Characteristics of Relative Growth for HPP Power Systems of Tajikistan

A Kirgizov¹, Sh Sultanov¹, M Johnonov², Kh Usmonov¹ and I Tolizboda¹

¹Department of the Power Stations, Tajik Technical University named after M.S. Osimi, Dushanbe, Tajikistan
²OSHC “Barki Tojik”, Dushanbe, Tajikistan

sultonzoda.sh@mail.ru

Abstract. The article discusses the main criteria for optimizing the operational modes of a hydropower power plant in terms of active power. Relative growth characteristics are used to calculate the distribution of active power between stations for more rational use of water resources. Also, this method allows to optimally distributing the load between the units of one station. Basically, the characteristic of the relative increase in the load of the units depends on the operational characteristics of the hydraulic turbines. The article provides calculations of the relative increase in load at the Nurek hydropower power plant.

1. Introduction

The article analyzes the latest innovations related to the development of hydropower technologies. For more than a century, hydropower has been providing electricity to consumers, and since ancient times, mechanical energy for the development of civilization (water wheels). Compared to other clean energy sources (such as wind and solar), it has reached a high level of technological maturity. Accordingly, there are fewer opportunities for identifying and implementing radical design concepts that revolutionize the operation of a hydropower plant. However, significant potentials for new approaches in planning, design, and operation of a hydropower plant still exists. These potentials are partly growing from the role of hydropower in transforming electrical systems [1]. Being an important source of the flexibility of the power system and the main technology for storing large volumes of water, hydropower must adapt to the opportunities and challenges posed by changing conditions. Any innovation is aimed at increasing the efficiency of hydropower, operating flexibility, service life, and reducing the cost of installation, operation, and maintenance of a hydropower plant.

The optimal operation of a single hydropower plant, nevertheless, has not been treated properly in the technical literature, as long as very few papers cover this subject [2, 3]. The great majority of published material regards to the hydro cascade operation, aiming at the maximum energy generation for a given inflow scenario [4].

For the system, such a regime is optimal in which the lowest consumption of equivalent fuel (water) or the lowest cost of supplied electricity is provided when a specific load plan of the system is covered. Traditionally the hydro units of HPS connected to the electrical power system (EPS) consist of the synchronous generator and turbines [5].

To determine the optimal mode of operation of the entire power system for each hydropower power plant, the following two types of characteristics must be built: the flow characteristic, that is, the
dependence of the flow of water through the hydraulic unit on its load and the characteristic of relative growth (CRG), that is, the dependence of the relative growth of the hydraulic unit on its load [6]. Both characteristics must be built with constant pressure. In Tajikistan, about 92% of electricity is generated at hydropower power stations and at the Vakhsh cascade, which requires additional studies to properly optimize their work with each other taking into account the influx.

One can conclude that the bigger the flow driven by the turbines, the lower the pressure at the end of the penstock will be. Therefore, maintaining the dispatched power met by the power generated by the power plant units, a reduction of the input flow means an increase in the overall power plant efficiency [7].

Relative growth characteristics are the main source for calculating the optimal distribution of active power between hydropower plants using the method of equality of relative growth. The correct choice of the system operation mode depends on the exact construction of the CRG [8]. Therefore, serious attention should be paid to their construction. From the CRG of the individual units of the hydropower plant, the CRG of the entire hydropower power plant is built. The aim of the work proposed in the article is to adapt long-term and short-term optimization methods to the operating regimes of the Tajik energy system containing a high proportion of hydropower power plants and to improve methods for calculating optimal modes.

2. Methods
There are many methods that can be used to obtain an optimal distribution of the dispatch power among the units of a power plant. One can, for instance, consider that the power plant has n-twin machines and divides the dispatched power using an equality criterion, others can use the previously measured efficiency curve of the units to achieve an optimal operation, or efficiency can be measured online for an optimal distribution. Such methods are described as follows [9].

