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# Water release policy of large reservoir with considerable infiltration losses

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***Abstract*-- The paper deals with planning and operation problems of the Orlovac hydroelectric system. The analysis is based on the control process of the Busko Blato reservoir as a key object. Operation planning of the Busko Blato reservoir is specific since the natural inflows of this reservoir are only slightly greater than its infiltration losses. The losses depend on reservoir water elevation that depends on water release policy and on very changeable natural inflows. The paper presents a model defining the control strategy of the Busko Blato reservoir, which would guarantee minimum infiltration losses and maximum power gains, at the same time respecting the established power demands and technical constraints. This is obtained on the basis of the calculated optimum desirable levels of the Busko Blato reservoir. The analysis has shown that it could be possible to increase electric power generation for 28% in relation to the present state.**

***Index Terms*-- Desirable Elevations, Hydroelectric System, Infiltration Losses, Reservoir Planning**

## I. INTRODUCTION

Planning the utilization of big reservoirs for electric power generation is a very complex and demanding task. In addition to requirements and constraints resulting from optimum power generation strategy, planning also depends on demands and limitations of the other users as well as on flood protection requirements [1]. Stochastic parameters should also be taken into account. Among these parameters, inflow forecasting usually poses the greatest problem. The need for excellent planning of reservoir utilization has lately become even more important with the expansion of electric power market. Appropriate control policy and adequate water distribution from reservoirs over the year can bring about significant economic effects [2],[3].

The paper deals with a description of a basically specific case of a big reservoir utilization planning which is conditioned by great infiltration losses. It is the Busko Blato reservoir, one of the biggest reservoirs in South-Eastern Europe. The reservoir was built 26 years ago, as a main part of the Orlovac hydroelectric system. Its generation data in the given period have shown great water losses caused mainly by infiltration and to a lesser extent by evaporation losses. A partial repair work of reservoir bottom was performed in 1989. However, it did not bring about any considerable decrease of losses. High losses could also be expected in further reservoir utilization, due to very high costs of possible further recovery works and unreliable estimate of their effects. High infiltration losses are caused by the reservoir soil structure. It is a markedly cavernous limestone area with a great number of precipices. Moreover, the reservoir covers a very big area ($57x10^6$ $m^2$) in relation to its volume ($800x10^3$ $m^2$). The hydrological research has produced the curve showing interdependence between losses and reservoir levels for the period before the partial recovery works and after them, shown on Fig.1, which also shows the frequency of daily elevations in the period between 1975 and 1999.

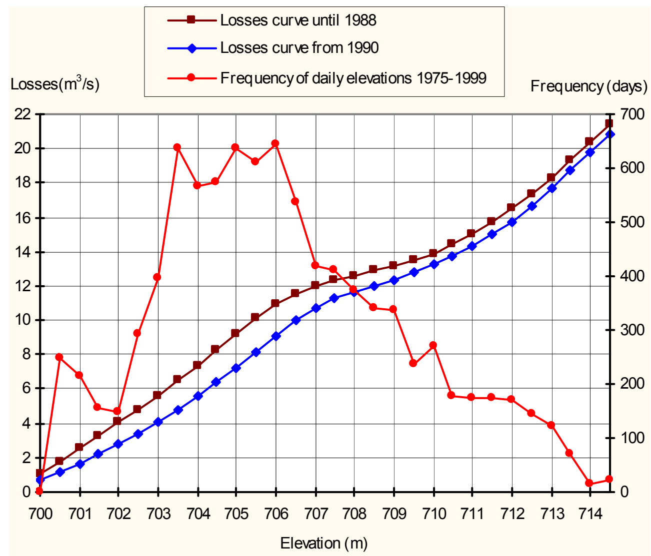


Fig. 1. Interdependence between infiltration losses and the Busko Blato elevation; implementation frequency of average daily elevations

If the curve of infiltration losses is compared to average annual natural inflow into the reservoir, amounting to approximately 10 $m^3/s$, it becomes evident that the exploitability rate is very low, particularly at higher reservoir elevations. One of possible ways of decreasing the losses is changing the existing way of planning and utilization of the waters from the Orlovac hydroelectric system by maintaining the Busko Blato reservoir level as low as possible.

