# Transient Phenomena at Energization and Deenergization of Capacitor Banks

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*Abstract* - **This paper presents the results of experimental investigations and calculations of transient phenomena during opening and closing operation of the capacitor bank circuit-breakers. Experimental investigations in seven networks with nominal voltage from 5,25 kV to 35 kV, have been carried out. In this paper are presented the results of calculations when energizing and deenergizing the capacitor banks in the 35 kV network only. On the basis of the analysis of the investigation results, the measures and facilities to moderate transient phenomena occurring during closing and opening operation of the capacitor bank circuit-breakers are suggested.**

**Keywords:** Capacitor bank, Overvoltage, Circuit-Breaker.

## I. INTRODUCTION

The necessities to compensate the reactive energy in certain parts of electric energy system require the capacitor banks to be introduced into exploitation on selected locations. These would have been energized and deenergized by circuit-breakers when necessary. The number of manipulations with a circuit-breaker per condenser bank during a year can be significant.

Closing and opening operations of a circuit-breaker introduce transitory phenomena in the capacitor bank circuits. In order to determine what kind of phenomena can be expected in the course of circuit-breaker switching operations, numerous experimental investigations and calculations have been carried out.

Experimental explorations of the transient voltages and currents in the course of the closing and opening operation of the capacitor bank circuit breaker are carried out in seven networks having nominal voltages from 5,25 kV up to 35 kV. The circuit-breakers of these capacitor banks were oil circuit-breakers and vacuum circuit-breakers. Transient phase-to-earth voltages were recorded with analogue and digital oscilloscopes by means of voltage capacitive measuring systems coupled to all three phases in front of, and behind the circuit-breaker. Transient currents of capacitor banks were recorded with transient recorders. Current measuring systems were based on the existing current transformers in the capacitor bank circuits.

The calculations of transient currents and voltages at energization and deenergization of the 6.3 Mvar capacitor banks were carried out in a 35 kV networks.

The transient phenomena in the case of changing network parameters were observed. The parameters varied were: the capacitor bank reactor inductivity, the capacitance of the 35 kV network and the power of the 110 kV network that supplies 35 kV network via 110 kV/35 kV transformer. The statistical approach was used, for the time changes of the transient voltages and capacitor bank currents are random values. When the circuit breaker is switched in, they depend on the exact moment of closing the poles of the circuit breakers that are also random values. In the case of switching the circuit breaker out, they depend on the number of reignitions and the exact moment of their appearance.

## II. EXPERIMENTAL INVESTIGATIONS OF TRANSIENT VOLTAGES AND CURRENTS AT CLOSING OPERATIONS OF CAPACITOR BANK CIRCUIT-BREAKERS

Experimental studies were carried out in seven networks with insulated neutral point:

- two 35 kV networks,
- one 15 kV network,
- three 6 kV networks,
- one 5,25 kV network.

The circuit-breakers of these capacitor banks were oil minimum circuit-breakers (of the new and old type) and vacuum circuit-breakers. The results of experimental investigations on transient phase-to-earth voltages and currents when energizing and deenergizing the capacitor banks are presented in Table 1. The signs in Table 1 have the following meaning.:

U - voltage level of the investigated network;

CB - kind of the circuit-breaker used for energization and deenergization of a capacitor bank (Ol,ot - old type of the oil minimum circuit-breaker; Ol,nt - new type of the oil minimum circuit-breaker; V - vacuum circuit-breaker) ;

$S_{cb}$ - power of the capacitor bank being energized and deenergized;

$S_{cb,b}$ - power of the capacitor bank already connected to the busbars on which the capacitor bank having

TABLE 1 Results of investigation of transient voltages and currents during closing and opening operation of capacitor bank circuit breakers.

