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RESEARCH, INNOVATION, RESULTS

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Optimization of the response time of microprocessor-based protection devices in phase-sensitive railway track circuits

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Abstract: Phase sensitive track circuits are very critical in the railway automation system and rely on the quick protection of track transformers against overload and short circuit faults. The traditional electromechanical circuit breakers (AVM-1, AVM-2) have large mechanical inertia, which results in slower fault isolation. In this paper, an optimized protection device (AVM-MP) based on a microprocessor is presented that overcomes the drawbacks of traditional mechanical protection devices and the preliminary digital prototypes. The first microprocessor designs incorporated the Hall-effect sensor to suit the ACS712, but were found to have several disadvantages: 5V to 3.3V logic level incompatibility, increased noise and limited bandwidth of 80 kHz. In response, the proposed architecture has an advanced ACS724 sensor that is easily compatible with the 3.3V logic of the dual-core ESP-32 microcontroller. The optimized system, which includes a dynamic current-derivative (di/dt) fault detection algorithm, provides a bandwidth of 120 kHz and removes voltage-divider noise. Results from the experimental test and simulation using virtual show that the response time of the sensor is decreased to less than 4µs, which makes it possible to detect and isolate any transient faults early (under 1.2ms). This quick response time also helps to avoid thermal damage to the transformer windings, significantly extending the operational lifespan and safety of the railway signaling system.
Keywords: Phase-sensitive track circuits, microprocessor protection, Hall-effect sensor, ACS724, fault detection, time-current characteristic, predictive maintenance, IIoT, Railway automation

1. Introduction

Reliability of signaling, centralization of signaling, and blocking (SCB) systems is fundamental in the absolute safety and uninterrupted operation of railway rolling stock [1]. Now 64% of stations inside the infrastructure are equipped with a control system, either electrical interlocking (EC) or route-relay interlocking (RRI). Phase-sensitive track circuits therefore carry out the critical function of on-going train tracking and monitoring of whether or not a block section is vacant within the infrastructure. These phase-sensitive circuits are tied to the track transformers and their operational stability is a crucial factor in the operational stability of the circuits [2, 3]. In railway distribution networks, however, there are often severe electromagnetic transients and short circuits that cause rapid degradation of the transformer insulation and create critical train schedule disruptions [4].According to the statistical analysis, the protection of track transformers from such overloads has been traditionally provided by electromechanical circuit breakers with bimetallic thermal elements such as AVM-1 and AVM-2 series introduced in the 1980s [5]. These are commonly used but, due to their mechanical inertia, their trip time during high current transients is as much as 100-150 ms which means that the initial short circuit (SC) shock is not being protected against by these devices. In view of these new deficiencies, recent research work strongly recommends the modernization of railway automation based on the use of microprocessor-based control. From the experience of countries with a more sophisticated railway transport, the ESP32 dual-core microcontroller with Industrial Internet of Things (IIoT) capability is being extensively employed as an extremely effective tool for such duties [6, 7]. Previous research in the field of basic protection of railway automation has suggested the conceptual design of an intelligent microprocessor-based protection device [8].Use of Hall-effect sensors in conjunction with microcontroller is highly recommended on Uzbekistan Railways, especially in 25 Hz phase-sensitive track circuits with DSSH-13/16 relays, for fast measurement of track circuit currents, and for fast selective protection of track transformers. In the first attempts to digitize AVM systems, the standard sensors were used in the system design [9,10]. This method did not require any mechanical moving parts, but on the hardware side there were serious bottle necks. The main problem is that the ACS712 sensor needs to be powered with 5V, while modern microcontrollers require 3.3V. This discrepancy is compensated with resistive voltage dividers which add a great deal of noise and distortion to the system readings by the Analog-to-Digital Converter (ADC). In addition, it was noted that the sensor is sensitive to the magnetic noise from the railway, which leads to errors in the current measurements obtained [11].In practice, this technological gap is addressed in the authors' prior work on real-time monitoring of track transformers and further solidifies the positive results of this. This paper presents an optimized design of AVM-MP based on the advanced, 3.3V compatible sensor, which is used in the latest automotive industry and has gained the **AEC-Q100** quality certification [9,12]. The primary goal of this study is to make a comparative analysis of the dynamics of the sensors, and to show that the 1st level of the proposed 2-level protection algorithm, i.e., the dynamic *di/dt* condition, can intelligently activate the protection mechanism and isolate the short circuit at its most incipient stage (less than 1 ms).

