Load Characterization in Medium Voltage of an Electric Distribution Utility Related to Active Filters

F. Corasaniti (*), *Student Member, IEEE*, M. B. Barbieri (*), *Senior Member, IEEE*, P. Arnera (*), *Senior Member, IEEE*, and M. I. Valla (**), *Senior Member, IEEE*

***Abstract*— The behavior of the actual load of an electric energy distribution utility by means of voltage and current measurements is analyzed in this paper. Steady and transient states are taken into account. The main attention is fixed in points where present shunt compensation is installed. Results of field measurements and the connection and disconnection of capacitor banks are shown. Studies for future compensation are detailed and the possible advantages of active filter incorporation are analyzed in order to replace or complement the existing compensation. The minimal requirements are established in order to consider the design of the active filters and their compatibility with the existing installations.**

***Index terms*--Active Filters, Compensation, Harmonic Studies, Measurements.**

I. Introduction

The increase of non-linear loads and equipments in the power systems has been demanding the compensation of disturbances caused by them. Voltage distortion due to current harmonics is becoming a major problem for the utilities at distribution levels. Utilities frequently encounter harmonic related problems, such as higher transformer and line losses, reactive power, and resonance problems, required de-rating of distribution equipment, harmonic interactions between the utility and loads, reduced system stability and reduced safe operating margins.

Provided the necessity of the reactive compensation in a network of an electric energy distribution utility, measurements were performed at different points of interest in the network in order to carry out harmonic studies. Harmonic and transient measurements were carried out in three different distribution substations where reactive compensation is required. The measurements were carried out in medium voltage levels (MV) where at present there is shunt compensation. The aim was to obtain load characteristics through measurements of voltage and current harmonics at key points.

The harmonic studies are performed considering the future configuration of the network. First, future compensation with capacitor banks is analyzed [2]. Voltage distortions in different points of the network [5] and the working conditions of the capacitor banks [6] are verified by means of harmonic flows.

(*) F. Corasaniti, M.B. Barbieri, P. Arnera are with IITREE-LAT. Facultad de Ingeniería Universidad Nacional de La Plata (FI-UNLP). (1900) 48 y 116. La Plata. Argentina (e-mail: iitree@iitree-unlp.org.ar).

(**) M.I.Valla is with CONICET and LEICI. Facultad de Ingeniería Universidad Nacional de La Plata (FI-UNLP). (1900) 48 y 116. La Plata. Argentina (e-mail: m.i.valla@ieee.org).

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Second, the advantages of carrying out the compensation with active filter type equipment or its combination with the traditional compensation are analyzed [1]-[2]. The transient requirements imposed to the active filter are taken into consideration in its design [3]-[4].

II. Network Description and Measurements

Fig. 1 shows the one line diagram of the transmission network of the electric distribution utility. The 132 kV network where the distribution substations (DS) under study are connected works meshed and connected to the 500 kV high voltage transmission system, through two points.

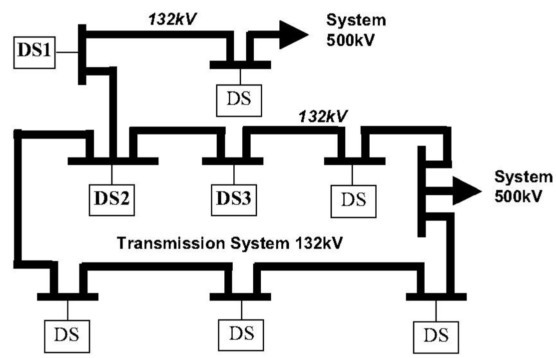

Fig. 1. One line diagram of actual network distribution utility.

The field measurements were carried out in the three DS where additional compensation will be required by the network reconfiguration (DS1 DS2 DS3). Harmonic levels of voltage and currents were recorded along one week.

Voltages and currents were also measured during connection and disconnection of the present capacitor banks in order to observe the transients produced by such switching.

A. Characteristics of DS1.

Fig. 2 shows the one line diagram of DS1.

