A METHOD FOR THE LONG-TERM SCHEDULING OF HYDROTHERMAL POWER SYSTEM WITH MULTIPLE USER RESERVOIRS

by

Elis SUTLOVIĆ, Matislav MAJSTROVIĆ, and Ivan SARAJCEV

Original scientific paper
UDC: 620.92
BIBLID: 0354-9836, *11* (2007), 3, pp. 75-83

This paper presents an optimization-based method for the long-term scheduling of hydrothermal power system with several multiple-user reservoirs. The proposed method maximizes the profit of various types of water utilization taking into account limited water resources and all accomplishable restrictions. Hydroelectric power plants and other water users are treated like a peer participant in the profit realization. The method has been implemented in a computer program and tested on real system.

Key words: *long-term hydrothermal scheduling, multiple-user reservoirs, power system planning, profit maximization*

Introduction

In a hydrothermal power system with significant percentage of hydro generation a long-term multireservoir management has a great impact on the production cost of thermal units. Besides hydroelectric power plants there are many other users of river flows and reservoirs.

Conservation pools usually serve multiple purposes and multiple users. Each reservoir, as well as a multiple reservoir system, has unique operating rules. Many conditions and considerations may be authoritative in the operation of reservoirs for municipal and industrial water supply, hydroelectric power production, irrigation, recreation, navigation, and other conservation storage purpose. The multiple purpose reservoir operation involves various interactions and trade-offs between purposes, which are sometimes complementary while often competitive or conflicting. For a multiple-reservoir system, with reservoirs in series (cascaded reservoirs) as well as reservoirs in parallel, release decisions require more precise and more complex approaches. If the reservoirs have significantly different evaporation potential or other losses possibility, minimization of losses must be taken into consideration [1].

Besides above, there are many limitations on reservoir operation policy, such as:

- amount of empty space available for storing future flood waters in order to reduce down stream damages, represented by the designated top of conservation pool elevation,

DOI:10.2298/TSCI0703075S

- reservoir release to maintain specified minimum flow rates, and
- water-surface-level fluctuation, *etc.*

In the usual approach for determining the optimal long-term operation policy of a multiple reservoir hydrothermal power system all other type of water use, except hydroelectric power, are treated like constraints. This traditional approach, irrespective of whether looking for the minimum of the total system cost (usually the thermal production cost) or looking for the maximum of the profit in power system, manages with the available amount of water for power production [2-9].

This paper describes the approach used by the authors for solving the long-term scheduling of power system with multiple purpose and multiple user conservation reservoirs. The main goal is to achieve the maximum profit of various types of water utilization taking into account limited water resources and all accomplishable restrictions. Consequently, the basic difference between the presented approach and the usual approach for reservoir operations in power system is in the treatment of other water users. Other water users can be, moreover, modeled like constraints (for example, municipal water supply) but also like a peer participant in the profit realization. The modeling of other water users and their profit functions is, up to this point, quite simple in comparison with modeling of hydroelectric plants and power system profit calculations. All input variables, like reservoir and river inflows, electricity demand, *etc.* are modeled deterministically.

Mathematical formulation

The total profit of water utilization from each conservation pool is the sum of profits, which are realized by multiple users during particular periods. The assumption is that all profits, except profits of hydroelectric plants, depend only on diverted water on one streamflow or on storage of water in one reservoir. The hydroelectric power plant production is coordinated with other power plants in power system. The profit in power system is a function of diverted water by turbines and reservoir level from all conservation pools.

In calculation, scheduling horizon is divided into the smaller time period, called basic time period *t*. According to mentioned above, the total profit of all reservoirs release usage *P*, which have to be maximized, can be mathematically expressed as follows:

$$\begin{aligned} P &= P_{\mathrm{A1}}(\mathrm{X}) + P_{\mathrm{B1}}(\mathrm{X}) + \ldots + P_{\mathrm{A2}}(\mathrm{Y}) + P_{\mathrm{B2}}(\mathrm{Y}) + \ldots \\ &\ldots + P_{\mathrm{AR}}(\mathrm{Z}) + P_{\mathrm{BR}}(\mathrm{Z}) + \ldots + P_{\mathrm{PS}}(\mathrm{X},\mathrm{Y},\ldots,\mathrm{Z}) \end{aligned} \tag{1}$$

where:

P_{ur} – profit of water utilization u (u = A, B, ...) from reservoir r (r = 1, 2, ..., R),

P_{PS} – profit in power system,

X – all spills and releases from reservoir 1 in whole period, $\mathrm{X} = [x_1, x_2, ..., x_{\mathrm{T}}]$,

Y – all spills and releases from reservoir 2 in whole period, $\mathrm{Y} = [y_1, y_2, ..., y_{\mathrm{T}}]$,

Z – all spills and releases from reservoir R in whole period, $\mathrm{Z} = [z_1, z_2, ..., z_{\mathrm{T}}]$,

$x_{\mathrm{t}}, y_{\mathrm{t}}, ..., z_{\mathrm{t}}$ – all spills and releases during period *t*, ($t = 1, 2, \ldots, \mathrm{T}$).

Constraints of limited water resources for all reservoirs can be expressed as follows:

$$\sum_{t=1}^{T} x_t \le \sum_{t=1}^{T} i1_t + V_1, \quad \sum_{t=1}^{T} y_t \le \sum_{t=1}^{T} i2_t + V_2, \ldots, \quad \sum_{t=1}^{T} z_t \le \sum_{t=1}^{T} iR_t + V_R \qquad (2)$$

where:

ir_t – inflow to the reservoir r (r = 1, 2, ..., R) during basic period of time t, (t = 1, 2, …, T),

V_r – available volume of the water which can be released from reservoir r, (r = 1, 2, ..., R) during whole period T.

The resulting problem is generally constrained non-linear mathematical optimization problem with an extremely high number of optimization variables and system parameters.

In the suggested method the optimization of R reservoirs is broken into R subproblems in which one reservoir is optimized, while other reservoirs release is temporarily kept constant. In a subproblem all hydroelectric (and thermoelectric) plants participate in the power system profit, while the power system profit is the function of only one release. Equation (1) can be written as:

$$P_{\mathrm{Y,...,Z = const.}} = \sum_{t=1}^{T} P_{(\mathrm{Y,...,Z = const.})_t} = \sum_{t=1}^{T} (P_{\mathrm{A1t}}(\mathrm{X}) + P_{\mathrm{B1t}}(\mathrm{X}) + \ldots + P_{\mathrm{PSt}}(\mathrm{X}) + P_{\mathrm{Ot}}) \qquad (3)$$

where constant P_{Ot} is the sum of all profits of multi users water utilization (except profit in hydroelectric plants) on other reservoirs in period t.

The solution for the problem (3) can be found with convenient non-linear programming algorithm for constrained problem. Thus, long-term operation policy or optimal solution for eq. (1) results from successive solving subproblems for all reservoirs. After the calculation of the subproblem (3) for the last reservoir, the whole procedure occurs again several times in iteration loop (until the total profit increase becomes neglectable).

The problem, which appeared in eq. (3), is the determination of power system profit function in dependence on water release from only one reservoir for each basic time period. According to the assumption, other water utilization profit functions for each basic time period t are mutual independent and known input dates. Power system profit functions are variable during computations. Therefore, before each optimization calculation for one reservoir release, while other reservoirs release is temporary constant, power system profit function (fig. 1) for each period t must be calculated. It is very hard to calculate these profit func-

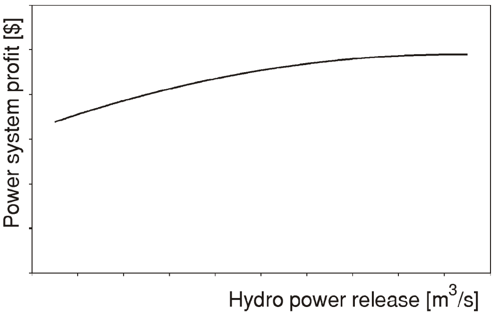

Figure 1. Example of power system profit function in dependence of hydro power release from reservoir in one basic period of time

tions analytically, so they are calculated by simulation model. In the automated search for the profit function, separate algorithm [10] repeatedly calculates the energy production cost in power system with different values for the considered reservoir release. Energy production cost algorithm for a given amount of water minimizes the cost of running the thermal unit. Load duration curve, generating unit characteristics and many others constrains are included in this algorithm. After that, the objective function (3) for one iteration step is re-formed and the optimal subproblem solution can be found.

