REPUBLIC OF AZERBAIJAN

On the rights of the manuscript

ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

IMPROVEMENT OF OPERATING MODES OF SMALL HYDRO POWER PLANTS BY APPLICATION OF CONTROLLED ELECTRIC GENERATORS

Specialty: **3340.01 – Electrotechnical systems and complex**

Field of Science: **Technical Sciences**

Applicant: **Musayev Musahil Musavar**

BAKU - 2024

The work was performed at Azerbaijan Scientific-Research Power Institute

Scientific Supervisor: Doctor of Technical Sciences
Mustafayev Rauf Ismayil

Official opponents: Doctor of Technical Sciences
Mammadov Fuad Faiq

PhD, Associate professor
Huseynov Ramiz Agali

PhD, Associate professor
Ahmadov Elbrus Nasi

Dissertation council ED 2.04 of Supreme Attestation Commission under the President of the Republic of Azerbaijan operating at Azerbaijan Technical University.

Chairman of the Dissertation council: Doctor of Technical Sciences, professor
Yusifbayli Nurali Adil

Scientific Secretary of the Dissertation Council: Candidate of Technical Sciences, dosent
Farhadov Vahid Gara

Chairman of the scientific seminar: Doctor of Technical Sciences, professor
Saidov Rasim Azim

Urgency of the topic and degree of usage

Within last several years in many countries of the world immense amount of work is being done in the field of using renewable energy sources. Small hydropower plants (P<10 MW) require relatively smaller investment while delivering high efficiency. The reduction of the effective water head, the use of frequency-controlled generators, the reduction of installation costs of auxiliary equipment and the introduction of technologies that cause less damage to the environment have made small hydropower more attractive to investors. Small hydropower is one of the most profitable and reliable energy technologies for producing environmentally friendly electricity. Small hydropower is usually of the "run-of-river" type, in other words, the dams required for such small systems are very small, resulting in basins with very small water volumes and flooded area compared to other more powerful type hydropower plants.

The intentions and objectives of the research. The primary objective of this dissertation work is to study the modes and transition processes of electromechanical converters based on mathematical models of various types of hydro turbines, synchronous, double-fed induction generators, and frequency inverters connected to the stator and rotor circuit of generators in small hydroelectric power plants (HPP) operating in parallel with the grid, researching, simplification of the technological composition of small hydropower plants and increasing their efficiency.

Research methods. The general theory of electrical systems and mathematical statistical methods were used to solve the issues raised in the work.

Scientific innovation.

In this dissertation work, mathematical models of various hydro power units consisting of water turbines and frequency controlled electric generators used in small hydropower plants operating in parallel with the power grid have been developed. Based on the developed mathematical models, various operating modes of small HPPs were studied.

The main scientific results obtained in the dissertation work are as follows:
- a mathematical model of the shaft torque was developed depending on the operating modes of the generator in a small HPP;
- operation modes of small hydropower plants were studied with the help of the known mathematical model of the asynchronous generator controlled by the frequency inverter connected to the stator circuit;
- operating modes of small hydroelectric power plants were studied based on the mathematical model of the double-fed induction generator controlled by the frequency inverter connected to the rotor circuit of the small HPP;
- the optimal voltage regulation algorithm for electromechanical converters in the control mode with a frequency inverter has been developed.

Justification and consistency of results. The integrity and justification of the received scientific results and recommendations are based on the application of modern theoretical and experimental methods in the study of the tasks. The developed methods, established mathematical models are compared with the data obtained by experimental and analytical methods.

Defended primary provisions are as follows:

1. Development of analytical mathematical description methods of torque and power characteristics of hydro turbines used in small HPPs - Francis, Pelton and semi-Kaplan turbines;
2. Development and research of the mathematical model of the operating modes of small HPPs consisting of a Francis turbine and a double-fed induction generator controlled by the frequency inverter;
3. Development a mathematical model of operating modes of small HPPs consisting of a Pelton turbine and a permanent magnet asynchronous machine controlled by a frequency inverter, and research the operating modes of such HPPs;

4. Increasing the efficiency of small HPPs equipped with a semi-Kaplan water turbine which rotation frequency is controlled with the help of electromechanical converters.

Theoretical and practical importance of research. Application of the developed mathematical models makes it possible to study quasi-steady state and dynamic operation modes in small hydropower plants. By applying the algorithm obtained as a result of optimization it is possible to perform voltage control in small HPPs with a given configuration. On the other hand, utilizing the advantages of electric frequency inverters connected in the control circuit allows to simplify the complex mechanical structural elements of small HPPs. The developed mathematical models make it possible to determine the optimal opening angle of the inlet water valve in such small HPPs.

Approbation of work.

The results of the dissertation work were presented at scientific seminars of the Azerbaijan Scientific-Research and Project-Research Energy Institute, "MEPS-2015 Modern Electrical Power Systems" held in Wroclaw, Poland (July 6-9, 2015, Wroclaw, Poland) and It was reported and discussed at international conferences called "Technical and Physical Problems of Electrical Engineering " held in Bilbao, Spain (ICTPE-2016, Bilbao, Spain).

Publications.

The dissertation's main findings were presented in 15 scientific works (1 of them are periodicals with high impact factor indexed in "Web of Science" database, 5 in Scopus databases) were published. 2 International conference materials have been published and 2 articles are not co-authored. The dissertation work was carried out at the Azerbaijan Scientific-Research and Project-Research Energy Institute

The structure and scope of the work.

The dissertation consists of 173 pages in total. The total volume of the work consists of 49 pictures, introduction, 3 chapters, conclusions and a bibliography with 108 titles used. The dissertation work has a total of– 193940 number of marks (excluding space in the text and pictures, graphs, appendices and bibliography).

Title page – 423 n.m. (1 pg.), table of contents – 1293 n.m. (1 pg.), Introduction – 9975 n.m. (6 pg.), Chapter I - 86464 n.m. (49 pg.), Chapter II – 18935 n.m. (19 pg.), Chapter III – 55790 n.m. (45 pg.), Conclusion - 5675 n.m. (5 pg.), References - 15385 n.m. (11 pg.)

GENERAL CHARACTERISTICS OF THE WORK

In the introduction, the relevance of the topic of the dissertation, the purpose of the research and the justified statement of the issues presented are given. The practical importance and scientific novelty of the work are described and information is given about the approbation of the scientific research. Also, statistical data, distribution of small hydropower plants in different regions of the world and their development potential are explained in detail in the introductory section.

The first chapter provides information on the current state of small hydropower and its development prospects. Currently, 148 countries of the world have small hydropower plants with a capacity of up to 10 MW. According to 2016 estimates, the total potential of small hydropower around the world is estimated at about 217 GW.

The following advantages of small HPPs should be listed: reduction of CO_2 gas emissions affecting global climate change, use of efficient technologies, relatively smaller construction and flooding area, positive impact on local and regional development, keeping rivers and canals clean, important role in electrification of rural areas, return on the investment in a short period of time and etc.

Currently, although there is no universally accepted concept of "small HPP" in most countries, its installed capacity (power) is taken as the main indicator of such plants. As a rule, small HPPs refer to Hydroelectric Power Plants with an installed capacity of up to 10 MW (in some countries up to 50 MW).

