Journal of the Serbian Society for Computational Mechanics / Vol. 3 / No. 1, 2009 / pp. 273-297
UDC: 621.311.21:519.863

Computer-Aided Optimization in Operation Planning of Hydropower Plants – Algorithms and Examples

N. Milivojević[1*], D. Divac[2], D. Vukosavić[3], D. Vučković[4], V. Milivojević[5]

Institute for Development of Water Resources "Jaroslav Černi", 80 Jaroslava Černog St., 11226 Beli Potok, Serbia; e-mail: [1]nikola.milivojevic@gmail.com, [2]ddivac@eunet.rs, [3]drmnv@sezampro.rs, [4]dejan.vuckovic@jcerni.co.rs, [5]vladimir.milivojevic@gmail.com
**Corresponding author*

Abstract

Due to complex relations present in hydropower markets, and having in mind the specific role of hydropower in common electricity generation and transmission grid systems, it is impossible to identify a unified approach to hydropower plant management. The ever-changing market behavior also presents a problem for unification of methodologies and all this imposes the interpretation of hydropower plant management as a dynamic set of rules that are adaptable to system complexity and market needs. Based on simulation models of water flow and hydropower generation, along with optimization techniques employing genetic algorithms controlled by fuzzy-logic, an approach is proposed for determination of rules for operation planning of hydropower plants.

This paper presents the approach to hydropower potential estimation and operational management applied to simulation of the hydropower plants "Iron Gates 1" and "Iron Gates 2", located on River Danube and shared by Serbia and Romania, using computer-aided optimization. The objective of the computer-aided optimization management system is to ensure efficient utilization of the Danube's hydropower potential, to address the demand of Serbian and Romanian electricity generation and transmission systems (that differ in terms of power and time) and to comply with a number of constraints, which are defined in bilateral agreements. In this paper it has been proven possible, unlike to the case of the old uncoupled model, to simulate the operation of the integrated system of cascaded power plants, with concurrent simulation of both hydraulic and electrical processes. The system is expected to provide daily management support and is a mean by which the outcomes of operational planning within different hydrologic, economic, legal and other frameworks can be assessed, and to attain conditions for optimum water resource management and the resolution of existing and potential conflicts in the region, with regard to any conflict of stakeholder interests.

Keywords: Optimization, modeling, genetic algorithm, hydropower

1. Introduction

In the environment of complex electricity market relations and due to the specific role of hydropower systems within the electricity generation systems, as well as to their coupling with other electricity generation systems (thermo power systems, nuclear power plants, solar systems etc.), one can conclude that there is no unified principle of hydropower objects management applicable in all situations (Wood and Wollenberg (1996); Batut and Renaud (1992). One of the specific problems of solution unification is the continuous transformation of the market, which is abandoning the ideas of centralized systems with fixed regulation principles (Baldick (1995); Zhang et al. 2000). As a consequence, management of hydropower objects must be treated as a dynamic set of rules that are adaptable to system complexity and market needs (Morozowski et al. 1997).

On the other hand, the progress of information-communication technologies, particularly in the spheres of software development (object-oriented architecture (Booch, 1991, 1994), distributed and parallel computing (Fujimoto, 2000; Coulouris et al., 1994; etc.), data mining (neural networks, expert systems, knowledge extraction from data (Barr and Figenbaum, 1982; etc.) and related theory of games, fuzzy-logic (Duckstein and Tecle, 1993; and alike, allowed for transformation of rigid traditional planning and management of hydropower objects (static, strictly hierarchical) into a dynamic process. It is particularly important to note that it is possible today to develop models facilitating full interaction between management staff and the technical approach to system management. This increases the management participation in the process of identification of the optimum management solution, while the creativity of technical staff is stimulated and their participation in decision making strengthened. Therefore, special attention will be paid to management methods based on contemporary information technologies and their application in basic level of management of hydropower objects.

The management of an individual hydropower object can be basically split into three levels: the strategic, tactical and operational one (Morozowski et al., 1998). The strategic level concerns the management issues in terms of electricity company's strategic goals and the system that the object is a part of. The tactical level corresponds to the translation of strategic-level decisions to tactical management plans while the lowest, operational level, corresponds to the actual implementation of tactical plans. Tactical plans are implemented through operational planning, resulting in physical system management.

Operational planning of electricity generation is a process applied constantly throughout the time of system exploitation. Broadly comprehended, operational planning is also applied at the level of a complex electricity generating system if the interactions between hydropower generation and large thermo- or nuclearpower plants are to be considered (Johnson, 1997). The problem here is to identify the optimum coupled units' operation, both in thermopower and hydropower plants (especially during thermopower units' start-ups and shut-downs) and use the energy potential in the optimum manner (especially regarding hydropower plants' operation and management of storages used also by other entities (Labadie, 2004). This type of planning is performed at the level beyond the operational management of the object itself. As the below presented considerations will refer only to hydropower objects, the operation of the remaining parts of the electricity generation and transmission system will not be taken into consideration. It will be assumed that the requirement for the operational management level has been defined at the higher level and that it has been harmonized with the optimum operation of the integrated system.

Operational planning of the hydropower system operation includes an activity of defining the unit commitment schedule as a response to distribution system requirements aimed at operational costs minimization, optimum use of hydropower potential and preserving the system's exploitation limitations. Planning is mainly related to one to seven days periods because it is very difficult to forecast generation demand for longer periods.

System operation must integrate structural limitations, such as the maximum and the minimum discharge through the turbine, maximum and minimum powers, the minimum unit operation time, duration of start-up and shut-down etc. All factors defining the possible unit operational dynamics must be considered as relevant limitations.

Apart from structural limitations and, in the case of hydropower systems, the ones arising from multi-purpose storage utilization, there are very complex exploitation limitations that are to be observed in any situation. Limitations are often related to danger of floods, jeopardizing the particular river course navigability, introducing destructive impact on flora and fauna etc. A special class of limitations occurs when two entities share the hydropower potential, and these entities are often two states. In order to protect interests of all sides it is necessary to introduce numerous limitations in the operation of individual subsystems.

In addition to above mentioned, one should bear in mind that hydropower systems are often comprised of two, three or more cascaded power plants, or coupled with a reversible power plant. The problem is considerably intensified in this case, because the operation of cascaded power plants is closely connected, resulting in a series of additional operational limitations.

2. Certain conventional possibilities of operational planning of electricity generation

High non-linearity of the problem observed and huge freedom in decision-making result in a situation where no one can develop a universal system able to solve all optimization problems of the operational planning of electricity generation, regardless of the problem severity. Anyway, due to the high importance of finding the solutions for these problems in practice, a substantial number of industrial solutions for specific real systems was implemented and published so far. The conventional approach to the solution of these problems involves the use of Lagrange multipliers, Benders's decomposition and mixed integer programming. Heuristic methods, such as simulated annealing, taboo search, genetic algorithms and various hybrid approaches are being frequently used lately.

2.1 Mixed integer programming in unit commitment problems

Linear programming tasks that impose the condition of variables being integer, all of them or only certain ones, are the tasks of integer linear programming. Tasks of the full integer programming impose the condition of having all problem variables as integers. In case of having certain variables with decimal values, one is solving the problems of mixed integer programming.

One of the algorithms used frequently for solving the problem of optimum unit commitment by virtue of mixed integer programming method is the method of branch and bound (Chen and Wang, 1993). The simplest approach to solving the problems of integer programming is about the enumeration of all acceptable integer values, evaluation of the target function in all possible solutions and selection of the optimum one. Although the algorithm is easy to implement, the time needed for computing all possible solutions may be overly long, even in case of a problem of medium dimensions. The method of branch and bound may be considered as an advanced approach to simple enumeration, where many inappropriate solutions are abandoned and target function computation is not needed.

2.2 Benders's method of decomposition

Benders's method of decomposition concerns the problem decomposition into the master problem, covering only discrete variables, and a sub-problem that deals only with continuous variables (Turgeon, 1978; Baptistella and Geromel, 1980; Habibollahzadeh and Bubenko, 1986; Ma and Shahidehpour, 1998). The sub-problem regards the economic aspects of market placement of generated electricity in a certain unit commitment scenario. Optimum values resulting from the sub-problem are used as limitations of the master problem optimization. On the other side, master problem is, after the optimization step, assigned to the sub-problem of unit commitment scenario. This is how convergence and optimum balance between two problems is achieved by an iterative process.

The main weakness of the Bender's method of decomposition is finding a solution to the master problem. In complex systems this still represents a large-scale problem of integer programming.

2.3 Dynamic programming in problems of unit commitment

Decisions about many practical problems are made sequentially at specific moments, relevant spatial points and different organizational levels. These problems are called the problems of sequential decision-making. As decisions are made in certain stages of process implementation, these problems are also called the problems of multi-stage decision-making. Dynamic programming is the best-known solution method for this type of problems (Bellman and Dreyfus, 1962).

Dynamic programming technique (when applicable) concerns the decomposition of the multi-level problem into a sequence of locally optimized stages. In such a way, an N-dimensional problem is transformed into a sequence of N one-dimensional problems, solved sequentially. In most cases, solving individual problems is simpler task than solving the integral optimization problem. Since the dynamic programming process of optimal N-dimensional problem is found as the combination of N optima of one-dimensional problems, the solution of an N-dimensional problem is not under impact of the selection of the optimization model applied to individual one-dimensional problems.

