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Reliability assessment of the TP62 executive unit in railway automation and telemechanics systems

E.G. Khujamkulov[1][a]

[1]Tashkent state transport university, Tashkent, Uzbekistan

Abstract: This article investigates the reliability of TP62 execution unit blocks, which are critical components of railway automation and telemechanics systems. The study employs a Markov continuous-time stochastic process model and a system of Kolmogorov differential equations to analyze the transition dynamics between operational, degraded, and failure states. To enhance system dependability, a structural parallel redundancy scheme is proposed, and its effectiveness is validated through rigorous mathematical derivations. Numerical results demonstrate that the Mean Time To Failure (MTTF) for the redundant TP62 configuration reaches 87,143 hours, equivalent to approximately 10 years of continuous operation. The findings hold significant practical value for the design and maintenance planning of safety-critical railway signaling and control infrastructure.

Keywords: railway automation, TP62 unit, reliability, Markov process, structural redundancy, failure rate, MTTF

1. Introduction

Transistor-based relay devices are extensively utilized in railway automation systems. The reliability of such devices—defined as their capacity for correct and sustained operational performance—is one of the fundamental requirements. This paper presents a methodology recommended for the determination and evaluation of the reliability of these devices.

In practice, determining the reliability indicators of railway automation systems remains a significant challenge. Addressing this issue is essential across various stages of the system's operational lifecycle.

The primary indicator characterizing the system's failure probability is *Q(t)*, representing the cumulative distribution function of the time to failure, also referred to as the failure probability. *Q(t)* denotes the probability that the device's failure occurs at a time less than *t*, or effectively, the probability of failure within the time interval *t*.

Another critical parameter in assessing system reliability is the probability of failure-free operation, denoted as *P(t)*. This indicator expresses the probability that the device will function without failure throughout a specified operating period t.

Consequently, the functions *Q(t)* and *P(t)* are of paramount importance in the assessment of railway automation systems. They facilitate the forecasting of potential malfunctions during system operation and enable the development of effective prevention strategies.

2. Research methodology

The relationship between the probability of failure-free operation and the probability of failure is defined by the following identity:

$$P(t) + Q(t) = 1 \quad (1)$$

The reliability function *P(t)* possesses the following fundamental properties:

P(0) = 1 signifies the operational state of the device at the initial time *t=0*;

$lim_{t\to\infty} P(t) = 0$ – indicates that the device cannot maintain its operational state indefinitely (Note: I corrected the '1' to '0' here for scientific accuracy);

$0 \le P(t) \le 1$ – the reliability value remains within the unit interval [0, 1];

$dP(t)/dt \le 0$– the function is monotonically non-increasing, reflecting that reliability diminishes over time.

The occurrence of a failure in a technical object is a stochastic (random) event, as a malfunction may or may not occur within a given time interval. Consequently, reliability theory is fundamentally rooted in the principles of probability theory.

The reliability indicator of the system, denoted as *λ(t)*, is defined as the failure rate intensity. This parameter plays a pivotal role in assessing the reliability of the system during both its design and operational phases. Accurately analyzing and managing this indicator is essential for enhancing the overall reliability of the system.

The calculation of the total system reliability is based on the reliability metrics of its constituent components. The specific computational methodology is determined by the system architecture and its classification. Railway automation systems are categorized into the following classes based on their reliability requirements (Fig. 1):

1. Primary (Base) Systems: Systems that demand high reliability and are directly responsible for ensuring functional safety.
2. Redundant (Reserve) Systems: Systems designed to replace or support the primary system in the event of a component failure.
3. Supportive Systems: Systems that perform auxiliary functions and serve to improve the overall robustness of the operation.

Specific analytical and computational methods are applied to each class to determine and optimize reliability levels. The calculation process utilizes the reliability indicators of individual elements, with the mathematical model being selected according to the system type.

[a] https://orcid.org/0009-0004-4556-0746

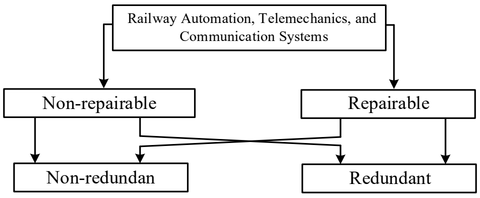

Fig. 1. Classification of railway automation, telemechanics, and communication systems

Redundancy strategies are generally classified into three types: information redundancy, time redundancy, and structural (hardware) redundancy. The system developed in this study is characterized as a structurally redundant and repairable system. The operational dynamics of such systems are modeled based on a discrete-state stochastic Markov process.

