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The influence of the design and method of short-circuit current measurement on the possibility of parallel operation of high-speed circuit breakers

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Abstract: This article describes various designs of high-speed DC circuit breakers used in the world and current detection methods using modern current sensor solutions. The criterion for selecting circuit breakers for testing was their certification for use in the European Union – the LOC&PAS TSI certificate of conformity (Commission Implementing Regulation (EU) 2023/1694). The possibility of parallel operation of circuit breakers from different manufacturers and different methods of switching off the short-circuit current were analyzed. Tests were carried out at a 3 kV traction substation in real operating conditions of circuit breakers, which allowed us to answer the question regarding the possibility of using two different types of circuit breakers on one traction vehicle.

Key words: circuit breaker, countercurrent, magnetic blow-out, parallel work, sensor of current

1. Introduction

The safety and reliability of rolling stock in Poland and worldwide is the most important requirement for manufacturers of new locomotives and traction vehicles. The improvement of the reliability of rail traction vehicles is achieved through the standard of redundant operation applied and widely used for over 25 years at CERN (the European Organization for Nuclear Research) to secure the Large Hadron Collider (LHC). In the world's rail traction, redundant operation is primarily the introduction of the standard of using two high-speed circuit breakers on one vehicle, two independent drives built from an inverter and an engine, and an extensive control and management system for the entire vehicle. The control system performs the functions of supervision over the devices used on the vehicle and collects and stores detailed da-ta about them, allowing for the assessment and decision-making on their correct operation. High-speed circuit breakers are widely used worldwide for a variety of applications and systems from low voltage to as high as 500 kV. The subject of hybrid circuit breakers, improvements in their design and technical parameters is covered in the literature [1–4]. The subject of redundant operation is also common in Poland, where it has been implemented, among others, by the Department of Electrical Apparatus at the Lodz University of Technology in the concept of designing and building ultra-fast DC circuit breakers. Ultrafast circuit breakers use the countercurrent switching principle to switch off the direct short-circuit current, where the high-energy capacitors are the countercurrent source [5, 6]. Parallel operation of circuit breakers that use countercurrent to switch off a permanent short-circuit current in 3 kV circuits is not obvious. In parallel operation, switching off one of the circuit breakers generates a countercurrent, which can be detected by the current sensor of the other circuit breaker and treated as a short circuit. In such a case, the other circuit breaker will be automatically switched off. Such a situation is not allowed by the manufacturers of traction vehicles. The article presents the construction, analysis and testing of ultra-fast 3 kV DC circuit breakers to determine the effect of one circuit breaker on the other during parallel operation:

– magnetic blow-out circuit breakers, in which the drive coil is the drive that opens and closes the switch contacts, and an arc-extinguishing chamber is used to extinguish the arc,
– circuit breakers using the countercurrent switching principle (the article de-scribes an example family of DCUHMD circuit breakers), in which the arc burns in a vacuum and an inductive-dynamic drive is responsible for opening and closing the circuit breaker.

Each of the three circuit breakers selected for testing is commonly used in rail traction to protect the traction vehicle against the negative effects of overvoltages and short circuits. The criterion for the selection of circuit breakers for testing was that the circuit breaker was certified for use in the European Union – LOC&PAS TSI certificate of conformity (Commission Implementing Regulation (EU) 2023/1694). The article presents the parallel operation of magnetic blow-out circuit breakers with the DCUHMD type circuit breaker and compares the methods of current detection by current sensors used in the tested circuit breakers. The comparison made it possible to determine whether there is an effect of the countercurrent circuit breakers on the work of the magnetic blow-out circuit breakers. Due to the requirements for unification and standardization of traction vehicles in the European Union, the possibility of using different types of circuit breakers on one traction vehicle was also checked.

2. Materials and methods

2.1. Construction of high-speed circuit breakers and the method of switching off the short-circuit current

Magnetic blow-out switches – are the most popular switch solution used in rail traction worldwide. These switches are most often equipped with an overcurrent re-lease, which allows for an automatic shutdown process after exceeding the set current value. The automatic shutdown process occurs as a result of the flow of short-circuit or overload current. Magnetic blow-out switches can also be equipped with an additional release system that responds to the voltage value or the steepness of the current increase. Each switch can be triggered by an external signal issued by the traction vehicle control system.

In railway traction, the tripping system used in the toggle-type blow-out switches may be:

– polarized (the trigger current must have a specific direction, a countercurrent will not cause a trip),
– non-polarized (the direction of the trigger current does not affect the switch-off process),
– partially polarized (the value of the tripping current depends on the direction of its flow through the main circuit breaker).

The construction of magnetic blow-out switches is shown in Fig. 1.

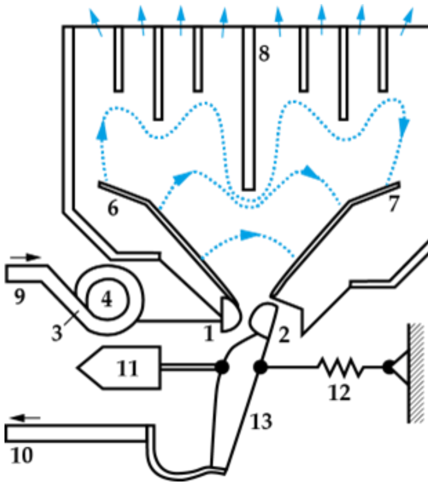

Fig. 1. Sketch of a DC magnetic blow-out switch
1, 2 – main contact, 3 – blow-off coil, 4 – blow-off coil core, 5 – arc chamber, 6, 7 – blowing cones, 8 – barrier of arc chamber, 9, 10 – upper and lower copper terminal, 11 – contact closing mechanism, 12 – contact opening mechanism, 13 – moving contact lever, dashed line – arc

The most important part of this type of high-speed DC switches is arc chamber 5, also referred to as the extinguishing chamber. The purpose of the chamber is to limit the space where the arc burns and to cool it quickly. As a result, the electric arc can be extinguished.

The circuit breaker is closed after its drive (not shown in Fig. 1) and the mechanism closing and holding the contacts 11 are switched on. Closing the contacts causes the contact separating mechanism 12 to be armed and the movable contact lever 13 to be blocked in the closed state. The contacts of the circuit breaker 1 and 2 are opened by the spring mechanism 12 after releasing the mechanism holding the contacts 11. When the contacts of the circuit breaker 1 and 2 are opened, an electric arc is ignited, which, under the influence of the electromagnetic field, the source of which is the blow-out coil 3, is directed to the arc horns 6 and 7 in the extinguishing chamber. In order to switch off the direct current, its value must be artificially reduced to zero and a con-tact gap must be provided to prevent the electric arc from re-igniting. This is achieved by increasing the resistance of the switching-off arc. This process can be divided into stages, the duration of which depends mainly on the construction of the circuit breaker and the parameters of the short-circuit circuit:

- Stage 1 current increases to the current setting value of the circuit breaker (de-pendent on the current rise rate *s* and the parameters of the short-circuit circuit).
- Stage 2 – beginning of the DC short circuit disconnection process (after the self-time t_i the contacts of switch 1 and 2 start to separate).
  The operating time of a circuit breaker depends, among other things, on its construction, the masses of the elements responsible for changing the operating state of the circuit breaker and the method of tripping.
- Stage 3: an electric arc ignites between the contacts (the arc voltage increases, the process of limiting the short circuit current begins).
  Initially the arc burns between the contacts and then between the arc horns.
- Stage 4 extinguishing the electric arc (the spreading contacts cause the electric arc to extend, which causes the arc voltage to increase).

