Comparative Research into Transients by Switching of High Voltage Shunt Reactor

S. Bojić, B. Babić, I. Uglešić

***Abstract*— This article deals with results of performed studies of transient phenomena in application of controlled switching technique by switching high voltage 123 kV, 100 MVAr shunt reactor. First, for switching a single-pole hydraulically operated SF_6 circuit breaker has been selected and after that, one with electric motor-drive. In preparing of experimental part of studies the EMTP-ATP software has been used in computer simulations, further for analyses the cases of optimal controlled switching and switching within time deviation limits. For simulation of uncontrolled switching with current chopping and arc-reignition dynamic model of arc behavior has been implemented. The field tests with both circuit breakers have been repeated in similar network conditions for further statistical analyses. During some tests, the transient phenomena of uncontrolled switching have been observed. The achieved experimental results were compared with the computer simulations.**

***Keywords*: controlled switching, shunt reactor, circuit breaker, transients, current chopping, arc-reignition, inrush current EMTP-ATP**

I. INTRODUCTION

TRANSIENTS PHENOMENA by switching-off a high voltage (HV) shunt reactor in general terms are the well known problem [1-2], [4]. In the overvoltage domain they are connected with the breaking of small inductive currents, related to the switching devices, to his mechanics and type of extinguishing media [1-4]. When current chopping or arc reignition or both phenomena have occurred, they usually lead to significant switching overvoltages. Contrary, during the process of switching-on, very high inrush currents as the transients can be observed if the moment of switching is not optimal. Because of that they can be potentially very stressful for insulation and mechanical system of shunt reactor as well for other equipment [5]. Therefore they have to be prevented or mitigated. As an effective measure in prevention of such transients the controlled switching technique is in use [6-7]. Additionally, for overvoltage protection of insulation system, metal oxide (MO) arresters are generally used [8].

This article deals with and compares the part of results of performed transient phenomena studies by switching of HV 123 kV, 100 MVAr shunt reactor with two different types of SF_6 circuit breaker (CB) in one 400/110 kV substation, first with single-pole hydraulically operated (CB1) [9], and second one with electric motor-drive system (CB2), the both equipped with the proper switching controller.

II. CASE STUDIES DESCRIPTION

First, for switching of HV shunt reactor a single-pole hydraulically operated CB have been installed. After installation, very soon some problems with instability of its mechanics have been observed resulting in the periodical incapability for switching of shunt reactor. For illustration, Fig. 1 shows the typical recorded “closing” and “opening” time of CB during some field test. Fig. 2 depicts much more details of recorded long term deviation in the switch-time operation of the CB1, and also shows the periods of incapability for switching [9].

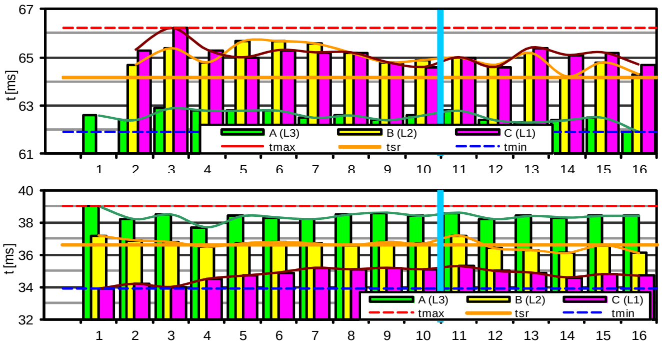

Fig. 1. Typical recorded ” closing” and “opening” time of CB1

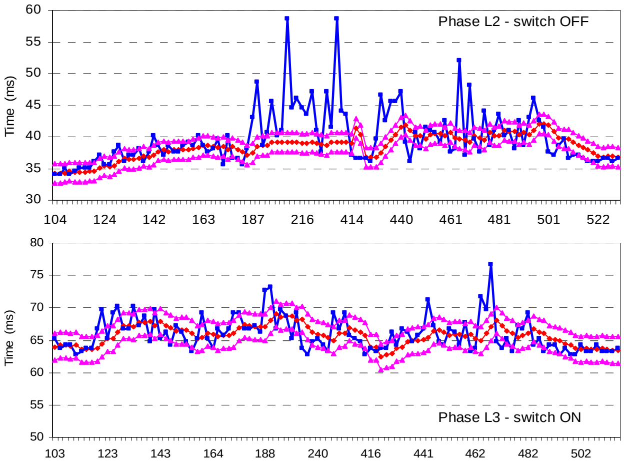

Fig. 2. Recorded long term switch-time deviation in operation of CB1, [9]

