Impact of the Competitive Environment on the Generating Units Maintenance

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***Abstract*-- Maintenance of the power generating facilities in due time is essential for economical and reliable operation of the power system. Economical aspects, which bring revenue, and technical aspects, which keep the power system above the desired level of reliability, have to be confronted and the cheapest solution, which complies with the strict technical limitations, has to be obtained.**

This paper addresses the problem of obtaining the optimal maintenance schedule for generating units. For this purpose, this paper discusses the mathematical programming method – Benders decomposition. After the brief description, an application of the Benders decomposition on the three Croatian hydroelectric power plants in a row on the river Drava is carried out.

***Index Terms*-- Benders Decomposition, Generating Units Maintenance, Maintenance Scheduling, Mathematical Programming, Optimization**

I. Introduction

PREVENTIVE generating units maintenance scheduling is among most vital decisions which generating companies have to make. An effective maintenance of the generating units helps reduce the forced outage rates. Therefore, rigorous technical restrictions have to be respected by all means. In vertically integrated power systems the maintenance was conducted properly. Since the economical factor was not the prime driver in investments, most of the elements of the power system were overdimensioned. This means that failures in the vertically integrated power systems were extremely rare. After the implementation of the electricity market, economic drive grew stronger and private companies have to take care of the each invested dollar so none of it goes in vain.

One of the biggest spending components of the generating companies is certainly the maintenance. Competitive environment generates an extra strain on the engineers to create maintenance programmes which have a minimal influence on the generation unit's availability. This is because reduced availability inflicts lower revenue. For this reason, the maintenance investments are often neglected by the shareholders, although they have very good long-term return of investment rate. Therefore, engineers have to find new methods for optimization of the maintenance procedures.

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II. Fundamentals of the Restructured Power System

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 influence the creation of preventive maintenance programmes. These restrictions are the outcome of the system stability and spinning reserves criteria issued by the independent system operator. 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.

A. Availability

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 by liberalizing the 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 already concluded contract, this company has to pay penalties. This results in increased electricity price on the wholesale market because there is an unexpected shortage of electricity on the market and the marketer has to provide the electricity contracted with the customers from another generating company. In this scenario, the shareholders of the other generating company may decide not to undergo 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 works are performed by the specialized crews. This may result in serious problems when generating the optimal maintenance schedule because these crews may not be available at the time period which is optimal for performing the preventive maintenance.

B. Reliability and Economy

Reliability and economy are almost always the opposing demands. The increase of reliability results in higher cost of maintenance due to investments in 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 [3].

III. Maintenance Planning

The prime goals of each generating company are extending generating units life span and generating profit by selling electricity. Transmission companies make profit by transporting electricity so they need to keep the lines in satisfying conditions. The Independent System Operator (ISO) has 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 the optimal maintenance schedule. In the second step, the ISO checks 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 verified by the ISO in the end [4].

The maintenance planning defines the off-line periods for a generating unit in order to perform a 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 maintenance should be performed.

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.

IV. Introduction to Mathematical Programming

Cost minimization is in mathematics equivalent to finding a 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 or inequalities. Therefore, new methods were created in order to solve complex problems of retrieving an extreme point. One of them is the mathematical programming, which was developed more than sixty years ago, and because of computational power of modern computers, this method is widely accepted on solving optimization problems in economics and engineering.

The mathematical programming problem is consisted 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, …, x_n defined in the set S of the Euclid space R^n, the mathematical programming problem is defined in the following way [5]:

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

with constraints:

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

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

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

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

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 is considered in the following form:

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

with constraints:

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

$$h_j\left(\mathbf{x}\right) \leq 0,\ j = 1, 2, \ldots, p \tag{6}$$

$$\mathbf{x} \in G \tag{7}$$

g_i and h_j are real functions. Constraints (5) are equations, constraints (6) are inequities, while constraints (7) are set constraints, generally non-negativity.

V. The Benders Decomposition

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 subproblem, the obtained solution is optimal, since the objective has been minimized over all constraints [1].

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

At each solving of the subproblem, the dual multipliers are generated. These dual multipliers are used to form a new constraint which is added to the master problem. This way, in the next step, the master problem is solved with more constraints. This process continues until the optimal solution is found, if one exists.

VI. The Application of the Benders Decomposition on the Hydro Power Plants on the River Drava

The Benders decomposition is applied to a part of the Croatian electric power system which contains three hydro power plants in a row on the river Drava: HPP Varazdin, HPP Cakovec and HPP Dubrava. Each hydro power plant has two generators. Information on these generators, along with the predictive maintenance duration, are given in table I.

