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Several Hydropower Production Management Algorithms

D. Vukosavić[1*], D. Divac[2], Z. Stojanović[3], B. Stojanović[4], D. Vučković[5]

Institute for Development of Water Resources "Jaroslav Černi", 80 Jaroslava Černog St., 11226 Beli Potok, Serbia; e-mail: [1]drmnv@sezampro.rs, [2]ddivac@eunet.rs, [3]zdravko.stojanovic@gmail.com, [5]dejan.vuckovic@jcerni.co.rs
Faculty of Science, University of Kragujevac, 12 Radoja Domanovića St., 34000 Kragujevac, Serbia; e-mail: [4]bobi@kg.ac.rs
Corresponding author

Abstract

In this paper the modes of operation of hydropower plants developed for use in a simulation model that is a part of a Hydro-Information System (HIS), are presented. Various methods of representation of performance of electricity generating units, turbines and generators, as well as the conduits or a plant as a whole, are described in detail. Various modes of operation of hydropower plants are presented: with specification of the daily electricity generation of the whole hydropower plant, with specification of the hydropower plant power during each hour of simulation, with the run-off-river hydropower plant operation and with explicit specification of the power, i.e. of the discharge for each unit in the plant during each hour of simulation. For each mode of operation the corresponding algorithms are described in detail. Examples of application of the modes of operation within a HIS are given. The example of operation of the "Višegrad" HPP demonstrates the hourly simulation of HPP operation with the specification of the power, while the examples of operation of the "Uvac" HPP demonstrate the simulation of the operation with the specification of daily and hourly electricity generation of the plant.

Keywords: Hydropower plants, turbine unit, management, mathematical simulation

1. Introduction

The problem of the optimum management of hydropower plant**s** includes the determination, for each unit in the hydropower plant, whether it is in operation under the given operating conditions, i.e. in which operating regime it operates.

The optimum management of a unit means the maximum adherence to the demands of the electricity generation and transmission system, with the minimum water consumption per unit of generated electricity. In modeling of the hydropower plant operation it is necessary to adhere to the limitations imposed by the characteristics of the plant itself, as well as to the other conditions present on a certain watercourse.

Planning of hydropower plant operation, as well as the simulation of its operation, can be short-term or long-term oriented.

In the literature there are several papers related to the planning of the power plant operation. About the methods for solution of unit commitment in thermal-power plants it was written, amongst the others, in Sheble and Fahd (1994), Tseng (1996), Svoboda et al. (1997), Feltenmark (1997), Lai and Baldick (1999). Planning of hydropower plant operation was treated in da Silva and Finardi (2003), Johnson (1997), Finardi and da Silva (2005), Li et al. (1997), Guan et al. (1999) and Arce et al. (2002).

According to Wood and Wollenberg (1996) and Batut and Renaud (1992), the complexity of hydropower plant operation is so high that so far there are no unique principles devised for their management that could be applicable in all situations. The reasons for that are:

- The inflow of water into hydropower plants depends upon a series of parameters that are difficult to forecast, so the plants have to adapt quickly to the actual situation,
- Water is a resource that is not used only for electricity generation, but also for water supply, melioration and other purposes,
- Hydropower plant operation is coupled with numerous limitations related to the environmental protection, valuable objects in the vicinity of the storages and watercourses etc. and
- The role of hydropower plants in the electricity generation and transmission system often dictates their dynamic operation (relatively frequent starts and shutdowns of their operation).

The main source of uncertainty in planning of development of an electricity generation and transmission system is the stochastic nature of availability of the units in thermal-power plants, as well as the water inflow into hydropower plants. The value of 95% is assumed as the limit for the probability of the fulfillment of the demanded electricity generation plan, because the design of an electricity generation and transmission system that would have the probability of fulfillment of electricity generation plan equal to 100%, would be economically unjustified, (Milić, 2000). The greatest influence upon the fulfillment of the electricity generation plan has the usable discharge of the water flow, while the key factors regarding the fulfillment of the demand related to power are rated discharge, head and, particularly, the size of the hydropower plant storage.

Hydropower plants also have a great significance regarding the attaining of a stable operation of the electricity generation and transmission system. This is valid particularly for the formation of the operating reserve (covering of all non-planned ceases of electricity generation in the system before the start of the cold reserve) and a part of the cold reserve (covering of longer non-planned ceases of operation of the thermal-power plant units) in the system.

This role of hydropower plants in the electricity generation and transmission system requires complex algorithms for their management. A simulation model, apart from these algorithms should also include the accurate models of hydropower plant elements. The models of some of the most important hydropower plant elements are presented in the following section.

The optimization of hydropower systems can be conveniently performed by the means of simulation of their operation. By simulation of plant operation it is possible to analyze numerically the situations that would be unsafe or expensive to observe on an actual plant. The simulations are based upon the simulation mathematical models, whose technical task is to describe as accurate as possible the properties of physical objects.

A detailed analysis of development of simulation models for use in hydro-information systems is given in Divac et al. (2009).

2. Modeling of hydropower plant elements

Depending on the disposition of their objects, hydropower plants can be of the diversion-type or with the powerhouse at the base of the dam. Diversion-type hydropower plants have long conduits that consist of a tunnel and a penstock.

In these plants water is directed through a common conduit system into multiple units and that can make the mathematical description of the plan of hydropower operation complex. Hydropower plants with the powerhouse at the base of the dam usually have short conduits for each unit, what makes the simulation of their operation simpler.

In the following figures the examples of hydropower plant dispositions are presented.

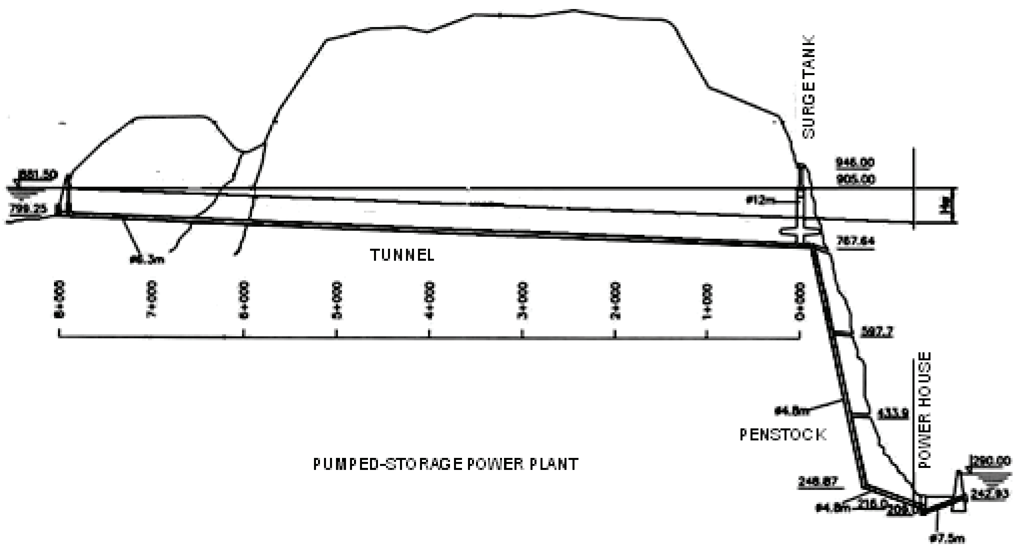

Fig. 1. Longitudinal section of the pumped-storage hydropower plant "Bajina Bašta", an example of a diversion-type hydropower plant.

The complexity and the structure of a hydropower plant model depend upon its application. In the field of automatic control IEEE had formed the systematization of the models that should be used for plant management (for instance, from the standpoint of operation of the turbine governor), Kishor et al. (2005).

For management of hydropower plants from the viewpoint of harnessing of the catchment hydropower potential there are several models to be found in the literature that are used as a part of software tools like WEAP21, Aquarius, RIBASIM, MIKE BASIN and HEC-ResSim.

