

Original scientific paper/Izvorni naučni rad

# DEVELOPMENT AND TESTING OF HV SF<sub>6</sub> CIRCUIT BREAKER FOR MINIMUM AMBIENT TEMPERATURE OF -40 °C

## RAZVOJ I ISPITIVANJE VN SF<sub>6</sub> PREKIDAČA ZA TEMPERATURU OKOLINE DO -40 °C

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**Abstract:** In order to prevent the liquefaction of SF<sub>6</sub> gas in circuit breakers intended to operate at very low temperatures, the filling pressure must be low enough. At certain ambient temperature, depending on filling pressure, the liquefaction of SF<sub>6</sub> gas starts and the density and pressure drop sharply. This process will jeopardize insulation characteristics and breaking capability of the circuit breaker. In order to prevent the liquefaction of SF<sub>6</sub> gas down to -40 °C of ambient temperature, filling pressure at 20 °C must not be higher than 0.45 MPa. Lower filling pressure will result in lower pressure rise in heating chamber during arc quenching. This is the reason why breaking capability of the circuit breaker (live tank, 123 kV 40 kA, manufactured by Končar) with lower filling pressure (0.45 MPa) must be proven even though the same interrupter unit has proven breaking capability (in GIS) with filling pressure of 0.65 MPa. The focus of the research was test duty L90 according to IEC 62271-100, which is considered as highly challenging for modern SF<sub>6</sub> circuit breakers.

The simulations (performed in HV CB Simulation) of interruption process with starting variant of interrupter unit (filling pressure 0.45 MPa) revealed that certain changes in the design and setting of circuit breaker are needed in order to satisfy existing empirical criteria in pressure of SF<sub>6</sub> gas in heating chamber and in the distance between arcing contacts at instant of current zero. Proposed design and setting changes were evaluated through the estimation of breaking capability by using calculated parameters of black box arc model in Matlab model of test circuit. The circuit breaker with improved interrupter unit for minimum ambient temperature of -40 °C has successfully passed the test duty L90 in high power laboratory KEMA. During the testing, special current zero measurements have been carried out. The results of current zero measurements were used for additional verification of the method for the estimation of breaking capability based on calculated parameters of black box arc model.

**Keywords:** HV SF<sub>6</sub> circuit breakers, short line fault L90, estimation of breaking capability, current zero measurement

**Sažetak:** Da bi se spriječilo utečnjavanje SF<sub>6</sub> gasa kod prekidača namijenjenih za rad pri veoma niskim temperaturama, pritisak punjenja mora biti dovoljno nizak. Kod određene temperature, koja ovisi o pritisku punjenja, dolazi do utečnjavanja gasa SF<sub>6</sub> kada naglo počinju opadati i pritisak i gustina. Tada se naglo gube i izolacione karakteristike i prekidna moć prekidača. Da ne bi došlo do utečnjavanja SF<sub>6</sub> gasa sve do temperature -40 °C, pritisak punjenja na 20 °C ne smije biti viši od 0.45 MPa. Niži pritisak punjenja rezultirat će manjim porastom pritiska SF<sub>6</sub> gasa u termalnom volumenu komore za gašenje luka. Zbog toga je bilo potrebno i pri tom pritisku izvršiti provjeru prekidne moći prekidača za vanjsku montažu 123 kV, 40 kA, proizvodnje Končar, čiji sklopni element ima dokazanu prekidnu moć u metalom oklopljenoj izvedbi pri pritisku od 0.65 MPa. Fokus istraživanja je postavljen na ispitni ciklus L90 prema IEC 62271-100, koji se smatra posebno zahtjevnim za savremene SF<sub>6</sub> prekidače.

Korištenjem računarskog programa HV CB Simulation izvršena je simulacija rada prekidača s polaznom varijantom sklopnog elementa, koja je pokazala da su, za pritisak punjenja od 0.45 MPa potrebne određene izmjene u cilju dostizanja ranije uspostavljenih kritičnih vrijednosti pritiska SF<sub>6</sub> gasa u termalnom volumenu i rastojanja između lučnih kontakata u strujnoj nuli. Predložene izmjene provjerene su kroz procjenu prekidne moći koristeći proračunate parametre black box modela luka u Matlab modelu ispitnog kola. Prekidač s poboljšanim sklopnim elementom za temperaturu okoline do -40 °C, uspješno je prošao ispitni ciklus L90 u laboratoriji velike snage KEMA. Tokom ispitivanja vršena su i specijalna mjerenja u okolini strujne nule. Rezultati tih mjerenja korišteni su za dodatnu verifikaciju procjene prekidne moći, koja je urađena na bazi proračunatih parametara black box modela električnog luka.

**Ključne riječi:** VN SF<sub>6</sub> prekidači, bliski kratki spoj L90, procjena prekidne moći, mjerenja u okolini strujne nule

### INTRODUCTION

It is well known that SF<sub>6</sub> gas due its specific physical and chemical properties is a dominant media for insulation and arc quenching inside high voltage circuit breakers.

Pure SF<sub>6</sub> is chemically and biologically inert, inflammable, non-toxic, colourless, tasteless and does pose any harm to the staff who handle it. However, it represents some inconveniences such as liquefaction at pressures lower to air or nitrogen, especially if it is used at high pressure as is the actual tendency in industrial practice [1].