This article discusses the problem of short-term optimal load distribution between hydropower plants in Tajikistan’s energy system. The problem is solved by the method of equality of relative growth according to the criterion of the minimum flow of water through the turbine. The main parameters of the hydropower plants under consideration are given in Table 1.

| HPP     | \( P_\Sigma \), MW | Turbine number and types | \( D, m \) | \( N_t, MW \) | \( H, m \) Max | Calc | Min | \( Q_{calc}, m^3/s \) |
|---------|---------------------|--------------------------|-----------|---------------|----------------|------|-----|----------------------|
| Nurek   | 3000                | 9xPO-310/957-B-475       | 4.75      | 310           | 275            | 230  | 207 | 152                  |
| Baipaza | 600                 | 4xPO-75/3123-B-620       | 6.2       | 153           | 60             | 54   | 40  | 309                  |
| Sangtuda 1 | 670            | 4xPO-75/728-B-600       | 6         | 171           | 64             | 58   | 56  | 324                  |
| Sangtuda 2 | 220             | 2xGB/T15468-2006        |           | 112.2         | 22             | 21   | 12.5| 515.8                |
| Golovnaya | 240              | 6xPL50/642-BB-550       | 5.5       | 36.5          | 31.2           | 23.3 | 15  | 172.1                |
| Kairakkum | 126              | 6xPL30/495-BB-500       | 5         | 23.6          | 24.5           | 15   | 13.2| 180                  |

To build the flow characteristics and the characteristics of the relative growth of hydropower units, a universal (operational) characteristic of each unit is used. Hydraulic turbines are required to operate in a wide range of conditions and to adjust its power output to the variations of water availability, energy demand, and energy generation from other resources. Depending on factors such as the available specific energy and discharge, the turbine may operate in non-optimal conditions, affecting their performance and shortening their lifespan [10].

The connectedness of power, pressure, and efficiency is the operational characteristic of the unit. The operational characteristics of each unit differ from the type of hydraulic turbine [11, 12]. The
operational characteristics of the hydraulic turbine RO-75-B-600. Sangtuda-1 hydropower plant is shown in Figure 1.

![Operational characteristic of a hydro turbine RO 75-B-600](image1)

To build the flow characteristics of \( Q = f(N, H) \), first using the operational characteristics built performance characteristics \( \eta = f(N, H) \). Consumption characteristics are built based on performance.

To do this, you need to calculate the points according to the formula:

\[
Q = \frac{N}{9.81 \cdot H \cdot \eta} \quad \left[ \frac{m^3}{s} \right]
\]

Operating and flow characteristics for a hydraulic turbine RO-75-B-600 at different pressure values are shown in Figures 2 and 3.

![Operating characteristic of one unit of the Sangtuda-1 hydropower plant. H= 63 m.](image2)
3. Results and discussion

3.1 CRG hydraulic unit

Relative growth is a derivative of the flow rate of water. The increase can be obtained by numerically differentiating the characteristics of the flow of water. However, this is almost impossible to do, since the flow rate is close to a linear relationship, and therefore the relative increase in water flow per unit of power will be constant, which is not true. Sometimes, to facilitate the calculation of the characteristics of relative growth, the approximate analytical expression of the flow characteristic (in the form of a polynomial of the third degree) is selected, differentiating this expression, an analytical expression of the characteristics of the relative growth is obtained, and CRG are constructed by points [13, 14]. In this work, to obtain the OSB, a working characteristic is used [15].

The characteristic of relative growths \( q_a(N_a) \) can be obtained by differentiating the operating characteristics of the hydraulic unit \( \eta = f(N, H) \) with a constant pressure of the unit \( H_a \) according to the formula:

\[
q_a = \frac{102}{H_a \eta_a} \left( \overline{\eta} - \overline{N_a} \frac{d\eta_a}{dN_a} \right)
\]

where \( d\eta_a, dN_a \) is the change in the efficiency and power of the unit in the estimated interval between two points of the operating characteristic of the unit; \( \overline{\eta}_a, \overline{N}_a \) - average efficiency and average power in the same interval.

