An ATP Simulation of Shunt Capacitor Switching in an Electrical Distribution System

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Abstract - **The quality of electric power has been a constant topic of study, mainly because inherent problems to it can lead to great economic losses, especially in industrial processes. Among the various factors that affect power quality, those related to transients originating from capacitor bank switching in the primary distribution systems must be highlighted. In this work, the characteristics of transients resulting from the switching of utility capacitor banks are analyzed, as well as factors that influence their intensities. The conditions under which these effects are mitigated can then be investigated. A circuit that represents a real distribution system, 13.8 kV, from CPFL (Cia Paulista de Força e Luz – a Brazilian utility) was simulated through the software ATP (Alternative Transients Program) for purposes of this study. Finally, a comparison with real-life data recorded at the distribution system was performed in order to validate the present simulation.**

Keywords: Power Quality, Transients, Capacitor Switching, ATP.

I. INTRODUCTION

Power quality has been a topic of constant study as problems inherent to it can lead to economical losses, mainly in industrial processes. Although other factors influence power quality, the work presented here focuses on transients originating from shunt capacitor bank switching in primary distribution systems.

In Brazil, the privatization of electric companies requires a regulation which, among other aspects, focuses on the quality of electric power, imposing patterns and limits that guarantee customers a clean and reliable supply of energy. This procedure avoids losses to the customers related to the presence of transients as well as interruptions. Research has been carried out in order to evaluate the costs related to interruptions of power supply and power quality (short duration interruptions and voltage sags). It was discovered that interruptions of one hour could generate losses of US$ 100,000.00 and US$ 1,000,000.00 respectively for commercial and industrial customers [1].

Electric Power Systems have predominantly inductive loads, so that the systems themselves must supply the reactive power consumed. The most practical and efficient way for the utility to supply the reactive power demanded is through the installation of Capacitor Banks (C.B.) in the system. The installation of shunt C.B. brings benefits concerning the reduction of system charging and electrical losses, system capacity release, and also improvements in the power factor. The use of such banks in distribution systems is intense where two types (either fixed or switchable) are utilized depending on the technical criteria adopted by the utility. One of the types of control regarding capacitor switching, which is mostly used nowadays in Brazilian electrical distribution systems, employs a current relay in order to monitor the load current magnitude. The load variations where the capacitor banks are installed can cause frequent switching when the banks are operated by current relays.

Customers are often motivated to install capacitor banks in order to avoid the penalties related to the low power factors imposed by utilities.

The C.B. switching provokes transient overvoltages that theoretically can reach peak phase-to-earth values in the order of 2.0 p.u. Amplified overvoltages in remote C.B. due to the oscillatory nature of the coupled circuit can also be generated [2]. Some factors that affect the amplification of the transient voltages during the C.B. switching should also be mentioned: the size of the capacitor switched, the short circuit capacity at the location where the capacitor is inserted, the power of the customer's transformer and the characteristics of the customer's load [3]. It is also worth noting that high transient currents can occur, reaching values superior to ten times the capacitor nominal current with duration of several milliseconds [4]. Several parameters that can determine the maximum inrush current were analyzed in [5], such as: pole spread, the dumping resistor inserted in the current limiting reactor, natural frequency and saturation of the current limiting reactor.

As mentioned before, characteristics of transients originating from utility capacitor bank switching were studied in this work. Moreover, factors that influence the intensity of such transients were investigated in order to identify the conditions in which these effects can be undermined. It should be pointed out that a circuit representing a real-life feeder of a primary distribution system, 13.8 kV, at CPFL (Cia Paulista de Força e Luz – a Brazilian utility) was simulated. The feeder supplies only one industry with a high consumption of energy (approximately 9,0 MMVA), having two capacitor banks installed by the utility (900 and 1,200 kVAr) in different locations. The software ATP (Alternative Transients Program) was utilized in the simulation process.

Some aspects regarding factors that influence the intensity of the transients were: load current value during bank switching, the order in which the utility banks are switched, consumer capacitor size, localization of the utility banks along the feeder, pole spread during switching and synchronization of capacitor switching. Finally, a comparison with real-life data recorded at the distribution system was performed in order to validate the present simulation.

II. BASIC CONCEPTS CONCERNING ENERGIZATION OF CAPACITORS

The capacitor switching phenomenon is shown in Fig. 1, where resistances were omitted by simplification.

