Scientific Journal of Silesian University of Technology. Series Transport
Zeszyty Naukowe Politechniki Śląskiej. Seria Transport

Volume 118 **2023**

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: https://doi.org/10.20858/sjsutst.2023.118.7

Journal homepage: http://sjsutst.polsl.pl

Article citation information:
Hełka, A., Wall, M. Measurement and analysis of the performance of the PVP-20 slip detection device. *Scientific Journal of Silesian University of Technology. Series Transport*. 2023, **118**, 93-108. ISSN: 0209-3324. DOI: https://doi.org/10.20858/sjsutst.2023.118.7.

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MEASUREMENT AND ANALYSIS OF THE PERFORMANCE OF THE PVP-20 SLIP DETECTION DEVICE

Summary. One of the most critical elements ensuring the proper operation of locomotives are devices that detect and eliminate slipping, especially during the start-up of the locomotive in difficult operating conditions. Various types of slip control systems and methods are used on traction vehicles, depending on the design of a given locomotive and the assumptions made related to the functionality of a given solution. This article describes the PVP-20 type slip detection device used in many older electric locomotives. A proprietary measuring system was developed, enabling it to be connected to the locomotive circuit, to perform measurements in conditions of large disturbances and high voltages prevailing on the electric locomotive. Using this measuring system, the PVP-20 device was tested under operating conditions for the ability to detect slips. It has been shown that the described device is highly insensitive. Hence, we propose our concept for solving this problem.

Keywords: slip detection and prevention, slip control system, locomotive start-up and operation in slip conditions

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1. Introduction

One of the most crucial parameters characterizing traction vehicles is the maximum power and curb weight, determining the possibilities of increasing the speed of travel for passenger trains and the gross weight of trains running on the railway network. In today's economic conditions, these two parameters are fundamental for railway operators. Locomotive power is directly translated into tractive force generated on the circumference of the driving wheels of the vehicle. However, the factor that has the greatest impact on limiting this force is the reduction in the value of the coefficient of adhesion between the wheel and rail at the point of their cooperation. The higher the value of the coefficient of adhesion, the greater the force can be generated without macro-slip. However, it should be noted that a slip can be considered a micro-slip (elastic slip) and a macro-slip [5]. At the same time, we demonstrate in this article our interest in the phenomenon of macro-slip, that is, when the traction vehicle wheels slide into full slip. Analyzing the forces and phenomena occurring between the traction vehicle wheel and the rail during start-up and while driving [5, 15] for slipping, we noticed that there are various reasons for the occurrence of this unfavorable mechanism. Situations conducive to slipping occur under certain operating conditions, for example, during the start-up of a locomotive, when the vehicle has a heavy train of wagons fastened on the hook and in difficult weather conditions: rain, snow, leaves fall on the tracks, etc. An additional unfavorable factor may be the situation when starting takes place on a section with a high slope (uphill); for example, the wheel running surface and the surface of the railhead at a given moment are characterized by a lower than normal coefficient of friction. Also, while driving the locomotive, slipping may occur when, for example, at a given moment, we increase the tractive force above the adhesion curve, causing the slipping of the driving wheels [5]. However, such cases occur because modern locomotives are designed in such a way that the drivers mounted on them enable the control of the drive so that the maximum power of the vehicle is used to the full by appropriate control of the coefficient of adhesion and slip speed [3, 5, 7].

As a result of the occurrence of wheel slip, apart from the reduction of tractive force, several unfavorable phenomena occur on the surface of wheels and rails. The so-called "flat spots" are formed on the wheel tread surface, necessitating the re-profiling (rolling) of such a wheel, which generates significant costs. In addition, in such a wheel, there are certain dangerous phenomena related to overheating of the material, which may be dangerous for further operation. On the other hand, on the surface of the rails, there is a defect called "buckling", which is dangerous from the viewpoint of further operation and causes costs related to the repair or replacement of the rail.

Therefore, the issues related to the detection and elimination of slips are critical in rail transport, hence many studies are carried out, and various solutions are introduced to monitor and prevent such phenomena. This is achieved by installing various types of devices and systems on traction vehicles. The type of drive and control used on a given locomotive is of fundamental importance for the applied solutions. In the literature, one can find various descriptions and criteria for classifying the slip control solutions used on locomotives. Exemplary solutions have been divided in the literature [12, 13, 17] into different groups of slip control methods: based on the control of the slip speed, based on the full use of the friction coefficient characteristics, based on the speed control of wheels and motors, based on work at a specific point of the adhesion characteristic and slip, as well as indirect and hybrid methods. The individual solutions for the method of operation, simulations, and calculations carried out, as well as practical applications, are presented in detail in works [1, 4, 9-11, 14, 16, 19, 20].

As mentioned, systems related to slip control are largely dependent on the applied drive and control on a given locomotive. For locomotives with DC series motors, traction motors and vehicle gears may be damaged due to uncontrolled slipping from exceeding the maximum speed. During start-up, when the developing slip is not detected, the motor may "run", and then a circular fire is created on the commutator, leading to the burning of its sections and winding. In such cases, the increase in rotational speed results in the mechanical destruction of the engine. This is another argument emphasizing the importance and necessity of using anti-slip devices in traction vehicles.

