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# 8th INTERNATIONAL CONFERENCE ON HARMONICS AND QUALITY OF POWER

## PROCEEDINGS

### VOLUME I

October 14-16, 1998
Athens GREECE

IEEE Catalog Number: 98EX227

ISBN: 0-7803-5105-3 (Softbound Edition)
0-7803-5114-2 (Microfiche Edition)

Library of Congress: 98-87424

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# Transient Analysis Resulting from Shunt Capacitor Switching in an Actual 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 bring great economic losses, mainly in industrial processes. Among the various factors that affect power quality, those related to the transients originated from capacitor bank switching in the primary distribution systems must be highlighted. In this work, the characteristics of the transients resulting from the switching of the 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. In addition, a spectral analysis of the current and voltage waves is made. This procedure can reveal the harmonic components which can affect the operation of control and protection equipment, as well as sensitive loads of the industry. 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.**

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

## I. INTRODUCTION

The demand concerning power quality of utilities increases at the same speed as customers install more sensitive control and protection equipment, as well as power electronic devices. In Brazil, the privatization of electric companies requires a regulation that, among other aspects, focuses on the quality of electric power, imposing patterns and limits that guarantee the customers a clean and reliable supply of power. This procedure avoids losses to the customers due to the alterations in terms 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 sag). It was revealed 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 systems. The installation of shunt C.B. brings benefits concerning the reduction of system charging and electrical losses, system capacity release, and also improvements on power factors, as well as voltage control. The use of such banks in distribution systems is intense where two types (whether 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 most 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 relay. 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 reach peak phase-to-earth values in the order of 2.0 p.u. It could also generate amplified overvoltages in remote C.B. due to the oscillatory nature of the coupled circuit [2]. Some factors that affect the amplification of the transient voltages during the C.B. switching should be mentioned, among them: the size of the capacitor switched, the short circuit capacity at the location where the capacitor will be inserted, the power of the customer's transformer and the characteristics of the customer's load [3]. It is also worth noting that high current transients can occur, reaching values superior to ten times the capacitor nominal current with a duration of several milliseconds [4]. Several parameters that can determine the maximum inrush current were analyzed in [5], such as: pole spread, dumping resistor

*Paper accepted for presentation at the 8th International Conference on Harmonics and Quality of Power ICHQP '98, jointly organized by IEEE/PES and NTUA, Athens, Greece, October 14-16, 1998*

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inserted in the current limiting reactor, natural frequency and saturation of the current limiting reactor.

This work evaluates the impact of the utility C.B switching. at the customer's plant. The utilized system was simulated using ATP (Alternative Transient Program) software. Some parameters that affect the intensity of the transients that appeared during the C.B switching were varied, such as: load current, capacitor size of the customer's plant, location of the utility banks along the feeder, pole spread during switching and synchronization of capacitor switching. The conditions which provide attenuation of the transient overvoltages and which can be applied in a practical way by the utilities were identified. In addition, a spectral analysis of the current and voltage waveforms was carried out which showed the harmonic components that arose during the process.

## II. BASIC CONCEPTS CONCERNING ENERGIZATION OF CAPACITORS

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

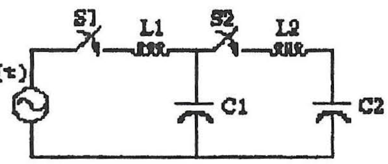


Figure 1 - Circuit with two L-C loops.

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 $\omega_1 = 1/\sqrt{L_1 C_1}$, 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 equation [2]:

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

where:

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

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

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

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

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

The amplified voltage at the remote capacitor is composed of three components: the source voltage and two oscillatory components $\phi 1$ 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 $\omega = 1/\sqrt{LC}$, 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. 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]:

$$I_2(t) = \frac{V_1 - V_{C2}(0)}{\sqrt{L_2\frac{(C_1+C_2)}{C_1C_2}}} sin\,\omega_2 t \qquad \omega_2 = \left(\sqrt{L_2\frac{C_1C_2}{C_1+C_2}}\right)^{-1}$$

$V_1$ - $C_1$voltage at $S_2$ closing

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

$\omega_2$ - 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 [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 a.c. 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

The Brazilian utility CPFL (Companhia Paulista de Força e Luz) is concerned about the quality of the energy supplied to its customers, problems and causes of power variations and what should be done to maintain power quality.