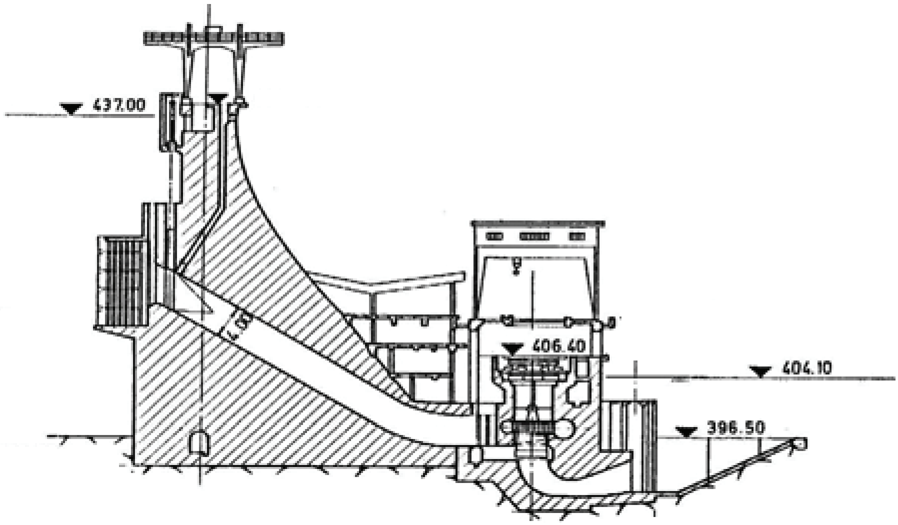

Fig. 2. Cross-section of the “Potpeć” HPP, an example of a hydropower plant with the powerhouse at the base of the dam.

In this paper the following hydropower plant elements are briefly outlined:

- The conduit and
- The unit (turbine and generator).

The remaining elements of hydropower plants significant for simulation models (dam, storage, tail water, spillway, outlet etc.) are described in Arsić et al. (2009).

2.1 Conduit

A conduit is an object characterized by the flow under pressure (the flow cross-section is completely filled with water).

In the hydropower plant the net head is the head available for electricity generation. In order to determine net head, apart from the hydropower plant gross head, it is also necessary to know head losses in the conduit.

The conduit is characterized by the head loss coefficient, K_w (s^2/m^5). Upon its value and the known discharge through the conduit, Q (m^3/s), the head loss, H_w (m), can be calculated:

$$H_W = K \cdot Q^2 \qquad (1)$$

Determination of the unit net head can be a relatively complex task in case of a diversion-type HPP equipped with several units. An example of such a hydropower plant is “Vrla 1” HPP that operates as a part of the system “Vlasinske HPPs”, whose conduit is presented in the following figure.

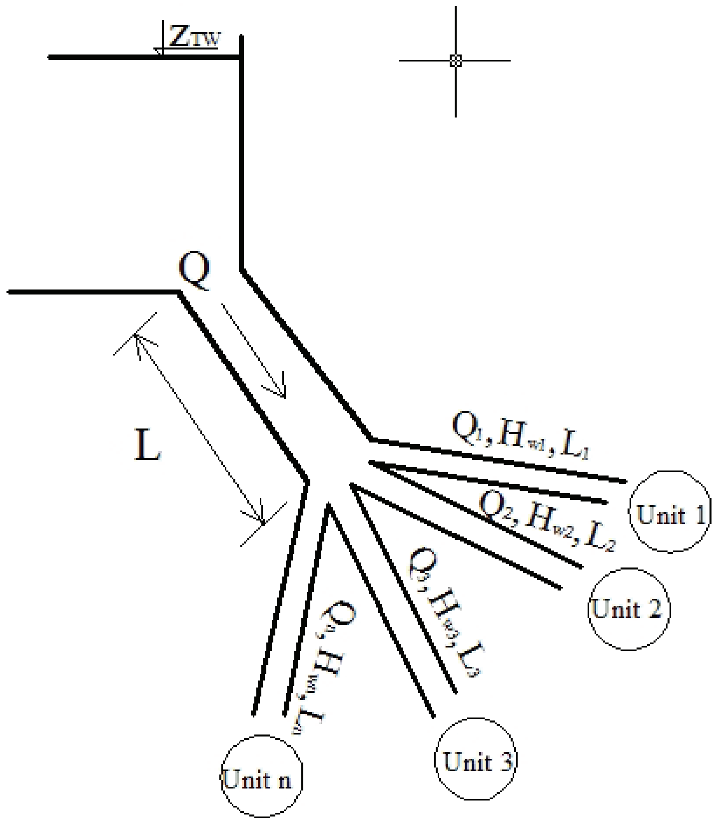

Fig. 3. Conduit of a diversion-type HPP equipped with several units.

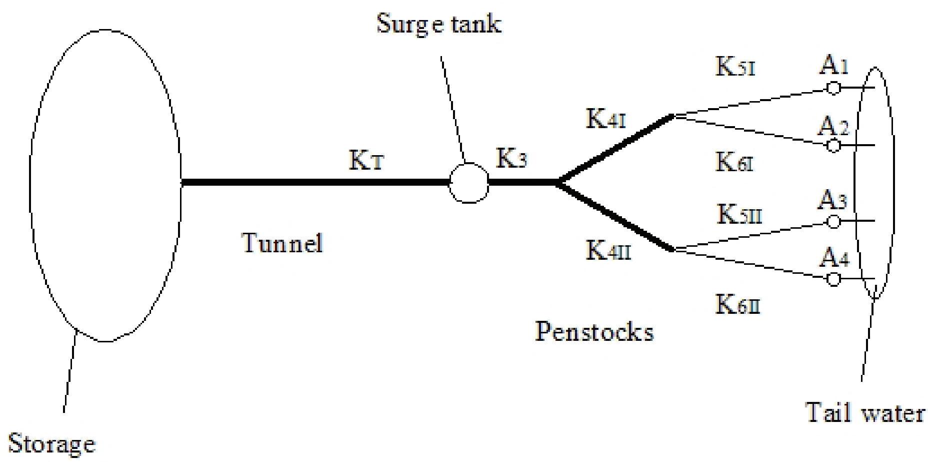

Fig. 4. Conduit system of the “Vrla 1” hydropower plant.

Head loss, for example for the Unit 1 in the "Vrla 1" HPP, $H_{W,A1}$, amounts to:

$$H_{w,A1} = K_{5I} \cdot Q_1^2 + K_{4I} \cdot (Q_1 + Q_2)^2 + (K_3 + K_T) \cdot (Q_1 + Q_2 + Q_3 + Q_4)^2 \quad (2)$$

With the total head loss in the conduit of the hydropower plant it is possible to determine the unit net head, $H_{n,A1}$ (m):

$$H_{n,A1} = H_{gr} - H_{w,A1} \quad (3)$$

2.2 Turbine

One of the main parameters used for description of turbine performance is its efficiency.

Turbine efficiency η_t (-) depends upon the net head and the discharge through it. Graphical means of representation of this dependence is the so-called hill chart. The hill chart contains the curves of constant turbine efficiency.

An example of the hill chart of a model of a Francis-type turbine is given in the following figure.

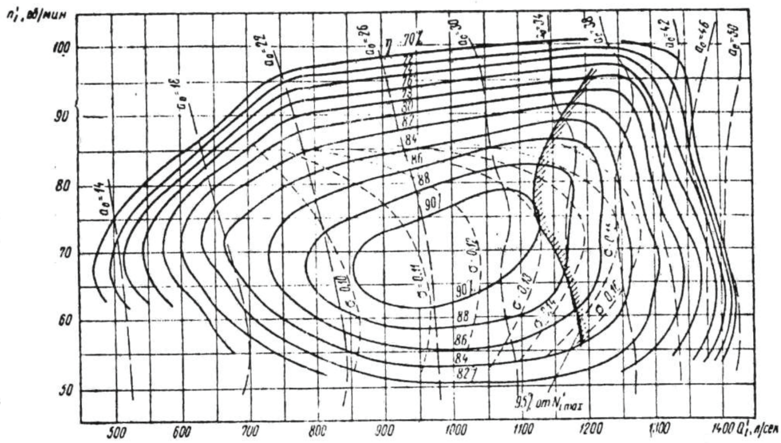

Fig. 5. Hill chart of a model of a Francis-type turbine

A chart of a turbine model is given in the non-dimensional coordinates. Upon the known dimensions and the rotational speed of the turbine runner another chart can be formed, with the discharge on the abscissa and the net head on the ordinate.

