Switching Transients in 400 kV Transmission Network due to Circuit Breaker Failure

S. Bojić, I. Uglešić, B. Filipović-Grčić

***Abstract*—The paper presents the case study of SF_6 circuit breaker failure during switching-off an unloaded and relative long 400 kV transmission line. Both breaking chambers of the circuit breaker were destroyed. Due to the specific place and type of fault the relay protection system did not operate during circuit breaker failure and transients have been recorded only by a power quality monitoring system installed in the nearby line bay. Recorded events were used for circuit breaker post-mortem analysis. Simulations and fault analysis were carried out using EMTP-RV software.**

***Keywords*: 400 kV circuit breaker failure, restrike, transient recovery voltage, switching**

I. INTRODUCTION

The severity of breaking conditions during de-energization of open-ended long transmission line may be such that it is these breaking conditions which dictate the size and type of the circuit-breaker (CB), in particular the selection of the number of breaking chambers. The major fact is that half a cycle after the interruption the CB must accept a voltage across its terminals at least equal to twice the peak value of the phase-to-ground voltage of the system prior to the interruption. Unfortunately, at the time of opening, it may happen that the phase-to-ground voltage of the pole which has to open has reached values much higher than the values stipulated in the standards for testing the CB in such interrupting conditions [1]-[2].

This dynamic voltage rise may be the result of a number of causes. In particular, the opening of a CB sited at the receiving end of a line transmitting a heavy load will leave the line open at its end. The voltage of the line increases owing to the sudden load interruption that is not immediately compensated by the voltage regulation and owing to the capacitive load of the transmission line (Ferranti effect), [3]. Consequently, the CB sited at the sending end may lead to the de-energization of the line while the phase-to ground voltage at the sending end has substantially exceeded the normal value.

These conditions are exceptional and it is quite normal that such situations are excluded from the verifications stipulated in the standards for line-charging current interruptions [4].

However, the fact that such situations may actually occur has made it necessary to check the ability of the CB to withstand such voltages. Such verifications are usually carried out on-site, despite of performed laboratory testing.

During de-energization of open-ended long transmission line CB interrupts capacitive current and transient recovery voltage (TRV) appears across the contacts. If TRV rate of rise is too steep or amplitude is too high, CB may restrike or re-ignite. Restrikes may repeat several times until the gap between the breaker contacts becomes sufficiently large so that its dielectric withstand exceeds the voltage across the breaker terminals. CB restrikes are an unwanted occurrence which can ultimately lead to breaker failure [5]-[6].

II. 400 kV Circuit Breaker Failure

The failure of the 400 kV SF_6 CB with a hydraulic operating mechanism has been investigated. The single-pole controlled CB contains two breaking chambers without grading capacitors added in parallel (Fig. 1). During exploitation in previous years, some initial problems were detected with its mechanical drive.

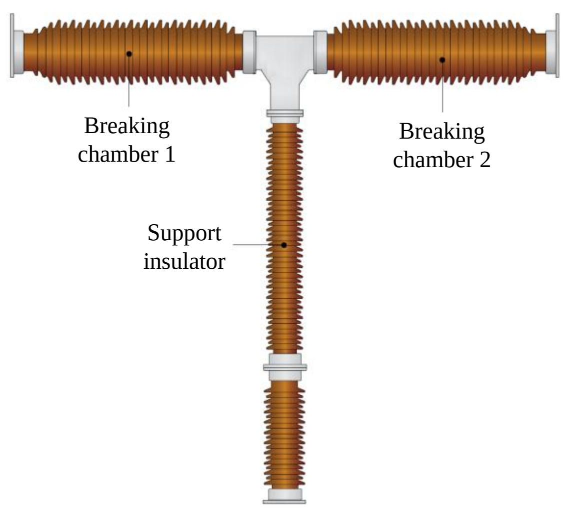

Fig. 1. 400 kV SF_6 circuit breaker with two breaking chambers

The CB fault happened during switching-off the 231 km long 400 kV unloaded single circuit line. Repetitive restrikes between CB contacts occurred which finally ended with the total damage of both breaking chambers.