| N° | Network U (kV) | CB | $S_{cb}$ (Mvar) | $S_{cb,b}$ (Mvar) | n | Overvoltage coefficient: Closing $U_m$ (p.u.) | Closing $U_{max}$ (p.u.) | Opening $U_m$ (p.u.) | Opening $U_{max}$ (p.u.) | Inrush current $I_m$ (p.u.) | Inrush current $I_{max}$ (p.u.) | $n_r$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 5.25 | Ol,nt | 0.45 | 0 | 11 | 1.20 | 1.90 | 1.04 | 1.20 | 8.5 | 16 | 0 |
| 2 | 5.25 | Ol,nt | 1.35 | 0 | 12 | 1.31 | 1.95 | 1.07 | 1.30 | 6.5 | 11 | 0 |
| 3 | 5.25 | Ol,nt | 3.6 | 0 | 6 | 1.33 | 1.90 | 1.11 | 1.35 | 4.6 | 7.8 | 0 |
| 4 | 5.25 | Ol,nt | 1.8 | 1.8 | 5 | 1.24 | 1.85 | 1.10 | 1.35 | 7.8 | 11 | 0 |
| 5 | 6 | Ol,nt | 1.2 | 1.2 | 10 | 1.21 | 1.60 | 1.03 | 1.40 | 13 | 21 | 1 |
| 6 | 6 | Ol,nt | 1.2 | 6 | 10 | 1.09 | 1.55 | 1.03 | 1.60 | 16 | 24 | 1 |
| 7 | 6 | Ol,nt | 1.8 | 0 | 7 | 1.36 | 1.75 | 1.07 | 1.25 | 5.9 | 9.2 | 0 |
| 8 | 6 | Ol,nt | 1.8 | 3.0 | 5 | 1.30 | 1.60 | 1.06 | 1.25 | 7.1 | 11 | 0 |
| 9 | 6 | Ol,nt | 1.8 | 7.8 | 6 | 1.22 | 1.50 | 1.08 | 1.30 | 9.9 | 16 | 0 |
| 10 | 6 | Ol,nt | 3.0 | 1.8 | 5 | 1.44 | 1.70 | 1.10 | 1.35 | 5.5 | 8.4 | 0 |
| 11 | 6 | Ol,nt | 3.0 | 6.6 | 5 | 1.27 | 1.50 | 1.09 | 1.35 | 7.8 | 12 | 0 |
| 12 | 6 | Ol,nt | 3.0 | 0 | 18 | 1.31 | 1.85 | 1.09 | 1.40 | 3.7 | 6.3 | 0 |
| 13 | 6 | Ol,ot | 3.0 | 3.0 | 11 | 1.17 | 1.35 | 1.09 | 1.35 | 5.8 | 11 | 0 |
| 14 | 15 | Ol,ot | 3.6 | 0 | 17 | 1.36 | 2.00 | 1.20 | 2.33 | / | 8.5 | 9 |
| 15 | 15 | Ol,ot | 3.6 | 3.6 | 9 | 1.14 | 1.33 | 1.14 | 1.60 | / | 15 | 6 |
| 16 | 15 | Ol,ot | 3.6 | 6.3 | 5 | 1.10 | 1.29 | 1.05 | 1.35 | / | 23 | 5 |
| 17 | 6 | V | 4.8 | 0 | 8 | 1.84 | 2.30 | 1.20 | 1.65 | / | / | 0 |
| 18 | 35 | Ol,ot | 6.3 | 0 | 13 | 2.27 | 3.85 | 1.55 | 4.05 | / | / | 11 |
| 19 | 35 | Ol,ot | 6.3 | 0 | 23 | 1.71 | 3.60 | 1.61 | 3.65 | 3.9 | 5.4 | 20 |

power $S_{cb}$ is being energized

n - number of closing - opening operations of the capacitor bank circuit-breaker carried out in the course of investigations;

$U_{max}$ - maximum value of the overvoltage of uniformalized phases (the sample of the overvoltage coefficient for all three phases together) at energization and deenergization;

$U_m$ - overvoltages mean value of uniformalized phases at energization and deenergization;

$I_{max}$ - inrush current maximum value of uniformalized phases at energization of the capacitor bank;

$I_m$ - mean value of inrush currents of uniformalized phases at energization of the capacitor bank;

$n_r$ - number of opening operations of the condenser bank circuit-breaker with arc re-ignition between its contacts.

Overvoltage is given in relative per unit (p.u.) values as the relation of the overvoltage maximum value and the voltage peak value immediately before and after the circuit breaker operation. The inrush current values are also given in relative (p.u.) values as the relation between inrush current maximum value and its peak value in steady state, immediately after the circuit-breaker operation. During energizing of the 4,8 Mvar capacitor bank by closing the vacuum circuit-breaker (serial number 17, table 1 ) repeated arc establishment occurred between circuit breaker contacts before completion of the closing operation.

