Transient Recovery Voltage Investigation on HV Circuit Breaker in Hydro Power Plant

Bozidar Filipovic-Grcic, Nina Stipetic, Franjo Vukovic, Ante Jerkovic, Miso Sanic

***Abstract*—Transient Recovery Voltage (TRV) analysis is a type of electromagnetic study that proves if the circuit breaker (CB) can withstand switching transients. Switching transients' incidence and severeness is determined by surrounding electrical system, hence special locations of CB installation require more attention. This paper shows TRV calculations on a CB that is placed at HV terminals of a step-up transformer in a hydro power plant. Since there is no classical generator CB placed on the MV terminals of the step-up transformer, the breaker placed on the HV terminals is used for synchronizations to the grid. The requirements for HV CB placed in such locations are given in IEC 62271-100, where it is stated that proximity of a generator is regarded as a special case.**

For TRV analysis, the CB and surrounding network were modeled in EMT-like software. TRVs are calculated for terminal faults, short-line faults, capacitive current and out-of-phase switching. Power-frequency voltage stress and arc influence on the short-circuit DC component are discussed. Due to the exceeded TRV envelopes and lack of their definition for out-of-phase switching, a CB of a higher voltage level is recommended for installation in the case study considered in this paper.

***Keywords*: generator circuit-breaker, high-voltage circuit breaker, out-of-phase switching, transient recovery voltage**

I. Introduction

Circuit breakers (CBs) are often chosen based on the required short-circuit breaking capability. However, each contact opening results in transient recovery voltage (TRV) that can have deleterious effect on a CB, even when interrupting currents lower than rated short-circuit current. The TRV manifests in different ways, depending on the surrounding circuit configuration. It is advisable to give importance to TRV studies, especially when CB is placed at specific locations. For example, requirements imposed on generator CBs differ from other transmission and distribution CBs. Among other technical requirements, generator CB needs to withstand fault currents and TRVs related to out-of-phase conditions that can occur more often because of numerous grid synchronizations. The CB intended for grid synchronizations can be located at the MV or at the HV side of a step-up transformer, as depicted in Fig. 1. The breaking currents and TRV ratings are given in IEEE/IEC 62271-37-013 [1] for generator circuit-breakers with rated voltages up to 38 kV, while IEC 62271-100 [2] covers requirements for high voltage circuit breakers.

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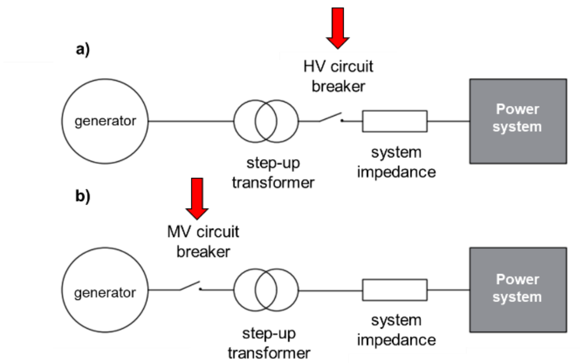

