Ultra-Fast Hybrid Systems for Protecting Direct Current Circuits with High Magnetic Energy

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Abstract.** The article presents a new generation of ultra-fast hybrid switching systems (USH) for reliable, ultra-fast protection of various medium and low voltage DC systems (MVDC and LVDC). The DC switch-off takes place in a vacuum chamber (VC) cooperating with a semiconductor module using current commutation of natural or forced type. Against the background of the current state of science and technology, the paper depicts the basic scopes of USH applications and their particular suitability for operation in high magnetic energy DC circuits. In the case of DC system failures, this magnetic energy should be dissipated outside the system as soon as possible. Usually magnetic blow-out switches (MBOS) with relatively low operating speed are used for this purpose. The article describes the theoretical basis and principles of construction of two types of novel USH systems: direct current switching system (DCSS) and direct current ultra-fast hybrid modular switch (DCU-HM). The DCSS family is designed for quench protection of superconducting electromagnets’ coils in all areas of application. The DCU-HM family is designed for the protection of all systems or vehicles of DC electrical traction and for related industrial applications. A conducted comparative analysis of the effectiveness of USH with respect to MBOS shows clear technical advantages of the new generation switching systems over MBOS.

** List of abbreviations used in the article is provided at the end.

Key words: DC, direct current, superconducting coils, quench, electromagnets protection, DC switches, ultra-fast switches, hybrid switches, vacuum - switches, DC electric traction.

1. Introduction

The DC ultra-fast shutdown technology started to be developed after 1930 in Sweden (ASEA). It has focused mainly on the high DC voltage (HVDC) range used in long-distance transmission systems or AC coupling lines. The types of DC circuit-breakers used at that time were assessed as insufficiently effective. These were usually circuit-breakers with sufficiently large breaking capacity, but with long total break times and current limitation coefficients which are usually known as insufficiently effective. For this reason, the types of DC circuit-breakers were designed for many different topologies, designed for networks and power systems, mainly in the HVDC range (e.g. [6, 7, 25]). This goes beyond the scope of this paper.

For the last 20 years, a very large number of publications has focused on vacuum, hybrid or solid state switches with many different topologies, designed for networks and power systems, mainly in the HVDC range (e.g. [6, 7, 25]). This goes beyond the scope of this paper.

1 Total break-time: \( T_b = t_t - t_0 \), where \( t_t \) - tripping instant, \( t_0 \) - arc extinction instant in main contact.

2 Current limitation coefficient \( C_0 \approx 1 \). Effective mitigation of the harmful effects of short circuit currents requires effective mitigation of these currents, i.e. breakers as fast as possible with the lowest possible \( C_0 \). Similar needs exist for medium DC voltages (MVDC) used in DC1 (3 kV) and DC2 (1.5 kV) systems of railway traction and in some propulsion or electrothermal devices, as well as in low voltage systems (LVDC, up to 1250 V) used in all types of city or mining electric traction and numerous industrial systems (converters, propulsion, etc.) [1–5].

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2. Current state-of-the-art of DC shutdown

For the protection of MVDC and LVDC systems, magnetic blow-out switches (MBOS) with an arc in atmospheric air are usually used. The devices are known for over 120 years and they are continuously improved.

The MBOS switches off short-circuit currents by an increase in arc resistance \( R_a \) in the ceramic extinguishing chamber, which absorbs the energy of the power source and the magnetic energy of the circuit. When the arc resistance increases sufficiently to meet the condition: \( R_a > U_s / i(t) - R_s \) (where \( U_s \) is the supply voltage, \( i(t) \) - current course, and \( R_s \) - short circuit resistance), the current derivative \( di/dt \) is always negative until the current reaches zero. Therefore, in DC circuits, when the magnetic energy increases, the switching life of MBOS decreases.

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The greatest magnetic energies, even up to 10 MJ, are found in superconductive electromagnets (SE). This exceeds the capabilities of extinguishing chambers used in MBOS. In emergency situations, to dissipate these energies a technique of bypassing the main switch with a dump resistor RD is used. After opening the switch and extinguishing the arc, the RD takes over the SE supply current. The magnetic energy of the SE is converted in the RD into heat released to the environment. In this case, the high speed of the switch operation, i.e. the shortest possible total break-time \( T_b \), has a great impact on reducing the harmful effects of SE's failure [8].

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The search for new technical solutions for DC circuit-breakers, much faster than MBOS, is stimulated by the increasing needs in rail transport in DC1 and DC2 systems. This is caused by the tendency to increase the acceleration and the speed of the rolling stock, the introduction of semiconductor devices into traction drives (e.g. for pulse start-up and braking with energy recovery and for the introduction of DC-powered AC drives via converters), and the dissemination of energy storage systems. It results in the increase of the substation supply voltage (on the AC side), in the increase of substation and vehicle motor power, and in the use of power amplification systems to limit voltage drops. The above mentioned factors cause the increase of the short-circuit power and the steepness of the short-circuit current change on the DC side [9].

New technical solutions of ultra-fast DC circuit-breakers (U DCCB), designed for rail transport, can be adapted to work in a variety of SE applications.

These requirements can hardly be met by the MBOS, which has too low short-circuit shutdown rate and too high Joule integral value (F 2t), especially for effective protection of semiconductor systems. This is one of the development barriers for railway traction.

There is no universal classification covering all DC switches. Traction switches are divided into 3 categories in terms of operating speed: S, H, V, with total break-time $T_b \leq 30; 20; 4$ ms (respectively) [10]. MBOS can be classified into categories S or H, i.e. it can achieve current limitation factors of $C_{0S} \geq 0.95$ or $C_{0H} \geq 0.7$. Hence, the current limitation efficiency in typical circuits with a time constant $\tau > 10$ ms is practically none (for S) or little (for H). The circuit-breakers in category V must have values $C_{0V} \leq 0.3$. This can easily be achieved with ultra-fast vacuum or hybrid switches. MBOS systems have reached the peak of their technical capabilities in all typical applications, which is due to their principle of operation. A multilateral research and implementation program, covering the issues of vacuum U DCCBs, has been carried out by the Authors in the Department of Electrical Apparatus from Lodz University of Technology since 1980. The developed theoretical basis made it possible to create and implement a new generation of ultra-fast DC vacuum circuit breakers, designed for substations and railway traction vehicles in the DC1 system (a total of 16 sizes with different voltages and currents) [9]. Fast technical progress in the field of railway and new needs and requirements created the necessity to retrofit the switches designed for DC1 and DC2 systems. After appropriate adaptation, new designs of circuit breakers have been developed and used among others for ultra-fast protection of SE against quench [3] effects.

