ISSN 1330-3651
UDC/UDK 621.311.21:[519.863: 658.58

HYDRO GENERATING UNITS MAINTENANCE SCHEDULING USING BENDERS DECOMPOSITION

Igor Kuzle, Hrvoje Pandžić, Miljenko Brezovec

Original scientific paper

Maintenance of the power generating facilities in due time is essential for reliable and secure operation of the electric power system. In liberalized electricity market the economical aspects, pointed to the greatest possible revenue, have to be satisfied. On the other hand, technical aspects, which keep the power system above the desired level of safety and reliability, i.e. which are opposed to economical aspects, have to be satisfied as well. Therefore, these two opponent standpoints have to be confronted in order to provide optimal solution which will comply with the strict technical limitations, and which will meet investor's economical requirements. This paper addresses the problem of obtaining the optimal maintenance schedule of hydro generating units. For this purpose, the paper discusses the mathematical programming method – Benders decomposition. After a brief description of the mathematical method, the application of the Benders decomposition on three Croatian hydroelectric power plants in a cascade on the Drava River is carried out.

Keywords: *Benders decomposition, hydro generating units maintenance, maintenance scheduling, mathematical programming, optimization*

Određivanje rasporeda održavanja hidrogeneratora korištenjem Bendersove dekompozicije

Izvorni znanstveni članak

Pravovremeno održavanje proizvodnih postrojenja od iznimne je važnosti za pouzdan i siguran pogon elektroenergetskog sustava. U uvjetima liberaliziranog tržišta električne energije ekonomski aspekti, orijentirani na najveću moguću dobit, moraju biti zadovoljeni. S druge strane, i tehnički aspekti, kojima je cilj održati elektroenergetski sustav iznad željenih granica sigurnosti i pouzdanosti, odnosno koji su protivni ekonomskim ciljevima, također moraju biti zadovoljeni. Stoga se dva suprotna gledišta sukobljavaju u svrhu pronalaska optimalnog rješenja koje će zadovoljiti sve tehničke kriterije i investitora u ekonomskom pogledu. U radu se obrađuje problem pronalaženja optimalnog rasporeda održavanja hidrogeneratora. U tu svrhu se koristi metoda matematičkog programiranja – Bendersova dekompozicija. Nakon kratkog opisa matematičke metode, iznesena je primjena Bendersove dekompozicije na tri hrvatske hidroelektrane u nizu na rijeci Dravi.

Ključne riječi: *Bendersova dekompozicija, matematičko programiranje, određivanje rasporeda održavanja, održavanje hidroagregata, optimizacija*

1 Introduction
Uvod

Preventive generating units maintenance scheduling is among the most vital decisions which electricity generating companies have to make. Effective generating units maintenance helps reduce the forced outage rates. Therefore, rigorous technical restrictions have to be respected by all means. Since the economical factor, i.e. profit generation, was not the prime driver in investments, the maintenance in vertically integrated power systems was carried out thoroughly and most of the elements of the power system were over-dimensioned. These proper maintenance procedures resulted in extremely rare failures in the vertically integrated power system operation. After the implementation of the electricity market, economic drive grew stronger and private companies wanted to avoid any unnecessary investments in order to increase their profit margin.

The maintenance enforcement expenses have two aspects. The first one is the cost of the maintenance itself, which includes the newly installed components, specialized teams hiring, etc. The other part of the expenses is the missed income due to undelivered electricity. Therefore, the maintenance has to be performed in the shortest period possible. Other factors, such as electricity and fuel prices also have to be taken into consideration. Since the hydro power plant's owners do not have to buy fuel, their objective is to predict the water inflows and schedule the maintenance in low river inflow period.

2 Maintenance in the restructured power system
Održavanje restrukturiranog elektroenergetskog sustava

Maintenance optimization of the independent subjects can generally be solved centrally by mathematical modeling. However, in the competitive environment subjects are not independent and many restrictions affect the creation of preventive maintenance programs. These restrictions are the outcome of system stability and spinning reserves criteria issued by the Transmission System Operator (TSO) or Distribution System Operator (DSO). Other restrictions may include maintenance crew availability, overhead lines or substation outage, consumption demands, etc.

There are three basic fundamentals of the restructured power system: availability, reliability and economy.

