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Electrical Endurance of DC Switching Devices

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Summary
The article focuses on the electrical endurance testing of direct current switching devices, such as high speed circuit breakers, switch disconnectors and contactors. It presents the normative requirements for these tests and provides sample results obtained during testing conducted in the electrical laboratory of the Department of Electrical Power Engineering at the Railway Research Institute. The most commonly tested switching devices have nominal voltages of 900, 1800, and 3600 V DC, with nominal currents of up to 6.5 kA. The article also discusses phenomena and hazards that may occur during electrical endurance testing.

Keywords: electrical endurance, high speed circuit breaker, switch disconnector, contactor, DC breaking

1. Introduction

Numerous articles have been dedicated to the study of switching devices. Primarily focusing on direct current high speed circuit breakers. Authors of articles [1, 19] focused on short-circuit current breaking. Publications [9–12] also delve into this issue. Some articles address specific parameters of high speed circuit breakers, such as critical current breaking [12, 14, 15], the speed of operation of circuit breakers, including the individual phases of direct current breaking [17, 18, 20], and the improvement of selected parameters of magnetic blowout circuit breakers [16, 21].

Electrical endurance tests of switching devices involve switching-on and breaking the current, typically rated. Analysing the standards for switching devices, the most time-consuming aspect is the mechanical endurance test, but this can be effectively automated, reducing the need for personnel involvement significantly. In terms of the time-consuming nature of the tests, the next in line are the electrical endurance tests. Due to the way these tests are conducted, and the risks involved, they cannot be fully automated, and continuous supervision by personnel is necessary.

2. Direct current switching devices

Direct current switching devices can be divided based on their function and place of application. In terms of function, switching devices can be divided into:

1. Circuit breakers – devices designed for switching on, conducting, and switching off operating, overload and short-circuit currents.
2. Switch disconnectors – devices designed for switching on, conducting, and switching off operating currents. They are also capable of conducting overload and short-circuit currents. They disconnect part of the circuit, creating a visible insulation gap.
3. Isolating switches – devices designed for switching on, conducting, and switching off voltage in part of the circuit, creating a visible insulation gap. They are also capable of conducting operating, overload and short-circuit currents. Switching operations are only possible in the current-free state.
4. Earthing switches – devices designed for grounding part of the circuit, capable of conducting short-circuit currents. Switching operations are only possible in the current-free state.
5. Contactors – devices designed for switching on, conducting, and switching off operating, overload and short-circuit currents. They are also capable of conducting overload and short-circuit currents. Unlike switch disconnectors, contactors do not create a visible insulation gap.

Switching devices are categorised based on their application, distinguishing between those designed for rolling stock, and those intended for fixed installations, including traction substations, sectional cabins, and overhead contact lines.

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Unlike alternating current, direct current does not have a natural, periodic zero-crossing. In the process of alternating current breaking, its value passing through zero causes its natural deactivation when the appropriate increase in back electromotive force between the contacts of the circuit breaker or switch disconnector is reached.

In the case of direct current, to disconnect it, its value must be artificially brought to zero and an air gap must be provided to prevent current flow. There are two methods of direct current breaking. One of them is forced breaking, which involves bringing the current to zero by increasing the arcing voltage. Each forced breaking of direct current is accompanied by an electrical arc (Fig. 1 and 2).

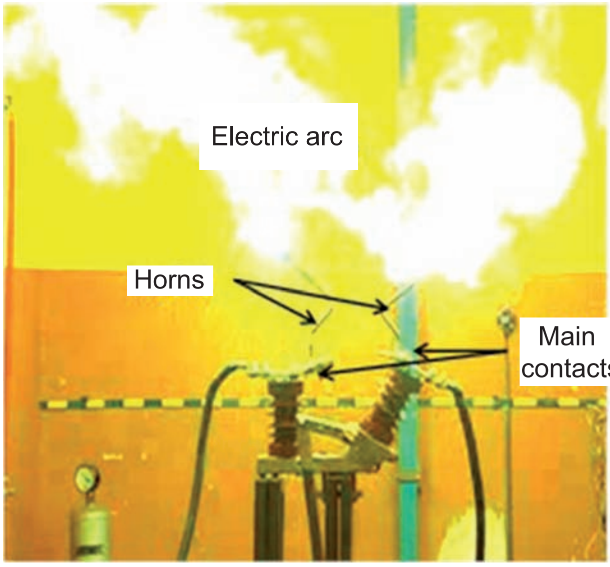

Fig. 1. Electrical arc formed during the disconnection of direct current by a switch disconnector [13]

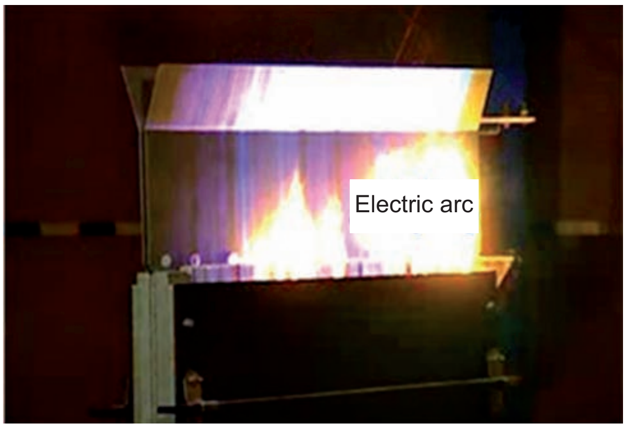

Fig. 2. Arc box and electrical arc formed during the disconnection of direct current by a high speed circuit breaker [13]

In general, forced breaking of direct current involves extinguishing the electrical arc that occurs between the contacts of the switching device. The rapid increase in arc voltage above the supply voltage affects the current value, limiting it to zero. As isolating switches and earthing switches are not equipped with components to extinguish the arc, they cannot be used for current breaking but only for disconnecting parts of the electrical circuit from voltage when there is no current flow to or from that part or for grounding a circuit where the voltage has already been disconnected.

