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Tripping Overvoltages in HV Transmission Networks Equipped with Shunt Reactors

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***Abstract*—Last years meant for Romanian power system huge efforts for increasing of its reliability and stability. A national program sustained financially a large-scale upgrading process of power system components. In this paper the authors present the results of an analysis regarding operation of different versions of equipments included in a HV substation. The performed tests outlined the dependency between the chopping current and the overvoltages rising due to switching-off operation of a shunt reactor in the presence of different types of circuit breakers. Further decisions about upgrading the substation components were based on these test results.**

***Index Terms*—compensation reactor, current chopping, high-voltage networks, transitory overvoltages.**

I. Introduction

THE compensation reactors are elements of great importance for the operation of the power transmission networks. Therefore they ask for a proper protection against the abnormal operation.

The analysis of a certain number of faults outlined the fact these are the effect of the insulation local damaging following the transitory overvoltages.

There can be mentioned some particularities of the switching operation of the compensation reactors:

- The interrupted current is equal to the rated current of the reactor, so that much lower than the breaking current of the circuit breakers with the lowest performances.
- There are some situations in which the current interruption is achieved shortly before the moment of the natural zero crossing; this phenomena is named *current chopping*.
- Due to the high value inductance of the reactor, the stored energy of magnetic nature is transferred to the own capacitance of the reactor, as well as to the other elements of the circuit. This is leading to an enhancing of the terminal voltage. This high value voltage means a hard stress for the reactor insulation.
- Depending on the circuit breaker performances and some random parameters (the moment of contacts opening with respect to the voltage zero crossing, the distance between contacts at the moment of current interruption, etc.) the arc in the circuit beaker can re-ignite. In this situation additional strains can be induced (voltages with high speed variation), influencing mostly the insulation of the reactor's first windings [1]. The current chopping is the consequence of the arc instability. This one is performing as a current oscillation of high frequency and rapidly increasing magnitude, overposed on the 50 Hz current component [2, 3].

So that, the zero crossing of the current arises sooner than the moment of the natural zero. At the zero crossing, according to the operation principle of the circuit breaker, the current is interrupted [4, 5].

The value associated to the 50 Hz current at its zero crossing moment is named *chopping current* (i_{chopp}).

The chopping current value depends on many parameters, the most important being [1, 5, 6, 7, 8]:

- The arc extinguish environment;
- The number of extinction chambers series connected on phase (the interrupted current value increases with the number of chambers on pole);
- The value of the equivalent capacitance related to the circuit breaker terminals (the bigger is the capacitance, the bigger is the chopping current).

II. Modeling of Overvoltages Resulted at Compensation Reactor's Switching Off

In order to analyze the chopping phenomena of the current and voltage resulting at the compensation reactor terminals after switching off, two equivalent circuits can be used, one for each of the state before, respectively after the arc extinction in power circuit breaker, as in Fig. 1 can be seen.

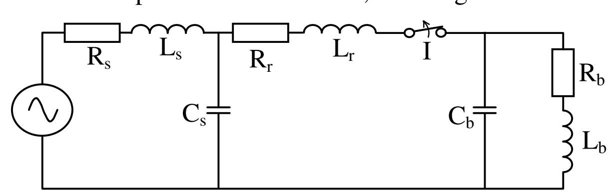

Fig. 1. Equivalent circuit before the arc extinction in power circuit breaker

In the previous configuration, three circuits can be distinguished:

a. The power source's circuit: R_s, L_s, C_s;
b. The circuit of the shunt compensator reactor: R_b, L_b, C_b;
c. The circuit of the circuit breaker wiring: R_r, L_r, I.

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According to numerous theoretical studies based on stability criteria in C_s–R_r–L_r–I–C_b circuit, as well as those using different models of the arc in circuit breaker, there was outlined a minimum instantaneous current for which the arc is stable. If the current value decreases bellow this limit, the arc instability exhibits by high frequency oscillations of the current (the circuit resonance frequency) overlaped on the 50 Hz current. The amplitude of these oscillations rises in time, so that the resulted current will reach the zero value before its natural zero pass. At this moment, the arc in circuit breaker is extinguished, as it is shown in Fig. 2.