The United Nations (UN) version of the classification of small HPPs according to their installed capacity is more widespread and as following:

- Micro HPP – installed capacity up to 100 KW
- Mini HPP – installed capacity from 0.1 MW to 1 MW

- Small HPP – installed capacity from 1 MW to 10 MW

In chapter one, a brief summary of small hydropower in Azerbaijan is given separately. This chapter also provides information on hydro turbines installed in small HPPs. Also, general information about the structural elements, design calculation, technical parameters of Pelton, Francis and Kaplan hydro turbines is described separately.

The second chapter is devoted to the analysis of the analytical expression of the torque of various water turbines used in small HPPs. It is known that the active power of a water turbine is determined by the following formula:

$$P = g \cdot \eta \cdot Q \cdot H \qquad (1)$$

where,

P – power, [kW];

η – efficiency;

Q – water consumption, [m^3/sec];

H – water head, [m];

g = 9.81– Earth gravity acceleration constant, [m/sec^2].

It is clear that in this case the nominal power of the water turbine will be as follows.

$$P_n = 9{,}81 \cdot \eta_n \cdot Q_n \cdot H_n \qquad (2)$$

Taking the nominal values as the basis, we can express the current power in relative units as follows

$$p^* = \eta^* \cdot q^* \cdot h^* \qquad (3)$$

where,

$$p^* = \frac{P}{P_n}; \quad \eta^* = \frac{\eta}{\eta_n}; \quad q^* = \frac{Q}{Q_n}; \quad h^* = \frac{H}{H_n}$$

The efficiency of the hydro turbine is defined by the following expression:

$$\eta^* = a \cdot q^{*2} + b \cdot q^* + c \qquad (4)$$

The coefficients *a*, *b* and *c* in equation (4) depend on the type of hydro turbine. In general, the nominal pressure is expressed as follows

$$H_н = H_0 \cdot (1 - \lambda) \tag{5}$$

where H_0 is the theoretical water head corresponding to the difference between the lower and upper levels of water retention (the friction losses not considered), λ is the coefficient that takes into account the losses during the transfer of water from the upper intake to the hydro turbine. Certainly, the value of the coefficient λ depends on the amount of water consumption, and this dependence is reflected in the expression of the current value of the pressure.

$$H = H_0 (1 - \lambda \cdot q^{*2}) \tag{6}$$

Thus, from expressions (5) and (6) we obtain the following expression for the current value of the water head expressed in relative units:

$$h^* = \frac{H}{H_n} = \frac{1 - \lambda \cdot q^{*2}}{1 - \lambda} \tag{7}$$

Taking into account expressions (4) and (6) in equation (3) and by making simple transformations we get the following final expression for the relative power of water turbines of small HPPs:

$$p^* = -A \cdot q^{*5} - B \cdot q^{*4} + C \cdot q^{*3} + D \cdot q^{*2} + E \cdot q^* \tag{8}$$

where

$$A = \frac{\lambda \cdot a}{1-\lambda} \qquad B = \frac{\lambda \cdot b}{1-\lambda} \qquad C = \frac{a - c \cdot \lambda}{1-\lambda} \qquad D = \frac{b}{1-\lambda} \qquad E = \frac{c}{1-\lambda}$$

Thus, expression (8) turns to a universal expression that relates turbine output power to water flow rate for all three types – Francis, Pelton and Kaplan water turbines. Here, only coefficients *a, b, c* and friction coefficient λ will change depending on the type of turbine. The results of $p^* = f(q^*)$ calculations for the case where the friction coefficient is λ=0.1 are given in Table 1 for the Francis turbine, Table 2 for the Pelton turbine, and Table 3 for the Kaplan turbine.

Table 1. The calculated values of $p^* = f(q^*)$ when λ=*0.1* for Francis turbine.

q^*	0,4	0,5	0,6	0,7	0,8	0,9	1	1,2	1,4

p^*	0,33	0,47	0,59	0,7	0,816	0,915	1	1,11	1,12

Table 2. The calculated values of $p^* = f(q^*)$ when λ=0.1 for Pelton turbine.

q^*	0,4	0,5	0,6	0,7	0,8	0,9	1	1,2	1,4
p^*	0,39	0,502	0,61	0,718	0,819	0,916	1	1,14	1,22

Table 3. The calculated values of $p^* = f(q^*)$ when λ=0.1 for Kaplan turbine.

q^*	0,4	0,5	0,6	0,7	0,8	0,9	1	1,2	1,4
p^*	0,39	0,5	0,61	0,716	0,818	0,914	1	1,1	1,2

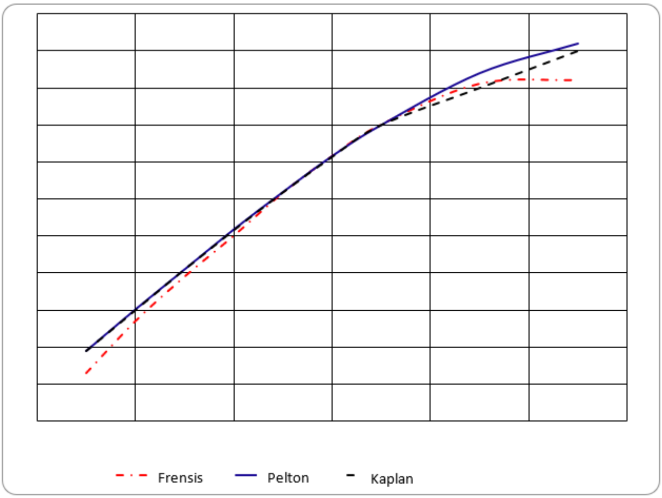

Figure 1. Chart of dependence of turbine output power on water consumption

Analyzing the data in Tables 1 ÷ 3, it can be unambiguously concluded that the output power values of the Pelton turbine and the Kaplan turbine completely match when the water consumption q* changes in the range of 0.4 ÷ 1.4 in relative units. When the water consumption q^* changes in the range of 0.4÷0.7, the power of the Francis hydro turbine p^* is slightly less than the power of other two types of turbines.

This shows that the efficiency of this turbine at small values of water flow rate is smaller than the efficiency of Pelton and Kaplan turbines. Figure-1 shows dependence curves $p^* = f(q^*)$ for hydro turbines of small HPPs. Depending on the load schedule, it is necessary to know the dependence that expresses $q_{qt} = f(p_{qt})$ the feedback when it is necessary to regulate the water flow rate through the opening angles of the guiding devices of water turbines. It needs to be noted that all the relations given above were obtained for a fixed rated value of the rotation frequency of the hydro turbine. If non-frequency electric generators - synchronous or asynchronous generators - whose rotation frequency is constant in a fixed mode are connected to hydro turbines, then equation (8) can be automatically written as the expression of the driving torque of the water turbine as the following expression:

$$m_{qt} = \frac{p^*}{n^*} = p_{qt} \tag{9}$$

where n^*=1.

