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# A TRANSIENT STUDY FOR SHUNT CAPACITOR APPLICATIONS

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## INTRODUCTION

The main aim of the paper is to present some important aspects regarding quality and management of electric power, aspects that have become manifest both in Romanian and European Community power systems. These problems are very typical taking into account the desire of Romania to join the European Community and to strengthen the relation between Romanian Power System (RPS) and Western European Power System (UCPTE).

The connection with UCPTE or at least with some UCPTE countries seems to have a major strategically importance. This importance can be similar of other East-European countries like Poland, Czech Republic, Serbia, Slovakia, Hungary, Ukraine or Bulgaria. The geographical position of Romania appears as very favorable and our country can become an important bridge among Western, South-Eastern Europe and Eastern Europe, respectively and further to Turkey.

The paper initiates some researches in the above mentioned fields, with specific remarks to the quality of electric power, to the manner in which some deviations from the accepted values of quality parameters affect the equipment working, respectively to the electric power management.

Capacitor banks are used for power factor improvement, elimination of voltage drops on long feeders, and control of reactive power. The capacitors at the transformer stations are switched on in the morning as the peak load increases to reduce the on-line generation and regulate system voltage. At night, the peak load is significantly decreased and therefore the capacitors can be switched off the line since there is no requirement. Due to load variations, a number of switching operations will occur daily. Voltage transients due to the switching operations of the capacitors at the transformer stations result in amplified overvoltages which propagate to the downstream distribution feeders.

The primary area of concern is typically with how the capacitor switching transients will affect power quality for nearby industrial and commercial loads. This paper evaluates several of the more common power quality problems associated with the application of transmission and distribution system capacitor banks.

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Power quality symptoms related to distribution capacitor switching include: customer equipment damage or failure (due to excessive overvoltage), adjustable-speed drive or other process equipment shutdown (due to DC bus overvoltage), computer network problems, etc.

## CAPACITOR BANK SWITCHING TRANSIENT ANALYSIS

Capacitor banks applied within distribution substations typically consists of one to four banks of switched capacitors. For the purpose of this study is used the circuit presented in Figure 1 which is a subystem of the Romanian Power System where two capacitor banks are used for power factor, vars, and/or voltage correction.

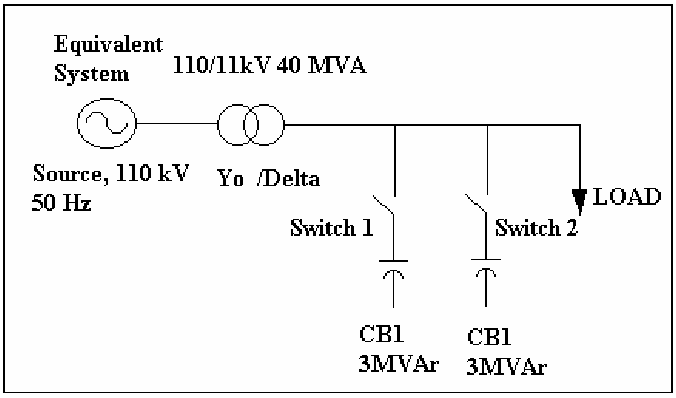


**Figure 1 The subsystem under study.**

The subsystem consists of primary distribution system with a source of 110 kV, 50 Hz and a transformer with the parameters 40 MVA, 110/11 kV (Yo/Delta). The configuration also shows a switched one or two capacitor banks size 3 MVAr ungrounded wye connection at the source bus, on the secondary side of the transformer station for power factor correction and reactive power/bus voltage control. The industry's load was represented by R-L loop with constant impedance at every case-study. The voltage and the current waves were measured at the transformer, at the load side and at the capacitor banks. Working with the customer, we collect and compile data for the model into a database for reference during the study. Several load conditions required by the industry were considered and are summarized in Table 1 taking into consideration the current value from the hourly operator report on peak load period.