The basic form of dynamic programming, in case of unit commitment problem, is based on search through all possible commitment scenarios at any time step. Certain scenarios are immediately eliminated as unfeasible. However, although certain solutions are eliminated for preventive purposes, the number of combinations for larger systems is increasing to such a degree that, time-wise, it is not acceptable for computer implementation any more. Therefore, many problem-simplifying techniques have been developed, for the purpose of computer implementation of problem solution within an acceptable time frame (Snyder et al. 1987).

2.4 Lagrangian relaxation method

Mathematically speaking, relaxation methods include the mitigation of strict constrains by virtue of their transformation into simpler forms, or their complete elimination from the algorithm. The method of Lagrangian relaxation is based on transformation of strict constrains into target function factors. Method of Lagrangian relaxation in problems of the unit commitment consists of the following three steps: defining a cost function which is a sum of factors defined for each unit individually, then defining a set of constrains related to individual units and finally of defining a set of coupled constraint for each hour of operation during subject period for all units.

Some researchers showed that an approximate problem solution can be achieved by replication of coupled limitations to cost function by applying the Lagrangian multipliers (Cohen and Sherkat, 1987). With two sets of Lagrangian multipliers related to generation balance and unit's structural limitations, the problem is transformed into a dual form (inter-dependent problems are called dual). The dual problem is separated into two simpler optimization problems, to be solved individually under the assumption of remaining constrains.

2.5 Heuristic methods in problems of unit commitment

Heuristic methods are empirical methods for selection of the optimum solution based on their quality under the assumption of all limitations regarding exploitation. Compared to other optimization methods they have several advantages in solving the unit commitment problem. Firstly, they are flexible and allow for application of all types of constrains. If acceptable solutions exist at all, in most cases these methods will result in an acceptable solution and they are not overly demanding in terms of computer time and memory used; hence, they are easy to implement on standard computers.

The main weakness of heuristic methods is that they cannot guarantee an optimum solution and they even cannot forecast the quality of a possible local optimum, resulting as the solution. This problem is particularly stressed out in large systems, where price differences of 0.5% between proposed solutions represent financially significant funds. This is the reason why deterministic methods are often applied, regardless of the fact that they are computational demanding. Heuristic methods, such as simulated annealing (Zhuang and Galiana, 1990), taboo search (Xiaomin et al., 1996), genetic algorithms (Kazarlis et al., 1996; Orero and Irving, 1998; Liyong et al., 2006) and hybrid approaches (Viana et al., 2002) are lately being used frequently.

3. New possibilities of operational planning of electricity generation

Previously considered optimization algorithms used for solving the problem of unit commitment mainly refer to management of mixed thermo-hydropower systems. The biggest step ahead has been made in the field of optimal management of generation in thermo power plant systems; hence, there are many industrial solutions in this field used in operation management (Sheble and Fahd, 1994; Tseng, 1996; Svoboda et al., 1997; Feltenmark, 1997; Lai and Baldick, 1999). On the other hand, there are far less published results for hydropower systems management (Li et al., 1997; Guan et al., 1999; Arce et al., 2002). Firstly, utilization conditions of hydropower potential are far more complex than those for exploitation of thermo power plants, because the reservoirs are also very often used for water supply, irrigation, meeting the water needs of industry etc. Also, water is a sensitive resource, directly related to flora and fauna and environment. In addition, the operation of hydro power systems, in contrast to thermo power plants, has a distinct dynamics during daily exploitation and, as already explained, these plants are often used as compensation factor in the electricity generation and transmission systems.

As mentioned in the introduction, there is not a single principle of management of hydropower objects applicable in all cases. Continuous transformation of the market moves it away from the idea of a centralized system with unchangeable regulation principles. Therefore, it is necessary to treat the hydropower systems management as a dynamic system of rules and methods which are individually changeable and adaptable to market needs.

The progress of communication infrastructure and information processing, as well as software development, allows for transformation of planning of the hydropower plant operation. Now it is possible to transform traditional planning and management of hydropower objects (that are static and strictly hierarchical) into dynamic processes. Of particular importance is the fact that presently one can develop models allowing for full interaction between management's actions and technical approach to management. This is how management's involvement in the process of identification of the optimum solution is intensified, while stimulating the creativity of technical staff and strengthening its influence on decision-making.

3.1. General remarks on the simulation of the hydropower system operation

Simulation model for hydropower calculations and management of hydropower systems' exploitation are the models of water flow through complex structures of the system and the transformation of mechanical energy into electricity in hydropower plants. Modeling of these processes requires good knowledge of relevant complex phenomena, as well as adequate assessment of the method and degree of their approximation (IEEE, 1992). Taking into account the spatial and operational complexity of these systems, a relevant spatial decomposition is performed by introduction of various elements that simulate different phenomena involved in the process of exploitation of hydropower potential.

In order to use the simulation model of a hydropower system for solving numerous problems, which can be treated by system dynamics theory, it is necessary to perform system decomposition at a required degree of complexity (Figure 1).

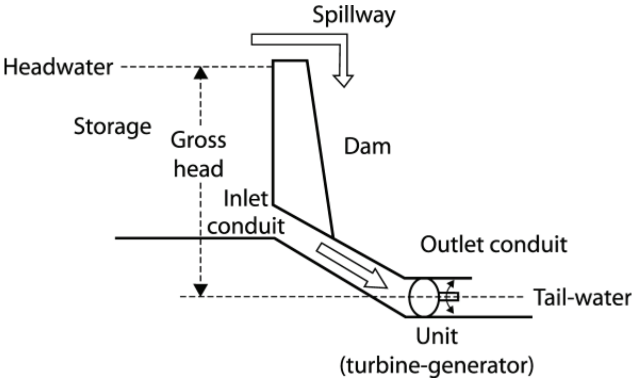


Fig. 1. Schematic presentation of the hydropower plant

Decomposition of the hydropower system into several sub-systems appears to be the most suitable approach in majority of cases, among which the most important are the storage, hydraulic and energy systems.

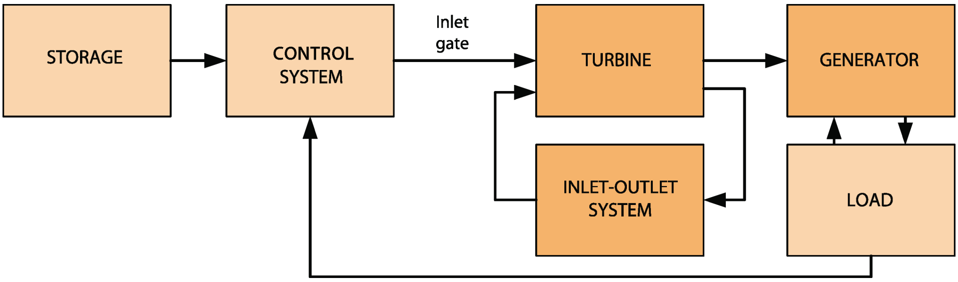


Fig. 2. Modular approach to hydropower plant modeling

Dynamics of changes in storages that hydropower plants take the water from or release the water into, depends also on the events taking place upstream and downstream from the intake area. Storage is a bounded area where the water level is maintained within a previously defined range, mainly at normal water level, and it is supplied from the surface waters, underground waters and by water transportation using the hydro-technical structures (tunnels). Water release from the storage can be through the hydropower plant, over the spillway, through the foundation outlet, by leakage, by evaporation off the water surface and by water intake for the needs of the user (water supply, irrigation etc.).

The selected simulation model of water flow through the storage systems is based on the systems of partial differential equations describing the flow of the fluid in the scope of the desired number of dimensions and the level of detail. The flow in open conduits, storages and similar spaces is characterized by the indefinite nature of the fluid current contours. One part of the contour is free surface whereon the pressure is equal to the surrounding pressure. Unsteady flow in open conduits is examined under certain assumptions. Firstly, flow is assumed to be linear or one-dimensional and values representing the cross-section are used. Instead of velocity components in each cross-section point, the discharge, i.e. mean velocity, are used as values that represent the entire cross-section. Two-dimensional and three-dimensional models can be applied depending upon the phenomena analyzed. Increasing the number of dimensions of the problem rapidly extends the time required for the problem implementation and computer simulation. Therefore, the most complex models are used, especially due to the fact that hydropower calculations do not require monitoring of all effects conceivable in a storage the hydropower plant is taking water from.

Most importantly, all relevant interactions of the storage, inlet/outlet system and hydropower plant operations are to be taken into consideration. Simply speaking, electricity is generated by conversion of the potential energy of stored water and its transportation to turbines, where it is transformed into mechanical energy. Mechanical power P_m of an ideal turbine is a product of the available head h and the discharge through the turbine q, but in reality this value is lower and this is defined by efficiency η that covers all losses. As a real turbine always transforms energy with certain losses, the notion of the part of discharge not used for electricity generation is introduced. Basic parameter describing the turbine operation is efficiency. Efficiency of a turbine is dependent upon the net head and discharge that the turbine is using in its operation. A graphic form used to represent this dependency is the so-called topographic (hill) chart. Hill chart presents the curves of constant values of turbine efficiency (Vukosavić et al., 2009). Turbine performance is substantially dependent upon the characteristics of the intake system that feeds the water into the turbine; hence, the model must be also used to treat this sub-system (Vukosavić et al., 2009). Electric sub-system plays the role of converting the turbine mechanical energy into electricity and transportation of electricity to the electricity transmission and distribution system. Electric sub-system operations are defined by the physical characteristics of the unit and the limitations imposed by the external system in the form of generation demand, i.e. the current load. Implementation of relevant numerical methods allows for simulation of integral unsteady flow model with operations of the hydropower objects (Grujović et al., 2009).