## II. BASIC CHARACTERISTICS OF THE ORLOVAC HYDROELECTRIC SYSTEM AND THE BUSKO BLATO RESERVOIR

The Busko Blato reservoir is a part of the Orlovac hydroelectric system (shown in Fig. 2.) which also includes:

- Lipa reservoir for daily water regulation,
- reversible channel Lipa-Busko Blato,
- hydro power plant Orlovac,
- small pumped storage plant Busko Blato,
- several smaller reservoirs whose water is collected into the Busko Blato reservoir and
- system of channels collecting water from the surrounding fields into the Lipa reservoir.

The reversible Lipa-Busko Blato channel provides a possibility of transferring water in both directions. Depending on elevation difference, transfer is made gravitationally or by means of the pumped storage plant Busko Blato. It operates in the pumping mode if water is transferred from the lower elevation reservoir to the higher one. In generation mode, it operates if water is transferred from the higher elevation reservoir to the lower one, requiring minimum elevation difference. The HP Orlovac receives water from the Lipa reservoir. This water is utilized in downstream hydroelectric power plants, which are a part of a wider hydroelectric system of the Cetina river. The HP Orlovac, with its installed power of 237 MW, usually operates as pure peaking unit, with average annual utilization factor amounting to 18%.

With regard to relatively high installed power of the HP Orlovac in relation to average annual discharges, as well as to the possibility of transferring water from Lipa to Busko Blato and vice versa, the short-term regulation of the Orlovac hydroelectric system is not a problem. Moreover, the HP Orlovac provides a possibility of highly flexible operation adapted to the requirements and demands of the Cetina hydroelectric system and of the Croatian power system in general. The main water control problem of the Orlovac hydroelectric system is shown on the annual level, i.e. on monthly utilization rate of the Busko Blato reservoir. Besides the described great infiltration losses depending on reservoir levels, variability of natural inflows also raises a great problem of reservoir utilization planning. On the annual level, the ratio of minimum and maximum annual natural inflows amounts to 1:3. The ratios of monthly values are far higher and amount from 1:6 in July to 1:60 in September. Fig. 3 shows the water balance of the Orlovac hydroelectric system in the period from 1975 to 1999 (average annual values), whereas Fig. 4 shows minimum, average and maximum monthly inflows into the Orlovac hydroelectric system (Lipa + Busko Blato).

