Transients Due to Switching of 400 kV Shunt Reactor

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Abstract - **Transients phenomena originating from switching of high voltage shunt reactor with solidly earthed neutral are considered. Two reactors (100 MVAr and 150 MVAr) were compared on the basis of results obtained from calculations of the transients. The unsymmetrical phase inrush currents during a shunt reactor energizing and overvoltages provoked by current chopping and reignition of electrical arc are analyzed. Successful synchronous switching can reduce the mechanical and electromagnetic stresses endured during normal switching operations.**

Keywords: Shunt reactor, Switching operations, Inrush currents, Chopping Overvoltages, Recovery voltage, Reignition, Controled switching.

I. INTRODUCTION

High voltage shunt reactors switching belongs to the normal system operations that can be performed several times a day.

Because of the shunt reactor technical characteristics and their special purpose, its current is mainly inductive and can be referred to as a small inductive current. It is considerably smaller (10 or 20 times) than nominal currents of today most commonly used SF_6 circuit breakers, and even up to 200 times smaller than the expected short-circuit currents.

The preliminary analysis of the switching operation with the first 400 kV shunt reactor designed for the Croatian transmission system is conducted. A high voltage reactor is relatively frequently switched: during the periods of the system operations with low loads it is energized and with the rise of load it is de-energized again. Shunt reactors switching operations result in electromagnetic transients and some mechanical effects. At closing, high, unsymmetrical currents with long time constant can occur. During opening, interruption of small inductive currents (current chopping) will cause overvoltages. Reignition between the circuit-breaker contact gap can lead to very steep overvoltages that represents a special problem.

The above mentioned transient phenomena are the main concern of this paper.

II. ENERGIZING OF HV SHUNT REACTORS

Unsymmetrical phase inrush currents occuring at HV shunt reactor energizing depend on the time instant of circuit breaker pole operation with respect to the reference signal. Switching operations at unfavorable instants can cause currents that may reach high magnitudes and have long time constants. During HV shunt reactor energizing, mechanical vibrations and buzzing of transformers were observed. At shunt reactors with solidly grounded neutral, unsymmetrical currents cause zero-sequence current flow which can activate zero-sequence current relays.

Current asymmetry becomes smaller if the circuit breaker closes near the maximal value of the power frequency voltage. On the other hand this causes switching overvoltages. Dielectric stress of reactor insulation caused by the very steep overvoltages originated from circuit breaker contact gap prestrike immediately before closing is similar to that caused by the reignition after reactor de-energizing with voltage across the circuit-breaker interrupter of 1 p.u. However, it is impossible to obtain reduction of inrush currents and stresses originated from the overvoltages during switching operations at the same time. It remains on the user to find the most acceptable solution.

A high voltage shunt reactor with the associated equipment is planned to be installed in the 400 kV switchyard, as shown in the simplified single-line diagram, Fig. 1., while in Fig. 2. the corresponding computer model scheme is presented.

The inrush currents at energizing of 100 MVAr and 150 MVAr HV shunt reactors have been observed for two cases: switching at a random small value and near the peak value of the phase voltage.

Parameters for the reactor with rated power 100 MVAr were L = 5.093 H/phase, C = 2 nF/phase and for the reactor with rated power 150 MVAr, L=3.395 H/phase, C = 2.6 nF/phase. The high voltage 400 kV circuit breaker consists of two breaking chambers. Across each a potential grading capacitor of C = 500 pF is connected.

Inrush currents can be expressed in the p.u., where 1 p.u. equals I_{Max}, which obtains following values, depending on the HV shunt reactor size:

$$\text{- 100 MVAr,}\quad I_{Max} = I_n\sqrt{2} = 205A \tag{1}$$

$$\text{- 150 MVAr,}\quad I_{Max} = I_n\sqrt{2} = 307A \tag{2}$$

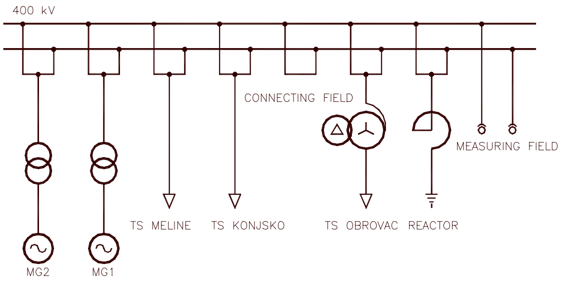

Fig.1. Single-line diagram of the 400 kV switchyard.

