPPs. The Hydro-Model's main task is the processing of hydrological inputs and the modelling of hydraulic states and hydraulic bonds of the hydro power plant cascade on the rivers Váh and Orava (the Váh Cascade). On the output side, a performance plan at individual HPPs is generated with due account of their regulatory reserve and in the determined time roster, as proposed under the main criterion of efficiency, namely, that the production plan should reflect as closely as possible the required shape of the business chart.

II. HYDRO-MODEL'S UNDERLYING SCHEMES

Depending on the manner of operation (manner of water efficiency) and the waterwork's (WW) conceptual solution, individual HPPs of the Váh Cascade can be associated with two underlying schemes:

- regulatory scheme
- accumulation scheme

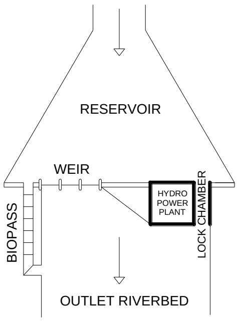
REGULATORY SCHEME

In operative terms, these HPPs are built on reservoirs with short-term flows regulation (daily or weekly). In respect to the waterwork's conceptual solution, the regulatory schemes can be divided into weir-surrounding schemes (see figure 2) and channel schemes (Fig. 3).

The weir-surrounding regulatory HPP of the Váh Cascade include HPP Žilina, HPP Kráľová and HPP Nosice. Among the regulatory channel HPP of the Váh Cascade are the HPP groups: Krpeľany - Sučany - Lipovec, Hričov - Mikšová - Považská Bystrica, Ladce - Ilava - Dubnica - Trenčín, Kostolná - Nové Mesto n/Váh. - Horná Streda, and the alone-standing channel HPP Madunice.

ACCUMULATION SCHEME

In terms of operation (water efficiency), these HPPs or pumped-storage HPPs are built at large accumulation reservoirs with long-term flows regulation (annual or more years). The accumulating reservoirs are connected to compensation reservoirs with downstream low-performance HPPs that are designed to generate electricity at given flow rates under these HPPs. The governing HPP of such group is the HPP or pumped-storage HPP built in a direct hydraulic bond to the accumulation reservoir (Fig. 4).



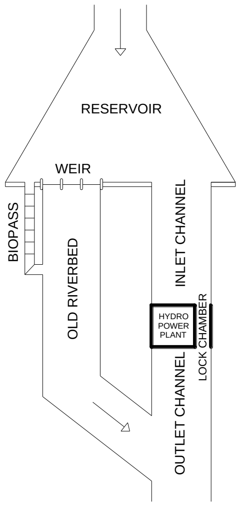


Figure 2. Weir-surrounding scheme. Figure 3. Channel scheme.

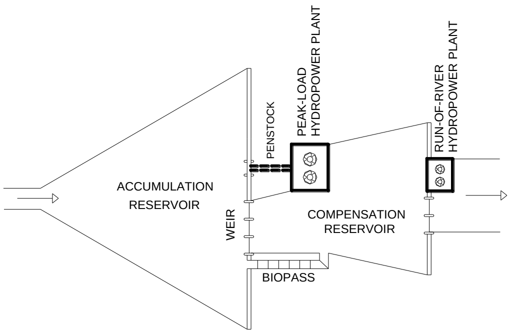


Fig. 4 Accumulation scheme.

The accumulation schemes of the Váh Cascade HPPs include HPP: Orava – Tvrdošín and pumped-storage HPP Liptovská Mara – Bešeňová.

III. UNDERLYING COMPUTATION SCHEME

The Hydro-Model's basic computation scheme is shown at Fig. 5.

The hydromodel's main inputs are as follows:

- required business chart or evaluation,
- required values of supporting services (SS) (i.e. primary regulation of power output (P_{PR}+/-), secondary regulation of power output (P_{SR}) and tertiary regulation of power output (P_{TR}+/-)),
- hydrological forecasts from Slovak Institute of Hydrometeorology Institute (SHMÚ),
- WW's construction parameters and limits,
- required manipulation at water structures,
  optimization criterion.

