EMTP MODELS FOR SIMULATION OF SHUNT REACTOR SWITCHING TRANSIENTS

L. PRIKLER G. BÁN G. BÁNFAI

Technical University of Budapest, Department Electric Power Systems
H-1111 Budapest, Egry J.u.18., Phone/Fax:+36 1463 -3015 / -3013
E-mail:priki@vmt.bme.hu

Abstract: *Long EHV transmission lines are generally compensated by means of shunt reactor sets. Reactor failures directed attention to the transient overvoltages generated by reactor switching off. A possible reason of such damages has been confirmed by site test performed in the 750 kV substation. This test has also strengthened that arrester operations or circuit breaker restrikes could cause in particular dangerous steep reactor voltages. The paper introduces a comprehensive EMTP model of the reactor and its surrounding system (busbar, breaker, arrester, transformer, supply side network behind the reactor). The computer model has been proved by field experiments. Similar computer model has been elaborated for the study of transients, caused by deenergizing reactors connected with the 18 kV tertiary winding of the 420/132 kV autotransformers. The model has been validated at pushing into service test of a new air core shunt reactor equipped with SF_6 circuit breakers. Both of the computer models are easy to use for "what if" type EMTP-based case studies, as well as in simulations to predict variables were not, or can not be measured in the field tests. The paper introduces elements of the elaborated EMTP model, some steps of model testing and verification. The paper contains the results of the computer analysis and of the field experiments.*

Keywords: EMTP, simulation, switching transients, EHV and MV shunt reactor model, measurement, verification, case studies, controlled switching.

INTRODUCTION

Shunt reactors are applied to regulate the reactive power balance of the system in order to compensate the surplus of the capacitive generation. Reactors are normally disconnected at heavy load and are connected to the lines at low loaded periods. Consequently, one of the significant characteristics of shunt reactors is that they are switched quite often to react the changing system load condition. Reactors are connected directly to the line terminals in the 750 kV substation Albertirsa (Hungary) and are connected with the 18 kV tertiary delta winding of the EHV 420/132 kV autotransformers.

A relatively large number of 750 kV reactor failures as a consequence of switching operations directed attention to the air-blast shunt reactor circuit breakers, as the possible source of the overvoltages. As it is well known, if a sinusoidal current supplying an inductive element, is interrupted before the natural current zero, high overvoltage with oscillating nature can be arise. The bigger the current chopped the higher the overvoltage peak arises. If the circuit breaker can not whitstand to the oscillating recovery voltage stress, a restrike will occur. In this case the voltage across the open contacts becomes a surge input to the network, leading to transient overvoltages.

In order to investigate the reason of reactor failures and to find out the possible measures to eliminate them, site experiment complemented by digital simulation were initiated. This paper concentrates on the simulation aspect of that investigation.

FIELD TESTS: REACTOR SWITCHING OFF WITH AIR-BLAST CIRCUIT BREAKER

Air-blast circuit breakers served for switching the reactors originally in the 750 kV substation, were being thought to be responsible for the overvoltages. This pre-assumption has been confirmed by field measurement performed at the substation shown in Fig.1.

Shunt reactor current interruption produced extremely high overvoltages, initiating gapped arrester operation in each phase and at every switching off cycle. Reignitions also occurred frequently. Fig.2 presents two examples of phase to ground reactor voltage transients recorded at field tests. Since no voltage transformers are installed between the reactor and the breaker, phase to ground reactor voltages have been measured by using a temporary capacitive voltage divider composed from the natural capacitance of the reactor bushing, as upper part and an auxiliary capacitance, as lower part. Fig. 2.a) and 2.b) show records without and with multiple breaker reignition, respectively. In both of cases interruptions have led operation of gapped arrester connected parallel with the reactor. In spite of arresters guarantee the peak voltage always below 2.1 p.u. protecting level, steep voltage change may result dangerous stresses in the turn-to-turn insulation of the reactor. The source of these steep wave fronts are restrikes between the contacts of the breaker and the arrester operation itself.