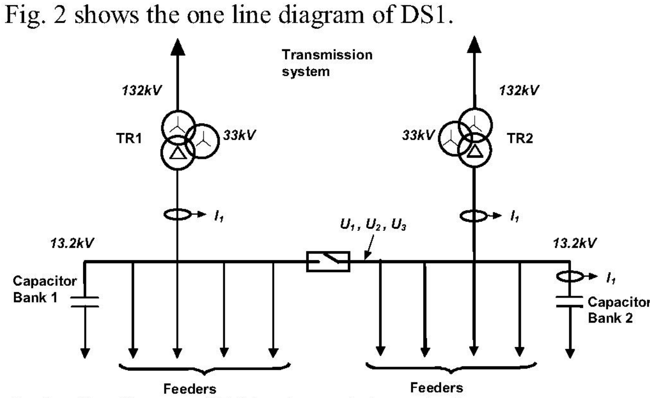

Fig. 2. One line diagram of DS1 and recorded magnitudes.

DS1 has two transformers of similar characteristics, 132/34.5/13.8 kV and 15/10/15 MVA. They are connected in parallel in 13.2 kV feeding the loads. DS1 has two capacitor banks of 4.8 MVAr each, which are connected to each busbar of 13.2 kV.

Fig. 2 also indicates where the harmonic record equipment was installed. The three phase voltages (U1 U2 U3) were measured in 13.2 kV. Currents were measured in only one phase in three different places: transformer 1, transformer 2 and capacitor bank 2.

Harmonics were recorded in voltages and currents along 8 days. Both 13.2 kV busbars were connected in the usual operating configuration. During measurements the capacitor bank 1 was always out of service while capacitor bank 2 was connected at certain moments as inferred from the measurement of the current through it. The voltage and current transients were recorded during connection and disconnection of this bank.

B. Characteristics of DS2.

Fig. 3 shows the one line diagram of DS2. It has two transformers of 132/34.5/13.8 kV and different powers, Tr 1 of 15/15/10 MVA and Tr 2 of 30/30/30 MVA. They feed loads in parallel at 33 kV. One capacitor bank of 4.8 MVAr is connected to each transformer in the 13.2 kV windings, where there are no loads.

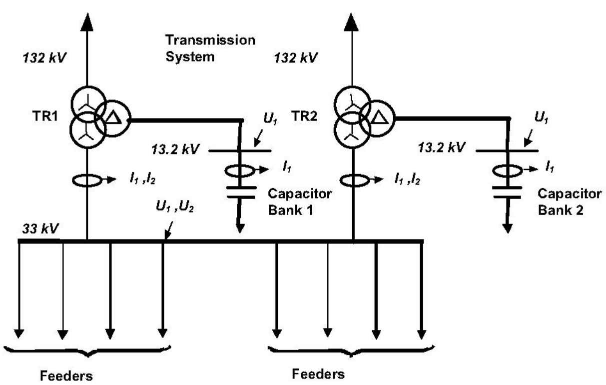

Fig. 3. One line diagram of DS2 and recorded magnitudes.

Voltage and current harmonics were recorded during 7 days. Fig. 3 also indicates where the harmonic record equipment was installed. Voltages and currents were measured in 2 phases in 33 kV. Voltage and current of one phase in each capacitor bank were recorded. Both capacitor banks were in service during almost all measurements during that week. As regards transients, voltage and currents were recorded during connection and disconnection of each capacitor bank.

C. Characteristics of DS3.

Fig. 4 shows the one line diagram of DS3. It has only one transformer of 132/34.5/13.8 kV and 15/10/15 MVA. Loads are connected to 33 kV and also to 13.2 kV. A single capacitor bank of 4.8 MVAr is connected in the 13.2 kV busbar.

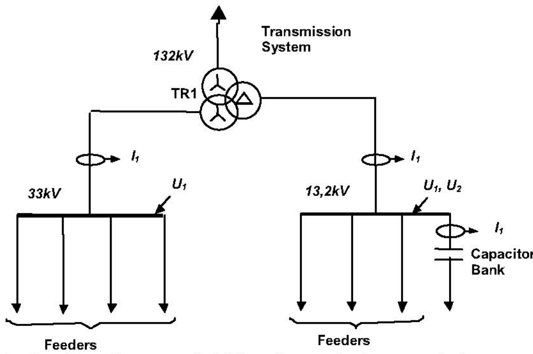

Fig. 4. One line diagram of DS3 and magnitudes recorded.

