Forecasting and managing the reliability of technological equipment of oil and gas pipelines with the use of real-time reserving

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Abstract. The paper deals with evaluation of reliability indicators of technological equipment of oil and gas pipelines using graph models. A special category is represented by evaluation techniques that describe complex facilities with a time reserve with the possibility of prompt restoration. Researchers at the Department of Hydrocarbon Transportation are carrying out research to create decision support systems with predictive, warning and reliability assessment functions. The proposed method can be used for systems with a structural and time reserve. When the system operates in real time and determines the exact type and parameters of failure distribution (physical or parametric), the results can be effectively used within the expert system of reliability management.

1. Introduction

Most units of the technological equipment of the oil and gas complex are recoverable complex objects or, formalizing, systems. Mathematical methods of applying graph methods described by the authors in [1, 5-13] provide for separate work with each technical facility. In the case where failure is considered and diagnosed as parametric, the nature of the parameter change should be considered.

The new requirements in the field of industrial safety were approved on January 24, 2018. The order of the Federal Service for Ecological, Technological and Nuclear Supervision No. 29 in the oil and gas industry started a new stage - the safety manual "Methodological recommendations on the classification of man-made events in the field of industrial safety at hazardous production facilities of the oil and gas complex" was approved [4].

Technogenic events in the field of industrial safety are now recommended to be classified on the basis of technological features of the facility, signs of the realization of the hazard of accidents, the severity of consequences into four levels of danger: level 1 - accident; level 2 - incident; level 3 - premise to the incident (hereinafter - premise); level 4 - violations in the system of industrial safety management or deviations of technological parameters, but without exceeding the maximum permissible values, including those registered by remote control. A modern classification requires novel approaches and technology of control, differentiation and management of events. For example, it is now recommended to evaluate the parameters for an anthropogenic event using models corresponding to the specifics of the facility. Let us consider the features of constructing a model on the basis of ensuring the status of working capacity, as the basic identifier for estimation on production.

Modern systems of automatic control of technological processes in the presence of a structural reserve make it possible to switch almost instantly, for example, a main unit into a repair mode with the connection of a backup unit in a "hot" reserve. It is assumed that the time of repair or running-in of the failed unit is carried out for some time, which we will consider as the recovery time. Analysis of regulatory industry documents shows that the usually acceptable time of loss of inoperability is from 8 to 72 hours, in particularly critical cases - about 1 hour. The presence of a replenishable reserve in the simulated system leads to the fact that the failure of an object does not mean simultaneous failure of the system, if the recovery of its operability occurs within the time not exceeding the permissible. Thus, the use of the technology of separate redundancy allows to avoid additional expenditure of material resources for increasing the reliability of elements and the entire facility.

2. Materials and methods

Most types of process equipment have different types of failure distribution, in addition, there is maintenance as a recovery procedure. It is proved that the statistical distribution of failures of complex equipment and systems is not limited to an exponential type of distribution, but requires a refinement in real time [1,2,3]. In this case, methods for assessing the risks of events require a fairly accurate prediction of events.