The hydromodel's main outputs are as follows:

- plan of power output and generation at individual HPPs of the Váh Cascade,
- offered supporting services (SS).

As the fundamental prerequisite, the search for the most efficient solution of any system must be based on derivation of the optimization criterion that, as concerning the HPP subsystem, must comply with the basic criteria of efficient management of the entire ES. The overriding optimization criterion of the pre-operation of the HPPs of the Váh Cascade is to achieve the closest business chart/proposed performance ratio, as required. The optimization criterion is, then, defined by the so-called criterial (objective) function. Optimization will thus be understood as minimizing (or maximizing, respectively) the purpose-driven function $f(x)$, which is represented by the dependent variable of parameters, whose optimum values $x^*=(x^*_1, x^*_2, \ldots, x^*_n)$ are to be sought. Tasks of this formulation can be resolved by using the theoretical methods of optimum system management. One of the suitable ways of solving the given optimization task usable for drafting pre-operation of the HPPs system is the use of the HPP system simulation model and the optimization method in the simulation model. The choice of suitable optimization method should take due account of that fact that the accuracy of computations in the management efficiency solution will be higher than the accuracy of possible acquisition of input data.

In view of the above, and in an effort to achieve the utmost efficiency of the HPP pre-operation process (in particular, regarding the Hydro-Model's "velocity"), all defined functions (i.e. purpose-driven function and all inherent restrictions) had necessarily been transformed to linear functions. As all coefficients of the task (coefficients of all functions) are real numbers, the problem of HPP's efficiency of operations could have been transformed to a linear programming task that can be briefly stated as the following matrix:

$$\max N = \left(\vec{c}\right)^T . \vec{Q}_{HPP} \quad \text{in compliance with} \quad A.\vec{Q}_{HPP} \leq \vec{b}\ ,\ \vec{Q}_{HPP} \geq 0$$

where

$\underline{A}$ - matrix of structural coefficients,
$\vec{c}$ - vector of evaluations,
$\vec{Q}_{HPP}$ - vector of solutions (optimum flow through HPPs profile),
$\vec{b}$ - vector of restrictions.

In the Hydro-Model, the solution of the defined task of linear programming is arranged by using the Simplex method. Parameters for computing the values of structural coefficients of the "A" matrix and of the "b" vector of restrictions (vector of the right sides) are arrived at by computations made in the Hydro-Model's additional modules.

