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Risk assessment in the operation of techno-economic systems with parallel non-loaded coupling

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Abstract— As a techno-economic system (TES) is defined the system of interacting manufacturing machinery (technology), automation technology, human operators and the economic and financial relationships between them. [3],[4]. In the article is discussed a TES, which consists of a certain number of functional elements (**FEs**) connected in parallel, as each subsequent node starts to operate upon failure of the functioning before it node. This type of coupling is known in the reliability theory of TES as **parallel non-loaded coupling**.

Index Terms— Techno-economic system, Functional elements, Parallel non-loaded coupling, Risk

1 Introduction

The failure of the functional elements (FEs) of a TES is the cause of **technogenic danger** (risk) that continues throughout the entire period of operation [3]. For example, in an aircraft (AC) during flight time, it is possible that a failure may occur, that necessitates for repairs be made by the service crew, unless the failed FE is backed up by another functioning element. In addition, the need to increase the technical resources of the FEs of the TES requires the installation of new technological information systems (connected in parallel or in series with the old ones) and compatible with the available standard systems installed by the manufacturer (in case of modernization of the TES) [1],[3].

For example, analogous is the state with the TES of a petroleum or natural gas pipeline, whose composite FEs (units of the pipeline) pass through a populated area. It must be taken into consideration, that the upper limit of the probability of failure of an arbitrary complex TES is 10^{-9}, i.e. out of one billion connections in nature, one of them is unsuccessful [1], [3], [5], [6-8].

The possible states of the TES are: *all of their constituent FEs are well-functioning and the system does not represent technogenic danger; at least one constituent FE has failed (**or went bankrupt for the financial-economic field**) and the system is in a state of recovery (repair), but its use continues, i.e. it constitutes technogenic danger.*

Since these states occur accidentally, the following questions arise: what are the estimates of the probability that the FEs of the TES will be in such a state at a random moment in time **t** $(0 < t < \infty)$; what are the marginal estimates of these probabilities over long periods of time ($t\to\infty$) and shorter period ($t\to\infty$) of operation (usage).

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The solution to the first question can be found in the famous works of Academician and Professor Evgeniy Gindev, D.Sc. (Tech). This article is dedicated to solving a new scientific problem, related to the non-loaded coupled in parallel elements of a TES.

In the beginning of the study, we shall determine the marginal estimates of the probabilities for a safe and hazardous state of a TES with connected in parallel FEs with **parallel non-loaded coupling**.

A constituent part of the TES is analyzed, which consists of two nodes (FE) with parallel coupling, as they have the following mode of operation**: the second node begins to function immediately after the first one fails**. It is assumed that the switchover is absolutely reliable, after which the recovery of the failed FE of the TES begins.

If the intensity of the recoveries of each FE from the tested constituent part of the TES is constant and equal to $\mathbf{M_1>0}$ for the first FE and $\mathbf{M_2>0}$ for the second FE ($\mathbf{M_1>M_2}$), then the intensity of the recoveries of the constituent part $\boldsymbol{\mu(t)}$ is determined by [9]:

$$\mu(t)=\frac{M_1.M_2\{1-\exp[-(M_2-M_1)t]\}}{\{M_2-M_1\exp[-(M_2-M_1)]t\}} \tag{1}$$

The total intensity of the flow of failures $\boldsymbol{\omega(t)}$ of the examined TES is determined by the following formula [3]:

$$\omega(t)=\frac{\Lambda_1.\Lambda_2\{1-\exp[-(\Lambda_2-\Lambda_1)t]\}}{\{\Lambda_2-\Lambda_1\exp[-(\Lambda_2-\Lambda_1)]t\}} \tag{2}$$

where:

- $\Lambda_2>\Lambda_1>0$ are the intensities of the flow of failure Λ_1 of the first FE and the intensity of the flow of failures Λ_2 of the second FE in the common TES.