As a result of the increase in the arc voltage, the short-circuit current reaches its maximum value limited by *Icut off*. The time in which the circuit breaker limits the short-circuit current depends on the speed of the circuit breaker contacts spreading, the increase in the arc resistance, and the efficiency of energy collection from the arc. Further increase in the arc voltage makes the current decrease until it disappears completely.

The release and opening of the magnetic blow-out switch is closely related to its design. Two basic types of designs are used in the world: a latching and magnetic catch.

Circuit breakers using the countercurrent switching off principle [7–10] – The publication focuses on circuit breakers that are operated on traction vehicles. These circuit breakers include the DCU, DCU-HM and DCUHMD families of circuit breakers manufactured between 1996 and 2025 under license from the Department of Electrical Apparatus of the Technical University of Lodz. Latest design of DCUHMD circuit-breakers are ultrafast hybrid DC circuit breakers with a parallel vacuum-thyristor hybrid topology, which operates on the principle of forced commutation, consisting in the forced reduction of DC current to zero in a vacuum using a current pulse in the opposite direction. DC circuit breakers of the DCUHMD type are designed to protect traction units, combined vehicles and locomotives against the dangerous effects of overvoltages and short circuits. Ultrafast hybrid DC circuit breakers of the DCUHMD type (Fig. 2) reduce the short-circuit current to zero using a countercurrent pulse generated by a series-connected *DK* choke and *CK* commutation capacitor. The countercurrent circuit is switched on using the *LP* countercurrent thyristor branch, while the main switching unit *KG* opens and closes the main circuit. The condition for the correct operation of the circuit breaker is the proper synchronization of *KG* and *LP*. It is required to switch on the *LP* countercurrent thyristor branch after a time of 1.5 ms from the moment of opening the vacuum chamber of the main switching unit *KG* on whose hisses an electric arc burns.

2.2. Current measurement methods

Fast current measurements have always been problematic in high-voltage circuits of devices, apparatus and traction vehicles. Commonly used current measurement methods use current shunts, Rogowski coils, current probes, transformers and non-contact LEM transducers. In the case of specialized measurements, dedicated current sensors are used:

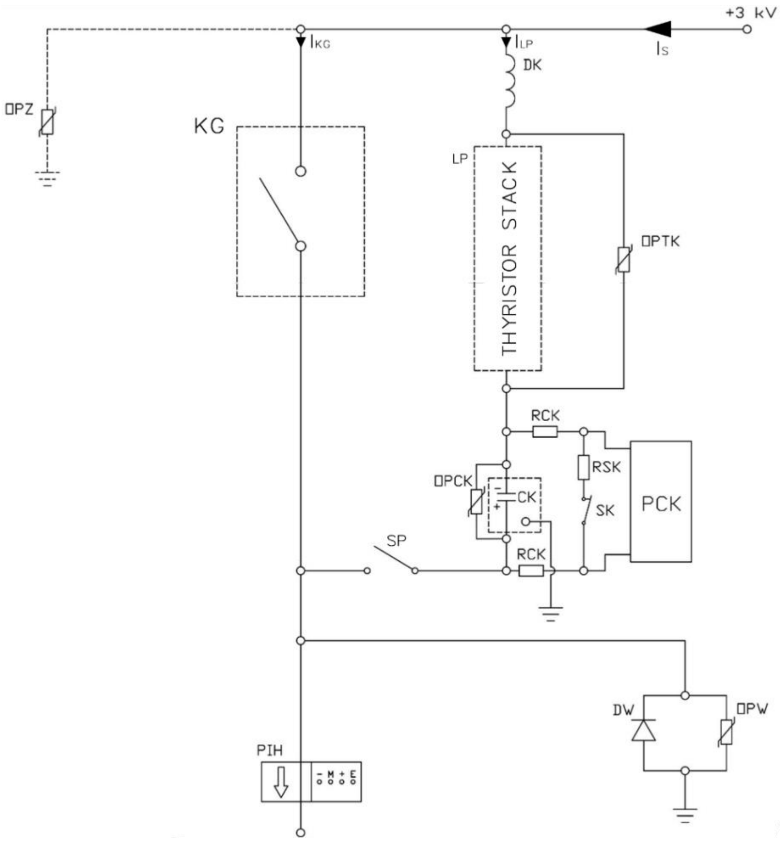

Fig. 2. Schematic diagram of circuit breaker type DCUHMD
KG – main switching unit with vacuum chamber, *SP* – countercurrent contactor, *LP* – auxiliary semiconductor element, *CK* – com-mutation capacitor, *LK* – a suppressor defining the parameters of the countercurrent pulse I_{LP}, *RCK*, *RSK SK* – *CK* capacitor charging circuit, *OPZ*, *OPW*, *OPCK*, *OPTK* – high voltage varistor, *DW* – reverse diode, *PIH* – overcurrent sensor, I_S – circuit current, I_{KG} – main chamber current, I_{LP} – auxiliary semiconductor element and capacitor current

1. Closed loop current sensor based on a circular magnetic field sensor system [11]
   The characteristic feature of the sensors is the application of the Kelvin–Stokes theorem through a closed loop using a circular arrangement of magnetic field sensors with a circular compensation coil. These sensors (Fig. 3) do not need ferro or ferrimagnetic cores; therefore, there are no phenomena of magnetic saturation, hysteresis and other magnetic nonlinearities. We can measure up to 2 kA with the sensors.
2. Optical probe/current sensor [12]
   The proposed current sensor solution (Fig. 4) is based on the Faraday effect of Bi:RIG crystals, which allows measuring currents flowing through 300 µm diameter SiC power semiconductors. The measurement method used allows for a more accurate assessment of the SiC modules' operation, which will probably improve their reliability.

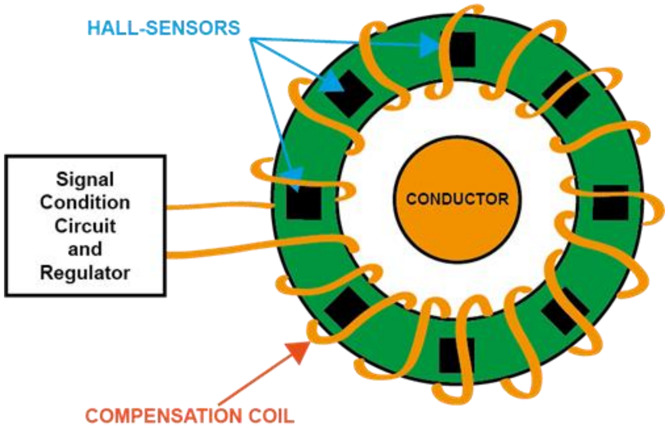

Fig. 3. Schematic of the sensor

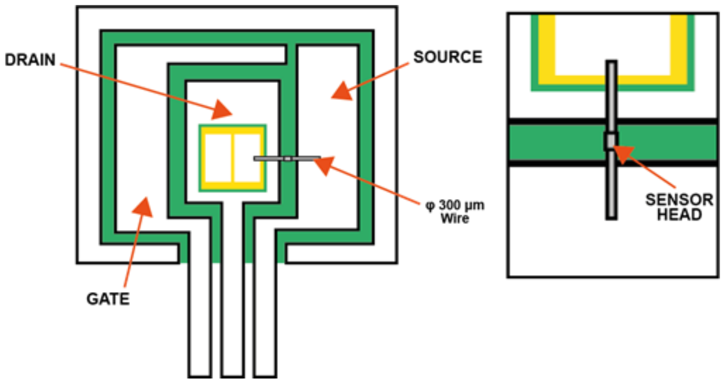

Fig. 4. Prototype circuit and the top view of the sensor head

3. Tunnel magnetoresistive sensor [13]

   A way to measure low-amplitude DC mixed with AC is a TMR current sensor, which was designed based on tunnel magnetoresistive sensors. Depending on the amplitude of the AC current (interference), TMR sensors with high or medium sensitivity are used for measurement. The sensor can accurately measure DC less than 40 mA combined with AC in the range of 100 mA to 2 A.