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Paper submitted: November 2017 Paper accepted: February 2018

According to Mollier chart for SF6 (Figure 1), density of 28.736 kg/m<sup>3</sup> will prevent SF6 to liquefy down to -41 °C. For the given density pressure of SF6 gas at 20 °C is 0.45 MPa. Hence, rated filling pressure of SF6 gas for the circuit breakers (and other GIS compartments) for minimum ambient temperature of -40 °C must not be higher than 0.45 MPa, excluding the use of heaters.

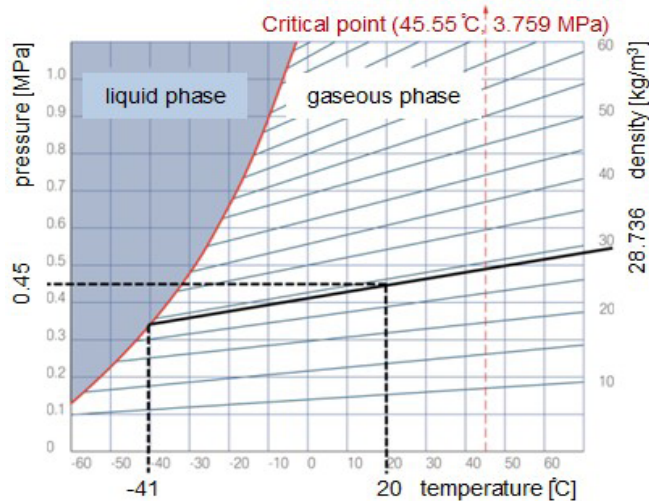


Figure 1: Pressure/temperature/density characteristics for SF6 [2]

This paper presents the results obtained during research and development of high voltage live tank circuit breaker 123 kV 40 kA 50 Hz for minimum ambient temperature of -40 °C (minimum pressure for insulation and for the interruption at 20 °C – 0.45 MPa). The starting variant of interrupter unit for this circuit breaker (self-blast principle) was an interrupter unit of GIS circuit breaker (145 kV 40 kA, rated filling pressure – 0.65 MPa). The manufacturer, Končar Električni visokonaponski aparati d.d. (Končar High Voltage Switchgear Inc.) already has proved breaking capability for the GIS circuit breaker [3]. Lower filling pressure will result in lower pressure rise inside heating chamber during arc quenching for the same short circuit current and arc duration (Figure 2). Since the main driving force for the arc extinguishing is the pressure of SF6 gas [4], the breaking capability (as well as dielectric performances) must be proven once again in case when the rated filling pressure is reduced, even though the design of interrupter unit is unchanged. The focus of research was test duty L90 according to [5], which is considered as highly challenging for modern SF6 circuit breakers.

Simulation results given in Figure 2 show 0.7 MPa lower pressure inside heating chamber at the instant of current zero (short circuit current of 36 kA, arc duration of 20 ms) if rated filling pressure was reduced from 0.65 MPa to 0.45 MPa. This confirms the above claim that lower filling pressure will have a negative influence on the breaking capability of high voltage SF6 circuit breaker. Reduced filling pressure show some influence on the contact stroke as well, but this has no significant effect on the breaking capability.

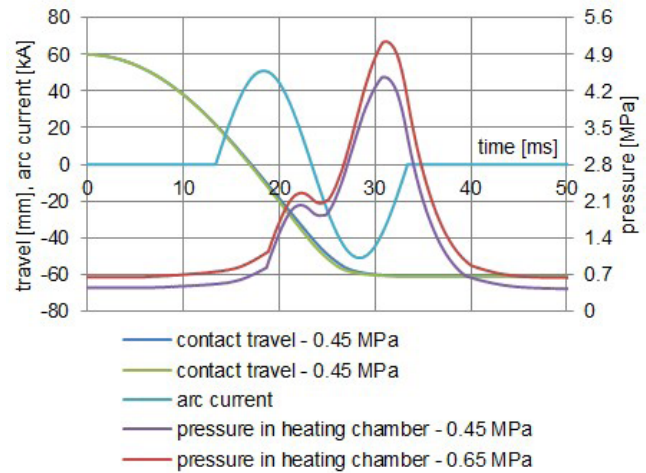


Figure 2: Comparison of simulation results - pressure rise inside heating chamber and contact travel in case of 145 kV 40 kA GIS circuit breaker (manufacturer: Končar High Voltage Switchgear Inc.) for different rated filling pressure

The simulation results were obtained through high voltage SF6 circuit breaker simulation software – HV CB Simulation (for the example of GIS circuit breaker 145 kV 40 kA, self-blast principle). HV CB Simulation is based on an integral-physical enthalpy flow arc model (Frost-Liebermann arc model [6]), and other models incorporated in HV CB Simulation are given in [7]. HV CB Simulation output results are validated on many circuit breakers with different ratings and working principles and from different manufacturers [7]-[11].

Since many test results and experimental measurements data were obtained in earlier phases of the current and other similar projects (pressure rise measurement during arc quenching, nozzle ablation and contact erosion intensity measurement and current zero measurement), the aim was to exploit existing empirical and establish new criteria in order to analyze breaking capability of starting variant of interrupter unit with reduced filling pressure of 0.45 MPa. Based on this analysis it will be known whether the design and/or setting changes on the starting variant are needed. This approach reduces (or in this case eliminates) the number of development tests in high power laboratory reducing the cost of the development of the new product.

