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Capacitor Banks Switching Transients in Power Systems

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Abstracts

This study provides an introduction to capacitor bank switching transients, illustrates the effects of the capacitor banks switching in the utility primary distribution system at different places of the power system, but specially at the customer's plant. Study covers different operational cases to find the suitable method or techniques can be used to limit the effect of capacitor switching transients.

Transient disturbances in power systems may damage key equipment, potentially having a great impact on system reliability. These transients may be introduced during normal switching operations, lightning strikes, or because the equipment failure. Therefore, time-domain computer simulations are developed to study dangers cases due to transient occurrences. The simulations are performed using the simulation software Electromagnetic Transient Program (EMTP). In this study, the Alternative Transients Program (ATP) version 5.7p2 was applied on a simple industry network.

Key words: Capacitor banks; Transient overvoltage and current; Energization inrush; Back-to-back switching; Preinsertion resistor and inductor

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Nomenclature

EMTP	Electromagnetic Transient Program	ac	alternating current
ATP	Alternative Transient Program	S1,2	Switch 1,2
dc	direct current	$V_{C1,2}(0)$	Initial voltage at C1,2
rms	root mean square	ω_1	Natural frequency
Vrms	root mean square voltage [V]	ω_2	Transient frequency
R	Resistance [Ω]	Z	Impedance [Ω]
C	Capacitance [F]	P.F.	Power Factor
V	Voltage [V]	S_K''	Short circuit power [VA]
IEEE	Institute of Electrical and Electronics Engineers	Rho	Earth resistance [Ωm]
Std.	Standard	C.B.1,2	Capacitor Banks 1,2
I	Current	Tc	closing time [s]
dc	direct current	p.u.	per unit

INTRODUCTION

Capacitor bank energizing transients are becoming increasingly more important with the growing number of capacitor bank installations in power systems. This is because capacitor bank switching is one of the most frequent utility operations, potentially occurring multiple times per day and hundreds of time per year throughout the system, depending on the need for system voltage/var support from the banks. There are a number of important concerns when capacitor banks are applied at the transmission system voltage level. Transient related currents and voltages appearing on a power system associated with utility capacitor bank installations include voltage transients at the capacitor bank substation and neighboring substations (include phase-to-ground or phase-to-phase overvoltages), power quality impact on sensitive customer loads due to variations in voltage, capacitor bank energization inrush currents and capacitor bank outrush currents due to faults in the vicinity of capacitor banks.

Utilities normally apply capacitors on three-phase sections[1]. Applications on single-phase lines are done but less common. Application of three-phase banks downstream of single-phase protectors is normally not done because of ferroresonance concerns. Most three-phase banks are connected grounded-wye on four-wire multigrounded circuits. Some are connected in floating wye. On three-wire circuits, banks are normally connected as a floating wye. Double-wye banks and multiple series groups are used when a capacitor bank becomes too large for the 3100 kvar per group for the expulsion type of fuses[2].

Properly applied capacitors return their investment very quickly. Capacitors save significant amounts of money in reduced losses. In some cases, reduced loadings and extra capacity can also delay building more distribution infrastructure.

Capacitor dielectrics must withstand high voltage stresses during normal operation, on the order of 78 kV/mm, and no other medium-voltage equipment has such high voltage stress[1]. Capacitors are designed to withstand overvoltages for short periods of time. New capacitors are tested with at least a 10 sec overvoltage, either a dc-test voltage of 4.3 times rated rms or an ac voltage of twice the rated rms voltage (IEEE Std. 18-2002).

Capacitors must have an internal resistor that discharges a capacitor to 50 V or less within 5 min when the capacitor is charged to the peak of its rated voltage √2Vrms. This resistor is the major component of losses within a capacitor. The resistor must be low enough such that the RC time constant causes it to decay in 300 sec as[1]:

$$\frac{50}{\sqrt{2}V} \leq e^{-300/RC} \tag{1}$$

Where
V- Capacitor voltage rating, V
R- Discharge resistance, Ω
C- Capacitance, F

Most utilities also include arresters and fuses on capacitor installations. Arresters protect capacitor banks from lightning overvoltages. Fuses isolate failed capacitor units from the system and clear the fault before the capacitor fails violently. In high fault-current areas, utilities may use current-limiting fuses. Switched capacitor units normally have oil or vacuum switches in addition to a controller. Depending on the type of control, the installation may include a control power transformer for power and voltage sensing and possibly a current sensor[1].

IEEE[3] guides suggest selecting a fuse capable of handling 1.25 to 1.35 times the nominal capacitor current (IEEE Std. C37.48-1997), a 1.35 factor is most common.

Capacitors are rated to withstand 180% of rated rms current, including fundamental and harmonic currents. Fusing is normally not based on this limit, and is normally much tighter than this, usually from 125 to 165% of rated rms current. Occasionally, fuses in excess of 180% are used. In severe harmonic environments (usually in commercial or industrial applications), normally fuses blow before capacitors fail, but sometimes capacitors fail before the fuse operates. This depends on the fusing strategy. The smallest size fuse that can be used is[1]:

$$I_{min} = \frac{1.35\ I_1}{1.5} = 0.9\ I_1 \tag{2}$$

Where
Imin - minimum fuse rating, A
I_1 - capacitor bank current, A

1. CAPACITOR ENERGIZATION

During the switching of shunt capacitor banks, high magnitude and high frequency transients can occur[4]. The transient is characterized by a surge of current having a high magnitude and a frequency as high as several hundred Hertz. There is also a transient overvoltage on the bus, caused by the surge of inrush current coming from the system source.

Basics concepts concern to capacitor energization are explained in Figure 1, where resistances were neglected for simplification. When the first capacitor C1 is energized (closing S1) the current and voltage in the capacitor are given by equations 3 and 4[4, 5, 6].

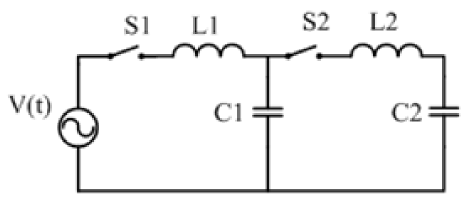


Figure 1
Capacitor Energization

$$V_{C1}(t)=V-[V-V_{C1}(0)]\sin\omega_1 t \tag{3}$$

$$I(t) = \frac{V}{Z_1}\sin\omega_1 t \tag{4}$$

Where
V – Switch voltage at S1 closing.
$V_{C1}(0)$ – Initial voltage at C1.

$\omega_1 = 1/\sqrt{L_1C_1}$ - Natural frequency.
$Z_1 = \sqrt{L_1/C_1}$ – Surge impedance.

