Impact of the Reactive Power Compensation on Harmonic Distortion Level

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Abstract - **The goal of this paper is to present a study about the impact of the application of 12 capacitors banks in substitution of one only bank on 23 (kV) utility system on the voltage distortion level. This analysis was based in the results obtained from measurements made with a Power Quality Analyser (P.Q.A) and in simulation results using the PSCAD/EMTDC computer program which is a powerful tool for power system simulation.**

Keywords: Power Quality, Harmonic Distortion, Measurements, PSCAD/EMTDC, Standards

I. INTRODUCTION

Shunt capacitors banks have been installed on distribution feeders to supply the type of reactive power or current to counteract the out-of-phase component of current required by the inductive loads. However their application can lead to Power Quality problems which need to be addressed.

Short time ago, the main concern of the electric utilities was to look for the form of assisting the demand of energy required by the market, based on assisting basic approaches of quality, that means, to verify the magnitude and frequency of the supplied voltage. Nowadays, it should consider several factors related to the power quality problem [1].

Taking advantage of the proposal to change a bank of 1.8 MVAr existent in the substation 1 (bus 0), for the other 12 capacitors banks which would be installed along the system in subject, a study was placed to verify the impact of this substitution on harmonic distortion level in this network.

The main idea is to analyze the problem of harmonic distortion based on a methodology that used obtained data from measurements at 13 buses of the distribution system, to model a system with realistic data and to accomplish comparisons with the results obtained in PSCAD/EMTDC software. This way, measurements were accomplished in different foreseen points of the network, before and after the installation of the capacitors banks, where was possible to accomplish a comparative investigation of the effects of the installation of these capacitors banks on harmonic distortion levels.

The considerations about the situation of the harmonic distortion level were based on IEEE Standard 519, 1992 as showed in [2].

II. DESCRITION OF THE NETWORK

For determination of the voltage distortion in a certain network node the following data are required:

- contents of forcing of harmonics currents source;
- system impedances for particular harmonics.

The general scheme of the two 23 (kV) systems configurations analysed are shown in Fig. 1.

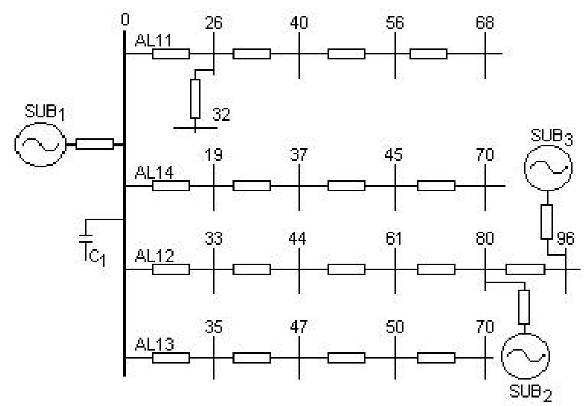

Fig. 1A. System with only one bank

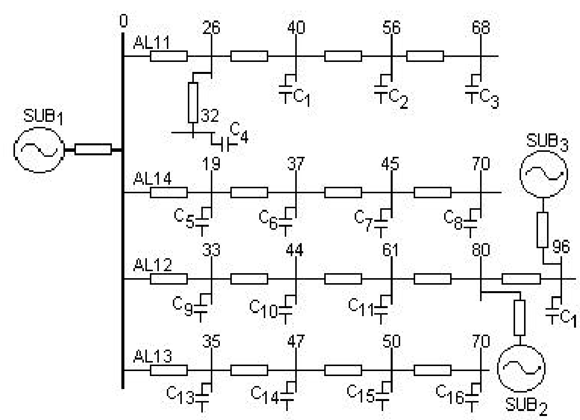

Fig. 1B. System with distributed banks

Fig. 1. One-line diagram of distribution network

The fedder 13 was not included in the analysis because it supplies another utility. The power of the capacitors banks and distribution trasformers of the buses from Fig 1 are showed in Table 1.

The distribution transformers impedances data are presented in Table 2.

