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Transient analysis concerning capacitor bank switching in a 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 (CB) switching in the primary distribution systems must be highlighted. In this work, the characteristics of transients resulting from the switching of utility CBs 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 Cia Paulista de Força e Luz (CPFL—a Brazilian utility) was simulated through the software Alternative Transients Program (ATP) 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: Transients; Capacitor switching; ATP

1. Introduction

Power quality has been a topic of constant study as both electric utilities and end users of electrical power are becoming increasingly concerned about it. There has recently been a great emphasis on revitalizing industry with more automation and more modern electronically controlled equipment. This equipment is more sensitive to deviations in the supply voltage if compared with the previous one and industrial customers are now more acutely aware of minor disturbances of the type described in this work in the power systems. Although other factors influence power quality, the work presented here focuses on transients originating from shunt capacitor bank (CB) 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). Interruptions of 1 h could generate losses of US$ 100 000.00 and 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 CBs in the system. The installation of shunt CB brings benefits concerning the reduction of system charging and

Abbreviations: ATP, alternative transients program; CI, capacitance; CB, capacitor banks; CPFL, Companhia Paulista de Força e Luz—a Brazilian utility.

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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 CB are installed can cause frequent switching when the banks are operated by current relays.

Customers are then often motivated to install CBs in order to avoid the penalties related to the low power factors imposed by utilities. However, the CB switching provokes transient overvoltages that theoretically can reach peak phase-to-earth values in the order of 2.0 pu. Amplified overvoltages in remote CB 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 CB 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 CB 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 Cia Paulista de Força e Luz (CPFL—a Brazilian utility) was simulated. The feeder supplies only one industry with a high consumption of energy (ca. 9.0 MVA), having two CBs installed by the utility (900 and 1200 kVAr) in different locations. The software Alternative Transients Program (ATP) 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, industry 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.

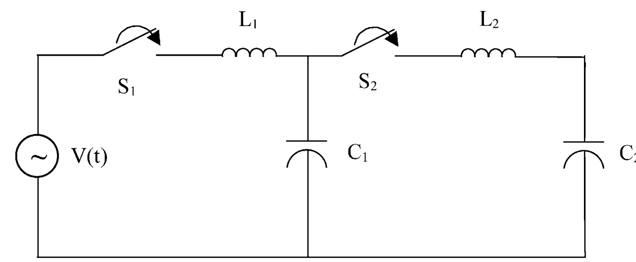

Fig. 1. Circuit with two L–C loops.

2. 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]:

$$V_{C1}(t) = V - [V - V_{C1}(0)]\cos \omega_1 t \tag{1}$$

$$I_1(t) = \frac{V}{Z_1} \sin \omega_1 t \tag{2}$$

where $\omega_1 = 1/\sqrt{L_1 C_1}$ is the natural frequency; $V_{C1}(0)$, initial voltage at C_1; V, switch voltage when S1 is closed; and $Z_1 = \sqrt{L_1/C_1}$ is the surge impedance.

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

$$\frac{V_{C2}}{V} = 1 + A \cos \phi_1 t + B \cos \phi_2 t \tag{3}$$

where:

$$A = -\frac{1}{2} \times \left[\sqrt{\left(\frac{\omega_1}{2\omega_2} + \frac{\Delta\omega_2}{2\omega_1}\right)^4 - \left(\frac{\omega_1}{2\omega_2} + \frac{\Delta\omega_2}{2\omega_1}\right)^2} - \left[\left(\frac{\omega_1}{2\omega_2} + \frac{\Delta\omega_2}{2\omega_1}\right)^2 - 1\right]\right]^{-1}$$

$$B = +\frac{1}{2} \times \left[\sqrt{\left(\frac{\omega_1}{2\omega_2} + \frac{\Delta\omega_2}{2\omega_1}\right)^4 - \left(\frac{\omega_1}{2\omega_2} + \frac{\Delta\omega_2}{2\omega_1}\right)^2} + \left[\left(\frac{\omega_1}{2\omega_2} + \frac{\Delta\omega_2}{2\omega_1}\right)^2 - 1\right]\right]^{-1}$$