## 1. METHOD FOR THE ESTIMATION OF HV CIRCUIT BREAKER CAPABILITY

The characteristics of combined electrical and thermal process in short time interval when current passes through natural zero will decide whether the current will be extinguished or not. This very complicated and extraordinary process demands prior knowledge (from earlier development tests or test results from related projects) in order to estimate breaking capability of the subjected circuit breaker. The usual approach is to use knowledge and results from earlier tests to calibrate the simulation models and enhance the criteria for successful interruption of short circuit current [8], [11]-[14].

Method for estimation of HV circuit breaker capability used in this paper is based on parallel use of the empirical criteria for successful interruption of short circuit current [11] and modelling of interaction between electric arc and test circuit (with black box arc model) [14].

### 1.1. Estimation of breaking capability based on empirical criteria

The main performance indicator of the circuit breaker in the process of arc quenching is the value of pressure of SF6 gas inside heating chamber (or compression chamber in case of puffer circuit breaker) at the instant of current zero. In exceptional cases, insufficient pressure rise can be compensated, in terms of short circuit current interruption, by increasing the distance between arcing contacts [8] or by ensuring more favourable gas density distribution inside the main nozzle [13].

For the subject circuit breaker (and its variants) empirical criteria is represented through the pressure of SF6 gas inside heating chamber and the distance between arcing contacts at current zero instant (characteristic quantities at current zero). The critical values were established based on the simulation results and an analysis of circuit breaker performances in more than 30 shots of short line fault (L90) current interruptions (5 test shifts – one live tank circuit breaker and four variants of GIS circuit breaker [15]-[19]. The criteria are: 2.82 MPa for the pressure inside heating chamber and 70.7 mm for the distance between arcing contacts at current zero. In case of increase in length of main nozzle throat there is additional criterion – gas flow cross-section through the nozzles (445 m<sup>2</sup> for L90).

Obviously, before the empirical criteria can be established, HV CB Simulation output results (pressure rise in heating chamber during arc quenching, contact travel and speed, nozzle ablation intensity, etc...) for subject circuit breaker must be validated. The validation of HV CB Simulation output results for the subject circuit breaker is given in [11].

### 1.2. Estimation of the breaking capability by taking into the account the interaction between electric arc and test circuit

The phenomenon of interaction between electric current and test circuit (power system) in short time interval around current zero explains current chopping, breakdown in thermal region and the challenge of test duty L90. One demonstration of the interaction between electric current and test circuit is that any capacitor placed in parallel with circuit breaker (parallel capacitor or capacitance from the rest of GIS) will delay the rise of voltage from the line side (a certain time delay already exist from the capacitance of the line itself). As a result, this will improve breaking capability of circuit breaker.

Other demonstration of the interaction between electric arc and test circuit is the change of the frequency. Change

of frequency from 50 to 60 Hz demands more favourable conditions at current zero in terms of short circuit current interruption. Estimation of the breaking capability in case frequency or value of parallel capacitor has been changed is not possible based only on presented empirical criteria. In these cases, different approach to estimation of breaking capability is needed including modelling of test circuit with black box arc model. This approach will also eliminate any uncertainty regarding whether lower pressure inside heating chamber will be compensated with longer distance between arcing contacts in terms of short circuit current interruption. In order to preserve the correlation between the design of circuit breaker and estimated breaking capability the parameters of black box arc model have to be calculated from output results of the HV SF6 circuit breaker simulation.

Estimation of the breaking capability by taking into the account the interaction between electric arc and test circuit is based on black box arc model. Black box arc model used in this research is developed by high power laboratory KEMA [14].

#### Black box arc model

The development of KEMA black box arc model [14] was based on the classical approach to arc modelling (Mayr and Cassie arc models) following a great deal of work on arc modelling carried out by CIGRE WG 13.01. One of the challenges in the development of (fast) black box arc model was due to very different time scales of the physical processes during arc quenching. The modelling concept is based in the division of the whole interruption process into the periods of “slow” or “fast” phenomena prevailing. In the slow period, the interaction between arc and circuit is essentially weak and the current is imposed by the circuit. In the slow period, physical conditions (pressure rise, arc temperature, etc.) are set to determine the initial conditions for the fast period. In the fast period, some tens of microseconds before current zero, the interaction between arc and circuit is strong and time constants are small. Obviously, it has been assumed that the outcome of short circuit current interruption depends only on the energy balance inside the contact gap. Additionally, the third sub-model, for the intermediate processes, was introduced to the composite black box arc model, Figure 3.

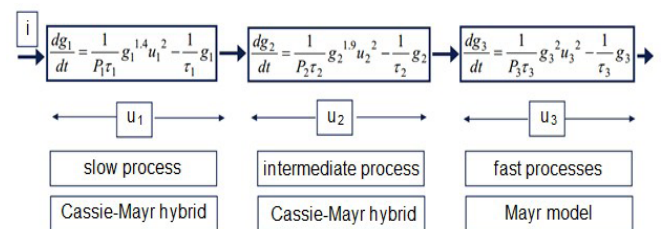


Figure 3: KEMA composite black box arc model ( $i$  – current,  $g_1, g_2, g_3$  – partial arc conductivity,  $u_1 + u_2 + u_3$  – arc voltage) [20]

KEMA black box arc model has 6 parameters: 3 time constants and 3 constants related to the cooling power.