Energizing the second bank C2 when the first bank C1 is already energized is called back-to-back switching, and is simulated by closing switch S2 when C1 is already operating in steady state. In this case, any potential difference between the two banks is eliminated by a redistribution of charge[5]. A circuit with two loops L-C, each one with a natural oscillation frequency of ($\omega = 1/\sqrt{LC}$), presents voltage amplification when the frequencies have close values. An increase of the amplification of the voltage when the surge impedance ($Z = \sqrt{L/C}$) of the second loop becomes larger than the surge impedance of the first loop was also verified. The resulting inrush to C2 is a high-frequency transient which primarily involves the series combination of C1, L2, and C2, driven by the voltage $V_{C1}(0)$ on C1 at the instant S2 is closed.

References provide approximate methods of calculating the inrush[7]. However, numerical methods of solving the needed differential equations have been developed in many software, such as the well known EMTP ATPDraw[8].

The voltage on the capacitor C2 can be represented by[6, 9]:

$$\frac{V_{C2}}{V} = 1 + A\cos\phi_1 t + B\cos\phi_2 t \tag{5}$$

$$I_2(t) = \frac{V_1 - V_{C2}(0)}{\sqrt{L_2 \frac{(C_1 + C_2)}{C_1C_2}}}\sin\omega_2 t \tag{6}$$

Where the coefficients A, B, $Ø_1$ and $Ø_2$ are calculated from C1, C2, L1 and L2 and given in[6, 9].
V_1 – Voltage at C1 at S2 closing.
$V_{C2}(0)$ – Initial voltage at C2.
$\omega_2 = \left(\sqrt{L_2(C_1C_2/C_1 + C_2)}\right)^{-1}$ - Transient frequency.

2. MODELLING THE NETWORK

Simulation of shunt capacitors switching is very simple in the ATPDarw. The network shown in Figure 2 was used for the purpose of this paper. The study focuses on the effects of the switching the capacitor banks in the utility primary distribution system, at the customer's plant. The network consists of one industry, which it's main load basically contains induction motors about 10 kW of installed power, with a total rated power about 10 MW at 22 kV, cosφ=0.85 and the industry has power factor (P.F.) correction capacitors to correct from 0.85 to 0.95, according to their needs. The network is fed by a cable in grounded structure and along the feeder two capacitor banks (950 and 1400 kVAr) were installed to simulate a real life case. The switching process is done by two switches, installed at the external phases, with the internal phase permanently energized.

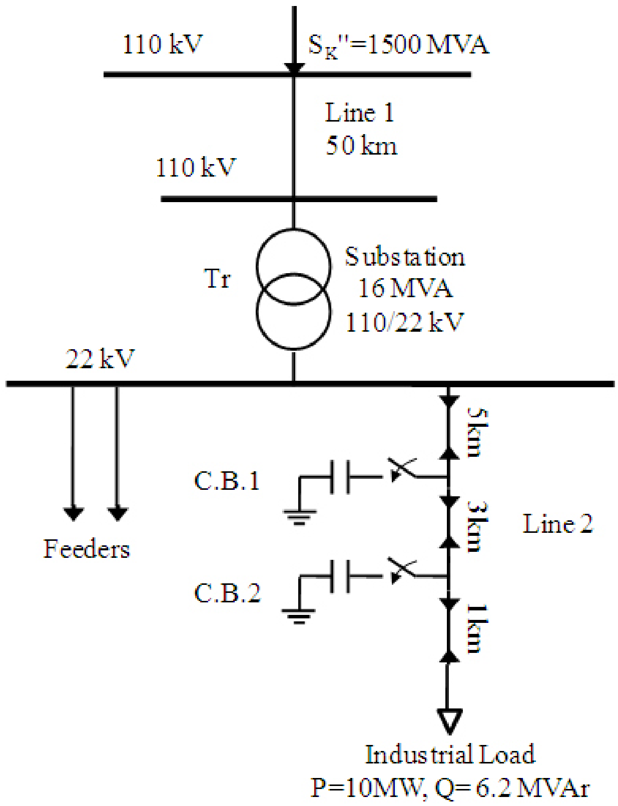


Figure 2
Scheme of the Network

2.1 110 kV Supply Network

The system equivalent was modelled by the ATP model AC3PH-type 14, with amplitude equals to ($110\times\sqrt{2}/\sqrt{3}$=89.804 kV) and internal impedance (R=0.8 Ω, L= 25.5636 mH) calculated from the value of S_K"=1500 MVA.

2.2 Substation Transformer

The substation transformer 110/22 kV is modeled by BCTRAN as 3-phase, Δ-Y, with ground Y and with the labels values as shown in Table 1 below.

Table 1
Parameters of the Transformer

Tr (110/22 kV)	Power(MVA)	Short-circuit voltage (%)	Open-circuit current (%)	Short-circuit losses (kW)	Open-circuit losses (kW)
	16	11,53	0,22	62.67	15,17

2.3 Transmission Line and Cables

The transmission line 1 is made of 240AlFe6, length 50km and was modeled by LCC Line/Cable procedure as an overhead line, 3-phase, type PI. Rho (ground resistivity)=100 Ωm, Freq. init=50 Hz. The parameters are in Table 2.

Table 2
The Parameters of the Transmission Line 110 kV

Phase no.	React. (Ω/km)	Rout (cm)	Resis (Ω/km)	Horiz (m)	Vtower (m)	Vmid (m)
1	0.421	0.8	0.234	-0.75	10.5	9.5
2	0.421	0.8	0.234	0	10.5	9.5
3	0.421	0.8	0.234	0.75	10.5	9.5

The cable line 2 is modeled by the Line/Cable too. All the three lengths are the same type AX240, 3-Phase, single core cable, PI-Model, grounded, Rho=100 Ω.m, f=50 Hz, total radius=0.05 m, position: Vert=0.7m, Hor=0 and their parameters are in Table 3.

Table 3
The Parameters of the Cables

	Rin (m)	Rout (m)	Rho (Ω·m)	mu	mu (ins)	eps (ins)
Core	0	0.00874	2.3E-8	1.0000207	0.9999905	2.3
Sheath	0.01674	0.01924	1.555E-8	1.0000207	0.9999905	2.3

2.4 Load

All loads are modelled by the ATP model RLC3, where the values of the model are calculated by the equations[10] $R=U^2/P$, $L=(U^2/Q)/2\pi f$ and $C=0$. The values are listed in the table below.

Table 4
Parameters of the Loads

P (MW)	Q (MVAr)	cos φ	R (Ω)	L (mH)
10	6.197	0.85	48.4	248.72

The reactive power of the P.F. capacitors to correct from 0.85 to 0.95 is calculated as $Q=P(\tan\varphi_1-\tan\varphi_2)=2.9$ MVAr, then $C=Q/2\pi fU^2=19$ μF.

2.5 Capacitor Banks

The capacitor banks (950 and 1400 kVAr) are modelled by the ATP model RLCD3, where the value of one phase capacitor is calculated as $C=Q/2\pi fU^2$ (C.B.1=6.25 μF and C.B.2=9.21 μF).