The state transition diagram (state graph) of the repairable redundant system is presented in Fig. 2. This graph illustrates the three primary operational states of the system:

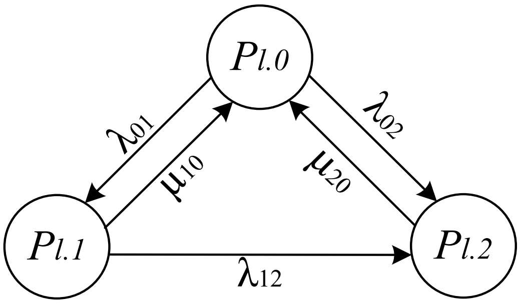

Fig. 2. State transition graph of a repairable redundant system

$P_{l.0}$ – Fully Operational State: The system is fault-free, and all functions are performed according to technical specifications;

$P_{l.1}$ – Partial Failure (Degraded) State: A fault exists within the system (e.g., failure of a redundant component), yet the system maintains its primary functional capacity;

$P_{l.2}$ – Total Failure (Inoperable) State: The system has completely lost its functional capabilities due to critical or multiple component failures.

The transitions between these states are governed by the failure rate (λ) and the restoration (repair) rate (μ), as depicted in the graph.

The state graph of the repairable redundant system, shown in Fig. 2, explicitly illustrates the transitions between system states and the subsequent restoration processes.

The system transitions from one state to another under the influence of failure and repair flows. If all event flows driving these transitions follow a Poisson distribution, the resulting stochastic process is classified as a Markov process. Such a process is mathematically characterized by a system of linear differential equations, known as Kolmogorov equations.

To construct the mathematical model based on the state transition graph, the following formal rules are applied:

1. Derivative of State Probability: The derivative of the probability of a given state is equal to the algebraic sum of the terms associated with all transitions (vectors) connected to that state.
2. Formation of Terms: Each term is defined as the product of the transition intensity (rate of the event flow) and the probability of the state from which the transition originates.
3. Sign Convention: A term is assigned a negative sign if the transition vector originates from the state in question (outward flow), and a positive sign if the transition vector points toward the state (inward flow).

The system of differential equations derived from these rules provides a precise mathematical description of the system's dynamics, enabling a comprehensive analysis of state transitions over time.

$$\frac{dP_{l.0}(t)}{dt} = -\lambda_{01}P_{l.0}(t) - \lambda_{02}P_{l.0}(t) + \mu_{10}P_{l.0}(t) + \mu_{20}P_{l.2}(t); \quad (2)$$

$$\frac{dP_{l.1}(t)}{dt} = \lambda_{01}P_{l.0}(t) - \mu_{10}P_{l.1}(t) + \lambda_{12}P_{l.2}(t); \quad (3)$$

$$\frac{dP_{l.2}(t)}{dt} = \lambda_{02}P_{l.0}(t) + \lambda_{12}P_{l.1}(t) - \mu_{20}P_{l.2}(t). \quad (4)$$

The parameters utilized in the system of differential equations are defined as follows:

- λ_{01} – transition rate from the fully operational state to the partial failure (degraded) state;
- λ_{02} – transition rate from the fully operational state to the total failure state;
- λ_{12} – transition rate from the partial failure state to the total failure state (complete loss of functional capability;
- μ_{10} – restoration (repair) rate from the partial failure state back to the fully operational state;
- μ_{20} – restoration (repair) rate from the total failure state back to the fully operational state;
- $P_{l.0}(t)$ – probability that the device is in the fully operational state at a given time;
- $P_{l.1}(t)$ – probability that the device is in the partial failure state while maintaining operational capacity at a given time *t*;
- $P_{l.2}(t)$ – probability that the device is in the total failure state (inoperable) at a given time *t*.

The aforementioned parameters are instrumental in the modeling and reliability assessment of technical systems. Utilizing these indicators enables a comprehensive analysis of the device's operational performance, as well as the dynamics of transition into failure states and subsequent restoration processes.

Fig. 3. illustrates the structural redundancy scheme for the execution unit block of the railway automation and telemechanics system.

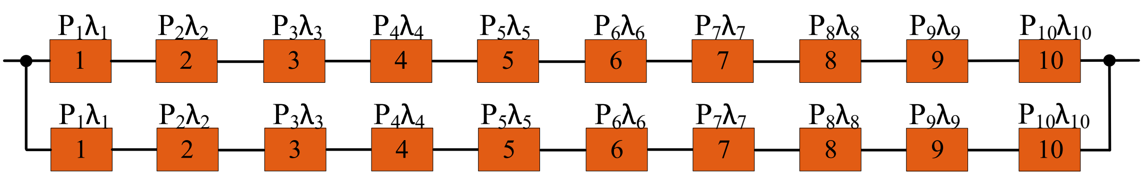

Fig. 3. Structural redundancy scheme of the execution group block units in the automation and telemechanics system

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The probability of failure-free operation of the system is determined by the following formula:

$$P_j(t) = 1 - \left(1 - \prod_{i=1}^{n} P_i(t)\right)^{m+1} \quad (5)$$

Where: $P_j(t)$ – is the probability of failure-free operation of the overall system; $P_i(t)$ – is the probability of failure-free operation of each individual channel; m – is the number of redundant (reserve) units.