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2. Research methodology

Scientists of Tashkent State Transport University-A. Azizov, E. Ametova, J. Kudratov prepared a preliminary prototype of the protection device with an intelligent microprocessor control based on the new two-level protection model. The prototype was going to be built around the ESP32-WROOM-32 dual core microcontroller as its logical base or “brain”. One of the microcontrollers distinguished by its high clock frequency (240 MHz), which renders an ability to perform the real time analysis of ultra fast transient processes in phase-sensitive track circuits, also called PSTC [13].

But there were several issues in the first prototype that prevented it from accurately measuring the current value in the PSTC and quickly sending it to logical analysis through the ADC. The sensor used in the measuring unit, ACS712, was much more convenient than the already available AVM-2 sensor devices and offered the possibility of easy integration into digital systems. However, steady magnetic interference from the railway prevented the accurate measurement of the current and its speedy transfer to the logical analysis unit of the device. This resulted in the triggering of the 1st level (short circuit) protection being delayed.

The first phase of the methodology is to change the functionally obsolete ACS712 current sensor to the ACS724 current sensor with higher technical parameters. The ACS724 sensor has been tested to the international standard AEC-Q100 that ensures high reliability under high levels of electromagnetic interference and mechanical vibrations common to the railway environment [14, 15]. The primary benefit of the ACS724 from a methodological point of view is that it runs at a 3.3V logic level. This enabled it to be connected directly to the analog-to-digital converter (ADC) of the ESP32 microcontroller without the need for extra noise generating resistor voltage dividers. In such a configuration, measurement errors are minimized and it also yields a very high bandwidth of up to 120 kHz, which is useful to capture the high frequency harmonics of the fault current with a high degree of accuracy [16].

2.2. Synthesis of the Two-Level Digital Protection Algorithm.

The effective protection of the track transformer is carried out according to the two-step logical condition of the method. This algorithm has been developed in particular to separate normal operational noise (e.g. inrush currents) from actual fault events.Level 1: Dynamic analysis of the position *di/dt*. In this stage, instead of the actual magnitude of current, the system computes the change of current with time (its derivative). When $(di/dt) > (di/dt)_{kr}$, the algorithm will dynamically sense the beginning of a short circuit and send a disconnect signal in less than 1ms [17]. Note the following level 2 digital filtering and thermal monitoring. The exponential moving average (EMA) methodology was used to analyse the temporary overloads that occur naturally during train movement and is given by (1):

$$I_f[k] = \alpha \cdot I_{raw}[k] + (1-\alpha) \cdot I_f[k-1] \quad (1)$$

In this expression, $\alpha = 1 - e^{-\Delta t/\tau}$ is the smoothing coefficient and $I_f[k]$ and $I_f[k\text{-}1]$ are the noise-cleared signals at the steps k and k-1 respectively, while $I_{raw}[k]$ is the raw signal acquired from the sensor[18].

$$\frac{di}{dt} \approx \frac{I_f[k] - I_f[k-1]}{\Delta t} \quad (2)$$

Using the above formula (2), we obtain the equality of a change of current in the case of determining the digital state of the track transformers[19]. In this equation, $\boldsymbol{\Delta}$t given in the denominator represents the sampling period, which is the time interval between two consecutive steps (3).

$$\Delta t = \frac{1}{f_s} = \frac{1}{10000\ \text{Hz}} = 0.0001\ \text{s} = 0.1\ \text{ms} \quad (3)$$

2.3. A conceptual model of the AVM-MP.

Device was created in order to show the logic of the system in operation. This model covers the entire signal flow from the sensor to the Analog-to-Digital Converter (ADC) to the microcontroller's dual core processor for analysis, and finally to execution through a Solid State Relay (SSR). Moreover, in the context of this conceptual model, the methodology proposes to collect the data stream and automatically transfer it to the Signaling Dispatcher (ARM-ShD) in real time through IIoT technologies (Figure 1).