The capacitor banks are in series with a 3-phase time controlled switch, which is modelled by SWIT_3XT and programmed to switch on and off at the desired time intervals, but the transients normally occur during the energisation of the capacitor banks[11].

3. RESULTS

In this study the amplification of the transient overvoltage was experienced. The simulations can be realized for different situations, for example, when the industry's load is modeled without, or with, the power factor correction capacitors, on the other hand the closing of the capacitors can be realized near the voltage peak or near zero crossing, with using preinsertion resistors and inductors or with out them. Generally, all simulations were done at the maximum load of the industry and for some different situations and the output data were taken just for A-phase. The ATPDraw scheme of the network is shown in Figure 3.

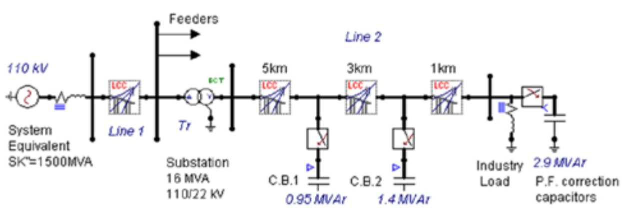
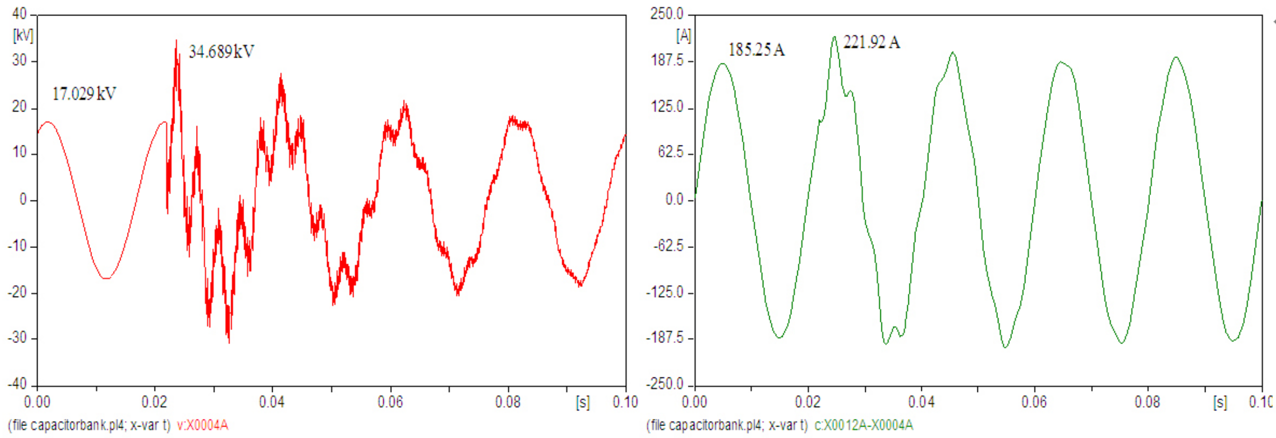


Figure 3
ATPDraw Scheme of the Network

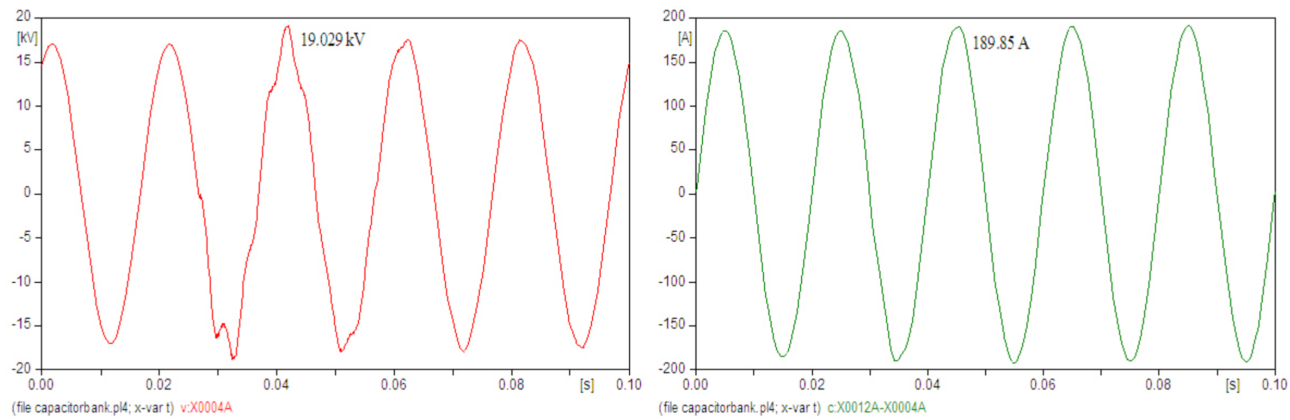
3.1 Inrush Transients

3.1.1 At the industry: The capacitor bank C.B.1 was energized for the situations whit and without using the power factor correction capacitors, near the voltage

peak at the time Tc=0.0218 sec (Figure 4a) and near zero crossing Tc=0.0267 sec (Figure 4b).



a. Inrush voltage and current, without P.F. capacitors, closing near the peak

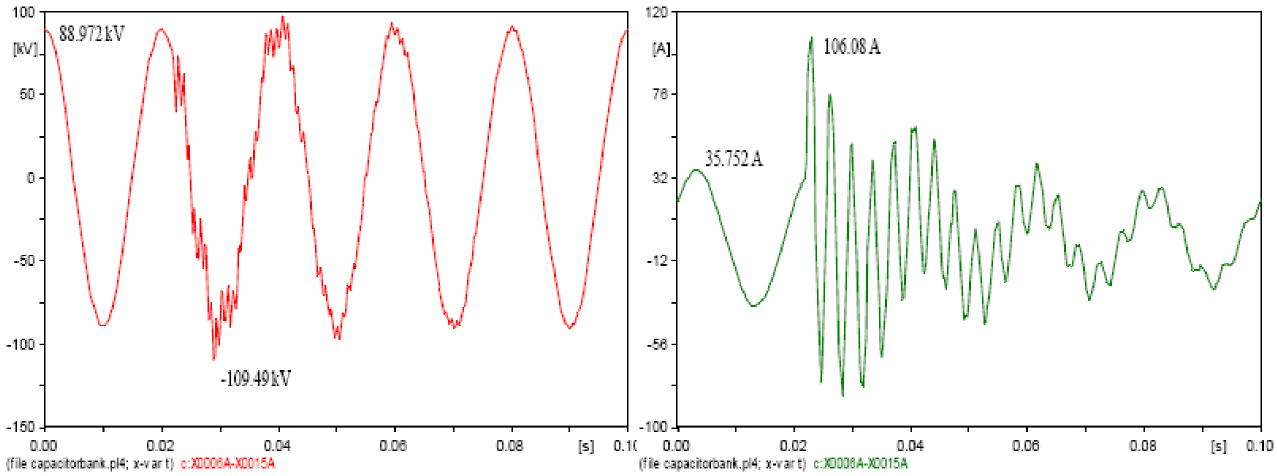


b. Inrush voltage and current, without P.F. capacitors, closing near zero crossing

