A STUDY OF SWITCHING OVERVOLTAGES ON SHUNT REACTORS

A. Ovsyannikov, O. Shiller

JSC “Electrosetservice ENES”
E-mail: oag@nspb.ru

Abstract. Failures of shunt reactors occur usually due to damage of turn insulation or bushings. An insulation damage can result from exposure of switching overvoltage. For example, a reactor switching-off can be accompanied by current cutting in circuit breaker. This effect leads to overvoltage on winding of reactor. An increased stress on the longitudinal insulation occurs due to the uneven distribution of high frequency overvoltage along the winding of shunt reactor. That may lead to ageing and breakdown of turn insulation.
This paper discusses the results of experimental and theoretical study of overvoltages on shunt reactors winding which occur during SF_6 circuit breaker operation.
Overvoltage values slightly exceeded the rated voltage of shunt reactor 60000/500 kV and were at switching-on with synchronizer 520 ...550 kV; at switching-on without synchronizer: 650 kV and at switching-off: 550 ...660 kV. Numerical simulations showed that overvoltages in all cases do not exceed the test voltage. An application of synchronizer reduces the magnitude of overvoltage in the most severe regime in 1.2-1.3 times.

Introduction. Power shunt reactors (SR) are used to control the operating voltage and to decrease a magnitude of switching overvoltages. They reduce the amplitude of the forced component and the frequency of natural oscillations in the transient processes, reduce probability of re-ignition in the circuit-breaker and facilitate the conditions for arc extinction at short-circuit on the line. Unfortunately, the failures of SR are not uncommon. They occur most often due to breakdown of main insulation or bushings. In turn, damages of insulation can be a consequence of switching overvoltages. For example, any closing of reactor may be accompanied by a droop of the current in circuit-breaker and lead to high magnitude and high frequency overvoltage on insulation. In this case, due to the uneven voltage distribution along the winding its longitudinal isolation may be overstressed and damaged.
The results of switching overvoltage study during SF_6 circuit breaker operation are discussed in this paper.

Experimental study. The object of experimental study was the group of SR 60000/500 kV (ONAN cooling system). In this group one failure occurred before experiments (Figure1).
SR was switched SF_6 circuit breaker type HPB 550 Br (drive BLG), which was manufactured by ABB company. Diagram of measurements is shown in Figure 2.
The capacitive division was used for high voltage measurement. The capacitance of bushing main insulation C1 played role of upper arm of voltage divider and C3 and additional capacitor Ca was used as low voltage chain of voltage divider.

Figure 1: breakdown of turn insulation

The buffer amplifiers (BA) were used to match the impedance of capacitive divider with wave resistance of coaxial cables. Their output signals were transmitted to digital oscilloscope Tektronix DPO 3014. Transfer coefficient of BA was equal to 1, the frequency band – 100 MHz, input impedance – 1 Mohm, output impedance – 50 Ohm (equal to the impedance of the cable). The exact definition of the division factor was made in the measurements of stable (operated) voltages on reactor.
Figure 3 shows typical waveforms of switching overvoltages.
Table 1 shows the sequence of experiments and results of measurements. One can show from traces on Figure 2 and data of Table 1 that the levels of overvoltage on the insulation of the reactor were slightly higher than the rated voltage: at switching-on controlled by synchronizer: 520

...550 kV; at switching-on without synchronizer: 650 kV; at switching-off: 550 ...660 kV.

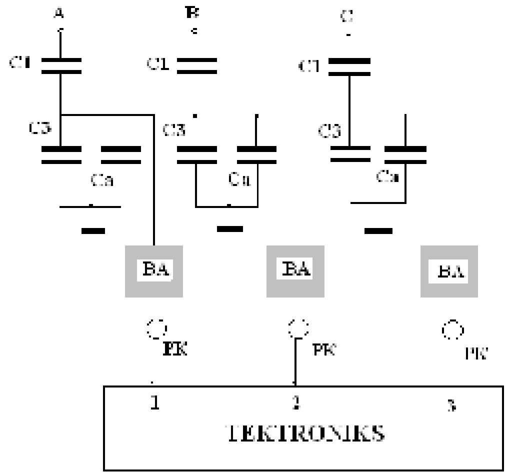
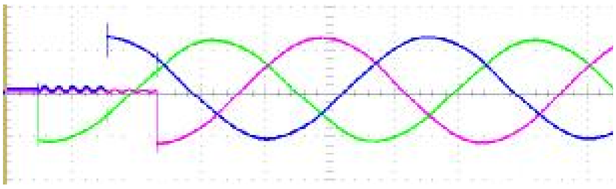