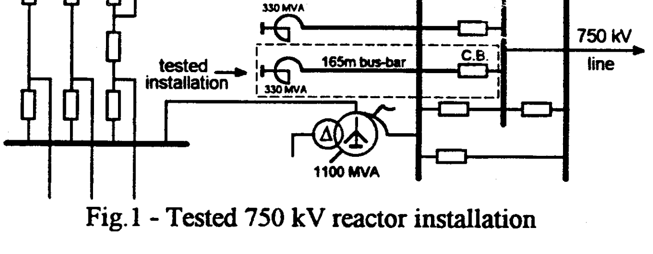

Fig.1 - Tested 750 kV reactor installation

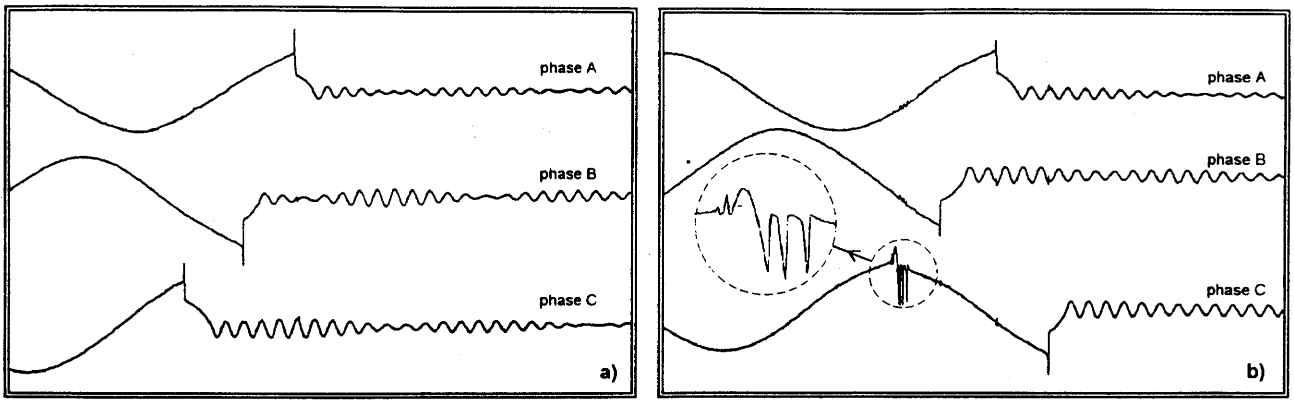

Fig.2 - Typical phase to ground reactor overvoltages initiated by current chopping of air-blast circuit breaker
a) No breaker regnition, arrester operation in each phase
b) Multiple breaker reignition in phase C, arrester operation in each phase

In order to investigate these turn to turn overvoltages a comprehensive computer model of the reactor and the surrounding network has been developed, using the ATP version of the Electromagnetic Transients Program [1].

EMTP MODEL OF THE SYSTEM AND DATA

Single line diagram of the complete model used in the EMTP is given in Figure 3. Installation includes the shunt reactor bank (consist of 3*110 MVAr single phase unit), surge protection device (conventional arrester) and the switching equipment (air-blast circuit breaker). 165 meter long bus-bar connects circuit breaker to the iron core reactor.

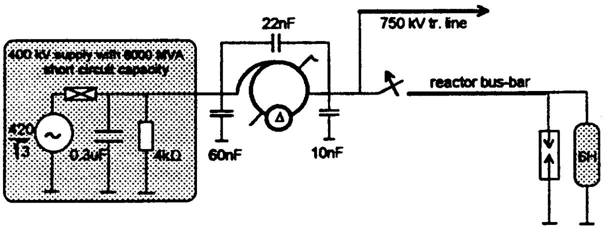

Fig.3 - EMTP model of the reactor installation

Elements of the model are as follows:

- Supply network behind the reactor:
The 750 kV transmission line and the transformer are taken into account individually in the model, while the remaining part of the 400 kV grid is assembled by an inductance, calculated from the symmetrical short circuit capacity and a sinusoidal voltage source. Bus-bar capacitances, the shunt admittance of the line and the frequency dependent losses are also important in higher frequencies, thus the feeding network has been completed by a shunt capacitor and a damping resistor as a simple model of that effects.

