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Maximizing Income of a Cascade Hydropower with Optimization Modeling

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P A P E R I N F O

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A B S T R A C T

This paper focuses on the short-term cascade hydro scheduling problem, especially in a competitive environment, namely in market conditions. A nonlinear stochastic optimization method is proposed to take into consideration the hydroelectric energy production as a function of hourly electricity market prices and water release rates. In order to solve a case study based on one of the Turkish cascaded hydropower facilities, the proposed method has been successfully applied to a wide variety of problems at a negligible computation time while providing a higher profit. The paper shows the benefits that could be achieved by applying a model based on the Quasi-Newton Method, which finds zeroes or local maxima and minima of solving a certain type of optimization functions because it can better handle the uncertainty, constraints, and complexity of the problem. Ten-year hourly water inflow data and electricity market prices were used as inputs, and the results of the cascade and single optimization were compared. A comparison study with the operation of each hydropower plant (HPP) separately showed that 18 % higher income was obtained with a cascade variant.

1. INTRODUCTION

Electrical energy has become one of the essential souls of developed and developing countries. Electricity can be generated from several kinds of energy sources that are basically listed into two groups as non-renewable and renewable. The efficient usage of renewable (clean and environmentally friendly energy option) energy resources these days is becoming considerably more important because of the limited non-renewable resources [1].

Hydropower is the most widely used renewable power source [2]. This paper aims to develop a control model scheme for cascade hydropower. The term cascade represents a series of hydropower plants (minimum two or more) located upwards the same river or in the same river basin. These energy facilities are hydraulically connected such that the water flows from the upstream powerhouse influencing the storage of the following downstream hydropower house. Therefore, the water flow rate from each power facility should be regulated to prevent needless discharge and overflow, keep the heads as high as possible, and manage reliable reservoir level and inflows.

Since many hydropower facilities are located on the main streams as a cascade, especially in a market environment, the operational optimization has turned into an important issue. During feasibility studies, the rate of return (IRR) is the main element of the initial investment selection and decision and, during the operation, the optimized use of sufficient water and related infrastructure is of great significance. From this perspective, instead of a random (classical) operation, a scheduled operation should consider uncertainties, and including defined constraints will increase the total income by the year-round electric energy production.

Because every hydropower facility and system can be different, each one has its own control schemes according to particular systems, regions, and operating objectives. There are various optimization functions and models that can be examined for various demands and purposes [3,4,5,6]. Mathematically solving the optimal control problems by means of nonlinear-programming (NLP) techniques and simulation for the purpose of investigating the effects of maximizing the income reviewed with reference to several kinds of literature. For a given purpose, they can have significantly differing abilities to perform and solve complexity [6]. In the literature, there are different optimization methods and algorithms available that have been successfully developed for solving optimization problems. It can be classified into two major categories of optimization algorithms widely used today: mathematical programming methods and heuristic search methods [7,8]. The first group covers mixed-integer linear programming [3,4,9,10,11], nonlinear programming [6,12], dynamic programming (DP) [13], and other methods. The second group includes genetic algorithm [4,14] and simulated annealing algorithm. After reviewing the literature, determining which variables are important and how those variables should be formed and optimized is an important designing decision and selection that diversifies in line with the scope of the suggested control strategy. Even though these methods have been shown to be successful in many different cases, there are certainly some disadvantages that cannot be neglected and programmers need to consider when resolving large and complicated HPP operation difficulties such as the incapability to address nonlinearity problems, long execution time, and high amount of memory utilization [9].

The main objective of this study is to maximize income by electricity generation for a cascade hydropower through a non-linear constrained optimization algorithm under the market conditions. From this point of view, the hydraulic design [15] of a cascade is investigated [5,6,16,17].

The data of the hourly water inflows to the reservoirs and electricity market prices [18] are studied. In this paper, a

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stochastic optimization approach is proposed for short-term operation planning of the power plant. The time-variant renewable generation based on conditional probabilities of the water inflow and electricity market price values are considered as stochastic variables. It has been proved that the problems of predicting random variables with multi-attributes can be solved better by Artificial Neural Network (ANN) than traditional methods [19].

