Calculation of specific rates of the electric energy consumption at frequency regulation of electric drives: A case study of pumping stations

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Abstract. The issues of developing a methodology for calculating the specific rates of electrical energy consumption during frequency regulation of electric drives of pumping stations are considered. When calculating specific consumption rates, experimental studies were carried out at the Chirchik pumping station. When developing the methodology, technological, design parameters, water consumption, as well as the total capacity of pumping units based on frequency-controlled electric drives are taken into account. At the same time, the characteristics of the main parameters that must be taken into account when choosing variable frequency drives for pumping units are determined.

1. Introduction
In all sectors of the economy of the Republic, in particular large-capacity pumping stations of pumping irrigation system are in the process of taking measures to increase the efficiency of electric energy consumption, to develop energy-saving modes of operation, as well as the introduction of energy and resource-saving techniques and technologies.

Population growth and economic development increases the demand for water year by year, therefore water scarcity is growing steadily year after year [1]. The Decree of the President of the Republic of Uzbekistan dated July 10, 2020 No. PF-6024 "On approval of the water resources development Concept for the Republic of Uzbekistan for 2020-2030" sets a number of tasks. One of those important issues is to save electricity and irrigation water at irrigation pumping stations and the development of methods for determining electric energy consumption for irrigation pumping stations.

In order to achieve the required lifting capacity in technical and economic support in establishing electric energy consumption rate which is according to the water consumption diagram - electricity regulation issues at pumping irrigation station, it is advisable to maintain centralized control of stand-by pumping units via frequency-regulated electric drives [2, 3].

In centrifugal frequency regulating the stand-by pumps of electric drives, developing the methodology of unit electric energy consumption rates, it is necessary to take into consideration the followings:
- rational and efficient use of electricity, a plan of organizational and technical measures, pumping units with a frequency-regulated electric drive - scientific and technological advances, the consideration of water conditions;
- Achieving the best economic performance in using energy resources, systematic consideration of the irrigation pumping station, taking into account the technical processes and developments in the field of water supply;
- determination of pumping station levels on the basis of provision of modern electrical technologies in the units, instead of operating modes.

All these requirements are met by the introduction of frequency-regulated electric drives in pumping units.

In centrifugal frequency-regulation of electric drives of standard-by-pumps unit electricity consumption rates are classified according to the following main features [4, 5,6]:

a) by level of unit - individually and in groups (scope of application);
b) according to the cost structure - technological and general production;
c) according to the working time - annually and quarterly.

In view of the above, consumption rate indicators at irrigation pumping stations can be formulated as follows [7, 8, 9].

Individual consumption rate is the electricity consumption rate for the volume of lifted irrigation water by the pumping unit, taking into account the basic structural configuration of the pressure transmission pipe [6, 10].

Technological consumption rate is the electricity consumption rate in the main and auxiliary technological processes in water supply, in the calculation of their costs.

The overall level of industrial consumption is the energy consumption that occurs in the electrical networks of the pumping station, as well as in the technology of the frequency regulator, the technological level of electricity consumption and the consumption of electricity by auxiliary devices in production.

2. Methods and Results

The value of the consumption rate is a unit of measure for the rate of electricity consumption for lifting 1 m³ of raised water to a height of one meter of the water column. Consumption rate is expressed as a fraction: the unit of electric energy measurement is in the numerator, and the unit of irrigation water measurement is in the denominator, i.e.:

\[
N_{cr} = \frac{W_{el,en}}{Q_{vdw}} \text{ kW} \cdot \text{hour} / \text{m}^3
\]  

(1)

where \( N_{cr} \) - consumption rate; \( W_{el,en} \) - electric energy consumption, kW hour, \( Q_{vdw} \) - volume of discharged water, m³.

The main means of determining the standard indicator values are mathematical calculation methods. Practical development of normative indicators is carried out by one of the following methods, namely: computational-analytical, experimental, static-computational, combined methods, etc. [7].

One of the main methods in the development of electric energy consumption rates for the volume of water delivered by pumping units is the computational-analytical method. In addition, experimental and static-computational, combined methods are used in some cases [4, 5, 11].

Information service on large hydro-installations of pumping stations, their technical parameters, assembly diagram and structure of the unit together with the pressure transmission pipe, as well as the main initial data of performance indicators obtained during the operation of the pumping station for an intermediate time are considered in determining the electric energy consumption rate for the volume of delivered water. It is accepted to calculate the parameters of the electric motor and the catalog characteristics of the pump on the basis of accurate data.
The pressure consumption curves for centrifugal stand-by pumps, Fick and power consumption characteristics [12, 13], as well as the exact character point coordinates, the determination of the constant value of the working shaft diameter (Di.sh.) and the pump rotational frequencies are given in the catalogs. When using the working shaft, the diameter of the pump or its rotation frequency differs from the values specified in the catalog, it is acceptable to carry out by means of effect coefficients (ηf,ηn) [12-17]. The following basic information is given in the calculation of electric energy consumption for the volume of lifted water: water discharge table, pump and electric motor types, pressure transmission pipeline assembly, pipeline composition and length, geometric height at pumping and the number of pumping units operating simultaneously in the next period and etc [2].