Research [20] has shown that there are 3 free parameters ( $\tau_1$ ,  $P_1$  and  $P_2$ ), and the rest are calculated by using other three constants ( $k_1$ ,  $k_2$  and  $k_3$ ) which represent circuit breaker design:

$$k_1 = \frac{\tau_1}{\tau_2}; k_2 = \frac{\tau_2}{\tau_3}; k_3 = \frac{P_2}{P_3} \quad (1)$$

The values of the free parameters (as well for the design parameters) are evaluated from current zero measurement data by software in a way that simulation results are matched to the measured ones.

#### Calculation method for the black box arc model parameters

The drawback of estimation of the breaking capability based on evaluated parameters of the black box arc model is that any design change requires additional testing with current zero measurement before it is possible to estimate the circuit breaker breaking capability. The method for the estimation of the breaking capability used in this research [16] overcomes this drawback by using a proven correlation between black box and physical arc model [8], [12]. In this case parameters of black box arc model are calculated from the characteristic quantities at current zero.

Based on the proven correlation between the measured value of the arc extinction voltage peak and simulated values of the pressure of SF6 gas inside heating chamber and the distance between arcing contacts at current zero, papers [8], [12] proposed a relation for calculation of the value of arc extinction voltage peak:

$$u_{peak} = a_1 \cdot l_a^\alpha \cdot p^\beta + a_2 \cdot p^{\beta+1} + a_3 \quad (2)$$

where:  $u_{peak}$  – arc extinction voltage peak (kV),  $l_a$  – distance between arcing contacts at current zero (m),  $p$  – pressure inside heating chamber at current zero (MPa),  $a_1$  – coefficient, represents circuit breaker design, defines voltage of the arc between contacts (kV/m $^\alpha$ /MPa $^\beta$ ),  $a_2$  – coefficient, represents circuit breaker design, defines increment of the voltage from its elongation due to gas flow (kV/MPa $^{\beta+1}$ ),  $a_3$  – cathode and anode voltage drop (kV),  $\alpha$ ,  $\beta$  – empirical coefficients.

Papers [8], [12] also proposed relations for the calculation of free parameters of the black box arc model (same symbols as in Figure 3):

Table I: Coefficients for calculation of black box arc parameters

Coefficients	$a_1$	$a_2$	$a_3$	$\alpha$	$\beta$	$b_1$	$b_2$	$c_1$	$c_2$	$d_1$	$\gamma$
circuit breaker from [8, 12]	66	0.19	0.07	2	0.4	800	-500	0.06	0.1	0.0105	1.5
subject circuit breaker	100	0.5	0.07	2	0.5	800	-500	0.06	0.045	0.0105	1.5

$$P_1 = b_1 \cdot u_{peak} + b_2 \quad (3)$$

$$\tau_1 = \frac{c_1}{l_a - c_2} \quad (4)$$

$$P_2 = d_1 \cdot P_1 \cdot \tau_1^\gamma \quad (5)$$

where:  $b_1$  – coefficient ((A $^{i-1}$ V $^{3-i}$ )/kV),  $b_2$  – coefficient (A $^{1-i}$ V $^{i-3}$ ),  $c_1$  – coefficient (m·s),  $c_2$  – coefficient (m),  $d_1$  – coefficient (1/s $^\gamma$ ),  $\gamma$  – coefficient.

In order to use upper relations for calculation of black box arc parameters in this research it was necessary to prove strong correlation between measured values of the arc extinction voltage peak and simulated values of the pressure of SF6 gas inside heating chamber at current zero for subject circuit breaker, Figure 4. Current zero measurement were carried out on the subject circuit breaker during two development test (short line fault L90) in high power laboratory KEMA.

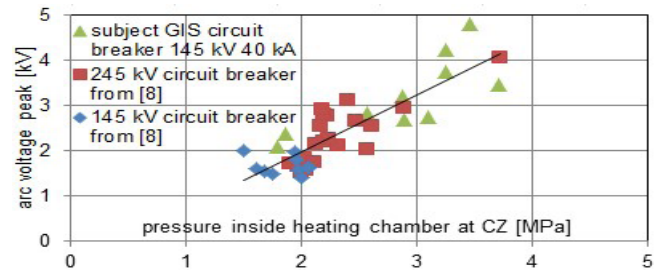


Figure 4: Correlation: measured arc extinction voltage peak – simulated pressure of SF6 gas inside heating chamber at current zero (CZ)

Figure 4 shows the correlation between measured values of the arc extinction voltage peak and simulated values of the pressure of SF6 gas inside heating chamber at current zero for the subject circuit breaker and two circuit breakers from [8]. Correlation is practically the same for all three breakers (Pearson's coefficient of correlation 0.86 for entire data set, assumptions of linear regression were tested prior to the calculation of Pearson's coefficient of correlation). Therefore, it is possible to use relations (2) – (5) for the calculation of the black box arc parameters for the subject circuit breaker. The empirical coefficients needed in these relations were found by matching simulation results with measured ones. The comparison between these empirical coefficients for subject circuit breaker and two breakers from [8] is given in Table I.

