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Hydropower Plants Cascade – Modeling of Short and Long-Term Management

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Abstract

For hydropower plants in a cascade, besides the requirements imposed on the hydropower plants that operate on their own, there are also certain additional requirements and constraints. In this case it is necessary to develop special modes for the optimum management of such HPPs from the standpoint of harnessing of the hydropower potential of watercourses they are built upon. In this paper the four modes of management used for modeling of operation regimes of such hydropower plants are described. The application of these modes is illustrated on the example of the system "Vlasinske HPPs" that is a cascade that consists of 4 hydropower plants. The use of the simulation model that incorporates the modes presented in the paper in the process of optimization of the parameters of the plant during the design phase is presented on the example of the designed cascade that consists of the "Buk Bijela" HPP and the "Foča" HPP on River Drina.

Keywords: Hydropower plants, management, cascade, storage

1. Introduction

The hydropower plants that form a cascade have their special characteristics that set them apart from the other HPPs. Their primary specific property is that the simulation of their operation, or the optimization of their management according to certain criteria, must be performed for all hydropower plants in a cascade simultaneously. A demand by the dispatcher, regarding electricity generation, is for these plants defined for the entire system, while the distribution of the demand over the particular plants is performed according to the defined rules, in accordance with a series of conditions and limitations.

An example of such hydropower plants is the system "Vlasinske hydropower plants" (that consists of the "Vrla 1" HPP, "Vrla 2" HPP, "Vrla 3" HPP and "Vrla 4" HPP), whose disposition is presented in the following figure.

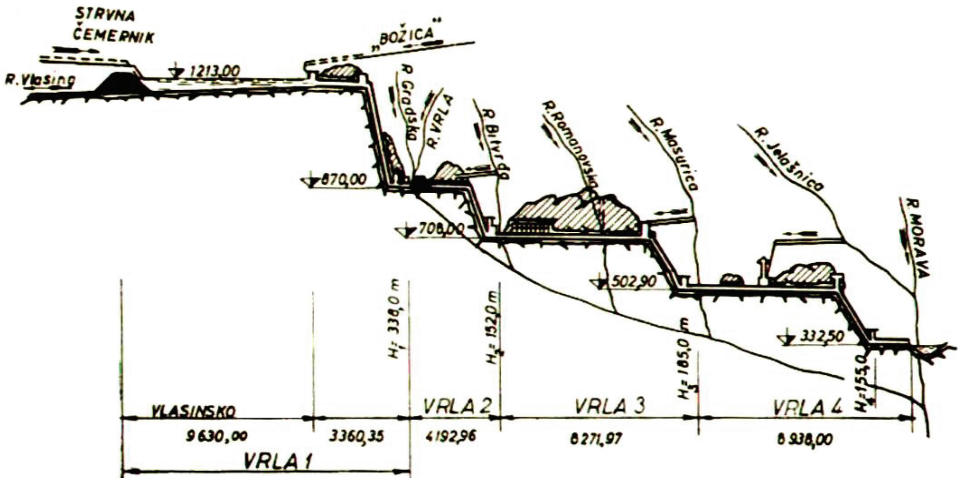

Fig. 1. Longitudinal section of the system “Vlasinske HPPs”.

In the systems of this type the operation of particular HPPs in a cascade cannot be analyzed separately from the remaining HPPs in the system (i.e. in the cascade). Due to the complexity of such systems, it is convenient to analyze them by the means of a mathematical simulation of their operation.

The problem of optimization of the operation of such systems has been solved in the literature by several approaches. In Rauschenbach (2005), a PID-concept and fuzzy-logic were used for the optimization of the operation of 4 HPPs on River Dunav (Danube). In that paper the objective function was defined in such a manner as to achieve the optimum management regarding the control of flood waves, navigation capabilities and electricity generation in the system.

In Lowery (1966) and Snyder et al. (1987) dynamic programming was used. In Mokhtari et al. (1988) an expert system was utilized for the solution of the problem of unit commitment. Integer programming was used in Takriti and Birge (2000).

Genetic algorithms that are used in this paper too, were utilized in Kazarlis et al. (1996), Liyong et al. (2006), Orero and Irving (1998) and with particular success in Milivojević (2008).

The details related to the analysis of development of simulation models in the context of the hydro-information systems are described in Divac et al. (2009).

2. Cascaded hydropower plants in Serbia

Most hydropower plants in Serbia can be considered to form a cascade and the hydropower plants and storages in a cascade exist on the following watercourses (including the capacities shared with the neighboring countries):

- On River Dunav: “Đerdap 1” HPP and “Đerdap 2” HPP (the “Iron Gate” HPPs),
- On River Uvac ("Limske HPPs"): “Uvac” HPP, “Kokin Brod” HPP and “Bistrica” HPP and
- On the system “Vlasinske HPPs": “Vrla 1” HPP, “Vrla 2” HPP, “Vrla 3” HPP and “Vrla 4” HPP.

The characteristics of the hydropower plants on River Uvac are presented in the following table.

HPP	Number of units	Rated discharge	Rated power	Range of heads
-	-	m^3/s	MW	m
"Uvac	1	43	36	55 to 100
"Kokin Brod"	2	2 x 18.7	2 x 11.25	36 to 72
"Bistrica"	2	2 x 18	2 x 52	344.64 to 378.30

Table 1. The characteristics of hydropower plants on River Uvac

The storages of hydropower plants on River Uvac have large enough relative volumes, with relatively small additional inflows, so that the optimization of their operation can be achieved by the means of the algorithms of moderate complexity. An illustration of the axiom that the operation of these HPPs should be strictly coupled is the fact that a bottom outlet is installed on the dam of the "Kokin Brod" HPP, with a capacity sufficient to fill up the "Radojna" storage ("Bistrica" HPP's headwater) during the periods of overhaul of the units in the "Kokin Brod" HPP.