In the second chapter, the results of the study of the steady state modes of the hydro power unit working together with the electromechanical converter at a constant rotation frequency in small HPPs are also described. In this section, the system of equations of the hydraulic unit consisting of a Francis turbine working in parallel with the power grid and a synchronous generator with conventional electromagnetic exitation was considered, and based on this system of equations, the steady state modes of the hydro power unit were studied with the help of computer modeling and simulation. The equation of a synchronous generator with electromagnetic induction, taking into account the equation of a hydroturbine, can be written in general as follows:

$$\left.\begin{aligned}
&p\Psi_{ds} = U_{ds} - \omega_r \cdot \psi_{qs} - r_s \cdot i_{ds}\\
&p\psi_{qs} = U_{qs} + \omega_r \cdot \psi_{ds} - r_s \cdot i_{qs}\\
&p\psi_{dr} = -\frac{r_{dr}}{x_{dr}} \cdot \psi_{dr} + \frac{r_{dr} \cdot x_{ad}}{x_{dr}} \cdot i_{ds} + \frac{r_{dr} \cdot x_{ad}}{x_{dr}} \cdot i_{df}\\
&p\psi_{qr} = \frac{r_{qr}}{x_{qr}} \cdot \psi_{qr} + \frac{r_{qr} \cdot x_{aq}}{x_{qr}} \cdot i_{qs}\\
&p\psi_{df} = \frac{r_{df}}{x_{ad}} \cdot U^{*}_{df} - r_{df} \cdot i_{df}\\
&p\omega_r = \frac{1}{T_j} \cdot m_{hv} - \frac{1}{T_j} \cdot m_{em}\\
&i_{ds} = \frac{x_{dr}}{\Delta d} \cdot \psi_{ds} - \frac{\Delta d_1}{\Delta d} \cdot i_{df} - \frac{x_{ad}}{\Delta d} \cdot \psi_{dr}\\
&i_{qs} = \frac{x_{qr}}{\Delta q} \cdot \psi_{qs} - \frac{x_{aq}}{\Delta q} \cdot \psi_{qr}\\
&i_{df} = \frac{x_{dr}}{\Delta d_2} \cdot \psi_{df} - \frac{\Delta d_1}{\Delta d_2} \cdot i_{ds} - \frac{x_{ad}}{\Delta d_2} \cdot \psi_{dr}\\
&m_{em} = \psi_{ds} \cdot i_{qs} - \psi_{qs} \cdot i_{ds}\\
&\omega_r = p\theta - 1\\
&m_{hv} = k_{пер} \cdot \left(- A \cdot q^5 - B \cdot q^4 + C \cdot q^3 + D \cdot q^2 + E \cdot q\right)
\end{aligned}\right\} \qquad (10)$$

where,

$U_{ds} = -U \cdot \sin\theta \quad U_{qs} = U \cdot \cos\theta$

U^{*}_{df} - the ratio of the induced voltage to the induced voltage in the case of no-load operation;

m_{hv} - the torque of the hydro turbine;

$k_{çev}$ - the coefficient that converts the base units of the hydro turbine into the base units of the synchronous generator;

q - is water consumption expressed in relative units.

In addition to the equation of the generator, the equation of the regulator must also be considered. The time constant of the regulation tact of the servo motor based regulators is 1-2 seconds. The equation of the inertial regulator is expressed as follows:

$$U_{çıx} = \frac{K}{Tp+1} U_{gir} \tag{11}$$

As mentioned above, the opening angle of the guide devices is used as the output value of the regulator, and this value determines the flow rate q of the water flowing through the turbine. As an input value the active power is set. The equation of the regulator and the expression of the current active power at the output terminals of the generator are added to the equations of the generator and the hydro turbine (10).

$$\left. \begin{aligned} pq &= \frac{k_{12}}{T_p}(p_{g_{ver}}) - \frac{q}{T_p} \\ p_{gen} &= U_{ds} \cdot i_{ds} + U_{qs} \cdot i_{qs} \end{aligned} \right\} \tag{12}$$

where,

p – derivative symbol $\tau=314 \cdot t$ according to synchronous time;

T_p – time constant of the regulator [rad];

k_{12} – regulator gain;

$p_{g\ ver}$ - generator requested output power.

coefficient k_{12} can be determined from the approximation of the $q = f(p)$ curve.

$$k_{12} = \begin{vmatrix} k_1 & q \le 1 \\ k_2 & q \ge 1 \end{vmatrix} \tag{13}$$

Then, an approximate calculations were made for small hydropower plants using a Francis turbine with the following parameters, and the following intermediate results were obtained: rated water head $H_n=50$ m, water flow rate $Q=56\ m^3/sec$ for the hydro turbine with diameter of D=2.45 m. With the given above values the nominal capacity of the small HPP can be expressed as following:

$$P_n=9,81 \cdot 0,9 \cdot 56 \cdot 50=24,72 \text{ MW}$$

After placing the parameters of the steady state of the system, the

generator, the turbine and the regulator and the obtained intermediate results in the system of equations, the mathematical model necessary for conducting the research was obtained. This mathematical model was adapted to the algorithm and presented in the form of fluctograms of the change of mode parameters of the generator of the small HPP. The values of the current output power of the generator were compared with the values of the required output power. It was determined that the difference between these values does not exceed 3%. In order to demonstrate the working principle of the system more clearly in the conducted studies, the system is simplified by considering the regulator as a first-order inertia ring. Choosing a more complex regulator does not affect the idea and algorithm of the general system modeling.

In the second chapter the problem of minimizing active power losses depending on the generator's operating mode and load curve also considered. In small HPPs the optimal control law of synchronous generator excitation has been determined where the losses of electrical energy are minimized due to the optimal flow of reactive power.

In Figure 2 shown the most common power supply topology scheme for connecting small HPPs to the grid in Azerbaijan.

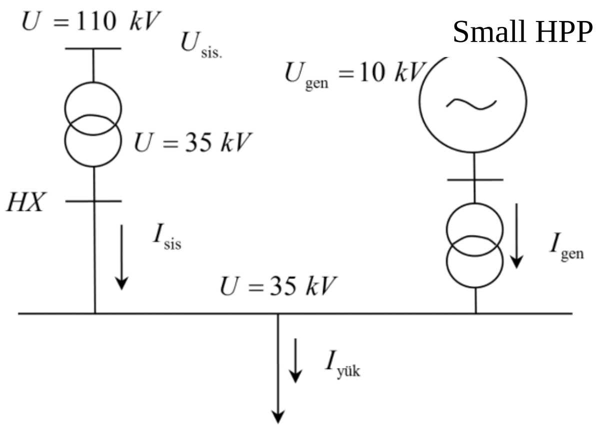

Figure 2. Power supply SLD

In this simple power supply scheme, the losses of electrical energy due to the additional current flow due to the transfer of active power as a whole depend on the active power schedule of the consumer and the small HPP. As for the reactive power, since the system has a controlled reactive power source as a synchronous generator of a small HPP, it is possible to determine the optimal law compliance of the control of the synchronous generator of a small HPP. Such an optimal control allows to minimize the losses of electric energy in the indicated scheme due to the transfer of reactive power with an optimal additional current.