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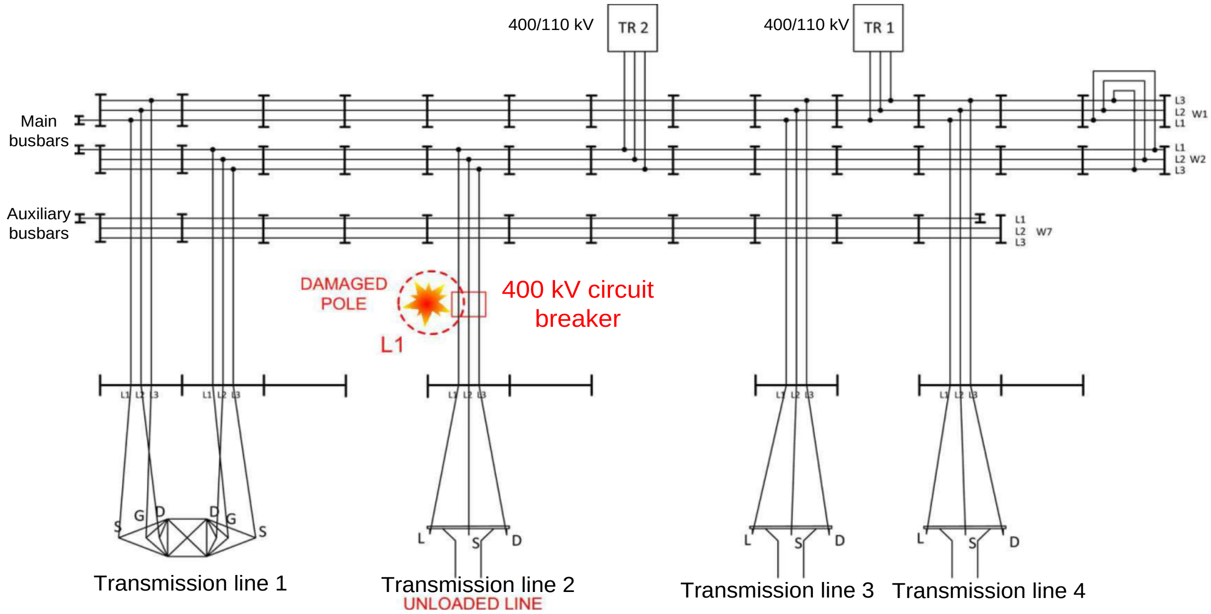

Fig. 2. Switching arrangement of transmission lines and power transformers in 400 kV switchyard

The switching arrangement of transmission lines and power transformers in 400 kV substation during the fault is shown in Fig 2. Fault transients have been recorded in line bay 2 with Wide Area Monitoring System (WAMS), (Fig.3a) and in neighbouring line bay 1 with the Power Quality Monitoring System (PQMS) connected to voltage and current transformers (Fig. 3b).

