DECISION SUPPORT PROGRAM FOR LONG TERM PRODUCTION PLANNING OF HYDRO-POWER PLANTS WITH MAJOR RESERVOIRS

Radu POPA[1], Andrei DRAGOMIRESCU[2], Bogdan POPA[3]

Articolul prezintă un program de suport decizional pentru operarea sistemului hidroenergetic ce constă în cele mai importante zece acumulări şi centralele hidroelectrice asociate. Programul permite selectarea politicii de operare strategice pentru următoarea lună, sau pentru un număr de luni următoare, în funcție de nivelurile în acumulări la începutul lunii şi de debitele afluente medii lunare prognozate, sugerând soluția de operare cea mai potrivită, în acord cu un model de optimizare de programare dinamică stocastică.

The paper presents a decision support program who takes into consideration the system which consists in the ten important reservoirs with the associated hydro-power plants. This program enables the selection of the strategic operation policy for the next month, or for a certain number of oncoming months, depending on reservoirs levels at the beginning of the month, and on the average monthly anticipated affluent flows; it suggests the most suitable operation solution according to an optimization model of stochastic dynamic programming.

Keywords: decision support program, stochastic dynamic programming, optimal hydropower reservoir operation

1. Introduction

The role of medium and long term planning for the energy production in the system of hydro-power plants (HPP) with major storage reservoirs on the inner rivers (on a monthly, trimestrial or seasonal basis) is essential in effective management and in putting to better use of water resources. If such planning is subsequently confirmed by the system's capability of obeying it under the emerging real life hydrological circumstances, then it becomes obvious that it will help the improved management of all the other primary energy sources in the national energy system. Hence, such planning becomes all the more useful if we take into account that it has greater chances of being obeyed, under probabilistic conditions regarding the natural water inflow in the major reservoirs in the system.

[1] Professor, Faculty of Power Engineering, University POLITEHNICA of Bucharest, Romania
[2] Lecturer, Faculty of Power Engineering, University POLITEHNICA of Bucharest, Romania
[3] Reader, Faculty of Power Engineering, University POLITEHNICA of Bucharest, Romania

This paper takes into consideration the system which consists in the ten important reservoirs, naming: Izvorul Muntelui, Vidraru, Vidra, Fântânele, Oaşa, Valea lui Iovan, Drăgan, Poiana Mărului, Siriu and Gura Apelor alongside with the associated hydro-power plants that run up to about 2000 MW installed capacity and up to an average annual production of approximately 3500 GWh. For each development, we considered that the flow used by the head fall hydro-power plant is also taken on by the other hydro-power plants downstream, on the same river, and on the river into which it flows, (for example Pângărați – Bacău on the Bistrița river and Galbeni – Călimăneşti on the Siret river or Malaia – Brădişor hydro-power plant on the Lotru and Gura Lotrului – Izbiceni on the Olt river, and the energy thus achieved is estimated by means of the flow coming from the origin storage reservoir.

The decision support program refers to the above mentioned system of reservoirs and hydro-power plants, and enables the selection of the strategic operation policy for the next month, or for a certain number of oncoming months, depending on reservoirs levels at the beginning of the month, and on the average monthly anticipated affluent flows; it suggests the most suitable operation solution according to an optimization model of stochastic dynamic programming which takes into account the frequency distributions of affluent monthly average flows, available from recordings or re-creations of the 40-70 previous years. However, the program allows the modification of this solution, be that at the level of the whole system, or at individual level for each development, according to the user's option.

2. Convened Modeling Hypotheses and Input Data

Except for Siriu and Gura Apelor reservoirs, (operated at levels much inferior to the designed ones, unable to achieve adequate regularization), for each of the remaining eight developments consisting in a major reservoir and an associated hydro-power plant, an optimization analysis on the long term operation under probabilistic conditions concerning the affluent flows was performed, being the same type as the one presented by [1] on Izvorul Muntelui reservoir and Stejaru hydro-power plant.