**TABLE 1 Load conditions.**

| | CB1 | | | | CB2 | | | |
|---|---|---|---|---|---|---|---|---|
| Load cosφ | 0.8 | 0.85 | 0.92 | 0.94 | 0.8 | 0.85 | 0.92 | 0.94 |
| $R_{Load}$ [Ω] | 9.29 | 9.87 | 10.69 | 10.92 | 9.29 | 9.87 | 10.69 | 10.92 |
| $X_{Load}$ [Ω] | 12.07 | 10.61 | 7.91 | 6.89 | 12.07 | 10.61 | 7.91 | 6.89 |
| L [mH] | 38 | 33.7 | 25.1 | 21.9 | 38 | 33.7 | 25.1 | 21.9 |

Study cases presented in this paper reffer to the following issues:

- transient overcurrent and overvoltage magnitudes for normal capacitor energizing operations;
- various transient control methods;
- arrester duties for voltage magnification conditions;
- transients at transformer terminations;
- impact of capacitor switching transients on lower voltage systems.

The mitigation techniques taking into consideration in this study are:

- pre-insertion resistors;
- pre-insertion inductors;
- MOV arresters;
- synchronous closing.

The performed simulation suggested that the effectiveness of these control methods is system dependent, and that detailed analysis is required to select the optimum control scheme. While often justifiable for large

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transmission applications, analysis of distribution system capacitor applications is rarely completed, and in general, capacitor banks are installed without transient overvoltage control. Each of these methods has various advantages and disadvantages in terms of transient overvoltage reduction, cost, installation requirements, operating/maintenance requirements, and reliability.

A time-domain simulation using Electromagnetic Transient Program (EMTP) was performed and for a detailed analysis a complete set of study cases presented in Table 2 are submitted to the simulation.

**TABLE 2 Summary of study cases.**

| Case study | Capacitor bank 1 | Capacitor bank 2 | Circuit breaker is close at | | | Mitigation technique |
|---|---|---|---|---|---|---|
| | | | *Phase 1* | *Phase 2* | *Phase 3* | |
| 1. | Connected | Disconnected | $t_0$ | $t_0$ | $t_0$ | No |
| 2. | Connected | Disconnected | $t_0$ | $t_0$+5ms | $t_0$+10ms | No |
| 3. | Connected | Disconnected | $t_0$ | $t_0$ | $t_0$+5ms | No |
| 4. | Connected | Disconnected | $t_0$ | $t_0$ | $t_0$ | Pre-insertion resistor |
| 5. | Connected | Disconnected | $t_0$ | $t_0$ | $t_0$ | Pre-insertion inductor |
| 6. | Connected | Disconnected | $t_0$ | $t_0$ | $t_0$ | MOV arrester |
| 7. | Connected | Disconnected | Voltage zero crossing | Voltage zero crossing | Voltage zero crossing | Synchronized closing |
| 8. | Connected | Switched | $t_0$ | $t_0$ | $t_0$ | No |
| 9. | Connected | Switched | $t_0$ | $t_0$+5ms | $t_0$+10ms | No |
| 10. | Connected | Switched | $t_0$ | $t_0$ | $t_0$+5ms | No |
| 11. | Connected | Switched | $t_0$ | $t_0$ | $t_0$ | Pre-insertion resistor |
| 12. | Connected | Switched | $t_0$ | $t_0$ | $t_0$ | Pre-insertion inductor |
| 13. | Connected | Switched | $t_0$ | $t_0$ | $t_0$ | MOV arrester |
| 14. | Connected | Switched | Voltage zero crossing | Voltage zero crossing | Voltage zero crossing | Synchronized closing |

Note: $t_0$ is an arbitrary time choose for circuit breaker close.

**RESULTS INTERPRETATION**

The peak voltage magnitude depends on the instantaneous system voltage at the moment of capacitor bank energization, and can reach till 2.0 times the normal system peak voltage (per-unit) under worst-case conditions. From the analysis of the simulation results, we can conclude that in all the cases performed, the maximum overvoltages that appear, occurs in the transitory period after the beginning of operation of the capacitor bank. In Table 3 are presented the maximum values of the overvoltages obtained, for different load conditions.

**TABLE 3 Maximum voltage in p.u. for capacitor bank energization.**

| Topology | Load cosφ | | | |
|---|---|---|---|---|
| | *0.8* | *0.85* | *0.92* | *0.94* |
| With one capacitor bank Maximum voltage in p.u. | 1.72 | 1.68 | 1.65 | 1.64 |
| With two capacitor bank Maximum voltage in p.u. | 1.34 | 1.33 | 1.33 | 1.33 |

Typical voltage waveforms are provided below after the capacitor bank 1 was energized (case study 2 in Table 1). When a capacitor is energized, a transient oscillation occurs between the capacitor and the system inductance. The capacitor creates a resonance between the 7th and 11th harmonics, magnifying both of these components. Figure 2 illustrates the waveform for the voltage, where the capacitor bank CB1 at the transformer station has been energized causing overvoltage, for the most adverse situation with power factor cos φ = 0.8.