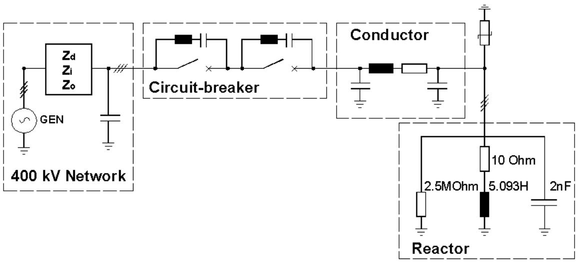

Fig.2. Equivalent circuit for 100 MVAr reactor, circuit breaker and network.

Maximal inrush currents obtained when energizing HV shunt reactor at a random small value of the phase voltage were:

- 100 MVAr, $I_{Max} = 2.09\ p.u.$ $\mathrm{I}_{0\max} = 0.975\,\mathrm{p.u.}$ t = 1.3 s
- 150 MVAr, $I_{Max} = 2.05\ p.u.$ $I_{0\max} = 0.970\ p.u.$ t = 1.0 s

where t represents approximate duration of the unsymmetrical currents.

The maximal inrush currents obtained when energizing HV shunt reactor near the peak value of the phase voltage were:

-100 MVAr, $I_{Max} = 1.57\ p.u.$ $I_{0\max} = 0.527\ p.u.$, t = 0.75 s

-150 MVAr, $I_{Max} = 1.49\ p.u.$ $I_{0\max} = 0.515\ p.u.$, t = 0.6 s.

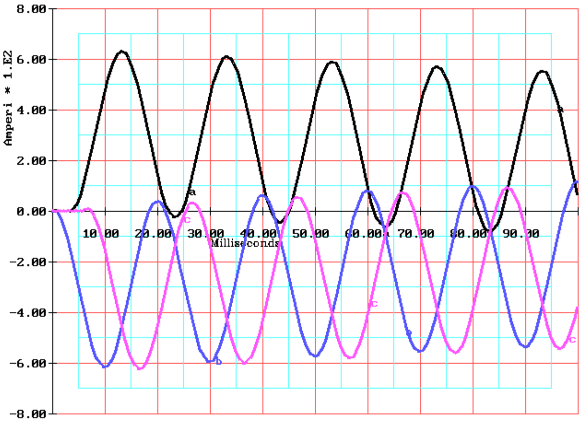

Fig.3. Initial inrush currents at energizing of 150 MVAr shunt reactor.

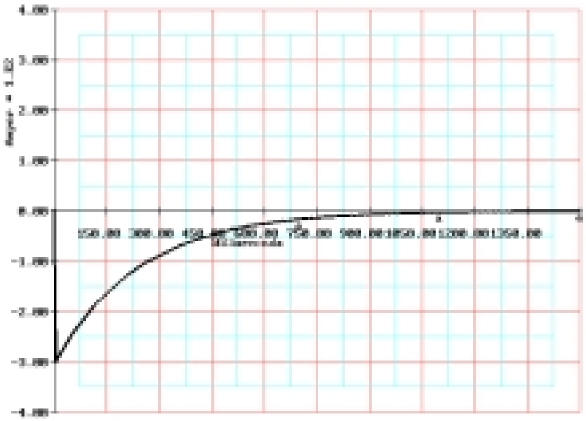

Fig.4. Zero-sequence current at energizing of 150 MVAr shunt reactor.