Let us determine the marginal stationary value of the probability for a safe state $\boldsymbol{P_6(t)}$ and the probability for a hazardous state $\boldsymbol{P_0(t)}$ of the constituent TES, which has non-loaded parallel coupling of the **FEs**. According to (2) $\lim_{t\to\infty}\omega(t)=\Lambda_1$, the formula (5.1.7) of [9] $\lim_{t\to\infty}\mu(t)=M_1$.

After the analysis of formulas (5.1.3) and (5.1.7) of [9],[11] the following mathematical limits should be defined:

$$\lim_{t\to\infty} P_Б(t)=K_Г^{(1)},\quad \lim_{t\to\infty} P_0(t)=K_П^{(1)} \qquad (3)$$

where:

- $K_Г^{(1)}=M_1/(\Lambda_1+M_1)$ is the coefficient of readiness of the first FE (the more reliable one);
- $K_П^{(1)}=\Lambda_1/(\Lambda_1+M_1)$ is the coefficient of idle time of this first FE, follows the conclusion that the marginal stationary values of the probability for safe and hazardous state of the constituent FEs of a TES with parallel non-loaded state and with loaded state (reviewed in [9]) coincide. Furthermore, it should be taken into consideration that the intensity of the flow of their failures is determined by using different formulas.

Let us examine the constituent part of the TES, which has "**cold**" back-up of the main node (FE). The elements of the TES are identical; therefore, the second FE starts working after the failure of the first FE (the primary one). The switchover between the two FEs is instant and absolutely reliable.

As a result of the assumptions stated above, it follows that the intensity of the flow of failures of the component of the TES with cold back-up of the main FE looks like:

$$\omega_1(t)=\frac{\Lambda^2 t}{(1+\Lambda t)} \qquad (4)$$

where:

- $\Lambda>0$ is the intensity of the flow of failures of TES. The intensity of recovery is determined by (1).

In accordance with [3] follows that $\lim_{t\to\infty}\omega_1(t)=\Lambda$, $\lim_{t\to\infty}\mu_1(t)=M$. By using the formulas (5.1.3) and (5.1.7) of [9], which look as follows:

$$P_Б(t)=1-P_0(t)$$

$$\lim_{t\to\infty} P_Б(t)=M/(\Lambda+M)$$

where

- $P_o(t)$ is the ***probability for hazardous state*** of the constituent part of TES;
- $\Lambda=\lim_{t\to\infty}\lambda(t)$; $M=\lim_{t\to\infty}\mu(t)$ the following result is obtained:

$$\lim_{t\to\infty} P_Б(t)=K_Г^{(1)}=M/(\Lambda+M),\quad \lim_{t\to\infty} P_0(t)=K_П^{(1)}=\Lambda/(\Lambda+M) \qquad (5)$$

where:

- $K_Г^{(1)}=M/(\Lambda+M)$ is the coefficient of readiness of the main FE (the more reliable one);
- $K_П^{(1)}=\Lambda/(\Lambda+M)$ is the coefficient of idle time of this main (primary) FE.

By comparing the formulas (5) and (5.1.9) of [9],[16] which look like:

$$\omega(t)=2\Lambda[1-\exp(-\Lambda t)]/[2-\exp(-\Lambda t)]$$

follows, that the marginal stationary values of the probability for safe and hazardous state of the constituent part of a TES with cold and hot back-up (reserve) at $t\to\infty$ coincide in the risk assessment of a TES with parallel non-loaded coupling.

Let us determine the estimates of the probability for safe and hazardous state of the component of the TES with a parallel non-loaded state at $t\to\infty$. For this reason, the following Theorem should be proven.