Total losses are defined as follows:

$$\Delta p_g = \frac{\left(\beta^2 \cdot P_n^2 + \alpha^2 \cdot Q_н^2\right) \cdot R}{U^2} +$$

$$+ \frac{R_f}{x_{ad}^2}\left[\frac{x_d \cdot x_q}{U^2}\left(\beta^2 \cdot P_n^2 + \alpha^2 Q_n^2\right) + \alpha\left(x_d + x_q\right) \cdot Q_n + U^2\right] \cdot \left[1 + R(Q)\right]$$

Losses in the generator can be expressed in the form of a linear expression with an error of 10% as follows:

$$\Delta p_g = a \cdot Q^3 + b \cdot Q^2 + c \cdot Q + d$$

Where,

$$a = \frac{\left(R_i - R_0\right) \cdot R_f \cdot x_d \cdot x_q}{S_{baz} \cdot x_{ad}^2 \cdot U^2}$$

$$b = \frac{R}{U^2} + \left(1 + R_0\right)\frac{x_d \cdot x_q \cdot R_f}{x_{ad}^2 \cdot U^2} + \frac{R_f \cdot \left(R_i - R_0\right)}{S_{baz} \cdot x_{ad}^2} \cdot \left(x_d + x_q\right)$$

$$c = \frac{R_f}{x_{ad}^2} \cdot \left(x_d + x_q\right) \cdot \left(1 + R_0\right) + \frac{\left(R_i - R_0\right) \cdot R_f}{S_{baz} \cdot x_{ad}^2}\left(\frac{x_d \cdot x_q}{U^2} \cdot \beta^2 \cdot P_n^2 + U^2\right)$$

$$d = \frac{R}{U^2} \cdot \beta^2 \cdot P_n^2 + \frac{R_f}{x_{ad}^2}\left(\frac{x_d + x_q}{U^2} \cdot \beta^2 \cdot P_n^2 + U^2\right) \cdot \left(1 + R_0\right)$$

After the algebraic simplifications shown in more detail in the dissertation work body, the dependence of the power losses Δρ on the reactive power of the generator in a small HPP generator can be expressed as follows:

$$\Delta p_g = b \cdot Q_{gen}^2 + c \cdot Q_{gen} + d \qquad (14)$$

In general, the reactive power is defined as:

$$Q_{üm} = Q_{gen} + Q_x \tag{15}$$

The total losses in the generator and in the overhead power line are found from the following expression:

$$\Sigma\Delta p = \Delta p_x + \Delta p_{gen} = m + n \cdot Q_x^2 + b \cdot Q_{gen}^2 + c \cdot Q_{gen} + d \tag{16}$$

If we minimize the losses only within the generator, the expression (16) takes the following form:

$$Q_{gen} = -\frac{c}{2b} \tag{17}$$

It should be noted that for salient-pole synchronous machines, the coefficients *b* and *c* do not depend on the active power, that is, when changing the torque of the generator shaft, the minimum losses are equal to the constant reactive power. Thus, it follows that the reactive power of the generator (and therefore the exitation current), taking into account the parameters of the generator and overhead power lines, should be adjusted in proportion to the value of the reactive load of the operator. When the reactive power of the actuator varies in such a relatively small interval, it is practically not feasable to adjust the reactive power of the generator depending on the reactive load. In this case, the value of the reactive power for the generator should be found so that, if this value remains unchanged, it does not lead to total power losses of more than 5% at the maximum and minimum values of the reactive load. Of course, this mode is considered quasi-optimal. Thus, in the case of relatively small fluctuations of the reactive load compared to the average power value (Figure 3), it is possible to tolarate the quasi-optimal mode. In this case, the reactive power of the generator remains unchanged, errors in this mode remain minimum and do not exceed 5% boundary.

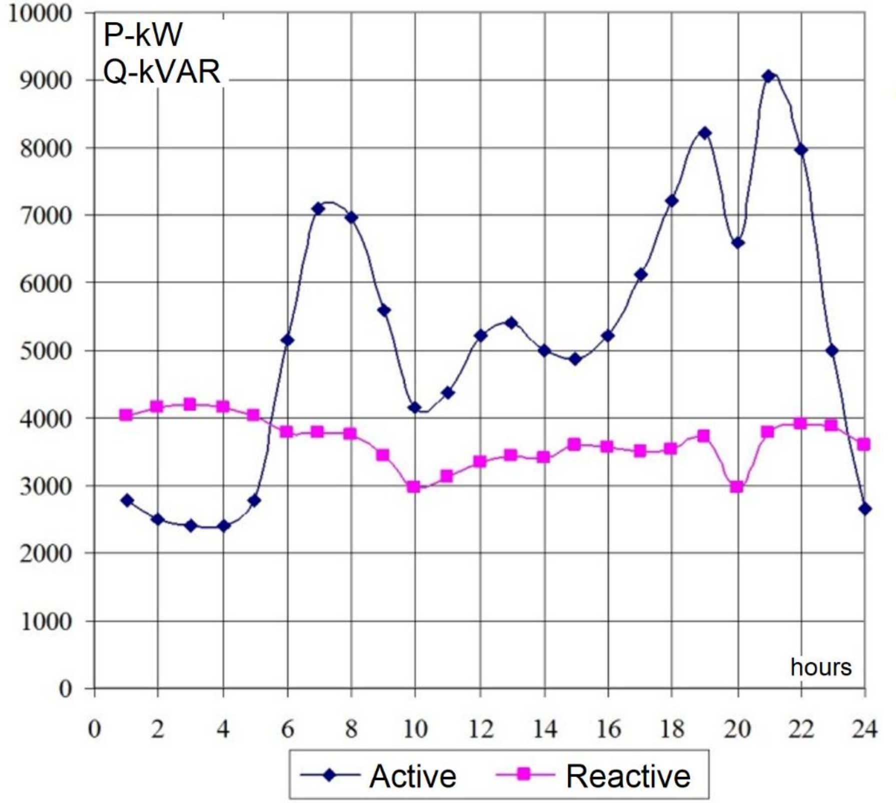

Figure 3. Load chart according to the readings of the Indigo power meter

In general, the results of the second chapter can be expressed as follows:

1. A mathematical model was developed to study the operating modes of small HPPs with Francis, Pelton and semi-Kaplan turbines. An analytical mathematical expression of the power of these turbines was obtained in the form of a polynomial, which expresses the dependence of the energy carrier - water flow.

2. An ultimate equation consisting of the synchronous motor, hydro turbine and controllers' equation has been developed. The accuracy, effectiveness and efficiency of the mathematical model have been demonstrated. For this reason, the model can be used in the

preliminary design calculations in the planning as well as in operation stages of the small HPPs.

3. In the case of relatively small fluctuations of the reactive load compared to the average value, it is possible to tolerate the quasi-optimal mode. In this case, the reactive power of the generator remains unchanged. In this mode of operation, errors remain minimum and do not exceed 5% boundary.