- Transformer:
Inductively coupled, linear, unsaturated BCTRAN model of EMTP simulates the 1100 MVA autotransformer, that consists of 3 single phase units. Shunt capacitances at the primary/secondary terminals and in between of them depict simply the ground capacitances and interwinding capacitances.

- 750 kV line:
Three phases, transposed distributed parameter transmission line model has been adopted. It is also possible to represent the line by a shunt resistor, equal to the line surge impedance, because its propagation time is nearly infinite long compared to that of the reactor bus-bar and the time constant of the reactor oscillation.

- Air-blast circuit breaker:
TIME CONTROLLED SWITCH with pre-defined current margin (60-80 Amperes), the most simple switch model of EMTP can be used. For simulation of breaker reignitions VOLTAGE CONTROLLED SWITCH has been used connected parallel with the main switch.

- Lightning arrester:
TYPE 99 non-linear resistor has been used. It was essential the accurate modelling of arrester non linearity in small (<100A) current region.

- Reactor bus-bar:
For modelling the bus-bar two kinds of line model have been selected:

a) Three phases, unsymmetrical, frequency dependent line, that represents the frequency dependency of line parameters more precisely.

b) 3 phase nominal PI circuit, with parameters at the base frequency of the reactor oscillation (870 Hz)

Both models take into account the coupling between the bus-bar phases. Model a) requires very small simulation time step and longer CPU time, so this model is preferred to use only in case of restrikes, when the role of travelling waves along the short bus-bar is fundamental.

- Shunt reactor:
A most simple reactor model is a two port equivalent of an inductance in parallel with a capacitor. The value of the capacitor can be predicted by substituting the frequency of the free oscillation (*f*) and the value of the reactor inductance (*L*) into the following formula:

$$C = \left(4\pi^2 f^2 L\right)^{-1}$$

Since the iron core has air gaps resulting in high saturation level, L means linear, unsaturated value of the reactor inductance. The bushing capacitance (C_b) and the bus-bar capacitances (C_{bb}) are also elements of the oscillating network, so the capacitance of the reactor (C_L) can be defined as:

$$C_L = C - C_b - C_{bb}$$

The copper losses of the winding, the iron and dielectric losses of the core can be easily represented by a lumped serial/parallel resistance. Fig.4 shows the simple model of the reactor defined above.

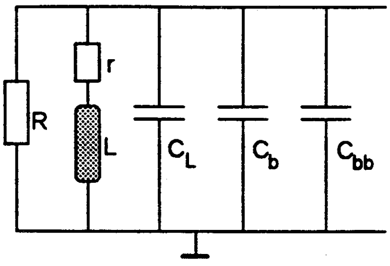

Fig.4 - Simple model of the reactor
(r=20Ω, R=2MΩ,L=6H, C_L=3nF, C_b=0.6nF,C_{bb}=2nF)

As Fig. 4 shows, the simplified model serves voltages at the high voltage terminal only and no information available about the magnitude and the time function of the internal stresses. In order to be able to predict the local overvoltages, more sophisticated reactor model has been elaborated.

DETAILED MODEL OF THE REACTOR

The comprehensive reactor model is based on 'n' part inductively coupled element of the EMTP. The homogeneous single-layer winding consists of n pieces of part-windings. Each of them has self inductance (L_{ii}) and n-1 mutual inductances (M_{ij}) to all of the others as it is shown in Fig.5. Moreover shunt (C_{ii})) and series ($K_{i-1,i}$) capacitances and the resistance of the losses (r_{ii}) and (R_{ii}) belong to each of them.