   Current sensors: Closed loop current sensor based on a circular magnetic field sensor system, Optical probe/current sensor and Tunnel magnetoresistive sensor have not been used in current measurement in high-speed circuit breakers.

   A separate issue is the measurement of direct current in 3 kV circuits performed by high-speed circuit breakers in order to detect the occurrence of overcurrent or short circuit in the circuit and initiate the shutdown procedure. Depending on the type and design of the high-speed circuit breaker, the current sensors described below are used.

4. Measurement of short-circuit current in a magnetic blow-out circuit breaker [14, 15]
The measurement of direct current in magnetic blow-out circuit breakers depends on the construction of the circuit breaker. The current sensor is designed for the needs of measuring current in a specific family of circuit breakers. The most popular solutions are:
   – *spring and magnetic core system*
   The device in Fig. 5 is a magnet with double magnetic circuits using magnetic energy from the main circuit for operation.

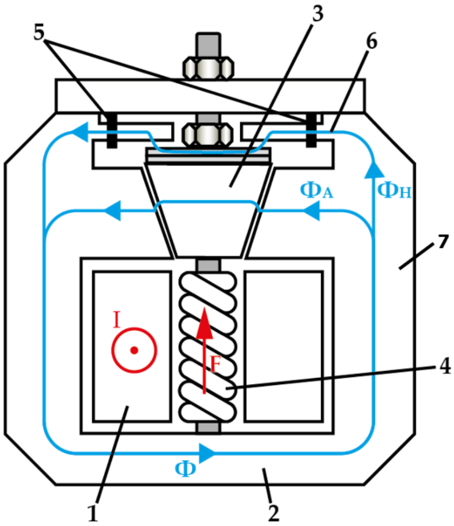

Fig. 5. Over-current tripping device
1 – current flow direction; 2 – magnetic core with two fluxes Φ_A and Φ_H; 3 – movable anchor; 4 – pressure spring for movable anchor; 5 – short circuit rings for high value di/dt; 6 – holding magnetic circuit; 7 – tripping magnetic circuit; Φ – electromagnetic flux; Φ_A – attracting flux; Φ_H – holding flux

   The equilibrium state of the mechanism is achieved when the armature 3 is held in position by the flux Φ_H and the force of the spring 4. When the main current exceeds the set threshold of the release, the value of the flux Φ_A is greater than the spring force and the value of the flux Φ_H. This causes the armature 3 to operate and the contacts to open immediately.
   – *design of the holding and releasing system with a magnetic catch*
   The device in Fig. 6 operates on the principle of magnetic capture – automatic opening of the switch occurs when the magnetic flux Φ_w generated by the main current sufficiently weakens the magnetic flux Φ_H of the holding coil. The force of holding the armature pulled by the spring is described by the formula:

$$F = \Phi_H - \Phi_w. \tag{1}$$

   If the value of the holding force F decreases below the value of the spring force, the armature 7 is separated from the core 1 and the contacts open automatically.

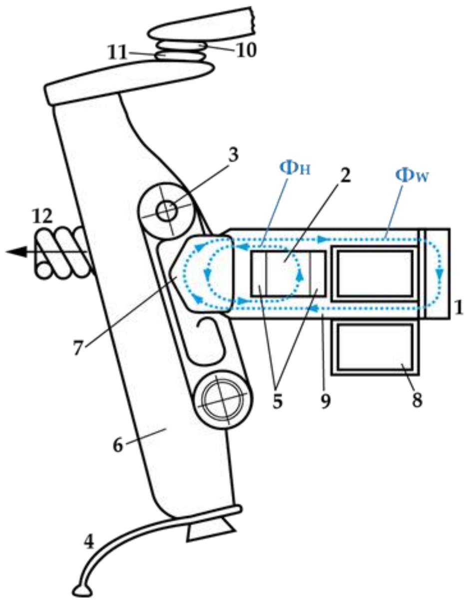

Fig. 6. Over-current tripping device

1 – holding electromagnet core; 2 – overcurrent release coil core; 3 – axis of the moving contact; Φ_W – trigger flux; Φ_H – holding flux; 4 – flexible terminal; 5 – overcurrent release coil; 6 – moving contact arm; 7 – magnetic catch armature; 8 – holding coil; 9 – holding electromagnet core; 10, 11 – main contact; 12 – contact springs

5. Current measurement in hybrid circuit breakers DCUHMD type

In hybrid circuit breakers, a specially designed sensor called *PIH* (Fig. 7) is used to measure direct current. The element that detects current is a Hall effect sensor. In circuit breakers, the *PIH* current sensor is mounted on a copper rail, which is the main current path of the circuit breaker (output copper bus).

The sensor is adjusted by screwing in or unscrewing steel screws which increase or decrease the sensitivity of the measuring element – the Hall effect sensor. A constant current flowing through a copper rail generates a magnetic field detected by the Hall effect sensor. The relationship between the current and the angle between the current and the field lines is presented by Formula (2).

$$I = \frac{F}{l * B * \sin\alpha}, \qquad \text{for} \quad \sin\alpha = 1, \quad I = \frac{F}{l * B}, \tag{2}$$

where: I is the current, B is the magnetic induction, F is the magnetic force, α is the angle between current direction and direction of the magnetic field lines, l is the length of conductor.

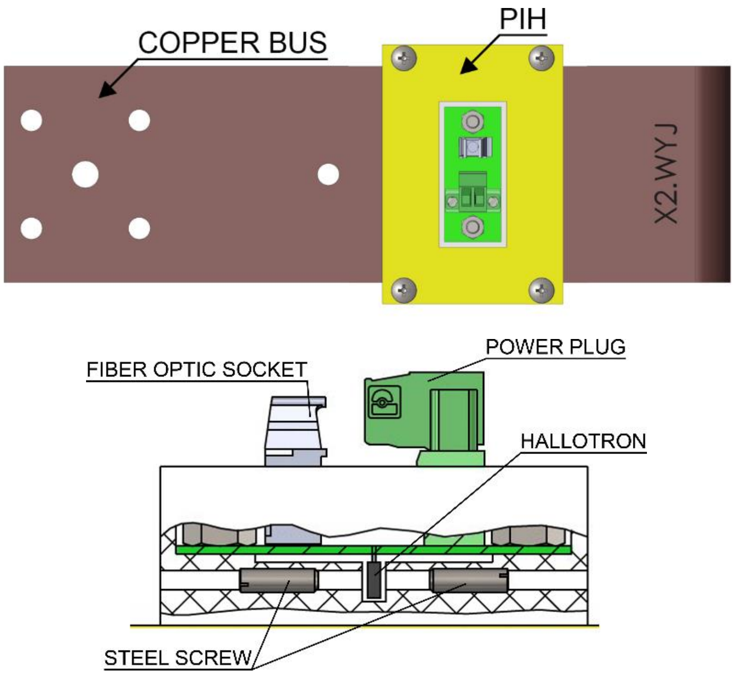

Fig. 7. Current sensor *PIH*

To adjust the *PIH* sensor, it is necessary to use a standard current source, which allows us to set the current value, after which the sensor will emit a light signal that will trigger the switch-off procedure in the switch.