3.2. General remarks on optimization algorithms in operational planning of hydropower system exploitation

As a result of the facts described above, it is clear that operational planning of the hydropower system exploitation essentially consists of finding the solution to optimization problems. Actually, this concerns the generation of hourly work plans for each unit, aimed at reaching predefined demand with observance of the physical, structural and exploitation limitations. Predefined demand can have different forms, for example, an hourly plan for each power plant or the maximum use of the hydropower potential according to defined hourly priorities.

Optimization algorithms are used for solution of optimization problems. They are based on generation and evaluation of numerous solutions. In this regard, a wide set of equations and inequalities along with logical limitations are to be observed. These problems are difficult to solve by application of classical models (gradient methods, dynamic programming methods etc.). A newly proposed approach is the solution using the adaptive genetic algorithms controlled by a fuzzy-logic controller. Selection of the evaluation method, improved by the fuzzy controller, provides expendability and capacity to adapt and improve without changing the main algorithm.

All optimization models relay on same evaluation mechanisms (Liyong et al., 2006). Definition of operation mode is based on the same procedure: defining the objective function (defining the form of function, weighting coefficients etc.), defining the control variables (selection of the coding method), defining the algorithms (basic steps of the algorithm, stopping criteria etc.), (Vose, 1999).

3.3. Implementation of the predefined plan with observance of limitations

In general, implementation of the predefined plan results in system operations with deviations from the plan to certain extent. Should the deviations occurring due to the conditions of electricity distribution be excluded, often a correction will be needed in order to meet the existing limitations. Having in mind the operational limitations of the subject electricity generation and transmission system, which are various in their nature and often interconnected time-wise and space-wise, the task of implementing the predefined plan with observance of limitations can be treated in a similar manner as the optimization problems. Since the simulation of system operation is performed simultaneously for all objects, their reciprocal impact and impact on the values covered by limitations is stressed out. Furthermore, certain limitations (for example, the minimum and maximum water level) can emerge within a certain simulation step, while a certain number of limitations (mean daily, short-term minimum and maximum values) refer to the entire simulation period. Conclusion from the above is that the process of control and meeting the limitations cannot be performed at the level of a single step, but only at the level of the entire subject period. Also, certain deviations from limitations can occur as displaced in time, relative to their cause, wherein the interval between the cause and consequence is not unambiguously set itself, but is dependent upon many other parameters in the system, as well as the realization of simulation.

Definition of the objective function. The objective function is supposed to describe the solution quality in terms of the lowest possible difference from the proposed hourly generation plan. Also, in case of unavoidable water spilling, minimization of spilled energy is something to strive for:

$$\min\left\{\alpha_1\sum_{j=1}^{m}\sum_{i=1}^{n}\left|P_{real_{i,j}}-P_{dem_{i,j}}\right|+\alpha_2\sum_{t=1}^{a}\sum_{s=1}^{b}p_{t,s}\right\} \tag{1}$$

wherein

- $P_{dem_{i,j}}$ - demanded power in step i,
- $P_{real_{i,j}}$ - electricity generated in step i,
- $p_{t,s}$ - spilling on dam profile s in step t,
- α_i - weighting coefficient.

Function factor $\alpha_1\sum_{j=1}^{m}\sum_{i=1}^{n}\left|P_{real_{i,j}}-P_{dem_{i,j}}\right|$ indicates the difference from the proposed hourly generation plan and its minimization reduces the deviation from the proposed plan. Weighting coefficient α_1 favors (or reduces the importance) of difference from the proposed plan relative to other two factors. The second factor of the function $\alpha_2 \sum_{t=1}^{a} \sum_{s=1}^{b} p_{t,s}$ impacts the quality of proposed solution in terms of overflow minimization.

For the purpose of improvement of algorithm efficiency, the distortion of the limitations by solutions is also treated; hence, the proposed correction of the plan is evaluated according to the observance of the limitations, which is done by introduction of the element of the objective function $\sum_{k=3}^{q} \alpha_k \sum_{l=1}^{r} \left| g_l \left(z_k \right) \right|$. The results of evaluation of the function $g_l \left(z_k \right)$ is a numerical value that describes the number and intensity of distortion of limitation on the profile k. For the sake of controllability of algorithm convergence, to each limitation is added a special weighting coefficient. It is necessary to stress out that the solution is acceptable ONLY IF $\sum_{k=3}^{q} \alpha_k \sum_{l=1}^{r} \left| g_l \left(z_k \right) \right| = 0$, because, in that case there will be no distortion of the system limitations. However, even though the objective of the procedure is to meet all limitations, introduction of this factor is a way to perform evaluation of the solutions that are distorting some of the limitations, but in a manner which in the next step allows for favoring of proposed correction that is closer to meeting the present system limitations.

Defining the weighting coefficients. Weighting coefficients α_i provide for prioritization of certain appropriateness function elements and, by virtue of that, setting of the “family” of goals. Weighting coefficient α_1 favors (or reduces the importance) of deviations from the proposed plan. Weighting coefficient α_2 favors (or reduces the importance) of minimization of spilling that results from the need to meet the limitations. For the purpose of control of algorithm convergence, each limitation is assigned with a special weighting coefficient in the additional internal element of the function.

Defining the control variables. Management is performed at the hourly level. During this period the power plant is operating in the regime of corrected generation plan.

Defining the algorithm. Initial simulation is exercised in the first step of the optimization process with preset hourly generation plan. If needed, the process can be repeated several times, but this time with variations, in order to generate the initial set of solutions that make the initial population.

The next step is rough testing of the solution validity with elimination of unacceptable (inapplicable) solutions; hence, there is no need to perform simulation of the full period. This is the way to save time and narrow down the population before performing genetic operations.

After the elimination of unacceptable or illogical options has been completed, the next step is the evaluation of remaining solutions through the fitness function, which is created only after the simulation according to the scenario defined by the gene for each gene variant is performed.

In case of reaching the optimum scenario or meeting the requirement of the maximum number of iterations, time limitations etc., the optimization process is finally completed. The result of the process is one or more genes which in reality represent the corrected hourly generation plans of the units of the plant.

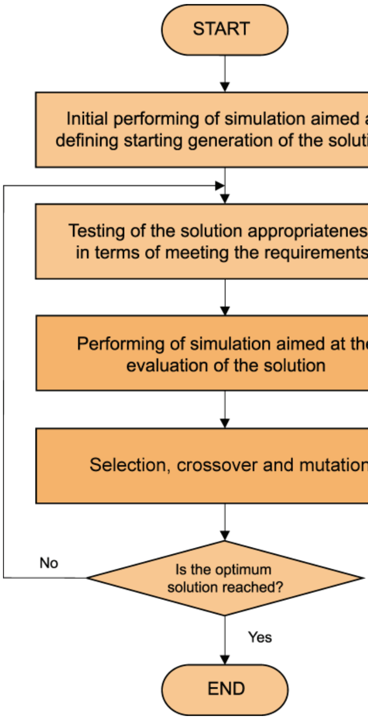


Fig. 3. Modification of the hourly generation plan aimed at meeting limitations

3.4. Defining the optimum operation aimed at maximum utilization of hydropower potential according to preset hourly priorities

In this mode optimization software should also provide for selection of the optimum operation of objects in the system, for the purpose of the maximum utilization of the hydropower potential according to the production priorities.

Defining the objective function. Objective function should describe the quality of the solution according to whether the generation is the optimum one in terms of the hourly priorities. The plan of priorities is defined for two separate systems (Serbian and Romanian sides) in table form by defining the preference through the level of priority instead of through the weighting coefficient for each hour.

The level of priority is expressed by an integer value. In general case, it can have values between 1 and 24, according to the 24-hour discretization. The starting point for this procedure is the fact that the criteria to be firstly met are the limitations; hence, they are designated as the highest priorities.

Weighting coefficients method used to solve the problem is the most frequently used method of multi-criteria optimization. According to this method, weighting coefficients w_i are introduced for all criteria functions $f_i^*, i = 1,\dots,n$; hence, the problem of vector optimization is reduced to the following scalar optimization: $\max \sum_{i=1}^{24} w_i P_i \Delta t$, wherein $P_i \Delta t$ is generated electricity E in the time interval Δt (1 hour) for n=24 hours of operation.

The price can be designated as the value of the weighting coefficient, which is basically most frequently directly proportional to the generation priority. With observance of the condition $w_i \geq 0$, norm can be introduced when $\sum_{i=1}^{n} w_i = 1$.

