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Application of Genetic Algorithms to Increase the Effectiveness and Improve the Efficiency of Hydroelectric Power Plants

Mohammad Rezaei valiceh

Ph.D. student in Civil Engineering, Water Engineering, National Academy of Sciences of Tajikistan, Dushanbe, Tajikistan

ABSTRACT

Decrease in precipitation, population growth and the specific geographical conditions of Iran, increasingly attracts the domestic managers' attention to surface water control and harness, and regard dam construction as a strategic factor in their agenda. On the other hand an optimal use and implementation of projects in line with sustainable development is one of the scientists concerns in this age. This study, understands the importance of this issue, and seeks to increase the effectiveness and efficiency of hydroelectric power plants in Iran. Regarding the science advancement and more accurate methods of developed equations solving, this study seeks to provide developed genetic algorithm method for solving hydraulic equations in hydroelectric power plants. In this study the Karkheh dam was analyzed as the case study. First, according to the nature of Karkheh hydroelectric power plan, the hydraulic equations governing the hydroelectric power plants were provided, and then the objective function and limitations in the genetic algorithm were presented. Finally, the optimal values of variables were provided. By comparing the results of genetic algorithm optimization model with the results of the cost-income curve, it was revealed that the peak energy production rate was increased about 125 MW/h and on other hand the flow rate of plant design was decreased about 4%.

Keywords: genetic algorithms, hydroelectric power plant, hydraulic equations of hydroelectric dams, increasing the effectiveness.

1 - INTRODUCTION

Today, the resuscitative source of water is increasingly interested as one of the three factors of composition and survival of the environment. Undoubtedly the maintenance of water resources and efficient, fair and economical utilization of water is a global problem, therefore in the 21st century the lack of water is regarded as a universal human challenge (Vedula, 2005). Plan, design and management of water resource systems to achieve sustainable development in an area, requires public participation. All those who are involved in development and management of water resources should always evaluate the effects of system in economical, social and environmental changes. To achieve sustainable development, the sustainability issue should be regarded in all aspects of plan, design, structure and utilization (Prillwitz, et.al, 2004). Economic and environmental not only analyzes shall consider the stages of development, utilization and system maintenance, but should consider the possibility of its destruction and the need of its replacement. According to the mentioned factors, it is clear that one of the fundamental bases of water resource management in the current conditions is optimum use of available resources. To consider the diverse and different size and complexity of water resource systems, nowadays managers and planners, have turned to use of optimization models as a useful tool to make optimal decisions. Various types of evolutionary and optimization, deterministic and uncertain, static and dynamic, and linear and nonlinear models are used in various aspects of water resource management (Ralph & Wesley, 2007). Expansion of human knowledge and creation of new tools and integrating them with existing optimization models, have provided new opportunities for better decision making in development and planning of water resources. This study attempts to present and simulate a model for one of the largest power plants in Iran -the hydroelectric power plan of Karkheh dam- by genetic algorithm tool. During this simulation using genetic algorithms and data of studied power plant, it has been tried to present optimal values for the system function according to the objective function and model limitation. Karkheh dam has been constructed on Karkheh River in Khuzestan province in Iran. This dam is one of the world's largest earth dams and is the largest earth dam in Iran and Middle East. The plant was designed with an annual average energy production of 934 GW/h. Currently the plant is operating with 3 units each have a capacity of 133.3 MW, with total capacity of 400 MW. This

***Corresponding Author:** Mohammad Rezaei valiceh, Ph.D. student in Civil Engineering,Water Engineering, National Academy of Sciences of Tajikistan, Dushanbe, Tajikistan

paper first presents the hydraulic model of hydroelectric power plant, and then provides the genetic algorithm and the objective function and limitations of the model, and finally solves and analyzes them.

2 - Hydraulic Model of Hydroelectric Power Plants

In this chapter the mathematical model of hydraulic power plants is described, including Penstock, Surge Tank and the turbine. Building Surge Tank in hydroelectric power plant is due to hydraulic stabilization of stream flows in the power plant, which shall be considered if necessary. In this study, using the component model of plant, the diagram block of nonlinear model in hydraulic power unit is provided - regardless the surge tank - and it will be used in simulation of hydraulic section and the full model of hydroelectric power plant in Karkheh (Alavi and others, 2010).