In each of these areas of application, there are different system, environmental and technical requirements. Therefore, ultra-fast hybrid systems have two design variants: DCSS for the area of superconductive electromagnets and DCU-HM for the area of electric traction. Both variants use the same theoretical basis and related principles of operation of the hybrid switch-off system. It must be emphasised that only those principles of operation and topologies, out of 17 types of DC circuit breakers classified in [4], which suitability for MVDC and LVDC has been verified experimentally [11-15], were analysed in the USH implementation programme.

3. The theoretical basis and principles of USH operation.

3.1. Ultra-fast opening of USH. Ultra-fast opening of USH has been achieved due to development of special vacuum switch with fixed position under the force of return spring, opened by one-way induction-dynamic drive IDD [1,2,5,7,16] of high power (ring driving disc electrodynamically rejected from the coil powered by the impulse of high-current from the energy storage), kept in open state by quick lock. Current pulses in the coil have the high first semi-wave amplitude and frequency. Changes in coil magnetic field induce current in the disc. Interaction of both currents generates the impulse of electrodynamic driving force.

The IDD construction sketch is shown in Fig. 1.

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3 Quench: accidental local decay of superconductivity in SE coil. The resistance area quickly spreads in the coil due to Joule heat generated by great coil magnetic energy. This causes significant damage.

4 So-called Thomson drive.
transmission of the disc motion onto the chamber's moving contact. This is an instant commencement of contact opening upon equalization of increasing driving force of the disc and the return force. USH uses selected series-produced vacuum chambers for MV AC circuit-breakers.

It is required that the coil and the vacuum chamber are suspended as rigidly as possible on the support structure and that the drive disc is rigidly connected to the vacuum chamber, in order to shorten the opening time of the vacuum interrupter, in which its mechanical structure is responsible for the largest part of the delay. This is directly justified by all three Newton's laws of dynamics, with respect to the interactions of the individual IDD components, causing deformations and axial elastic oscillations.

IDD current pulses, generated by an oscillatory discharge of the capacitor charged to \( U_{\text{CO}} \) voltage by the coil, have usually first halfwave amplitude \( > 1 \) kA and time up to 300 \( \mu \)s. Change in the magnetic field of a coil induces current in the toroidal disc, which cross section is rectangular. The interaction of currents generates a pulse of electrodynamic driving force \( F_D \) repelling from the coil the drive, which is coupled to the rest of the components of the moving body (see elements 5 – 9 in Fig. 9c).

### 3.2. Vacuum interrupters for USH application

Industrial AC vacuum chambers can be used in USH for DC if they meet certain requirements \([13,17,18]\). The prerequisite is that only the diffusion form of the vacuum arc is present in the vacuum interrupter. The properties of the diffusion arc are essential for the use of vacuum interrupters for ultra-fast DC switching off by USH. There must be no constricted arc. Only vacuum chambers with contact generating axial magnetic field (AMF) may be used. This is shown in Fig. 2.

![Fig. 2. Effect of magnetic field on the arc in a vacuum. a) Examples of contacts generating radial magnetic field RMF or axial magnetic field AMF: a1) spiral contact, a2) crown contact, a3) coil contact, a4) ferro - contact (field shaped by multi-layer horseshoe-shaped steel inserts placed under the contact tips). b) Forms of the vacuum arc: b1) diffusion arc at currents below 10 kA limit, both at RMF and AMF, b2) constricted arc with active anode at currents greater than the 10 kA limit at RMF, b3) diffusion arc with passive anode at much higher currents than 10 kA limit at AMF. B – magnetic flux density, A – anode, C – cathode, d – contacts distance, \( d_0 \) – critical distance of contacts. (Phot. acc. to [19], own description).](image)

There is a large safety margin for USH under real operating conditions, while using vacuum chamber with AMF for AC circuit-breakers with contact material without low melting components (typically CuCr alloys are used), at experimentally verified limit current \( i \approx 60 \) kA and \( d > d_0 = 0.3 \) mm. With typical geometric dimensions of the contact system, after the current is reduced to zero and the diffusion arc is extinguished, the initial parameters of the post-arc plasma are subcritical and the mean free path of atoms is greater than the distance between the contacts \( d \).

Under these conditions, after current zero, the recovery strength increases rapidly to the static electrical strength of the cold vacuum gap, \( u_{\text{kd}} = K \cdot d \), where \( K \) denotes static flashover intensity in vacuum. The \( K \)-value is high and it depends on the contact material, e.g. for Cu, flat contacts \( K \approx 80 \) kV/mm. If the current reaches zero for \( d \) in the range 0.3 - 0.5 mm, the breakdown voltage is in the range 24 - 40 kV. Hence, arc reignition is impossible.

The presence of a constricted arc is excluded, as the active anode is a strong source of metal vapour for contact gap. This greatly reduces the \( K \) value. If the direct current goes to zero with high steepness, it may not be switched off. At diffusion arc in AMF, assuming a surge protection level of approx. 10 kV, a reduction of current to zero at \( d \geq d_0 = 0.3 \) mm may be safely realized. To minimize the total break-time \( T_B \), the highest opening speed \( v_o \) of the vacuum chamber (given by producer) must be assumed.

### 3.3. Quench phenomenon

Superconducting coils supplying all types of electromagnets in accelerators are usually made of Rutherford multi-wire cables, spliced from multiple filament wires, in order to reduce the number and inductance of coils. Despite of very rigid structure of superconducting coil (due to compression in dedicated steel flanges) in order to eliminate any movements of cable wires, Lorentz forces affect the wires and may locally exceed friction forces, causing micro movements of wires and instantaneous release of sufficient heat to cause local loss of superconductivity.

Resistance area is generated at random, at the unknown location of the coil, and propagates rapidly due to conduction of heat generated by Joule losses in the resistance area, including magnetic energy dissipation. This is accompanied by overvoltage on the coil, much higher than the supply voltage. This enables quench detection. Under typical conditions, quench propagates transversally (coil to coil) within ca. 10 ms and the electromagnet undergoes damage due to local overheating or voltage breakdown. The issue of shortening the coil current off time and superconducting coil energy discharge is essential to reduce the damage caused by quench. There are no overvoltages, overloads and short circuits in the power supply circuits of superconducting coils, so this does not apply to anti-quench protection systems. The high magnetic energies of the coils are transferred ultra-fast to dump resistors and converted to heat (see section 2).
3.4. Operating principles of USH. Depending on the purpose of the USH system, two variants of ultra-fast DC hybrid switches (DCS) with different operating principles are used alternatively: DCSv.1 with forced commutation and DCSv.2 with natural commutation. Diagrams of both DCS variants are shown in Fig. 3.

