Modeling of Transient Phenomena at Controlled Switching of Shunt Capacitor

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Abstract---In the paper the results of model-ling of controlled switching operation for reducing of overvoltages and overcurrents at closing or opening operation of single and back-to-back shunt capacitors bank are presented.

Modern vacuum and SF$_6$ medium voltage circuit-breakers, with low spreading of closing and opening time, are fully adequate for using of proposed method of controlled switching operations

I.INTRODUCTION

The switching operation of shunt capacitor bank used for compensation of local inductive power consumption, may cause hazardous overvoltages and large inrush currents with very high values of the current rate-of-rise [1]. The capacitor banks may be installed like single shunt capacitor bank composed from one capacitor section, or back-to-back shunt capacitor banks set up from one section connected to supplying side and a regulating sections with the power limited by the admissible voltage changing after its energizing.

At closing operation high values of inrush currents and unadmissible overvoltages may be generated. At the opening operation, the overvoltages due to the possible reignitions or restrikes after current succesful breaking may appear.

The moment of restrikes after current breaking at the opening operation, as well as the voltage phase angle at the moment of closing operation are stochastic in nature and depends from system and switchgear conditions. Therefore, in determined conditions, the uncontrolled switching operation may occure at any phase angle.

By using of controlled switching operations the overvoltages and overcurrents may by highly diminished [2,3,4,5]. The succesful controlled switching operation depends on switching device operation times. The closing and opening times for modern vacuum and SF$_6$ medium voltage circuit breakers ($U_n \le 72$ kV) are given in table 1 (values received from producers and publication [6]).The prestriking time due to nominal voltage is’nt for medium voltage circuit-breaker important The distance between contacts at the moment of prestriking is for vacuum circuit breaker less than 0,2 mm and for SF$_6$ is in the range 0,8 to 1 mm.

TABLE 1.

Switchgear	Vacuum		SF$_6$	
The voltage of auxilliary circuits	110 % U_n	95 % U_n	110% U_n	95 % U_n
Closing time [ms]	33,9	34,5	38,4	39,7
The spread of closing time [ms]	+0,3 to -0,5	+0,3 to -0,3	+1,0 do -0,9	+1,1 to -0,8
Opening time [ms]	43,5 - 50		52 - 60	
The spread of opening time [ms]	± 0,6		±1,3	

The mathematical simulation of nonsimultaneous operation of three phase capacitor banks operations were divided into switching operations for single capacitor bank, and switching operations of the back-to-back capacitor bank with two sections, (the main section on the supplying side of the system and switched on/off regulating section).

For both cases, the closing and opening operations were analysed by using the EMTP/ ATP program or analysed by using simplified formula given in Appendix.

Peak values of such transients depend from the closing angle and unsimultaneities between successively closing poles of switchgear. High frequency components of currents and voltages are depending from the network configuration and values of their parameters like capacitances, inductances and resistances.

In the paper the characteristic results of inrush currents at closing operation, and overvoltages at closing or opening operation of single and back-to-back shunt capacitor banks are presented.

II. CONTROLLED SWITCHING OF SINGLE SHUNT CAPACITOR BANK.

At simultaneous closing of three phases single shunt capacitor bank, the maximal values of inrush current coefficient k_{max} may be expressed by [1]:

$$k_{max} = \frac{(i_z)_{max}}{I_n} = \left(1 + \sqrt{\frac{S_z}{Q}}\right) \qquad (1)$$

where: $(i_z)_{max}$ - peak value of the inrush current,

I_n - nominal current of capacitor bank,

S - short-circuit power at the point of shunt

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capacitor bank instation,
Q - nominal power of closed capacitor bank.

The calculated maximal values of inrush current coefficient for simultaneous closing in the function of short circuit power S to nominal capacitor bank power Q, are shown in fig.1.

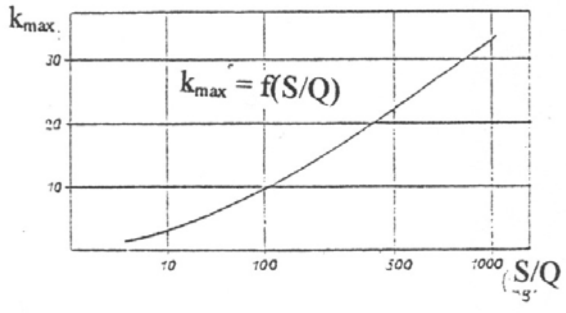


Fig.1.Maximal values of inrush current coefficient at simultaneous closing of single shunt capacitor bank

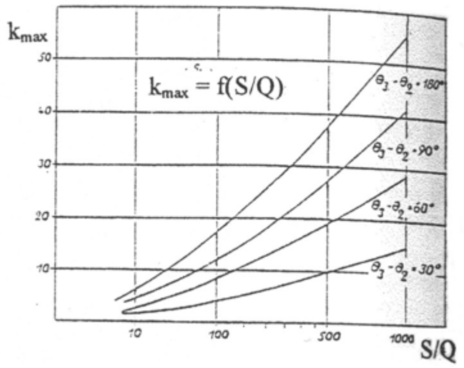


Fig.2.Maximal values of inrash current coefificient at nonsimultaneous closing of single capacitor banks.

