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Design Improvement of a 245-kV SF₆ Circuit Breaker With Double-Speed Mechanism Through Current Zero Analysis

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Abstract—This paper presents the results of current zero measurements during short-line fault interruption tests performed on three variants of an SF₆ circuit breaker (CB) (245 kV, 40 kA) with a new mechanism for increasing the contact motion speed, shortly named double-speed mechanism, in order to distinguish between double-motion systems where both contacts are moving. The application of a double-speed mechanism provides the necessary increase of contact separation speed, without a significant increase of opening energy. Besides that, it does not require any fixed mechanical connection between the stationary and moving contacts through the nozzle. This feature has a positive impact on the CB reliability and creates the possibility of easier assembly and dismantling of the interrupter from its insulator. High-resolution measurements of near current-zero arc current and voltage were carried out during these tests. Different levels of information on the “quality of interruption,” obtained from current zero measurements are presented. Direct observation of arc current and arc voltage data are analyzed. The arc conductivity very shortly (500 and 200 ns) before current zero, as an indicator of the performance of the breaker under test is discussed. All information obtained during current zero measurement is in correlation with the direct results of testing and with design improvements in successive variants of the CB.

Index Terms—SF₆, circuit breakers, current zero, high voltage, measurement, testing.

I. INTRODUCTION

THE interrupting unit of the tested 245-kV SF₆ circuit breaker (CB) is based on an already tested design of interrupting units used in the CBs of the same family for a rated voltage up to 170 kV and for rated short-circuit currents up to 40 kA [1]. Basically, this interrupter is a classical puffer improved by adding an auxiliary piston on the support of the fixed contact, with suitable design of the nozzle (Fig. 1).

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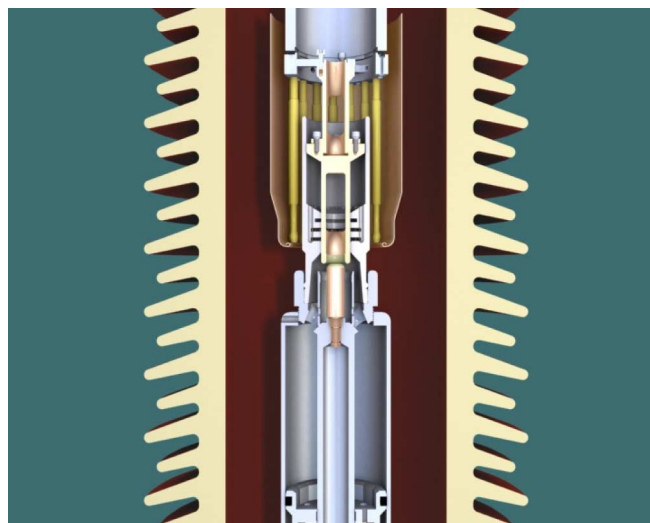


Fig. 1. Interrupting unit of the tested 245-kV, 40-kA SF₆ CB.

During opening, just after contact separation, the so called “closed-in arc” appears for a few milliseconds causing pressure rise in the volume between the compression and auxiliary pistons. Increased pressure under the auxiliary piston generates an additional force acting in the same direction and helping the operating mechanism. After the moment when the auxiliary piston emerges from the nozzle, a strong gas stream cools the arc using the accumulated arc energy and opening spring energy in compression volume. At current zero, the arc disappears. From this moment until the end of the stroke, there is no difference between this interrupter and the classical puffer.

This interrupting unit was equipped with double-speed mechanism (Fig. 2) which provides a necessary increase of contact separation speed, without a significant increase of opening energy for 245-kV applications [2]. Besides, as the result of the analyses, some additional design improvements of the initial interrupter variant were made.

