Analysis of transient recovery voltage on SF_6 circuit breakers when switching unloaded 400 kV transmission lines

Božidar Filipović-Grčić, Ivo Uglešić, Srećko Bojić

***Abstract*—This paper presents analysis of transient recovery voltage (TRV) on SF_6 circuit breakers (CBs) when switching unloaded 400 kV transmission lines. On site testing of circuit breakers was performed when switching unloaded 400 kV transmission lines. Switching was performed with and without grading capacitors connected in parallel to CB breaking chambers. Simulations were conducted in EMTP-RV software [1] and calculation results were compared to on-site measurements.**

***Index Terms*— SF_6 circuit breaker, transient recovery voltage, EMTV-RV simulations, unloaded 400 kV transmission line, on site testing.**

I. Introduction

When an unloaded line is regularly switched-off the electric arc distinguishing occurs at current natural zero-crossing. Voltage on the line side remain highest in the phase which is firstly switched-off due to the electromagnetic coupling of the other phases and due to Ferranti effect. In case when capacitor voltage transformers are installed on both sides of the line the discharging of trapped charge is slow. Such discharging depends on weather conditions, mainly on humidity. So, the trapped charge has a very significant influence on CB transient recovery voltage.

Besides the peak value of TRV the voltage distribution between breaking chambers is very important for CB dielectric stresses during switching operations. In case when CB is not equipped with grading capacitors pretty unequal voltage distribution between breaking chambers occurs and this in some cases may lead to CB failure. The voltage distribution between the breaking chambers could be improved by installing the grading capacitors, which are especially important in cases when switching-off relatively long lines.

This paper presents analysis of transient recovery voltage TRV on SF_6 CBs when switching unloaded 400 kV transmission lines. On-site measurements on two switching configurations in transmission network were performed in order to verify the performance of CBs with and without grading capacitors. Measurements were compared to calculations results obtained from the model developed in EMTP-RV software.

II. Modeling of Test Configurations in EMTP-RV

Figs. 1 and 2 show test configurations 1 and 2.

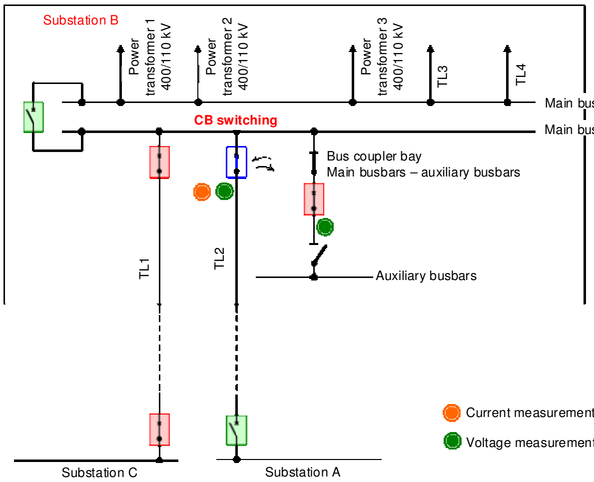

Fig. 1. Test configuration 1: Testing of circuit breaker in 400 kV line bay TL2 when switching unloaded transmission line TL2

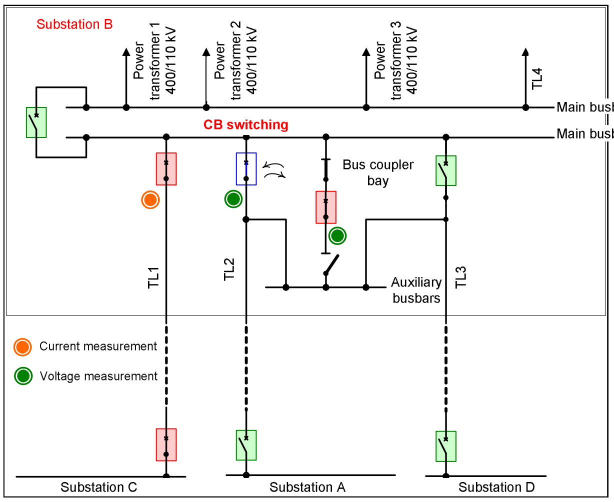

Fig. 2. Configuration 2: Testing of circuit breaker in 400 kV line bay TL2 when switching unloaded transmission lines TL2 and TL3