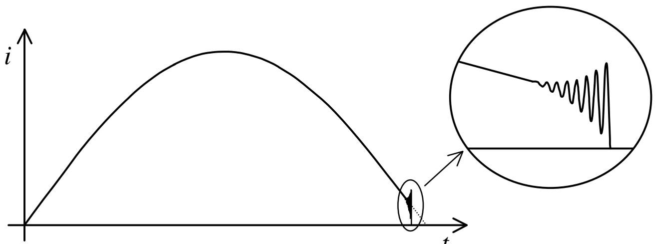

Fig. 2. Current evolution during arc breaking

The oscillations' frequency in the circuit of the shunt compensation reactor is low due to high value of reactor inductance. This one does not allow the current through reactor to decrease at the same time as the current through the circuit breaker. Therefore, when the circuit breaker splits the circuit, the shunt reactor is crossed by a current almost equal to that at the oscillations damping This current generates oscillatory phenomena damped in R_b–L_b–C_b circuit and produces overvoltages.

The possible theoretical maximum value is given as following:

$$U_{\max} = \sqrt{U_{ph,\max}^2 + \frac{L_b}{C_b} i_{chopp\max}^2} \tag{1}$$

where $U_{ph,max}$ is the peak value of phase voltage;
$i_{chopp\,,max}$ – maximum value of the chopping current;
C_b - total capacity of the reactor and equipments connected to the breaker terminal;
L_b - total inductance of the reactor and connection.

The maximum value of the chopping current is impossible to be practically determined. This aspect makes difficult to model the maximum voltage. The experimental evaluation is quite difficult due to the high frequency and the low value of the chopping current related to the amplitude of the normal steady-state current. Even in that case the chopping current is experimentally measured, its value can be much lower than the maximum possible value due to the fact the phenomena are not replicable. For each measurement different value is obtained. This is because the influence of some random factors internal or external to the circuit breaker: the moment of contact part related to the current pass via zero value, pressure and stretch variations in circuit breaker, the arc length, harmonics of the supply voltage, etc.

III. MEASUREMENTS RESULTS IN THE TEST NETWORK

A couple of measurement sessions were performed by a team of the High Power Laboratory ICMET Craiova (Romania), in order to determine the behavior of a high voltage substation of Romanian power system.

The analyzed substation was included in a large national rehabilitation program. The study meant to outline the performances of substation endowed with the old equipments, as well as with the new ones.

The configuration of the high voltage substation on which the tests were performed is given in Fig. 4.

A set of experimental results was achieved for a compensation reactor of DFAL 8056 400 kV/100 Mvar type, with the following characteristics: 400 kV nominal, 144.3 A, 50 Hz; inductance: 5.017 H (medium value); phase to earth capacitance: 3531 pF (medium value); (longitudinal) phase winding capacitance: 345 pF (medium value).

In order to compare the different loads of the compensation reactor during the switching off operation, the following equipment solution were analyzed:

- circuit breaker with minimum oil IO 400 kV/1600 A;
- SF_6 circuit breaker of HPL 400 kV/1600 A type (ABB product) – for old version of substation;
- SF_6 circuit breaker of HPL 400 kV/1600 A type, endowed with device for synchronized switching of SWITCHSYNC F236 type - for upgraded version of substation.

IV. RESULTS IN THE CASE OF SWITCHING-OFF USING THE MINIMUM OIL CIRCUIT BREAKER

In the case of IO type circuit breaker there was constantly obtained current chopping on each phase, joined by simple or multiple re-ignitions of the arc in the circuit breaker. A typical experimental current shape-form is given in Fig. 3.

