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ANALYSIS AND TESTS OF THE IMPACT OF PERMANENT MAGNETS ON CURRENT INTERRUPTION IN A MEDIUM VOLTAGE ROTARY LOAD BREAK SWITCH

ANALIZA I ISPITIVANJA UTJECAJA PERMANENTNIH MAGNETA NA PREKIDANJE STRUJE KOD SREDNJENAPONSKE ROTACIONE SKLOPKE

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Abstract: The breaking capacity of a medium voltage (MV) rotary SF₆ load break switch (LBS) can be improved by incorporating permanent magnets into the stationary contacts. The magnetic field is intended to blow the switching arc root towards a recessed space at the stationary contacts thereby preventing reignition of the arc after current zero. Making and breaking tests of load current 630 A were performed comparing the switching performance of load break switches equipped without a permanent magnet, with a ferrite and with a neodymium magnet. The impact of different polarity arrangements of the magnets in the three phases is also considered and analysed. In order to understand the arc behaviour caused by the effect of permanent magnet, arcing times and arc voltage were measured and evaluated. The results show that the arc voltage depends on the direction of the electromagnetic force, which is determined by the phase current direction but also by the polarity of the magnets. When the force is directed towards the recessed space at the stationary contacts, the arc voltage is notably higher than in the case where the arc is blown in the opposite direction. The higher arc voltage is a reliable indication that the length of the arc is increased, which significantly reduces the risk of both thermal and dielectric breakdowns after the first current zero. The consequences are noticed first in the reduction of the number of missed current zeroes and second in shorter minimum arcing times. An adverse arrangement of the magnet polarity in the three phases increases the number of missed current zeroes.

Keywords: load break switch, permanent magnets, electromagnetic force, switching arc, arc voltage

Sažetak: Prekidnu moć rotacione srednjenaponske (SN) SF₆ sklopke je moguće unaprijediti dodavanjem permanentnih magneta unutar nepokretnih kontakata. Uloga njihovog magnetnog polja je da oduva korijen sklopnog luka prema zaklonjenom mjestu na nepokretnim kontaktima, čime se sprječava ponovno uspostavljanje luka nakon strujne nule. Provedena su sklopna ispitivanja strujom opterećenja 630 A uspoređujući izvedbu sklopki bez ugrađenih permanentnih magneta, zatim izvedbe sa ugrađenim feritnim i neodimijskim magnetom. Analiziran je i utjecaj rasporeda polariteta magneta u tri faze. Da bi se bolje razumjelo ponašanje luka pod dejstvom permanentnih magneta, mjerena su i evaluirana trajanja luka, kao i napon luka. Rezultati pokazuju da napon luka zavisi od smjera elektromagnetske sile, koja je određena smjerom struje u posmatranoj fazi i polaritetom magneta. Kada je elektromagnetska sila usmjerena prema zaklonjenom mjestu na nepokretnima kontaktima, napon luka je znatno veći nego u slučaju kada je luk oduvavan u suprotnom smjeru. Veći napon luka je pouzdan pokazatelj povećanja dužine luka, što značajno smanjuje rizik od termalnih i dielektričnih proboja nakon prve strujne nule. Posljedično dolazi do smanjenja broja propuštenih strujnih nula, kao i do kraćeg minimalnog trajanja luka. Nepovoljan raspored polariteta magneta u tri faze povećava broj propuštenih strujnih nula.

Ključne riječi: sklopke, stalni magneti, elektromagnetne sile, sklopni luk, napon luka

INTRODUCTION

Switches (mechanical) are mechanical switching devices capable of making, continuously carrying and breaking rated normal current under normal service conditions. They may also be capable of making and carrying, for a specified duration, the rated short-circuit and related

peak currents under abnormal conditions, such as a short circuit [1]. A switch is not required to break short-circuit currents and therefore may be used in combination with a short-circuit current interrupting device, usually a fuse. The target of this paper is to demonstrate experimentally that the breaking capacity of a medium voltage (MV) rotary three-phase SF₆ load break switch (LBS) can be improved

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by a permanent magnet incorporated into the stationary contact. The current breaking capacity depends on the magnet strength and the direction of the electromagnetic force, which is determined by the phase current direction and the polarity of the magnet.

1. DESIGN OF THE ROTARY SF₆ LBS

In comparison to other types of MV switches known today, the rotary SF₆ LBS (Figure 1) is mechanically the simplest. It basically consists only of stationary and rotary knife-contacts located in an SF₆ gas compartment (Figure 1).



Figure 1: Rotary SF₆ load break switch-disconnector (LBS)

When the contacts separate, an electric arc arises across the contact gap. The arc is supported by ionized gas and its resistance is approximately proportional to the arc length. Therefore, the arc voltage is rising when the arc is moved through the SF₆ gas and elongated by "magnetic blowing" by the Lorentz force created by the self-induced magnetic field of the breaking current. Current will be interrupted at current-zero, if the cooling of the conductive path after current zero is more effective than its thermal heating after current zero [2].

In order to increase the breaking capacity of this simple arc-quenching principle, arc chutes could be added to segment and/or cool the arc. Alternatively, the relative motion between the arc and SF₆ gas could be intensified by gas compression (puffer assistance) providing efficient blasting of the arc which favours its extinction. Such devices are complicated and require a notably increased operating mechanism energy.

In order to preserve the simplicity of the principle, the switches investigated here utilize only the interaction of the arc channel with a magnetic field. The two most practical methods use the interaction with: 1) the magnetic field produced by the current itself and 2) the magnetic field of a permanent magnet.

The first method is already part of the principle used in the rotary SF₆ LBS as explained above. The second method can provide a remarkable increase of the breaking capac-

ity of the LBS without further modification of the switch. Only permanent magnets need to be incorporated into one of the stationary contacts of all poles. It imposes a faster movement of the arc root towards a recessed space at the stationary contact thereby reducing the probability of reignitions of the arc after current zero [3].

The interrupting unit of the switch comprises two breaks in series (Figure 2). The rotating knife-contact (2) cooperates with two stationary contacts, upper (1) and bottom one (3). The permanent magnet is incorporated only in the upper stationary contact.

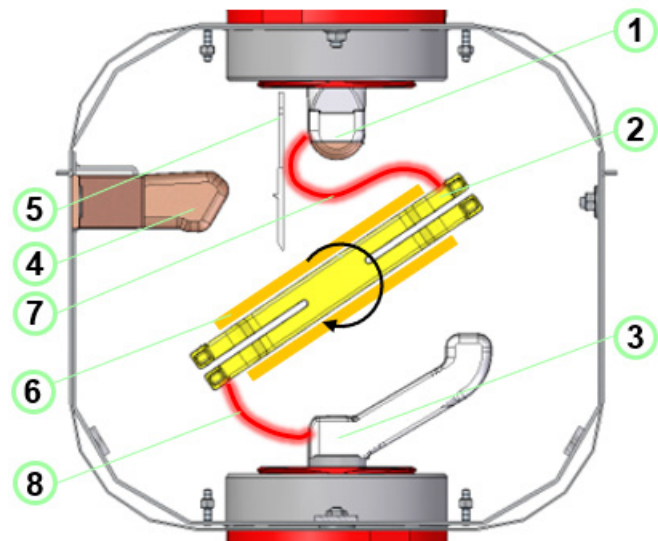


Figure 2: Cross-sectional view of one pole of LBS during current interruption

LEGEND: 1 upper stationary contact with magnet; 2 rotating knife-contact; 3 bottom stationary contact; 4 ground contact; 5 insulation barrier; 6 insulating case; 7 magnetically blown arc; 8 free-burning arc

The rotary SF₆ LBS (24 kV, 630A) under investigation is a three-positions, three-pole operated switch, equipped with a dead centre type spring operating mechanism for independent opening and closing operations either manually (independent from the operator's speed) or by motor (Figure 3).