Similarly on fig.2 maximal values of inrush current coefficients, (calculated from equations given in Apendix) for nonsimultaneous closing $\Delta\Theta = \Theta_3 - \Theta_2$, in the function of short circuit power to nominal capactor bank power, are presented.

From above data may be concluded that for nosimultaneous closing of three phases unearthed single capacitor bank with unsimultaneity between phases lower than $\Delta\Theta$ = 60 el deg., the overcurrent coefficients d'not overrun the values at simultaneous contact closing.

Optimum voltage phase angle for proper nonsimultaneous closing appeares at the moment at equal phase voltages for the two closing phases, and with delayed third closing phase equal to 90 el.deg. Maximal values of above coefficients are received at maximal value of the voltages between contacts before their closing. On the contrary, the minimal values of overcurrent coefficients will appear at zero voltage between contacts at the moment of their closing

By using the equations given in Appendix, the overvoltages at nonsimultaneous closing may be calculated. For simultaneous closing, the maximal value of overvoltage coefficient is equal to 2, and at nonunsimultaneous closing above coefficient may reach the values up to 2.867.

Controlled switching of circuit breaker at the proper time instant at closing or opening of single shunt capacitor bank may be used for drastic reducing of inrush currents and transient overvoltages. Controlled opening of shunt capacitor bank is realised by controlling the moment of contact separation at the breaking of capacitive currents. The proper moment of contact separation shown in fig.3, may be established experimentally. Accordingly long arcing time ensures the long distance between contacts at current zero and large withstand voltage which eliminates the restrikes. For modern vacuum and SF_6 circuit breakers with very low time spread during opening operation, the problem of overvoltages due to restrikes may be eliminated or, as minimum, drastic diminished.

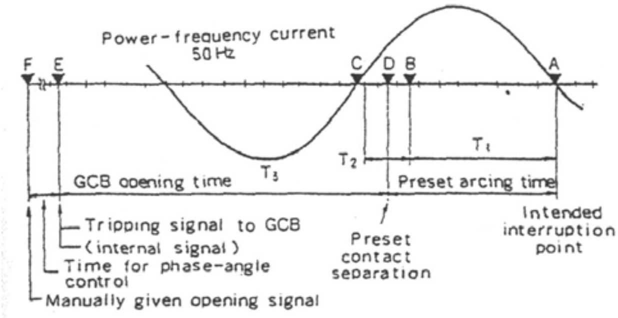


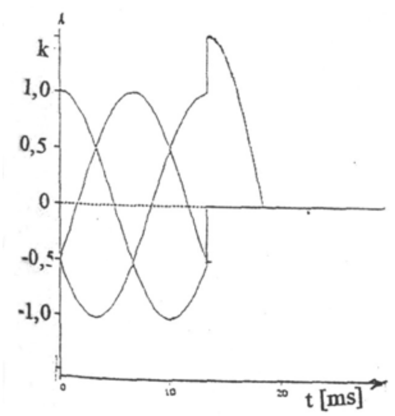
Fig. 3. Controlled switching principle for reignition free breaking of capacitor currents

III.CONTROLLED SWITCHING OF BACK-TO-BACK SHUNT CAPACITOR BANK.

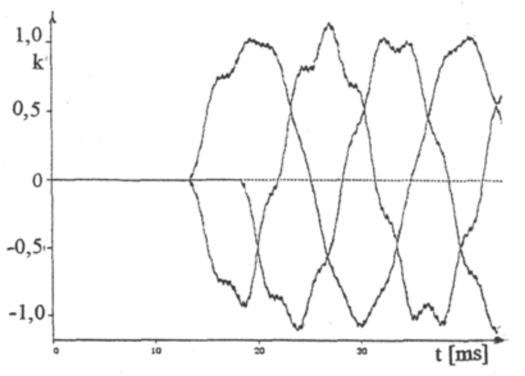
The calculation of electromagnetic transients on back-to-back shunt capacitor bank at nonsimultaneous switching was conducted for S= 100 MVA, Q_1= MVA$_r$, Q_2=0,9 MVA [7].