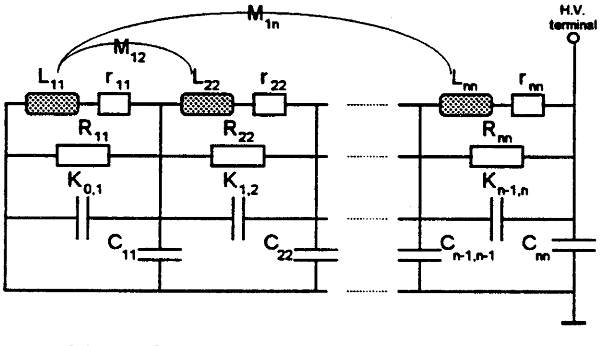

Fig.5 - Sophisticated model of the reactor

Mutual inductance between two coupled coils can be given as function of the self inductances and the coupling factor (q):

$$M_{ij} = q\cdot\sqrt{L_{ii}\cdot L_{jj}}$$

In case of homogeneous winding $L_{ii}=L_{jj}$, and the mutual inductance between two neighbouring windings is equal to $L_{ii}\cdot q$. That reduces exponentially by the factor of q if the distance between the two part-windings increases. Generally the mutual inductance between the j-th and the k-th part-winding is

$$M_{ij} = L_{ii}\cdot q^{|i-j|}$$

The inductance matrix $\underline{\underline{L}}$ of the reactor contains n pieces of L_{ii} in the main diagonal and n-i pieces of L_{ii} multiplied by the i-th power of q in the i-th parallel subdiagonal. Taking into account the total inductance of the entire winding must remain the same regardless how many pieces the winding has been split into, the sum of the elements of the matrix must be equal to the resultant inductance of the entire winding [3]. Accordingly, the elements of $\underline{\underline{L}}$ can be derived from the known reactor inductance L, devided by the sum of q factors.

$$L_{ii} = L\cdot\left(n+2\cdot\sum_{k=1}^{n-1}(n-k)\cdot q^k\right)^{-1}$$

The value of the coupling factor q has been obtained in an out of service, low voltage experiment. Computer model of the test arrangement gives the best agreement with measurements in case of setting q=0.8. So that value has been used in the subsequent simulations.

VERIFICATION AND APPLICATION OF THE MODEL

a) Comparison with field test records:

Verification of the model is shown in connection with the field measurement. Fig.6 shows voltage stresses in the reactor terminal and gives very well agreement with the measured curves in Fig 2.a.

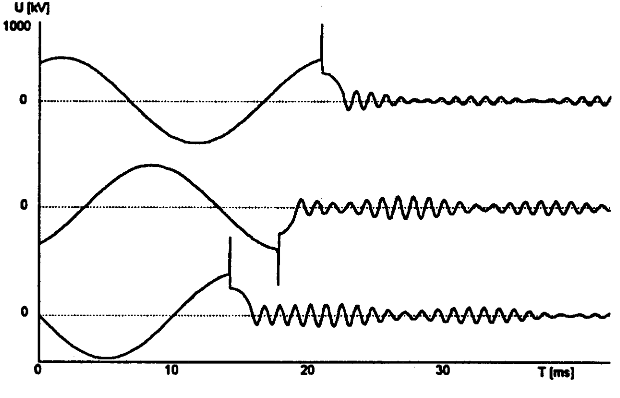

Fig.6 - Calculated phase to ground reactor voltages

b) Using reactor model in a study to obtain voltage distribution along the winding:

Using the detailed reactor model described above, internal overstresses of the turn-to-turn insulation caused by the arrester operation can be demonstrated as it is shown in Fig.7. Overstress of similar character can be revealed as a consequence of a breaker restrike.

Results of a computer simulation study in which the reactor winding has been split into 10 equal parts, show that 17% of the whole reactor voltage occurs at the 1/10th section of the winding closest to the H.V. terminal.

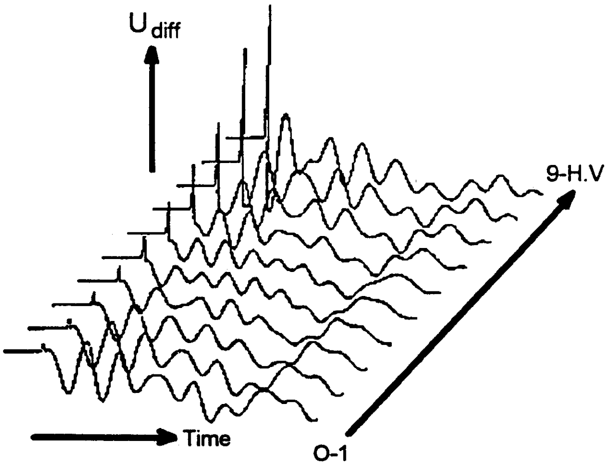

Fig.7 - Voltage differences between part-windings along the reactor length

c) Using the model in 'what if' type case studies:

The elaborated model is easy to use in 'what if' type case studies. Fig.8 shows the results of a study in which the parameters of the aged air-blast circuit breaker and the conventional arrester have been replaced by that of a modern SF$_6$ breaker and metal oxide arrester. The study showed that no high overvoltage and consequently, no arrester operation can be expected [2].

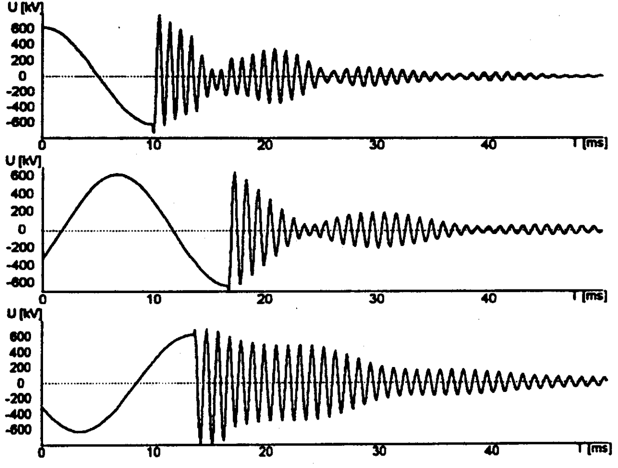

Fig.8 - Calculated phase to ground reactor voltages (switching off by SF$_6$ breaker)

Considering the results of the simulation study the air-blast circuit breakers have been replaced by SF$_6$ ones and the overvoltage protection of the line and the substation configuration have been modified by installing MOAs connected directly to the 750 kV line [4]. The results of the simulation have been verified by a test before pushing into operation the new circuit breaker. A typical oscillogram recorded at the field tests is shown in Fig.9.

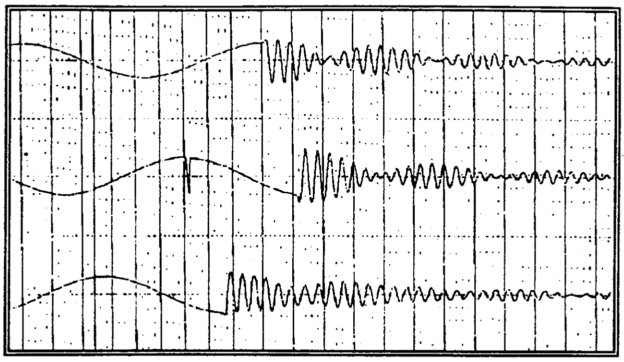

Fig.9 - Typical voltage curves succeeding the reactor switching off by SF$_6$ breaker (reignition in phase B)

d) A method for continuous monitoring the controlled reactor switching:

Field experiments show that SF$_6$ circuit breakers also produce a relatively high number of reignitions. Out of 50 shunt reactor current interruptions have been realised, reignition in one phase occurred in 80% of the tests, reignitions in two phases occurred in 10 % of the tests. So the breakers operated without reignition only in 10 % of the tests. Being the accuracy of the SF6 circuit breaker's operation satisfactory for controlled switching, synchronous relays have been installed and adjusted in such a way, that the duration of arcing in the circuit breaker is between 4,5 and 9,5 ms.

The exact operation of controlled switching has to be proved periodically. Using digital simulation of the reactor a simple continuous monitoring method of controlled switchings have been elaborated [5]. Setting the synchronous relay for a fixed tripping sequence (A$^+$-C$^-$-B$^+$ in this case, A is the reference phase), the polarity of the zero sequence reactor current (I_0) is positive and its duration is equal to 1/3rd of the power frequency cycle, if no restrike arises. (see. Fig.10).