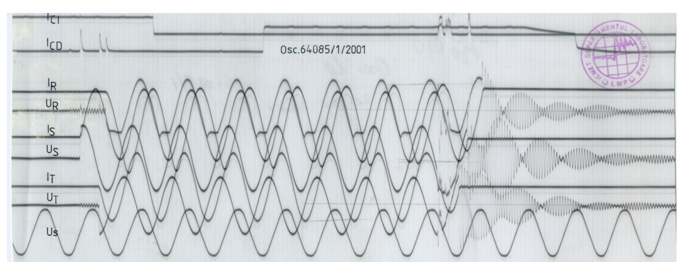

Fig. 3. Experimental current at the reactor switching off in the case of IO circuit breaker

The maximum value obtained for the overvoltage factor k was 2.32, bellow the maximum value admitted by norms (k=2.478) [9], but close to that.

Because the chopping current was small by comparison with the normal current, it was not possible to determine its value according to the experimental current shape-forms.

Nevertheless it was indirectly computed, according to the maximum value of the voltage (2):

$$i_{chopp} = \sqrt{\frac{C_b}{L_b}\left(u_{\max}^2 - u_0^2\right)} \tag{2}$$

where i_{chopp} is the chopping current;
u_{max} - maximum voltage after chopping;
u_0 - voltage at the moment of current interruption.