Table 1. Power of Capacitor Banks and Distribution Transformers of each point

Bus	32	40	56	68	19	37	45	70	33	44	61	96
Capacitor Banks (kVAr)	150	300	300	150	150	300	300	150	300	300	300	300
Distribution Transformers (MVA)	0.225	0.225	0.150	0.150	0.150	0.150	0.075	0.075	0.075	0.075	0.075	0.500

Table 2. Distribution Transformers rated characteristics

Power (MVA)	Z (%)	R (%)	X (%)
75	4.0	1.700	3.621
150	4.0	1.430	3.736
225	5.0	1.293	4.823
500	5.0	1.470	4.779

The power transformer, in the substation 1, has the following parameters:

$Y_{GROUNDED}(P)/Y_{GROUNDED}(S)/delta(T)$, rated 25 MVA

Short-circuit reactances (primary P, secondary S, and tertiary T):

$$X_{PS} = 8.10\,(\%) \quad X_{PT} = 14.02\,(\%) \quad X_{ST} = 3.69\,(\%)$$

Point of Common Coupling (PCC) - this is the location where the harmonic currents are evaluated. It will probably be determined by the utility. Likely locations are the metering point or the high side of the customer step down transformers [7]. In this case, all the high sides of the step down distribution transformers.

III. EXPERIMENTAL RESULTS

The field tests which were carried out, had been planned in order to verify the correspondence of the measured distortion harmonic and computed by simulation.

The points for the accomplishment of the measurements were selected by the proximity of the bus foreseen for the installation of the capacitors banks. In order to determine the network harmonic distortion the measurements were done in the secondary of these transformers. All the experimental tests were accomplished during the period of the afternoon and morning with the system operating. as usual.

A. Network configuration with only one capacitor bank

Figures 2, 3, 4, and 5 show the measurements carried out at some buses. The informations about Figures 2, 3, 4 and 5 are showed in Table 3. Table 5 shows the summary of monitoring results obtained in all the buses of the network in Fig. 1A.

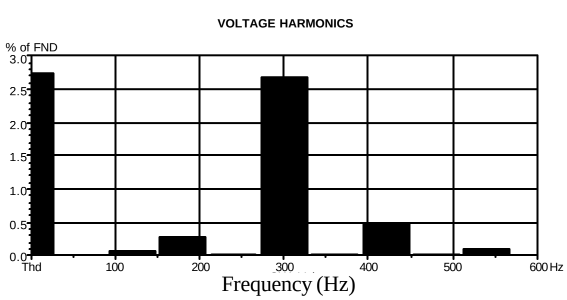

Fig. 2. Voltage harmonic spectrum on bus 0

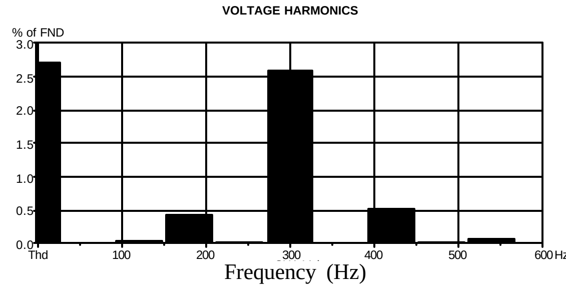

Fig. 3. Voltage harmonic spectrum on bus 32

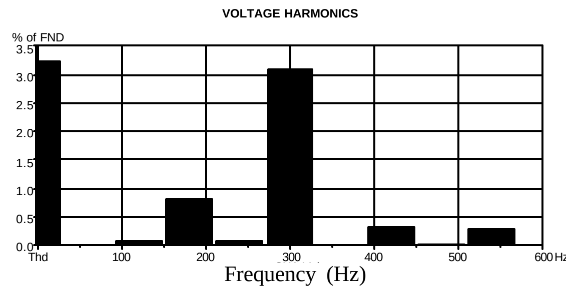

Fig. 4. Voltage harmonic spectrum on bus 33

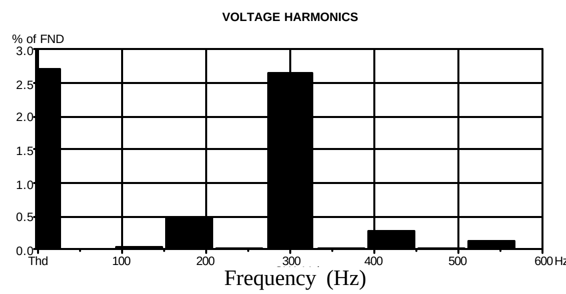

Fig. 5. Voltage harmonic spectrum on bus 19

Table 3. Measurements data

Bus	0	32	33	19
Total RMS (Volts)	22899	222.8	231.7	224.7
Fund. (H1) RMS (Volts)	22890	222.7	231.6	224.8
Total Harmonic dist.(%)	2.20	2.70	3.24	2.80

