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Development and Application of PIKH-Type Current Sensors to Prevent Improper Opening of Parallelly Connected DC Vacuum Circuit Breakers

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Abstract: This article describes the development of current sensors used in DCU-type high-speed circuit breakers. DCU-type circuit breakers use the principle of turning off a constant short-circuit current by means of countercurrent. The article presents a new current sensor design called PIKh, which uses Hall sensors to measure current and determine its direction. PIKh sensors allow parallel operation of high-speed circuit breakers during the "parking" operation. The article includes the algorithm and principle of operation of the PIKh sensor. The proposed solution was verified on an electric traction vehicle.

Keywords: vacuum chamber; circuit breaker; parallel work; countercurrent; sensor of current

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1. Introduction

The parallel operation of commonly used electrical apparatuses is now a standard for increasing the reliability of in-service urban traction vehicles, railroads, subways, as well as vehicles used in the global open-pit mining industry where operational reliability is a priority not only in economic terms, but also for the safety of users. The standard of redundant operation was applied and has been widely used for more than 25 years at CERN (the European Organization for Nuclear Research) for the safety of the Large Hadron Collider (LHC—Large Hadron Collider) and is still being developed [1]. Redundant work is permeating various industries, especially rail transport, and is positively influencing the elimination of transport exclusion and the sustainable development of all European regions within the Trans-European Transport Network (TEN-T). Also, in Poland, there is a dynamic implementation of redundant work standards. A pioneer in the implementation of this technology using vacuum chambers is the Department of Electrical Apparatuses of Lodz University of Technology. An outline of parallel operation has already been presented by the authors in the 2018 publication titled "The new design of the vacuum circuit breaker mounted on the roof of Electric Traction Units" [2], which describes a new family of DCU-type circuit breakers with variants DCU-800MNL and DCU-800MNLD. The research carried out at the Short-Circuit Laboratory of the Department of Electrical Apparatuses of Lodz University of Technology focused on the technical verification of the new circuit breaker design and its location on the traction vehicle without taking into account the possibility of recuperation and the introduction of the "parking" mode to the standard of use of the traction vehicle. In the indicated article, the possibility of parallel operation is provided only in the case when parallel operation is realizable, for example, during the process of testing and certification of a new traction vehicle ETU (ETU—electric traction unit). Proper parallel operation is possible only when the process of switching off one of the closed switches is preceded first by lowering the pantograph and then a signal is given to switch off the switch.

Since not all ETU manufacturers accepted the above limitation, it was necessary to carefully examine the traction vehicle's operating algorithm and guarantee the unrestricted use of vacuum circuit breakers.

The standard of operation of traction vehicles has become a mode of operation "parking" occurring only at a standstill. This mode is characterized by the following:

- In the case of a change of direction of the ETU, the driver additionally raises the second pantograph and closes the second breaker. Then, he turns off the first switch and lowers the first pantograph. After moving to the end of the train, he starts the driving process. In such a situation, self-exclusion of the circuit breaker is not allowed. This results in the need to reset the entire traction vehicle and prolong the shutdown of the vehicle.
- In the case of leaving the ETU overnight with pantographs raised and circuit breakers closed, which is intended to ensure that the batteries are adequately charged and that the vehicle remains in service, the vehicle's automation can autonomously close the switched-off circuit breaker only if the cause of the shutdown is not a short circuit. In the case of parallel operation of vacuum circuit breakers, the disengagement of one circuit breaker makes the other one shut down and issue a signal to the vehicle's main control unit signalling a short-circuit disengagement.

In addition, the widespread introduction of recuperation in Poland has forced the need to expand the measurement capabilities of vacuum circuit breakers and introduce the ability to detect and recognize different types of currents flowing through the circuit breaker.

In this article, parallel operation will be presented as a backdrop to demonstrate the development and application of PIKh current sensors to prevent abnormal opening of parallelly connected ultra-fast DC vacuum circuit breakers of the DCU type powered by 3 kV DC. The process of the tests and technical considerations will be presented for the ultra-fast DC vacuum circuit breaker type DCU-800MNL. The family of ultra-fast DC-type DC vacuum circuit breakers has been widely applied in protecting ETUs from the dangerous effects of surges and short circuits. Ultra-fast circuit breakers of DCU type are manufactured under the license of the Department of Electrical Apparatus of Lodz University of Technology by the Electrical Apparatus Plant "Woltan" Ltd. (Poland, Lodz). DCU-type circuit breakers use the principle of countercurrent, the source of which is high-energy capacitors, to switch off a constant short-circuit current [3–6]. The beginning of ultra-fast vacuum circuit breakers in Poland is dated for 1996 and the serial production of the first DCV-type circuit breaker for 3 kV DC voltage and 250 A rated current started at the same time. The last two decades of dynamic development of technology have allowed for the designing, manufacturing, and implementing DC circuit breakers of the DCU-630J, DCH, DCN-L, DCN-T, DCN, and DCU-800M types as well as the SVB AC circuit breaker and the DWT dual-system circuit breaker.

The topic of an ultra-fast vacuum circuit breaker has been discussed many times at international conferences and in the world literature [7–29].

The article also presents the problems arising from the parallel operation of DCU circuit breakers and ways to solve them. The new PIKh current sensor has been designed with the functionality of detecting the direction of current flowing through the circuit breaker and the ability to distinguish the types of current, i.e., rated current, short-circuit current, overcurrent, and countercurrent, of the other breaker in the case of parallel operation.

2. Materials and Methods

2.1. Identification of the Problem

The process of measuring short-circuit current in DCU-type circuit breakers will be discussed first. The current sensor, named PIK, Figure 1, uses reed switches for detecting short-circuit current, constructed from a hermetic glass bulb in which ferromagnetic metal contacts are embedded in a vacuum environment. The ferromagnetic contacts attract and close each other under the influence of an appropriately directed external magnetic field. In the case of DCU circuit breakers, the PIK current sensor is mounted on a copper rail which is the main current path of the circuit breaker.

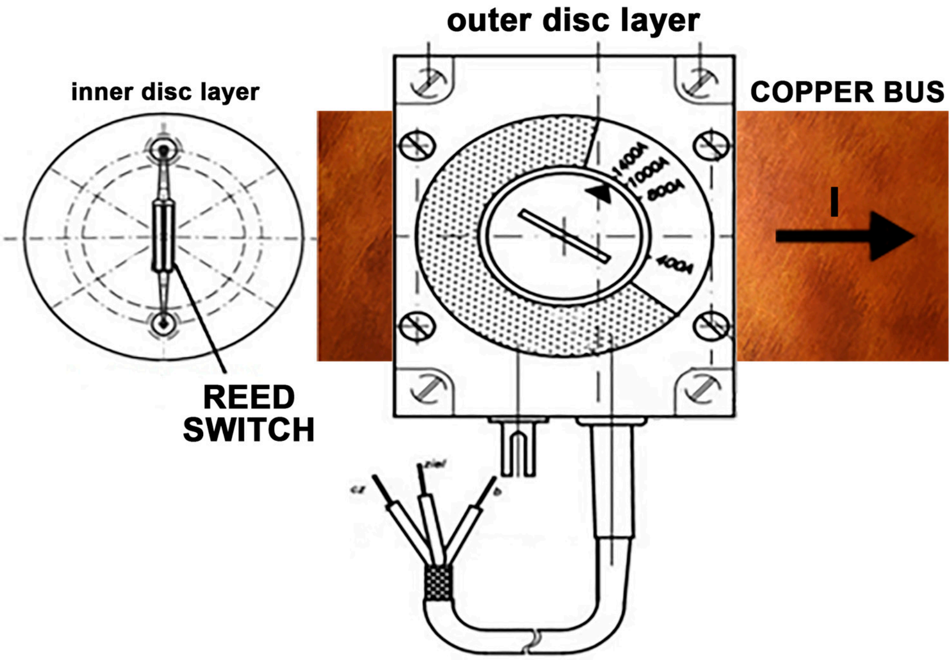


Figure 1. Sensor PIK.