3. Normative Requirements

Electrical endurance tests are conducted for switching devices intended for switching current, hence these tests are performed for circuit breakers, switch disconnectors, and contactors. They involve switching-on and breaking rated current (CO cycle) for a specified number of cycles with a defined time interval between cycles, often conducted in series.

The requirements for the electrical endurance of direct current switching devices and the procedures for conducting tests and evaluating their results are specified in two series of standards. For rolling stock devices, standards from the EN 60077 series are applied, including:

- general requirements for all types of devices – EN 60077-1 [6],
- requirements for switch disconnectors and contactors – EN 60077-2 [7],
- requirements for high speed circuit breakers – EN 60077-3 [8].

For fixed installation devices, standards from the EN 50123 series are applied, including:

- general requirements for all types of devices – EN 50123-1 [2],
- requirements for high speed circuit breakers – EN 50123-2 [3],
- requirements for indoor switch disconnectors – EN 50123-3 [4],
- requirements for outdoor switch disconnectors – EN 50123-4 [5].

In the EN 60077 series standards, for rolling stock switching devices, a classification of contactors, switch disconnectors, and circuit breakers based on their operating frequency is provided. In the case of contactors and switch disconnectors, EN 60077-2 [7] specifies the division into devices with the following operating frequencies:

- C1: light operational frequency (e.g. a component which is part of the protection and/or isolation equipment which operates only when a failure is detected);
- C2: medium operating frequency (e.g. a component which is part of equipment that operates in

any of the following cases: at each commencement of service, each start, each stop, each neutral section, each sectioning point, each end of service);
- C3: heavy operational frequency (e.g. component which is part of equipment that operates during each traction sequence or braking sequence, or component such as a compressor contactor).

The number of test series for electrical endurance tests is associated with the operating frequency of contactors and switch disconnectors. For frequency C1, tests are conducted in one series, for C2 in five series, and for C3 in ten series.

A similar classification is defined in the standard EN 60077-3 [8] for rolling stock high speed circuit breakers. Their operating frequency is specified as:
- C1: light operational frequency (e.g. the circuit breaker is only opened when a short circuit is detected);
- C2: medium operational frequency (e.g. in addition to C1, the circuit breaker is opened upon a command generated by exceeding a predetermined limiting value, such as overvoltage or overload);
- C3: heavy operational frequency (e.g. in addition to C2, the circuit breaker is opened for other reasons, such as passing through isolation gaps, sectioning points in the network, etc.).

For frequency C1, electrical endurance tests for circuit breakers are conducted in one series, for C2 in two series, and for C3 in four series. The total number of CO cycles is:
- C1: 100 cycles;
- C2: 400 cycles;
- C3: 800 cycles.

In the vast majority of cases, testing of rolling stock high speed circuit breakers is carried out by performing 800 cycles. Between series, the standards EN 60077-2 [7] and EN 60077-3 [8] allow to perform an inspection of the tested device. In addition, the EN 60077-2 [7] standard introduces the division of contactors and switch disconnectors into categories related to their performance and application. These categories include:
- A1: switches for auxiliary circuits or low-voltage circuits (e.g. relays, auxiliary contactors, and their accessories, etc.) regardless of their control nature, except for manually operated elements;
- A2: switches for power circuits (e.g. power contactors), regardless of their control nature, except for manually operated elements;
- A3: manually operated switching devices (e.g. switches, push buttons, etc. for control devices);
- A4: power switchgear which does not operate on load (e.g. isolating switch, system switch, etc.);
- B: other elements not covered by the above categories.

It should be noted that according to the EN 60077-2 [7] standard, electrical endurance tests are only conducted for categories A1, A2, and A3.

Taking into account the combinations of operating frequencies and categories of contactors and switch disconnectors, the total number of cycles during the electrical endurance tests of these devices ranges from 200 for A2C1 to 1,000,000 for A1C3. However, the majority of tests are conducted for A2C3 contactors, meaning 8,000 cycles are performed.

As mentioned earlier, requirements for switching devices used in fixed installations are governed by standards from the EN 50123 series. Standard EN 50123-2 [3] divides high speed circuit breakers into the following types:
- interconnector circuit breaker (I), also known as bus-section, used in sectioning cabins or traction substations to connect two sections of a DC switchgear;
- line circuit breaker (L), also known as feeder circuit breakers, mounted in the feeder cells of DC switchgear;
- rectifier circuit breaker (R) used to connect rectifiers to DC switchgear; currently not in use.

Electrical endurance tests for high speed circuit breakers intended for fixed installations are conducted in one series. The number of CO cycles is as follows:
- type L circuit breaker – 200 cycles;
- type I and R circuit breakers – 100 cycles.

For isolating switches, switch disconnectors and earting switches, both indoor and outdoor, standards EN 50123-3 [4] and EN 50123-4 [5] introduce a classification into categories:
- I: disconnector and earthing switch used in locations where the purchaser has taken all precautions to inhibit making on to a fault current;
- II: switch disconnector required only for disconnecting the load current;
- III: switch-disconnector in series with the feeder, required for making and breaking the rated current only;
- IV: switch disconnector as in III, but required for making and beraking the train's starting current;
- V: disconnector and earthing switches used in locations where there is a possibility of an inadvertent make on to a fault current;
- VI: switch disconnector as in IV, but required for making on to a fault current.