Criteria functions are defined through the difference between the realized power P_i and the maximum available power of the power plant $P_i^{\max}$ for the given time interval (available power is dependent on the system conditions, water level and discharge):

$$f_i^* = w_i \left(P_i^{\max} - P_i \right) \tag{2}$$

By adopting 1 as the highest priority and, further, 2, 3... as the indexes of declining priorities and by adopting that the respective values of weighting coefficients belong to the geometric progression, it can be written:

$$\begin{aligned} &\frac{w_1}{w_2} = \frac{w_2}{w_3} = \ldots = \frac{w_{n-1}}{w_n} = b \\ &w_1 = w_n b^{n-1} \\ &\sum_{i=1}^{n} w_i = w_n \frac{b^n - 1}{b - 1} \end{aligned} \tag{3}$$

By adopting that the last sum is equal to 1 and $b = 2$ the result is:

$$w_n = \frac{1}{2^n - 1} \tag{4}$$

In case of only two levels of priorities (n=2), the obtained values are $w_1 = 0.67, w_2 = 0.33$. The values of parameters b and n can easily be changed in the program.

The form of the objective function for generation optimization in terms of preset hourly priorities is as follows:

$$\max \left\{ \sum_{j=1}^{m} \sum_{i=1}^{n} w_{i,j} P_{ost_{i,j}} \right\} \tag{5}$$

wherein:

- $w_{i,j}$ - priority on the power plant j in the step i,
- $P_{real_{i,j}}$ - realized power on power plant object j in the step i.

Present objective function describes the quality of the solution in terms of whether the generation is the optimum one according to hourly priorities. For the purpose of improvement of algorithm efficiency, the solutions that violate the limitations are also treated; hence, the proposed plan is to be evaluated relative to observance of limitations, by internally adding the element to the objective function $\sum_{k=1}^{q} \alpha_k \sum_{l=1}^{r} \left| g_l \left(z_k \right) \right|$. The result of evaluation of the function $g_l \left(z_k \right)$ is a numerical value that describes the number and intensity of violation of limitation l on profile k. For reasons of manageability of algorithm convergence, to each limitation is added a special weighting coefficient.

Solution is acceptable ONLY IF $\sum_{k=1}^{q}\alpha_k\sum_{l=1}^{r}\left|g_l\left(z_k\right)\right|=0$, because, in that case, no violation of the system limitations exists. However, even though the main goal of the procedure is to meet the limitations, the introduction of this factor is providing for the evaluation of the solutions that violate certain limitation. This is performed in a way that in the next step allows for favoring of the proposed plan, which is closer to meeting the predefined limitations of the system. The second internal factor of the target function $\alpha_{k+1}\sum_{t=1}^{a}\sum_{s=1}^{b}p_{t,s}$ affects the quality of the proposed solution in terms of spilling minimization. Weighting coefficients α_i provide for favoring certain internal elements of appropriateness function.

Defining the control variables. This control is performed at the level of one hour, during which a power plant object is engaged according to the proposed generation and units are committed according to the minimum water consumption.

Defining the algorithm. In contrast to the previous algorithm, in this case there is no “rough” testing of acceptable solutions, i.e. only the correction of the required spilling is performed.

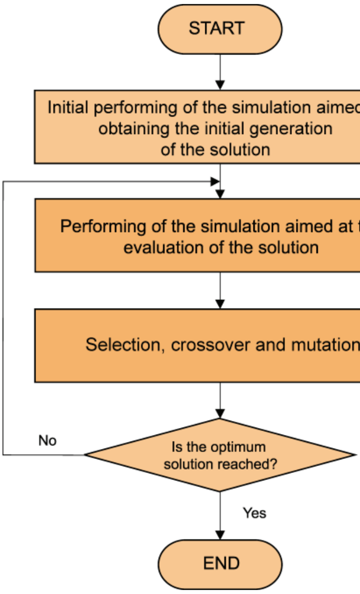


Fig. 4. Algorithm of the optimum operation aimed at reaching the maximum utilization of the hydropower potential according to hourly priorities

Since the generation hourly priorities are defined, the initial simulation is performed once or several times, as needed, in the first step of the optimization process, when the power plant operates in the regime with the preset approximate power plant generation plan, with the optimum unit commitment. If needed, this process can be repeated, but with variations in order to generate the initial set of solutions that make the initial population.

The next step is evaluation of the solution through the fitness function which is created only after the simulation according to the scenario defined by the gene for each individual gene is performed.

In case of reaching the optimum solution or meeting the requirement of the maximum number of iterations, time limitations etc., the optimization process is finally completed. Result of the process is one or more genes which represent the optimum hourly operation plan.

3.5. Adaptive genetic algorithms managed by the fuzzy-logic controllers

Being that the canonic form of genetic algorithms does not have the mechanisms needed for introduction of expert knowledge in order to improve the optimization process, many efforts were made to combine genetic algorithms with other artificial intelligence methods. One of the solutions is the use of fuzzy-logic (Baker, 1985; Herrera and Lozano, 1997; Sanchez et al., 1996). As a way to solve the subject problem, it was proposed to apply the fuzzy-logic controller to control the genetic algorithm parameters (Herrera and Lozano, 1996a). Fuzzy-logic controller is an efficient way to apply expert knowledge to the problem to be optimized. Fuzzy-logic controllers are used in two ways to solve the problem of system optimization (Herrera and Lozano, 1996b).

The first way is improvement of the genetic algorithm performance in order to eliminate divergence, as well as to avoid their premature convergence (Arnone et al., 1994, Bergmann et al., 1994; Herrera and Lozano, 1996a, 1996b; Lee and Takagi, 1993, 1994). The premature convergence is the feature of the optimization method such that the solution converges to the local instead of the global minimum, which is solved with genetic algorithms as described in the above mentioned literature.

The second approach introduces the expert knowledge into the initial population generation, evaluation, additional gene modification and adaptation of genetic operators (Meyer and Feng, 1994; Cordón et al., 2007). Expert knowledge base is extendable and, as such, it is a unit that is to be improved in time based on previous experience and experience acquired through the utilization of the software package.

3.5.1. Description of the fuzzy-logic controller structure

Fuzzy-logic controller concept is presented in Figure 5, with its basic components: the knowledge base, decision-making block, fuzzification block, de-fuzzification block and subject of control.

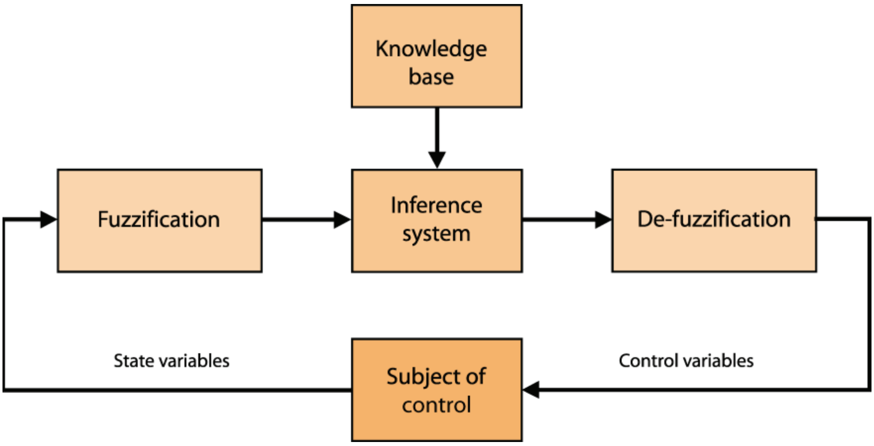


Fig. 5. Fuzzy-logic controller concept

Knowledge base is a set of rules given in the linguistic form: fuzzification block (transforming the input values into the fuzzy sets), decisions-making block (which uses fuzzified input values and knowledge base rules to make decisions and generate fuzzy control) and, finally, de-fuzzification block (which transforms fuzzy control into the actual control values). In case of adaptive genetic algorithms the system to be controlled is the genetic optimization process itself.

The most important element of the controller is the knowledge base because the other blocks were already determined by the existing theory and tested in practice. Knowledge base is used to code the expert knowledge as the set of “if-the-level-is-close-to-the-maximum-increase-discharge"-type rules. Hence, the first part of the knowledge base is the set of these fuzzy rules. The second part of the base is the set of membership functions used to define in quantitative terms the notions of “close”, “high”, “fast” etc., as constant functions which are assigned by ranges of values with the fuzzy terms. These functions are used in the process of fuzzification and de-fuzzification.

3.5.2. Fuzzy –logic controller used in control of adaptive genetic algorithms

The principal idea of fuzzy-logic controller use in control of adaptive genetic algorithms is to use available measurable performances of the genetic algorithms as the input in the controller, along with the algorithm parameters (degree of mutation, crossover type, crossover parameters, population size etc.), (Herrera and Lozano, 1996a, 1996b; Lee and Takagi, 1993; Cordón et al., 2007). On the other hand, the controller generates new parameters used by the genetic algorithm.