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It was pretty clear that this time deviation in CB mechanics, more than ± 2 ms, can lead to serious cases of uncontrolled switching in despite of implemented CB controller with adaptive feedback. Therefore, the hydraulically operated CB1 has been replaced with the new one (CB2) with electric motor-drive system in order to provide much more reliable controlled switching. Prior to replacement, first experimental study (Case I) of transients has been performed, in order to collect and compare the real measured data before and after the replacement. The switching of shunt reactor has been carried out in controlled and uncontrolled conditions, within different time margins. Some of the first collected data were analyzed and compared to the results of performed EMTP/ATP computer simulation and were presented in [9]. In several cases of shunt reactor switching-off the arc-reignition has been recorded with significant transient phenomena. Also, by switching-on in time out of optimal margins for controlled switching, high inrush currents have been expected and observed. Because of that, after replacement of CB1 with the new CB2, the second study (Case II) has been prepared, much more detailed in the experimental part, as well as in the computation work.

III. PREPARATION OF MEASUREMENTS (CASE II)

The principle schematic diagram for field measurements by switching is shown in Fig. 3. It was the same as in the previous performed field testing (Case I).

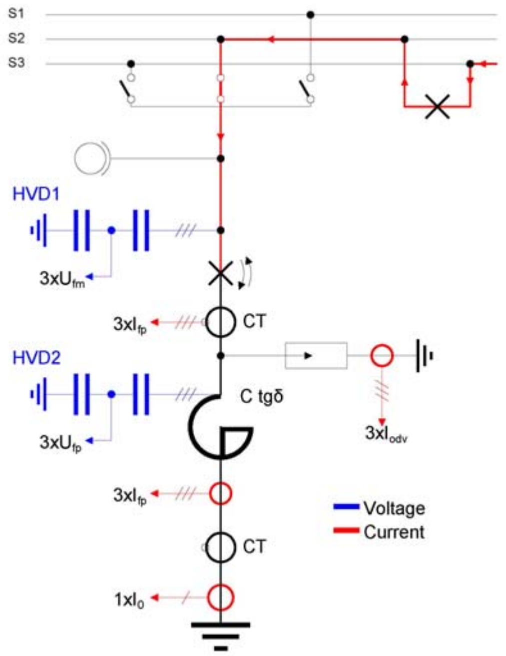

Fig.3. Principle single-phase schematic diagram of shunt reactors bay in HV 110 kV substation with voltage and current measurement points

In order to ensure enough data for further comparison and analyses with mathematical statistic, the shunt reactor switching has been repeated several times too, in the same network, both in the controlled and uncontrolled conditions.

Due to previous observed several cases with arc-reignition during shunt reactor switching-off, in further preparation for field tests, additional analyses and reconstruction of HV voltage divider have been done, based on computation results and laboratory tests. The target was to achieve and verify the proper transfer characteristic of capacitive low-damped HV divider for field measurements according to expected amplitude and frequency spectrum of transients up to several hundred kHz [1], [9]. Fig. 4 depicts the model of HV divider (HVD1) analyzed in EMTP-RV software [10].