The system "Vlasinske HPPs" has the leading storage with a large volume, located upstream from the hydropower plants that makes it possible to perform a good regulation of the water flows. However, the hydropower plants located downstream from it have the storages with relatively small volumes (in the same time there are additional inflows into them), what makes the optimization of their operation very complex.

The characteristics of the hydropower plants in the system "Vlasinske HPPs" are presented in the following table.

HPP	Number of units	Rated discharge	Rated power
-	-	m^3/s	MW
"Vrla 1"	4	18.5	2 x 11.2 + 2 x 14.2
"Vrla 2"	2	18.5	1 x 10.7 + 1 x 13.3
"Vrla 3"	2	18.5	1 x 12.8 + 1 x 16.6
"Vrla 4"	2	18.5	1 x 11.2 + 1 x 14.2

Table 2. Characteristics of the hydropower plants in the system "Vlasinske HPPs"

Future hydropower plants on the upper part of the River Drina course are elaborated in the corresponding technical documentation. The design characteristics of these hydropower plants are shown in the following table.

HPP	Rated discharge	Rated power
-	m^3/s	MW
"Buk Bijela"	450	121
"Foča"	450	45

Table 3. The characteristics of future hydropower plants on the upper part of the River Drina course

The task of modeling (calculation) of a cascade is the determination of the optimum operating regimes of the HPPs that it consists of (in the case of the existing HPPs), i.e. the choice of the optimum performance of particular cascade elements (in case of the future HPPs), while the system of HPPs in a cascade is treated as a whole.

The use of a simulation model is in certain cases the only way to define a high-quality system management. Such situation shall exist in newly built systems on the middle and lower parts of the River Drina course.

3. Modeling of operation of the cascade "Vlasinske HPPs"

In the scope of the first example of planning, the simulation of the operation of the system "Vlasinske HPPs" that is schematically presented in the following figure shall be described.

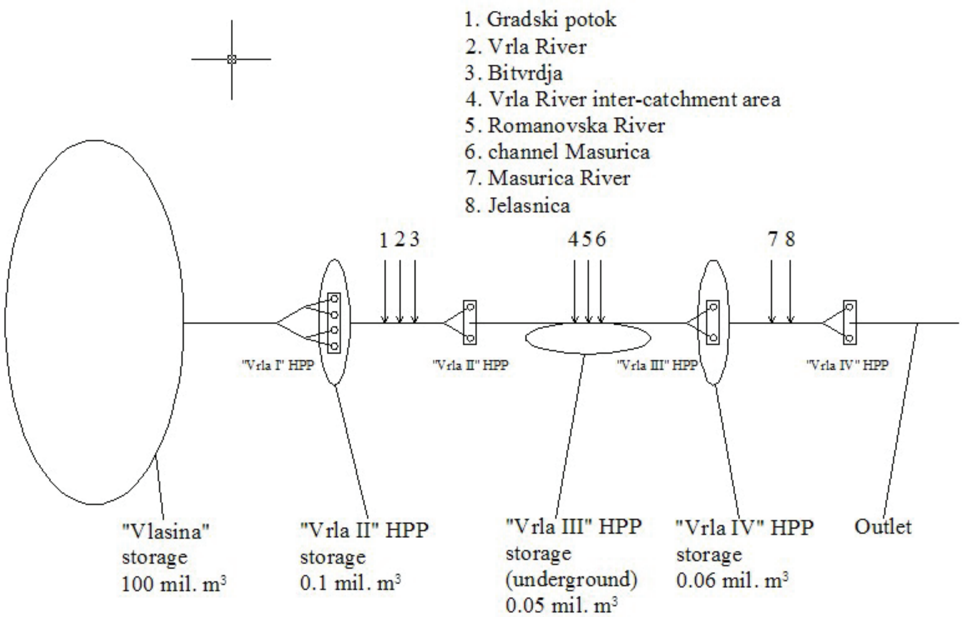

Fig. 2. Schematic representation of the system "Vlasinske HPPs"

The volumes and water levels in the storages of the HPPs in the system "Vlasinske HPPs" are shown in the following table.

HPP storage	Volume	Minimum water level	Maximum water level
-	millions of m^3	m a.s.l.	m a.s.l.
“Vrla 1”	100.50	1206.0	1213.5
“Vrla 2”	0.10	858.0	868.0
“Vrla 3”	0.05	704.7	710.0
“Vrla 4”	0.06	502.1	503.6

Table 4. Volumes and water levels in the storages of the HPPs in the system “Vlasinske HPPs”

The additional inflows into the storages of the HPPs forming the system “Vlasinske HPPs” are presented in the following table.

Nr.	Watercourse	Mean inflow	Inflow into the storage of the HPP
-	-	m^3/s	-
1	River Gradski potok	0.135	“Vrla 2“
2	River Vrla	0.565	“Vrla 2”
3	River Bitvrđa	0.082	“Vrla 2”
4	Inter-catchment of River Vrla	0.169	“Vrla 3”
5	River Romanovska reka	0.229	“Vrla 3”
6	Channel “Masurica kanal”	0.666	“Vrla 3”
7	River Masurica reka	0.108	“Vrla 4”
8	River Jelašnica	0.100	“Vrla 4”

Table 5. Additional inflows into the storages of the HPPs that form the system “Vlasinske HPPs”

System management can be short-term or long-term oriented and in accordance with that the modes for simulation of the HPP operation were developed.

