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Optimal control of pumping station operation modes by cascades of the Karshi main canal

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ABSTRACT:In the world, much attention is paid to the development of criteria, mathematical models, methods, and algorithms for optimal management of water resources of main canals and other water management facilities, using modern information systems. In this direction, also in other countries of the world, where water management and irrigation are developed, one of the necessary tasks is to develop optimal water management of large main canals with cascades of pumping stations, which is carried out on the example of the Karshi main canal with a cascade of pumping stations. This is done based on criteria and methods of optimal management, mathematical models and algorithms that ensure the economy of water resources.

KEY WORDS: mathematical model, unsteady flow of water, main canals, optimal control problems, fundamental solution, differential equations, hydraulic structures.

I.INTRODUCTION

One of the largest and most unique machine water lifting systems for irrigation in the world operates in the Republic of Uzbekistan, which provides water to more than 2 million hectares of irrigated land. They include various cascades of pumping stations and hydraulic structures, powerful hydro-mechanical and electrical equipment, pressure pipelines with different diameters and lengths, supply and discharge canals, substations and power supply networks of various capacities. Such systems include the Karshi main canal with a cascade of pumping stations, the Amu-Bukhara Machine Canal with two cascades of pumping stations, the Jizzakh cascade of pumping stations and the Amu-Zang cascade of pumping stations.

As an object of research, we selected the Karshi main canal with a cascade of pumping stations, which is one of the largest and most unique machine water lifting systems for irrigation in the republic. As part of the Karshi main canal cascade, there are six pumping stations, each of them is equipped with six pumping units with axial pumps of the OPV-11-260, EGOPV-10-260EGI type and six synchronous electric motors of the VDS 375/130-24 type with a capacity of 12.5MW. The total installed capacity of all pumping stations is 450MW, and the normal capacity of the cascade of pumping stations is , the forced capacity is . The total height of the water rise of the PS cascade is 138.6m, and the length of the machine part of the Karshi main canal is 80km. As part of the Karshi main canal, the seventh pumping station is also functioning to fill the Talimarjan reservoir with a capacity of 1.3 billion cubic meters in the low-water period, the water resources of which are additionally used for irrigation of the irrigated lands of the Kashkadarya region during the growing season along the gravity part of the Karshi main canal.

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II. METHODS

To determine the operating modes of an axial pump, it is necessary to have their load characteristics $N = f(Q)$. They can be constructed using the universal characteristic of the pump [1,2,3], where the dependences $H = f(Q)$ and $\eta = f(Q)$ are given according to the well-known formula of power on the shaft of the pump unit

$$N = g\frac{QH}{\eta}, \quad (1)$$

where Q is the pump flow rate; H is the pump head; η is the pump efficiency.

The flow rate of the axial pump depends on the lifting height H and the angle of rotation of the blades φ.

$$Q = Q(H,\varphi), \quad (2)$$

where H is the lifting height; φ is the angle of rotation of the pump blades; Q is the flow rate of the pump unit.

In catalogs and reference books, the flow characteristic of the axial pump is set as a family of curves at different angles of rotation of the blades

$$Q_i = Q_i(H,\varphi_i), \quad i = 1,2,...,N,$$

where φ_i is the angle of rotation of the blades corresponding to the i-th curve; N is the number of curves.

The performance characteristics of the pump unit are presented in the form of a family of curves that depend on the height of the water rise at different angles of rotation of the impeller blades of the axial pump

$$\Omega_э^i = \Omega_{H,Q,\varphi} \cup \Omega_{H,\eta,\varphi}, \quad i = \overline{1,N}, \quad (3)$$

where $\Omega_{H,Q,\varphi} = \left\{ \begin{matrix} Q_j^i & i=\overline{1,N}, & (j=\overline{1,K}) \\ H_i & i=\overline{1,N}, & \\ \varphi_j & j=\overline{1,K}, & \end{matrix} \right\}$ is the flow characteristics of the pump unit;

$\Omega_{H,\eta,\varphi} = \left\{ \begin{matrix} \eta_j^i & i=\overline{1,N}, & (j=\overline{1,K}) \\ H_i & i=\overline{1,N}, & \\ \varphi_j & j=\overline{1,K}, & \end{matrix} \right\}$ is the energy characteristic of the pump unit;

φ_j is the angle of rotation of the blades corresponding to the j-th curve; η_j^i — Efficiency of the i-th pump unit for the j-th curve.