2.1 Availability
Raspoloživost

Availability, which is defined as the number of operating hours of the facility divided by the overall number of hours in the specific time period, is gaining significance in liberalized electricity market because of the bilateral contracts between the generating companies and the marketers [1]. Therefore, if the generating company, due to forced outage, breaks the existing contract, it has to pay acute penalties. This results in increased electricity price on the wholesale market because of unexpected shortage of electricity on the market and the marketer has to provide the electricity arranged with the customers from other generating companies on the spot market. In this scenario, the shareholders of these other generating companies may void the scheduled preventive maintenance in order to maximize their profit during the higher electricity price on the wholesale market. Because the shareholders of the generating companies wish to deliver electricity when its price is high, and to perform maintenance when the electricity price is low [2], progressive deterioration on the important equipment may occur.

Outsourcing may provide additional problems in performing maintenance in due time. Since power plants are complex facilities which contain variety of the specific equipment, most of the complex maintenance actions are performed by the specialized crews. This may result in serious problems when generating the optimal maintenance schedule because these specialized crews may not be available at the time period optimal for performing the preventive maintenance of the facility.

2.2 Reliability
Pouzdanost

Generating units need to be maintained once in a specific period of time, which is usually one year. Naturally, it is not always possible to perform maintenance exactly after the expiry of the given time period, but deviation in both directions causes negative effects. If a unit is maintained before the expiration of the given time period, the maintenance will be more costly because the unit could have worked longer without maintaining, as shown in Fig. 1. In other words, the expected reliable operation period since the last maintenance is shortened [3].

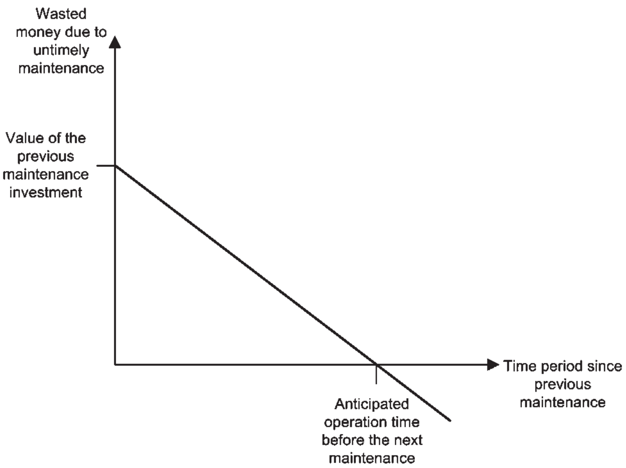

Figure 1 *Correlation between the wasted money and untimely maintenance enforcement*
Slika 1. *Odnos između nepotrebno potrošenog novca na održavanje i vremenskog razdoblja od prethodnog održavanja*

On the other hand, prolonging maintenance procedure upon the anticipated operation time before the next preventive maintenance causes progressive deterioration of many elements in the entire facility, which increases the expected maintenance cost, as shown in Fig. 2. Also, the reliability of the facility is reduced which may have serious impact on the operating conditions and forced outage rate.

Overall maintenance costs include both previous aspects of maintenance and the optimum maintenance period is obtained by the summation of curves in Fig. 1 and Fig. 2. The minimum of this new curve in Fig. 3 represents theoretical optimal time period for performing maintenance.

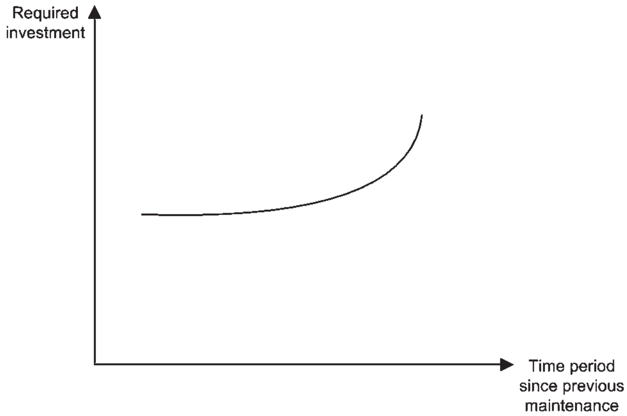

Figure 2 *Correlation between the required maintenance investment and untimely maintenance enforcement*
Slika 2. *Odnos između potrebne investicije u održavanje i nepravovremenog provođenja održavanja*

