Assessment of reliability and safety of work large pumps of machine irrigation systems

Tolyagan Kamalov[1,*] , *Solixjon* Halikov[2]

[1]Institute of Energy of the Academy of Sciences of the Republic of Uzbekistan, 700100, Tashkent city, Republic of Uzbekistan
[2]Tashkent State Technical University, 700111, Tashkent city, Republic of Uzbekistan

Abstract. The article provides an assessment of the reliability and safety of large pumps of machine irrigation systems in case of violations occurring in abnormal conditions and mechanical malfunctions of pump elements.

In terms of energy consumption, pumping stations of machine irrigation systems (PSMIS) of the Republic of Uzbekistan are one of the energy-intensive facilities in the region. The installed capacity of electrical equipment at PSMIS is more than 2700 thousand kW with a consumption of 8 billion kW of electricity or about 17% of the total amount of electricity consumed in the republic.

Currently, there are more than 1300 pumping stations (PS) and over 9000 vertical drainage wells operating for irrigation, including such large PS of the Karshinsky main canal with PS No.1-No.6 with a capacity of 200 m^3/s each, Khamza-2 (150 m^3/s), Kizil-Tepa (150 m^3/s), Amu-Zang-1 (37.2 m^3/s), Amu-Zang-2 (37.2 m^3/s), etc. Along with large NS many medium and small pumping stations are in operation.

Long-term operation of pumps installed in irrigation pumping stations led to a deviation of their technical characteristics from the factory ones. Existing PSs and cascades of pumping stations (CPS) of the country's machine water-lifting systems are age-appropriate for the wear-out failure phase. This period of operation is characterized by an increase in the rate of failures and accidents, an increase in the volume of repair work and reconstruction and modernization of structures, structures and equipment and, accordingly, an increase in the costs and expenses of electric energy per unit volume of pumped water. And here is the question of determining the reliability and safety of large pumps.

The terms “reliability”, “safety”, “danger” and “risk” are often confused, and their meanings overlap. In [1], the terms “safety analysis” or “hazard analysis” are used as equivalent concepts. Along with the term “reliability analysis” they refer to the study of both operability, equipment failure, loss of operability, and so on the process of their occurrence. If, as a result of the analysis, it is necessary to determine the parameters characterizing safety, it is necessary, in addition to equipment failures and system malfunctions, to consider the possibility of damage to the equipment itself or other damage caused by them. If at this stage of the safety analysis the possibility of failures in the system is assumed, then a risk analysis is carried out in order to determine the consequences of failures in the sense of damage to equipment and the consequences for people near it. One of the goals of risk analysis is to assess the frequency (probability) of these or other possible subsequent other possible consequences due to failures in the system.

At present, methodological approaches and the corresponding regulatory documentation on the assessment, determination and standardization of safety and operational reliability of pumps have not been developed.

Risk assessment can be determined in monetary terms - arbitrary units or in the point system. In this case, we assess the risk assessment in monetary terms - conventional units, in terms of:

$$R_{P}=\sum_{i=1}^{n}\left\{\left[Q_{Pi}+M\cdot\Delta Q_{Pi}\cdot T_{i}\right]\cdot P_{Pi}+Q_{Pi}^{EX}\right\}\frac{1}{T_{\text{year}}}\ [(\text{monetary unit})/\text{year}] \qquad (1)$$

where P_{Pi} = f (EFR, P),

Q_{Pi} – damage caused to the pump by the *i*-th event [monetary unit (денежный единица)],

EFR – expected failure rate;

ΔQ_{Pi} – loss of water flow per hour of the pump from idle time at the *i*-th event [m^3/hour];

T_i – pump idle time at event *i*;

M – the cost of one m^3 of water [monetary unit / m^3];

P_{Pi} – probability of occurrence of the *i*-th event on the pump;

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[*] Corresponding author: t.kamalov@yandex.ru

[*] Corresponding author: salih.halikov@yandex.ru

P – probability of an initial event;
Q_{Pi}^{EX} – external damage to crop yields due to water loss during the *i*-th event at the pump [monetary unit];
T_{year} - overhaul period of the pump unit for a year [year].

The resulting risk values are divided into 4 security categories in the amount of conventional monetary units, and the amount of economic damage is taken as:

Security category	Economic and social consequences
I	Economic damage can be very significant. R ≥ 100 million monetary unit/year
II	Economic damage can be significant. R ≥ 1 million monetary unit/year
III	The amount of possible damage is negligible. R ≥ 100 thousand monetary unit/year
IV	Minimal damage in the future is practically absent. R ≤ 100 thousand monetary unit/year

Thus, the derived expressions for calculating the risk of the pump allow us to assess the risk and monitor their safety indicators.