In systems where the natural frequencies of the LC loop are higher than the fundamental frequency (60 Hz), the overvoltages should continuously increase as the ratio of the natural frequencies approach unity since the fundamental voltage will be essentially constant [6]. The equations for the current and voltage in the capacitor C1 during the closing of the switch S1 in Fig. 1, with switch S2 open, are given respectively by [7]:

$$V_{C1}(t) = V - [V - V_{C1}(0)].\cos w_1 t \qquad (1)$$

$$I_1(t) = \frac{V}{Z_1} sin\, w_1 t \qquad (2)$$

$w_1 = 1/\sqrt{L_1 C_1}$ - natural frequency

$V_{C1}(0)$ - initial voltage at C_1

V - switch voltage at S_1 closing

$Z_1 = \sqrt{L_1/C_1}$ - surge impedance

Considering Fig. 1 once more, now with the closing of the switch S1, with switch S2 already shut, the voltage on the remote capacitor C2 (p.u.) can be represented by the following [2]:

$$\frac{V_{C2}}{V} = 1 + A\cos f_1 t + B\cos f_2 t \qquad (3)$$

where:

$$A = -\frac{1}{2}\left[\sqrt{\left(\frac{w_1}{2w_2} + \frac{\Delta w_2}{2w_1}\right)^4 - \left(\frac{w_1}{2w_2} + \frac{\Delta w_2}{2w_1}\right)^2} - \left[\left(\frac{w_1}{2w_2} + \frac{\Delta w_2}{2w_1}\right)^2 - 1\right]\right]^{-1}$$

$$B = +\frac{1}{2}\left[\sqrt{\left(\frac{w_1}{2w_2} + \frac{\Delta w_2}{2w_1}\right)^4 - \left(\frac{w_1}{2w_2} + \frac{\Delta w_2}{2w_1}\right)^2} + \left[\left(\frac{w_1}{2w_2} + \frac{\Delta w_2}{2w_1}\right)^2 - 1\right]\right]^{-1}$$

$$f_1 = \sqrt{\left(\frac{w_1^2}{2} + \frac{\Delta w_2^2}{2}\right) - \sqrt{\left(\frac{w_1^2}{2} + \frac{\Delta w_2^2}{2}\right)^2 - w_1^2 w_2^2}}$$

$$f_2 = \sqrt{\left(\frac{w_1^2}{2} + \frac{\Delta w_2^2}{2}\right) + \sqrt{\left(\frac{w_1^2}{2} + \frac{\Delta w_2^2}{2}\right)^2 - w_1^2 w_2^2}}$$

$$\Delta = \left(1 + \frac{C_2}{C_1}\right), \quad w_1 = \frac{1}{\sqrt{L_1 C_1}}, \quad w_2 = \frac{1}{\sqrt{L_2 C_2}}$$

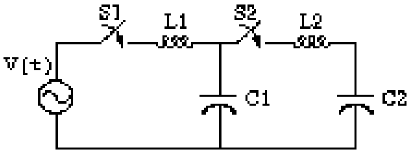

Fig. 1. Circuit with two L-C loops

The amplified voltage at the remote capacitor is composed of three components: the source voltage and two oscillatory components $\phi 1$ and $\phi 2$. This phenomenon, known as amplification of the voltage, was analyzed in reference [2]. A circuit with two loops L-C, each one with a natural oscillation frequency of $w = 1/\sqrt{LC}$, 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. A factor that contributes considerably to the amplification of transient voltages is the shunt capacitors located in several voltage levels of the power system. When new L-C loops are formed, transient overvoltages provoked by the capacitor switching of the first L-C loop (higher voltage) becomes more elevated in the capacitor in the last loop (lower voltage)[6]. Computer simulations and in-plant measurements have indicated that magnified transients are possible on a wide range of low voltage capacitor sizes.

In Fig. 1, the closing of switch S2, with switch S1 already shut, is considered. In this case, any potential difference between the two banks is eliminated by a redistribution of charge. The equalizing current that flows in the inductance L_2, is given by [8]:

$$I_2(t) = \frac{V_1 - V_{C2}(0)}{\sqrt{L_2 \frac{(C_1 + C_2)}{C_1 C_2}}} sinw_2 t$$

$$w_2 = \left(\sqrt{L_2 \frac{C_1 C_2}{C_1 + C_2}}\right)^{-1}$$

V_1 - C_1voltage at S_2 closing

$V_{C2}(0)$ - initial voltage at C_2

w_2 - transient frequency

The oscillatory phenomenon of the capacitor switching transient results from the energy exchanged between the inductive and capacitive elements in the circuit. The energy stored in the capacitor elements ($\frac{1}{2}CV^2$) flows into the inductive elements ($\frac{1}{2}LI^2$). The transient oscillations that appear during the capacitor switching in electric systems can be of low frequency (300 to 600 Hz) when the bank interacts with the source. On the other hand, they can be of medium frequency (2 to 10 kHz) when the bank is switched in parallel with another bank or other capacitive elements such as cables [9]. Other authors have also contributed to the study of harmonics and transient overvoltages due to capacitor switching, and have presented interesting results, such as [10] and [11].