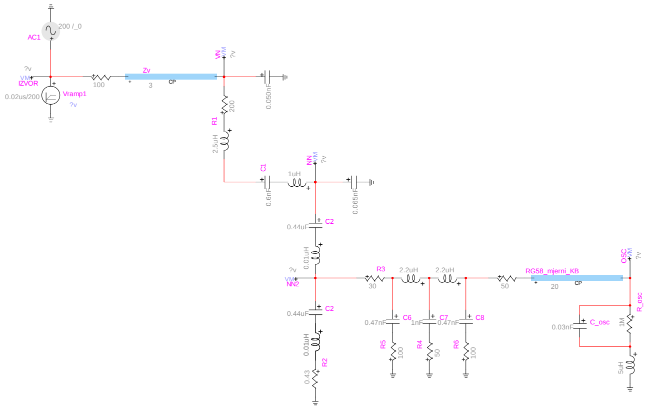

Fig.4. Model of HV divider in EMTP-RV software

The calculated response on "step" input voltage of 40 V_{pp} with the rise time of 110 ns is shown on Fig. 5. Fig. 6 depicts the laboratory test result performed on the real physical and custom made model of dividers for measuring the voltages on the network (D1) and on the shunt reactor side (D2).

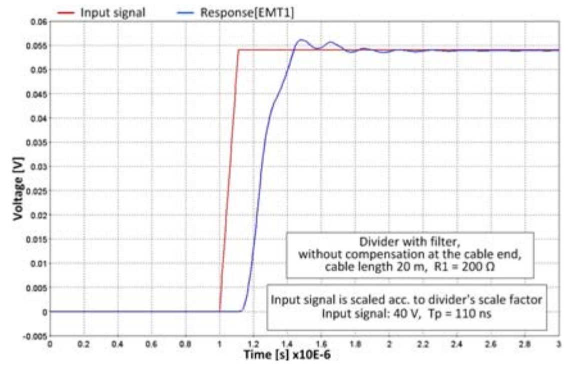

Fig. 5. "Step" response of HV divider on model in EMTP-RV [10]

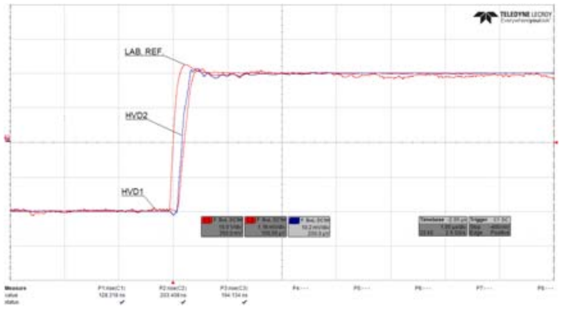

Fig. 6. "Step" response of laboratory model of HV dividers, (reference input voltage: U_{in}= 40 V_{pp}; rise time: Tr=128 ns)

The amplitude-frequency characteristic of the real physical models verified in the laboratory with determined upper frequency margin of ≈ 2 MHz, – 3 dB depicts Fig. 7.

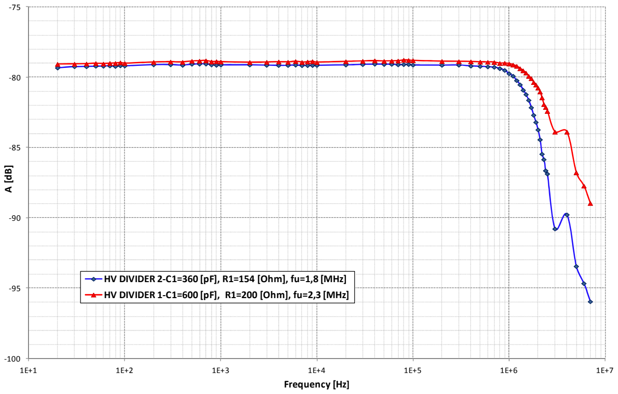

Fig. 7. Amplitude-frequency transfer characteristic of HV dividers

Also, for final verification, the standard HV AC and impulse test have been performed on both physical models of dividers before the field tests and measurements. The example of typical oscillogram of HV impulse test, performed on the both dividers, depicts Fig. 8.