2.3. Parallel operation of high-speed circuit breakers 3 kVDC [16]

The parallel operation standard, which aims to increase the reliability of the traction vehicle, is also commonly used in Poland. Manufacturers of new traction vehicles use redundant protection when designing the main circuit. Figure 8 shows the two most popular methods of powering traction motors and transferring drive from one carriage to another.

Method 1 – transferring power between carriages *A* and *B* at the level of the traction motors,

Method 2 – shows the power transfer between carriages *A* and *B* at the switch output level.

For method 2, with the pantographs raised, the circuit breakers operate in parallel. Parallel operation causes the main current to be distributed over two circuit breakers and doubles the value of the main current, after which the circuit breakers will start the automatic short circuit disconnection procedure.

For method 2:

$$\begin{gathered} I = I_{w1} + I_{w2}, \\ \text{because} \quad I_{w1} = I_{w2}, \quad \text{then} \quad I = 2I_w, \end{gathered} \tag{3}$$

where I is the main current and I_{w1}, I_{w2} represent the value of overcurrent sensor.

For method 2 (parallel operation of circuit-breakers, Fig. 8), the process of forced switching off of one of the circuit-breakers and the reaction of the second closed circuit-breaker will be analyzed.

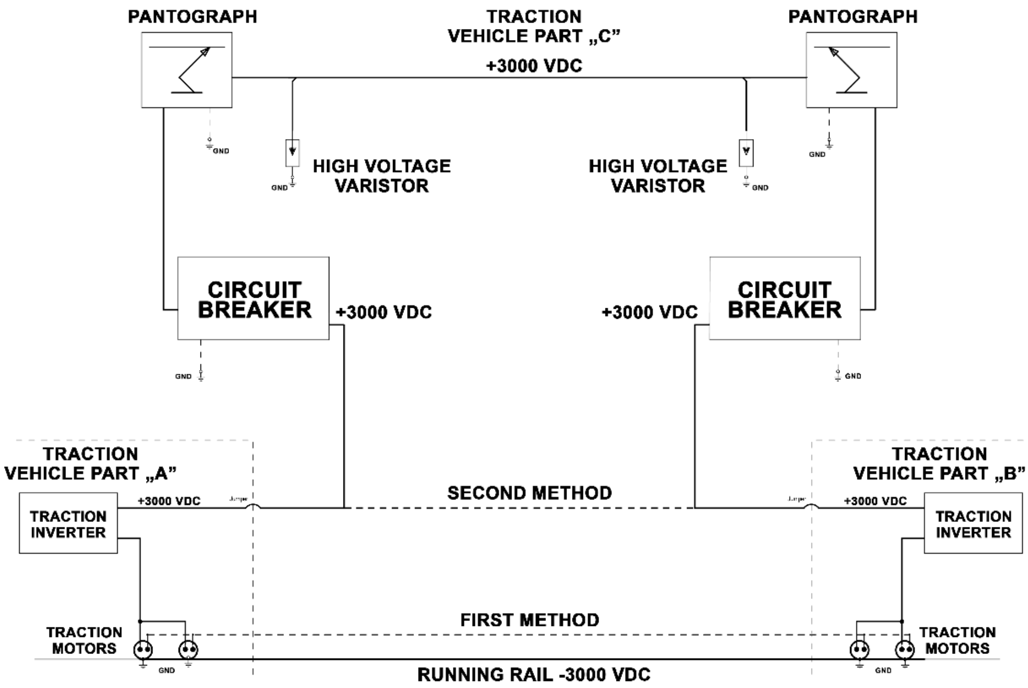

Fig. 8. Simplified main circuit of a traction vehicle [20]

Parallel operation of magnetic blow-out circuit breakers is nothing new and is not a problem in the case of a forced shutdown of one of the circuit breakers. The effect of such a shutdown is that the current is taken over by the circuit breaker that remained closed.

The problem is the parallel operation of circuit breakers that use countercurrent to extinguish the electric arc. For these circuit breakers, countercurrent is necessary to switch off operating, rated and short-circuit currents. During such a switch-off, the countercurrent can be detected by the current sensor of the other breaker under parallel operation and treated as a short circuit. As a result, self-acting tripping will occur.

In order to analyse the parallel operation of countercurrent circuit breakers with magnetic blow-out circuit breakers, it is first necessary to analyse the process of switching off the short-circuit current through the DCUHMD circuit breaker Fig. 9(a).

Assumptions:

1. U = 3 000 VDC,
2. *KG* is the main vacuum chamber,
3. A short circuit current flows through the *KG* chamber.

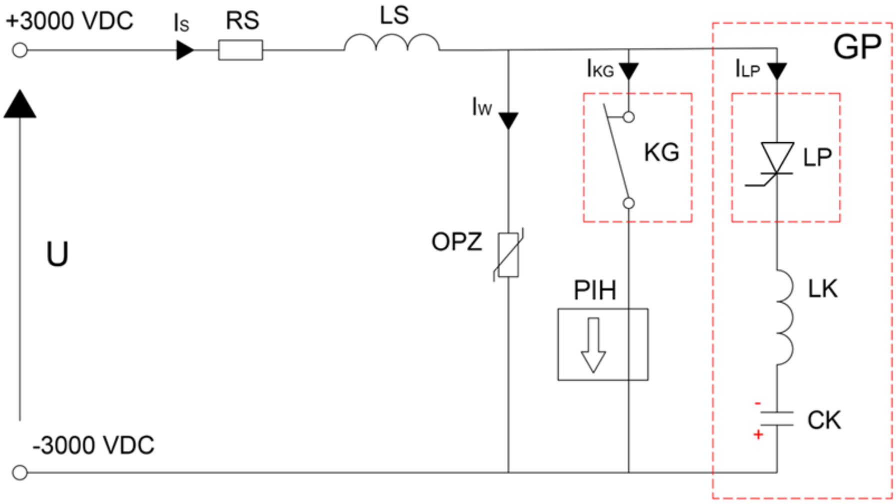

Fig. 9(a). Schematic diagram of a DC circuit turned off by circuit breaker type DCUHMD
KG – main vacuum chamber, *LP* – auxiliary semiconductor element, *CK* – commutation capacitor, *LK* – a suppressor defining the parameters of the countercurrent pulse I_{LP}, *OPZ* – high voltage varistor, *PIH* – overcurrent sensor, I_S – circuit current, I_{KG} – main chamber current, I_{LP} – auxiliary semiconductor element and capacitor current, *RS* – line resistance, *LS* – line inductance, *U* – power supply, *GP* – countercurrent generator

When the *PIH* sensor detects a short circuit current, the contacts of the *KG* vacuum chamber open and an arc voltage appears on its contacts. Then, after a set time of 1.5 ms, the *LP* semiconductor element is closed and the I_{LP} current starts to flow. In this case, the equation is correct:

$$I_s = I_{KG} + I_{LP} = \text{const} \tag{4}$$

and

$$\frac{\mathrm{d}I_{KG}}{\mathrm{d}t} = -\frac{\mathrm{d}I_{LP}}{\mathrm{d}t}. \tag{5}$$

The equation shows that the absolute value of the rate of decrease in the current I_{KG} will be equal to the absolute value of the rate of increase in the current I_{LP} in the *GP* countercurrent generator branch. The current in the circuit will be switched off when the currents are equal

$$I_S = I_{LP}, \tag{6}$$

because the current I_{KG} will reach a value equal to zero. From the above equation one can conclude that the maximum value of the short-circuit current that can be interrupted by the vacuum circuit-breakers with vacuum chamber is limited to the maximum value of the current I_{LP} generated by the *GP* generator.