The sensor is adjusted by rotating a disc on which contacts placed in a field created by a conductor with a current are mounted. A constant current flowing through the copper rail produces a magnetic field. The dependence of the current on the angle between the current and the field lines is shown in Equation (1):

$$I = \frac{F}{l \times B \times \sin\alpha} \tag{1}$$

where I—current, B—magnetic induction, F—magnetic force, and α—angle between the current direction and the direction of the magnetic field lines.

The above solution does not provide the possibility to measure the current in real time, but it only allows us to determine whether the current flowing through the circuit breaker is lower or higher than the set threshold value of the PIK sensor trip. The process of setting the sensor tripping threshold value is complicated and needs to be carried out in the laboratory. The presented solution worked well only for DCU-type circuit breakers operating as a single protection for a traction vehicle.

The widely promoted and disseminated standard of parallel operation, which aims to increase the reliability of the traction vehicle, has also been introduced in Poland. Manufacturers of new traction vehicles placed two circuit breakers on the roof of the traction vehicle. Figure 2 shows the two most popular ways of powering traction motors and transferring the drive from one train car to another.

Method 1 shows the power transmission between car A and car B at the level of traction motors. In this case, despite the parallel operation of circuit breakers relative to rail electric traction and running rails, the problem of interaction of vacuum breakers with each other does not occur. The countercurrent circuit of one circuit breaker is isolated from the other via traction inverters.

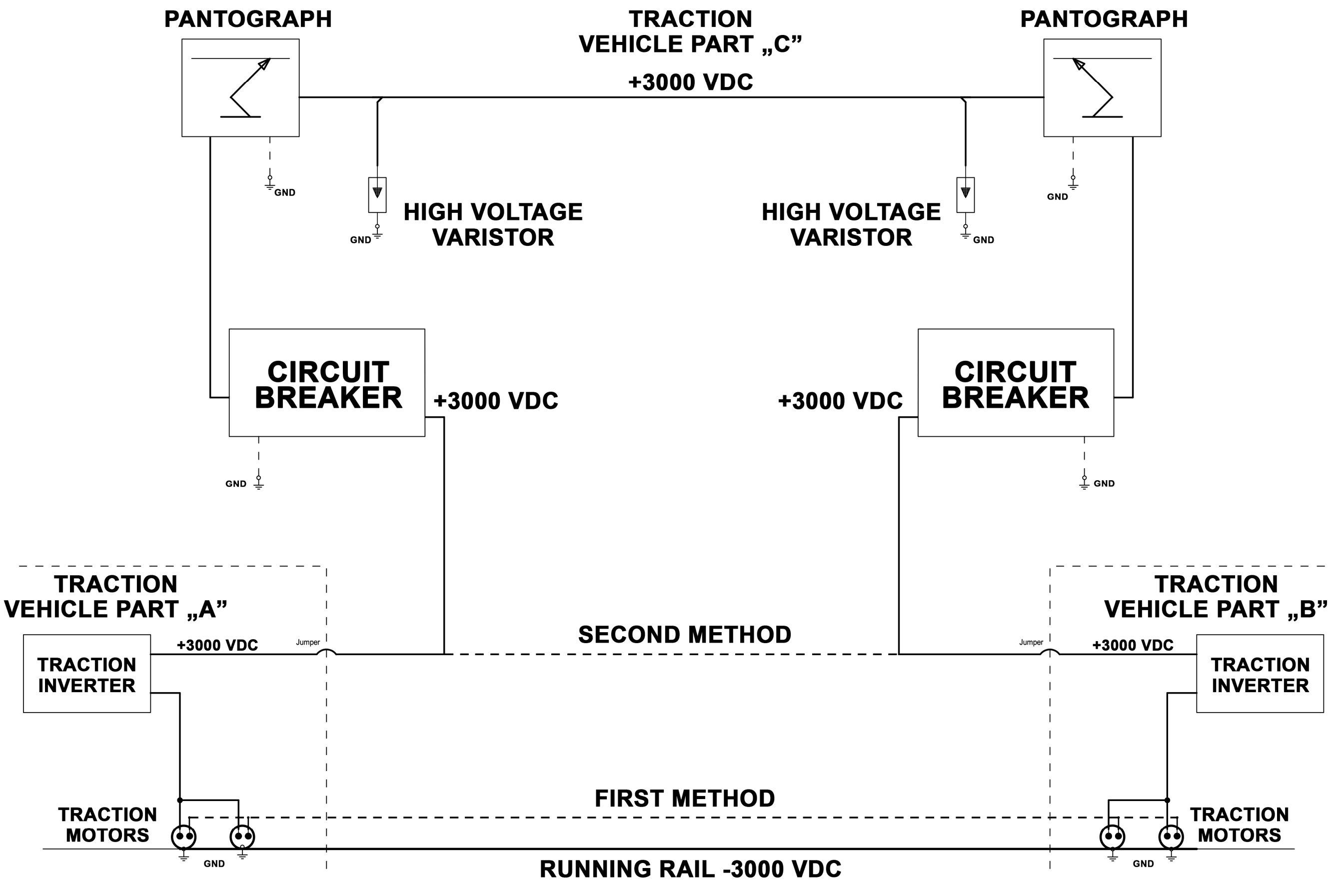


Figure 2. Simplified main circuit of a traction vehicle.

Method 2 shows the transmission between car A and B at the level of the outputs of the circuit breakers. If two pantographs are raised, the circuit breakers are connected parallelly to the electric traction line. Two pantographs can be raised and two circuit breakers can be closed only when the traction vehicle is at a standstill during the "parking" mode of operation. This mode is used in order to:

- reduce the time required to change the direction of the traction vehicle; one needs to take into account the driver's change of cab,
- maintain charged batteries also during disconnection of the circuit breaker for reasons of voltage failure of the 3 kV overhead line (switching on the circuit breaker again is carried out automatically by the main controller of the traction vehicle).

The operation of vacuum circuit breakers in the "parking" mode results, when one circuit breaker is switched off, in switching off the other circuit breaker as well.

In order to introduce the problem of the parallel operation of vacuum circuit breakers, the principle of operation of an ultra-high-speed vacuum circuit breaker of the DCU type will be discussed, which will make it easier to understand the phenomena occurring in DC electrical circuits rated at 3 kV during the parallel operation of circuit breakers. Figure 3 shows a circuit consisting of a 3 kVDC power supply, resistance and inductance of the power supply, and a closed circuit breaker (KG—closed). When a short circuit occurs in the circuit shown in Figure 3, the short-circuit current increases with an initial steepness that depends on the supply voltage and inductance of the circuit:

$$s = \frac{dIs}{dt} = \frac{U}{Ls} \tag{2}$$

where s—initial rate of short-circuit current rise, Is—circuit current, U—power supply, and Ls—suppressor of countercurrent.