For category I, electrical endurance tests are not performed, while for the remaining categories, these tests are conducted by making and/or breaking the current specified in the standards, which may have a rated value, three times the rated value, or a predetermined value of short-circuit current. In Poland, in traction substations, sectional cabins, and overhead contact line systems, isolating switches (category I) are often used, along with earthing switches, and switch disconnectors of category III, also equipped with earthing switches. For this reason, the majority of electrical endurance tests are conducted for category III switch disconnectors, switching the rated current of the device on and off.

Regardless of the type of switch disconnector, electrical endurance tests are conducted by performing 50 CO cycles, which can be divided into series of at least 10 CO cycles.

Regardless of the type of switching device, its operating frequency, and category, after each series of CO cycles, in addition to an inspection, dielectric strength of insulation and contact gap, as well as the resistance of the main circuit, must be checked. If there is a significant, norm-defined increase in this resistance, a heating test must be conducted.

4. Tests

In the short-circuit laboratory of the Railway Research Institute, switching devices with rated voltages of 900, 1800, and 3600 V DC, and rated currents of up to 6.5 kA, are most commonly tested. Electrical endurance tests are conducted in the measurement system shown in Figure 3, where the colours of the measurement instruments (voltage and current measurement) correspond to the colours of the exemplary voltage and current waveforms presented later in the article.

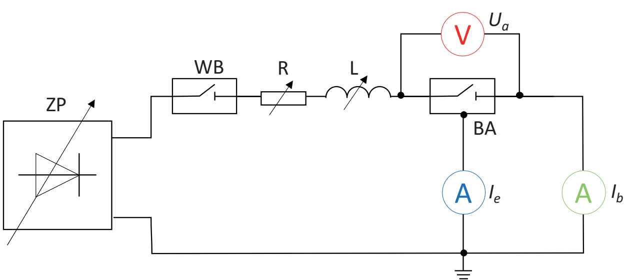

Fig. 3. Schematic of the measurement system for electrical endurance testing (description in the text) [own work]

The measurement system for testing the electrical endurance of DC switchgear is powered by a regulated rectifier unit (ZP), the output voltage of which is set as required. The system is protected by a safety breaker (WB). The desired value of the current switched on and off by the tested switching device (BA) is achieved by adjusting the variable resistor (R). The tests are conducted at a specified time constant of the circuit, as mentioned earlier, which depends on the value of the adjustable choke (L). This system was designed for devices with forced current breaking. However, an increasing number of connecting devices now utilise different methods for DC breaking. Changes to the standards listed in Chapter 2 or the development of appropriate standards should be considered for these devices.

During the tests, regardless of the number of CO cycles, waveforms and voltage and current values shown in Figure 3 are recorded in each cycle. In the test report for selected CO cycles, as determined with the client, the following data are specified:

- t_d – time between consecutive CO cycles,
- U_d – supply voltage of the measurement circuit,
- I_b – making and breaking current,
- U_{amax} – maximum arc voltage,
- I_e – earth fault current,
- t_a – arcing time,
- correctness of current making and breaking.

Due to the high number of CO cycles required for electrical endurance testing of switching devices, these tests are time-consuming. Within one hour, approximately 15 to 30 CO cycles can be performed, depending on the value of the connected current. Considering this, the time required to complete 8,000 CO cycles at currents exceeding 2000 A exceeds 530 hours. Additionally, time is needed for preparation, verification, and setup of the measurement system, as well as time for inspections and measurements mentioned in point 2 of the article.

Although these tests may seem straightforward, they require significant experience and commitment from the research personnel. The first challenge is the aforementioned time required for testing, during which the measurement system must be supervised by at least two people at all times. This is because improper current switching, failure to break the current, arcing between contacts, or grounding may occur during any CO cycle. Mechanical failure of the tested device is also possible. Furthermore, as mentioned earlier, DC breaking is accompanied by an electrical arc reaching temperatures of tens of thousands of degrees Celsius and switching overvoltages, posing a risk to the dielectric endurance of the measurement system components (especially the rectifier) and the tested switching device. Partial automation of the tests is possible, but it requires equipping the laboratory and the test chamber with electrical, fire protection, and other safety systems.

4.1. Tests of high speed circuit breakers

In the short-circuit laboratory of the Railway Research Institute, electrical endurance tests have been conducted on high speed circuit breakers designed for rolling stock and fixed installations with rated currents ranging from 1000 to 6500 A. Apart from the number of series and CO cycles, the testing of these two variants of high speed circuit breakers does not differ significantly.

During the electrical endurance testing of high speed circuit breakers, no improper current switching has been recorded thus far. Only mechanical failures of the circuit breaker drive system prevented the closure of the circuit breaker.

The scenario is different during current breaking. The correct course of breaking current is depicted in Figure 4, where a brief arcing time (t_a = 25.1 ms) and a slight switching overvoltage can be observed, with $U_{amax} \approx 1{,}7U_d$.

However, current breaking does not always proceed correctly. Figure 5 illustrates the voltage and current waveforms when a breakdown of the contact gap occurred after the circuit breaker opened. In this case, current breaking occurred due to the operation of the safety breaker. Switching overvoltages are evident in Figure 5, where the arc voltage caused multiple breakdowns of the circuit breaker's contact gap and a subsequent increase in current in the circuit.