Fig. 3. Ultra-fast DCS switches: a) v.1 version with forced commutation, b) v.2 version with natural commutation. V – vacuum interrupter; 1T, 2T – main terminals; Th1, Th2 – thyristors; C – commutation capacitor, L – air-core reactor. BSM – bidirectional semiconductor module; c) BSM types: c1) – IGBT, c2) – IGCT, c3) – GTO. Currents: I – main c. (any direction); i1, i2 – counter-current; iTh1, iTh2 – thyristor c. – iSM – BSM current. UC0 – initial voltage of C capacitor. Note: The C capacitor is charged from an inverter supplied with auxiliary voltage (for DCSv.1), or from the overhead contact line (for DCU-HMv.1).

DCSv.1 with forced commutation (Fig. 3a) is ultra-fast, unpolarized DC hybrid switch with parallel hybrid topology of vacuum-thyristor type that brings the direct current to zero in vacuum with a counter-current pulse from an additional source switched with thyristor module.

The countercurrent is sinusoidal. Its source is a capacitor C charged to voltage UC0. C is unloaded due to switching on the thyristors. Th1 and Th2 thyristors are switched on sequentially. The current in a vacuum chamber is the difference between the main current and the countercurrent. Depending on the direction of the main current, it can be reduced to zero as a result of a single (during the first counter-current half-wave, see Fig. 4d) or a double (during the second counter-current half-wave, see Fig. 4e) commutation.

DCSv.2 with natural commutation is ultra-fast, unpolarized DC hybrid switch with parallel hybrid topology of vacuum- semiconductor type. It brings the direct current to zero in vacuum with the difference between the arc voltage u0 = 10 - 27 V (18 - 21 V for Cu contact) of the diffusion arc in the vacuum chamber and the conducting voltage UBSM ≈ 2 V of the parallel connected bidirectional semiconductor module (BSM), activated for a short time. The BSM can be an anti-parallel combination of IGBT transistors, or IGCT thyristors (possibly GTO). In each BSM both transistors or thyristors are controlled simultaneously. The current-compatible element takes over its conduction.

After the diffusion arc has been ultra-fast extinguished, vacuum chamber V becomes an isolation gap. This changes the configuration of the external circuit. A naturally disappearing transition state appears, depending on the parameters of the circuit. For each range of USH applications the course of phenomena in this state is different.

4. Detailed specification of USH application areas.

4.1. Area of superconductive electromagnets. DCSS family for anti-quench protection. Coils of superconducting electromagnets for:

- elementary particle accelerators,
- tokamaks and stellarators for nuclear fusion,
- accelerators in industry, medicine (cancer treatment, imaging techniques, NMR, manufacturing processes and new materials, food preservation), in the army,
- traction (MAGLEV) and magnetic cushion bearings,
- plasma generators, energy storage, etc.

General conditions of DCSS operation: conduction and deactivation of direct current of a given value. There are no short circuits and overloads. There are no switching overvoltages. Overcurrent releases and surge arresters are not required. An ultra-fast shutdown is required (shutdown as short as possible). Both DCSv.1 and v.2 variants are used.

4.2. Area of electric traction. DCU-HM family for substations and vehicles protection.

- DC1 railway traction system (U = 3 kV).
- DC2 railway traction system (U = 1.5 kV).
- Urban traction systems, LV (U ≤ 1 kV), trams, trolley buses, buses etc.
- Mining traction systems, LV (U ≤ 0.6 kV).
- Industrial applications, LV (U = 0.25 - 1.25 kV) and related.

DC DCU-HM types for railway traction:

- P type circuit breakers (stationary), for substations.
- Vehicle circuit breakers (mobile): PZ type for combined trains, L for locomotives and others.

Roof, deck or sub-deck versions are possible. General DCU-HM operating conditions: direct current on and off of any value possible in a given traction system at the highest supply voltage, as well as limiting overvoltages. There are operating, overload and short-circuit currents. There are two-sided switching overvoltages (external – network or atmospheric and internal - receiver). Overcurrent releases and surge arresters are necessary. An ultra-fast short-circuit breaking (shortest possible total break-time) and energy recuperation are required. Both DCSv.1 and v.2 variants are used. None of them must operate due to typical driving disturbances [20].

5. DCSS as modern protection system.

A simplified scheme of powering the superconducting magnet coil, containing the energy extraction system (EES), is shown in Fig. 4a, while the simulated waveforms of voltages and currents presented in Fig. 4b - e) illustrate the ultra-fast operation of DCSv.1 and v.2.
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Fig. 4. General principle of ultra-fast protection of the superconducting coils against the quench effects. a) Simplified scheme for superconducting coil power supply, equipped with an energy extraction system containing ultra-fast DCSS. Currents and voltages when DC is switched off: with natural commutation - Fig. b) with positive current polarity, Fig. c) with opposite current polarity, for the DCSSv.2 shown in Fig. 3b; with forced commutation - Fig. d) with consistent current and counter-current direction (ie. iV = 1 – iC, single commutation); Fig. e) with opposite current and counter-current direction (ie. iV = 1 + iC, double commutation), for the DCSSv.1 shown in Fig. 3a. DCPS – direct current power supply, SM – superconducting magnet coil, BC – bypass circuit, QDS – quench detection system, EES – energy extraction system, DCSS – redundant switching system (two identical ultra-fast DCSSv.1 or v.2 switches (A and B), RD – dump resistor (for coil energy discharge); T1, T2 – terminals.

Each DCSS v.1 or v.2 is unpolarized and redundant, i.e. it consists of two identical DCSSv.1 or v.2 (respectively), marked A and B in Fig. 4.a). Due to the natural dispersion of phenomena, one of the DCS (A or B) works first (in random order). The second one opens currentless. So, the ultrafast DCSS and DCS shutdown sequences are the same. Ultra-fast DCSS in all required conditions may be a replacement for the MBOS used so far in EES.