The current I_{LP} can be described by the equation

$$I_{LP} = -\frac{U_k}{\omega_o L_k} e^{-\alpha t} \sin(\omega_o t), \tag{7}$$

where: U_k is the voltage on capacitor *CK*, ω_0 is the pulsation of natural oscillation of the circuit, α is the damping constant, *LK* is the inductance of the *GP* generator.

If the *RCK* resistance seen from the terminals of the capacitor *CK* (*RCK* is the self-resistance of the series connection of the *KG, LP, LK* elements) is much smaller than the wave impedance *Zf*, one can assume that the maximum current $I_{LP\,\max}$ is

$$I_{LP\,\max} = \frac{U_k}{Z_f}, \tag{8}$$

where:

$$Z_f = \sqrt{\frac{LK}{CK}}, \tag{9}$$

$$\alpha = \frac{R_{CK}}{2LK}, \tag{10}$$

$$\omega_o = \sqrt{\omega_n^2 - \alpha^2}, \tag{11}$$

$$\omega_n = \frac{1}{\sqrt{LKCK}}. \tag{12}$$

For DCUHMD circuit breakers the maximum current value $I_{LP\,\max}$ is 10–17 kA (the value is dependent on the parameters of the countercurrent generator).

In order to determine whether the countercurrent of the DCUHMD circuit breaker could cause an unintentional shutdown of the magnetic blow-out circuit breaker, the fault current with rise steepness *s* and the half-wave countercurrent generated by the *GP* (countercurrent generator) was simulated. The simulation was carried out for the system shown in Fig. 9(b), while the obtained relations between the currents are shown in Fig. 9(c).

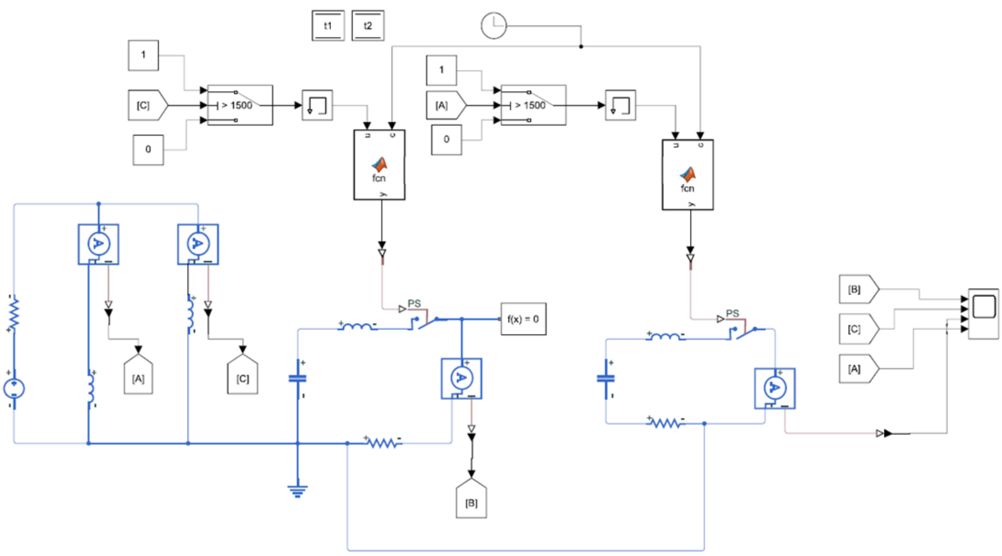

Fig. 9(b). Diagram of the circuit for testing the dependence of the short-circuit current with the steepness *s* and the countercurrent half-wave switching

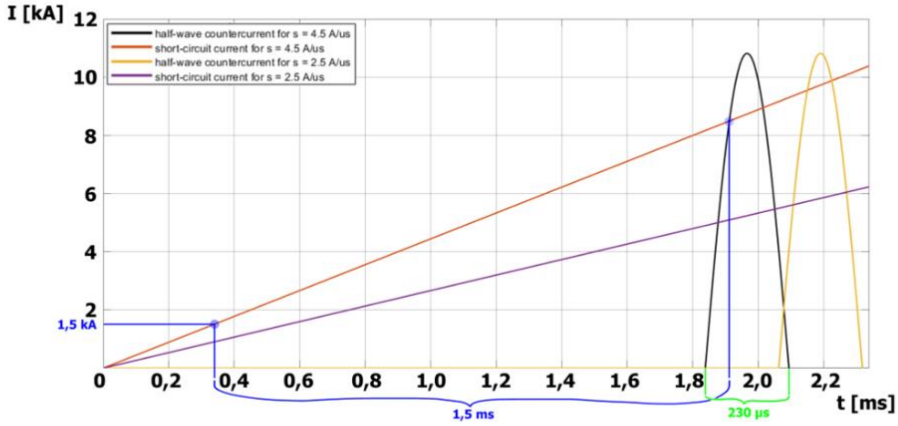

Fig. 9(c). Graph of the dependence of the short-circuit current with the steepness s and the switching on of the countercurrent half-wave

The analysis shows that:

- for DCUHMD circuit breakers, the steepness of current rise $s = (2.5 - 4.5)$ A/µs affects the rate at which the circuit breaker detects the short-circuit current. A further increase in the steepness of the rise of the short-circuit current will result in the amplitude of the countercurrent half-wave being too small to switch off the short-circuit current. Studies have shown the need to recalculate *GP* (countercurrent generator) parameters for different overhead contact lines worldwide,
- the time from the detection of the short-circuit current (current above 1 500 A) by the DCUHMD breaker is constant at 1.5 ms,
- the total switch-off time is no more than 2.2 ms,
- the countercurrent duration is less than 230 µs.

  Note: In order to show the equalization point of currents $I_S = I_{LP}$, the half-wave of the countercurrent is placed in the positive part of the I current axis (in reality, the half-wave is negative).

Knowing the maximum value of the countercurrent duration t_{LP} for DCUHMD circuit breakers, an analysis of parallel operation can be carried out. The analysis of the parallel operation of the DCUHMD circuit breaker and the magnetic-blast circuit breaker was carried out in the circuit of Fig. 10.

Assumptions:

1. $U = 3\ 000$ VDC,
2. $I_s = 1\ 000$ A,
3. First switch – DCUHMD switch is closed,
4. Second switch – magnetic blow-out switch is closed,
5. The first and second circuit breakers have a current sensor set to 1 500 A.