Several available techniques can be applied in order to attenuate the transient overvoltages during the capacitor switching. Some techniques include the pre-insertion of inductors and resistors together with the capacitors, the synchronous closing and the installation of metal oxide varistor arresters. The last two are more effective in the mitigation of the transients [12]. In reference [13], it is suggested that adjustable speed drivers (ASDs) are equipped with reactors at the AC busbar, together with one of these attenuation techniques, so that the overvoltages are limited to values that do not cause the trip of the protection devices.

III. CASE STUDY

As mentioned, this work was developed together with the Brazilian utility CPFL (Companhia Paulista de Força e Luz), which is concerned with the quality of the energy supplied to its customers.

This paper focuses on the effects of the C.B. switching in the utility primary distribution system, at the customer's plant (industry). The circuit shown in Fig. 2 was used for the purpose of this study. It consists of a primary distribution system with a feeder that exclusively supplies one single industry whose demand was approximately 9.0 MVA, at 13.8 kV. The substation transformer was modeled considering its saturation curve. Two C.B. (900 and 1,200 kVAr) were installed along the feeder in order to simulate the real life case. This feeder consists of a CA-477 MCM bare cable in conventional overhead structure, and it was represented by coupled RL elements. The industry's load basically comprises induction motors whose power varies from 0.25 to 600 HP, which corresponds to 10,750 kW of installed power.

The effects of the C.B. switching in the distribution system were simulated using ATP software. The industry's load shown in Fig. 2 was represented by two elements: one represents the R-L loop with constant impedance and the other represents the capacitor used for power factor correction.

The ordinary C.B. installation pattern at CPFL consists of a structure with only two oil switches, with a nominal capacity of 200 A, installed at the external phases, with the internal phase permanently energized.

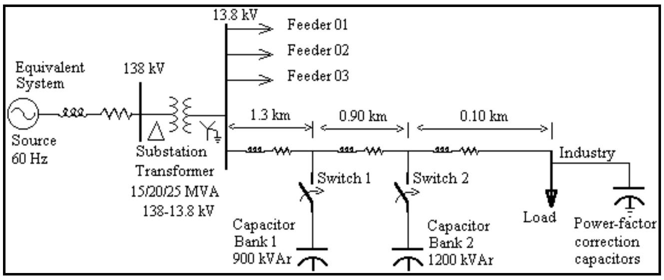

Fig. 2. One-phase diagram of the distribution system studied

IV. ANALYSING THE RESULTS

Several load conditions required by the industry were considered for the utility C.B. energization (900 kVAr and 1,200 kVAr), which are summarized in Table 1. It was assumed that the power factor of the industry was corrected from 0.80 to 0.92, according to their needs.

A. Transient Voltages

Several cases were simulated using ATP software in order to evaluate the conditions that affect the associated C.B. energization transient intensity. The case in which the 900 kVAr C.B. is energized during a 90 A load current was used as a reference for several simulations where other variables were modified. In Table 2 some of the obtained maximum overvoltage values of the distribution system are presented. The peak voltage at different locations of the distribution system for the switching of the 900 kVAr C.B. is shown. Apart from the specified cases, simultaneous closing was adopted.

For the first three cases, amplification of the transient overvoltage at the industry was experienced. The largest value of 2.08 p.u. was obtained when the pole spread was considered, with phase A closing 5 ms after the other and near the voltage peak. For the last three cases, the transient overvoltage at the industry was attenuated. As noticed in the literature, the synchronous switch closing is very efficient in the mitigation of the transient overvoltage. When the industry's load is modeled without the power factor correction capacitors, a low transient overvoltage is noticed. This situation is also observed for the case in which the industry has all his capacitors switched on (1995 kVAr).

Fig. 3 illustrates the voltage waves at the load for the 900 kVAr C.B. switching (reference case). Transients in the voltage waves can be observed up to four cycles after the bank switching.