In the scope of the short-term planning of system operation, the hourly demands related to the power of the entire system are specified, while the water levels in the storages of the “Vrla 2”, “Vrla 3” and “Vrla 4” HPPs are specified as the additional requirement. The “Vrla 1” storage is very large and the daily variations of water level in it are on the order of magnitude of several centimeters. The storages of the plants located downstream from it are considerably smaller, and, moreover, there are additional inflows into them.

The main principle of operation of this system is that the spillage of water must be kept to the absolute minimum. When “Vrla 1” HPP is in operation, during the period of peak-load electricity generation, all plants located downstream from it operate synchronously with it. The daily operation time of these plants is longer than the operation time of the “Vrla 1” HPP, so that they can utilize the additional inflows into their storages. In the same time, the starting time of the HPPs located downstream is delayed in respect to the starting time of the "Vrla 1" HPP, in order to avoid water spilling.

In the case of the long-term system management the daily demands regarding electricity generation of the whole system of HPPs are specified, with the additional requirement regarding the value of water level in the storage of "Vrla 1" HPP. This requirement is such that the storage can be used for the seasonal, i.e. yearly water regulation, so that during the rainy periods the storage can accommodate the whole inflow in it without spillage, and so that during the rest of the year a high water level is kept in it, but under the condition that water spilling should be avoided.

The mean annual water level in the storage of "Vrla 1" HPP during the period from the year 1986 to the year 2003 is presented in the following figure.

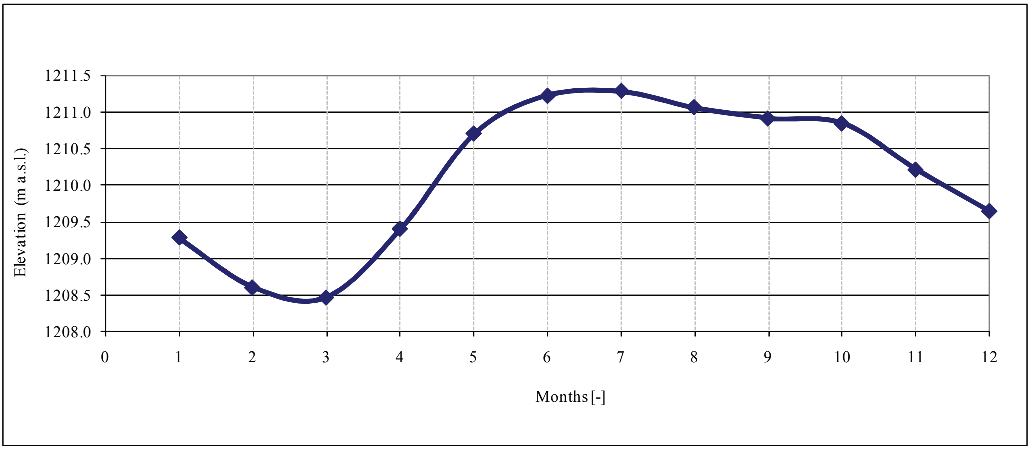

Fig. 3. The variation in water level in the storage of the "Vrla 1" HPP (averaged for period between the year 1986 and the year 2003).

3.1 Modes of operation

In the simulation model the following modes (regimes) of operation of hydropower plants are incorporated:

- Mode 1: with specification of the hourly demand regarding the power of the system of HPPs - short-term planning,
- Mode 2: with specification of the daily demand regarding electricity generation in the system of HPPs - long-term planning,
- Mode 3: with optimization of the revenue and
- Mode 4: with the explicit specification of power or discharge for each unit - the analysis of historical time series.

In the following text the description of each of above mentioned modes of operation is given, in order to present the possibilities of their application in the scope of the developed model and the corresponding computational procedures.

3.1.1 Mode 1: with specification of the hourly demand related to the power of the system of HPPs

In this mode for each hour of operation the demanded power of the entire system is specified, i.e. for each hour during the simulation period the power that the system of HPPs should realize should be specified.

In this mode, beside the demand related to the power of the whole system of HPPs, the demand related to water level in particular storages in the system is additionally specified.

An example of the specification of the water level in the storages in the case of the system "Vlasinske HPPs" is given in the following table.

Hour	Power of the system	Water level in the storage of "Vrla 2" HPP	Water level in the storage of "Vrla 3" HPP	Water level in the storage of "Vrla 4" HPP
-	MW	m a.s.l.	m a.s.l.	m a.s.l.
1	78	858	705	502.5
2	82	858	705	502.5
...	...	...	...	...
24	89	858	705	502.5

Table 6. Specification of the power of the system and the water levels in the storages of HPPs in the system "Vlasinske HPPs" (except for the storage of the "Vrla 1" HPP)

The specification of water levels must be performed in accordance with the real operation of the hydropower plants. In the system "Vlasinske HPPs", for instance, it is important that the shutdown of the hydropower plants "Vrla 2", "Vrla 3" and "Vrla 4" should be performed when their storages are empty. For that reason it is necessary to specify as the target water level in the storage a value of the water level that is close to the minimum water level in it.

The specified water level in the storage has a higher priority than the demanded electricity generation. Namely, should the maximum water level in the storage be attained, the hydropower plants should start with operation, irrespective of the fact that no explicit demand from the electricity generation and transmission related to electricity generation exists.

For instance, in the course of the simulation of the operation of the system "Vlasinske HPPs" in the Mode 1 the initial value of water level in Lake Vlasina, as well as the power of the system, should be specified. It is important to bear in mind that, beside the initial one, no values of water level in the leading storage should be specified.

