

WAYS TO REDUCE ENVIRONMENTAL DAMAGE IN RURAL AREAS FROM UNRELIABLE PUMPING STATIONS OF SEWAGE SYSTEMS

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Abstract. An important problem with rural drainage is the low capacity and low re-liability of the equipment. High depreciation of fixed assets leads to constant failures, and lack of funds at management companies does not allow timely replacement of equipment. The reliability of the drainage system affects the amount of environmental damage to the atmosphere, water bodies and soil. Pumping pumps are an important element of drainage equipment. Statistics of pump failures in rural areas show that it is necessary to look for low-cost ways to increase reliability of their operation. Functional dependences of ecological damages on the availability factor of technical systems are offered. The equations for calculation of the readiness factor of the electric drive are presented, considering statistics of failures of separate elements of the equipment and functional protective characteristics of devices of protection of electric motors from emergency modes of operation. The offered technique of estimation of the factor of readiness and probable ecological damage gives the chance to reveal directions of improvement of the electric drive of sewerage pump stations. Using the obtained formulas, the environmental damage reduction for the water basin at the electric motor protection device modernization is calculated. It is proved that even the increase of the coefficient of readiness of the electric drive of the pumping pump of the sewage pumping station operating in the territory of the Krasnodar Territory of the Russian Federation by 0.02 gives a significant economic effect – 20000 RUR per year.

Keywords: agriculture, electric drive, ecology, damage, sewerage, pump.

Introduction

Sewage systems have always been an important part of urban and agricultural development. Wastewater contains organic and mineral impurities that may be in a dissolved, colloidal and insoluble state. The most dangerous are wastewaters that contain organic substances, which are degraded under influence of microorganisms. A typical feature of the drainage system in rural areas is the high wear and tear of the fixed assets of such systems. In most cases, public utilities have a lack of funding to raise the level of equipment operation and replace it with a new, modern one. Low capacity is also one of the problems of rural sewage systems. Intensive development of cottage construction, farms and small subsidiary farms, low-rise residential settlements, leads to the need to increase the productivity of sewage pumping stations and improve their reliability [1; 2].

Equipment failures of pumping stations, besides the damage associated with the replacement of the failed element, are harmful for the environment - additional emissions of ammonia, polluting water bodies due to the failure of communications, deterioration of the microclimate, damage to soil fertility, etc. Sufficient amount of works is devoted to increase the efficiency of sewage pumping stations and their electric drive [3-8].

Ecological and economic assessment of the damage caused to the environment aims to determine the actual and possible (preventable) material and financial losses and damages from deterioration of qualitative and quantitative parameters of the natural environment as a whole, and its individual environmental resource components (water resources, land resources, resources of flora and fauna) as a result of anthropogenic impact. The magnitude of possible damage is related to probabilistic indicators of technical systems. The following are considered to be probabilistic indicators of the technical system reliability in most cases: probability of uptime operation, mean operating time between failures, average recovery time, complex indicator – availability. Definition of these indicators is based on statistical data on failures of system elements.

There are two ways to improve the availability of equipment: to increase the mean time to failure or to reduce the mean recovery time. The most effective way is to reduce the recovery time. This indicator is associated with explicit and implicit failures, which are probabilistic in nature. The search for correlation between environmental damage indicators and probabilistic estimates of reliability of technical systems is the research objective. Previously, researchers did not take into account hidden equipment failures in the calculation of reliability indicators. As publications [3; 5] show, it is latent failures that have a strong influence on the probability value of the technical system availability factor.

Materials and methods

According to literature [9-11], the formula for determining the damage from atmospheric pollution considering the reliability index of a technical system, which can be recommended for the calculation of damages from failures of sewage pumping stations is as follows:

$$Y_A = y_a \cdot k_s \cdot k_r \cdot t_y \cdot (1 - k_g) \sum_i m'_i \cdot A_i, \quad (1)$$

where y_a – specific damage for a conditional ton of pollution, USD per cond. ton;
 k_s – coefficient characterizing the relative danger of atmospheric pollution over areas of different types;
 k_r – coefficient taking into account the nature of dispersion of impurities-pollutants in the atmosphere (taken from special tables);
 m'_i – hourly mass of the i -th pollutant, ton·h⁻¹;
 A_i – indicator of relative danger (aggressiveness) of the i -th pollutant (cond. ton per ton), determined taking into account TLV (1/TLVi);
 t_y – equipment operation time per year, hour;
 k_g – equipment availability.