The values presented in the chart for the turbine model were obtained by measurement. The values of efficiencies of a model and a built turbine are different, due to the differences in their dimensions. This correction has to be taken into account in the process of determination of turbine efficiency.

During the operation of a turbine unit in a specific plant it is necessary to adhere to a series of conditions and limitations, such as:

- The range of unit net heads,
- The scope of discharges through the plant,
- The maximum opening of the turbine wicket gate,

- The power limitation because of the generator and
- The limitation of turbine operation regarding cavitation that is related to the turbine suction head etc.

The task of the exploitation chart is to couple the characteristics of the turbine unit with the limitations of the plant. The exploitation chart of a turbine built into the "Bajina Bašta" hydropower plant is given in the following figure.

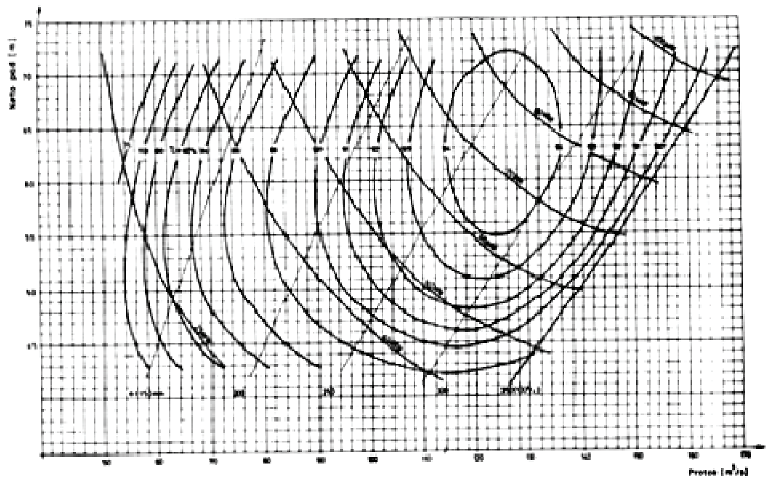

Fig. 6. Exploitation chart for a turbine in the "Bajina Bašta" hydropower plant.

Upon the net head, turbine discharge and turbine efficiency it is possible to determine the power with which the turbine operates, P_t (MW):

$$P_t = \rho \cdot g \cdot H_n \cdot Q \cdot \eta / 1000 \tag{4}$$

where:

- ρ (kg/m^3) - water density,
- g (m^2/s^2) - gravity acceleration,
- H_n (m) - net head,
- Q (m^3/s) - turbine discharge and
- η (-) - turbine efficiency.

For the purpose of simulation it is often convenient to use a chart that utilizes the values of constant power with which the turbine operates instead of the curves of constant efficiency. In the following figure such a chart for the turbines in the "Bajina Bašta" hydropower plant is presented.

If a turbine has its own conduit, then upon the curves of constant power with the discharge on the abscissa and the net head on the ordinate, the curves of constant power can be formed, with the discharge on the abscissa and the gross head on the ordinate. This is most often the case with HPPs with the powerhouse at the base of the dam. In certain cases, the approximate methods of description of dependence of the turbine efficiency upon its head and discharge can be used.

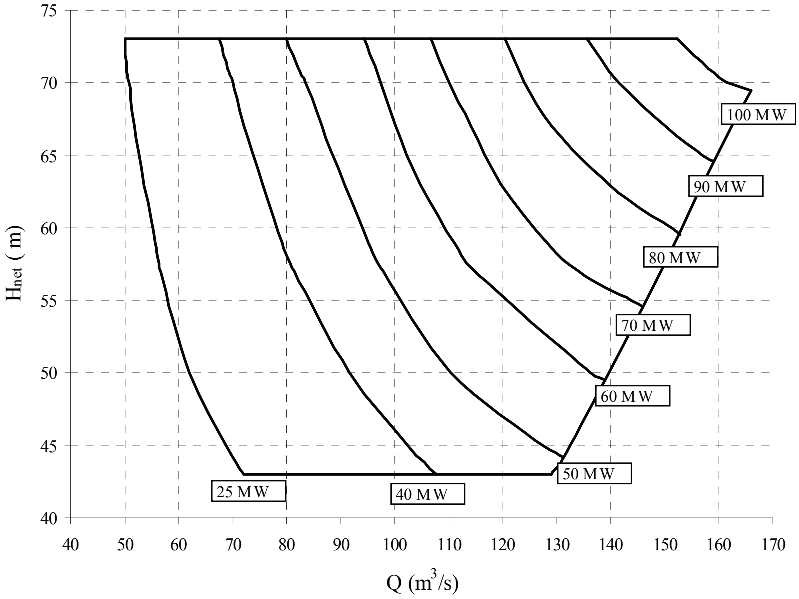

Fig. 7. Curves of constant power with the discharge on the abscissa and the net head on the ordinate for the turbines in the "Bajina Bašta" HPP.

On the following diagram the turbine efficiency curves in dependence upon the discharge through the turbine, for three different values of net head, are presented.

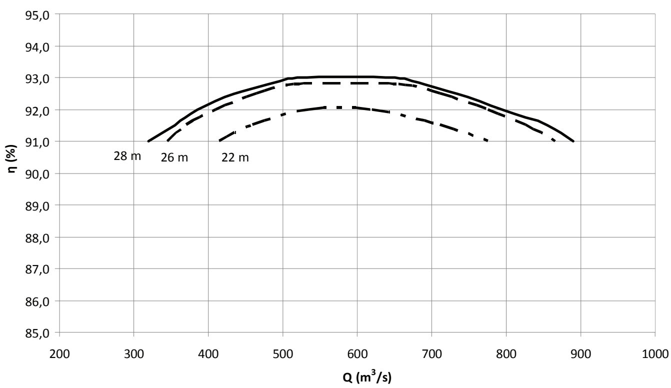

Fig. 8. Turbine efficiency in dependence upon the discharge through it for three different values of net head.

If in the hydropower plant, during its regular exploitation, the net head changes within the relatively narrow limits, then for all values of the net head one representative line, $\eta = \eta(Q)$, can be assumed, while the dependence of the efficiency upon the net head can be neglected.

In units with the so-called double regulation and the so-called combinatory control that have high efficiency in a wide range of operating regimes, it is possible to neglect the dependence of efficiency upon discharge, i.e. to assume that the condition η = const. holds true.

There are many cases of the use of the chart that describes the dependence of the unit water consumption (per kWh of generated electricity), q (m^3/kWh), upon the hydropower plant gross head. An example of such dependence is shown in the following figure.

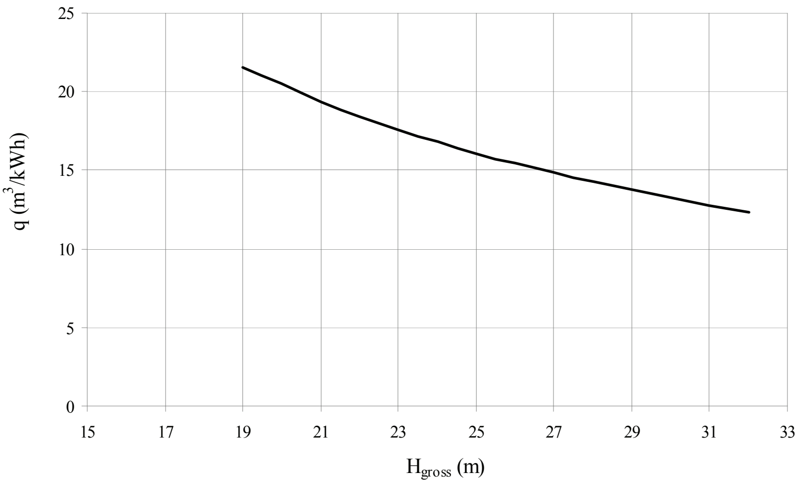

Fig. 9. A curve that depicts the dependence of the unit water consumption (per kWh of generated electricity) q (m^3/kWh) upon hydropower plant gross head.