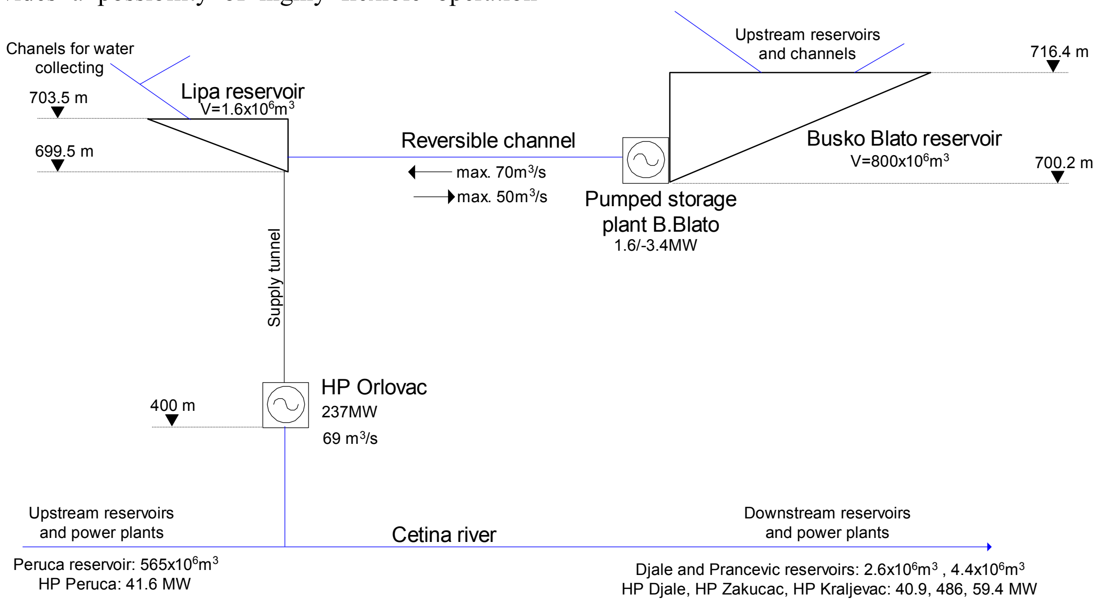


Fig. 2. Orlovac hydroelectric system

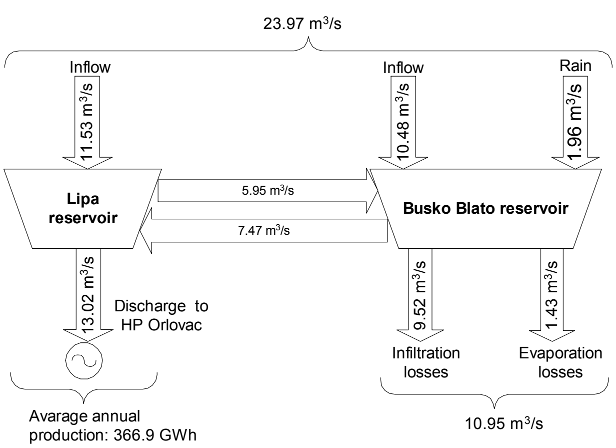


Fig. 3. Water balance of the Orlovac hydroelectric system in 1975-1999 period

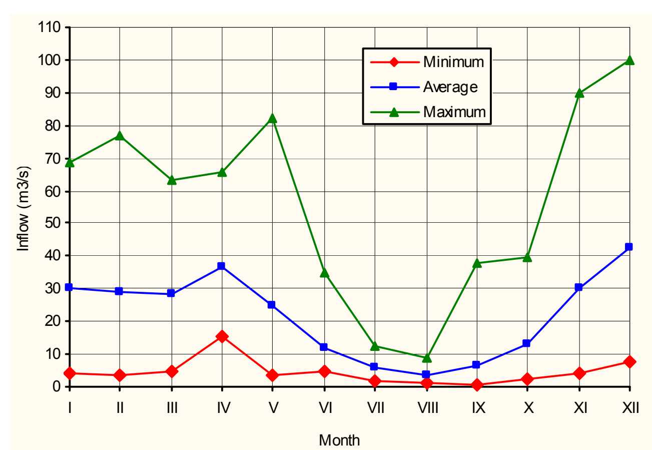


Fig. 4. Monthly inflows (Lipa + Busko Blato) in 1975-1999 period

## III. SIMULATION MODEL FOR DETERMINING DESIRABLE ELEVATIONS AND WATER RELEASE POLICY

Basic demands defining optimum utilization strategy of the Orlovac hydroelectric system within the frame of the Croatian power system are:

1. The highest water value in the Orlovac hydroelectric system is effectuated by using the HP Orlovac as a peaking unit. A direct consequence of this requirement is the limitation the HP Orlovac power generation on daily and monthly levels. It is only very rarely, in the events of great natural inflows into the Lipa reservoir, that the power plant does not operate as a peaking unit. In that case the flow limitation in the Lipa – Busko Blato channel demands for the forced generation of the HP Orlovac.
2. The most important role of HP Orlovac in the Croatian power system consists in providing the power reserve in the peaking load covering system. A specific minimum of monthly generation must therefore be guaranteed for HP Orlovac, regardless of hydrological conditions. A specific minimum quantity of available water is therefore necessary from the Busko Blato reservoir and from the natural inflows in order to meet the requirements of minimum monthly generation rate.
3. The volume of the Busko Blato reservoir provides the possibility of its utilization as annual or even multiannual reservoir, i.e. it provides a theoretical possibility of supplying a big power reserve to meet the needs of the Croatian power system. However, the real state of the reservoir with regard to its great infiltration and evaporation losses at higher elevations, allows for this possibility only with great losses and with a substantial decrease of total power generation. The Busko Blato reservoir must therefore be used only as a seasonal reservoir. Exceptions are accepted only in certain specific situations, e.g. in conditions of prolonged unavailability of some major interconnecting lines or inability of utilization of other reservoirs in a longer period.
4. The Busko Blato elevation should not drop under the minimum allowed value, regardless of hydrological conditions and the Croatian power system requirements. Minimum allowed elevation amounts to 701.0 m, which has been adopted as a strict constraint to be provided by the recommended water release policy and the desirable elevations.
5. Due to the Busko Blato reservoir characteristics, there are no constraints regarding the highest allowed elevation.
6. The desirable elevations in the Busko Blato reservoir must be defined in such a way as to provide the maintenance of the lowest possible reservoir levels, at the same time providing all the above quoted conditions and constraints, regardless of future hydrological circumstances. This stipulation assures maximum power utilization of available waters of the Orlovac hydroelectric system in the given conditions.
7. Possible changes of the preceding requirements are possible in case the value of the generated energy and available power by the HP Orlovac varies considerably during the year, which may result in greater economic effect in spite of lower generation of electric power. This condition has not been fulfilled, due to current state of the Croatian power system.