$$\phi_1 = \sqrt{\left(\frac{\omega_1^2}{2} + \frac{\Delta\omega_2^2}{2}\right) - \sqrt{\left(\frac{\omega_1^2}{2} + \frac{\Delta\omega_2^2}{2}\right)^2 - \omega_1^2\omega_2^2}}$$

$$\phi_2 = \sqrt{\left(\frac{\omega_1^2}{2} + \frac{\Delta\omega_2^2}{2}\right) + \sqrt{\left(\frac{\omega_1^2}{2} + \frac{\Delta\omega_2^2}{2}\right)^2 - \omega_1^2\omega_2^2}}$$

$$\Delta = \left(1 + \frac{C_2}{C_1}\right), \quad \omega_1 = \frac{1}{\sqrt{L_1 C_1}}, \quad \omega_2 = \frac{1}{\sqrt{L_2 C_2}}$$

The amplified voltage at the remote capacitor is composed of three components: the source voltage and two oscillatory components ϕ_1 and ϕ_2. This phenomenon, known as amplification of the voltage, was analyzed in reference [2]. In two L–C loop systems, the maximum transient overvoltage component was found to occur when the natural frequency of each L–C loop is the same [6].

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

$$I_2(t) = \frac{V_1 - V_{C2}(0)}{\sqrt{L_2[(C_1 + C_2)/C_1 C_2]}} \sin \omega_2 t$$

$$\omega_2 = \left(\sqrt{L_2 \frac{C_1 C_2}{C_1 + C_2}}\right)^{-1}$$

where $V_1 - C_1$ is the voltage when S2 is closed; $V_{C2}(0)$, initial voltage at C_2; and ω_2 is the 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 ($1/2CV^2$) flows into the inductive elements ($1/2LI^2$). The transient oscillations that appear during the capacitor switching in electric systems can be of low frequency (300–600 Hz) when the bank interacts with the source. On the other hand, they can be of medium frequency (2–10 kHz) when the bank is switched in parallel with another bank or other capacitive elements [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 [10,11].

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.

3. Case study

As mentioned, this work was developed together with the Brazilian utility CPFL, which is concerned with the quality of the energy supplied to its customers [14].

This paper focuses on the effects of the CB 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 CB (900 and 1200 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 CB 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.

Fig. 3 shows the 900 kVAr CB at CPFL. It 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 B permanently energized.

4. Analyzing the results

Several load conditions required by the industry were considered for the utility CB energization (900 and 1200 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.

4.1. Transient voltages

Several cases were simulated using ATP software in order to evaluate the conditions that affect the associated CB energization transient intensity. The case in which the 900 kVAr CB 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 per unit overvoltage values of the distribution system are presented. The per unit overvoltage at different locations (considering phases

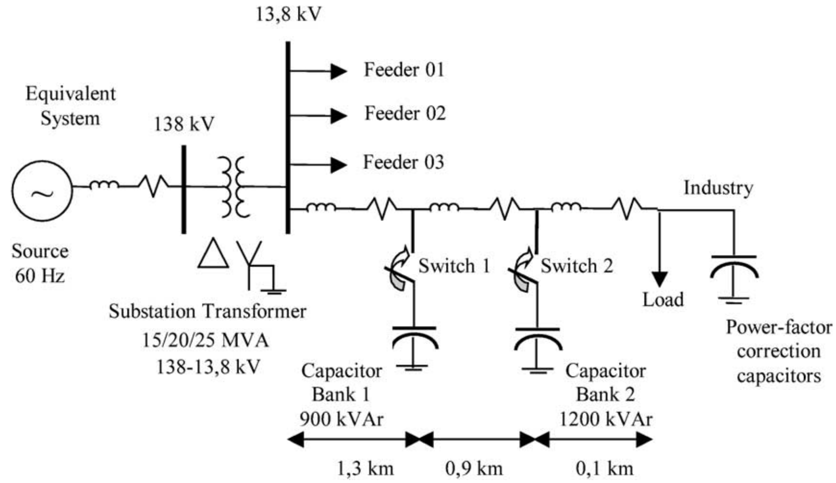

Fig. 2. One-phase diagram of the distribution system studied.

