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Model for Calculating the Reliability of a Wireless Sensor Telecommunication System for Monitoring the Gas Transmission Network State

Ivanov O., Avdeuk O., Bushmeleva K., Ivanov I., Uvaysov S.

Abstract— **The paper presents the analysis results of the main causes of emergency situations on main gas pipelines and the state of the monitoring problem of their technical condition. Possible ways to solving this problem with the use of modern telecommunication facilities are also proposed. The paper proposes a model for calculating the reliability of a wireless sensor telecommunication system for monitoring the gas transmission network state, allowing the performance of the required probability level of failure-free operation when a certain number of wireless sensor modules fail. The reliability calculation of the system includes two stages: the module reliability and the reliability of the radio channel for transmitting information. The application technique for the Monte Carlo simulation method calculation is described. Since nowadays there are no known unified means for designing and building wireless STS, the paper proposes the main process stages of designing wireless sensor telecommunication networks using a well-known mathematical apparatus. The choice of the system dynamic type as the basis for further consideration in solving the specific task above is also substantiated.**

Keywords - communication systems, communication networks, ad hoc networks, ZigBee, telemetry, mobile antenna, power integrated circuit, radio communication equipment, telecommunication network topolog.

I. Introduction

The most important stage of the products life cycle is the design stage, which in most cases is impossible without the use of modern methods and means of automation. In general it concerns the design of electronic devices and, systems and devices of telecommunications in particular.

Currently, information and telecommunication technologies are increasingly used in various sectors of the national economy, including oil and gas producing, gas transport, as the most important part of Russia's fuel and energy complex.

According to experts, the most part of the oil and gas pipelines have developed a planned resource by 60-70%, which is a huge environmental hazard. In Russia, about 34% of gas pipelines, 46% of oil pipelines are operated for more than 20 years. Thereof: 15% of gas pipelines, 25% of oil pipelines, 34% of product pipelines were built more than 30 years ago (conditionally normative service life), including 3.5% of gas pipelines - more than 40 years. After 20-25 years of operation, the number of accidents is steadily growing. The reason of this grow is that defects in the pipe wall and cyclic loads have a negative effect on the strength characteristics of the metal and welded joints.

The analysis of the emergencies causes has shown that the most common defects on main gas pipeline (MGP) are corrosion and damage due to mechanical impact. However, in Russia, the huge length and branching of gas pipelines, their passage through territories with complex terrain and diverse climatic conditions, as well as the lack of a developed and extensive communication system, significantly complicates, and in some cases makes it inapplicable, many of the modern methods of nondestructive testing of technical condition gas transmission networks (GTN).

For today the most promising solution that allows for continuous monitoring of GTN linear sections and promptly automatically informs about the fact and location of gas leakage to the control center is the use of wireless sensor telecommunication systems (STS) built on the protocols and standards of self-organizing networks [1 , 2, 4, 7]. It should be noted that to design new pipeline sections, all the necessary technical control and monitoring facilities have already been laid. However, in the case of already operating areas, a continuous and operational monitoring system is necessary to prevent possible emergencies [3].

The main concept of this system is the wireless modules (WM) location (Figure 1), including a gas leak detector, along a given section of the main gas pipeline.

Currently, there are no unified means of designing and building wireless STS: each company-manufacturer uses its

Oleg A. Ivanov, Graduate student, Department of Design and Production of Radioelectronic devices, Moscow Technological University (MIREA), Moscow, Russia. (e-mail: ivanov_o_a88@mail.ru)

Oksana A. Avdeuk, assistant professor, Volgograd State Technical University (e-mail: oxal2@mail.ru)

Kiya I. Bushmeleva, full professor, Surgut State University (e-mail: bkiya@yandex.ru)

Ilya A. Ivanov, assistant professor, Department of Electronic engineering National Research University Higher School of Economics, Moscow, Russia (e-mail: ivanov_i_a@mail.ru)

Saygid U. Uvaysov, full professor, Department of Design and Production of Radioelectronic devices, Moscow Technological University (MIREA), Moscow, Russia. (e-mail: uvaysov@yandex.ru)

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own closed, even for the analysis of development characteristics. Therefore, solutions created for one particular task cannot be used in another subject area.