Experimental studies on the calculation of consumption rates were conducted at the "Chirchik" pumping station. The research process was conducted in two stages. In the first stage, in the case of uncontrolled pump unit capacity (f=50 gts) (02.06.2020-13.06.2020), measurements were carried out at regular intervals and electricity consumption was indicated. In this case, a technological consumption rate of electricity for the volume of lifted water for No.2 pumping unit was developed, on the basis of the computational-analytical method. All data are given in Tables 1, 2.

**Table 1.** In uncontrolled pumping unit capacity (f=50 gts), the average technological consumption of electric energy for the volume of lifted water

| Number of measurements | The volume of lifted water, m³ | Electric energy consumption, kW-hour | Electricity consumption rate for the volume of lifted water kWh/m³ | (aver.value.)² |
|------------------------|-------------------------------|-------------------------------------|---------------------------------------------------------------|--------------|
| Measurement №1 02.06.2020 | 21288.0 | 3242.80 | 0.152 | 0.00076 |
| Measurement №2 03.06.2020 | 20580.0 | 2958.21 | 0.144 | 0.00130 |
| Measurement №3 04.06.2020 | 18832.0 | 3324.57 | 0.177 | 0.00001 |
| Measurement №4 05.06.2020 | 21072.0 | 3686.56 | 0.175 | 0.00002 |
| Measurement №5 06.06.2020 | 17840.0 | 2905.59 | 0.163 | 0.00029 |
| Measurement №6 07.06.2020 | 19032.0 | 3300.60 | 0.173 | 0.00004 |
| Measurement №7 08.06.2020 | 19536.0 | 3355.16 | 0.172 | 0.00007 |
| Measurement №8 09.06.2020 | 14304.0 | 3622.71 | 0.253 | 0.00539 |
| Measurement №9 10.06.2020 | 13842.0 | 2662.39 | 0.192 | 0.00016 |
| Measurement №10 11.06.2020 | 19824.0 | 3500.59 | 0.177 | 0.00001 |
| Measurement №11 12.06.2020 | 14712.0 | 3158.42 | 0.215 | 0.00121 |
| Measurement №12 13.06.2020 | 15480.0 | 2567.86 | 0.166 | 0.00020 |
| **216342.0** | **38285.5** | **0.180** | **0.00946** | **0.00086** |

**Control measurement error in electric energy consumption error is as follows Δ (%)**:

\[ \Delta = 1.28 \]

**Probability of error in control measurement, 0<5%**

In qualitative selection of electric energy values indicated after static analysis, it is necessary to estimate the expected mathematical value of electric energy. Therefore, the arithmetic mean of the sample is counted as the assessment of the level of mathematical accuracy.

\[ X_{av} = 0.180 \]

Size \(\sigma = \sqrt{S} \)

\[ \sigma = 0.03 \]

\( X_{av} \) the confidence interval of the estimate is calculated by the following formula:

\[ P(X_{av} - S/\sqrt{n}*T_{a,n-1}<a<X_{av} + S/\sqrt{n}*T_{a,n-1})=1-\alpha. \]

Where \(\alpha\) – the actual value of electricity consumption \(T_{av}\) Student’s coefficient.

With a reliability indicator \(P = 0.95\), the current of the actual value of electric energy can be equal to:

\[ \Delta = \pm 0.00007815 \]
In the second stage, the efficiency of the pumping unit in a controlled (f = variable) state (16.06.-27.06.2020) measurements were carried out in the time interval and the power consumption is indicated. In this case, based on the use of the analytical-computational method for pumping unit No. 2, the technological electricity consumption rate for the volume of lifted water was developed (Figure 1). All data are shown in Tables 3-4.