To determine damage from water pollution due to pump station failures, we use the formula [9]:

$$Y_w = y_w \cdot k_o \cdot t_y \cdot (1 - k_g) \sum_j A_{jw} \cdot m'_{jw}, \quad (2)$$

where y_w – specific damage from water pollution, USD per cond. ton;
 k_o – coefficient of ecological situation and ecological significance of the state of art of water bodies (relative hazard of pollution for different water management areas);
 A_{jw} – coefficient of aggressiveness of the j -th admixture, the indicator of relative danger of the discharged pollutant in comparison with other admixtures (cond. ton per ton);
 m'_{jw} – weight of the hourly discharge of the j -th impurity, ton·h⁻¹).

The formula for determining the environmental damage from the emission of solids into the soil, considering the reliability of technical systems, is as follows:

$$Y_p = y_p \cdot k_p \cdot M_f \cdot t_y \cdot (1 - k_g), \quad (3)$$

where y_p – specific damage from emission of 1 ton of pollutant, USD per cond. ton;
 k_p – factor that takes into account the value of land resources;
 M_f – hour mass of waste discharged into soil during a year, ton·h⁻¹.

Pumping units at wastewater pumping stations are facilities that can be restored in the process of use, for which short-term interruptions in operation are acceptable. At present, the reliability of the pumps of these systems is very low, which is partly due to the long service life of the equipment and low quality of maintenance. The electric drive of the pumps is located in special wells, where it is practically inaccessible for maintenance and there is high humidity of the ambient air (Fig.1).



Fig. 1. Appearance of pumps mounted at sewage pumping stations in small towns and villages

It is known that an event that consists in interruption of the working condition is called a failure. By nature of detection, failures can be explicit and implicit. Implicit failures can only be detected with a special procedure – testing carried out during maintenance often with special technical means. Examples of implicit failures are the following: wear of the pump impeller, ingress of soft elements into the pump and their accumulation, reduction of insulation resistance of the electric motor, overheating of the motor stator winding, increased wear of bearings, change of thresholds of emergency protection devices, etc. Implicit failure under a certain set of circumstances may become an explicit failure. Therefore, its revealing at an early stage is a relevant task.

It is better to calculate a complex reliability index – the availability k_g for the electric drive by the following expression [9; 10]:

$$k_g = \left(1 + \sum_i^n \frac{T_{Bi}}{T_{Oi}} + \sum_j^m \frac{T_{Bj}}{T_{Oj}} \right)^{-1} \quad (4)$$

where T_{Bi} – mean recovery time of the i -th machine element in case of an explicit failure, h;
 T_{Oi} – mean operating time per explicit failure of the i -th machine element, h;
 T_{Bj} – mean recovery time of the j -th machine element in case of a hidden failure, h;
 T_{Oj} – mean operating time per hidden failure of the j -th machine element, h.

Mostly, implicit and explicit pump failures result in drive motor failures. The motors switch to overload mode and can either operate in emergency mode with damage to insulation (wear and tear and shortened service life), or switch to braked rotor mode and fail. Moreover, the electric machines themselves can switch to emergency mode due to several reasons: deterioration of power quality, change in environmental parameters, inadequate regulation of operating modes from the control system, wear and tear and failure of the control elements, breakdown or wear of the motor insulation. In this regard, the motor control system with a set of various sensors controlling the parameters of the pump and the electric machine plays a major role in this case. This protection detects hidden failures in time, signals them and switches off the drive, when a certain level is reached.

The equation of stationary probability - availability - can be presented as follows:

$$k_g = \left(1 + \frac{\sum \lambda_{mex}}{\mu_{mex}} + \frac{\sum \lambda_{mh}}{\mu_{mh}} + \frac{\sum \lambda_{aex}}{\mu_{aex}} + \frac{\sum \lambda_{ah}}{\mu_{ah}} \right)^{-1}, \quad (5)$$

where $\lambda_{mex}, \lambda_{mh}$ – intensity of motor failures under explicit and implicit failures respectively h^{-1} ;
 μ_{mex}, μ_{mh} – intensity of motor recovery under explicit and implicit failures respectively, h^{-1} ;
 μ_{aex}, μ_{ah} – intensity of control equipment element recovery under explicit and implicit failures respectively, h^{-1} ;
 $\lambda_{aex}, \lambda_{ah}$ – total control equipment failure rate under explicit and implicit failures respectively, h^{-1} .

Obviously, a high value of this indicator can be achieved by improving the technical operation and application of reliable equipment. To improve the availability, it is recommended to carry out a set of well-known preventive measures regulated by the system of scheduled preventive inspections and repairs. Nevertheless, financial difficulties in agriculture do not allow implementing the recommended measures in full, as the energy services are forced to engage only in emergency repairs. This leads to the fact that 20-25 % of electric motors fail annually in rural areas, and the average operating time for failure of control equipment is from three to five years.