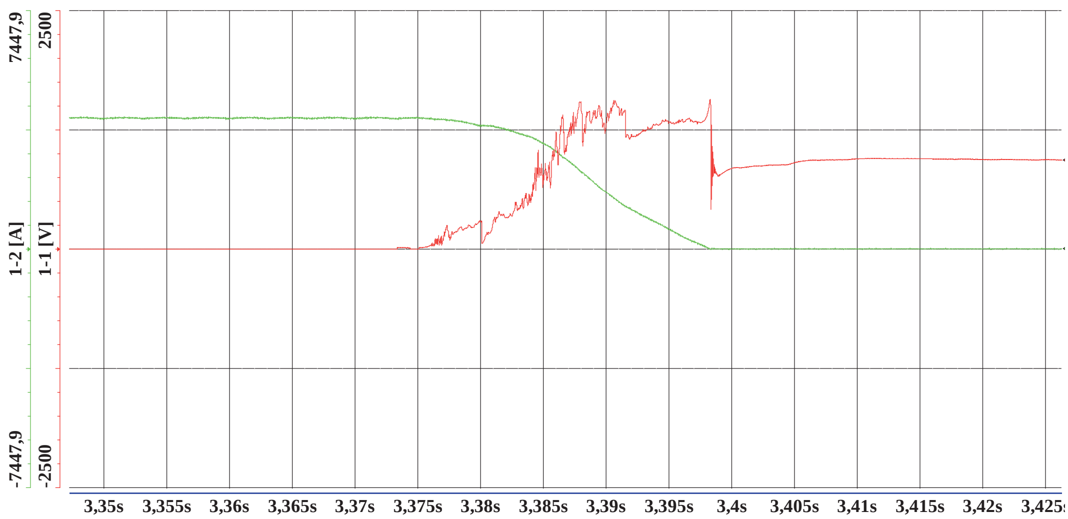

Fig. 4. The waveforms of the switched current and arc voltage when properly switched off by a high speed circuit breaker[2]

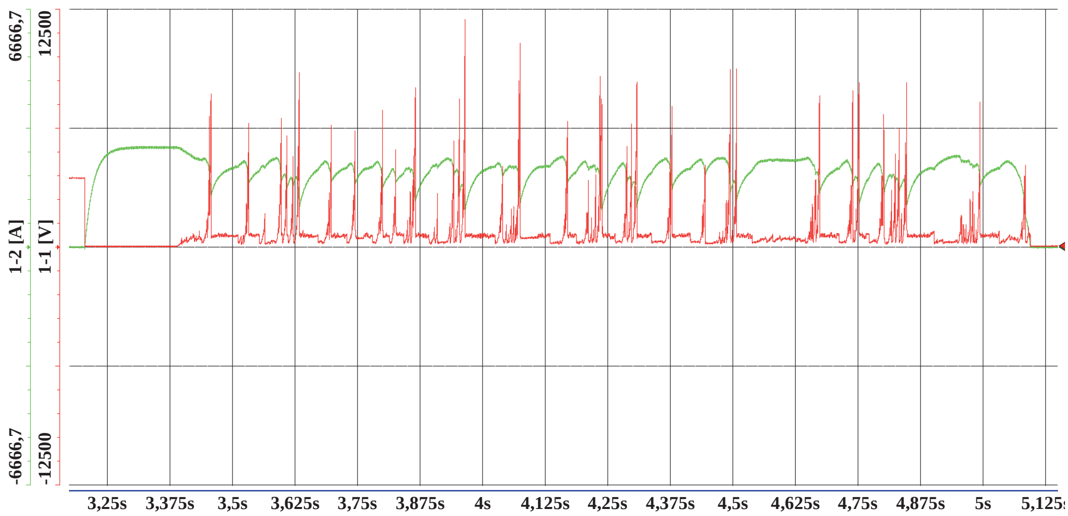

Fig. 5. Waveforms of the switched-off current and arc voltage during multiple breakdowns of the inter-contact gap of the high speed circuit breaker due to poor technical condition of the arc box

[2] The article does not provide sources for the drawings showing the waveforms of voltages and currents recorded during tests of switching devices to avoid associating the test result with the type of device or its manufacturer.

Another dangerous phenomenon is ground fault. In such a scenario, an electrical arc ignites between the main contact and the metallic part of the circuit breaker, such as the drive system element. The voltage and current waveforms recorded in the event of ground fault are depicted in Figure 6. Again, in this case, current breaking occurred due to the operation of the safety breaker.

In many cases, contact gap breakdowns or ground faults occur as a result of high arc voltage values, which weaken the dielectric endurance of the circuit breaker's insulation. Figure 7 illustrates an example waveform of arc voltage, with a maximum value of nearly 18 kV, almost five times the value of the circuit voltage. It is worth mentioning that the maximum arc voltage value should be agreed upon between the manufacturer and the user of the circuit breaker. It is often assumed that $U_{amax} \leq 4U_d$, and in the case of Polish substations, $U_{amax} \leq 2U_d$.

In addition to conventional magnetic blowout circuit breakers, which operate based on forced current breaking, the Institute's short-circuit laboratory conducted tests on a high speed (hybrid) circuit breaker using the countercurrent principle. An example waveform of voltages and currents in the circuit during current breaking with such a circuit breaker is depicted in Figure 8. A characteristic feature of these types of circuit breakers is their short breaking time (a few milliseconds), a momentary voltage drop below zero at the circuit breaker, resulting from the action of the countercurrent, and the visible flow of current to the ground connected to the negative terminal of the power source, caused by the operation of the overvoltage limiting device (not shown in Figure 3), which is an accessory of the circuit breaker. The flow of current to the ground, in this case, is a normal phenomenon. If there were no overvoltage limiting device in the circuit, the overvoltage could reach very high values, which is due to the rapid change in current (di/dt) in the circuit.