Test circuit model

The current circuit is not part of the Matlab Simulink model of the test circuit. The symbols on the simulation model of the voltage circuit (Figure 5) are the same as in KEMA test report and it is simple to find the values of those parameters. Parameters of artificial line are calculated from artificial line data given also in the test report.

KEMA uses this simulation model for the analysis of current zero measurement data. Parameters of black box arc model are evaluated from those measurement data, and simulation model from Figure 5 is used to find the limit value of arc current derivation near current zero  $SL$  in terms of short circuit current interruption. Hence, it is possible to determine safe margin in breaking capability ( $SL > S$ ) or how far the circuit breaker is from success ( $SL < S$ ).  $S$  is current derivation near current zero defined by circuit breaker ratings.

Validation of simulation results

Table II gives the comparison between simulation and the test results in the outcome of the short circuit current interruption (in the region of thermal breakdown) for the subject circuit breaker (145 kV 40 kA GIS) [18]. Table II also reveals good match between measured values of arc extinction voltage peak and simulated ones (with calculated parameters of black box arc model). Arc extinction voltage peak is also a powerful performance indicator regarding the breaking capability.

Figure 6 shows comparison in  $S/SL$  value from KEMA (evaluated parameters of black box arc model) and when parameters were calculated from characteristic quantities. Both ways show very similar trend revealing that in some shots test object was on the limit of its performance ( $S/SL \approx 1$ ). Observing the simulation results carefully, it can be concluded that in order to clear the current in the conditions of short line fault L90 following must be achieved: arc conductivity 200 ns before current zero lower than 1 mS and  $SL$  larger than  $S$  by 3-4 A/ $\mu$ s (in order to minimize the effect of the stochastic nature of the arc on estimated breaking capability).

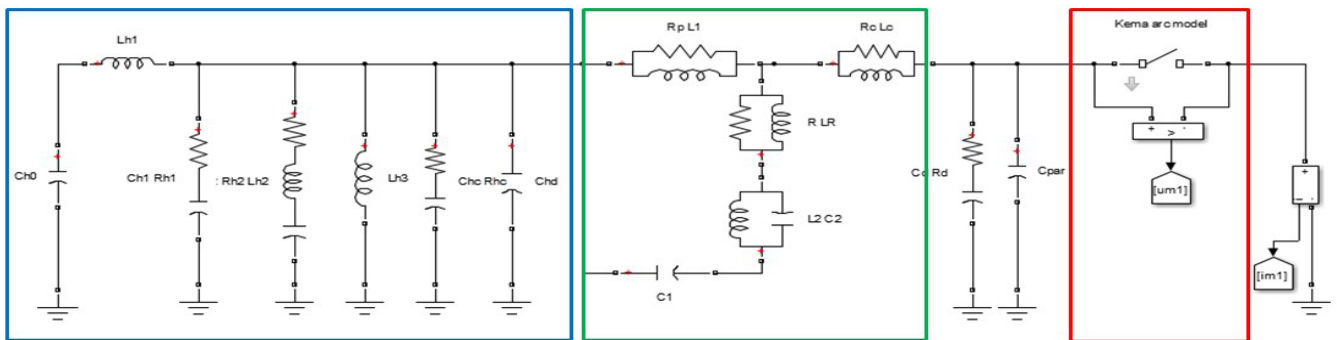


Figure 5: Matlab Simulink model of KEMA test circuit for short line fault (blue – voltage circuit, green – artificial line, red – test object, circuit breaker)

Table II: Comparison between simulation (Sim) and test (Test) results (C – current cleared (no breakdown in thermal region), R – reignition (breakdown in thermal region))

Test No.	SC current (kA)	Arc duration (ms)	Arc extinction voltage peak (kV)		Arc conductivity 200 ns before CZ (mS) Sim	The outcome of SC current interruption		S/SL Sim
			Sim	Test		Sim	Test	
1	36	14.9	3.47	2.75	0.65	C	C	16/21.5
2	36.4	16.6	3.69	4.23	0.53	C	C	16/22.9
3	35.8	25.3	3.34	2.7	0.69	C	R	16/21.7
4	36.2	15.2	3.92	4.8	0.45	C	C	16/24.1
5	35.8	14.2	3.63	3.72	0.59	C	C	16/22.1
6	36	23.1	4.31	3.45	0.29	C	C	16/22.9
7	36	18.6	3.36	3.2	0.64	C	C	16/22.1
8	36	18.4	2.99	2.83	0.85	C	C	16/20.5
9	36	27.6	2.12	2.37	1.85	R	C	16/15.7
10	36	18.2	2.08	2.09	1.87	R	R	16/15.6

The simulation and test results match in 8 out of 10 cases in the outcome of short circuit current interruption. Looking into the  $S/SL$  value (Figure 6) according to both, simulation and test results, the test object was on the limit of its breaking performance in shot number 9 (from Table II). Having in mind the extraordinary complexity of the modelled process it can be stated that comparison between simulation and test results reveals a very good match. Therefore, the presented method could be used for the estimation of the breaking capability in case of the subject circuit breaker for minimum ambient temperature of  $-40^{\circ}\text{C}$ .

