Researches and tests of high-speed circuit breakers for rolling stock and substations in 3 kV DC traction power system

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Summary

Before placing in service in the railway electrical traction high-speed circuit-breakers shall be the subject of conformity tests with standards.

The high-speed circuit breakers are an essential safeguard against the flow of an excessive current in the circuit overhead line and vehicles being powered by it. That is the reason why the circuit breakers must be equipped with systems which allow extinguish the high-energy arc. Additionally, the short circuit currents must be switched off as soon as possible to minimize the risk of damage, protected by circuit breakers, elements of an electric traction power supply system.

The main document identifying requirements and a scope of the high-speed DC circuit breaker's research for traction substation and sectioning cabins is the PN-EN 50123-2 standard. In the case of the on- board high-speed DC circuit breakers, requirements and scope of the research regulates the PN-EN 60077-3 standard. Although, two standards – PN-EN 50123-2 and PN-EN 60077-3 – apply to the same type of electric gear, the symbols and volume and parameter indexes used therein are different, what causes some inconvenience in analysis and results comparison, especially in terms of circuit breaker cooperation (f.e. in ensuring the coordination of short circuit protection in the traction vehicle – traction substation relation). Besides above standards, the requirements for high-speed DC circuit breakers are contained in PN-EN 50388 standard and technical specification for interoperability of the subsystem "Energy" (TSI "Energy").

For most of the test points and high speed D.C. circuit breaker checks, requirements that are contained in standards, testing and results are not problematic. However, part of the research and their result may be the basis of a discussion about real properties and parameters of circuit breakers. These tests and checks are contact life research, switching capacity check, designation and critical currents switching off and coordination of short circuit protection in the traction vehicle – traction substation relation.

The data analysis presented by the producers of circuit breakers show that none of them classifies their products as one of the type: H, V or S, that are defined by PN-EN 50123 standard. Based on many measurements performed by Instytut Kolejnictwa it is possible to determine the type of high-speed D.C. circuit breakers designed to 3 kV D.C. system, produced by the leading European

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companies. The example of the current limiting very high-speed circuit breaker type V that is produced in Poland can be taken only one of a type DCN. The current limiting high-speed circuit breaker type H is a one of a series BWS, while circuit breakers UR40 is classified to the semi-high-speed circuit breaker type S.

The next „imperfection" of the standards containing the requirements for high-speed D.C. circuit breakers is a guideline for short circuit. In such a short circuit should be only inductance and resistance. Whereas in the real conditions in short circuits, where high-speed circuit breakers are working, there are capacities, for example as filters in traction substations or input filters in traction vehicles.

Analyzing the short circuit current flow it can be stated that switching on of resonance filter caused extra switching off time about 10%. As a result of later release and oscillating changes of short circuit current, the value of maximum limiting short circuit current increases about 15%.

The critical currents switching off are bonded with relatively long burning arc on the contacts of circuit breaker. The burning time of an arc while small values of currents switching off is from over a dozen to ten times longer, than short circuit currents. By this time, which can be up to few or even several seconds, the circuit breaker contacts are exposed to arc, arcing horns and arc chamber. It causes significant arcing erosion of these elements.

The standards do not define at what time critical currents should be switched off and do not specify which critical currents value should be taken as a result of tests.

To achieve selectivity of short circuit and overload currents switching offs forming in rolling stock is possible while on-board circuit breaker switches off the current before the circuit breaker for use in substations and sectioning cabins will get tripped. It will happen only when on-board circuit breaker limits the current to a value lower than the tripping level of the circuit breaker for use in the fixed installations. It will happen when steepness of short circuit grow is small enough that on-board circuit breaker starts to limit the current before it reaches the tripping level of high-speed circuit breaker for use in substation. The limit value d*i*/d*t*, at which short circuit current will be switched off only by the on-board circuit breaker depends on independent opening time of on-board circuit breaker, its limiting current capacity and the difference between the values of setting of on-board circuit breaker and circuit breaker for use in fixed installations.

The results of the simulation, analysis and tests show, that it is not, at the moment, possible to obtain selective short circuit switching offs in rolling stock. At the European market of circuit breakers the greatest range of selectivity show vacuum circuit breakers DCN-L and DCU using in rolling stock.

Keywords: high-speed circuit breaker, short circuit, critical currents, coordination of protection.

Introduction

The high-speed circuit breakers of D.C. used in the railway systems, that are installed both in rolling stock and substations and sectioning cabin, are a subject to a process of placing them to service. The on-board high-speed circuit breakers need to be certified as interoperability elements based on technical specification for interoperability that refers to a subsystem ”Rolling stock - locomotives and passenger rolling stock” [2] (TSI “Loc&Pas”), while high-speed circuit breakers for use in substations according to Regulation of the Minister of Transport, Construction and Maritime Economy [15], [16]. Regardless of the legal basis and the place of installation, to be placed in service, the high-speed circuit breakers must be tested for compliance with the relevant standards.

The functions and operation of the high-speed circuit breakers

The high-speed circuit breakers are designed to switch on and off both operating currents and overload and short circuit currents. These devices are an essential safeguard against the flow of an excessive current in the circuit overhead line and vehicles being powered by it. Currents that are being switched off by the high-speed circuit breakers can reach the values exceeding even 50 kA in 3 kV D.C. system. In case of the systems of lower voltage, the short circuit currents values may reach level of 100 kA. That is the reason why the circuit breakers must be equipped with systems which allow extinguish the high-energy arc.

Additionally, the short circuit currents must be switched off as soon as possible to minimize the risk of damage, protected by circuit breakers elements of an electric traction power supply system.

The main part of a electromagnetic blow-out high-speed DC circuit breaker is an arc chamber, whose mission is to limit the space of burning arc, its cooling and deionization. After opening the contacts of circuit breaker, the arc lights up, that is, under the influence of electromagnetic field that is produced by a blow-out coil, directed to arcing horns in arc chamber.