On different types of hydro scheduling, for example in [20], a non-linear model represents the features of hydroelectric energy production more accurately and takes into account the head dependency of short-term optimal hydro generation scheduling, but water inflow uncertainty is entirely neglected as in most short-term optimization studies [21]; further, similarly, in [22], the determined linear programming model takes into account hourly water flow rates so that it can estimate the uncertainty limited by the volatility of electricity market prices.

In the previous work [23], on optimal hydro scheduling on a single dam operation and feasibility studies was established. Here, this study considered two or more dam operations at minimum and operation management.

The current section clarifies the scope and purpose of this study. Also, it presents the problem statement and compiles relevant literature sources in a review format. The structure of the remaining paper is organized as follows. The optimization process and the objective function formulation of the decision variables subject to constraints for power production and its formulation in MATLAB are explained in Section 2. The third section gives a brief description of chosen power plants as the case study with the optimization procedure. Also, this section shows the results of multi-objective optimization by the proposed algorithm for a real-world hydroelectric power plant (HPP). Finally, the last section concludes the paper and discusses and points out future challenges.

2. PROBLEM FORMULATION

The optimization scheme mainly pictures the efficiency degree, especially for the relationship among the head pond, turbine discharge, water inflow, and power plant generation in the market conditions by taking into account uncertainties. The profit has a stochastic nature and is subject to the electricity market price. Another important assumption is that these hydropower plants are hydraulically coupled cascade water storage systems, where the upstream power plant affects the water level of the reservoir of the downstream hydropower plant. Therefore, the size of reservoirs, as an essential factor in this study, is relatively not large, and the constraint concerning reservoir water level, both upstream and downstream, must be taken into account. Thus, in an overall case, energy generation is directly related to the structural and functional net effective head, where water level fluctuations affect the generating units.

The profit of each power plant can be expressed as follows:

$$Pr = \sum_{t=1}^{T} c_t . p_t - o_t \quad (1)$$

where c_t is energy market price at time t ($/kWh); p_t is energy generated at time t (kWh); T and t is set and index of production hours in the scheduling horizon and o_t is variable operational costs.

It is assumed that the variable cost of production for HPP operation ranges from 1 % to 4 % of the investment costs per kW per year; in further calculations for our case study as small hydropower, operation cost is assumed to be 2.2 % of the annual income [24].

2.1. The objective function

The optimization process can be conducted after water inflow data, and the electricity market prices for the next day are known. A simplified structure of the power plant optimization algorithm is shown in Figure 1. Also, a model based on Artificial Neural Network (ANN) can be used to predict variables and the advantages of the ANN, making it highly suitable for certain problems [23]. In this study, the historical data including 10-year hourly water inflow data and electricity market prices were used as inputs, and results of the cascade and single optimization were compared.

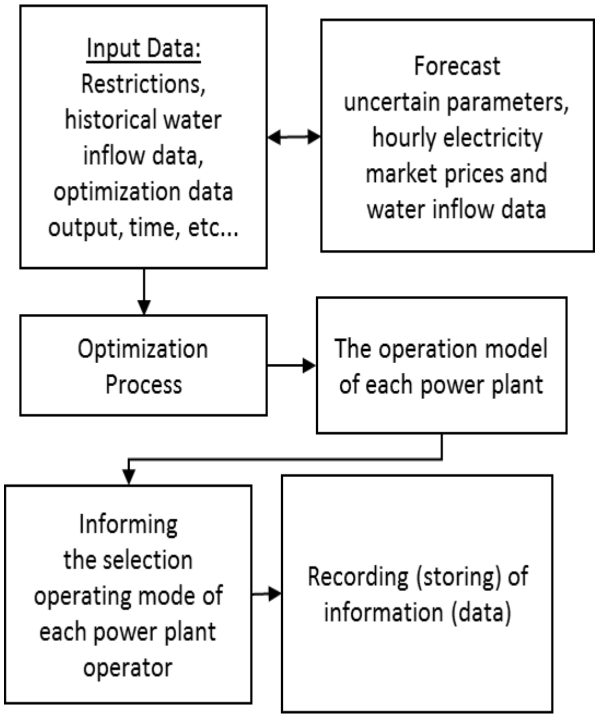

Figure 1. Structure of the cascade power plant optimization chart.