In the third chapter of the dissertation work, the use of electric machines and their control algorithms in small HPPs were considered. The main advantage of small hydropower is that they have little impact on the environment, and they are considered practically environmentally friendly energy sources. The main disadvantage of small hydropower is that the installation of small HPPs based on the technology of large HPPs leads to a significant increase in capital investment. Simplification of the technological composition of small HPPs by applying modern controlled electric machines was mentioned as one of the main technical tasks. In small power plants, as a rule, the turning mechanism of the blades of the guiding apparatus is built on the base of servo-motors. This in its turn requires presence of pressurized hydraulic units in small hydropower plants' design. The main objective is to consider the use of double-fed induction machines those rotor circuit connected to the semiconductor-based frequency inverters as generators in small HPPs and to study their operation modes in conjunction with hydro turbines. This will allow to control the rotation frequency of the generator rotor and the impeller of the turbine coupled to it within the certain range, which in turn leads to the regulation of output power of the hydro turbine.

As is known, the power of a water turbine is determined by the following expression:

$$\mathrm{P_t} = 9{,}81 \cdot \mathrm{Q} \cdot \mathrm{H} \cdot \eta \qquad (18)$$

where,

P_t – output power [kW];

Q – water flow rate [m^3/sec];

H- water head [m];

η – Efficiency [p.u.].

When conducting design calculations of hydro turbines, the hill diagrams are widely used. It makes possible to calculate the *D* and *H* indicators of the actually operated(designed) turbine by substituting the intermediate values obtained from the hill diagram in the conversion formulas.

$$n = \frac{n'_{м}\sqrt{H}}{D}\sqrt{\frac{\eta_{gм}}{\eta_{gм}}}; \quad Q = Q'_{м}\cdot D^2\cdot\sqrt{H}\cdot\sqrt{\frac{\eta_{gм}}{\eta_{gм}}} \qquad (19)$$

In formula (19), η_{gt} and $\eta_{gм}$ are the hydraulic efficiency of the model and real hydro turbines respectively. The dependence of two important parameters determining the output power of the turbine - water consumption Q' and the efficiency η - on the shaft rotation speed was considered. These values are the nominal parameters corresponding to the position of the opening angle $\alpha_0=26°$ of the guiding device for the PO400/683 type turbine: n_n=65 rpm; Q'_n=178 liters/second and efficiency; η_n=0.9 (point 1 in Figure 4).

If we increase the rotation speed of the turbine to n'_1=82 rpm at this value of the opening angle of the directional device α_0=26° (point 2), the water flow rate will reach to Q'_1=148 liters/sec and the efficiency will decrease down to 70% (η_1=0.7). Accordingly, the water flow rate, efficiency, output power and rotation speed can be expressed in relative values as follows:

$$p^*_t = \frac{P}{P_{t_n}}; \; q^*_t = \frac{Q'_1}{Q'_n} = \frac{148}{178} = 0{,}83; \; \eta^*_t = \frac{0{,}7}{0{,}9} = 0{,}778$$

$$p^*_t = q^*\cdot\eta^* = 0{,}83\cdot 0{,}777 = 0{,}65; \; \eta^*_t = \frac{n'_1}{n'_n} = \frac{82}{62} = 1{,}26$$

Thus, increasing the rotation frequency of the PO400/683 type turbine by 26% leads to a decrease in the output power of the turbine by 35%.

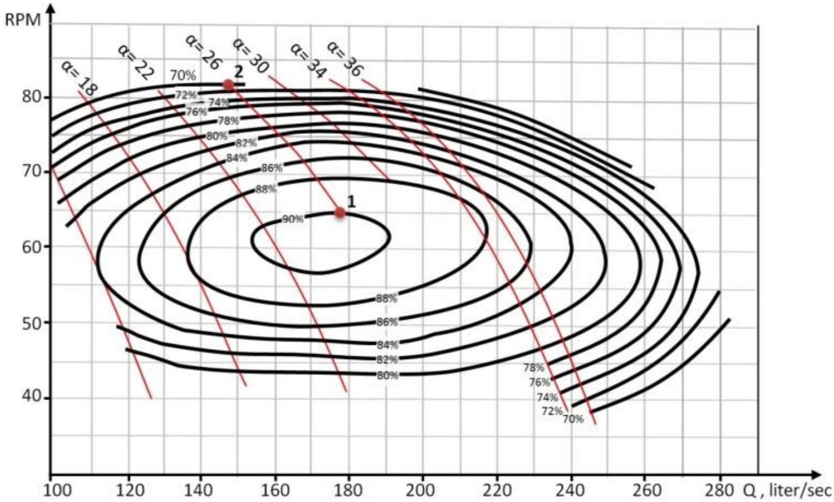

Figure 4. The hill diagram of the high-pressure PO400/683 turbine

The purpose of the study is to control the output power of the power unit not by changing the angle of inclination of the guide vane, but by changing the rotational frequency of the water turbine itself (the electric generator coupled to the hydro turbine).

$$S_{baz} = S_n = \frac{P_n}{\eta_g \cdot \cos\varphi_g} \qquad (20)$$

where,

P_n –the generator shaft rated active power;

η_g=0.95 – electrical efficiency of the generator;

$\cos\varphi_g$=0.9 is the power factor.

The regulator’s equation is proposed as following:

$$\Delta k_{fr} = \frac{k_a}{T_p \rho + 1} \Delta p_{em} \qquad (21)$$

where,

$\rho = \frac{d}{d\tau}$ – derivative symbol for synchronous time $\tau=314\cdot t$,

t-time [sec],

τ-rotor rotation angle [rad];

T_p – time constant of the controller (regulator);
k_a – controller (regulator) gain;
Δk_{fr} – frequency change of the current supplied to the rotor winding of the double-fed induction generator.

Then, the obtained mathematical model was demonstrated on the example of transient and steady-state operation modes of a double-fed induction generator, coupled to the water turbine with known parameters.

Another subject considered in the third chapter is the study and modeling of the operating modes of permanent magnet synchronous machines used in small power plants. An empirically obtained load graph was used to perform this task.

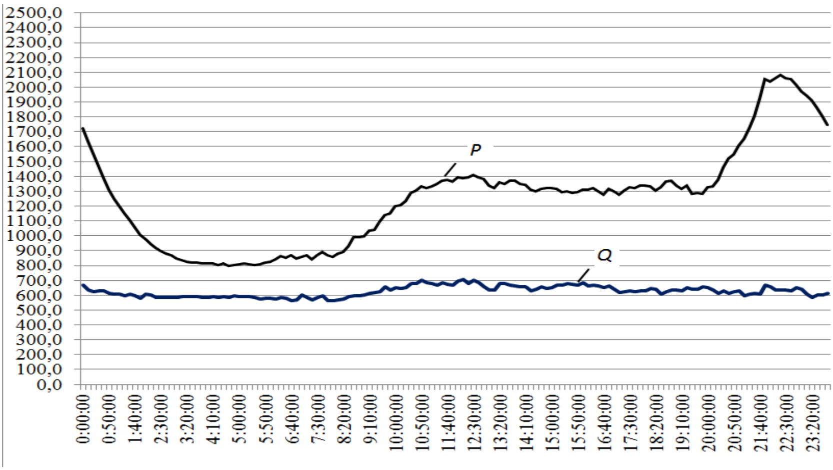

Figure 5. Typical load chart of consumers in rural areas of Azerbaijan (*P* active and *Q* reactive)