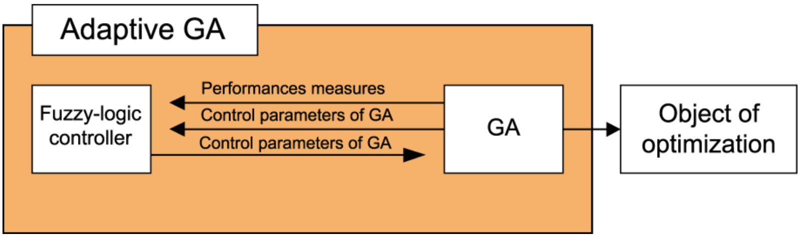


Fig. 6. Effects of the fuzzy controller on optimization parameters

A specific procedure is required to implement this system:

1. **Defining the input and output.** Inputs can be divided into those used for the improvement of the genetic algorithm performances and those used for introduction of expert knowledge into initial population generation, evaluation and gene modification. The first group of inputs includes the basic indicators of population diversity, extreme and median values etc., and even the current values of the algorithm parameters – degree of mutation, crossover, population size and similar. The second group of inputs includes data resulting from system operations, such as generation demand, violations of limitations, water levels in the system, discharges, efficiency etc. For the purpose of faster convergence additional improvements are introduced, based on these data and the expert knowledge. In the first case, the outputs are the parameters of the algorithm, while in the second case, the modification of the evaluation and selection process is performed, along with the “intelligent” modification of the gene.
2. **Defining the membership functions.** All input-output values must have the name, range of values and the defined membership function.

3. **Defining the fuzzy rules.** Finally, using the defined membership functions, it is possible to set the fuzzy rules according to the previous experience and expert knowledge.

3.5.3. Implemented adaptive genetic algorithm

The following aspects were taken into consideration in the process of designing the fuzzy-logic management of parameters of the optimization algorithm (Cordón et al., 2007):

- inputs – robust measures of genetic algorithm efficiency and the effects of the algorithm parameters: mutation probability and measure of convergence,
- outputs – values or the change of values of the control parameters of the genetic algorithm - in this case, a new probability of mutation,
- knowledge base – linguistic descriptions of inputs and outputs, usually presented through the membership functions,
- rule base – set of fuzzy rules linking the mentioned aspects.

The applied principle of genetic algorithm management defines for each 3 generations the value of mutation probability (p_m) based on its value in the previous three generations and improvement of the fitness of the best species (f_n). The set of fuzzy rules appropriate for this principle is used and this will be presented below.

The inputs selected are those that can improve diversity and extend the search space and, accordingly, reduce the possibility of premature convergence, as follows (Herrera and Lozano (1999)):

- current mutation probability, p_m^0, within the interval $[0.001, 0.01]$
- measure of convergence $CM = f_n^t / f_n^0$ wherein f_n^t the fitness of the currently best individuals, a f_n^0 the fitness of the best individuals for 2 earlier generations. Value CM can be within the interval $[0,1]$. If the value of CM is high, than the convergence is prominent and no progress occurred in the last 2 generations.

Linguistically, mutation probability p_m^0 is described as $\{low, medium, high\}$ as shown in Figure 7. For the parameter CM only $\{low, high\}$ set is used. The output is the new value of the parameter p_m, within the interval $[0.001, 0.01]$, marked as p_m^n, to be used in the next two generations. The linguistic description is also presented in Figure 7.

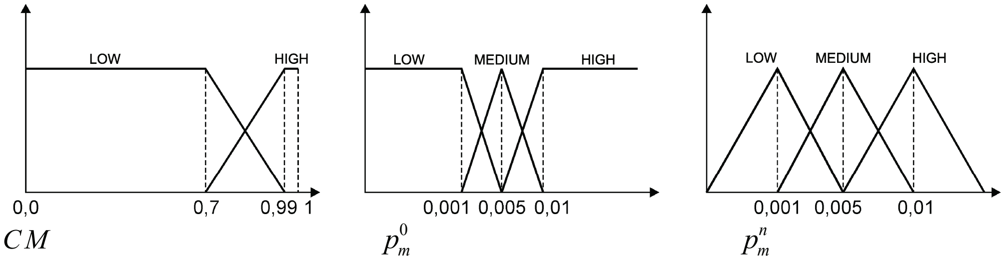


Fig. 7. Linguistic description of input and output values (Herrera and Lozano, 1999)

Fuzzy rules formed according to presented input and output values presented in Table 1.

Rule	CM	p_m^0	p_m^n
1	low	low	medium
2	low	medium	high
3	low	high	low
4	high	low	low
5	high	medium	low
6	high	high	medium

Table 1. Fuzzy rules for control of the mutation probability (Herrera and Lozano, 1999)

Rules 1, 2, 4, 5 and 6 indicate that p_m is to be reduced in case of progress, and increased in case of no progress. Rule 3 solves the special case of high values of CM and p_m^0, when high mutation probability is unproductive due to prominent convergence.

4. Application of the proposed algorithms in the management of the hydropower system of “Iron Gate 1” HPP and “Iron Gate 2” HPP

The mathematical model for hydropower calculation and management of utilization of hydropower plants “Iron Gate 1” and “Iron Gate 2” system was developed as a part of the Hydro-Information System “Iron Gate” (Divac et al., 2009). The goal of mathematical model development is the rational use of River Danube hydropower potential and fitting into the requirements of electricity generation and transmission systems of Serbia and Romania (which differ in terms of power and time) with the task to meet the set of limitations on control profile on the River Danube, defined in bilateral documents. Mathematical model provides for simulation and optimization of operation of the complex hydropower system “Iron Gate 1” and “Iron Gate 2”, aimed at defining the performance of objects, meeting the requirements of the electricity generation and transmission systems of Serbia and Romania, observing the limitations of water level and discharge on control profile and the initial conditions and boundary conditions through several variants of initial data and required results. This allows for efficient decision-making on daily basis in regard to method of exploitation.

Relevant information on water regime collected through the monitoring system is available for solving this task. A network of telelimnimeter stations that perform water level measurements on the Danube River was developed. Data on current levels is collected in real-time and archived on the computer system. Real-time measurements on “Iron Gate 1” HPP include: discharge through turbines, generators' active power, generators' reactive power, headwater level, head loss on trash-racks, tail-water level and electricity generation and the degree of spillway field opening. Real-time measurements on “Iron Gate” HPP include only measurement of electricity generation and the degree of spillway field opening.

The one-dimensional model of unsteady flow was also developed and it includes River Danube flow from the City of Novi Sad to the Timok River confluence (Grujović et al., 2009), as well as the parts of flows of the River Danube major tributaries. This model was formed in accordance with the method to be used in optimization packages.

Management of the hydropower plants “Iron Gate 1” and “Iron Gate 2” includes meeting the requirements of the electricity generation and transmission systems of Serbia and Romania, meeting the set of limitations on the control profiles on the River Danube, as well as preserving the appropriate conditions of navigation and river bank stability. System limitations include the exploitation limitations defined in the Rule Book from the year 1998 and structural limitations defined in the main design and built-state projects for “Iron Gate 1” and “Iron Gate 2” dams. Water level limitations are defined on the profiles of the Nera River confluence, headwater of “Iron Gate 1” dam, in the City of Kladovo, headwater of “Iron Gate 2” dam and the Timok River confluence, as well as the mean or extreme values of mean daily or short-term water levels. Exploitation limitations vary according to the utilization regime and the sub-system. Water level limitations for each utilization regime are presented in the form of discharge curves. Structural limitations are identical for all utilization regimes and they are presented in the form of the maximum level. In this regard, the operation of “Iron Gate 2” system is coupled with the operation of the “Iron Gate 1” system.

4.1. Example of the generation plan according to the hourly priorities

One of the problems to be solved is the case when no hourly generation plan has been defined. Hourly priorities are set instead of the hourly generation plan, as to favor certain daily periods. The plan of priorities is set both for the Serbian and Romanian sides of the system in the form of two series that define the priority degrees by hour. The use of this mode is aimed at identifying the hourly plan for unit commitment in line with the preset hourly priorities preventing, on one side, violation of the limitations and maximizing the generation, on the other.

As a demonstration of how the optimum production plans is generated according to the hourly priorities, a practical situation from September 8th, 2006 is presented here. Since hourly priorities are set instead of hourly generation, by favoring the certain periods of day, the demand of a real scenario presented in Figure 8 is created.

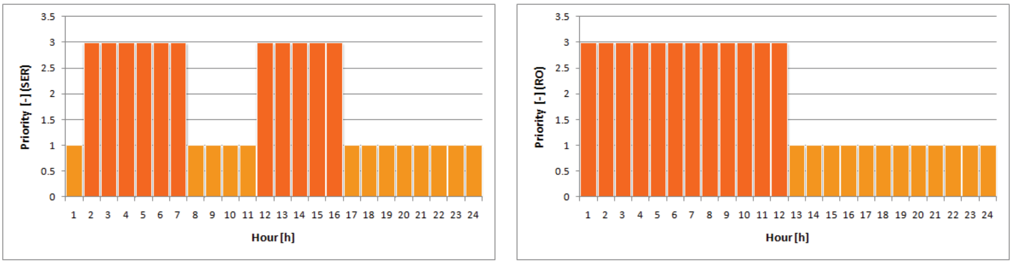


Fig. 8. Proposed hourly generation priorities on “Iron Gate 1” HPP on September, 8th, 2006

As this is the period with a small river water level, i.e. a low inflow in the storage and a high water level in the storage, the most important limitation in this case in practice is the behavior of the water level at the Nera River confluence (profile “Ram"). On one hand, it is possible to reach a rather “dynamic” reaction, but the minimum mean water level at Ram must not be jeopardized, along with water level oscillations in the downstream system, especially for the reasons of navigability and effects on the Timok River confluence and further downstream flow. Figure 9 presents the implemented historical plan and the plan proposed by the optimization module on the basis of priorities.