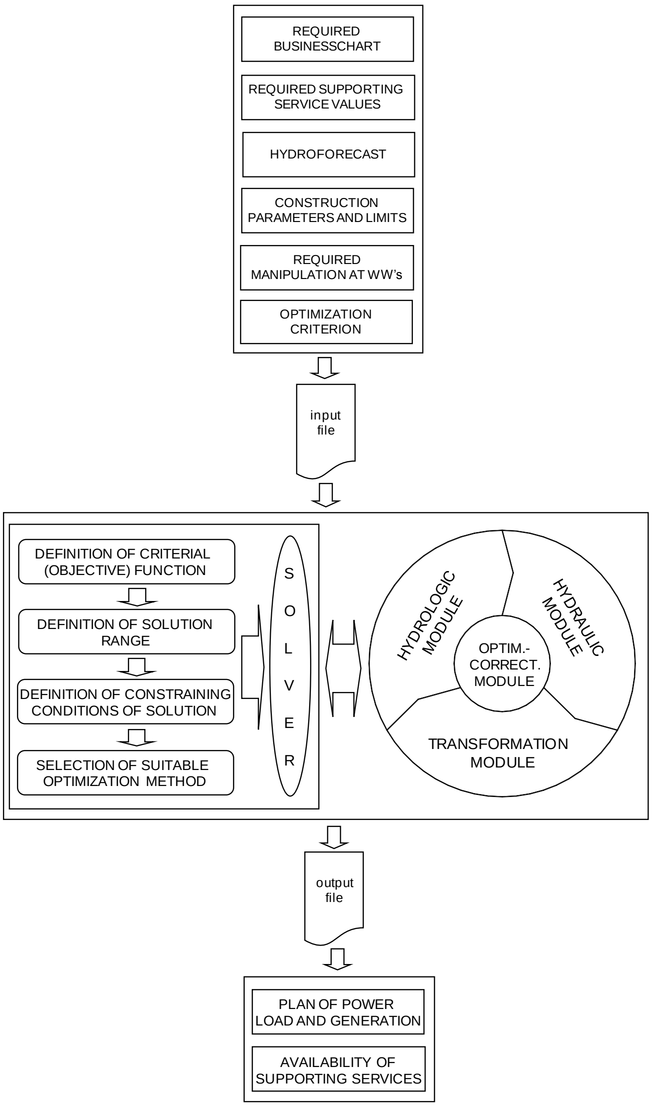


Figure. 5 Basic computation scheme of the solution.

HYDROLOGICAL MODULE

The hydrological module provides data as to the flow management in the individual elements of the system. Its task (output) is to provide real data on available water flows for individual HPPs. The hydrological module is based on the following:

- the system's elements/flow management impact rate,
- determination of priority bonds among the system's reservoirs.

Based on the setting of possible bonds (interactions) and the system's elements/flow management impact rate, the hydromodel can be divided as follows:

- sections: profile of reservoir's intake – HPP intake profile,
- sections: outlet profile from the group-ultimate HPP – intake profile of the next HPP group,
- sections: weir (profile of idle outlet from HPP group) – orifice of the ultimate HPP's outlet channel to the old riverbed.

The hydrological module serves to provide data on flows in the sections between individual HPPs or HPP groups that, although hydraulically uncoupled, have substantial impact on the time sequence of the regulated flows, and, as a result, impact the engagement of individual HPPs in time. The „inefficient" sections include: Bešeňová – Krpeľany, Tvrdošín – Krpeľany, Lipovec – Žilina, Žilina – Hričov and Madunice – Kráľová.

Additionally, the hydrological module also serves to provide data on flows in the sections located between weir (profile of idle outlet from HPP group) and the orifice of the group-ultimate HPP's outlet channel to the old riverbed.

HYDRAULIC MODULE

The purpose of the hydraulic module is to provide data on heads for individual HPPs. It allows to determine their following characteristics:

- water surface level in reservoir,
- hydraulic losses in HPP intakes and outlets,
- hydraulic bonds of individual HPPs.

The proposed structure of the hydraulic module stems from the configuration of HPPs. In terms of solving hydraulic bonds and hydraulic losses, the module is divided as follows:

- reservoirs,
- channels divided into sections: reservoir – HPP, HPP – HPP, HPP – reservoir of the next HPP group (the downstream water surface level is impacted by the operation of the next HPP group), HPP – inefficiently used flow section,
- penstocks (section reservoir – HPP).

The job of the reservoir's hydraulic module is to set, on the basis of supply volume, the reservoir's immediate water surface level or the reservoir's immediate water supply volume as based on the water surface level. The job of the hydraulic module of channels is to set the hydraulic losses resulting from water flow in these structures. The job of the hydraulic module of pressure inlet channels (pipes) is to set the hydraulic losses resulting from pressured water flow in these structures.

TRANSFORMATION MODULE

The purpose of the transformation module is to transform, based on the results of both the hydrological and hydraulic modules, the flow rates (hydrological modules) and heads (hydraulic module) to electrical power.

Additionally, the transformation module has also the job of determining the values of flow rates equivalent to the required supporting services values. Transformation of the required regulatory outputs to equivalent flow rates is apparent from the scheme at Fig. 6.