On next figures 4 and 5 some most interesting currents and voltages outprints at nonsimul-taneous closing of back-to-back shunt capacitor bank are presented.

a)



b)



c)

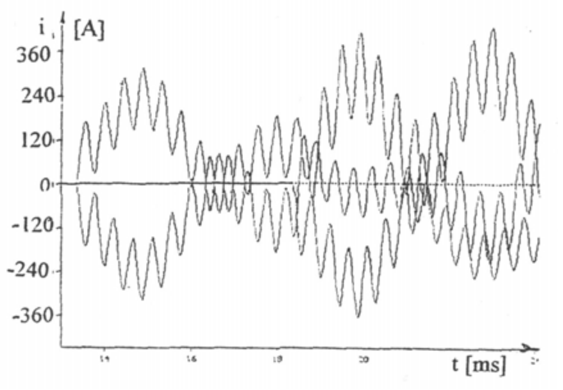
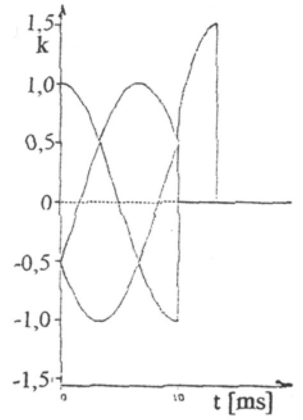
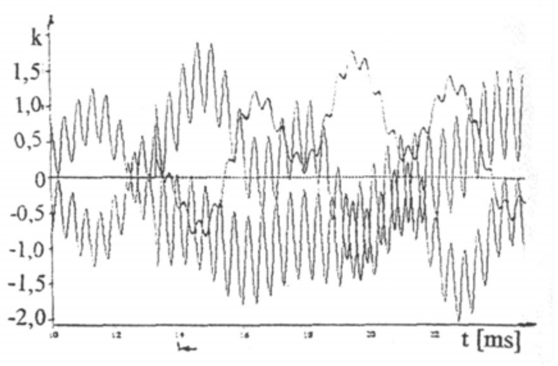


Fig.4. Most convenient nonsimultaneous controlled switching of back-to- back capacitor bank;

a) phase voltages on supplying side,
b) overvoltage traces,
c) inrush current trace

a)





b)

c)

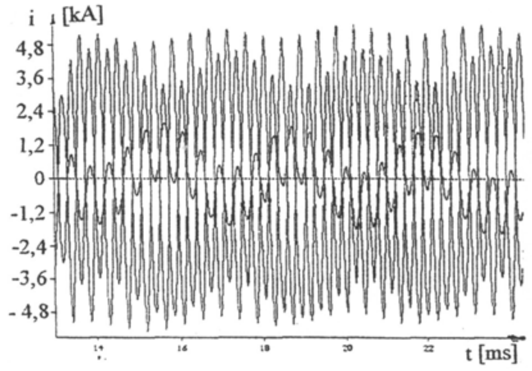


Fig 5. Most unconvenient nonsimultaneous controlled switching of back-to- back capacitor bank ;

a) phase voltages on supplying side,
b) overvoltage traces,
c) inrush current traces.

From above presented simulation of closing operations is visible that by using the controlled closing of back-to-back shunt capacitor banks the inrush currents may be substantially diminished.
Similarly to single shunt capacitor bank at opening operation the controlled switching may be used for controll of the of contacts separation phase.

IV. CONCLUSIONS.

Taking into account results received by mathematical simulation of nonsimultaneous closing or opening of shunt capacitor banks may be generally concluded:

- by using controlled switching the inrush current at closing of the shunt capacitor bank may be highly diminished,
- interrupting of the capacitive current with controlled contacts separation make possible the elimination of the restrikes and reignitions after current breaking,,
- controlled switching has probably no influence on hazardeous late restrikes [6],
- for controlled closing of single capacitive bank simple control equipment may be used, with the last switching pole mechanically delayed, and
- the control switching of back-to -back capacitor banks is more sofisticated in the comparison to the

to single capacitor bank and have to be individually analysed

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APPENDIX

E - amplitude of supplying voltage
ω - nominal pulsation,
L,R - inductance and resistance of supply side of the network,
C - capacitance of the condensor bank,
α - free frequency,
- attenuation factor of the current free component
u_a , u_b ,u_c - initial values of the voltages at the moment of the beginning of the current flow (at the moment of two phase closing) refering to the phase a
θ_2 - phase angle at the moment of two phase current flow, refering to phase a
θ_3 - phase angle at the moment of three phase current flow refering to phase a.
t_2 - time between two and three phases current flow,
t - time from the moment of three phase closing.