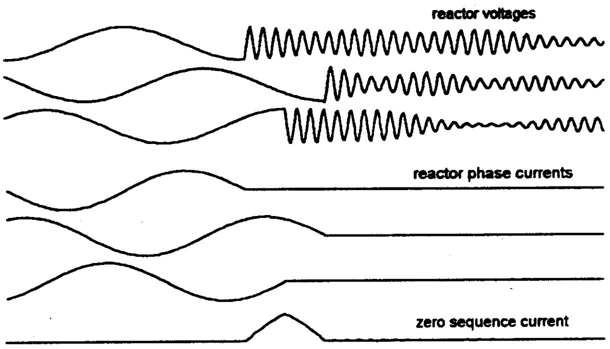

Fig.10 - Reactor switching with no restrike

If a restrike appears in one phase, due to relay misoperation or instability of the breaker time opening span, the polarity and/or duration of the I_0 changes. (see. Fig.11). It has been found that the duration and the polarity of the zero sequence current exactly characterise the behaviour of the circuit breaker during the reactor interruption.

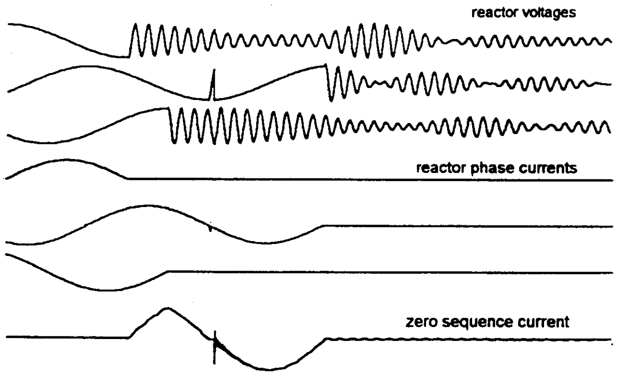

Fig.11 - Reactor switching with restrike in phase B

A simple logic can be established: If the duration of I_0 does not exceed 6.6 ms *and* no current flows in the reference phase when I_0 is not equal zero, controlled tripping operates well and no restrike arises at any phase. The method can be easily realised by superimposing the current of phase A (ref) and the zero sequence current in the disturbance recorder. According to our experience no reignition occurred during controlled switching of the shunt reactors.

e) Recovery voltages when the 750 kV line is disconnected:

There are intervals of low load, when the 750 kV line is out of operation. In such cases the 750 kV shunt reactors can be used for the compensation of the reactive power generated by the 400 kV network. Simulation studies showed that the absence of the 750 kV transmission line doesn't influence the supply side oscillation of the shunt reactor circuit breaker significantly (see Fig.12). Consequently, controlled switching can be applied for this configuration as well. Field experiments have been carried out later for checking the results of the computer simulation. The results of the field test verified the correctness of the simulation.

MODEL OF THE REACTOR CONNECTED TO TERTIARY WINDING OF TRANSFORMERS

On 420 kV level, shunt reactors are connected with the delta connected 18 kV tertiary winding of the 420/132 kV autotransformers in many cases. In the current practice minimum oil filled breakers are used for switching on and off the oil insulated iron core reactors. The neutral point of the reactors is generally isolated. In the new installations air core reactors are planned and modern SF_6 insulated circuit breakers are expected.

A three phase comprehensive EMTP model for computer simulation of the transients initiated by closing and interrupting of reactors connected with the tertiary windings is shown in Fig. 12.

To the H.V. terminals of the transformer similar feeding network model is attached as it was introduced in connection with Fig.3.

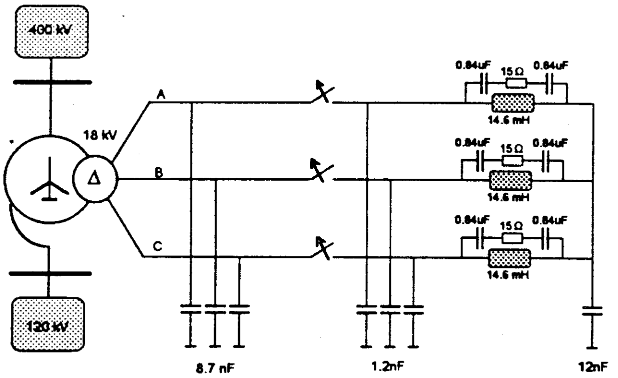

Fig.12 - EMTP model of the 18kV reactor installation

Capacitances connected parallel with the ungrounded neutral reactors are applied for the reduction of the recovery voltage frequency subsequent the current interruption. A relatively high capacitance in the star point represents a medium voltage polyethylene cable between the neutral points of the reactor and of the cable.