2-1 The dynamic model of Penstock

The efficiency of a water turbine is highly influenced by the characteristics of the water column that feeds it. Penstock tunnels in fact are part of the waterways and water systems that are responsible to transfer water to power plant. Regarding the water column in non-elastic state, characteristics of penstock are determined by the following basic equations. These equations are related to the water velocity in the penstock, water acceleration under the influence of gravity, and the power produced in turbines (Power & Energy Society, 1992).

$$(1)\ (H_{\circ} - H - H_f)\,\rho g A = \rho A l \frac{dU}{dt}$$

$$(2)\ H_f = f \times \frac{L}{D} \times \frac{U^2}{2_g} = f_P \times Q^2$$

$$(3)\ f_P = \frac{L}{D} \times \frac{f}{2_g} \times \frac{1}{A^2}$$

Where $H_{\circ}$ is the static height of water column (m), H is the height of water in the turbine inlet (m), H_f is the high losses due to friction (m), U is water velocity in the penstock (m / s), L is the length of pipe (m), D is the pipe diameter (m), f is the friction coefficient, and f_p is the head loss coefficient m / (m^3 / s)^2. Friction coefficient is a function of Reynolds number that is extracted graphically from the moody chart for pipe friction. Changes of flow rate in penstock are expressed by the following normalized equation:

$$(4)\ \frac{d\bar{Q}}{dt} = (1 - \overline{H} - \overline{H}_f)\,\frac{H_{base}\, gA}{LQ_{base}}$$

Here H_{base}, is the same as $H_{\circ}$ i.e. the water level that is equal to the difference between the height level of lake water tank and the height level of coastal. The base flow or downstream Q_{base} is equal to the turbine flow when the guide vanes are fully open. T_w is the time constant of water inertia or water start:

$$(5)\ T_w = \frac{LQ_{base}}{H_{base}\, gA} = \frac{LU_{base}}{H_{base}\, g}$$

The relation (4) can be written as follows:

$$(6)\ \frac{d\bar{Q}}{dt} = \frac{(1 - \bar{H} - \bar{H}_f)}{T_W}$$

Water starting time, is the duration needed for water in H_{base} height so that in penstock, to reaches the U_{base} speed from the static state. For a non uniform penstock with different levels of time constant, the water inertia is calculated by the following equation:

$$(7)\ T_w = \frac{\Sigma\, LU}{gH}$$

ΣLU is the sum of length multiplied in velocity in different parts of the stream, such as pressure tunnels, penstock, and spiral turbine.

2-2 The Surge Tank model

Waterway wall elasticity makes the waves travel as pressure and flow that is generally known as water hammer or the hammer. When a change occurs in the water inner pressure - higher or lower than normal pressure - hammer happens which in fact is the result of a sudden change in water flow rate. In the plant drainage, two important phenomena can create hammer: opening and closing the inlet valve of the power plant, and change in the openness of conductor blades. To overcome the destructive effects of the hammer in hydroelectric power plants, surge tank is constructed.

The time in which the pressure wave or a hammer travels over the penstock to reach the free surface of water is called wave traversal time or in some resources as the elastic time, and it is shown by T_e that is obtained by equation (8):

$$(8)\quad T_e = \frac{L}{a}$$

Considering the penstock as a uniform conduit fed by a large reservoir (lake), the transfer function related to the height and flow in turbine inlet will be as follows:

$$(9)\quad \frac{H(S)}{Q(S)} = -\frac{T_W}{T_e} \tanh(T_e s + F) = -z \tanh(T_e s + F)$$

In which *s* is the complex frequency of Laplace variable, *F* is the friction losses in penstock and *z* is the surge impedant. In a rigid system, if high losses in tunnel are not considered, then the hit oscillation period (T_{st}) and reserves constant in surge tank are calculated by the following relations (Dezab Consulating Engineers, 2005):

$$(10)\quad T_{st} = 2\Pi\sqrt{\frac{lA_S}{g^A}}$$

$$Cs = \frac{A_S . H_{base}}{Q_{base}}$$

In which *l* is the tunnel length between the dam reservoir and surge tank, A_s is the cross-sectional area of surge tank, and *A* is the tunnel cross-sectional area.