**Table 2.** In the case of uncontrolled capacity of the pumping unit (f=50 gtf) electric energy consumption (02.06.-13.06.2020) in the time interval

| Date of measurements | Technical data of the electric motor | Technical passport of Pump | Experimental data |
|-----------------------|-------------------------------------|---------------------------|-------------------|
|                       | Motor power, N [kW] | Rotat/sec, min | Electric motor type | Efficiency, % | Water lifting volume, Q, m³/hour | Pressure H, m | Voltage U | Current, I | cosφ | Time worked during the day, 1 | Actual electricity consumption per day, W | Actual electricity consumption per day, W day, kW-hour, W | Actual electricity consumption per day, kW-hour, W |
| 02.06.2020            | 160                  | 1000            | 5AM315MBY          | 94.5          | 1080                         | 37          | 384          | 239       | 0.85 | 24                     | 3242.80                      | 3242.80 |
| 03.06.2020            | 160                  | 1000            | 5AM315MBY          | 94.5          | 1080                         | 37          | 382          | 263       | 0.85 | 20                     | 2958.21                      | 2958.21 |
| 04.06.2020            | 160                  | 1000            | 5AM315MBY          | 94.5          | 1080                         | 37          | 383          | 268       | 0.85 | 22                     | 3324.57                      | 3324.57 |
| 05.06.2020            | 160                  | 1000            | 5AM315MBY          | 94.5          | 1080                         | 37          | 385          | 271       | 0.85 | 24                     | 3686.56                      | 3686.56 |
| 06.06.2020            | 160                  | 1000            | 5AM315MBY          | 94.5          | 1080                         | 37          | 381          | 259       | 0.85 | 20                     | 2905.59                      | 2905.59 |
| 07.06.2020            | 160                  | 1000            | 5AM315MBY          | 94.5          | 1080                         | 37          | 386          | 242       | 0.85 | 24                     | 3300.60                      | 3300.60 |
| 08.06.2020            | 160                  | 1000            | 5AM315MBY          | 94.5          | 1080                         | 37          | 386          | 246       | 0.85 | 24                     | 3355.16                      | 3355.16 |
| 09.06.2020            | 160                  | 1000            | 5AM315MBY          | 94.5          | 1080                         | 37          | 384          | 267       | 0.85 | 24                     | 3622.71                      | 3622.71 |
| 10.06.2020            | 160                  | 1000            | 5AM315MBY          | 94.5          | 1080                         | 37          | 382          | 263       | 0.85 | 18                     | 2662.39                      | 2662.39 |
| 11.06.2020            | 160                  | 1000            | 5AM315MBY          | 94.5          | 1080                         | 37          | 387          | 256       | 0.85 | 24                     | 3500.59                      | 3500.59 |
| 12.06.2020            | 160                  | 1000            | 5AM315MBY          | 94.5          | 1080                         | 37          | 382          | 234       | 0.85 | 24                     | 3158.42                      | 3158.42 |
| 13.06.2020            | 160                  | 1000            | 5AM315MBY          | 94.5          | 1080                         | 37          | 383          | 253       | 0.85 | 18                     | 2567.86                      | 2567.86 |

Individual consumption rate of electricity does not fully demonstrate the electric energy consumption of the water supplied by each pumping unit to a water column with one-meter height. Taking into account the energy efficiency of irrigation pumping stations, it is logical to determine the rate of technological electrical energy consumption [4]. This figure includes the entire complex associated with the delivery of water to a height of a water column of up to one meter.

In this regard, the technological consumption rate is as follows:

$$N_{cr} = \frac{Q \cdot H \cdot \frac{Y}{\eta} \cdot t}{Q_{vdw}}, \text{ kW} \cdot \text{hour} / \text{m}^3$$ (2)

Theoretically, electric energy consumption needed to lift 1 m³ of water to a height of one meter must remain unchanged. But here appear other factors that must be taken into account while controlling the efficiency of the pumping unit using a frequency-regulated electric drive: the efficiency coefficient of all equipment required to lift 1 m³ of water to one-meter height, including an asynchronous motor, the efficiency coefficient of an additional frequency converter in addition to the efficiency coefficient of pump and the transmission pipeline [16, 18, 19]. The efficiency of the power equipment was assumed to be constant in the frequency regulation of the pump efficiency. In that case, productivity, pressure and electricity consumption will vary depending on the water consumption schedule. The resulting technological unit electricity consumption rate according to the given value of the pump water lifting schedule is as follows:
\[ \Delta E_{\text{result}} = \frac{\Delta E_1 Q_1 + \Delta E_2 Q_2 + \cdots + \Delta E_i Q_i}{Q_1 + Q_2 + \cdots + Q_i} \]  \quad (3)

Here: \( \Delta E \) - is the unit rate for graph 1, \( Q_1 \) is the water consumption according to the graph of water transfer over time.