Studying the causes of disturbances in violations of normal operation (VNO) of large pump irrigation pumps indicates the need to develop an accident risk management methodology and safety assessment that will allow us to assess the balance between the extent of possible damage from potential accidents of this system and its technical-economic advantages.

In the existing method of safety analysis, in order to correctly introduce complex indicators of the risk type characterizing operational safety, a violation development model is used, which is represented by a right-handed dichotomous “event tree” [2].

In the considered risk calculation methods, in many cases, the conduct of a probabilistic safety analysis (PSA) (determining the function P_{Pi} = f (ОЧО, P)) in full can be difficult, especially in the absence of information about individual processes. Risk calculation is accompanied by a high degree of uncertainty that requires a significant investment of time.

From this point of view, it was proposed to use artificial intelligence systems (AI) based on artificial neural networks, genetic algorithms, expert systems, and systems of odd logic for conducting PSA pumps [2].

The basis of each artificial neural network is elements (cells) imitating the work of brain neurons (hereinafter referred to as a neuron an artificial neuron, an artificial neuron cell, an artificial neural network cell). Each neuron represents a pump element and events occurring as a result of VNO and is characterized by its current state by analogy with nerve cells in the brain that can be excited or inhibited. It has a group of synapses - unidirectional input connections connected to the outputs of other neurons, and also has an axon - an output connection of this neuron, from which (excitation or inhibition) goes to the synapses of the following neurons. Each synapse is characterized by the value of synoptic connection or weight W_{ij}, which is equivalent in physical meaning to electrical conductivity [3].

The current state of a neuron is defined as the weighted sum of its inputs:

$$S_{ij} = \sum_{\substack{i=1 \\ j=1}}^{n} X_{ij} \cdot W_{ij} \qquad (2)$$

The output of a neuron is a function of its state:

$$y = f\,(s) \qquad (3)$$

The nonlinear function *f* is called activation and can take the following forms: unit jump function; linear threshold (hysteresis); sigmoid.

For our case, the type of function is chosen - sigmoid - hyperbolic tangent, here the input of the function will be the running time t, the parameter of the function is the failure rate - λ, and the output is the probability of failure operation - P (t). The theory of fuzzy sets is used to evaluate criticality indices.

Violation of the normal operation of the pump elements occur due to abnormal operation of the pump and mechanical malfunctions of its elements [4].

Fig. 1 shows the existing 9 types of pump failures, and Fig. 2 shows 16 types of initial disturbance events during abnormal pump operation, which are indicated by neurons, respectively, S_{11}-S_{19} and S_{21}-S_{216}. Fig. 3 shows the existing 10 types of failures due to mechanical malfunctions of the pump elements, and Fig. 4, 5 - 26 types of initial events of pump disturbances during mechanical malfunctions of its elements, which are indicated by the neurons S_{31}-S_{310} and S_{41}-S_{426}, respectively.

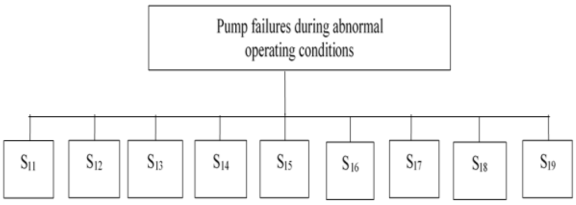


Fig. 1. Failures of the pump during abnormal modes of operation:

S_{11} - the appearance of vibration and an increase in the runout of the pump shaft, accompanied by shocks, knocks in the impeller; S_{12} - the pressure and pump flow pulsate and do not correspond to the operating mode; S_{13} - vibration with prevailing cavitation frequencies of 800-20000 Hz; S_{14} - the pressure pulsates and is higher than the permissible one, the supply is much less than the calculated one; S_{15} - the unit vibrates strongly with cavitation frequencies; S_{16} - the pump does not supply water when the motor is overloaded, permissible hydraulic resistance of the pipeline and backwater; S_{17} - enhanced vibration at frequencies that are multiples of the blade and rotation frequencies; S_{18} - the pump does not provide the required pressure, vibration at the blade frequencies; S_{19} - the pump does not provide the required flow. Vibration within acceptable limits.

