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USING THE FAULT TREE METHOD FOR RELIABILITY ANALYSIS OF A COLD MONOJET WATER METER

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Abstract: *The paper presents the fault tree method and the structure of the system considered - a cold monojet water meter. The construction of the faults tree was done considering the three stages: preliminary analysis, definition of the specifications and construction of the failure tree for the water meter considered. The logical scheme of reliability was created for a cold monojet water meter. The evaluation of the considered device was performed according to the faults tree method.*

Key words: *reliability, faults tree, water meters.*

1. Introduction

Faults tree method represents an analytical technique for assessing deductive systems, method which determines the probability of producing a top event or an undesirable event. The undesirable event is a state of failure in the system, highlighted in the context of the operating conditions, appropriate for the specific environment for the operation of the system under review [3], [4].

Faults tree method is primarily a qualitative analysis, which can be pursued in a quantitative analysis, expressing the probability of production of the top event or any other event in between. Quantitative analysis itself depends on the variety of system failure models, quantifying the probability of producing the event, in case of a particular model, but that does not change the qualitative analysis.

Faults tree consists of a series of complex entities known as operators or logic gates that allow or inhibit the propagation of a failure to the top of the faults tree. Logical operators highlight the relations between events that can ensure production of another event. Logical operator entry events or events on the lower level are combined in different ways to produce the output event, which is the event on the upper level.

Quantitative assessment or evaluation of probabilistic faults tree consists of determining the probability of producing a top event, taking into account the probabilities of events based on the fault tree [3].

For quantitative analysis it is necessary to determine the structure or function of the characteristic function, the event containing the top or, more broadly, all events of fault tree. Among the methods of quantitative analysis used in estimating the reliability and security of water meters, one can mention:

- direct method;
- descent method - algorithm Mocus;

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- ascending method;
- dual tree;
- method of minimal assemblies.

If the faults tree does not contain repeated events, probabilistic assessment is performed directly, determining probabilities of events, starting with primary operators until the top event. In contrast, if the tree contains failure events repeated, probabilistic assessment is based on minimum assemblies.

Faults tree method is done in four phases namely:

- identify the event/top events to be analyzed;
- identify events that contribute to the top event;
- the building of the faults tree of the system, using symbols to describe specific events and the links between them;
- quantitative and qualitative assessment of the faults tree, based on data obtained in the graphic construction; it is possible to do calculations to evaluate system reliability.

The system can decompose into subsystems and elements, based on three criteria:

- technological criterion, that considers the achievement of the item;
- maintenance criterion, that considers the maintenance and replacement of the items;
- data entry criterion for the related study, in which the decomposition of the system will be based on data on the functioning of elements, on their failure probabilities. In case for some elements the input data are not known or insufficient, the decomposition is done to unit level.

2. Faults Tree Construction

Construction of the faults tree involves a laborious and a thorough knowledge of system analysis [1], [2]. This requires knowledge in several areas: physics, electronics, informatics, chemistry, mechanical engineering etc. But also knowledge of the correct representation of top event, which in turn, implies a perfect knowledge of how operates the system, the links between different components and how they malfunction.

The construction of the failure tree starts by defining the top event, called also as undesirable event. The top event is decomposed into mediate events which may occur while the considered system operates, until reaching the primary factors that determine the occurrence of this event.

The three stages in the construction of the failure tree are: preliminary analysis, definition of the specifications and construction of the failure tree [1].

The preliminary analysis for construction of the failure tree consists in considering the following phases:

- physical decomposition of the system into subsystems and elements, according to the following criteria: technological criteria, maintenance criteria and the input data for the considered study criteria;
- identification of the component elements of the system; the decomposition is done to unit level;
- definition of the modes of failure of the component elements;
- reconstitution of the system using the component elements, considering the functionality of the system and all the decomposition levels.