This paper focuses on the effects of the C.B. switching in the utility primary distribution system, at the customer's plant. The circuit shown in Fig. 2 was used for the purpose of this study. It consisted 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. This feeder consists of a CA-477 MCM bare cable in conventional overhead structure, and it was represented by coupled RL elements. The industry load basically comprises induction motors whose power varies from 0.25 to 600 HP, which corresponds to 10,750 kW of installed power. In Fig. 2 the system components can be observed.

The effects of the C.B. switching in the distribution system were simulated using ATP software. The customer's load 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.

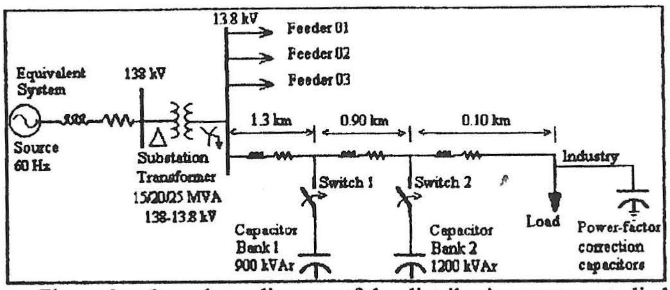


Figure 2 – One-phase diagram of the distribution system studied

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.

## IV. ANALYSING THE RESULTS

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

Table 1- Load impedances related to load currents.

| | | C.B. - 900 kVAr | | | C.B. - 1200 kVAr | | |
|---|---|---|---|---|---|---|---|
| | Load current(A) | 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 |
| Customer | 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 |

### IV.1. Transient Voltages

Several cases were simulated using ATP software in order to evaluate the conditions which 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 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. Except for the specified cases, the other ones had simultaneous closing.

Table 2 - Maximum transient overvoltage

| C.B. energization – | Maximum voltage (p.u.) | | |
|---|---|---|---|
| 900 kVAr - Load 90 A | 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 |

For the first three cases, amplification of the transient overvoltage at the customer's plant 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 customer's plant was attenuated. As noticed in the literature, the synchronous switch closing is very efficient in the mitigation of the transient overvoltage. When the customer load is modeled without the power factor correction capacitors, a low transient overvoltage in the load is noticed. This situation is also observed for the case in which the customer has all his capacitors switched on ( 1995 kVAr).

Fig. 3 illustrates the voltage waves at the load for the 900 kVAr C.B. switching concerning the reference case. Deformations in the voltage waves are present in up to four cycles after the bank switching. In Fig. 4 the voltage waves are shown 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 and in a steady state. In this case, high frequency components appear defined by the interaction of the L-C loops formed in the circuit.

Fig. 5 shows 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.

### IV.2. Transient Currents

High current values can appear in the customer'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 customer'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 customer's plant, especially because of its protection and control equipment, as mentioned before.

In Figs. 6 and 7, the currents which appear at the customer's plant for the switching of 900 kVAr and 1,200 kVAr C.B. respectively are presented. High frequency components can be observed for various milliseconds.

### IV.3. Voltage and Current Harmonic Components

In order to complete the study, an analysis of the voltage and current harmonics during the C.B. switching was performed. In Fig. 8 the main voltage and current harmonic components for the switching of the 900 kVAr bank can be observed. It should be noted that in the case of the voltage at the customer's plant the 60 Hz component mainly appears, as well as the presence of components in the range of 100-600 Hz and 2,000-2,400 Hz. In the case of the current, the harmonics are predominantly in the range of 1,900-2,400 Hz.

Fig. 9 shows the main voltage and current harmonic components for the switching of the 1,200 kVAr bank. It should be noted that in the case of the voltage, the 60 Hz component mainly appears once more, and components in the range of 100-400 Hz and 5,300-5,600 Hz are present. In the case of the current, the harmonics are predominantly in the range of 5,000-6,000 Hz.

