High-speed circuit breakers (HSCB) used in DC circuits are one of the basic elements of overload, short-circuit and electric shock protection. Such breakers are used in transport (trams, trolleybuses, subways and railways) in electric power supply facilities and in vehicles. The performance and capability of limiting the current depend on the HSCB design and solutions applied in it. The circuit parameters, particularly its inductance also affect the performance. Additionally, each DC breaking in the RL circuit is accompanied by overvoltages whose level depends on the circuit parameters and breaker design. The paper discussed the process of direct current breaking by magnetic blowout high-speed circuit breakers and factors that affect the HSCB performance, i. e. opening time and arcing time. The influence of the circuit parameters and HSCB design on the value of arc voltage is outlined. The results of laboratory tests of 4 types of high-speed circuit breakers produced in Europe are presented. The test results were used to analyze the effect of current changes in the short circuit on the time of current breaking and the value of switching overvoltages – arc voltage. The results of simulation of the short-circuit breaking in the RL DC circuit made at the rate-of-rise of current in the circuit are presented. Based on the tests and simulations, the current breaking times, values of arc voltage generated in this process and arc energy that is acquired and dissipated by the arc chamber are determined. The objective of the tests and simulations was to answer the question whether it is possible to turn off direct current quickly without generating high arc voltage values – overvoltages in the circuit and how di/dt changes should be formed by a high-speed circuit breaker to achieve the shortest possible time with the lowest possible arc voltage and its lowest energy

Keywords: high-speed circuit breaker, breaking time, arcing time, arc voltage

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AN EXPERIMENTAL ANALYSIS OF DC MAGNETIC BLOWOUT HIGH-SPEED CIRCUIT BREAKERS' PARAMETERS

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1. Introduction

High-speed circuit breakers (HSCB) used in DC circuits are one of the basic elements of overload, short-circuit and electric shock protection. They appear in transport (trams, trolleybuses, subways and railways), in electric power supply facilities and in vehicles. They are used in energy storage, industrial processes and wherever there is a necessity to switch off large DC current values and/or a voltage higher than 1 kV DC is used. Currently, the most commonly used type of HSCB are magnetic blowout breakers.

High-speed circuit breakers are installed in traction substations and field coupling as fixed breakers as well as tramways, traction vehicles, locomotives and metro carriages as vehicle breakers. They intentionally break operating currents, while they automatically break overload and short-circuit currents. The ability to break short-circuit currents is particularly important. In overhead contact lines (OCL), these currents have very different values, depending on the location of the short circuit, which is described, among others, in [7, 8]. Moreover, due to the constant growth in the power of installed traction devices and the necessity to increase the stiffness of power supplies, the short-circuit current values also increase. These currents should be turned off as soon as possible, well before reaching the sustained value. In addition, each short circuit in the DC system affects the power system [3], which is an additional reason for the necessity of swift short-circuit current breaking.

The performance rate and capability of limiting the current depend on the HSCB design and solutions applied in it like blowout circuits and arc displacement from contacts to the arc chute. The circuit parameters, particularly its inductance also affect the performance rate. Additionally, each DC breaking in the RL circuit is accompanied by overvoltages whose level depends on the circuit parameters and the breaker's design, the arc chute including. In general, the faster the current breaking the greater the overvoltage. The overvoltage value is affected by the way the current changes are formed in the circuit by the high-speed circuit breaker – the arc voltage.

Therefore, the studies devoted to the theoretical analyses concerning changes in arc voltage and other HSCB parameters and their impact on the breaking rate and accompanying overvoltages (power surges), which form the current changes by HSCB have significant importance.

2. Literature review and problem statement

Magnetic blowout high-speed breakers have been used for about 100 years. With the developments of semiconductor technology, magnetic blowout circuit breakers are superseded by hybrid circuit breakers and ones with vacuum chambers. An example of a solution with a vacuum chamber may be the circuit breakers intended for rolling stock described in [4]. The vacuum DC circuit breaker for traction substations is described in [5]. However, it has too low ability to cut off short-circuit currents compared to those currently required for a 3 kV DC system. The application of circuit breakers with a vacuum chamber in the rolling stock allows for a high degree of coordination of short-circuit protection, as described in the publication [6].