In order to fulfill the above requirements, the desirable states of the Busko Blato reservoir should be determined on at least three levels:

- The desirable elevations of the Busko Blato reservoir and its utilization rate should be determined for the broadest set of possible hydrological situations, with the given general constraints as a basis for defining the annual reservoir utilization plan.
- The desirable elevations of the Busko Blato reservoir and its utilization rate should be determined for the given year, depending on expected circumstances in the Croatian power system and the corrected limitations regarding the operation plan of the other power plants.
- Periodic replanning of the annual operation plan should be performed, depending on hydrology, real state of the reservoir, and changes in the system requirements.

Taking into account the defined requirements and the relevant hydrological and technical operation parameters for the Orlovac hydroelectric system, a simulation-based optimization model has been developed to define the desirable elevations of the Busko Blato reservoir [4]. The desired reservoir states should realize the objective of defining such water release policy that will provide maximum power supply during a sufficiently long time period (taking into consideration inflow variability). The objective function is expressed by the requirement for maintenance of the lowest possible elevations of the Busko Blato reservoir, thus minimizing infiltration and evaporation losses:

$$\min\{H_1, H_2, ..., H_{12}\}, \tag{1}$$

Fundamental constraints are:

$$H_i^{min} \le H_i \tag{2}$$

$$W_i^{Orl\_min} \le W_i^{Orl} \le W_i^{Orl\_max} \tag{3}$$

where:

$H_i$ - elevation of B.B reservoir at the beginning of $i^{th}$ month

$H_i^{min}$ - the lowest allowed elevation of B.B. reservoir at the beginning of $i^{th}$ month

$W_i^{Orl\_min}, W_i^{Orl\_max}$ - the lowest/highest allowed monthly generation of the HP Orlovac in $i^{th}$ month

$W_i^{Orl}$ - monthly generation of the HP Orlovac in $i^{th}$ month

Water flow equations for Lipa and Busko Blato reservoirs must also be satisfied:

$$V_L^{t+1} = V_L^t + V_{d\_L}^t + V_{BB-L}^t - V_{L-BB}^t - V_{Orl}^t \tag{4}$$

$$\begin{aligned} V_{BB}^{t+1} &= V_{BB}^t + V_{d\_L}^t - V_{BB-L}^t + V_{L-BB}^t + \\ &+ V_{r\_BB}^t - V_{i\_BB}^t - V_{e\_BB}^t \end{aligned} \tag{5}$$

where:

t – time interval (day or month)

$V^t_L$, $V^{t+1}_L$ – Lipa volume

$V^t_{BB}$, $V^{t+1}_{BB}$ – Busko Blato volume

$V^t_{d\_L}$, $V^t_{d\_BB}$ – volume of natural inflows into Lipa and B.B.

$V^t_{r\_BB}$ – volume of precipitation on B.B.

$V^t_{Orl}$ – volume of water discharge from Lipa towards HP Orlovac (decision variable)
$V^t_{BB\_L}$, $V^t_{L\_BB}$ – volume of channel flow from B.B. to Lipa and vice versa (decision variable)
$V^t_{i\_BB}$, $V^t_{e\_BB}$ – volume of infiltration and evaporation losses from B.B.