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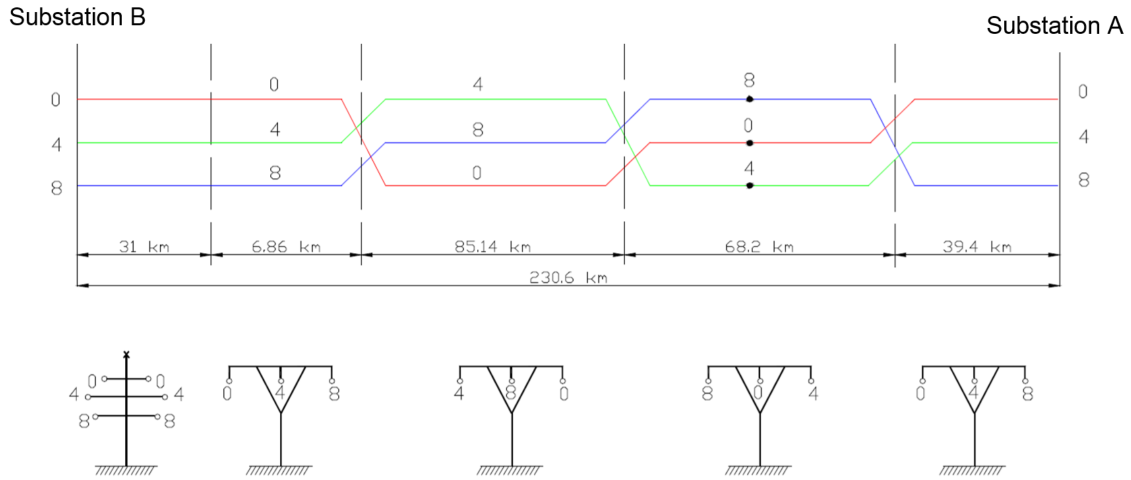

Fig. 3. Transpositions on 400 kV transmission line TL2

The simulation model includes the 400 kV substations and connected transmission lines shown in Figs. 1 and 2. The equipment in high voltage substation was represented by surge capacitances, whereas transmission lines, busbars and connecting leads by a frequency depending model [2, 3]. Phase conductors ACSR 490/65 mm^2 are bundled and consist of 2 sub-conductors separated by a distance of 0.4 m. Lengths of the transmission lines: TL1 62 km; TL2 230 km; TL3 and TL4 (double-circuit transmission line) 167,8 km. The phase transpositions of the transmission line TL2 have been taken into account (Fig. 3). Towers of the transmission line TL1 are shown in Fig 4.