Hybrid circuit breakers, which use power electronic elements to break the current are applied in high-voltage systems. Exemplary solutions of such devices and simulation results are described by the authors of [7, 8] and [9]. On the other hand, the authors of the publication [10] present a solution to a hybrid circuit breaker of high load capacity and capacity to break short-circuit currents at 20 kV. This breaker consists of a mechanical main switch with three contacts to conduct continuous current as well as a parallel semiconductor switch for current transmission.

Although magnetic blow circuit breakers still constitute the vast majority of applications in electric traction power supply systems and in traction vehicles. Due to the above, the number of studies on this type of circuit breakers is very low, which translates into a small number of publications in this area.

Direct current breaking by magnetic blowout high-speed breakers consists in bringing the current to zero by increasing the resistance of the arc igniting between the contacts (increasing the arc voltage) and obtaining an inter-contact gap ensuring that the current will not flow again. The process of breaking the current by the HSCB is shown in Fig. 1. This process has also been described in detail in many publications.

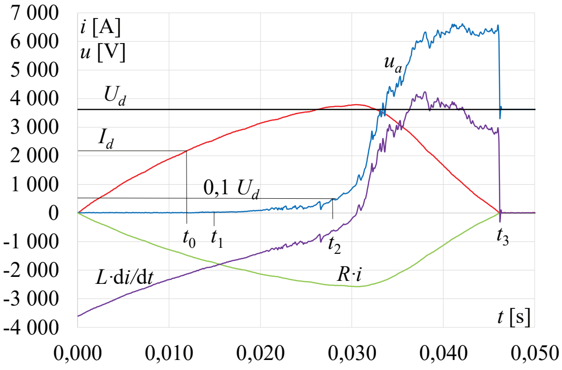


Fig. 1. Time dependences of the characteristics of the process of direct current breaking by HSCB

The RL serial system power supplied from a source with U_d voltage, with a circuit breaker with u_a voltage on its contacts can be described by the formula:

$$U_d = R\cdot i + L\frac{\mathrm{d}i}{\mathrm{d}t} + u_a. \qquad (1)$$

The instantaneous values of the equation terms (1) are shown in Fig. 1. The breaking process can be divided into several stages. At t=0, a short circuit and current flow occur, the value of which increases according to the equation:

$$i = \frac{U_d}{R}\left(1 + e^{-\frac{t\cdot R}{L}}\right). \qquad (2)$$

The rate of current rise depends on the time constant of the circuit t_c=L/R. At the moment t_0, the current acquires the value of the HSCB trigger setting I_d. The breaking process begins then. In the initial phase from t_0 to t_1 there is the breaker's opening time t_i, after which at t_1 the contacts open. An arc ignites between the contacts, whose voltage is very low in relation to the voltage supplying the circuit U_d. The time from t_1 to t_2 is called the contact arcing time t_s [11, 12]. The t_s time is not defined in the standards, however, it has a significant impact on the breaking time [13]. In [11–13], this time was defined as calculated from the moment of opening the contacts (t_1) until the arc reaches the voltage u_a=0.1 U_d. From the moment of t_2, the arc extends rapidly increasing its voltage to the moment of t_3, when the arc extinguishes and breaks the current flow. The total time of arc igniting – from t_1 to t_3 is defined as the arcing time t_a. The total time of the current breaking t_b is determined from t_0 to t_3, i. e. it is the sum of the opening time t_i and the arcing time t_a.

The arc voltage value u_a can be defined transforming equation (1) to:

$$u_a = U_d - R\cdot i - L\frac{\mathrm{d}i}{\mathrm{d}t}. \qquad (3)$$

The increase of the arc voltage causes the decrease of current in the circuit. Having exceeded the maximum – limited value ($I_{cut\ off}$), di/dt has a negative value. Therefore, the voltage on the inductance L is added to the voltage of the power source U_d, as shown in Fig. 1. Due to the fact that as the current decreases, the voltage drop across the circuit resistance decreases, the voltage on the HSCB (arc) u_a begins to exceed the U_d value until the current breaking and the voltage drop on the resistance and inductance of the circuit.

The voltage value of the power source U_d, as well as L and R values in the circuit can be assumed as constant during the whole breaking process. From this assumption and equation (3) it follows that the instantaneous and maximum values of the arc voltage u_a depend on the value of current i and the rate of its changes di/dt. It follows that the highest arc voltage values u_a will occur at a low current value and its rapid drop.