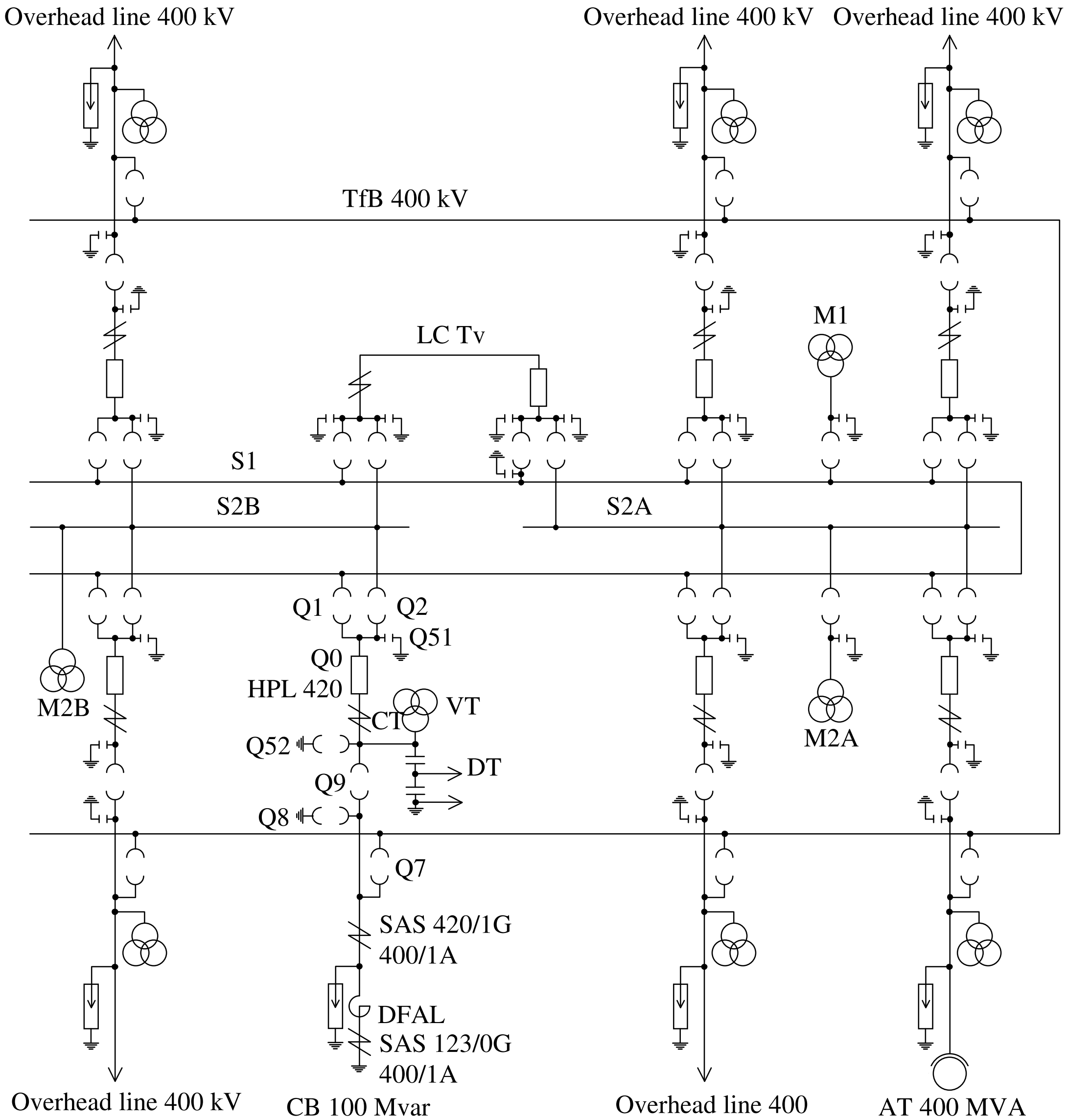

Fig. 4. The configuration of studied high-voltage substation

The obtained values for the chopping current are given in increasing order in Table I.

TABLE I
VALUES CALCULATED FOR CHOPPING CURRENT

No.	1	2	3	4	5	6	7	8	9
$i_{chopp}(A)$	7.8	8.3	9.7	9.8	10.4	10.7	10.8	11.2	11.3
No.	10	11	12	13	14	15	16	17	18
$i_{chopp}(A)$	11.5	11.6	11.8	12.1	12.7	12.8	12.9	13.4	13.9

The dependency between the number of achieving of chopping current, N and its values, i_{chopp}, is depicted in Fig. 5.

The high number of registered choppings made possible to perform a statistic data analysis. This one results in the maximum probable value of the chopping current.

The estimators for the medium value of the chopping current, $i_{chopp,ned}$ and standard deviation, s_1, are given by (3) and respectively, (4):

$$i_{chopp,med} \approx \frac{\sum_{j=1}^{N} i_{chopp,j}}{N} = 11.26 \text{ (A)} \tag{3}$$

$$s_1 \approx \sqrt{\frac{\sum_{j=1}^{N} \left(i_{chopp,j} - i_{chopp,med}\right)^2}{N-1}} = 1.6525 \text{ (A)} \tag{4}$$

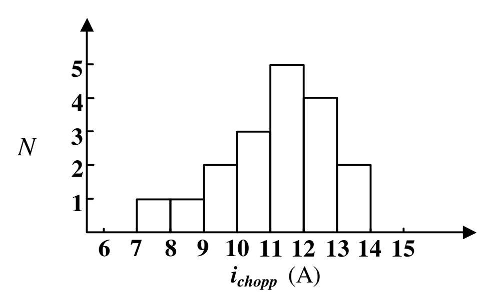

Fig. 5. Dependency value of chopping current–number of chopping achieving

There is considered that the obtained data correspond to a normal repartition, given by (5), (6):

$$f_I(i;\mu,\sigma^2) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(i-\mu)^2}{2\sigma^2}} \qquad (5)$$

$$F_I(i;\mu,\sigma^2) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{i} e^{-\frac{(z-\mu)^2}{2\sigma^2}} dz \qquad (6)$$

where: $\mu \cong i_{chopp,med}$ and $\sigma \cong s_1$.

In this case a maximum current is obtained, with a probability of appearance bigger than 1 % of 15.1 A. Due to the high number of switching performed by the reactors during its exploitation, the 1% probability cannot be neglected.