Optionally, when regulating the efficiency of the pumping unit, the \( \Delta E_{\text{result}} \) will be smaller than the not regulated unit rate, i.e.

\[ \Delta E_{\text{result}} < \Delta E_{\text{uncontrolled}} \]

Table 3. Average technological consumption of electric energy for the volume of lifted water in the controlled (f=variable) position of the pumping unit

| Date of measurements | The volume of lifted water, m³ | Electric energy consumption, kW-hour | Electric energy consumption rate for the volume of lifted water, kW.l.m³ | (aver.value, %) |
|---------------------|-----------------|-------------------------------|-------------------------------------------------|----------------|
| 16.06.2020          | 19560           | 3065.56                       | 0.157                                           | 0.00008        |
| 17.06.2020          | 17000           | 2540.86                       | 0.149                                           | 0.00027        |
| 18.06.2020          | 15700           | 2800.77                       | 0.178                                           | 0.00016        |
| 19.06.2020          | 18040           | 3165.28                       | 0.175                                           | 0.00009        |
| 20.06.2020          | 15620           | 2413.82                       | 0.155                                           | 0.00013        |
| 21.06.2020          | 14274           | 3066.84                       | 0.215                                           | 0.00024        |
| 22.06.2020          | 19320           | 3047.76                       | 0.158                                           | 0.00006        |
| 23.06.2020          | 17380           | 3052.84                       | 0.176                                           | 0.00010        |
| 24.06.2020          | 15380           | 2292.49                       | 0.149                                           | 0.00028        |
| 25.06.2020          | 14400           | 2783.28                       | 0.193                                           | 0.00076        |
| 26.06.2020          | 20640           | 3249.22                       | 0.157                                           | 0.00007        |
| 27.06.2020          | 19200           | 2425.14                       | 0.126                                           | 0.00155        |
|                     | 206514.0        | 33903.9                       | 0.166                                           | 0.00596        |
|                     |                 |                               | 0.0054                                          |                |

Control measurement error in electric energy consumption error is as follows \( \Delta \) (\%):

\[ \Delta = 1.11 \]

Probability of error in control measurement, 0<5%

In qualitative selection of electric energy values indicated after static analysis, it is necessary to estimate the expected mathematical value of electric energy. Therefore, the arithmetic mean of the sample is counted as the assessment of the level of mathematical accuracy.

\[ \overline{x} = 0.166 \]

Size \( \sigma = \sqrt{S} \)

\[ \sigma = 0.02 \]

\( \overline{x} \) the confidence interval of the estimate is calculated by the following formula:

\[ P(\overline{x} - S/\sqrt{n} T_{n-1} < a < \overline{x} + S/\sqrt{n} T_{n-1}) = 1 - \alpha. \]

Where \( a \) – the actual value of electricity consumption \( T_{n} \) - Student’s coefficient

With a reliability indicator \( P = 0.95 \), the current of the actual value of electrical energy can be equal to:

\[ \Delta = \pm 0.000049 \]
Table 4. In a controlled state \( f = 46-48.5 \text{ gts} \) of the performance of the pumping unit electric energy consumption (16.06.-27.06.2020) over time

| Date of measurements | Technical data of the electric motor | Technical passport of Pump | Experimental data |
|----------------------|--------------------------------------|---------------------------|-------------------|
| 16.06.20             | 160 1000 5AM315MB 94.5 1080 37 47.5 360 241.0 0.85 24 |
| 17.06.20             | 160 1000 5AM315MB 94.5 1080 37 47.5 360 239.7 0.85 20 |
| 18.06.20             | 160 1000 5AM315MB 94.5 1080 37 47.5 360 240.2 0.85 22 |
| 19.06.20             | 160 1000 5AM315MB 94.5 1080 37 48 364.6 245.7 0.85 24 |
| 20.06.20             | 160 1000 5AM315MB 94.5 1080 37 46 353.2 232.1 0.85 20 |
| 21.06.20             | 160 1000 5AM315MB 94.5 1080 37 47.5 360 241.1 0.85 24 |
| 22.06.20             | 160 1000 5AM315MB 94.5 1080 37 47.5 360 239.6 0.85 24 |
| 23.06.20             | 160 1000 5AM315MB 94.5 1080 37 47.5 360 240.0 0.85 24 |
| 24.06.20             | 160 1000 5AM315MB 94.5 1080 37 47.5 360 240.3 0.85 24 |
| 25.06.20             | 160 1000 5AM315MB 94.5 1080 37 47.5 360 238.7 0.85 22 |
| 26.06.20             | 160 1000 5AM315MB 94.5 1080 37 48.5 370.2 248.4 0.85 24 |
| 27.06.20             | 160 1000 5AM315MB 94.5 1080 37 48.5 370.2 247.2 0.85 18 |

Electrical energy consumption $W$ measurement time $33903.87$

Figure 1. Technological consumption rate of electric energy for the volume of lifted water to the pumping unit 2
3. Conclusions
The methodology for measuring the unit electric energy consumption rate for centrifugal pumps in the frequency regulating of electric drives of pumping units was developed taking into account the energy efficiency of "Chirchik" pumping station. In general, unit consumption rate reports should be available for each pump station and this report should be reviewed every five years. At present, the Scientific and Technical Center develops a methodology for calculating the unit consumption rate, taking into account the requirements of regulatory documents, technical rules and regulations for all areas of production.

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