The definitions of the specifications are the following:

- phases are different ways of functioning of the system. Almost all systems have several ways of functioning;
- limit conditions refer to the definition of the interaction of the system with the environment in which the system works;
- specific hypotheses present the hypotheses done for the system;
- initial conditions contain hypotheses on the functioning start for the studied phase.

In constructing the failure tree the following elements are to be considered:

- the definition of the undesirable event (top event) of the failure tree should consider, with no ambiguity, the former specifications;
- the decomposition of the events - the undesirable event is decomposed in events-immediate causes, and these, at their turn, into events-subordinate causes;
- the construction of the failure tree is considered to be achieved if the events-causes which are not decomposed represent the failure modes of the component elements of the system or the failures are produced by the environment.

3. Logical Scheme of Reliability for a Cold Monojet Water Meter

Depending on the structural scheme of a water meter one constructs the functional block diagram of the mechanical mean for measuring volumes.

Reliability of water meter cannot be treated as the reliability of a product, which consists of an element [2]. Water meter includes a number of elements forming a system comprising a set of elements connected in a whole, which performs a specific function technique.

These elements included in the composition of a water meter (Figure 1) are:

- sub input - water meter body;
- unit of measurement - rotor (turbine);
- transmission unit (magnetic coupling);
- integration and indicating subassembly;
- mechanical integrator (Figure 2).

Water meter consists of:

- brass meter body provided with inlet channels for admission/exhaust of the water. The exhaust channel is provided with a filter;
- turbine - measuring device operating under the water pressure;
- magnetic coupling, which ensures the transmission of motion from the measurement unit to the integration unit;
- integrating unit consisting of eight cylindrical drums and a dial with pointer and a graduated scale with division value of 0.05 dm^3. The mechanism is equipped with a device for removing condensation from the rolls.

Fluid flow through the meter produces the movement of the rotor, whose speed is proportional to the circulating water flow through the device. Rotational motion is demultiplicated and transmitted to the integration and indicating unit.

Transmission of motion is achieved by magnetic coupling since the mechanism is dry type.

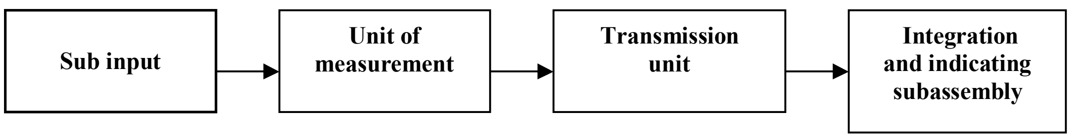

Fig. 1. *Logical scheme of reliability of a cold monojet water meter*

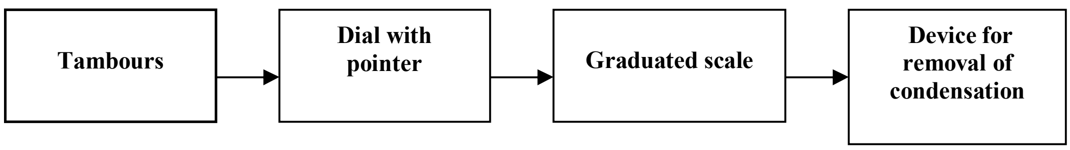

Fig. 2. *Integration and indicating subassembly*

4. Fault Tree Model

The method of faults trees for the study of the foreseeable reliability of complex equipments is based on the idea that the failure can be quantified at the structural level so that any malfunction of the equipment is the result of a sequence of measured states of the fault [1].

The level of quantification is elected by the analyst, according to the goal and the desired accuracy, till up to the components, the results being as close to reality as the level of quantification will be more detailed [4].