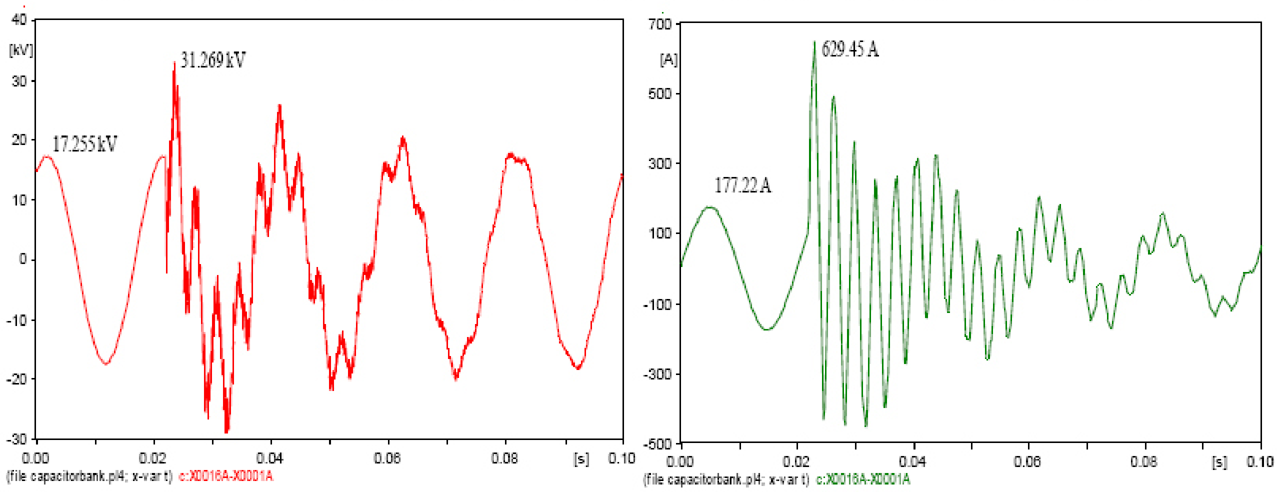
Figure 4
Energization Inrush at the Industry

The results in Figure 4 show that the synchronous switch closing is very efficient in the mitigation of the transient. The largest value of the voltage and the current occur for the situation without P.F. correction capacitors, switching near the voltage peak. The values of the voltage reached 2.04 p.u. and the current reached 1.198 p.u.

3.1.2 At the substation: applying the same conditions as above, when switching near the voltage peak, the values of the voltage and the current at the primary side reached 1.23 p.u. and 2.97 p.u., respectively (see Figure 5a). At the secondary side the values of the voltage and the current reached 1.81 p.u. and 3.55 p.u., respectively (see Figure 5b).



a. Primary inrush voltage and current, without P.F. capacitors, closing near the peak



b. Secondary inrush voltage and current, without P.F. capacitors, closing near the peak

Figure 5
Energization Inrush at the Substation

3.1.3 At the C.B.1: applying the same conditions as above, the value of the peak voltage reached 28.978 kV, then established at 17.572 kV. The peak current flows to C.B.1 reached -923.89 A, then established at 370.34 A (see Figure 6).

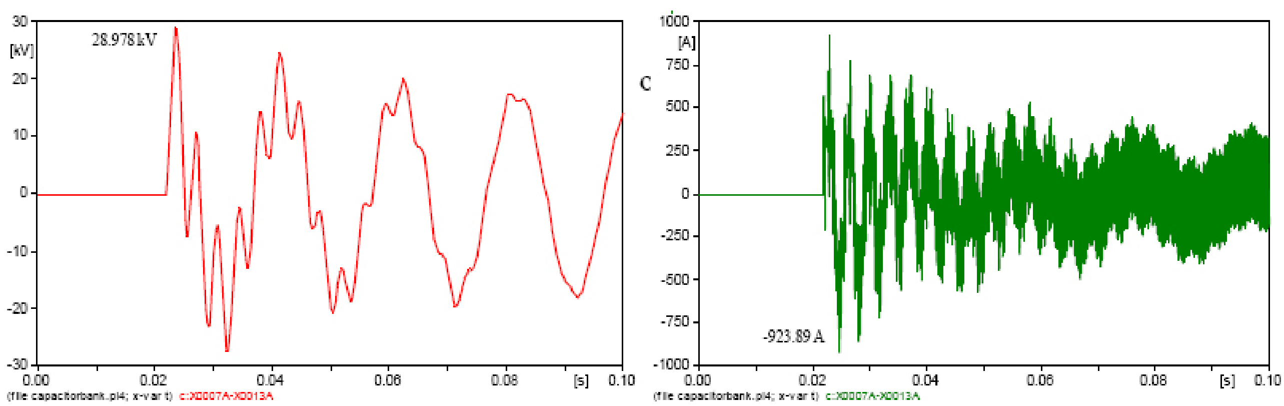


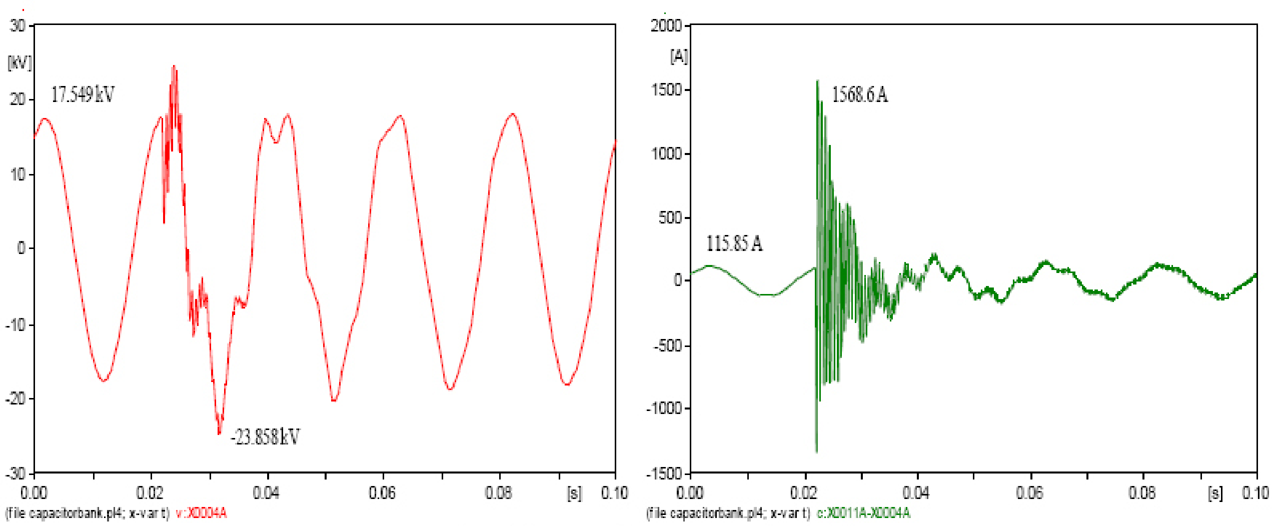
Figure 6
Energization Inrush at the C.B.1

The results of all situations explained above are obtainable in Table 5.