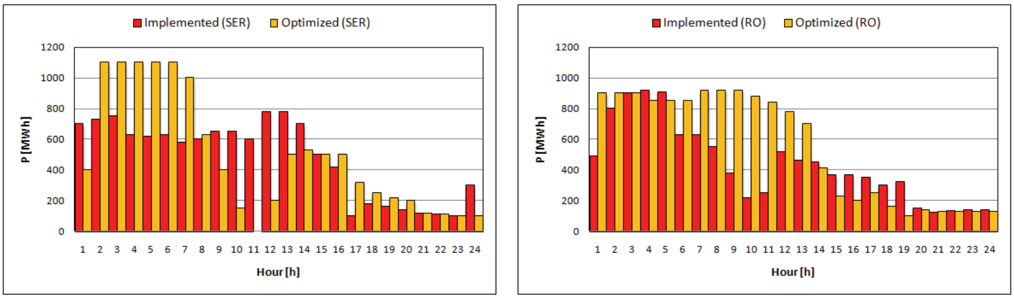


Fig. 9. Implemented and optimized production of "Iron Gate 1" HPP on September 8th, 2006

Firstly, one can identify the outstanding dynamics of the proposed plan, i.e. the major differences in generation in priority periods as compared to the historical (implemented) plan. Figure 10 also indicates the growth of the total generation by 12.5%. Here, there is a double effect: generation growth and its placement during the favorable periods. At the same time, no applicable system limitation was violated.

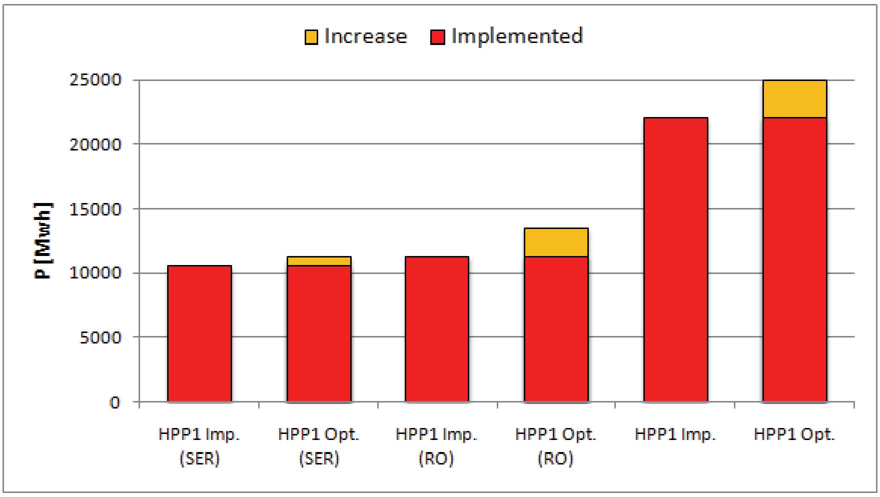
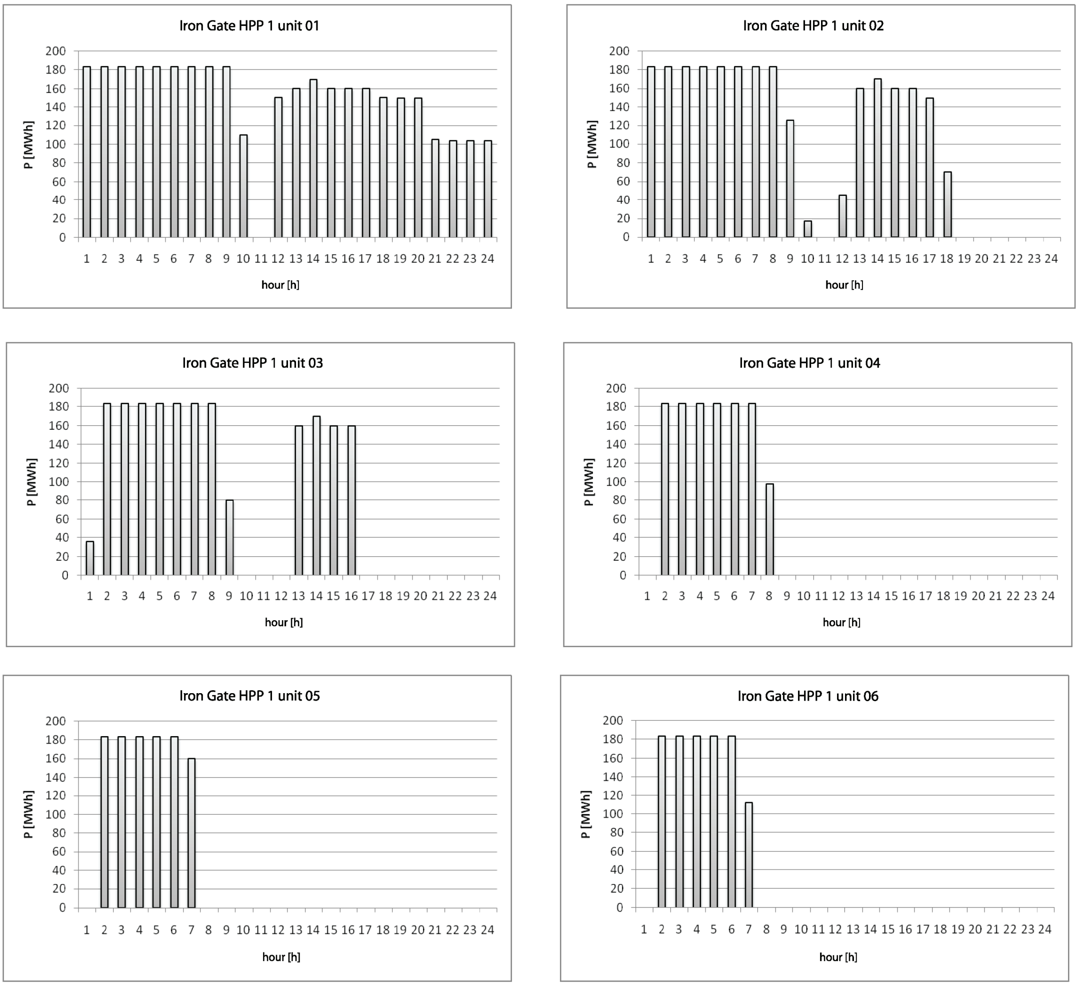


Fig. 10. Historically implemented and proposed system generation

Following figures present the individual plans of unit commitment that are actually a result of the algorithm applied for selection of the committed units performed within each step with predefined targeted generation for "Iron Gate 1" HPP (Serbian part, the system of first 6 units).



Iron Gate HPP 1 unit 01

Iron Gate HPP 1 unit 02

Iron Gate HPP 1 unit 03

Iron Gate HPP 1 unit 04

Iron Gate HPP 1 unit 05

Iron Gate HPP 1 unit 06

Fig. 11. Commitment of “Iron Gate 1” HPP units (Serbian part)

Following figures present the individual plans of units commitment that are actually a result of the algorithm applied for selection of the committed units performed within each step with predefined targeted generation of “Iron Gate 1” HPP (Romanian part, the system of second 6 units).