At the moment of forced tripping of the DCUHMD circuit breaker, in accordance with the analysis performed above, countercurrent I_{LP} will be generated, the value of which will be proportional to the tripping current Is. In this case, the equation is true.

$$I_s = I_{KG} + I_2(-I_{LP}). \tag{13}$$

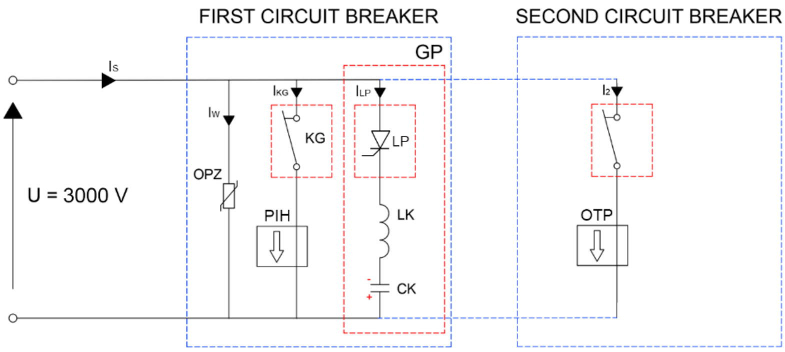

Fig. 10. The view of parallel work of circuit breaker DCUHMD and magnetic blow-out switch
KG – main vacuum chamber, *LP* – auxiliary semiconductor element, *CK* – commutation capacitor, *LK* – a suppressor defining the parameters of the countercurrent pulse I_{LP}, *OPZ* – high voltage varistor, *PIH*, *OTP* – over-current sensor, I_{KG} – main chamber current, I_{LP} – auxiliary semiconductor element and capacitor current, *U* – power supply 3 kV, *GP* – countercurrent generator

Since the switches operate in parallel, opening one of them does not cause an electric arc to ignite. The current of the main circuit I_{KG} of the switched off switch is taken over by the closed second switch. The current flows in the circuit described by the equation.

$$I_s = I_2. \tag{14}$$

If you carry out the same test, but for a short-circuit current limited to 10 kA, which flows through the circuit in Fig. 10, the countercurrent I_{LP} will not be greater than

$$I_{LP\,\max} = \frac{U_k}{Z_f} = 10\text{ kA}. \tag{15}$$

Since the duration of the countercurrent t_{LP} is less than 230 µs, it follows from the technical data of the magnetic blow-out circuit breakers that the opening time of these circuit breakers is between 2 and even 11 ms, depending on the steepness of the short-circuit current rise. In contrast, the time required for the magnetic blow-out circuit breaker current sensor t_{OTP} scaled to 1 500 A to detect the countercurrent is approximately 350 µs for $s = 4.5$ A/µs. In this case, the magnetic blow-out switch should not open spontaneously. This is evident from a comparison of the times at which the countercurrent t_{LP} of the DCUHMD breaker flows (230 µs) and the time required for the magnetic blow-out circuit breakers t_{OTP} to detect a short circuit and trigger the shutdown procedure (2–12 ms).

$$t_{LP} \ll t_{OTP}. \tag{16}$$

3. Results and tests

The main objective of the conducted research was to determine the possibility of parallel cooperation of ultrafast hybrid circuit breakers DCUHMD with DC magnetic blow-out circuit breakers and to determine the unfavorable phenomena that may occur in the case of such cooperation. In Europe and worldwide, several types of magnetic blow-out circuit breakers are used. Due to the possibility of borrowing circuit breakers for testing, 5 basic types of circuit breakers were selected with their variations. Table 1 presents the types of magnetic blow-out circuit breakers and their selected technical parameters.

Table 1. Basic parameters of selected types of magnetic blow-out and hybrid switches [17–23]

Parameter[1)]	**Symbol**	**Values**						**Unit**
		Hybrid Switch DCUHMD	**WSe**	**BWSe**	**UR40-64**	**IR6040**	**Gerapid 2607 Gerapid 4207**	
Nominal voltage	U_{Ne}	4	3	4	3.6	3	4	kV
Rated operating current	I_{Ne}	1 600	600 1 000 2 000 3 000	1 000 1 600 2 000 2 500 3 150	3 600	4 000	2 600 4 200	A
Rated short circuit current for time constant of the circuit	I_{Nss}; t_c	60/20	20/20 or 40/20	50/10	40/31.5	70/0 100/0[3)] 40/20 70/20[3)]	30/31.5 42/31.5[3)]	kA/ms
Maximum steepness of short circuit current rise	$\mathrm{d}i/\mathrm{d}t_{\max}$	3 5 – special execution	–	5	–	–	–	kA/ms
Own time	t_i	2.2	≤ 5[2)]	≤ 5[2)]	≤ 14[2)]	–	≤ 5[4)]	ms
Switching overvoltage	u_a		7	7	8	–	7	kV
Connection durability	–	20 000	–	1 000	–	5 000	1 000	Connection cycle
Mechanical durability	–	20 000	5 000	25 000	–	20 000	20 000	Cycle[5)]
Construction type	–	–	with magnetic catch		ratchet			–

[1)] – designation according to PN-EN 50123-2 [24]
[2)] – for $\mathrm{d}i/\mathrm{d}t \geq 0.5$ kA/ms
[3)] – current value in the pulse
[4)] – for $\mathrm{d}i/\mathrm{d}t \geq 5$ kA/ms
[5)] – close-open cycle

The following circuit breakers were selected for testing the parallel operation of high-speed circuit breakers:

– ultrafast hybrid circuit breaker DCUHMD,
– non-polarized magnetic blow-out circuit breaker Gerapid 4207 (Gerapid),
– polarized magnetic blow-out circuit breaker BWSe-2500 (BWS).

3.1. Configuring breakers and scaling current sensors

Parallel operation tests were performed with the circuit breaker configurations and trip sequences shown in Table 2.

Table 2. Configuration of tests for parallel operation of circuit breakers

Sample no.	Sequence of operation	Switch polarity
1	DCUHMD – Gerapid	–
2	Gerapid – DCUHMD	–
3	DCUHMD – BWS	Compatible polarity
4	BWS – DCUHMD	Compatible polarity
5	DCUHMD – BWS	Opposite polarity

Figure 11 shows the measurement system for parallel operation of circuit breakers. The tests were performed for the same supply voltage value of 3 620 V, constant total cur-rent value of 1 520 A and time constant of the circuit of 8.6 ms.

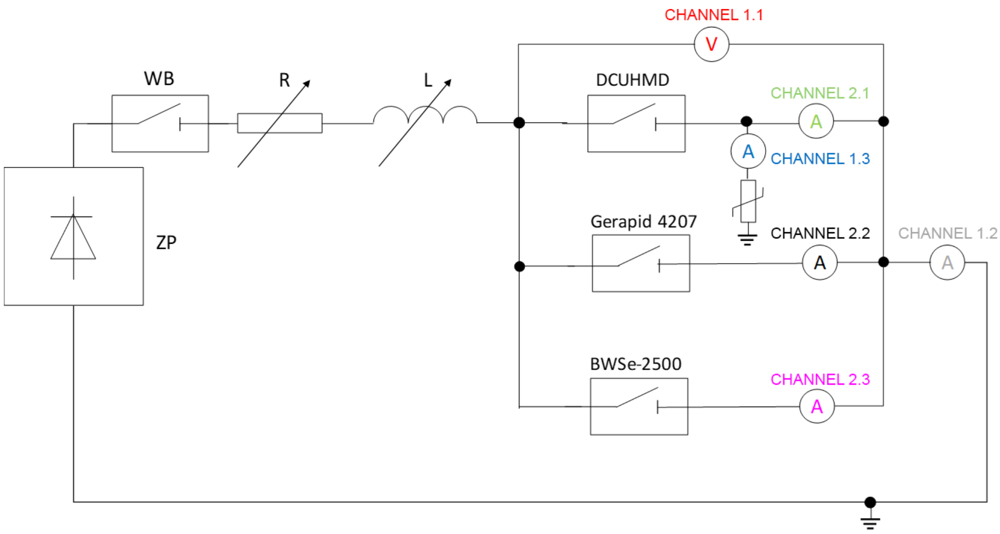

Fig. 11. Measuring diagram
ZP – rectifier unit, *WB* – safety switch, *R* – adjustable resistance *LK* – adjustable inductance, DCUHMD, *BWS*, Gerapid – circuit breakers, *A* – current measurement, *V* – voltage measurement; the color of the measuring instruments *A*, *V* corresponds to the colours of the waveforms shown in the Figs. 12, 13

Before starting the measurements, the current sensors of the tested high-speed circuit breakers were calibrated. The measured current settings of the circuit breakers were the following:

– DCUHMD – 1 800 A,
– Gerapid – 2 000 A,
– BWS – 1 970 A.