Figure 1 – En example of WM location.

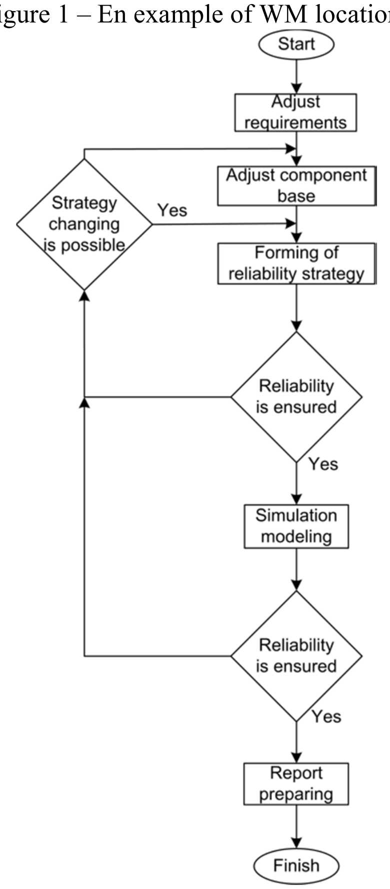

Figure 2 – The stages of designing a wireless STS.

The process of designing a wireless STS largely depends on its specific target. However, the development of separate routes for each task is a rather laborious and inexpedient waste of available resources. As a classification attribute can be a type of topological structure (TS). In accordance with TS static, weakly dynamic and dynamic systems are distinguished. As for the organization of a wireless system for monitoring the GTN state, the networks with a self-organizing topology are the most suitable, so in this case dynamic systems should be considered. Figure 2 shows a block diagram of the stages of designing a wireless STS.

II. Reliability Requirements

Given the gas sector critical importance for the Russian economy, the issue of reliability is one of the key issues in the design of any single radio electronic facility and a distributed data network in general [5,6].

The question of ensuring the reliability of the STS can be divided into several tasks:

- reliability indicators calculation of the wireless STS module;
- reliability indicators calculation of the radio data channel;
- reliability indicators calculation of the distributed network;
- analysis of calculated reliability indicators at each stage for compliance with specified requirements

The main reliability indicator is the probability of failure-free operation.

Calculation of the faultlessness of the wireless sensor telecommunication system module is carried out in accordance with GOST 27.301. (State Standard-Setting Authority that is used nowadays as well) The initial data for the calculation are formed on the basis of the technical assignment that defines following requirements:

- average time between failures;
- guaranty period;
- life time;
- failure criteria;
- requirements of survivability and resistance to external influences;
-requirements for operation, storage, convenience of maintenance and repair.

The overall reliability of the system part consists of the probability of failure-free operation of the modules R_M and the reliability of the radio link R_{RL}, i.e.

$$R_{SN}(t) = R_M(t)R_{RL}(t)$$

III. Reliability Model

The overall structure will be represented by a sequential chain of modules with a probability of failure-free operation R_i in accordance with the proposed construction concept of STS monitoring the technical state of main gas pipelines, The total probability of failure-free operation in this case must correspond to the product of the probabilities of each module, i.e.

$$R = \prod_{i=1}^{N} R_i ,$$

where N- number of wireless sensor network (WSN) modules at line segment under consideration, i.e. between base receiving and transmitting stations.

But using this approach it is possible to obtain only a lower estimate of the system reliability, as for a large number the probability of failure-free operation will tend to 0, i.e. for $N \to \infty$, $R \to 0$ that is not true.

Unlike the reliability model for an individual wireless STS module, which can be obtained as a set of analytical expressions, statistical simulation methods should be used to calculate the probability of the wireless STS failure-free operation.

In this case, in the absence of adequate analytical models, it is possible to use simulation modeling. The simulation modeling is a universal calculation method for distributed structure objects and for any distributions of operation time between failures.

Two methods of simulation modeling are recommended (GOST R 51901.5). There are the method of moments and the Monte-Carlo method. The first one requires the construction of an analytical reliability model of the telecommunications system (in the form of a polynomial) and mainly is used for tolerances calculation, therefore, it is not used in paper.