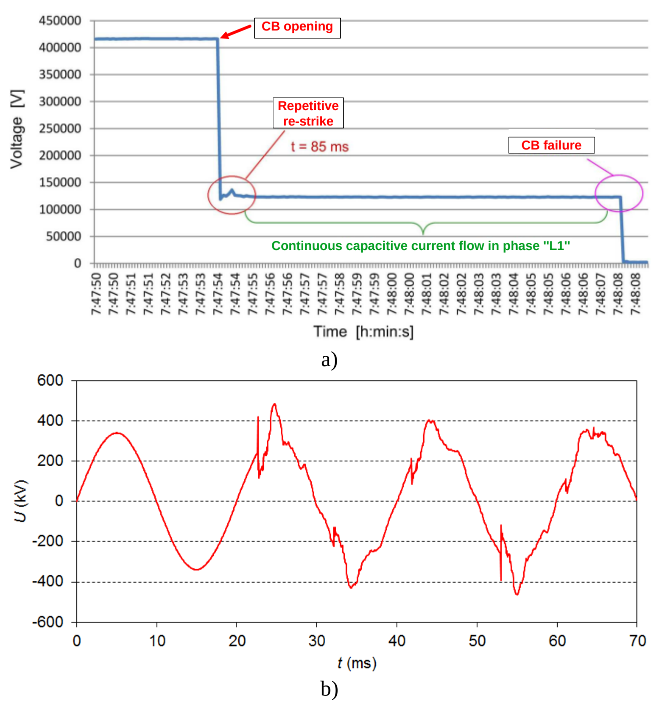

Fig. 3. a) WAMS record from the moment of CB opening up to failure; b) Transients recorded by PQMS during repetitive restrikes

WAMS are essentially based on the new data acquisition technology of phasor measurement and allow monitoring of transmission system conditions over large areas in view of detecting and further counteracting grid instabilities.

Current, voltage and frequency measurements are taken by Phasor Measurement Units (PMUs) at selected locations in the power system and stored in a data base. Measured quantities include both current and voltage magnitudes and phase angles which are time-synchronised via Global Positioning System (GPS) receivers with an accuracy of one microsecond. Additionally, Fig. 3 shows the line voltage condition (average sum of positive sequence phase-to-phase voltage) according to real time development of the fault during and after the CB opening. The CB successfully opened poles in phases L2 and L3 but not in phase L1.

During CB switch-off the repetitive restrikes occurred in phase L1 lasting 85 ms, followed by the appearance of the permanent electric arc lasting around 14 seconds. Since the single phase-to-ground fault had not occurred the relay protection system did not operate. During the permanent arc the capacitive current was approximately 150-200 A, leading to a gradual increase of the temperature and pressure of the SF_6 gas in breaking chambers, which resulted in the damaging of both breaking chambers.

Due to limited frequency response of the instrument transformers the recorded transients are damped. Its wave shape, duration and repetitiveness indicate repetitive restrike phenomena (Fig. 3 b). Recorded events were used for CB post-mortem analysis. In order to clarify the circumstances of the event, simulations and fault analysis were carried out using EMTP-RV software [7].

III. Modelling of 400 kV Substation and Transmission Lines

The simulation model includes the 400 kV substation and connected transmission lines. The 3 phase simulation model for computation and analyses of CB failure in EMTP-RV is depicted in Fig. 4.