TABLE I
HYDRO POWER PLANTS DATA

HPP	Varazdin		Cakovec		Dubrava	
Gen.	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 the invariable expenses are always the same, the optimization is based on the minimization of the variable expenses, i.e. the water that does not flow through the turbines. All six generators have the installed capacity of 250 m^3/s. Therefore, if one generator of any HPP is off-line and water flow is above 250 m^3/s, the surplus will be wasted. The goal is to minimize the unutilized water volume. Since the future water flow cannot be determined in advance, it is considered that the water flow will be the same as the average water flow of previous ten years.

The time period is discretely divided into weeks and time window in which the maintenance of all six generators has to be performed lasts for 18 weeks. Each week's average water flow is calculated and given the linear penalty factor. This means that the week with the smallest water flow has the penalty factor 1,00, and all other have the penalty factor proportional to their average water flow, as shown in the table II.

The regarded part of the 110 kV Croatian power system is shown in Fig. 1. Numbers by arrows represent the peak power needed in the specific network node. The total generating power in the regarded part of the grid is 253,6 MW, and the total peak load is 166 MW.

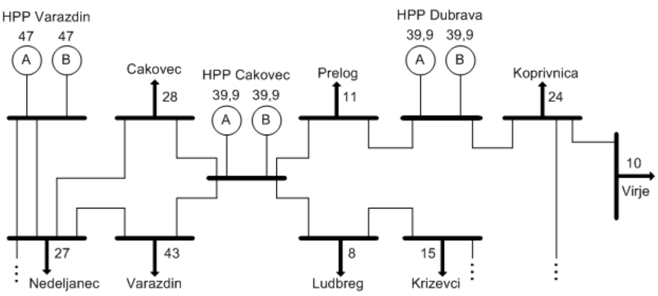

Fig. 1. The regarded part of the 110 kV Croatian electric power system.

TABLE II
AVERAGE WATER FLOWS AND PENALTY FACTORS FOR EACH WEEK

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

Regardless to the maintenance period, all consumption must always be satisfied from these three power plants.

VII. The Results of the Calculation

The first iteration maintenance schedule generated by the master problem is shown in Fig. 2. 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 the table III.

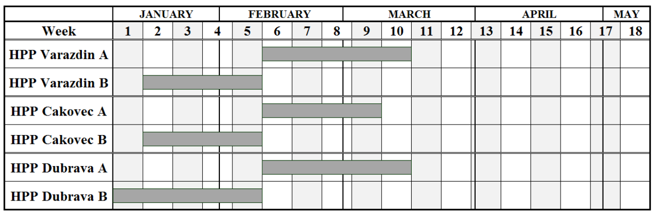

Fig. 2. Optimal maintenance schedule after the first iteration.

TABLE III
ELECTRICITY SHORTAGE PER WEEKS AFTER THE FIRST ITERATION

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 [1] is generated and assigned to the master problem. The solution of the master problem in the second iteration is shown in Fig. 3.

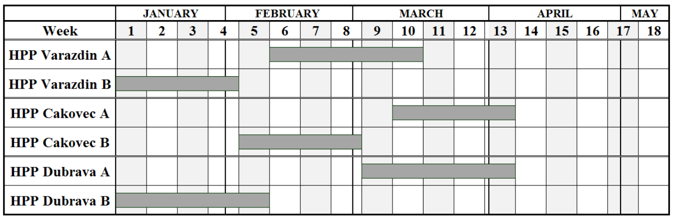

Fig. 3. Optimal maintenance schedule after the second iteration.

TABLE IV

ELECTRICITY SHORTAGE PER WEEKS AFTER THE SECOND ITERATION

Week	Electricity shortage [MW]
10	39,9

Since there is still an electricity shortage, a new iteration is conducted. The optimal maintenance schedule is given in Fig. 4. There is no lack of electricity in any week, so 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.

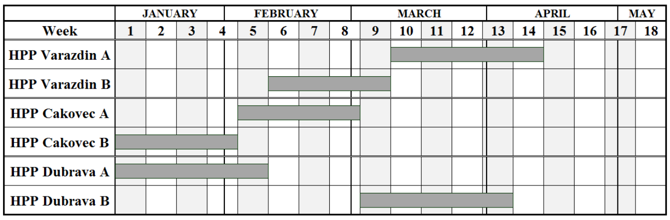

Fig. 4. Optimal maintenance schedule after the third iteration.

VIII. CONCLUSIONS

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 programmes which are not optimal for the generating company itself, but are optimal considering the safety and reliability of the entire power system.

IX. REFERENCES

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X. BIOGRAPHIES

Igor Kuzle (S'94-M'97-SM'04) received the B.S, M.S. and Ph.D (in the field under frequency load shedding) degree from the Faculty of Electrical Engineering in Zagreb, Croatia, in 1991, 1997 and 2002 respectively. He was awarded with faculty annual award "Josip Loncar".
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