In hydropower plants with large storages the range of recommended unit operating regimes can be reduced to the so-called optimum and maximum operating regimes only:

- The turbine operation with the maximum efficiency for the given net head or
- The turbine operation with the maximum power for the given net head.

An example of this method of description of unit operating regimes is presented in the following figure.

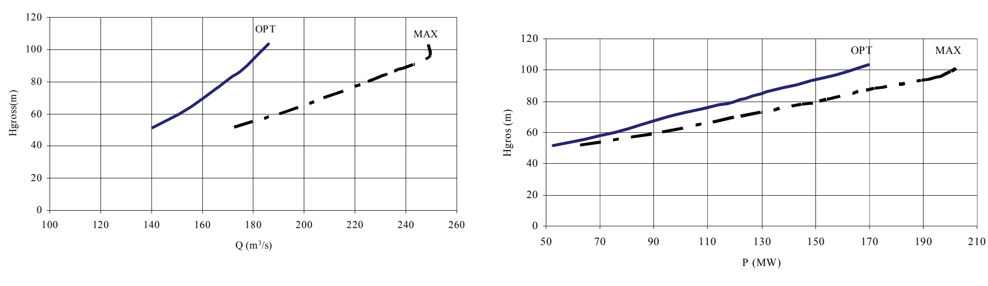

Fig. 10. Curves of the optimum and the maximum discharge (left) and the optimum and the maximum power (right) of a turbine unit.

In certain situations, the unit can operate in the so-called “idle” operating regime. In this regime the water flows through a turbine that rotates with the synchronous rotational speed, but the unit generates no electricity at all. In this case the discharge through the turbine depends upon the net head. An example of the dependence of the discharge through the turbine upon the net head in the idle operating regime is presented on the following chart.

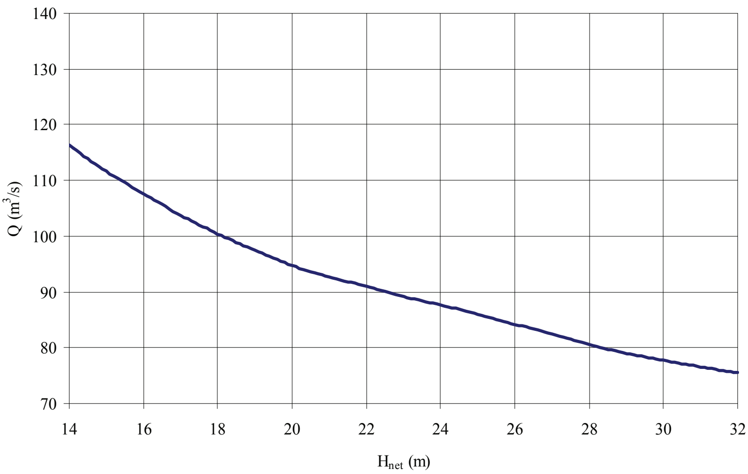

Fig. 11. The dependence of discharge through a Kaplan-type turbine upon its net head in the idle operating regime.

In the literature the different approaches to mathematical modeling of turbine efficiency can be found.

In the HEC-5, (U.S. Army Corps of Engineers 1998), the following methods of modeling are used:

- The use of constant efficiency,
- The use of dependence of the efficiency upon the storage volume,
- The use of dependence of the efficiency upon the hydropower plant head and
- The use of dependence of the ratio between the turbine power and discharge [kW/(ft^3/s)] upon the storage volume, where the value of the turbine efficiency is included in the turbine power.

In RETScreen International (2004) an array of empirical formulae is used for determination of the turbine efficiency, depending on:

- The turbine type,
- The diameter of turbine runner,
- The turbine specific speed and
- The ratio between the actual turbine discharge and the discharge through the turbine in the optimum operating regime.

Depending on the form of the curves for a specific turbine and the unit operating conditions of the plant, the various forms of linearization of turbine performance curves, or mathematical functions that these curves can be approximated by, can be used in the simulation model.

2.3 Generator

The generator model described here is relatively simple, but entirely adequate for use within the simulation model.

For use within the simulation model, the generator is described by the means of dependence of the efficiency upon the generator power.

An example of the dependence of the generator efficiency η_g (-) upon the power with which it operates is given in the following figure.

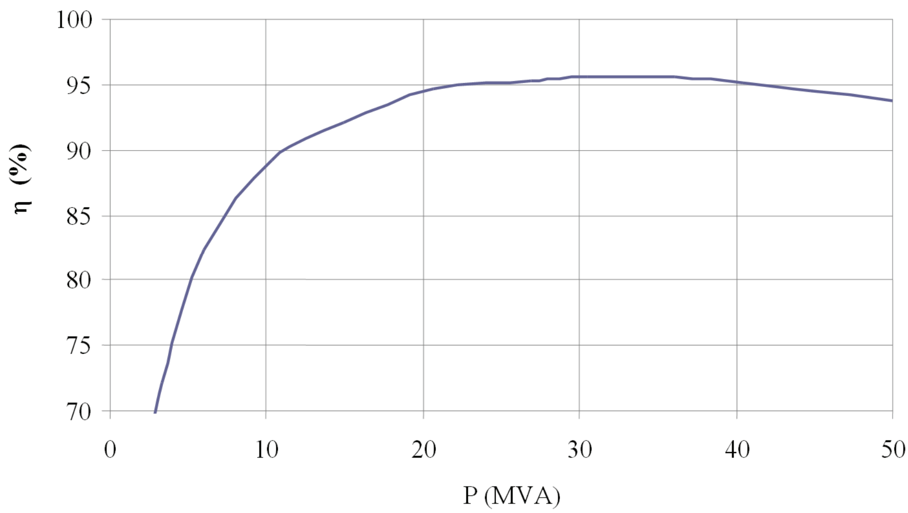

Fig. 12. Dependence of the generator efficiency upon its power.

The useful power, with which the unit operates, P_a (MW), can be determined upon the turbine power and the generator efficiency:

$$P_a = P_t \cdot \eta_g \tag{5}$$

2.4 Transformer

In order to determine the transmitted power (at the HPP threshold), it is necessary to take into account the transformer efficiency η_{tr} (-). In the simulation model used it was assumed that transformer efficiency has a constant value, $\eta_{tr} = 0.99$.

3. Modes of operation of hydropower plants

The methods of management of hydropower plants define the operation of hydropower plants in the following manner:

- The short-term management defines the hydropower plant operation in duration from one up to several days and the simulation time step is one hour and
- The long-term management defines the operation of the hydropower plant during a period longer than one year and the simulation time step is one day.

In order to model the short-term and the long-term management of the different types of hydropower plants and to fulfill to the demands of the electricity generation and transmission system, the following modes are used:

- Mode 1: the specification of the daily electricity generation, with the optimum HPP operation,
- Mode 2: the specification of the daily electricity generation and the HPP operating regime,
- Mode 3: the specification of the hydropower plant power, with an uniform distribution of unit loads,
- Mode 4: the specification of hydropower plant power with an arbitrary unit load distribution,
- Mode 5: the operation of the hydropower plant according to the actual water inflow and strictly run-off-river operation,
- Mode 6: the operation of the hydropower plant approximately according to the water inflow, with the optimum operating regime,
- Mode 7: the operation with specification of units powers and
- Mode 8: the operation with specification of units discharges.

In the following overview the application of the developed modes of management is described. Computation details common to several modes are described once only.

Mode 1: the specification of the daily electricity generation with the optimum HPP operation

This mode is used for the long-term planning of hydropower plant operation.

For each day of operation the electricity that the hydropower plant should generate, E_{dn} (MWh), should be specified.