The external OFF command or QDS quench detection signal immediately activates commands 1 - 3 (Fig. 4.a) causing the DCPS to be turned off, BC to be turned on, switches A and B to be opened at the same time (at the instant t50 in Fig. 4.b) - e). After T50 opening time, at the instant tae, contacts of the vacuum chamber V split and move away at the set speed. When the contact distance d increases above d0 (see section 3.2), at the instant t00, the command ON starts the ultra-fast shutdown sequence. This sequence is slightly different for DCSSv.1 and v.2.

The SSv.1 unified shutdown algorithm sequence is very simple for forced commutation (green colour in Fig. 3a). It contains only three consecutive control signals separated by strictly defined two delay times (Tae, T00 in Fig. 5.c):

\[
\text{OFF}\text{DCSS (}t_{50}\text{)} \rightarrow T_{ae} (T_{50-60}) \rightarrow \text{ON}_{\text{SM}} (t_{60}) \rightarrow T_{ae} (T_{50-70}) \rightarrow \text{ON}_{\text{SM}} (t_{70})
\]

The delay times can be adjusted to synchronize the operation of both DCSSv.1, cooperating in series in the DCSSv.1. Depending on the direction of the main current, it can be reduced to zero at the instant tae as a result of a single or a double commutation (Fig. 4.d), e); (See also section 3.4). After the instant tae, RD resistor quickly takes over the main current and starts discharging energy from SM.

The SSv.2 shutdown algorithm sequence for DCSSv.2 is even simpler than SSv.1. It consists of only two successive control signals separated by a specified delay time T_{50-60}:

\[
\text{OFF}\text{DCSS (}t_{50}\text{)} \rightarrow T_{50-60} \rightarrow \text{ON}_{T1, T2} (t_{60}) \rightarrow (t_{70}) \rightarrow \text{OFF}_{T1, T2} \rightarrow (t_{90})
\]

where the ON \text{OFF}_{T1, T2} is the command for IGBT modules, in the form of voltage single pulse of duration T_{60-70} (Fig. 4.b), c).

As a result of the auto-adaptation of the IGBT module to the direction of the main current I, first V/T
commutation between V and T1 or T2 is performed spontaneously by one of the transistors T1 or T2, having the direction of conduction in accordance with the direction of main current. After the instant $t_{m}$, resistor RD quickly takes over the main current and starts discharging energy from SM (Fig. 4.b, c). The coil current flows in the SM - BC - RD loop (Fig. 4.a), until the magnetic energy is completely lost as a result of conversion into heat in the RD (see section 2).

### 6. DCS operation.

Detailed block diagrams of DCSv.1 / v.2, having principles of operation shown in Fig. 3, and unified DCSv.1 and DCSv.2 ON / OFF cycle are presented in Fig. 5. The DCSv.1 and the DCSv.2 have different principles of operation and construction, but they are functionally fully equivalent. Each of them must be able to independently and reliably switch off the main current of the superconducting coil. Therefore, each DCS is equipped with a similar control system, with slight differences in software and control elements of thyristors or transistors. The DCSv.1 version becomes v.2 when the ThU and CCU modules are replaced by an IGBT module (Fig. 5.a).

Full switching cycle (ON/OFF) of DCSS consists of four sequences: preparation sequence, switching on sequence, main current conduction sequence and ultra-fast shutdown sequence (intentional or as a result of a quench). Three of them shown in Fig. 5.b (preparation, switching on and current conduction sequences) are identical for DCSv.1 and DCSv.2. Small differences between DCSv.1 (Fig. 5.c) and v.2 (Fig. 5.d) exist during shutdown sequence only.

During the DCS preparation sequence (time $T_{1c-2c}$), the auxiliary voltage is switched on at the instant $t_{c}$ and the signal S1 starts self-control of all monitored parameters R1-Rn. DCS automatically sets itself in the open position and goes into standby mode, sending the standby signal S2 at the instant $t_{2c}$ (Fig. 4). The DCS conduction sequence has an indefinite time $T_{4c-5o}$. The current is conducted until the instant $t_{5o}$ when the current and voltage range. DCSv.2 with natural commutation is useful in the lower range.
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Fig. 5. Unified DCSv.1 and DCSv.2 ON/OFF cycle for both directions of main current I and for the circuit features shown in Fig. 2 - 4. a) Block diagram of the DCSv.1 / v.2 for any polarity of main current I. b) Sequence of switching on the circuit (identical for DCSv.1 and DCSv.2). Unified shutdown sequence, its elements and times: c) for DCS v. 1, of thyristor-vacuum type with forced commutation; d) for DCS v. 2, of transistor-vacuum type with natural commutation. Pictograms showing the states of contact of the vacuum chamber V (see also VC in Fig. 9 b, c) O - open, C - closed (no current), C1 - closed (current flow), A1 - arc ignition, DA - diffuse arc; [E] - beginning of the energy discharge. The markings in Fig. a): VCU – vacuum contact unit; V – vacuum interrupter, PS - position sensor, LS – lock set, IDDS – inductive-

dynamic drive set, ACS – auxiliary contact set (instead of ACS, a second PS can be used); ThU – thyristor unit; CCU – counter-current unit; VD – voltage dividers, 1u, 2a, 3u, 4a – voltage measurement points; T1, T2 – terminals; 1, 2 – connection points; SCU – control unit of DCS switch with input/output interface I/OI; OEC – optical or electrical control connections; WH – wiring harness; APSU – auxiliary power supply unit. Signals: S1 – sequence start (as a result auxiliary voltage: UaW → ON and nUcO ON, see Fig. a) and b); S2 – ready state of DCS; S3 – command to close DCS; S4 – DCS closed state; S5 - opening command (OFF DCS s.), S6 – command to turn on thyristor Th1 (ON Th1 s.), S7 - command to turn on thyristor Th2 (ON Th2 s.). The markings in Fig. d): Signals: S5 – as previously, S6 - command to turn on simultaneously transistor T1 and T2 (ON T1,2 s.); S7 – command to turn off simultaneously transistor T1 and T2 (OFF T1,2 s.).

The main parameters of each of the DCSS/DCS v.1 and v.2 variants differ. For the needs of CERN, DCSS with the following parameters were developed and implemented for unit production:

DCSS v.1: U = 1500 V; I = 600, 2000, 13000 [A]. Planned ➔ 24000 A.

DCSS v.2: U = 1500 V; I = 600 A.