The objective of the hydropower plant is to maximize its own profit in an electricity market, where the total operating costs are subtracted from the revenues. The operating costs consist of generation costs and start-up costs. In this paper, the start-up costs and production/maintenance costs are fixed as 2.2 % of the annual income. Since the price of generated electricity is given on an hourly time scale, it is proposed that the objective function based on variables be considered on an hourly basis as follows:

$$R[f] = \sum_{z=1}^{2} R[f_z] \rightarrow \max \quad (2)$$

The mathematical formulation of the problem is summarized as the generated electric power P [W] is related to the potential energy of the (constant) water head H [m]; then, we have:

$$f_z = QgH\eta; \quad (W) \quad (3)$$

where

$$\eta = \eta_{trb} . \eta_{gen} . \eta_{trn} \quad (4)$$

Head is a vertical change in elevation defined as a function of storage.

$$H_t = L_t^{bgn} - Q_t^{usd} + w_t^{inflw} \quad (5)$$

$$L_t^{bgn} = L_{t-1}^{bgn} \sum_{u,\in U_t} Q_{ut}^{usd} + S_{ut}^{spl} \quad (6)$$

$$Pr = \sum_{t=1}^{24} c_t(P_t^A + P_t^B) \rightarrow \max \quad (7)$$

Water storage constraints: note that we did not take into account evaporations from the reservoirs. The lower and upper reservoir bounds traditionally show the adequacy of available water.

$$h_z^{min} \leq h_{zt} \leq h_z^{max}; \qquad z \in Z \quad (8)$$

Water discharge constraints across the time horizon with lower and upper bounds:

$$q_z^{min} \leq q_{zt} \leq q_z^{max}; \qquad z \in Z \quad (9)$$

Generated power constraints: Generated power has minimum and maximum bounds:

$$0 \leq P_{zt} \leq P_z^{max}; \qquad z \in Z \quad (10)$$

Water spillage constraints: Environmental flow requirements are considered. The environmental flow determined and recommended by the State Hydraulic Works General Directorate is at least 10 % of the 10-year average lead [25,26].

$$s_{zt} \geq \%\, 10.\, w_t^{inflw}; \qquad z \in Z \quad (11)$$

where Pr is profit; z is index of HPP in the cascade; t is hour; g is gravity acceleration (9.81 m/s^2); u is upstream power plant; η_{trb} is turbine (mechanical) efficiency; η_{gen} is generator (electrical) efficiency; η_{trn} is transformer (electrical) efficiency; H is the net head; c_i \$/MWh is the price for 1 MWh during the tth hour; L_t^{bgn} is initial level of water in the reservoir; Q_t^{usd} is water through the turbine(s) for the tth hour; w_t^{inflw} is water inflow rate in the river for the tth hour; Q_{ut}^{usd} is water discharge of upstream plant at time t; S_{ut}^{spl} is the water spillage of the upstream reservoir at time t; P_i^A, P_i^B MW is unknown electrical powers of HPPs for the tth hour; h_z^{min} is the minimum storage; h_z^{max} is the maximum storage; q_z^{min} is the minimum discharge; q_z^{min} is the maximum discharge, P_{zt} is generated power for the tth hour; P_z^{max} is maximum producible power; s_{zt} is the water spillage for fish gate in hour t.

The travel time "t_z" between reservoir "z-1" and reservoir "z" is normalized by the optimization time step t_z. The distance between the HPPs is approximately 6 km. Due to the short distance and based on the information taken from operators in this work, it is implicitly set that $t_z = 15$ mins.

Herein, η is the total efficiency rate that consists of turbine, transformer, and generator efficiency; it is taken as η= 0,89 as a real data [27] and, in principle, these values for production are not so variable and, thus, an average is of little significance.

This paper poses a question to answer: "How to perform a cascade hydropower analysis using short-term optimization and ensure profit maximization?" The optimization goal is to maximize the benefit of produced energy according to electricity market conditions.

Many optimization techniques have been successfully performed in reservoir operation studies that are summarized and referenced in the first section. Meanwhile, linear [28,29] and non-linear optimization methods are extensively used and reported by researchers [30] as a powerful technique to optimize water resources. In this research, the Quasi-Newton method is used to optimize the cascade hydropower reservoir system; the objective of optimization is to maximize the income by power generation on a daily basis (24h). The necessary data for optimization are given below:

- Maximum and minimum reservoir levels/elevations (Equation 8)
- Power plant efficiency (Equation 4)
- HPP and unit(s) operation constraints and limitations (Equation 5)
- HPP maximum and minimum load (Equation 10)
- HPP restricted zones at different reservoir levels (Equation 11)
- Turbine discharge (Equation 9)
- Electricity market prices.