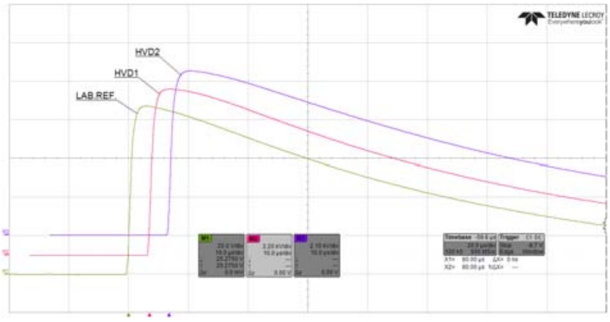

Fig. 8. Oscillogram of HV impulse test performed in HV laboratory; (U_m ≈ 90 kV, 1,2/50 µs, positive)

IV. COMPUTATION OF TRANSIENTS (CASE II)

In Case II, the additional computation work has been prepared based on previous calculations and measurements with CB1 [9], as well on performed field tests with CB2. In EMTP-ATP computation some additions in models have been implemented to simulate and analyze particular cases obtained in measurements more precisely.

A. Shunt reactor switching-on

In computation, a 3-phase simulating model of shunt reactor was used, based on nonlinear inductance with serial-parallel connection of resistors representing the losses in reactor windings and iron core, [11-12]. Due to phase star connection and earthed neutral point, a zero sequence reactance is included, [12]. To represent the transients due to inter-phase coupling and energy exchange the capacitors have been added. As well, in the other part of simulation model, the main parameters of 110 kV substation and of neighbouring network have been included as depicts Fig. 9.

The same model has been also used in computation of shunt reactor switching-off, except the CB's part. In simulation of switching-on the CB is modeled as an ideal switch only [10].

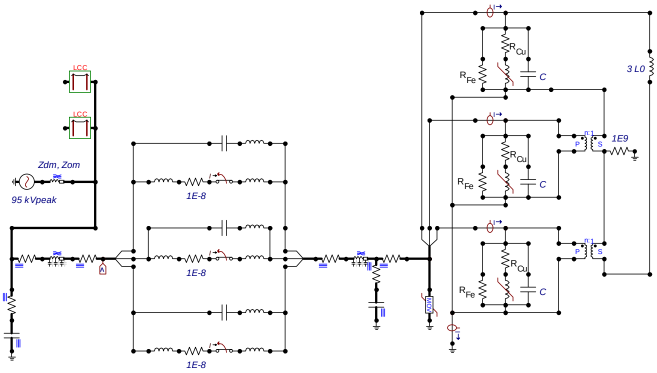

Fig. 9. EMTP-ATP model for computation of transients by switching-on

In model some of input parameters have been adjusted according to the measurement results. In this way a small changes have been made in the magnetizing curve ψ-i of shunt reactor in area of saturation which has not been considered in previous calculations [9] in cases of switching-on.

In additional computation of transients when shunt reactor has been switched-on with CB2 in optimal controlled condition, the cases within time margin of ± 1 ms have been considered first. The calculated peak inrush current will not excide 1,63 p.u., (1 p.u.= 663 A), [9]. According to expected precision of CB, in reality all of measured peak inrush currents did not exceed 1,25 p.u. One of such considered real cases in computation work depicts Fig.10, as well Fig.11.