In Figure 3 is presented voltage and current waveforms when the first capacitor bank (CB1) is connected and the second capacitor bank (CB2) is switched on (case study 8 in Table 1) for the most adverse situation with power factor cos φ = 0.8.

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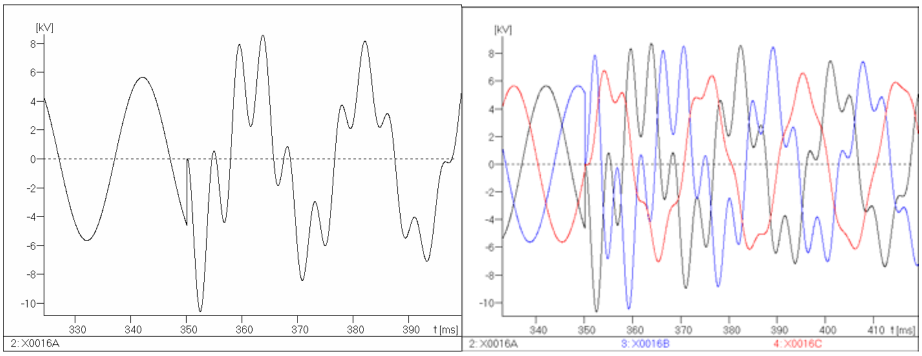
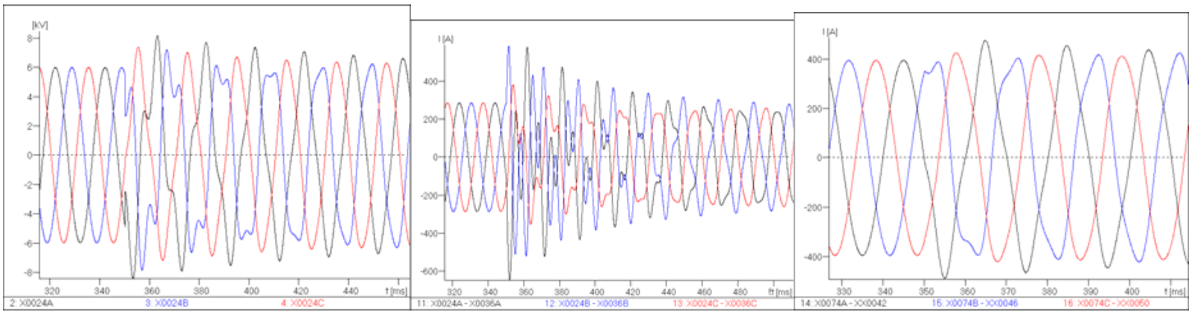


a) Phase a b) Phase a, b and c

**Figure 2 The voltage evolution for the first capacitor bank energizing.**



Voltage waveform Current at transformer side Current at load side

**Figure 3 The voltage and current evolution for CB1 connected and CB2 is energized.**

In addition, information is provided on how the capacitor bank switching transients can be reduced or nearly eliminated.

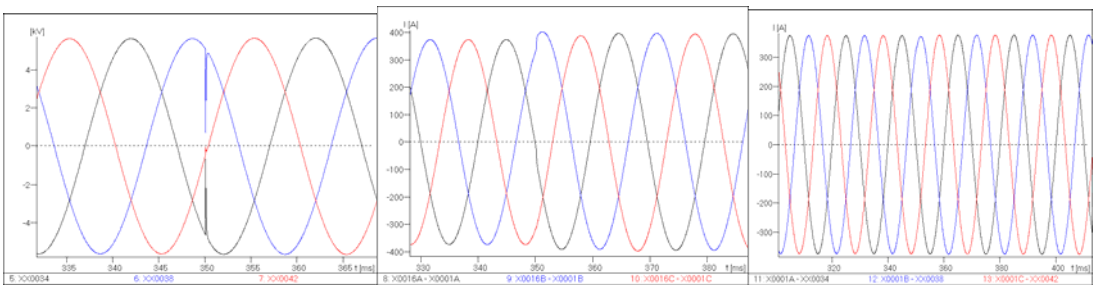
## MITIGATING TRANSIENTS ASSOCIATED WITH CAPACITOR BANK SWITCHING

In purchasing and specifying capacitor banks, the cost associated with nearby electrical equipment miss-operation or damage should be evaluated against the cost of additional equipment to eliminate switching transients. In the following subheadings the transformer and load-side voltage and current are shown during the capacitor energizing in the presence of different mitigation devices.