The closing time instants of the circuit-breaker contacts influence values of the switching currents and the duration of the unsymmetrical currents. Controlled closing of the circuit breaker has a significant influence on the switching currents magnitudes and on the current asymmetry.

III. DE-ENERGIZING OF HV SHUNT REACTOR

When interrupting small inductive currents, the medium used for arc extinguishing will develop fast increase of the residual column resistance, and abrupt current interruption before its natural zero crossing occurs. Release of energy stored in the reactor inductance will cause the electromagnetic transients that lead to the switching overvoltages.

The switching overvoltage can be dangerous for the equipment if their peak value surpasses the rated switching impulse withstand voltage of the equipment. Before making a decision about the choice of equipment or the technical solutions of the facilities, it is very important to know the level of dielectric stress that can occur during operation in the system in order to avoid insulation failures.

The electric arc in the high voltage 400kV circuit breaker was simulated with its conductance-dependent parameters. The method is based on the Cassie and Mayr-arc-equation:

$$\frac{dg}{dt} = \frac{1}{\Theta(g)}\left(\frac{i_s^2}{P(g)} - g\right) \tag{3}$$

where g is the arc conductance, i_s is the switching current, P is the arc cooling power and Θ is the arc thermal time constant. Parameters P and Θ are conductance dependent. P is defined for two rates that correspond to the ignition and burning phase:

$$\text{- Ignition: } P_i = 23 g^{0.748} \quad (MW) \tag{4}$$

$$\text{- Burning: } P_b = 387 g^{2.5} \quad (MW) \tag{5}$$

In calculations a constant value of $\Theta = 1\mu\mathrm{s}$ was used. Parameters P_i, P_b and Θ are selected as recomended in [1].

Switching overvoltages that can occur during normal reactor switching operations place additional demands on the dielectric strength of the equipment.

A. Chopping Overvoltages

If the current is chopped before its natural zero crossing, in the reactor remanent accumulated energy has to be released through the oscillations in the L-C circuit. The overvoltage is caused by the release of magnetic energy stored in the reactor inductance at the moment of current chopping.

Chopping overvoltages during de-energizing of reactors with nominal powers of 100 MVAr and 150 MVAr have been analyzed.

Field tests on the existing 400 kV switchyards with similar reactors and circuit-breakers [2], have shown that the values of the chopping current will typically range from 2 to 14 A.

Fig.5. shows voltage oscillograms after current chopping for the 100 MVAr reactor. Capacitive and inductive interphase coupling can be observed. In the foregoing interrupted phase, there will be an increase in oscillations after the second and third pole clearance. However they do not exceed the value of the first maximum. Voltage in the phase which was last interrupted, decreases with an exponential factor. The oscillation frequency was approximately 1500 Hz for 100 MVAr reactor and around 1600 Hz for the 150 MVAr reactor.

Transient recovery voltage will be established across the circuit breaker contacts after current interruption. Its maximal expected value is equal, if damping is neglected, to the sum of the peak voltages of the source and overvoltage provoked by current chopping.

For the 100 MVAr reactor the highest suppresion peak overvoltage factor was 2.05 p.u. but only when surge arrester was not connected. With connected surge arrester this overvoltage factor never exceeded 1.5 p.u. Overvoltage factors in the cases with 150 MVAr reactor were lower, as it would be expected. Without surge arrester the overvoltage factor was 1.67 p.u., and with connected surge arrester 1.47 p.u.

In all cases switching overvoltages were lower than the peak value of the switching impulse withstand voltage of the isolation (1050 kV, wave shape 250/2500 µs). As a result of the low oscillation frequency on the reactor side (around 1.5 kHz), the overvoltage slope is gentle and is equally distributed along the winding, what results in small potential differences between turns.

It is suggested [3] that maximal switching overvoltages between the circuit-breaker contacts generated by current chopping should not exceed 80% of the peak value of the switching impulse withstand voltage which is 3.63 p.u. (900 kV+345 kV).