The critical period for CBs to interrupt high currents, especially in the case of switching short-line faults currents, is the period around the moment when current crosses the zero. In the “current zero” (CZ), the energy input into the arc is zero and the quenching of the arc by forced energy removal by SF₆ gas has optimal prerequisites to make the interruption successful. The critical current zero period lasts only a few tens of microseconds, and insight into the physical processes in this period is

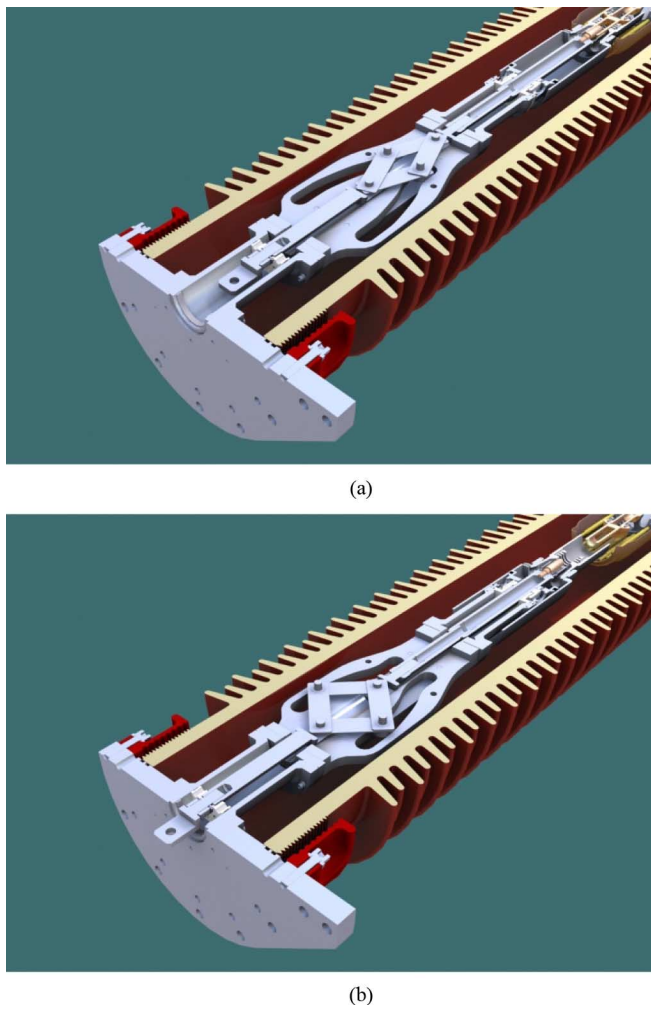


Fig. 2. Double-speed mechanism. (a) Closed position. (b) Open position.

TABLE I
TEST PROGRAM (CURRENT APPROXIMATELY CONSTANT)

No	Tested CB variant	No of tests	Arcing times (ms)	Short circuit current (kA)
1.	A	4	13.8 – 16.9	36.2 – 37.3
2.	B	9	13.2 – 21.8	35.8 – 36.7
3.	C	7	14.0 – 23.7	36.3 – 37.0

thus directly related to the quenching properties. Results of current zero measurement can give us information on CB breaking capability in the specific interruption conditions and can help with further improvement.

II. TEST PROGRAM

Three series of short-line fault interruption tests L90 (defined in standard IEC 62271-100 as a short-line fault test with 90% of the rated short-circuit breaking current) were performed in the KEMA High Power Laboratory during 2007 (see Table I). All tests were performed in a synthetic test circuit. The test object was one pole of a 245-kV, 40-kA SF₆ CB for outdoor installation.

Three variants (A, B, and C) of the interrupter were tested. During some of the tests, a capacitor in parallel with the interrupting unit was used.

The first variant (A) was tested in order to catch the “fingerprints” of the double-speed mechanism, its basic impact on the arc-driving mechanism interaction, and behavior of the whole CB during high-power tests. A capacitance of 0.87 nF was in parallel with the interrupting unit in order to improve the interruption capability [3]. In this variant, the diameter of compression cylinder was equal to one used in interrupters of the same CB family, but for lower rated voltages 123–170 kV and for the lower short-circuit breaking current of 31.5 kA. Axial geometry was changed (enlarged) since total stroke was longer for about 27% compared to stroke for the same family CBs but for lower rated voltages up to 170 kV. Total opening energy was set to be equal as for the aforementioned CBs with a lower rating voltage and lower-rated short-circuit breaking currents. The analysis of CZ measurements data indicated that, for variant A, the arc conductivity characteristics were above the limiting value (see Section V).