Infiltration and evaporation losses from the Busko Blato reservoir are nonlinear functions depending on reservoir volume and elevations:

$$V^t_{i\_BB} = f_1(V^t_{BB}) \tag{6a}$$

$$V^t_{e\_BB} = f_2(V^t_{BB}) \tag{6b}$$

Due to specific requirements described above, it has not been possible to utilize standard simulation/optimization models in order to solve the problem described above. Besides, in order to achieve minimum Busko Blato reservoir levels that would satisfy all the constraints, the model should result in optimum desirable elevations. On the basis of desirable elevations control decisions are made regarding:

- range of daily/monthly generation in the HP Orlovac
- daily/monthly flows through the Lipa – Busko Blato channel

Genuine models have therefore been developed to meet the needs of utilization planning of the Orlovac hydroelectric system. These models define the desired monthly elevations of the Busko Blato reservoir. The resulting desired elevations help to provide minimum average monthly levels in the Busko Blato reservoir, which provide maximum exploitation of natural inflows. Two models have been developed:

- a deterministic model, using a day as a basic time unit
- a probabilistic model, using a month as a basic time unit

The deterministic model implies the known daily inflows into the Lipa and Busko Blato, as well as the precipitation inflows. Daily inflows realized in the past 25-year operation period of the Orlovac hydroelectric system have been used. The advantage of the deterministic approach is a possibility of modeling the Orlovac hydroelectric system on a daily basis, i.e. maximum simulation truth has been achieved in accordance with daily model of the Orlovac hydroelectric system operation planning. Besides, the observed 25-year succession of daily inflows, which also makes the total interval of all the simulations, provides a sufficiently high hydrological sample which takes into account high inflow variation.

The probabilistic model takes into account total monthly inflows into the Orlovac hydroelectric system as input parameter, neglecting daily dynamics of water interchange between the Lipa and the Busko Blato. Monthly inflows into the Orlovac hydroelectric system are formed by means of the Monte Carlo simulation as synthetic hydrological sample modeled on the basis of the probability functions of total inflows into the system for the given month (J. von Neumann's Acceptance-Rejection Method, [5]). The probability function of natural inflows is approximated on the basis of the realized monthly inflows. The inflows are generated by means of stochastic numbers for each month in the simulated 1000-year sample. The monthly model offers the advantage of simulation a great range of possible hydrological variants. However, there is a partial loss of accuracy due to constraint neglect on daily level.

In both calculation variants the simulation of the Orlovac hydroelectric system operation is performed in the observed time interval on the basis of the desired monthly elevations. The required generation of the HP Orlovac resulting in the lowest departure of the Busko Blato reservoir elevation from the desired elevation at the end of the month, is determined for each fundamental time unit, taking into account all the constraints. The first simulation is performed on the basis of the assumed initial desired elevations. Before each subsequent simulation the correction of the desired elevations is performed on the basis of the difference of simulated mean values of elevations and the desired elevations of the current iteration. Optimum desired elevations are adopted when the iterative process converges on the basis of the difference of total generation of electrical power in current iteration and in the previous one.

## IV. Results

Calculations have been performed for four different variants of power constraints, defined via minimum required and maximum allowed monthly generation in the HP Orlovac. The constraints are shown in Table I.

TABLE I
LEAST/HIGHEST ALLOWED MONTHLY GENERATIONS IN HP ORLOVAC (GWH)

| Month | A | | B | | C | | D | |
|---|---|---|---|---|---|---|---|---|
| | Min | Max | Min | Max | Min | Max | Min | Max |
| I | 13 | 85 | 15 | 85 | 13 | 70 | 15 | 70 |
| II | 12 | 75 | 14 | 75 | 12 | 60 | 14 | 60 |
| III | 12 | 85 | 14 | 85 | 12 | 70 | 14 | 70 |
| IV | 12 | 82 | 14 | 82 | 12 | 67 | 14 | 67 |
| V | 12 | 85 | 14 | 85 | 12 | 70 | 14 | 70 |
| VI | 14 | 82 | 16 | 82 | 14 | 67 | 16 | 67 |
| VII | 16 | 85 | 20 | 85 | 16 | 70 | 20 | 70 |
| VIII | 16 | 85 | 20 | 85 | 16 | 70 | 20 | 70 |
| IX | 12 | 82 | 14 | 82 | 12 | 67 | 14 | 67 |
| X | 12 | 85 | 14 | 85 | 12 | 70 | 14 | 70 |
| XI | 12 | 82 | 14 | 82 | 12 | 67 | 14 | 67 |
| XII | 13 | 85 | 14 | 85 | 13 | 70 | 14 | 70 |