Water flow rate in turn, depends on the diameter of the water nozzle, which is regulated by the position of the needle of the injector. The speed of the water jet coming out of the injector is very high and its value is determined by the following expression:

$$v_c = \varphi\sqrt{2g \cdot H} \qquad (22)$$

where:

φ – speed coefficient φ=0.98–0.99;

H – water head, [meter];

$g = 9{,}81 \mathrm{m}/sec^2$ – gravitational acceleration:

The calculated parameters of the hydro turbine used in the model are given. Using the calculation formulas, assuming that the basic values of the nominal output power of the turbine are Q_n, H_n, η_n and P_{tn}, the following expression was obtained in relative units:

$$p_t^* = q^* \cdot h^* \cdot \eta^* \tag{23}$$

where,

$$p_t^* = \frac{P_t}{P_{tn}}\ ;\ q^* = \frac{Q}{Q_n}\ ;\ h^* = \frac{H}{H_n}\ \text{və}\ \ \eta^* = \frac{\eta}{\eta_n}$$

On the other hand, according to the Pelton turbine hill diagram, it is noted that the water head (water pressure) h^* and water flow rate q^* do not depend on the rotation frequency of the shaft of the hydropower unit, only the value of efficiency η^* depends on the rotational frequency of the shaft.

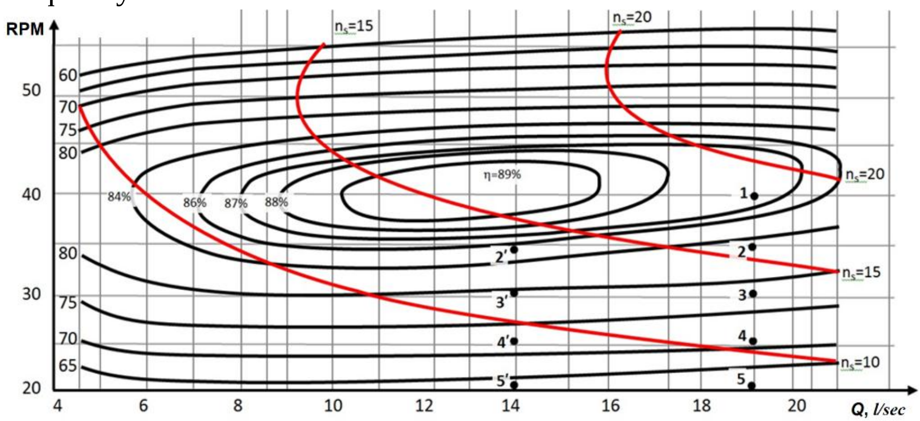

Figure 6. The Hill diagram of Pelton turbine

Then, according to the expression (23) and the following expression of the torque of the water turbine

$$m_t^* = \frac{p_t^*}{n^*} \tag{24}$$

the equation relating turbine output power and torque are determined depending on the rotation frequency. It is clear from the results of the calculations that when the rotation frequency of the shaft of the hydropower unit is reduced by 50% from the nominal, the power of the turbine decreases by 32% only due to the efficiency, however the flow rate remains constant and is equal to Q'=19 l/sec.

To reduce the water flow rate of the studied turbine by 26%, it is enough to reduce the diameter of the water nozzle by just 5 mm or 14%. If the time required for the complete closure of the injector considered to be 20-40 seconds, then reducing the diameter of the water nozzle to the above-mentioned portion should not take more than 3-6 seconds. The control algorithm proposed by this method allows to adjust the rotation frequency and output power of the hydropower unit in the range of $(1\div0.5)\cdot n_n$. However, it is only required to reduce the water flow rate by 26% at once. This method makes it possible to abandon the complex mechanical adjustment system, which is implemented with the alternating co-operation of the deflector and the injector needle in the range of variation of the proposed output power.

A few more advantages of frequency controlled permanent magnet synchronous electric machines application as generators of hydro power units in small HPPs with Pelton turbines are listed. Since Pelton turbines work in impulse mode, a heavy flywheel is additionally attached to the shaft of hydropower units with this type of turbine to suppress rotational frequency oscillations. This, in turn, naturally leads to a significant increase in the inertia and weight of the rotating parts of the hydropower unit. As a result, in cases of significant reduction of water flow rate, such a situation may arise that the energy of the water jet cannot overcome the stationary torque of the unit. In this case, the presence of a frequency inverter connected to the stator circuit of the synchronous generator will allow the unit to be started with the frequency inverter even in cases of very low water flow rate.

Finally, when there is no water flow at all, starting with a frequency converter will allow the use of the generator of a small HPP as a synchronous compensation unit. In the following sections of the chapter, a mathematical model corresponding to the modes listed above was developed and the results were illustrated in tabular and graphical form. A model of a permanent magnet synchronous generator controlled by a frequency converter is given. The equations of the synchronous generator are expressed as follows:

$$\left.\begin{aligned}
p\Psi_{ds} &= U_{ds} - \omega_r \cdot \psi_{qs} - r_s \cdot i_{ds} \\
p\psi_{qs} &= U_{qs} + \omega_r \cdot \psi_{ds} - r_s \cdot i_{qs} \\
p\psi_{dr} &= -\frac{r_{dr}}{x_{dr}} \cdot \psi_{qr} + \frac{r_{dr} \cdot x_{ad}}{x_{dr}} \cdot i_{ds} + \frac{r_{dr}}{x_{dr}} \cdot M_f \\
p\psi_{qr} &= -\frac{r_{qr}}{x_{qr}} \cdot \psi_{qr} + \frac{r_{qr} \cdot x_{aq}}{x_{qr}} \cdot i_{qs} \\
p\omega_r &= \frac{1}{T_j} \cdot m_t - \frac{1}{T_j} \cdot m_{em} \\
p\alpha &= \omega_r \\
U_{ds} &= 0{,}707 \cdot k_{us}\left[\cos\left(k_{fs} \cdot \tau\right) \cdot \left(\cos\alpha - \sin\alpha\right) - \sin\left(k_{fs} \cdot \tau\right) \cdot \left(cos\alpha + \sin\alpha\right)\right] \\
U_{qs} &= 0{,}707 \cdot k_{us}\left[\cos\left(k_{fs} \cdot \tau\right) \cdot \left(\cos\alpha + \sin\alpha\right) + \sin\left(k_{fs} \cdot \tau\right) \cdot \left(\cos\alpha - \sin\alpha\right)\right] \\
i_{ds} &= \frac{x_{dr}}{x_{ds} \cdot x_{dr} - x_{ad}^2} \cdot \psi_{ds} - \frac{x_{dr} \cdot x_{ad}}{x_{ds} \cdot x_{dr} - x_{ad}^2} \cdot M_f - \frac{x_{ad}}{x_{ds} \cdot x_{dr} - x_{ad}^2} \cdot \psi_{dr} \\
i_{qs} &= \frac{x_{qr}}{x_{qs} \cdot x_{qr} - x_{aq}^2} \cdot \psi_{qs} - \frac{x_{ad}}{x_{qs} \cdot x_{qr} - x_{aq}^2} \cdot \psi_{qr} \\
m_{em} &= \psi_{ds} \cdot i_{qs} - \psi_{qs} \cdot i_{ds} \\
p_s &= U_{ds} \cdot i_{ds} + U_{qs} \cdot i_{qs} \\
q_s &= U_{qs} \cdot i_{ds} - U_{ds} \cdot i_{qs}
\end{aligned}\right\} \quad (25)$$