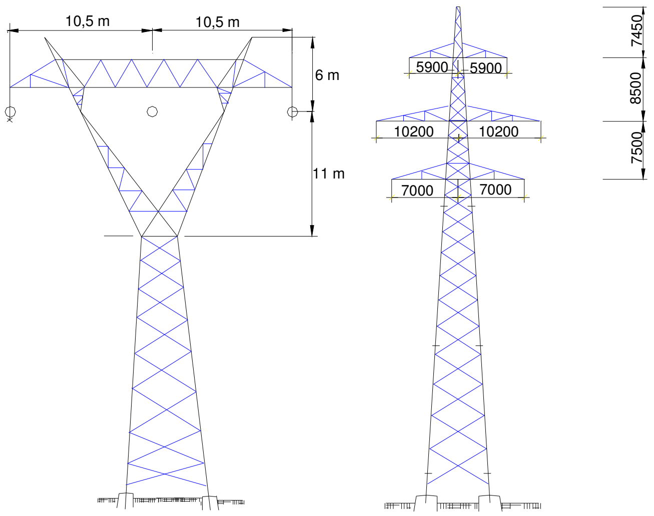

Fig. 4. Towers of the transmission line TL1

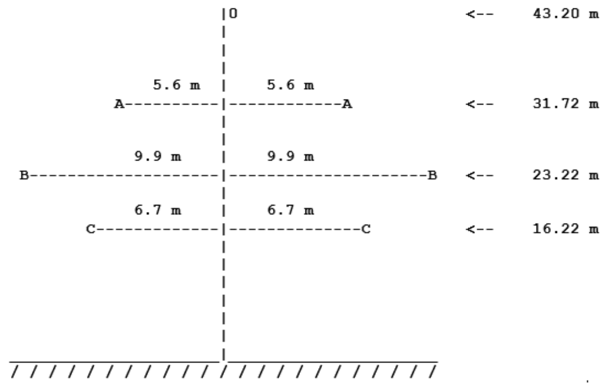

Fig. 5. Position of conductors at towers and their average heights (first section of transmission line 97.798 km)

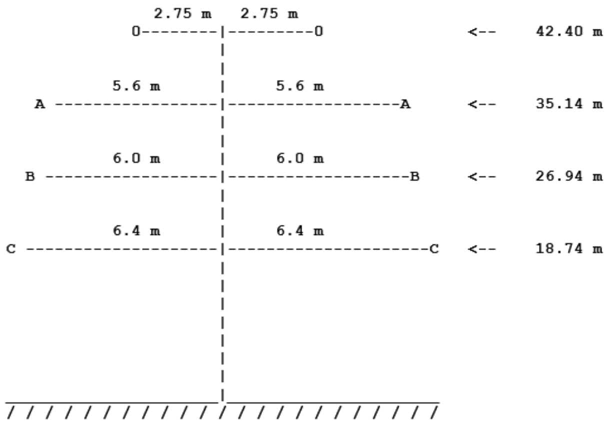

Fig. 6. Position of conductors at towers and their average heights (second section of transmission line 69.972 km)

The position of conductors at towers and their average heights for double-circuit transmission line (TL3 and TL4) are shown in Figs. 5 and 6. The model of CB with two breaking chambers is shown in Fig. 7. The capacitance between the open contacts of breaking chambers is 10 pF and inherent earth capacitances were taken into account as depicted in Fig. 7. Busbars in 400 kV substations are made of aluminum alloy E-AlMgSi 0.5 F 22. Outside pipe diameter is 220 mm and internal diameter is 204 mm.