The equations of overvoltages at unsimultaneosly closing of three phase ungrounded single condensor bank

for first closing phase (phase a)

$$u_{Ca} = E\sin(\omega t + \theta_3) - E\sin\theta_3 \exp(-\delta t)\cos\alpha t -$$
$$-\frac{\sqrt{3}}{2}E\left[\cos(\theta_3 + 60^0) - \cos(\theta_2 + 60^0)\cos\alpha t_2\right]\cos\alpha t +$$
$$+\frac{1}{3}\left[-\frac{3}{2}(u_a - u_c) - \frac{u_a - u_c}{2}\cos\alpha t_2\right](1 - \cos\alpha t) +$$
$$+\frac{u_a + u_c}{2} - \frac{u_a - u_c}{2}\cos\alpha t_2$$

for the second closing phase (phase c):

$$u_{Cc} = E\sin(\omega t + \theta_3 - 240^0) - E\sin(\theta_3 - 120^0)\cos\alpha t -$$
$$-\frac{\sqrt{3}}{2}E\left[\cos(\theta_3 + 60^0) - \cos(\theta_2 + 60^0)\cos\alpha t_2\right]\cos\alpha t -$$
$$-\frac{1}{3}\left[-\frac{3}{2}(u_a + u_c) - u_b - \frac{u_a - u_c}{2}\cos\alpha t_2\right](1 - \cos\alpha t) -$$
$$-\frac{u_a + u_c}{2} - \frac{u_a - u_c}{2}\cos\alpha t_2$$

for the third closing phase (phase c):

$$u_{Cb} = E\sin(\omega t + \theta_3 - 120^0) + E\sin(\theta_3 - 240^0 \exp(-\delta t)\cos\alpha t -$$
$$+\frac{1}{3}\left[2u_b + (u_a - u_b)\cos\alpha t_2\right](1 - \cos\alpha t) - \mathrm{u}_\mathrm{b}$$

The equations of phase currents at nonsimultaneosly closing of three phase ungrounded single condensor bank

for the first closing phase (phase a); the time t is counted from the moment of three phase closing:

$$i_c = E\omega C\cos(\alpha t + \theta_3 - 240^0) + E\alpha C\sin(\theta_3 + 120^0)\exp(-\delta t)\sin\alpha t +$$
$$+\frac{1}{3}(2u_c - u_b - u_a)\frac{1}{Z}\exp(-\delta t\ )\sin\alpha t +$$
$$+\frac{1}{3}(2u_c - u_a - u_b)\frac{1}{Z}\exp(-\delta t)\sin\alpha t +$$
$$+\frac{\sqrt{3}}{2}E\alpha C\exp(-\delta t)\left[\cos(\theta_3 + 60^0) - \exp(-\delta t_2)\cos(\theta_2 + 60^0)\sin\alpha t\right] +$$
$$+\frac{1}{3}\left[\frac{5u_a + u_c}{2} - \frac{u_a - u_c}{2}\cos\alpha t_2\right]\frac{1}{Z}\exp[-\delta(t + t_2)]\sin\alpha t$$

for the second closing phase (phase c); the time t is counted from the moment of three phase closing:

$$i_c = E\omega C\cos(\omega t + \theta_3 - 240^0) + E\alpha C\sin(\theta_3 + 120^0)\exp(-\delta t)\sin\alpha t +$$
$$+\frac{1}{3}(2u_c - u_b - u_a)\frac{1}{Z}\exp(-\delta t\ )\sin\alpha t +$$
$$+\frac{1}{3}(2u_c - u_a - u_b)\frac{1}{Z}\exp(-\delta t)\sin\alpha t +$$
$$+\frac{\sqrt{3}}{2}E\alpha C\exp(-\delta t)\left[\cos(\theta_3 + 60^0) - \exp(-\delta t_2)\cos(\theta_2 + 60^0)\sin\alpha t\right] +$$
$$+\frac{1}{3}\left[\frac{5u_a + u_c}{2} - \frac{u_a - u_c}{2}\cos\alpha t_2\right]\frac{1}{Z}\exp[-\delta(t + t_2)]\sin\alpha t$$

for the third closing phase (phase b); the time t is counting from the moment of three phase closing:

$$i_b = E\omega C\cos(\omega t + \theta_3 - 120^0) + E\alpha C\sin(\theta_2 - 120^0)\exp(-\delta t)\sin\alpha t +$$
$$+\frac{1}{3}(2u_c - u_b - u_a)\frac{1}{Z}\exp(-\delta t\ )\sin\alpha t +$$
$$+\frac{1}{3}(2u_b - u_a - u_c)\frac{1}{Z}\exp(-\delta t)\sin\alpha t +$$
$$+\frac{1}{3}\left[(u_a - u_c) - (u_a - u_c)\cos\alpha t_2\right]\frac{1}{Z}\exp[-\delta(t + t_2)]\sin\alpha t$$