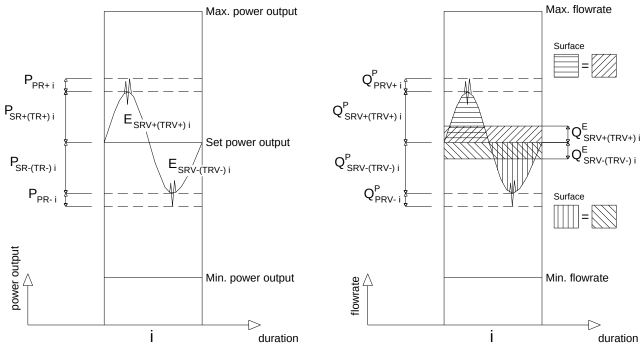


Figure 6. Transformation of required regulatory outputs to equivalent flow rates.

MODULE OF OPTIMIZATION AND CORRECTION

The purpose of the optimization module is to propose, on existing conditions and marginal criteria of water management and energy management, as well as other criteria, the output plan for individual HPPs of the Váh Cascade, while using the main optimization criterion. The HPP Output Plan with headroom for regulatory reserve in the determined time roster is proposed for the stated optimization interval.

The corrective part of the efficiency module serves to make corrections of the values of structural coefficients of the *"A"* matrix and the *"b"* vector of restrictions for and after each computation of the values of the solutions vector $Q_{HPP}=(Q_{HPP1},Q_{HPP2}, ..., Q_{HPPn})$. Subsequently, more accurate values of the Q_{HPP} solutions vector will be recomputed using the corrected values.

IV. CONCLUSION

VET paid considerable attention to efficient use of convenient, in particular, dynamic properties of the HPP subsystem within Slovakia's ES. Solutions of efficient operation were prepared for all HPP groups within this subsystem. VET has been applying efficiency solutions for preparing operation and real-time operative management for more than 20 years. Nevertheless, the issue of efficient hydro power plan operation fails to be adequately solved. The complexity of efficient HPP management arises mainly in the cascade operation, where individual HPPs are interconnected by comples hydraulic bonds.

Additional problem is posed by the fact that efficient load distribution among individual energy output facilities based on the criterion of regime efficiency fails to be resolved by the Slovak Energy Dispatching Center (SED). Currently, operation of individual ES sources based on the system estimated load balance and staff experience is being prepared. As a result, the coordinating signals for the management of subsystems coming from the first level ES management SED tend to be inaccurate and mere estimates, in which case any accurate efficiency solution for management of the Váh Cascade HPPs fails to comply with the principle of intercompatibility of objectives on individual management levels, and fails to comply with the global objective as set by the first management level.

ACKNOWLEDGEMENTS

This paper was supported by the VEGA Grant agency under Contract No.1/0578/11 the Slovak Research and Development Agency under Contract No. APVV-0680-10.

REFERENCES

[1] Šulek, P., Dušička, P.: *Popis algoritmov hydromodelovania navrhnutých pre SW model prípravy prevádzky VE - technická dokumentácia*. STU Bratislava, 2006

[2] Seewald, V.: *Návrh modelu optimalizácie prevádzky Vážskych vodných elektrární*. Inštitút riadenia v Bratislave, Bratislava, 1975.

[3] Kolcun, M. a kol.: *Riadenie prevádzky elektrizačných sústav*. Bratislava, 2001.

[4] Starý, M.: *Nádrže a vodohospodářské soustavy*. Ediční středisko VUT, Brno, 1986.

[5] Laščiak, A. a kol.: *Optimálne programovanie*, STNL, Bratislava, 1983.

ADDRESSES OF AUTHORS

Peter Šulek, Ing., PhD., Slovak University of Technology, Faculty of Civil Engineering Radlinského 11, 813 68 Bratislava, peter.sulek@stuba.sk
Peter Dušička, Prof. Ing., PhD., Slovak University of Technology, Department of Hydraulic Engineering, Radlinskeho 11, 813 68 Bratislava, Slovakia, peter.dusicka@stuba.sk