The power with which the plant shall operate is determined upon the demanded power of the entire system, required discharges through each plant (that consist of the corresponding additional inflows, outflows for other uses and target water levels in the storages), as well as the average plant-specific electricity generation.

The active power of the plant during the actual hour of operation is obtained as a sum of the power realized upon the required discharge and the power realized upon the discharge coming from the leading storage (in the case of the system "Vlasinske HPPs", from the storage of the "Vrla 1" HPP). In the described manner, in an ideal case, the required value could be distributed over each of the hydropower plants in a cascade, so that is should be realized approximately with the required variation of the water level in each of the storages located downstream (in the case of the system “Vlasinske HPPs”, in the storages of “Vrla 2” HPP, “Vrla 3” HPP and “Vrla 4” HPP).

In the manner described above the first iteration of the simulation of the operation of the system of power plants should be performed. As a result of the calculation for the giver hour, the realized power of each unit (and consequently, the realized power of each plant and the system as a whole) and the water level in the storage at the end of that hour, are obtained.

By an iterative procedure the discharges and powers that correspond to all defined conditions are determined.

3.1.2 Mode 2: with specification of the daily demands related to electricity generation for the whole system

This mode is intended for the daily discretization. The demanded electricity generation refers to the generation of electricity by the whole system of HPPs during one day.

For each day of simulation the electricity that the whole system of HPPs has to generate, as well as the target water level in the system's leading storage, are specified.

An example of the specification of the water level in the leading storage in the case of the system “Vlasinske HPPs” is given in the following table.

Day	Electricity generated by the system	Water level in the storage of “Vrla 1” HPP
-	MWh	m a.s.l.
1	1287	1212.57
2	1560	1212.52
...	...	...

Table 7. Specification of daily electricity generation in the system and water levels in the storage of the “Vrla 1” HPP

For water levels in the remaining storages in the system the constant values – the estimated average water levels during the simulation period - are specified. Should the volumes of these storages be significantly smaller than the volume of the leading storage (as in the case of the system “Vlasinske HPPs") the changes in water levels in these storages should not be taken into account.

In the course of the simulation the daily electricity generation of each plant is determined upon the demanded total generated electricity in the system and the required discharge through each power plant. The required discharge through the hydropower plants located downstream is formed as a consequence of the additional inflows into their respective storages.

For the given gross head, upon the data regarding the specific electricity generation at the minimum and maximum discharge, a range of discharges with which each of hydropower plants in the system can operate should be determined. By taking into account these ranges, the additional inflows and the required discharges that keep water levels in the storages located downstream constant, a range of discharges through the leading hydropower plant that can be successfully transported through the rest of the system is calculated.

3.1.3 Mod 3: with optimization of the revenue

This mode is intended for the optimization of operation of a system of HPPs, in order to realize the maximum possible revenue available from its operation, while still adhering to the defined boundary conditions.

It is used for both hourly and daily discretization.

In the calculation of the revenue the prices of band-generated electricity, peak-load generated electricity and the referent power should be used and these terms are defined in the following manner:

- The band-generated electricity is obtained by scaling of the electricity generated during the period of the day that corresponds to the band operation to the full-day operation,
- The peak-load generated electricity is obtained by reduction of the electricity generated during the peak-load operation by the band electricity generated during the same period and
- The referent power is obtained by division of the electricity generated during the peak-load operation by the duration of the period that corresponds to the peak-load operation.

The revenue from electricity generation in the system is calculated upon the following prices:

- a – the charge for the referent power,
- b – the price of the peak-load generated electricity and
- c – the price of the band-generated electricity.

The optimization of the operation of a system of hydropower plants in a cascade with defined boundary conditions yields an extremely non-linear problem that can hardly be solved by conventional methods. For this reason, the solution by the means of genetic algorithms (Milivojević 2008) was chosen.

The basic step in solution of this type of problem is the definition of the objective function, whose maximum value shall be determined. The target function in the case of “Buk Bijela” HPP and “Foča” HPP has the following form:

$$F = a \cdot \left(P_{obr}^{BB} + P_{obr}^{F} \right) + b \cdot \left(E_{v}^{BB} + E_{v}^{F} \right) + c \cdot \left(E_{b}^{BB} + E_{b}^{F} \right) \qquad (1)$$

where:

- P_{obr}^{BB} – the daily referent power of the “Buk Bijela” HPP,
- P_{obr}^{FO} – the daily referent power of the “Foča” HPP,
- E_{v}^{BB} – the daily peak-load generated electricity of the “Buk Bijela” HPP,
- E_{v}^{FO} – the daily peak-load generated electricity of the “Foča” HPP,
- E_{b}^{BB} – the daily band-generated electricity of the “Buk Bijela” HPP and

- E_b^{FO} – the daily band-generated electricity of the "Foča" HPP.

The maximization of the objective function yields the powers and electricity generations in the system of HPPs during the analyzed period.

3.1.4 Mode 4: with explicit specification of power or discharge for each unit

This mode is intended for hourly discretization.

The specification is performed separately for each unit. For each hour of simulation the power or the discharge with which each unit should operate are specified.

The method of specification of these values for the system "Vlasinske HPPs" is given in the following tables.