In brief, such an analysis went through the following stages:

1. *Defining an optimization model for the long term operation taking into account the probabilistic nature of the mean monthly inflows*

A stochastic dynamic programming model was used, having as objective function minimizing the mathematical expectation of the sum of the squares of the differences between the planned monthly energies and the achieved ones, throughout a year. The monthly planned energies were imposed as fractions of the mean annual designed energy, with the fractions chosen so that they would represent 55% of the annual production in the season October-March, and 45% for the remaining interval of the year.

As operation restrictions, the following were imposed: obeying the balance equation of the reservoir stocks; keeping the reservoir volume ranging between the minimum and the maximum ones specified for each month, and insuring a monthly minimum outflow (for energy generation or for other uses).

For each month of the year, the affluent flows known from previous recordings were sorted out in 5 groups, and the representative flow in each class was determined, together with the associated probabilities of such values emerging again. Such data were used in defining the recursive functional equation of the dynamic programming model, in a probabilistic context.

By means of solving the functional equation, the table of the optimal decisions under probabilistic conditions is obtained. For each month of the year, and for various discrete values of the volume present in the reservoir at the beginning of the month, this table indicates the most adequate reservoir volumes at the end of the month, according to the objective function, to the restrictions and to the frequency distributions of the mean monthly affluent flows adopted in the model.

On basis of the respective table, the optimum probabilistic trajectories can be projected, (the monthly variation of the volume in the reservoir), corresponding to the different levels existing in the reservoir at the beginning of the year, but such a trajectory may, or may not rigorously occur in a current operation year, depending on the actual hydrological regime of that year.

2. *Imagining a long term operation simulation model based on the table of optimum probabilistic decisions*

If the optimum probabilistic trajectory cannot be followed one month, because of the actual affluent flow to the reservoir (which might lead to physically impossible situations, non-profitable from the energy perspective, or dissatisfactory for other users), then it must be adjusted according to a set of rules enforced as a whole. Briefly, the set includes the following:

- The monthly energy generation in the cold season should coincide with the amount planned, unless there is a decrease below the minimum admissible level, and/or the descent gradient imposed for the reservoir level is not exceeded.
- During warm season months, there should be at least a minimum monthly production, specified according to the amount required by the downstream users as well.
- In any month of the year, the generated energy should be limited to the planned amount, without exceeding the maximum level allowed in the reservoir.

• If one of the previous alterations leads to exceeding the level corresponding to the current month on the highest optimum probabilistic trajectory, (the level in the reservoir on the 1st of January being the normal retention level – NRL), then the supplementary water should be used, so that the required level should be reached, without exceeding turbine capacity, however.

• If turbine capacity were exceeded for one reason or another, the used flow should be limited to the respective value, without exceeding the maximum permitted level.

Therefore, the operation simulation model follows the optimum probabilistic solution, but corrects it in the months where the above rules do not apply.

3. *Verification of long term operation simulation model*

The operation simulation program designed for the previously described model was run month after month and year after year using the known monthly average inflows from the records. Seeing that long term mean performances (the mean annual energy production, the interval of time with operation levels close to NRL etc.) are better than the design estimations, it is only normal that the simulation algorithm should be incorporated in a decision support program for planning medium and long term operation.

4. *Decision support program elaboration*

The decision support program, naturally, includes the simulation model algorithm and forecasts the solution suggested by it, but it must also include user intervention opportunities, either for modifying some implicit data, or for imposing the desired/necessary energy production, etc.

The previously described stages were performed on each of the reservoirs with significant regularization potential, and the individual results were assembled in a support program at the level of the group of developments. For Siriu and Gura Apelor reservoirs, a very simplified scheme was used, which requires linear filling from minimum operation level (MOL) up to the maximum permitted level at that moment, in the interval April-September, and linear emptying in the season October-March.

Table 1 indicates some implicitly admitted data for the decision support program (DSP), such as:

• Planned annual energy, according to the design provisions.

• The maximum allowed volume in the reservoir (corresponding to NRL).

• The minimum volume, above which the capacity curve of the reservoir is specified.

• The ΔV step, by which the discretization of the volume was made in the probabilistic optimization analysis.

• The installed flow in the associated hydro-power plant (in the case of Stejaru hydro-power plant limits were set to the minimum installed flow from the downstream fall, for avoiding spills).