Fig. 1. Possible locations for circuit-breakers used for grid synchronizations

A. TRVs in power systems

There are many aspects of TRV that need to be perceived. When breaking a capacitive current, the TRV oscillations are practically absent as large capacitance suppresses the oscillatory frequency, and the rate of rise of the TRV is low. When breaking an inductive current, the capacitance of the disconnected side is low and the frequency of the isolated circuit is high, therefore the TRV is oscillatory. Breaking a short-line fault (SLF) produces a very steep initial rate of rise because of the high-frequency oscillation of the line-side terminal, which is in some cases a limiting factor of the breaker. On the other hand, the TRV related to SLF close to gas insulated stations (GIS) can be neglected. Terminal faults lead to the maximal short-circuit current, because there is no fault current damping by line impedance, but then the TRVs are the lower. The steepest rates of rise of the TRV occur when breaking a fault beyond transformers and reactors that are connected to a system of high short-circuit power. In all cases, the TRV refers to the voltage across the first pole to clear since it is generally the highest. The interrupting capability of the CB is related to TRV and the envelopes that define the withstand boundaries are defined in [1]-[2] depending on the rated voltage, fault-current amplitude, and fault type. In the literature [3] it was recognized that standard TRV ratings are not adequate for all applications. If the specified TRV envelope is exceeded in any application, a different circuit breaker should be used, or mitigation methods should be applied [4],[5]. These are all reasons why TRV studies and calculations are important, especially in configurations that are known to cause hefty TRVs and when the reliability of the equipment is critical to system operation. In [6], a sensitivity analysis was done in the initial phase of the electrical system design, to acknowledge the TRV influential parameters and determine the mitigation methods if needed. In [7], a TRV study was done for a CB on a very long (half-wavelength) UHV transmission line. It was shown that TRV parameters for faults along the line differ from the cases on normal lines and that surge arresters along the line greatly reduce the TRV. In [8] it was shown how grading capacitors connected in parallel to CB terminals greatly increase the interrupting capability in SLF conditions.

B. CBs located close to generators

CBs located close to generators have additional aspects that contribute to their stress [9]-[14]. Because of the generator vicinity, the DC time constant of the fault current can be high, causing prolonged first zero crossing or high degree of asymmetry at contact separation. Additionally, these CBs are used for synchronization. During the synchronization, the CB experiences additional voltage stress across the open contacts, especially when the grid side voltage is already very high, potentially exceeding the maximal permissible operating voltage. If the out-of-phase synchronization occurs, the CB must have the capability to interrupt the out-of-phase current. The out-of-phase synchronization can occur due to wiring errors, which leads to out-of-phase angles of 60° or its multiples; polarity errors which cause synchronising at 180° out-of-phase angle; or settings error/malfunction of the synchronising equipment which leads to any value of the out-of-phase angle [9]. The defined envelopes for out-of-phase conditions given in [1] and [2] do not adequately cover all CB applications. For out-of-phase switching, only one envelope is defined, based on an out-of-phase angle of 90° el. – in [1] it is based on breaking 50 %, and in [2] as 25 % of the rated short-circuit breaking current. The need for re-evaluation and re-definition of the requirements for the out-of-phase switching is already recognized and discussed in [11]-[14]. Because of these reasons, failures and explosions of CBs close to generators are often reported [15].

II. Case Study – TRV calculations on generator CB placed at HV side of a step-up transformer

A case study is caried out on an example of a CB placed close to a 14.4 kV, 140 MVA salient pole generator in a hydro power plant (HPP). The generator is connected to a 14.4/242 kV step-up transformer. At the HV side, there is a cable connection to 245 kV GIS, where a SF_6 CB is placed together with other HV switching and measuring equipment and surge arresters. At the other GIS terminal, there is again cable connection to a 12.5 km long 220 kV overhead line (OHL) (Fig. 2).

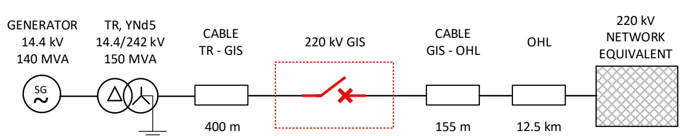

Fig. 2. Equivalent scheme of considered case study for analyzing TRV

A. Modeling of main system components

Since the TRV is high-frequency phenomena, the available data should be used to build the best suitable model for higher frequency range (~ 10 kHz [4]). The salient pole generator is modelled using the synchronous machine model available in EMT-like software, with added capacitances 0,672 μF of stator windings to ground. The appropriate transformer model for TRV studies is discussed in [16]-[18]. In this study, a BCTRAN model extended with interwinding capacitances and capacitances to ground was used, since no frequency measurement or geometry data was available for developing more complex and accurate black-box or a grey-box models. In [19], it was shown that the extended BCTRAN model is accurate for frequencies up to 10 kHz or even higher when the transformer geometry is not complex. The frequency of the single-frequency TRVs due to terminal faults range from 20 to 10000 Hz [5], while for double-frequency TRVs due to faults on the line it can be higher. The HV equipment inside GIS were modeled as concentrated capacitances with busbars in-between represented as distributed transmission line with surge impedance of 60 Ω. The surge arresters integrated at both entrances to GIS were modeled using *U-I* characteristic and added capacitance to ground. The 220 kV network equivalent was modeled as voltage source behind short-circuit impedances. Cables and OHL are modelled using a frequency-dependent models. The data used for modelling are given in the Appendix I.