The DCSS family implementation programme has been carried out for the European Organization for Nuclear Research CERN. All manufactured DCSS (600 A and 2000 A) were installed at CERN in 2019 for quench protection of superconducting electromagnets operating in LHC Large Hadron Collider systems.
A new technique of ultrafast commutation of the current between the DCSS/DCS and the dump resistor RD has been experimentally verified. It improves the effectiveness and reliability of the anti-quench protection. The development potential of DCSS is high because they can be useful in all fields of application of superconducting electromagnets described in section 4.1. Selected examples from the DCSS family photo-documentation are shown in Fig. 9.

Fig. 7. Oscillograms of the main current of 600 A commutation between DCSV.2 and the dump resistor RD with forced commutation: a) single, b) double (sec. 3.4 and Fig. 4.d, e).

Fig. 8. Oscillograms of the main current of 2000 A commutation between DCSV.1 and the dump resistor RD with forced commutation: a) single, b) double (sec. 3.4 and Fig. 4.d, e).

Fig. 9. Selected examples from the DCSS family photo-documentation:

a) DCSS v.1 and v.2, 600 A systems mounted in the eurorack: 1 – DCSVv.1 compartment; 2 – compartment of DCSVv.1 main circuit flexible connections; 3 – DCSV v.2 compartment; 4 – compartment of DCSVv.2 main circuit flexible connections; 5 - compartment of HBCS master controller of EES and RD dump resistors; A, B – individual DCs switches (see Fig. 4.a).

b) Ultra-fast vacuum contact unit (VCU), main assemblies and components. Terminals of VC vacuum interrupter: T1 – fixed terminal cooled by R heat sink, T2 – movable terminal with flexible connections; LA – lock assembly and LE – lock engine; IDD – inductive-dynamic drive: C - coil, B – bumper, D – disc; S – spring set, IB - insulation bracket, SP – supporting plate, SS – supporting structure.

c) DCSV.1 switch overview and its subassemblies, for DCSS v.1, 2000 A system, panoramic left side view: T1, T2 – main terminals, FP – front panel; 1 – terminal strip, 2 – local control panel, 3 – power supplies of lock release electromagnet, 4 – vacuum contact unit VCU, 5 – vacuum interrupter VC, 6 – lock assembly LA, 7 – position sensor PS, 8 – inductive-dynamic drive set IDD, 9 – contact spring set S, 10 – filter capacitor, 11 – commutation reactor L, 12 – commutation capacitor (CC), 13 – IDD coil diode, 14 – drive capacitor, 15 – drive release thyristor, 16 – converter for charging the commutation capacitor 12, 17 – controller of thyristors, 18 – converter for charging the drive capacitor 14; 19 - insulators, 20 – elements of mounting cage.

Note: all symbols in brackets – see Fig. b) or d).


Note: VCU1, 2, 3 have the same design.
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Sample oscillograms taken during switching off of the current of 13000 A by DCSS13v.1 shown in Fig. 9.d are presented in Fig. 10. Fig. 10.a and Fig. 10.b depict the obtained waveforms with forced commutation: a) single, b) double (sec. 3.4 and Fig. 4.d, e).

7. DCU-HM as modern protection system for DC1 and DC2 railway traction systems

Similar to DCSS, ultra-fast DCU-HM in all the required conditions may be a replacement for the MBOS used so far in electric traction. The origin of the work on the DCU-HM family is described in section 2. DCU-HM are designed for railway traction vehicles used in both DC1 and DC2 systems and also in other DC LV systems. They have an optimised operating principle and a new breaker topology.

The latest technical conditions are taken into account. The switching off of DC by natural commutation (version v.2) is only useful in the low voltage range. Switching DC off by forced commutation (version v.1), i.e. by counter-current (see section 3.4, Fig. 3.a, DC Sv.1), makes the devices applicable for the whole range of traction voltages. In DC1 and DC2 systems (the MVDC range), a hybrid circuit-breaker DCU-HMv.1 with a topology shown in Fig. 11 is used. An algorithm of switching on sequence is practically the same as in DC Sv.1 (see section 6, Fig. 5.b). A unified shutdown sequence of DCU-HMv.1 occurs during \( T_{w1} = t_{w1} - t_{w0} \). Its course is analogous to that shown in Fig. 5.c (see also see section 5 and formula (1)). The values of individual times may vary, depending on many parameters. In the counter-current generator GP, the commutation capacitor CK is charged from the overhead contact line (see Fig. 11.a). The main current is always reduced to zero at the instant \( t_{w0} \) as a result of double commutation (Fig. 8.b). (See also section 3.4 and 5, Fig. 4.e).

![Fig. 10. Oscillograms of the main current of 13000 A commutation to the dump resistor RD obtained for DCSS13v.1 with forced commutation: a) single, b) double (sec. 3.4 and Fig. 4.d, e).](image)

![Fig. 11. a) Main circuit diagram of the new DCU-HMv.1 circuit-breaker illustrating the basic principles of construction and operation. b) Stylized currents and voltages illustrating the ultra-fast switching off sequence (see Fig. 5.c). Symbols in Fig. a): VZL - vacuum switch; VC - main vacuum chamber; P - drive rod; IN - drive insulator; Niz - inductive-dynamic drive (b - base, c - coil, d - drive, a - bumper); Fd - return force, Ff - drive force; Z - lock (main; alternatively, a second auxiliary/release lock Z'); CP - optical position sensor, ZP - auxiliary switch, WS - optical fiber harness conducting contact position signals; ZN - drive power supply; CN - drive capacitor, TN - drive thyristor, PN - drive converter; ZZ - lock power supply; PZ - lock converter, CZ - lock capacitor, TZ - lock thyristors; GP - counter-current generator; CK - commutation capacitor, LK - commutation choke, RK - commutation resistor; Th - main thyristor module 1 and 2; A - anode, B - gate, K - cathode; DP/AP - overcurrent relay: ss - special bus, DP - current discriminator, AP - current analyzer with ADC - analog-digital converter. O - disconnecter (optional); N - disconnecter drive; Surge arresters: external W (oxide varistor) and internal OP (W - as above and D - return diodes); ODB - traction vehicle receivers; DN - voltage dividers. **N** and "-" - main connection terminals. Terminal "+" effectively earthed (to rail). USW - central switch control unit: IWW - input - output interface, ZNP - auxiliary voltage supply. Symbols in Fig. 11. b): Voltages: \( +U \) - mains \( v \), \( u_{sv} \) - arc \( v \) and \( v \) on vacuum chamber VC; \( u_{ck} \) - \( v \) on CK capacitor, \( u_{ck} \) - initial value of \( u_{ck} \), \( u_{ck} \) - initial value of \( u_{ck} \) after overload of CK, \( u_{vk} \) - \( v \) on varistor W, \( u_{ph} \) - maximum value of \( u_{ph} \). Currents: \( i_{k1} \) - short circuit \( c_1 \), \( i_{k} \) - maximum value of \( i_{k} \), \( i_{ck} \) - overload current of CK, \( i_{pm} \) - maximum value of \( i_{pm} \), \( i_{pm} \) - maximum value of \( i_{pm} \), \( i_{ck} \) - counter-current, \( i_{pm} \) - maximum value of \( i_{pm} \), \( l_{v} \) - limited current,
i\textsubscript{s} - setting current of discriminator DP, \(i_{VC}\) - c. in VC chamber, \(i_{CK}\) - c. in CK capacitor, \(i_{Th1}\) - c. in W varistor, \(i_{VC}\) - maximum value of \(i_{VC}\), \(i_{iz}\) - internal control signals; \(t\) - time.