Fig. 6. Waveforms of circuit currents and arc voltage during ground fault

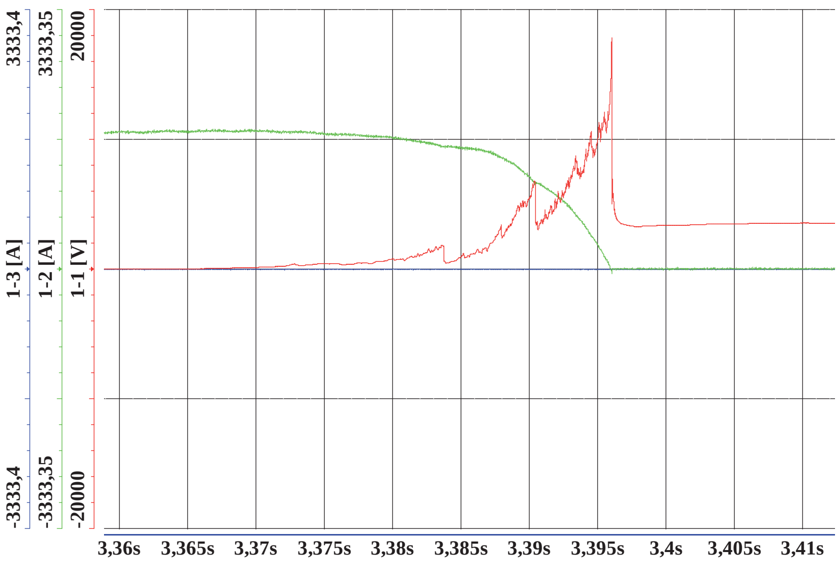

Fig. 7. Waveforms of switched-off current and arc voltage reaching excessively high values

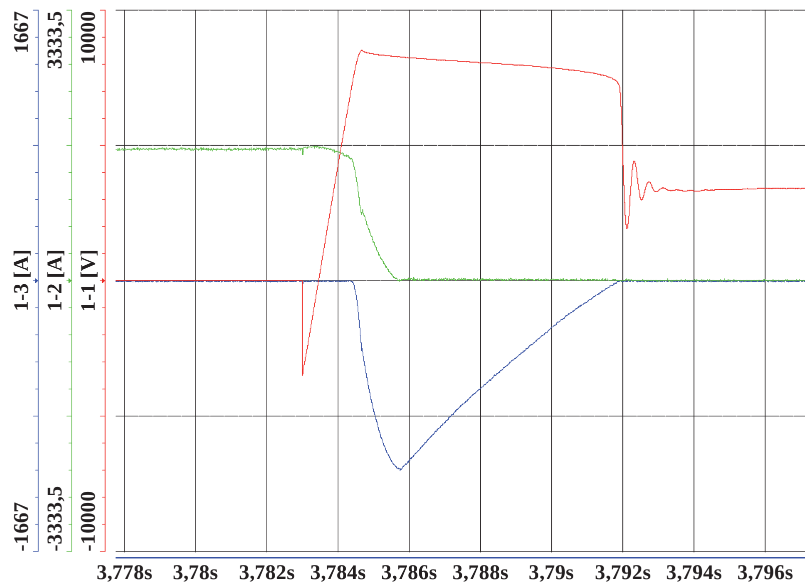

Fig. 8. Switching off the rated current by a circuit breaker using the principle of counter-current (overvoltage limiting device current – the blue colour is intentionally polarised in reverse)

4.2. Tests of contactors

So far, in the Institute's short-circuit laboratory, electrical endurance tests of contactors have been mainly conducted based on the EN 60077-2 standards [7]. These were devices with rated voltages of 900, 1800, or 3600 V and rated currents ranging from 250 to 1700 A.

Because contactors, like high speed circuit breakers, have arc chute, similar adverse phenomena can occur during current breaking, including excessive arc voltage values, contact gap breakdowns, or ground faults.

Due to the fact that a very large number of CO cycles are performed during the electrical endurance tests of contactors (usually 8000), common causes of failure to achieve positive test results are mechanical faults in the drive system or overheating of the arc chute.

The primary difference in breaking the rated current by contactors, compared to high speed circuit breakers, lies in the speed of breaking and the arcing time. On average, the arcing time of contactors is several tens of milliseconds (Fig. 9).