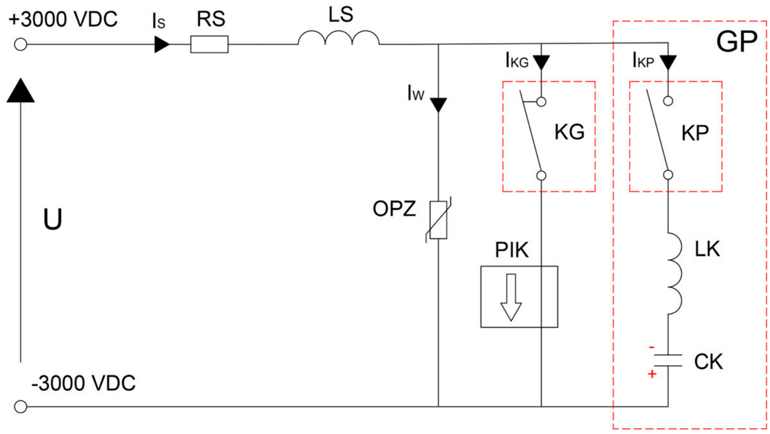


Figure 3. Schematic diagram of a DC circuit turned off by circuit breaker type DCU. KG—main vacuum chamber, KP—auxiliary vacuum chamber, CK—commutation capacitor, LK—a suppressor defining the parameters of the countercurrent pulse I_{kp}, OPZ—high-voltage varistor, PIK—overcurrent sensor, Is—circuit current, I_{KG}—main chamber current, I_{KP}—auxiliary chamber and capacitor current, RS—line resistance, LS—line inductance, U—power supply, GP—countercurrent generator.

A further increase in the short-circuit current triggers the PIK sensor, which triggers the procedure for switching off the short-circuit current by the DCU-type vacuum circuit breaker.

First, the contacts of the KG vacuum chamber are opened and the arc voltage appears on its contacts. Then, after a fixed time (1.2–1.6 ms), the KP chamber is closed and the I_{KP} current begins to flow. In this case, the equation is correct:

$$Is = I_{KG} + I_{KP} = const \quad (3)$$

and

$$\frac{d\,I_{KG}}{dt} = -\frac{dI_{KP}}{dt} \quad (4)$$

The equation shows that the absolute value of the decreasing steepness of the I_{KG} current will be equal to the absolute value of the increasing steepness of the I_{KP} current in the GP countercurrent generator branch. Switching off the current in the circuit will occur when the currents equalize

$$I_S = I_{KP} \quad (5)$$

because the I_{KG} current will reach a value equal to zero. It shows that the maximum value of short-circuit current possible to be switched off by vacuum circuit breakers is limited to the maximum value of the current I_{KP} generated by the GP generator.

We can describe the current I_{KP} with the following equation:

$$I_{KP} = -\frac{U_k}{\omega_o L_k} e^{-\alpha t} \sin(\omega_o t) \quad (6)$$

where U_k—voltage on capacitor CK, ω_o—pulsation of natural oscillation of the circuit, α—damping constant, and L_K—inductance of GP generator.

In the case when the resistance of R_{CK} seen from the terminals of capacitor CK (R_{ck}—the intrinsic resistance of the series connection of elements KG, KP, LK) is much smaller than the wave impedance $Z_{f,}$, then we can assume that the maximum current I_{KPmax} is

$$I_{KPmax} = \frac{U_k}{Z_f} \quad (7)$$

where

$$Z_f = \sqrt{\frac{LK}{CK}} \quad (8)$$

$$\alpha = \frac{R_{CK}}{2LK} \tag{9}$$

$$\omega_o = \sqrt{{\omega_n}^2 - \alpha^2} \tag{10}$$

$$\omega_n = \frac{1}{\sqrt{LKCK}} \tag{11}$$

For vacuum circuit breakers, the maximum value of I_{KPmax} current is approximately 15 kA (we will return to the maximum value of I_{KPmax} current when analyzing the parallel connection of circuit breakers).

The correctness of operation of the switch, with a simplified diagram presented in Figure 3, is ensured by the properly synchronized operation of the vacuum chambers KG and KP. The process of closing and opening the vacuum chambers is performed by means of a thyristor-triggered induction-dynamic drive [30] (not shown in Figure 3). In the described circuit breaker, the parallel operation of the vacuum chambers is used, which determines the DC shutdown by means of forced commutation. The countercurrent impulse is generated by means of a series connection of the commutation capacitor CK and the commutation choke LK. Vacuum chamber KP is responsible for closing the countercurrent circuit whereas chamber KG opens and closes the main circuit of the circuit breaker. The breaker's readiness for the next switch on is achieved after a few seconds, after charging the commutation capacitor CK. Achievable times for switching off permanent short-circuit currents by vacuum circuit breakers are approximately 2 ms. Protection for the railway traction and the receiver is provided by a high-energy surge arrester OPZ. The arrester used ensures protection-free operation not only for vehicles, but also for other equipment operating on the same railway traction.

The modular subdivision of the components that make up a DCU-type vacuum circuit breaker makes it easy to adopt the configuration of the components and their arrangement to the customer's limited working space. An example of a DCU-type vacuum circuit breaker is the DCU-800MNL breaker (Electrical Apparatus Plant "Woltan", Poland, Lodz) (Figure 4). Two circuit breakers of the DCU-800MNL type can operate in parallel, in series, or each separately as independent protection for the vehicle or selected circuits of the vehicle.

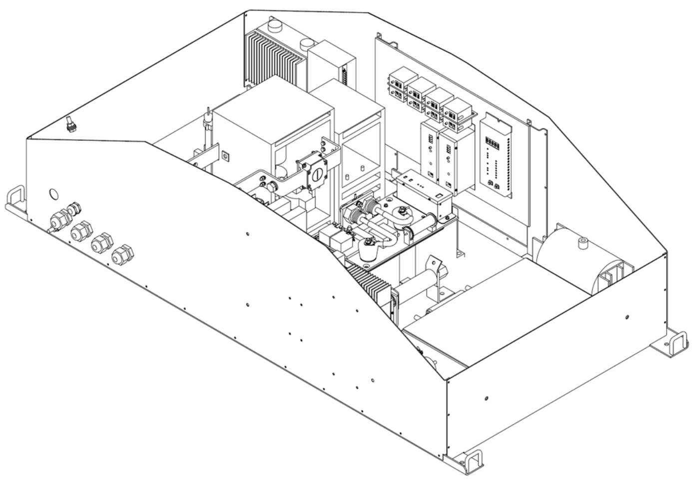


Figure 4. View of circuit breaker DCU-800MNL after removing the top cover [2].

Before discussing the parallel operation of DCU-800MNL-type vacuum circuit breakers, it is first necessary to discuss the voltage and current oscillograms (Figure 5) during the short-circuit current shutdown procedure by the DCU-800MNL circuit breaker. All vacuum circuit breakers of the DCU family turn off the current in the same way without distinguishing its nature (rated current, overload current, short-circuit current). However, the value of the limited current and the rate of the current rise depend on the parameters of the circuit.