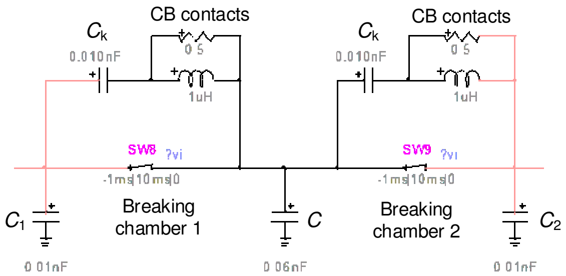

Fig. 7. Model of SF_6 circuit breaker with two braking chambers

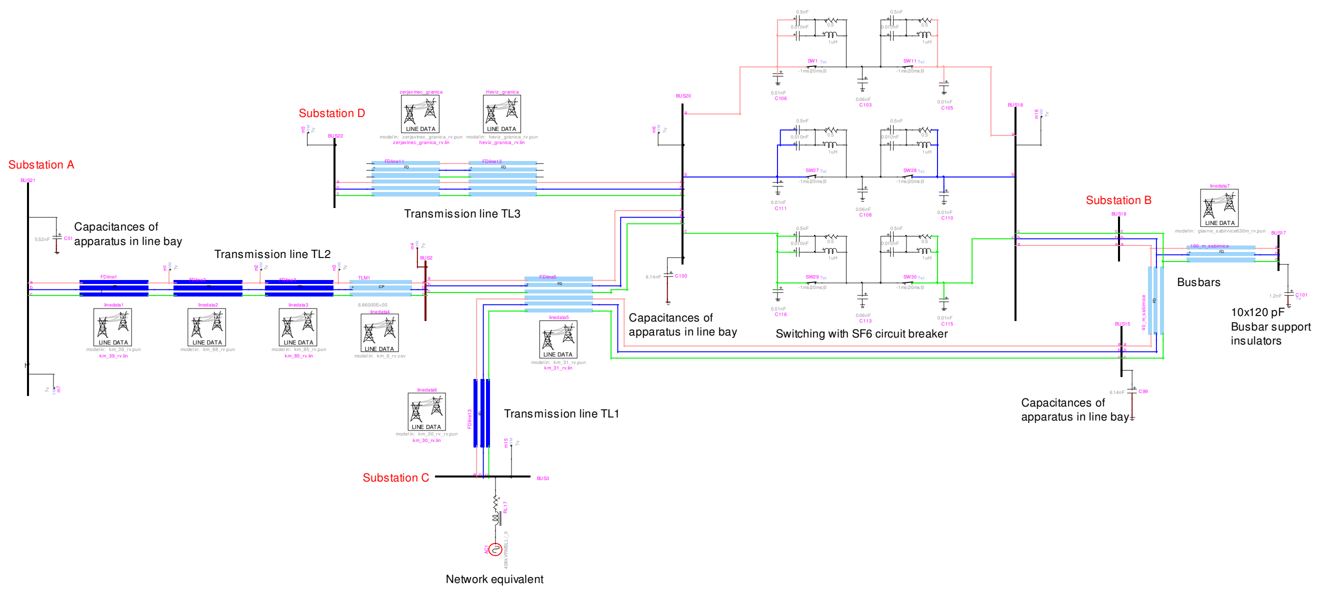

Fig. 8. EMTP-RV model of the of 400 kV transmission network

The equipment in high voltage substation was represented by the following capacitances to ground [2]: current transformers 680 pF, capacitive voltage transformers 4400 pF, inductive voltage transformers 550 pF, disconnectors 200 pF, circuit breakers 60 pF, busbar support insulators 120 pF, power transformers 2700 pF. During the testing both switching configurations were supplied from the 400 kV substation C with connected two transmission lines and power transformer 400/110 kV. The equivalent networks were represented with a voltage source in series with sequences impedances, which are obtained from short circuit currents for the analyzed switching configurations. EMTP-RV model of the of 400 kV transmission network is shown in Fig. 8.

A. *Test configuration 1*

Testing of circuit breaker in 400 kV line bay TL2 was performed when switching unloaded 230 km transmission line TL2. Currents and voltages were measured in substation B at TL2 bay and voltages were measured at bus coupler bay. Capacitive voltage transformers are installed at both ends of transmission line TL2. During the testing both switching configurations were supplied from the 400 kV substation C with connected two transmission lines and power transformer 400/110 kV. Tables 1 and 2 show calculation results and measurements (RMS values) in stationary state after energization of transmission line TL2.

Switching off unloaded transmission line TL2 was analyzed in EMTP-RV. When an unloaded line is regularly switched-off electric arc extinguishes at current natural zero-crossing [3]. Opening of CB contacts was simulated at t=20 ms and electric arc extinguishes when capacitive currents reach zero-crossing point in all three phases (Fig. 9). Trapped charge remains on the line side after opening of CB (Fig. 10). The voltage is highest in the phase C which is firstly switched-off due to the electromagnetic coupling of the other phases [4, 5]. TRV on CB is shown in Fig 11, while distribution of TRV across the breaking chambers is shown in Fig. 12.

Table 1. Measurements (RMS values) in stationary state after energization of transmission line TL2

Phase	U_{rms} at substation B	I_{rms} at substation B	U_{rms} at substation A
A	427 kV	214 A	443,7 kV
B	428 kV		
C	427 kV		

Table 2. Calculation results (RMS values) in stationary state after energization of transmission line TL2

Phase	U_{rms} at substation B	I_{rms} at substation B	U_{rms} at substation A
A	429,1 kV	205,1 A	442,5 kV
B	429,1 kV	206,3 A	442,4 kV
C	429,3 kV	207,4 A	442,2 kV