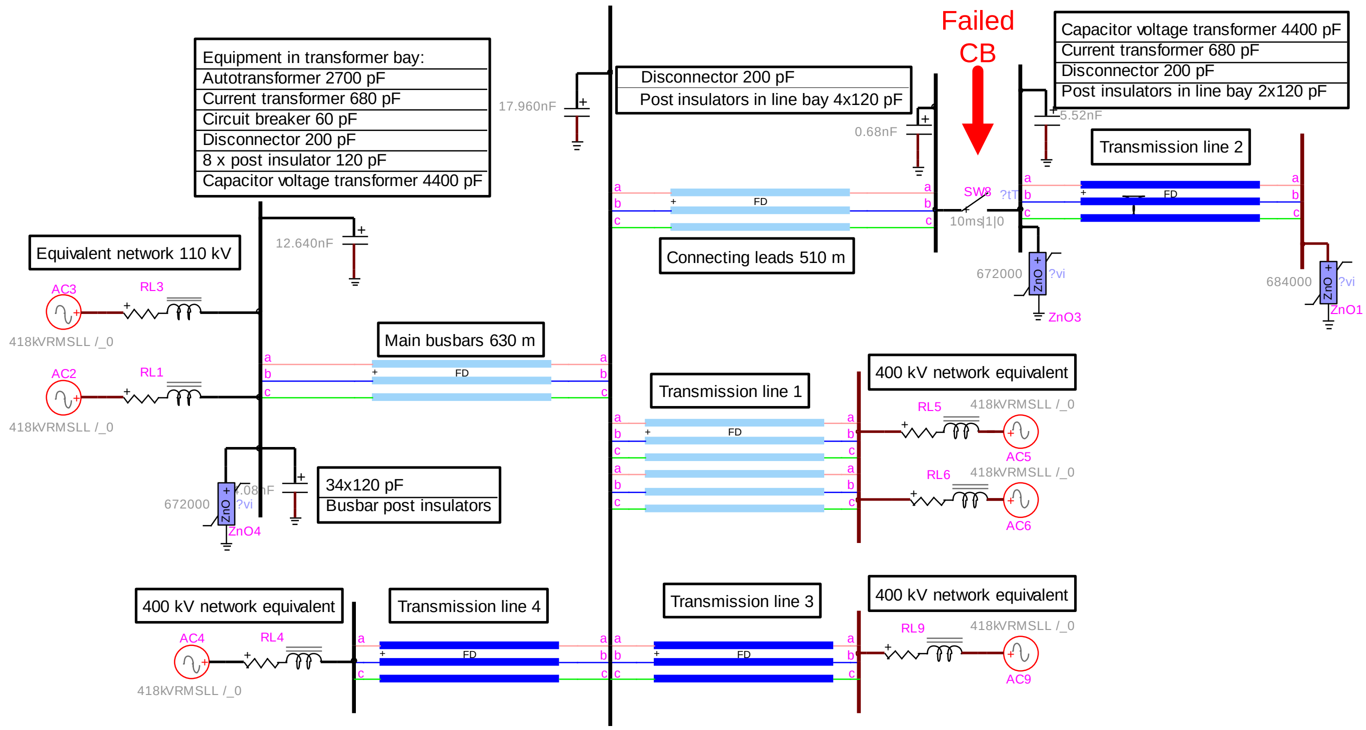

Fig. 4. Model for computation and analyzes of circuit breaker failure in EMTP-RV

It shows switching arrangement of 400 kV transmission lines and 400/110 kV power transformers prior to the CB fault.

The equipment in high voltage substation was represented by surge capacitances, whereas transmission lines, busbars and connecting leads by a frequency depending model [8].

The phase transpositions of the transmission lines have been taken into account. The MO surge arresters were modelled with nonlinear U-I curves for switching overvoltages.

The model of CB with two breaking chambers for switching the transmission line 2 is shown in Fig. 5.

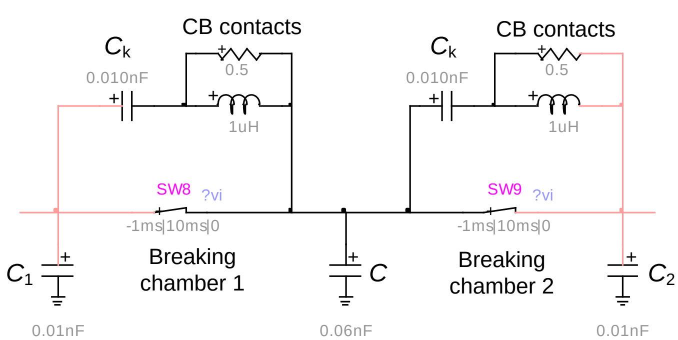

Fig .5. Model of circuit breaker with two braking chambers

The capacitance between the open contacts of breaking chambers is 10 pF and inherent earth capacitances were taken into account as depicted in Fig. 5.

The equivalent networks were represented with a voltage source in series with sequences impedances, which are obtained from short circuit currents in case of switching state prior to a fault (Table I).