• Minimum level of energy generation operation.

• Minimum admitted monthly energy for the warm season months.

• Monthly outflow gradient allowed in the cold season, and

• Specific production estimated for all downstream hydro-power plants that use the water coming from the major reservoir.

Table 1

Implicitly admitted data for the DSP for the ten major reservoirs system

Reservoir	E_{plan}	V^{max}	V^{min}	ΔV	Q_{inst}	Z_{MOL}	E_{min}	ΔZ_{max}	e_{aval}
	GWh/y	mil.m^3	mil.m^3	mil. m^3	m/s	mdM	GWh/mo	m/mo	GWh/mil.m^3
Oaşa	250	126.1	7.1	1	40	1205	5	8	1.005
Fântânele	390	220	20	1	60	946.6	10	8	0.3407
Vidraru	400	464.77	41.17	3.53	90	740	10	8	0.6187
Drăgan	190	112	8	1	40	785	3	10	0.4708
Izv. M	422	1130	205	5	84	470	12	7	0.6331
Vidra	1080	340	42	2	80	1237	25	8	0.959
V. Iovan	120	124	4	1	39	612	3	10	0.5199
P. Măr.	137	96.2	7.2	1	55.4	555	5	12	0
G. Ape.	300	27.85	9.923	-	70	974.5	-	-	0.4767
Siriu	122	40	10.2	-	32	523.5	-	-	0.1077

Energy calculation is achieved by means of the specific production, and linear regression equations were searched for in the case of each reservoir, using the recorded operation data for the interval 1996-2006 on: the monthly average flow used, the monthly generated energy, and the average monthly level in the storage reservoir. In estimating the specific production for the downstream falls, the powers and the flows installed in the hydro-power plants were considered, which leads to an underestimation of production as compared to the actual real situation.

In the case of the first five reservoirs, the minimum allowed implicit level was limited to the safety level set by Hidroelectrica for each month and reservoir with an associated hydro-power plant cleared for system services. In the case of the reservoirs Valea lui Iovan, Drăgan and Poiana Mărului, the minimum allowed level was limited to MOL, and Siriu, together with Gura Apelor are operated on the previously described simplified scheme.

The capacity curves were introduced by pairs of values (*Z*, *V*) between which linear interpolations are performed.

3. On DSP interface Program

For beginning to run, DSP requires: the desired name of the folder with witness results, the current month for which the analysis is being performed, and then the level existing in the reservoir at the beginning of the month and the anticipated affluent flow for each of the 10 reservoirs in the system (figure 1).

Then, for each development and for the whole system, the program shows: the amounts of energy that can be generated in the respective hydro-power plant and in the downstream fall from that outflow (reservoir operation at a constant level); amounts of energy lying in the stock above the safety levels (MOL) possible to be generated in that specific hydro-power plant or on the downstream fall, as well as the sum of all these energy amounts. Such information proves useful to the user for orientation, if he does not accept the solution suggested by DSP (figure 2).

Then the solution suggested by the optimization model is posted, and, for each reservoir, it includes: the initial level and the monthly average affluent level (entry data); the average monthly flow used; the level in the reservoir at the end of the month; the minimum allowed level in the reservoir at the end of the month (and the monthly planned energy – implicit data); energy amounts generated in the associated hydro-power plant, on the downstream fall and the total amount for the development; the monthly average power for the development and the reservoir filling degree at the end of the month. As well as these, the amounts of energy produced by the system are posted, in its own hydro-power plants, on the falls and as a sum (figure 3).

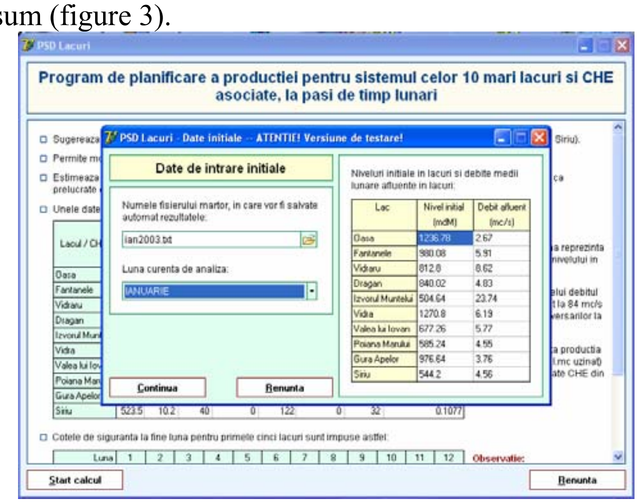

Fig. 1. Implicitly admitted data for the DSP.