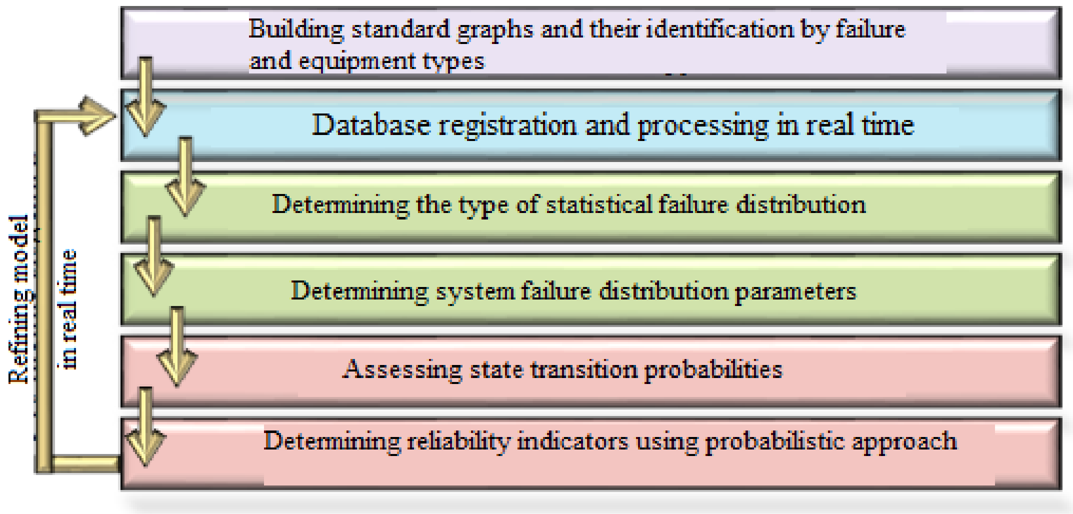

Figure 1. General algorithm for realizing the probabilistic approach when predicting reliability in real time on a structural node of a station or pipeline.

Let us consider the basic model most applicable in assessing the reliability of technological equipment of oil and gas pipelines with a recovery time reserve. The main assumptions used in this reliability assessment algorithm will be the assumption of the exponential nature of the distribution and the total of two basic states of the object - operable (0) and inoperable (1). The basics of constructing mathematical expressions are detailed in [4-13].

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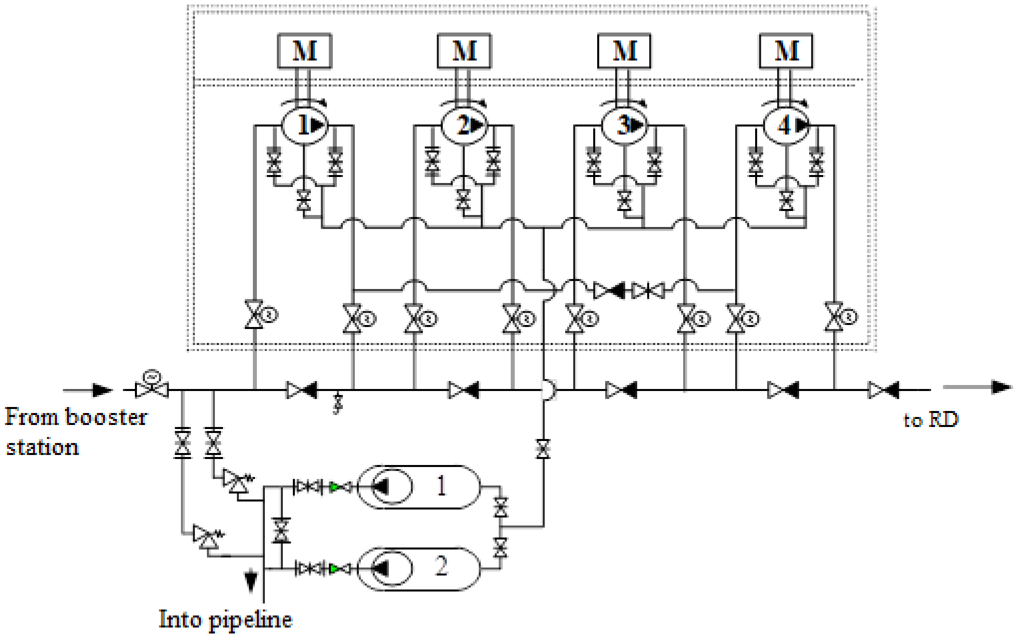

Figure 2. An example of fitting of pump and power units in a pumping station with the possibility of structural redundancy and provision of a time reserve.

According to this feature, two classes of systems are distinguished: first class (the use of only time redundancy) and second class (the sharing of time and structural redundancy). Both models are applicable in the system of operation of pipeline transport facilities for hydrocarbons.