In accordance with previously defined requirements the calculation results are shown in Fig. 5-8, according to the given variants. The results refer to the simulated monthly levels of the Busko Blato reservoir, the calculated desirable elevations of the Busko Blato, and the mean monthly generation of the HP Orlovac. Daily elevations frequency curves in the Busko Blato reservoir are also shown in extreme variants (A or D), in parallel with the curve realized in the 1975-1999 period. The enclosed graphs clearly show the influence of power requirements on the desirable monthly levels of the Busko Blato reservoir and the resulting mean realized levels. Each narrowing of the allowed span of the monthly generation in the HP Orlovac decreases the elevation control flexibility of the Busko Blato reservoir, leading to the increase of mean monthly levels. The limitation of the minimum required monthly generation in the HP Orlovac is thereby shown as a more influential factor in relation to the limitation of maximum allowed monthly generation. This requirement is reflected in the first place on bigger desirable levels of the Busko Blato reservoir with the aim of providing the necessary volume supplies to be used during the dry period (June to September).

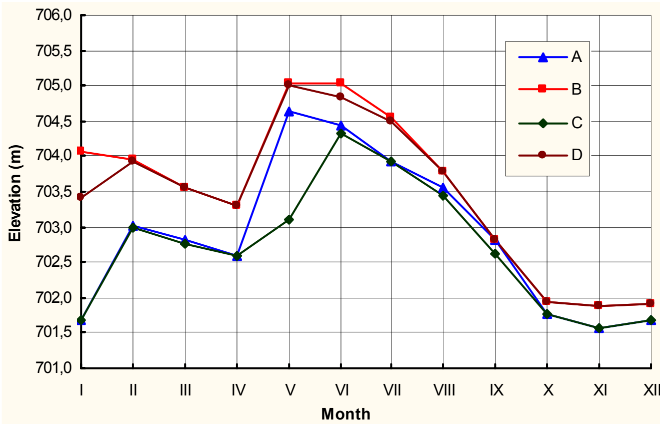


Fig. 5. Desirable monthly elevations of the Busko Blato reservoir

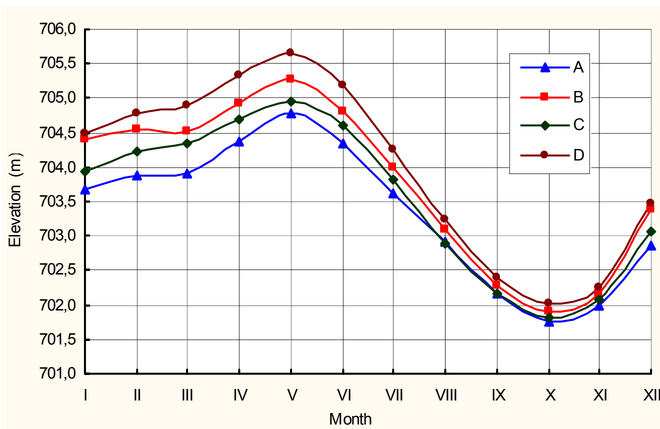


Fig. 6. Average monthly elevations of the Buško Blato reservoir