Harmonics were measured for 7 days. Fig. 4 also indicates where the harmonic record equipment was installed. All the measurements included: one phase voltage and current in 33 kV, two phase voltages and one phase current in the 13.2 kV busbar, and one phase current in the capacitor bank. The capacitor bank was in service at certain moments during the week of measurements. Voltage and currents during one connection and one disconnection were recorded in the capacitor bank.

III. Measurement Presentation

All measurements recorded along one week are organized in the following. They are separated between harmonic measurements in steady state and voltage measurements during transients.

A. Harmonics in voltage and currents in steady state

- THD (Total Harmonic Distortion) profile in the measured voltages.
- Tables with individual harmonics up to 20th. Each harmonic is weighted by means of the normally used statistic parameters, which are the mean value, P_{95} (compared to levels established by ENRE, National Regulating Entity of Electricity, in its Res. 184/00 [5]) and the maximum value.

In all Figures and Tables, the harmonics in voltages are presented in [%] of their fundamental value, while those in currents are presented in [A], as it is required according to International Standards and existing regulation.

B. Voltage measurements during transients

- Phase to ground voltages in the busbar were measured during bank energization. In some cases restrike and overvoltage were recorded.
- Voltages measurements during bank de-energization show no restrike or overvoltage.

IV. Measurement Results

A. DS1

1) Voltage harmonics in steady state.

Fig. 5 presents the THD profile in the 3 phases of the 13.2 kV busbar voltage.

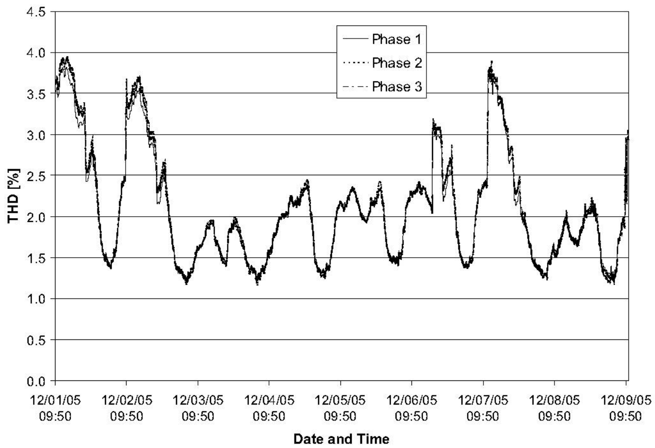

Fig. 5. DS1 THD profile in the three phase voltages (13.2 kV).

Table I shows the summary of the 13.2 kV voltage harmonic distortion, mean, P_{95} and maximum values. Also the limit values imposed by ENRE [5] are presented. Only the most significant harmonics, the odd ones, are shown.

TABLE I
DS1 VOLTAGE HARMONIC DISTORTION IN 13.2 KV BUSBAR.

	THD [%]	**h_3 [%]**	**h_5 [%]**	**h_7 [%]**	**h_9 [%]**	**h_{11} [%]**	**H_{13} [%]**	**h_{15} [%]**	**h_{17} [%]**	**h_{19} [%]**
ENRE Limits	*8*	*5*	*6*	*5*	*1.5*	*3.5*	*3*	*0.3*	*2*	*1.5*
Phase 1										
Mean	2.09	0.07	1.89	0.81	0.03	0.12	0.09	0.02	0.04	0.03
P_{95}	3.51	0.10	3.42	1.07	0.05	0.22	0.15	0.02	0.06	0.05
Maximum	3.82	0.18	3.75	1.29	0.07	0.26	0.18	0.03	0.07	0.06
Phase 2										
Mean	2.12	0.08	1.92	0.80	0.03	0.12	0.10	0.03	0.04	0.03
P_{95}	3.64	0.11	3.57	1.09	0.04	0.24	0.16	0.04	0.06	0.05
Maximum	3.94	0.19	3.87	1.26	0.06	0.28	0.18	0.05	0.07	0.07
Phase 3										
Mean	2.11	0.13	1.91	0.78	0.03	0.12	0.10	0.02	0.04	0.04
P_{95}	3.63	0.17	3.56	1.05	0.04	0.23	0.16	0.03	0.06	0.06
Maximum	3.92	0.28	3.86	1.28	0.06	0.28	0.19	0.03	0.07	0.08

2) Current harmonics in steady state

Fig. 6 shows the THD profile in one phase current of 13.2 kV of both transformers.