TABLE I
SHORT CIRCUIT CURRENTS IN 400 KV SUBSTATION

Connections:	I_{3ph} (kA/°)	I_{1ph} (kA/°)
Transmission line 1 (86.3 km)	3.4/-85.5	2.4/-82.2
	3.4/-85.5	2.4/-82.2
Transmission line 2 (231 km)	2.4/84.8	1.8/-80.0
Transmission line 3 (91.5 km)	4.1/-84.9	3.3/-79.9
Transmission line 4 (152 km)	3.9/84.9	3.0/-80.1
Power transformer TR 1 (400/110 kV)	1.2/-81.5	1.3/-84.8
Power transformer TR 2 (400/110 kV)	1.1/-81.5	1.3/-84.8
Total:	19.5/-84.7	15.6/-81.6

IV. COMPUTATION RESULTS

Two different cases were analysed:

A) CB failure with post-mortem analysis based on previously shown recorded events from WAMS
B) Regular switching-off

A. CB failure

In order to explain the circumstances leading to CB failure the recorded transients have been analysed (Fig. 6). Voltage and current waveshapes indicate repetitive restrikes during CB opening. According to this, computation has been performed with simulation of repetitive restrikes in CB that are shown in Fig. 7.

First restrike occurred in the breaking chamber on the substation side (Fig. 8) due to a higher TRV magnitude compared to the breaking chamber on line side (Fig. 9).