The main prerequisite for the use of this mode is a small variation in water level in the storage during one simulation step. For this reason, this mode is suitable only for hydropower plants with large storages.

The application of this mode makes it possible to generate the demanded electricity with the minimum water consumption. In this case the units in the hydropower plant can operate in one of the following two regimes:

- With the maximum efficiency that can be achieved with the actual water level in the storage (i.e. with the hydropower plant gross head) and
- With the maximum power that can be realized with the actual water level in the storage. The maximum unit power is usually limited by the maximum opening of the turbine wicket gates.

The input data for the computation includes:

- The specified electricity generation by the hydropower plant,
- The water level in the storage,
- The minimum water level in the storage,
- The head losses in the conduit for the reference discharge,
- The characteristics of unit discharge and power in the optimum and the maximum operating regimes and
- The number of units in the hydropower plant.

The mean power, P_{av}, (MW) with which the hydropower plant should operate in order to generate the demanded electricity generation during 24 hours E_{da} (GWh) amounts to:

$$P_{av} = \frac{E_{da}}{24} \tag{6}$$

In the course of the simulation it is assumed that all units in the hydropower plant are in operation. Upon the water level in the storage and the chart that describes the dependence of the unit power upon the head, the following powers can be identified:

- The power during the operation in the optimum operating regime, P_{opt}, (MW) and
- The maximum power, P_{max}, (MW).

Upon P_{av}, P_{opt} and P_{max} it is necessary to determine the power that the plant should operate with, P_o (MW). The following two cases can be identified:

- $P_{av} < P_{opt}$ and
- $P_{opt} < P_{av} < P_{max}$.

The rules for selection of the power P_o are:

$$P_{av} < P_{opt} \Rightarrow P_o = P_{opt} \tag{7}$$

$$P_{opt} < P_{av} < P_{\max} \Rightarrow P_o = P_{av} \tag{8}$$

In the second computational step the value of operation time can be determined from:

$$t_o = \frac{E_{da}}{P_o} \tag{9}$$

The following holds true: $t_o \leq 24$ hours.

The realized electricity generation in the hydropower plant, E_{re}, (MWh), in these two cases amounts to, respectively:

- $E_{re} = E_{da}$ and
- $E_{re} = P_o \cdot 24$, $E_{re} < E_{dn}$.

The discharge through the hydropower plant is determined from the chart that describes the dependence of the discharge through the hydropower plant upon the hydropower plant head according to the following rules:

$$P_o = P_{opt} \Rightarrow Q_o = Q_{opt} \tag{10}$$

$$P_{opt} < P_o < P_{\max} \Rightarrow Q_o = Q_{opt} + \left(Q_{\max} - Q_{opt}\right) \cdot \frac{P_o - P_{opt}}{P_{\max} - P_{opt}} \tag{11}$$

$$P_o = P_{\max} \Rightarrow Q_o = Q_{\max} \tag{12}$$

If the demanded electricity generation cannot be realized, then the fulfillment of the demand, defined as the ratio between the realized and the demanded electricity generation, should be determined.

The results of the simulation are:

- The electricity generated by each unit,
- The electricity generated by the hydropower plant,
- The fulfillment of the demand,
- The realized hydropower plant power,
- The water discharge through each unit,
- The water discharge through the hydropower plant,
- The water consumption and
- The unit water consumption.

The Mode 1 has a wide field of application and can be used for long-term analyses of operation of hydropower plants with large storages.

Mode 2: the specification of daily electricity generation and HPP operation regime

This mode is used for the long-term planning of the hydropower plant operation.

For each day of operation the electricity generation, E_{dt}, (MWh) and the power with which a hydropower plant should operate, P_{dt} (MW), should be specified.

The input data for the computation includes:

- The specified electricity generation by the hydropower plant,
- The specified average hydropower plant power,
- The water level in the storage,
- The minimum water level in the storage,
- The head loss coefficient of the conduit,
- The characteristics of the units in the hydropower plant,
- The number of units in the hydropower plant and
- The rule for selection of the number of units as a function of the water level in the storage and the hydropower plant power.

For determination of the number of units in operation, n_{un} (-), the chart that describes he dependence of the hydropower plant power upon the water level in the storage and the number of units in operation is used. This chart is most often formed under the condition that the demanded hydropower plant power should be realized with the maximum possible efficiency of the hydropower plant as a whole, i.e. with the minimum water consumption. In the course of the formation of the chart the additional conditions can be specified too, for instance that the hydropower plant should realize the power demand with the maximum possible spinning reserve.

An example of such a chart is presented in the following figure.

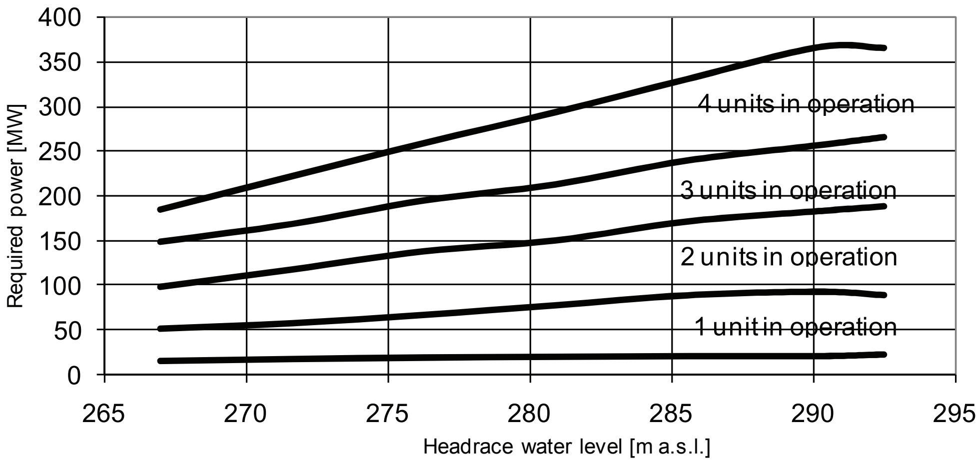

Fig. 13. The number of units in operation in dependence upon the hydropower plant power and the water level in the storage.

The results of simulation are:

- The realized power in the hydropower plant,
- The electricity generated in the hydropower plant,
- The fulfillment of the demand,
- The number of units in operation,
- The discharge through one unit,
- The discharge through the hydropower plant,
- The water consumption and
- The specific water consumption.

More details on the applied computation algorithm are given in the description of the Mode 3.

The Mode 2 is an important extension of the Mode 1. One typical situation for its application is the peak-load operation, as in this regime is would be desirable for the hydropower plant to operate exclusively with the maximum power.

Mode 3: the specification of the hydropower plant power with the uniform distribution of unit loads

This mode is used for the short-term planning of hydropower plant operation, so-called operative planning, according to the daily (or weekly) demand by the dispatcher of the electricity supply and transmission system.

For each hour of operation the power with which a hydropower plant should operate, $P_{HPP,h}$ (MW) should be specified.

The prerequisites for the application of this mode of operation are:

- That all units in the hydropower plant should have identical performances and
- That all units in operation should operate in the same operating regime.

The input data for the computation includes:

- The demanded power with which the hydropower plant should operate,
- The water level in the storage,
- The minimum water level in the storage,
- The coefficient of head loss of the conduit,
- The number of units in the hydropower plant,
- The characteristics of the units and
- The rule for selection of the number of units in operation as a function of the water level in the storage and the HPP power, as shown in Figure 13.

The computational algorithm has the following form:

- The number of units in operation is determined as in the Mode 2,
- The power with which one unit operates $P_{un,h}$, (MW) is determined from the formula:

$$P_{un,h} = \frac{P_{HPP,h}}{n_{un}} \tag{13}$$

- Upon the water level in the storage and the power of one unit the discharge through each unit is determined (if necessary by an iterative procedure),
- Upon the discharge through one unit and the number of units in operation the discharge through the hydropower plant is determined.