**Moments:** \(t_{kw}\), \(t_{k1}\) - moments when an external S3 signal or an internal \(k_{w}\) signal (which initiates the shutdown sequence) is given to the USW and \(k_{1}\) signals (Fig. b) are sent immediately, \(i_{CK}\) - m. of change of \(u_{CK}\) voltage polarization, \(i_{iz}\) - m. of VC contacts separation and the arc ignition, \(i_{iz}\) - m. when the critical contact distance is reached, \(i_{iz}\) - m. of the \(k_{2}\) energies, \(i_{iz}\) - m. of arc extinguishing, \(t_{ipm}\) - m. of maximum counter-current (\(t_{ipm}\) in Fig. b), \(t_{CK}\) - m. of maximum main current, \(t_{iw}\) - m. of varistor W activation \(t_{iw}\) - m. of commutation end between CK and W as well as the peak value of the switching overvoltage \(u_{CK}\), \(i_{iz}\) - m. of reaching zero by main current, \(i_{iz}\) - m. of sending \(S_{a}\) signal ending the switching off sequence.

**Times:** \(T_{iw-rs}\) - own time of VZŁ opening, \(T_{iz}\) - arc time, \(T_{iz-rs}\) - time of reaching critical distance of contacts, \(T_{iz-rs}\) - reserve time (safety reserve, delay \(k_{2}\)) \(T_{iz}\) - delay time of \(k_{2}\), \(T_{iz}\) - \(T_{iz-rs}\) - commutation times, \(T_{iz}\) - \(T_{iz-rs}\) - break time, \(T_{iz}\) - transient state time (\(= T_{iz-rs}\) - time of delay of \(S_{a}\) signal).

The ultra-fast shutdown sequence is triggered by an external control signal S3 (in Fig. 11.a) under operating conditions, or an internal \(k_{w}\) signal from the overcurrent protection DP/AP at a short circuit or overload, causing the drive Niz to be tripped, the chamber VC to be opened, the thyristors Th1 and Th2 to be (successively) switched on (i.e. GP to be started), the current in the chamber VC to be reduced to zero by means of the counter-current and the arc extinguished. The switching overvoltages generated then are limited by the varistor arresters W and with the use of reversible diodes D. The overcurrent relay DP/AP under overload conditions operates after exceeding the set threshold value of the Joule integral, calculated from the measured and analysed current course, i.e. it operates as a typical thermal overcurrent tripping device. Such signal can also come from external overload relays. Under short-circuit conditions, the DP/AP relay operates as an instantaneous tripping device that reacts to the set current. In any case, the ultra-fast shutdown sequence has the same course until the arc is extinguished.

According to the diagram shown in Fig. 11.a, vacuum chamber VC and counter-current generator GP are connected in parallel. Generator GP is serially connected to a unit of thyristors Th1 and Th2 connected anti-parallelly. The GP generator circuit is a resonant circuit with very low attenuation, consisting of a capacitor CK, which is an energy storage, charged by the resistor RK from the overhead line to \(+U = U_{0}\), and the choke LK. The effect of the commutation of \(i_{iz}\) in the VC contact is to reduce to zero the \(i_{iz}\) current and extinguish the diffusion arc. The contact gap in the out-of-state immediately achieves very high electrical strength, which ends the process of ultra-fast \(i_{iz}\) current shutdown. Then a natural, spontaneously fading transient state, depending on the circuit parameters, occurs in time \(T_{w}\). VC becomes an isolation breaker, which results in a change in the configuration of the circuit. A further CK discharge process takes place in a series-connected closed circuit:

**terminal \(\cdot\) \(\rightarrow\) **

Since LS and RS depend on the parameters of the power supplies in the overhead contact line substation and the unit parameters of the overhead contact line etc., they may have different values that depend on the position of the vehicle on the railway line section during a short circuit. The sum of the remaining energy in CK and the magnetic energy of the overhead contact line causes the overcharging of the capacitor CK. Increase of \(u_{CK}\) with polarization according to \(+U\) causes reduction of discharge current and increase of switching overvoltage on CK to the value of the tripping voltage. W is a tripping varistor that takes over the remaining current and completely discharges the circuit energy.

The characteristic times of the ultra-fast multi-stage shutdown sequence shown in Fig. 8.b are an illustration of the dynamic capabilities of DCU-HM (see also section 5, formula (1) or (2)). Exemplary time values \(T_{w}\) for DCU-HM 3 kV, 1600 A following the notation from Fig. 11.b, are:

\[
T_{iw-rs} = 500 \mu s, \quad T_{iz} = 1300 \mu s, \quad T_{iz-rs} = 1200 \mu s, \\
T_{iz-rs} = 40 \mu s, \quad T_{iz-rs} = 60 \mu s, \quad T_{w} = 1740 \mu s; \quad T_{iz} \geq 1 ms.
\]

The time interval \(T_{w} \leq 2 ms\) is the sum of the vacuum switch own time \(T_{iw-rs}\) with the value of 300 - 800 \(\mu s\) and the arc time \(T_{iz}\) with the value of 1.2 - 1.7 ms. It is a design parameter of the circuit breaker only. On the other hand, the time interval \(T_{iz} \geq 1 ms\) depends on both the parameters of the breaker and the parameters of the switched-off circuit, especially its inductance. As the value of the inductance increases, the time \(T_{iz}\) rises. However, when switching off low inductance circuits with short-circuit currents of the order of 50 kA (traction circuits), this time may reach a value of approx. 1 ms and results in total brake time of approx. 4 ms, which is the limit value for class V circuit breakers [21].
Similar to DCS (see formula (1)), unified shutdown sequence is very simple. It contains only two consecutive control signals separated by strictly defined delay times $T_{oT}$ (Fig. 11.b):

$$\text{OFF} = k_1, k_{Sn}, k_{w} (t_{3w}) \Rightarrow T_{oT} \Rightarrow k_2 (t_e)$$  \hspace{1cm} (5)

For the needs of DC1 system, DCU-HMv.1 family has two base sizes with the following parameters:

DCU-HM 3/1.6: $U = 3kV; I_{sh} = 800, 1250, 1600 A.$  \hspace{1cm} (6)

DCU-HM 4/4.0: $U = 4kV; I_{sh} = 2500, 3150, 4000 A.$  \hspace{1cm} (7)

where: DCU-HM 3/1.6 is designed for PZ, EZT and EW up to 5 MW

DCU-HM 4/4.0 is designed for high power locomotives (over 5 MW) or substations.