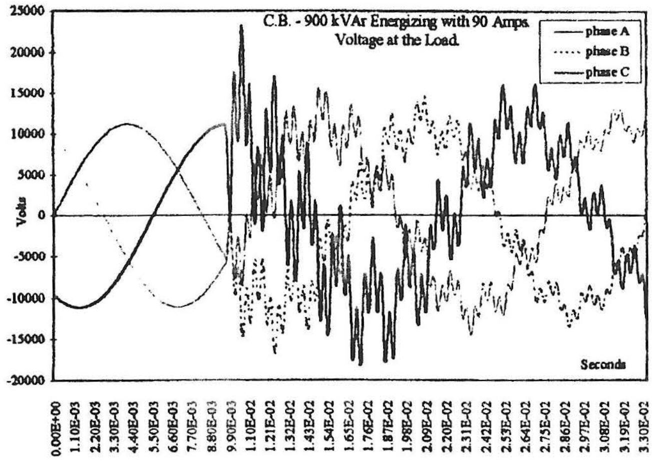


Figure 3 - 900 kVAr bank energization - load voltage

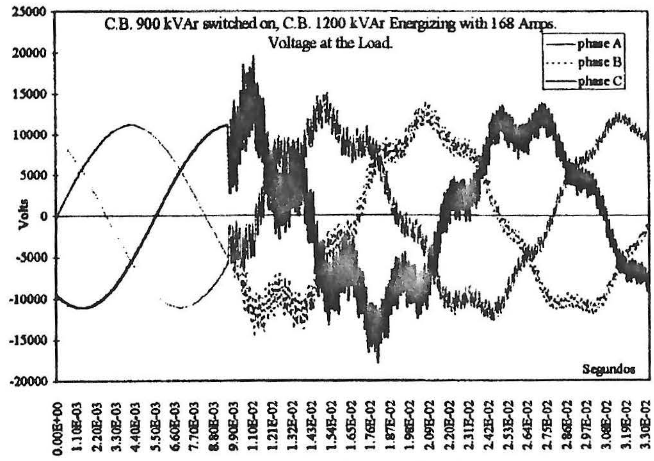


Figure 4 – 1,200 kVAr bank energization - load voltage

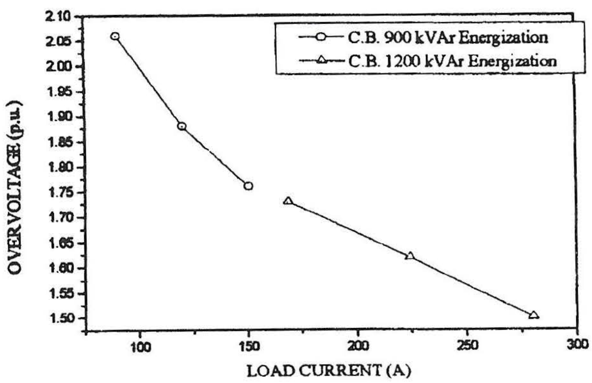


Figure 5 - Load current variation effect for the maximum overvoltage values

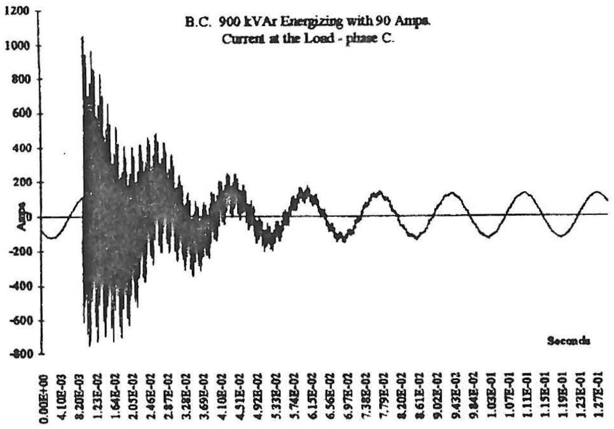


Figure 6 - 900 kVAr bank energization - load current

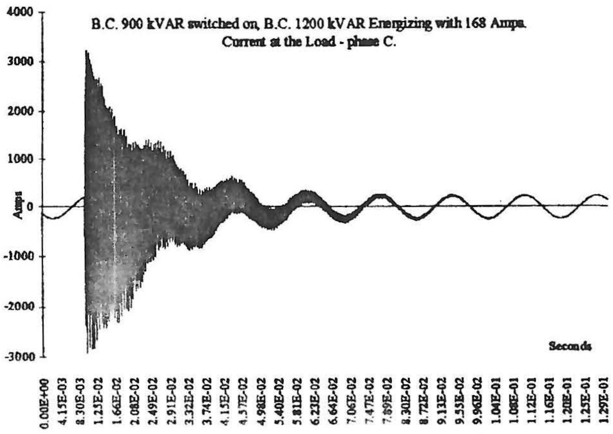


Figure 7 – 1,200 kVAr bank energization - load current

## V. 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.

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