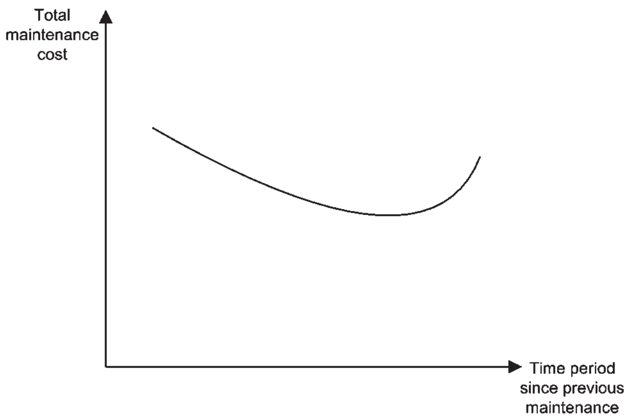

Figure 3 *The total maintenance cost in relation to the time period since the previous maintenance*
Slika 3. *Ukupni troškovi održavanja u odnosu na vremensko razdoblje od prethodnog održavanja*

2.3 Economy
Gospodarstvo

The economy demands are almost always opposing the system reliability and security demands. The increase of reliability results in higher maintenance cost due to investments, primarily in the diagnostic equipment. On the other hand, unnecessary equipment outages may incur economic losses and pose a serious danger to the power system and its security. Therefore, in maintenance scheduling optimization models the cost minimization is considered as the optimization objective and reliability is presented by many constraints. These restrictions include the availability of the maintenance crew, seasonal limitations, maintenance period during which the facility can be maintained, fuel limitations and all kinds of network limitations, such as load demand and system reliability [4].

3 Maintenance planning
Planiranje održavanja

The prime goals of each generating company are extending generating units' lifetime and generating profit by selling electricity at the highest price achievable. On the other hand, transmission companies make profit by electricity transmission. Therefore, transmission companies must invest in the maintenance of transmission lines and substations, which results in occasional unavailability of some parts of transmission electricity network.

Since transmission and generating companies may have different goals, the system operator has a task to ensure the system reliability and safety. Therefore, it is very difficult to find mutual goals of optimization in the competitive environment. The goals and necessities of all the previously mentioned subjects are often in conflict so the maintenance problem solution is obtained in two separate steps. In the first step, the generating company creates an optimal maintenance schedule. In the second step, the TSO examines if this schedule complies with all the power system demands. If necessary, the generating company has to adjust the maintenance schedule which has to be authorized by the TSO in the end [5].

The maintenance planning defines the off-line periods for a generating unit in order to perform preventive maintenance. Generally, the maintenance schedule is created for a year ahead. The year is divided into a shorter time periods, such as weeks, and the optimization goal is to define consecutive weeks in which the preventive maintenance should be performed.

Creating an optimal preventive maintenance schedule which fulfils all the constraints imposed by the system operator is a major challenge. Therefore, a proper implementation of mathematical programming is proposed.

Planning may be either deterministic or stochastic. While deterministic approach assumes that all the necessary information is known in advance, the stochastic approach is more realistic because it assumes that future events are unknown and can only be predicted with certain accuracy [2]. Therefore, the generating unit maintenance has the property of stochastic planning based on heuristics. Due to this stochastic nature of the maintenance system, an unexpected disruption in the generating system is not negligible. This is known as fictitious cost approach and is used to penalize alterations of the ideal power plant maintenance schedule.

Another, much more often applied, approach is the maintenance window approach, in which the ideal schedule is represented by time intervals in which the maintenance should be performed. This means that costs do not depend on time, as long as the maintenance actions are done within these time intervals. Mathematical model presented in this paper is based on the maintenance window approach.

4 Introduction to mathematical programming
Uvod u matematičko programiranje

In mathematics cost minimization is equivalent to finding the minimum of the cost function. The classical mathematical apparatus of integral and differential calculus is not convenient for solving this problem because of the very large number of variables and constraints, which may be equations, inequalities or set constraints. Therefore, new methods are required to solve complex problems of retrieving an extreme point. One of them is mathematical programming, which because of computational power of modern computers, is widely accepted in solving optimization problems in economics and engineering.

The mathematical programming problem consists in finding the extreme value, either minimal or maximal, of a specific function in a given range. If f: $S \rightarrow R$ is a function of n variables $x_1, x_2, \ldots, x_n$ defined in the set S of the Euclid space R^n, the mathematical programming problem is defined in the following way:

$$\text{minimize } f(\mathbf{x}) \tag{1}$$

with constraints:

$$\mathbf{x} \in S, \tag{2}$$

where is $\mathbf{x} = [x_1, x_2, \ldots, x_n]^{\mathrm{T}}$.