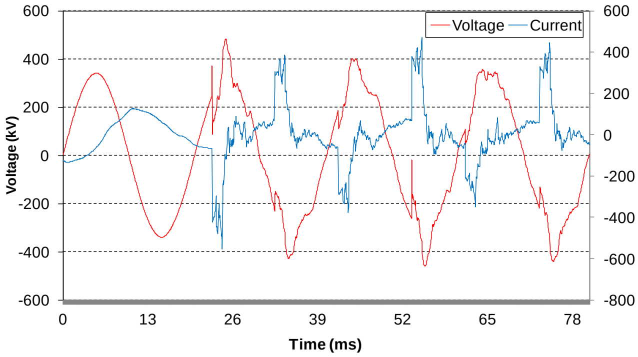

Fig. 6. Transients recorded with PQMS during CB fault

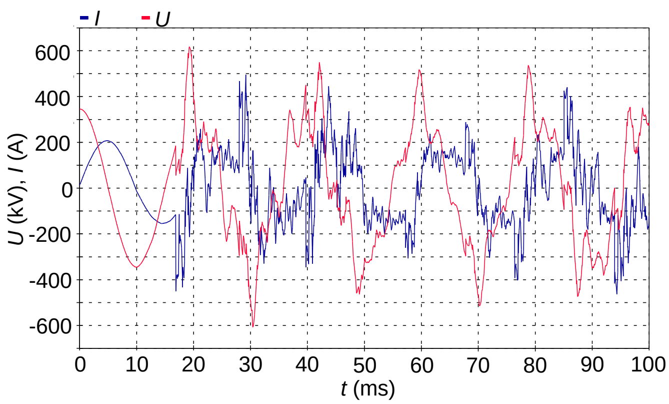

Fig. 7. Calculated voltage and current during CB fault

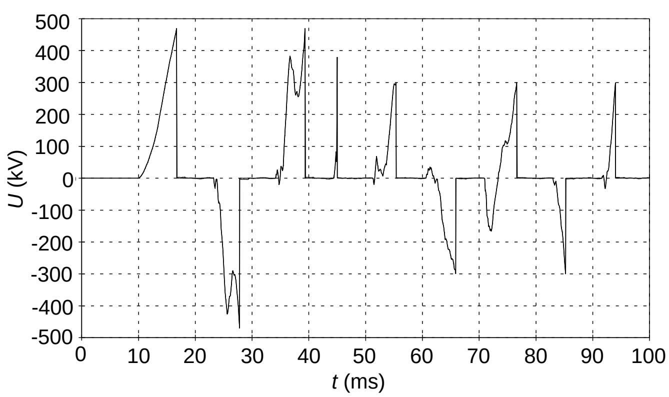

Fig. 8. TRV of CB chamber on substation side

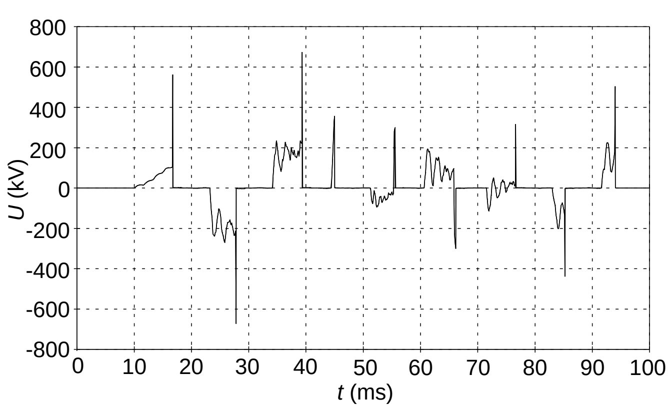

Fig. 9. TRV of CB chamber on line side

Phase voltages on CB terminals are shown in Fig. 10 and the total TRV is depicted in Fig. 11.

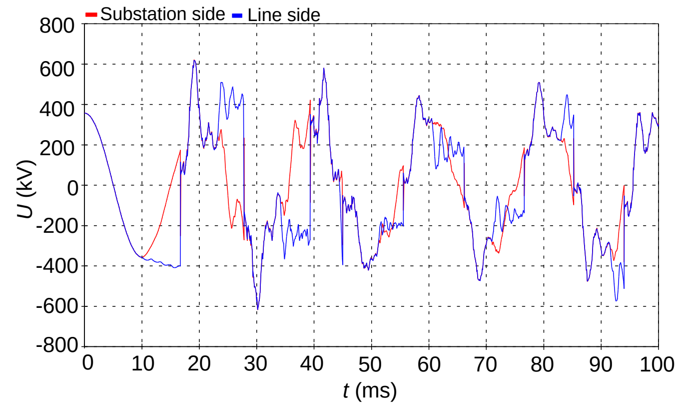

Fig. 10. Phase voltages of CB terminals

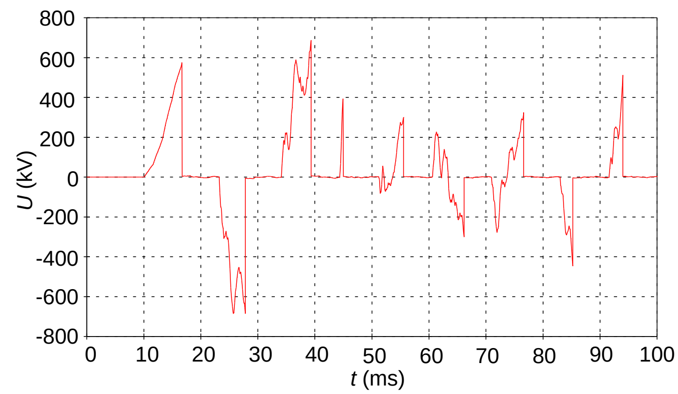

Fig. 11. Total TRV of CB terminals

The repetitive restrikes in chambers are accompanied with rash current jumps that ignite and extinguish several times (Fig. 12.).

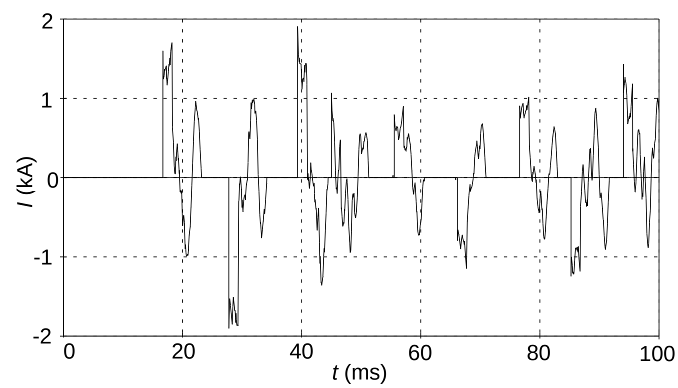

Fig. 12. Current across breaking chamber on substation side

B. Regular switching-off

Previously shown model was used for the analysis of regular switching-off of the unloaded 400 kV line. When an unloaded line is regularly switched-off the arc distinguishing occurs at current natural zero-crossing. Fig. 6 shows phase voltages on line-side after regular switching-off.