Fig. 3. Nine hundred kVAr CB at CPFL.

Table 2
Maximum transient overvoltage (phases A, B and C)–900 kVAr CB

CB energization 900 kVAr—load 90 (A)	Maximum voltage (pu)		
	At the bank	At substation	At load
Reference case	1.7746-A	1.4960-A	2.0542-A
	1.3652-B	1.2398-B	1.3885-B
	1.2840-C	1.1870-C	1.3024-C
5 ms pole spread	1.5823-A	1.3692-A	1.7664-A
	1.5180-B	1.3409-B	1.5504-B
	1.4688-C	1.3003-C	1.4698-C
10 ms pole spread	1.5823-A	1.3692-A	1.7664-A
	1.5527-B	1.3628-B	1.5624-B
	1.7468-C	1.4884-C	2.0197-C
CB at substation	1.8059-A	1.8059-A	1.9954-A
	1.2894-B	1.2894-B	1.3956-B
	1.2642-C	1.2642-C	1.3401-C
Synchronous closing	1.2795-A	1.1832-A	1.3825-A
	1.2411-B	1.1525-B	1.2900-B
	1.0033-C	1.0014-C	0.9887-C
Load without capacitors	1.9216-A	1.5911-A	1.9098-A
	1.3838-B	1.2525-B	1.3758-B
	1.3184-C	1.2094-C	1.3110-C

Table 1
Load impedances related to load currents

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

A, B and C) of the distribution system for the switching of the 900 kVAr CB is shown.

For almost all the cases, amplification of the transient overvoltage at the industry (load) was experienced. A 5 ms pole spread, as well as 10 ms was considered. As shown in the table, the per unit transient overvoltage was increased considering phases B and C. On the other hand, a mitigation considering phase A was found. It should be noted that, when the CB was moved to the substation, a higher per unit transient overvoltage at the substation was verified. As noticed in the literature and also shown in the table, the synchronous switch closing is very efficient in the mitigation of the per unit transient overvoltage for the three phases. Finally, the case study where the industry's load is modeled without the power factor correction capacitors was also presented. It should also be mentioned that, considering the low voltage power factor correction in the industry location, the transient overvoltages may reach values as high as 2.0–4.0 pu.

Fig. 4 illustrates the voltage waves at the load for the 900 kVAr CB switching (reference case). Transients in the voltage waves can be observed up to four cycles after the bank switching.

Fig. 5 shows the voltage waves for the case where the 1200 kVAr CB is switched at the 168 A load current, with the 900 kVAr CB already switched on and in a steady state. In this case, higher frequency components are present due to the interaction of the L–C loop formed in the circuit. However, the per unit overvoltages are mitigated if compared with the switching of the 900 kVAr CB.

Fig. 6 illustrates the maximum per unit overvoltage peak (considering phase A) with relation to the load current for the switching of the 900 and 1200 kVAr CBs, respectively. It can be observed that the overvoltage transients are mitigated when the CBs are switched at higher load currents.

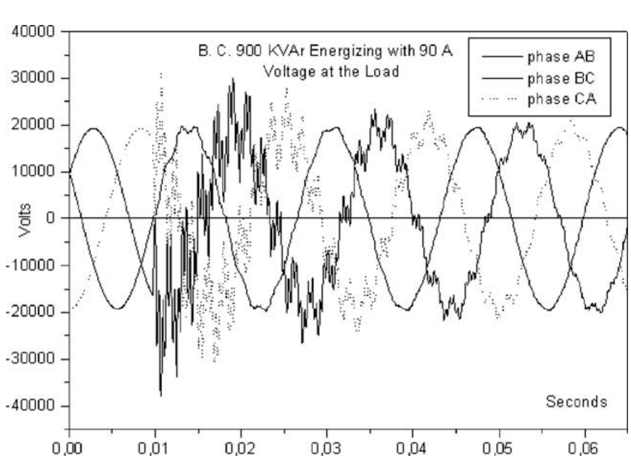

Fig. 4. Nine hundred kVAr bank energization-load voltage.

