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Enhancing the reliability of railway track circuit power supply systems using a microcontroller-based self-checking dual-channel architecture

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Abstract: This article analyzes the types of track circuits currently used at railway stations of Uzbekistan Railways and their distribution. The study is based on operational data collected from 244 stations. Using statistical analysis and diagrammatic visualization methods, the frequency ranges, design characteristics, and application shares of the track circuits were identified, and their operational efficiency was evaluated. The results indicate that 25 Hz and 50 Hz track circuits constitute the dominant share; however, the presence of numerous low-share yet diverse modifications reveals a high level of system fragmentation. This condition complicates operation, maintenance, and modernization processes. The paper substantiates the prospects for standardizing track circuits and modernizing them through the implementation of microcontroller-based power supply and phase-sensitive devices.

Keywords: track circuit, railway signaling, 25 Hz frequency, 50 Hz frequency, modern power supply, phase-sensitive device

1. Introduction

Traffic safety in railway transport directly depends on the reliable operation of signaling and interlocking systems. One of the key elements of these systems, track circuits play a crucial role in detecting train presence and occupancy, route locking, and signal control processes. In railway sections equipped with electric traction systems, the electromagnetic stability of track circuits and their immunity to interference represent particularly important technical challenges.

Within the railway infrastructure of Uzbekistan, track circuits introduced during different historical periods are currently operated simultaneously. This has led to the concurrent use of 25 Hz, 50 Hz, and low-frequency track circuits, as well as the coexistence of various design and functional modifications. As a result, the track circuit system exhibits an uneven distribution of technical solutions and a low level of standardization.

Operational practice shows that the existence of numerous types of track circuits complicates maintenance procedures, expands the range of spare parts required, and reduces the efficiency of diagnostic activities. Therefore, analyzing existing track circuits, determining their actual application share, and substantiating directions for modernization constitute an important scientific and practical task.

Figure 1 presents the distribution of track circuit types used at railway stations of Uzbekistan Railways, clearly reflecting the current state of the system.

Distribution of Track Circuits at Railway Stations of Uzbekistan Railways

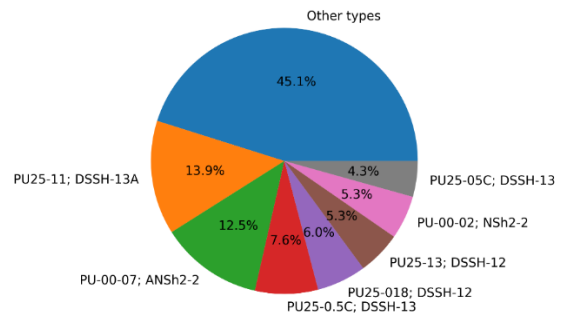


Fig. 1. Distribution of track circuit types at railway stations of Uzbekistan Railways


The main objective of this study is to conduct a statistical analysis of the track circuits used at railway stations of Uzbekistan Railways, evaluate their technical diversity, and examine the feasibility of integrating the functions of power supply and phase-sensitive devices into a unified microcontroller-based unit. The paper also discusses the technical advantages of the proposed solution.

2. Research methodology


In this study, taking into account the technical diversity of track circuits currently used at railway stations of Uzbekistan Railways and the operational characteristics of their supporting equipment, a modern solution was developed that integrates power supply and phase-adjustment functions within a single microcontroller-based unit. The methodology is based on analyzing existing conventional solutions and proposing a new architecture aimed at overcoming their functional limitations.

First, the widely used single-channel track circuit power supply and phase-adjustment system was analyzed from a functional perspective. This configuration represents the

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classical solution that has been employed in railway signaling systems for many years.