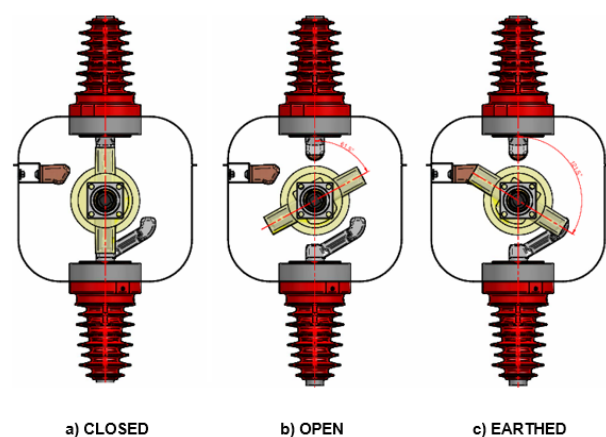


Figure 3: Illustration of closed, open and earthed positions of the three-pole LBS

2. THE EFFECT OF PERMANENT MAGNETS

In alternating-current (AC) networks, the arc current naturally passes through zero after each half cycle regardless of the degree of ionization of the arc. If the arc reignites, the arc voltage changes its sign together with the change in the sign of the current.

The probability of reignitions can be reduced by the use of permanent magnets. The permanent magnet forces the arc into a loop as shown in Figure 4 and moves its root towards the recessed space at the stationary contact, which is the farthest away from the other arc root on the rotary knife-contact. This location is shielded by the stationary contact stud. The movement of the arc root reduces the heat rise of the insulating gas as well as the presence of hot spots on the contact surface, capable of emitting electrons by thermionic emission. Avoiding that the remnants of the arc roots on the two contacts face each other, effectively decreases the risk of arc reignition after current zero.

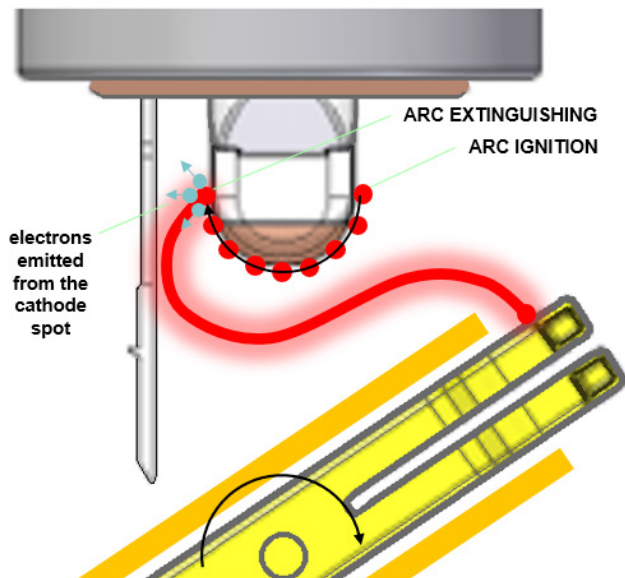


Figure 4: Arc root movement on the curved track at stationary contact with magnet

The direction of arc movement is determined by the direction of the breaking current at the given moment and by the polarity of the permanent magnet.

The direction of force moving the arc is automatically reversed in the following current loop. All four possible arrangements of magnet polarity and current direction in one phase are illustrated in Figure 5. The term “good force direction” means that the Lorentz force acts on the arc in the direction of the hidden location (to the left on Figure 5), while the term “bad force direction” means the opposite direction of the force.

The magnets in the three phases may be mounted in different polarity arrangements. Arrangements “a)” and “b)” in Figure 6 have the same polarity in all three phases while in arrangements “c)” and “d)” the middle phase has op-

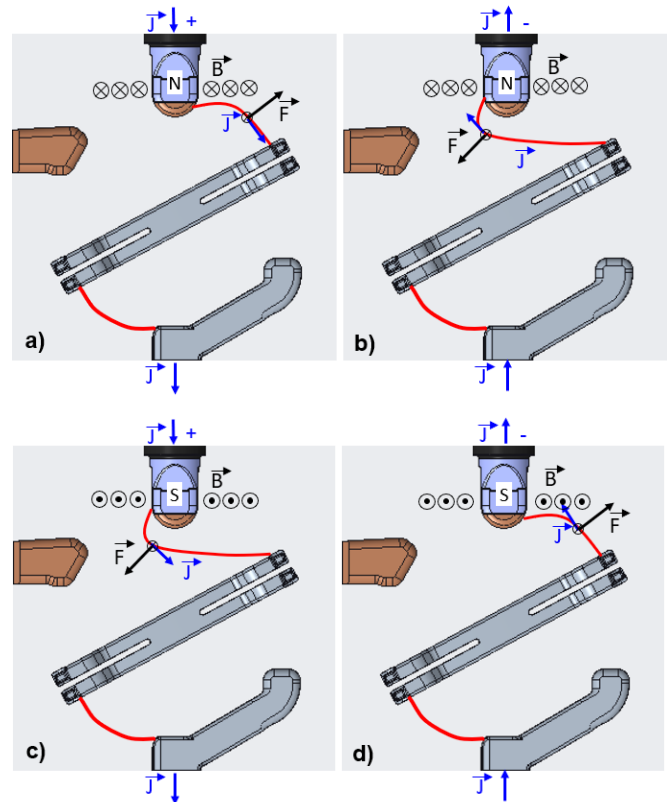


Figure 5: Directions of Lorentz force depending on the breaking current direction and the polarity of the magnet
a) bad force direction; b) good; c) good; d) bad

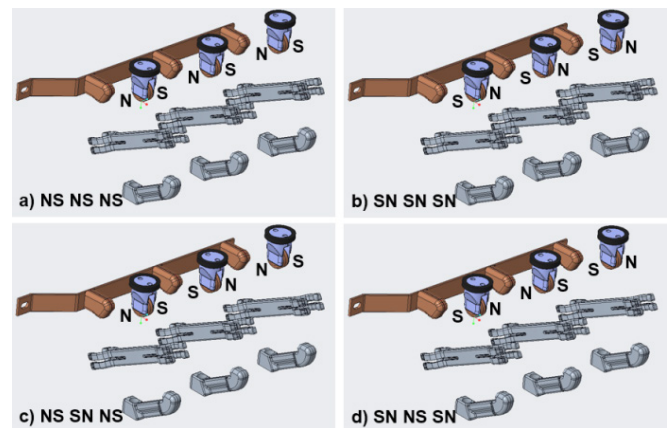


Figure 6: Four possible arrangements of the magnet polarity in the three phases

posite magnet polarity. The arrangement of the magnet polarity has a relevant effect on the breaking capacity of the LBS, which is explained in Figure 7.

Current direction marked with “+” means positive current loop before current zero (i.e. falling current before CZ), while the direction marked with “-” means negative current loop before CZ (i.e. rising current before CZ).

Magnet pole S (outward-pointing magnetic field) and current direction +, as well as magnet pole N (inward-pointing magnetic field) and current direction -, provide “good” force direction.