	"Vrla 1" HPP				"Vrla 2" HPP		"Vrla 3" HPP		"Vrla 4" HPP	
Hour	A1	A2	A3	A4	A1	A2	A1	A2	A1	A2
-	MW	MW	MW	MW	MW	MW	MW	MW	MW	MW
1	7.8	7.8	9.9	9.9	7.5	9.3	9.0	11.6	7.8	9.9
2	6.7	6.7	8.5	8.5	6.4	8.0	7.7	10.0	6.7	8.5
...	...	...	...	...	...	...	...	...	...	...
24	9.0	9.0	11.4	11.4	8.6	10.6	10.2	13.3	9.0	11.4

Table 8. Specification of power for each unit in the hydropower plants in the system "Vlasinske HPPs"

	"Vrla 1" HPP				"Vrla 2" HPP		"Vrla 3" HPP		"Vrla 4" HPP	
Hour	A1	A2	A3	A4	A1	A2	A1	A2	A1	A2
-	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s	m^3/s
1	3.5	3.5	4	4	7	8	7	8	7	8
2	3	3	3.5	3.5	6	7	6	7	6	7
...	...	...	....	...	...	...	...	...	...	...
24	3.5	3.5	4.5	4.5	7	9	7	9	7	9

Table 9. Specification of discharge for each unit in the hydropower plants in the system "Vlasinske HPPs"

During the calculation it is necessary to keep track of the minimum water levels in all storages.

4. Modeling of short-term planning of the operation of the system "Vlasinske HPPs"

In the following example the operation of the system "Vlasinske HPPs" in the Mode 1 was analyzed.

In the following figure the realization of the plan related to the power of the system "Vlasinske HPPs" during two days is presented.

In the diagram above it can be seen that the demand (requirement) related to the power of the system had been met in entirety. During the nighttime there is no demand regarding electricity generation, but the power plants still operate. This operation is a consequence of the inflow into the storages of "Vrla 2", "Vrla 3" i "Vrla 4" HPPs. The algorithm of simulation of the required water levels in the storages located downstream is defined in such a manner that in the case of an increase in the water level in the storages the inflow should be used for electricity generation, what corresponds to the actual plant management.

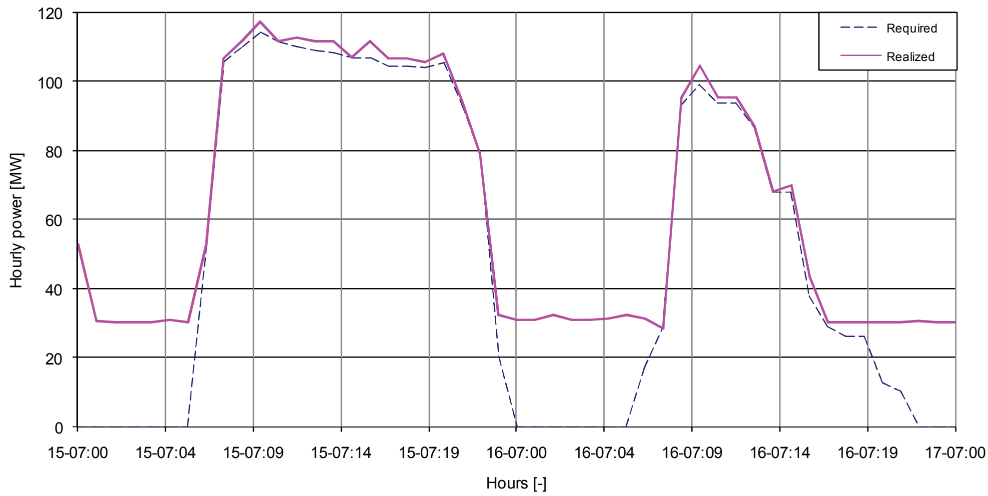

Fig. 4. Realization of power in the system "Vlasinske HPPs" during July 15th and 16th, 1998.

In the following figure the diagrams of the demanded (required) and simulated power of the system "Vlasinske HE" for one day of exploitation are presented.

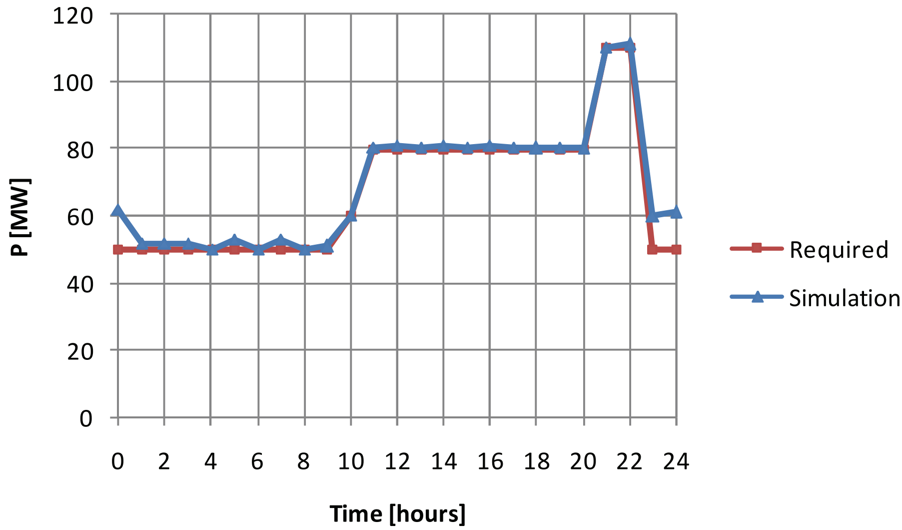

Fig. 5. Power of the system "Vlasinske HE" during one day of operation.

In the following figure the power determined by the simulation model for each HPP in the system "Vlasinske HPP" is shown.