This article focuses on the PVP-20 anti-slip device used on 303E, 203E, and 201E vehicles (PKP series EU07, ET41 and ET22, respectively). The locomotives of this series are locomotives with resistance starting, using direct current motors for propulsion. For the largest freight carrier in the country, PKP CARGO S.A., vehicles of this type account for almost 95% of all electric locomotives with a valid certificate of technical efficiency. As mentioned above, due to the drive characteristics in these types of locomotives, there may be serious effects on the effective starting of the train in the event of the occurrence and development of uncontrolled spinning of the sets. That is why it is so important to use an effective anti-slip device.

The purpose of this article is to present the measurements made and analyze them for the effectiveness of the PVP-20 drive wheel slip detection solution used on the above-mentioned locomotives. These tests were conducted using a self-developed and self-made measuring system that allows for these types of measurements in difficult conditions prevailing on an electric locomotive related to interference and high voltages. The presented measurements are intended to demonstrate the real efficiency and sensitivity of PVP-20 relays in the most critical situation of train starting - starting in unfavorable weather conditions and with limited adhesion. After analyzing the results, a design change to increase the effectiveness of the existing solution was proposed.

2. SLIP DETECTION DEVICE PVP-20

As mentioned, PVP-20 anti-slip relays are used in locomotives type 4E/303E (EU07), 203E (ET41), 201E (ET22) and derivatives. They are connected to the main circuit of the vehicle in a bridge system; therefore, one relay works with a pair of traction motors. The exception is the six-axle locomotive type 201E (ET22 series), which has only two PVP-20 relays. The relay protects motors 1, 3, 4 and 6 – motors 2 and 5 do not have this protection. This is due to the connection systems of the traction motors that are implemented on the ET22; motors no. 2 and 5 are connected in series only on the third (the last one when starting up) motor connection system.

In locomotives, usually, a set of two PVP-20 devices is mounted on a common insulating plate, which is placed in the high voltage compartment. The relay is made of a coil with a magnetic circuit used to drive the device, fixed and moving contacts and the anchor. At one of the ends of the anchor, there are movable contacts; the anchor itself is kept in its rest position by a spring, which also serves to adjust the setting of the relay operation. The fixed contacts are located on top of the insulating plate and in the relay's de-energized state; they have no contact with the moving contacts.

The mode of operation of the relay is shown in Figure 1. During normal operation, the rotors of S1 and S2 traction motors rotating at the same speed do not create a potential difference between points A and B. When the slip occurs, one of the motors rotates at a higher speed and generates a greater electromotive force - there is a higher voltage at its terminals. For example, a slip of the set connected to motor S2 will result in a higher voltage between points B and D than between points C and B. Since the upper branch of the system (set of R_o resistors) symmetrically divides the total voltage drop between points C and D, a potential difference U_p is created on the terminals of the PVP-20 relay coil (points A and B), forcing the current to flow.

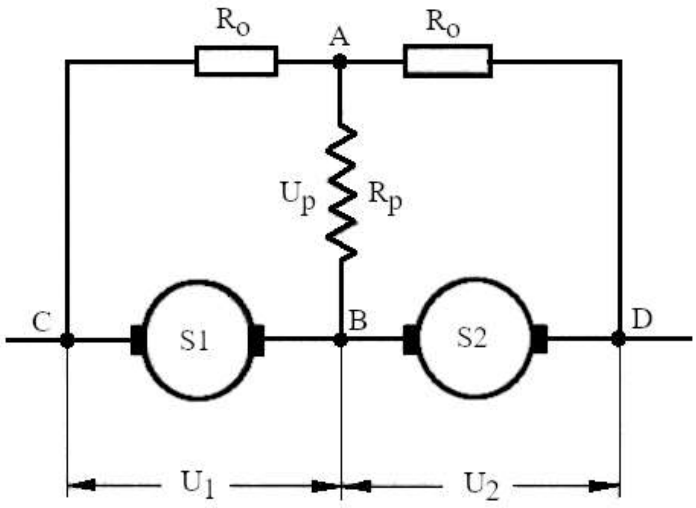

Fig. 1. Connection system of the anti-slid relay [8]

If the value of the voltage difference is greater than the operating voltage of the relay, the anchor is attracted by the electromagnet and connects the fixed and movable contacts. These contacts activate the appropriate low voltage systems (110 V), such as light and sound signals in the driver's cabins, sandblasting of wheelsets and the solenoid valve for braking the anti-slip disengagement valve of the Oerlikon system, which forces compressed air with a value of about 0.01 MPa to the brake cylinders. The relay opens its contacts when the voltage on the U_p coil drops to 40 V.

Additionally, in locomotives of this type and their derivatives, a system of adjusting the forces to axle loads is used to reduce the possibility of the first sets slipping in the direction of travel. The system works by partially weakening the excitation of the motors driving the axles most exposed to unloading at start-up. Before starting the start-up, the driver activates the system with the packet switch or by setting the directional switch to the N1 position (depending on the vehicle type). The adjustment of the forces is performed only on the serial system of engine connections, and more importantly, it automatically disconnects the signaling of the operation of anti-slip relays. This is due to how the above-mentioned relays detect wheel spinning.

3. CONDUCTED MEASUREMENTS

This section presents the structure and operation of the measuring device as well as the methodology of its calibration. The measurement results and their interpretation are given below.