The 245 kV, 50 kA CB was modeled using a special breaker for TRV studies, which is available in EMT software. This model is convenient for TRV studies since it calculates and plots the TRV envelopes automatically. The IEC or IEEE envelopes can be readily used as well as constructed, user defined curves. Depending on the real fault current to be interrupted in the network, two- or four-parameter envelopes are plotted, and the interpolation is used to calculate the exact parameters, based on 100 %, 60 %, 30 % and 10 % of rated short-circuit CB capability (I_{SC}) curves defined in standards. The model of electric arc is normally neglected in TRV studies [13], since the parameters of TRV prospective curves defined in the standards are obtained based on ideal circuit breaker without the arc influence [20]. Table I gives maximum values and steepnesses of envelopes for the mentioned percentages of I_{SC}, as well as the maximum values and steepnesses for terminal fault, SLF (interrupting 100 % I_{SC}) and out-of-phase breaking (interrupting 25 % I_{SC}) from [2].

TABLE I
Standard TRV envelope magnitude and steepness [2]

Test	u_c [kV]	u_1/t_1 [kV/μs]	Amplitude [kV]	Rate-of-rise [kV/μs]
	245 kV		420 kV	
Terminal fault	364	2	624	2
SLF	280	2	480	2
Out-of-phase	500	1.54	854	1.54
Values based on SC current to be interrupted				
T100, 100 % I_{SC}	364	2	624	2
T60, 60 % I_{SC}	390	3	669	3
T30, 30 % I_{SC}	400	5	687	5
T10, 10 % I_{SC}	459	7	787	7

From Table I it can be seen that for lower currents to be interrupted, the higher TRV magnitudes and steepnesses are allowed.

III. SIMULATION RESULTS

Simulations of out-of-phase switching, three-phase faults, SLF and breaking a capacitive current of the unloaded overhead line are carried out. The power frequency voltage stress during synchronization is discussed. Additionally, the influence of arc on reducing the short-circuit DC component is shown.

A. *Out-of-phase switching*

Interrupting the out-of-phase current is simulated for 30°, 60°, 90°, 120° and 180° out-of-phase angles. The simulation results are given in Table II.

TABLE II
OUT-OF-PHASE SIMULATION RESULTS

$\Delta\varphi$	I [kA]	TRV amplitude [kV]	TRV rate-of-rise [kV/µs]
180°	4.22	660.92	3.05
120°	3.66	642.71	2.96
90°	2.99	614.73	2.50
60°	2.11	526.14	1.99
30°	1.09	361.34	0.09

The interrupted currents are in range from 1 kA to 4.5 kA for the chosen out-of-phase angles. In [2], only one envelope is defined, based on 25 % of the rated short-circuit breaking current. According to Table I, for 245 kV, 50 kA CB, the only requirement on TRV is having an amplitude lower than 500 kV and steepness lower than 1.54 kV/µs when breaking 12.5 kA at 105° out-of-phase angle. In the case considered in this paper, the maximum out-of-phase current is 4.22 kA, and TRV amplitudes and slopes are exceeding the permitted values in all cases except when the out-of-phase angle is 30°. The network and generator voltages and the TRVs for out-of-phase angle of 30° and 180° are shown in Fig. 3.