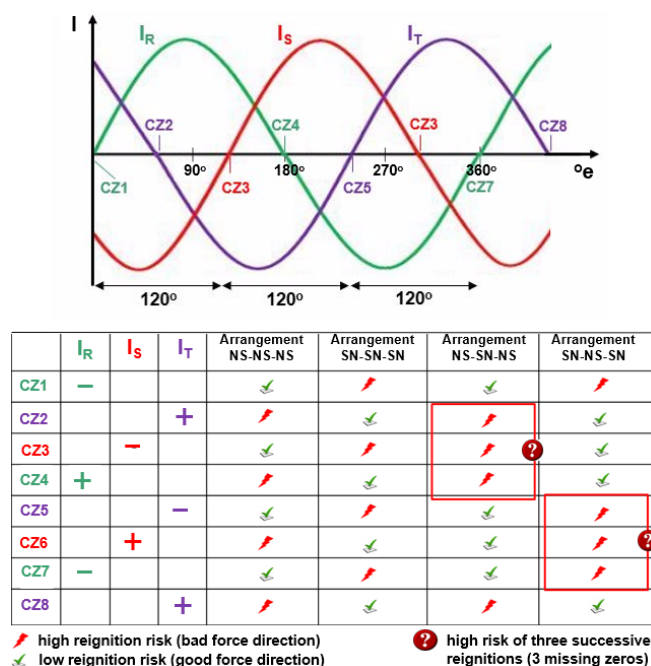


Figure 7: Reignition risk related to the arrangements of the magnet polarity in the three phases

Magnet pole S (outward-pointing magnetic field) and current direction $-$, as well as magnet pole N (inward-pointing magnetic field) and current direction $+$, provide “bad” force direction.

It can be seen in the table of Figure 7 that the NS-NS-NS and SN-SN-SN arrangements are more favourable than the NS-SN-SN and SN-NS-SN arrangements, because the former arrangements prevent the “bad” force direction occurring in two successive current zeroes. Even three successive “bad” directions might occur for the latter arrangements increasing the risk of reignitions at successive current-zeroes significantly. In that case, arcing times in all three phases will be prolonged.

The arc extinguishing efficiency also depends on proper selection of the magnet type (magnet strength) to provide sufficient magnetic force on the arc resulting in its rapid elongation and fast movement of its root. In principle, the higher the strength of the magnet, the more efficient the magnetic blowing. This is demonstrated experimentally by the power tests on three samples of the same LBS, but with different permanent magnet strengths.

3. LOAD BREAKING TESTS

The purpose of the power tests, which are described in this chapter, is to demonstrate experimentally that the strength of permanent magnets, their arrangement and the direction of the electromagnetic force have a significant effect on the arc extinguishing efficiency and the breaking capacity of the above-described LBS.

The development power tests were performed in CESI High Power Laboratory (Italy) in accordance with client's

instructions based on IEC 62271-103 test duty TDload2 applying the test circuit for mainly active load current switching (Figure 8). Three series of load breaking tests were performed (see Table I) with three LBS installed in an air insulated metal enclosure. They were all the same, but equipped differently in order to investigate the impact of magnetic field strengths:

1. the first test object had no magnets,
2. the second test object had Ferrite magnets (remanence $B_r > 0.375$ T), and
3. the third test object had sintered Neodymium magnets (remanence $B_r > 1.180$ T).

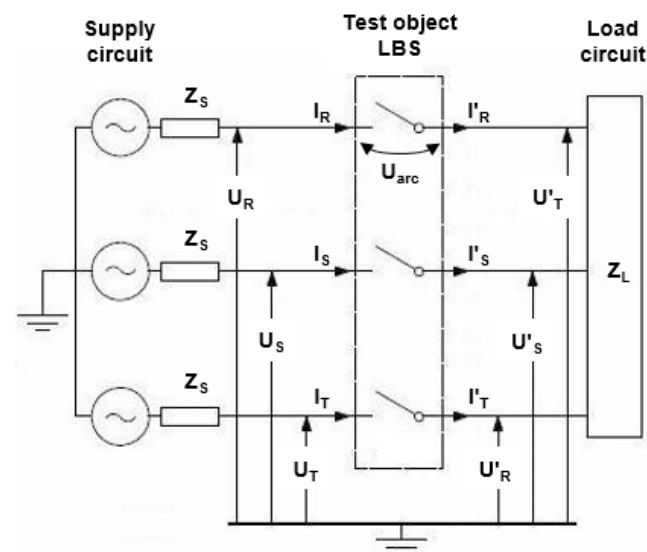


Figure 8: Three-phase test circuit for mainly active load current switching for test duty TD_{load2}

The magnets orientation is indicated in Figure 9.

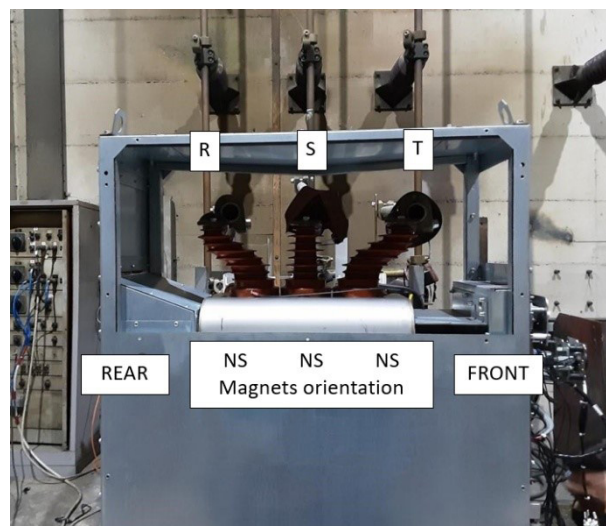


Figure 9: Test object in test arrangement with indication of magnet polarity

The test objects were subjected to three series of at least 20 make-break operating cycles at 100% of mainly active load current (630 A, $\cos\phi = 0.7$) as required for test duty TDload2. Rated voltage was 24 kV. For all

breaking operations, the instant of contact separation was random.

At the beginning of each of the three series, six tests were performed at reduced voltages and currents: three with 13 kV and 315 A, and three tests with 17 kV and 480 A. These attempts were used to analyse the influence of a smaller breaking current on the breaking performance of the LBS.

In addition to the measurements of test parameters required by the standard, arc voltage has been recorded on the R phase.

An example of successful interruption without missed current zeroes is illustrated in Figure 10 for the LBS with Neodymium magnets. The first pole in which current zero occurred after contact parting was pole T. The good force direction contributed to successful interruption in this phase. Arcing time of the first-pole-to-clear was 2.5 ms. At the moment of interruption, the currents in the other two phases shifted by $\pm 30^\circ$ and changed their amplitudes. These currents reached their zeroes together and interrupted at the same time. Since the currents had opposite directions and same magnet polarity, one of these two poles must have had the good force direction, which is enough for successful interruption. Arcing time of the last two poles-to-clear was 6 ms.