3.1. Measuring device

The construction of the measuring device is based on two Arduino Due boards (ARM Cortex-M3 microcontroller), both equipped with a radio communication module. The first one is the base for the transmitter, and the second one works as a receiver. The general diagram of the transmitting device is shown in Figure 2. The receiver is connected to a PC, where the data is saved to a file. The transmitter is powered by a portable battery.

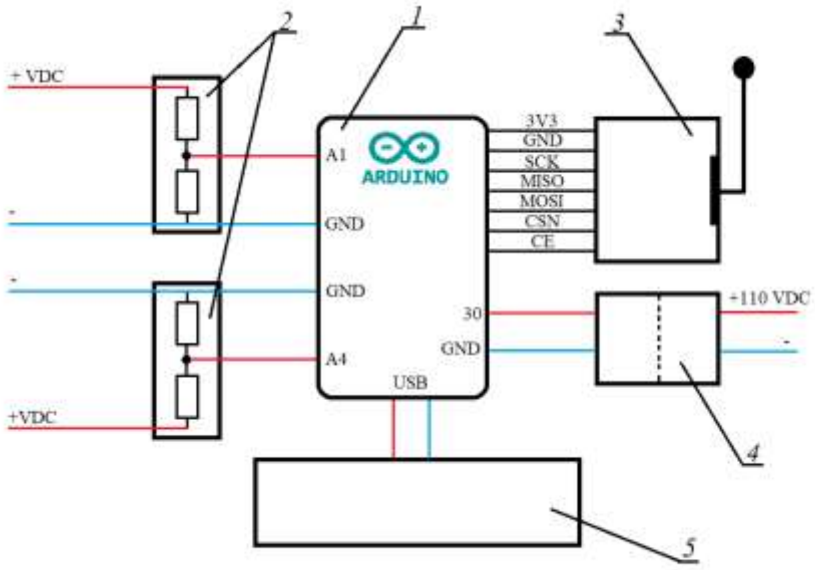

Fig. 2. Diagram of the transmitting device. 1 – Arduino Due, 2 – voltage dividers, 3 – radio module, 4 – activity registration module SCR, 5 – power supply

This measuring device uses voltage dividers to be able to connect the measuring system to the circuit of the traction motors. Additionally, the anti-slip relay operation recording module was used to galvanically separate the locomotive's 110 V system from the microcontroller. When the auxiliary contacts of the PVP-20 device are short-circuited, the flowing current powers the optocoupler LED, which, by emitting light onto the phototransistor, closes the 3.3 V supply circuit from the Arduino. The device processor reads the input/output status as low or high. In the case of closed SCR contacts, the low state is signaled (logical "0").

Data is sent to the receiver every 20 ms in the form of a five-element array, which consists of: a check number (compared by the receiver and only after their compliance is the data presented and saved), data downloaded by an analog-to-digital converter from two voltage dividers, output status low/high and the time elapsed since switching on the transmitter (in ms). The purpose of introducing the check number is to eliminate the influence of disturbances from the operation of the vehicle's devices, which may distort the received data. The received signal is displayed by the Serial Oscilloscope software for monitoring the serial port - it can save data to a TXT or CSV file. Real-time data observation is facilitated by the oscilloscope screen built into the program.

3.2. Measurements and data analysis

To establish the correlation between the data from the analog-to-digital converter and the actual voltage, the device was calibrated. For the initial calibration, an LSPa-740 DC generator was used in a diesel locomotive with an electric transmission type 6D (SM42 series). The voltage prevailing at the terminals of the generator was checked with a multimeter while the generator was operating in all 11 driving positions, and at the same time, data from the transmitting device (Arduino ADC with dividers) connected in the same place was recorded.

The actual measurements were made on a 303E (EU07) locomotive. For this purpose, a specially developed measuring device was mounted on it in a suitable place. During the analysis of the obtained data, the focus was on starting the train from a speed of 0 km/h - the voltage at the terminals of the anti-slip relay coil was compared, the actuation moment of this relay was compared, and this information was superimposed on the data obtained from the Hasler Teloc series speedometer. Figure 3 shows a diagram of the connection of the measuring device on a vehicle based on the example of a EU07 locomotive.

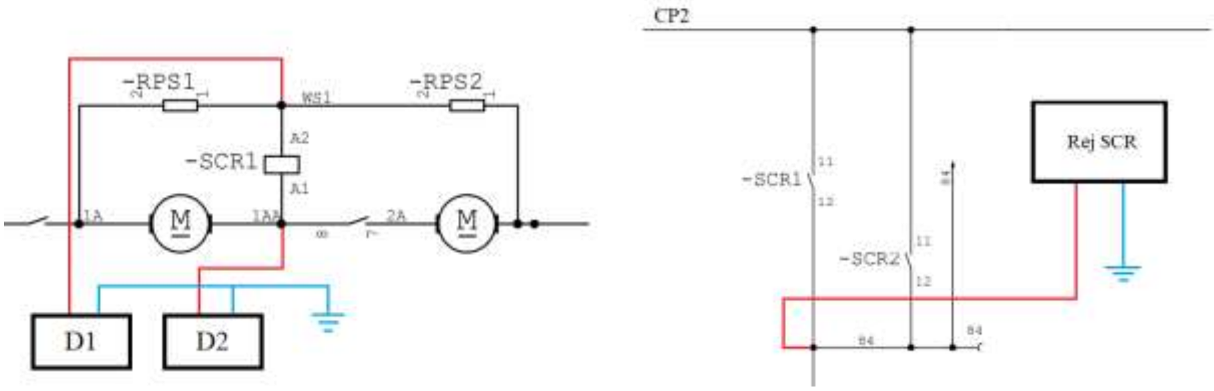

Fig. 3. Transmitter connection. D1, D2 – voltage dividers,
Rej SCR – contact operation recorder SCR

