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DEVELOPMENT OF A DECISION SYSTEM SUPPORT BASED ON GENETIC ALGORITHMS FOR THE OPTIMAL OPERATION OF HYDROELECTRIC POWER PLANTS ON THE DAY AHEAD MARKET

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The River Olt hydropower cascade has a major role in National Energy Grid. The cascade has certain advantages compared to any other energy production systems. Because of the configuration of the lakes, it has the ability to accumulate hydraulic energy for different periods of times in order to regulate the flow downstream. They respond excellent at energy demand and provide reliable and quality grid services when needed. This paper presents a new method to improve the operation of the cascade in order to increase the economic efficiency on the spot market.

Keywords: optimization, genetic algorithms, hydro power plants

1. Introduction

Water is one of the most important natural resources available in the world. Every modern society and economy uses the water for multiple purposes: supply for population, irrigation for agriculture, industrial applications, electrical and thermal energy generation. The quantity and quality of water are two parameters of high importance. Because of the continuous increase of water needs in the last years, different techniques have been developed and successfully applied in order to optimize the use of the resource. These techniques used for reservoir and multi-reservoir water systems, have been created and then improved in order to enhance their performances (better, faster and reliable results) [1],[2]. In the specific literature different optimization techniques are available: dynamic programming (DP), nonlinear programming (NLP), linear programming (LP), fuzzy logic (FL), genetic algorithms (GA) etc. Determining the optimal strategy becomes more challenging when operating a large number of reservoirs with multiple uses because of the complex mathematical model required, which

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becomes difficult to solve by classical methods. Therefore, two typical approaches have been widely used: mathematic programming and the artificial intelligence. The Genetic Algorithm (GA), included in the artificial intelligence optimization approach, has been used successfully in reservoir optimization [3-5]. Although represents an effective method for searching through the optimal solutions domain, some difficulties such as premature convergence and infeasible solutions still occur in solving constrained nonlinear optimization problems of reservoir operation. In order to improve the results, researchers have enhanced the main algorithm with specific methods like use of constrains (penalty functions, restrictions in solutions, etc.) and the use of GA in addition with other optimization methods and techniques [6-11]. This paper presents the results obtained by a Decision System Support (DSS) based on genetic algorithms, developed in order to generate solutions for the optimal operation of River Olt cascade of hydroelectric power plants. The performance of the GA was enhanced by the use of penalty functions and restrictions for each possible solution. The penalty functions were applied for the spilled volumes of water (in order to minimize energy lost) and for the final levels in the lakes (an important condition for the lakes operation schedule). The approach selected for the management of penalty function values, is to start with an initial value and to increase it, according to the penalties obtained for not reaching the targeted levels in the lakes at the end of the day. The scope was to obtain within few iterations of this value the given levels in the lakes, with zero penalties for the final solution. The main objective of the developed system is to determine the best operation scenario that will comply with the current market condition on a day-to-day basis. In order to demonstrate the importance of the energy market, this paper presents the results of two different optimal scenarios with different objectives: producing the maximum energy and generating the maximum income. The two objectives are very different, at a fundamental level, in terms of "when" and "how". Having the same initial conditions (hydrological regimes, configuration of the cascade, levels in lakes, etc.), when maximizing the energy production, the operation scenario must keep the highest possible levels in the lakes in order to assure the maximum available head (*how*). Any decrease of the level in the lake will reduce the head and therefore the output power. In order to generate more income, the most important aspect is *when* the energy is produced within the day, and the algorithm has to plan the energy production in the trading intervals with the higher prices in order to assure a the highest economic efficiency.

2. The day ahead market

The Romanian Electricity Market Operator (OPCOM) manages different markets for electrical energy trading: the day-ahead market, the intra-day market and the centralized market for electricity bilateral contracts, with the goal of developing a competitive and transparent environmental for the participants. The most competitive market on OPCOM platform is the Day Ahead Market (DAM – called also the Spot Market). DAM is part of the electricity wholesale market where firm quantities of energy are traded for each trading interval (one hour) of the corresponding delivery day – the next day. Every participant is offering, for every trading interval, a quantity of energy and an asking price. OPCOM then establishes based on the received offers correlated with the energy demand estimations, the Market Closing Price (MCP) for every hour, which represents the final price given to every participant accepted within the energy demand. [12].

3. Mathematical model

In order to develop the DSS, a mathematical model was necessary to elaborate for the GA optimization for both objectives described before. Examples were used from the technical literature [13] as shown in Fig. 1.