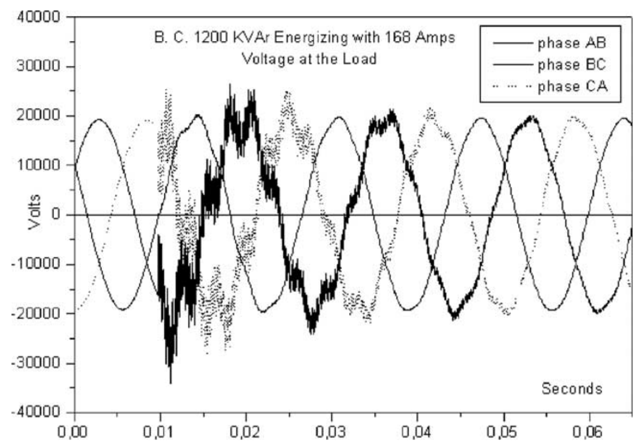

Fig. 5. One thousand and two hundred kVAr bank energization-load voltage.

4.2. Transient currents

High current values can appear in the industry's plant due to CB switching and they can last various cycles. For the 900 kVAr CB switching with load currents of 90 and 150 A, the maximum current peaks at the industry's plant were 1051 and 1231 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. 7 and 8 show the current waves which appear at the industry's plant resulting from the switching of 900 kVAr and 1200 kVAr CB, respectively. As for the voltage cases, high frequency components can be observed for various milliseconds.

5. 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 Basic Measuring Instrument (BMI) Model 7100 equipment was utilized for such a purpose.

Fig. 9 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. 10 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 and 1750–2250 Hz can be observed. In the case of the current, the harmonics are predominantly in the range of 1500–2500 Hz.

Fig. 11 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

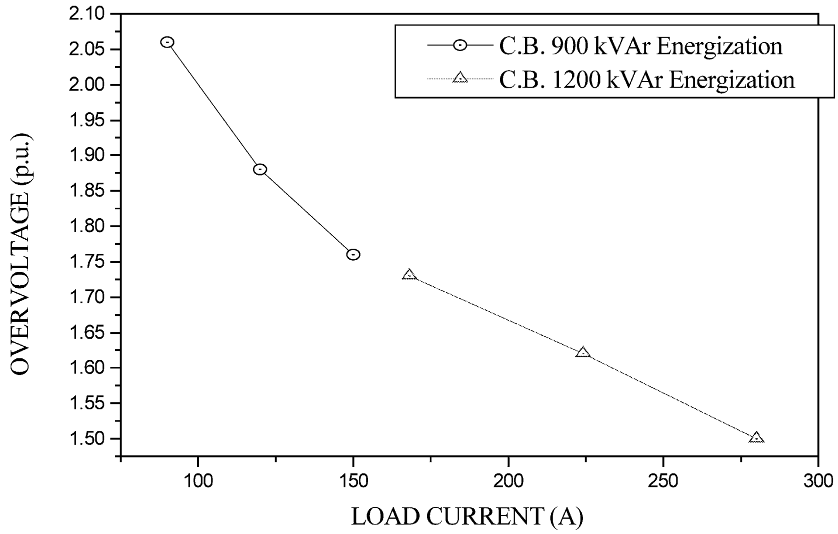

Fig. 6. Load current variation effect for the maximum overvoltage values.