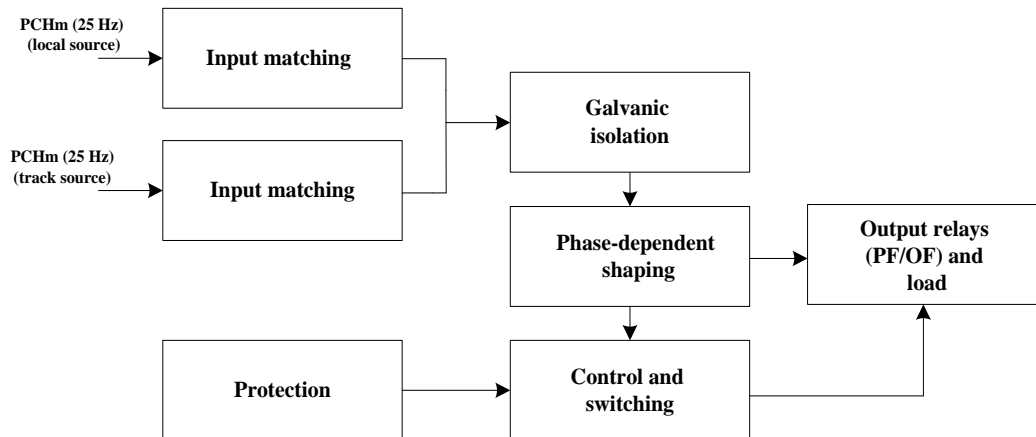


Fig. 2. Functional diagram of a single-channel track circuit power supply and phase-dependent control system

In this configuration, the 25 Hz signal is received from local and track sources and normalized in the input matching units according to electrical parameters. At the next stage, the signals are isolated from the control circuits through galvanic separation, thereby limiting the adverse effects of electromagnetic interference and overvoltages.

The phase-dependent shaping unit evaluates the phase state of the signal in accordance with the classical operating principle of the FU3 device and ensures that the necessary conditions are met for phase-sensitive track receivers. Through the protection, control, and switching units, the PF/OF relays are energized only under permitted conditions, allowing the 25 Hz signal to be transmitted to the track circuit.

Although this solution is structurally simple, the presence of a single signal path means that a failure can lead to the shutdown of the entire system.

To overcome these limitations, the study proposes a self-diagnostic dual-channel architecture with extended diagnostic capabilities, integrating the functions of the PCH50/25 frequency converter and the FU3 phase-adjustment device on a microcontroller-based platform.

Figure 2 presents a microcontroller-based unit designed for railway track circuit power supply systems using a self-checking dual-channel (redundant) architecture. This architecture integrates the PCH50/25 frequency conversion function and the FU3 phase-sensitive control algorithm within a single system, aiming to ensure a high level of functional safety and reliability.

Each of the A and B channels incorporates an internal self-monitoring scheme. These schemes continuously supervise the operational state of the microcontroller, computational processes, memory and input/output interfaces, as well as the correct execution of the FU3 phase-control algorithm.

The internal monitoring mechanisms are implemented at both the hardware level (supply voltage, output signal

parameters, relay status) and the software level (watchdog timers, logical verification routines, and timing constraints). If a fault or deviation from permissible limits is detected in one of the channels, that channel is automatically blocked, and the system prepares to transition to a safe state.

The output signals and monitoring data generated by both channels are transmitted to an inter-channel supervision and comparison unit. The primary function of this block is to determine the consistency between the signals produced by channels A and B, detect discrepancies or fault indications, and activate the appropriate protective measures.

Based on the results of the inter-channel comparison, the system identifies which channel remains reliable or, if necessary, completely blocks the output to ensure a safe operating condition.

At the system output stage, a safety comparison and output conditioning unit is implemented. This block transmits control signals to the output relays (PF/OF) and the load only when the signals received from channels A and B are fully consistent. If a fault is detected in at least one channel or an inter-channel discrepancy occurs, the output is automatically switched to a protected (fail-safe) state, preventing the transmission of a hazardous signal to the track circuit.

The proposed self-checking dual-channel architecture has been developed in accordance with the high reliability, continuous operation, and stringent safety requirements characteristic of railway signaling systems. The presence of internal and inter-channel monitoring mechanisms, together with a safe output stage, significantly enhances the operational stability of the system.

As a result, the dual-channel system integrating the functions of the PCH50/25 and FU3 devices on a microcontroller-based platform can be regarded as a modern, reliable, and technically promising solution for the power supply and control of track circuits.