One of the methods to limit the arc voltage value is to apply a thyristor limiter connected in parallel with the reactor [14]. This solution limits the voltage drop on inductance by shorting it, i. e. reducing the inductance L in the circuit.

During the direct current breaking, the arc energy is released, which must be dissipated by the arc chute. The power of the arc can be determined by the formula

$$P_a(t) = U_d i - Ri^2 + iL\frac{\mathrm{d}i}{\mathrm{d}t}, \qquad (4)$$

whereas the arc energy A_a while it is burning (at arcing time t_a) is:

$$A_a = \int_0^{t_a} P_a = U_d\int_0^{t_a} i\,\mathrm{d}t - R\int_0^{t_a} i^2\,\mathrm{d}t + \frac{Li_{\max}^2}{2}. \qquad (5)$$

The energy value A_a is influenced by the arcing time, the value of the current and arc voltage. According to [15], the arc energy is affected by the polarity of the breaker. The author of the paper [15] observed that applying a positive voltage to a movable contact causes a higher value of arc energy than in reverse polarity.

In classic DC magnetic blowout circuit breakers, in the first stage, the current increases to the level of the HSCB setting I_d. The time required for the short-circuit current to reach the value of the set current depends on the steepness of the current rise, i. e. on the short-circuit circuit parameters. The breaking process begins then.

The opening time t_i starts when the current exceeds the setting value I_d. It depends on the HSCB design, the steepness of the current rise and the value of the expected I_{SS} or peak of short-circuit current $\hat{I}_{SS}$. The test results described in [16] confirm that the higher the expected short-circuit current $\hat{I}_{SS}$ and the greater the steepness of current rise di/dt, the shorter the opening time t_i. The dependence of the t_i value on di/dt is also confirmed by one of the HSCB manufacturers, giving the graphs $t_i=f(\mathrm{d}i/\mathrm{d}t)$ in their catalogs [17].

The opening time t_i of currently produced magnetic blowout high-speed circuit breakers ranges from 1–2 ms to even tens of milliseconds. Due to the principle of operation of triggering systems and mechanical switches, shortening of the opening time is not viable. Such reconstruction of HSCB systems would be labor-consuming and would require large financial resources.

The rate of breaking and the capability of current limiting are largely dependent on contact arcing time t_s. The tests described in [11] and [13] have shown that the value of the contact arcing time t_s translates into the value of the cut off current $I_{cut\ off}$. The research [18] showed that the contact arcing time t_s is slightly dependent on the short-circuit circuit parameters, however, to a large extent on the design of the circuit breaker – the design of contacts, blowout systems, etc. An example of these correlations is shown in Fig. 2.

The arc voltage is one of the basic parameters of the high-speed circuit breaker. The value of the arc voltage u_a and the rate of voltage changes du_a/dt affect the rate of current changes di/dt and thus the arcing time t_a and the total breaking time t_b.

The arc chute structure influences the steepness value of current changes during breaking di_b/dt. This affects the rate of arc elongation and its deionization. In addition to blowout circuits, implemented mainly as blowout coils, the arc elongation in the arc chute is influenced by the arc chute structure and dimensions [19], the material used to receive the arc energy. Fig. 3 shows in a simplified way of arc elongation in the arc chute of similar design, but differing in partitions material.

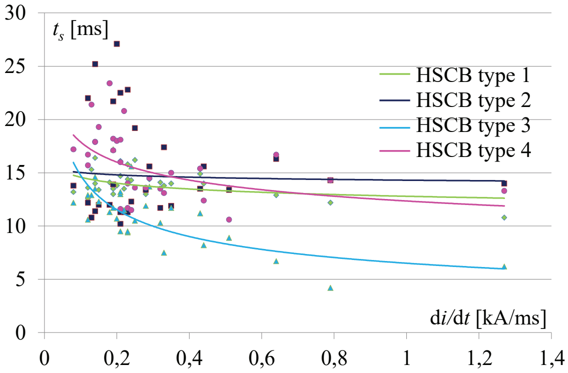


Fig. 2. Values of the contact arcing time t_s depending on the steepness of current rise di/dt [18]

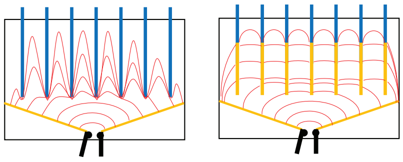

a *b*

Fig. 3. Arc elongation in an arc chute with partitions made of: *a* – insulating material; *b* – partly of conductive material

The arc chute partitions in Fig. 3, *a* are made entirely of insulating material (blue). In such kind of arc chute, the arc (red line) is inserted between these partitions giving off its energy and quickly elongating. This causes high arc voltage values.