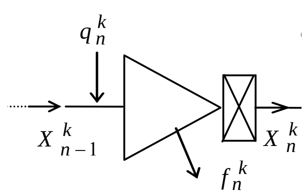

Fig. 1. Notations used for power plant mathematical model

The parameters noted in Fig. 1 are: q_n^k - affluent volume for hour k for the remaining hydrographic basin in lake n; X_n^k - effluent volume from lake n in hour k; f_n^k volume of water used for other purposes . Furthermore, the water volumes equation for each lake is presented by equation (1):

$$V_n^k = V_n^{k-1} + X_{n-1}^k + q_n^k - f_n^k - X_n^k \tag{1}$$

The effluent volume from each lake, the solution of the problem, is made of the volume used for power generation noted T_n^k and the spilled volume noted D_n^k in equation (2):

$$X_n^k = T_n^k + D_n^k \tag{2}$$

Constrains were considered according to technical limitations. The effluent flow from the lake must be positive or zero according to equation (3):

$$X_n^k \geq 0 \tag{3}$$

The volume used for power generation must be between minimum usable flow per turbine and maximum installed discharge per power plant, equation (4).

$$Q_{\min} < T_n^k < Q_i \tag{4}$$

The equation (5) computes the output energy, for each time step, k, for each power plant *n*, based on the formula of hydraulic energy. Depending on the level in the lake and the level downstream the gross head is computed. Estimation for the net head is based on the term related to the used flow (volume) for energy generation:

$$E_n^k = a_n \left[b_n \left(V_n^{k-1} + V_n^k \right)^{c_n} - Z_{av} - d_n \left(\frac{X_n^k}{Q_n} \right)^2 \right] \cdot T_n^k \tag{5}$$

The constants a_n, b_n, c_n and d_n are determined for each lakes from the capacity curves obtained from special measurements (Fig. 2 – blue line). The red line was determined by mathematical analysis of the measured data in order to create a mathematic relation between the volume in the lake and the level only between the minimum and the maximum allowed levels in operation, to enhance the precision of the equation to reflect exact situation. The restrictions in the levels are according to the technical limits of each lake.

The first objective is to maximize the energy production. This is achieved by using the equation (6):

$$\max \left\{ Energy = \sum_{n=1}^{N} E_n^k \left(\overline{V}_n^k, T_n^k \right) \right\} \tag{6}$$

where E_n^k is computed according to equation (5), for every power plant and every time step, as defined previously depending on the average level $\overline{V}_n^k$ (per time step) and flow (volume) used for power generation T_n^k

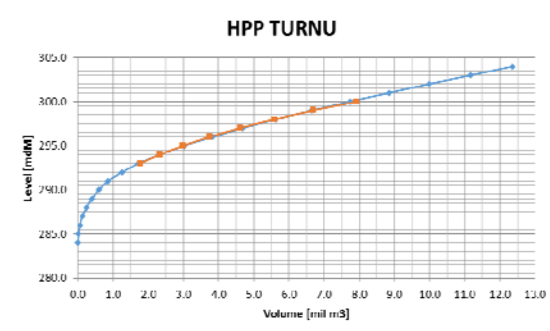

Fig. 2. Capacity curve for HPP Turnu

The maximization of the generated income is achieved by planning the energy production according to the specific conditions of the DAM, in the most expensive trading intervals in order to achieve the best economic data. Therefore, equation (6) was modified in order to take into consideration the prices offered, into equation (7):

$$\max\left\{ Income = \sum_{k=1}^{24} p_k \sum_{n=1}^{N} E_n^k\left(\overline{V}_n^k, T_n^k\right)\right\} \tag{7}$$

The parameter p_k in the mathematical model represents the **M**arket **C**losing **P**rice (MCP) for each trading interval. In Fig. 3 is presented the MCP for the data used in the simulations:

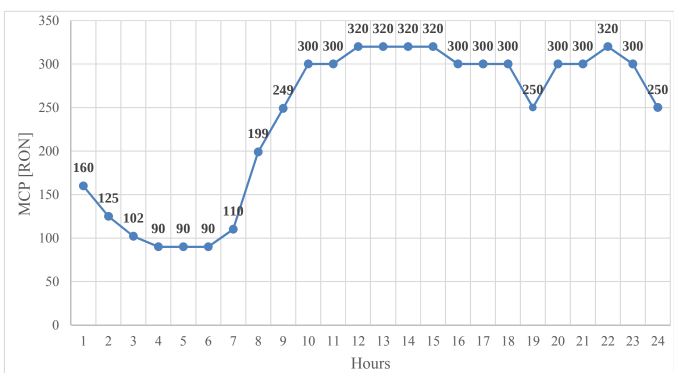

Fig. 3. Market closing prices on DAM

4. Optimization program

The DSS, has two subprograms corresponding to each objective. The algorithms were developed under Pascal programming environment and have a set of parameters which are specific to any GA such as: selection type (roulette wheel, tournament, normalized geometric sorting), mutation type (boundary, non-uniform) and crossover techniques. Multiple simulations were completed with different sets of input data (various hydrological regimes, different levels in the lakes, different MCP on the DAM, availability scenarios, etc.) in order to determine what are the best parameters for the GA program to converge fast to reach an optimal solution. The results presented in this article, were obtained heuristic crossover, boundary mutation and normalized geometric sorting. Other parameters of the algorithm used in the simulations, can be adjusted in order to tune up the DSS, like crossover probability - 0.8, mutation probability - 0.03 or maximum generations used - 4000. The algorithm has the ability to compute the solutions based on different time steps. As shown above, the time step is correlated to the trading interval of the DAM - one hour, but can be also modified to be higher, for example 2 – 3 hours or even more. The decision of selecting a different time step for the simulations belongs to the administrator of the cascade and can be economical or technical. From the operation and maintenance experience, also confirmed by different studies in the modern literature [14] and presented in other articles by the author [15], when starting and stopping a hydro unit, fatigue of the mechanical parts is increasing. Therefore, for the purpose of this paper, a three hour time step was considered. For the middle sector of Olt River, (15 power plants), a total number of 120 variables of decision are required (effluent flows from each lake per each time step). Also for this paper, because time was not an issue, a higher number of generations were used to compute the optimal solutions (24000). When a higher number of generations are used and some iteration are needed to assure zero penalties as specified before, the necessary time for simulation is increasing considerably to more than 5-10 minutes. However, this is not a very long period, but when this system is used to test different scenarios of the market data, different input data, the process of determining the final solution can take some consistent time until the final approval of operation scenario. In order to reduce the simulation run time, fewer generations can be considered that will lead to also finding an optimal solution. The equation system used for the algorithm was determined by applying the equations described above, to the cascade between Gura Lotrului HPP and Arcesti HPP (Fig. 4 and Fig. 5):

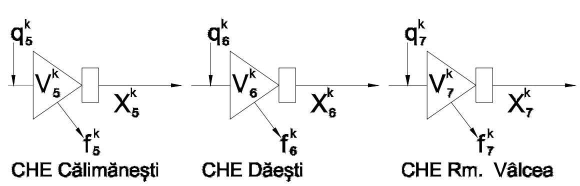

Fig. 4. Example of HPP cascade layout used for the cascade operation simulation

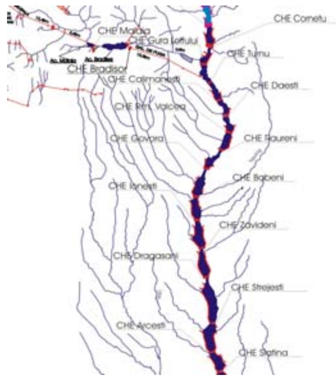

Fig. 5. River Olt HPP cascade used for the cascade operation simulation

5. Results

The presented results are based on the same initial conditions: levels in the lakes, availability of power plants, inflows, hydrological data and technical data of the turbines, equipment availability and market conditions. The levels at the beginning of the day are the same as the levels at the end of the day, while a hydrological regime below average conditions was used. These values can be changed if the policy for operation on weekly basis is to lower or to raise the levels in the lakes, based on different operation considerations. A special rule was imposed to the algorithm in order to comply with this request; the level in the lakes must decrease until middle of the day (to produce energy and allow the accumulation of water for evening hours) and then has to increase in order to achieve the end volume given. A penalty function will amend if the level at the end of the day will be different than the given one. This penalty function is adjusted during different iterations in order to obtain the requested levels.

The hydrological regime (inflows in the first lake) is presented in Table 1.

Table 1

Hydrological regime at the first lake of the cascade

Time step	1	2	3	4	5	6	7	8
Flow [m^3/s]	35	35	165	165	35	165	165	35

The average energy price for the entire day according to the data in Fig. 3 is 238.13 RON/MWh. The operation scenario for objective 1, presented in Table 2, is generating an energy production of 9321.96 MWh with a gross income of 2,424,270 RON, an average value of 260.06 RON per generated MWh is obtained. The operation scenario for objective 2, presented in Table 3, is generating an energy production of 9,241.32 MWh, but a gross income of 2,901,130 RON which gives a better economic efficiency. The average price obtained for the energy is 303.11 RON/MWh.