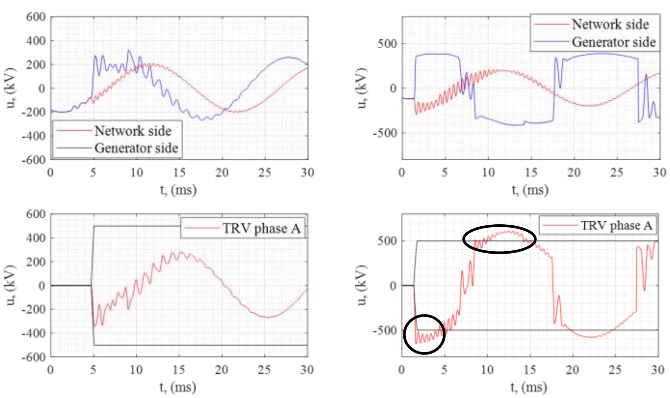

Fig. 3. Network and generator side voltages and TRVs when performing out-of-phase switching at angle 30° (left) and 180° (right)

B. *Three-phase faults*

To check the TRV due to terminal fault, a three-phase faults, grounded and ungrounded, are simulated at CB terminals. Since the GIS is single-phase encapsulated, it is impossible that an ungrounded three-phase fault occurs at CB terminals, and even at the GIS terminals it is highly unlikely. However, to check the TRV, 3 simultaneous single-phase to-ground faults are simulated at the CB terminals and an ungrounded fault on GIS terminals. Additionally, the fault is simulated at the cable-OHL transition point at the 155 m distance from the CB, since it can be the "weak" point. The results are given in Table III.

TABLE III
THREE-PHASE-FAULTS SIMULATION RESULTS

Phase	TRV amplitude [kV]	TRV rate-of-rise [kV/µs]
Faults at CB terminals on the network side, I_{SC} = 2.65 kA		
Phase A	401.00	1.60
Phase B	413.16	1.88
Phase C	463.18	1.64
Faults at CB terminals on the generator side, I_{SC} = 9.88 kA		
Phase A	330.88	1.64
Phase B	317.47	1.43
Phase C	333.50	1.61
Fault on the OHL, 155 m distance, I_{SC} = 2.64 kA		
Phase A	401.00	1.60
Phase B	413.19	1.88
Phase C	463.55	1.64

For the faults that occur at the network side, the short current is around 2.6 kA. Since that is lower than 10 % of the rated I_{sc}, the envelope T10 is considered, with 459 kV amplitude. This envelope is exceeded in one phase for the fault at the CB terminals and at the cable-OHL transition point. The simulation results for faults at CB terminals are given in Fig. 4 and Fig. 5. The flat part of TRV in Fig. 4 is an indication of surge arrester operation. Fig. 6 shows the results for a fault at the network side, but without surge arresters integrated in GIS. It can be seen how arresters greatly reduce the TRV.