Figure 2: Diagram of phase voltage measurement



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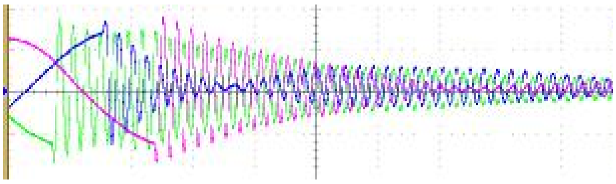

b

Figure 3: Waveforms of overvoltages at the reactor switching on (a) and off (b)

Table 1

The sequence of experiments and results

Action	U_{max}, kV
1-st switching-on with synchronizer	± 460
Measurement of operated voltages	± 410
1-st switching-off with synchronizer	+550 - 480
2-nd switching-on with synchronizer	+450 – 520
3-rd switching-on with synchronizer	+ 470 - 550
3-rd switching-off with synchronizer	± 610
4-th switching-on without synchronizer	+ 425 - 610
4-th switching-off without synchronizer	+561 -658

Simulation. These processes were simulated with the help of "MAES" software in order to estimate a switching overvoltages and to determine the most severe regimes. Model scheme of the reactor and adjacent network is shown in Figure 4.

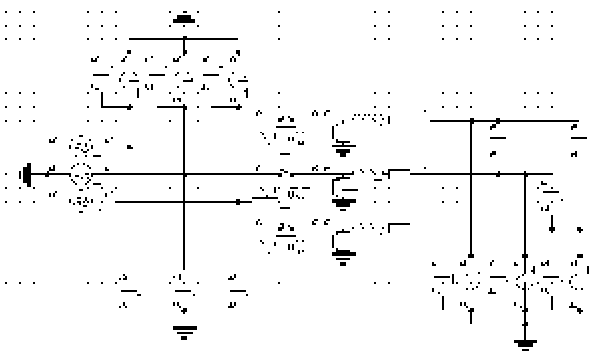

Figure 4: Network with SR and SF_6 circuit breaker for simulation of transient processes

Table 2 shows the most significant characteristics of the oscillations: the frequency, the front duration and amplitude of the overvoltage. There is good agreement between calculated and experimental data. That confirms the adequacy of the model to real circuit.

Table 2

Comparison of measured and calculated data

Characteristic	Test	Calculation	Error, %
Frequency, Hz	953	950	0,3
Front, µs	350	350	0
U_{max}, kV	570	560	1,7

An amplitude of overvoltage essentially depend on the moment of reactor switching-on. When a reactor is switched on at the maximum voltage on the buses of 500 kV there is a danger of breakdown of turn insulation (especially in a weakening place).

Table 3 summarizes data obtained from numerical experiments that simulate some cases of shunt reactor switching-on. These cases were not observed in the experiments but they may occur:

1 - the switching-on of the phase of the reactor at zero of voltage value on phase "A";

2 – the same case but with 1 ms deviation of triggering moments of the breaker poles;

3 - the switching-on of the phase reactor at a maximum voltage on phase "A";

4 - the same but with 1 ms deviation of triggering moments of the breaker poles.

Table 3

The switching-on of the phase reactor

#	U_{max}, kV	Front duration, µs	Oscillation frequency, kHz
1	684	29.5	12.5
2	786	26.5	12.9
3	790	26.7	12.1
4	795	28.5	12.4

Figure 5 shows the calculated waveforms of voltages at the "ideal" reactor switching-on, i.e. at the moments of zero points of each phase voltages.

Figure 6 shows waveforms for the case when the switching-on occurs at the maximum voltage on phase "A", and all poles of circuit breaker trigger simultaneously.