Computer simulation showed that interruption of the shunt reactor current by an up to date SF_6 breaker, characterised by low current chopping value, does not produce dangerous overvoltages even in installations without parallel condensers and that the frequency of the recovery voltage can be effectively reduced by parallel condensers.

Fig. 13.a shows calculated phase-to-ground voltages of the reactor, in case of parallel condensers are installed. Lack of this auxiliary devices the frequency of the recovery voltage would extremely increase, as it can be seen on Fig.13.b. In the latter case not only the value of the recovery voltage frequency increases, but the multifrequency oscillation is also dominant. This can be seen on Fig.14, that shows voltage oscillation in the first interrupting phase.

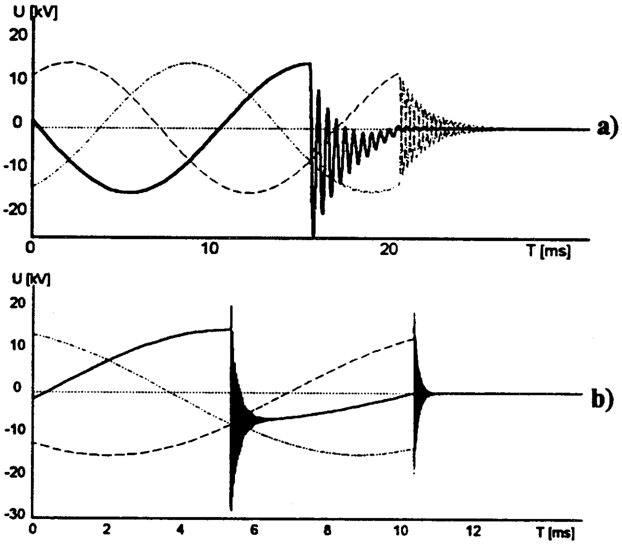

Fig.13 - Calculated phase to ground reactor voltages
a) with parallel condensers, b) without condensers

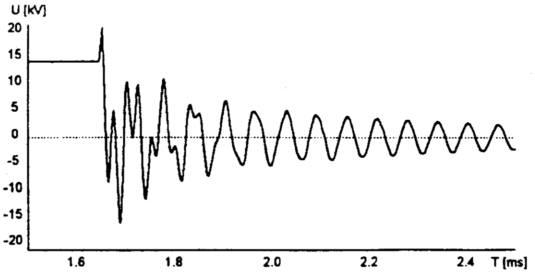

Fig.14 - Multifrequency oscillation at the reactor side in case of no parallel condenser applied

The results of computer simulation have been proved at pushing into exploitation test of a new 18 kV air core shunt reactor set equipped with SF_6 circuit breaker. Tests have been carried out with a condenser set in parallel with the reactors and without condensers. Fig.15 shows recorded phase-to-ground voltages.

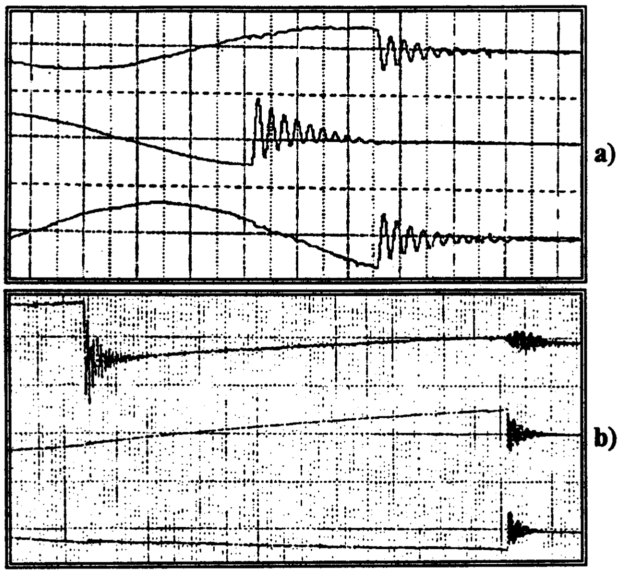

Fig. 15 - Measured phase to ground reactor voltages a) with parallel condensers, b) without condensers