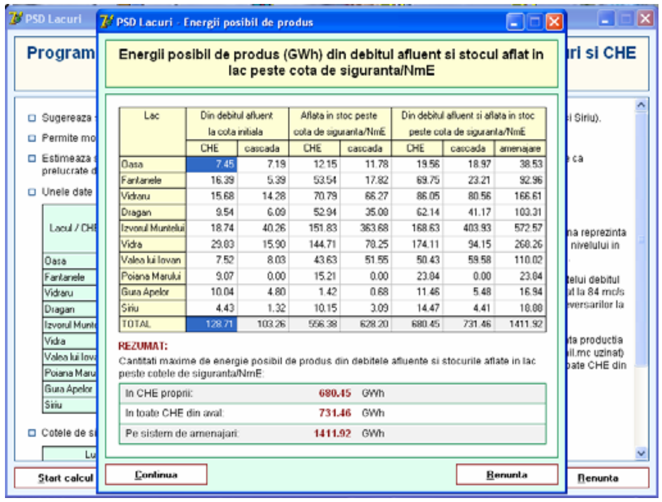

Fig. 2. The amounts of energy that can be generated in hydro-power plants.

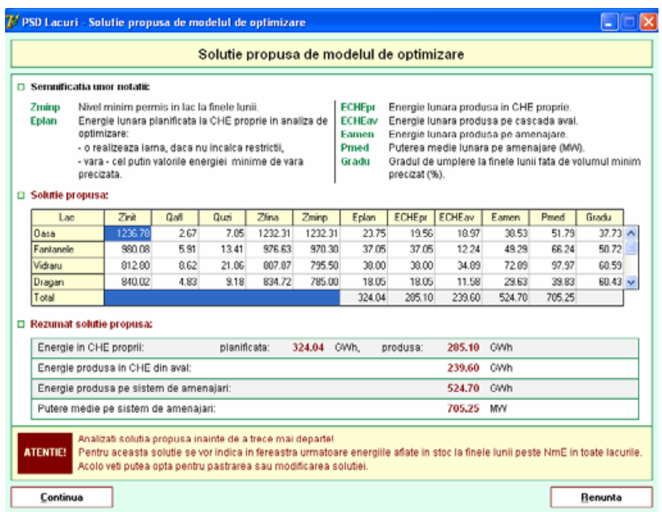

Fig. 3. The solution suggested by the optimization model.

The next stage is to announce the amounts of energy in stock at the end of the month, on hydro-power plants, on developments, and on the whole system and future options are provided:

- **A.** If the solution suggested by DSP is convenient, the program allows going on to the analysis for the next month and requests introducing data on anticipated affluent flows or termination of the analysis process.
- **B.** If the solution suggested by DSP is not convenient, two alternatives are possible: increasing or decreasing production at the level of the whole system

according to a personal algorithm, or individual modifications for those developments in which it is desired and in agreement with the user's option.

Figure 4 shows such a situation for Oaşa reservoir and Gâlceag hydro-power plant. The initial data and the results suggested by DSP are posted, but energy generation increase was requested, so as to reach the planned value. We can notice that the program issues a warning on the decrease below the safety level under these circumstances.