By the time of each next object failure, the time reserve is replenished to the original value regardless of the number of failures, the time for elimination and the time between failures. The distribution law D (t) is assigned, which means that the form of the distribution law D (t) and its parameters remain unchanged with each use of the time reserve. The total recovery time of the object is not limited. Consequently, the restriction on the duration of each recovery of the operability of an object is the only restriction here on the way of using the time reserve.

Different load modes of backup elements, cases of "quick" recovery of the operability of elements, the possibility of switch failures and other factors characterizing the actual functioning of systems.

Let us consider a system that includes an object represented by one structural element, and a recoverable time reserve. The non-failure operating time between adjacent failures tn has the same distribution F(t) as the operating time t_0 before the first failure. The recovery time t_r is $F_r(t)$, independent of the failure location and the previous non-failure operating time of the object. During the repair process, the object completely restores its original properties. The time reserve t_d used in the system is $D(t) = P(t_d < t)$. We assume that F(t), $F_r(t)$ and D(t) have continuous distributions densities.

The functioning of the system is as follows: the object, having worked for a random time t_{n1}, fails and then is recovered at a random time t_{r1}; after recovery of operability it again works for a random time t_{r2}, then it is recovered again for a time t_{r2}, then it is recovered for a time t_{n2} and so on. In view of the assumptions, the values of t_{ni} and t_{ri} are independent, and $P(t_{ni}<t)=F(t)$ and $P(t_{ri}<t)= F_r(t)$, i and j=1,2,..

At the time of each object failure, the time reserve is "switched on". If the recovery of the operability of the object ends before the expiration of the time reserve, it is considered that this object failure violates the normal functioning of the system. The peculiarity of the system under consideration is that short intervals of recovery time for the operability of the object $t_r < t_d$ refer to the useful time.

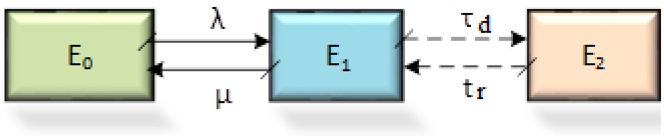

Figure 3. Graphical representation of the process of functioning of an object (a) and system (b) in time.

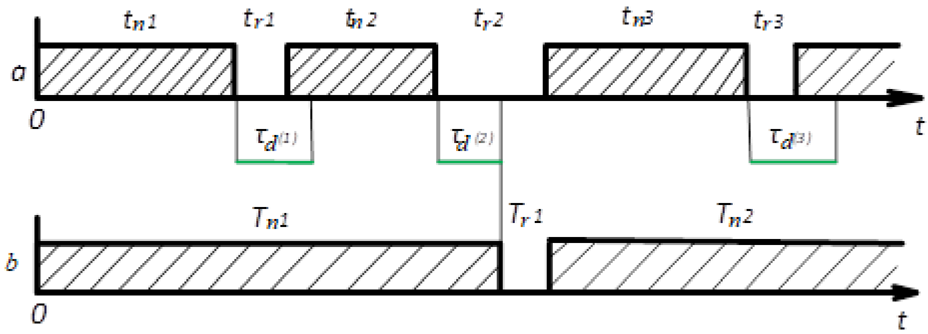

Figure 4. Graphical representation of the process of real-time functioning of an object (a) and system (b) for a node.

Determination of the probability of failure-free operation of the system. The state of the system works in two states: e_0 (the object is operable) and e_1 (the object is inoperable, in recovery for a period of time), state e_2 is inoperable.