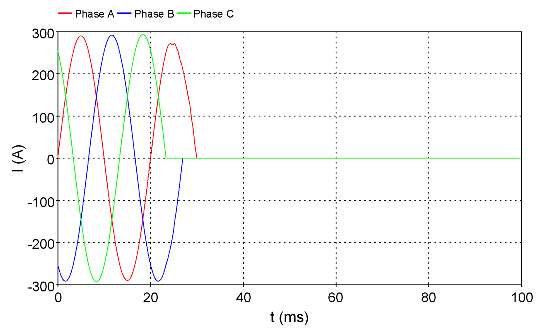

Fig. 9. Currents when switching off unloaded transmission line TL2

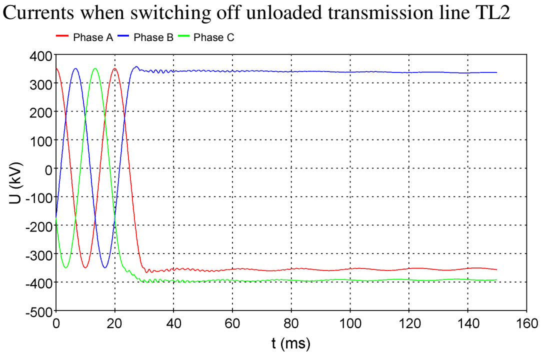

Fig. 10. Voltages on the line side in substation B

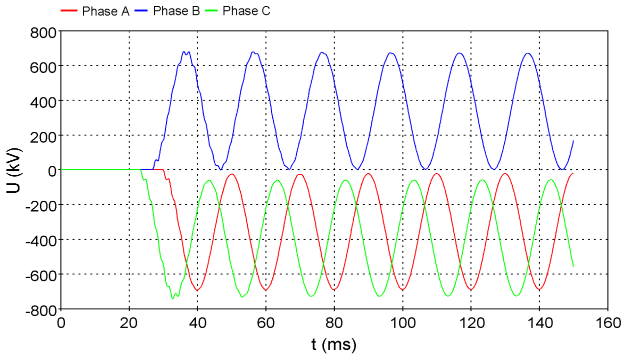

Fig. 11. TRV on CB without grading capacitors

Besides the peak value of TRV the voltage distribution between breaking chambers is very important for CB dielectric stresses during switching operations. Fig. 12 shows distribution of TRV across breaking chambers in case without grading capacitors.

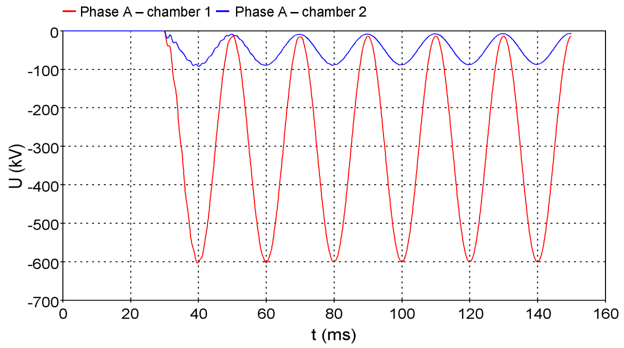

Fig. 12. Distribution of TRV across breaking chambers in phase A (without grading capacitors)

Simulation results show pretty unequal voltage distribution between breaking chambers. The greatest part of TRV stresses the breaking chamber 1 closer to the substation. Calculation results show the following distribution of TRV peak values across breaking chambers in phase A: 603,7/92,9 kV, (86,7/13,3 %). Further analyses show the influence of 500 pF grading capacitors on voltage distribution between breaking chambers. Total TRV on CB remains the same as in the case without grading capacitors, while significant improvement of voltage distribution and reduction of TRV amplitude across the breaking chambers is achieved (Fig. 13).