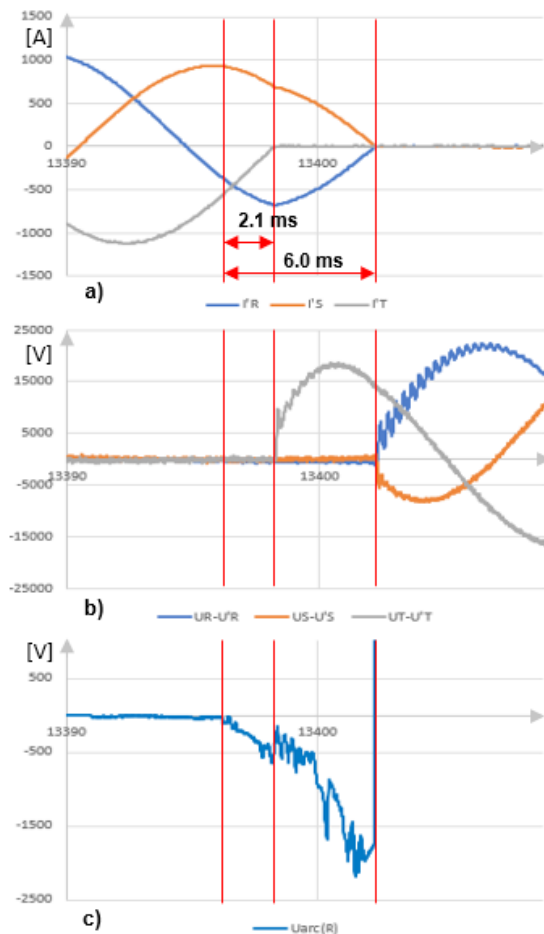
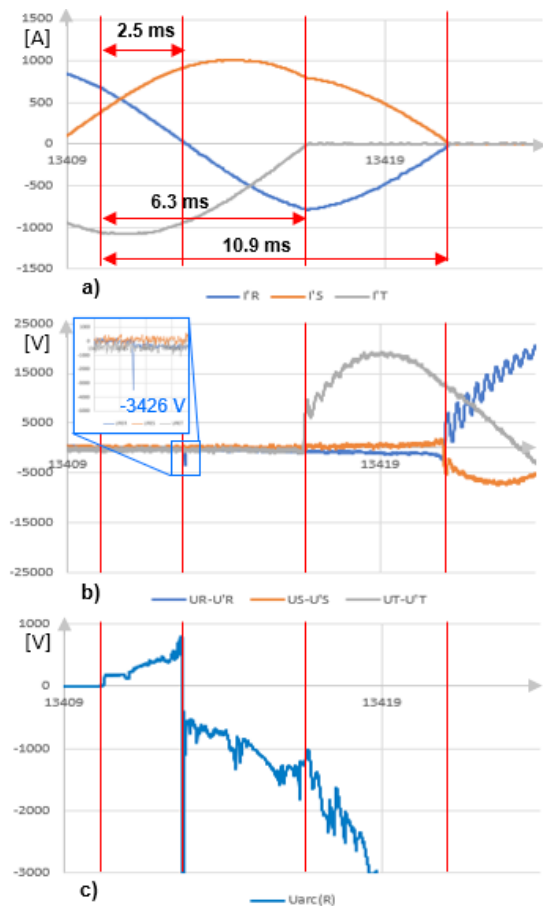


Figure 10: Example 1 of successful interruption of LBS with Neodymium magnet when no missing current zero occurred. The good force direction happened and contributed to the successful interruption. a) load-side breaking currents, b) recovery voltages, c) arc voltage (phase R)

Another example of successful interruption of the LBS with Neodymium magnet is illustrated in Figure 11. However, in this case one missed current zero occurred in phase R. Dielectric breakdown occurred in this phase after 2.5 ms arcing time. The bad force direction happened and might have contributed to the dielectric breakdown. The interruption of phase T at its first current-zero after 6.3 ms occurred at the good force direction. The table below Figure 11 explains in detail how the good and bad force directions are evaluated for each occurring current-zero.



Phase	R			S			T		
First pole to clear	NO			NO			YES		
Current zero	CZ1	CZ2	CZ3	CZ1	CZ2	CZ3	CZ1	CZ2	CZ3
Magnet polarity	N			N			N		
Current direction	+	-		+			-		
Good force direction	NO	YES		NO			YES		
Interruption success	NO	YES		YES			YES		
Good prediction	YES	YES		NO(1)			YES		
Thermal breakdown									
Dielectric breakdown	YES								
NOTE	(1) R and S interrupt together. One "YES" is enough.								

Figure 11: Example 2 of successful interruption of LBS with Neodymium magnet when only one missed current zero occurred after 2.5 ms arcing. The bad force direction happened and contributed to the dielectric breakdown. a) load-side breaking currents, b) recovery voltages, c) arc voltage (phase R)

The third example (Figure 12) presents successful interruption of the LBS with no magnet. In this attempt even three missed current-zeroes occurred. Thermal breakdown occurred in each of these three missed current zeroes.

Thermal breakdown is a reignition in the interval of time immediately after current zero in which interruption depends on the energy balance between the arc and the circuit. If the energy balance is favourable and a thermal failure does not occur, this still does not mean that the current interruption is definite and successful. The contact gap with the recently conducting arc column must still withstand the recovery voltage (RV), which produces dielectric stresses. If the RV is too high, a dielectric breakdown occurs. Our criterion for judgment, which is applied in this analysis to determine the kind of breakdown, is the voltage excursion of the RV after CZ. If the value is below 2000 V, then the breakdown is considered as thermal. Otherwise, it is considered as dielectric.

The first current zero was missed in phase T after 0.3 ms, the second one was missed in phase S after 3.2 ms, and last one was missed in phase R after 5.9 ms. The first-pole-

to-clear was pole T with an arcing time of 9.2 ms. Arcing time of the last two poles-to-clear was 15.3 ms. Absence of permanent magnets and their efficient magnetic blowing contributed to the occurrence of thermal rather than dielectric breakdowns. Other tests have shown that the LBS with no magnets had a high failure rate in extended test duties.

4. ANALYSIS OF THE TEST RESULTS

For the analysis and comparison of experimental results, the following parameters were used as criteria for arc extinguishing efficiency:

- number of **missed current zeroes** and type of arc reignitions (thermal or dielectric breakdown);
- minimum **arcing time** (arcing times of the first-pole-to-clear) and average arcing time of all three poles obtained during a complete test series;
- rate of rise of the **arc voltage** (dU_{arc}/dt) for "good" and "bad" force directions obtained during complete test series.

4.1. Missed Current Zeroes

Results of all three series of the load breaking tests, including the test voltage and current, arcing times and information about missed current zeroes, are presented in Table I.

Number of missed current zeroes, type of arc reignitions and arcing times have been compared. Table II allows for quick and easy comparison between each test object. Column "Test Object" in the table represents three LBS test objects: with no magnet, with Ferrite magnet, and with Neodymium magnet.

Total number of missed current zeroes at full test voltage and current is highest for LBS with no magnet (27), significantly lower for LBS with Ferrite magnet (20), and lowest for LBS with Neodymium magnet (13). LBS with no magnet has at least one missed CZ in each attempt. At the same time, it has the highest number of attempts with two missed CZs (6), and one attempt with even three missed CZs. For exactly the same switch conditions in particular the same opening speed, LBS with Neodymium magnet had no single attempt with more than one missed CZ. Reignition at the first current-zero after contact separation mostly is a matter of voltage withstand of the small contact distance that has been reached after a short arcing time. The magnets obviously have a positive impact on the arc plasma, since geometry and speed of the rotary contacts haven't changed.

Analysis of the type of arc reignitions reveal that LBS with no magnet practically always had thermal breakdowns. Only 1 of 27 breakdowns was a dielectric one. In contrast, in LBS with Neodymium magnet most reignitions were of the dielectric breakdown type. This difference in behaviour can be explained by more efficient magnetic blowing even at small contact distances, which results in faster movement of the arc and smaller heating of the contact surface under the arc root.