We denote by Q_0 (s, t_d) and Q_1 (s, t_d) the Laplace-Stieltjes transformations of time to failure of the system from the states e_0 and e_1, respectively. We can write the following system of equations:

$$\begin{cases} Q_0(s,t_d) = P_{01}(s)Q_1(s,t_d), \\ Q_1(s,t_d) = P_{10}(s)Q_1(s,t_d) + P_{12}(s), \end{cases} \quad (1)$$

Solving the system of equations for Q_0 (s, t_d), we get (2):

$$Q_0(s,t_d) = \frac{P_{01}(s)P_{12}(s)}{1-P_{01}(s)P_{10}(s)} \quad (2)$$

Let us determine the values of the quantities in (2).

From the state e_0, only a transition to the state e_1 is possible, hence $P_{01}(t) = F(t)$, under the condition of exponential distribution, we obtain:

$$P_{01}(s) = \int_0^\infty e^{-st} dF(t), \quad (3)$$

And the probability of transition to the state e_1 in time to t is determined as

$$P_{10}(s) = \int_0^t [1 - D(t)] dF_{\text{в}}(t). \quad (4)$$

The probability of transition to an inoperable state e2 is calculated as

$$P_{12}(s) = \int_0^\infty e^{-st} [1 - F_{\text{в}}(t)] dD(t). \quad (5)$$

Since in the special assumption the distribution is exponential

$$F(t) = 1 - e^{-\lambda t}, \quad (6)$$

$$F_{\text{в}}(t) = 1 - e^{-\mu t}, \quad (7)$$

$$D(t) = 1 - e^{-\gamma t}. \quad (8)$$

The Laplace transform will have the form:

$$LP(t,t_d) = \frac{s+\lambda+\mu+\gamma}{s^2+s(\lambda+\mu+\gamma)+\lambda\gamma}, \quad (9)$$

$$P(t,t_d)=\frac{1}{C}[Be^{-At}-Ae^{-Bt}], \quad (10)$$

$$A=0.5(\lambda+\mu+\gamma-C), \quad (11)$$

$$B=0.5(\lambda+\mu+\gamma+C), \quad (12)$$

$$C=\sqrt{(\lambda+\mu+\gamma)^2-4\lambda\gamma} \quad (13)$$

If the time reserve is a non-random, constant value t_d for the probability $P(t, t_d)$ an exact calculation relation can also be found:

$$P(t,t_d)=1-\sum_{i=0}^{[t/t_d]-1}\frac{k_{av}^{i}(1-k_{av})^{i+1}}{(i!)^2}e^{-(1+i)\mu t_d}\cdot\left\{-k_{av}\frac{(2i+1)!}{i+1}+\sum_{j=0}^{i}\binom{i}{j}(i+j)!\times\right.$$

$$\left.[a--(i+1)b]^{i-j}\cdot\left[(-1)^{i+j}\left(1+k_{av}\frac{a-(i+j)b}{i+1-j}\right)-(1-k_{av}\frac{i+j+1}{i+1}e^{-a+b(i+1)}\right]\right\} \quad (14)$$

$$k_g=\mu/(\lambda+\mu) \quad (15)$$

$$a=(\lambda+\mu)t \quad (16)$$

$$b=(\lambda+\mu)t_d \quad (17)$$

Calculation relationships for the probability of failure-free operation $P(t, t_d)$:

$$P(t,t_d)=\exp(-\lambda qt)\,,t\gg t_d \quad (18)$$

$$P(t,t_d)=\begin{cases}1, t\le t_d\\ exp[-\lambda(t-t_d)(1-F_r(t_d))], t>t_d\end{cases} \quad (19)$$