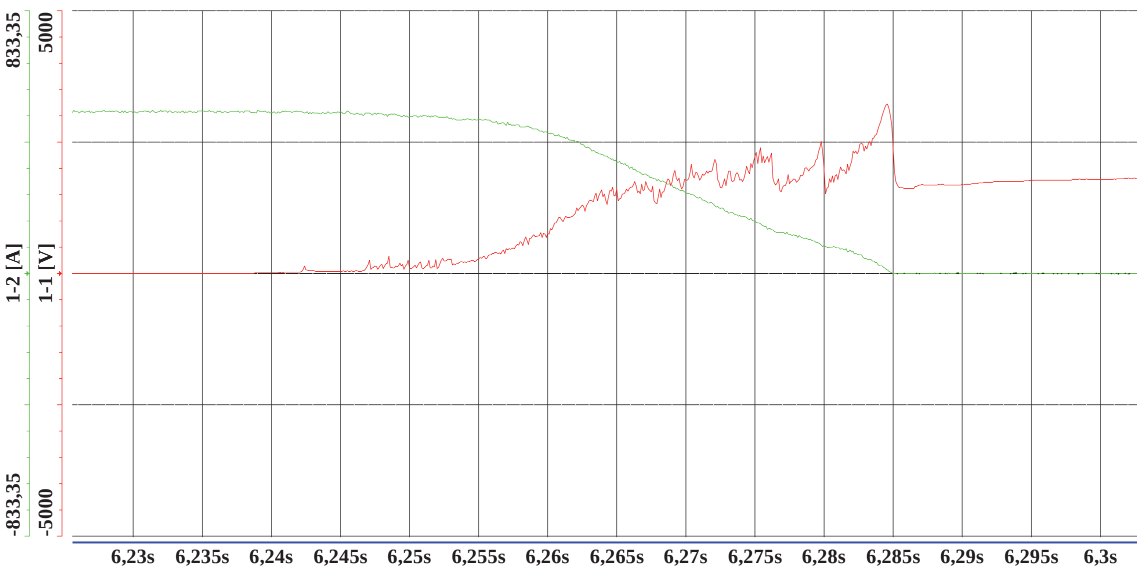

Fig. 9. Typical voltage and current waveform during current breaking by a contactor

Contactors have smaller arc chutes compared to high speed circuit breakers. Consequently, this leads to poorer conditions for quickly achieving the necessary arc voltage required for current breaking. This is particularly significant in the case of contactors with high rated voltages, such as 3600 V. This can cause multiple arcing events, leading to increased current and prolonging the breaking process. An example of such a phenomenon is illustrated in Figure 10, where the breaking arcing time (similar to the arcing time) exceeds 100 ms. The long arcing time results in significant heating of the arc chute, posing a risk of overheating and thermal damage. The high temperature of the arc chute hampers the arc from achieving the necessary voltage to break the current, potentially resulting in a failure to break it. Such a situation is depicted in Figure 11, where the breaking occurred due to the operation of the safety breaker.

4.3. Tests of switch disconnectors

The switch disconnectors do not have arc chutes. When breaking currents, and sometimes during making them, the electrical arc burns freely in the air between the arc horns, as shown in Figure 1.

The high temperature of the arc heats the surrounding air and melts the arcing horns. Consequently, in many cases, a fireball forms above the switch disconnector, consisting practically of plasma, highly

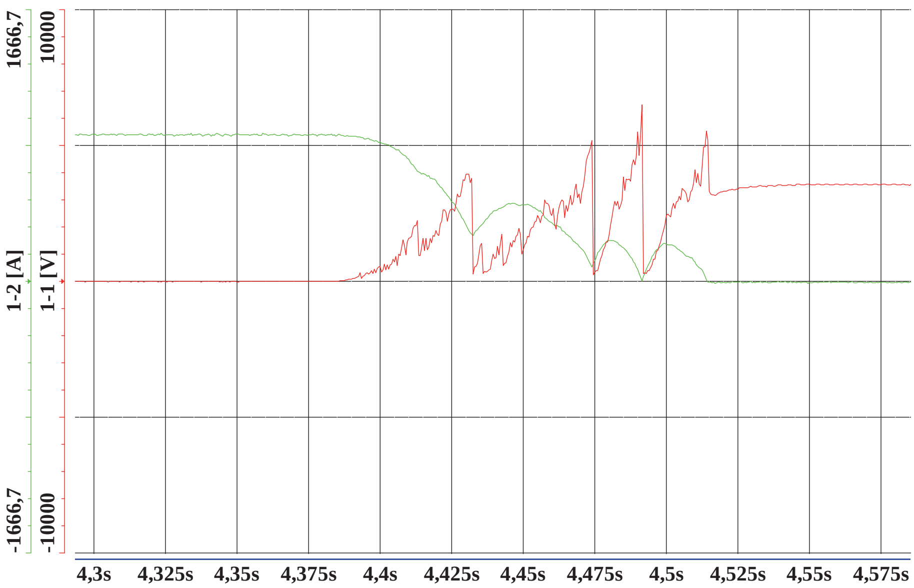

Fig. 10. Multiple arcing events during current breaking by the contactor due to poor condition of the arc box