With connected surge arrester computed ovevoltages in all cases were below recommended values. Maximal recovery voltage on the circuit breaker contacts was $k_r=2.5\ p.u$ (69% of the rated peak value).

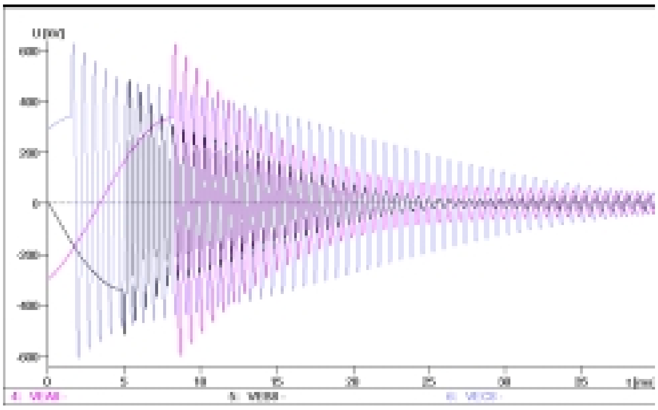

Fig.5. Chopping overvoltages on the reactor 100 MVAr.

B. Reignition Overvoltages

Reignition overvoltages are generated by the reignition following the initial interruption and arc extinction. Reignitions are provoked when the recovery voltage across the circuit breaker contact gap exceeds the dielectric withstand of the residual column.

Reignition can be usually expected near the peak value of the recovery voltage. In that moment the voltage difference across the circuit breaker is around 2 p.u. If reignition occurs at that moment, the voltage across the reactor will very rapidly assume the value of instantaneous voltage on the network side. The transient voltage across reactor can surpass 1 p.u., and because of its oscillating nature can assume the opposite polarity with a value between 2 p.u. and 3 p.u.

For an analysis of dielectric stresses of the reactor insulation, besides overvoltages to the ground, the differences in voltages between the two consecutive peak values of the opposite polarity after reignition need to be considered.

Several reignitions may occur before the final arc-extinction. This phenomenon is denoted as voltage escalation, and can occur when interrupting currents with very steep slopes at the zero crossings. In praxis it was observed that in some cases reignition lead to circuit breaker interrupter damage (nozzle, contacts). For this reason, and since it may also affect shunt reactor insulation, it is desirable to eliminate reignition occurrence.

The occurrence of reignition depends on the shunt reactor current to be switched. The lower the inductive current, the higher possibility of reignitions.

Overvoltages caused by reignitions depend greatly on the network configuration and on the circuit-breaker characteristics. They expose the shunt reactor and other device insulation to stresses similar to those of lightning overvoltages.

In computer simulation elements of the substation are modeled with their surge impedance and corresponding length, similar to the study of lightning overvoltages. Calculations were conducted with and without connected surge arresters, to observe their protective influence.

Reignition was observed for the 100 MVAr and 150 MVAr reactors under the same conditions. In Fig.6. the voltage oscillogram obtained during reignition after reactor de-energizing, without MO surge arresters is shown. The maximal overvoltage across reactor evolves immediately after reignition. Transients are strongly damped and oscillation frequency on around 400 kHz can be noticed. The voltage slope is very steep as the change between the two, consecutive peak values of the opposite polarity lasts less than 1µs.

Calculation results are given in the Table 1. The highest overvoltage of 703 kV appears, as it could be expected, when the 100 MVAr reactor is de-energized without connected surge arresters. With connected surge arresters voltage across reactor to the ground is lowered on 655 kV. The voltage rate of rise (kV/µs) between the positive and negative peak value was approximately thesame in both cases.