A slightly modified and improved next variant B was able to interrupt the short-line fault currents in test duty L90 efficiently in the whole extinction window of 10 ms. Compared with the initial variant (A), in this variant, the diameter of compression volume was increased for about 8% and consequently the total opening energy was increased for about 15%. Existing axial openings in the nozzle throat were completely removed from the nozzle design. Variant B can be divided into two sub-variants: B₁ and B₂. Subvariant B₁ had an attached capacitor of 0.87 pF in parallel with the interrupting unit while in variant B₂, the parallel capacitor was removed.

The ultimate goal was the 245-kV, 40-kA interrupter without a parallel capacitor, so small additional improvements were necessary. This goal was achieved with a final variant C which eight times successfully cleared SLF currents (L90) with arcing times between 15 and 24 ms and, thus, covering the whole extinction window for 50 Hz. Compared with variants B, in variant C, only opening energy was increased for about 12%.

All of the aforementioned improvements were based on:

- detailed analysis of current zero measurement data (results) from every test;
- computer simulations of each interruption based on a simplified physical arc model [4];
- MatLAB simulations with a blackbox model of the electric arc and used test circuit.

III. CURRENT ZERO MEASUREMENT SYSTEM

All tests were recorded with the high-resolution, high-frequency current zero measurement system [5] that works as a stand-alone system in addition to the standard laboratory data-acquisition system. This system is a 40-MHz, 12-b, 256-k sample system with single channel digitizers, connected through an isolated digital optical data-transmission system to the laboratory’s control room. The digitizers operate on floating potential. Current is measured with a special high-frequency Rogowski coil located as close as possible to the arcing chamber of the test object, directly outside the terminal, at the grounded side. The coil should be placed as close as possible to the arc in

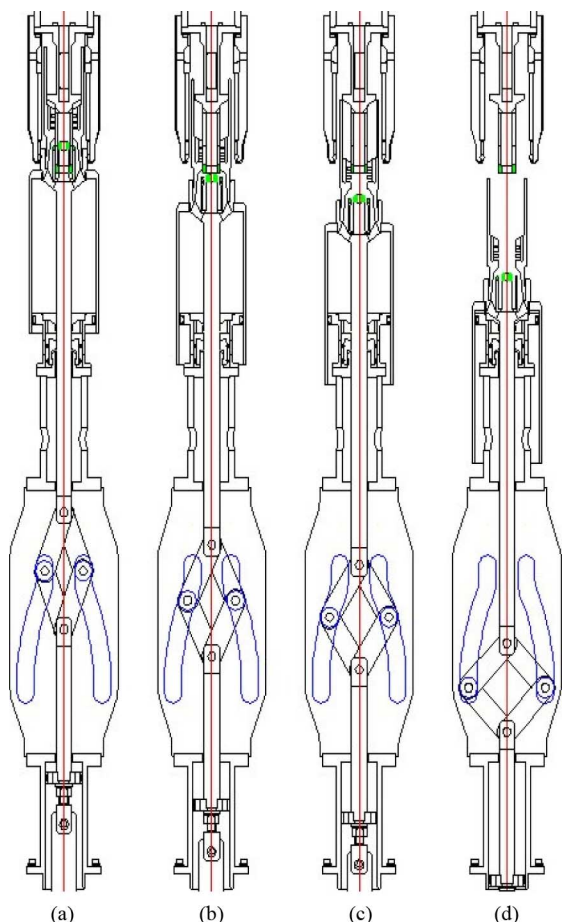


Fig. 3. Interrupter with double-speed mechanism. (a) Closed position. (b) Contact separation. (c) Auxiliary piston emergence from the nozzle. (d) Open position.

order to avoid fractions of the arc current to “leak” away into stray capacitances between the arc and the coil location, thus disappearing from measurement. This negative effect can be essentially reduced by the correct placement of the coil [5], [6]. The coil was connected with a 2-m coaxial cable to the current digitizer.