Theorem. For the probability of safe state $P_б(t)$ and the probability of hazardous state $P_0(t)$ of the component of a TES, consisting of two non-loaded nodes (FEs) in parallel, the intensity of the flow of failures for which is respectively $\Lambda_1>0$ and $\Lambda_2>0$ are applicable the following correlations:

$$\lim_{t\to 0}[1-P_Б(t)].t^{-2}=0{,}5\Lambda_1\Lambda_2,\quad \lim_{t\to 0} P_0(t).t^{-2}=0{,}5\Lambda_1\Lambda_2 \qquad (6)$$

2. Proof

In order to prove the Theorem, a decomposition is performed by using Maclaurin series of the probability for safe state ***$P_б(t)$*** of the component of the TES. The decomposition is realized in the vicinity of point **t=0** according to degrees of the current time **t**, as they are limited to the second order.

Furthermore, if **t→0**, then follows:

$$P_Б(t)=P_Б(0)+P_Б'(0).t+0{,}5P_Б''(0).t^2+o(t^2) \qquad (7)$$

where:

- **$o(t^2)$** is an infinitely small value of a higher order than t^2

According to formula (5.1.1) of the scientific research [9],[12] for the intensity of the flow of failure **ω(t)** of the constituent part of TES is valid the following:

$$\omega(t)=\frac{\Lambda_1+\Lambda_2\exp[-(\Lambda_2-\Lambda_1)t]-(\Lambda_2+\Lambda_1)\exp(-\Lambda_2 t)}{1+\exp[-(\Lambda_2-\Lambda_1).t]-\exp(-\Lambda_2 t)}$$

and according to (5.1.2) for the intensity of the recoveries $\boldsymbol{\mu(t)}$ of the component of the TES follows that [12],[13]:

$$\mu(t)=\frac{M_1M_2\{1-\exp[-(M_2-M_1)t]\}}{\{M_2-M_1\exp[-(M_2-M_1)t]\}}$$

where :

- it is assumed that :

$$\omega(0)=0;$$
$$\mu(0)=0$$

By accounting for the above fact and correlation (5.1.5) in the differential equation (5.1.4) deduced in [9], the equality **$P_Б'(0)=0$** is determined.

By taking into account the mentioned above mathematical conclusions and formula (7), follows that:

$$P_Б(t)=1+0,5P_Б''(0).t^2+o(t^2) \quad (8)$$

For the determination of the value of **$P_Б''(0)$** is used the differential equation (5.1.4) of [9], whereby follows:

$$P_Б''(0)=\mu'(t)-[\omega'(t)+\mu'(t)]P_Б(t)-[\omega(t)+\mu(t)]P_Б'(t) \quad (9)$$

From (2) follows that $\omega'(0)=\Lambda_1\Lambda_2$, and from (9) results the equation:

$$P_Б''(0)=-\omega'(0) \quad (10)$$

As per (2) and (10), it follows that $P_Б''(0)=-\Lambda_1\Lambda_2$. The substitution of the so obtained expressions in (8) results in the proof of the above Theorem.

The determination and assessment of the risks of the TES depends on the information regarding their structural status and functional operation, on chance and the normally occurring errors of the subjective factor in the creation of the operating system of the TES.

It is thus necessary in the economic and financial research to use reliability studies of the effectiveness of management of systems under conditions of non-loaded coupling.

The results, information and knowledge from such studies shall optimize management models, thus increasing the overall reliability of systems (eco-nomic, accounting, insurance, etc.) [14], [15].

The experience gained from the reliability testing and studies of the systems is of value for the innovative development of embedded systems (subsystems) with parallel loaded – non-loaded coupling that are typical of modern digital society (economy).

3. Conclusions

1. The probability of a hazardous state of the main part of the TES with loaded functional elements in parallel is twice higher than the analogous probability of a hazardous state of a TES, which has parallel non-loaded elements in its structural and functional state.

2. The probability of a safe state of the component of a TES with parallel non-loaded functional elements is greater than the probability of a safe state of a TES with loaded elements in parallel.

3. The parallel non-loaded coupling (connecting) of the functional ele-ments of TES increases its reliability. This fact is used in the assessment of contemporary dynamics of the state of the techno-economic systems, the digital society and the human factor managing it.

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