3. RESULTS AND DISCUSSION (CASE STUDY)

This section presents an effective scheme for real-time operation on the Turkish hydropower system. The system consists of two reservoir types of the hydropower plant along the Karaman River in Posof, Ardahan city. The aim of the research is to analyze performance improvements while optimizing real-time operations. The formulation of the objective function is to maximize the sum of income by each hydropower plant.

A real-world cascade power plant with separate dams as a case study is examined. Then, there is an opportunity to compare the results by a single dam operation. The operation of the HPPs is subject to several constraints due to safety and environmental issues. Table 1 below summarizes the technical specifications of the HPPs. During optimization studies, all these constraints are taken into account. Both power plants have 2 turbines, while the installed capacity of Sogutlukaya HPP is 6.1 MW/h, Merekler is 11.2 MW/h. Although the hydroelectric power plants are in the same river, the amount of energy to be produced is different due to the different levels of heads and Merekler HPP feeds by two rivers. The following table shows rated discharge as 4.5 m^3/s and rated head of turbine discharge as 11.1 m^3/s, with wicket gates in a fully open position to meet the rated power capacity.

Table 1. The characteristics of hydropower plants on River Karaman.

HPP	Number of units	Rated discharge	Rated power	The heads
Sogutlukaya (Posof III) HPP	2	4.5 m^3/s	6.1 MW/h	155 m
Merekler weir and Alagolu HPP	2	11.1 m^3/s	11.2 MW/h	115 m

An illustration of a cascade hydropower system is shown in Figure 2, where downstream reservoirs are fed by the release from the upstream reservoirs and, additionally, the second reservoir is also fed by an intermediate flow.

Generally, the highest observed electricity prices correspond to the hours when generation is at its highest capacity; it can only be influenced by reservoir size and level. It is a great opportunity that hydropower plants can be employed by increasing their energy generation during periods of peak loads, reducing the need for the dispatch of expensive natural-gas power plants and reducing the overall system costs. In other words, HPPs represent the insurance for Turkey's electricity. Each power facility operates in line with the scheme shown in Figure 3. The optimization results and water level statistics in reservoirs are shown in Figures 4 and 5, respectively.

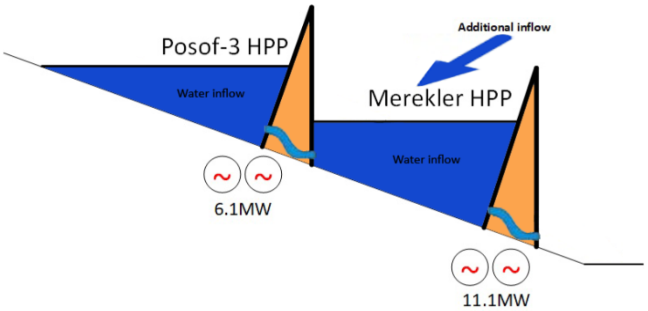

Figure 2. The illustration of the studied cascade HPPs.

Figure 3. Disposition of the system of cascade HPPs on the lower part of the River Karaman.

Figure 4 shows the generated power (MW/h) in Posof HPP and Merekler HPP and electricity market prices (EUR/MWh). The method stores energy in the form of water in the reservoir during off-peak time. During the peak demand for electricity, the stored water is released from the reservoir through turbines. In this way, energy can be stored so that it can be released quickly when needed.

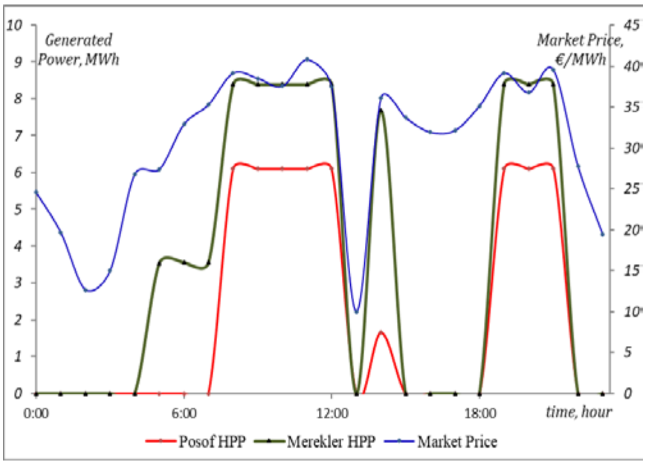

Figure 4. Dispatch schedule of the cascade HPPs.