The place of connection was the SCR coil terminals (relay coil contacts of the PVP-20 device) on trolley No. 1 due to the possibility of obtaining data from the speedometer - the transmitter is located on the second axis of the vehicle. Due to this, the slip speed was obtained when the second wheelset was spinning, and information about driving with the current consumption was obtained.

While driving with the current consumption, when the slip was not present, the voltage on the coil of the anti-slip relay fluctuated in the range of 0-10 V. To better visualize the data in the graphs below, the obtained voltage was presented in the form of the absolute value of the difference of the measurement results, which is the voltage on SCR coil terminals.

Figure 4 shows data from start-up No. 1, start-up carried out in bad weather conditions - ambient temperature 3°C, wet rails. Set 1 (first in the direction of travel) slipped at a speed of vt = 11.79 km/h. The increasing voltage difference after 560 ms reached the value of 77.4 V (from the initial value of 8.77 V) and was signaled by the anti-slip relay. During the relay operation (5040 ms), sandblasting and braking of the vehicle axle were automatically started, which did not lead to a slip. Only switching off the tractive force by the driver eliminated the slippage of the set - consequently, the acceleration of starting decreased.

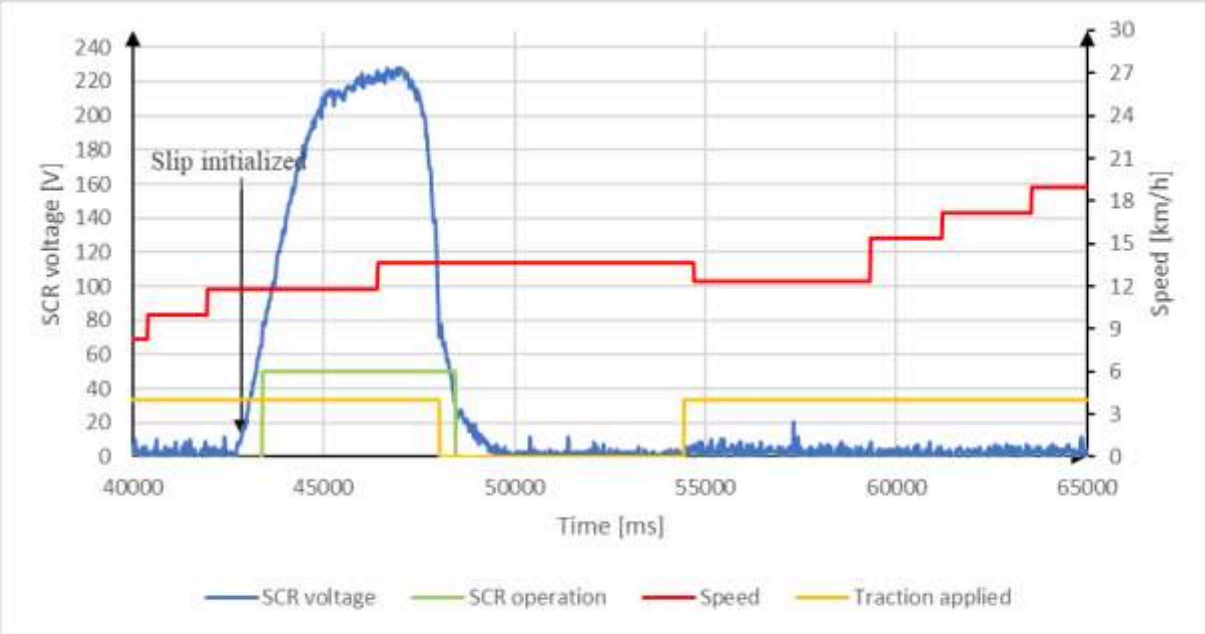

Fig. 4. Start-up no. 1

Figure 5 shows the start-up and macro-slip that occurred on the second wheelset - train speed v_t = 0 km/h. Start-up in bad conditions - wet rails with mud contamination (coal mine siding).