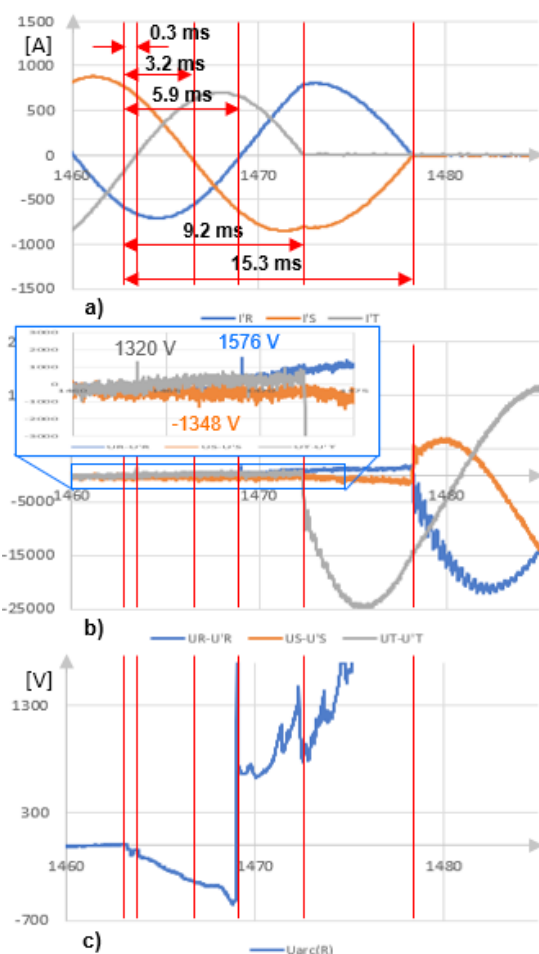


Figure 12: Example 3 of successful interruption of LBS with no magnet when even three missed current zeroes occurred. A thermal breakdown occurred in each of them. Absence of permanent magnets and efficient magnetic blowing contributed to thermal rather than dielectric breakdowns occurring.

a) load-side breaking currents,
b) recovery voltages, c) arc voltage (phase R)

Table I: Table of results

Test object 1: No magnet										Test object 2: Ferrite magnet (remanence B _r >0.375 T)										Test object 2: Neodymium magnet (remanence B _r >1.180 T)																				
Test No.	Test voltage	Breaking current	Arcing time of the first pole to clear	Arcing time of the last two poles to clear	Missed current zeros: TB - thermal breakdown DB - dielectric breakdown								Test No.	Test voltage	Breaking current	Arcing time of the first pole to clear	Arcing time of the last two poles to clear	Missed current zeros: TB - thermal breakdown DB - dielectric breakdown								Test No.	Test voltage	Breaking current	Arcing time of the first pole to clear	Arcing time of the last two poles to clear	Missed current zeros: TB - thermal breakdown DB - dielectric breakdown									
					1st		2nd		3rd		(ms)	T/D						(ms)	T/D	(ms)	T/D	(ms)	T/D	(ms)	T/D						(ms)	T/D								
					(ms)	T/D	(ms)	T/D	(ms)	T/D																							(ms)	T/D	(ms)	T/D	(ms)	T/D	(ms)	T/D
					(ms)	T/D	(ms)	T/D	(ms)	T/D																							(ms)	T/D	(ms)	T/D	(ms)	T/D	(ms)	T/D
1	13	315	7.0	10.8	0.7	TB	3.7	DB			1	13	315	4.5	9.3	0.7	TB					1	13	315	3.2	9.0														
2	13	315	7.9	12.9	0.8	TB	3.6	DB			2	13	315	3.8	8.9	0.2	TB					2	13	315	2.0	5.8														
3	13	315	4.9	10.7	2.2	TB					3	13	315	3.3	7.7	0.5	TB					3	13	315	3.6	9.3														
4	17	470	9.9	14.1	1.9	TB	5.6	DB			4	17	470	4.1	8.3	0.8	TB					4	17	470	4.5	8.5	1.0	TB												
5	17	470	5.9	11.2	0.4	TB	2.5	DB			5	17	470	5.8	11.1	0.1	TB	3.0	TB			5	17	470	2.9	7.6														
6	17	470	4.8	8.7	1.8	TB					6	17	470	3.9	9.0	1.0	TB					6	17	470	5.4	9.7	1.7	DB												
7	24	630	9.2	15.3	0.3	TB	3.2	TB	5.9	TB	7	24	630	7.0	11.4	2.0	TB					7	24	630	5.5	11.4	1.8	DB												
9	24	630	8.4	14.3	0.3	TB	4.6	DB			9	24	630	6.8	12.5	0.7	TB					9	24	630	3.9	10.1														
10	24	630	7.0	11.6	0.8	TB					10	24	630	6.2	11.1	0.6	TB					10	24	630	6.3	10.9	2.5	DB												
11	24	630	8.5	12.3	0.6	TB	4.5	TB			11	24	630	5.4	9.5	2.1	TB					11	24	630	4.4	8.8	0.6	TB												
12	24	630	5.1	9.0	1.6	TB					12	24	630	4.5	9.4	1.9	TB					12	24	630	3.6	8.8														
13	24	630	7.4	12.9	1.9	TB	3.7	TB			13	24	630	3.2	8.9							13	24	630	3.8	8.1														
14	24	630	7.4	11.4	3.9	TB					14	24	630	3.9	8.8	0.2	TB					14	24	630	3.7	8.5	1.2	DB												
15	24	630	6.4	10.9	0.6	TB	3.8	TB			15	24	630	2.7	7.0							15	24	630	3.6	8.3	1.2	DB												
16	24	630	5.1	9.6	2.2	TB					16	24	630	7.6	11.6	0.7	TB	4.6	DB			16	24	630	4.2	9.9	0.9	TB												
17	24	630	7.6	12.8	3.6	TB					17	24	630	4.1	9.6	0.5	TB					17	24	630	5.2	11.2	1.9	DB												
18	24	630	9.0	13.2	2.9	TB					18	24	630	5.7	9.8	2.6	TB					18	24	630	2.9	8.2	0.4	TB												
19	24	630	4.9	8.3	0.1	TB					19	24	630	2.2	7.5							19	24	630	4.7	10.5	0.8	TB												
20	24	630	5.0	9.5	2.0	TB					20	24	630	1.7	6.1							20	24	630	6.9	12.6	2.9	DB												
21	24	630	4.9	9.0	1.8	TB					21	24	630	4.5	9.6	0.5	TB					21	24	630	2.1	6.0														
22	24	630	3.9	7.9	0.5	TB					22	24	630	8.0	12.2	0.5	TB	4.6	DB			22	24	630	4.2	10.3	0.8	TB												
23	24	630	6.1	10.9	0.2	TB	3.3	TB			23	24	630	3.3	8.3	0.4	TB					23	24	630	2.3	7.8														
24	24	630	6.0	10.8	2.1	TB					24	24	630	3.1	8.8	0.1	TB					24	24	630	2.7	7.9														
25	24	630	5.2	9.3	1.8	TB					25	24	630	5.4	10.8	1.4	TB					25	24	630	4.1	10.1		TB												
26	24	630	4.4	8.5	1.1	TB					26	24	630	4.4	9.5	0.5	TB					26	24	630	5.3	11.7	2.4	DB												
27	24	630	4.9	10.3	0.8	TB					27	24	630	5.6	9.8	2.7	DB					27	24	630	2.6	6.9														

Table II: Comparison table

Test Object	Test voltage (kV)	Test current (A)	No. of tests	Number of missed current zeros				Type of arc reignitions		Average arcing times (ms)	
				1 missed	2 missed	3 missed	TOTAL	Thermal breakdown	Dielectric Breakdown	first-pole- to-clear	all three poles
No magnet	13	315	3	3	2	0	5	4	1	6.6	9.8
	17	470	3	3	2	0	5	4	1	6.9	9.8
	24	630	20	20	6	1	27	26	1	6.4	9.4
Ferrite magnet	13	315	3	3	0	0	3	3	0	3.9	7.0
	17	470	3	3	1	0	4	3	1	4.6	7.8
	24	630	20	16	4	0	20	16	4	4.8	8.0
Neodymium magnet	13	315	3	0	0	0	0	0	0	2.9	6.3
	17	470	3	2	0	0	2	1	1	4.3	7.2
	24	630	20	13	0	0	13	6	7	4.1	7.6

4.2. Arching Times

From results shown in Table II it is obvious that the higher the strength of the magnet, the shorter are the average arcing times, which is valid for both the arcing time of the first pole-to-clear (minimum arcing time) and the average arcing time in all three poles. The average arcing times could be deemed a criterion for the arc extinguishing efficiency.