In arc chutes (Fig. 3, *b*), in which partitions made of conductive material (yellow) were used, the arc is divided into several parts, with lengths equal to the distance between the partitions. The arc gives off its energy, but its total length increases slowly. Further arc elongation occurs only when the arc reaches the insulating part of the partitions.

Shortening the opening time of magnetic blowout high-speed breakers is not realistic. The quick breaking of the short-circuit current and limiting its value are therefore dependent on the arcing time t_a. In order to shorten this time, it is necessary to increase arc voltage u_a as soon as possible. In the RL circuit, the arc voltage is closely related to the voltage at the circuit inductance (L·di/dt), i. e. the steepness of the di/dt current change. The steepness of current changes in the circuit till the circuit breaker's contacts opening depends on the parameters of this circuit. After the opening of the contacts, di/dt is still dependent on the circuit parameters, but to a large extent on the operation – the design of the circuit breaker.

Thus, the work aimed at the experimental determination of the parameters of DC magnetic blowout high-speed circuit breakers is relevant to ensure fast and reliable breaking of short circuits in traction power supply systems.

3. The aim and objectives of the study

The aim of the study is to determine the parameters of DC magnetic blowout high-speed circuit breakers currently operated in traction substations in Europe.

To achieve this aim, the following objectives are accomplished:

– to analyze how current changes in the short-circuit affect the time of the current breaking;

– to define the value of breaking overvoltages – arc voltage.

4. Materials and methods

In order to compare the real HSCB parameters of different designs and solutions, laboratory tests were carried out. Four HSCB types A, B, C and D manufactured in Europe were tested. They are magnetic blowout circuit breakers with a rated voltage of 3 kV DC. The settings of all circuit breakers were I_d=2 kA±100 A.

The tests were conducted in a circuit powered from a 6-pulse rectifier unit. The parameters of the short circuit were as follows: supply voltage U_d=3622 V, circuit time constant t_c=22.2 ms, total resistance R=0.68 ohm, inductance L=15.1 mH.

The tests started with the determination of the sustained current parameters whose flow is presented in Fig. 4. The short-circuit current sustained value is I_{SS}=5,276 A. Then the short-circuit current breaking was recorded by 4 types of circuit breakers.

Using the test results, a model was developed to analyze direct current breaking and values accompanying this process. The calculations assumed that the HSCB opening time is t_i=2.6 ms.

The current rises according to equation (2) until the contacts open. It was assumed that since the contacts' opening, the current changes in the circuit are similar to achieved measurements when HSCB B was used. These changes were approximated with mathematical functions assuming that the contact arcing time is shortened to t_s=7 ms and until the arc voltage u_a reaches the value of about 5.5 kV.

Then di/dt values were assumed to change in a linear way, as a function of the polynomial and constants. The adopted diagrams of the rate of di/dt current change over time are shown in Fig. 5.

The di/dt changes shown in Fig. 5 were used to perform simulations of the short-circuit current breaking.