2-3 Turbine model:

The equation of turbine mechanical power in a permanent state is as follows:

$$(11)\quad P_m = \eta Q \rho g H$$

In which P_m is the turbine power output, η is the turbine efficiency, *Q* genuine flow of turbine, ρ is density of water, and *H* is the height of the turbine inlet.
Since in real conditions, turbine efficiency is not 100%, the sterility flow of turbine (*Qnl*) must be reduced from the main flow to create an effective flow and achieve mechanical power. Also the damping effect of the turbine that is a function of guide vanes openness and the rotor speed changes is considered. (Bin Ng, et.al, 2004). As a result the formalized mechanical power of turbine is calculated as follows (Mahmoud, et.al, 2004):

$$(12)\quad \overline{P}_m = A_t \overline{H} (\overline{Q} - \overline{Q}_{nl}) - D_n \overline{G} \Delta \overline{\omega}$$

The turbine efficiency, *At* is obtained by the ration of valve position its actual position:

$$(13)\quad A_t = \frac{1}{G_{fl} - G_{nl}} \times \frac{\text{Turbine MW rating}}{\text{Generator MW rating}}$$

In which G_{fl} is the position of guide vanes at full load and G_{nl} is the position of guide vanes in sterility state. The equation of flow rate for turbine that uses the Q_{base} as base rate of turbine flow, and H_{base} which is equal as the static height of $H_{\circ}$ is shown as follows:

(14) $\bar{Q} = \bar{G} \, . \sqrt{\bar{H}}$

By combination of equations (12) and (14), the mathematical model of turbine is obtained.

3 - Genetic Algorithm

Genetic algorithm is a comprehensive method of random search and its principles are a mimic of natural biological evolution (Goldberg, 2001). Genetic algorithm in each stage, finds better solutions by using the survival of the fittest principle on a population of possible solutions. This process, same as the natural pattern leads to evolution of members of the next generation (Farshi Rafi and Mousavi, 2005). Genetic algorithms in search atmosphere is not completely randomized, but intelligently searches for solutions in areas that has better improved the objective function, thus genetic algorithm is faster than other search methods. In this algorithm the design atmosphere shall turn into genetic atmosphere. Therefore, genetic algorithm works with series of coded variables (Rasheed, Gelsey, 2001).

Genetic algorithm of optimization needs a simulation model to evaluate the performance of the study system. So first, a simulation model is developed based on reliability according to the successive flood flow, similar to the recent simulation model. In simulation model a monthly time step is used for flood. Simulation model is implemented for all investigated parameters in an optimization algorithm to achieve the research objective function. In addition to objective function, some limitations are used during optimization, which are offered below.

4 - The objective function and limitations

The main variables are decision, normal figures of repository, capacity of power plant installation, penstock diameter, and water demand. In this function it is assumed that the produced peak energy is a function of head of design at any time period, the dam hydroelectric power plant demand in peak mode, and total efficiency of power plant. In this study, the objective function is maximizing the peak energy production during annual utilization of hydroelectric power plants. So the model searches a combination of decision variables that can maximum the peak annual energy production. The objective function consists of two parts:

A) If the condition V_{adj} (n, t)> P.P.D (n, t) is established:

(15) $Maximizez = \dfrac{\sum_{n=1}^{N} \sum_{t=1}^{T} \dfrac{P.P.D\,(n,t) \times \eta \times 9806 \times H_d(n,t)}{3600 \times 1000}}{N}$

B) Otherwise:

(16) $Maximizez = \dfrac{\sum_{n=1}^{N} \sum_{t=1}^{T} \dfrac{V_{adj}(n,t) \times \eta \times 9806 \times H_d(n,t)}{3600 \times 1000}}{N}$

In the above equations $H_d\,(n, t)$ is the design head in t^{th} month and n^{th} is year per cubic meters, *P.P.D (n, t)* is the hydroelectric power dam demand in peak mode per cubic meters, $V_{adj}\,(n, t)$ is the reservoir water volume regulatory per cubic meter, *N* total number of years in the case time-series, and *T* the total number of studied months in a year. Also the objective function in this study regarding the climatic conditions in Iran is as follows.