The permissible area D of the pump unit operation in the coordinates $Q-H$ is determined by the following external boundaries:

$$\left. \begin{matrix} D_{1\max}^i = \Omega_T^{i\max} \cap \Omega_{H,Q,\varphi}^i, \\ D_{1\min}^i = \Omega_T^{I\min} \cap \Omega_{H,Q,\varphi}^i, \\ D_{2\max}^i = \Omega_{H,Q,\varphi\max}^i, \\ D_{2\min}^i = \Omega_{H,Q,\varphi\min}^i, \end{matrix} \right\} \quad (4)$$

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where $\Omega_T^{i\max}, \Omega_T^{I\min}$ is the characteristic of the pipeline at the maximum and minimum geometric lifting height; $\varphi_{\max}, \varphi_{\min}$ is the maximum and minimum rotation angles of the axial pump blades.

At present, it is convenient to use modern methods using various finite polynomial functions to approximate the flow characteristics of pumping units.

$$\Pi_m(x,y) = \sum_{k+l=0}^{m} a_{kl} x^k y^l , \quad (5)$$

where x, y - are the arguments of a function of two variables, in our case they represent the water pressure and the rotation angles of the axial pump blades. In this case, the area of determining the consumption characteristic is divided into triangular elements. For example, in the linear approximation of a two-dimensional function on a triangle $(m=1)$, the interpolation polynomial has the following form:

$$\Pi_m(x,y) = a_1 + a_2 x + a_3 y = \sum_{i=1}^{3} U_i p_i(x,y), \quad (6)$$

where $U_i \quad (i=1,2,3)$ is the value of the approximated function $U(x,y)$ at the vertices of the triangle $p_i(x,y)$,

$$p_i(x,y) = \frac{1}{C_{jkl}}(\tau_{kl} + \eta_{kl} x + \xi_{kl} y) = \frac{D_{kl}}{C_{jkl}}, \quad (7)$$

where $\tau_{kl} = x_k y_l - y_k x_l$, $\eta_{kl} = y_k - y_l$, $\xi_{kl} = x_k - y_l$.

$$D_{kl} = \det\begin{bmatrix} 1 & x & y \\ 1 & x_k & y_k \\ 1 & x_l & y_l \end{bmatrix} \quad C_{jkl} = \det\begin{bmatrix} 1 & x_j & y_j \\ 1 & x_k & y_k \\ 1 & x_l & y_l \end{bmatrix}, \quad (8)$$

Moreover, (j,k,l) is an arbitrary permutation of (1, 2, 3), and $|C_{jkl}|$ is the doubled area of the triangle $P_1P_2P_3$; it is easy to see that

$$p_i(x_k, y_k) = \begin{cases} 1 & (j=k) \\ 0 & (j \neq k), \quad 1 \le j,k \le 3 \end{cases}.$$

The lifting height (statistical head) of a pumping unit is defined as the difference between the upstream and downstream levels of a pumpin:

$$H = z_{us} - z_{ds}, \quad (9)$$

where z_{us} – upstream water level mark, z_{ds} - downstream water level mark.

The characteristics of the pressure losses in the pipeline of the pumping station are presented in the catalogues-reference books in the form of functional curves depending on the supply and lifting height

$$\Omega_T^i = \begin{Bmatrix} Q_j^i & J = \overline{1, K}; \ (i = \overline{1,N}), \quad N \le M \\ H_T^j & J = \overline{1,K} \end{Bmatrix}, \quad (10)$$

where, Q_j^i is the argument of the pressure characteristic of the pipeline, i.e. the supply of the i-th pumping unit; K is the number of points in the pressure characteristic; N is the number of working pumping units; $H_T^j = H + \nabla H_j$ is the function of the pressure characteristic; ∇H_j is the head loss.

If the set values Q and H are located inside the area D, it is assumed that the required water flow can be provided by this unit, otherwise this mode cannot be implemented by this unit. When operating multiple units, the limits of the permissible area are determined by summing the costs within the boundaries of the areas at a constant lifting height.

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The flow rate, the manometric lifting height and the efficiency of the working pump unit, i.e., the state of each working pump unit, is characterized by a triple: $\left(z_{us}, z_{ds}, \varphi_i^p\right)$ where: φ_i^p is the angle of rotation of the blades of the i -th working axial pump. Therefore, the flow rate and efficiency of the i -th pumping unit is determined from the expressions

$$\Omega_p^i(Q_p^i, H_p^i) = (\Omega_t^i \cap \Omega_{H,Q,\varphi}) \cap \Omega_{H,Q,\eta}, \quad \phi_i = \varphi_i^p, \quad \Omega_{H,Q,\varphi} \subset \Omega_э^i, \quad \Omega_{H,\eta,\varphi}^i \subset \Omega_э^i \qquad (11)$$

This expression is the intersection of the pressure loss curve on the pipeline and the flow characteristics of the units operating at the specified φ_p^i -angles of rotation of the axial pump blades [11]. The point $\Omega_p^i\left(H_p^i, Q_p^i\right)$ is the working point of the i -th pump unit.