B. Network configuration with 12 capacitor banks

Figures 6, 7, 8, and 9 show the measurements carried out at the same buses as the other case. The informations about Figures 6 , 7, 8 and 9 are showed in Table 4. Table 6 lists the summary of results in all the buses of the network in Fig. 1B.

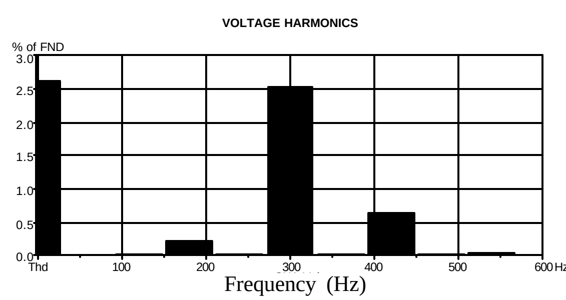

Fig. 6. Voltage harmonic spectrum at bus 0

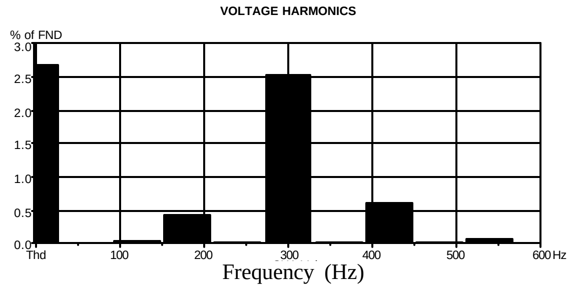

Fig. 7. Voltage harmonic spectrum on bus 32

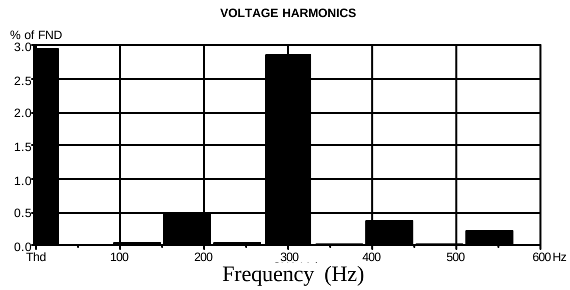

Fig. 8. Voltage harmonic spectrum on bus 33

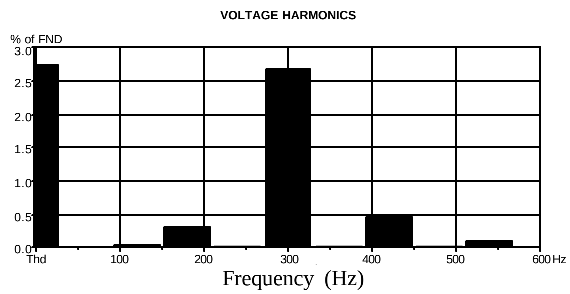

Fig. 9. Voltage harmonic spectrum on bus 19

Table 4. Measurements data

Bus	0	32	33	19
Total RMS (Volts)	23288	223.0	229.3	223.8
Fund. (H1) RMS (Volts)	23278	222.9	229.2	223.7
Total Harmonic dist.(%)	2.60	2.67	2.92	2.76

IV. HARMONIC SIMULATIONS

The simplified single line diagram of the power system considered in the following analysis is shown in Fig. 10. The system was summarized only as substation 1 linked to one of the capacitors instalation points (PCC).

Trying to simplify the analysis the substations 2 and 3 weren't considered in the modeled system, because the short circuit levels in both of them, are a lot inferior of the substation 1.

The systems showed in Fig. 10 were modeled in PSCAD/EMTDC considering the three basic elements:

- 23 (kV) similar network of the three feeders that assist the studied electric utility system. The model coupled PI section was used; to represents the buses.