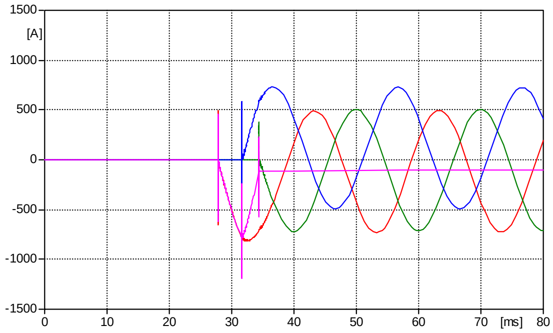

Fig. 10. Computation of currents, switching-on, time dev. of ≈ ± 0,5 ms

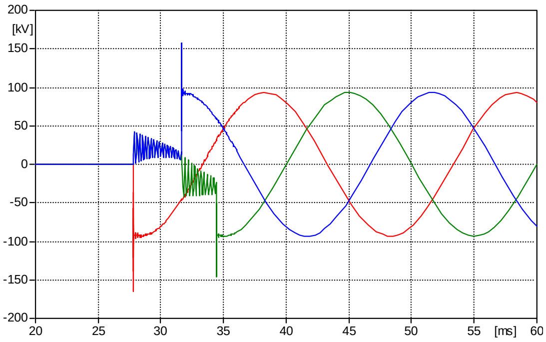

Fig. 11. Computation of voltages, switching-on, time dev. of ≈ ± 0,5 ms

The further increase of time deviation out of optimal margins (± 1 ms) leads to significant value of inrush currents. For illustration, Fig. 13 depicts computation result in one of analyzed cases of uncontrolled switching-on with time deviation more than ± 2 ms according to performed measurement, in provoked uncontrolled conditions. Fig. 14 describes the corresponding measured oscillogram.

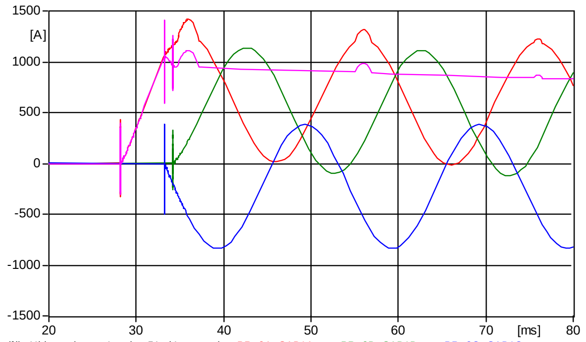

Fig. 13. Computation of currents, switching-on, time dev. > ± 2 ms

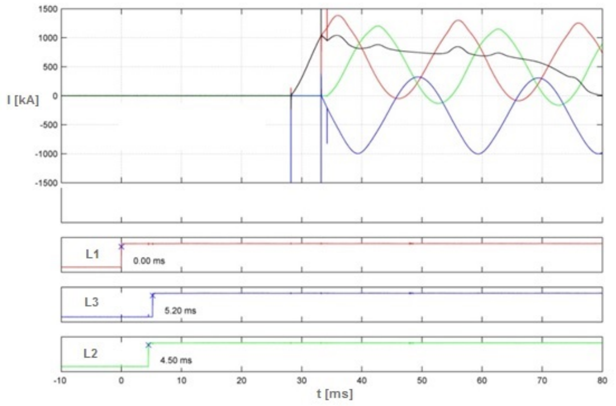

Fig. 14. Measured currents, uncontrolled switching-on, time dev. > ± 2 ms

In such cases of uncontrolled switching-on the peak currents have always exceed 2 p.u. or more, depending on real time deviation of each CB's pole to the optimal switching time.

B. Shunt reactor switching-off

Regarding to expected transients, when shunt reactor is switching-off, two important cases have to be considered. The first one is with supposed real current chopping, and the another one, like the first, but with consecutive CB arc-reignition. In earlier computation work the supposed current chopping was on level of 4 A. In calculation, by using the CB model as an ideal switch, the computed overvoltages did not exceed 1,10 p.u., [9]. After performed measurements (CB1), the more realistic chopping current has been assessed from measured overvoltage factor k_a according to the next expression, [1]:

$$k_a = \sqrt{1+\frac{3i^2_{ch}}{2\omega C_t Q}} \ \text{p. u.} \qquad (1)$$

where C_t is shunt reactor phase capacitance; 3,98 nF and Q is reactive power of 100 MVAr.

According to that, the corresponding chopping current is 4,2 A, (for k_a=1,10 p.u.), or 6,7 A, (for k_a=1,24 p.u.), if it is calculated with the maximal measured overvoltage in case with CB1 [9].

In Case II, in shunt reactor switching-off, the maximal measured overvoltage did not exceed the level of 1,12 p.u., [10], and by using the expression (1), the corresponding current chopping is 4,6 A.