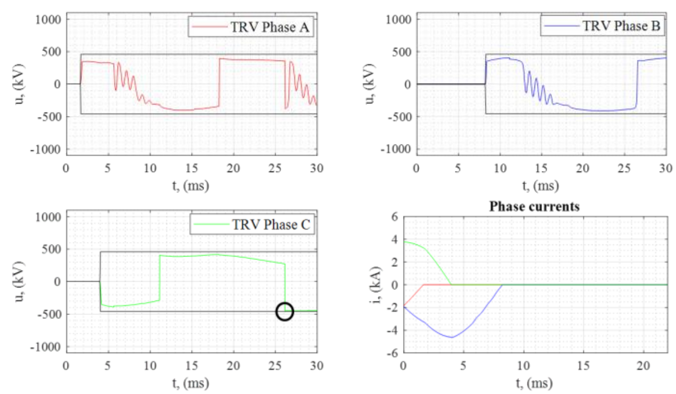

Fig. 4. Results for 3 single-phase terminal faults at the network side

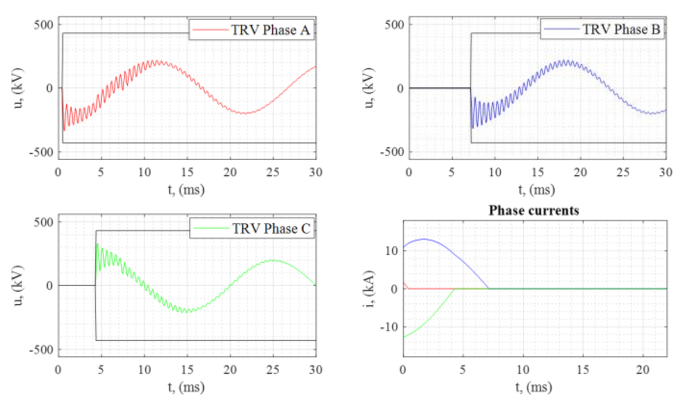

Fig. 5. Results for 3 single-phase terminal faults at the generator side

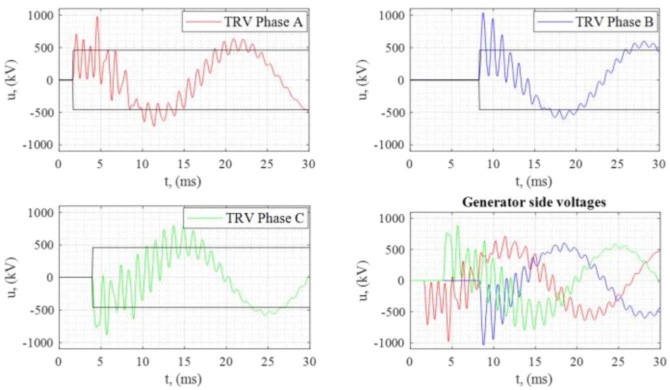

Fig. 6. Results for 3 single-phase terminal faults at the network side without surge arresters

Ungrounded three-phase faults are also simulated at GIS terminals and on OHL. Such type of fault could theoretically occur e.g., after maintenance or measurements due to human errors, when phases remain short circuited before the re-commissioning. An ungrounded three-phase fault on the generator side caused TRV exceeding the envelopes in two phases. The simulation results are shown in Fig. 7.

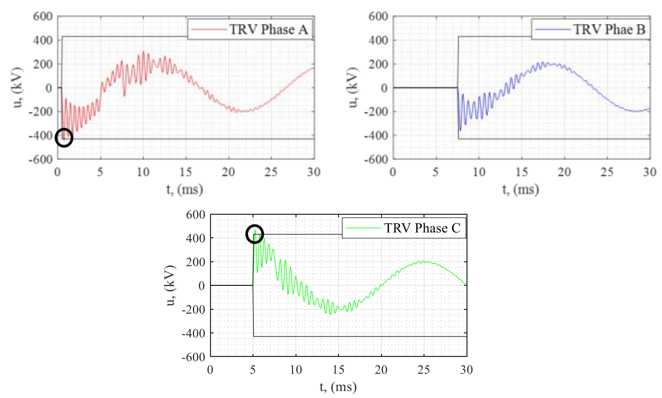

Fig. 7. Results for ungrounded three-phase fault on the generator side

C. *Short-line-fault*

The single-phase fault in proximity of the CB is a SLF. When a SLF occurs at a critical distance of a few kilometers from the CB, the initial rate of rise of the TRV (ITRV) can be very high. This phenomenon is known to be critical for CB operation for AIS-OHL connection. The ITRV is proportional to the busbar surge impedance and the current. Since in GIS the surge impedance is low compared to AIS, no critical rate-of-rise is expected. The ITRV in case of the fault at the cable-OHL connection, 155 m away from the CB is shown in Fig. 8.

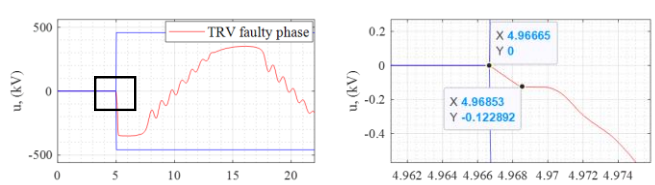

Fig. 8. TRV and the zoom of ITRV in case of SLF at the cable-OHL connection point

The ITRV and its characteristic saw tooth waveform is not pronounced in the considered case. The steepness of ITRV from Fig. 8 is equal to 0.065 kV/µs. The short-circuit current to be interrupted and the TRV amplitude for different distances from the CB are given in Fig. 9.