Voltage is measured with a Haefely RCR950 voltage divider with 2-m Haefely cable between the low-voltage arm and terminator unit. Current in the range down to approximately $50 \cdot \cdot \cdot 200$ mA (depending on the noise level) can be measured with high accuracy, voltages down to a few tens of volts. Information was obtained from the measurements, including direct observation of the current zero arc current and arc voltage traces and the arc conductivity. Examples and applications will be discussed.

IV. DOUBLE-SPEED MECHANISM

Fig. 3 shows the tested interrupter, coupled with the spring operating mechanism through the new, simple, and robust double-speed mechanism [2].

Its simple principle is evident from Fig. 4. A couple of shaped guides are used for steady driving of the interrupter’s moving part and direct its motion in a straight line. At the same time, the shape of the guides controls the speed of the moving part. The

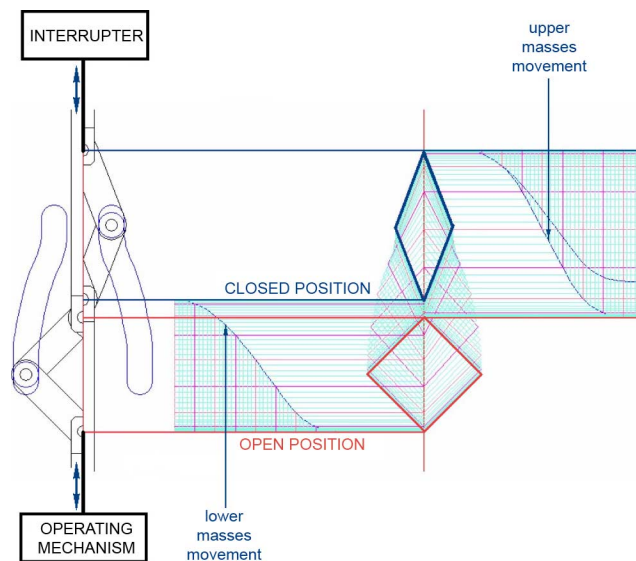


Fig. 4. Illustration of the double-speed mechanism principle.



Fig. 5. Moving part of the interrupter with double-speed mechanism.

first part of the guides is rectilinear and parallel, providing identical movement on both sides. The curvilinear part of the guides starts about a dozen millimeters before the arcing contact separation. Then acceleration of the upper masses (interrupter) starts as well as retardation of the lower masses of the whole kinetic chain. The increased speed (>10 m/s) is only maintained for 10 ms after contact separation. After that, the guides become rectilinear and parallel, equalizing both speeds again below 7 m/s. The rest of the stroke is the same as without the double-speed mechanism. The upper (interrupter) speed is also dependent on the ratio of the masses on drive and interrupter sides of the kinetic chain.

The interrupter with a double-speed mechanism needs only a limited increase of opening energy. At the same time, the mechanical simplicity of the interrupting unit is completely preserved. These are the crucial features for the selection of this interrupter variant for the test.

Comparing the double-speed principle with the principles without fixed mechanical connection between the stationary and moving contacts through the nozzle (like a pure puffer principle), the presence of double-speed mechanism increases the number of moving parts and theoretically causes a decrease in reliability of the entire CB. It should be taken into consideration.

V. RESULTS OF THE CURRENT ZERO MEASUREMENT

From the current and voltage traces in the current zero region, the following characteristics are obtained:

- electrical conductivity $G_{(-500)}$ and $G_{(-200)}$, 500 ns and 200 ns before current zero, respectively;
- du/dt at current zero;
- di/dt at current zero;
- u_{peak} , arc voltage extinction peak;
- t_{peak} , time of occurrence of peak before current zero;
- I_c , current commutated through the capacitor at current zero in case a capacitor has been added parallel to the interrupting unit.