The well-known implementations of the Monte-Carlo method [10], used for reliability calculations, also require the construction of a unified topological model of the STS reliability in the form of a modules connection (component parts (CP)). The CP parameters in this model characterize their state. They are represented by a binary variable: "1" - workable "," 0 "- not workable.

Based on the principles of application the Monte-Carlo method, it is required to conduct K repeated tests, i.e. simulation experiments on formal modules models, which are mathematical models that communicate with a causal relationship between the modules MTBF (Mean time between failures) and the WSN as a whole.

To construct a formal model and a reliability structural scheme (RSS) for wireless STS, it is necessary to determine the failure criterion. The WSN failure criterion: failure of n-1 elements installed sequentially. The transceiver is capable to transmit information to the n element. Graphical interpretation of the failure criterion is shown in Figure 3. As a whole n is calculated from the ratio:

$$n = \left[\frac{L}{l}\right],$$

where L - the maximum signal transmission distance by the module WSN, l – distance between modules STS.

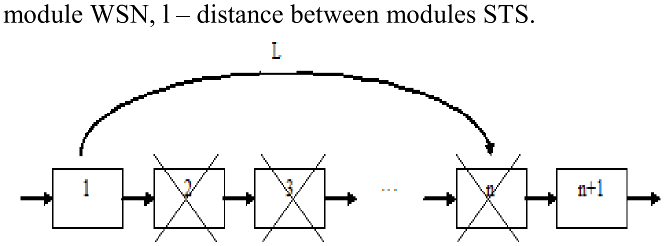

Figure 3 – WSN failure criterion

Thus, the STS failure occurs when the transmitter and receiver cannot transmit information as a failure result of the n-1 elements following it.

In accordance with the used failure criterion, the entire chain of N elements can be represented as a sequential connection the M groups of loaded reservation (Figure 4).

The model output characteristic is a continuous random variable characterizing the module operation time, the model coefficients are continuous random variables characterizing the modules operation time, and the model parameters elements are the distribution functions of the operating time to the failure of the modules.

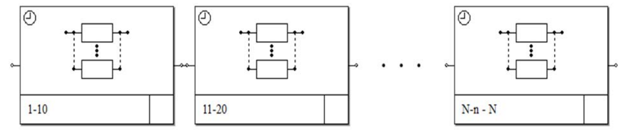

Figure 4 – WSN reliability structural scheme

The minimum realizations number of the simulation experiment is calculated with the ratio:

$$K \geq \frac{P_{TZ}(t)\cdot\left[1-P_{TZ}(t)\right]}{\varepsilon^2}\left[\Phi^{-1}P_a\right]$$

Where $P_{TZ}(t)$ - probability of failure-free operation at the request of the technical specification, Φ^{-1} - inverse Laplace function, P_α - confidence coefficient , ε - absolute uncertainty.

Each realization of the random variable x in the interval from 0 to 1 allows us to calculate the STS operating time till failure based on the known relation:

$$t_n = -\frac{\ln x}{\Lambda},\ \forall x \in (0,1),$$

where Λ - failure rate of the STS module.

Repeated implementation of the simulation experiment allows the generation of an MTBF time chart (Figure 5), to show the frequency of simulation results hits for the minimum permissible production limits.

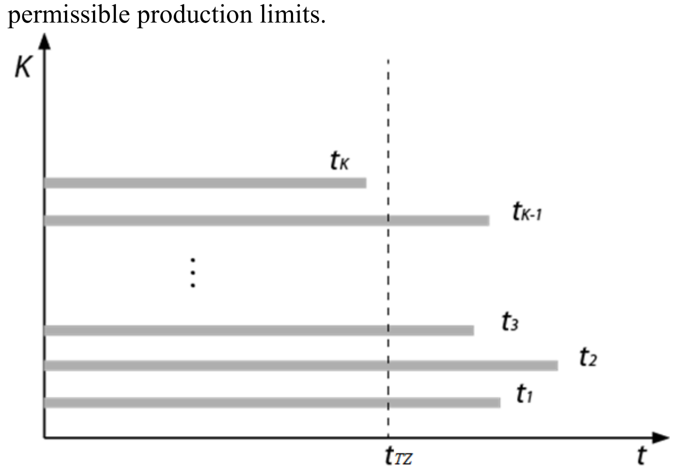

Figure 5 - MTBF Time Chart

The frequency of imitation simulation hits over the minimum permissible limits is calculated as

$$R^*(t) = \frac{k}{K},$$

where k is the number of the simulation experiments, in which the value of the obtained MTBF has exceeded the minimum set value according to the technical specification.