V. Results regarding switching-off using the SF_6 circuit breaker

In the case of a SF_6 circuit breaker, the number of current choppings is much smaller (usually on only one phase of the breaker). During this measuring session, no re-ignition of the arc in the breaker resulted. The results obtained in case of switching off using the SF_6 circuit breaker without and with synchronization device are depicted in Fig. 6, and respectively Fig. 7.

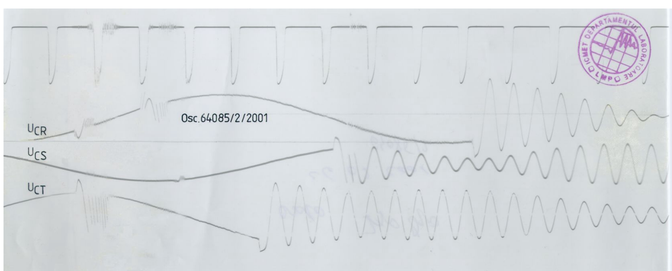

Fig. 6. Experimental current at the reactor switching off in the case of HPL circuit breaker without synchronization circuit

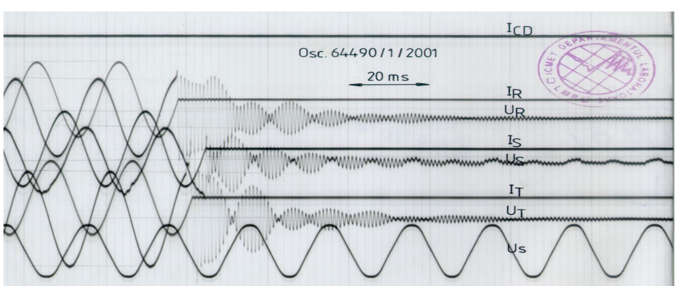

Fig. 7. Experimental current at the reactor switching off in the case of HPL circuit breaker with synchronization circuit

The maximum values of the overvoltage factor were 2.29 for the breaker without synchronization device and 1.89 in case with synchronization device. Due to the small number of registered choppings made irrelevant a statistical analysis of the results. Nevertheless some much smaller differences between the values of the chopping currents could be observed. It can be stated that the standard deviation is smaller than in case of IO circuit breaker.

VI. Conclusion

The results achieved after measurement session and based on a charging modeling led to the following conclusions:

1. In the case of IO circuit breaker (minimum oil circuit breaker) the switching overvoltages had the highest values (574.1 kV, k=2.32).
2. The dispersion of the chopping currents is very high. In case of a great number of tripping the values of the switching overvoltages can be even bigger. Such value was obtained by simulation (for a 15 A chopping current, a k- factor equal to 2.58 was obtained, bigger than norms prescriptions).
3. Currently simple or multiple re-ignitions are obtained on one or more phases. These ones generate rapid overvoltages, with values bigger than those associated to current choppings.
4. Using of the SF_6 circuit breaker without synchronization device leads to measured overvoltages smaller than in the first case (561.04 kV, k=2.29). Some current choppings appear, but their values are also smaller than in the case of the minimum oil circuit breaker, due to the dependency of the chopping current on the number of arc chambers series connected.
5. Neither re-ignitions of the electrical arc appear and consequently, nor rapid transient voltages of high values.
6. Using of the synchronization device leads to decreasing of the arc burning time in the circuit breaker. The arc will extinct at the first zero crossing after contacts separation, so that the arc will burn 10 ms the most.
7. In the case of SF_6 circuit breaker, the chopping current grows with the arc time. Consequently, the overvoltages are smaller for the minimum chopping current as in the case of SwitchSynch device using. This observation was extracted according to the experimental session, when for all measurements with synchronization device the resulted overvoltage factors have values smaller than 1.9 (k < 1.9).

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VIII. Biographies

Marian Ciontu graduated Electrical Engineering in 1980 and received in 1995 M.Sc. in Informatics from University of Craiova, Romania. In 2000 he received the Ph.D. degree in Electrical Engineering from University "Politehnica" of Bucharest.

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