The goal is to find a point (vector) $\mathbf{x}^* \in S$, which does not necessarily exist, with the following property:

$$f(\mathbf{x}^*) \leq f(\mathbf{x}), \ \forall \mathbf{x} \in S. \tag{3}$$

The function to minimize is the object function, set S is the set of all possible solutions, and $\mathbf{x}^*$ is the optimal solution of the problem (1) - (2).

Generally, the mathematical programming problem of finding the minimum value of the function f is considered in the following form:

$$\min f(\mathbf{x}) \tag{4}$$

with constraints:

$$g_i(\mathbf{x}) = 0, \ i = 1,2,\ldots,m, \tag{5}$$

$$h_j(\mathbf{x}) \leq 0, \ j = 1,,\ldots,p, \tag{6a}$$

$$\mathbf{x} \in G, \tag{6b}$$

where g_i and h_j are real functions, and G is a set. Constraints (5) are equations, constraints (6a) are inequities, while constraints (6b) are set constraints, generally non-negativity.

5 Benders decomposition
Bendersova dekompozicija

Since generating and transmission companies are independent subjects in competitive environment, the mixed-integer programming is used for optimization and coordination of the maintenance planning. The Benders decomposition algorithm is developed for exploiting mixed-integer programs [6]. The basic idea is to decompose the original problem into a master problem and a subproblem. The master problem solving process starts with only a few, or no constraints at all. The subproblem is used for testing if the solution obtained in the master problem satisfies all the imposed constraints. If the solution of the master problem satisfies all the constraints of the objective has been minimized over all imposed constraints [1].

In restructured power system the master problem in Benders decomposition represents the generating company solving procedure, and the subproblem includes all the network restrictions imposed by the system operator. Therefore, the master problem is the relaxation of the original problem, as it does not contain all the constraints.

At each subproblem solving, the dual multipliers are generated. These dual multipliers are used to form the least satisfied constraint, the Benders cut, which is then added to the master problem. This way, in the next step, the master problem is solved with more constraints. These iterations are continued and new constraints are being added to the master problem until all the constraints of the subproblem are satisfied. This process continues until the optimal solution is found, if one exists.

Generally, the generating unit is either down for maintenance or running, and therefore it is a binary variable with values 0 or 1. Accordingly, the master problem is a mixed integer programming problem. The subproblem is a linear programming problem.

The formulation of the maintenance problem is as follows [1]:

$$\min \sum_t \sum_i \left\{ C_{it} \left(1 - x_{it}\right) + c_{it} g_{it} \right\}. \tag{7}$$

Maintenance constraints are:

$$x_{it} = 1 \text{ for } t \le e_i \text{ or } t \ge l_i, \tag{8}$$

$$x_{it} = \{0,1\} \text{ for } e_i \le t \le l_i \,. \tag{9}$$

System constraints:

$$\mathbf{Sf} + \mathbf{g} + \mathbf{r} = \mathbf{d}, \tag{10}$$

$$\mathbf{g} \le \bar{\mathbf{g}} \cdot \mathbf{x}, \tag{11}$$

$$\left|\mathbf{f}\right| \le \bar{\mathbf{f}}, \tag{12}$$

$$\sum_i r_{it} \le \varepsilon, \tag{13}$$

where is:

C_{it} - maintenance cost of generating unit i at time t, pu

c_{it} - generation cost of unit i at time t, pu/MW

x_{it} - unit maintenance status

g_{it} - generation of unit i at time t, MW

e_i - earliest possible period to begin generating unit i maintenance

l_i - latest possible period to end generating unit i maintenance

S - node-branch incidence matrix

f - active power flow vector

g - active power generation vector at time t, MW

r - lack of active energy vector at time t, MW

d - demand vector at time t, MW

$\bar{\mathbf{g}}$ - maximum generation capacity vector, MW

$\bar{\mathbf{f}}$ - maximum line flow capacity vector, MW

ε - acceptable amount of missing active energy, MW.

The unknown variables x_{it} in (7) are integer variables, while C_{it}, c_{it}, and g_{it} are continuous variables. The goal is to minimize the objective function (7), which represents maintenance and operational costs of the generating units. Constraints (8) and (9) represent the maintenance window interval. If a unit i is scheduled for maintenance in time interval t, x_{it} is 0, otherwise it is 1. Accordingly, the value of x_{it} is always 1 outside the maintenance window.

Constraint (10) is a peak load balance equation, while constraints (11) and (12) represent generation and transmission capacity. Finally, constraint (13) grants the unserved amount of electrical power.