In additional computation, first for simulation of switching-off, the model from Fig. 9 has been used in order to compute and compare the transients in cases with different supposed current chopping. The CB is modeled as an ideal switch. For illustration, as one of results, Fig. 15 depicts shunt reactor switching-off by chopping current at the level of 6 A. The activity of MO arresters, due to appearance of overvoltages, is visible in Fig.16. Now by using expression (1) the calculated overvoltage in phase "A", follows the smaller corresponding level of current chopping (5,6 A) due to MOA activity.

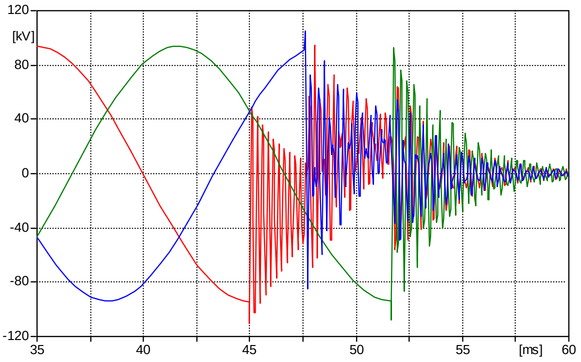

Fig. 15. Computed overvoltages at switching-off; CB as ideal switch; (i_{ch}=6 A, k_A=1,17, k_B=1,15, k_C=1,11)

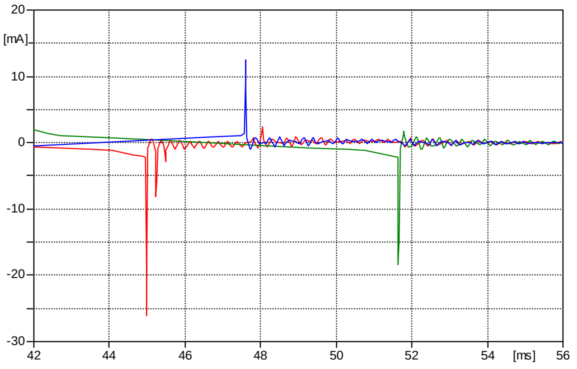

Fig. 16. Computed MO arrester currents during switching-off

In computation of transients, due to current chopping and arc-reignition, the model of CB with included arc behavior has been involved in order to explain and analyze more precisely the results from performed measurements. The model is based on "black-box" model [2] for modeling the thermal phase of electrical arc [13]. For current interruption Swartz-Avdonin equation (modified Mayr-Avdonin equation) has been chosen [13-14].

$$\frac{1}{g}\frac{dg}{dt} = \frac{1}{T(g)}\left[\frac{u\cdot i}{P(g)}-1\right] \qquad (2)$$

The functions, $T(g)$ and $P(g)$ are defined as follows:

$$T(g) = T_0 \cdot g^{\alpha} \qquad (3)$$

$$P(g) = P_0 \cdot g^{\beta} \qquad (4)$$

T_0, P_0, α, and β are the constants, g is the arc conductivity. In this way, in the CB model, the arc is presented as variable parameter, from the moment of contacts opening up to phase of arc extinguishing. The complete model, for simulation of shunt reactor switching-off in EMTP-ATP software, depicts Fig. 17.

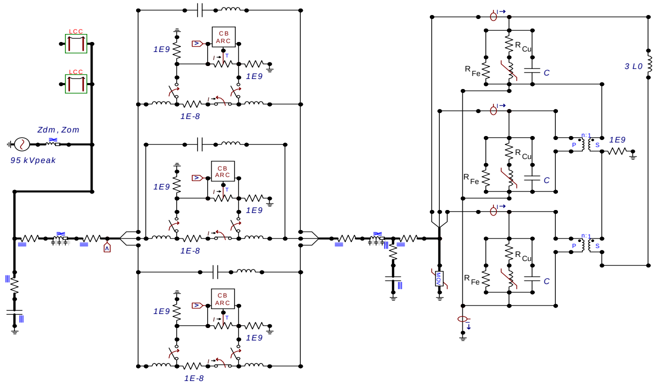

Fig.17. EMTP-ATP model for computation of transients at switching-off

In computation of shunt reactor switching-off, the influence of arc-behavior on current chopping and overvoltages has been researched. For illustration, Fig. 18 depicts one typical oscillogram of current chopping in simulation CB with and without presented model with arc behavior.