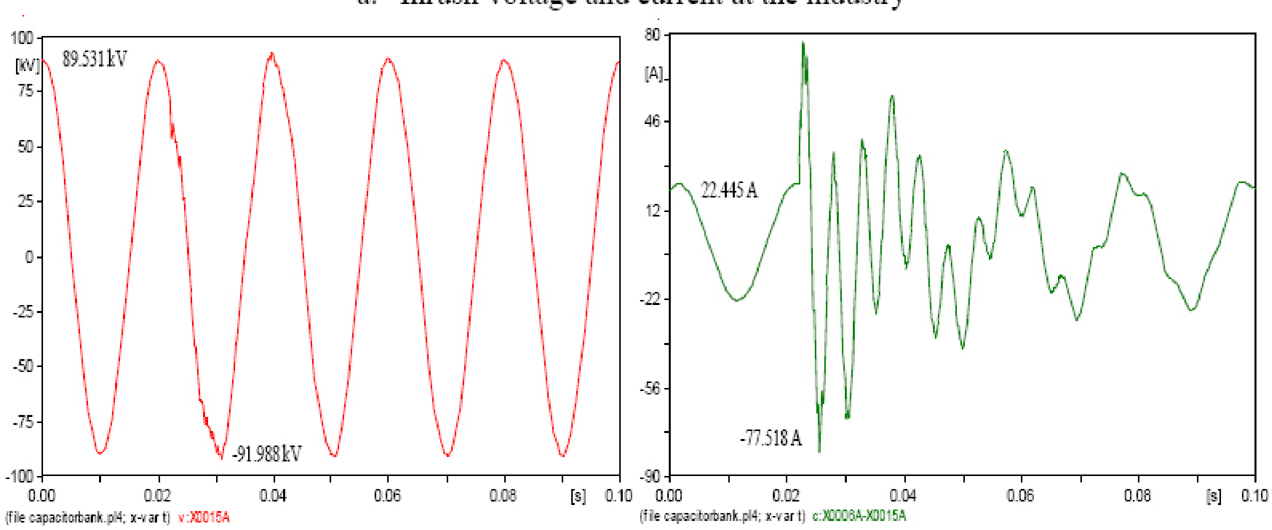
Table 5
Maximum Transient Overvoltages and Currents

Energization of C.B.1 with out P.F. capacitors	At the industry		At the substation				At the C.B.1	
	(kV)	(A)	(kV)		(A)		(kV)	(A)
			Prim.	Sec.	Prim.	Sec.		
Before	17.029	185.25	88.972	17.255	35.752	177.22	-	-
closing near the voltage peak	34.689	221.92	-109.49	31.269	106.08	629.45	28.978	-923.89
closing near zero crossing	19.029	189.85	-	-	-	-	-	-

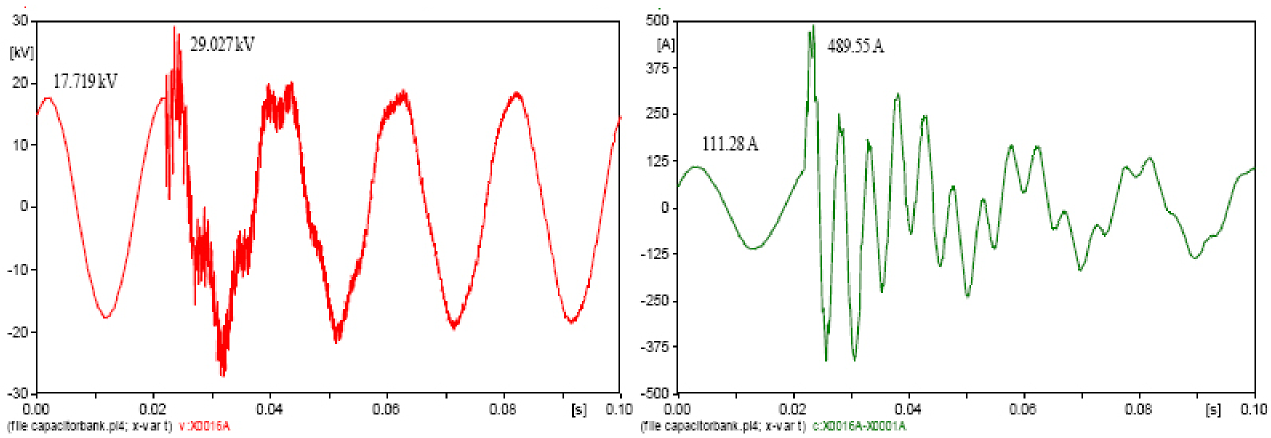
Now we will observe the situations in which the industry has all his P.F. correction capacitors switched on and just for the switching near the voltage peak. The results are shown in Figure 7 and Table 6, where low transient overvoltages are noticed. The values of the voltage and the current at the industry reached 1.36 p.u. and 13.54 p.u., respectively (Figure 7a). At the substation, at the primary side the values of the voltage and the current reached 1.03 p.u. and 3.47 p.u., respectively (Figure 7b) and at the secondary side reached 1.64 p.u. and 4.4 p.u., respectively (Figure 7c). At the C.B.1 the voltage reached 25.016 kV, which is 1.38 p.u. and the current 1597.1 A, which is 14.92 p.u. in comparison if C.B.1 was already in steady state.