5.1 The problem solving procedure
Postupak rješavanja problema

When using Benders decomposition, first it is necessary to divide an original problem into a master problem and a subproblem. The master problem is a mixed integer programming problem and it generates preliminary solution to the problem. This trial solution is the lowest possible cost that the original maintenance scheduling problem can achieve. Therefore, this trial solution is the lower bound of the optimal value of the original minimizing maintenance costs problem.

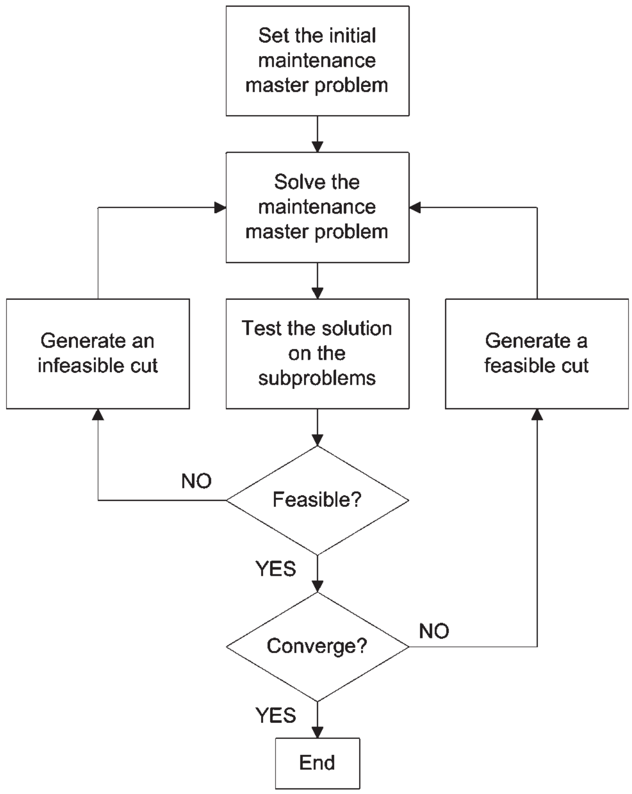

Figure 4 *The flow chart of the Benders decomposition*
Slika 4. *Dijagram toka Bendersove dekompozicije*

After calculating the optimal x_{it} values, these are used to solve a set of subproblems. After solving each subproblem, a set of dual multipliers is generated and they are added to the master problem in the next iteration forming one or more additional constraints, known as the Benders cuts. After finding a feasible solution close enough to the lower bound, i.e. the optimal maintenance schedule satisfying all the constraints, the iteration process stops. The flow diagram is shown in Fig. 4.

6
The application of the Benders decomposition on the cascaded hydro power system on the Drava River
Primjena Bendersove dekompozicije na kaskadni hidroenergetski sustav na rijeci Dravi

The Benders decomposition is applied to a part of the 110 kV Croatian electric power system which contains three hydro power plants in a cascade on the Drava river in Croatia: HPP Varaždin, HPP Čakovec and HPP Dubrava. Each hydro power plant has two generators. Information on these generators, along with the predictive maintenance duration, is given in Tab. 1.

***Table 1** Hydro power plants data*
***Tablica 1.** Podaci o hidroelektranama*

HPP	Varaždin		Čakovec		Dubrava	
Generator	A	B	A	B	A	B
Power /MW	47	47	39,9	39,9	39,9	39,9
Maintenance duration /weeks	5	4	4	4	5	5

In order to avoid great energy losses due to water overflow, only one generator of each hydro power plant may be off-line in any time period. Since invariable expenses are independent on the maintenance period, the optimization is based on the minimization of the variable expenses, i.e. the water which does not flow through turbines.

The optimization goal is to minimize the unutilized water volume. Since the future water flows cannot exactly be determined in advance, it is considered that the future water flows will resemble average water flows of previous ten years.

The time period for maintenance is discretely divided into weeks and the time window in which the maintenance of all six generators has to be performed lasts for 18 weeks, during low inflow period. Each week's average water flow is calculated and given the linear penalty factor, calculated by the following formula:

$$pf_i = \frac{w_i}{w_{\min}}, \tag{14}$$

where is:
pf_i - penalty factor for performing maintenance in the i-th week
w_i - average water flow in the i-th week
$w_{\min}$ - minimum water flow.