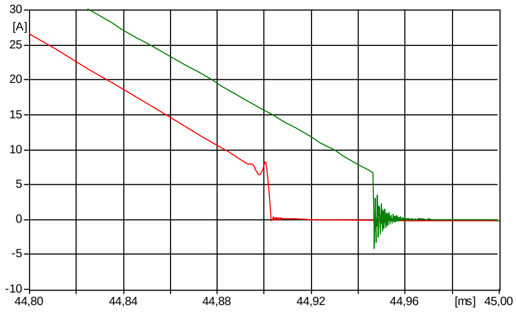

Fig.18. Computed oscillogram of current chopping; CB with arc-model (red), CB as ideal switch (green), (i_{ch}=6,7 A)

For comparison, Fig. 19 shows the influence of the arc in damping of overvoltage due to its resistive character.

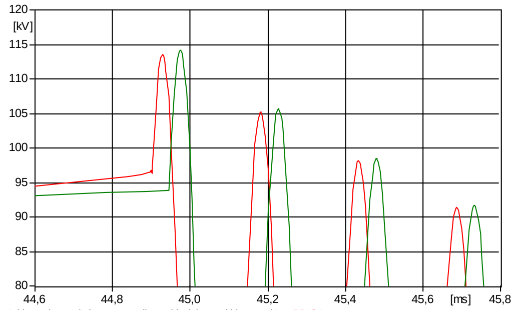

Fig.19. Computed oscillogram of peak voltage on shunt reactor after current chopping; CB with arc-model (red), CB as ideal switch (green), (i_{ch}=6,7 A)

The data relevant for arc-behavior in the model of CB are contained in Table I.

TABLE I

DATA RELATED TO THE ARC MODEL USED IN THE COMPUTATION WORK

Parameter/Constant	Unit	Value
T_0	µs	3
P_0	kW	500
α	-	0,5
β	-	0,53
R_0	Ω	0,01
Diel. strength recovery	kV/µs	0,3

In further performed computation work the case with arc-reignition has been simulated and analyzed too. Fig. 20 and Fig. 21 depict the results of computation, simulating the real case when significant transients occurred and were measured in one of previous field tests with CB1, presented in [9]. For this simulation, some changes in input data from Table I have been made as follows: T_0=2,3 µs, α=0,29, β=0,7; CB dielectric strength recovery=0,72 kV/µs.

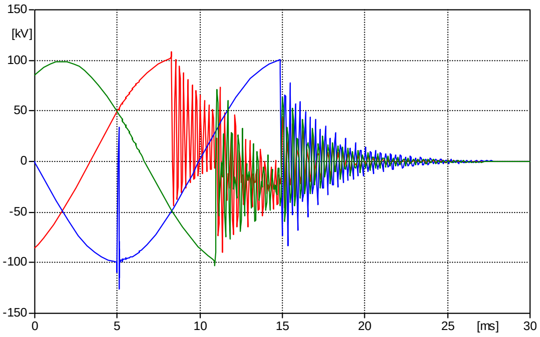

Fig. 20. Computed voltages on shunt reactor at switching-off; unsuccessful current interruption in phase "B" due to arc-reignition

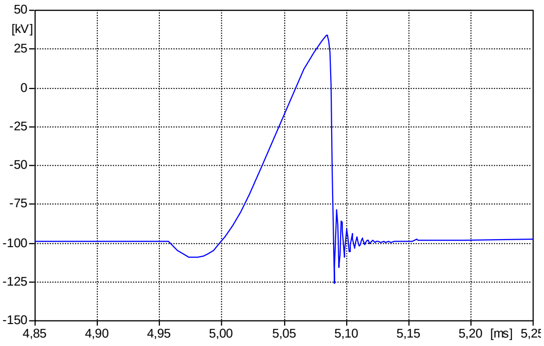

Fig. 21 Computed overvoltage at shunt reactor switching-off; steep HV "excursion" in phase "B", superimposed HF oscillations due to arc-reignition

At the moment of arc-reignition in phase "B", a very steep voltage "excursion" (up to 160 kV) has occurred with superimposed HF oscillations (≈ 244 kHz). As well, HF current has been calculated with the peak up to ≈ 300 A.