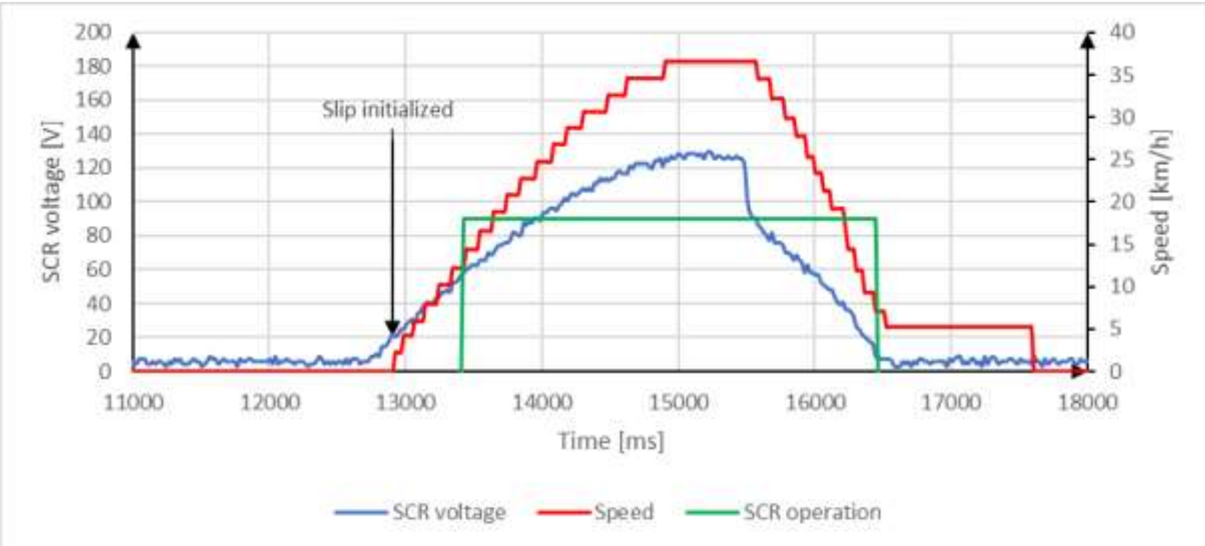

Fig. 5. Start-up no. 2

The activation of the anti-slip devices occurred at a coil voltage of 58.4 V, which corresponds to the speed of the rolling set v_s = 12.2 km/h. For factory settings (for a voltage of 70 V), the signaling would be at 16.58 km/h. As in the case of start-up no. 1, the slip was eliminated by the driver switching off the drive and restarting. The acceleration and speed of set 2 are shown in Figure 6 - the average acceleration is 5.5 m/s^2. Slip duration 4802 ms, SCR duration 3040 ms.

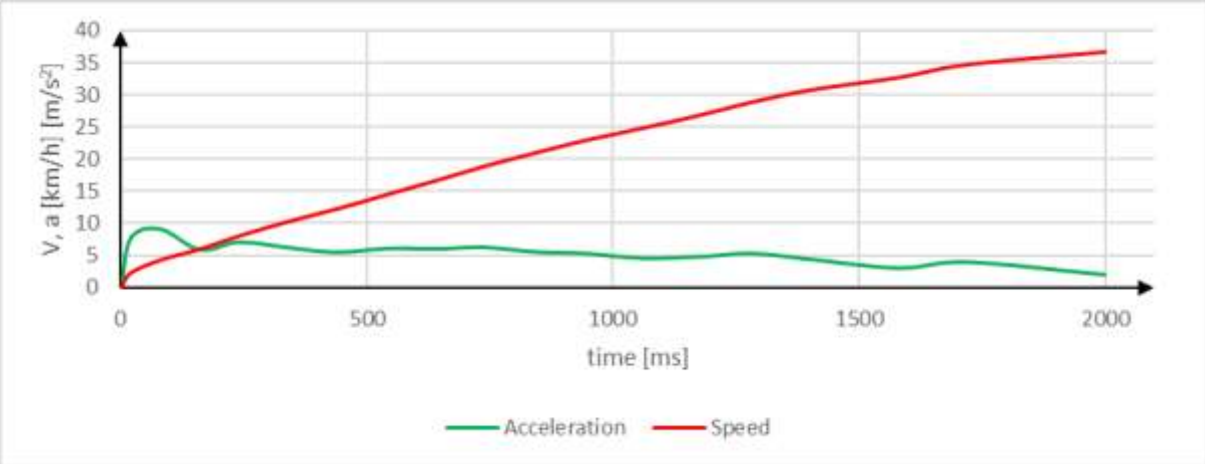

Fig. 6. Acceleration and sliding speed – start no. 2

Figures 7 and 8 show two successive slips (70.5 seconds from the beginning of the first to the beginning of the second) during start-up no. 3. Conditions: wet, dirty rails.