- distribution transformer with the similar characteristics of those connected at buses monitored. This consideration is very important because in the detailed system, the transformers are a important source of the lower system harmonics. It is because sinusoidal magnetisation of iron needs a third harmonic, also 5th and 7th etc., components of current.

- harmonic currents were modeladed using harmonic current injection. The frequency and magnitude of the injected harmonic currents was obtained in measurements carried outat the specific buses.

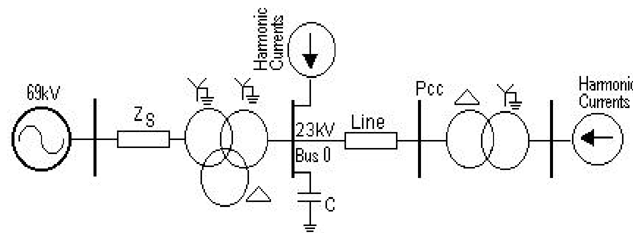

Fig. 10A - Network with only one bank at bus 0

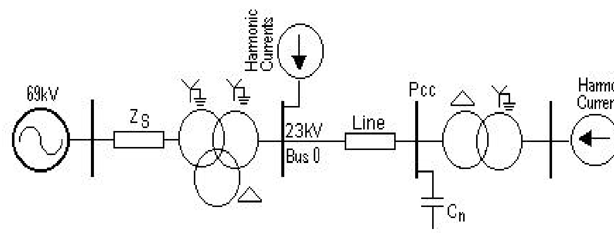

Fig.10B - Network with distributed banks

Fig. 10. The power system considered

A. Transfomer Modeling

In this paper, the transfomers were modeled considering the normal magnetizing curve approximated as four-linear sections shown in Fig. 11. The General Transformer Model available in PSCAD was used.

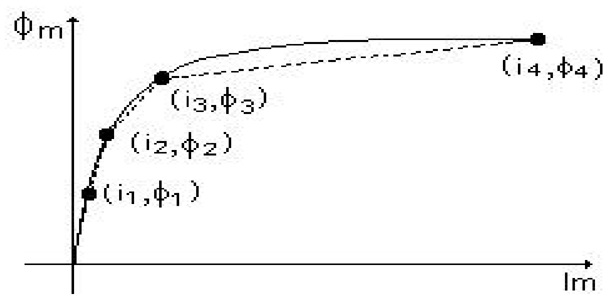

Fig. 11. Normal Magnetizing Curve

Where Φ_m is the instantaneous mutual flux link (Wb), I_m is the instantaneous magnetizing current (A).

The rated current I_N (A), and the rated flux, Φ_N (Wb), can be calculated as follows:

$$I_N = \frac{S_N}{\sqrt{3}\ V_N} \qquad (1)$$

$$\Phi_N = \int \frac{\sqrt{2}}{\sqrt{3}} V_N \ dt \qquad (2)$$

Where S_N is the rated power (VA), V_N is the rated voltage (V).

The three basic parameters required for representing saturation curve in the Saturation Property Sheet for the General Transformer component was obtained by as follows from the data in the Normal Magnetizing Curve of the transformers.

Winding air core reactance: X_{AIR} (p.u.) is determined based on the two highest points.

$$X_{AIR} = \frac{\Delta\Phi_m}{\Delta I_m}\frac{w}{Z_{BASE}} = \frac{\Phi_4 - \Phi_3}{I_4 - I_3}\frac{w}{Z_{BASE}} \quad (3)$$

Rated magnetizing current: I_{MR} (%) is determined using a point closest to the rated flux.

$$I_{mN} = \frac{\Phi_N}{\Phi_1}\frac{I_1}{I_N}100 \quad (4)$$

knee point of the magnetizing curve: X_{KNEE} (p.u.) is determined based on the highest point.

$$L_{AIR} = \frac{X_{AIR}\, Z_{BASE}}{w} \quad (5)$$

$$X_{KNEE} = \frac{\Phi_4 - (L_{AIR}\, I_4)}{\Phi_N} \quad (6)$$

The choice of the base voltage must be related to the same side of the winding of the magnetizing curve that was modeled. The Saturation Property Sheet allows to choose the winding to place the saturation.