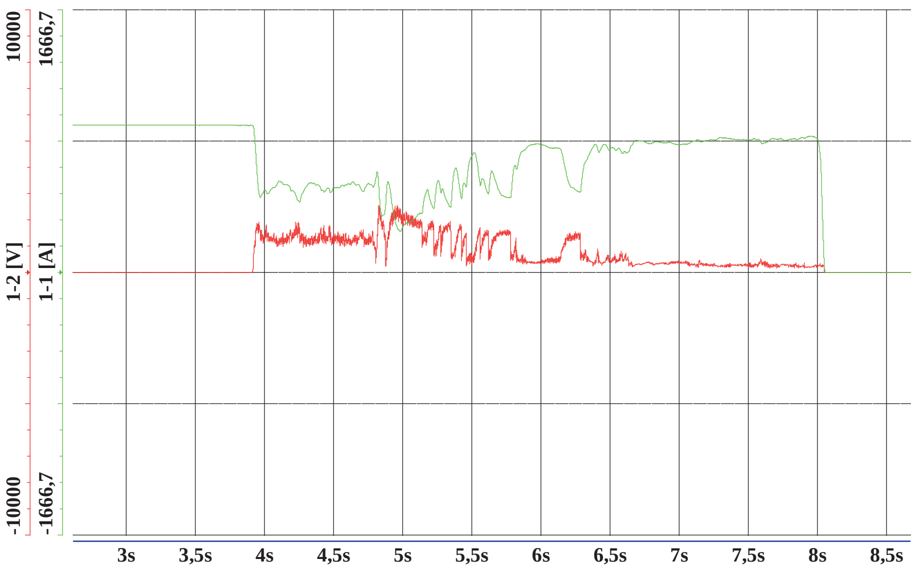

Fig. 11. Failure to break the current due to too low arc voltage

ionised particles of air, and molten metal. This phenomenon is shown in Figure 12. It is particularly dangerous when it occurs indoors. If the fireball reaches structural components, especially conductive ones, it can cause not only thermal damage but also arcing from the switch disconnector to these components.

Fig. 12. Plasma ball after current breaking by the switch disconnector [photo taken by M. Marszałek]

The movement of the movable contact of the switch disconnector is much slower compared to high speed circuit breakers and contactors. As a consequence, the current breaking time often exceeds 200 ms. This is illustrated in Figure 13. Additionally, during switching on, the arcing horns make contact first, followed shortly by the main contacts. The process of opening the switch disconnector occurs in the reverse order. This means that during the making and breaking of current, for a certain period, the entire current flows only through the arcing horns, which have a smaller cross-section and contact force compared to the main contacts. As a result, an electrical arc may appear even during the switching on phase, especially when the arcing horns are overheated or do not contact properly. Figure 14 shows the waveform of properly switched current, while Figure 15 depicts a scenario where arcing occurred during switching.

During operation, the components of the switch disconnector may wear out. For example, during each disconnection, the arcing horns are melted. Degradation of the switch disconnector can lead to a state where the electrical arc ignites between the main contacts. The distance between the open main contacts is much smaller than the ends of the arcing horns. Therefore, the arc is relatively short and burns stably. Only after some time, under the influence of electromagnetic fields and thermal convection, does the arc transition to the arcing horns, elongate, and extinguish. The duration of such disconnection can be counted in seconds (Fig. 16), and its consequence is partial melting of the main contacts, thus leading to the destruction of the switch disconnector.

5. Conclusions

Electrical endurance testing of switching devices may seem straightforward – making and breaking the current, usually rated, a number of times as specified

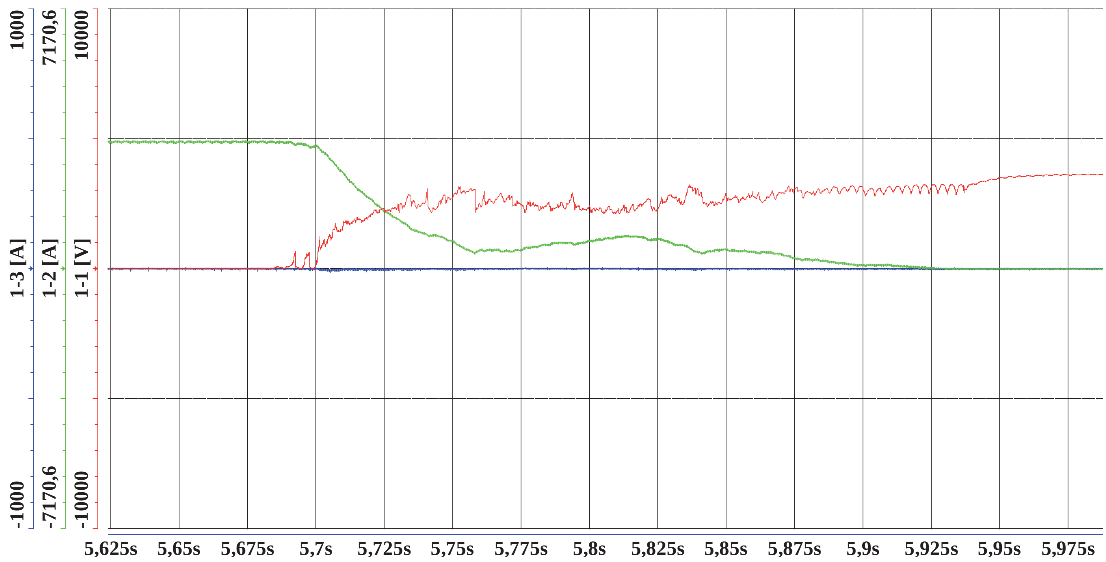

Fig. 13. Voltage waveform across the switch disconnector and switched-off current