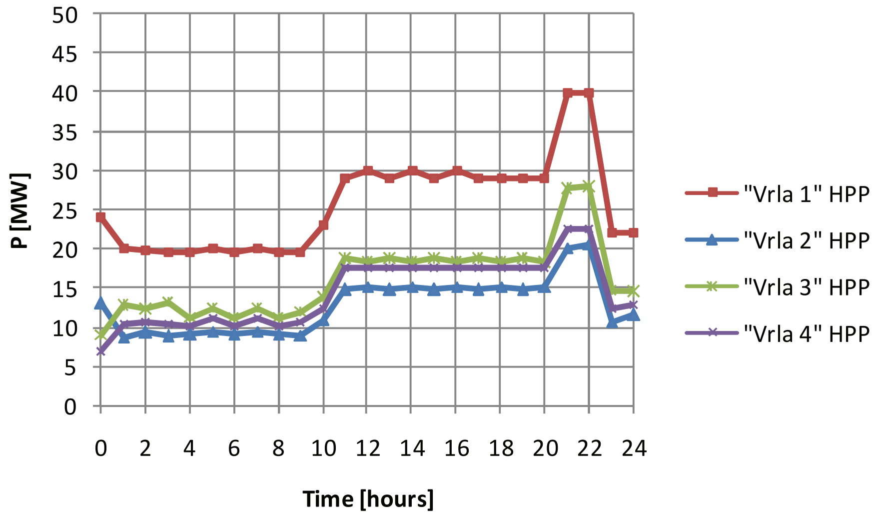

Fig. 6. Powers of individual HPPs in the system "Vlasinske HPP" during one day of operation.

5. Modeling of the long-term operation of the system "Vlasinske HPPs"

In the following example the operation of the system "Vlasinske HPPs" in the Mode 2 is analyzed.

In the following figure the realization of the plan of electricity generation in the system "Vlasinske HPPs" during a one-year period is presented.

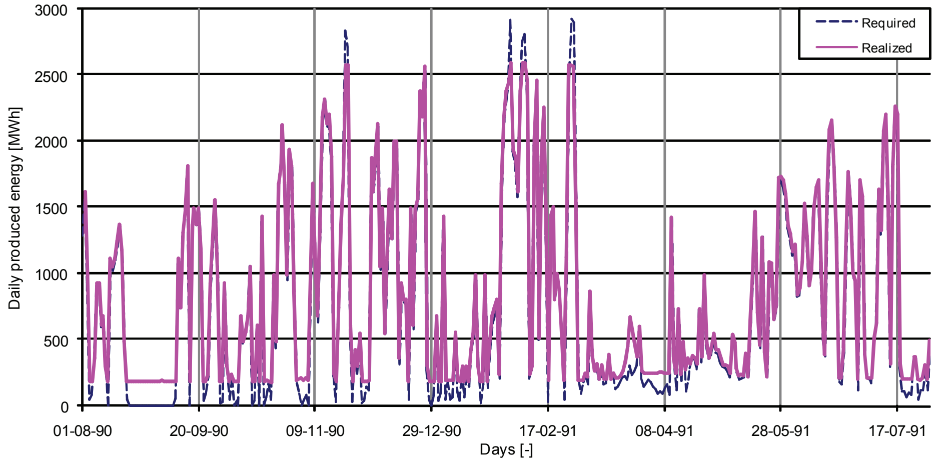

Fig.7. Electricity generation in the system "Vlasinske HPPs" during the period between August, 1st, 1990 and July, 31st, 1991.

From the diagram above it can be seen that, for instance, in the period between, approximately, the twentieth and the fortieth day of operation there is certain electricity generation, although there is no corresponding demand from the electricity generation and transmission system. Electricity generation in this case is a consequence of the additional inflows into the storages of HPPs located downstream.

Variation in the water level in the storage "Vlasina" that corresponds to electricity generation shown in the previous figure is presented in the following figure.

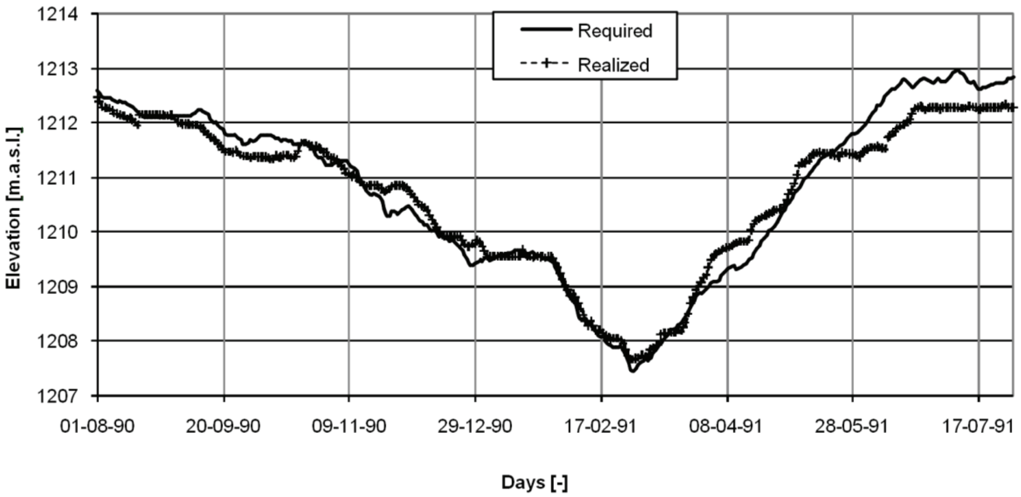

Fig. 8. Variation in the water level in the storage "Vlasina" during the period between August, 1st, 1990 and July, 31st, 1991.

From the diagram shown above it can be seen that there is a certain difference between the specified water level in the storage and the water level obtained by simulation. This means that the specified demand regarding electricity generation is not compatible with the inflow into the storage, so that it is necessary to correct it, i.e. reduce the demanded values of electricity generation, if the realization of the specified water level in the storage at the end of the simulated period is targeted.