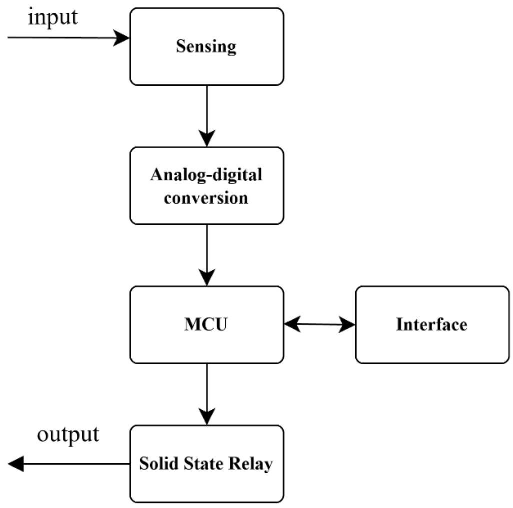

Fig. 1. Simplified conceptual model and signal flow block diagram of the AVM-MP system

3. Results and Discussion

3.1. Current Sensing Devices and Comparative Analysis of Current Sensing Technologies and Protection Devices.

The sensors' dynamic response and measurement accuracy is a key factor in rapid fault detection. Analyses conducted showed that the use of the resistive voltage divider as a connection method of the ACS712 sensor to the modern ESP32 microcontroller, which was used in the first prototypes, has a significant impact on the deterioration of the signal-to-noise ratio (SNR) [20]. The optimized AVM-MP system, on the other hand, connects the ACS724 sensor directly with ESP32 at the native 3.3V logic level with maximum signal integrity [21]. In addition, it was demonstrated that the wider bandwidth of the ACS724 sensor up to 120kHz is necessary to collect the high frequency transient components of short circuits (SC) in phase-sensitive track circuits [22].

3.2. Dynamic Time-Current Characteristics Analysis of the 2-Level Protection Algorithm.

The proposed two-level digital protection algorithm performance and reliability were tested by virtually modelling zero-impedance short circuit conditions. The analyses show that there is a need to extend the protection to ultra-fast protection for short circuit. The proposed AVM-MP intelligent protection device was analyzed in the tripping processes under various fault conditions.

The current-time dependence graph during the activation of 1st level protection of the traditional electromechanical AVM-2 and the proposed microprocessor based AVM-MP protection is shown in Figure 2 under a zero-impedance short-circuit (SC) condition. During this ultra fast transient process, the current is much higher than the nominal value. The graph shows the points *k* and (*k−1*), which are the discrete digital samples taken by the microcontroller of the continuous signal. The system is designed to analyze the growth gradient at the current (*I[k]*) and previous (*I[k−1]*) measurement point across a time interval Δt to determine the current growth gradient (*di/dt*) [23]. If this difference is greater than the threshold, the algorithm will detect the SC at the earliest stage and sends the trip command (TRIP-1) immediately in 0.8–1.2 ms. The mechanical inertia of the traditional bimetallic element introduces a delay in the trip time of 100-150ms, while the reaction of the AVM-MP is only 1ms which fully eliminates the possibility of thermal degradation of the transformer windings.

The system response to an overload regime is shown in picture 3 as the activation graph of the 2nd level protection. The current surge is not high enough to set the 1st level protection when train movement starts or when the transformer is loaded with excessive loads for a prolonged period of time. In this case, the algorithm will be continuously adding the current values at each discrete point k based on an exponential moving average (EMA) filter. The following graph illustrates that, when the present magnitude is greater than the set thermal limit I_{kr} t is the time period when and and remains for some amount of time limit.

Fig. 2. Time-current characteristic graph of the 1st level protection activation

Fig. 3. Time-current characteristic graph of the 1st level protection activation

The system performs a 2nd level trip (TRIP-2) to avoid thermal degradation of the transformer.