It can be noted that the average arcing times, in the case of LBS with no magnet, practically do not depend on the breaking current, while this dependence is clearly noticeable for both LBS with Ferrite and LBS with Neodymium magnets: the smaller the breaking current, the shorter are the average arcing times. The dependence is more pronounced in the case of the Neodymium magnets, which exert the strongest magnetic field. The effect is due to the persistent magnetic strength of the permanent magnets, whereas the self-induced magnetic fields become smaller at lower currents.

In case of LBS with Neodymium magnet, it can be noted that a thermal breakdown occurs only if the arcing time is less than 1 ms, regardless of the force direction. Also, regardless of the force direction, a dielectric breakdown occurs only if the arcing time is higher than 1 ms and less than 3 ms.

4.3. Arc Voltage

Analysis of the arc extinction peak values at current zero and values of rate of rise of the arc voltage (dU_{arc}/dt) are relevant information in evaluating LBS performance. Results of arc voltage measurements in phase R for all three LBS test objects are presented in Figures 13 to 15.

For the evaluation of the arc voltage, it is important to distinguish between the “good” and “bad” force direction as introduced in section 2. In the case of LBS with no magnets, the arc movement direction is only determined by the direction of the breaking current and polarity of the self-induced magnetic field at the place of the arc, which is the sum of the fields generated by the three phase currents. However, since the magnetic field of the breaking current is predominant and since the breaking current and its magnetic field change direction at the same time, only one force direction is practically possible, which is pushing the arc outwards of the current-carrying loop (in principle equivalent to the “bad” arc movement direction). In the case of LBS with no magnets the rate of rise of the arc voltage is the smallest and has no dependence on the direction of the current (Figure 13). For this evaluation, the absolute values of the arc voltage were taken.

In the case of LBS with Ferrite magnet (Figure 14) or Neodymium magnet (Figure 15) the magnitude and the rate of rise of the arc voltage is dependent on the force direction, which is determined by the phase current direction and by the polarity of the magnets. Average rate of rise of the arc voltage for both directions is calculated and plotted in the diagrams.

The arc voltage is supposed to increase with time after contact separation in relation to the increase of the arc length. Obviously, the rate of rise can be approximated here by a linear slope. It should be noted that the arc voltage is the sum of the arc voltages measured across both gaps at the ends of the rotary contact. Since the magnet is only placed in one of the stationary contacts, the effect of the magnets on the arc voltage is approximately twice the value deduced here.

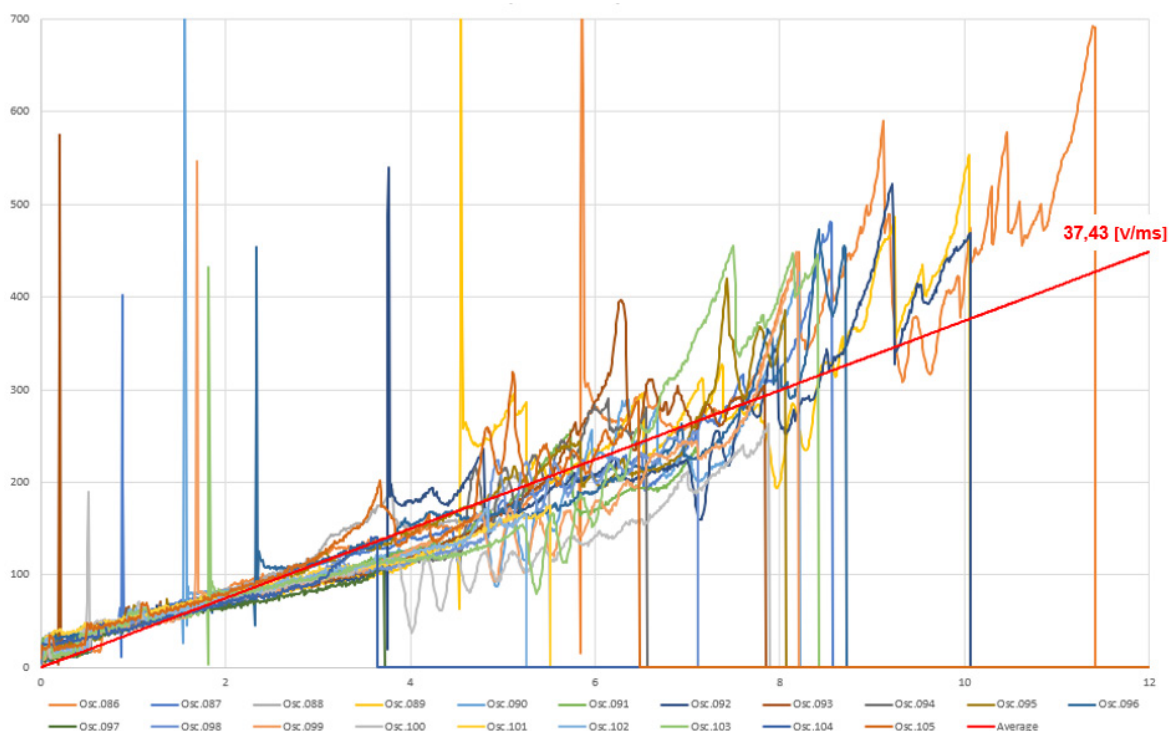


Figure 13. Absolute values of arc voltage [V] measured during CESI power tests on LBS with no magnet