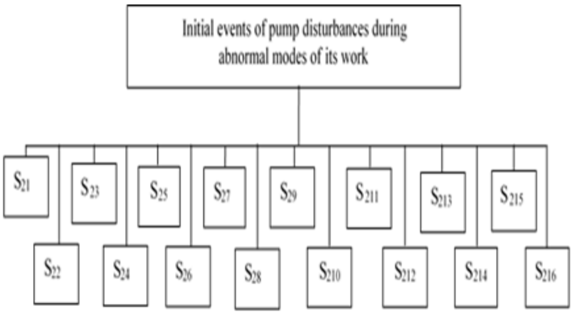


Fig. 2. Initial events of pump disturbances during abnormal modes of its operation:

S_{21} - clogging grids; S_{22} - air entering the suction pipe; S_{23} - the formation of air bags in the pipelines; S_{24} - siltation of the suction pipe; S_{25} - critical cavitation mode with characteristic knocks similar to stone blows against iron; S_{26} - a sharp curve of the decline in the level in the chamber with funnels at a low level of the lower buff; S_{27} - increased flow swirl in the advance chamber in the plan; S_{28} - surge phenomena; S_{29} - hydraulic resistance exceeds permissible; S_{210} - the pump operates in braking or reverse mode during reverse rotation; S_{211}- fragment of the blades and the alignment of the pump rotor; S_{212} - significant wear on the ends of the impeller blades and the chamber; S_{213} - wear of the sealing rings of the front wheel disc; S_{214} - the non-working angle of rotation of the axial pump vanes is set; S_{215} - the valve on the pipeline is covered or fully open; S_{216} - Vacuum stall valve is leaking.

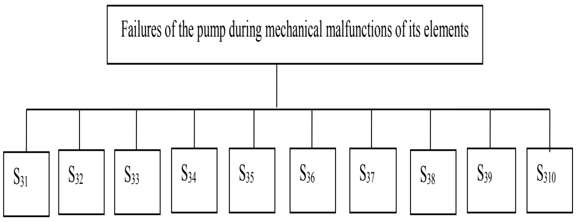


Fig. 3. Failures of the pump during mechanical malfunctions of its elements:

S_{31} - heating water in the reservoirs of water lubricated bearings; S_{32} - invalid shaft runout; S_{33} - increased power while providing working feed and pressure; S_{34} - oil seals allow water to pass above normal; S_{35} - the appearance of smoke or the smell of burning coming from ligno-foil and quick wear of the liners due to the increased content of abrasive suspended matter in water lubricant; S_{38} - Inadmissible heating of the thrust bearing; S_{39} - temperature increase in babbit bearings and heel with oil lubrication; S_{310} - the oil system does not provide the bearing with the necessary amount of oil (for pumps with forced lubrication).

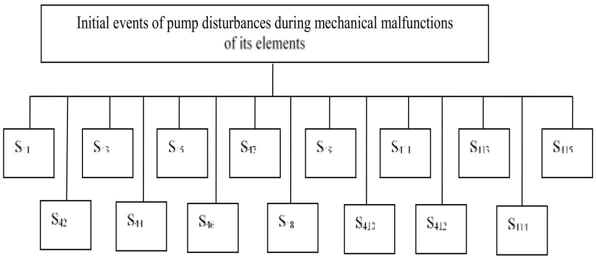


Fig. 4. Initial events of pump disturbances during mechanical malfunctions of its elements:

S_{41} - coagulation of the blades of the wheels of axial pumps at different angles; S_{42} - violation of the alignment of the axis of the shaft; S_{43} - inaccurate alignment of the shaft and bearings; S_{44} - getting foreign objects into the flow part; S_{45} - bearing displacement; S_{46} - the rotor of the pump (unit) is poorly balanced or the balance is broken; S_{47} - incorrect boring of couplings; S_{48} - wear and grazing of seals, uneven wear of the wheel blades; S_{49} - small clearances between the shaft and bearing shells; S_{410} - strong tightening of the seals or separation of the seal; S_{411}- a shirt or shaft surface has grooves due to the tightness of the gland; S_{412} - cessation of supply of technical clean water to bearings; S_{413} - grease ring jam, oil contamination or leakage; S_{414} - cessation of cooling water supply; S_{415} - small gaps in the bearing shells.