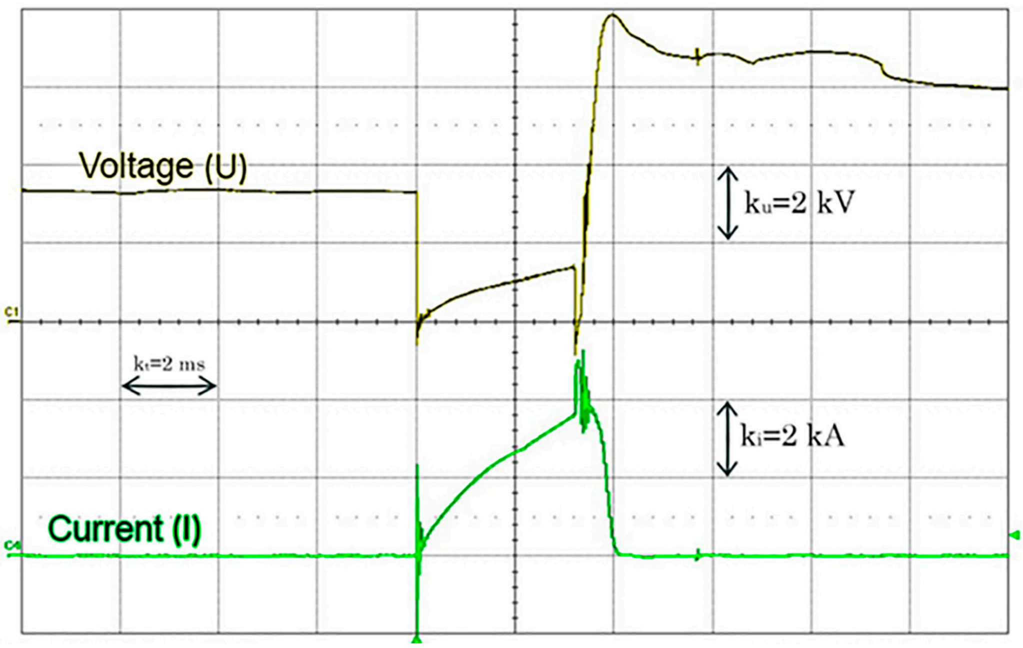


Figure 5. Oscillogram of the process of switching off the short-circuit current for the vacuum circuit breaker DCU-800MNL (I—short-circuit current, U—traction voltage). ki—current signal amplification factor, kt—time base, ku—voltage signal amplification factor.

The oscillogram of Figure 5 shows an example of the power supply voltage and current waveforms during the short-circuit switch-off process. At the onset of the short circuit, the current begins to increase with a rate of current of 1.25 A/us, reaching a maximum value of 4 kA. The response of the system is a generated overvoltage of up to 8 kV and a duration of up to 1 ms.

Because the circuit breaker measures the "current" and voltage of the power supply, spontaneous shutdown is possible in two cases:

- exceeding the threshold value of the current set on the PIK current discriminator,
- exceeding the permissible value of the circuit breaker supply voltage.

We will analyze the parallel operation of circuit breakers for the redundant combination of circuit breakers shown in Figure 6. The redundant use of protection on the ETU allowed the introduction of the "parking" mode of operation when the traction vehicle is stationary.

The operation mode "parking" during parallel operation of the circuit breakers shown in Figure 6 is effective when one circuit breaker is switched off, the other circuit breaker is also switched off. Such action of DCU-type vacuum circuit breakers is unacceptable to manufacturers and users of electric traction vehicles.

Figure 7 shows the parallel connection of circuit breakers of the DCU-800MNL type. For such a case, let us analyze the process of the forced shutdown of one of the circuit breakers in the situation when the supply voltage U = 0 V and there is no sub-connected consumer.

The process of preparing circuit breakers of the DCU-800MNL type for switching on requires:

- charging the internal CN drive capacitors (not shown in Figure 6),
- charging the commutation capacitor CK and CK2 (through the internal transformer, not shown in Figure 7),
- issuance of the SGot signal (information that the switch is ready to be switched on).

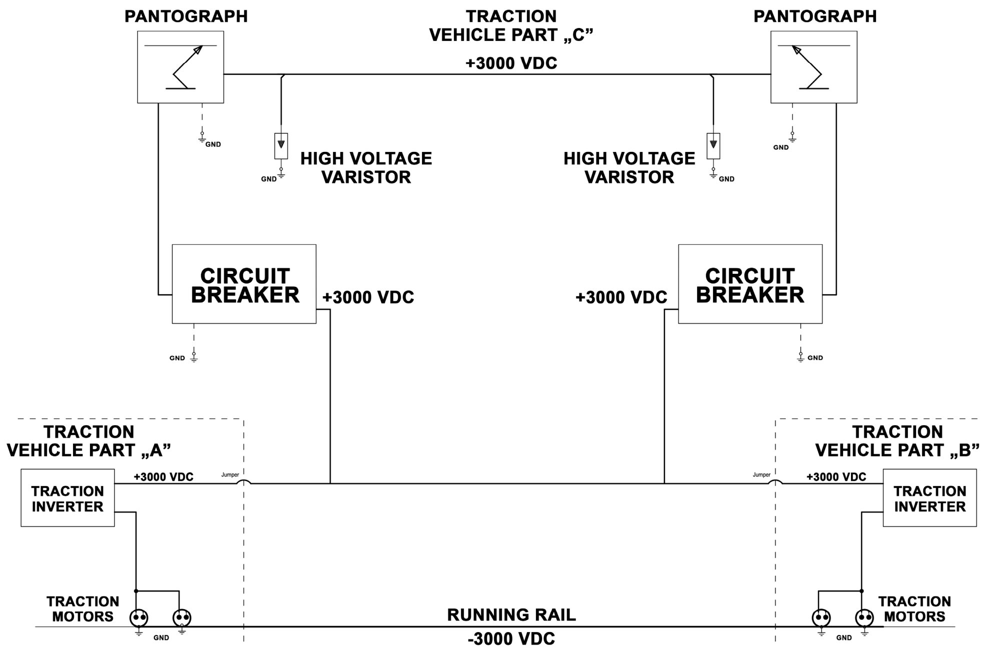


Figure 6. Simplified main circuit of a traction vehicle—operating mode "parking".