The direction of the electromagnetic field forces of a blow-out coil on the arc needs to be consistent with the direction of the electrodynamic impact forces of arcing horns. In the blow-out coil the main current of the circuit breaker flows, causing, that the produced by it field force is proportional (within the limits of linear characteristics of a blow-out coil) to the values of a current being switched off.

The bigger blow-out coil field, the faster arc elongates.

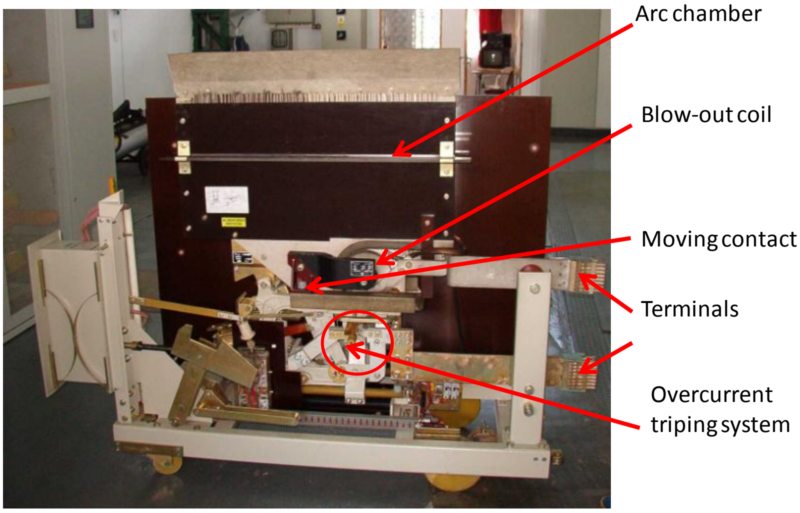

Fig. 1. The high-speed circuit breaker BWS on a voltage of 3 kV DC, placed on a cart
[photo A. Rojek]

In the arc chamber, the arc is elongated and cooled, in some types of arc chambers is also divided. The arc chamber has deionization interior partitions, in which the arc is brought into by the forces acting on it. These interior partitions cause, that the arc has much greater length and greater cooling surface. This results in a rapid increase of the resistance of the arc that causes rapid reduction of the value of current flowing through the high-speed DC circuit breaker.

To receive a fast opening of a circuit breaker contacts, the movable contact is driven by springs. The movable contact is connected to a core placed in a holding coil. In the closed condition of the contacts, the springs' force is balanced by magnetic field produced by holding coil, what immobilizes and tighten movable contact to immovable one.

The high-speed D.C. circuit breaker can be intentionally opened by disconnecting the holding coil voltage, or automatically. Automatic opening happens, when magnetic flux, produced by current flowing through the overload relay coil, sufficiently weakens the holding coil magnetic flux.

The values of a field produced by blow-out and overload relay coils are dependent on the values of the currents flowing through them. Depending on the solution, the values of the blow-out and overload relay currents are equal to the total value of switching off current or its parts.
For this reason, in - electromagnetic blow-out high-speed D.C. circuit breaker the process of switching off the current is the shorter the bigger its value.

Proper short circuit shutdown by the high-speed circuit breaker takes from a few to tens of milliseconds. Switching off the D.C. by an electromagnetic blow-out high-speed DC circuit breaker it is expected that the bunch of sparks will escape beyond the arc chamber. These sparks are heated copper components from contacts and cones, pollutions accumulated in the arc chamber and small material components of a chamber. Figure 2 [21] presents a proper short circuit current switching off.

Fig. 2. The proper short circuit current switching off of an expected value of 50 kA [the frame of the film recorded by P. Andrzejewski]

In case of arc chamber's pollution or its too low arc quenching properties (f.e. because of its over temperature), there is a possibility of a few arc ignitions during one switching off or re-raise of an insulating gap between the circuit breaker contacts under the influence of switching overvoltage.

That is a malfunction causing the short circuit current flows for more than 100 ms, and the high-speed DC circuit breaker can be easily damaged by a separate energy.

During such a malfunctioned switching off devices surrounding the high-speed DC circuit breaker are exposed to the impact of gases and components of a high temperature coming from an arc chamber.

Figure 3 [21] shows the flow of a short circuit current during the malfunctioned switching off, while figure 4 [21] illustrates one of the video frames recorded during this switching off.

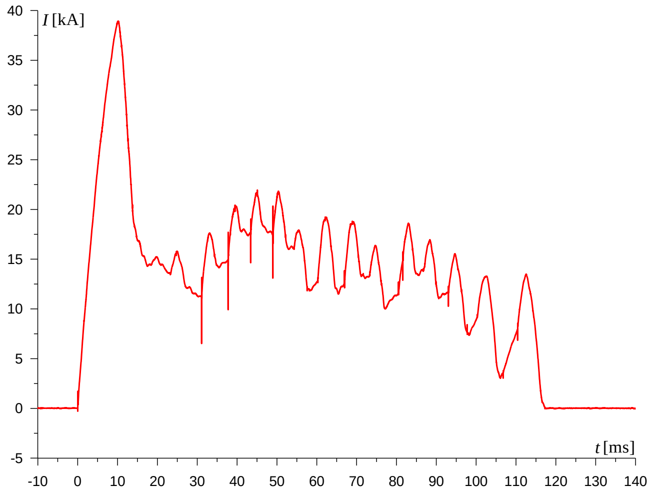

Fig. 3. Short circuit current during a malfunctioned switching off.