3.2. Parallel operation tests

Parallel operation tests were carried out in the Short-Circuit Laboratory of the Railway Institute in Mińsk Mazowiecki at a 3 kVDC traction substation.

Example of a test run according to the measuring system Fig. 11:

1. For circuit breaker configuration Table 2 sample no. 1,
2. 24 V DC control voltage is applied to the DCUHM circuit breaker (the process of charging the internal capacitors starts. Once they are charged, the circuit breaker will issue a signal ready to switch on),
3. Activation of *ZP*,
4. Closure of safety switch *WB*,
5. Closure of the DCUHMD and Gerapid breaker,
6. Shutdown of the DCUHMD breaker,
7. Record of voltage and current waveforms.

Measured currents and voltages and the designation of the channel on which they were measured:

– U_{ov}, $U_{a\,\max}$ – switching overvoltage while being switched off by DCUHMD, maximum arc voltage of Gerapid or BWS circuit breakers – red color – channel 1–1;
– I_c – total current – grey colour – channel 1–2;
– $I_{s\,\max}$ – surge arrester current – blue color – channel 1–3;
– I_{bH} – current switched off by the DCUHMD switch – green color – channel 2–1;
– $I_{H\,\max}$, $I_{G\,\max}$, $I_{B\,\max}$, $I_{c\,\max}$ – maximum values of currents flowing through the DCUHMD, Gerapid or BWS circuit breaker and the maximum value of the total current.

The testing process was repeated according to the switch configurations shown in Table 2.

Examples of the recorded voltage and current waveforms are shown in Figs. 12–13 (sample no. 1–2), and all the results are summarized in Table 3.

Note: In the figures, the current waveform of the $I_{S\,\max}$ surge arrester has reversed polarity to improve the readability of the waveforms.

The measurements carried out during the parallel operation of the DCUHMD circuit breaker with the Gerapid circuit breaker confirmed that during the forced tripping of one of the circuit breakers, the other one does not trip spontaneously, Figs. 12, 13. The same test was carried out for the parallel operation of the DCUHMD and BWS circuit breakers. In this case, because the BWS circuit breaker is polarized, the test was carried out in two variants, Table 2 (samples 3–6). The measured values of currents and voltages are presented in Table 3. During the tests, the second circuit breaker did not trip spontaneously.

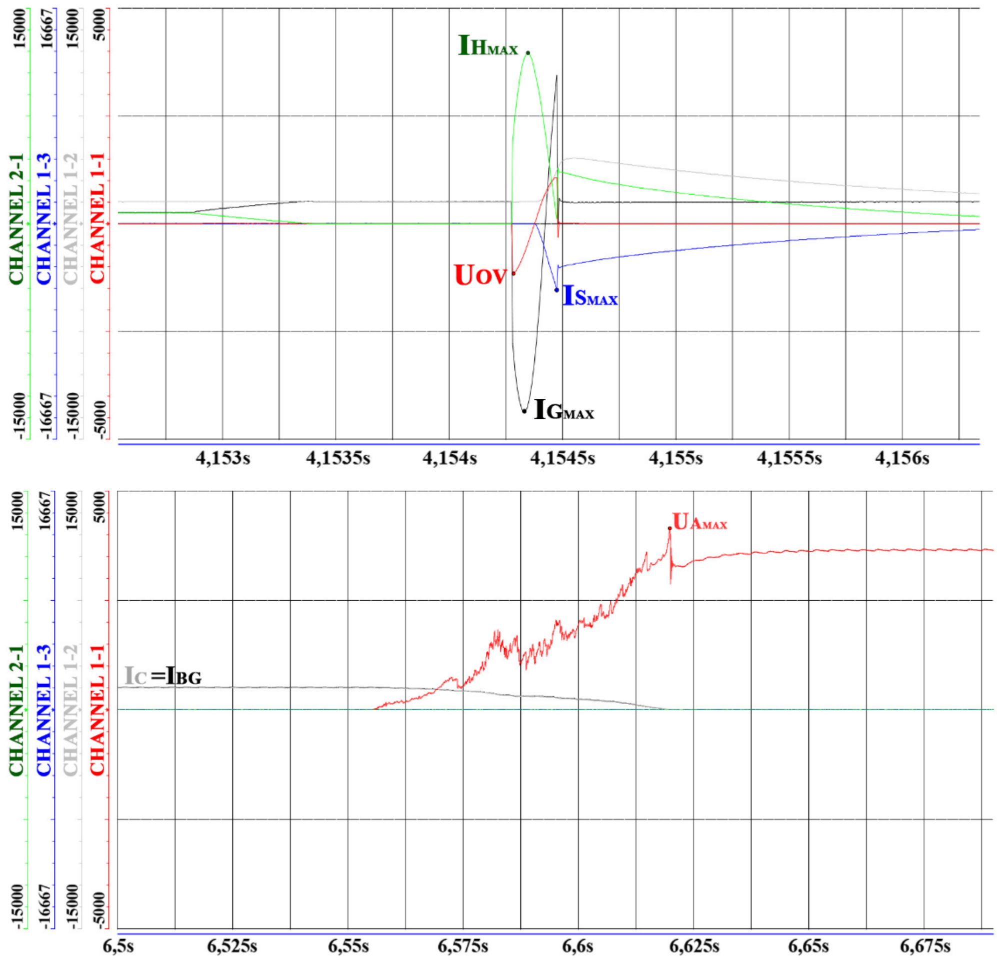

Fig. 12. DCUHMD-Gerapid parallel operation test
ZP – rectifier unit, *WB* – safety switch, *R* – adjustable resistance *LK* – adjustable inductance, DCUHMD, Gerapid – circuit breakers, *A* – current measurement, *V* – voltage measurement, The colour of the measuring instruments *A*, *V* corresponds to the colours of the waveforms shown in the Figs. 12, 13

To sum up, during the parallel operation it does not matter whether the circuit breaker is polarized or not. Switching off one of the circuit breakers does not cause the other one to trip spontaneously. For all the tests carried out, the time of current transfer from the circuit breaker being opened by the circuit breaker remaining in the closed state is shorter than 0.5 ms.

The simulation and laboratory studies carried out do not conclude the subject of parallel operation of circuit breakers when one of the circuit breakers uses the countercurrent to switch off the current in the circuit. The need to adapt the *GP* countercurrent generator to the different parameters of the traction system is a significant limitation to the use of this type of circuit breaker.