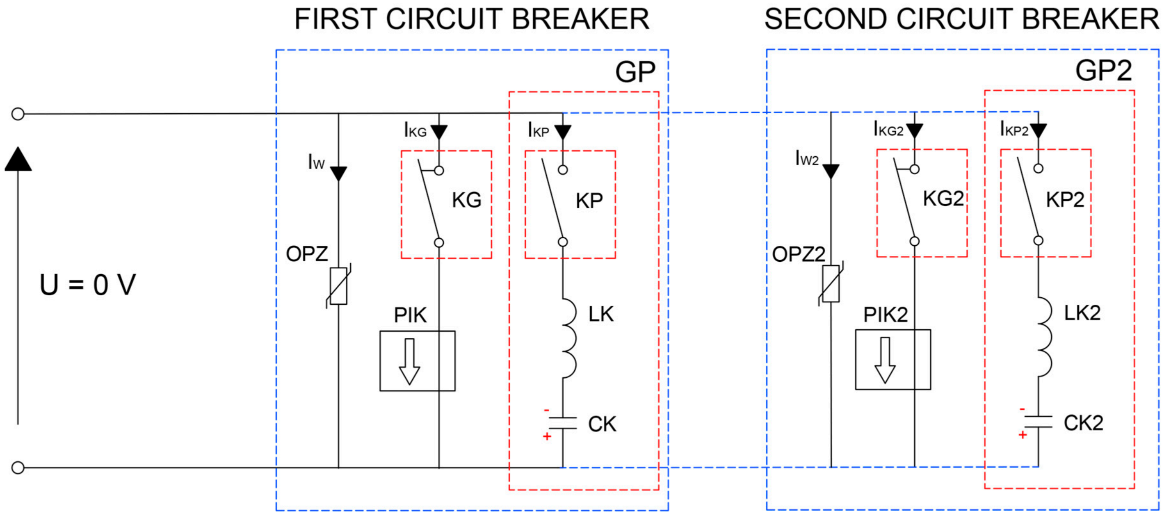


Figure 7. View of the parallel work of two circuit breakers type DCU-800MNL. KG, KG2—main vacuum chamber, KP, KP2—auxiliary vacuum chamber, CK, CK2—commutation capacitor, LK, LK2—a suppressor defining the parameters of the countercurrent pulse Ikp, OPZ, OPZ2—high-voltage varistor, PIK, PIK2—overcurrent sensor, I_{KG}, I_{KG2}—main chamber current, I_{KP}, I_{KP2}—auxiliary chamber and capacitor current, U—power supply, GP, GP2—countercurrent generator.

Then, both circuit breakers are switched on, which is equivalent to closing the main contacts of vacuum chambers KG and KG2. The counterflow chambers KP and KP2 remain open. At the moment when the traction vehicle controller issues a signal to switch off circuit breaker one:

- the main chamber KG opens (since the supply voltage is 0 volts no arcing occurs),
- after a time of 1.4 ms (the time specified by the manufacturer of the switches), the auxiliary chamber KP is closed.

In this situation, capacitor CK is discharged, which is equivalent to the flow of current I_{KP} through the closed chamber KG2. The flowing current through the KG2 chamber causes the tripping of the current sensor PIK2 and the initiation of the procedure of automatic shutdown of the second circuit breaker. An electric arc ignites on the open contacts of chamber KG2. Then, the chamber KP2 is closed. In this situation, the I_{KG2} current is

$$I_{KG2} = I_{KP} + I_{KP2}$$

The process of turning off the current and extinguishing the arc in the I_{KG2} chamber will occur at the second half-wave of the countercurrent I_{KP2}. As a result, capacitors CK and CK2 are discharged to a value close to zero.

Problem found—Forced shutdown of one circuit breaker will cause self-acting shutdown of the other circuit breaker [31].

To confirm the above statement, according to the layout shown in Figure 8, a test of parallel operation of two DCU-800MNL circuit breakers was performed in the Laboratory of the Department of Electrical Apparatus. As in the analytical assumptions described above, the supply voltage U = 0 V and there is no consumer connected. An LEM current transducer was used to independently measure the current flowing in the circuit of the connected circuit breakers. The LEM transducer was previously calibrated with a DC generator in such a way that it was possible to accurately measure fast variable currents of ms duration. The scaled transducer was then connected to an oscilloscope using the circuit shown in Figure 9.

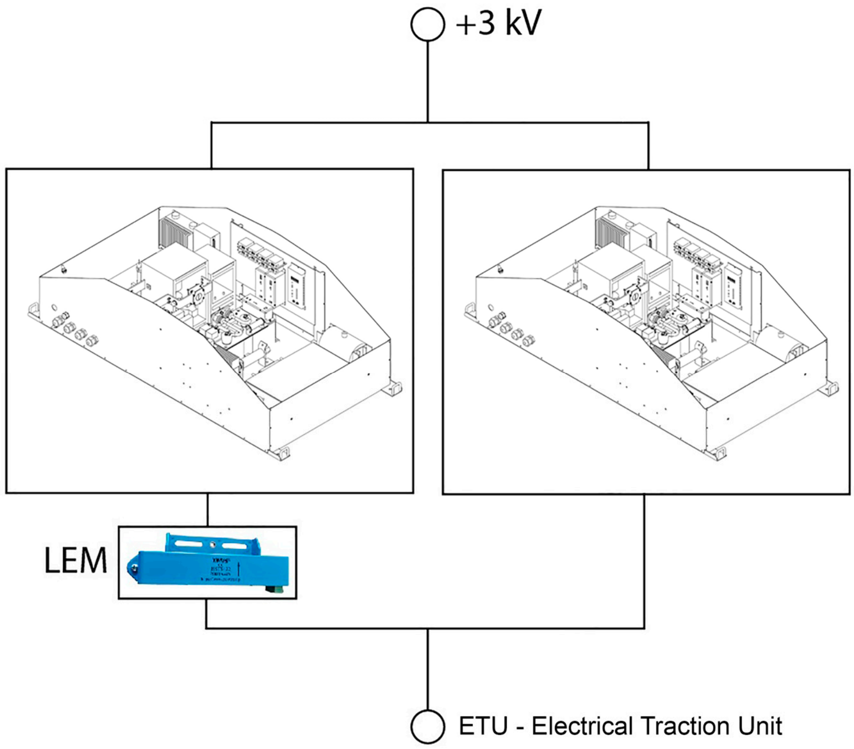


Figure 8. Parallel work of vacuum circuit breakers type DCU-800MNL.

An attempt to close both circuit breakers (Figure 8) and the forced opening of one of them caused the flow of current to the other circuit breaker and its automatic shutdown. The recorded current is shown in Figure 10.

The analysis and measurements carried out confirmed the fact that the cause of triggering the circuit breaker's automatic shutdown procedure during equilateral operation is the detected countercurrent of the circuit breaker we switched off. The source of this countercurrent is the high-energy CK capacitor, while the LK choke and the voltage value to which the CK capacitor was charged are responsible for the shape and amplitude of the countercurrent.

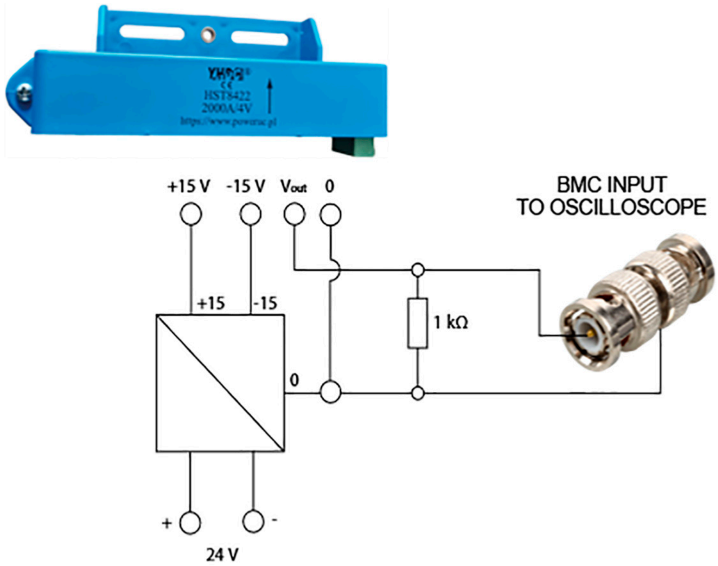


Figure 9. Current measurement using LEM converter.