B. Sytem with only one capacitor bank

Fig. 12, and 13, show the simulation results on two points on the distribution transformers low voltage side (LV). The simulation results on distribution transformers high voltage side (PCC or HV) are represented by Fig. 14 and 15. The considered harmonic currents were those showed in Table 4. Table 7 shows the summary of results obtained in the points of the network in Fig. 1A on the distribution transformers low voltage side. The results for the PCC are showed in Table 8.

Table 5. Monitoring Results

Bus	Total Voltage Distortion THD_V (%)			Harmonic Voltages Vn (V)				Harmonic Currents In (A)			
	Min.	Med.	Max.	V_1	V_3	V_5	V_7	I_1	I_3	I_5	I_7
0	2.37	2.87	3.26	23285	40	588.0	143.0	265	1.8	12.5	2.5
32	2.18	2.72	3.03	223.0	0.9	6.2	1.5	329.0	21.0	5.8	1.0
40	2.52	3.00	3.49	226.5	1.0	6.0	1.6	48.5	3.2	2.9	0.9
56	2.54	2.81	2.98	214.1	1.6	5.1	1.5	256.0	16.0	9.9	1.2
68	2.50	2.86	3.09	224.5	0.8	6.2	1.4	98.2	5.80	5.20	0.9
19	2.53	2.75	2.93	224.0	1.1	6.0	1.0	60.0	6.8	4.0	0.6
37	2.14	2.38	2.84	223.0	1.1	6.7	1.2	43.8	3.9	1.2	0.3
45	1.91	2.19	2.67	231.7	0.7	5.9	1.2	61.0	1.5	3.4	1.1
70	2.11	2.48	2.80	225.7	0.8	6.1	1.2	61.0	4.5	4.9	1.3
33	2.47	2.90	3.21	231.6	1.2	6.6	0.9	33.0	2.6	2.2	0.8
44	2.72	3.02	3.08	229.0	1.4	6.8	1.1	69.0	1.3	3.3	1.1
61	2.43	3.14	3.30	230.0	1.5	6.7	1.0	45.4	3.7	4.3	1.2
96	2..92	3.09	3.17	231.0	1.1	6.6	0.9	77.0	5.1	4.9	1.0

Table 6. Monitoring Results

Bus	Total Voltage Distortion THD_V (%)			Harmonic Voltages Vn (V)				Harmonic Currents In (A)			
	Min.	Med.	Max.	V_1	V_3	V_5	V_7	I_1	I_3	I_5	I_7
0	2.06	2.32	2.67	23245	35	570	145	318.0	2.0	12.0	2.4
32	2.46	2.75	2.76	223.2	1.1	5.8	1.4	343.0	22.0	6.0	1.1
40	2.20	2.54	2.66	225.7	1.4	5.4	1.2	47.0	2.9	1.4	0.8
56	2.42	2.56	2.86	210.8	1.6	5.2	1.4	244.0	17.0	8.2	1.2
68	2.43	2.72	2.75	222.5	0.9	5.6	1.5	184.0	9.6	6.2	1.1
19	2.23	2.30	2.55	223.2	0.8	5.9	1.0	51.0	3.1	3.5	1.4
37	2.49	2.74	2.89	222.8	1.5	5.7	1.2	46.0	3.9	0.9	0.3
45	2.48	2.84	2.92	222.7	0.5	5.8	0.8	57.0	1.3	3.4	1.0
70	2.55	2.69	2.74	221.9	0.6	5.0	0.9	58.0	4.3	4.5	1.3
33	2.65	2.75	2.91	228.6	1.1	6.2	0.9	34.0	2.6	3.1	1.0
44	2.56	2.58	2.77	228.8	0.8	6.1	1.1	64.0	1.1	3.2	1.1
61	2.28	2.59	2.93	232.3	1.0	6.2	1.3	47.0	3.9	4.2	1.3
96	2.89	2.96	2.98	233.4	1.0	6.4	0.8	69.0	4.9	5.1	0.8