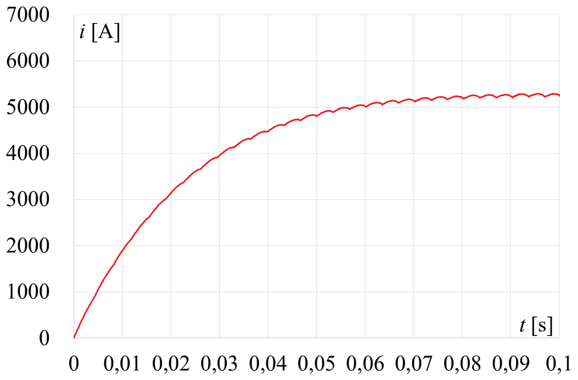
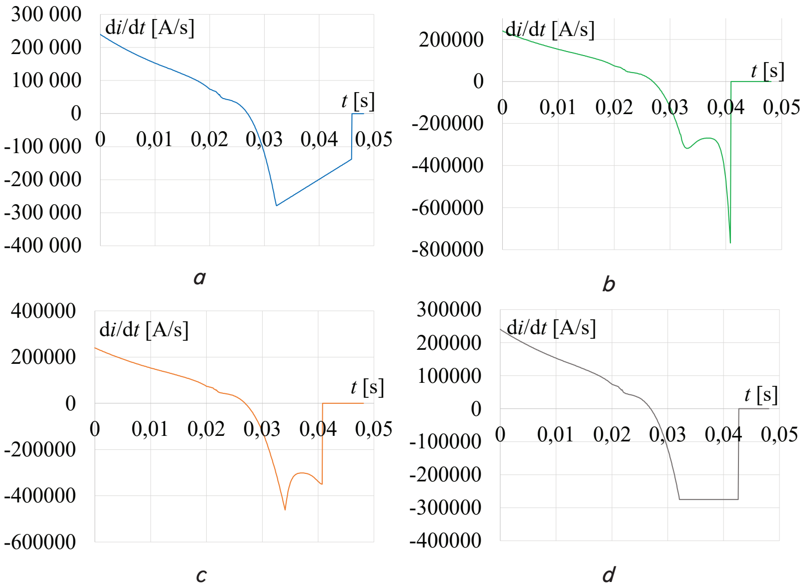


Fig. 4. Flow of sustained short-circuit current



a b c d

Fig. 5. di/dt diagrams adopted in short-circuit breaking simulations: *a* – linear function; *b, c* – polynomial; *d* – constants

5. Results of the analyses

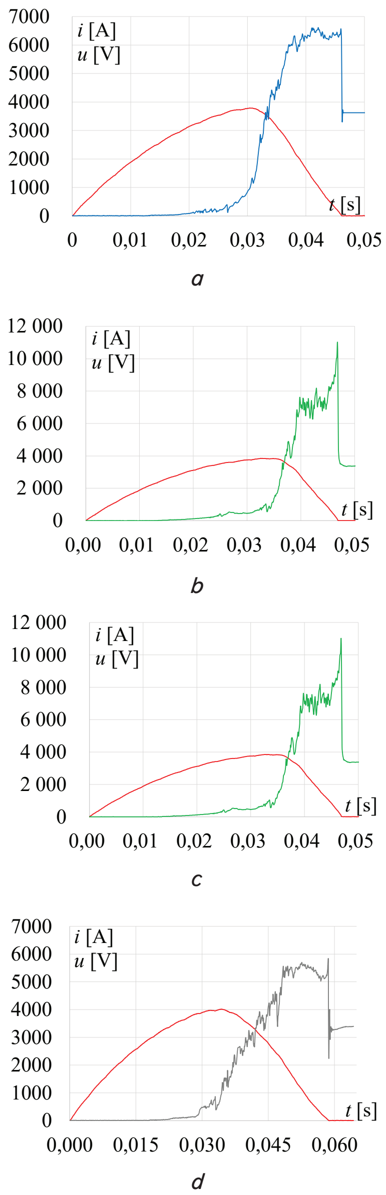
5. 1. Results of the analysis of the impact of current changes in the short-circuit on the breaking time

The recorded current and voltage flows at the circuit breaker terminals during laboratory tests are shown in Fig. 6, detailed results are presented in Table 1. The arc energy A_a was also calculated for each circuit breaker.

Table 1

Test results

Type	t_i, ms	t_s, ms	t_a, ms	t_b, ms	$I_{cut\ off}$, A	$u_{a\max}$, kV	A_a, kJ
A	2.9	13.1	32.9	35.8	3.788	6.61	158.6
B	2.1	12.3	33.6	35.7	3.847	11.02	163.9
C	8.6	15.6	51.3	59.9	3.964	6.61	251.6
D	7.1	11.5	40.7	47.8	4.018	5.82	200.0



a b c d

Fig. 6. Flows of short-circuit current and voltage on contacts of HSCB type: *a* – A, *b* – B, *c* – C, *d* – D

5. 2. Defining the value of breaking overvoltages – arc voltage

As mentioned earlier in the paper, both the arcing time t_a and thus the total breaking time t_b and the arc voltage u_a depend on the current changes in the di/dt circuit during its breaking. For this reason, di/dt changes during current breaking by each of the tested HSCB types were determined on the basis of measurement data, which are shown in Fig. 7.