(17) $0.17 \leq \dfrac{\sum_{n=1}^{N} \sum_{t=1}^{T} P.F.(n,t)}{N} \leq 0.25$

In the inequality (17), $P.F.\,(n,t)$ is the coefficient function of hydroelectric power plant peak in year *t*, and month *n*.

To evaluate the influence of genetic parameters amount on the performance of genetic algorithm, the initial values of 0.1 for mutation probability, number of generations equal to 55, and initial population equal to 30 (desired number of options), and apply of random mutation, and apply of uniformly integration are used (Mitchell, 1999). Also top chromosomes were chosen in order to produce a new generation according to the tournament method. Then the genetic algorithm was implemented per integration probability values of 0.5 to 0.95. Total results of optimized values of genetic algorithm parameters in developed optimization model are as follows: the initial population size is equal to 100 chromosomes, the number of generations is equal to 350, mutation probability is equal to 0.91, and the integration probability is equal to 0.16. Also in the present model the genetic algorithm will stop if in 100 consecutive generations the amount of value (objective function value) ratio will not change.

5 - RESEARCH RESULTS

Assuming a 5% of engineering tolerance and comparing the results of developed optimization model (Table 1) with the results obtained by the cross between two curves of tank design cost variations and tank design parameters with maximum water figures, it is observed that the design parameters optimized by genetic algorithm optimization models, have an acceptable estimation error percentage and this represents efficiency and the ability of genetic algorithm optimization models developed to optimize these parameters. A summary of results are presented in Table 2.

Table 1: Optimum values of objective function and repository design and hydroelectric power plants variables

Parameter	value
Peak energy production (MW/h)	2875.11
Normal figures of repository (m)	324.23
Repository volume at normal figures (million cubic meters)	79.56
Peak power performance coefficient	0.34
Downstream flow design in each power plan unit (cubic meters per second)	90.28
Optimum capacity of plant installation (MW)	392.36
Pure Power Plant head (m)	409.63
Time of peak function in power plant (hours)	5.20

Table 2: Results of the relative error of design parameters estimation by optimization model

Parameters	Optimum value resulted from genetic algorithms model	The optimal value of cost and revenue curves	Relative error of the estimation
Design flow (cubic meters per second)	*90.28*	*93.94*	*3.97*
Peak operating hours (h)	*5.20*	*5.36*	*3.10*
Peak energy production (MW/h)	*2875.11*	*2749.21*	*4.34*
Normal figures of repository (m)	*324.23*	*324.70*	*0.04*

6 - Summary

Comparing the results of genetic algorithm optimization model with the results of cost - income curve revealed that in peak energy level production has increased about 125 MW/h, and on the other hand design flow rate of power plant has decreased about 4%, this decrease helped to cost savings in administrative costs of the project. As the study results show, the difference between the optimal solution of genetic algorithm model and simulation model is remarkable. Two major reasons can be outlined as follows: First high-accuracy of genetic algorithm compared to simulation model, because it searches much more parts in search area. The number of search points in genetic algorithms model is equal to the number of produced generations multiplied in the number of members of population, which is much more than search points by simulation model. Second, large difference between simulation model and genetic algorithm is certainly due to the use of definite exploitation policy in simulation model. Although using definite utilization policies is easy, these policies do not provide any feedback of future status in the water supply. While in developed genetic algorithm model, the policy of reservoir exploitation (the amount of peak or certain energy produced) is also considered as the decision variable. Thus the system by taking into account the future of water situation; tends to use the maximum available water in a way that by decrease of tank overflow rate, energy production is increased.

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