In “Fig. 1”, “Fig. 2” and “Fig. 3” the phase-to-earth transient voltages are presented at energization and deenergization of condenser bank. “Fig. 4” presents the inrush current of one phase of the condenser bank at its energization.

## III. CALCULATION OF TRANSIENT VOLTAGES AND CURRENTS DURING SWITCHING OPERATIONS OF CAPACITOR BANK CIRCUIT BREAKERS

The calculation of transient phenomena at closing and opening operation of the condenser bank circuit-breaker was carried out in 35 kV networks. The results of calculations for energizing and deenergizing of the 6.3 Mvar capacitor banks (in the network presented in Fig.5.) are presented in this chapter. The results of the calculation were previously verified by the results achieved in the experimental investigations of the similar 35 kV network. The adequate dumping of the transient phenomena and satisfactory correlation of the calculation and the experimental investigation results, were achieved by the introduction of the resistance R=3 Ω (Fig. 5). Resistance R=3 Ω models the losses in the capacitor bank circuit while energizing and deenergizing. The resistance value depends on the circuit topology of which the capacitor bank is a part. It is determinated by the comparison of the experimantal and calculation results.

The overvoltage calculations are carried out by the use of EMTP-ATP.

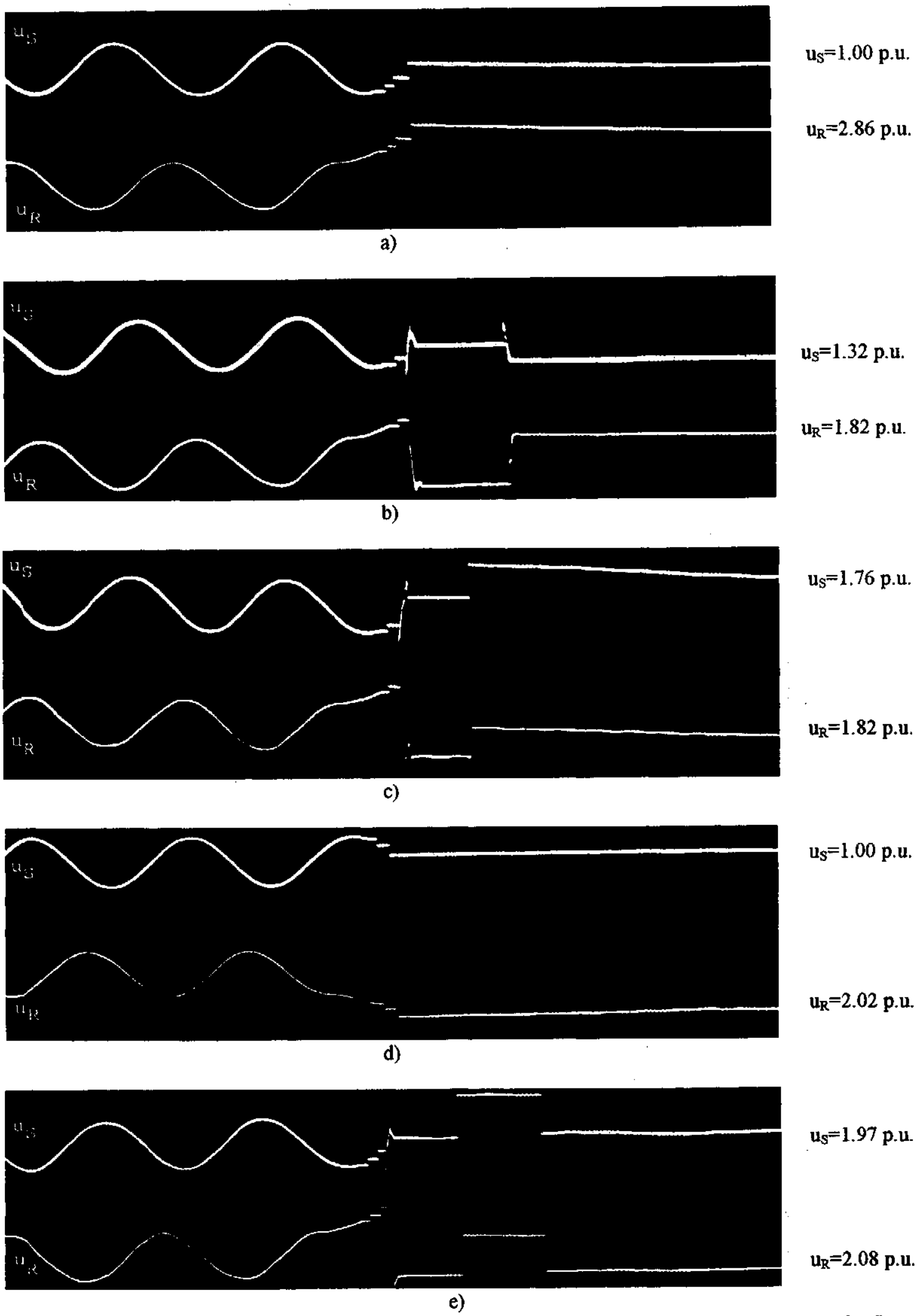
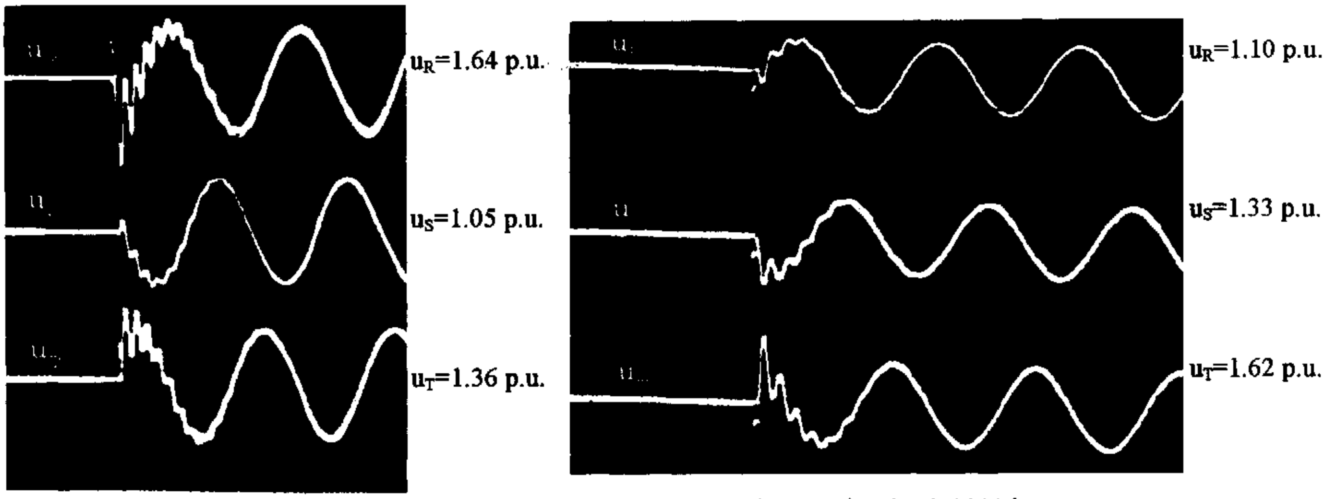