Assuming the di/dt changes shown in Fig. 5, a simulation of the short-circuit current breaking shown in Fig. 4 was performed in a circuit with parameters as during measurements. The resulting current and arc overvoltage flows are shown in Fig. 8, and the resulting values are shown in Table 2.

The table above does not include the cut off current values $I_{cut\ off}$=3,397 A, because the current limitation occurred at 27 ms since the short circuit, i. e. in the time when di/dt changed for all simulations in the same way.

Table 2

Simulation results

di/dt acc.to Fig.	t_a, ms	t_b, ms	$u_{a\max}$, V	A_a, kJ
5, *a*	32.6	35.2	6022	171.3
5, *b*	27.8	30.4	15227	162.5
5, *c*	27.5	30.1	9171	158.7
5, *d*	29.6	32.2	7773	168.2

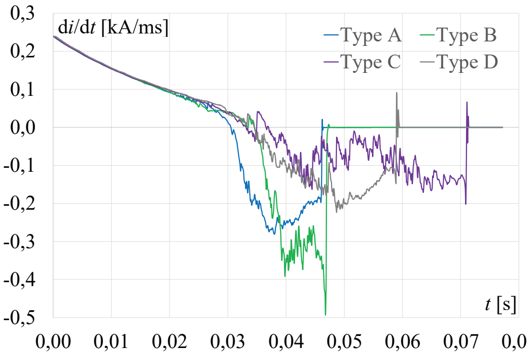
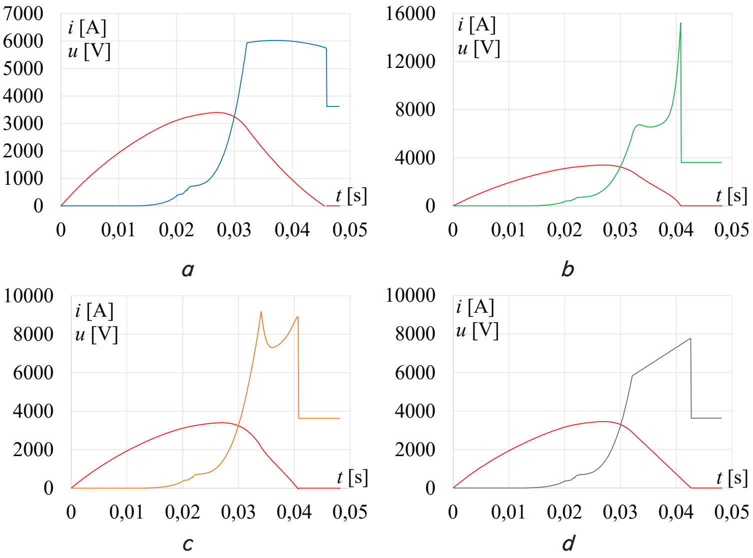


Fig. 7. Changes in di/dt during short-circuit current breaking by four tested HSCB types



a *b* *c* *d*

Fig. 8. Current and arc voltage flows at the di/dt steepness of current changes as: *a* – Fig. 5, *a*; *b* – Fig. 5, *b*; *c* – Fig. 5, *c*; *d* –Fig. 5, *d*

6. Discussion of the results of HSCB parameters' impact on the breaking rate and accompanying overvoltages

Analyzing the results of the laboratory tests – Fig. 6, 7 and data from Table 1, it can be concluded that circuit breakers A and B breaking time was similar. However, circuit breakers C and D breaking time is much longer and will not be analyzed further.

HSCB A, in comparison to HSCB B, is characterized by a slightly longer opening time t_i and slightly shorter arcing time t_a. Consequently, it results in a similar total breaking time t_b of both circuit breakers. The arc energy A_a also has a similar value.