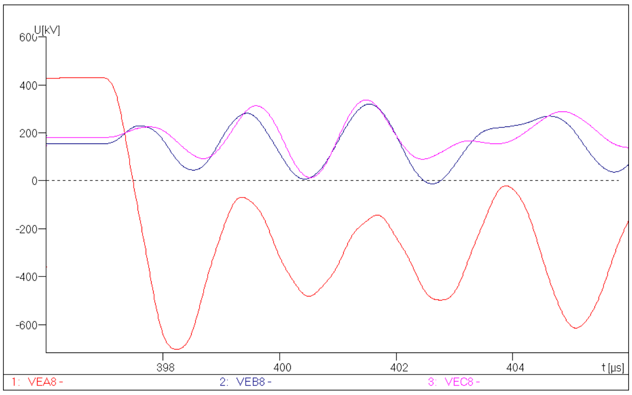

Fig.6 Reignition after 100 MVAr reactor de-energizing, without MO surge arresters connected at the reactor.

Table 1. Overvoltages caused by reignition

Reactor	Surge arrester	U_{MAX} (kV)	$S_{av}(kV/\mu s)$
100 MVAr	No	703.5	1322
	Yes	654.8	1320
150 MVAr	No	666.6	1159
	Yes	632.7	1155

When reactors were protected with surge arresters overvoltages to the ground were never critical. In all cases the voltage rate of rise on the reactor was very steep.

The protective influence of the surge arresters can be observed in limiting overvoltages caused by current chopping. In this way reignition is indirectly avoided. However, the surge arresters have practically no influence on the voltage steepness.

It can be seen that the surge arresters can limit peak values of overvoltages, caused by current chopping and reignitions to an acceptable level that will not cause insulation damage. In all cases overvoltages caused by reignition had smaller peak value than the nominal lightning impulse withstand voltage U_w =1425 kV, with wave shape 1.2/50 µs.

For the reactor insulation, however, the voltage rate of rise is more dangerous than its peak value. For transients caused by reignition the period of the wave crest usually lasts from one to couple of microseconds. Very steep overvoltages are distributed unevenly along the reactor winding and the first few turns are exposed to the largest potential differences. Overvoltage slopes during reignitions, critical for insulation, are smaller for the 150 MVAr reactor.

At reignition, the electric arc resistance decays very rapidly and in a few nanoseconds drops to a couple of Ohms. Basically, such a fast change has no influence on the voltage slope, although it slightly reduces overvoltage value. The acceptable voltage rate of rise can be defined from the slope of the standard 1.2/50µs wave. The average steepness of the nominal lightning impulse withstand voltage, with peak value of 1425 kV, is determined in the interval between 30% and 90% of the crest value. During that interval (t=0.72µs), wave can be approximated with a straight line.

Average steepness is:

$$S_{av} = \frac{(0.9-0.3)\cdot 1425kV}{0.72\mu s} = 1187\frac{kV}{\mu s} \qquad (8)$$

To avoid accelerated wearing of the insulation, safety factor of 0.65 is recommended [4], which corresponds to the crest value of the standard wave limited to 65 %. In that case average rate of change becomes:

$$S'_{av} = 0.65\cdot S_{av} = 772\frac{kV}{\mu s} \qquad (9)$$

The initial part of the standard wave limited to 65% can be described with the following function:

$$u(t) = 463kV(1-\cos\omega t) \qquad (10)$$

with a half-cycle T/2 = 1.2 µs, frequency of 417 kHz and crest value of 926 kV.

The maximall instantenuous rate of change determined for the same case may be obtained from:

$$S_{\max} = \frac{du(t)}{dt} = 1211\frac{kV}{\mu s} \qquad (11)$$

It is assumed [4] that insulation can withstand such an overvoltage rate of rise applied twice a day.

In the computer simulations conducted, the maximum overvoltage slopes were steeper or close to recommended values and as such represent the danger for the reactor insulation, since a high frequency transient is unevenly distributed along the reactor winding, stressing the incoming turns with high interturn voltages. It has to be considered that the reactor switching operations can be performed several times a day. Frequent exposure to those overvoltages causes aging and wearing of the insulation and the application of measures for their limitation is recommendable. The internal reactor insulation is class A (paper in oil), that is not self-renewable. Even the testing voltages that do not cause damages can influence the insulation characteristics. Because of the testing limitations, there are no statistical data about the real withstanding voltage level for the equipment.