Fig. 4. View of a malfunctioned circuit switching off [frames of the film recorded by P. Andrzejewski]

The regulations in high-speed DC circuit breaker research

The main document identifying requirements and a scope of the high-speed DC circuit breaker's tests for traction substation and sectioning cabins is the PN-EN 50123-2 standard [4], relying on the provisions of PN-EN 50123-1 standard [3]. In the case of the on-board high-speed DC circuit breakers, requirements and scope of the research regulates the PN-EN 60077-3 standard [6].

The scope of the high-speed DC circuit breaker for use in substation and sectioning cabins research includes tests, trials and researches, is divided into 3 groups [4]:

1. General performance characteristics:
   a) verification of conformity to the manufacturing drawings and to characteristics of the circuit breaker,
   b) mechanical operation,
   c) dielectric withstand,
   d) temperature rise,
   e) verification of the adjustment of the relays and releases,
   f) electrical endurance,
   g) mechanical endurance.
2. Short circuit behaviour:
   a) verification of the making and breaking characteristics in short circuit contentions and of the H, V or S characteristics,
   b) verification of the short-time withstand current of rectifier circuit breaker R,
   c) verification of the adjustment of the relays and releases.
3. Search for critical currents and low current test duty.

The on-board circuit breaker research are divided into 6 parts, including tests, trials and research [6]:

1. General performance characteristics:
   a) operating limits,
   b) temperature rise,
   c) dielectric properties,
   d) operational performance capability,
   e) verification of dielectric withstand,
   f) verification of temperature rise,
   g) verification of tripping operation.
2. Rated short circuit making and breaking capacities:
   a) ability to make and break under short circuit conditions at time constant $T2$
   b) ability to make and break under short circuit conditions at time constant $T3$
   c) ability to make and break under short circuit conditions at time constant $T4$
   d) ability to make and break under short circuit conditions at minimum time constant $T1$
   e) verification of dielectric withstand,
   f) verification of temperature rise,
   g) verification of tripping operation.
3. Capability to withstand vibration and shock:
   a) vibration,
   b) shock,
   c) verification of mechanical operation,
   d) verification of tripping operation,
   e) verification of dielectric withstand.
4. Critical currents – searching of critical currents.
5. Climatic conditions – environmental tests (dry heat, damp heat, cold, etc.).
6. Other tests:
   a) electromagnetic compatibility (EMC),
   b) acoustic noise emission.

A larger scope of the on-board circuit breaker research (parts 3, 5 and 6 of research) results from their destiny and working conditions, in which they are exposed to vibrations and shocks, and their work cannot have a negative impact on other devices and systems installed in a traction vehicle.

Although, two standards – PN-EN 50123-2 [4] and PN-EN 60077-3 [6] – apply to the same type of electric apparatus, the symbols and volume and parameter indexes used therein are different, what causes some inconvenience in analysis and results comparison, especially in terms of circuit breaker cooperation (f.e. in ensuring the coordination of short circuit protection in the traction vehicle – traction substation relation).

Besides above standards, the requirements for high-speed DC circuit breakers are contained in PN-EN 50388 [5] standard and technical specification for interoperability of the subsystem “Energy” [1] (TSI “Energy”). First of these documents contains the information, that for 3 kV D.C. system should be taken the maximum short circuit current of a value 50 kA, while second document specifies the requirements on coordination of short circuit protection in the traction vehicle – traction substation relation. This specification requires that in case of short circuit in train, the on-board circuit breaker will work so quickly to make sure that circuit breaker for use in traction substation will not tripped.

For most of the research points and high speed D.C. circuit breaker checks, requirements that are contained in standards, testing and results are not problematic. However, part of the research and their result may be the basis of a discussion about real properties and parameters of circuit breakers. These tests and checks are:

- contact life research,
- switching capacity check,
- designation and critical currents switching off,
- coordination of short circuit protection in the traction vehicle – traction substation relation.

Electrical endurance tests

The results of electrical endurance tests of circuit breakers for use in traction substations and sectioning cabins performed according to PN-EN 50123-2 standard [4] are clear and there is no difficulty in their interpretation.

It is different in case of on-board circuit breakers . According to the PN-EN 60077-3 standard [6] the electrical endurance of circuit breakers designed to frequent switching offs is tested by getting 800 rated current switching offs in four series, 200 operations each. Between the series, the service actions are acceptable, such as exchange of contacts and other parts that are exposed to an electric arc activity (for instance: arc chamber and its components). The producers of on-board high-speed D.C. circuit breakers use this requirement and exchange contacts and arc chambers after first 3 series.

Therefore, the question arises, is it right to talk about contact life of a high-speed DC circuit breaker that equals 800 switching offs, if the contacts exchange is necessary after 200 switching offs? The solution of this problem may be a change of PN-EN 60077-3 standard [6] requirements relying on removing the admissibility of the exchange of contacts and components, on which the electric arc influences or determining the amount of switching offs, which could be performed without the necessity of exchanging any of the components of the high-speed D.C. circuit breaker.

Short circuit making capacity check

The PN-EN 50123-1 [3] standard make the division of high-speed DC circuit breakers for use in traction substations and sectioning cabins in terms of their speed operation into three types:

– current limiting high-speed circuit breaker (type H);
– current limiting very high-speed circuit breaker (type V);
– semi-high-speed circuit breaker (type S).

The current limiting high-speed circuit breaker type H, it is a circuit breaker of a capacity fast enough to open up, so short circuit current will not reach the peak value, which would be reached in case of the absence of its activity. The current limiting high-speed circuit breaker type H should have the time of opening (opening time) not longer than 5 ms, and the total breaking time shorter than 20 ms, for current of an expected value at least 7 times greater than setting of tip and steepness of initial current grow greater than 5 kA/ms.

The current limiting very high-speed circuit breaker type V is a circuit breaker, whose opening time does not exceed 1 ms, and total short circuit breaking time is no longer than 4 ms, irrespective of circuit parameters.