Fig. 4 shows the voltage waves for the case where the 1,200 kVAr C.B. is switched at the 168 A load current, with the 900 kVAr C.B. already switched on and in a steady state. In this case, high frequency components are intensified due to the interaction of the L-C loop formed in the circuit.

Fig. 5 illustrates the maximum overvoltage peak with relation to the load current for the 900 kVAr and 1,200 kVAr C.B. respectively. It can be observed that the overvoltage transients are mitigated when the C.B. are switched at higher load currents.

Table 1- Load impedances related to load currents

		C.B. - 900 kVAr			C.B. - 1200		
	load	90	120	150	168	224	280
Load with	R (Ω)	61.58	46.18	36.94	32.99	24.73	19.79
pf.= 0.92	Xl (Ω)	46.19	34.64	27.71	24.74	18.55	14.84
(per phase)	L (mH)	122.5	91.89	73.50	65.64	49.19	39.38
Industry	KVAr	214	285	356	399	532	665
C.B.	Xc (Ω)	296.6	222.7	178.3	159.1	119.2	95.46
(per phase)	μF	8.94	11.91	14.88	16.67	22.25	27.79

Table 2 - Maximum transient overvoltage

C.B. energization – 900 kVAr Load 90 (A)	**Maximum voltage (p.u.)**		
	at the bank	**at substation**	**at load**
Original situation	1.77	1.49	2.06
C.B. at substation	1.80	1.80	2.00
5 ms pole spread	1.77	1.51	2.08
Load without capacitors	1.92	1.60	1.91
1995 kVAr at the load	1.80	1.50	1.44
Synchronized closing	1.34	1.21	1.35

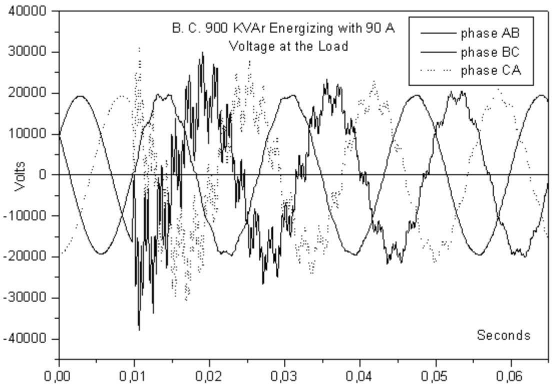

Fig. 3. 900 kVAr bank energization - load voltage

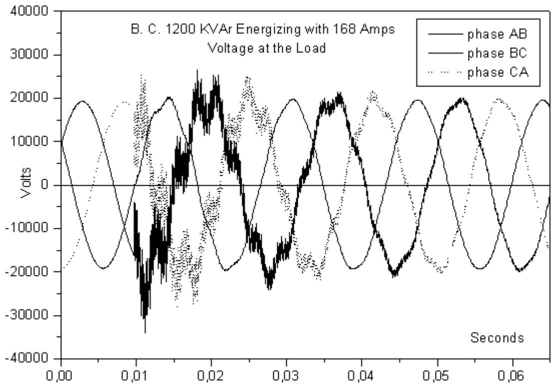

Fig. 4. 1,200 kVAr bank energization - load voltage

B. Transient Currents

High current values can appear in the industry's plant due to C.B. switching and they can last various cycles. For the 900 kVAr C.B. switching with load currents of 90 and 150 A, the maximum current peaks at the industry’s plant were 1,051 and 1,231 A, respectively. At the substation, peaks of 615 and 670 A were observed. Special attention should be given to the currents observed at the industry’s plant, especially because of its protection and control equipment.

Figs. 6 and 7 show the current waves which appear at the industry’s plant resulting from the switching of 900 kVAr and 1,200 kVAr C.B., respectively. As for the voltage cases, high frequency components can be observed for various milliseconds.