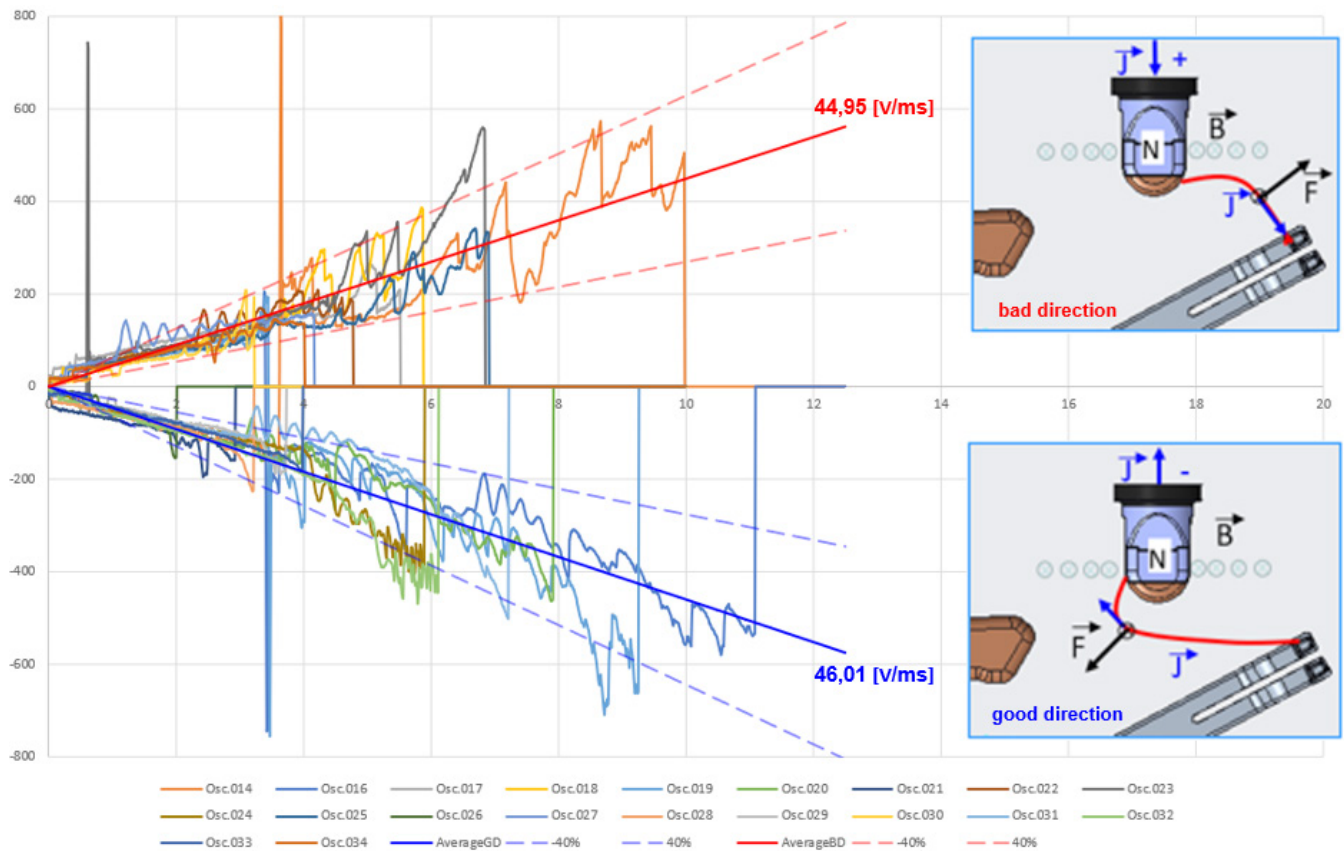


Figure 14. Arc voltage [V] measured during CESI power tests on LBS with Ferrite magnet

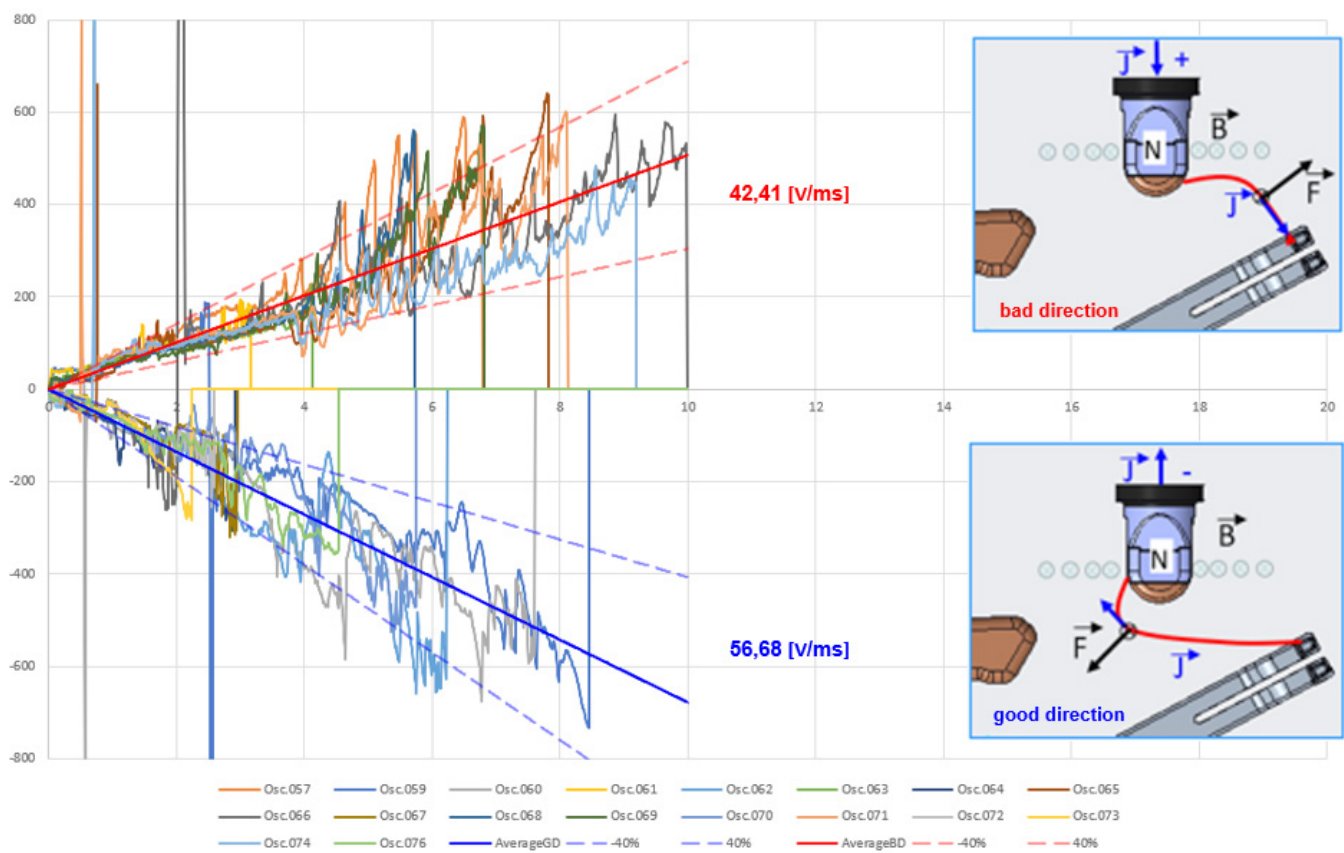


Figure 15. Arc voltage [V] measured during CESI power tests on LBS with Neodymium magnet

When the force is directed towards the recessed space at the stationary contacts, the arc voltage is notably higher ("good" force direction) than in the case where the arc is blown in the opposite direction ("bad" force direction). The higher arc voltage, particularly its arc extinction peak value [5], is a reliable indication that the length of the arc is increased, which significantly reduces the risk of both thermal and dielectric breakdowns after the first current zero. The consequences are first the reduction of the number of missed current zeroes (see A) and second the shorter minimum arcing times (see B).

Figure 16 and Figure 17 compare the average rate of rise of arc voltage values for the "good" and "bad" force directions.

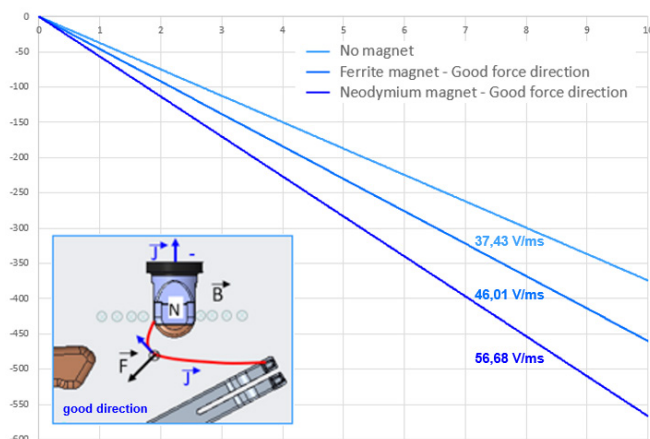


Figure 16. Average rate of rise of arc voltage values for „good“ force direction

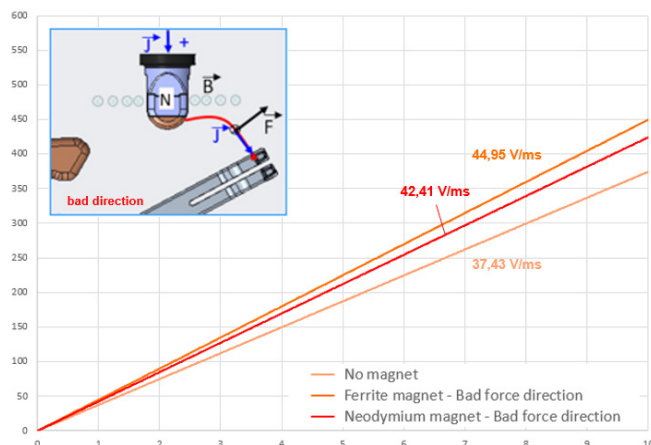


Figure 17. Average rate of rise of arc voltage values for „bad“ force direction

In case of "good" force direction, dU_{arc}/dt shows a good correlation with the magnet strength. The average rate of rise of arc voltage with Ferrite magnet is higher by approximately 30% and even by 60% with Neodymium magnet compared to the dU_{arc}/dt with no magnet. The correlation is in accordance with the stronger field of the Neodymium magnet.