Since \( q_a(N_a) \) may have a sufficient error in its calculation, because it is very sensitive to the accuracy of the parameters included in its calculated dependence, it is, therefore, more expedient to use not a working characteristic, but a characteristic of its power losses \( \Delta N'_{a}(N_a) \). In this case, the differential characteristic has the form:

\[
q_a = \frac{1000}{9.81H_a} \left( 1 + \frac{d\Delta N'_{a}}{dN_a} \right)
\]
where \( d\Delta N_a \), \( dN_a \) are the changes in power losses of the unit \( \Delta N_a \) and the power of the unit itself \( N_a \) in the design interval.

The power loss of the unit is calculated by the formula:

\[
\Delta N_a = \frac{N_a}{\eta_a} - N_a
\]

The calculation of the CRG of the unit at a constant pressure value is given in Table 2.

| \( N_a \), MW | \( \eta_a \), % | \( \Delta N_a \), MW | \( dN_a \), MW | \( d\Delta N_a \), MW | \( 1+\frac{d\Delta N_a}{dN_a} \), \( m^3/(s\cdot MW) \) | \( \bar{N}_a \), MW |
|---|---|---|---|---|---|---|
| 100 | 0.876 | 14.15525 | | | | |
| 105 | 0.8835 | 13.8455 | -0.30975 | 0.93805 | 1.517806 | 102.5 |
| 110 | 0.8916 | 13.37371 | -0.47179 | 0.905642 | 1.465369 | 107.5 |
| 115 | 0.8986 | 12.97685 | -0.39686 | 0.920629 | 1.489618 | 112.5 |
| 120 | 0.9047 | 12.64065 | -0.3362 | 0.93276 | 1.509248 | 117.5 |
| 125 | 0.9111 | 12.1968 | -0.44386 | 0.911228 | 1.474408 | 122.5 |
| 130 | 0.9185 | 11.53511 | -0.66168 | 0.867663 | 1.403918 | 127.5 |
| 135 | 0.9241 | 11.08809 | -0.44703 | 0.910595 | 1.473383 | 132.5 |
| 140 | 0.9279 | 10.87833 | -0.20976 | 0.958048 | 1.550165 | 137.5 |
| 145 | 0.931 | 10.74651 | -0.13182 | 0.973636 | 1.575387 | 142.5 |
| 150 | 0.9341 | 10.58238 | -0.16413 | 0.967174 | 1.56493 | 147.5 |
| 155 | 0.936 | 10.59829 | 0.015912 | 1.003182 | 1.623194 | 152.5 |
| 160 | 0.936 | 10.94017 | 0.34188 | 1.068376 | 1.72868 | 157.5 |
| 165 | 0.9341 | 11.64062 | 0.700446 | 1.140089 | 1.844715 | 162.5 |
| 170 | 0.9262 | 13.54567 | 1.905054 | 1.381011 | 2.234537 | 167.5 |
| 175 | 0.909 | 17.51925 | 3.973581 | 1.794716 | 2.903931 | 172.5 |

The differential characteristic \( q_a = f(N, H) \) of one unit of the Sangtuda-1 hydropower plant with a constant pressure value is shown in Fig. 4.
3.2 Building CRG plants

When constructing the flow characteristics of the hydropower power plant, the unit capacity and unit consumption are multiplied by the number of units: 
\[ N_{HPP} = n \cdot N_{HU}, \quad Q_{HPP} = n \cdot Q_{HU} \]  (Figure 5). For the operating characteristics of the hydropower plant 
\[ N_{HPP} = n \cdot N_{HU}, \] 
this 
\[ N_{HPP} = n \cdot N_{HU} \]  does not change (Figure 6). To characterize the relative gains 
\[ N_{HPP} = n \cdot N_{HU}, \]  and 
\[ q_{HPP} = q_{HU} \]  (Figure 7).

