Determination of probability of nominal mode of main product pipeline operation with consideration of ageing of pumping units

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Abstract. Aim. *The article provides a method and a formula for calculation of probability of nominal operating mode for main product pipeline (MPP) – further as the text goes, MPP availability function – with consideration of ageing of its pumping units which are periodically maintained in accordance with a normative service strategy. This availability function is determined in the following assumptions: 1. MPP is composed of two basic parts: passive part – high reliable line part; and active part including pump stations which ensure nominal operating mode for the product's pumping-over. MPP may contain any finite number of pump stations. 2. Each pump station includes the system of main pumping units (MPU system) which are active elements of the station, instrumentation and control, pipeline accessories and shutoff valves, as well as other essential technological equipment. MPU system is the part of pump stations ensuring nominal conditions for the oil products pumping-over and which is usually consists of four homogeneous MPUs. 3. MPU arrangement makes it possible to bring each working unit into standby, and substitute it with any standby unit. 4. A required nominal mode for MPP operation is determined by hydraulic and cost calculations as the result of which a required operating mode is indicated for each pump station. For each station the number of MPU is indicated which must be in a working order, and the rest MPU shall be either in standby, or under restoring repair performed in accordance with a normative service strategy. Thus, nominal mode of MPP operation is ensured by the respective modes of pump stations, which with regard to pumping units are determined by the number of active MPUs. Analysis of statistics related to the failures of pumping units maintained in accordance with a normative service strategy makes it possible to define the units' failure rate in each interval between overhauls. In particular, failure rates are increasing on the respective intervals which means the ageing of units with their operation. Then the method for calculation of availability function for any pumping unit within the scope of MPP is offered. Initial conditions and differential equations are written to find an availability function for each MPU system at pump stations, obtained using the "death and reproduction" scheme. Basic results of calculations per each of three sequential intervals between overhauls are represented in form of graphs that show the influence of ageing of the units on the values of MPU availability function at a pump station: values of derivatives of availability function are sequentially decreasing for the respective times counted from the start of each recurrent overhaul. The expression to calculate availability function of MPP with several pump stations is also provided. The results of calculation of the availability function can serve as the grounds for modernization of a normative periodic strategy on order to increase the probability of MPP nominal mode, as well as other technical and economic performance indicators of MPU systems, in particular, energy efficiency indicators. In particular, it is pointed out that certain types of non-periodic service strategies, built on the basis of a normative strategy may significantly increase the values of indicated.*

Keywords: *main product pipeline, pumping unit, reliability, ageing, availability function, probability of nominal operating mode.*

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1. Introduction

Main oil product pipeline (MPP) is a complex developing technical system for an uninterrupted and scheduled supply of oil products to consumers during the whole time of a product pipeline operation. MPP is composed of two basic parts: passive part, i.e. a pipeline line part, and active part including pump stations which ensure nominal operating mode for the product's pumping-over.

Each pump station includes the system of main pumping units (MPU system) which are active elements of the station, instrumentation and control, pipeline accessories and shutoff valves, as well as other essential technological equipment. MPU system is the main active part of pump stations ensuring nominal conditions for the oil products pumping-over, it consists of n of homogeneous MPUs with the respective pipeline arrangements, where n is normally equal to 4. MPU arrangement makes it possible to bring each working unit into standby, and substitute it with any standby unit. A required nominal mode for MPP operation is determined by hydraulic and cost calculations as the result of which a required operating mode is indicated for each pump station. For each ν-th station the number m_ν of MPU is indicated which must be in a working order, and the rest $(n-m_\nu)$ MPU shall be either in standby, or under restoring repair, where $\nu = 1, \dots, N$, N is the number of pump stations within MPP. Then, nominal mode of MPP operation is ensured by the respective modes of pump stations, and this mode of MPP operation in part related to the working units at the stations is determined by the following set of parameters:

$$(m_1, \dots, m_N). \qquad (1)$$

Each MPU is a set of two main coupled parts:

1) main line pump (MLP); 2) motor driver (MD), which is a MLP drive. MLP and MD are ageing equipment [1, 2], specified during the period of operation by wear of its constituents and damage accumulation where the term "damage" is understood [2] as "the event when the state is not fault-free anymore, though the equipment is still serviceable". MPU ageing is exerted in both, degradation of MPU reliability indices, and in degradation of its technical and economic characteristics [3].