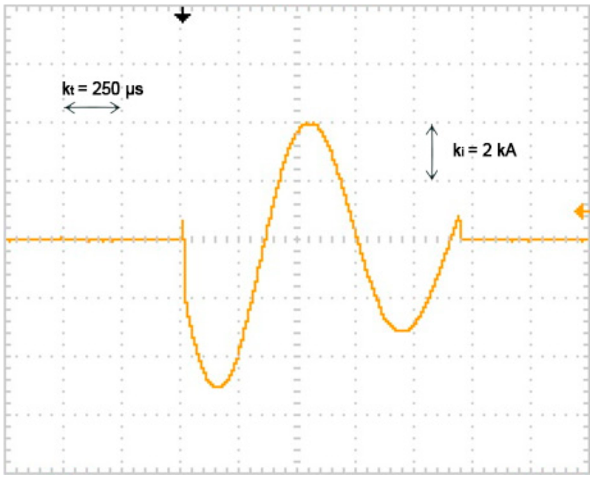


Figure 10. Current oscillogram. Based on the above oscillogram, a current oscillation time of 1.2 ms, maximum amplitude of the recorded current 5 kA (1 V–2 kA), and a countercurrent generated by the circuit breaker, switched off by us, was measured.

The above-described situation occurring during the parallel operation of all DCU-type circuit breakers is unacceptable during the operation of traction vehicles. This type of switch-off circuit breakers prolong the time of scheduled trips of the ETU and generate excessive overvoltages, which overload the KP chambers and high-energy OPZ varistors.

2.2. Control Algorithm of New Current Detector PIKh

The main switch of a traction vehicle must be a reliable apparatus that is not sensitive to interference generated by other apparatuses that make up the vehicle's main circuit. Depending on the needs of the designers of modern rolling stock, the circuit breakers must be able to operate independently, in series and in parallel. In order to enable the parallel operation of DCU-type vacuum circuit breakers, there is a suggestion to design a new current sensor called PIKh, which will detect the direction of the flowing current and its type (short-circuit, overload, countercurrent, rated current). The new current sensor will enable the use of DCU-type vacuum circuit breakers on any ETU and in any configuration and spatial arrangement. The element used to detect the current and its direction is a hallotron. Figure 11 shows the algorithm of operation of the PIKh current sensor, in which three hallotrons H1, H2, H3 are responsible for measuring the current and detecting its direction.

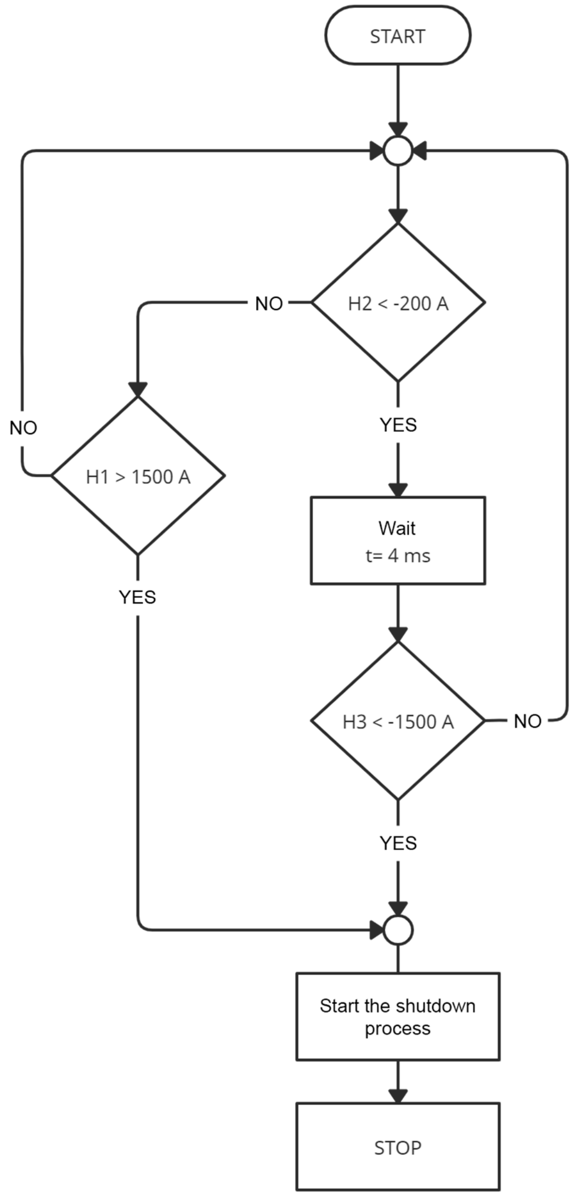


Figure 11. Control algorithm of PIKh.

First, hallotron H2 checks whether the measured current has a value less than −200 A (Figure 11):

(a) H2 > −200 A: The current flowing through the circuit breaker is the rated or short-circuit current. Then, hallotron H1 checks if the value of the flowing current is greater than 1500 A; if not, the measurement cycle ends, and the measurement procedure starts again. If it is, the current flowing through the circuit breaker is a short-circuit current (the value of 1500 A is the threshold value after exceeding, which the procedure of automatic disengagement of the circuit breaker begins).

(b) H2 < −200 A: The countercurrent flows through the circuit breaker during the parallel operation of the circuit breakers. After the time t = 4 ms, hallotron H3 checks whether the value of this current is less than −1500 A; if so, the circuit breaker's automatic shutdown procedure is started (short-circuit current detected—recuperation). If not, the measurement cycle starts again.

The value of the H2 current and the delay time were determined experimentally during short-circuit tests of DCU-type circuit breakers carried out at the Short-Circuit Laboratory of the Electrical Apparatus Department of Lodz University of Technology.

Sample oscillograms for different circuit time constants are shown in Figures 12 and 13. The measurements were carried out using two Tektronix P 6015A high-voltage courts and a Yokogawa DL7480 oscilloscope.

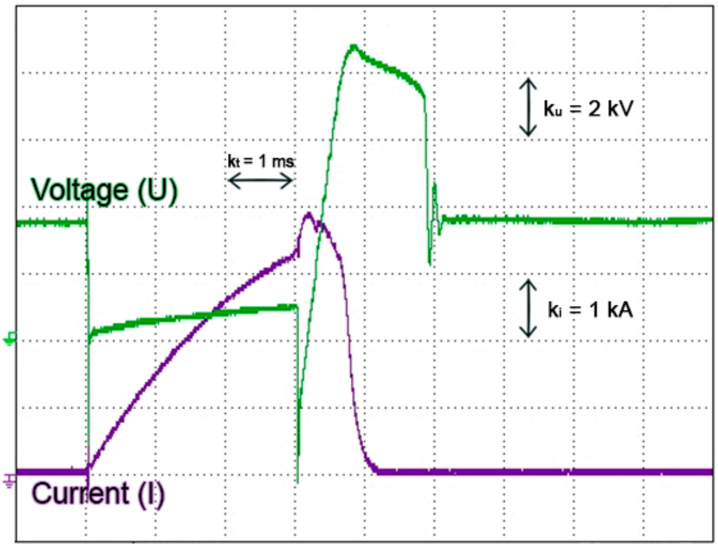


Figure 12. Oscillogram of the process of switching off the short-circuit current for resistance 0.2 Ohm and inductance 0.5 mH. ki—current signal amplification factor, kt—time base, ku—voltage signal amplification factor.