The probability that the failure of the object will lead to the failure of the entire system is determined as

$$q=P\{t_r>\tau_d\}=\int_0^{\infty}\big(1-F\text{в}(t)\big)dt(t) \quad (20)$$

Time between failures:

$$\overline{T_n}(\tau_d)=\frac{1}{q}(t_n+Mmin(t_r,\tau_d)), \quad (21)$$

The average recovery time of the system is determined as:

$$\bar{T}_r(t_d)=\int_{t_d}^{\infty}\frac{(t-t_d)dF_r(t)}{1-F_r(t_d)}=\frac{\bar{t_r}-\text{M}\min(t_r,t_d)}{1-F_r(t_d)} \quad (22)$$

$$\bar{T}_r(t_d)=\frac{1}{q}[\bar{t_r}-\text{M}\min(t_r,\tau_d)] \quad (23)$$

The system availability factor is determined by the formula:

$$K_{av}(t_d)=k_{av}+(1-k_{av})(1-q) \quad (24)$$

Dependencies (22-24) are designed to determine time between failures, average recovery time, system availability and operation availability factors. The advantage of this algorithm is flexibility and the ability to be complicated in real time. More complex models using different types of distribution are presented by the author in [1].

3. Conclusion

Thus, using the presented calculation technique, it is possible to predict key reliability parameters by the dynamics of the failure rate and the type of distribution. The algorithm and methodology are designed for functioning within the framework of an expert control system for reliability of energy-mechanical equipment of oil and gas pipelines. When the system operates in real time and determines the exact type and parameters of failure distribution (physical or parametric), the results can have different accuracy, complexity, and a list of diagnosed indicators. Based on the monitoring results of the technological facility, not only management solutions can be adopted, but also solutions on constructive system improvement.

References

[1] Zemenkova M Yu 2017 *System Analysis and Technological Monitoring of Reliability and Safety in the Transport and Storage of Hydrocarbons* (Tyumen: IUT) 270 p

[2] Gorelik J B, Shabarov A B and Sysoyev Yu S 2016 The dynamics of frozen ground melting in the influence zone of two wells *Earth's Cryosphere* 12 (1) pp 59

[3] Vlasenko V S, Slesarenko V V, Gulkov A N and Lapshin V D 2015 Preparation of arctic oil and gas condensate deposit formation fluid for storage and transport in the form of hydrocarbon hydrate-containing dispersed system *Proc. of the Intern. Offshore and Polar Eng. Conf.* 1863
[4] 2018 Safety guide *Methodological Recommendations on the Classification of Man-made Events in the Field of Industrial Safety at Hazardous Production Facilities of the Oil and Gas Industry* Approved by the Order of the Federal Service for Environmental, Technological and Nuclear Supervision of January 24, 2018 No. 29 [Electronic resource]. - Access mode: http://sudact.ru/law/prikaz-rostekhnadzora-ot-24012018-n-29-ob/rukovodstvo-po-bezopasnosti-metodicheskie-rekomendatsii/ (access date: 1.04.2018)
[5] Sukharev M G 1994 *Reserving of Main Pipeline Systems, Reliability of Gas and Oil Supply Systems* ed M G Sukharev Book 1 **3** (Moscow: Nedra) 414 p
[6] Sukharev M G and Stavrovskiy E R 1987 *Reserving of Main Pipeline Systems* (Moscow: Nedra) 167 p
[7] Sennova E V et al 1994 *Reliability of Energy Systems and their Equipment, Reliability of Heat Supply Systems* **4** (Moscow: Energoatomizdat) 480 p
[8] Sukharev M G 2010 *Methods of Forecasting* (Moscow: MaxPress) 76 p
[9] Antonov G N et al 1994 *Reliability of Energy Systems and their Equipment* ed Yu N Rudenko **1** (Moscow: Nedra) 414 p
[10] Kredentser B P 1978 *Forecasting the Reliability of Systems with Time Redundancy* (Kiev: Naukova dumka) 240p
[11] 1983 *Questions of the Mathematical Theory of Reliability* ed B V Gnedenko (Moscow: Radio and Communication) 376 p
[12] Pevzner L D 2013 *Theory of Control Systems* (St. Petersburg: Lan) 424 p
[13] Belov V V 1976 *Theory of Graphs* (Moscow: Vysshaya Shkola) 391 p
[14] Diestel R *Theory of Graphs* (Novosibirsk: Institute of Mathematics Press) 2002 336 p