In case of "bad" force direction, the increase of dU_{arc}/dt is limited to about ten percent. Although the increase is limited, successful interruption is possible and the arc extinguishing efficiency is noticeably better compared to LBS with no magnets.

Analysis of the breakdown voltages shows that, in all cases where the force direction is "good", its peak values are approximately twice as high compared to the cases when the force direction is "bad" with approximately the same or even shorter time after CZ to the breakdown.

5. CONCLUSIONS

Permanent magnets incorporated into the contacts of an SF6 load break switch improve the current breaking efficiency of a switch considerably. One major impact is the elongation of the arc and related increase of the arc voltage. However, the highest benefit is achieved when the arc root is blown towards a recessed space at the contacts thereby avoiding reignitions efficiently. This condition is ensured only in the "good" direction of the blowing electromagnetic force, which is determined by the phase current direction and the polarity of the magnets.

Power tests with the same LBS equipped with different types of magnets (no magnet, Ferrite magnets, Neodymium magnets) have shown that the magnitude of the arc voltage depends on this direction and increases with the strength of the magnets. The effect vanishes when there are no magnets. A detailed analysis reveals the importance of the "good" force direction at current-zero for current breaking efficiency. The consequences are noticed in the reduction of the number of missed current zeroes and in shorter minimum arcing times.

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BIOGRAPHY

Sead Delić was born in 1972 in Tuzla. He graduated from the Faculty of Electrical Engineering and Mechanical Engineering in Tuzla in 1997, and received his master's degree from the Faculty of Electrical Engineering in Sarajevo in 2009. He defended his doctoral dissertation in 2018 at the Faculty of Electrical Engineering, University of Sarajevo. He is a member of BH K CIGRE and a member of the Study committee of SC B3 International CIGRE. He was regular member of CIGRE Study Committee SC A3 International CIGRE, from 2012-2016. His career started in Energoinvest's Electric Power Institute IRCE, R&D department of HV circuit breakers and GIS from 1997. From 2008- 2010 he has been assistant and from 2011- 2020 Part-Time Lecturer at the Faculty of Electrical Engineering, University of Sarajevo. From 2011, he is employed in ErgoBos ILJIN d.o.o. Sarajevo. His areas of professional orientation are the development of HV circuit breakers and GIS, development of software for simulating the operation of HV circuit breakers and the calculation of electric fields.

Amer Smajkić was born in Mostar, Bosnia and Herzegovina, in 1990. He obtained his bachelor's, master's and doctoral degree at the Faculty of Electrical Engineering Sarajevo, University of Sarajevo in 2011, 2013 and 2020 respectively. His first employment experience was as R&D engineer at ErgoBos ILJIN where he worked at development of new HV circuit breakers up to 420 kV and development of simulation software for HV circuit breakers. Currently he works as Teaching assistant at Faculty of Electrical Engineering, University of Sarajevo. His fields of interests are design and modelling of HV circuit breakers. Amer Smajkić is member of national CIGRE committee of Bosnia and Herzegovina since 2013 and IEEE member since 2018.

Edgar Dullni was born in Rheinhausen, Germany, in 1953. He obtained his Ph.D. from the Institute of Experimental Physics at the university of Bochum in 1983 with a thesis on the detection of sputtered Ti using laser-induced fluorescence. He joined the ABB research centre in Switzerland in 1985, where he researched the physics of vacuum interrupters. Three years later, he continued his work with ABB Calor Emag Mittelspannungs GmbH, Ratingen, Germany. He managed the development of vacuum circuit breakers until 2004, when he started to work as senior expert in several working groups of IEC and IEEE on behalf of ABB. He also participated in CIGRE working groups in SC B3 and A3 related to SF₆, until he became convener of CIGRE WG A3.38 investigating shunt capacitor switching in T&D systems. Since May 2019, he is officially retired, however, still active as consultant and honorary professor at the University of Essen-Duisburg in Germany. Dr. Dullni is member of the scientific committee of ISDEIV and senior member of IEEE. In 2015, he received the 1906 Award from IEC TC17 and became a CIGRE distinguished member in 2020.

Sergio Santamaria was born in Bari (Italy) in 1971. He obtained his master's degree in mechanical engineering at the Politecnico di Bari. His first employment experience was as R&D engineer at Tozzi Electrical Equipment, where he worked at development of medium voltage air insulated switchgears for primary distribution. In 2017 he started attending / performing type tests according to the IEC62271-200 standard. Currently he works as NPD senior engineer at G&W s.r.l. (Foggia, Italy). He is working in developing of medium voltage gas and air insulated switchgears, equipped with circuit breakers, load break switches and switch disconnectors, designed according to the IEC and ENEL global standards. He is managing the G&W s.r.l. Laboratory and attending type tests performed at the main European Laboratories.

Nenad Uzelac graduated from the School of Electrical Engineering in Belgrade, Serbia, in 1995, with a major in electrical power engineering and completed Master of Science in product development at Northwestern University, Evanston, USA, in 2004. In 1999, he joined G&W Electric Company as an R&D Engineer, and in 2005, he became R&D Manager for developing new MV switchgear including reclosers and fault interrupters. Starting in 2015, he became responsible for G&W Global Research, tasked to develop new technologies. His research interests include AC and DC switching, materials and insulation technologies, condition monitoring and diagnostics, sensors, and arc fault studies. He was a convener of CIGRE A3.24 WG on "Tools for simulation of internal arc on MV and HV switchgear" and CIGRE A3.32 WG "Non-intrusive methods for condition assessment of distribution and transmission switchgear." Currently, he is a chair of CIGRE A3 study committee on T&D Equipment. He is also a senior member of IEEE and a chair of IEEE Switchgear Technology and Innovation subcommittee.

Mirsad Kapetanović was born in Visoko, Bosnia and Herzegovina, in 1953. He received his M.Sc. degree for research work on electrical endurance of HV circuit breakers from the Sarajevo University, Bosnia and Herzegovina, in 1993 and the Ph.D. degree for discovery of the algebra of fractal vector (Bosnian algebra) from the same University, in 1997 (Ph.D. thesis: "Algebra of Fractal Vector as a Contribution to Electric Field Calculation"). He has worked for the Energoinvest Electric Power Institute (IRCE) in Sarajevo since 1977. As of 1982, he has been the Head of the HV Circuit Breakers Design Department. As of 1995, he has been a Lecturer and in 1997 he was appointed Part-Time Professor at the Faculty of Electrical Engineering, University of Sarajevo. At present, he is Part Time R&D Manager of ErgoBos ILJIN Company, Sarajevo. He was Member of IEEE, 2001-2017; Distinguished Member of CIGRE; Regular Member of CIGRE Study Committee SC A3 (High Voltage Equipment), 2002-2008; Regular Member of SC 13 (Switching Equipment), 1996-2002; Member of CIGRE WG 13.01 (Practical application of Arc Physics in Circuit Breakers), as of 1990.