IV. SHUNT REACTOR CONTROLED SWITCHING

All circuit breakers exhibit a high probability of reignition for arcing times shorter than $T_{a\ min}$ (maximal arcing time at which reignition is still probable). Provided the arcing time can be controlled such that it exceeds $T_{a\,min}$, the probability of reignition is practically negligible.

Small inductive current interruption is similar to that of no load and may be approximated by the cold gas dielectric recovery characteristic [5]. The increase of power frequency (50 Hz) withstand voltage as a function of time and contact gap for cold SF_6 gas can be, based upon experiments on a 400 kV circuit breaker, approximated by equation [6]:

$$U_d(d) = 10 \times 10^{-3} d^2 + 20.7d + 7.1 \qquad (12)$$

with $d = v \times t$, where U_d is the circuit breaker contact gap withstand voltage, d is the contact gap at a time instant t *(ms)* and v is the contact velocity at opening (9 m/s for the study case circuit breaker).

Dielectric recovery characteristic for the cold gas is shown in Fig.7.

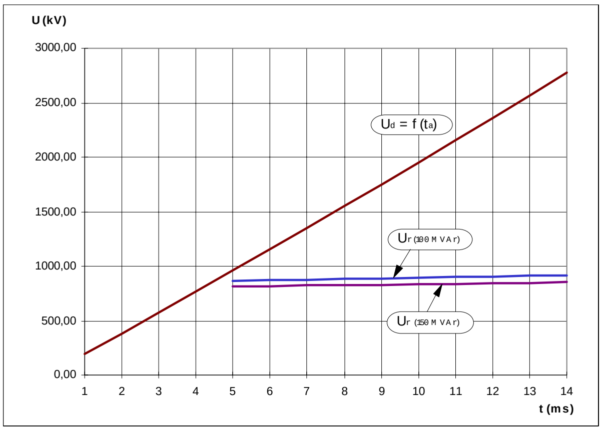

Fig .7. Dielectric recovery charact. for the cold gas

In the same figure, recovery voltage (U_r) characteristics as a function of arc duration, i.e. chopping number λ (in the range 5 ms < T_a < 14 ms), for both study case shunt reactors (100 MVAr and 150 MVAr) are shown. It can be seen that the probability of reignition is inversely proportional to the arcing time T_a and shunt reactor rated power.

For the study case circuit breaker, chopping number λ, based on the experimental records in accordance with IEC 61233, can be approximated by the equation:

$$\lambda_{mean} = (0.22T_a + 9) \times 10^4 \qquad A/\sqrt{F} \qquad (13)$$

within the range of arcing times 5 ms < T_a < 14 ms, and with the standard deviation $s = 0.8 \times 10^4$.

A principle of synchronous trip operation is shown in Fig. 8.

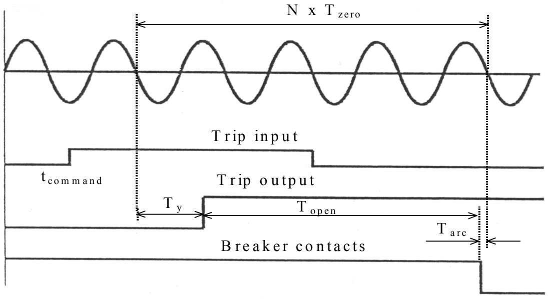

Fig. 8. The principle of synchronous trip operation

The circuit breaker switching command is a random event with respect to the reference signal, at a time instant $t_{command}$. As soon as the command is received, the synchronous control device is blocked and a time delay is initiated awaiting the first voltage zero crossing. After initial checking and calculations, the controller triggers off count-down of intentional synchronizing delay (T_y) determined by the opening time (T_{open}) and a targeted contact separation instant with respect to current zero crossing at which extinguishing occurs. This delay can be, in simple terms, expressed by the equation:

$$T_y = N \times T_{zero} - T_{arc} - T_{open} \qquad (14)$$

where N is an integer number of half cycles, T_{zero} is half cycle duration calculated immediately before synchronous delay calculation, T_{arc} is an arcing time and T_{open} is a mechanical opening time. The calculation is performed for each phase separately, taking into account initial values measured at site at the circuit breaker commissioning and values measured immediately before delay calculation.