Figure 5 represents the water evacuation of water in meters in Posof and Merekler dam.

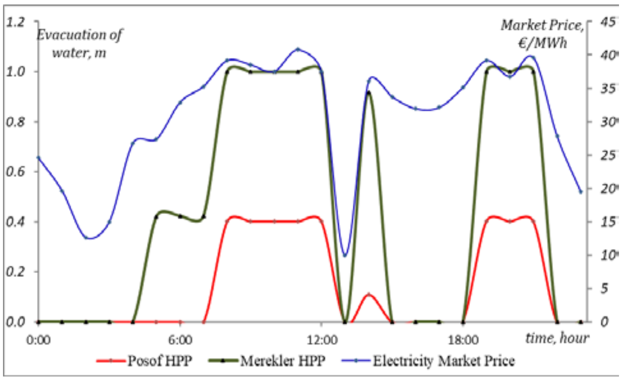

Figure 5. Evacuation of water schedule of the cascade HPPs.

Figure 6 shows optimized reservoir elevations for each hydropower plant. When there is low consumption (off-peak), the water existing in the accumulation reservoirs is used. When it is needed, this cumulated water could be used for electricity production. There is no overflow depending on the water levels in the reservoirs.

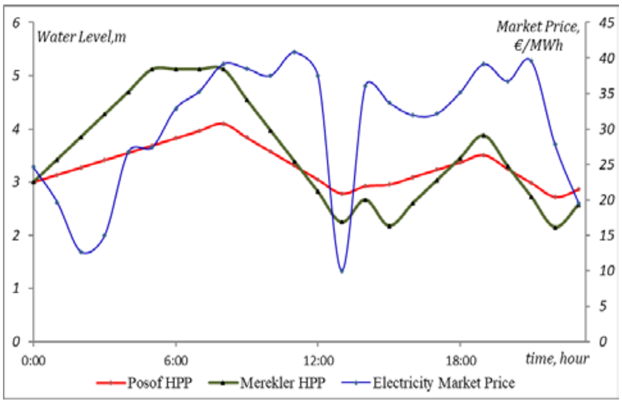

Figure 6. Water level in the reservoir basin.

A comparison of optimization performance can be made in terms of computational time and income rate. The results of the study showed that the revenue values of each HPP increased by approximately 18 %. Figure 7 shows the income comparison of HPPs. The results of optimization in real-life income and multi-reservoir system demonstrate that the use of the optimized HPPs would manage the system more efficiently in the multi-reservoir than in a single reservoir. It is very important to share information about the water level in reservoirs, the timing of water release, the planning produced power, etc.

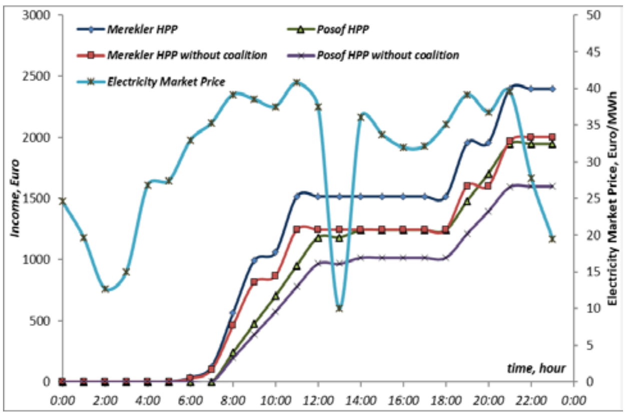

Figure 7. Pre- and post-optimized results versus electricity market price.

The results showed that the developed MATLAB script could approach an optimal solution that meets constraints and variables. The comparison made with individual runs of each power plant showed that 18 % higher income was attained with the cascade variant. The program was run for the cascade dam operation. Calculation time was approximately 46 seconds for the single runs in the 24-hour cascade case. This implies that runtime for the cascade case is within an order of magnitude and can easily be figured out with a regular office PC. The calculations were carried out on an Intel® Core™ 2 Duo CPU E7500 machine with 4GBs of RAM and Windows 10 operating system. A possible improvement can be achieved by submitting a more efficient algorithm with better performance for many decision variables.