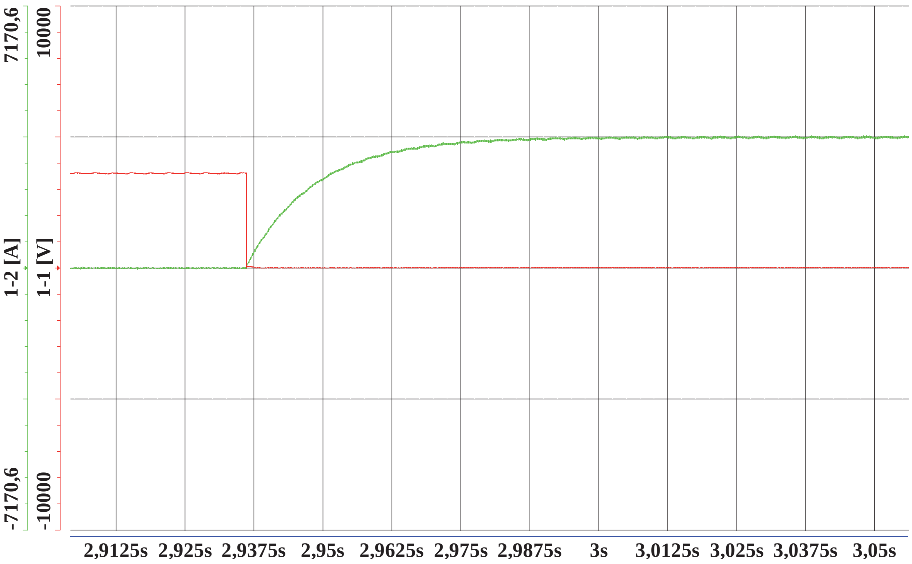

Fig. 14. Waveform of correctly switched-on current by the switch disconnector

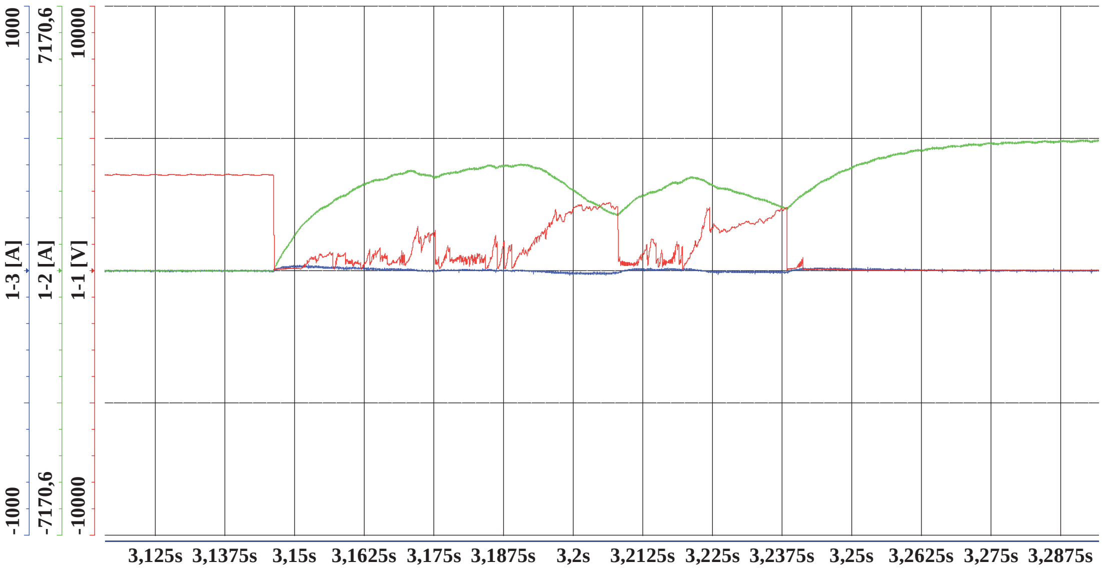

Fig. 15. Arc ignition during current switching by the switch disconnector due to insufficient contact condition

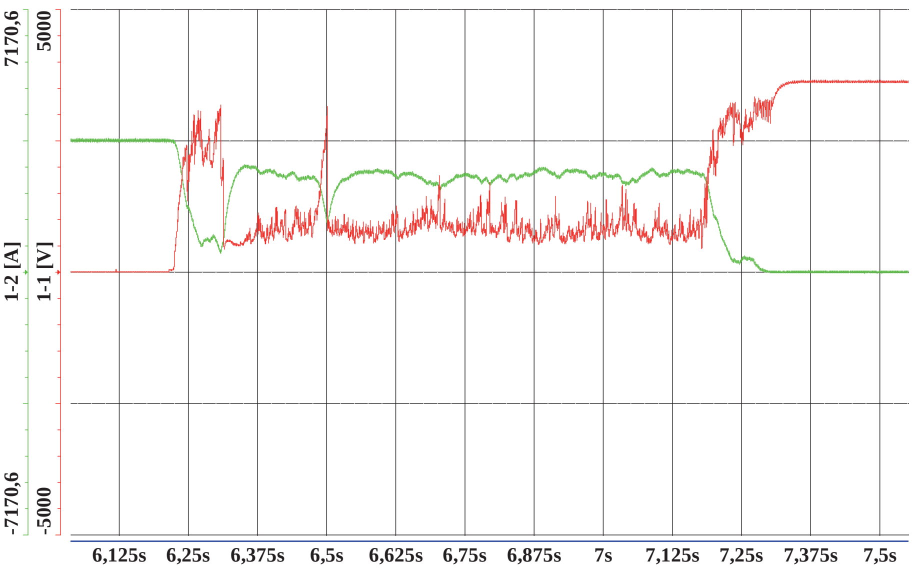

Fig. 16. Arc ignition between the main contacts of the switch disconnector during current breaking

by the discussed standards. However, as shown in the article, such testing carries risks stemming from the physics of forced DC current breaking, especially since switching operations are performed at high voltage and large currents reaching values of several thousand amperes. Additionally, one must consider overvoltages with values much higher than the supply voltage.

Undesirable phenomena occurring during electrical endurance testing largely depend on the type of switching device, whether it has an arc chute or the arc develops freely in the air. They also depend on the number of CO cycles to be performed during testing, depending on the type and future application of the specific switching device.

The article demonstrates that electrical endurance testing is time-consuming, and the research personnel must supervise it continuously.

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