The semi-high-speed circuit breaker type S is a device whose opening time is shorter than 15 ms, and total breaking time no longer than 30 ms, assuming, that the value of an expected current is at least 3,5 times greater than circuit breaker setting of trip and the steepness of initial current grow is greater than 1,7 kA/ms. The limit for short circuit peak value of current for this type of circuit breaker is not required.

The data analysis presented by the producers of circuit breakers [17], [18],[19], [20] show that none of them classifies their products as one of the types above. Based on many measurements performed by Instytut Kolejnictwa [7], [8], [9], [10], [11] and [13] it is possible to determine the type of high-speed D.C. circuit breakers designed to 3 kV D.C. system, produced by the leading European companies. The example of the current limiting very high-speed circuit breaker type V that is produced in Poland is the one of a type DCN produced by Woltan Sp z o.o. Its fast activity is achieved by using a counter-current to D.C. switching off and vacuum chambers and operating mechanism with a very short running time.

The current limiting high-speed circuit breaker type H is a one of a series BWS produced by General Electric (previously Apena), while circuit breakers UR40 produced by Secheron is classified to the semi-high-speed circuit breaker type S.

Figure 5 [22] illustrates the curves of short circuit currents switching off by mentioned high-speed D.C. circuit breakers. Short circuit parameters were consistent with the requirements for research of circuit breakers type S, that is steepness of initial current grow was greater than 1,7 kA/ms, and a value of prospective current was 32 kA, at the circuit breakers setting of 2,5 kA is much greater value than required 3,5 times of a circuit breaker setting.

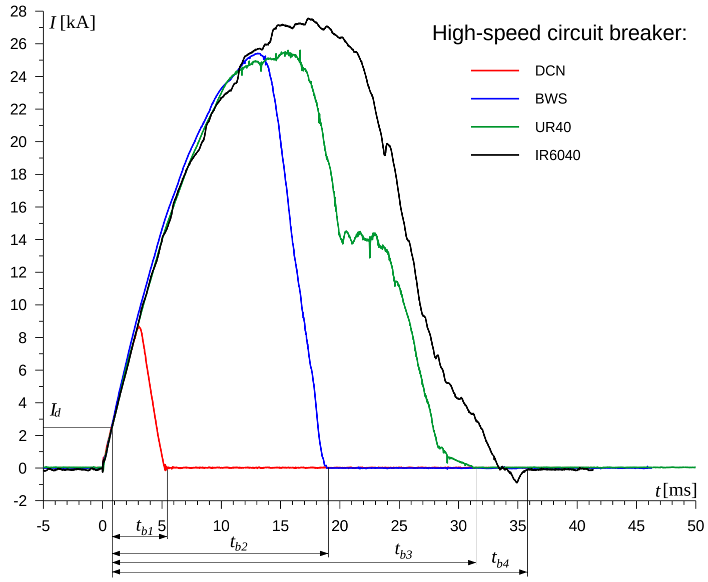

Fig. 5. The curves of short circuit current switching off by many different types of high-speed D.C. circuit breakers for use in fixed installations produced in Europe: I_d – value of the setting of trip of the high-speed circuit breaker; t_b – total breaking time; t_{b1} = 4,4 ms, t_{b2} = 18,0 ms, t_{b3} = 30,5 ms, t_{b4} = 35,1 ms

In terms of on-board circuit breakers the PN-EN 60077-3 standard [6] does not define the total breaking time of current. The analysis of on-board high-speed D.C. circuit breakers on voltage 3 kV D.C. offered by particular producers shows that the speed of their action is appropriately comparable with circuit breaker for use in substations.

The PN-EN 50388 standard [5] requires that circuit breakers were able to short circuit currents switching off of a value 50 kA, without specifying short circuit time constant. It is used by some manufacturers who declare the short circuit switching off of a value 50 kA and more, while the short circuit time constant is equal to 0 ms. The problem is the fact, that time constant that equals 0 does not exist in a real conditions. It concerns, most of all, the on-board circuit breakers on voltage 3 kV, which according to the PN-EN 60077-3 standard [6] should be tested with short circuit time constant equaled 0, 15, 30 and 50 ms.

Short circuit making capacity research is carried out once short circuit current switching off and in a commutating cycle. The cycle for on-board circuit breakers has a form:

O – t_1 – CO – t_2 – CO

where: O – short circuit switching off,

CO – short circuit switching on and short circuit switching off,

t_1 = 20 s,

t_2 = 60 s.

For the circuit breakers for use in fixed installations the cycle is defined as:

O – t_1 – CO – t_1 – CO – t_2 – CO

where: t_1 = 15 s,

t_2 = 60 s.

The next „imperfection" of the standards containing the requirements for high-speed D.C. circuit breakers is a guideline for short circuit. In such a short circuit should be only inductance and resistance. Whereas in the real conditions in short circuits, where high-speed circuit breakers are working, there are capacities, for example as filters in traction substations or input filters in traction vehicles.

It causes that in case of short circuit with an added f.e. resonance filter, capacitors are getting discharged, and a discharged current affects the short circuit current, causing its oscillation. Afterwards, while short circuit current is switched off by the high-speed circuit breaker, voltage arises causing charging of resonance filter capacitors.

In resonance filters, which are widely used in fixed installations, capacitors have relatively small capacities; more than that – most of them is serial connected with a suppressor making resonance branches. These inductances do not allow for rapid capacitor's discharging and charging in short circuit time. However, besides that, the capacities of a resonance filter affect the character of the voltage and short circuit curve. The comparison of short circuit curves both with a resonance filter and without it is shown on the figure 6 [22].