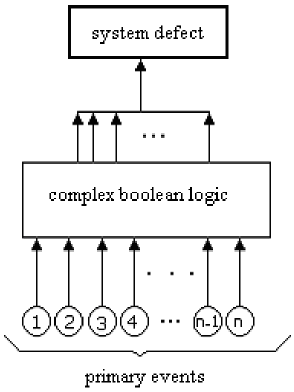

Fig. 3. *Scheme of principle of a faults tree*

The scheme of principle of a faults tree contains a number of primary events, independent, interconnected via a Boolean logical structure, which shows many possibilities in which these events may be combined to generate in the final the damage of the equipment studied Figure 3.

From the structural point of view, the faults tree uses the following concepts:

- primary elements - are components or building blocks from the base of the quantification of the damage of equipment;
- primary defects - defects of the primary elements;
- critical event - the state of defective equipment;
- failure mode - is the set of faulty elements which simultaneously remove from the service the equipment;
- minimum failure mode - is the smallest set of primary elements simultaneously defective which leads to equipment failure;
- hierarchical level - are all elements that are structurally equivalent and occupying equivalent positions in the faults tree structure.

The method is based on binary logic, the formal function of the equipment required is treated as a binary function, whose variables are the primary defects that can be synthesized with elements AND, OR and NOT.

Based on analysis by the method of faults tree, one can obtain either the probability of failure or the failure rate:

a) Assessing the probability of failure use the properties of the logic gates AND, OR and NOT.

Thus, out of three logic gates, the probability of having a defect is:

- AND gate output = probability (A and B defect) =

$$=P(\mathrm{A}\cap\mathrm{B})=\begin{cases}P(\mathrm{A})\cdot P(\mathrm{B}); & \textit{if } \mathrm{A} \textit{ and } \mathrm{B} \textit{ independent},\\ P(\mathrm{A/B})\cdot P(\mathrm{B})=P(\mathrm{A})\cdot P(\mathrm{B/A}); & \textit{dependent events};\end{cases} \tag{1}$$

- exit gate OR = probability (A or B fault) =

$$=P(\mathrm{A}\cup\mathrm{B})=\begin{cases}P(\mathrm{A})+P(\mathrm{B})-P(\mathrm{A}\cap\mathrm{B}); & \textit{dependent events},\\ P(\mathrm{A})+P(\mathrm{B})-P(\mathrm{A})\cdot P(\mathrm{B}); & \textit{independent events};\end{cases} \tag{2}$$

- exit gate NOT = probability (A is not defective) = $P(\overline{\mathrm{A}}) = 1 - P(\mathrm{A})$. (3)

b) Assessing the intensity of failure of equipment is made on the assumption that the component failures are independent events and the failure is of exponential type.

To determine the failure rate of equipment one starts from the following considerations:

- The probability that an item is defective in (0, t) is $P(\mathrm{A}) = F\mathrm{A}(t)$;
- The probability that item B defects in (0, t) is $P(\mathrm{B}) = F\mathrm{B}(t)$.

In these circumstances, at the exit of a port OR, one obtains the probability that the equipment is defected in the interval (0, t) due to item A or item B:

$$P(\mathrm{A} \cup \mathrm{B}) = P(\mathrm{A}) + P(\mathrm{B}) - P(\mathrm{A})\, P(\mathrm{B}) = F_{\mathrm{A}}(t) + F_{\mathrm{B}}(t) - F_{\mathrm{A}}(t)\, F_{\mathrm{B}}(t) = F_E(t). \tag{4}$$

The reliability of the equipment is:

$$\begin{aligned} R_E(t) &= 1 - F_E(t) = 1 - F_{\mathrm{A}}(t) - F_{\mathrm{B}}(t) + F_{\mathrm{A}}(t)\, F_{\mathrm{B}}(t) \\ &\Rightarrow R_E(t) = \left[1 - F_{\mathrm{A}}(t)\right]\left[1 - F_{\mathrm{B}}(t)\right] = R_{\mathrm{A}}(t)\, R_{\mathrm{B}}(t). \end{aligned} \tag{5}$$