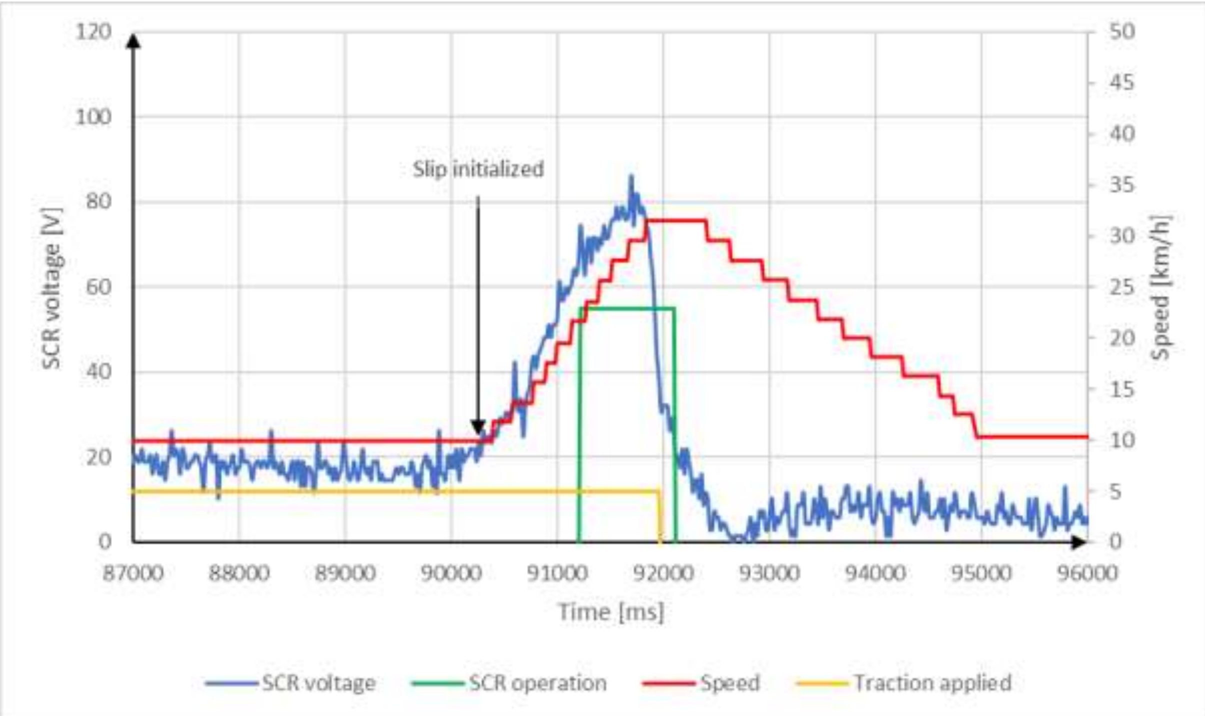

Fig. 7. Start-up no 3 – slip 1

Slip 1 at a speed of v_t = 9.93 km h, slip duration 4856 ms, activation of the signaling after 1120 ms from the coil voltage increase (at slip speed v_s = 7.65 km/h), SCR operation time 900 ms. The slip was eliminated by switching off the tractive force current driving.

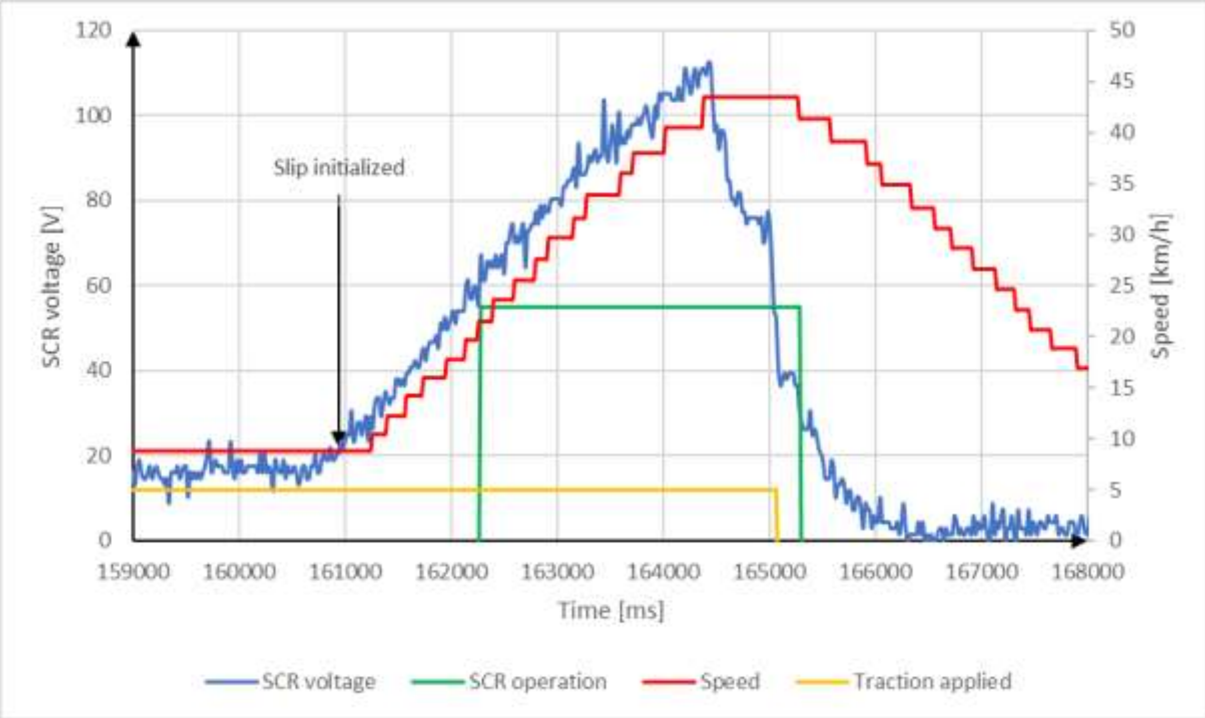

Fig. 8. Start-up no. 3 – slip

Slip 2 - speed v_t at the beginning of the slip 8.82 km/h, SCR activation at a voltage of 67.2 V (1660 ms after increasing the coil voltage and slip speed vs = 8.95 km/h), slip duration 7346 ms. Liquidation by switching off tractive force current driving.