The SLF in this configuration is not critical. Aside from low GIS surge impedance, the TRV is additionally attenuated by the cable capacitance. The same conclusion applies for single-phase faults on the generator side (CB terminal, GIS terminal and HV side of the step-up transformer).

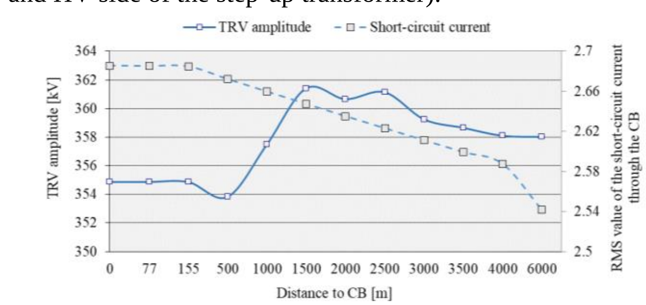

Fig. 9. TRV amplitude and short-circuit current to be interrupted at different fault distances from CB

D. *Capacitive current interruption*

Interrupting a capacitive current in the considered configuration can occur when switching off unloaded OHL. It can happen e.g. due to faults, when the other side of the OHL has already tripped. There are several capacitive current switching test types and cycles defined in [2]. Tests with specified TRV are defined by parameters u_c, u_1, t_1 and t_2 shown in Fig. 10. As it is highlighted, there is a characteristic voltage bump in the initial part of the recovery voltage.

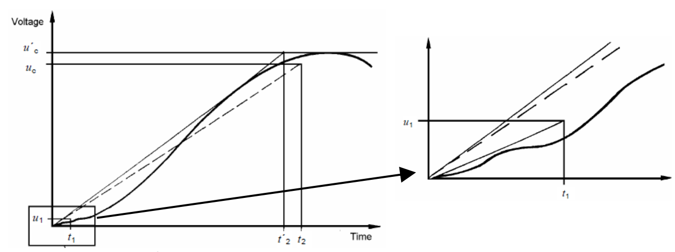

Fig. 10. TRV for capacitive current breaking tests, parameters u_c, u_1, t_1 and t_2 given in [2]

The prospective TRV should remain below the line from the origin to the point defined by u_1 and t_1, and the amplitude of the actual TRV should not exceed the test voltage of the corresponding single-phase direct test (1-cos curve) by more than 6 %. In this case the capacitive current of the unloaded cable and OHL equals 9.8 A. According to simulation results, the TRV remains under the defined line from the origin to the u_1, t_1 point in all phases. The simulation results are given in Fig 11 and Table IV.

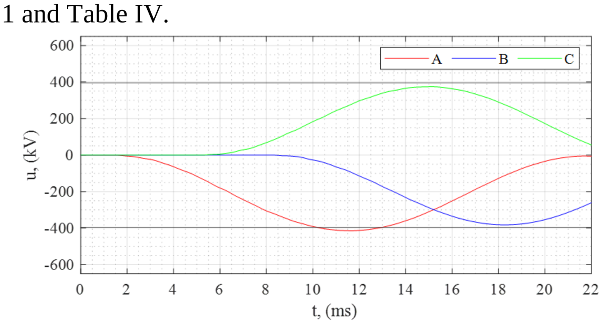

Fig. 11. TRV when breaking capacitive current of the unloaded OHL

TABLE IV
CAPACITIVE CURRENT BREAKING SIMULATION RESULTS

Phase	TRV amplitude [kV]	TRV rate-of-rise [kV/μs]
A	414.90	0.0597
B	383.11	0.0566
C	374.16	0.0574

E. Dielectric stress of CB during generator synchronization

The dielectric stress in the area between the CB contacts depends on their geometry and distance (electric field on contact tips) and the dielectric strength of the gas in the chamber. During the synchronization, CBs experience additional dielectric stress across open contacts, which can cause dielectric breakdown, especially in case of relatively long duration synchronizations and an increased number of synchronizations during the CB lifetime. An average number of grid synchronizations in large accumulation HPPs in Croatia can be 130 per year, depending on HPP operating regime. The synchronization in some cases can last up to 140 s, which leads to 5 hours of additional voltage stress per year, or 200 hours in a 40-year lifetime. The AC voltage stress for the open contact of CB in this case study can reach 312 kV, when high voltages in the network and out-of-phase condition are met.