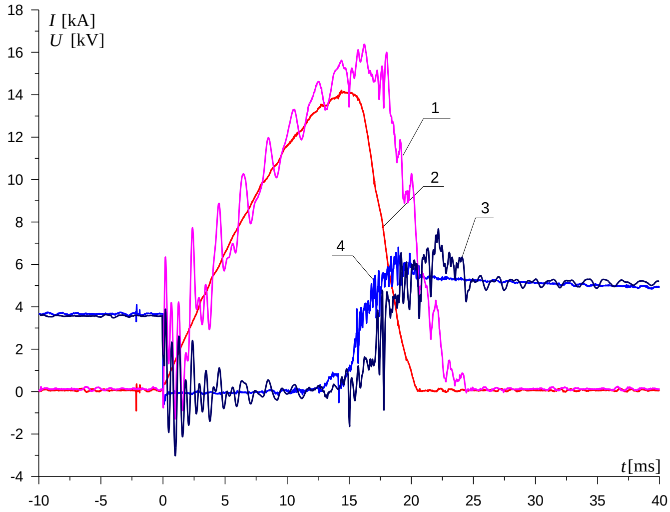

Fig. 6. Short circuit and voltage curves at the clamps of circuit breaker BWS switching off the short circuit current in the system with a resonance filter and without it: 1 – short circuit when the resonance filter works; 2 – short circuit when the resonance filter does not work; 3 – voltage at the terminals of circuit breaker when resonance filter works; 4 – voltage at the terminals of circuit breaker when resonance filter does not work.

The influence of the resonance filter on the short circuit curve is noticeable especially while the vacuum circuit breakers are used to switch off the short circuit current. This situation is showed at the figure 7. Just for the comparison, the figure 8 illustrates the curves of voltage and short circuit current in the same system, but with a resonance filter, that does not work. In both cases short circuit is switching off by the ultra-high-speed vacuum circuit breaker DCN.

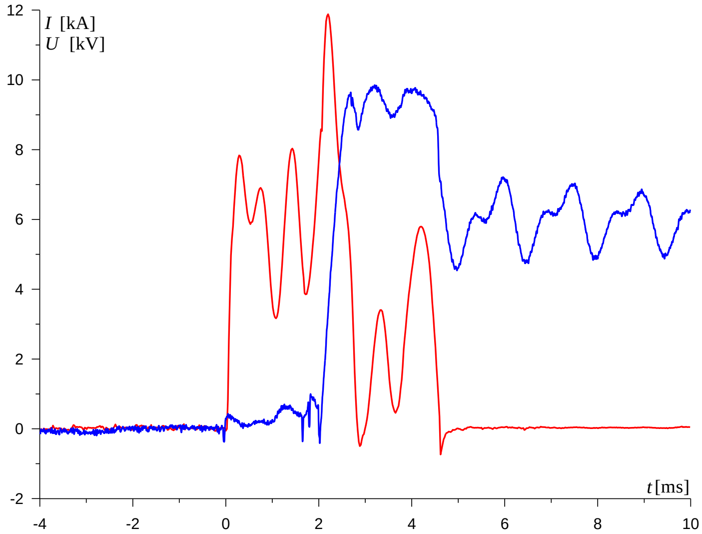

Fig. 7. The voltage curves (blue curve) and short circuit curves (red curve) switching off by circuit breaker DCN while the resonance filter works

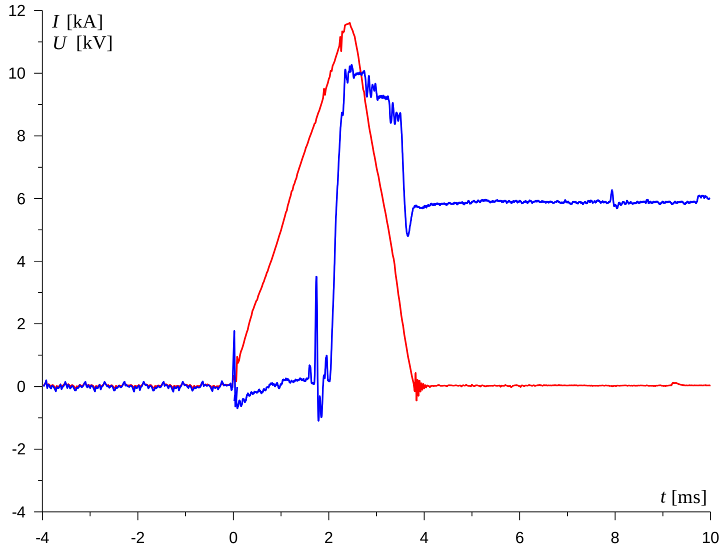

Fig. 8. The voltage curves (blue curve) and short circuit curves (red curve) switching off by circuit breaker DCN while the resonance filter does not work

The oscillating short circuit changes and reverse voltages are visible at the figure 6 and 7. These oscillations have two frequencies: about 750 and 1500 Hz. These are resonance frequencies of a resonance filter for a 12-pulse set. Moreover, the rapid discharge of a resonance filter capacitors at the time of a short circuit causes sharp increase of current, whose steepness of growing in researched short circuit is about 39 kA/ms. So big changes of current entail very fast increase of elecrodynamic forces that influence on all parts of short circuit. For comparison, the steepness of short circuit current grow in a tested circuit is about 4,9 kA/ms while the resonance filter is switched off.

Additionally oscillating changes of current cause later release of electromagnetic blow-out high-sped D.C. circuit breaker BWS. It is caused by oscillating alternating current that flows through the coil of a release causes alternating magnetic field, what results with the later release of a circuit breaker. As a result of it there is a higher value of limiting short circuit and longer time of switching off. Analyzing the short circuit current flow shown at the figure 6 it can be stated that switching on of resonance filter caused extra switching off time about 10%. As a result of later release and oscillating changes of short circuit current, the value of maximum limiting short circuit current increases about 15%.