The results of the simulation are:

- The number of units in operation,
- The generated electricity,
- The fulfillment of the demand,
- The realized hydropower plant power,
- The discharge through one unit,
- The discharge through the hydropower plant,

- The water consumption and
- The unit water consumption.

The Mode 3 presents a typical method for short-term planning of operation of hydropower plants with identical units, as is very often the case.

Mode 4: the specification of the power of the hydropower plant with an arbitrary distribution of unit loads

This mode is used for the short-term planning of hydropower plant operation, so-called operative planning. It represents a generalization of the Mode 3.

For each hour of operation the power with which a hydropower plant should operate, $P_{HPP,h}$ (MW) should be specified.

This mode can simulate the operation of the hydropower plant in the cases:

- Of the units with different performance characteristics and
- Of the units with identical characteristics that operate in different operating regimes.

The input data for the computation includes:

- The demanded power of the hydropower plant,
- The water level in the storage,
- The minimum water level in the storage,
- The coefficient of head loss of the conduit,
- The number of units in the hydropower plant,
- The characteristics of each unit and
- The rule for distribution of the load on particular units in the hydropower plant.

The power with which the i^{th} unit operates, $P_{un,i}$, (MW), is determined upon the demanded power of the hydropower plant and the load coefficient for that unit, $K_{opt,i}$, (-):

$$P_{un,i} = P_{HPP,h} \cdot K_{opt,i} \tag{14}$$

The sum of the unit load coefficients must equal 1 (or 0. if the plant generates no electricity), i.e.:

$$P_{HPP,h} = \sum P_{un,i} \tag{15}$$

The values of load coefficients are defined upon the power that the hydropower plant should operate with and the water levels in the hydropower plant storage, as shown in the following table. Each table of this type corresponds to one range of values of the water level in the storage.

Power range (MW)	A1	A2	A3	A4	Sum of coefficients
0-25	0.00	0.00	0.00	0.00	0.00
25-50	1.00	0.00	0.00	0.00	1.00
50-100	0.55	045	0.00	0.00	1.00
100-150	0.34	0.33	0.33	0.00	1.00
150-185	0.25	0.25	0.25	0.25	1.00

Table 1. Load coefficients for units for the range of water levels in the hydropower plant storage between 267 and 272 m a.s.l.

The computational algorithm has the following form:

- Upon the demanded HPP power and the rule for distribution of the load on particular units in the hydropower plant the power of each unit in operation is determined,
- Upon the water level in the storage and the power of a single unit the discharge through one unit is determined (if necessary, by an iterative procedure) and
- The discharge through the hydropower plant is determined by summation of discharges through the units.

The results of the simulation are:

- The power with which each unit operates,
- The number of units in operation,
- The hydropower plant power,
- The electricity generated by each unit,
- The electricity generated in the hydropower plant,
- The discharge through the units,
- The discharge through the hydropower plant,
- The volume of water consumed in the HPP and
- The unit electricity generation.

The Mode 4 can be used for short-term planning of operation of plants that are equipped with the units of different types. It is also convenient for the analysis of the possibility of reconstruction and extension of the capacities of the existing hydropower plants, in case that the characteristics of the existing units should be altered (for instance, after an overhaul) or that the new units should be built into the plant, while their characteristics differ from the characteristics of the existing units.

Mode 5: the operation of the hydropower plant according to the actual water inflow, strict run-off-river operation

This mode is used both for the short-term and the long-term planning of the hydropower plant operation. The simulation time step equals one hour or one day.

The input data for the computation includes:

- The water inflow into the storage,
- The water level in the storage,
- The minimum water level in the storage,
- The coefficient of head loss of the conduit,
- The characteristics of unit discharge and power (exploitation chart),
- The number of units in the hydropower plant and
- The parametric curve for selection of the number of units in operation as a function of the water level in the storage and the actual water inflow (Figure 14).

In this mode no explicit demand related either to electricity generation, or to power, is specified, but the plant operating regime is influenced by the inflow into the hydropower plant storage.

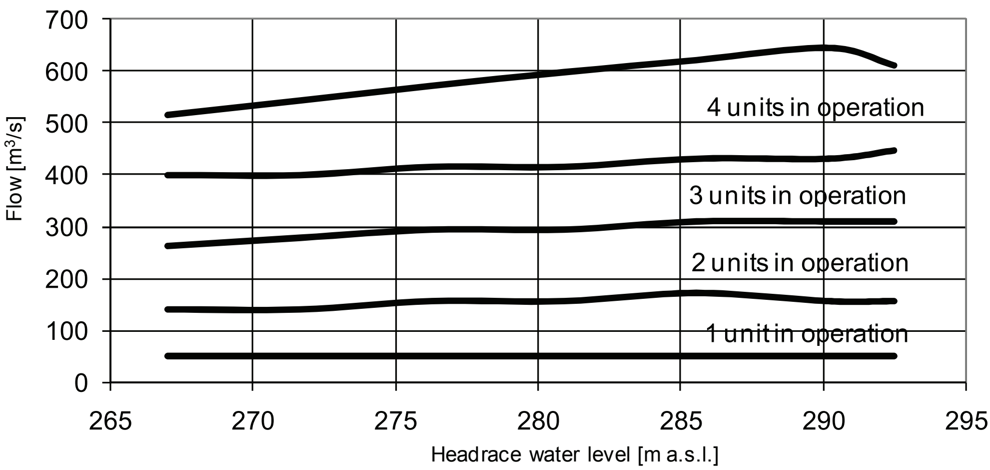

Fig. 14. Number of units in operation in dependence upon the inflow and the water level in the storage.

The computational algorithm has the following form:

- Upon the water inflow into the storage, the water level in it and the parametric curve for selection of the number of units in operation, the number of units in operation is determined,
- Upon the number of units in operation and the water inflow into the storage the discharge through the unit is determined,

- Upon the water level in the storage, the discharge through the units and the coefficient of head loss of the conduit, the unit net head and its operating regime are determined,
- The power of each unit and the entire HPP are determined and
- Upon the HPP power, the electricity generation by the HPP is calculated.

For the definition of the appropriate unit operating regime the complete exploitation chart is used.

The results of the simulation include:

- The electricity generated by the hydropower plant,
- The discharge through each unit and
- The discharge through the hydropower plant.

Mode 6: the operation of the hydropower plant approximately according to the water inflow, with the optimum operating regime

This mode is used for both the short-term and the long-term planning of hydropower plant operation. The simulation time step equals one hour or one day.

It is used for simulation of the plant operation in the run-off-river regime of hydropower plants with large storages.

The input data for the computation includes:

- The water inflow into the storage,
- The minimum water level in the storage,
- The coefficient of head loss of the conduit,
- The characteristics of discharge and power for the unit in the optimum operating regime,
- The number of units in the hydropower plant and
- The parametric curve for selection of the number of units in operation as a function of the water level in the storage and the actual water inflow.

In this mode no explicit demand related to either electricity generation or the power is specified, but the operating regime is driven by the water inflow into the hydropower plant storage.

The computational algorithm is similar to the one used in the Mode 5, but in this case the units in the HPP operate in the optimum operating regime.

The results of the simulation include:

- The electricity generated by the hydropower plant,
- The discharge through each unit and the total discharge through the hydropower plant and
- The power of the hydropower plant.

The principal difference between the Modes 5 and 6 is that in the Mode 5 the complete unit exploitation chart is used, while in the Mode 6 only the characteristics for the discharge and the power of the unit in the optimum operating regime are utilized. In the Mode 5 the hydropower plant operates strictly according to the water inflow, therefore in this mode it is possible to simulate the operation of a hydropower plant equipped with a small storage. In the Mode 6, because of the criterion that the unit operation should be the optimum one, the discharge through the hydropower plant should not be completely equal to the water inflow into the storage, meaning that the hydropower plant must be equipped with a storage with a volume large enough to compensate for the difference between the water inflow and the discharge through the hydropower plant.

Mode 7: the operation with specification of unit powers

This mode is used for the short-term planning of hydropower plant operation. The simulation time step equals one hour.