- Regarding the 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 customer capacitor bank size.

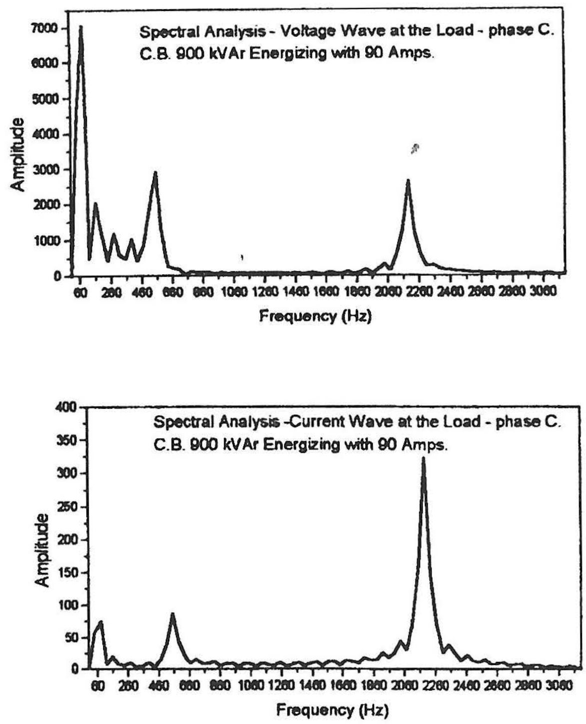


Figure 8 - Voltage and current waves frequency spectrum during the 900 kVAr bank energization

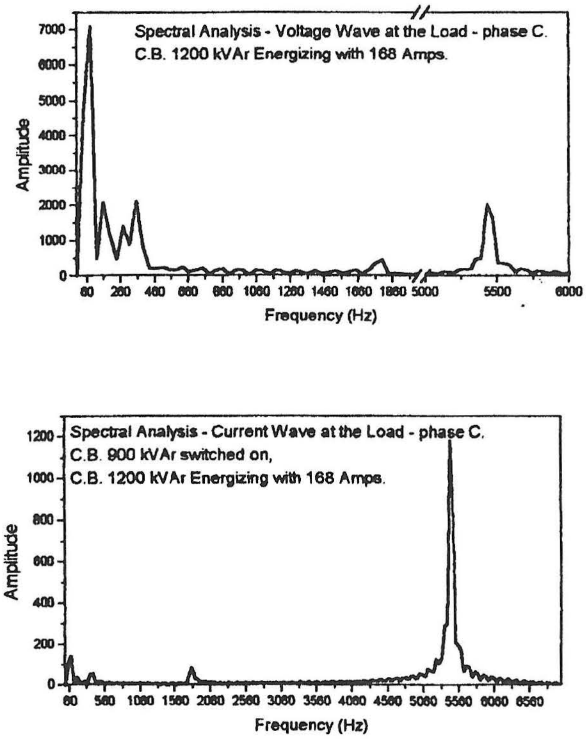


Figure 9 - Voltage and current waves frequency spectrum during the 1200 kVAr bank energization

- 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.

## VI. ACKNOWLEDGEMENT

The authors would like to thank CPFL and University of São Paulo for their support, which allowed the development of this paper.

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