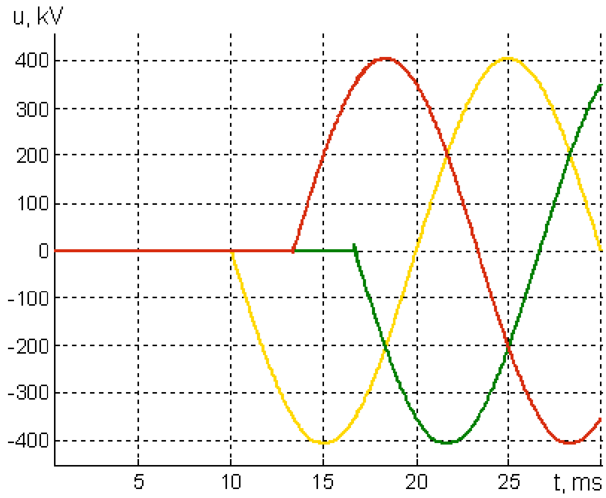

Figure 5: Waveforms of voltages during reactor switching-on in moments of zero-voltage values

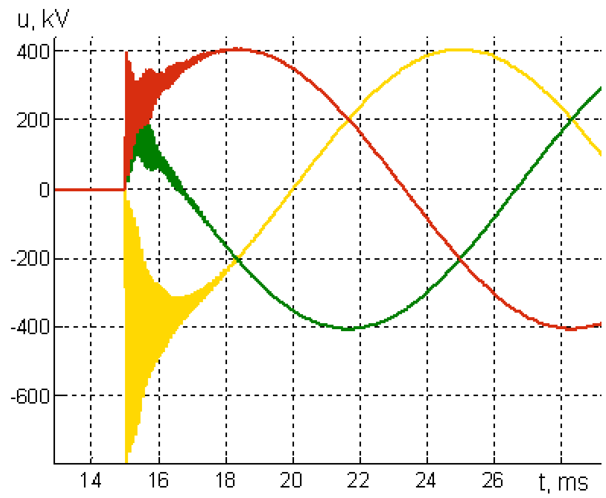

Figure 6: Waveforms of voltages while the switching-on the phase of the reactor at the maximum voltage on phase "A"

According to standard [1] the insulation test voltage at switching pulse is 1050 kV. The calculated overvoltage amplitude is less than this value in a by 1.3 time even in the most severe of the cases. Note, however, that in this case SR insulation is stressed by series of pulses with a steep front and a frequency of about 12-13 kHz which differs from single switching test pulse.

It is known that overvoltage, occurred at SR switching-off, mainly depends on the design of circuit breaker chamber. There are important two characteristics: the value of current cutoff and admissible rate of voltage recovering which defines a possibility of re-ignition of the arc between contacts. In addition, the current value of the cutoff depends on the moment of SR switching-off. So the use of synchronizer allows to disconnect contacts at a time when the voltage on switchable phase passes through its maximum value ($y \approx 0$), which gives almost zero current cutoff. Therefore a dangerous overvoltage in such SR switching-off should not occur.

Manufacturers of circuit breakers did not indicate the value current cutoff in the documentation but some authors indicated the current cutoff is 3-10 A for SF_6 circuit breaker.

The following cases were chosen the reactor closing:

1) disconnecting of contacts occurs at the maximum value of the voltage on each phase;
2) disconnecting of breaker's contacts occurs simultaneously with the maximum voltage on phase "A";
3) disconnecting of breaker's contacts occurs simultaneously at zero voltage on phase "A";
4) disconnecting of breaker's contacts occurs simultaneously at zero voltage in phase "A" with a spread in the moments of pole breaker triggering;
5) disconnecting of breaker's contacts occurs at zero voltage on phase "A" with the value of the current cutoff of 1, 3, 7 and 10 A.

In numerical experiments #1 - #4 the current cutoff in the circuit breaker has been banned.

Numerical results are summarized in Table 4.

Table 4

The simulation results for switching-off the reactor

#	The current cutoff value, A	U_{max}, kV	The voltage on contacts of breaker, kV	The rate of recovery voltage on the switch, kV / µs
1	No	462	840	2.24
2	No	462	840	2.12
3	No	486	842	2.31
4	No	486	842	2.41
5	1	487	846	2.28
	3	497	860	2.32
	7	543	912	2.56
	10	600	976	2.74

Figure 7 shows the voltage waveforms obtained from the results of experience # 4. The same results were obtained in experiments 1-2 and 3-4. It follows from the fact that the circuit disconnecting occurred at the current transition through zero in numerical model.