Fig. 1. Transient phase voltages $u_S$ and $u_R$ on the 6.3 Mvar capacitor bank side, behind the sircuit-breaker for five cases of its deenergization from 35 kV busbars in TS 110 kV/35kV, with the appearance of multiple electric arc reignition between contacts of the oil minimum circuit-breaker (old type) in its all three poles.




a) capacitor bank 1800 kvar. b) capacitor bank 3000 kvar.

Fig. 2. Transient phase-to-earth voltages $u_R$, $u_S$ and $u_T$ when energizing the capacitor bank by closing the oil minimum circuit-breaker onto 6,3 kV busbars.

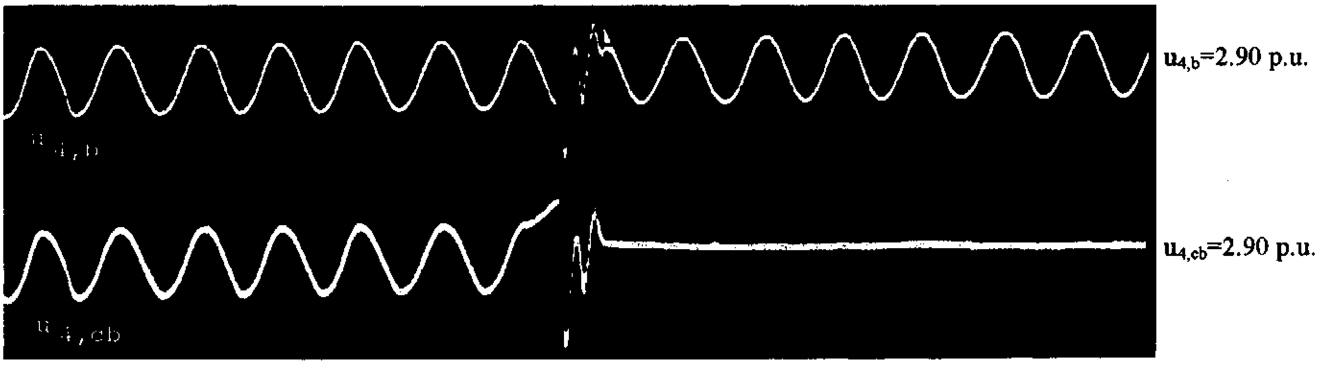
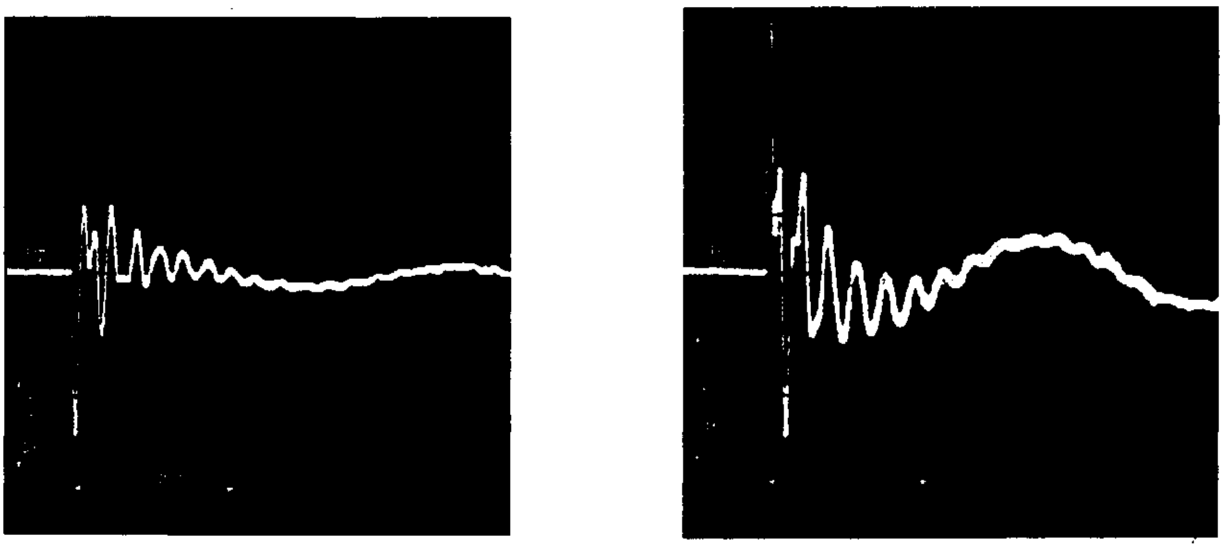



Fig. 3. Transient phase-to-earth voltages of the phase 4 on the 35 kV busbars – $u_{4,b}$ and on the terminals of the 6.3 Mvar capacitor bank, $u_{4,cb}$ while deenergized by oil minimum circuit-breaker (old type), with the appearance of electric arc reignition in all three phases.



a) capacitor bank 450 kvar. b) capacitor bank 1350 kvar.

Fig. 4. Transient current $I_T$ of the capacitor bank, when connected to the 5,25 kV busbars.

The research of transient voltages and currents when energizing the capacitor bank was carried out for different values of the scheme parameters.

The following parameters were varied: network inductance $L_N$ from 10 mH to 200 mH, inductance of the capacitor bank reactor $L_{cb}$, from 10 μH to 200μH, network capacitance $C_N$ from 5 nF to 2 μF, and capacitances of the capacitor bank $C_{cb}$ from 1 μF to 20 μF. For the sake of obtaining an accurate insight into the switching in and out of the capacitor bank transient phenomena, capacitance $C_N$ should be replaced by the existing lines with distributed parameters. The research was carried out with and without the presence of 35 MVA load at $\cos\varphi=0.95$ on the 35 kV network. The research was also carried out with and without presence of the second condenser bank in the 35 kV network. For each change of the parameters in the scheme presented in "Fig. 5", 200 opening and closing operations of the condenser bank circuit-breaker was performed; the closing times of the circuit-breaker poles were chosen at random, from the normal distribution, with the mean value $t_m$=5 ms and dispersion $\sigma$=1,6 ms. Investigations of transient voltages and currents when energizing and deenergizing the capacitor banks have shown the following:

- the change of power in 110 kV level (network inductance $L_N$) introduces small changes of the overvoltages and inrush currents magnitude;
- changing the inductance of the reactor $L_{cb}$ in the capacitor bank, introduce small change of the overvoltages, but significantly influences the magnitude of inrush currents; when increasing the inductance $L_{cb}$ , the inrush currents are decreased;
- changing the network capacitance $C_N$ has not appreciable influence on overvoltages but influences the magnitudes of inrush currents; with increased network, capacitance the overvoltages decrease gradually but inrush currents increase;
- when changing the capacitance $C_{cb}$ of the capacitor bank the magnitudes of overvoltages and inrush currents are changed; when increasing the capacitance $C_{cb}$ the overvoltages are decreased gradually but inrush currents are increased;
- introduction of the second capacitor bank on the same 35 kV busbars decreases the overvoltages, but significantly increases the inrush currents,
- when 35 kV network is loaded the overvoltages are decreased but the influence of the load on inrush currents is small,
- residual voltages on the capacitor bank (capacitor bank charged) affect appreciably the increment of overvoltages and inrush currents.

When energizing the unloaded capacitor bank, the overvoltages did not get higher than 2 p.u. In the case of pre-charged condenser bank, they overpassed 4 p.u. The inrush currents when energizing the uncharged capacitor bank, at normal values of the reactor $L_{cb}$ indctance, with the second capacitor bank out of service, were reaching $10I_{cb}$ ($I_{cb}$-peak value of the condenser bank current in steady state). With the second condenser bank in service, the inrush currents reached the values up to $30I_{cb}$. When switching-in the pre-charged capacitor bank, the inrush currents reached the values up to $15I_{cb}$; with the presence of another capacitor bank on 35 kV busbars they reached the values up to $50I_{cb}$.

As an example, in "Fig. 6", the variations of the maximum ($U_{max}$) and the mean ($U_{avg}$) values of overvoltages as well as the maximum ($I_{max}$) and mean ($I_{avg}$) of inrush currents, registered during 200 closing operations of the 6,3 Mvar capacitor bank, were presented as the function of changing the inductances $L_N$ and $L_{cb}$ and the capacitance $C_N$, the 35 kV network being loaded with 35 Mvar at $\cos\varphi$ =0,9.

In the case of deenergization of the capacitor bank, without occurrence of re-ignition of the electric arc between circuit-breaker contacts, the overvoltages were

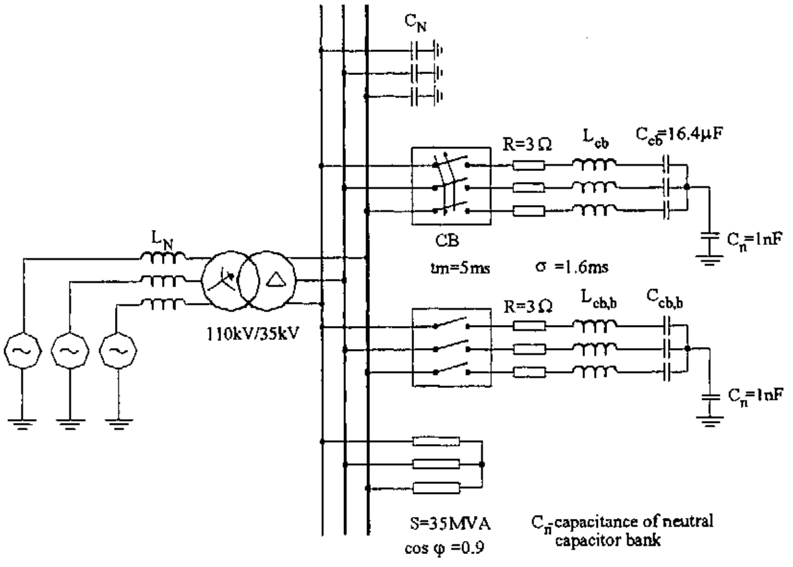



Fig. 5. The scheme for the calculation of the transient voltages and currents at energizing of the capacitor bank on the 35 kV busbars.