To prevent from negative developments of a random process of ageing a unit periodically goes through maintenance. MPU maintenance includes 1) diagnostic monitoring and inspections, as well as 2) different types of preventive maintenance (PM). This maintenance is performed in accordance with a certain rule approved earlier – PM strategy. It is clear that the ageing of MPU greatly depends on the type and scope of PM strategy. All types of repairs within the scope of PM strategy largely but not fully eliminate negative effects of the MPU ageing. That is why the method of estimation of the probability $k(m_1, \dots, m_N, t)$ of nominal mode of MPP operation in each moment of time t under MPU ageing is of practical and scientific interest. And we shall consider that the MPP mode of operation is specified by the set (1).

This paper describes one analytical method of estimation of probability $k(m_1, \dots, m_N, t)$, which shall be further called the availability function of MPP.

2. Ageing process affecting a failure rate of MPU serviced by the MP periodic strategy

Periodic strategy s of MPU PM can be represented in the following form: $s = (s_{mlp}, s_{md})$, where s_{mlp} is a PM strategy of the main line pump (MLP), s_{md} is a PM strategy of the motor driver (MD). And the preventive maintenance for MLP and MD by the strategies s_{mlp} and s_{md} are carried out consistently in time, i.e. when routine repairs are conducted for MLP, similar repair is carried out for MD, etc. Each constituent s_{mlp}, s_{md} of the strategy s specifies the periodic sequence (cyclic recurrence) of diagnostic inspections, routine, intermediate repairs and overhauls, as well as the events when the emergency restoring repairs (ERR) are immediately carried out, and some other characteristics of service of the respective MPU equipment. For instance, it may contain time limits for all types of the repairs, it may sometimes indicate the specified lifetime, after which the equipment shall be written off, or the events when the equipment is placed into a standby (from a standby) and other essential details. Formal transcripts of standard periodic (cyclic) strategies s_{mlp}, s_{md}, currently used for the maintenance of MLP and MD, are listed in the papers [4, 5] and have the following form:

$$s_{mlp} = \{\theta_{or}, n_{or}, n_{ir}, n_{rr}^{mlp}, n_{di}, C_{or}^{mlp}, C_{ir}^{mlp}, C_{rr}^{mlp}, C_{err}^{mlp}\},$$

$$s_{md} = \{\theta_{or}, n_{or}, n_{rr}^{md}, C_{or}^{md}, C_{rr}^{md}, C_{err}^{md}\},$$

where θ_{or} is an overhaul repair cycle (OR) equal to the time period between the nearest overhauls, which is defined by an MPU operating time, n_{or} is the amount of overhaul repair cycles, n_{ir} is the amount of cycles of intermediate repairs (IR) "inside" the OR cycle, n_{rr}^{mlp} is the amount of cycles of routine repairs (RR) of MLP "inside" the IR cycle, n_{di}^{mlp} is the amount of cycles of diagnostic inspection of MLP "inside" the RR cycle, n_{rr}^{md} is the amount of cycles of routine repairs of MD "inside" the OR cycle, C_{or}^{mlp}, C_{ir}^{mlp}, C_{rr}^{mlp}, C_{err}^{mlp}, C_{or}^{md}, C_{rr}^{md}, C_{err}^{md} are the rules and scope of the works carried out at any type of the repair of MLP and MD respectively. In particular, $C_{err}^{(\cdot)}$ is the rule of emergency restoring repair, in the rule $C_{err}^{(\cdot)}$ it is necessary to indicate the scope of works to be carried out in case of the MLP emergency shutdown, as well as other essential details, for example, the regulations for ERR. Sometimes the strategy $s = (s_{mlp}, s_{md})$ contains the following normative standard indicators: 1) calendar time t_p till the MPU write-off; 2) time limit θ_p for MPU operating time till its write-off.

For instance, major parameters of the strategy s may have the following values:

$$\Theta_{or} = 6\cdot10^4 \text{ h}, n_{or} = 2, n_{ir} = 4, n_{rr}^{mlp} = 1,$$
$$n_{rr}^{md} = 10, \theta_p = 3\cdot\theta_{or}, t_p = 2\cdot\theta_p. \qquad (2)$$

And the calendar time period t_{or} from the start of MPU operation up to its nearest overhaul, or between the nearest overhauls is equal to $2\cdot\theta_{or}$.