4. CONCLUSIONS AND FUTURE WORK

This paper considered reservoir-based cascade hydropower to achieve the objective of maximizing the income from selling electricity in the day-ahead market. Within this scope, it supported a tool that allowed a power producer company to determine the short-term (24 h, but it can be easily extended) self-planning of its cascading facilities along a river basin. This paper proposed a dynamic non-linear programming model to account for each power plant based on the relationship among the head, the installed power capacity, and the water discharged, considering limitations. The mathematical model for the daily optimal scheduling of a hydropower plant cascade was successfully tested on a real-world case study. A MATLAB script was developed according to the electricity initial reservoir level and water inflow values as inputs, and the constructed script was used in the optimizer. The optimization method, used to solve the parametric equations, produced a stochastic optimization algorithm. As a result, it was found that hydroelectric power plants could increase their income by sharing information such as operation scheduling and reservoir levels.

As a future study, units might be divided, and the travel time between the upstream dam and downstream should be considered in a more detailed study. Additionally, the startup costs of implementing efficient algorithms should be considered as well. Further, any future work is advised to include the implementation of different objective functions for maximizing water use efficiency and assessment of the scheme based on various power generation and constraint scenarios.

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REFERENCES

1. Application of non-conventional renewable energy sources, Bureau of Energy Efficiency, p 147.
2. World Energy Council, World Energy Resources Report, (2016), p 3.
3. Zicmane, I., Mahnitko, A., Kovalenko, S., Georgiev, G. and Kim, D., "Algorithmization in the task of optimization of cascade hydro power plants", ***Proceedings of 2017 IEEE Manchester PowerTech***, Manchester, UK, (2017), 1-6. (DOI: 10.1109 / PTC.2017.7980989).
4. Feng, Z.K., Liu, S., Jiang, Z.Q., Luo, B. and Miao, S.M., "Multi-objective operation of cascade hydropower reservoirs using TOPSIS and gravitational search algorithm with opposition learning and mutation", ***Water***, Vol. 11, No. 10, (2019), 2040. (DOI: 10.3390/w11102040).
5. Zhang, Y., You, J., Ji, C. and Wu, J., "Short-term operation optimization of cascade hydropower reservoirs with linear functional analysis", ***Proceedings of International Conference on Geo-Spatial Knowledge and Intelligence***, Springer, Singapore, (2017), 107-116.
6. Cuvelier, T., Archambeau, P., Dewals, B. and Louveaux, Q., "Comparison between robust and stochastic optimisation for long-term reservoir management under uncertainty", ***Water Resources Management***, Vol. 32, No. 5, (2018), 1599-1614.
7. Marko, V., "Value of stochasticity in hydropower planning optimization", Master Thesis, XR-EE-ES 2012:008, (2012).
8. Technical report, "Advanced algorithms for hydropower optimization", U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Denver, Colorado, (2012), S&T-2011-486, (2011).
9. Chang, G.W., Aganagic, M., Waight, J.G., Medina, J., Burton, T., Reeves, S. and Christoforidis, M., "Experiences with mixed integer linear programming based approaches on short-term hydro scheduling", ***IEEE Transactions on Power Systems***, Vol. 16, No. 4, (2001), 743-749. (DOI: 10.1109/59.962421).
10. Belsnes, M.M., Wolfgang, O., Follestad, T. and Aasgard, E.K., "Applying successive linear programming for stochastic short-term hydropower optimization", ***Electric Power Systems Research***, Vol. 130, (2016), 167-180. (DOI: 10.1016/j.epsr.2015.08.020).