The start-up with the *axle load adjustment* system on is shown in Figure 9. There is an observed increase in the voltage on the SCR1 coil terminals to over 70 V and a sharp drop in this voltage when switching to the non-resistance driving position - the axle load adjustment system is then disconnected. The switching on of the anti-slip relay at a voltage of about 49 V is also recorded - it probably results from the voltage on the coil of the second relay (SCR2) because they are connected in parallel in the signaling circuit. The driver is not informed about the slipping by a lamp on the desk, and braking and sandblasting are not activated because simultaneously with the activation of the system of adjusting the forces to axle loads, the slip signaling is disconnected. Failure to disconnect would result in a false indication of a slip of the assemblies.

The list of selected results is presented in Table 1. Due to the lack of monitoring of the speed of other vehicle axles by the measuring system, data on the slip velocity vs are included in the table only when the set with the Hasler speedometer transmitter slipped.

All registered slips occurred at speeds of up to 25 km/h, and despite the operation of the braking system and sandblasting, they had to be eliminated either by switching off the current drive or by moving the controller to lower positions.

When using force adaptation to axle loads, the protection system is disengaged, leaving the driver's senses to detect slipping. This detection consists of careful observation of the ammeters and listening to the characteristic sound of rolling the sets. It is, undoubtedly, very absorbing for the driver, who is already occupied with the observation of the foreground, signals and route. In the two-section 203E (ET41) locomotive, the observation of the currents flowing in the main circuit of the second unit is difficult, as there are two ammeters installed in the cabin, which can indicate the current of the second unit after manual switching by pressing a button on the panel.

Fig. 9. Start-up with the attached system of adjusting the forces to the axle loads

Tab. 1

Measurements

Start-up no.	1	2	3/1	3/2	4	5
Vehicle speed before slip v_t [km/h]	11.79	0	9.93	8.82	22.12	20.06
Slip speed v_s when triggered SCR [km/h]	-	12.2	7.65	8.95	-	-
Maximum speed v_s of slip [km/h]	-	36.61	31.53	43.48	-	-
Time from SCR coil voltage rise to SCR actuation [ms]	560	620	1120	1660	1000	1660
Maximum voltage on the SCR coil [V]	227.9	130.0	86.2	112.5	169.4	78.9

Summing up, the results of the measurements indicate a significant insensitivity of the applied anti-slip system based on the PVP-20 type relay. When starting at low speeds, slip is signaled at a slip speed vs 8-10 km/h. When the train starts moving, the difference in speed between the wheels of the two sets, which will attract the armature of the coil, is even higher - up to 15 km/h. In practice, such a high speed slip cannot be eliminated by sandblasting and braking the vehicle axle. The intervention of the driver is necessary, and he is forced to throw more resistors into the system - which, combined with the low speed, entails the need to stop and restart. Due to the lack of a system for the discussed types of locomotives, which automatically interferes with the control circuits, the slip time increases. All the above-mentioned factors imply the low efficiency of the current solution in detecting and eliminating wheel spinning.

4. SUGGESTIONS FOR CHANGES IN CONSTRUCTION SOLUTIONS

According to the test results presented in the literature [2], the most effective method of eliminating slipping and minimizing its duration on electric locomotives with resistance starting is the automatic reduction of the torque by inserting resistors into the motor circuit. To implement this anti-slip concept, it is necessary to use a different method of detecting wheel spin and introduce automatic addictions to the vehicle control system.

For the detection of slip by measuring voltages on traction motors and its automatic elimination, voltage-current converters of the LV 100 series by LEM, cooperating with the PLC Wago Ethernet 750 XTR controller, were proposed. These devices are successfully used in modernized traction vehicles of the EU/EP07 series operated by PKP Intercity.

Fig. 10. LEM 100-3000/SP12 [6]

The LEM LV 100-3000/SP12 converters (Figure 10) are intended for installation on traction vehicles; the principle of their operation is to use the Hall effect to measure voltage, LV 100 measures voltage in the range of up to 5 kV with an accuracy of 0.5% [6]. In the modernized EU/EP07 PKP Intercity electric locomotives, they were installed in place of PVP-20 anti-slip relays. However, the technical possibilities offered by the use of digital devices were not fully used, and the current principle of operation of the slip detection devices was retained - the threshold values of the activation voltages are the same as in the original design from the 1960s, and the system does not indicate a slip when using force compensation for axle loads. LV 100 were also used in locomotives type 201Ek and 201Em (modernized ET22 series) - however, they were not used there to detect slipping.

The Wago 750 XTR Ethernet module (Figure 11) is used as a controller for high voltage cabinets. XTR series products are characterized by increased resistance to shocks, extreme temperature conditions and EMC disturbances [18], and the modular design of the elements allows for easy expansion of the system. Two-state and analog input modules enable receiving information from sensors, and the vehicle's electrical devices (contactors, relays) are controlled by two-state output modules.

Fig. 11. System Wago 750 XTR [18]

In the proposed design, LEM converters measure the voltage on each of the traction motor rotors (Figure 12) - instead of comparing the voltages on the two rotors. The measured voltage values in the form of an amplified current signal are sent to the analog input module of the PLC controller, where they are compared with each other. The lowest voltage should be taken as the reference value, and in the case of the axle load adjustment system, the microcontroller must separately compare the voltages of motors with full excitation and with weakened excitation.