The decrease in the efficiency of the existing recommendations for the operation of electrical equipment is due to the introduction of its new modifications. For example, with the release of electric motors of AI, AIR series, there was a need to improve the accuracy of control of the thermal condition of the electric machine stator windings in emergency modes. Introduction of current frequency converters for regulation of pump productivity has led to the fact that at low speed electric motors take from own fan an air flow insufficient for effective cooling. The thermal condition of electric motors can be assessed most reliably using built-in temperature protection systems. Along with improving the reliability of the electric motor and switching equipment, it is necessary to pay attention to the

protection devices. In this regard, it is advisable to develop and implement such protection devices, which could monitor their serviceability and diagnose major faults of the working machine, control system, electric motor. Let us analyze how this will affect the availability factor of the entire drive. In order not to calculate separately the intensity of failures of control devices for hidden and apparent failures, it is better to enter the self-control coefficient k_g in the formula. This factor shows the ability of the control device to convert latent failures into explicit failures, i.e. the ability of the device to control its functionality. Then formula (5) takes the form [9; 10]:

$$k_g = \left(1 + \frac{\sum \lambda_{mex}}{\mu_{mex}} + \frac{\sum \lambda_{mh}}{\mu_{mh}} + \frac{\sum \lambda_{aex} k_c}{\mu_{aex}} + \frac{\sum \lambda_{ah} (1 - k_c)}{\mu_{ah}} \right)^{-1}. \quad (6)$$

The intensity of the motor failure has two components, which are defined as follows:

$$A_m = \lambda_{mex} + \lambda_{mh} = \lambda_{m0} \sum_{i=1}^n P_i Q_i + \lambda_{m0} \sum_{j=1}^m P_j Q_j, \quad (7)$$

where λ_{m0} – intensity of motor failures in the absence of protection or its incorrect setting, h^{-1} ;
 $P_i Q_i$ – probability of the motor failure and the protection device failure in the i -th emergency mode detected during the working day (explicit failure);
 $P_j Q_j$ – product of the probability of the motor failure and the protection device failure in j -th emergency mode, respectively, detected during the next technical inspection (implicit failure).

Explicit motor failures include supply phase failure and electrical machine shaft jamming. The other emergency modes refer to implicit faults. Values of probability of electric motor failures depend on the branch of agricultural production and are given in special literature or are taken from statistical data for a certain enterprise. Probabilities of failures of protection devices on emergency modes depend on the installed protection devices and can also be found in special publications. The intensity of recovery in the case of explicit failure for an electric motor is related to the time of failure detection and the time of replacement of the electric machine. In most cases, this is done during the working day, and therefore the recovery rate will be inverse to the drive operating time per day. If there is an explicit failure of the motor, more time is spent for replacing the machine, then, if there is an explicit failure of the control and protection equipment – in the latter case more time is spent on fault detection. However, the recovery rates in the case of explicit failure can be assumed to be the same for both the motor and the control equipment:

$$\mu_{mex} = \mu_{aex} = \frac{1}{t_{day}}. \quad (8)$$

The operating time per day of individual mechanisms t_{day} , is calculated from the actual operating time of an equipment at a particular enterprise or the average value from relevant literature is taken [10].

The intensity of implicit motor and control equipment failure recovery is related to the frequency of maintenance. Since an implicit failure is equally likely to occur the day after maintenance or just before its prevention, the detection time should be taken as much as half the period between successive inspections. Thus, the recovery rate of hidden failures can be calculated by the following formula:

$$\mu_h = \frac{2}{N_{ser} \cdot t_{day}}, \quad (9)$$

where N_{ser} – the frequency of maintenance, days.

Intensity of failures of electric motors is connected with service life of electric machines (in years) N_{my} and annual operating time t_y [10]:

$$\lambda_{m0} = \frac{1}{N_{my} \cdot t_{my}}. \quad (10)$$

The failure rate of control and protection devices can be calculated in a similar way. For example, to calculate the failure rate of individual devices, the actual data must be used or taken from the literature [10], and the following formula must be used:

$$\lambda_a = \frac{1}{N_{ay} \cdot t_{ay}} \quad (11)$$

Considering that all components of the electric drive operate in the same way over time, and taking into account the above formulae, the expression for calculating the availability can be presented in the following form:

$$k_g = \left(1 + t_{day} \left[\left(\sum \lambda_{mex} + \frac{1}{2} N_{ser} \sum \lambda_{mh} \right) + \sum \lambda_a k_c + \frac{1}{2} N_{ser} \sum \lambda_a (1 - k_c) \right] \right)^{-1} \quad (12)$$

The expression (12) can be simplified, as the self-control coefficient of most control apparatuses is equal 0.5. Therefore, with a negligible error, the electric drive availability can be calculated by the formula as follows:

$$k_g = \left(1 + t_{day} \left[\left(\sum \lambda_{mex} + \frac{1}{2} N_{ser} \sum \lambda_{mh} \right) + \sum \lambda_a \left(\frac{1}{2} + \frac{1}{4} N_{ser} \right) \right] \right)^{-1} \quad (13)$$