V. SUMMARY OF RESULTS

The results of performed studies of transients, in application of controlled switching by HV shunt reactor switching, are based on comprehensive field measurements and computation work by using EMTP-ATP software.

In the real switchyard, by daily shunt reactor switching, the proper conditions for optimal controlled switching should be provided to prevent the shunt reactor from analyzed transient phenomena. In consideration of that, the accuracy and stability of CB mechanics are the most important, regardless of proper control device. The results, based on statistical evaluation of measurements by shunt reactor controlled switching-on, with considered two types of CB's, depicts Fig. 22. By switching-on with CB2, with motor-driven system, the inrush currents are on significantly lower level.

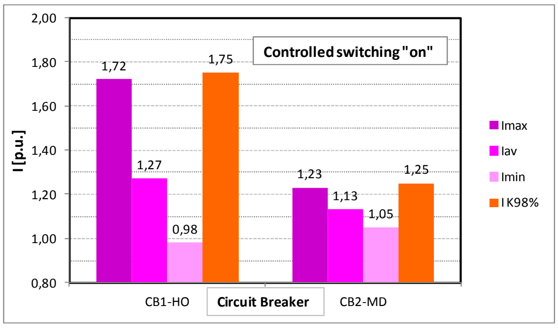

Fig. 22 Statistical evaluation of measured peak currents at controlled switching-on; CB1-hydraulically operated; CB2-electrical motor-drive

The comparison of overvoltages by controlled switching-off, depict Fig. 23. The switching-off with hydraulically operated CB1, leads to 10% higher values of overvoltages.

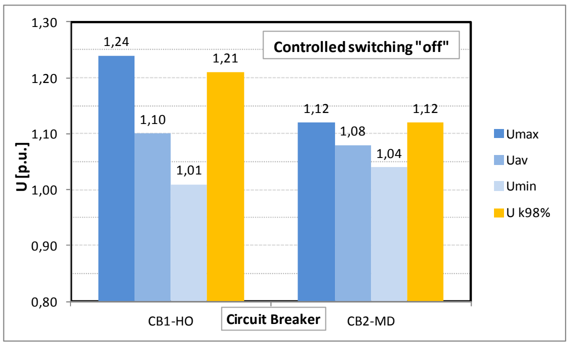

Fig. 23 Statistical evaluation of measured overvoltages at controlled switching-off; CB1-hydraulically operated; CB2-electrical motor-drive

VI. CONCLUSIONS

The results of performed studies and comparative research into transient phenomena by shunt reactor switching, with two different types of SF_6 circuit breakers, can be summarized as follows:

At shunt reactor switching-on in desired optimal controlled conditions, within time deviation of ± 1 ms, the peak values of inrush currents strictly depend on preciseness of CB drive mechanics. In case of switching-on with hydraulically operated CB, they can achieve the values up to 1,75 p.u. of current. Contrary, at switching-on with CB equipped with motor-driven system in the same conditions, they are significantly lower, only up to 1,25 p.u.

At controlled switching-off, in both researched cases no significant values of overvoltages were found. In case of switching with hydraulically operated CB, they can achieve the values up to 1,24 p.u., and respectively lower, 1,12 p.u. only, in the case with CB with motor-driven system. Such values of overvoltages assume the low level of current chopping, mainly in the range of ~ 3,5 - 4,5 A at both considered CB, but up to 6,7 A in case of hydraulically operated CB.

The achieved results of studies emphasize the importance of accuracy and long-term stability of CB mechanics for optimal controlled switching of HV shunt reactor. Relating to the probability of high values of inrush currents and arc-reignition appearance, the CB with motor-driven system, equipped with proper control device, offers high level in prevention from considerable transient phenomena.

VII. ACKNOWLEDGMENT

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