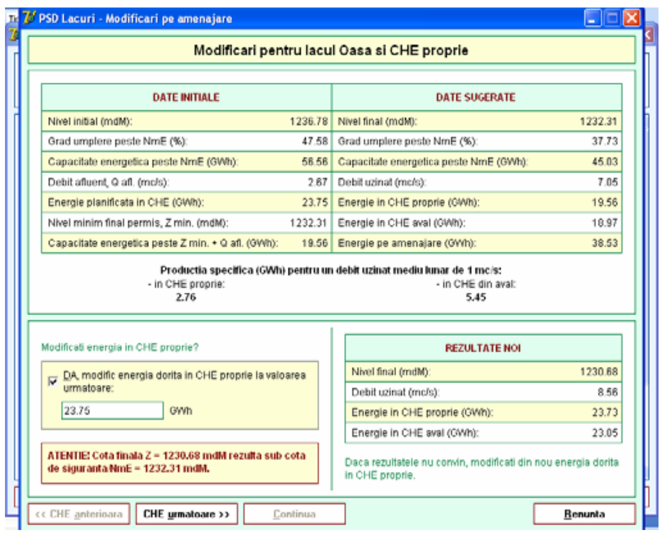

Fig. 4. Situation when the solution suggested by DSP is not convenient.

After posting the modified solution, the analysis of the next month is possible, or the program run can be stopped.

The modification algorithm for the system centers on the idea of additionally generating in each hydro-power plant an amount of energy commensurate with the energy in stock above the minimum allowed level, as compared to the total capacities of the whole system (increasing production).

If decreased production is the target, as compared to the one suggested by the program, the algorithm shows diminishing the energy amount commensurate with the capacity of the empty volume up to NRL, as compared to the total capacities of the whole system.

DSP enables screen visualization of the witness folder, editing it, printing it, as well as other facilities for the user, this presentation focusing only on some of the dialogue boxes.

4. Numerical Applications and Conclusions

The runs by DSP using recorded operation data demonstrated that it reflects reality accurately enough. After some calibration operations, the program could be successfully used for production planning in this system of big developments, in various scenarios of anticipated average monthly affluent flows.

In order to illustrate this by a numerical application, a sequence formed by the first three months of 2003 was taken into account, and DSP was run, starting with the levels existing in the reservoirs on January the 1st indicating the average monthly affluent flows reported in the operation.

Table 2 presents only the energy generation in their own hydro-power plants achieved in operation, E_{op}, and, respectively, suggested by DSP, E_{DSP}, (in GWh).

Table 2

The energy generation in the HPP achieved in operation and suggested by DSP, in GWh

Reservoir	January		February		March	
	E_{op}	E_{DSP}	E_{op}	E_{DSP}	E_{op}	E_{DSP}
Oaşa	9.78	19.56	13.08	13.26	4.04	20.92
Fântânele	21.70	37.05	33.67	35.05	32.34	36.84
Vidraru	23.20	38.00	22.49	35.95	20.60	37.91
Drăgan	10.00	18.05	19.80	17.05	13.90	16.88
Izv. M	42.11	40.09	39.68	37.98	38.90	39.95
Vidra	44.82	102.60	54.94	92.51	46.55	75.87
V. Iovan	4.45	11.40	10.06	10.80	7.63	11.40
P. Măr.	3.64	0.00	13.59	12.29	5.03	12.86
G. Ape.	6.80	10.52	7.92	6.92	5.62	7.15
Siriu	6.86	7.83	3.48	5.95	5.81	10.62
TOTAL	173.36	285.10	218.71	267.75	180.42	270.41

By summing up on trimesters, in actual operation, 572.5 GWh were achieved, and DSP suggested that 823.3 GWh could be produced, without falling below safety levels or MOL in any of the reservoirs, but on the contrary, enabling them to more effectively take in high waters in the next trimester.

At the level of the system of developments (their own hydro-power plants and falls), in running with the operation energy amounts imposed in big hydro-power plants, 1104 GWh resulted, and, in running with the solutions suggested by the model, 1520 GWh resulted, for the first trimester.

Therefore, DSP suggested an operation program that increased system production by over 37% as compared to the real actual production, obeying the hydro-energetic requirements and the ones regarding the rational management of water resources.

5. Conclusion

As a conclusion, the decision support program could be a useful instrument in long term energy production planning in the system we have discussed. It can be run using various scenarios of affluent flows. The current month policy can be updated every week or every 10 days, on basis of adjusted forecasts regarding the average monthly affluent flows, and, in the case of multiple months planning, the operation solution will be monthly updated, using the latest hydrological information.

R E F E R E N C E S

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