6. Modeling of the operation of the cascade of "Buk Bijela" and "Foča" hydropower plants

The system of HPPs on the upper part of the River Drina course consists of the "Buk Bijela" HPP, "Foča" HPP and "Paunci" HPP. The disposition of this system is presented in the following figure.

This location of this system is not a part of the territory of Serbia, but is included into the present analysis for the following two reasons:

- River Drina is the subject of the "Drina" HIS, developed by the Institute "Jaroslav Černi" and
- This system is a perfect example of application of the Mode 3.

The future "Buk Bijela" and "Foča" HPPs should be equipped with the storages with modest volumes (with water regulation on the order of a single day).

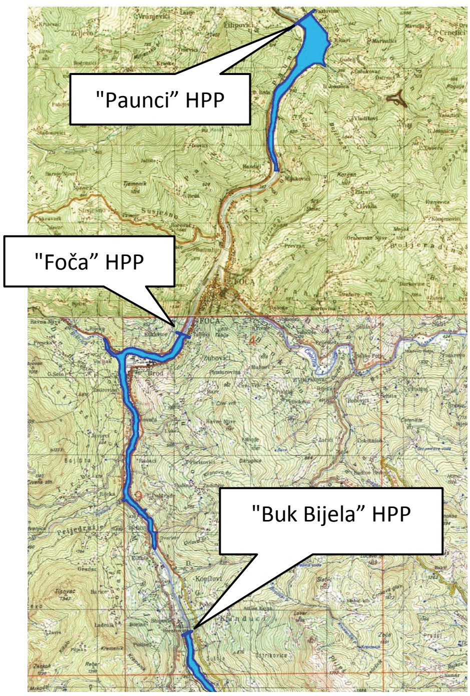

Fig. 9. Disposition of the system of HPPs on the upper part of the River Drina course.

The "Foča" HPP should be located in the vicinity of the city of Foča, meaning that the plant operation followed by large discharge variations should be avoided. The storage of the "Foča" HPP should in the same time serve as the compensation basin for the "Buk Bijela" HPP that should operate during the peak-load period as much as possible. The maximum daily variation in water level in the city of Foča is specified as a boundary condition for the operation of the subject system.

In the course of optimization of operation of this system there are several opposing conditions that should be satisfied:

- The “Buk Bijela” HPP should operate as much as possible during the peak-load period, but the volume of the storage that should compensate for its operation is relatively small,
- The water level in the storage of the “Foča” HPP should be high from the standpoint of electricity generation, but low from the standpoint of compensation of operation of the “Buk Bijela” HPP.

The additional constraint in this analysis is that the “Foča” HPP should make provision for the guaranteed discharge downstream from it.

The task described above is solved by the application of the Mode 3.

The general form of daily dynamics of operation of the “Buk Bijela” HPP and the “Foča” HPP used in the Mode 3 is presented in the following figure.

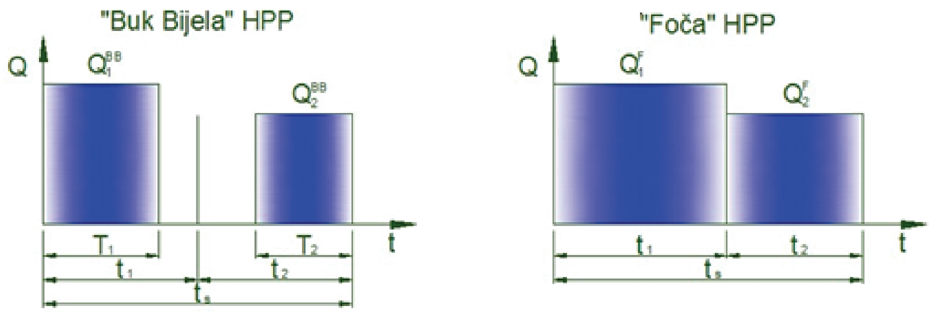

Fig. 10. Modes of operation of the “Buk Bijela” HPP and the “Foča” HPP.

In the figures shown above a day is divided into the period that corresponds to the peak-load operation (left) and the period that corresponds to the band operation (right).

The “Buk Bijela” HPP operates mainly during the peak-load period and is in operation outside this period only if water spilling is to be avoided. The discharge through it should be as close as possible to the rated one.

The “Foča” HPP, due to the requirement regarding the guaranteed flow, operates during the whole day with a variable discharge and its operation adheres to the boundary condition mentioned above.

In the following figures the examples of the operation of this system during a day with a characteristically small inflow and a day with an average inflow are presented.

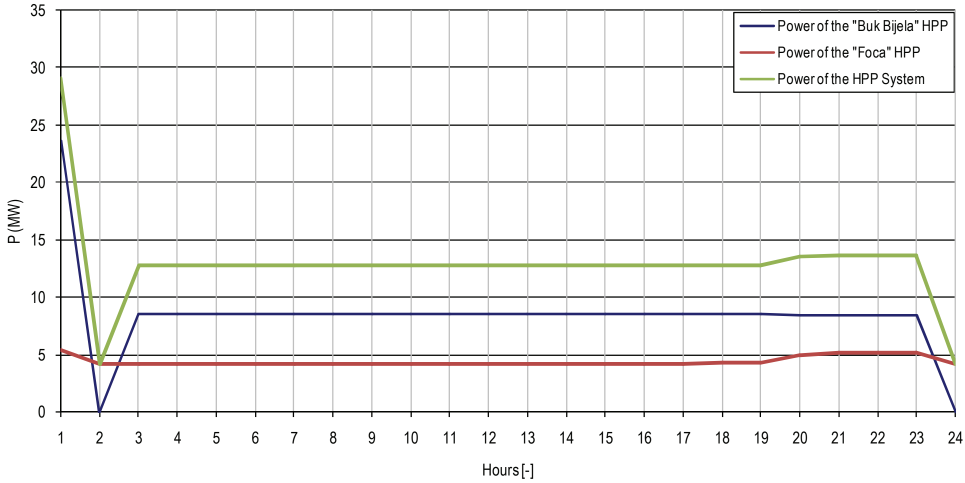

Fig. 11. Operating regime of the “Buk Bijela” HPP and the “Foča” HPP, as well as the system of HPPs, during a day with a characteristically small inflow.