The voltage is highest in the phase which is firstly switched-off due to the electromagnetic coupling of the other phases and due to Ferranti effect.

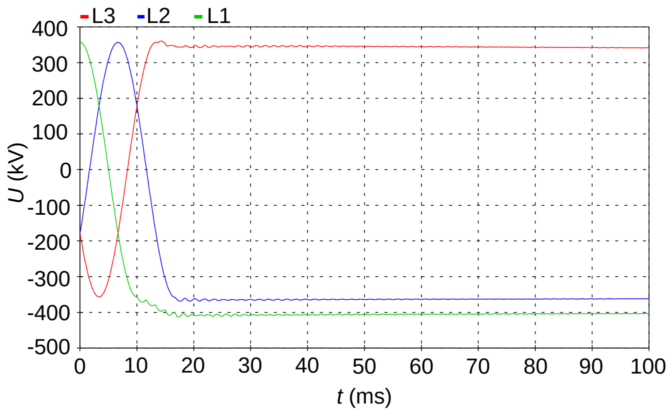

Fig. 6. Phase voltages on line-side after regular switching-off

Since the 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 which was low on-site at the instant of CB failure. So, the trapped charge has a very significant influence on CB transient recovery voltage (Fig. 7).

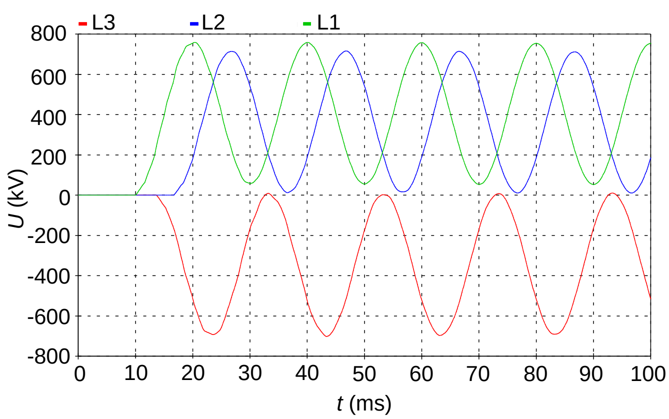

Fig. 7. TRV in case of regular switching-off; peak values: U_{L1}=758 kV (2.32 p.u.), U_{L2}=713 kV (2.18 p.u.), U_{L3}=692 kV (2.12 p.u.)

Besides the peak value of TRV the voltage distribution between breaking chambers is very important for CB dielectric stresses during switching operations. Simulation results show pretty unequal voltage distribution between breaking chambers in phase L1 where the maximum peak of TRV occurs (Fig. 8).

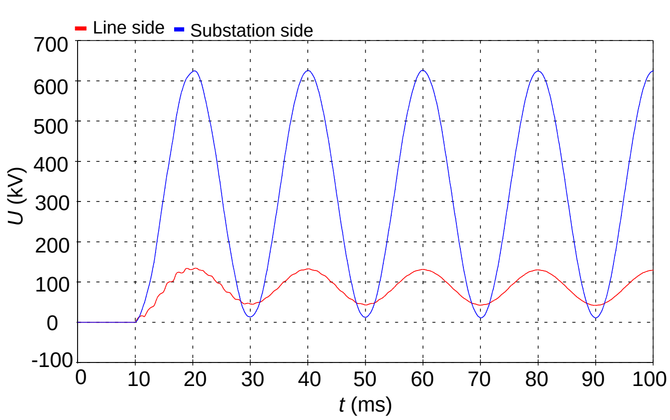

Fig. 8. Distribution of CB recovery voltage between breaking chambers

V. Final Analyses

According to [4] the CB should withstand the following test voltage U_c across the open contacts:

$$U_c = \frac{U_r \cdot k_c \cdot 2 \cdot \sqrt{2}}{\sqrt{3}} \tag{1}$$

where:

U_r – rated voltage (420 kV);

k_c – capacitive voltage factor (1.2 for effectively earthed neutral).