A. Arc Conductivity

Arc (electrical) conductivity at a certain time (t_0) before current zero has been found to be a very reliable indicator for the short-line fault interruption performance of a CB [7]. The conductivity is calculated using the arc current (i_a) and the arc voltage (u_a) traces just before current zero using the equation

$$G(t_0) = \frac{i_a(t_0)}{u_a(t_0)}. \tag{1}$$

The choice of t_0 must be as close as possible to current zero, but not too close since the measurement of the conductivity G becomes more uncertain near current zero. Also, time t_0 cannot be too far away from the current zero because the calculated value as a CB performance indicator becomes less and less effective [3], [8].

For high-voltage SF₆ CBs, it is possible to find the limiting conductivity G_{lim} that separates interruptions and reignitions. Most probably, there will be interruptions for all cases when conductivity G is smaller than the limiting conductivity G_{lim} , and opposite, there will most probably be reignitions in all cases when conductivity G is higher than the limiting conductivity G_{lim} . The range between measured conductivities with observed failures on one side and interruptions on the other side can be established from a limited number of tests. The limiting value is in this range with high probability [3], [7], [8].

By experience [8], the value of t_0 which is appropriate for most SF₆ high-voltage CBs is 200 ns, but also the value of 500 ns can be taken into consideration as well, when the performance of the breaker is such that the conductivity at 200 ns before zero is already below the measurement limit.

In Fig. 6, all data for the arc conductivity $G_{(-200)}$ and $G_{(-500)}$, recorded during testing with all three CB variants, are presented. Reignitions (failures to interrupt) are presented with

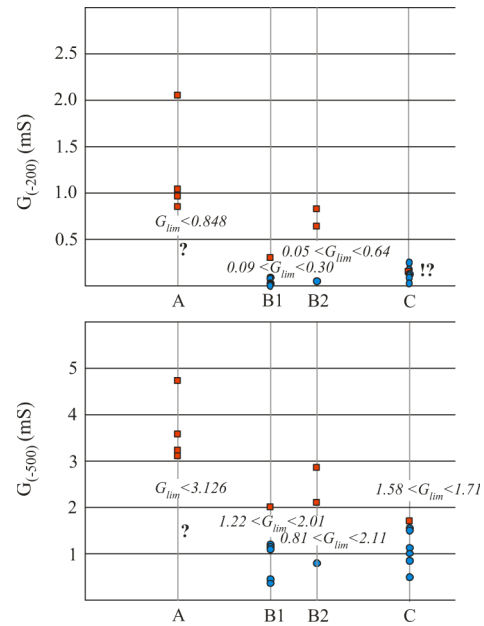


Fig. 6. Arc conductivity measured for all three variants (A, B, C) of the tested CB.

squares and interruptions with circles. The variant B is divided into two subvariants: B₁ and B₂. The only difference is the 0.87-nF parallel capacitor: the subvariant B₁ is with and the subvariant B₂ without the capacitor. For variant A, the limiting conductivity could not be determined since there were no successful interruptions. It is obvious that limiting conductivity $G_{(-200)lim}$ is smaller than 0.85 mS and $G_{(-500)lim}$ is smaller than 3.1 mS.

For tested CB variant B, it was possible to determine limiting values G_{lim} for both times of interest (500 ns and 200 ns before the current zero) and for both subvariants. The obvious positive influence of the parallel capacitor, especially near current zero, calls for separate consideration of the B subvariants. Values of the limiting conductivity G_{lim} can be obtained from Fig. 6.

In case of variant C, the values for the arc conductivity of 200 ns before current zero $G_{(-200)}$ did not fully correlate with the interrupting results since the measured conductivity in case of one successful interruption was higher than in one case when reignition occurred. The very small value of the arc conductivity $G_{(-200)}$ of this variant caused large measurement inaccuracy and, for this interrupter variant, it is better to take into consideration the conductivity 500 ns before current zero $G_{(-500)}$. The limiting value $G_{(-500)lim}$ in case of variant C is between 1.58 and 1.71.