This extra switching off time can cause that the high-speed D.C. circuit breaker, based on the tests according to PN-EN 50123-2 [4] classified as a type f.e. H, in real conditions, with resonance filter switched on, will have the parameters corresponding to the high-speed D.C. circuit breaker type S.

Designation and critical currents switching off

Most of the manufacturers of high-speed circuit breakers focus on the parameters related to the values of rated current and short circuit currents and overload currents making and breaking. There is a determined value or range of values for each circuit breaker, at which switching off time is the longest. This value or range of values is called critical currents. The general analysis of available materials that focus on high-speed circuit breakers produced in Europe [17], [18], [19], [20] shows that none of the manufacturers present in their catalogues and commercial materials information of currents switching off capacity of a small value (called critical currents) by proposed devices.

When small values of current are switched off, the voltage of electromagnetic field produced by the blow-out coil is little. When dealing with small currents the field effects on electric arc so weak, that arc elongation happens only in natural way, resulting from the shape of arcing horns and thermal events.

During the normal operation of power supply devices and traction vehicles it is impossible to avoid switching off small and very small values of current flowing through the high-speed circuit breaker. In the case of fixed installations such switching offs can appear during maneuvering switching offs, or when high-speed circuit breaker action is forced by the automatic system. The reason of small values of current flowing through power supply's high-speed circuit breaker for use in substation is low current consumption by traction vehicle during a stop (for instance: power supplying only traction vehicle's nontraction needs), traction vehicle's power supplying that is far away from the fixed installations and equalizing currents flowing between substations of a different values of initial voltages.

The on-board circuit breaker is exposed to switching off small values of currents while only auxiliary circuits of locomotive and the train will be power supplied from catenaries.

The critical currents switching off are bonded with relatively long burning arc on the contacts of circuit breaker. The burning time of an arc while small values of currents switching off is from over a dozen to ten times longer, than short circuit currents. By this time, which can be up to few or even several seconds, the circuit breaker contacts are exposed to arc, arcing horns and arc chamber. It causes significant arcing erosion of these elements.

The PN-EN 50123-2 standard [4] requires to determine the value of critical currents for circuit breakers for use in substations worth 25. 50, 100, 200 and 400 A. For on-board circuit breakers, according to the PN-EN 60077-3 standard [6] it should be critical currents switching off tests carried out in the range of rated current to 0. Both standards do not define at what time critical currents should be switched off. That is why the circuit breakers producers can declare, that device is compliance with the standard regardless if or how fast the circuit breaker switches off its critical currents.

Furthermore, the standards do not specify which critical currents value should be taken as a result of tests. There are few trails for each current value. Tests of high-speed circuit breakers of different producers [7], [8] show that switching off time for critical currents of a specified value in some trials may fall into wide range (fig. 9 [21], [22]). It causes, that the average value of critical currents switching off may significantly differ from the maximum values. Therefore it is necessary to add to the standards some information about maximum times in which critical currents should be switched off.

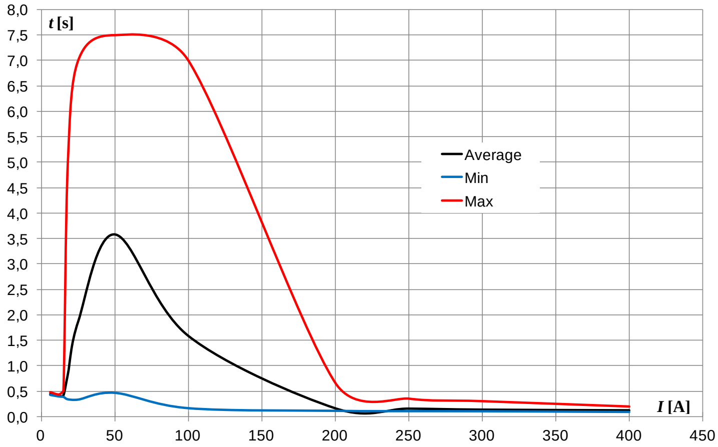

Fig. 9. The characteristics of critical currents switching off time as a function of their values for one of the European producers of circuit breaker

The Regulation of the Minister of Transportation, Construction and Maritime Economy [15, 16] proclaims improvement of the situation in terms of requirements for critical currents switching off. This Regulation determines the scope of necessary research and tests to obtain the certificate of type release to service, inter alias high-speed circuit breakers for use in substations and sectioning cabins. Mentioned Regulation also says that it is necessary, inter alia, to test the values and time of critical currents switching off. The complementation to this legal act is a Regulation of the Minister of Transportation, Construction and Maritime Economy that specifies the list of documents and technical specifications of required parameters of devices [16]; in there is mentioned that the critical currents switching off time should not exceed 500 ms (Fig. 10).

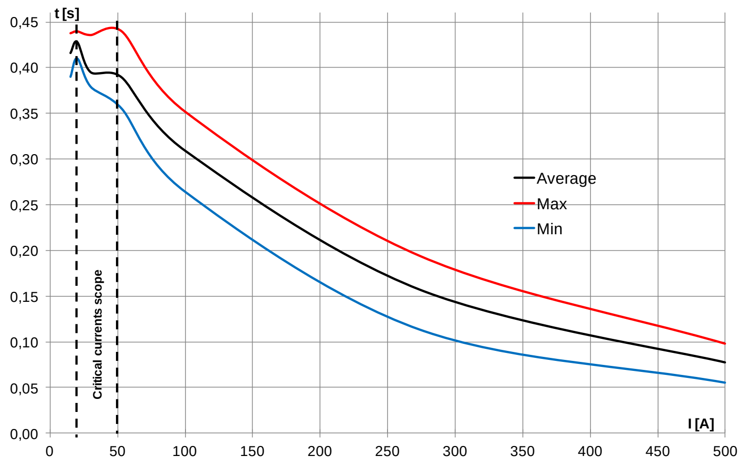

Fig. 10. The characteristics of critical currents switching off time in the function of their values for the circuit breaker that meets the Regulation's requirements [16]

Coordination of short-circuit protection

In technical specification for interoperability (TSI) "Loc&Pas" [2], for interoperability component is written: "The [circuit breaker] tripping shall be immediate (no intentional delay) as specified in the Annex K of the CR ENE TSI […]". Whereas in TSI "Energy" [1] it is required that in case of short circuit occurring in the rolling stock, the on-board circuit breakers and circuit breaker for use in substation should be tripping as soon as possible. Additionally, in TSI "Energy" [1] is a footnote saying that on-board circuit breaker should work much as possible to avoid opening of the circuit breaker for use in fixed installations.