With the standardisation rules [21], both base sizes are rated according to the needs and requirements of users, including the DC2 system. DCU-HM 3/1.6 in roof version for PZ or EZT is shown in Fig. 12 (horizontal installation).

DCU-HM 3/4.0 in deck version is mounted in the locomotive's HV cabinet (vertical installation). It has the same assemblies and functions, larger cross-sections of the main current circuit elements.

The work of DCU-HM is managed by a specialized microcomputer (control unit 14 in Fig. 12a) with multifunctional proprietary software, which enables processing of data necessary for all the above mentioned activities and functions. It is composed of a microprocessor controller, input/output interface, power supply, lock and drive power unit controllers, and CAN network module for internal and external communication. All these units are integrated in a common casing and have mutual optical or electrical communication (as required). A control panel for external communication is placed on the housing. It is equipped with standardized, multi-channel electrical or fibre optic connections enabling receiving and sending all necessary control (S1, S2, S3) or information (Sso, Ssg, Ssz) signals (Fig. 11a).

Standardisation also includes all outputs of active or passive auxiliary contacts (multiplied by relays if necessary), indicating the position (state) of the switch, as well as a special connection for sending information to via CAN network. This enables visual signalling of the breaker status and other parameters required by the user.

The controller has typical computer connectors and is equipped with an energy reader. Correct and reliable operation of DCU-HM under all current conditions requires high resistance to all types of internal and external electromagnetic interferences. In addition to known and typical methods of shielding, the breaker uses the principle of maximum use of fibre optic technology for digital communication between the breaker's controller and the assemblies. Analog electrical signals are used in necessary cases only. Each of the main switch assemblies is installed in a separate housing equipped with unified fibre optic and electrical connectors, cooperating with USW by means of unified WS and WE bundles, maintaining (if necessary) the principle of redundancy and according to the accepted principles of modularisation and standardisation of DCU-HM circuit-breaker.

It was impossible to compare the new (DCU-HM) and the old (MBOS) construction of the circuit breakers operating in the same circuits. Hence, the estimated parameters of DCU-HM were compared with the MBOS manufactured by GE Power Control (BWS circuit breakers). The oscillograms (Fig. 13) show the switching off of the short-circuit current in slightly different circuits with unequal initial short-circuit current steepness. Moreover, there is a large difference in the settings of overcurrent releases of both circuit breakers, reaching approx. 50%. This may suggest that the limited current value recorded on the oscillogram for ultrafast circuit breaker is too low in relation to the circuit in which BWS circuit breaker was tested. To explain this, it should be recalled that the ultrafast breakers have an arc time in the vacuum chamber of approx. $T_e \leq 2 \text{ ms}$. 

Fig. 12. Top view of the complete prototype of the DCU-HM 3/1.6 circuit breaker in the roof version. a) Design sketch with visible assemblies. b) Photograph of the prototype: 1 – mains connection terminal, 2 - vacuum switch assembly, 3 - induction-dynamic drive, 4 - counter-current capacitor, 5 - commutation choke, 6 - resistor, 7 - thyristor unit, 8 - overcurrent relay, 9 - receiver connection terminal; 10 - internal surge arresters: 11 - diode, 12 - varistor; 13 - external surge arrestor (varistor); 14 - control unit, 15 - energy measurement system, 16 - fuse, 17 - measuring shunt, 18 - energy meter, 19 - contacts unit.
After this time, from the moment the overcurrent release is tripped, the circuit current reaches a limited value $I_o$. Thus, if DCU-HM is used in the same circuit as BWS breaker, that is:

$$U_c = 3.9 \, [kV], \quad I_{op} \approx 44 \, [kA], \quad \tau = 10 \, [ms],$$

$$\frac{di}{dt} \approx 4.4 \, [A/\mu s], \quad I_i = 4800 \, [A] \quad (8)$$

it reduce short-circuit current after time:

$$t = \frac{4800}{4.4 + 2000 \, [\mu s]} = 3090 \, [\mu s] \quad (9)$$

and the current reaches the value:

$$I = I_{op} \cdot * \left(1-e^{-3.09/10}\right) [A] = 11.4 \, [kA] \quad (10)$$

where: $U_c$ – network voltage, $I_{op}$ – steady prospective short-circuit current, $\tau$ – time constant, $\frac{di}{dt} = \frac{s_i}{\tau} = I_{op} / \tau$ – initial rate of short-circuit current rise, $I_i$ – trip current.

![Fig. 13. Comparison of short-circuit current breaking performed by new (a) and conventional construction of the circuit breakers.](image)

Hence, the comparison of the selected parameters based on the appended oscillograms is possible, and it is presented in Table 1.