For a 245 kV CB, 460 kV is used for the initial 1-min power-frequency voltage test. However, the standard does not cover the open contact test with AC voltage test on both terminals for 245 kV CBs, which would simulate the synchronization conditions. If a 245 kV CB would be chosen for the location in this case study, additional tests proofing the reliability of the dielectric strength of the inter-contact area during synchronization is recommended to be requested (i.e. voltage at CB terminals of 312 kV, 50 % voltage on the generator side, 50% of the voltage on the network side, voltages in the opposite phase, duration 200 h).

In terms of dielectric strength, a CB with rated voltage of 420 kV would have a significantly higher dielectric reserve. The 420 kV CBs are tested using 1-min power-frequency voltage test of 520 kV between phases and between phase-to-ground. Additionally, 1-min power-frequency voltage test is done with 610 kV across open contacts, using the opposite-phase voltages on both terminals, providing the out-of-phase conditions (IEC 62271-1, point 6.2.5.2). The maximum out-of-phase voltage stress in this case study equals 51 % of the test voltage between the contacts.

Aside from power-frequency voltage stress, during the synchronization, the switching or lightning overvoltages may occur and superimpose to the AC voltage on the line side terminal. In terms of switching and lightning impulses, the 420 kV again has the advantage and greater dielectric reserve. It has to withstand the 900 kV standard switching surge on one terminal while AC voltage of 345 kV is on the other terminal, and 1425 kV standard lightning surge on one terminal while AC voltage of 240 kV is on the other terminal. In practice, the dielectric breakdown across the open contacts due to superimposed overvoltages will depend on surge arrester characteristic and location on the line side terminal of the CB. These combined tests are not defined in [2] for CBs of 245 kV rated voltage. For the particular case described in this paper, simulations of an extreme lightning strike of 200 kA close to the substation were done. The maximal voltage on the open contacts of a CB in case of lightning strike reaches 497 kV.

Considering the discussed dielectric stress, the recommendation from [2] can be applied to the CB from this case study. In [2] it is stated that CBs with rated voltage of 300 kV and above intended for use in synchronization operations simultaneously with a substantial transient or temporary overvoltage, the insulation of a standard CB may be insufficient. In such cases it is suggested to use a standard CB having a higher rated voltage or to use a special CB, increasing the severity of the open-contact tests. Due to the synchronizations at studied location, a CB with higher rated voltage would be a reasonable option to consider.

F. Influence of CB electric arc on short-circuit DC component attenuation

When faults occur in proximity of a generator, a demanding condition called “delayed current-zero crossing” can occur due to high *X*/*R* ratio of the circuit and the operating conditions of the generator. The longest duration to the first current-zero crossing is normally determined in short-circuit studies, where no electrical arc models are considered. However, in special cases where the total CB arcing time is critical, an electrical arc model should be used. To check the electric arc influence on the first current zero-crossing, an electrical arc is modeled based on Schwarz/Avdonin differential equation, using the constants acquired from arc voltage and current measurements on 245 kV, single-chamber SF_6 CB from [21]. The simulation result for interrupting a three-phase generator-fed fault is shown in Fig. 12. The dynamical variation of electric arc resistance additionally attenuates the short-circuit current and the first zero-crossing occurs 60 ms earlier when considering the arc model. This means that in real operating conditions electric arc resistance will reduce CB arcing time, which can be critical in some cases, especially in the case of high DC component of short-circuit current.