By comparing the signals received from the converters, the controller makes the appropriate adjustments in the circuit of the resistance contactors according to a predetermined program of operation. From the use of the digital technique, it is possible to determine several threshold values for the difference and the speed of the rise of the voltage difference on individual motors, and thus, significantly accelerate the detection of the difference in the rotational speed. The exact values should be determined in the course of further field tests.

Regulation involving the insertion into the circuit of starting resistors corresponding to two driving positions lower than those set by the travel controller. The exceptions are the first and second driving positions of each engine connection system - to prevent the controller from changing the starting system. In the event of the elimination of the slip, the controller includes the previously opened resistance contactors with a certain time delay to the position program following the setting of the travel switch. Control of resistance contactors is by relays with a control voltage of 24 V (adjustment to the voltage level of the digital output module of the Wago controller).

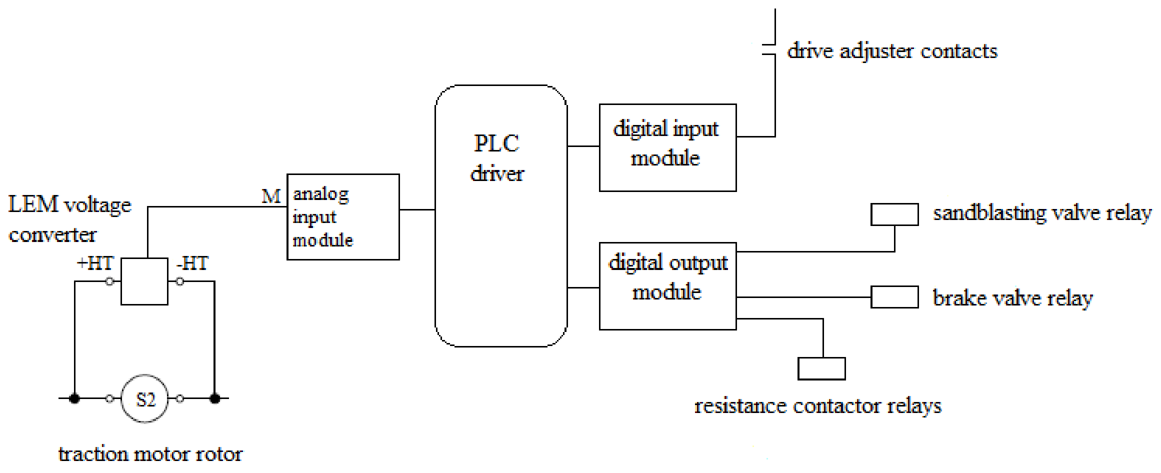

Fig. 12. Scheme of the slip detection and elimination system solution

The proposed change in the structure of the system allows for a significant extension of the usability and effectiveness of the anti-slip system of electric locomotives with resistance starting. This solves the problem of slip-proof motors on six-axle locomotives by monitoring the voltage of each motor. Also, it eliminates the need to disconnect the slip signaling during start-up with the axle load adaptation on. The use of programmable PLC controllers makes it possible to adjust the sensitivity level - to define the threshold values of the activation voltage, including the dynamic one.

9. SUMMARY AND CONCLUSIONS

This article presents the issue of anti-slip protection used in electric traction vehicles. The very unfavorable effects of slips in the form of damage to infrastructure and traction rolling stock were accentuated. The next part focused on the construction and operation of the PVP-20 type slip-detection relay generally used in Polish locomotives. Measurements and analysis of the obtained results were also carried out to assess the effectiveness and suitability of this device in the field of locomotive slip detection and elimination.

The main measuring instrument was a device constructed as part of our own work based on two Arduino boards with radio communication, allowing us to perform tests in difficult conditions prevailing on an electric locomotive. Measurements were made on the EU07 locomotive during train starts in unfavorable weather conditions, which enhances the formation and development of slip.

The obtained measurement data allowed for the formulation of the following conclusions:

- The designed and constructed device allowed for effective measurement of the operation of the PVP-20 anti-slip device. The use of voltage dividers allowed for trouble-free connections to the circuits of the locomotive. Thanks to the use of radio transmission of data, it was possible to send them to the recording device without interference and direct observation and save the data to a file.

- The analysis of the measurement data shows that the slip detection devices in the form of a PVP-20 type relay, used in electric locomotives with a resistive start, do not allow for the detection of the slip of the set in the range of slip speeds up to approx. 10 km/h.
- To detect slips earlier, a new solution based on digital technology solutions of slip detection and elimination system should be applied-. This will allow one to automate the most effective process of eliminating wheel slip - reducing the torque of the rolling motor.

Therefore, a new start-up slip detection system has been proposed, based on the components already used in the construction of locomotives, in the form of LEM voltage-current converters and a PLC controller. These components allow for an increase in the sensitivity of the protection system and introduce the possibility of a significant increase in functionality - software sensitivity setting and control of the main circuit of the vehicle. Due to the introduction of dependencies in the control of resistance contactors, the process of removing the slip will be automated and shortened. The device will relieve the driver from performing these activities manually, and in the case of using the system of adjusting the forces to axle loads, it will relieve him of the necessity of organoleptic detection of wheel spinning. In addition, the issue of lack of anti-slip protection for engines 2 and 5 on the ET22 locomotive will also be resolved.

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Received 28.10.2022; accepted in revised form 20.01.2023