The global objective function (1) decomposition simplifies optimization problem and enables it to be solved. The iterative computation with systematic optimization process managing and apropos programming algorithm application for continual solving the local objective function (3) leads to the optimum.

The local objective function (3) includes significant lower number of decision variables. Due to problem decomposition, some of less dominated parameters, previously disregarded, can participate in each phase of calculation and simulation. A possible longer calculation time is a neglected factor in such problems.

Implementation and testing results

The proposed long-term optimization method is the basis of the new developed software package. The developed program has been tested on power system model, which is very similar to Croatian Power System of the year 2000. In median weather condition hydroelectric power plants production in Croatia is about 45% of electrical demand. The testing model includes 5 hydro chains with 6 reservoirs for seasonal regulation, several small sized reservoirs, and 9 storage hydroelectric plants [11]. The generation system also contains 12 thermal plants (various fuels) as well as several run-off river hydroelectric plants. The constraints in the hydro chains include minimum and maximum conservation storage levels for pollution and flood control, maintenance of minimum flows specified for ecological reasons, amount of water for water supply, *etc*. The relationships between the gross head and the storage capacity are modeled for all reservoirs. The scheduling horizon in this example is defined as one year. The basic time period is one month. The monthly electricity requirements are externally calculated and represented by the use of load duration curves.

The program output list includes:

- volume, release and gross head for reservoirs in each basic period,
- hydroelectric power plants and thermal plants production in each basic period, and
- system profit in each basic period, *etc*.

The described model was applied to two cases. In the first case irrigation demands were disregarded. In the second case irrigation demands on two locations (on the river Cetina and on the river Trebisnjica) were counted in. Revenues for supplying irrigation were modeled with non-linear profit functions for six months of the year.

The monthly productions of the storage of hydroelectric plants and diverted water for irrigation are presented in tabs. 1 and 2. The total annual revenue in the second case is higher in spite of smaller annual power production in hydroelectric plants.

Table 1. Monthly power production of storage of hydroelectric plants and irrigation diversion in case 1

Month	Storage hydroelectric plants [GWh]										Irrigation [m^3/s]	
	Peru.	Orlo.	Djale	Zaku.	Sklo.	Senj	Vinod.	Veleb.	Dubr.	ΣMonth	Cetina	Trebisn.
1	10.95	34.43	12.73	168.80	9.08	114.95	24.27	47.56	65.40	**488.17**	0	0
2	1.06	0.00	6.31	77.21	6.44	87.34	0.00	86.96	60.53	**325.84**	0	0
3	4.45	60.18	10.59	136.37	8.91	112.44	11.49	19.62	65.39	**429.43**	0	0
4	9.67	30.65	11.53	150.17	6.60	97.34	0.00	33.84	59.13	**398.92**	0	0
5	6.13	0.00	7.49	92.67	8.90	103.94	62.50	57.31	67.23	**406.16**	0	0
6	20.15	55.31	12.11	158.32	9.33	95.95	0.00	0.00	66.66	**417.83**	0	0
7	19.28	44.50	10.68	137.66	5.74	62.06	5.48	0.00	64.98	**350.36**	0	0
8	13.82	35.44	9.21	116.91	13.34	110.39	26.18	0.00	64.61	**389.91**	0	0
9	9.87	0.00	6.31	76.34	9.15	79.95	1.38	24.17	59.61	**266.77**	0	0
10	17.44	39.36	13.14	175.95	12.59	115.62	11.56	43.22	63.48	**492.36**	0	0
11	7.08	34.03	10.77	139.38	8.57	100.82	0.00	3866	61.60	**400.91**	0	0
12	8.81	34.55	13.30	177.62	9.02	115.34	2.10	46.33	65.44	**472.51**	0	0
Σ	**128.71**	**368.44**	**124.15**	**1607.40**	**107.67**	**1196.13**	**144.96**	**397.67**	**764.05**	**4839.16**		