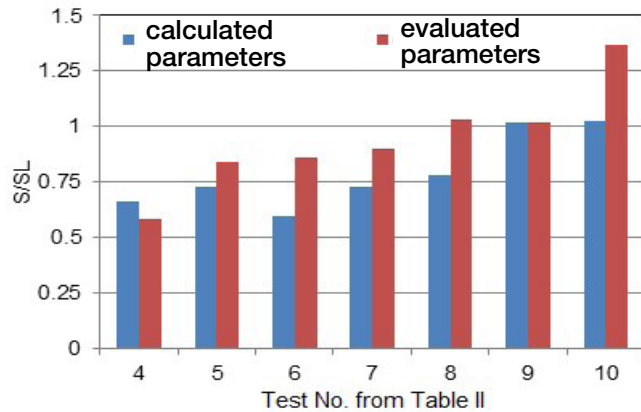


Figure 6:  $S/SL$  values from KEMA (evaluated parameters of black box arc model) and when parameters were calculated from characteristic quantities, tests no. 4-10 from Table II

## 2. ESTIMATION OF THE BREAKING CAPABILITY OF 123 KV 40 KA 50 HZ CIRCUIT BREAKER FOR MINIMUM AMBIENT TEMPERATURE OF $-40^{\circ}\text{C}$ FOR SHORT LINE FAULT L90 CONDITIONS

All simulations take into consideration the calibration by the high power laboratory (O with half short circuit current and O – CO with half short circuit current prior to the max-

imum arcing time shot). Also, simulations were performed in sequence according to [5] in order to preserve the correlation between breaking capability and the wear of the nozzle and arcing contacts.

Table III gives the simulation results (HV CB Simulation) in characteristic quantities at current zero for the starting variant of interrupter unit (filling pressure 0.45 MPa, 123 kV 40 kA, live tank circuit breaker).

Minimum arcing time (shot number 1 from Table III) was optimistically assumed (\*) since empirical criteria was not fulfilled (but is very close). This value of minimum arcing time was preserved in this case because Matlab simulation results (Table IV) reveal positive outcome (current cleared), but with narrow safe margin. According to the HV CB Simulation results, starting variant is not able to clear minimum arcing time (shot number 4 from Table III) in given conditions.

Further, the parameters of black box arc model were calculated from characteristic quantities at current zero (Table III) and Matlab simulations were performed with simulation model given in Figure 5. Table IV gives Matlab simulation results in short time interval around current zero for L90 conditions (these simulations are not applied in case nozzle throat is clogged by pin contact).

Simulation shows high arc conductivity 200 ns before current zero and very narrow safe margin ( $S/SL$ ) for minimum arcing time (shot number 1 from Table IV). As said before, it is possible this variant has longer minimum arcing time than assumed. Similar applies for medium arcing time (shot number 4 from Table IV) and having in mind stochastic nature of the arc it is not likely this variant is able to clear the current in given conditions. Hence, starting

Table III: Characteristic quantities for the starting variant for short line fault L90 50 Hz conditions (red – below the empirical criteria, C – current cleared (no breakdown in thermal region), R – reignition (breakdown in thermal region))

Test No	SC current (kA)	Arc duration (ms)	Arcing contact distance at CZ (mm)	Pressure inside heating chamber at CZ (MPa)	Gas flow cross-section ( $\text{mm}^2$ )	The outcome of SC current interruption
1	36	13	67.23	2.76	511	C (*)
2	36	12	62.7	2.39	368	R
3	36	22	75.36	3.05	672	C
4	36	17.5	75.35	2.52	695	R

Table IV: Matlab simulation results for the starting variant for short line fault L90 50 Hz conditions

Test No	SC current (kA)	Arc duration (ms)	Arc extinction voltage peak (kV)	Arc conductivity 200 ns before CZ (mS)	$S/SL$	The outcome of SC current interruption	
1	36	13	2.9	1.38	16/16.5	C	
2	36	12	closed-in arc				R
3	36	22	3.4	0.78	16/20.2	C	
4	36	17.5	2.8	1.21	16/17.5	C	

variant does not satisfy the referent values (arc conductivity 200 ns before current zero lower than 1 mS and SL larger than S by 3-4 A/μs).

Therefore, the design and setting changes are suggested. The new, enhanced variant of subject circuit breaker has 15% longer nozzle throat and longer contact travel and higher opening speed, both by 5%. Table V gives the simulation results (HV CB Simulation) in characteristic quantities at current zero for the enhanced variant of interrupter unit (and circuit breaker). Strictly, this variant also does not fulfil empirical criteria for medium arcing time. It

has been assumed that longer arcing contact distance will compensate lower pressure inside heating chamber (\*\*). Matlab simulation results (Table VI) are the argument for this assumption.

The Matlab simulation results (Table VI) reveal that the enhanced variant satisfies the referent values and it has been assumed this variant will pass the test (test duty L90). The prototype of 123 kV 40 kA live tank circuit breaker (for minimum ambient temperature of -40 °C) was built based on enhanced variant and prepared for type test (short line fault L90).