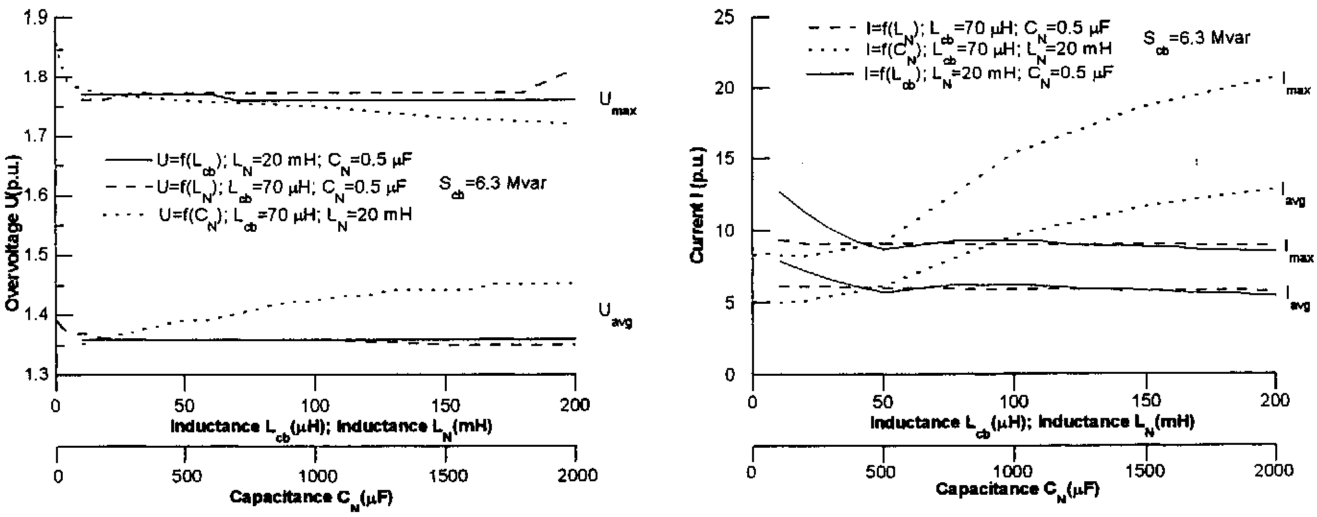



Fig. 6. Alterations of the maximum and mean values of transient phase-to-earth voltages and inrush currents of the 6,3 Mvar capacitor bank while energized.

not higher than 1,6 p.u. Re-ignitions of the electric arc between contacts when occurring at all three phases in the same time, and especially when multiple, can lead to extremely high overvoltages and inrush currents. Numerous reignitions were simulated during switching out of the circuit breaker. Maximumum values of overvoltages and inrush currents depended on the number of reignitions and the exact moment of their appearances. In certain simulations, overvoltages surpassed 6 p.u. while the inrush currents surpassed 20 p.u.

## IV. CONCLUSIONS

On the basis of experimental investigations and calculations of transient voltages and currents at switching operations of the condenser bank circuit-breakers, the following can be concluded:

- Transient voltage and current processes occurring at switching operations of the condenser bank circuit-breakers can impose significant stresses on the equipment in the circuits of the condenser bank. High overvoltages impose significant dielectric stresses and high inrush currents produce dynamic , thermal and mechanical stresses on the equipment in the circuits of capacitor banks.
- Transient voltages and currents during energization and deenergization are significantly dependent on the circuit-breaker operation. The overvoltages and the inrush currents are significantly decreased in the cases without multiple arc re-ignition between circuit-breaker contacts during its closing operation; the same is valuable for circuit-breaker opening operation without occurrence of multiple arc re-ignition.
- Switching in the pre-charged capacitor bank onto network, leads to the appearance of high overvoltages and inrush currents.
- The reactor inductance in the capacitor bank circuit, influences significantly the amplitude of inrush currents.

On the basis of above presented facts, the conclusion can be brought, that with the adequate selection of the circuit-breaker and the reactor for a capacitor bank, as well as the use of equipment for deenergizing the capacitor bank immediately after its switching out, the transient voltage and current processes at energization and deenergization of capacitor banks are significantly moderated and thus the consequential stresses on the equipment caused by them.

## V. REFERENCES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