Generally, for all variants of the tested CB, the conductivity $G_{(-500)}$ seems to be a better indicator of its breaking capabilities and in all cases, there is a direct correlation with interrupting results. Also, the improvement in CB design, from initial variant A to final variant C, can easily be followed, looking at the values of the arc conductivity $G_{(-500)}$. The arc conductivities for variant A are considerably higher than the same values measured for variant B. This is also applicable comparing variant B with variant C, where the smallest values of the arc conductivity were measured. Design improvement of the variant C can

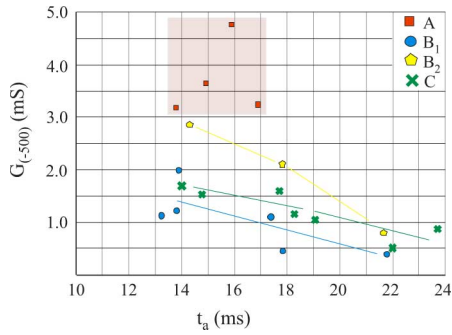


Fig. 7. Arc conductivity $G_{(-500)}$ versus arcing time.

be evaluated especially by the comparison with the subvariant B_2 since both variants have no parallel capacitor. At any arcing time, the arc conductivity of variant C is essentially lower than that of subvariant B_2 with about the same limiting conductivities. In Fig. 7, data for the arc conductivity $G_{(-500)}$ as a function of arcing time are presented. A general observation has been that there is a correlation (nearly a functional dependence) between arcing time and arc conductivity for each type of SF₆ CBs [3], [7], [8]. The tendencies denoted by the straight lines for variants B_1 , B_2 , and C in Fig. 7 justify this observation despite the small number of tests. The first variant, variant A, did not have tests with longer arcing times (>20 ms) so this correlation could not be directly proved. Also, for this breaker, the pressure in the compression cylinder, (which has a strong influence on the arc cooling and, thus, on the conductivity) is significantly higher at longer arcing times (>20 ms).

For longer arcing times (>20 ms), it seems that the parallel capacitor does not have a significant impact on the arc conductivity $G_{(-500)}$. The CB performance for longer arcing times is considerably better than at shorter arcing times.

B. Arc Voltage Extinction Peak

The arc voltage extinction peak u_p just before interruption is also a very important parameter [3], [7]. In the last microseconds, the decaying arc voltage (du/dt) causes commutation of a portion of the main circuit current into the (stray) parallel capacitor (C), thus reducing the arc current and creating a brief pause that allows additional cooling. The commutated current is equal to $C \cdot (du/dt)$. In general, stronger commutation of the main current can be achieved by higher voltage extinction peak and with voltage extinction peak as close as possible to current zero (high du/dt) and larger capacitance.

In Figs. 8 and 9, data for the arc voltage extinction peak u_p and time of occurrence of the peak before the current zero t_p are presented, respectively. As in Fig. 6, squares represent reignitions and circles represent interruptions.

From Fig. 8, it can be concluded that higher arc extinction voltage peaks u_p are associated with interruptions and opposite, lower values of u_p with reignitions. For all tested interrupter variants, it is clear that a specific limiting value of the arc voltage extinction peak u_p exists.

In case of variant A, very low arc voltage extinction peaks are recorded. An improved subvariant B_1 had higher values of arc

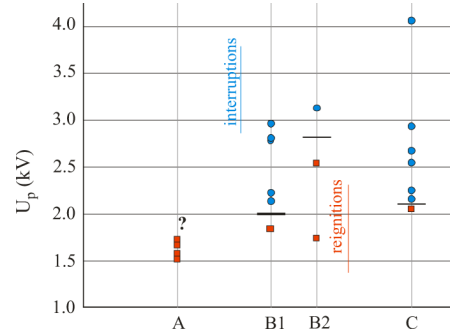


Fig. 8. Arc voltage extinction peaks.