Similar considerations are valid for the shunt reactor close operation.

In accordance with the study case circuit breaker experimental record [2], the longest arcing time at which reignition still occurred was $T_{a\,min} \approx 7.5$ ms. Consequently, the synchronous switching controller shall be set in a way to enable circuit breaker contact separation at the time instant $t_{separate}$ = 8 ms prior to the natural current zero crossing (T_{arc} = 8 ms), when reignition occurrence is improbable.

Assuming the power frequency equals 50 Hz and initial parameters for the study case circuit breaker: T_{open} = 25 ms; T_{arc} = 8 ms, a simplified calculation gives the synchronous trip delay: T_y = 7 ms.

Chopping number for T_{arc} = 8 ms equals to $\lambda_{max} = 12.36 \times 10^4$ A/√F. The magnitude of the suppression peak overvoltage for worse case (shunt reactor 100 MVAr) will be approximately equal to:

$$k_{a_{\max}} = \sqrt{1 + \frac{3N\lambda_{\max}^2}{2\omega Q}} = 1.57\,p.u. = 538.5\,kV \qquad (15)$$

and the magnitude of recovery voltage across the circuit breaker:

$$k_{r_{\max}} = 1 + k_{a_{\max}} = 2.57\,p.u. = 881.5\,kV \qquad (16)$$

Both values, even if MO surge arresters were not taken into consideration, are below the allowable values.

The reignition and voltage escalation will not occur since the synchronous switching controller allows the contact separation at the time instant for which reignition is improbable after natural current zero crossing.

Regarding circuit breaker close operation, contact gap pre-strike will occur when the voltage magnitude reaches the peak value, with arc duration up to 5 ms (1/4 cycle) prior to contact touch. With such closing, inrush current is maximally reduced. Since it is impossible to achieve simultaneous reduction of inrush current and insulation stress due to steep voltage transient at prestrike, the compromise solution is to be reached.

Experiments have shown [7] that at synchronous switching of circuit breaker with independent poles a phase inrush current can be limited to less than 1.5 p.u. with the zero-sequence current lower than 0.5 p.u. Thus, mechanical stresses of the shunt reactor and adjacent transformers are reduced and false operation of zero-sequence current protection prevented.

V. CONCLUSION

Switching operations of shunt reactor are relatively frequent and primarily depend on power network loading. With regard to its inductive character, switching of shunt reactor rated current results, without exceptions, in transients that can jeopardize insulation of shunt reactor itself and other switchyard elements, and create mechanical stresses.

Conducted computer simulation, based on real switchyard, shunt reactor and other apparatus technical data, has suggested the following conclusions:

- switching transients are inversly proportional to the shunt reactor rated power;
- chopping overvoltages at de-energizing, without reignition, never exceeded the insulation switching impulse withstand voltage (1050 kV, 250/2500 μs), since MO surge arresters provide low voltage level;
- dependant on contact separation instant with respect to the natural current zero crossing, after current chopping, the reignition voltages that developed had lower peak value than insulation lightning impulse withstand voltage (1425 kV, 1.2/50 μs);
- calculated reignition transients steepnesses were bigger or close to recommended values (eq. 9&11) and represent danger for reactor insulation;
- surge arresters have practically no influence on overvoltage steepness;
- shunt reactor energizing may produce either mechanical stress (inrush current) or dielectric stress (prestrike);
- since frequent exposure of shunt reactor insulation to transients, especially steep reignition overvoltages accelerates aging and wearing, means for their limitation are recommended;
- shunt reactor controlled switching can influence (reduce) inrush current magnitude or prestrike overvoltage at energising and decrease or completely eliminate the probability of circuit breaker reignition at de-energising.

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