![Figure 5. Consumption characteristic of Sangtuda-1 HPP units. H = 63 m.](image)

The number of units that must operate at a given HPP load is determined using switching lines that correspond to the intersection point of the operating characteristics (Fig. 3.6). Consequently, the CRG of a hydropower power plant at a given pressure consists of a series of sections corresponding to a different number of operating units (Fig. 3.7). CRG plants with an unchanged number of units included in the work gradually increase with increasing load. However, after the launch of the next block and the corresponding reduction in a load of each of the existing blocks, the relative increase in each of them, therefore, the entire plant decreases sharply. As a result, the CRG plant takes the form of a sawtooth curve with discontinuities at those load values at which the number of working units changes [16, 17]. This leads to the fact that some values of the relative increase correspond not to one, but several loads of hydropower power plants.
Figure 6. Operating characteristic of the Sangtuda-1 hydropower plant at $H = 63$ m

Figure 7. Characterization of the relative growth of the Sangtuda-1 hydropower plant at $H = 63$ m.
Figure 8. The resulting CRG of the Sangtuda-1 HPP at \( H = 63 \text{m} \).

The rectified characteristic (Figure 7) corresponds to almost the same relative increase, that is, one value of the relative increase corresponds to several values of the active power, which can lead to uncertainties in the calculations. Therefore, to avoid these uncertainties, this section is slightly inclined (Figure 8).

In [9], the construction of CRG presented in the form of polynomials for the considered hydropower power plants was shown. However, the polynomial form of cardiovascular disease of HPP is only suitable for medium interval characteristics. For instantaneous characteristics, this gives a big error, especially in the case of limiting the maximum power of the blocks, since in this case, the HPS CVD is difficult.

Such characteristics are best represented as an array of points \( (N_i, q_i) \) and find one parameter through another using the piecewise-linear approximation [9]. It should be recalled that the equality of relative growth gives an optimal solution only in those cases when with an increase in load the relative increase increases, that is, when the second derivative of the flow characteristic is positive.

The relative incremental characteristics for the remaining hydropower power plants (Table 3.1) were constructed similarly. The ranges of the relative increase in the considered hydropower power plants at constant pressure are given in Table 3.3.

| HPPs     | \( P_{j_{\text{max}}} \text{MW} \) | \( q_{j_{\text{min}}} - q_{j_{\text{max}}} \) / \( \text{m}^3 / (\text{MW} \cdot \text{s}) \) |
|----------|---------------------------------|--------------------------------------------------|
| Nurek    | 3000                            | 0.36-0.64                                        |
| Baipaza  | 600                             | 1.65-3.1                                         |
| Sangtuda 1 | 670                         | 1.5-2.88                                         |
| Sangtuda 2 | 220                         | 5-7.5                                            |
| Golovnaya | 240                           | 3.88-4.28                                        |
| Kairakkum | 126                           | 3.9-4.3                                          |

Table 3 shows that the Nurek hydropower power plant has the smallest relative increase. This is explained by the fact that the Nurek hydropower power plant has the highest pressure. Therefore, it has the smallest relative increase in water flow. Sangtuda–2 HPP has the lowest pressure, hence it has the largest relative increase in water flow. The relative increase in water flow shows the efficiency of using \( \text{m}^3 \) of water at hydropower power plants, the smaller the relative increase, the more efficient the hydropower plant. First, those power plants with small relative gains are loaded.
CRG of hydropower plants varies with pressure. Each pressure value has its CRG. For each hydropower power plant, it is possible to obtain a family of CRG at different pressure values. The family of characteristics of relative increments at various head values for the Nurek hydropower plant is shown in Figure 9.

![Figure 9. The family of CRGs of the Nurek hydropower plant at different pressure values.](image)

**4. Conclusions**

It is seen that CRG varies depending on the pressure at the plant. The relative increase in water flow decreases with increasing pressure. Optimization of the daily regimes of hydropower plants in Tajikistan’s energy system according to the criterion of minimum water consumption allows for additional generation of electricity, which reduces the winter energy deficit by 6.2%.

Thus, long-term and short-term optimization of hydropower plant regimes can reduce the winter shortage of electricity in Tajikistan’s energy system to 15-17%.

The developed methods and results of the research can be used to create optimization programs for planning modes by dispatch services of Tajikistan’s energy system, as well as to optimize short-term and long-term system operation modes.