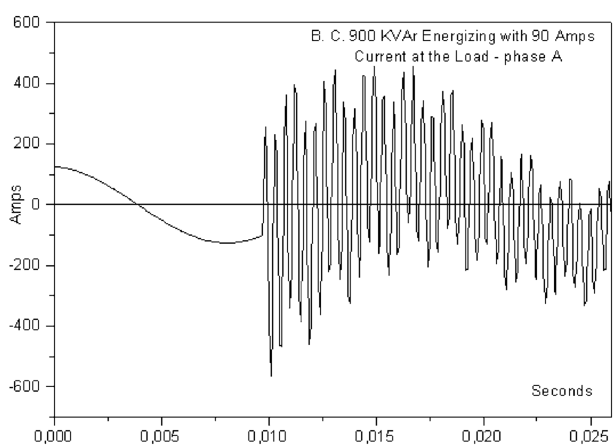

Fig. 7. Nine hundred kVAr bank energization-load current.

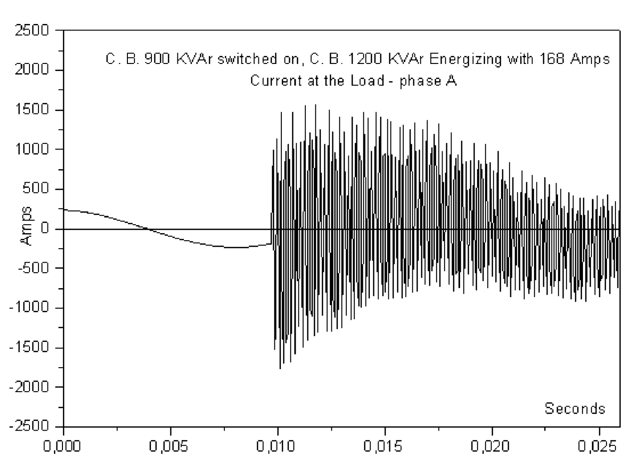

Fig. 8. One thousand and two hundred kVAr bank energization-load current.

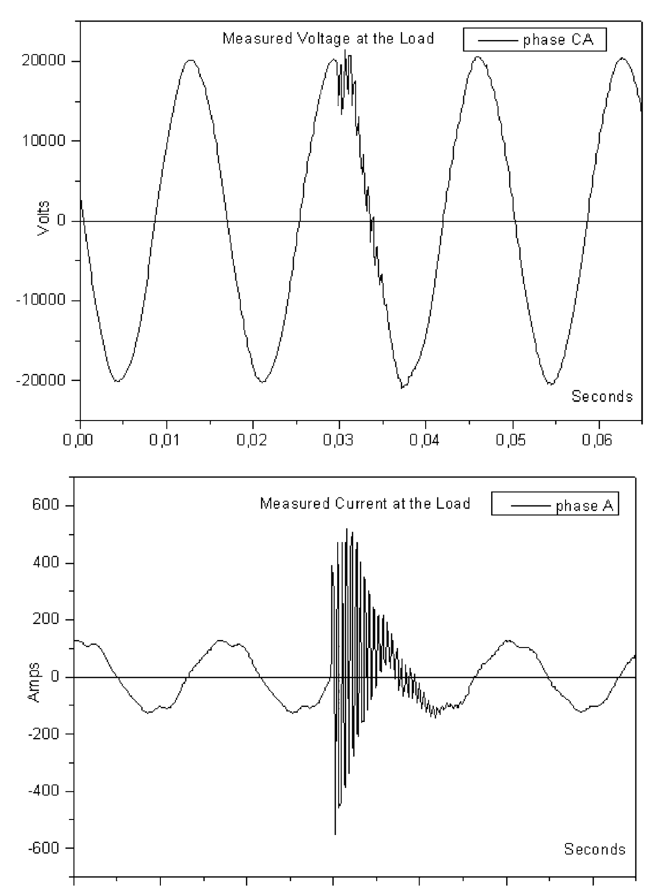

Fig. 9. Measured voltage and current waves at the load.