Therefore, the CB should withstand the maximum voltage of 823 kV (2.4 p.u.) across the open contacts. Compared to this, the computed value of recovery voltage is only 10 % smaller (758 kV/2.2 p.u.). However, the greatest part (nearly 80 %) of TRV stresses the breaking chamber closer to the substation.

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.

Further analyses show the influence of grading capacitors of 500 pF on voltage distribution. Simulation results show significant improvement of voltage distribution and reduction of TRV amplitude (Fig. 9).

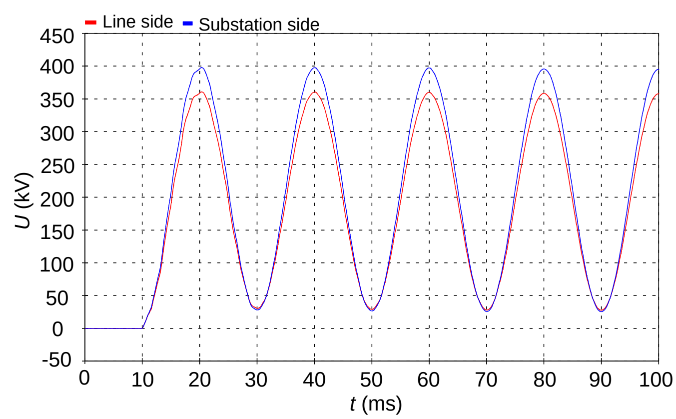

Fig. 9. Distribution of CB recovery voltage between breaking chambers in case with grading capacitors

Table II shows the comparison of TRV peak values in cases with and without grading capacitors.

TABLE II
TRV Distribution Between CB Chambers

Phase TRV (kV)	Peak value TRV (kV) Without grading capacitors	Peak value TRV (kV) With grading capacitors
L1/758	*624/134	*398/360
L2/713	*619/94	*376/337
L3/692	*611/81	*366/326

*Higher value corresponds to breaking chamber closer to substation

Therefore, the calculated values shown in Table II are not much less than the laboratory short duration AC test voltage between the open contacts of CB (according to [4], 863 kV peak value).

In real conditions, besides unequal voltage distribution between CB chambers, numerous additional factors can have an influence on the dynamic withstand voltage between contacts during the switching such as: speed of contact separation, state of SF_6 gas, surface pollution and maintenance issues. These additional factors may increase the risk of restrike occurrence and CB failure.

VI. Conclusions

The post-mortem analysis of SF_6 CB during switching-off an unloaded 400 kV transmission line showed that the CB failure was initiated by the repetitive restrikes occurrence between the contacts. Due to the specific place and the absence of phase-to-ground fault and voltage breakdown, the relay protection system did not operate during the CB failure.

The bases for further analysis were only transients recorded by a Power Quality Monitoring System installed in the nearby line bay and by Wide Area Monitoring System which is a very useful modern and additional toll that could be used in such and maybe similar circumstances.

In order to clarify the circumstances of the event, computer simulations were carried out using EMTP-RV software. Therefore, a detailed simulation model had to be developed which includes real operating conditions of 400 kV substation and connected transmission lines prior to CB failure.

Calculated transients due to CB restrikes coincide very well to the recorded disturbances.

Additional analysis of regular switching-off operation shows pretty unequal voltage distribution between breaking chambers, which in real conditions of this particular case with relatively high TRV, can lead to restrike occurrence.

Despite the fact that the calculated TRV crest value is under permitted maximum, the additional grading capacitors could be installed in order to equalize the voltage distribution between the breaking chambers for significantly reducing the risk of CB damage in such and similar service conditions.

After reconstruction and repairing of CB the future work will include the on-site measurements according to performed computation results in order to verify CB performance.

VII. References

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