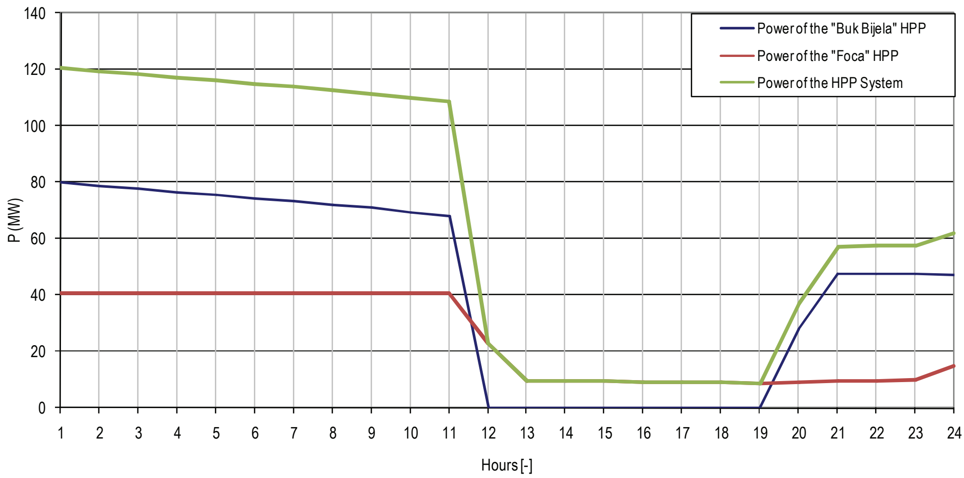

Fig. 12. Regime of operation of the “Buk Bijela” HPP and “Foča” HPP, as well as the system of HPPs, during a day with an average inflow.

In the following figure the diagram with the average annual values of peak-load, band and total electricity generation in the system of the “Buk Bijela” HPP and the “Foča” HPP during the period between the year 1946 and the year 1989 is presented.

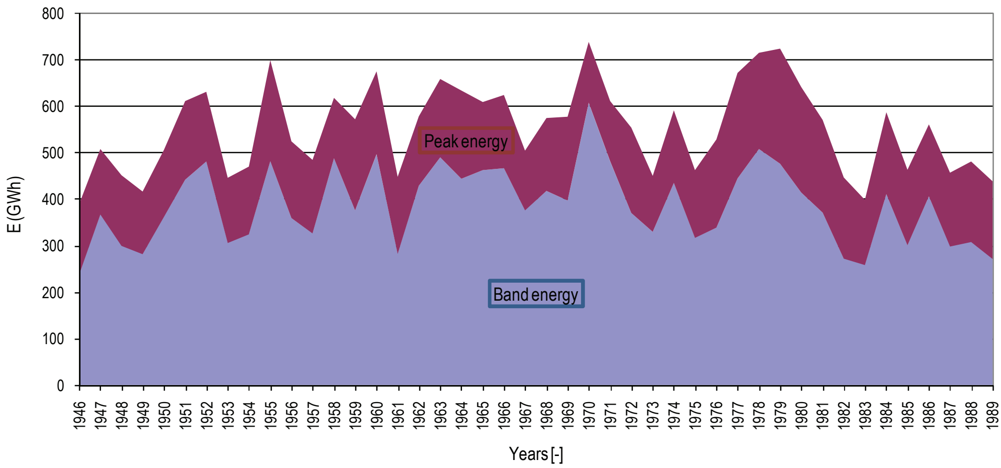

Fig. 13. Diagram of the mean annual values of peak-load, band and total electricity generation in the system consisting of the "Buk Bijela" HPP and the "Foča" HPP during the period between the year 1946 and the year 1989.

7. Conclusions

The successful management of complex hydropower systems, for example, the system "Vlasinske HPPs", is difficult to realize without the use of mathematical simulations and optimization of HPPs' operation, due to a series of opposing requirements. Simulation models used for such simulations should successfully model the characteristics of such systems, as well as the demands that the electricity generation and transmission system imposes on them.

The modes of operation of systems of HPPs in a cascade, described in this paper, model the characteristic demands of the electricity generation and transmission system. Besides that, they take into account the specific limitations of particular systems, for instance the limitation of the daily variation of the water level in the compensation basin.

The results presented in Sections 3 and 4 were obtained by the use of HISs developed in the Institute for Development of Water Resources "Jaroslav Černi". From these results it can be seen that the developed models successfully describe the behavior of a system of HPPs in a cascade and that they can be used for the reliable determination of the most important parameters of their operation, for instance of the water level in the storage, the discharge through the powerhouse and the power and electricity generation realized by hydropower plants.

In this paper, a large potential of the described models and algorithms in the context of design of new systems of HPPs is demonstrated, as well as the possibility of application of modern numerical methods, like genetic algorithms, in the optimization of such systems.

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