11. Grygier, J.C. and Stedinger, J.R., "Algorithms for optimizing hydropower system operation", ***Water Resources Research***, Vol. 21, No. 1, (1985), 1-10. (DOI: 10.1029/WR021i001p00001).
12. Arunkumar, R. and Jothiprakash, V., "Optimal reservoir operation for hydropower generation using non-linear programming model", ***Journal of The Institution of Engineers (India): Series A***, Vol. 93, No. 2, (2012), 111-120. (ISSN: 2250-2149, (Print) 2250-2157 (Online)).
13. Feng, Z.K., Niu, W.J., Cheng, C.T. and Wu, X.Y., "Optimization of hydropower system operation by uniform dynamic programming for dimensionality reduction", ***Energy***, Vol. 134, (2017), 718-730. (DOI: 10.1016/j.energy.2017.06.062).
14. Al-Aqeeli, Y.H., Lee, T.S. and Aziz, S.A., "Enhanced genetic algorithm optimization model for a single reservoir operation based on hydropower generation: Case study of Mosul reservoir, northern Iraq", ***SpringerPlus***, Vol. 5, No. 1, (2016), 797. (DOI: 10.1186/s40064-016-2372-5).
15. Rai, R. and Nagasaka, K., "Modeling and development of run-of-river cascade hydropower plants in Nepal", ***Journal of Clean Energy Technologies***, Vol. 5, No. 6, (2017), 469-474. (DOI: 10.18178/JOCET.2017.5.6.418).
16. Li, S., Li, Y. and Zhao, D., "Study on optimal operation of cascade hydropower stations under complex constraints", ***Journal of Residuals Science & Technology***, Vol. 13, No. 6, DEStech Publications Inc., (2016). (Doi: 10.12783/issn.1544-8053/13/6/58).
17. Wolf, A.J. and Lindber, P.O., " Optimal short-term operation of a cascade of hydropower Stations", ***Transactions on Ecology and the Environment***, Vol. 12, WIT Press, (1996). (ISSN 1743-3541).
18. Statistical data from Nordpool spot, (www.nordpoolspot.com).
19. Masters, T., Practical neural network recipes in C++, Morgan Kaufmann, (1993).
20. Xi, E., Guan, X. and Li, R., "Scheduling hydrothermal power systems with cascaded and head-dependent reservoirs", ***IEEE Transactions on Power Systems***, Vol. 14, No. 3, (1999), 1127-1132. (DOI: 10.1109/59.780941).
21. Guan, X., Svoboda, A. and Li, C.A., "Scheduling hydro power systems with restricted operating zones and discharge ramping constraints", ***IEEE Transactions on Power Systems***, Vol. 14, No. 1, (1999), 126-131. (DOI: 10.1109/59.744500).
22. Conejo, A.J., Arroyo, J.M., Contreras, J. and Villamor, F.A., "Self-scheduling of a hydro producer in a pool-based electricity market", ***IEEE Transactions on Power Systems***, Vol. 17, No. 4, (2002), 1265-1272. (DOI: 10.1109/TPWRS.2002.804951).
23. Coban, H.H., "Optimization techniques in short and long-term power production at small hydropower plants", Ph.D. Thesis, (2016).
24. Renewable energy technologies: Cost analysis series, Hydropower, Volume 1: Power sector, Issue 3/5, International Renewable Energy Agency(IRENA), (2012).

25. Yaşar, M., Baykan, N.O. and Bulbul, A., "Akişaşagisina Birakilmasi Gerekli Debi Yaklasimlari", ***Proceedings of II. Su Yapıları Sempozyumu, 16-18 Eylül 2011, Diyarbakır***, (2011), 211-218.

26. Karakoyun, Y. and Yumurtaci, Z., "Hidroelektrik Santral Projelerinde Çevresel Akis Miktarinin ve Çevresel Etkinin Değerlendirmesi", ***Tesisat Mühendisliği Dergisi***, (Kasim/Aralik, 2013), 1-16.

27. Datasheet of turbine, generator and transformer of Posof HPP and Merekler HPP.

28. Gullhamn, E., "Control of water content and retention in hydropower plant cascades", Master Thesis, IR-RT-EX-0410, Stockholm, Sweden, (2004).

29. Hamann, A. and Hug, G., "Real-time optimization of a hydropower cascade using a linear modeling approach", ***Proceedings of 2014 Power Systems Computation Conference***, IEEE, (2014), 1-7. (DOI: 10.1109/PSCC.2014.7038354).

30. Apostolopoulou, D. and McCulloch, M., "Cascade hydroelectric power system model and its application to an optimal dispatch design", ***Proceedings of IREP'2017-10th Bulk Power Systems Dynamics and Control Symposium***, Espinho, Portugal, (2017).