<table>
<thead>
<tr>
<th>No</th>
<th>Parameter name</th>
<th>$P_{DCU-HM}$ symbol and value</th>
<th>$P_{BWS}$ symbol and value</th>
<th>$P_{DCU-HM}/P_{BWS} \times 100$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Opening time</td>
<td>$T_o \leq 500 , [\mu s]$</td>
<td>$T_o \leq 5 , [ms]$</td>
<td>10 %</td>
</tr>
<tr>
<td>2</td>
<td>Total break-time</td>
<td>$T_{e} \leq 2 , [ms]$</td>
<td>$T_{e} \leq 17 , [ms]$</td>
<td>12 %</td>
</tr>
<tr>
<td>3</td>
<td>Cut-off current at $s_i = 4.4 , [A/\mu s]$</td>
<td>$i_e \leq 13.6 , [kA]$</td>
<td>$i_e \leq 37 , [kA]$</td>
<td>37 %</td>
</tr>
<tr>
<td>4</td>
<td>Current limitation factor* at $4.4 , [A/\mu s]$</td>
<td>$C_i \approx 0.3$</td>
<td>$C_i \approx 0.84$</td>
<td>36 %</td>
</tr>
<tr>
<td>5</td>
<td>Maximum magnetic energy</td>
<td>$E_{m} \leq 60 , [kJ]$</td>
<td>$E_{m} \leq 616 , [kJ]$</td>
<td>10 %</td>
</tr>
<tr>
<td>6</td>
<td>Maximum Joule’s integral</td>
<td>$P_t \leq 240 , [kA \cdot s]$</td>
<td>$P_t \leq 12250 , [kA \cdot s]$</td>
<td>2 %</td>
</tr>
<tr>
<td>7</td>
<td>Maximum arc energy</td>
<td>$E_{a} \leq 400 , [J]$</td>
<td>$E_{a} \leq 700 , [kJ]$</td>
<td>0.06 %</td>
</tr>
<tr>
<td>8</td>
<td>Switching durability at $I_{th}$ current $C/O _c.$</td>
<td>$n_{ov} \geq 30000$</td>
<td>over 10 times larger</td>
<td>10000%</td>
</tr>
<tr>
<td>9</td>
<td>Switching durability at $I_{op}$ current $C/O _c.$</td>
<td>$n_{ov} \geq 30000$</td>
<td>over 10 times larger</td>
<td>10000%</td>
</tr>
</tbody>
</table>

* $P_{DCU-HM}$ parameter; $P_{BWS}$ - the equivalent parameter for MBOS.
* $C/O \_c.$ – close/open cycle (i.e. ON/OFF $I_{th}$ or $I_{op}$).

With the capabilities listed in Table 1 and the work management described above, DCU-HM has the properties specified below, not available for MBOS.

**When switching off a short-circuit**, one DCU-HM with high switching durability (Table 1) is equivalent to approximately 100 MBOS. At comparable prices, the investment costs over the lifetime of one DCU-HM is about 100 times lower. The estimated cost of a single short-circuit shutdown by DCU-HM is also about 100 times lower. Economic benefits cumulate at the user side.

**Special systemic and electrical functions:**

- **two-sided limitation of overvoltage**
- **two levels of limitation for DC1 and DC2**
- **emergency arc protection**
- **protection of semiconductors with currents $I_{th}$**
- **no critical currents**
- **no interference with the recuperative braking process**
- **no interference with the recuperative braking process**
- **low arc energy and contact wear**
- **short-circuit switching durability equal to mechanical life**
- **full environmental neutrality**
- **full selectivity at short circuits in relation to MBOS's in substations**

**Ultra-fast shutdown in vacuum:**

- **low arc energy and contact wear**
- **short-circuit switching durability equal to mechanical life**
- **no critical currents**
- **unnecessary protective zone and periodic service**
- **full environmental neutrality**
- **full selectivity at short circuits in relation to MBOS's in substations**
Ultra-fast hybrid systems for protecting direct current circuits with high magnetic energy

► Modular construction: • variable spatial configuration, • adaptability to mounting spaces in various electric vehicles or substations, • roof, deck or sub-deck version possible.

► Selective operation with respect to substation breakers improves traffic run and passenger safety.

8. Conclusions.

The paper presents the developed and patent pending ultra-fast hybrid switching systems for efficient and reliable protection of various medium and low voltage DC circuits with high magnetic energy. The excellent dynamic properties of USH result from unique construction of inductive-dynamic drive that allows decreasing the total break-time below 2 ms. This is crucial to limit the harmful effects of quench and short circuits in railway systems. That is why USH has the performance capabilities not available for MBOS.

It could have been achieved due to the new technique of ultra-fast commutation of the current in vacuum. Technical details concerning the structure and operation of USH (i.e. DCSS and DCU-HM) are given in [22, 23]. New technique has been experimentally verified. It improves the effectiveness and reliability of the anti-quench protection and the railway systems protection. In fact, the reliability of the novel construction of the switching system is mainly limited by durability of a vacuum chamber. Commercially available AC vacuum chambers, in practice, allow building unpolar USH in the current range up to 4 - 5 kA. For higher currents, parallel configurations are needed. The development potential of USH is high because they can be used in all fields of application of superconducting electromagnets (installed in CERN to protect LHC) and DC/1,2 electric traction systems. MBOS are still fully usable and have development potential in low power LVDC circuits [24].

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The authors declare no conflict of interest.

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20. The applicable standards: PN-EN 50121-3-2; PN-EN 50123-1; PN-EN 50123-2; PN-EN 50123-5; PN-EN 50124-1; PN-EN 50153; PN-EN 50155; PN-EN 50163; PN-EN 60068-1 (also: 60068-2-1; 60068-2-2; 60068-2-52); PN-EN 60077-1 (also: 60077-2). PN-EN 60077-3; PN-EN 60529; UIC Charter 550/1997.


**LIST OF ABBREVIATIONS USED IN THE ARTICLE.**

AC – alternating current.
AMF – axial magnetic field.
APSU - auxiliary power supply unit.
BSM – bidirectional semiconductor module.
DC – direct current.
DC1 or DC2 - systems of railway traction of 3 kV or 1.5 kV voltage.
DCPS – direct current power supply.
DCS – ultra-fast DC hybrid switch.
DCSS – direct current switching system.
DCU-HM – direct current ultra-fast hybrid modular switch.
DP/AP – overcurrent relay.
EES – energy extraction system.
EW – electric vehicle.
EKT – electric traction unit.
GP – counter-current generator.
HV, MV or LV – high, medium or low voltage.
HVDC, MVDC or LVDC – high, medium or low voltage DC systems.
IDD – induction-dynamic drive.
L – locomotive.
LHC – Large Hadron Collider.
MBOS – magnetic blow-out switches.
PZ – combined train.
QDS – quench detection system.
RD – dump resistor.
SE or SM - superconductive electromagnet or magnet.
SSv.1 – shutdown algorithm sequence for forced commutation.
SSv.2 – shutdown algorithm sequence for natural commutation.
UDCCB – ultra-fast DC circuit-breaker.
U CCB – ultra-fast DC circuit-breakers.
USH - ultra-fast hybrid switching systems.
v.1 – variants of DCS or DCSS with forced commutation.
v.2 – variants of DCS or DCSS with natural commutation.
VC – vacuum chamber.
Other symbols were defined in the text.