Although the installed water flow of all six turbines is approximately 250 m^3/s, this calculation is regarded as stochastic. Therefore, the week with the minimum average water flow will have the penalty factor 1,00, and all the others will have penalty factors proportional to their average water flows, as shown in the Tab. 2.

Penalty factors from Table 2 are in direct correlation with variable expenses, which represent an opportunity cost. Ideally, variable expenses would be zero and each unit's maintenance cost would involve only invariable cost. In this case each unit's maintenance cost would be 1 pu, which makes total minimum maintenance cost 6 pu.

***Table 2** Average water flows and penalty factors for each week*
***Tablica 2.** Prosječni dotoci i penalizirajući faktori za svaki tjedan*

Week	Average water flow /m^3/s	Penalty factor
1	176	1,26
2	164	1,17
3	157	1,12
4	151	1,08
5	147	1,05
6	140	1,00
7	160	1,14
8	154	1,10
9	169	1,21
10	171	1,22
11	179	1,28
12	208	1,49
13	212	1,51
14	239	1,71
15	244	1,74
16	253	1,80
17	287	2,05
18	312	2,23

The part of the 110 kV Croatian power system included in the calculation is shown in Fig. 5. Numbers by arrows represent the peak power needed in network nodes. The total generating capacity of hydro power plants is 253,6 MW, and the total peak load is 166 MW. Regardless of the maintenance period, all consumption must always be satisfied from these three hydro power plants.

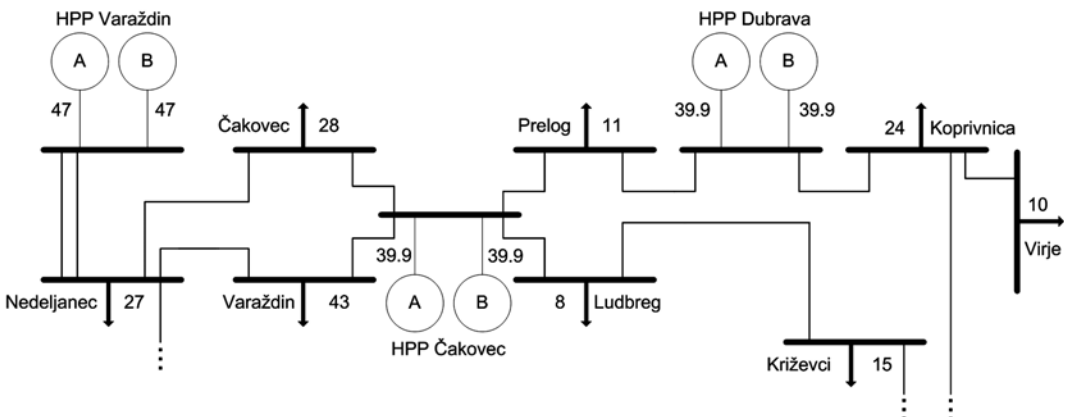

***Figure 5** The part of the 110 kV Croatian transmission network included in the calculation*
***Slika 5.** Dio hrvatske 110 kV prijenosne mreže razmatrane u proračunu*

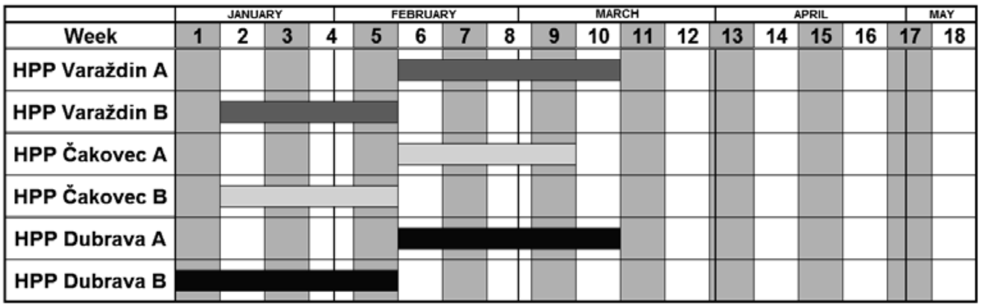

Figure 6 *Optimal maintenance schedule after the first iteration*
Slika 6. *Optimalni raspored održavanja nakon prve iteracije*