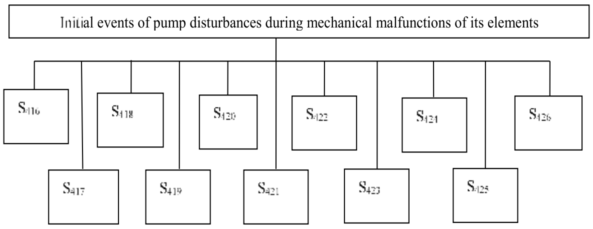
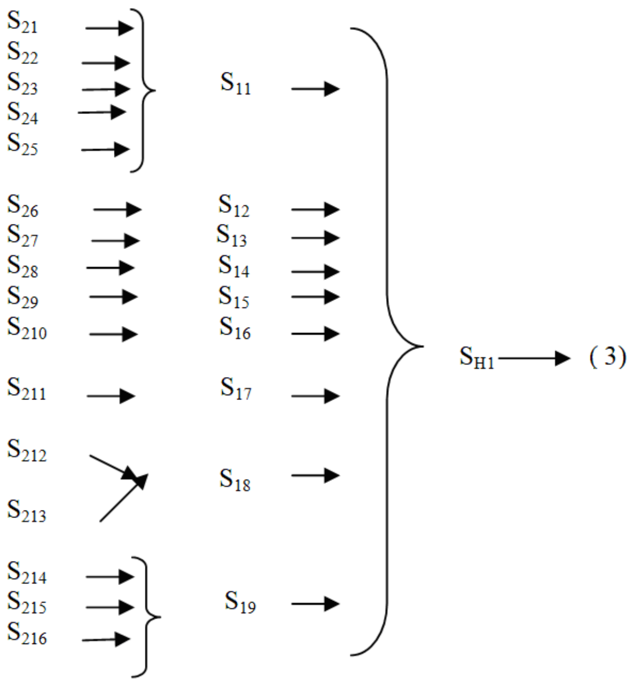


Fig. 5. Initial events of pump disturbances during mechanical malfunctions of its elements:

S_{416} - high abrasive content in water lubricant and pumped water, especially sulfate or chloride class; S_{417} - too tight pinching of the balls between the support rings; S_{418} - uneven fit of pads or ridges in thrust bearings; S_{419} - contamination or mismatch of the brand of oil, insufficient quantity; S_{420} - Incorrect clearance between guide bearings and shaft; S_{421} - misalignment between the bearings and the heel mirror; S_{422} - uneven loading of thrust bearing segments; S_{423} - the oil pump does not supply the required amount of oil, end clearances have been developed; S_{424} - the oil system is clogged (oil pipe, filter, oil cooler); S_{425} - insufficient supply of cooling water to the oil cooler; S_{426} - Water is detected in the oil, flow in the oil cooler.

Based on the above disturbance events, a block diagram of the PSA pump neural network is compiled for abnormal operating conditions, and for the pump neural network with violations of its operating mode, the expressions can be written:



Here, each violation can be represented from series-connected neurons characterizing the path of the failure, for example, from the expression it can be imagined that one of the following events develops from the failure due to the appearance of vibration and increased runout of the pump shaft, accompanied by knocks, knocks in the impeller (S_{11}): driving in gratings (S_{21}); air entering the suction pipe (S_{22}); the formation of air bags in the pipelines (S_{23}); siltation of the suction pipe (S_{24}); critical cavitation mode with characteristic knocks similar to stone blows against iron (S_{25}). Here, the set of neurons S_{21} ... ... S_{25} characterizes the initial events, the set of signals X_{21} ... ... X_{25} is the output of these neurons, these output signals correspond to the signals arriving at the synapses of the biological neuron and each of them is multiplied by the corresponding weight W_{21} .... W_{25} and arrives at the input of a failure neuron. Each weight corresponds to the "weight" of one biological synaptic connection S_{11}. Neuron S_{11}, corresponding to the body of the biological element, adds the weighted inputs algebraically, creating an output, which we will call NET. In vector notation, this can be written as follows:

$$NET_{11} = X_{11}W_{11} \tag{4}$$

The signal NET_{11} then, as a rule, is converted into the activation function F_{12}

$$OUT_{11}=K(NET_{11}) \tag{5}$$

and gives an output neural signal.

The value of the function will be the probability of failure of the pump $P_{11}(t)$ during abnormal modes of its operation. From the expression (3) it follows that from the outputs of the neurons S_{12} - S_{19} we get the probability of failure-free operation P_{12} (t) - P_{19} (t). Here, many S_{12} - S_{19} neurons characterize failures, many X_{12} .....X_{19} signals are the output of these neurons. These output signals correspond to the signals arriving at the synapses of the biological neuron and each of them is multiplied by the corresponding weight W_{12} .... W_{19} and goes to the input of the failure neuron. Each weight corresponds to the "weight" of one biological synaptic connection S_P. The neuron S_{P1}, corresponding to the body of the biological element, adds the weighted inputs algebraically, creating an output, which we will call NET. In vector notation, this can be written as follows:

$$NET_{H1} = X_{H1}W_{H1} \tag{6}$$

From the output of the neuron S_{P1}, we obtain the values of the probability of failure-free operation of the pump $P_{P1}(t)$ under abnormal modes of its operation.

Knowing the probability of failure-free operation, we can diagnose the technical condition of the pumps, calculate the risk, determine the severity of each violation and evaluate the safety of each pump element, addressing each of them, display their status on the computer screen and effectively identify emergency factors, take the necessary emergency corrective measures aimed to increase the safety of the pump.

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