**References**

[1] Tsvetkov E V, Alabyshcheva T M and Parfyonov L G 1984 Optimal modes of power plants in energy systems Energoatomizdat Publ Moscow p 304

[2] Liu P, Nguyen T D, Cai X, and Jiang X 2012 Finding multiple optimal solutions to optimal load distribution problem in hydropower plant Energies 5(5) pp 1413–1432 doi.org/10.3390/en5051413

[3] Soares S, Salmazo CT 1997 Minimum loss predispatch model for hydroelectric power systems IEEE Trans PAS August 12(3) p 1220

[4] Yamin H Y 2004 Review on methods of generation scheduling in electric power systems Electric Power Systems Research 69(2–3) pp 227–248 https://doi.org/10.1016/j.epsr.2003.10.002

[5] Diyorov R, Glazyrin M and Sultanov S 2017 Mathematical model of francis turbines for small hydropower plants Proceedings - 2016 11th International Forum on Strategic Technology,
[6] Gorshtein V M 1959 The best operating modes of hydropower power stations in energy systems Gorenenergoizdat Publ. Moscow p 248

[7] Bortoni E C, Bastos G S and Kawkabani B 1987 Online unit management for optimal operation of hydro power plants Retrieved from http://www.ighem.org/Papers_JGHEM/398

[8] Kokin S E, Safaraliev M H, Rasulzoda K, Otashbekov R A, Rahimov J B and Sultonov S 2019 Transient stability analysis in rotor winding of hydrogenerator at various short circuit values in power grid in consideration with AEC 2019 16th Conference on Electrical Machines, Drives and Power Systems, ELMA 2019 - Proceedings Institute of Electrical and Electronics Engineers https://doi.org/10.1109/ELMA.2019.8771504

[9] Bortoni E C, Bastos G S, Abreu T M and Kawkabani B 2015 Online optimal power distribution between units of a hydro power plant Renewable Energy 75 pp 30–36 https://doi.org/10.1016/j.renene.2014.09.009

[10] Gomes P J, Andolfatto L, and Avellan F 2018 Monitoring a Francis turbine operating conditions. Flow Measurement and Instrumentation 63 pp 37–46 https://doi.org/10.1016/j.flowmeasinst.2018.07.007

[11] Kirgizov A K, Sultonov S M 2018 Mathematical Simulation of Energy Transformation Processes in an Energy Center Applied Solar Energy (English Translation of Geliotekhnika) 54(5) pp 314–317 https://doi.org/10.3103/S0003701X18050110

[12] Inoyatov M B, Kirgizov A K 2008 On the use of small hydropower in relation to the conditions of the Republic of Tajikistan. Bulletin of the Tajik Technical University 2(2) pp 38-42

[13] Fisher M L 1981 Lagrangian relaxation method for solving integer programming problems Management Science 27(1) pp 1–18 https://doi.org/10.1287/mnsc.27.1.1

[14] Sultonov S M, Asadullo B and Usmonov K I 2018 Stator Winding Partial Discharge Rise Due to Surface Humidity 2018 14th International Scientific-Technical Conference on Actual Problems of Electronic Instrument Engineering, APEIE 2018 - Proceedings pp 449–452 Institute of Electrical and Electronics Engineers https://doi.org/10.1109/APEIE.2018.8546171

[15] Manusov V Z, Kirgizov A K and Sultonov Sh M 2018 Optimization of the Operating Mode of a Hybrid Power Complex Consisting of Renewable Energy Sources XIV International Scientific-Technical Conference on Actual Problems of Electronics Instrument Engineering (APEIE-2018) Proceedings pp 286-289 Novosibirsk Russia 2018 IEEE Conferences DOI: 10.1109/APEIE.2018.8545665

[16] Kokin S E, Safaraliev M Kh and Sultonov Sh M 2017 Features of the management of hydropower power plants in the energy system of the Republic of Tajikistan. News of the Scientific and Technical Center of the Unified Energy System 2(77) pp 109–118

[17] Sultonov Sh, Secretarev Yu and Mitrofanov S 2015 Implementation of the Method of Lagrange for Optimal Modes of Energy System of Tajikistan Applied Mechanics and Materials 698 pp 726-731