The frequency of oscillations at switching-off of the reactor was much lower than at switching-on, and was about 960 Hz. This value roughly corresponds to the calculated value. Evaluation of the fundamental frequency of natural oscillations of the switching SR can be done in the first approximation as $f_p = 1/2p\sqrt{L_pC_p}$ = 1.07 kHz.

Calculated data were slightly overestimated, since the capacitance and inductance of bus bars were not taken into account in calculations.

Figure 8 shows waveforms of voltage across the contacts of circuit breaker.

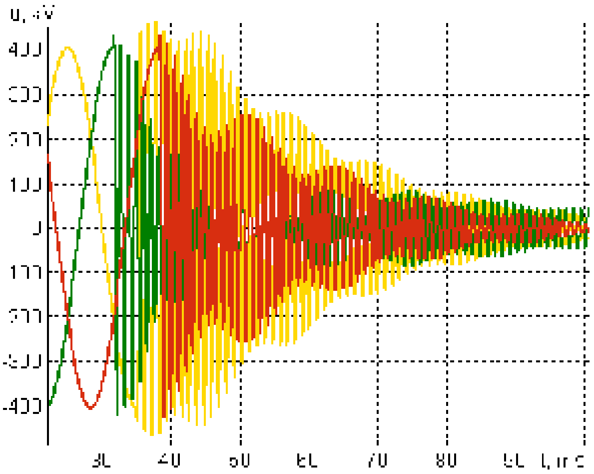

Figure 7: Waveforms of the overvoltages at disconnecting of contacts simultaneously at zero voltage on phase "A" with a spread in moments of pole breaker triggering

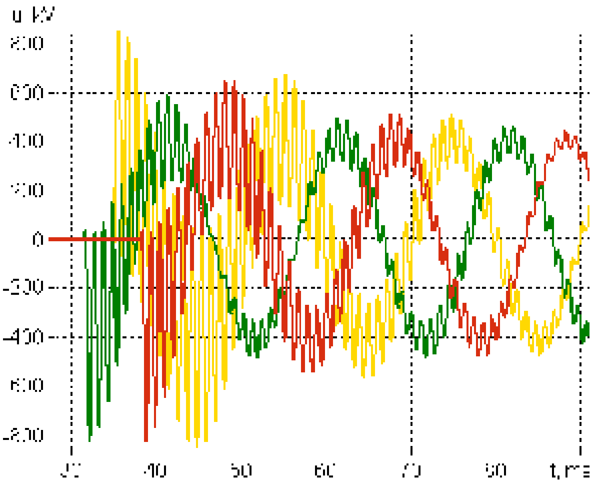

Figure 8: Waveforms of the voltage across the contact breaker

Wave front durations of both voltages (on reactor winding and across contacts of breaker) were equal T_f = 350 μs.

In the most severe case with the current cutoff 10 A, the estimated value of the voltage across the breaker contacts rose up to 976 kV. The manufacturer guarantees the nominal level of switching impulse withstand voltage between the contacts 900 (+450) kV for breaker type HPL550B2, in accordance with requirement the IEC standard. The power frequency voltage on one pole of circuit breaker is indicated in parentheses. According to the native standard [3], the switching impulse withstand voltage between the contacts has to be not less than 1660 kV.

The value of recovery voltage on the contacts of circuit breaker is at approximately 2 times less than the own dielectric strength of the restoring intercontact gap. For this reason the repeated breakdowns in intercontact gap are extremely low probable.

The numerical simulation showed the insulation of the reactor is not affected by overvoltage exceeding the level of test voltage. The use of devices for controlled switching reduces the value of overvoltage in 1.2-1.3 times in comparison with the most severe regime.

However, the recorded oscillations are significantly different from the standard switching impulse. For example, when you turn on the winding of the reactor affected by oscillations from the front of 30 μs and a frequency of 12.5 kHz. Therefore it is not correct to assume that the impact of this oscillation on the insulation is the same as of the standard switching pulse.

Conclusion. The experimental data and numerical simulations have shown that the appearance of switching overvoltage of large amplitude is unlikely in such circuits.

REFERENCES

[1] GOST 1516.3-96 (2003). Electrical equipment for a.c. voltages from 1 to 750 kV. Requirements for dielectric strength of insulation.

[2] GOST R 52565-2006. Alternating-current circuit-breakers for voltages from 3 to 750 kV. General specifications.