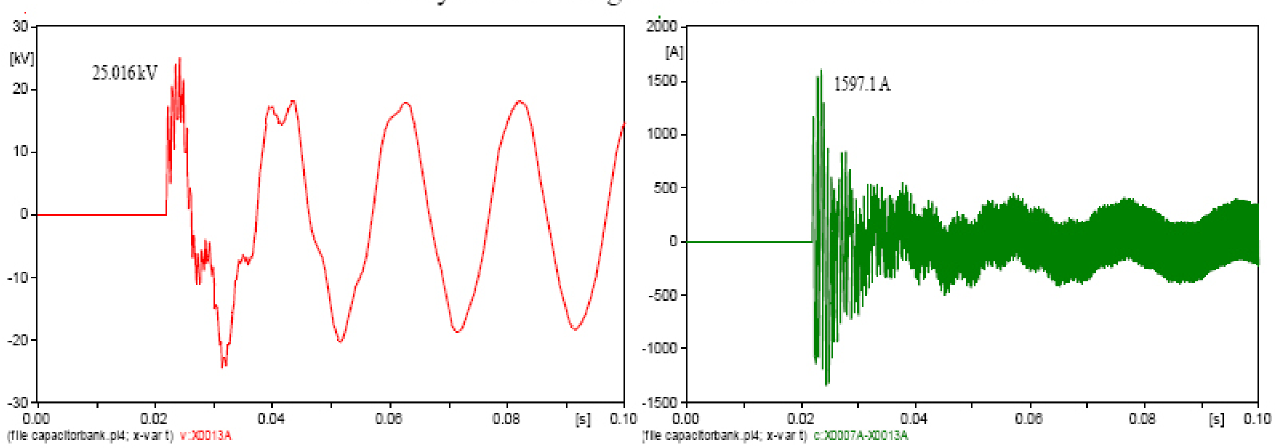
a. Inrush voltage and current at the industry



b. Primary inrush voltage and current at the substation



c. Secondary inrush voltage and current at the substation



d. Inrush voltage and current at the C.B.1

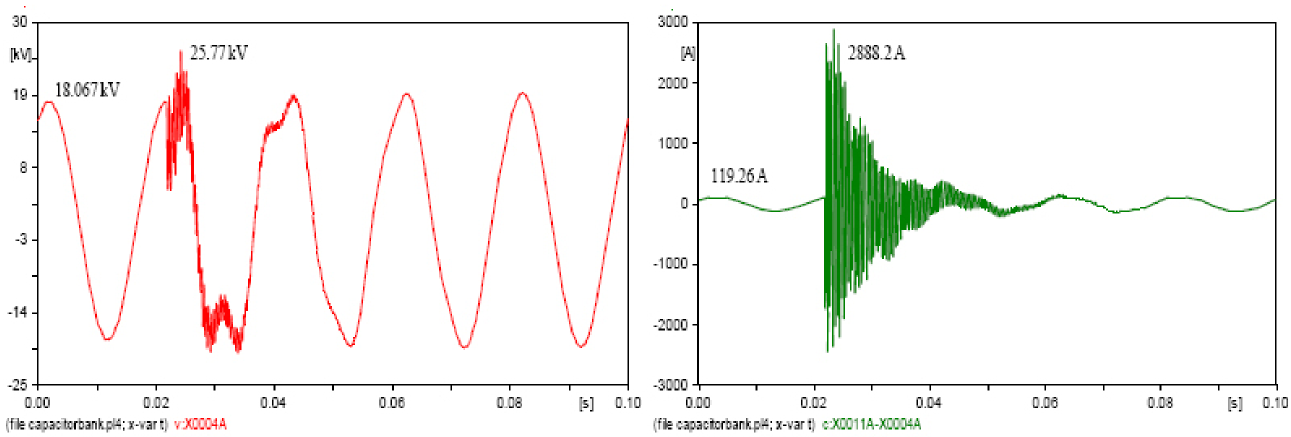
Figure 7
Energization Inrush with P.F. Correction Capacitors

Table 6
Maximum Transient Overvoltages and Currents

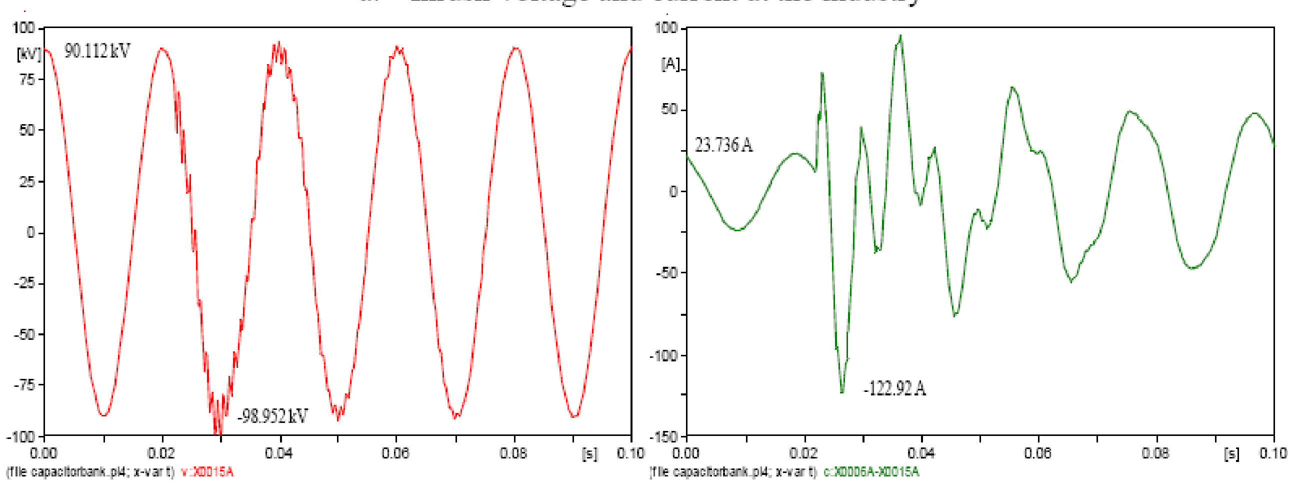
Energization of C.B.1 with out P.F. capacitors	At the industry		At the substation				At the C.B.1	
	(kV)	(A)	(kV)		(A)		(kV)	(A)
			Prim.	Sec.	Prim.	Sec.		
Before	17.549	115.85	89.531	17.719	22.445	111.28	-	-
closing near the voltage peak	-23.858	1568.6	-91.988	29.027	-77.817	489.55	25.016	1597.1