The input data for the computation includes:

- The demanded unit powers,
- The minimum water levels in the storage,
- The coefficient of head loss of the conduit,
- The number of units in the hydropower plant and
- The characteristics of the unit (exploitation chart).

The unit powers should be specified in the tabular form, as shown below.

Time (h)	A1 (MW)	A2 (MW)	A3 (MW)	A4 (MW)	Sum (MW)
1	86	66	73	49	274
2	40	55	40	40	175
3	40	43	40	92	215
4	89	40	83	40	251
...	...	...	...	...	...

Table 2. Hourly values of specified unit powers

The results of this simulation are:

- The electricity generated by the hydropower plant,
- The discharge through each unit and
- The discharge through the hydropower plant.

Mode 8: the operation with specification of discharges through each unit

This mode is used for both short-term and the long-term planning of hydropower plant operation. The simulation time step equals one hour or one day.

The input data for the computation includes:

- The demanded discharges through the units,

- The minimum water level in the storage,
- The coefficient of head loss of the conduit,
- The number of units in the hydropower plant and
- The characteristics of the units (exploitation diagram).

The powers of the units are specified in the form of a table, such as the one given below.

Time (h)	A1 (m^3/s)	A2 (m^3/s)	A3 (m^3/s)	A4 (m^3/s)	Sum (m^3/s)
1	80	80	111	142	413
2	100	80	190	80	450
3	120	80	96	80	376
4	136	80	125	96	437
...	...	...	...	...	...

Table 3. Hourly values of specified discharges through the units

The results of this simulation are:

- The electricity generated by the hydropower plant,
- The power of each unit and
- The hydropower plant power.

Modes 7 and 8 are used for the analysis of historical time series that describe hydropower plant operation, in order to verify the correctness (accuracy) of the simulation model.

Recommendations for application of the modes

The field of application of the modes described above is summarized in the following table.

Mode	Simulation time step		Storage size	
	Hour	Day	Run-off-river	Storage available
1	-	+	-	+
2	-	+	-	+
3	+	-	+	+
4	+	-	+	+
5	+	+	+	+
6	+	+	-	+
7	+	-	+	+
8	+	-	+	+

Table 4. Field of application of the modes incorporated into the simulation model

Above mentioned modes of operation can be used for the completion of the two very significant tasks of plant management:

- The verification and modification of possible dispatching plans and
- The maximization of electricity generation.

Possible dispatching plans can be short-term and long-term oriented, therefore in their verification and modification both daily and hourly discretizations should be used.

The maximization of the electricity generation is a type of analysis where the operation of a plant, or a system of plants, is analyzed, in order to maximize the electricity generation.

Beside the application in the case of the existing objects, the simulation model is also used in the process of design of new objects of a hydropower plant built on a certain watercourse.

4. Examples of simulations

4.1 Examples of "Uvac" HPP operation

4.1.1 Operation in Mode 1

In the following example the analysis of the operation of the "Uvac" HPP that is managed upon the request related to the daily electricity generation, was performed. To that means, the simulation of the operation of the "Uvac" HPP in the Mode 1 was performed, for the period between July 1st, 1982 and July, 1st, 1983.

In the following diagrams a comparison between the results obtained by the simulation and the measurements performed on the objects of the "Uvac" HPP was made. The following results are displayed:

- The specified (measured) and computed electricity generation,
- The measured and the calculated water level in the storage and
- The measured and the calculated discharge through the units.

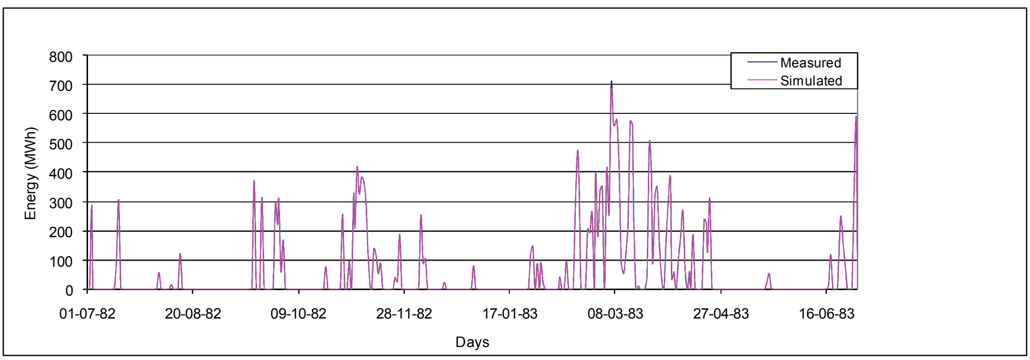

Fig. 15. Comparison of measured and calculated generation of electricity in the "Uvac" hydropower plant.

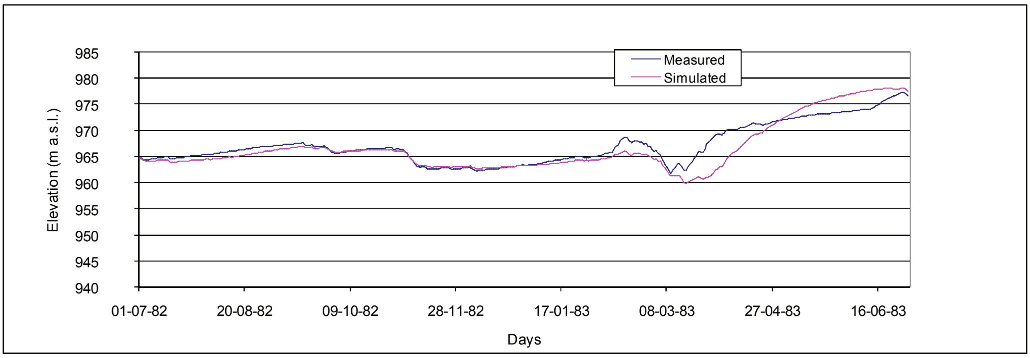

Fig. 16. Comparison of the measured and the calculated water level in the "Uvac" hydropower plant storage.

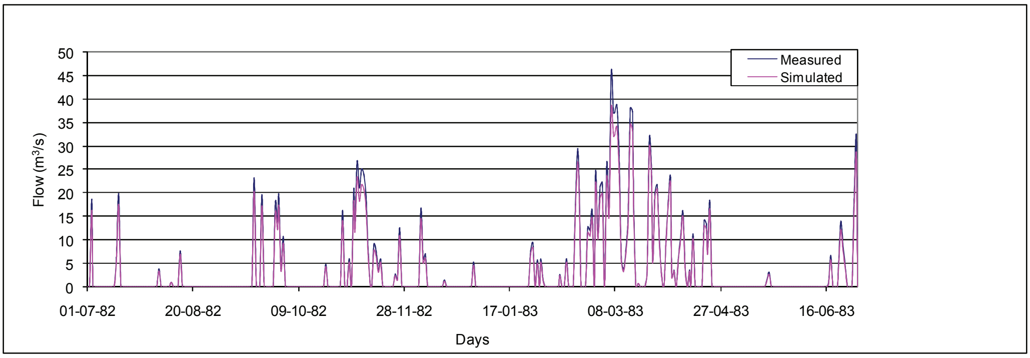

Fig. 17. Comparison of the measured and the computed discharge through the "Uvac" hydropower plant units.

4.1.2 Operation in Mode 3

In the simulation of hydropower plant operation in Mode 3 the values of power during each hour of the simulation period are explicitly specified. In the example shown below the simulation of the operation of the "Uvac" hydropower plant for the period of five days, from September, 28th, 1982 to October, 2nd, 1982, was performed.