Table 7. Simulation Results on LV side - Distribution Transformers

Bus	32	40	56	68	19	37	45	70	33	44	61	96
V_1 (V)	222.0	221.0	220.8	224.1	223.3	221.0	225.0	221.8	227.0	225.0	226.2	225.0
V_3 (V)	1.0	0.9	1.1	1.0	1.1	1.0	0.8	0.9	1.5	0.9	1.2	1.1
V_5 (V)	5.9	5.8	4.9	6.0	6.0	6.4	5.7	6.6	6.7	5.9	6.8	6.4
V_7 (V)	1.6	1.7	1.4	1.6	1.6	1.5	1.5	1.5	1.3	1.1	1.2	1.0
THD_V (%)	2.6	2.7	2.3	2.8	2.9	2.9	2.4	2.7	2.9	2.3	2.8	2.6

Table 8. Simulation Results on HV side - Distribution Transformers

Bus	32	40	56	68	19	37	45	70	33	44	61	96
V_1 (V)	14020	14000	14000	14000	13620	13580	13420	13390	13480	13390	13340	13350
V_3 (V)	15.6	16.0	15.6	15.3	15.9	17.0	15.9	16.1	17.2	16.0	15.8	14.8
V_5 (V)	297.6	296.4	294.2	281.6	289.7	286.0	294.8	295.4	293.1	290.4	293.1	293.3
V_7 (V)	99.2	100.0	96.2	98.8	82.3	82.1	81.7	82.9	85.6	81.8	84.0	83.6
THD_V (%)	2.4	2.4	2.2	2.0	2.3	2.3	2.3	2.4	2.5	2.4	2.5	2.4

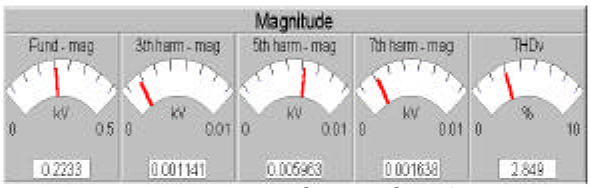

Fig. 12. Harmonic Voltages on bus 19 LV

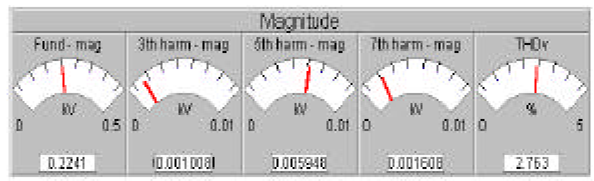

Fig. 13. Harmonic Voltages on bus 68 LV

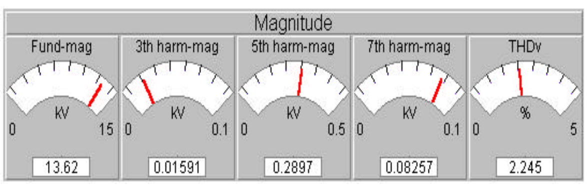

Fig. 14. Harmonic Voltages on bus 19 HV

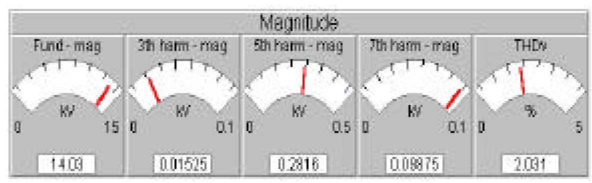

Fig. 15. Harmonic Voltages on bus 68 HV

C. Sytem with distributed capacitor banks

Fig. 16 and 17, give the simulation results in two points on LV. HV simulation results are represented by Fig. 18 and 19. The considered harmonic currents are shown in Table 6.

Table 9 lists the summary of results obtained in the points of the network in Fig. 1A on low voltage side. The results for the high voltage side (PCC) are shown in Table 10.

V. CONCLUSIONS

This paper has presented an investigation carried out in thirteen points of a 23 (kV) network, it was based on field tests whose data were used on the modeling of a particular reducted system allowing the harmonic analysis of this utility system. The arisen specific conclusions from this study could be summarized as follows:

From the application point of view, this analysis showed that is very difficult to compare experimental with simulation results. However the proposed modeling is pratical and provides good results take in consideration the complexity of the harmonic analysis. Harmonic voltage levels determined through simulations and measurements can be compared in Tables 5 and 7, and Tables 6 and 9. We have included the loads in bus 0 and PCC obtained in measurements.

Established impedance values of the circuit allow the determination of the impact of circuit parameters changes on voltage distortion levels caused by harmonic currents obtained in field tests. This makes the simulations possible of both existing and planned systems.