3.2 Back-to-Back

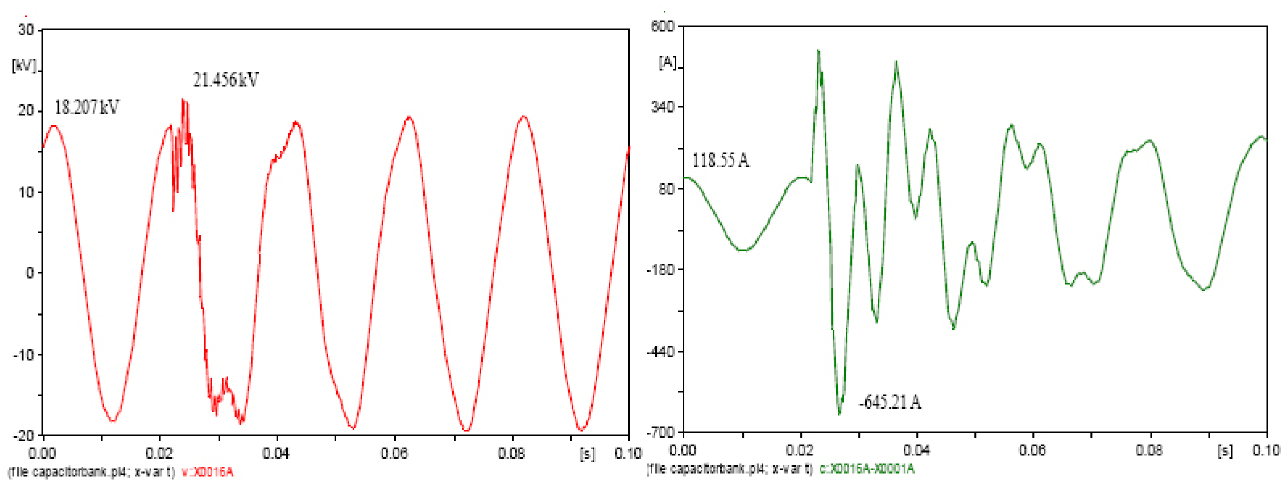
With consideration that the capacitor bank C.B.1 was already energized and the industry used the power factor correction capacitors, the C.B.2 is energizing near the voltage peak at the time Tc=0.0217 sec. The plot of the inrush voltages and currents, resulting from energizing the C.B.2 in the presence of the C.B.1, is presented in Figure 8 and Table 7.



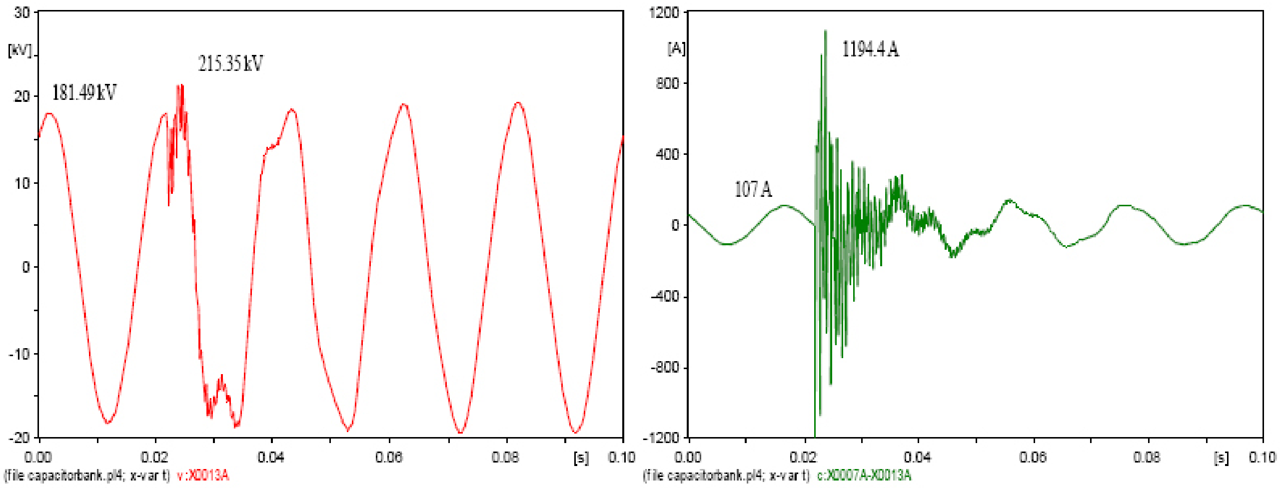
a. Inrush voltage and current at the industry



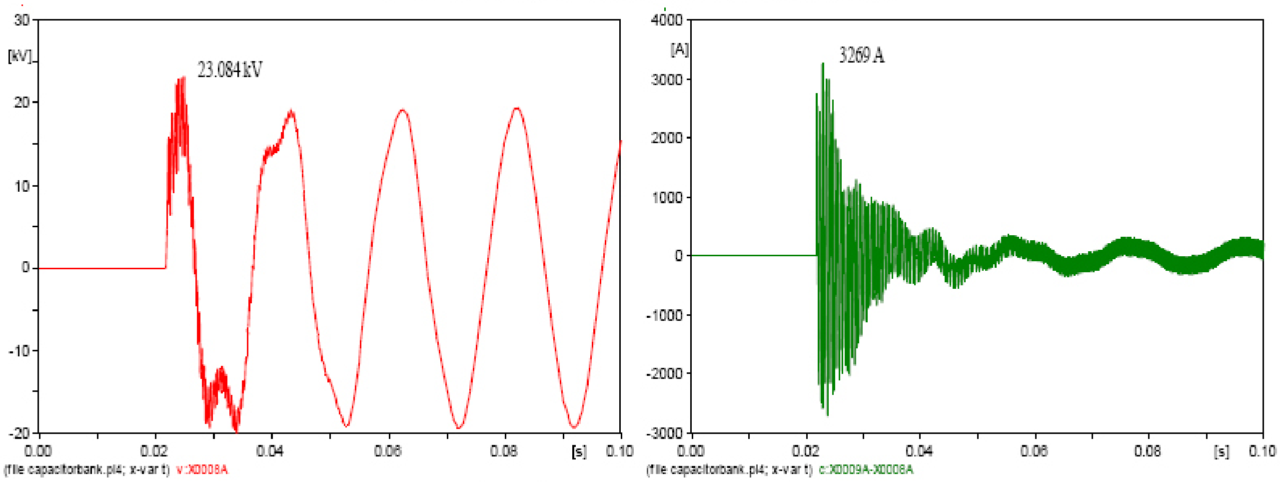
b. Primary inrush voltage and current at the substation



c. Secondary inrush voltage and current at the substation



d. Inrush voltage and current at the C.B.1



e. Inrush voltage and current at the C.B.2

Figure 8
Energization Inrush with P.F. Correction Capacitors

Table 7
Maximum Transient Overvoltages and Currents

Energization of C.B.2	At the industry		At the substation				At the C.B.1		At the C.B.1	
	(kV)	(A)	(kV)		(A)		(kV)	(A)	(kV)	(A)
			Prim.	Sec.	Prim.	Sec.				
Before	18.067	119.26	90.112	18.207	23.736	118.55	181.49	107	-	-
closing near the voltage peak	25.77	2888.2	-98.952	21.456	-122.92	-645.21	215.35	1194.4	23.084	3269

The transient, in general, no higher than 2.0 p.u. on the primary distribution system, although ungrounded capacitor banks may yield somewhat higher values. Transient overvoltages on the end-user side may, under some conditions, reach as high as 3.0 to 4.0 p.u. on the low-voltage bus with potentially damaging consequences for all types of customer equipment[12].