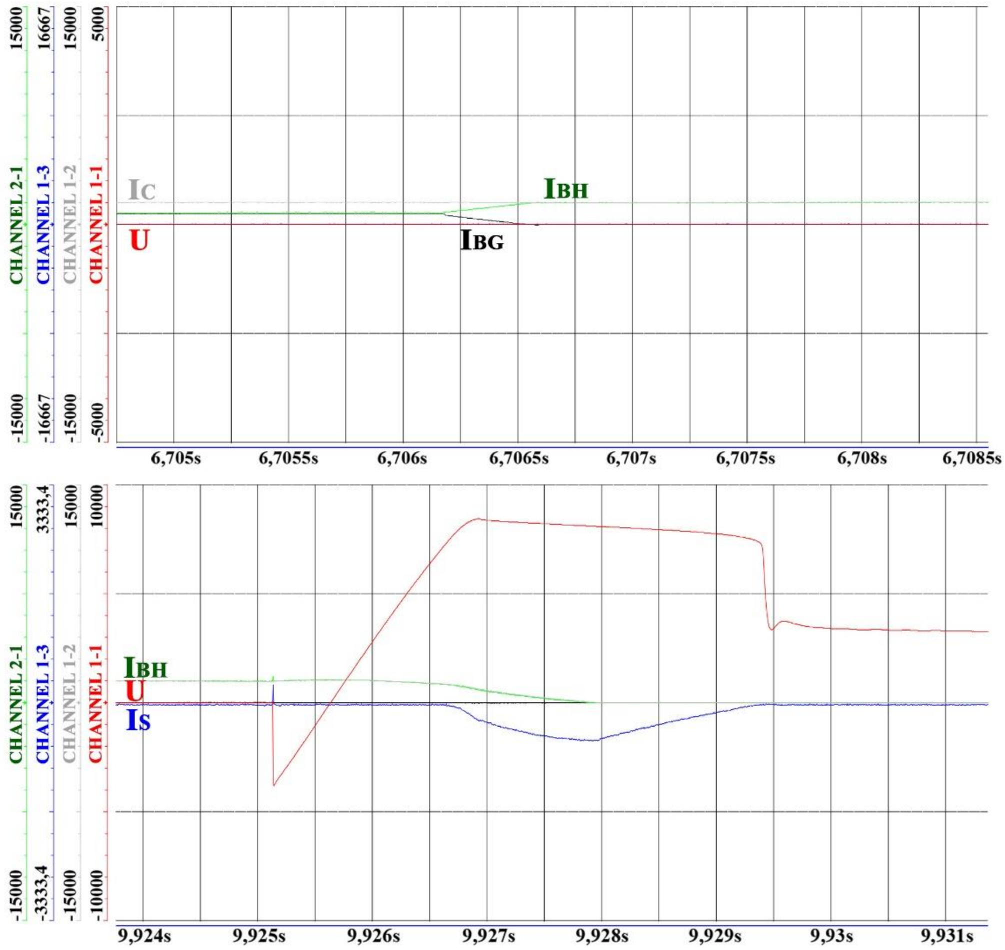

Fig. 13. Gerapid-DCUHMD parallel operation test

ZP – rectifier unit, *WB* – safety switch, *R* – adjustable resistance *LK* – adjustable inductance, DCUHMD, Gerapid – circuit breakers, *A* – current measurement, *V* – voltage measurement, The colour of the measuring instruments *A, V* corresponds to the colours of the waveforms shown in the Figs. 12, 13

In industrial versions, manufacturers are making a compromise between the price of the breaker and its applicability. This problem does not apply to magnetic blow-out circuit breakers, which, according to their principle of operation, more easily and quickly switch off steady short-circuit currents with a high value of the steepness of current rise. The limitation of the use of magnetic blow-out circuit breakers is the value of the critical current (I_{cr}), which can be approximately written with the formula

$$I_{cr} = 0,1 * I_{rt}, \tag{17}$$

where I_{rt} is the rated current.

Table 3. Results of tests on parallel cooperation of high-speed circuit breakers

Sample no.	DCUHMD			Gerapid			BWS			Symbol	Value	Unit
	Symbol	Value	Unit	Symbol	Value	Unit	Symbol	Value	Unit			
1	U_{ov}	–1 144	V	$U_{a\,\max}$	4130	V	$U_{a\,\max}$	–	V	$I_{c\,\max}$	4 587	A
	I_{bH}	777	A	I_{bG}	1526	A	I_{bB}	–	A			
	$I_{H\,\max}$	11 881	A	$I_{G\,\max}$	–13135	A	$I_{B\,\max}$	–	A			
	$I_{S\,\max}$	5 053	A	–	–	–	–	–	–			
2	U_{ov}	8 460	V	$U_{a\,\max}$	0	V	$U_{a\,\max}$	–	V	$I_{c\,\max}$	1 597	A
	I_{bH}	1 510	A	I_{bG}	737	A	I_{bB}	–	A			
	$I_{H\,\max}$	1 830	A	$I_{G\,\max}$	737	A	$I_{B\,\max}$	–	A			
	$I_{S\,\max}$	589	A	–	–	–	–	–	–			
3	U_{ov}	–1 022	V	$U_{a\,\max}$	–	V	$U_{a\,\max}$	4 666	V	$I_{c\,\max}$	4 518	A
	I_{bH}	855	A	I_{bG}	–	A	I_{bB}	1 543	A			
	$I_{H\,\max}$	11 550	A	$I_{G\,\max}$	–	A	$I_{B\,\max}$	–10 886	A			
	$I_{S\,\max}$	5 229	A	–	–	–	–	–	–			
4	U_{ov}	8 481	V	$U_{a\,\max}$	–	V	$U_{a\,\max}$	0	V	$I_{c\,\max}$	1 601	A
	I_{bH}	1 526	A	I_{bG}	–	A	I_{bB}	656	A			
	$I_{H\,\max}$	1 601	A	$I_{G\,\max}$	–	A	$I_{B\,\max}$	656	A			
	$I_{S\,\max}$	595	A	–	–	–	–	–	–			
5	U_{ov}	–1 019	V	$U_{a\,\max}$	–	V	$U_{a\,\max}$	4 760	V	$I_{c\,\max}$	4 162	A
	I_{bH}	843	A	I_{bG}	–	A	I_{bB}	1 512	A			
	$I_{H\,\max}$	11 773	A	$I_{G\,\max}$	–	A	$I_{B\,\max}$	–10 968	A			
	$I_{S\,\max}$	4 471	A	–	–	–	–	–	–			
6	U_{ov}	8 488	V	$U_{a\,\max}$	–	V	$U_{a\,\max}$	0	V	$I_{c\,\max}$	1 612	A
	I_{bH}	1 525	A	I_{bG}	–	A	I_{bB}	713	A			
	$I_{H\,\max}$	1 612	A	$I_{G\,\max}$	–	A	$I_{B\,\max}$	713	A			
	$I_{S\,\max}$	6 16	A	–	–	–	–	–	–			

4. Conclusions

The article presents the construction of three selected, commonly used high-speed circuit breakers in the European Union and the methods of measuring and detecting the constant short-circuit current by these circuit breakers. The effect of the conducted scientific analysis and the needs and requirements of manufacturers and users of traction vehicles among others in Poland are the tests conducted in real operating conditions of high-speed circuit breakers. The tests conducted at a 3 kV traction substation confirmed the possibility of parallel operation of circuit breakers that reduce the constant short-circuit current to zero in a different way.

The parallel operation standard commonly used in railway traction forces manufacturers of modern high-speed DC circuit-breakers not only to enable parallel operation of circuit-breakers of the same type, but also to respond to the possibility of replacing one type of a circuit-breaker on a traction vehicle with a circuit-breaker of a different type.

An additional aim of the article was to draw attention to the subject of 3 kV direct current circuit-breakers and to present available solutions, directions of development of circuit-breakers and methods of their adaptation to the changing requirements of manufacturers of modern traction rolling stock.

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