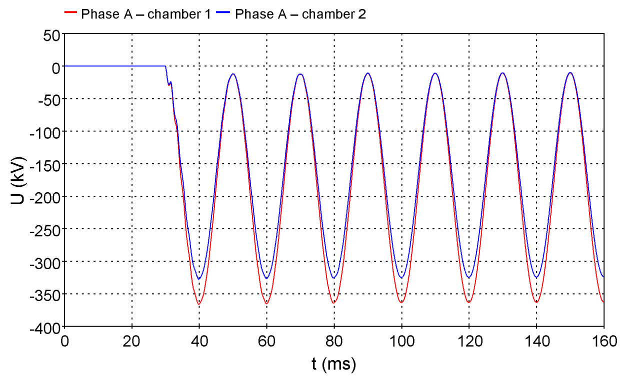

Fig. 13. Distribution of TRV across breaking chambers in phase A (with grading capacitors)

The following distribution of TRV peak values across breaking chambers in phase A is obtained: 366,5/327,8 kV, (52,8/47,2 %). Simulations were also performed in case of grading capacitors 1600 pF and 2000 pF and in each case maximum rate of rise of recovery voltage (RRRV) was determined. Calculation results are shown in Table 3.

Table 3. Comparison between calculation results and measurements of TRV on CBs in substation B after switching off unloaded transmission line TL2

Phase	TRV amplitude on breaking chamber 1 closer to substation (kV)	TRV amplitude on breaking chamber 2 closer to transmission line (kV)	TRV amplitude on CB (kV)	Maximum RRRV on CB (kV/μs)
Without installed grading capacitors				
A	603,7	92,9	694,3	0,1203
B	603,9	79,4	682,0	0,1280
C	613,4	131,4	744,6	0,1342
With installed grading capacitors 500 pF				
A	366,5	327,8	694,2	0,1197
B	360,8	321,2	682,1	0,1231
C	390,5	354,1	744,7	0,1244
With installed grading capacitors 1600 pF				
A	353,4	340,8	694,2	0,1203
B	347,5	334,6	682,2	0,1324
C	378,3	366,5	744,8	0,1376
With installed grading capacitors 2000 pF				
A	352,1	342,0	694,2	0,1183
B	346,3	335,9	682,2	0,1240
C	377,2	367,7	744,8	0,1084

Table 4 shows comparison between calculation results and measurements of TRV on CBs in substation B after switching off unloaded transmission line TL2.

Table 4. Comparison between calculation results and measurements of TRV amplitude on CBs after switching off TL2

Phase	Measurement		Calculation results	
	Without grading capacitors	With grading capacitors 500 pF	Without grading capacitors	With grading capacitors 500 pF
A	699,4	700,3	694,3	694,2
B	671,0	673,4	682,0	682,1
C	717,8	719,7	744,6	744,7

Tables 5 and 6 show comparison of voltage amplitudes from the both sides of CBs (line side and substation side). Measurements were carried out in case without grading capacitors and with 500 pF grading capacitors.

Table 5. Comparison between calculation results and measurements of voltage amplitudes at 400 kV busbars in substation B after switching off TL2

Phase	Measurement		Calculation results	
	Without grading capacitors	With grading capacitors 500 pF	Without grading capacitors	With grading capacitors 500 pF
A	358,7	358,0	351,1	351,1
B	352,2	351,9	352,4	352,4
C	347,0	346,0	350,5	350,5

Table 6. Comparison between calculation results and measurements of voltage amplitudes at 400 kV line bay in substation B after switching off TL2

Phase	Measurement		Calculation results	
	Without grading capacitors	With grading capacitors 500 pF	Without grading capacitors	With grading capacitors 500 pF
A	358,0	356,0	367,6	367,6
B	349,2	347,9	357,6	357,6
C	385,8	386,4	402,3	402,2

B. *Test configuration 2*

Testing of circuit breaker in 400 kV line bay TL2 was performed when switching unloaded transmission lines TL2 (230 km) and TL3 (167,8 km). Beginning and end of the transmission line TL3 was disconnected from all other apparatus in line bays including inductive voltage transformers. Capacitive voltage transformers are installed at both ends of transmission line TL2. During the testing substation B was supplied from the 400 kV substation C with connected two transmission lines and power transformer 400/110 kV. Tables 7 and 8 show the comparison of calculation results and measurements (RMS values) in stationary state after energization of transmission lines TL2 and TL3.