Besides of the benefits usually expected with the optmization of the reactive power flow, the distortion voltage level has presented an improvement as can be verified from the obtained results in the measurements and also in the simulations. In all of the points of common coupling (PCC) analysed the harnonic distortion levels atempt the demand of the IEEE Standard 519, 1992, in terms of voltage and current, showing that the substitution of the capacitor banks were profitable, considering the impact on power quality focusing harmonic concerns.

The transformers modeling was realized based on normal magnetizing curves and rated current of each.

The saturation curves were adjusted to give a better fit, by changing X_{KNEE} and X_{AIR} because was considered that transformers were responsible for part of the harmonics.

VI. ACKNOWLEDMENTS

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Table 9. Simulation Results on LV- Distribution Transformers

Bus	32	40	56	68	19	37	45	70	33	44	61	96
V_1 (V)	222.1	223.6	216.8	222.9	220.7	220.2	219.7	221.8	225.2	224.8	224.9	225.0
V_3 (V)	1.3	0.9	1.2	1.1	1.0	1.0	0.7	1.0	1.1	0.8	1.0	1.1
V_5 (V)	5.6	5.7	5.3	5.5	4.8	5.6	5.5	6.1	6.0	5.5	6.1	5.9
V_7 (V)	1.5	1.5	1.6	1.7	1.5	1.4	1.3	1.5	1.4	1.3	1.6	1.4
THD_V (%)	2.4	2.4	2.5	2.6	2.5	2.6	2.3	2.6	2.6	2.2	2.7	2.6

Table 10. Simulation Results on HV- Distribution Transformers

Bus	32	40	56	68	19	37	45	70	33	44	61	96
V_1 (V)	13490	13470	13390	13490	13560	13470	13350	13340	13430	13370	13410	13340
V_3 (V)	16.9	17.0	16.4	16.1	15.2	15.1	14.7	14.8	17.3	15.3	15.7	15.2
V_5 (V)	269.8	272.0	265.2	270.0	279.5	249.2	237.9	239.4	276.2	265.7	262.0	261.0
V_7 (V)	93.7	87.4	83.5	91.9	82.9	77.9	68.	81.1	88.4	74.0	76.6	77.9
THD_V (%)	2.1	2.1	2.0	2.0	2.1	2.0	2.0	2.1	2.2	2.0	2.0	2.0

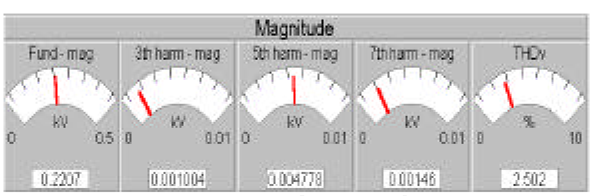

Fig. 16. Harmonic Voltages on bus 19 - LV

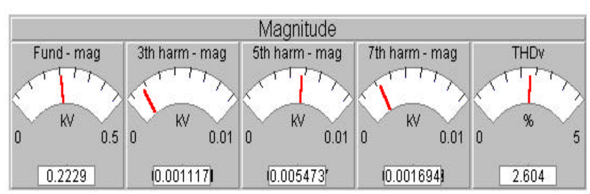

Fig. 17. Harmonic Voltages on bus 68 - LV

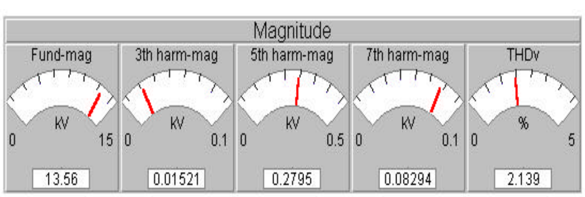

Fig. 18. Harmonic Voltages on bus 19 - HV

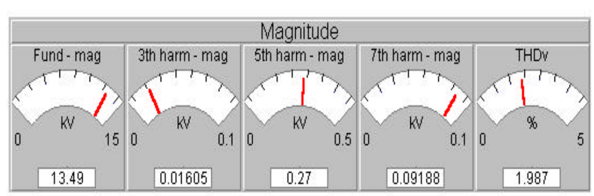

Fig. 19. Harmonic Voltages on bus 68 - HV