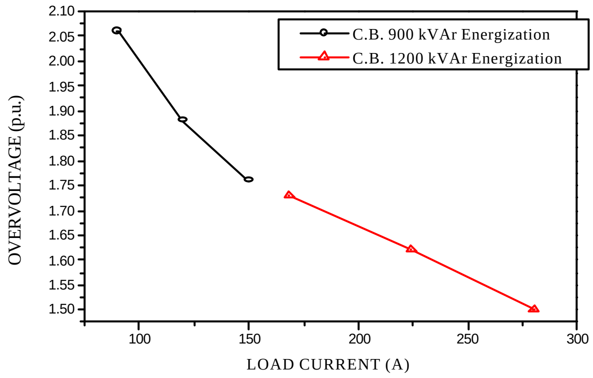

Fig. 5. Load current variation effect for the maximum overvoltage values

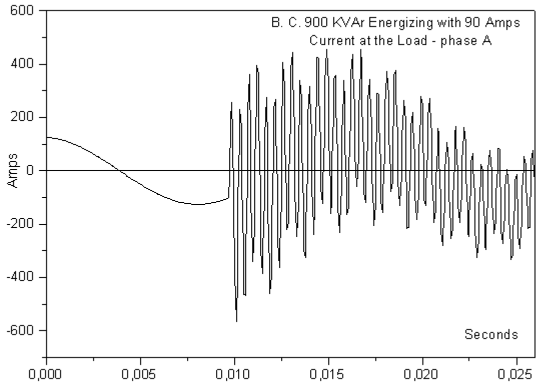

Fig. 6. 900 kVAr bank energization - load current

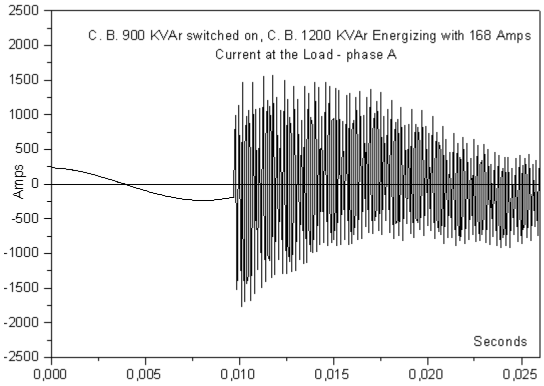

Fig. 7. 1,200 kVAr bank energization - load current

V. VALIDATION OF THE PRESENT SIMULATION WITH REAL LIFE DATA

In order to complete the study, a comparison with real life data recorded at the distribution system was performed. A BMI (*Basic Measuring Instrument*) Model 7100 equipment was utilized for such a purpose.

Fig. 8 shows the measured phase CA voltage and current waves in the industry's plant with the switching of the 900 kVAr bank.. It should be noted that the mentioned equipment has a sample rate of 7.7 kHz.

Fig. 9 illustrates the frequency spectrum for the measured voltage and current waves described earlier. The presence of the 60 Hz component for the voltage as well as small components in the range of 100-500 Hz and 1,750-2,250 Hz can be observed. In the case of the current, the harmonics are predominantly in the range of 1,500-2,500 Hz.

Fig. 10 shows simulated voltage and current harmonic components for the same situation (switching of the 900 kVAr bank). It should be noted that in order to reproduce the effect of the equipment, the harmonic content for the voltage and current signals was limited to 2000 Hz by a *Butterworth* filter. In addition the ATP output at 20 kHz (illustrated at Figs. 3, 4 6 and 7) was resampled at approximately 7 kHz in this section. Due to this procedure the harmonic contents of the simulation data was greatly attenuated. It can be observed in Fig. 10 the presence of the 60 Hz component in the case of the voltage as well as small components around 600 and 2,250 Hz respectively. In the case of the current, the harmonics are predominantly in the range of 450-550 Hz as well as 2,000-2,500 Hz. The similarities between the measured and simulated cases can be clearly observed.