Table V: Characteristic quantities for the enhanced variant for short line fault L90 50 Hz conditions (red – below the empirical criteria, C – current cleared (no breakdown in thermal region), R – reignition (breakdown in thermal region))

Test No	SC current (kA)	Arc duration (ms)	Arcing contact distance at CZ (mm)	Pressure inside heating chamber at CZ (MPa)	Gas flow cross-section (mm <sup>2</sup> )	The outcome of SC current interruption
1	36	13	71.39	2.9	511	C
2	36	12	66.44	2.54	368	R
3	36	22	81.28	3.18	672	C
4	36	17.5	81.09	2.62	695	C (**)

Table VI: Matlab simulation results for the enhanced variant for short line fault L90 50 Hz conditions

Test No	SC current (kA)	Arc duration (ms)	Arc extinction voltage peak (kV)	Arc conductivity 200 ns before CZ (mS)	S/SL	The outcome of SC current interruption	
1	36	13	3.1	1.04	16/18.1	C	
2	36	12	closed-in arc				R
3	36	22	3.7	0.55	16/22.7	C	
4	36	17.5	3.1	0.89	16/19.7	C	

### 3. SHORT LINE FAULT L90 50 HZ TEST RESULTS FOR 123 KV 40 KA CIRCUIT BREAKER FOR MINIMUM AMBIENT TEMPERATURE OF -40 °C

The 123 kV 40 kA 50 Hz live tank (enhanced variant) was subjected to type testing (test duty short line fault L90). In accordance to [5], circuit breaker (Figure 7a) passed short line fault L90 test. The ratings of subject circuit breaker are given in Figure 7b. Figure 8 shows the oscillogram (O – CO sequence) for the maximum arc duration test (short circuit current 35.7 kA, arc duration 23.8 ms). Current zero measurements were also carried out during this test shift. Current zero measure-

ment results in case of maximum arc duration are also given in Figure 8.

Test results, including current zero measurements, are summarized in Table VII. Table VII contains also the comparison of measured and simulated arc extinction voltage peak. Test results showed that minimum arcing time was longer than estimated. The reason is the early dielectric reignition in shot number 1 from Table VII (1.7 μs after current zero at 12.2 kV of transient recovery voltage), Figure 9. Therefore, shot number 1 in Table VII was marked as “C” (no reignition in thermal region). Figure 9 shows the comparison between simulation and test results in short time interval around current zero for shot number 1, Table VII.

Table VII: Test (Test) and Matlab simulation (Sim) results for enhanced variant for short line fault L90 50 Hz conditions

Test No	SC current (kA)	Arc duration (ms)	Arc extinction voltage peak (kV)		Arc conductivity 200 ns before CZ (mS) - Sim	The outcome of SC current interruption Sim/Test
			Sim	Test		
1	36.6	13.7	3.3	3.1	0.84	C/C (***)
2	36.7	14.9	3.6	3.1	0.52	C/C
3	36.6	23.8	3.6	4	0.58	C/C
4	36.7	19	3.1	3.2	0.85	C/C



a)

Ratings/characteristics of the object tested

Voltage	123 kV
Normal current	2500 A
Number of poles	3
Frequency	50/60 Hz (1)
Operating sequence	O-0,3 s-CO-3 min-CO
Short-time withstand current	40 kA
Peak withstand current	104 kA
Duration of short-circuit	3 s
Short-circuit making current	104 kA
Short-circuit breaking current	40 kA
DC time constant of rated short-circuit current	45 ms
DC component	46 %
First-pole-to-clear factor	1,3/1,5
Pressure for interruption and insulation SF <sub>6</sub> at 20 °C	0,51 MPa
Supply voltage of closing and opening devices	220 Vd.c.
Class	C2, E2, M2

b)

Figure 7: a) Circuit breaker prototype (enhanced variant) during type test in high power laboratory KEMA; b) circuit breaker ratings [21]