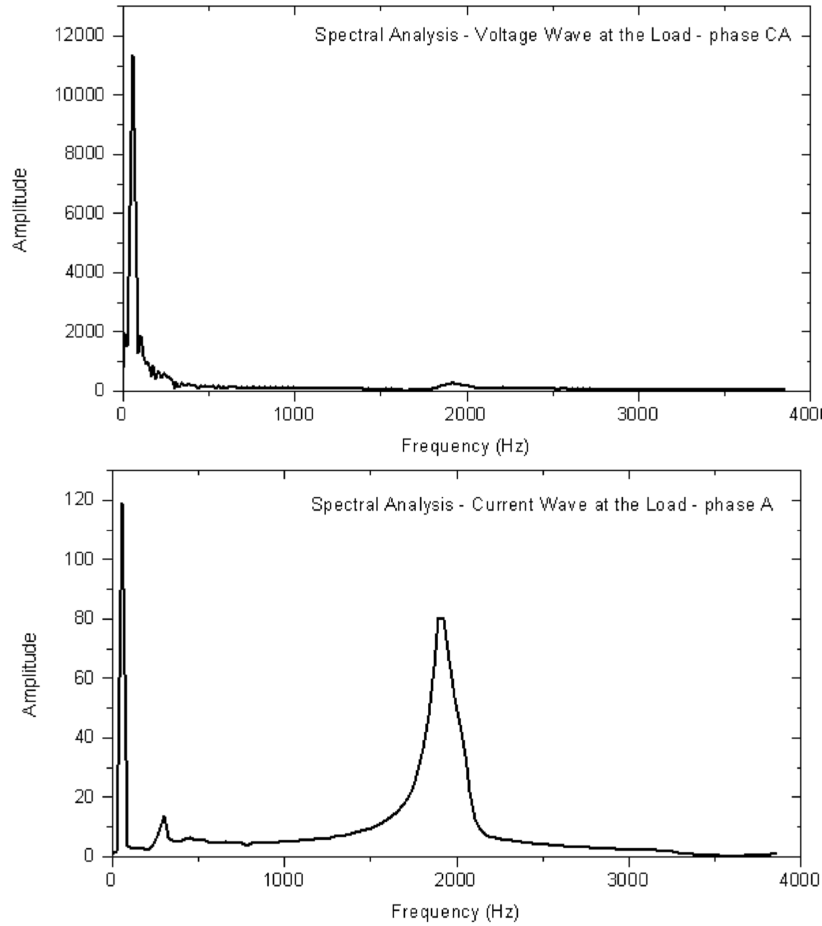

Fig. 10. Measured voltage and current frequency spectrum at the load.

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. 4, 5, 7 and 8) 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. 11 the presence of the 60 Hz component in the case of the voltage as well as small components around 600 and 2250 Hz, respectively. In the case of the current, the harmonics are predominantly in the range of 450–550 Hz as well as 1500–2500 Hz. The similarities between the measured and simulated cases can be clearly observed. It should also be emphasized that the oscillations observed in the simulation and measurements concerning the switching of the 1200 kVAr CB were mainly in the range of 5300–5600 Hz.

6. Conclusions

In this paper characteristics of transients, which originated from utility CB 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 was successfully utilized for such a purpose. A comparison with actual data recorded at the distribution system was performed to validate the simulation. In order to perform such a validation, the ATP output was resampled at 7 kHz and a simulation of a Butterworth filter was included.

The following aspects regarding factors that influence the intensity of the transients were observed:

a) Regarding synchronous closing, it was observed that transient voltages where reduced when switches were closed at zero voltage, as expected. It was also noticed that pole spread can intensify the magnitude of transients on phases B and C.
b) It was observed that a potential side effect of having low voltage power factor correction capacitors in the customer is that they can increase the impact of the utility CB switching concerning the customer equipment. Transient overvoltages in the industry location may reach values as high as 2.0–4.0 pu. This level of overvoltages can cause damage for all