The system of equations of the synchronous generator (25) is written in relative units, considering the basic value of power as the full power of the electric machine:

The parameters of the considered synchronous generator are as follows:

Power	P = 1500	kW
Voltage	U_n = 400	V

Current	$I_n = 2165$	A
Frequency	$f_n = 50$	Hz
Rotation speed	$\omega = 500$	rpm
Pair of poles	p = 6	

Then, the numerical values of the parameters calculated with relative units were found and a suitable solution algorithm was proposed. Fluctograms were obtained by solving the system of equations based on the data corresponding to the different operating modes of the hydro power unit. From the obtained fluctograms, it can be seen that the proposed algorithm of electric control of the output power of the hydropower unit consisting of a turbine and a frequency-regulated permanent magnet synchronous generator is completely feasible and such algorithms allow to avoid the mechanical control of the output power with the help of deflectors within preset output power control interval in such small HPPs. In addition, the use of a controlled electric machine allows the frequency inverter to start the generator even in cases when the hydro turbine produces very small power to the shaft (seasonal water minimum) and there is no water flow at all.

Another issue addressed in the third chapter is the study and modeling of the operating modes of small HPPs equipped with a semi-Kaplan turbine. In this part of the chapter, the main goal is to study the expediency of the application of electric machines controlled in small HPPs from the point of view of increasing the economic efficiency of the operation of hydro turbines used in such hydropower units. For this purpose, three types of hydro turbines applied in small hydroelectric power stations were considered - Francis turbine, Pelton turbine and semi-Kaplan turbine.

The experience of operation in modern wind power plants where frequency controlled electromechanical converters application has been reviewed. The main universal characteristics of Francis and Pelton turbines are presented. Comparative tables were compiled and dependencies between turbine rotation frequency, water flow rate and efficiency have been analyzed. Then, the operating modes of the semi-Kaplan turbine were considered. Using the Kaplan turbine's propeller characteristics, the values of rotation frequency and efficiency at different values of water flow rate were analyzed in tabular form, and as a result, it was shown that it is necessary to control the rotation frequency in proportion to water flow rate when the consumption of the energy carrier - water changes. Graphically, the above-mentioned idea is illustrated more clearly in the figure below.

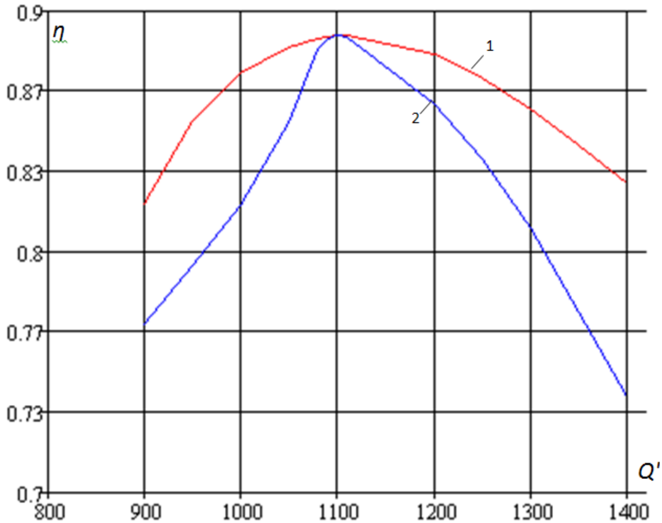

Figure 7. Chart describing relationship between water flow rate and the rotation frequency of the turbine. Regulated (1). Not regulated (2)

To determine the dependence of the relative efficiency on the rotation frequency, the dependence was sought in the form of a parabolic expression:

$$\eta^* = a \cdot n'^{*2} + b \cdot n'^* + c \tag{26}$$

Expressions for the output power and torque of the turbine have been obtained. As an intermediate result obtained from these statements, analogously to wind energy, it was noted that the produced power is proportional to the cubic value of the rotation frequency (respectively, to the cubic value of water flow rate) and the torque is proportional to the square value of the rotation frequency. As a continuation of the work, a mathematical model of the system was worked out, static and dynamic characteristics of the object were studied on the example of a hydro unit consisting of a semi-Kaplan turbine and a permanent magnet frequency controlled synchronous machine.

In general, the equations for frequency-controlled permanent magnet synchronous machines are given. The parameters of the synchronous generator regulated by the permanent magnet frequency inverter and its related data were given, and the power and torques for different frequencies has been calculated in mentioned units. Also, for some of them calculations have been carried out based on the rated data of the generator. The converted torque m_{cf} of the hydro turbine can be written as follows:

$$\boldsymbol{m}_{\boldsymbol{çf}} = -\text{К}_\text{р}\left[-0{,}887(\boldsymbol{\omega_r} \cdot \boldsymbol{n}^*_{\boldsymbol{max}})^{\boldsymbol{3}} + 1{,}657(\boldsymbol{\omega_r} \cdot \boldsymbol{n}^*_{\boldsymbol{max}})^{\boldsymbol{2}} + 0{,}263 \cdot (\boldsymbol{\omega_r} \cdot \boldsymbol{n}^*_{\boldsymbol{max}}) - 0{,}032\right] \tag{27}$$

The parameters of the synchronous generator controlled by the permanent magnet frequency inverter and its related data are given, the power and torques calculations for different frequency values have been performed. Fluctogram of the change of the mode parameters of this type of small hydropower plant is described. Analysis of the fluctogram shows that the reactive power q_s at the output of the generator decreases to 12% when the active load p_s of the generator decreases. It is possible to compensate for this reduction by increasing the amplitude k_{us} of the generator voltage at lower frequencies when necessary.

Another interesting arrangement is a double-fed induction generator with a frequency inverter in the rotor circuit. Such electromechanical converters are usually used in wind power plants, but in recent years they have been proposed to be used in small HPPs.

Using a double fed induction machine with a frequency inverter in the rotor circuit allows to regulate the rotor rotation frequency in ±(25÷30)% range of the synchronous rotation frequency. The rated power of the frequency inverter is approximately equal to 30% of the installed power of the generator. During power unit frequency start up the rotor voltage and frequency change according to the expression (28).

$$k_{ur} = k_{fr} = 0{,}1 + 0{,}00038 \cdot \tau \tag{28}$$

Table 4 shows the parameters of the steady-state mode obtained after increasing the frequency and voltage to the minimum operating mode while implementing frequency start-up.

Table 4. Parameters of the steady state mode

k_u=k_f	ω_r	m_{em}	s_{em}	p_{em}	q
0,4	0,401	–0,1	0,041	–0,04	0,01
0,5	0,502	–0,15	0,062	–0,06	0,014
0,6	0,602	–0,2	0,124	–0,12	0,03
0,7	0,703	–0,25	0,181	–0,176	0,043
0,78	0,784	–0,3	0,217	–0,235	0,09

As we know, small HPPs with double fed induction generators allow controlling the rotation frequency of the shaft proportional to the water flow rate in the range of 25÷30%. In such a case its power factor may vary from 0.9 (inductive) to 0.9 (capacitive). The inductive power factor $cos\varphi$=0.9, that is when the reactive power is consumed from the grid, it is accompanied by a low load corresponding to the low rotation frequency of the generator shaft of the small HPP. The average value of the required reactive power in such a mode is equal to $q_{req} \approx 0.5$.