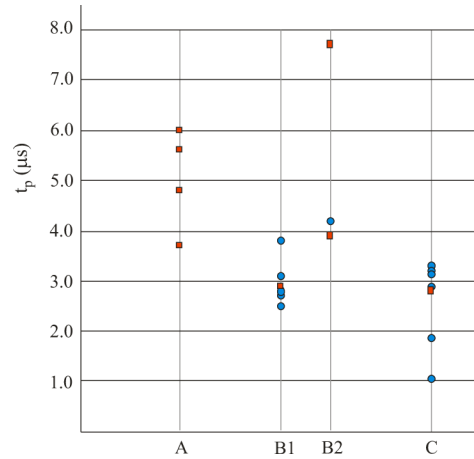


Fig. 9. Time of occurrence of arc voltage extinction peaks before current zero.

extinction peaks which lead to many successful interruptions. Subvariant B_2 , without a parallel capacitor, requires higher arc voltage extinction peaks. A positive influence of the parallel capacitor is evident: the subvariant B_1 had interruptions with lower values of u_p than the subvariant B_2 .

However, the highest values of u_p are recorded on the last interrupter variant C, where all interruptions were successful, except in the case when the arcing time was shorter than the minimum arcing time for this interrupter (14.8 ms).

Design improvements in variant C were so efficient that the design itself fully substituted a positive influence of the parallel capacitor. It is evident from the comparison of the variant C and subvariant B_1 . The limiting values of u_p for variant C and subvariant B_1 are almost the same.

The increasing tendency of u_p from variant A to variant C indicates significant design improvements. It is also clear that variant C was able to interrupt even with lower recorded values of the arc voltage extinction peak.

A design improvement of the variant C can be evaluated by comparing the u_p values of variants C and B_2 since both variants do not have a parallel capacitor (it was similarly done before with the comparison of their conductivity values). From Fig. 8, it can be seen that the limiting value of u_p for variant C is lower than the limiting value for subvariant B_2 .

The graphs presented in Fig. 10, which compare the test results obtained on design A (reignition) with a similar test on design C (interruption) having similar arcing time, current, and

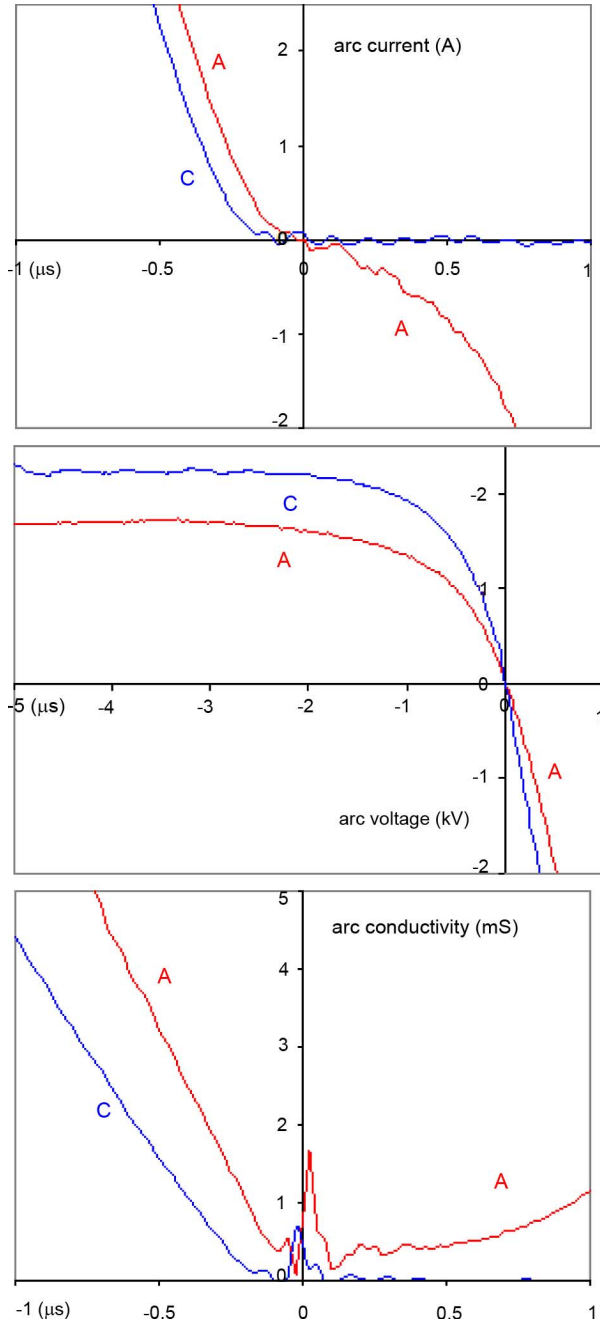


Fig. 10. Comparison of current zero arc traces (current: upper; voltage: middle and conductivity: lower) for initial design A and modified design C. The time scale is in microseconds.

history, show the effect of the modifications (design improvements) very clearly.