The key difference between HSCB A and HSCB B is the maximum value of arc voltage $u_{a\max}$. This phenomenon is explained in Fig. 8, which shows that the di/dt value at breaking time reaches 0.49 kA/ms for HSCB B and 0.28 kA/ms for HSCB A. Moreover, the maximum value of di/dt for HSCB B occurs in the final phase when current i in the circuit has a low value, thus the voltage drop on circuit resistance R is low. Because di/dt is negative, thus, according to equation (3), the voltage on inductivity L is added to the voltage of the power source U_d.

Additionally, di/dt for HSCB A reaches zero earlier than HSCB B, which means a faster arc voltage rate and earlier limiting of the breaking current. Furthermore, changes di/dt for HSCB A after the opening of the contacts are less rapid in relation to HSCB B.

The reason of the above is different design of arc chutes and applied materials there as well as differences in blowout systems solutions.

The proposed results allow closing the problem of DC current breaking quickly without generating high overvoltages in the circuit in part of choosing the form of di/dt changes in circuit breaker. Maintaining a linear di/dt drop allows the arc voltage to be almost constant. By using this solution, there is a possibility of protection against the occurrence of an excessive u_a value resulting from the maximum absolute di/dt value. In this case, the breaking time will depend on the value of arc voltage u_a at the moment after which di/dt decreases. The higher the u_a value is allowed, the shorter the breaking time will be. Maintaining a constant di/dt value causes a linear rise of arc voltage u_a. This results from a decreasing value of voltage drop on the circuit resistance proportionally to the drop of the breaking current value.

Analyzing the results of simulations and calculations – Fig. 5, 8 and the data in Table 2, attention must be paid to the flows presented in Fig. 8, *b*, *c*. In both cases, the arcing time t_a, and thus the total breaking time t_b are similar. It is essential that by shaping di/dt changes differently, similar and even slightly shorter breaking times are achieved with approximately 40% lower maximum arc voltage. This result can be considered as the advantage of this study in comparison with known works on this subject.

It should be noted that the main drawback of the above study is the fact that the discussed form of di/dt changes in circuit breakers should be verified on HSCB with the proposed parameters and choosen blowout systems and arc chutes design. It is planned in future works.

7. Conclusions

1. One of the conditions to minimize breaking time is for the arc to reach voltage as soon as possible, which would stop the increase of short-circuit current rapidly and at the lowest possible level. This means that the opening time t_i and contact arcing time t_s should be as short as possible and the rise in the arc voltage u_a value should be as fast as possible. The opening time t_i of currently produced DC magnetic blowout high-speed circuit breakers is short, particularly in case of high values of the steepness of current rise. A further improvement of this parameter would be connected with the necessity of significant changes in the HSCB drive and tripping system, which seems economically unjustified. Shortening the contact arcing time t_s requires a special design of HSCB contacts' and arc chute's and blowout systems. This will allow the fastest

possible arc displacement from between the contacts to the arc chute, in which its rapid extension takes place.

2. In the breaking phase when the current has already been limited ($\mathrm{d}i/\mathrm{d}t\leq 0$), a further rapid rise of the arc voltage u_a should occur. After the arc voltage u_a reaches the limit value, further arc elongation and reduction of its conductivity should occur so that the absolute value of $\mathrm{d}i/\mathrm{d}t$ decreases, preferably linearly. Maximum $\mathrm{d}i/\mathrm{d}t$ values should occur at the highest current value – as soon as possible. Due to this, the voltage drop on the circuit inductance is most compensated by the voltage drop on the circuit resistance. However, in the final phase of breaking, when the current is low, $\mathrm{d}i/\mathrm{d}t$ should be as low as possible. Under the above conditions, the shortest breaking times are obtained while maintaining the voltage on the circuit breaker within acceptable limits. The proper arc shaping and causing the desired changes in the breaking current depend on the arc chute design, including the materials used, and the blowout systems solutions.