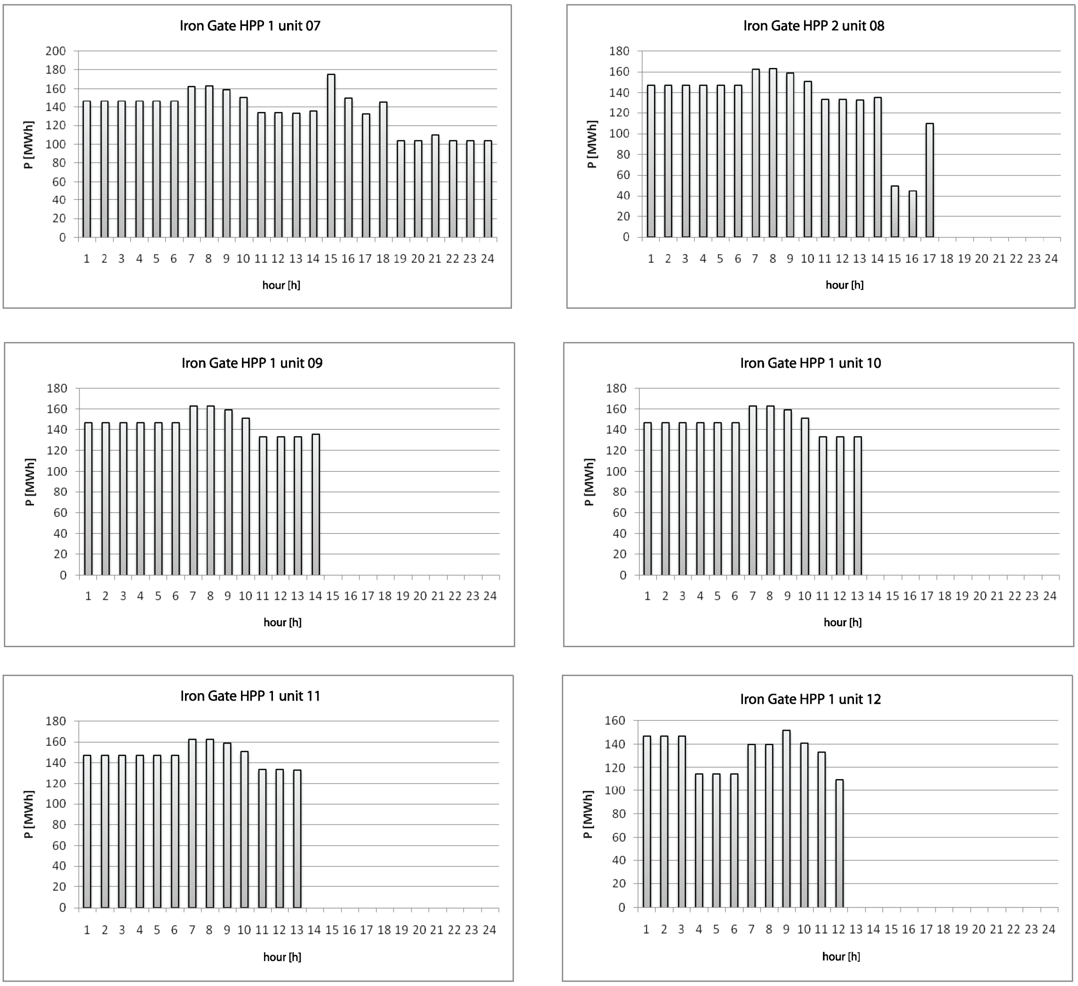


Fig. 12. Commitment of "Iron Gate 1" HPP units (Romanian part)

The commitment of units, which is defined in each step, results in a unit load that is more correct than the actual load in practice, as presented in Figures 11 and 12. In reality, exploitation conditions and generation placement are dictated by the externalities which do not have a clearly determined form. As a result, the dispatchers in their everyday work face a situation when they are forced to abandon the solution that is the optimum one from the aspect of the local system.

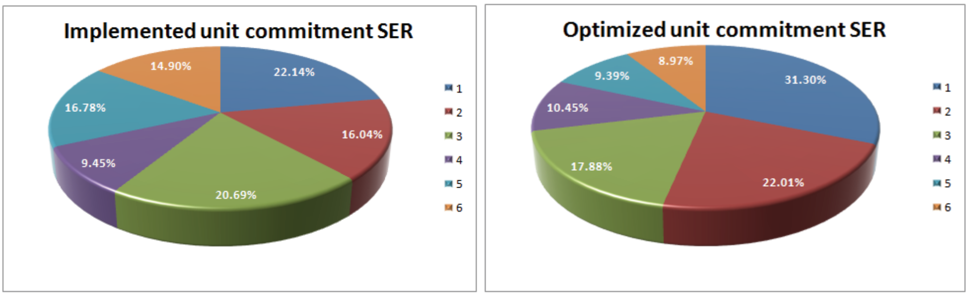


Fig. 13. "Iron Gate 1" HPP – Serbian units' load in percentages

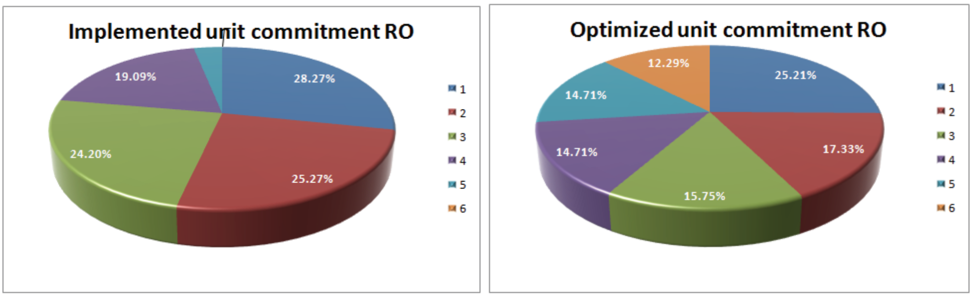


Fig. 14. "Iron Gate 1" HPP – Romanian units' load in percentages

4.2. Effect of the fuzzy-logic controller on the algorithm convergence

In order to understand the effect of the fuzzy controller on algorithm convergence, it is necessary to perform the comparison with the canonical form of the GA (the canonical form is a genetic algorithm as defined by the original definition given in (Holland, 1975)). Figure 15 presents the evolution of two optimization algorithms. Blue line denotes the canonical genetic algorithms and the red line the evolution of the algorithm in case of fuzzy-logic controller implementation, which was defined in the previous chapter. One can notice from this particular example that the solution with the same quality was reached by the genetic algorithms after 40 generations, while it took more than 10 generations to get the same solution using the adaptive genetic algorithm.

Convergence speed is of essential significance for operational use of the system, because the time need to design the optimum work plan is limited. Use of the fuzzy-logic controller has significantly improved the characteristics of the GA and facilitated identification of the satisfactory solution with fewer steps. An additional method that can be used to accelerate the procedure of defining the optimum plan is the parallelization of the GA. This method is very efficient, due to the fact that the evaluation of factors (usually time as the most demanding part of the algorithm) can be performed in parallel.

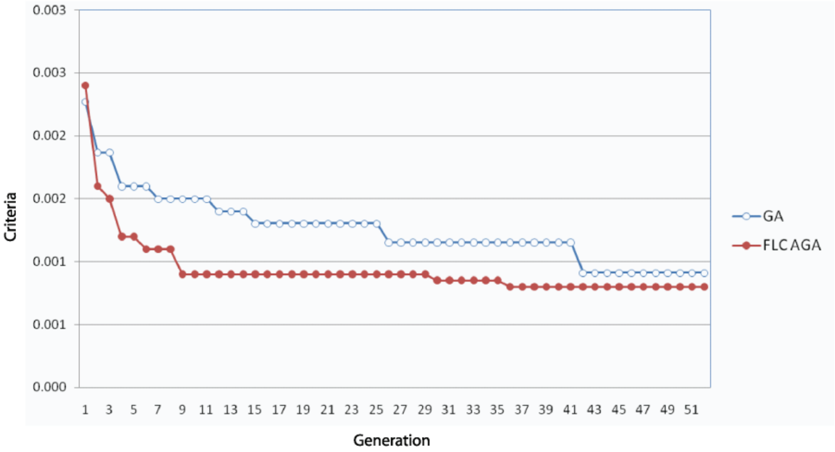


Fig. 15. Convergence of canonical (GA) and adaptive genetic algorithms managed by fuzzy-logic controller (FLCAGA)

5. Conclusions

Important aspects of the proposed approach can be singled out as the conclusions. Planning in the industry of electricity generation is one of the most important aspects of water resources management. This is a consequence of not only the nature of the problems in this area (which are clearly structured, but also demanding and connected with the cost minimization), but also of the support to decision-making and data availability.

Having in mind the trend of growing competitiveness in the electricity generation market, planning models and methodologies must be adapted to face the broader spectrum of objectives, which are not only strategic, but financial and social, too. That is how indefiniteness and risk become dominant, partially due to effects of competitiveness and, partially, due to the nature of market and legal framework. As a result of growing competitiveness, error probability grows.

Consequence of the described environment is that the models become less definite, the analyses of possible scenarios more frequent and, most importantly, the manager, management bodies and annalists take part in their development. In order to transform the rigid traditional ways of planning and management in hydropower objects into dynamic processes, advance information technologies must be applied. The fact that today it is possible to develop models facilitating full interaction between the management and technical approach to system management is of utmost importance because this is the way to further involve management in the process of identification of the optimum solution.

Since it is not possible to define the universal solution for problems of the optimum management of hydropower objects applicable in all cases, each proposed methodology will have to be adapted to the specific class of problems. Proposed methodology concerns a specific class of problems in major hydropower systems and the optimum management based on requirements resulting from the integrated power system operation.

Judging by the presented results, the conclusion is that the application of computer-aided optimization in operation planning of exploitation contributes to a more efficient management of complex hydropower systems in terms of profit growth (placement of production in favorable periods) and better utilization of hydropower potential (correct commitment of units).

Considering the fact that the existing operation planning is based on application of rules and procedures and major impact of dispatcher's subjective assessment, it is quite clear that application of the methodology will facilitate and improve decision-making in a management of the given system. Implementation of presented basic models in existing hardware platforms results in plan proposals at the level close to the operational. However, for the purpose of reaching full operational use (timely preparation of the power generation plan, at any given moment) the performance of genetic algorithms was improved through the application of fuzzy-logic controllers for algorithm parameters adaptation.

Proposed adaptive genetic algorithms managed by fuzzy-logic controller were used to improve the genetic algorithm performance for the purpose of elimination of divergence of the numerical solution, as well as to avoid premature convergence. Further researches will focus on defining of efficient procedures of controller self-tuning depending on the given problem, i.e. specific features of the process, as well as on parallelization of the algorithm. In addition, the method of introduction of expert knowledge into the generation of initial population, evaluation, additional gene modification and adaptation of genetic operator will be also defined.