In Table-I the results of computer simulation and the field measurement are compared with the results obtained by using formulas defined in [6]. The frequency of the recovery voltage can be calculated as:

$$f_1 = \frac{1}{2 \cdot \pi \sqrt{1.5 \cdot LC_L}} \quad \text{and} \quad f_{2,3} = \frac{1}{2 \cdot \pi \sqrt{LC_L}} \quad [\text{Hz}],$$

at the first and at the other two interrupting phases, respectively. L and C_L are the reactor inductance and the capacitance connected parallel with that. The peak value of the oscillating recovery voltage is given by:

$$k + \sqrt{\left(1 + k + \frac{U_{arc}}{U_0}\right)^2 + \frac{(1+k) \cdot L \cdot i_{ch}^2}{U_0^2 \cdot C_L}} \qquad [p.u.]$$

In case of ungrounded installations k=0.5 p.u. Since the present SF_6 breakers neither produce high arc suppression peak (U_{arc}<0.1 p.u) nor significant current chopping (I_{ch}<3A), the peak voltage given by the previous expression does not exceed 2.3 p.u.

Table-I

	Phase-to-ground overvoltage (*) [p.u.]		Frequency of the transient (*) [kHz]	
	without condenser	with condenser	without condenser	with condenser
computer simulation	1.94	1.71	27.2	2.02
field test	1.51-1.53	1.41-1.73	29.5	2.03
by using formulas in [6]	2.3	2.1	30	2

(*) The data refer to the phase interrupting at first

As it can be seen in table above, both the computer simulation and formulas well agree with the measured frequency. The overvoltage values are however slightly overestimated by using formulas and even the computer simulation gives significantly higher values then the measured ones in case of no condenser connected.

CONCLUSIONS

High voltage circuit breakers may produce reignitions during current interruption. Steep front waves and high frequency oscillation initiated by reignitions overstress the interturn insulation of shunt reactors connected with the breaker. A computer model, that results in identical transients with the field tests has been developed and applied successfully for case studies. The results of the studies show that overstresses can be avoided by controlling the switching off operation. To predict the efficiency of controlling, to adjust the synchronous relay optimally and to find a suitable way for checking the correctness of the operation a preliminary simulation study is suggested. Field tests verified, that the depth of the simulation described in the paper is satisfactory to prepare the implementation of controlled switching off. Field experiments confirmed that the modern SF_6 circuit breakers interrupt inductive currents smoothly and do not produce significant overvoltages. The frequency of the recovery voltage can be effectively reduced by means of capacitors connected parallel with MV shunt reactors.

ACKNOWLEDGEMENTS

This activity has been partly supported by the Hungarian Research Fund under contract OTKA 748. Authors also acknowledge the contribution to the field tests of the Hungarian Power Grid Company Ltd.

REFERENCES

[1] Alternative Transients Program (ATP) Rule book, Can/Am EMTP User Group - Leuven EMTP Center, 1992

[2] L.Prikler: Switching off 750 kV shunt reactors, Proc. of 19th European EMTP User Group Meeting, Leuven , 1990

[3] L.Burger, L.Prikler: Modelling of voltage transformers by means of ATP at high frequency, Proc. of 22nd European EMTP User Group Meeting, Leuven, 1992

[4] G.Ban, I.Benko, G.Banfai: Interaction of the reactive power compensation and the insulation co-ordination at a 750 kV power transmission, CIGRE 1990 Session, Paper 33-201.

[5] Contribution at the 1994 CIGRE Session (Group 23)

[6] IEC Technical Report No.1233, High voltage alternating current circuit breakers inductive load switching, 1993