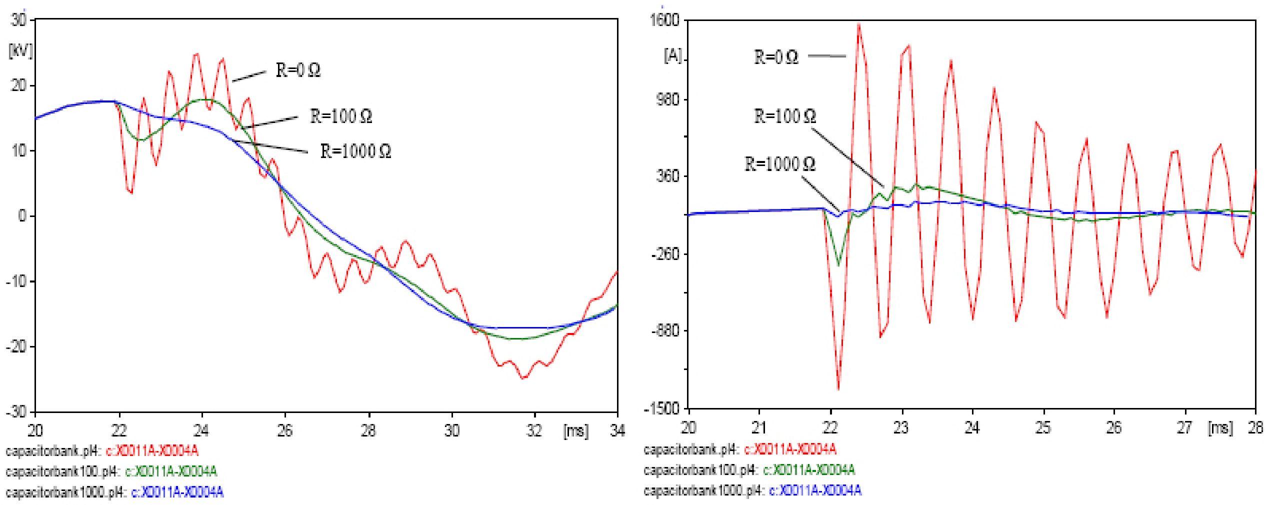
From the figures mentioned above it can be seen, that the transient represents a variation of a percentage in voltage or current for a fraction of a cycle, but that can have a damaging effect. The worst case situation was with switching occurring at the peak voltage. Now that a good result has been obtained from the simulation, what techniques can be used to limit the effect of capacitor switching? Some solutions are switching times, preinsertion resistors and inductors, synchronous closing of circuit breakers (it is a three-phase SF6 breaker that uses a specially designed mechanism with three independently controllable drive rods. It is capable of closing within 1 ms of voltage zero), capacitor location and metal oxide varistors (MOVs) or surge arresters are used to reduce these transients[5, 12].

3.3 Effect of Preinsertion Resistors and Inductors

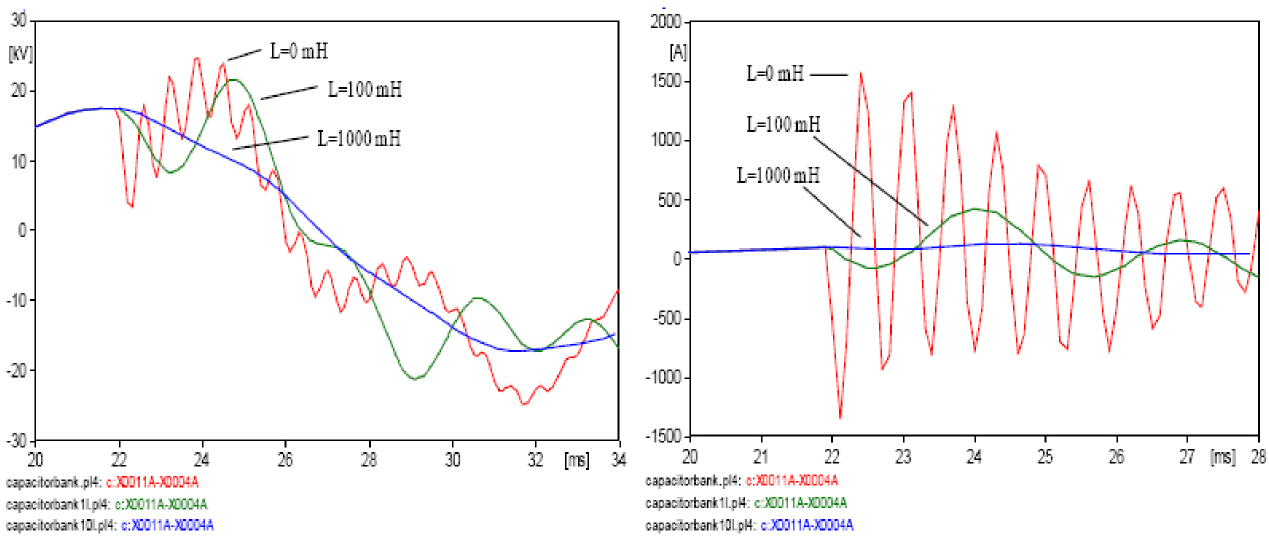
Preinsertion resistor is one of classical methods, which have been used for years by the electric utility industry for controlling capacitor-bank energization overvoltages. The preinsertion is accomplished by the movable contacts sliding past the resistor contacts first before mating with the main contacts.

Switches with preinsertion reactors have also been developed for this purpose. The inductor is helpful in limiting the higher-frequency components of the transient. In some designs, the reactors are intentionally built with high resistance so that they appear lossy to the energization transient, this damp out the transient quickly[12].

The following Figure 9 illustrates the situation at the industry as shown in Figure 7a, explained previously, with using two sizes of resistors and inductors in series with the capacitors. It can be seen that with the increase in size, the inrush decreases.



a. Inrush voltage and current at the industry with using resistors



b. Inrush voltage and current at the industry with using inductors

Figure 9
Energization Inrush with Preinsertion Resistors and Inductors

CONCLUSION

Transients originating from utility capacitor bank switching were the purpose of this study. Moreover different factors that result in intensity of the transients were studied too to find the optimal methods or techniques can be used to limit the transients. For realization such purposes a simple electric network representing a real life case was used and the software ATPDraw was helpful to simulate the transients of voltages and currents at different places of the network.

The results shown in the figures and tables give a detailed perfect view about the factors that affect the transients. Switching near the voltage peak magnifies transient voltages and currents, while switching near zero crossing reduces them. Depending on the industry power factor correction capacitors operation the transient voltages and currents can be amplified or mitigated. Finally, as seen in Figure 9, the use of resistors and inductors with the capacitors it can be seen that with the increase in size, the inrush decreases.

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