Table 2

Operation policy – energy maximization examples

Time step	HPP 2 [MWh]	HPP 3 [MWh]	HPP 9 [MWh]	HPP 11 [MWh]	HPP 13 [MWh]	HPP 15 [MWh]	Cascade [MWh]	Income [thousand RON]
1	159.62	13.46	16.72	14.62	0.00	0.00	554.03	71.47
2	190.33	0.00	0.00	62.50	88.12	46.28	715.04	64.35
3	155.77	29.37	14.15	54.83	228.83	49.48	1,077.99	200.51
4	132.39	28.46	55.76	51.26	365.62	54.63	1,379.71	423.11
5	139.59	18.52	61.31	51.09	449.23	58.16	1,317.81	421.70
6	0.00	27.45	63.03	54.98	505.01	61.83	1,278.35	383.51
7	0.00	38.58	106.89	62.44	555.39	73.08	1,514.61	429.13
8	0.00	18.68	132.55	65.27	617.41	80.9	1,484.42	430.48
Total	777.70	184.52	450.41	416.99	2,809.61	424.33	9,321.96	2,424.27

Table 3

Operation policy – income maximization

Time step	HPP 2 [MWh]	HPP 3 [MWh]	HPP 9 [MWh]	HPP 11 [MWh]	HPP 13 [MWh]	HPP 15 [MWh]	Cascade [MWh]	Income [thousand RON]
1	0.00	7.44	0.00	0.00	0.00	0.00	7.44	0.96
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	36.08	0.00	0.00	0.00	0.00	220.60	41.03
4	330.37	42.91	75.74	62.17	789.49	70.93	2,508.46	769.27
5	343.75	31.88	132.65	118.07	789.40	113.63	2,788.07	892.19
6	100.95	13.83	131.69	103.55	789.10	101.87	2,200.03	660.01
7	0.00	30.21	0.00	48.29	0.00	50.26	326.82	92.60
8	0.022	18.82	103.32	78.00	431.49	81.17	1,189.90	345.07
Total	775.07	181.17	443.40	410.08	2,799.48	417.86	9,241.32	2,801.13

The second operation scenario generates a slightly smaller energy compared to the first one. The main reason is the variation of levels in the lakes that concludes in smaller operation heads, and therefore a limitation of output power. The second operation scenarios, is giving the best solution in terms of revenues mostly because a higher energy production is distributed during the most *expensive* trading hours on the Day Ahead Market. The comparison between the two scenarios is presented in table 4.

Table 4

Energy production comparison

Objective	Energy [MWh]	Income [RON]	Average Energy Price [RON/MWh]
Energy Maximization	9,321.96	2,424,270	260.06
Income Maximization	9,241.32	2,901,130	303.11
Difference [%]	-0.87%	+19.67	+16.55

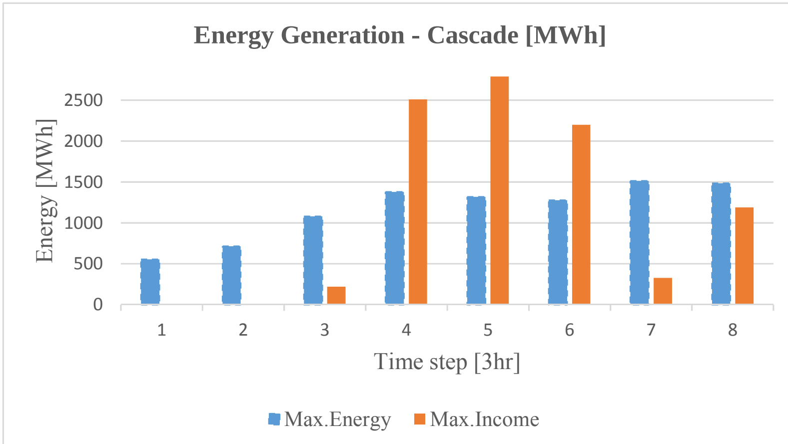

Fig. 6. Energy Production for the day

6. Conclusions

The operation policy that maximizes the economic benefit by planning the energy generation according to the DAM offers very good results compared to the other scenario from the financial aspect. The presented results have the scope of exemplifying the ability of the proposed DSS based on GA, to establish feasible operation scenarios that are able to improve the financial data of the energy generation. The developed system can be used to determine operation scenarios for every type of cascade. The main conclusion of this paper would be to produce "clever" and "expensive" energy rather than "efficient" energy if we take into consideration that the same volume of water is used. The main part for the cost of production, the used water (1.1 RON/1000 m^3) has an important impact on this cost. Therefore the optimal scenario for income maximization generates the best operational profit (EBITDA) and will increase the economic value of the administrative company. The new DSS was improved consistently to give better results as compared to results obtained by the author according to [15]. The repeated subprograms developed to have different penalty function which is increased according to each loop gives better results in term of overall penalties (which generally occur because some restrictions are not fully respected). For the results obtained with this method, there are no penalties for the final solution, leading to a full compliance to technical restrictions of operation.

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