Statistical analysis of the impact of the ageing on the MLP and MD reliability performance is given in papers [4, 5]. Particularly, they contain the tables with the values of MLP and MD failure rates per each time interval between the nearest restoring repairs carried out in accordance with the strategy s. These tables also show that due to the ageing process an average failure rate of MPU λ_i in each interval $J_i =$

$[(i–1)\cdot t_{or}, i\cdot t_{or}]$, where $i = 1, 2, 3$ increase monotonously. And the variables λ_i , $i = 1, 2, 3$ have the following values:

$$\lambda_1 = 3{,}51\cdot10^{-5},\ \lambda_2 = 1{,}41\cdot10^{-4},\ \lambda_3 = 6{,}50\cdot10^{-4}, \qquad (3)$$

where the dimension of the given variables is 1/h.

Below is the modification of the famous mathematical model represented in [6] used to calculate the availability function $k_\nu(t)$ of the MPU system at the ν-th pump station with consideration of ageing of the pumping units serviced by the periodic strategy s with the parameters defined by the equations (2).

3. Determination of the availability function of a pump station and MPP

Paper [6] contains the description and substantiating of the mathematical model used to calculate the availability function $k(t)$ of the MPU system of one pumping station where $k(t)$ is a probability of the system with 4 identical MPUs being in the time moment t in the state when two and more MPUs are in operable condition. The strategy s is considered to be fixed in the period $[0, t_p)$ of MPU operation, and MPU is not getting aged, i.e. its failure rate remains constant through the whole period of operation. This mathematical model is a homogeneous Markov process, which has n+1 of states where $n = 4$, and which is set by a graph of the “death and reproduction” scheme [7].

In this case the calendar period $[0, t_p)$ of the MPU operation for each ν-th pump station is a sum of three sequential intervals $J_i = [(i–1)\cdot t_{or}, i\cdot t_{or})$, in which the failure rates $\lambda^{(i)}$ of MPU are different, where $i = 1, 2, 3$; and the amount of units being in operable condition on each ν-th pump station should be not less than m_ν in order to ensure the nominal mode of MPP operation. Considering the mentioned peculiarities the Markov process described in [6] becomes an inhomogeneous process $\eta_\nu(t)$, (t□$[0, t_p)$, $\nu = 1, …, N$), which is defined in each interval J_i, $i = 1, 2, 3$ by a homogeneous Markov process $\zeta_\nu^{(i)}(x)$, where x □ $[0, t_{or})$. The process $\zeta_\nu^{(i)}(x)$ is set by the graph of the “death and reproduction” scheme shown in Figure 1.

In Figure 1 each j-th node of the graph corresponds to the MPU system state when j pcs. of MPU are in non-operable condition, $j = 0, 1, …, n$. And μ is the MPU repair rate with one repair team, λ_i is the MPU failure rate in the interval J_i , $b_j\cdot\lambda_i$ is the rate of transition from the state (j) to the state (j+1) of the MPU system where $b_j = m_\nu$, if $j = 0, 1, …, n–m_\nu$, и $b_j = m_\nu–k$, если $j = n–m_\nu+k$, $k = 1,…, m_\nu–1$.

The components of the vector $a^{(i)} = [a_0^{(i)}(0), …, a_3^{(i)}(0)]$ of the initial distribution of the process $\zeta_\nu^{(i)}(x)$ are defined by the following equation:

$$a_0^{(i)}(0) = p_0^{(i)}(0,\nu) = 1,\ a_j^{(i)}(0) = p_j^{(i)}(0,\nu) = 0, \qquad (4)$$

where $i = 1, 2, 3$, $j = 0, 1, …, n$, $p_j^{(i)}(x, \nu)$ is the probability of the process $\zeta_\nu^{(i)}(x)$ being in the state j in the time moment $x \in [0, t_{кр})$, $\nu = 1, …, N$.

For any $t \in [0, t_p)$ there is such an interval $J_i = [(i–1)\cdot t_{or}, i\cdot t_{or}]$, where $t \in J_i$, where $i = 1, 2, 3$. Then t can be represented as $t = (i–1)\cdot t_{or} + x$, $x \in [0, t_{or})$. And the probability

$$\mathbf{P}^{(i)}(x, \nu) = p_0^{(i)}(x, \nu) + p_1^{(i)}(x, \nu) + \ldots + p_{n-m\nu}^{(i)}(x, \nu), \quad (5)$$

is the availability function $k_\nu(t)$ of the MPU system of the ν-th pump station, i.e. the following equation holds true:

$$k_\nu(t) = k_\nu((i–1)\cdot t_{or}+x) = \mathbf{P}^{(i)}(x,\nu). \qquad (6)$$

For each $i = 1, 2, 3$ the probabilities $p_j^{(i)}(x, \nu)$ are defined by the solution of the following differential equation system:

$$\begin{aligned} dp_0^{(i)}(x, \nu)/dt &= – b_0\cdot\lambda^{(i)}\cdot p_0^{(i)}(x, \nu) + \mu\cdot p_1^{(i)}(x, \nu),\\ dp_j^{(i)}(x,\nu)/dt &= \mu\cdot p_{j+1}^{(i)}(x,\nu) – (b_j\cdot\lambda^{(i)} + \mu)\cdot p_j^{(i)}(x,\nu) +\\ &+b_{j-1}\cdot\lambda^{(i)}\cdot p_{j-1}^{(i)}(x,\nu),\ j = 1, …, n–1,\\ dp_n^{(i)}(x,\nu)/dt &= b_{n-1}\cdot\lambda^{(i)}\cdot p_{n-1}^{(i)}(x,\nu) – \mu\cdot p_n^{(i)}(x,\nu). \end{aligned} \qquad (7)$$

The initial condition for system (7) is the initial distribution vector, whose components are defined by equation (4).

Let any ν-th pump station have $m_\nu = 2$ and $n = 4$, where $\nu \in (1, …, N)$. Then the calculation of the availability function $k_\nu(t)$ in the time interval $[0, t_p)$ with initial data defined in equations (2), (3) and with $\mu = 0{,}5\cdot10^{-2}$ (1/h) will give the result shown in Figure 2.

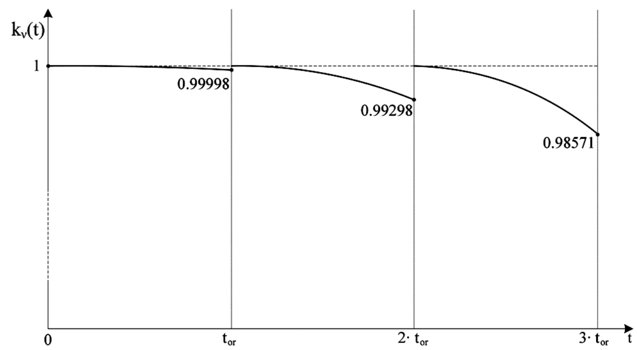

Fig. 2. Graph $k_\nu(t)$ in the time interval $[0, t_п)$

The availability function $k(m_1, …, m_N, t)$ of MPP, whose nominal mode is set by (1), is defined (in case statistically

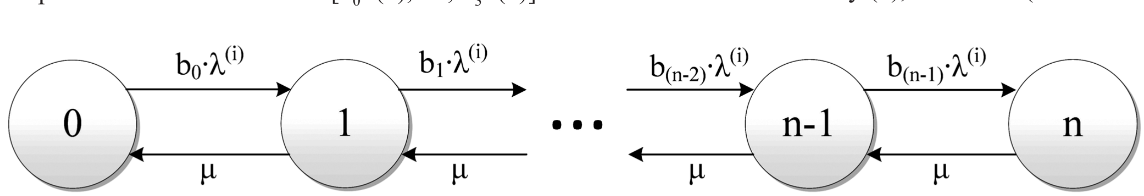

Fig. 1. Graph of the “death and reproduction” scheme for the process $\zeta_\nu^{(i)}(x)$

independent operation of pump stations is provided) by the equation:

$$k(m_1, \ldots, m_N, t) = k_1(t) \cdot k_2(t) \cdot \ldots \cdot k_N(t). \qquad (8)$$

4. Conclusion

The availability function $k_\nu(t)$ of MPU system of each ν-th pump station where $\nu = 1, \ldots, N$ within MPP is a function monotonously decreasing with time in each i-th interval J_i, where $i = 1, 2, 3$. Accordingly, in each interval J_i a decreasing function is $k(m_1, \ldots, m_N, t)$ which is a probability of the nominal mode of operation of the whole MPP including N of pump stations. And for any $\nu \in (1, \ldots, N)$ a decrease of function $k_\nu(t)$ grows in the operation interval J_{i+1} in comparison to the interval J_i, where $i = 1, 2$, which is caused by the ageing (accumulation of failures) of the main line pumping units serviced in accordance with a periodic PM strategy *s*. In particular, this fact may denote that non-periodic PM strategies mitigating the ageing effect can be more effective than the current periodic (cyclic) strategies.

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