Results and discussion

Using the statistical data on failures of electric motors on certain emergency modes and statistics on probability of failure on these modes of separate protective devices [10], and also considering the data on reliability of control elements, it is possible to calculate availability of electric drives. So, for example, for the electric drive of the pump having in its structure the electric motor, two buttons of control, a magnetic starter, an automatic switch, reliability indicators with various variants of protection were calculated. The results are as follows: without a protection device or with an incorrectly set thermal relay, the availability factor was 0.967; with a properly set thermal relay $k_g = 0.968$; with a built-in temperature protection device $k_g = 0.988$. The more protective functions at the device of protection, the greater share of the latent failures can be prevented and the factor of readiness of the electric drive is increased by that. If a hidden fault is detected by the protection device, it is possible to carry out appropriate preventive maintenance work during the process breaks and to under-run accidents during active operation and damage. If an accident occurs, the equipment will be stopped and the overall performance of the process system will be reduced.

Such pump is usually equipped in pumping operating stations of small capacity – up to $25 \text{ m}^3 \cdot \text{h}^{-1}$. Let us calculate the value of environmental damage reduction (ΔY) in an aggregated way for a station with a capacity (Q_n) of $10 \text{ m}^3 \cdot \text{h}^{-1}$. Calculation will be made for the case of environmental damage to the water basin. For this purpose, we will convert formula (2) as follows:

$$\Delta Y_w = y_3 \cdot k_o \cdot k_i \cdot A_w^* \cdot m_w^* \cdot t_y \cdot (k_{gb} - k_{gn}), \quad (14)$$

where k_i – price index of reduction to the available data;
 A_w^* – average coefficient of aggressiveness of all impurities, cond. ton per ton;
 m_w^* – total mass of the hourly discharge of pollutants, $\text{ton} \cdot \text{h}^{-1}$;
 k_{gb}, k_{gn} – availability of equipment, the basic and proposed variants respectively.

The total mass of the hourly discharge can be determined by the pump capacity and the concentrations of substances. It is better to calculate the concentrations of each pollutant separately, but it is possible to determine the aggregated concentration through the average pollutant content. Usually faeces are classified as Hazard Class 4. Thus, for this case, we take the total average concentration of hazardous substances as $0.5 \text{ kg} \cdot \text{m}^{-3}$ and then the total mass of the hourly discharge of hazardous impurities will be as follows:

$$m_w^* = Q_n \cdot C_\Sigma = 10 \cdot 0.5 = 5 \text{ kg} \cdot \text{h}^{-1} \quad (15)$$

Let us calculate the decrease in damage due to replacement of the protection device of type thermal relay on the device with the built-in temperature protection with corresponding availability in

the pump electric drive. As there are data on specific damage-bars for 1999 [10], then having accepted an index of transfer of prices by 2019 equal to 9.38, we will receive following value of decrease in ecological damage for reservoirs of Krasnodar territory of Russia:

$$\Delta Y_w = y_3 \cdot k_o \cdot k_i \cdot A_w^* \cdot m_w^* \cdot t_y \cdot (k_{gb} - k_{gn}) =$$

$$129.9 \text{ USD} \cdot 2 \cdot 9.38 \cdot 0.15 \cdot 5 \cdot 10^{-3} \cdot 8760 \cdot (0.988 - 0.968) \approx 320.2 \text{ USD} \quad (16)$$

The received calculations show high efficiency of modernization of the system of protection of electric motors from emergency modes of operation. Similar calculations can be made also for cases of air and soil pollution.

Of course, with the increase of the pumping station productivity up to hundreds of cubic meters per hour, the amount of damage will start to be calculated already in thousands of dollars. Therefore, such stations already have backup pumps, which will certainly raise the availability of all equipment.

Conclusions

The amount of environmental damage to the atmosphere, water resources and soil is influenced by the reliability of electrical equipment of the pumping stations. One of the probabilistic indicators that make a comprehensive assessment of reliability is the availability factor. The peculiarity of this approach is the division of all refusals into hidden and explicit. It allows to define the degree of influence of separate elements of the technical system on the general complex index of reliability. The greatest influence on the probabilistic value of the availability factor is made by latent failures. Their timely detection by diagnostic elements, such as the electric motor protection device, leads to an increase in the availability factor of the equipment and a reduction in damages from sudden accidents.

The proposed methodology of availability and probabilistic environmental damage assessment allows determining the directions of modernization of the electric drive for sewage pumping stations. Assessment of the impact of the main functions of the motor protection device on the reliability of the pump with a capacity of $10 \text{ m}^3 \cdot \text{h}^{-1}$ has shown that the replacement of the protective device leads to an increase in the availability factor by 0.02 and leads to a further reduction in the environmental damage up to 320.2 annually USD (around 20000 RUR per year).

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