The total flow rate and power consumption for a pumping station as a whole is defined as the algebraic sum of the costs and capacities of the operating unit

$$Q_{PS} = \sum_{i \in N^P} Q_i, \qquad N_{PS} = \sum_{i \in N^P} N_i, \qquad (12)$$

where: $N_i = \dfrac{\gamma H_i Q_i}{102\eta_i}$ is the capacity of the i -th pumping unit; γ is the volume weight of the pumped liquid.

Thus, the water consumption and the power consumption of the pumping station are determined by algorithmic dependencies [15]

$$Q_{PS}(t) = F_q\left(t, N^P(t), z_{us}(t), z_{ds}(t)\right), \quad N_{PS}(t) = F_n\left(t, N^P(t), z_{us}(t), z_{ds}(t)\right) \qquad (13)$$

where $N_p(t)$ is the set of working pumping units, $z_{вб}(t)$ is the upstream water level, $z_{нб}(t)$ is the downstream water level.

The operating modes of a pumping station equipped with axial pumps are represented algorithmically as

$$Q_i^{PS} = F_1^i\left[z_i^{DS}, z_i^{US}, \left(N_i, N_i^P, \varphi_i^P\right)\right], \quad N_i^{PS} = F_2^i\left[z_i^{DS}, z_i^{US}, \left(N_i, N_i^P, \varphi_i^P\right)\right], \; i=1,\ldots,6 \qquad (14)$$

where F_1^i, F_2^i algorithmic operators.

III. RESULTS

Calculations of algorithms for solving problems of optimization mode of pumping stations of the Karshi main canal are necessary in order to obtain optimization of the intra-station mode of pumping stations of the Karshi main canal are necessary in order to obtain optimized intra-station modes of operation of pumping stations by adjusting the rotation angles of the axial pump blades in order to minimize electricity consumption by synchronous electric motors of pumping units of pumping stations. The tables show the results of solving the problems of optimizing the intra-station mode of operation of the pumping stations of the Karshi main canal cascade at different values of the rotation angles of the axial pump blades, as well as the associated performance of the axial pump and the electric power consumption of the pumping units of the pumping stations at different values. Based on the results of the calculations, the optimal variants of the intra-station mode and the optimal variants of the intra-station mode of each of the six pumping stations of the Karshi main canal were determined.

Results of solving problems of optimization of the in-plant mode of 1-pump stations of the cascadeThe data of the Karshi Main Canal are shown in Table 1.

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Table 1.
Optimization of intra-station operation modes of 1-pumping stations of the Karshi Main Canal cascade
The specified flow rate = 190,00. Downstream level = 7,00. Upstream level = 24,00.

Option	Unit Number	U-turn angle	consumption	Power output
		degrees	m^3 / sec	MW
1 Optimal mode	UN - 1	-2,00	40,80	11,73
	UN - 2	-2,00	40,70	11,77
	UN - 3	-2,00	40,80	11,73
	UN - 4	-4,00	37,10	9,96
	UN -5			
	UN - 6	-8,00	30,70	9,45
PS-1			189.80	54.6

The optimal option is shown in bold, and other options that implement the specified mode are shown in normal font. From Table 1, the specified water supply mode of 190 m^3/sec is provided with an absolute accuracy of 99,8%, i.e. 189.80 m^3/sec with the lowest power consumption of 54,6MW.

The results of solving the problems of optimizing the intra-station mode of the 2-pumping stations of the Karshi Main Canal cascade are shown in Table 2.

Table 2.
Optimization of intra-station operation modes of the 2-pumping stations of the Karshi Main Canal cascade
The specified flow rate = 180,00. Lower water level = 31,00. Upstream level = 55,00.

Option	Unit Number	U-turn angle	consumption	Power output
		degrees	m^3 / sec	MW
5 Optimal mode	UN - 1			
	UN - 2	-8,00	30,70	9,45
	UN - 3	-8,00	30,70	9,45
	UN - 4	-8,00	30,70	9,45
	UN -5	-8,00	30,70	9,45
	UN - 6	-8,00	30,70	9,45
PS 2			153,5	47,25

The optimal option is shown in bold, and other options that implement the specified mode are shown in normal font. From Table 2, the specified water supply mode of 180 m^3/sec is provided with an absolute accuracy of 85,3%, i.e. 153,5 m^3/sec with the lowest power consumption of 47,25 MW.

The results of solving the problems of optimizing the intra-station mode of the 3-pumping stations of the Karshi Main Canal cascade are shown in Table 3.

Table 3
Optimization of intra-station operation modes of 3-pump stations of the Karshi Main Canal cascade
The specified flow rate = 190,00. Lower water level = 55,00. Upstream level = 79,00.