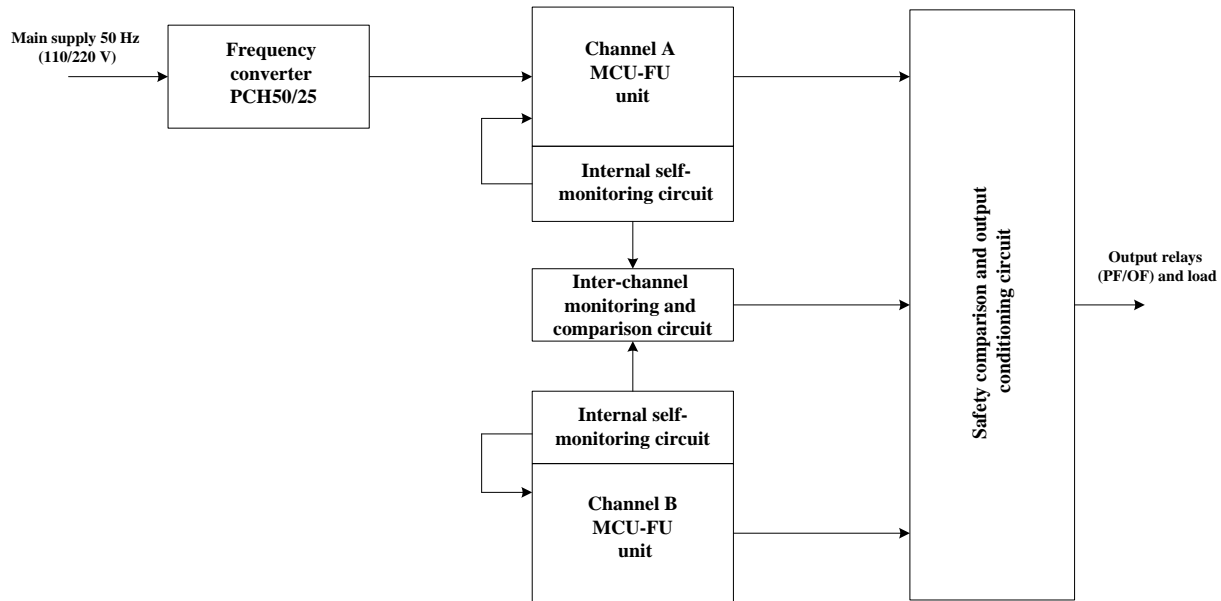


Fig. 2. General structure of a microcontroller-based self-checking dual-channel track circuit power supply and phase control system

3. Results and discussion

The effectiveness of the proposed microcontroller-based self-checking dual-channel track circuit power supply and phase-control solution was evaluated through both quantitative and qualitative comparison with a conventional single-channel system. The evaluation considered system reliability, probability of continuous operation, and the likelihood of failure as the primary criteria. The analysis was based on the structural approach and active diagnostic algorithms described in the methodology section.

A single-channel track circuit power supply system can be considered as a set of functionally connected blocks arranged in series. For such a system, the overall reliability function is determined by the product of the reliabilities of the individual blocks:

$$R_{SC}(t) = \prod_{i=1}^N R_i(t) \quad (1)$$

Where: $R_{SC}(t)$ — single-channel system reliability, $R_i(t)$ — reliability of the i -th functional block, N — number of functional blocks.

Assuming a constant failure rate for electronic power supply and phase-adjustment devices, the reliability of each block can be described by an exponential law:

$$R_i(t) = e^{-\lambda_i t} \quad (2)$$

As a result, for a single-channel system:

$$R_{SC}(t) = e^{-(\sum_{i=1}^N \lambda_i) t} \quad (3)$$

This expression shows that the failure of a single functional block leads to the failure of the entire system. This mathematically confirms the principal drawback of single-channel architectures — the presence of a single point of failure.

In the proposed dual-channel solution, the power supply and phase-control functions are implemented in parallel through two independent channels. Such a system can be considered a parallel redundant structure, and its reliability is determined as follows:

$$R_{DC}(t) = 1 - [1 - R_A(t)][1 - R_B(t)] \quad (4)$$

If both channels have identical parameters:

$$R_A(t) = R_B(t) = R_c(t) \quad (6)$$

then:

$$R_{DC}(t) = 1 - [1 - R_c(t)]^2 \quad (7)$$

when the reliability of each channel is expressed by an exponential law:

$$R_c(t) = e^{-\lambda t} \quad (8)$$

reliability of the self-checking dual-channel system:

$$R_{DC}(t) = 1 - (1 - e^{-\lambda t})^2 \quad (9)$$

takes the following form. For any $t > 0$:

$$R_{DC}(t) > R_{SC}(t) \quad (10)$$

the inequality holds, which means that the superiority of the dual-channel system has a rigorous mathematical basis.

To obtain a quantitative estimate of the reliability advantage, the failure rate $\lambda = 1 \times 10^{-5} \text{ hour}^{-1}$ and the operating time $t = 10000 \text{ hours}$ were assumed.

for a single-channel system:

$$R_{DC}(10000) = 1 - (1 - 0.905)^2 = 0.991 \quad (11)$$

that is, the probability of continuous operation reaches 99.1%.