Since: $R_{\mathrm{A}}(t) = \exp(-\lambda_{\mathrm{A}} t)$, $R_{\mathrm{B}}(t) = \exp(-\lambda_{\mathrm{B}} t)$ we obtain for the reliability the following relation:

$$R_E(t) = \exp(-\lambda_{\mathrm{A}} t - \lambda_{\mathrm{B}} t). \tag{6}$$

At the exit of logical gate OR one obtains:

$$\lambda_E = \lambda_{\mathrm{A}} + \lambda_{\mathrm{B}}. \tag{7}$$

To determine the rate of failure at the logical exit gate AND, N elements are considered and one resumes the reasoning above:

$$\lambda_E = \frac{\sum_{i=1}^{N} \lambda_i (\alpha_i - 1)}{\prod_{i=1}^{N} \alpha_i - 1}, \tag{8}$$

where:

$$\alpha_i = \frac{1}{1 - \exp(-\lambda_i\, t)}. \tag{9}$$

5. Fault Tree for a Cold Monojet Water Meters

Faults tree for the water meter considered is shown in Figure 4 [1]. Table 1 presents the probabilities of failure for the minimal cuts [1], [2], [4].

The probability of the critical event can be determined knowing the probabilities of the primary events, by using relationship (10) established according to the faults tree presented in Figure 3:

T - Top event - incorrect measurement;

E_1, E_2, E_3, E_4 - Mediate events: E_1 - Locking of the mechanism for indicating; E_2 - Locking of the mechanism for transmission; E_3 - Locking of the mechanism for measuring; E_4 - Filter clogged;

$B_1, \ldots, B_7$ - Minimal cuts: $C_1 = B_1$ - friction drum; $C_2 = B_2$ - lock needle indicator; $C_3 = B_3$ - malfunction of the device for removing condensation; $C_4 = B_4$ - magnetic coupling failure; $C_5 = B_5$ - turbine failure; $C_6 = B_6$ - damage the filter; $C_7 = B_7$ - presence of impurities in water.

The probability of generating the top event for the case considered is:

$$P(T) = P(C_1) + P(C_2) + P(C_3) + P(C_4) + P(C_5) + P(C_6) + P(C_7) = 6.18 \cdot 10^{-6}. \tag{10}$$

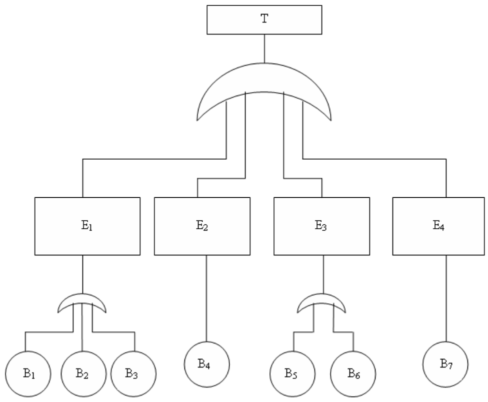

Fig. 4. *Faults tree for the cold monojet water meter*

Probabilities of failure for the minimal cuts Table 1

Symbol	Probability of failure
B_1	$2.14 \cdot 10^{-6}$
B_2	$0.02 \cdot 10^{-6}$
B_3	$2.14 \cdot 10^{-6}$
B_4	$0.6 \cdot 10^{-6}$
B_5	$0.68 \cdot 10^{-6}$
B_6	$0.3 \cdot 10^{-6}$
B_7	$0.3 \cdot 10^{-6}$

6. Conclusions

This paper presents the structure of a cold monojet water meter, the construction of the failure tree and the evaluation of the considered system according to the failure tree.

The fault tree method is a technique which is very useful in establishing fast all factors that can contribute to the occurrence of an undesired major operation in functioning of a system and for this reason it is used in different fields.

The main idea of this paper is to use this technique for the analysis of the cold monojet water meters reliability. As further work it is intended to apply this method to different types of water meters and to compare the results obtained.

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