References

1. Ahmad, M., Wang, Z. (2019). A Hybrid DC Circuit Breaker with Fault-Current-Limiting Capability for VSC-HVDC Transmission System. Energies, 12 (12), 2388. doi: https://doi.org/10.3390/en12122388
2. Alferov, D., Budovsky, A., Evsin, D., Ivanov, V., Sidorov, V., Yagnov, V. (2008). DC vacuum circuit-breaker. 2008 23rd International Symposium on Discharges and Electrical Insulation in Vacuum. doi: https://doi.org/10.1109/deiv.2008.4676747
3. Bingjian, Y., Yang, G., Xiaoguang, W., Zhiyuan, H., Longlong, C., Yunhai, S. (2015). A hybrid circuit breaker for DC-application. 2015 IEEE First International Conference on DC Microgrids (ICDCM). doi: https://doi.org/10.1109/icdcm.2015.7152036
4. Borkowski, P., Nowak, Ł., Szymański, S. (2018). The new design of the vacuum circuit breaker mounted on the roof of Electric Traction Units. PRZEGLĄD ELEKTROTECHNICZNY, 1 (8), 136–139. doi: https://doi.org/10.15199/48.2018.08.32
5. Kowalak, R. (2007). Influence of short-circuits switched-off by current-limiting circuit breakers on MV network supplying the traction substations. Electrical Review, 83 (3), 19–22.
6. Ma, R., Rong, M., Yang, F., Wu, Y., Sun, H., Yuan, D. et. al. (2013). Investigation on Arc Behavior During Arc Motion in Air DC Circuit Breaker. IEEE Transactions on Plasma Science, 41 (9), 2551–2560. doi: https://doi.org/10.1109/tps.2013.2273832
7. Maciołek, T., Mierzejewski, L., Szeląg, A. (2001). Breaking the short-circuits in DC traction by high-speed circuits breakers and power-switch. Technika Transportu Szynowego, 3, 40–47.
8. Mierzejewski, L., Szeląg, A. (1999). Research of short circuits and overvoltages in DC electric traction circuits with single-stage transformations110/3 kV. IVth International Conference MET'99, 58–64.
9. Pei, X., Smith, A. C., Cwikowski, O., Barnes, M. (2020). Hybrid DC circuit breaker with coupled inductor for automatic current commutation. International Journal of Electrical Power & Energy Systems, 120, 106004. doi: https://doi.org/10.1016/j.ijepes.2020.106004
10. Rojek, A, Zbieć, A. (2012). Co-ordination of Short Circuit Protection Devices in Motive Power Unit - Sub-station System. Problemy Kolejnictwa, 154, 27–46.
11. Rojek, A. (2015). Switching-off time of electromagnetic blow-out high-speed DC circuit breaker. Problemy Kolejnictwa, 169, 53–60.
12. Rojek, A. (2018). Parameters of DC high-speed circuit-breakers. MATEC Web of Conferences, 180, 06006. doi: https://doi.org/10.1051/matecconf/201818006006
13. Rojek, A. (2020). Investigation of the impact of the contact arc time on the breaking time of high-speed circuit breakers. Prace Instytutu Kolejnictwa, 164, 28–41.
14. Rojek, A., Skrzyniarz, M. (2019). Contact arc time – important parameter of DC high-speed circuit-breakers. MATEC Web of Conferences, 294, 05002. doi: https://doi.org/10.1051/matecconf/201929405002
15. Sécheron, S. A. (2019). High-speed DC circuit breakers for fixed intallations (EN/IEC) Type UR. Available at: https://www.secheron.com/wp-content/uploads/docs/SG101001BEN_F15_Brochure_Circuit-breaker-DC_UR26-80S_09.19.pdf
16. Szeląg, A., Tuliński, K. (2003). Analysis of technical effectiveness of application of a thyristor short-circuiting device in parallel with inductance in rectifier traction substations – simulations and measurements. VIth International Conference „Modern Electric Traction in Integrated XXI Century Europe" MET 2003.
17. Wójcik, F. (2011). Influence of short-circuit parameters and construction of commutation circuit of ultra-high-speed vacuum circuit breakers on dynamics of its operation. Electrical Review, 87 (11), 201–208.
18. Xingguang, H., Hua, L., Zhiquan, S., Zhigang, R., Shusheng, W., Cunwen, T., Peng, F. (2020). Concept design of 100 kA hybrid DC breaker on China fusion engineering test reactor. Fusion Engineering and Design, 158, 111740. doi: https://doi.org/10.1016/j.fusengdes.2020.111740
19. Żukowski, P., Kozak, C. (2010). Testing dc arc energy depending on the polarity of contacts connection. Mechanizacja i Automatyzacja Górnictwa, 48 (7), 137–140.