MAIN RESULTS OF THE WORK

1. A mathematical model was developed to study the operating modes of small HPPs with Francis, Pelton and semi-Kaplan turbines. An analytical mathematical expression was obtained in the form of a polynomial reflecting the dependence of the power of these turbines on the water flow rate.

2. A combination mathematical model of a synchronous motor, a hydro turbine, and a regulator based on complete equations has been developed. The results of research conducted on the basis of this mathematical model have demonstrated its accuracy, effectiveness and efficiency. For this reason, the model can be used in the preliminary calculations both during the design and operation stages of the small HPPs.

3. A simplified methodology for determining the torque using the turbine hill diagram according to the control mode of the output power of the hydro turbine depending on its rotation frequency is proposed.

4. A generalized mathematical model of the hydropower unit consisting of the mathematical models of the hydro turbine, double-fed induction generator and the automatic current/frequency controller in the rotor circuit of the double-fed induction generator was developed.

5. The research conducted on the basis of the developed mathematical model confirmed the correctness of the main concept of controlling the active power of the power unit by regulating the current in the rotor winding of the double-fed induction generator through the frequency inverter.

6. Application of a frequency-controlled fixed magnet synchronous generator as a generator in small HPPs with a Pelton turbine hydropower unit allows to ensure a high degree of adaptation to the frequently changing power demand of the grid and to avoid mechanical regulation of output power with the help of deflectors in the preset control interval.

7. On the basis of the developed mathematical model of the hydropower unit equipped with a controlled permanent magnet synchronous machine, the operating algorithm of the hydropower unit

was simulated in the case rotation frequency regulation in the rotor rotation frequency interval (which allows the output power to change in the same ratio) with the help of a modern IGBT based frequency inverter.

8. A system consisting of a frequency-controlled synchronous machine working together with a turbine with a significantly larger mass of the flywheel allows to operate efficiently even in cases with very little water flow rate. In addition, frequency start-up allows maintaining the system's functionality even in the absence of water flow, in this case, the generator will work as a synchronous compensator unit as shown in the mathematical model.

THE MAIN PROVISIONS OF THE DISSERTATION ARE REFLECTED IN THE FOLLOWING WORKS

1. Mustafayev R.I., Hasanova L.H., Musayev M.M. Some subjects of compensation of the induction generators reactive power in wind-power and small hydroelectric power plants // e-Journal "Reliability: Theory & Applications" USA-San Diego, v.8, No.4 (31), December, 2013, pp. 2–13.
2. Mustafayev R.I., Hasanova L.H., Musayev M.M. Modelling starting regime work of the induction generators of wind turbine and small hydroplaning // International Journal of Recent Development in Engineering, v.1, Issue 3, December 2013, pp.16–23.
3. Mustafayev R.I., Hasanova L.H., Aliyev Q.M., Musayev M.M. The excitation control and stability of small hydroelectric power stations synchronous generators when operation in power system // e-Journal "Reliability: Theory & Applications" USA, San Diego, v.9, No.4 (35), December, 2014, pp. 29–36.
4. Mustafaev R.I., Gasanova L.G., Musayev M.M., Nabiev Kh.I. Some subjects of regulating the excitation of synchronous generators of small hydro power plants // Problems of Energy. 2014, No. 2, p. 3–7
5. Mustafaev R.I., Gasanova L.G., Musayev M.M., Mammadov E.M., Nabiev Kh.I. Some aspects of double-fed induction generators' application in small hydro power plants. News of Higher Education Institutions Electromechanics, 2015, No. 6, pp. 59–66.
6. Mustafaev R.I., Gasanova L.G., Musayev M.M., Mamedov E.M., Nabiev Kh.I. Modeling and study of operating modes of small hydroelectric power plants with double-fed induction generators // Electromechanics, Moscow, 2016, No. 6, pp. 59–66.
7. R.I. Mustafayev, L.H. Hasanova , M.M. Musayev, E.M. Mamadov , Kh.I. Nabiyev Modeling and Study of Operating Modes of Small Hydro Power Plants with Double Fed Induction Generator. Modern Electric Power Systems 2015 - MEPS'15, Wroclaw, Poland - July 6-9, 2015.

8. Mustafaev R.I., Gasanova L.G., Musayev M.M. Modeling and study hydropower units with frequency-controlled permanent magnet synchronous generators of small hydro power plants // News of CIS Universities Power Engineering, 2016, No. 2, pp. 102–117.

9. Mustafaev R.I., Gasanova L.G., Musayev M.M. Study of steady state and dynamic characteristics of hydropower units of small hydroelectric power plant // Electro. Electrotechnica, Electro energetics, electrical engineering industry. 2016, No. 4, pp. 17–21.

10. Mustafaev R.I., Gasanova L.G., Musayev M.M. Application of controllable electric machines in hydropower units of grid tied small hydroelectric power plants // Electrical Engineering, Moscow, 2018, No. 5, pp. 38–44.

11. Mustafayev, R.I., Hasanova, L.H., Musayev, M.M. Using Regulated Electrical Machines in Small Hydropower Plants Operating in a Power Network. *Russian Electrical Engineering*., 2018, 89(5), 322–327 SCOPUS.

12. Musayev, M.M. Study of operating modes of small hydroelectric units equipped with synchronous generator // International Journal on "Technical and Physical Problems of Engineering" (IJTPE). – March 2020, v.12, No 1, – p.44-48.

13. Musayev M.M. Summary of small hydropower plants in Azerbaijan // Problems of Energetics, 2020, No. 3 pp. 38 - 43

14. Gasanova L.G., Aliyev H.S., Musayev M.M.. Study of operating modes of small HPSS' hydroelectric units equipped with synchronous generator.// e-Journal "Reliability: Theory & Applications" - USA, San-Diego:- June 2023,Vol.18 No.2 (73), p. 79-86.

15. Gasanova L.G., Musayev M.M. Modeling and research of electrical machines in hydropower units of small hydro power plants. Monograph // Under the general editorship of L.G. Gasanova, M.M. Musayev - Publishing House "Elm", 2024. - 171 p.

Author's personal participation

The book [13] listed in the bibliography for the PhD dissertation were written by the author. The author owns the context of the scientific problem, as well as the approach taken to solve it in publications [1-12,14,15] those were co-authored.

The defense will be held on 11 October 2024 at 11:00 at the meeting of the Dissertation council ED 2.04 of Supreme Attestation Commission under the President of the Republic of Azerbaijan operating at Azerbaijan Technical University.

Address: AZ1073, Baku city, Huseyn Javid avenue 25.

Dissertation is accessible at the Library of Azerbaijan Technical University.

Electronic versions of dissertation and its abstract are available on the official website of Azerbaijan Technical University.

Abstract was sent to the required addresses on 27 august 2024.

Signed for print: 20.08.2024

Paper format: A5

Volume: 42548

Number of hard copies: 30