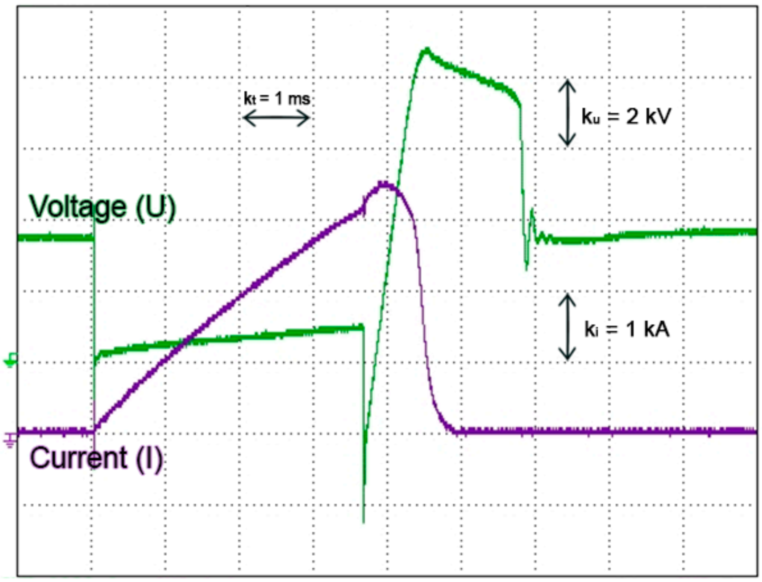
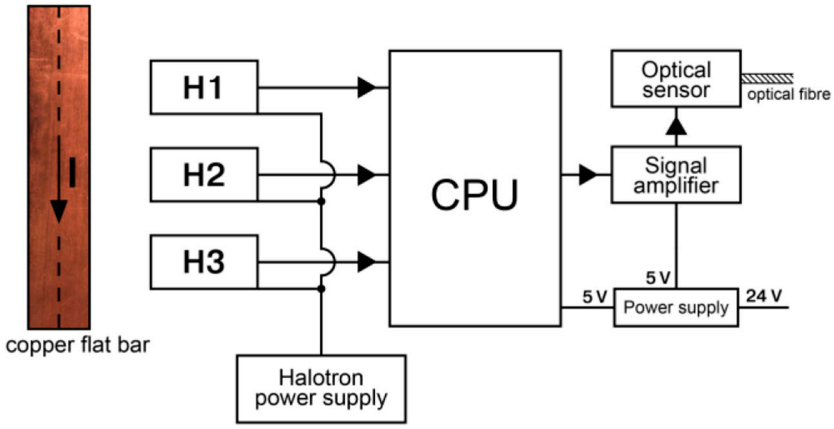


Figure 13. Oscillogram of the process of switching off the short-circuit current for resistance 0.2 Ohm and inductance 1 mH. ki—current signal amplification factor, kt—time base, ku—voltage signal amplification factor.

Figure 14a shows a block diagram of a new DC current sensor named PIKh, while Figure 14b shows a view of the circuit board on which hallotrons H1, H2, H3 are mounted.

H1, H2, H3—hallotrons responsible for detecting the direction and value of the steady current flowing through the main circuit of the circuit breaker, where:

H2 is responsible for detecting reverse current in the circuit breaker, the cause of which is the recuperation or countercurrent of the second circuit breaker in the case of the parallel operation of two circuit breakers, H3 detects the short-circuit current of opposite polarity to one of the circuit breakers (Figure 8), and H1 detects the short-circuit current of agreement with the switch polarity.



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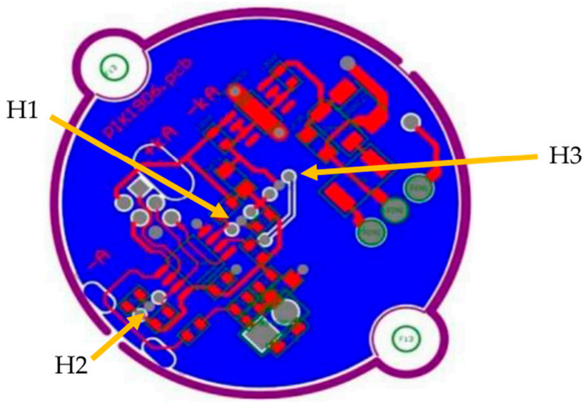

(**b**)

Figure 14. (**a**) Block diagram of the new DC sensor named PIKh. (**b**) Printed circuit board view of the PIKh sensor.

The set threshold values of hallotron tripping currents depend on the rated current of the circuit breaker and the type of vehicle (EZT, locomotive, dual-system vehicle) on which the circuit breaker is mounted. In the conducted tests, the rated current of the circuit breaker was 1200 A, while the tripping threshold of the current sensor protection was 1500 A. The PIKh current sensor is built with a central unit that receives information from hallotrons according to the block diagram shown in Figure 14. When the CPU detects a short circuit, the information is sent to a signal amplifier. The amplified signal is converted into a light signal that is not sensitive to electromagnetic fields and is sent to the main switch controller via an optical fiber. Consequently, the process of ultra-fast shutdown of the constant short-circuit current begins.

In order to standardize the assembly and eliminate additional costs of replacing the PIK sensor with a PIKh sensor, the designed and manufactured printed circuit board can be mounted in the previously used housing shown in Figure 1.

3. Results and Tests

The new PIKh current sensor was installed in a DCU-type circuit breaker after positive testing at the Department of Electric Apparatus of the University of Technology in Łódź. The circuit breaker was then delivered to a traction vehicle manufacturer for certification of ETU. The process of solving the problem of parallel operation of DCU-type vacuum circuit breakers, which switch off direct short-circuit current by means of countercurrent, was verified at the experimental track in Żmigród at the Railway Institute during the tests for releasing new vehicles (ETUs) for operation.

The tests performed consisted of repeatedly carrying out the process of switching off the operating currents through one of the circuit breakers and observing whether there would be an independent shutdown of the other circuit breaker.

Figure 15 shows the measurement system for the parallel operation of two circuit breakers equipped with a PIKh current sensor. Both circuit breakers 1 and 1′ are energized with 3 kV DC voltage by raising the traction pantographs. The outputs of circuit breakers 2 are connected. Voltmeters V1–V2 are used to measure the voltage of the circuit breakers, while V3 and V4 are used to measure the voltage of the commutation capacitors (measurements are made by the circuit breaker′s internal measurement system using measuring dividers to measure voltage). A LEM sensor was used to measure current. It was connected to an oscilloscope.