### Pre-insertion resistors

Pre-insertion resistors are one of the most effective means for controlling capacitor energizing transients (Figure 4); however, reliability issues have often caused utilities to select other means. The optimum resistor value for controlling capacitor energizing transients depends primarily on the capacitor size and the source strength. It should be approximately equal to the surge impedance ($Z_s$) formed by the bank and source:

$$R_{optimum} \approx \sqrt{\left( L_s / C \right)} \quad (1)$$



*Voltage waveform* *Current at transformer side* *Current at load side*

**Figure 4 Capacitor-bank energizing with pre-insertion resistor.**

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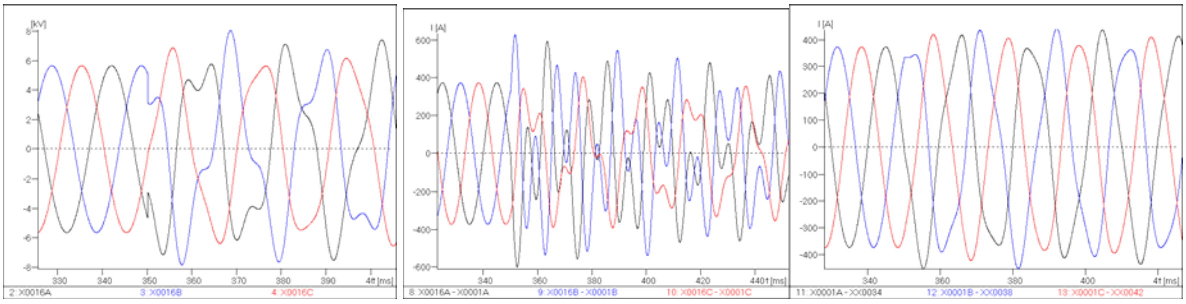
**Pre-insertion inductors**

Pre-insertion inductors furnish an impedance, which is frequency dependent, in series with the bank capacitance during the initial energization of the capacitor bank. This impedance reduces the collapse in bus voltage (Figure 5) by the amount of voltage developed across the inductor during the inrush of current into the bank. The pre-insertion inductor also limits the magnitude of the initial inrush current. Since the impedance of the pre-insertion inductor is frequency dependent, its value appears to be quite large during initial inrush current into the bank when the frequency is quite high.



*Voltage waveform* *Current at transformer side* *Current at load side*

**Figure 5 Capacitor-bank energizing with pre-insertion inductor.**

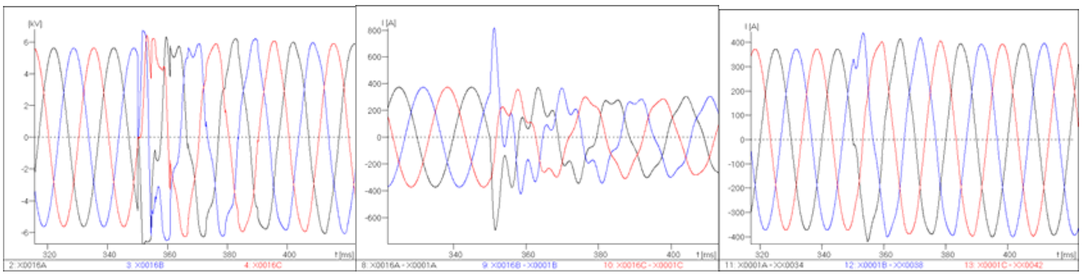
The level of overvoltage reduction using pre-insertion inductors is presented in Table 4.