References

Arce A, Ohishi T, Soares S (2002), Optimal dispatch of generating units of the Itaip´u Hydroelectric Plant, IEEE Trans. Power Syst. 17, February, 2002.

Arnone S, Dell'Orto M, Tettamanzi A (1994), Toward a fuzzy government of genetic populations, 6th IEEE Conference on Tools with Artificial Intelligence. Los AlamitosCA: IEEE Computer Socity Press, 1994. pp. 585-591.

Baker JE (1985), Adaptive Selection methods for genetic algorithms. Hillsdale, MA: First Int. Conf. on Genetic Algorithms, 1985.

Baldick R (1995), The generalized unit commitment problem, IEEE Trans Power Syst 10. pp. 465-475.

Baptistella LFB and Geromel JC (1980), Decomposition approach to problem of unit commitment schedule for hydrothermal systems, IEEE Proceedings D, 1980. pp. 250-258. No. 6. Vol. 127.

Barr E, Figenbaum A (1982), The Handbook of Artificial Intelligence, London: Vitman.

Batut J, Renaud A (1992). Daily generation scheduling optimization with transmission constraints: a new class of algorithms, IEEE Trans Power Syst 7.

Bellman RE, Dreyfus SE (1962), Applied dynamic programming. New Jersey: Princeton University Press, 1962. pp. 4-16.

Bergmann A, Burgard W, Hemker A (1994), Adjusting parameters of genetic algorithms by fuzzy control rules. Singapore: World Scientific Press, 1994.

Booch G (1991), Object-Oriented Design, Menlo Park, CA: Cummings, 1991.

Booch G (1994), Object-Oriented Analysis and Design, Menlo Park, CA: Cummings, 1994.

Chen CL, Wang SC (1993), Branch-and-bound scheduling for thermal generating units, IEEE Trans. Energy Convers. 8, 1993. pp. 184- 189.

Cohen AI, Sherkat VR (1987), Optimization based methods for operations scheduling, Proceedings of the IEEE, 1987. pp. 1574-1591. No. 12. Vol. 75.

Cordón O, Alcalá R, Alcalá-Fdez J, Rojas I (2007), Special Issue on Genetic Fuzzy Systems. What's Next. IEEE Transactions on Fuzzy Systems, 2007. Vol. 15.

Coulouris G, Dollimore J, Kindberg T (1994), Distributed Systems: Concepts and Design. Addison-Wesley.

Divac D, Grujović N, Milivojević N, Stojanović Z, Simić Z (2009), Hydro-Information Systems and Management of Hydropower Resources in Serbia, *Journal of the Serbian Society for Computational Mechanics*, Vol. 3, No. 1

Duckstein L, Tecle A (1993), Multiobjective analysis in water resources, Part II: a new typology of MCDM techniques. In Stochastic Hydrology, Water Resources Systems Simulation and Optimization. London: Kluwer Academic Publishers, 1993. pp. 333-343.

Feltenmark S (1997), On optimization of power production, Doctoral Thesis, Royal Institute of Technology. Stockholm, Sweden: Department of Mathematics, 1997.

Fujimoto M R (2000), Parallel and Distributed Simulation Systems. Wiley Interscience.

Grujović N, Divac D, Stojanović B, Stojanović Z, Milivojević N (2009), Modeling of One-Dimensional Unsteady Open Channel Flows in Interaction with Reservoirs, Dams and Hydropower Plant Objects. *Journal of the Serbian Society for Computational Mechanics*, Vol. 3, No. 1

Guan X, Svoboda A, Li CA (1999), Scheduling hydro power systems with restricted operating zones and discharges ramping constraints, IEEE Trans. Power Syst. 14, February, 1999.

Habibollahzadeh H, Bubenko JA (1986), Application of decomposition techniques to short-term operation planning of hydrothermal power system, IEEE Trans. on Power Systems, 1986. pp. 41-47. No. 1. Vol. 1.

Herrera F and Lozano M (1996a), Adaptation of genetic algorithm parameters based on fuzzy-logic controllers. Genetic Algorithms and Soft Computing, 1996. pp. 95-125.

Herrera F and Lozano M (1996b), Adaptive Genetic Algorithms Based on Fuzzy Techniques. Granada, Spain: Proc. Of IPMU'96, 1996. pp. 775-780.

Herrera JE and Lozano M (1997), Fuzzy Connectives based crossover operators to model genetic algorithms population diversity. Fuzzy Sets and Systems, 1997. pp 31-30.

Herrera F and Lozano M (1999), Fuzzy genetic algorithms: issues and models, Technical Report No. 18071. Granada, Spain: 1999.

Holland JH (1975), Adaptation in Natural and Artificial Systems, *Ann Arbor: University of Michigan Press*.

IEEE Committee Report (1992), Hydraulic Turbine and Turbine Control Models for System Dynamic Studies, IEEE Transaction on Power Systems, vol. 7, no. 1, pp. 167-179, Febr. 1992.

Kazarlis SA, Bakirtzis AG, Petridis V (1996), “A genetic algorithm solution to the unit commitment problem,” IEEE Trans. on Power Systems, 1996. pp. 83-90. No. 1. Vol. 11.

Labadie JW (2004), Optimal operation of multireservoir systems: state-of-the-art review, Journal of Water Resources Planning and Management, 2004. pp. 93-111.

Lai S, Baldick R (1999), Unit commitment with ramp multipliers. IEEE Trans. Power Syst. 14, February, 1999.

Lee MA, Takagi H (1993), Dynamic control of genetic algorithms using fuzzy logic techniques. San Mateo: Morgan Kaufmann, 1993. pp. 76-83.

Lee MA, Takagi H (1994), A framework for studying the effects of dynamic crossover, mutation, and population sizing in genetic algorithms. Berlin: Springer-Verlag, 1994. pp. 111-126.

Li CA, Svoboda A, Tseng CL, Johnson RB (1997), Hydro unit commitment in hydro-thermal optimization. IEEE Trans. Power Syst. 12, May, 1997

Liyong S, Yan Z, Chuanwen J (2006), A matrix real-coded genetic algorithm to the unit commitment problem, Electric Power Systems Research, 2006. No. 9-10. Vol. 76.

Ma H, Shahidehpour SM (1998), Transmission-constrained unit commitment based on Benders decomposition, International Journal of Electrical Power and Energy Systems, 1998. pp. 287-294. No. 4. Vol. 20.

Meyer L, Feng X (1994), A fuzzy stop criterion for genetic algorithms using performance esimation. Third IEEE Int. Conf. of Fuzzy Systems, 1994. pp. 1990-1995.

Morozowski MF, Carlos M, Cardozo F (1997), A System Dynamics Based Strategic Planning Model for Hydroelectric System, 15th International System Dynamics Conference. Istambul, Turkey.

Morozowski MF, Carlos M, Cardozo F (1998), Hydrosystem Operation in Competitive Market: A System Dynamic Approach, 16th International Conference of the System Dynamic Society. Quebec, Canada.

Orero SO and Irving MR (1998), A genetic algorithm modeling framework and solution technique for short term optimal hydrothermal scheduling, IEEE Trans. on Power Systems, 1998. pp. 501-516. No. 2. Vol. 13.

Sanchez, Shibata E, Zadeh LA (1996), Genetic Algorithms and Fuzzy Logic Systems. Soft Computing Perspectives. World Scientific, 1996.

Sheble GB, Fahd GN (1994), Unit commitment literature synopsis, IEEE Trans. Power Syst. 9, February, 1994.

Snyder WL, Powell HD, Rayburn JC (1987), Dynamic programming approach to unit commitment, IEEE Trans. on Power Systems, 1987. pp. 339-351. No. 2. Vol. 2.

Svoboda AJ, Tseng CL, Li CA, Johnson RB (1997), Short-term resource scheduling with ramp constraints, IEEE Trans. Power Syst. 12, February, 1997.

Tseng CL (1996), On power system generation unit commitment problems, Doctoral Thesis, Engineering-Industrial and Operations Research. Berkeley: University of California, 1996.

Turgeon A (1978), Optimal scheduling of thermal generating units, IEEE Trans. on Automatic Control, 1978 pp. 1000-1005. No. 6. Vol. 23.

Viana A, de Sousa JP, Matos M (2002), A new metaheuristic approach to the unit commitment problem, 14th Power Systems Computation Conference. Sevilla, Spain: 2002.

Vose MD (1999), The Simple Genetic Algorithm: Foundations and Theory, MIT Press, Cambridge, MA.

Vukosavić D, Divac D, Stojanović Z, Stojanović B, Vučković D (2009), Several Hydropower Production Management Algorithms. *Journal of the Serbian Society for Computational Mechanics*, Vol. 3, No. 1

Wood AJ and Wollenberg BF (1996), Power generation, operation, and control. New York. Wiley.

Xiaomin B, Shahidehpour SM, Erkeng Y (1996), Constrained unit commitment by using tabu search algorithm, in Proc. Int Conf. on Electrical Engineering, 1996. pp. 1088-1092. Vol. 2.

Zhang D, Wang Y, Luh PB (2000), Optimization based bidding strategies in the deregulated market, IEEE Trans Power Syst 15.

Zhuang F and Galiana FD (1990), Unit Commitment by Simulated Annealing, IEEE Trans. on Power Systems, 1990. pp. 311-317. No. 1. Vol. 5.