The proposed solution also incorporates an active diagnostic mechanism, characterized by a fault detection probability of P_d . When diagnostics are taken into account, the effective reliability is determined as follows:

$$R_{DC}^*(t) = 1 - (1 - R_c(t))^2 (1 - P_d) \quad (12)$$

If it is assumed that $P_d = 0.9$:

$$R_{DC}^*(10000) = 1 - 0.009 \cdot 0.1 = 0.9991 \quad (13)$$

This result indicates that the probability of failure occurrence is reduced by more than two orders of magnitude compared with a single-channel system.



Table 1

Reliability comparison of single-channel and dual-channel architectures

Parameter	Single-Channel	Dual-Channel	Dual-Channel with Diagnostics
Failure rate, λ (h^{-1})	1×10^{-5}	1×10^{-5}	1×10^{-5}
Operation time, t (h)	10 000	10 000	10 000
Reliability, $R(t)$	0.905	0.991	0.9991
Failure probability, $1-R(t)$	0.095	0.009	0.0009
Relative improvement	–	$\approx 10 \times$	$\approx 100 \times$

The quantitative evaluations presented in Table 1 demonstrate that, under identical failure rates and operating conditions, the use of a dual-channel architecture significantly reduces the probability of interruptions in the track circuit power supply and phase-control system. In particular, the implementation of hardware-level parallel redundancy eliminates the single point of failure inherent in single-channel systems and reduces the probability of failure by approximately an order of magnitude. This substantially increases the system's continuity of operation and ensures stable performance of the track circuit.

Moreover, the application of microcontroller-based active diagnostic algorithms further elevates system reliability. Early detection of faults and the automatic isolation of the faulty channel reduce the probability of interruption by an additional order of magnitude. As a result, the overall effective reliability increases by up to two orders, fully meeting the stringent safety and continuous operation requirements imposed on railway signaling systems.

At the same time, such an approach not only ensures a high level of technical reliability but also improves the efficiency of diagnostics, maintenance, and fault detection during operation. This provides both scientific and practical justification for the implementation of redundant, diagnostic-enabled architectural solutions in the modernization of track circuit systems.

4. Conclusion

This study analyzed the technical diversity and operational challenges of track circuits currently used at railway stations of Uzbekistan Railways and proposed a microcontroller-based, self-checking dual-channel power supply and phase-control solution aimed at their modernization. The quantitative and qualitative analyses demonstrated that conventional single-channel track circuit power supply systems contain a single point of failure and, from the standpoint of continuous operation requirements, cannot fully meet the needs of modern railway signaling.

The proposed self-checking dual-channel architecture, combining parallel redundancy with microcontroller-based active diagnostic mechanisms, significantly improves system reliability. Numerical evaluations show that, under identical failure rates and operating conditions, the probability of interruption decreases by one order of magnitude, and by up to two orders when diagnostics are applied, which is mathematically substantiated. These results confirm the high effectiveness of the proposed approach in ensuring continuous operation of track circuits and enhancing traffic safety.

In addition, integrating power supply and phase-control functions within a single microcontroller-based unit reduces the fragmented nature of track circuit systems, simplifies diagnostics and maintenance procedures, and creates the

conditions for gradual standardization. As a result, the proposed solution can be considered a technically and economically viable option for modernizing existing railway infrastructure without fundamental structural changes.

Overall, the findings of this work substantiate the prospects of applying microcontroller-based dual-channel power supply and phase-control devices in railway track circuit systems and provide a scientific and practical foundation for the development of highly reliable, flexible, and standardized signaling solutions in the future.

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G. Samatov, B. Kholmatov, I. Absattorov

The location of transport and logistics centers in Uzbekistan included in the list of international dry ports: regional opportunities and their integration with international transport corridors66

M. Mamatkulov, A. Yuldashev

Ecology and roads: environmental impact of road transport and sustainable solutions80

E. Tokhirov, R. Aliev, M. Aliev

Methods and solutions for reducing the amount of dust in order to ensure the sustainability of cities84

E. Tokhirov, R. Aliev

Details and solutions to safety issues at railway LC89

Z. Adilova, S. Asenova, M. Yokubjonov, A. Sadikova

Selection of a method for market segmentation in the field of transport and logistics services96

S. Boltaev, Z. Toshboev, I. Yoldashev, B. Ganijonov, Sh. Kholboev

Enhancing the reliability of railway track circuit power supply systems using a microcontroller-based self-checking dual-channel architecture101

M. Karimova, R. Bozorov, E. Asatov

Analysis of the freight transportation technology efficiency on the “Bukhara – Miskin” and “Angren – Pap” railway lines106