Impact of irrigation demands on water release policy is much better seen on the Trebisnjica river basin then on quite complex Cetina river basin. The Cetina reservoir/river system includes two storage reservoirs, Peruca and Busko Blato, with significantly different characteristics. Active storage capacity of the Peruca reservoir is about 50% lower than active storage capacity of the Busko Blato reservoir but mean annual natural inflow of the Peruca reservoir is approximately twice as high as mean annual natural inflow of the Busko Blato reservoir. Seepage and evaporation losses are negligible for the Peruca reservoir but they are significant for the Busko Blato reservoir. The first reservoir supplies water for the Peruca impoundment hydroelectric power plant (with variable gross head of 24 to 55 m) and irrigation diversion down stream, while the second provides water for the Orlovac diversion hydroelectric power plant of approximately 400 m gross head. Releases from both reservoirs plus incremental local inflows, after merging, flow trough next two hydroelectric power projects, Djale and Zakucac. Model of the Trebisnjica river basin includes the Bileca storage reservoir, irrigation diversion down stream and the Dubrovnik hydroelectric power project further down stream.

It is clearly seen in fig. 2 that monthly releases from the Bileca reservoir are lower in case 2 then in case 1 in wet season and higher in case 2 then in case 1 in irrigation season. Sum of monthly reservoir releases in both cases is equal. Sum of monthly reser-

Table 2. Monthly power production of storage of hydroelectric plants and irrigation diversion in case 2

Month	Storage hydroelectric plants [GWh]										Irrigation [m^3/s]	
	Peru.	Orlo.	Djale	Zaku.	Sklo.	Senj	Vinod.	Veleb.	Dubr.	ΣMonth	Cetina	Trebisn.
1	11.81	53.19	14.03	184.64	9.21	115.89	33.62	39.98	61.52	**523.89**	0	0
2	1.05	0.00	6.31	77.21	6.63	88.72	0.00	86.91	57.44	**324.27**	0	0
3	12.60	60.54	14.00	185.86	9.30	115.19	19.05	48.58	61.81	**126.91**	0	0
4	13.56	0.01	12.00	156.87	6.82	98.88	0.00	40.69	55.28	**384.11**	0	0
5	8.71	31.53	10.23	131.42	8.98	104.53	0.00	4.58	69.08	**369.06**	0	0
6	9.97	30.69	8.55	108.10	4.03	57.94	0.00	0.00	58.28	**277.57**	1.862	8.438
7	1.28	3.17	1.52	8.65	10.57	96.05	25.24	28.43	59.39	**234.30**	9.736	12.311
8	17.85	52.39	10.88	140.61	11.45	97.00	26.62	0.00	59.56	**416.35**	0	6.308
9	12.39	2.24	7.56	94.03	9.58	83.01	5.60	21.01	55.33	**290.76**	0	0
10	15.17	48.74	12.78	167.45	13.18	119.79	18.80	34.71	59.38	**490.02**	0	0
11	7.26	38.98	11.08	143.82	8.90	103.16	0.00	37.98	57.63	**408.81**	0	0
12	8.93	48.56	14.10	185.63	9.06	115.61	15.88	54.72	61.52	**514.03**	0	0
Σ	**120.60**	**370.04**	**123.06**	**1584.29**	**107.71**	**1195.79**	**144.82**	**397.57**	**716.21**	**4760.08**		

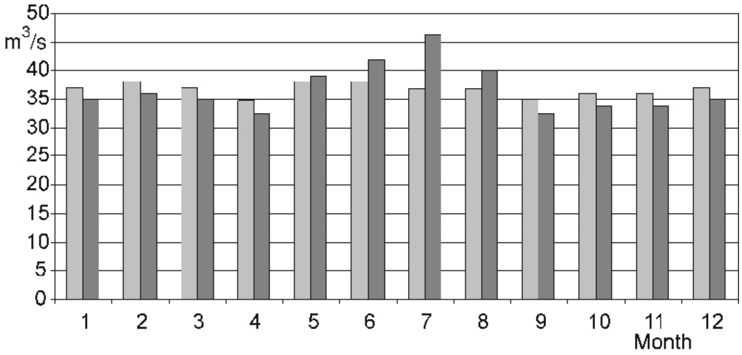

Figure 2. Monthly release from the Bileca reservoir ▨ Case 1, ■ Case 2

voir releases in one year is equal to sum of net monthly reservoir inflow in one year for each reservoir. According to reservoir releases in each month end-of-month storages of