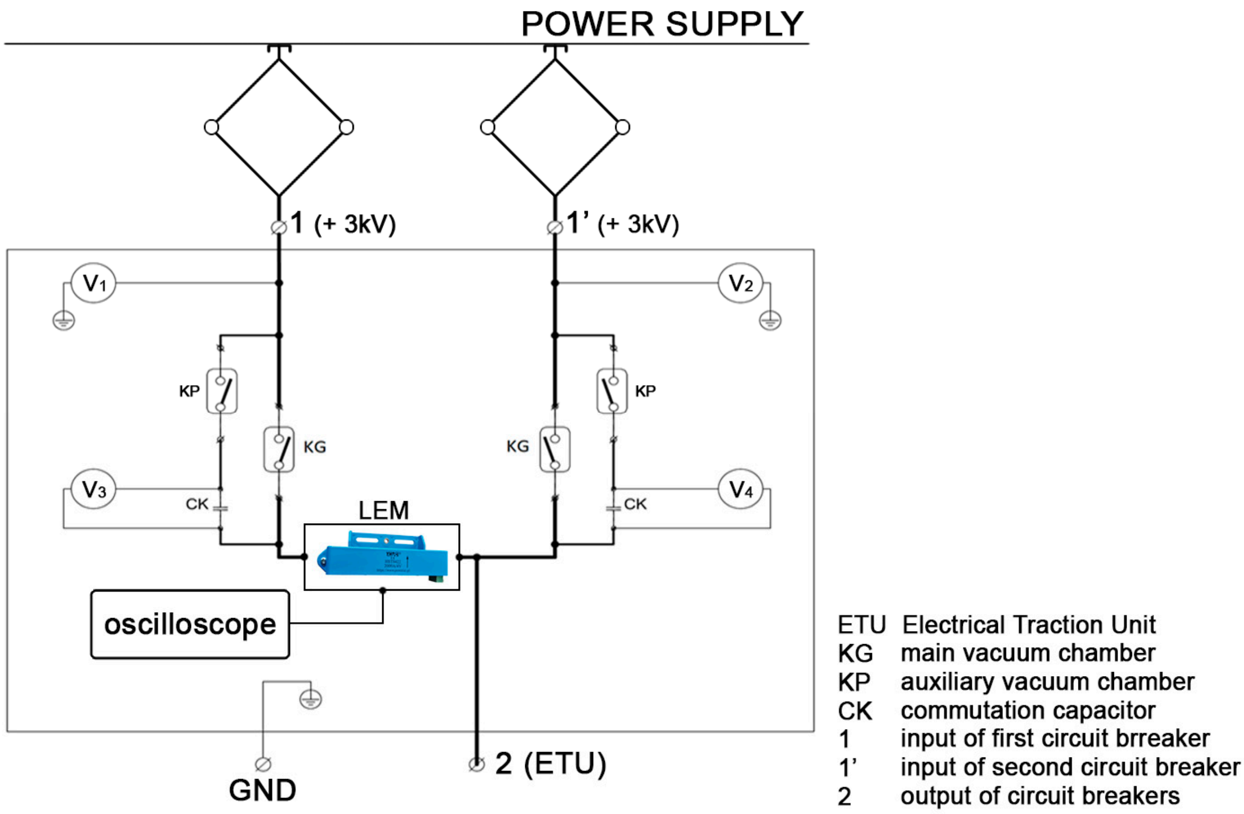

Figure 15. Measuring diagram.

The recorded, exemplary current waveforms are shown in Figure 16. The maximum measured current amplitude was 12 kA, while the oscillation time was no more than 2 ms. The recorded waveforms have a distorted shape depending on the inductance of the catenary. The current oscillations have a fading character. According to the PIKh current sensor operation algorithm described in point 2.2, it was found that the vehicle is operating in the "parking" mode and the installed switches are connected in parallel. This is due to the measured oscillation time of 1.9 ms and 1.5 ms. The measured times are less than 4 ms and the current value after this time is equal to 0 A. Tests carried out in real conditions of the parallel operation of circuit breakers of the DCU-800MNL type confirmed the effectiveness of the new PIKh current sensor and the elimination of the inappropriate phenomenon of spontaneous activation of one circuit breaker during the de-activation of the other.

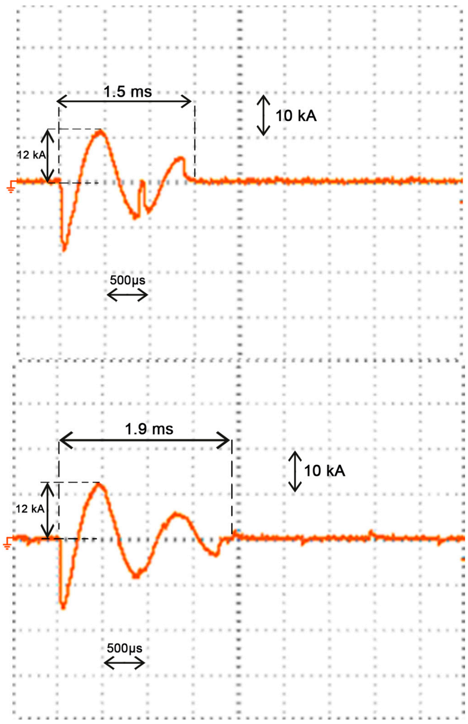

Figure 16. Exemplary current waveforms.

The solutions described in the article were verified from 2020 to 2022. DCU-type switches are operated on traction vehicles (ETU) in Poland. The three-year period of operation confirmed the effectiveness of the new PIKh current sensor in detecting different types of currents and the possibility of parallel operation of DCU-type vacuum circuit breakers.

4. Summary

This article presents the development of current sensors used in DC high-speed switches to detect short-circuit current. The result of the scientific analysis and the needs and requirements of manufacturers and users of traction vehicles in Poland is a new PIKh current sensor. The sensor enables the correct operation of ultra-fast DC circuit breakers of the DCU type during the operation of a traction vehicle in the "parking" mode of operation.

The standard of parallel operation commonly used in railroad traction has necessitated the need to adjust the parallel operation capabilities of the DC apparatuses used, especially ultra-fast DC switches of the DCU type. The new PIKh current sensor is a response to the need for the parallel operation of vacuum circuit breakers. The proposed solution makes it possible to detect the direction of the flowing current and its nature. The information sent from the sensor to the main controller of the circuit breaker via optical fibers is not sensitive to electromagnetic fields, which is a guarantee of protection of the circuit breaker from unwanted triggering of the shutdown procedure. PIKh current sensors are widely used in all DCU circuit breakers, guaranteeing the reliability of the breaker's operation and the highest standard of protection of the traction vehicle from the dangerous effects of overvoltage and short circuits.

The proposed solution meets all the requirements for the implementation of the new PIKh current sensor for applications in the railway, tram, and open-pit mining industries. The designed PIKh sensor is characterized by a simple structure, low price of production and start-up of production, as well as the use of generally available components, insensitivity to external interference, as well as small external dimensions of 100 $\times$ 85 $\times$ 50 and the possibility of programming the activation thresholds of the Hall effect sensors used.

An additional purpose of the article was to highlight the possibilities, but also the problems, during the parallel operation of vacuum circuit breakers using the principle of switching off short-circuit currents by means of countercurrent. In future publications, the authors will present parallel operation and the "parking" mode of operation for different types of circuit breakers, in particular, for hybrid and magneto-blow circuit breakers.

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