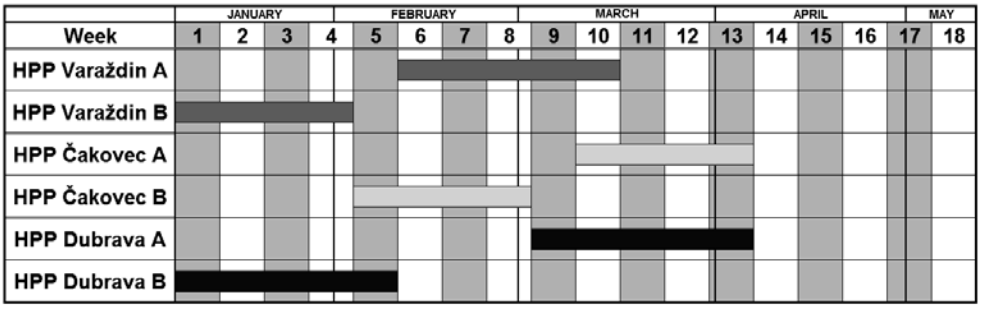

Figure 7 *Optimal maintenance schedule after the second iteration*
Slika 7. *Optimalni raspored održavanja nakon druge iteracije*

7 The results
Resultati

The first iteration maintenance schedule generated by the master problem is shown in Fig. 6. According to this schedule, one generator of each hydro power plant is being serviced simultaneously. After testing this solution by the subproblem, there are expected electricity shortages in weeks 2-9, as shown in Tab. 3. The total expected maintenance expenses, i.e. variable and invariable, in first iteration are 6,7265 pu.

Table 3 *Electricity shortage per weeks after the first iteration*
Tablica 3. *Manjak proizvodnje električne energije po tjednima nakon prve iteracije*

Week	Electricity shortage /MW
2	39,9
3	39,9
4	39,9
5	39,9
6	39,9
7	39,9
8	39,9
9	39,9

Since the optimization requirement is to satisfy the peak load in every week, a Benders cut is generated and assigned to the master problem. The solution of the master problem in the second iteration is shown in Fig. 7. After testing this solution by the subproblem, there is an expected electricity shortage in week 10, as shown in Tab. 4. The overall maintenance cost in second iteration is issued to 7,2170 pu.

Since there is still an electricity shortage, a new iteration is conducted. New optimal maintenance schedule is given in Fig. 8. Since there is no lack of electricity in any week, this solution satisfies all the imposed constraints. It is important to perceive that the final optimal maintenance schedule will cause more losses, but the consumption will always be satisfied. The total expected maintenance expenses, including both variable and invariable, in the third iteration are 7,2625 pu.

Table 4 *Electricity shortage per weeks after the second iteration*
Tablica 4. *Manjak proizvodnje električne energije po tjednima nakon druge iteracije*

Week	Electricity shortage /MW
10	39,9

In order to verify and extend the obtained results, additional calculations have been performed for cases of atypical water inflows of the Drava River. The calculus, similar to the one performed for average water inflows, was performed for the following four scenarios:
1. average without the year with the highest inflow
2. average without the year with the lowest inflow
3. year with the highest inflow
4. year with the lowest inflow.

7.1 Average without the year with the highest water inflow scenario
Prosjek bez scenarija godine s najvišim priljevom vode

This scenario takes into consideration the information on average water inflows of the Drava River for nine out of ten previous years. The year not taken into consideration is the one with the highest average water inflow. The results for this scenario are identical to the original calculation which takes into consideration the water inflow information for the previous ten years.

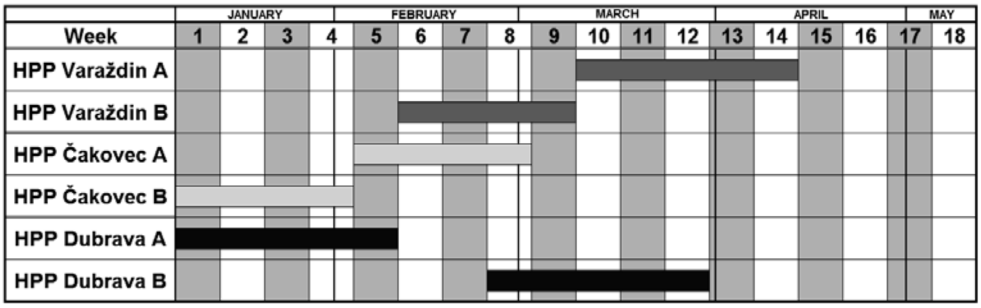

Figure 8 *Optimal maintenance schedule after the third iteration*
Slika 8. *Optimalni raspored održavanja nakon treće iteracije*