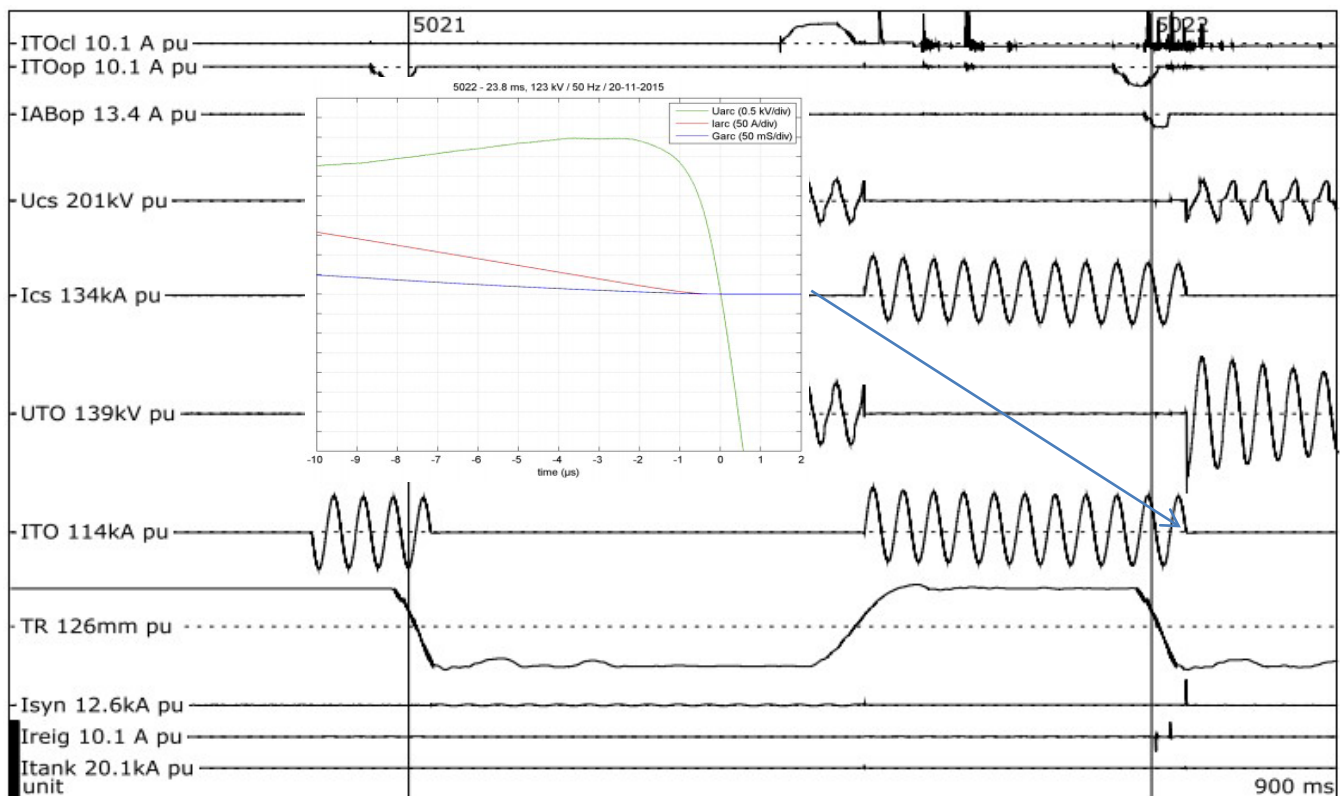
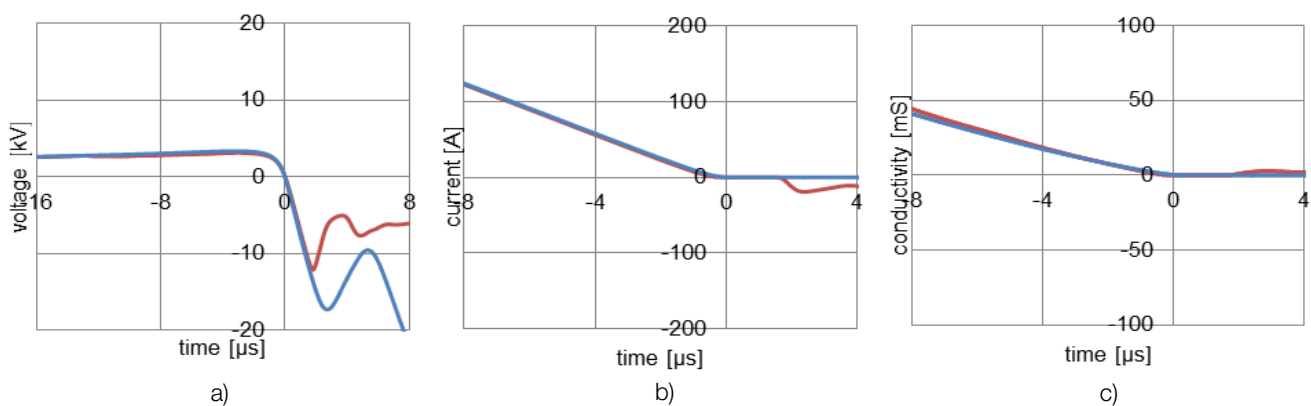


Figure 8: Oscillogram of maximum arc duration (O - CO sequence) [21]



a)

b)

c)

Figure 9: Comparison between simulation (blue) and current zero measurement results (red) for shot number 1 from Table VII; a) arc voltage; b) arc current; c) arc conductivity

Current zero measurement results clearly show the sudden drop (to the level of arc voltage) in the early stage of transient recovery voltage (early dielectrical reignition). Simulation results have no drop in the voltage (arc voltage turns in to transient recovery voltage) since region of dielectric breakdown was not modelled.

Taking everything into the account, and especially the data given in Tables VI and VII, it can be concluded that estimated breaking capability of subject circuit breaker was consistent with subsequent test results.

#### 4. CONCLUSION

This paper presents the results obtained during research and development of high voltage live tank circuit breaker 123 kV 40 kA 50 Hz for minimum ambient temperature of  $-40\text{ }^{\circ}\text{C}$  (minimum pressure for insulation and for the interruption at  $20\text{ }^{\circ}\text{C}$  – 0.45 MPa). It is evident that lower rated filling pressure will reduce pressure rise inside heating chamber during arc quenching process, thus it will reduce the breaking capability of circuit breaker. Hence, breaking capability of the circuit breaker with rated filling pressure of 0.45 MPa (filling pressure required for for minimum ambient temperature of  $-40\text{ }^{\circ}\text{C}$ ) must be proven once more, even though it is already proven for the same interrupter unit with filling pressure of 0.65 MPa. The focus of research was test duty L90 according to IEC 62271-100, which is considered as highly challenging for modern SF6 circuit breakers. It has been estimated that the starting variant of circuit breaker has no required breaking capability. By using presented method for estimation of breaking capability the enhanced variant of circuit breaker was defined. The circuit breaker prototype was built based on the enhanced variant and type tested (short line fault L90) in high power laboratory KEMA in accordance with IEC 62271-100. The circuit breaker passed the test, i.e. circuit breaker has demonstrated required breaking capability.

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