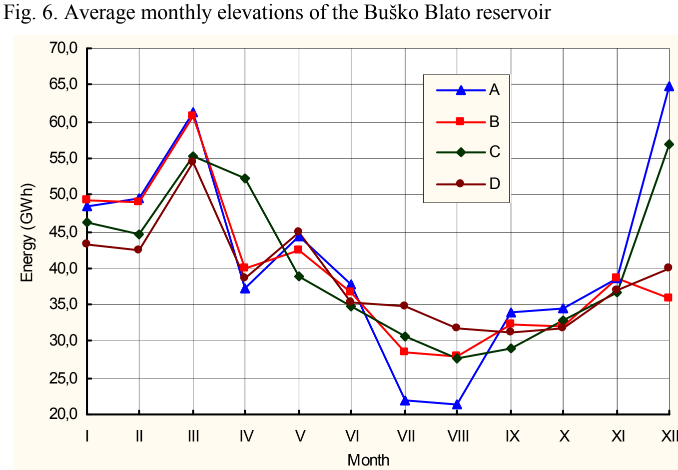


Fig. 7. Average monthly generation of HP Orlovac

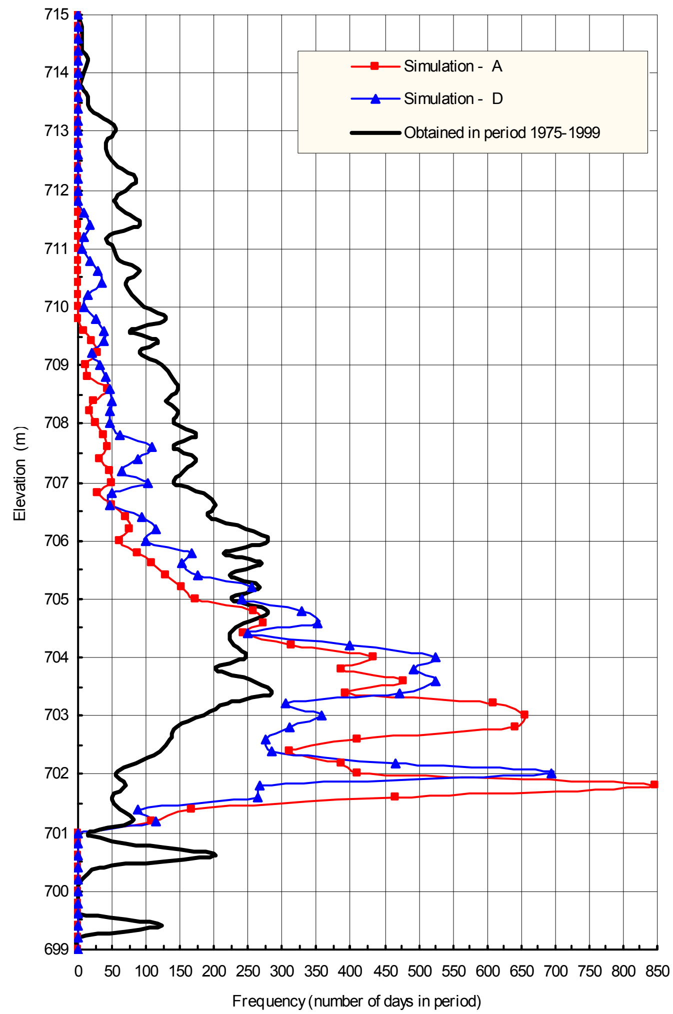


Fig. 8. Frequency of daily elevations of the Busko Blato reservoir

Generation in the HP Orlovac varies considerably during a year, as a consequence of relatively broad spans of allowed monthly generation. This provides a partial adaptation of the HP Orlovac generation to the fundamental requirement i.e. to the regulation of levels in the Busko Blato reservoir with the aim of maximizing the electric power generation during the year. Namely, a possible additional stipulation demanding the equalization of the HP Orlovac generation during a year (or a forced operation in a particular month), could be accepted and applied. However, it would result in higher desirable and mean realized levels of the Busko Blato reservoir, as well as in decreased total power gain. Average generation in the HP Orlovac in summer months (June – September) ranges from 22 to 35 GWh, depending on the observed variant. In most cases this makes the generation in the HP Orlovac during the dry period of the year higher than the preset constraints on minimum allowed monthly generation. The following table show mean annual values of hydrology and power operating parameters of the Orlovac hydroelectric system for the four simulated variants, together with referential (realized) values in 1975-1999 period.