3.3. Integral Indicators and Multi-Dimensional Comparison.

A multi-dimensional qualitative and quantitative analysis was used to comprehensively assess the operational efficiency of current AVM-2 and the proposed AVM-MP devices [24,25]. The traditional AVM-2 device can't change the nominal current 5 A and has a fixed trip limit of 7 A, whereas the AVM-MP system offers real-time software adjustable nominal current and trip limit (0 - 50 A).

The radar chart analysis was conducted using integral evaluation criteria (thermal endurance, SC trip speed, current range, 2.1 kV galvanic isolation and the presence of a digital monitoring). The qualitative indicators used were awarded a higher point by the intelligent AVM-MP device than by the legacy AVM-2, with an average of 9.2 points compared to 2.5 points for the legacy AVM-2, thus proving its absolute technological and operational superiority picture 4.

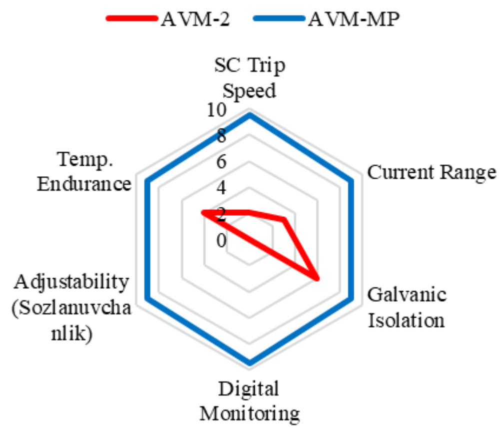

Fig. 4. Radar chart analysis of the quality indicators for the traditional AVM-2 and the proposed AVM-MP devices

3.4 Analysis of Operational Stability and Information Integration

Under the research scope, the sensitivity of the traditional protection device and the proposed protection device to the ambient temperature were compared. The Bimetallic strips used in the devices AVM-2 are degraded in extreme climatic conditions in Uzbekistan, where during the summer period the temperature in railway relay cabinets often exceeds +50°C, which affects their physical and mechanical properties. This degradation consequently results in device failure and in high number of unprovoked false trips within the system. In contrast, the solid-state design of the AVM-MP based on the AEC-Q100 qualified sensors and ESP32 microcontroller is completely immune to thermal ambient changes. It is absolutely stable over a wide range of temperature from -40°C to +85°C and is suitable for severe climatic operations. In addition, the system's intellectual ability is greatly enhanced with the incorporation of Industrial Internet of Things (IIoT) innovations. The AVM-MP device not only cuts the electrical circuit, but also has the ability to transfer the monitoring data in real-time to the Automated Workstation of the Signaling Dispatcher (ARM-ShD) and store one month of monitoring data in its internal memory. This diagnostic feature will enable detecting hidden defects in the infrastructure at an early stage of their life before they become critical, laying a solid basis for the implementation of predictive maintenance in the railway automation network as a whole.

4. Conclusion

Based on the study, an intelligent microprocessor-based protection device (AVM-MP) was successfully developed and theoretically validated to replace the existing electromechanical AVM-2 circuit breakers in railway phase sensitive track circuits. For the first time the critical 3.3V logic-mismatch problems of previous prototypes were overcome by making the transition to the AEC-Q100 certified ACS724 sensor, which enabled reliable measurement bandwidth expansion to 120 kHz and hardware response time was reduced to less than 4 µs. A novel two-level digital protection algorithm was implemented: dynamic di/dt for instantaneous short-circuit protection and an Exponential Moving Average (EMA) filter for sustained overloads, and this was extremely successful. Virtual simulation results were also obtained showing that the AVM-MP can detect and isolate zero impedance faults in less than 0.8–1.2 ms, which is much faster than the detect and isolate time of a traditional bimetallic system of 100–150 ms. This fast fault clearing action prevents a thermal degradation of the track transformer windings and thus significantly enhances the reliability and safety of the signaling system as a whole. Moreover, the integration of IIoT capabilities enables real-time data transmission to the centralized Automated Workstation of the Signaling Dispatcher (AW-SD), facilitating predictive maintenance and substantially reducing both operational and lifecycle costs.

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