The calculated value is assumed equal to the probability of failure-free STS operation R_M .

$$R^*(t) \underset{K\to\infty}{\longrightarrow} R_M(t)$$

In accordance with the failure rate of a separate wireless STS module Λ is calculated as the sum of the electronic-radio elements (ERE) failure rate λi:

$$\Lambda = \sum_i \lambda_i$$

The structural scheme of reliability is represented in the form of consecutively connected electronic-radio elements (Figure 6), this structure is justified by the chosen failure criterion, which is the failure of any element on the printed circuit board (PCB).

The intensity of each ERE is calculated in accordance with the reference book [8], where for each element a model is described in the next form:

$$\lambda_e = \lambda_b \prod_i K_i$$

where λi – the basic failure rate calculated for the ERE type by the test results, Ki – a coefficients set determined by various factors. The main coefficients can be identified as: mode factor, acceptance factor, exploitation factor etc.

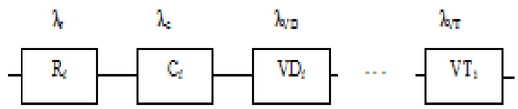

Figure 6 – Structural reliability diagram of wireless sensor telecommunication system module

For example, for the key control element (microcontroller) the failure rate model assumes the form:

$$\lambda_e = \lambda_b K_{CT} K_{corp} K_V K_E K_{PR}$$

where K_{CT}– mode factor (coefficient) depending on the complexity of the integrated microcircuit (number of elements, bits) and ambient temperature; K_{CORP} – coefficient of dependence on the type of item body ; K_V – coefficient of dependence on the maximum values of supply voltage; K_E– coefficient that takes into account the operating conditions for a particular class of equipment [9]; K_{PR} – acceptance coefficient reflects item quality levels, value is selected according to the type of acceptance using the directory, the following types of acceptance are distinguished: «1» – acceptance for elements and products of mass production, «3» – acceptance for elements and products commissioned by ministries, «5» – acceptance for elements and products for general military application, «7» – acceptance of elements and products of special quality, produced in small batches, «9» – elements and products of increased stability and reliability.

The channel of information transmission via a radio link is used to have some failures characterized by temporary complete or partial loss of information as a result of the external factors influence.

The failure-free operation probability of the radio channel is determined by the reliability of the forward and reverse communication channels and reliability, depending on the weather conditions, i.e.:

$$R_{RL} = R_{RL-PK} \cdot R_{RL-OK} \cdot R_{PU}$$

where $R_{RL-PK} \cdot R_{RL-OK}$ – the failure-free operation probability of the forward channel (reverse channel); R_{PU} – failure-free operation probability, depending on the influence of weather conditions.

Failure-free operation probability R_{PU} depends on the influence of weather conditions and is calculated based on the statistics for the selected region. The calculation takes into account the influence of weather conditions in each month for a specific location of the wireless sensor network modules installation.

Failure-free operation probability of the forward channel (reverse channel) $R_{RL-PK} \cdot R_{RL-OK}$ is calculated for the various signal-to-noise ratios. The calculation uses the average power of the signal at the receiver input, the average noise factor taking into account atmospheric, fluctuation and internal noise, the deviation of signals from the sight line etc.

IV. Conclusion

Thus, this model allows not only to calculate the current reliability of the wireless sensor telecommunication system to monitor the technical state of the GTN, but also, considering the critical importance of the gas transmission industry, to explore possible ways to optimize the system in order to ensure a given level of reliability. One of the features of the proposed model is the possibility of integrating it into the design process at any stage with the use of already known mathematical and software apparatus.

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