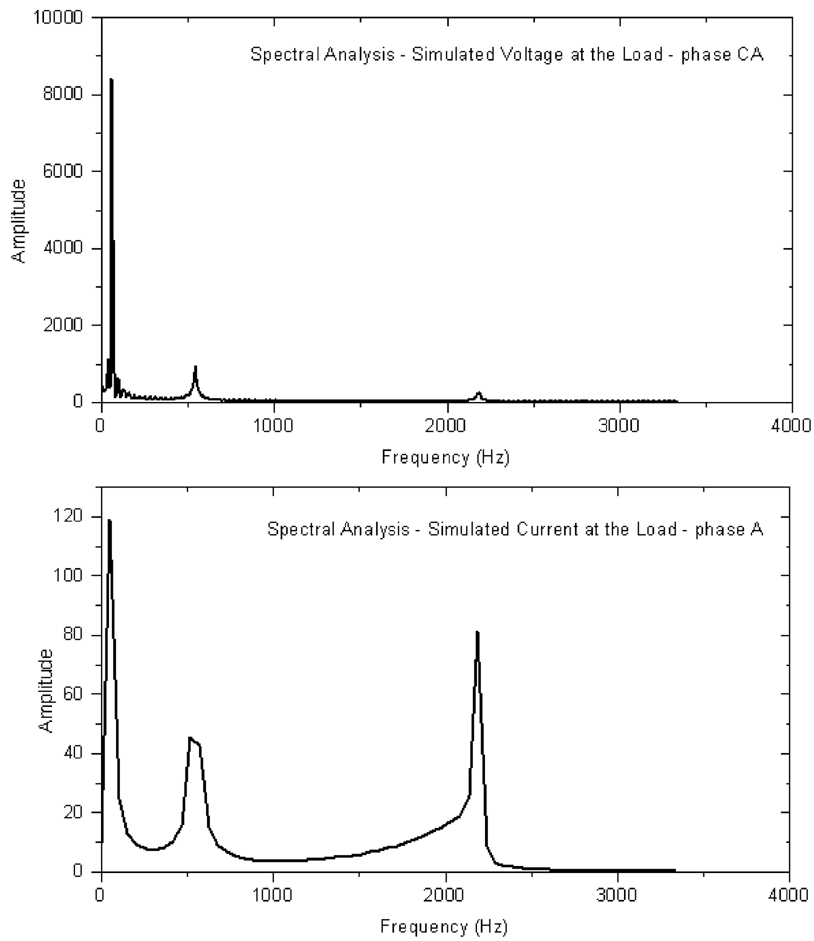

Fig. 11. Simulated voltage and current frequency spectrum at the load.

types of customer equipment as well as reduce equipment lifetime, as observed by CPFL. Some mitigating measures can be taken at the customer such as the use of surge arresters as well as converting low voltage power factor correction banks into harmonic filters.

c) As the utility banks switching simulated in this work were controlled by load current, it was observed that the overvoltage transients were mitigated when the banks were inserted at a higher load current condition (Fig. 6). This was an important conclusion since, with a simple adjustment, the utility can limit the transient voltage magnitude at the customer bus.

d) The equivalent circuit parameters (Fig. 2) were used to calculate the approximate frequencies of oscillation of the capacitor switching transient at the busbar. The oscillatory phenomenon of the CB switching could be verified according to the equations presented in Section 2, considering a two and three loop capacitor switching (low voltage industry capacitor, 900 and 1200 kVAr CB). Frequencies of oscillation were calculated for each individual connected distribution CB considering the L–C circuit. The resultant frequencies theoretically calculated were 2140 and 5509 Hz (for the 900 and 1200 kVAr CB switching, respectively). Actual frequencies simulated by the ATP software and validated in this work are slightly different from the calculated values due to effects of damping from the system loads and losses. The simulations have also shown that transient overvoltages and overcurrents observed during the switching of the 900 kVAr CB were lower in frequency when compared with the transients related to the switching of the 1200 kVAr CB. The oscillations observed in the simulation and measurements were mainly in the range of 1500–2500 and 5300–5600 Hz, respectively.

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Appendix A: Nomenclature

L_i	inductance
S_i	switch
$V_{C1}(0)$	initial voltage at C_1
$V_{C2}(0)$	initial voltage at C_2
V_1–C_1	voltage when S2 is closed
V	switch voltage when S1 is closed
Z_1	surge impedance
ω_1	natural frequency
ω_2	transient frequency

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