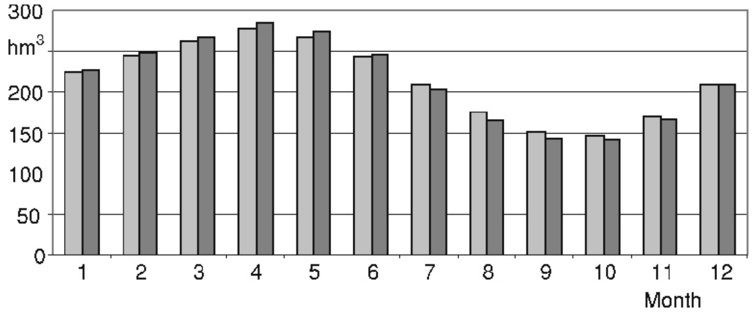

Figure 3. End-of--month storage of the Bileca reservoir ■ Case 1, ■ Case 2

reservoirs are calculated (fig. 3). Monthly power productions in the Dubrovnik hydroelectric plant (fig. 4) are lower in case 2 for almost all months due to smaller releases from the Bileca reservoir in wet season and due to irrigation diversions up stream in dry season. Monthly releases and end-of-month storages of Peruca and Busko Blato basins, as well as power production of hydroelectric plants on the Cetina river (fig. 5), are result of correlations and different characteristic of these two parallel reservoirs on the Cetina river basin.

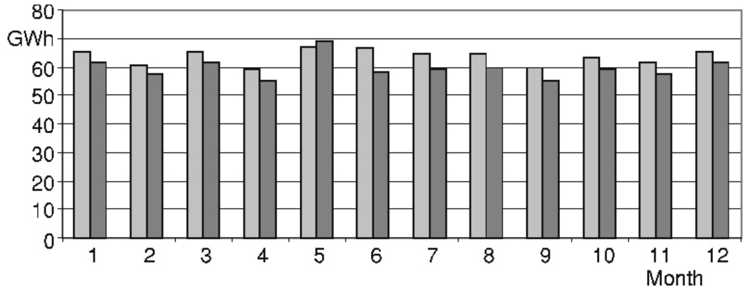

Figure 4. Monthly power production of the Dubrovnik hydroelectric plant ■ Case 1, ■ Case 2

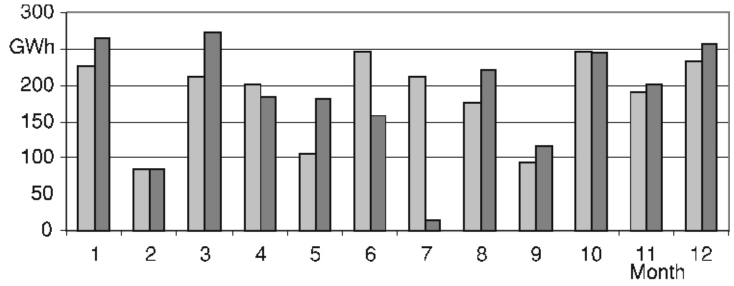

Figure 5. Monthly power production of hydroelectric plants on the Cetina river ■ Case 1, ■ Case 2

Conclusions

A multiple purpose reservoir serves a variety of project purposes. The sharing of reservoir storage capacity and limited water resources by multiple users involves conflicting demands. The presented method for determining the optimal long-term operation policy of multiple user reservoirs in hydrothermal power system treats other water users like a peer participant in the profit realization.

If no other significant water users coexist on reservoir releases, or if other water users are modeled only like constraints, the suggested method for maximizing a profit of the water usage by multiple users will give the same result as a conventional long-term optimization method.

Long-term scheduling of hydrothermal power system with significant percentage of hydro generation is highly stochastic problem due to stochastic nature of system parameters such as hydro inflows, energy demand, and energy price. The presented algorithms are currently being integrated with the Monte Carlo simulation technique to get on with uncertainty of system parameters. The suggested method with given parameters for each time interval is base of long-term multireservoir optimization.