TSI „Energy" recommends the use of on-board circuit breakers of making capacity that allows independent switching off all of the short circuit currents. In TSI "Energy" [1] is defined the concept of "immediate opening" meaning work of a circuit breaker with no intentional delay. It is also given, that for D.C. systems flow time of short ircuit current through the circuit breaker is in the range of 20 to 60 ms, which is met by circuit breakers: WSe and BWS for use in traction substations in Poland.

The main issue is the lack, in mentioned above standards, of description how to manage the coordination of protection research, methodology of the results interpretation and to determine when they can be considered positive.

To achieve selectivity of short circuit and overload currents switching offs forming in rolling stock is possible while on-board circuit breaker switches off the current before the circuit breaker for use in substations and sectioning cabins will get tripped. It will happen only when on-board circuit breaker limits the current to a value lower than the tripping level of the circuit breaker for use in the fixed installations. The following parameters decide if short circuit in rolling stock causes tripping of circuit breaker for use in substation:

– levels of on-board circuit breaker and circuit breaker for use in substation settings;
– individual opening time and on-board circuit breaker’s current limiting capacity;
– steepness of short circuit current grow.

When on-board circuit breaker has a greater current tripping than circuit breaker for use in substation, each short circuit in traction vehicle will be switched off by the circuit breaker installed in substation.

The circuit breaker for use in fixed installations will not be switching off the short circuit when steepness of short circuit grow is small enough that on-board circuit breaker starts to limit the current before it reaches the tripping level of high-speed circuit breaker for use in substation. The limit value di/dt, at which short circuit current will be switched off only by the on-board circuit breaker depends on independent opening time of on-board circuit breaker, its limiting current capacity and the difference between the values of setting of on-board circuit breaker and circuit breaker for use in fixed installations. This relation [12], [14], [21] can be written as:

(1) $$\mathrm{d}i/\mathrm{d}t_l = \frac{I_{ds} - I_{dv}}{t_{Sv}} = \frac{\Delta I_d}{t_{Sv}}$$

where: $\mathrm{d}i/\mathrm{d}t_l$ – the limit value of the steepness of short circuit current grow, at which it is possible to obtain selective short circuit protection; I_{ds}, I_{dv} – the value of current of high-speed circuit breaker setting of trip for use in substation, on-board; t_{Sv} – time from exceeding by current value I_{dv} to limit the current by on-board circuit breaker.

The results of the simulation, analysis and research [12], [14] show, that it is not, at the moment, possible to obtain selective short circuit switching offs in rolling stock. At the European market of circuit breakers the greatest range of selectivity show vacuum circuit breakers DCN-L and DCU using in rolling stock. It is made possible by very small opening time and very good limiting properties of current, which are basically independent from short circuit.

Based on the research it is possible to determine the relation between $\mathrm{d}i/\mathrm{d}t_l$ and ΔI_d for any pair of circuit breaker: the on-board one and the one for use in substation. This relation has a form:

(2) $$\mathrm{d}i/\mathrm{d}t_l = a(\Delta I_d)^2 + b\,\Delta I_d + c$$

where: a, b, c – function coefficients empirically determined, with values ≥ 0,

$\mathrm{d}i/\mathrm{d}t_l$ w [A/ms]

ΔI_d w [A].

The tests show that for a pair of circuit breakers: on-board circuit breaker DCU-800 and circuit breaker for use in substation BWS, the coordination of protection can be obtain with the same, for both circuit breakers, settings but with very low value of steepness of current grow – 100 A/ms. ΔI_d should have a value above 1700 A for large values of d*i*/d*t*, on the level of 3,5 kA/ms.

For a pair of circuit breakers BWSp – BWS coordination of protection is possible only for a narrow range of values d*i*/d*t* when large values of ΔI_d. To obtain coordinated short circuit switching off in rolling stock, with d*i*/d*t* = 300 A/ms setting of circuit breakers of more than 2 kA is necessary.

In coordination of protection research while circuit breaker for use in substation BWS or circuit breakers of other European producers are used, the selective short circuit switching off was not obtained, even for very little values of steepness of current grow (150 A) and the difference of settings above 1100 A.

It is though impossible to clearly define, that using of a specifying circuit breaker will provide, required in technical specification of interoperability, coordination of protection. To carry out the certification process for on-board circuit breaker, as an interoperability element, it is necessary to point out the range of values for d*i*/d*t*, and ΔI_d, for which the TSI "Loc&Pas" [2] and TSI "Energy" [1] are met.

Moreover, it is necessary to develop procedures and methodology of high-speed circuit breakers' coordination of protection research and evaluation of their performance. The document should be set up as an European standard established in TSI.

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Badania pojazdowych i podstacyjnych wyłączników szybkich w systemie zasilania trakcji 3 kV DC

Streszczenie

Przed dopuszczeniem do eksploatacji w kolejowej trakcji elektrycznej wyłączniki szybkie prądu stałego muszą być poddane badaniom na zgodność z normami.