Option	Unit Number	U-turn angle	consumption	Power output
		degrees	m^3 / sec	MW
5 Optimal mode	UN - 1			
	UN - 2	-6,00	33,90	9,96
	UN - 3	-8,00	30,70	9,45
	UN - 4	-6,00	33,90	9,96
	UN -5	-4,00	37,20	10,87
	UN - 6	-2,00	40,80	11,73
PS-3			176.50	51.97

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The optimal option is shown in bold, and other options that implement the specified mode are shown in normal font. From Table 3, the specified water supply mode of 190 m^3/sec is provided with an absolute accuracy of 92,9%, i.e. 176,5 m^3/sec with the lowest power consumption of 51,97 MW.

The results of solving the problems of optimizing the intra-station mode of 4-pumping stations of the Karshi main Canal cascade are shown in Table 4.

Table 4
Optimization of intra-station operation modes of 4-pump stations of the Karshi Main Canal cascade
The specified flow rate = 190,00. Lower water level = 79,00. Upstream level = 103,00.

Option	Unit Number	U-turn angle	consumption	Power output
		degrees	m^3 / sec	MW
1 Optimal mode	UN – 1	-6,00	33,90	9,96
	UN – 2	-4,00	37,10	10,90
	UN – 3	-2,00	40,80	11,73
	UN – 4	-6,00	33,90	9,96
	UN –5			
	UN – 6	-8,00	30,70	9,45
PS-4			174,4	52

The optimal option is shown in bold, and other options that implement the specified mode are shown in normal font. From Table 4, the specified water supply mode of 190 m^3/sec is provided with an absolute accuracy of 91,8%, i.e. 174,4 m^3/sec with the lowest power consumption of 52,0 MW.

The results of solving the problems of optimizing the intra-station mode of 5-pumping stations of the Karshi main Canal cascade are shown in Table 5.

Table 5
Optimization of intra-station operation modes of 5-pump stations of the Karshi Main Canal cascade
The specified flow rate = 190.00. Lower water level = 103.00. Upstream level = 127.00.

Option	Unit Number	U-turn angle	consumption	Power output
		degrees	m^3 / sec	MW
5 Optimal mode	UN – 1			
	UN – 2	-8,00	30,80	9,39
	UN – 3	-2,00	40,80	11,73
	UN – 4	-2,00	40,80	11,73
	UN –5	-4,00	37,20	10,87
	UN – 6	-8,00	30,80	9,39
PS-5			180,40	53,11

The optimal option is shown in bold, and other options that implement the specified mode are shown in normal font. From Table 5, the specified water supply mode of 190 m^3/sec is provided with an absolute accuracy of 94,9%, i.e. 180,40 m^3/sec with the lowest power consumption of 53,11 MW.

The results of solving the problems of optimizing the intra-station mode of the 6-pumping stations of the Karshi main Canal cascade are shown in Table 6.

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Table 6.
Optimization of intra-station operation modes of the 6-pump stations of the Karshi Main Canal cascade
The specified flow rate = 190.00. Lower water level = 127.00. Upstream level = 151.00.

Option	Unit Number	U-turn angle	consumption	Power output
		degrees	m^3 / sec	MW
5 Optimal mode	UN – 1			
	UN – 2	-4,00	37,20	10,87
	UN – 3	-6,00	33,90	9,96
	UN – 4	-2,00	40,80	11,73
	UN –5	-6,00	33,90	9,96
	UN – 6	-8,00	30,80	9,39
PS-6			176.60	51.91

The optimal option is shown in bold, and other options that implement the specified mode are shown in normal font. From Table 6, the specified water supply mode of 190 m3/s is provided with an absolute accuracy of 92.9%, i.e. 176.60 m3 / s with the lowest energy consumption of 51.91 MW.

Thus, using the developed algorithms for solving problems of optimal management of objects of main canals with cascades of large pumping stations, they can be managed according to the specified criteria with minimal unproductive losses of water and energy resources, which can reach up to 10% for water resources, and up to 3% for energy resources, which is a great economic effect for such objects as main canals with cascades of large pumping stations.

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IV. CONCLUSION

Based on the above, it can be concluded that the developed mathematical models and algorithms accurately reflect the qualitative and quantitative parameters of the main canal section and pumping stations. This justifies the possibility of using them to control the processes in the main canals with cascades of pumping stations.

Based on the selected algorithmization methods, numerical algorithms are developed for solving problems of optimal control of a section of the canal bounded by two pumping stations, a pumping station and hydraulic structures on a section of the Karshi main canal, which solve the problems of unsteady water movement on the sections of the canal and the process of water supply of the cascade of pumping stations of the Karshi main canal.

The results of calculations of algorithms for solving problems of optimization of the intra-station mode of pumping stations of the Karshi main canal are presented, which show that NS-1 operates in the optimization mode in option 1, PS-2 in option 5, PS-3-5, PS-4-1, PS-5-5 and PS-6-5, with these specified values of the rotation angles of the axial pump blades of the pumping units of the PS cascade of the Karshi main canal.

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