**TABLE 4 The voltage recorded without/with pre-insertion inductors.**

| Topology | Load cosφ | | | |
|---|---|---|---|---|
| | *0.8* | *0.85* | *0.92* | *0.94* |
| Without pre-preinsertion inductor Voltage in p.u. | 1.72 | 1.68 | 1.65 | 1.64 |
| With pre-insertion inductor Voltage in p.u. | 1.24 | 1.23 | 1.22 | 1.21 |

**MOV arresters**

The transient voltages on a capacitor bank and the recovery voltages across the switch can be reduced by installing arresters on the capacitor side of the switching device (Figure 6). If the switch is rated for the recovery voltages involved, then the arresters can be located on either the capacitor side or source side of the switch.



*Voltage waveform* *Current at transformer side* *Current at load side*

**Figure 6 Capacitor-bank energizing with MOV arresters.**

To evaluate arrester energy duty, simple expressions can be derived for grounded and ungrounded capacitor banks in terms of capacitor size, source inductance, peak system voltage, and arrester protective levels. It is also important to consider the coordination of MOV arresters (at the capacitor location) with any conventional gapped type arresters in the substation. It is important that the protective level of the MOV arresters be low enough to prevent operation of the gapped arresters and this is often difficult to achieve.

**Synchronized closing**

Application of synchronized switching to the energization of capacitor banks can be effective, since the magnitudes of the produced transients are strongly dependent on the closing instants of the three poles of the

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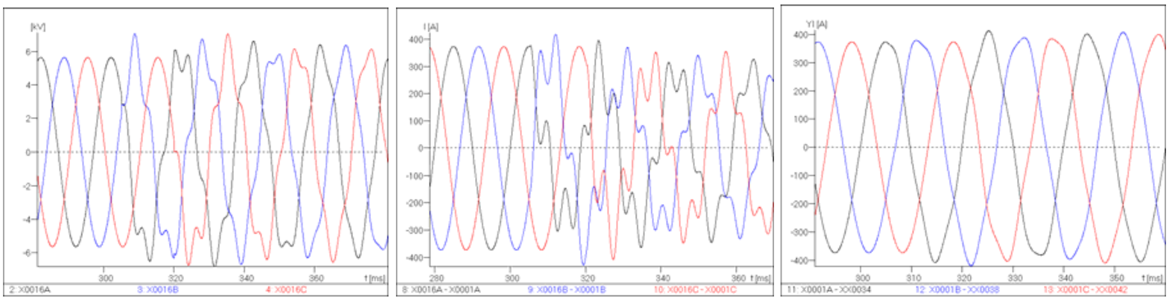
switching device. Fundamental requirement for all controlled switching applications is the precise definition of the optimum switching instants. Synchronous closing for capacitor-bank applications is independent contact closing of each phase near a voltage zero. This definition is probably not trivial, since the switching instant leading clearly a minimization of a resulting voltage or current (Figure 7 and Table 5).



*Voltage waveform* *Current at transformer side* *Current at load side*

**Figure 7 Synchronized closing of capacitor-bank.**

**TABLE 5 The voltage recorded without/with synchronized closing.**

| Topology | Load cosφ | | | |
|---|---|---|---|---|
| | *0.8* | *0.85* | *0.92* | *0.94* |
| Without synchronized CB1closing Voltage in p.u. | 1.72 | 1.68 | 1.65 | 1.64 |
| With synchronized CB1 closing Voltage in p.u. | 1.09 | 1.07 | 1.05 | 1.04 |

## CONCLUSIONS

EMTP simulations had been performed in relation to capacitor bank switching in a particulary Romanian Power distribution subsystem. Generally speaking, the voltage magnification occurs in the transitory period after the beginning of operation of the capacitor bank will not result in capacitor damage. The problem that usually occurs is the failure or mis-operation of sensitive loads in the facility where the low voltage capacitors are installed. With this simulation study carry out the overvoltages that affect the producers connected to the low voltage network, in different exploration situations could be predicted.

If voltage transients resulting from utility switching are having an effective on power quality at a facility, consideration can be given to discussing different mitigation techniques with the utility. The most common control techniques are pre-insertion devices, MOV arresters and controlled closing. When pre-insertion is used, a resistive/reactive element is inserted into the circuit briefly to damp the first peak of the transient. When reactors are used, they are helpful in limiting the higher frequency components. Controlled closing involves using a control system to ensure that the capacitor switching mechanism closes when the voltage on the capacitor closely matches the system voltage when the contacts mate. This avoids the step voltage that causes the circuit to oscillate.

Based on simulation results it is possible to proceed with the selection of the protections, in order to minimize the impact of the switching in the consumers and equipment.

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