The probability of failure-free operation for each branch of a redundant system is equal to the product of the probabilities of failure-free operation of its constituent elements.

$$P_{l.1}(t) = P_i(t) = P_1(t) \cdot P_2(t) \cdot P_3(t) \cdot P_4(t) \cdot P_5(t) \cdot P_6(t) \cdot P_7(t) \cdot P_8(t) \cdot P_9(t) \cdot P_{10}(t); \quad (6)$$

The probability of failure-free operation is determined by equations (4.9) and (4.10).

$$P_{l.1}(t) = e^{-\lambda_{01}(t)}; \quad (7)$$

$$P_{l.2}(t) = e^{-\lambda_{02}(t)}. \quad (8)$$

Using the established mathematical models and the structural redundancy scheme, we determine the failure rates λ_{01}, λ_{02}, $\lambda_{12}$and the state probabilities $P_{l.1}(t)$ va $P_{l.2}(t)$.

$$\lambda_{01} = \lambda_{12} = 256(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + \lambda_6 + \lambda_7 + \lambda_8 + \lambda_9 + \lambda_{10});$$

$$\lambda_{02} = \frac{2 \cdot \lambda_{01}}{3};$$

$$P_{l.1}(t) = e^{-(256(\lambda_1+\lambda_2+\lambda_3+\lambda_4+\lambda_5+\lambda_6+\lambda_7+\lambda_8+\lambda_9+\lambda_{10}))t} = e^{-17{,}213 \cdot 10^{-6} t};$$

$$P_{l.2}(t) = 1 - \left(1 - P_{l.1}(t)\right)^2 = 2 \cdot P_{l.1}(t) - P_{l.1}^2(t) = 2e^{-17{,}213 \cdot 10^{-6} t} - e^{-34{,}426 \cdot 10^{-6} t}.$$

The Mean Time To Failure (MTTF), denoted as T, represents the expected operational time of the system before a total failure occurs. It is calculated by integrating the reliability function over an infinite time horizon:

$$T = \int_0^{\infty} \left(2e^{-17.213 \cdot 10^{-6} t} - e^{-34.426 \cdot 10^{-6} t}\right) dt = 87143 \ soat$$

The correlation between the system's failure probability and its probability of failure-free operation is presented in Fig. 4. The failure rates are detailed in Tables D.3 and D.4.

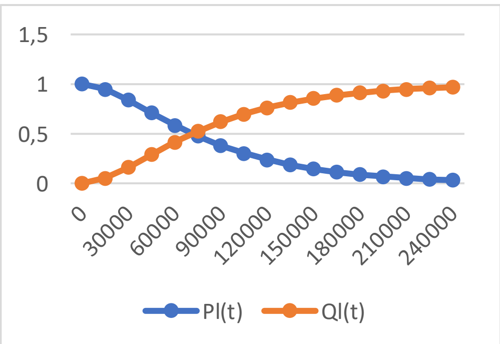

Fig. 4. Graph of $P_{l.2}(t)$ and $Q_{l.2}(t)$ as a function of time

3. Conclusion

This research conducted a comprehensive reliability analysis of the TP62 unit within railway automation and telemechanics systems using structural redundancy and stochastic modeling. The following key conclusions were derived from the study: Mathematical Modeling: A discrete-state Markov process was successfully developed to model the operational dynamics of the system. The use of Kolmogorov differential equations provided a precise mathematical framework to analyze transitions between fully operational, degraded, and failed states. Redundancy Effectiveness: The analysis of the structural redundancy scheme (Fig. 4) demonstrated that implementing a parallel-series architecture significantly mitigates the risk of total system failure. The probability of failure-free operation, $P_{l.2}(t)$, confirmed that redundant channels effectively compensate for individual component malfunctions. Quantitative Reliability Metrics: Numerical calculations revealed that the Mean Time To Failure (MTTF) for the redundant TP62 unit is 87,143 hours. This result indicates a high level of operational stability, equivalent to approximately 10 years of continuous service under standard conditions. Visual Correlation: The established dependency graphs between reliability $P_{l.2}(t)$ and unreliability $Q_{l.2}(t)$ (Fig. 4) provide a vital visual tool for maintenance planning, allowing for the prediction of optimal intervention intervals before the system reaches critical wear-out phases.

In summary, the integration of structural redundancy combined with rigorous Markovian analysis ensures that the TP62 unit meets the stringent safety and reliability requirements of modern railway infrastructure. Future research may focus on the impact of external environmental factors on the failure rate intensities λ to further refine the model.

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Information about the author

Eldor Khujamkulov	Toshkent davlat transport universiteti “Avtomatika va telemexanika” kafedrasi assistenti, E-mail: xujamkuloveldor916@gmail.com Tel.:+998903317209 https://orcid.org/0009-0004-4556-0746

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