TABLE II
MEAN VALUES OF REFERENTIAL AND SIMULATED HYDROLOGY AND POWER PARAMETERS ORLOVAC HYDROELECTRIC SYSTEM

| Parameter | Ref. | A | B | C | D |
|---|---|---|---|---|---|
| Lipa natural inflow ($m^3/s$) | *11.5* | 11.6 | 11.6 | 11.6 | 11.6 |
| Busko Blato natural inflow ($m^3/s$) | *12.2* | 12.2 | 12.2 | 12.2 | 12.2 |
| Channel flow from Busko Blato to Lipa ($m^3/s$) | *7.5* | 7.4 | 7.1 | 7.1 | 6.9 |
| Channel flow from Lipa to Busko Blato ($m^3/s$) | *5.9* | 1.8 | 2.2 | 1.8 | 2.3 |
| Busko Blato evaporation losses ($m^3/s$) | *1.4* | 1.3 | 1.3 | 1.3 | 1.3 |
| Busko Blato infiltration losses ($m^3/s$) | *9.6* | 5.3 | 5.9 | 5.5 | 6.2 |
| Busko Blato elevations (m) | *706.2* | 703.4 | 703.8 | 703.6 | 703.9 |
| Discharge to HP Orlovac ($m^3/s$) | *13.0* | 17.2 | 16.5 | 16.9 | 16.2 |
| HP Orlovac annual production (GWh) | *367* | 493 | 473 | 486 | 465 |

Mean simulated annual values of HP Orlovac operation parameters show a slight decrease of discharge by channel from Busko Blato to Lipa, at the same time showing a high decrease of inflow from Lipa to Busko Blato. The difference is a result of decrease of infiltration losses from the Busko Blato reservoir due to decreased operating elevations, which is provided by greater direct utilization of natural inflows into the Lipa, without transfer and accumulation in the Busko Blato. Thus the discharge into the HP Orlovac is considerably increased, i.e. mean annual generation is increased in relation to the referential one. The increase ranges from 98 GWh for D variant to 126.3 GWh to A variant. On the average, possible generation increase in the HP Orlovac amounts to 28% in relation to the generation achieved so far.

## V. CONCLUSION

The analysis of inflows and power parameters of the Orlovac hydroelectric system, as well as investigations related to the new control model and water release policy of the Busko Blato reservoir and of the Orlovac hydroelectric system as a whole, have shown great possibilities of improving the degree of power utilization. If the model and the suggested desirable elevations are operationally accepted, a considerable power gain can be obtained, amounting to 28% increase in mean annual generation in the HP Orlovac. Average power gain depends in the first place on the preset power requirements which can vary from year to year and on minimum allowed elevation of the Busko Blato reservoir that can change in case of demands of the other reservoir users and ecological requirements. All the other essential power parameters of the HP Orlovac would thereby be preserved, except for the shortening of the leveling period of the Busko Blato reservoir, which would have practically no effect on security and economy of the Croatian power system operation.

In a strict mathematical sense, the solution of the problem which follows from the described models is not completely optimal, but it is sure near optimal and certainly feasible. Moreover, with regard to the inflow variability it is questionable whether there is an optimum solution at all, and to what extent it differs from the obtained quasi-optimum solution. In any case, it is a matter of further research and improvement of the models suggested here.

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## VII. BIOGRAPHIES

**Ranko Goic, M.Sc**, born on the island of Brac, Croatia, on April 11, 1969. He graduated from the Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, where he also received his M.Sc. degree in 1997. Ever since graduation, he has been working at the same faculty, in the Power System department. His main research interests are the power system network analysis and power system planning and optimization. His research and engineering interests are directed towards design of software tools for network analysis and power system planning, which are in operative use in Croatia and Bosnia and Herzegovina. He has also been engaged in many research and practical investigation projects for the Croatian Power System Utility. He is member of IEEE and Croatian Committee of CIGRE.

**Mladen Petricec, Ph.D**, born in Zagreb on July 16, 1950. He received his B.Sc. and M.Sc. degree from the Faculty of Civil Engineering - The University of Zagreb, while he earned his Ph.D. from the Faculty of Civil Engineering at University of Split. Following his graduation he lectured at the Faculty of Civil Engineering at Zagreb until 1979, after which he held a position at the Energy Institute Ltd. Zagreb until 2000. His current title is the Director of the Water Management Department at Croatian Water. He specializes in research activities which include planning development and exploitation in the fields of water management and hydroelectric systems. He is a member of numerous professional civil engineering and water resources associations in Croatia and also a member of the International Hydrological Programme - Croatian National Committee, and serves on the editorial board of the Croatian Water magazine.

**Marko Lovric, B.Sc**, born in Livno, Bosnia and Herzegovina, on April 19, 1949. He graduated from the Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split in 1972. He has been working in Croatian Power System Utility (HEP) from 1974 as operative dispatcher, local dispatching centre manager and general manager of south part of Croatian transmission network. His interests include planning, control and expansion of power system. He is member of Croatian Committee of CIGRE.