Nomenclature

i – inflow to the reservoir, [m^3]
P – profit of water utilization, [\$]
P_{PS} – profit in power system, [\$]
t – basic time period, [s]
X – all spills and releases from reservoir 1 in whole period, $\mathrm{X} = [x_1, x_2, ..., x_{\mathrm{T}}]$, [m^3]
x – all spills and releases from reservoir 1 during period t, [m^3]
Y – all spills and releases from reservoir 2 in whole period, $\mathrm{Y} = [y_1, y_2, ..., y_{\mathrm{T}}]$, [m^3]
y – all spills and releases from reservoir 2 during period t, [m^3]
Z – all spills and releases from reservoir R in whole period, $\mathrm{Z} = [z_1, z_2, ..., z_{\mathrm{T}}]$, [m^3]
z – all spills and releases from reservoir R during period t, [m^3]
V – available volume of the water which can be released from reservoir, [m^3]

References

[1] Wurbs, R. A., Modeling and Analysis of Reservoir System Operations, Prentice Hall PTR, Upper Saddle River, N. J., USA, 1996

[2] Wood, A. J., Wollenberg, B. F., Power Generation, Operation and Control, John Willey & Sons, New York, USA, 1984

[3] Niessen, S., Haubrich, H. J., DelaFuente, J. L., Garcia, C., Nabona, N., Heredia, F. J., Dobiasch, R., Stelzner, P., Albrecht, J., Short and Long-Term Optimization of Electricity Generation and Trading in a Competitive Electricity Market – The SLOEGAT project, *Proceedings*, XXXVII CIGRE, Paris, 1998, paper 38-206

[4] Sherkat, V. R., Campo, R., Moslehi, K., Stochastic Long-Term Optimization for a Multireservoir System, *IEEE Transactions on Power Apparatus and System, PAS-104* (1985), 8, pp. 2040-2049

[5] Duran, H., Puech, C., Diaz, J., Sanchez, G., Optimal Operation of Multireservoir Systems Using an Aggregation-Decomposition Approach, *IEEE Transactions on Power Apparatus and System, PAS-104* (1985), 8, pp. 2086-2092

[6] Yu, Z., Sparrow, F. T., Bowen, B. H., A New Long-Term Hydro Production Scheduling Method for Maximizing the Profit of Hydroelectric System, *IEEE Transactions on Power System, 13* (1998), 1, pp. 66-71

[7] Duncan, R. A., Seymore, G. E., Striffert, D. L., Engberg, D. J., Optimal Hydrothermal Coordination for Multiple Reservoir River Systems, *IEEE Transactions on Power Apparatus and System, PAS-104* (1985), 5, pp. 1154-1159

[8] Maceira, M. E. P., Melo, A. C. G., Costa, A. P. C., Mercio, C. M., Gorenstin, B. G., Commercialization Risks in the Brazilian Market, *Proceedings*, IEEE Power Tech '99 Conference, Budapest, 1999, paper BPT99-495-13

[9] Marwail, M. K. C., Shahidehpour, S. M., Coordination between Long-Term and Short-Term Generation Scheduling with Network Constraints, *IEEE Transactions on Power System, 15* (2000), 3, pp. 1161-1167

[10] Požar, H., Power and Energy in Electric Power Systems (in Croatian), *Informator*, Zagreb, 1983

[11] ***, Hydroelectric Power Plant in Croatia (Ed. Z. Sever, Elektroprojekt Consulting Engineers Ltd.) (in Croatian), Croatian National Electricity, Zagreb, 2000

Authors' addresses:

E. Sutlović, I. Sarajčev
University of Split,
Faculty of Electrical Engineering,
Mechanical Engineering and Naval Architecture
21000 Split, Croatia

M. Majstrović
Energy Institute Hrvoje Pozar
10000 Zagreb, Croatia

Corresponding author E. Sutlović
E-mail: sutlovic@fesb.hr

Paper submitted: July 24, 2006
Paper received: February 7, 2007
Paper accepted: March 15, 2007