Wyłączniki szybkie są podstawowym zabezpieczeniem przed przepływem nadmiernych wartości prądu w obwodach sieci trakcyjnej oraz zasilanych z niej pojazdów. Dlatego muszą one być wyposażone w układy umożliwiające zgaszenie łuku o dużej energii. Dodatkowo prądy zwarciowe muszą być wyłączone w jak najkrótszym czasie, aby zminimalizować ryzyko uszkodzenia chronionych przez wyłączniki elementów systemu zasilania trakcji elektrycznej.

Podstawowym dokumentem określającym wymagania i zakres badań wyłączników szybkich prądu stałego przeznaczonych do podstacji trakcyjnych i kabin sekcyjnych jest norma PN EN 50123-2. W przypadku wyłączników szybkich przeznaczonych do eksploatacji w pojazdach trakcyjnych wymagania i zakres badań reguluje norma PN-EN 60077-3. Pomimo, że obydwie normy dotyczą tego samego typu aparatów elektrycznych, stosowane w nich oznaczenia i indeksy wielkości i parametrów są inne, co powoduje pewne niedogodności w analizach i porównywaniu wyników, w szczególności w aspekcie współpracy wyłączników, np. przy zapewnianiu koordynacji zabezpieczeń zwarciowych w układzie pojazd trakcyjny – podstacja trakcyjna.

Oprócz powyższych norm, wymagania dla wyłączników szybkich zawarte są w normie PN-EN 50388 oraz specyfikacji technicznej interoperacyjności podsystemu „Energia".

Dla większości punktów zakresu badań i sprawdzeń wyłączników szybkich wymagania zawarte w normach oraz przeprowadzenie i wyniki badań nie są problematyczne. Jednak część badań i ich wynik mogą być podstawą dyskusji odnośnie rzeczywistych właściwości i parametrów wyłączników. Do tych badań i sprawdzeń należą badanie trwałości łączeniowej, sprawdzenie zdolności łączeniowej prądów zwarciowych, wyznaczenie i wyłączenie prądów krytycznych i koordynacja zabezpieczeń zwarciowych w układzie pojazd trakcyjny – podstacja trakcyjna.

Wyniki analizy danych przedstawianych przez producentów wyłączników pokazują, że żaden z nich nie klasyfikuje produkowanych wyłączników jako jednego z typów: H, V lub S, zdefiniowanych w normie PN-EN 50123. Na podstawie pomiarów prowadzonych przez Instytut

Kolejnictwa możliwe jest określenie typu wyłączników szybkich prądu stałego przeznaczonych do systemu 3 kV DC, produkowanych przez czołowe firmy europejskie. Za wyłącznik typu V można uznać jedynie wyłącznik typu DCN. Wyłącznikiem typu H jest wyłącznik serii BWS, natomiast parametry wyłączników typu UR40

Kolejną „niedoskonałością" norm zawierających wymagania dla wyłączników szybkich prądu stałego jest wytyczna dotycząca obwodu zwarciowego. W obwodzie tym powinny występować jedynie indukcyjność i rezystancja. Natomiast w warunkach rzeczywistych w obwodach zwarciowych, w których pracują wyłączniki szybkie występują pojemności, np. w postaci urządzeń wygładzających w podstacjach trakcyjnych lub filtrów wejściowych w pojazdach trakcyjnych.

Analizując wyniki badań zwarciowych można stwierdzić, że załączenie urządzenia wygładzającego spowoduje wydłużenie czasu wyłączania o około 10 %. W wyniku późniejszego wyzwolenia oraz oscylacyjnych zmian prądu zwarciowego, wartość maksymalnego ograniczonego prądu zwarcia zwiększa się o około 15%.

Wyłączanie prądów krytycznych wiąże się ze stosunkowo długotrwałym paleniem łuku na stykach wyłącznika. Czas palenia się łuku przy wyłączaniu prądów o małej wartości jest od kilkunastu do kilkudziesięciu razy dłuższy, niż w przypadku wyłączania prądów zwarciowych. Przez ten czas, który może dochodzić do kilku, a nawet kilkunastu sekund, na działanie łuku narażone są styki wyłącznika, rożki łukowe i komora łukowa. Powoduje to znaczną erozję łukową tych elementów.

Normy nie definiują w jakim czasie prądy krytyczne powinny być wyłączane oraz nie określają jaką wartość prądów krytycznych należy przyjmować jako wynik badań.

Uzyskanie selektywności wyłączeń prądów zwarciowych i przetężeniowych powstających w taborze jest możliwe wówczas, gdy wyłącznik taborowy wyłączy prąd zanim zostanie wyzwolony wyłącznik w podstacji trakcyjnej lub kabinie sekcyjnej. Nastąpi to tylko w przypadku, gdy wyłącznik taborowy ograniczy prąd do wartości niższej od poziomu wyzwolenia wyłącznika podstacyjnego.

Wystąpi to w przypadku, gdy stromość wzrostu prądu zwarciowego będzie na tyle mała, że wyłącznik taborowy zacznie ograniczać prąd zanim osiągnie on poziom wyzwalania wyłącznika szybkiego w podstacji. Wartość graniczna di/dt, przy której prąd zwarciowy będzie wyłączany tylko przez wyłącznik taborowy, zależy od czasu własnego otwarcia wyłącznika w pojeździe, jego zdolności ograniczania prądu i różnicy pomiędzy wartościami nastaw wyłączników taborowego i podstacyjnego.

Wyniki symulacji, analiz i badań pokazują, że nie jest obecnie możliwe uzyskanie każdorazowo selektywności wyłączeń prądów zwarciowych w taborze. Największy zakres selektywności można uzyskać w przypadku zastosowania w taborze próżniowych wyłączników serii DCN-L i DCU.

Słowa kluczowe: wyłącznik szybki, zwarcia, prąd krytyczny, koordynacja zabezpieczeń.