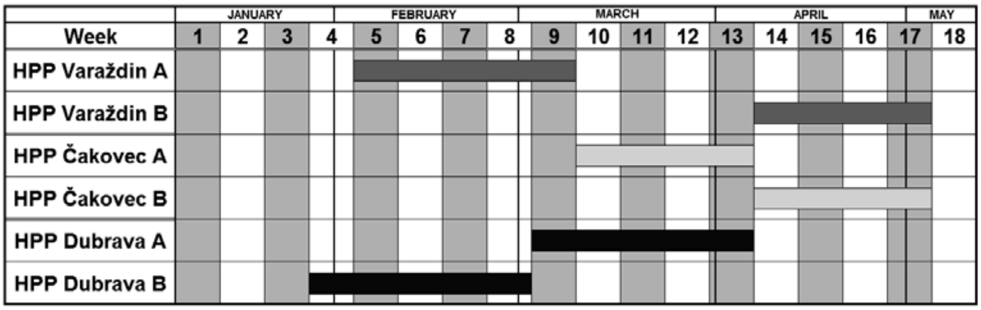

Figure 9 *Optimal maintenance schedule for the scenario with the lowest water inflow*
Slika 9. *Optimalni raspored održavanja za scenarij najmanjeg prosječnog dotoka*

7.2 Average without the year with the lowest water inflow scenario
Prosjek bez scenarija godine s najnižim priljevom vode

This scenario takes into consideration the information on average water inflows of the Drava River for nine out of ten previous years. The year not taken into consideration is the one with the lowest average water inflow. The results for this scenario are identical to the original calculation which takes into consideration the water inflow information for the previous ten years.

7.3 Year with the highest water inflow scenario
Scenarij godine s najvišim priljevom vode

This scenario is based only on the water inflows for the year with the highest average water inflow, which was highly atypical. The results are unexpected because the conducted calculation resulted in optimal time period for maintenance in October and November.

If these highly atypical water inflows of the Drava River occur during the year for which the calculation is carried out the losses will be extremely high and this calculation will be irrelevant.

7.4 Year with the lowest water inflow scenario
Scenarij godine s najnižim priljevom vode

This scenario is based only on the water inflows for the year with the lowest average water inflow. Results obtained in this calculation, shown in Fig. 9, indicate that the maintenance should be performed approximately one month later if this scenario occurs. This result was obtained in the second iteration and the total expected maintenance came out to 6,4385 pu.

8 Conclusions
Zaključci

The application of the Benders decomposition to a real part of the power grid in Croatia presented in this paper images the real problems generating companies may face in the liberalized power systems. This results in maintenance programs which are not optimal for the generating company itself, but are optimal considering the safety and reliability of the entire power system, especially regarding transmission network safety and reliability.

The future work should include more generating facilities and bigger part of the transmission network of Croatia. Eventually, the goal is to acquire maintenance information on all generating facilities of the Croatian Electrical Utility and create an optimal maintenance program, satisfying all numerous transmission power flow and transmission maintenance constraints.

9 References
Literatura

[1] Shahidehpour, M.; Marwali, M; Maintenance Scheduling in Restructered Power Systems. Kluwer Academic Publishers Group, 2000.
[2] Al-Sultan, K. S.; Daffuaa, S. O. Maintenance Control via Mathematical Programming. // Journal of Quality in Maintenance Engineering, 1, 3, 36-46.
[3] Dopazo, J. F.; Merrill, H.M. Optimal Generator Maintenance Scheduling Using Integer Programming. // IEEE Transactions on Power Apparatus and Systems, 94, 5(1975), September/October 1975.
[4] Yellen, J.; Al Khamis, T. M.; Vemuri, S.; Lemonidis, L. A Decomposition Approach to Unit Maintenance Scheduling. // IEEE Transactions on Power Systems, 7, 2, May 1992.
[5] Marwali, M. K. C.; Shahidehpour, S. M. Integrated Generation and Transmission Maintenance Scheduling with Network Constraints // IEEE Transactions on Power Systems,

13, 3, August 1998.
[6] Benders, J. F. Partitioning Procedures for Solving Mixed Variables Programming Problems // Numerische Mathematik 4(1962), 238-252.

Authors' addresses
Adrese autora

Igor Kuzle, PhD
Faculty of Electrical Engineering and Computing
University of Zagreb

Hrvoje Pandžić, MEE
Faculty of Electrical Engineering and Computing
University of Zagreb

Miljenko Brezovec, MSc
Croatian Power Board
(Hrvatska elektroprivreda d.d, HEP)
power generation area Hydro North