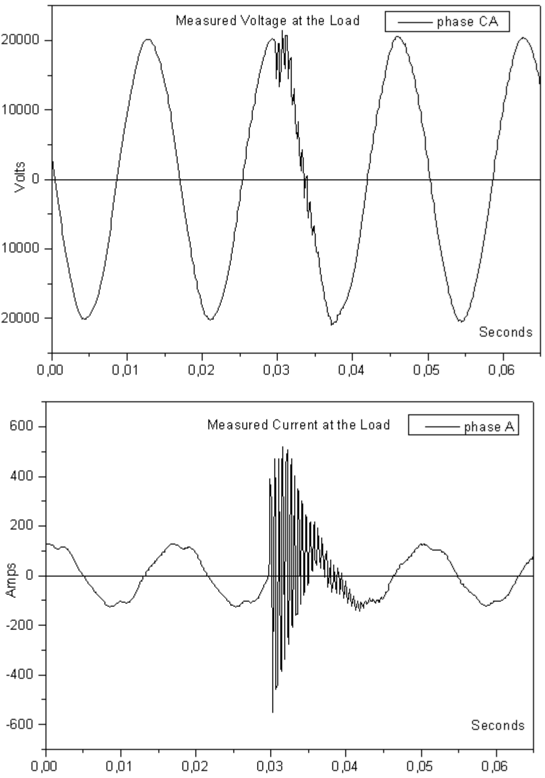

Fig. 8. Measured voltage and current waves at the load

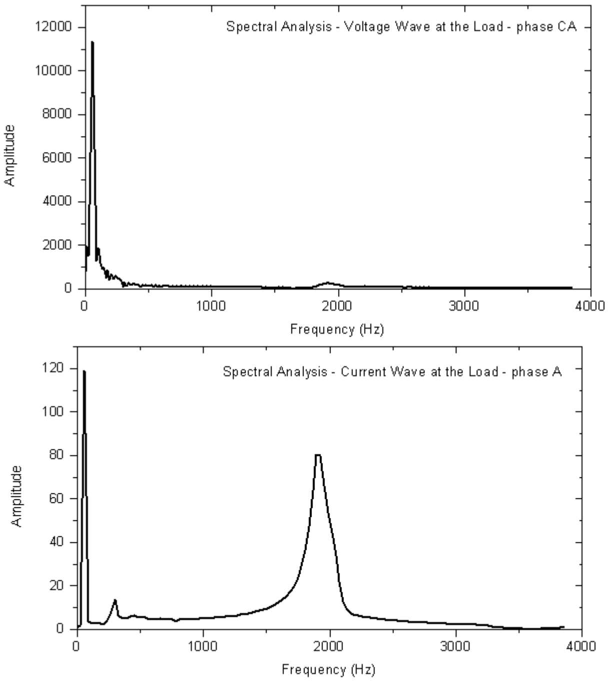

Fig. 9. Measured voltage and current frequency spectrum at the load

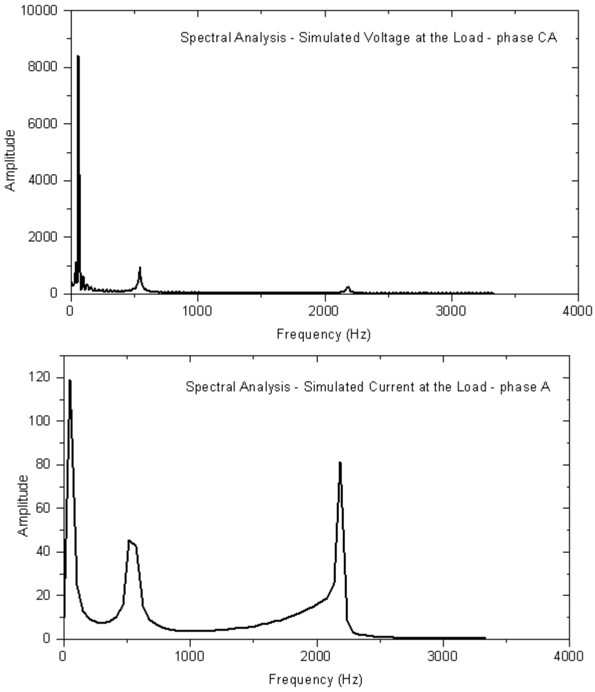

Fig. 10. Simulated voltage and current frequency spectrum at the load

VI. CONCLUSIONS

In this paper characteristics of transients, which originated from utility capacitor bank switching, were studied. Moreover, factors that influence the intensity of such transients were investigated in order to identify the conditions in which these effects can be undermined. It should be pointed out that a circuit representing a real-life feeder of a primary distribution system, 13.8 kV, at CPFL was simulated. The software ATP (Alternative Transients Program) was utilized for such purposes. A comparison with real life data recorded at the distribution system was performed in order to validate the simulation.
The following aspects regarding factors that influence the intensity of the transients were observed:

- Regarding the industry’s load current value during utility bank switching, it was observed that the overvoltage transients were mitigated when the banks were inserted at a higher load current condition.
- Regarding synchronous closing, it was observed that transient voltages where reduced when switches were closed at zero voltage, as expected. Pole spread can intensify the magnitude of transients.
- Transient overvoltages can be additionally amplified or mitigated depending on the industry capacitor bank size.
- Transient overvoltages and overcurrents observed during the switching of the 1200 kVAr capacitor bank were higher in frequency when compared to the transients related to the switching of the 900 kVAr capacitor bank.

VII. ACKNOWLEDGEMENTS

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