Table 7. Measurements after energization of transmission lines TL2 and TL3

Phase	U_{rms} at substation B	I_{rms} at substation B	U_{rms} at substation A/C
A	434 kV	386 A	451,5 kV/ 422,6 kV
B	436 kV		
C	435 kV		

Table 8. Calculation results after energization of transmission lines TL2 and TL3

Phase	U_{rms} at substation B	I_{rms} at substation B	U_{rms} at substation A/C
A	438,2 kV	360 A	451,8 kV/ 422,9 kV
B	438,4 kV	376 A	452,0 kV/ 423,6 kV
C	438,9 kV	368,4 A	451,6 kV/ 423,2 kV

Simulations were performed in case of grading capacitors 1600 pF and 2000 pF and in each case maximum rate of rise of recovery voltage (RRRV) was determined. Calculation results are shown in Table 9.

Table 10 shows comparison between calculations and measurements of TRV amplitude on CBs in substation B after switching off unloaded transmission lines TL2 and TL3. Tables 11 and 12 show comparison of voltage amplitudes from the both sides of CBs (line side and substation side). Measurements were carried out for two cases: without grading capacitors and with 500 pF grading capacitors.

Table 9. Comparison between calculation results and measurements of TRV on CBs in substation B after switching off unloaded transmission lines TL2 and TL3

Phase	TRV amplitude on breaking chamber 1 closer to substation (kV)	TRV amplitude on breaking chamber 2 closer to transmission line (kV)	TRV amplitude on CB (kV)	Maximum RRRV on CB (kV/μs)
Without installed grading capacitors				
A	618,6	94,4	712,9	0,1367
B	611,6	73,8	685,3	0,1761
C	628,5	122,9	751,0	0,1746
With installed grading capacitors 500 pF				
A	376,2	336,7	712,9	0,1323
B	363,0	322,4	685,3	0,1683
C	394,6	356,4	751,1	0,1828
With installed grading capacitors 1600 pF				
A	362,9	350,0	712,9	0,1045
B	349,3	336,1	685,4	0,1253
C	381,8	369,4	751,2	0,1455
With installed grading capacitors 2000 pF				
A	361,6	351,3	712,9	0,1075
B	348,0	337,4	685,4	0,1391
C	380,6	370,6	751,1	0,1573

Table 10. Comparison between calculation results and measurements of TRV amplitude on CBs after switching off unloaded transmission lines TL2 and TL3

Phase	Measurement		Calculation results	
	Without grading capacitors	With grading capacitors 500 pF	Without grading capacitors	With grading capacitors 500 pF
A	706,7	696,3	712,9	712,9
B	672,4	676,1	685,3	685,3
C	730,1	722,2	751,0	751,1

Table 11. Comparison between calculation results and measurements of voltage amplitudes at 400 kV busbars in substation B after switching off unloaded transmission lines TL2 and TL3

Phase	Measurement		Calculation results	
	Without grading capacitors	With grading capacitors 500 pF	Without grading capacitors	With grading capacitors 500 pF
A	368,8	369,5	359,4	359,4
B	362,9	358,5	362,3	362,3
C	357,7	355,5	358,3	358,3

Table 12. Comparison between calculation results and measurements of voltage amplitudes at 400 kV line bay in substation B after switching off unloaded transmission lines TL2 and TL3

Phase	Measurement		Calculation results	
	Without grading capacitors	With grading capacitors 500 pF	Without grading capacitors	With grading capacitors 500 pF
A	365,4	369,1	370,4	370,4
B	355,7	353,5	362,3	362,3
C	396,6	391,7	397,8	397,8

III. Conclusion

On site testing of circuit breakers was performed when switching unloaded 400 kV transmission lines. Switching was performed with and without grading capacitors connected in parallel to CB breaking chambers. Simulations were conducted in EMTP-RV software and calculation results were compared to on-site measurements.

The calculation results give slightly higher TRV amplitudes compared to measurements (maximum difference 20 kV). This is acceptable and expected, since the electric arc resistance was not taken into account in simulations. Moreover, measurement circuit introduces certain attenuation and distortion of the recorded voltage waveforms.

Significant improvement of voltage distribution and reduction of TRV amplitude across the breaking chambers is achieved with application of grading capacitors.

Similar calculation procedure could be performed prior to on site testing in order to assess the level of switching overvoltages in transmission network.

IV. Acknowledgment

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References

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