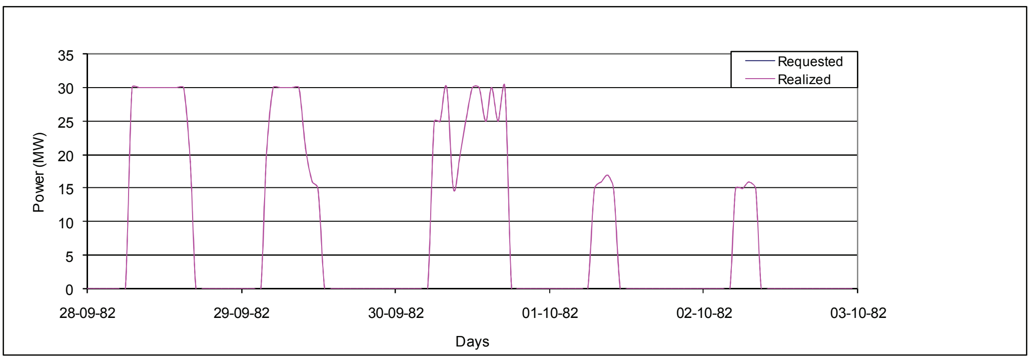

Fig. 18. Comparison of the demanded (requested) and the calculated (realized) power of the "Uvac" hydropower plant.

The diagram in Figure 18 shows the plant power as a function of time. The complete coincidence between the demanded and the calculated power can be observed.

The diagram in Figure 19 displays the variation in the water level in the HPP storage as a function of time.

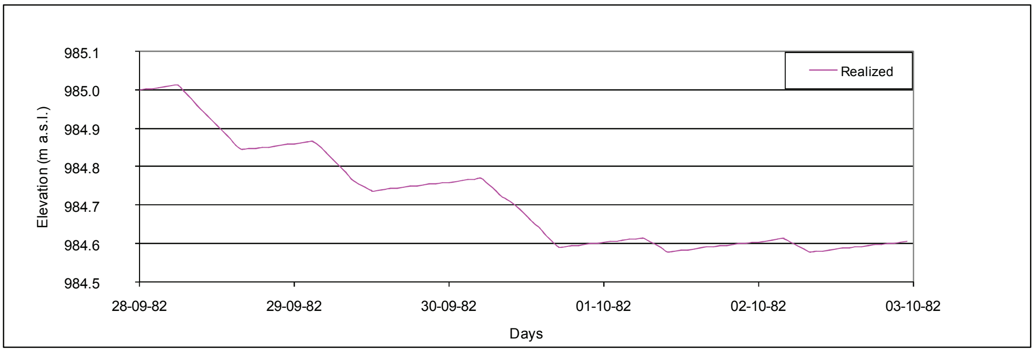

Fig. 19. Calculated (realized) water level in the storage of the "Uvac" hydropower plant.

4.2 Example of operation of the "Višegrad" HPP

4.2.1 Example of short-term planning - operation in Mode 3

In the next example the analysis of operation of the "Višegrad" HPP that is managed upon the demand related to the realized power of the hydropower plant, under the condition of the uniform unit load, was performed. To that means the simulation of operation of the "Višegrad" HPP in the Mode 3, for the period between July, 23rd, 2004 and July, 30th, 2004, was performed.

The following diagrams display the comparison between the results of the simulation and the measurements performed on the objects of the "Višegrad" hydropower plant. The following results are shown:

- The specified (measured) and the calculated power,
- The measured and the calculated water level in the storage and
- The measured and the calculated discharge through the units.

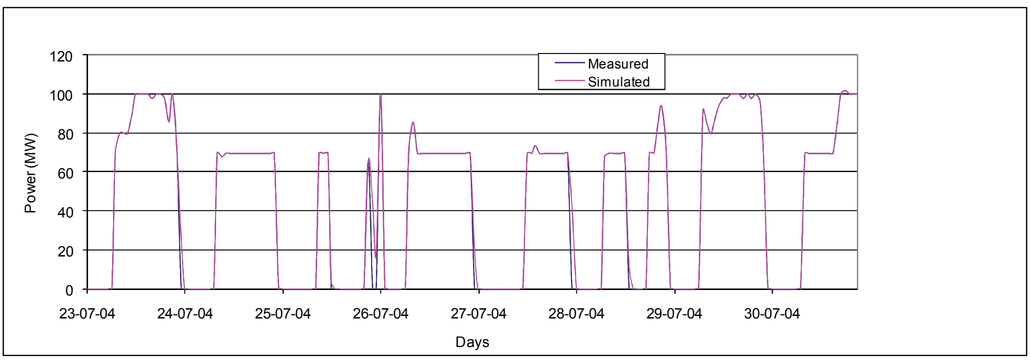

Fig. 20. Comparison between the measured and the calculated power realized in the "Višegrad" hydropower plant.

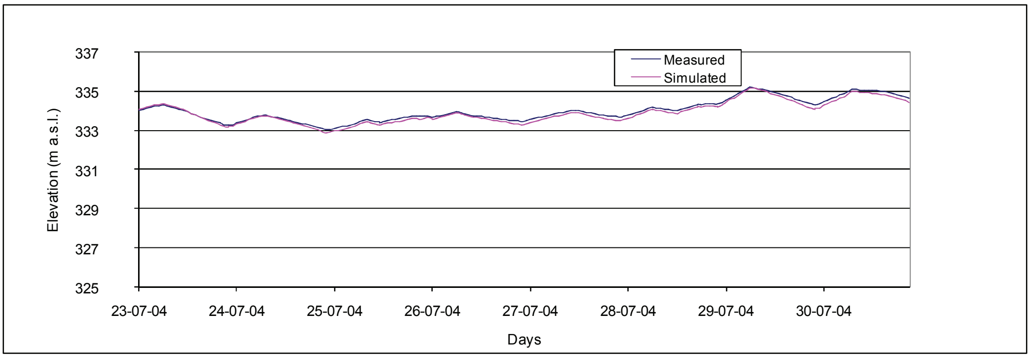

Fig. 21. Comparison between the measured and the calculated water level in the storage of the "Višegrad" hydropower plant.

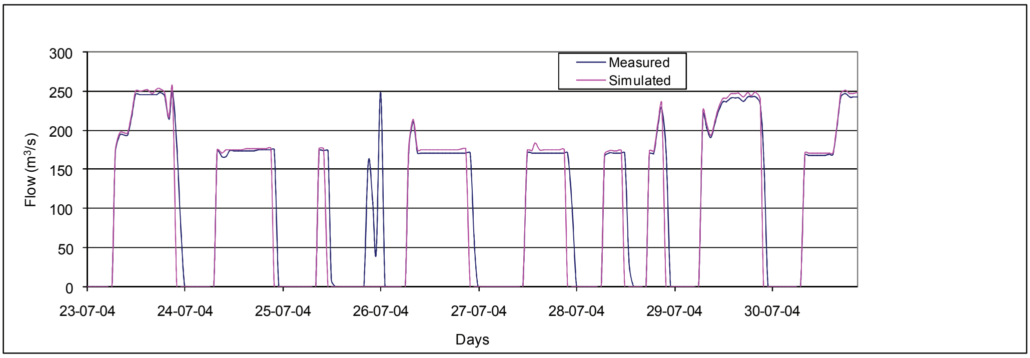

Fig. 22. Comparison between the measured and the calculated discharge through the "Višegrad" hydropower plant units.

In all examples mentioned above a very good congruence between calculated and measured values can be observed.

5. Conclusions

By the application of the modes of operation of hydropower plants described in this paper it is possible to simulate with success the majority of typical requests imposed on the hydropower plant by the electricity generation and transmission system. These modes can be used in a wide range of hydrologic situations. They are also applicable to all types of hydropower plants, regardless of the storage volume and they allow for the hourly and the daily plant management.

The algorithms used for numerical implementation of these modes are stable and have relatively short execution times, meaning that they can be successfully used for decision-making support by the means of the expert systems.

The simulation model based upon the models of the hydropower plant objects and the modes of operation described in the paper forms the theoretical foundation of hydro-information systems, such as the ones that the Institute for Development of Water Resources "Jaroslav Černi" had with success developed for several catchments and hydropower plants in Serbia and Republic Srpska.

The examples presented in Section 4 indicate that the developed models can accurately describe the operation of hydropower plants and that the developed hydro-information systems present a reliable tool for the analysis of operation of these plants.

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