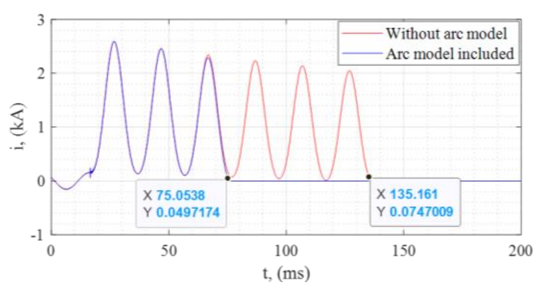

Fig. 12. Interrupting a short-circuit current in phase A. CB contact separation occurs at 60 ms. Current interrupted at 75 ms (arc included) and at 135 ms (without arc)

IV. CONCLUSIONS

Selecting an appropriate generator CB at HV side of step-up transformer requires a special attention, where a comprehensive TRV study should be made. This paper deals with TRV analysis in a case study where a HV CB is placed in the GIS connecting a HPP to the grid. The conducted analyses show that SF_6 CB with rated voltage of 245 kV does not satisfy the IEC standard requirements due to unallowed TRVs in cases of three-phase faults and out-out-phase switching for out-of-phase angles greater than 30°. Additional concerns are the power frequency voltage stress during the grid synchronizations and the combined voltage stress in case if a switching or lightning overvoltages occur during the open contact period. The IEC standard states that CBs intended for use in synchronization operations simultaneously with a substantial transient overvoltages, the insulation of a standard CB may be insufficient. In such cases, the standard recommends a CB of a higher rated voltage or special open contact tests with increased severity. A 420 kV CB would fulfill the TRV requirements in the analyzed case study. It was also shown how surge arresters reduce the TRV, hence the arresters' energy capability and residual voltage should be carefully selected. The procedure of choosing the CB regarding TRV stress cannot be generalized, since it is affected by the surrounding network configuration and surge arrester characteristic and location. The EMT simulations should be carried out to calculate the TRVs and compare the results with IEC/IEEE requirements.

The longest duration to the first current zero-crossing is normally determined in short-circuit studies. However, in critical configurations where DC component is high, the simulation to determine the longest CB arcing time should be done considering the dynamic model of electric arc. It was shown how arc resistance greatly reduces the arcing time.

V. Appendix

TABLE V

Data used for modelling the main network components

GIS data			
Cable connection	50 pF		
Surge arrester	200 pF, U_c=154 kV, U_r=192 kV, I_n=10 kA		
Circuit breaker	220 pF		
Earthing switch	45 pF		
Current transformer	40 pF		
Disconnector	70 pF		
Voltage transformer	100 pF		
Generator data			
S_n	140 MVA	No. of poles	20
cosφ	0.9	I'_{f0}	495 A
U_n	14.4 ± 5% kV	U_{fn}	276 V
I_{gn}	5613 ± 5% A	I_{fn}	994 A
R_n *at neutral point*	1660 Ω	*C stator winding to ground*	0.6717 µF/ph.
X_d	1.11 pu	X_0	0.15 pu
X_q	0.61 pu	X_2	0.25 pu
X_l	0.14 pu	T'_{do}	8.34 s
R_s	0.002631 Ω	T'_d	2.34 s
X'_d	1.11 pu	T''_{do}	0.146 s
X''_d	0.21 pu	T''_d	0.096 s
X''_q	0.30 pu	T''_{qo}	0.157 s
Transformer data			
S_n	150 MVA	$C_{HV\text{-}LV}$	2097 pF/ph.
U_{n1} / U_{n2}	242 / 14.4 kV	$C_{HV\text{-}N}$	1106 pF/ph.
I_{n1} / I_{n2}	357.9 / 5013 A	$C_{LV\text{-}N}$	5619 pF/ph.
connection	YNd5	$C_{HV\text{-}LV} + C_{HV\text{-}N}$	3204 pF/ph.
u_k	13.05 %	$C_{HV\text{-}LV} + C_{LV\text{-}N}$	7716 pF/ph.
P_{Cu}	441.61 kW		
P_{Fe}	57.27 kW		
i_m	0.059 %		

VI. References

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