The time of occurrence of the arc voltage extinction peak t_p has also a positive tendency from variant A to variant C. It becomes shorter and shorter, and the shortest value was recorded in variant C. For this parameter, it was not possible to find a critical value. It was also not possible to establish a strong correlation with interruption results. This parameter has to be evaluated together with the value of arc voltage extinction peak u_p .

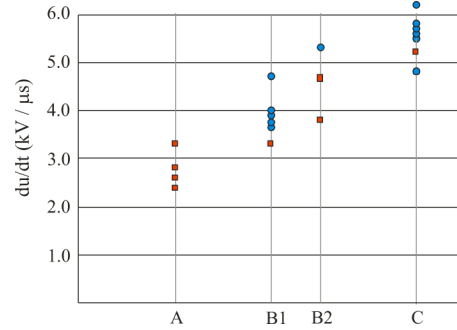


Fig. 11. Values of (du/dt) at current zero.

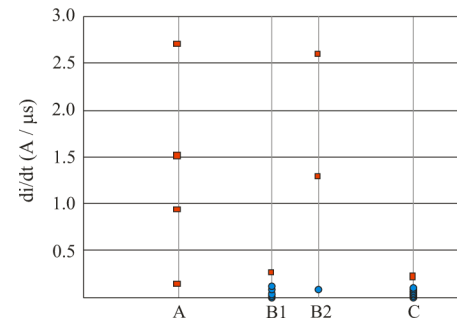


Fig. 12. Values of (di/dt) at current zero.

C. du/dt

The value of du/dt at current zero is also relevant information in evaluating CB performance.

From the data presented in Fig. 11, a clear correlation of the interrupter improvements with an increase of du/dt at current zero can be recognized. Higher du/dt causes more intense commutation of the main current to (stray) parallel capacitor, reducing the arc current and consequently the arc conductivity.

Due to the parallel capacitance, variant B₁ is able to interrupt even if the current zero du/dt is relatively low. Comparing variant C and subvariant B₂ again (both without parallel capacitance), it is evident that there is a range around $du/dt = 5 \text{ kV}/\mu\text{s}$ so that above this range, the breaker interrupts and below this, it fails. Inside this range, there is no firm correlation with interruption success. The better performance of variant C is clear again.

D. di/dt

The slow approach of the interrupting current to zero (small di/dt) is also very important for successful interruption, and if di/dt is too high, the breaker will not interrupt [6].

Design improvements in the final interrupter variant C lead to a very effective reduction of di/dt at current zero (see Fig. 12). The limiting value of di/dt can also be determined. In the case when di/dt at the current zero is lower than the limiting value, the probability of current interruption is very high.

VI. CONCLUSION

Comprehensive short-line fault testing of one pole of a 245-kV, 40-kA SF₆ CB for outdoor installation, equipped with

a double-speed mechanism, was performed. A high-resolution and high-frequency current-zero measuring system were used for arc voltage and arc current recording.

All recorded data are fully in accordance with the test results. Some measured parameters have a direct correlation with interruption success.

For the tested CB, it has been found that the arc conductivity 500 ns before current zero $G_{(-500)}$ is a very good parameter to evaluate the CB interrupting capability.

Also, the arc voltage extinction peak can be used as a measure of the interrupting capability for this type of CB. When the peak is higher, the probability of current interruption is also higher.

The used performance indicators (value of the arc voltage extinction peak and value of the arc conductivity 500 ns before current zero) say much more about the quality of the performance than the simple interruption/failure indication. In this way, design improvements can be clearly evaluated.

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