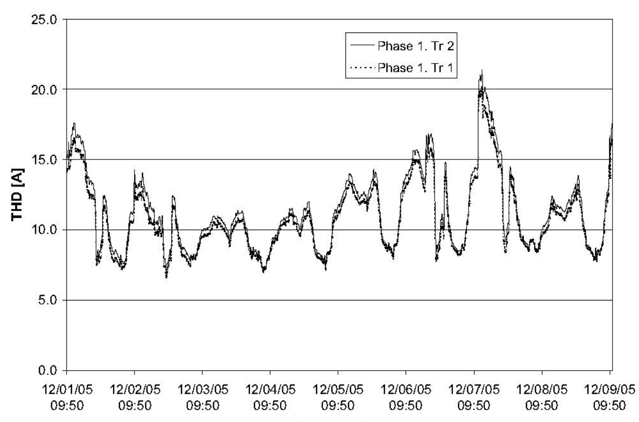

Fig. 6. DS1 THD current profile of both transformers, Tr 1 and Tr 2.

Table II presents the harmonics distortion summary of the current in the 13.2 kV line: mean, P_{95} and maximum values.

TABLE II
DS1 CURRENT HARMONIC DISTORTION.

	THD [A]	**h_3 [A]**	**h_5 [A]**	**h_7 [A]**	**h_9 [A]**	**h_{11} [A]**	**h_{13} [A]**	**h_{15} [A]**	**h_{17} [A]**	**h_{19} [A]**
Phase 1 Tr 1										
Mean	10.83	1.40	10.34	2.32	0.20	0.63	0.28	0.13	0.17	0.15
P_{95}	15.66	1.89	15.48	3.80	0.32	0.85	0.44	0.15	0.23	0.20
Maximum	20.17	2.28	20.02	4.47	0.39	1.07	0.54	0.18	0.28	0.23
Phase 1 Tr 2										
Mean	11.34	0.81	10.92	2.21	0.24	0.71	0.29	0.14	0.17	0.17
P_{95}	16.68	1.24	16.54	3.77	0.40	0.97	0.52	0.17	0.23	0.22
Maximum	21.37	1.59	21.26	4.65	0.48	1.21	0.65	0.20	0.28	0.27

3) Transient behavior

Figure 7 shows the energizing transient of capacitor bank 2.

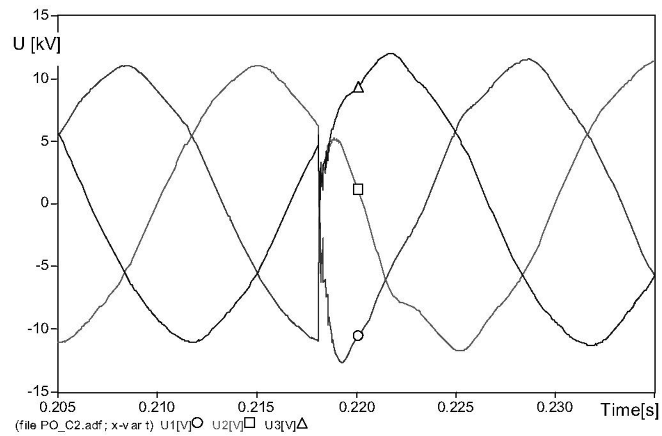

Fig. 7. DS1 Phase to ground voltage during energization transient of capacitor bank.

B. DS2

1) Voltage harmonics in steady state.

Fig. 8 shows the voltage THD profile in one phase of 13.2 kV windings of Tr 1 and Tr 2, respectively. They also corresponds to the voltages of capacitors bank 1 and 2.

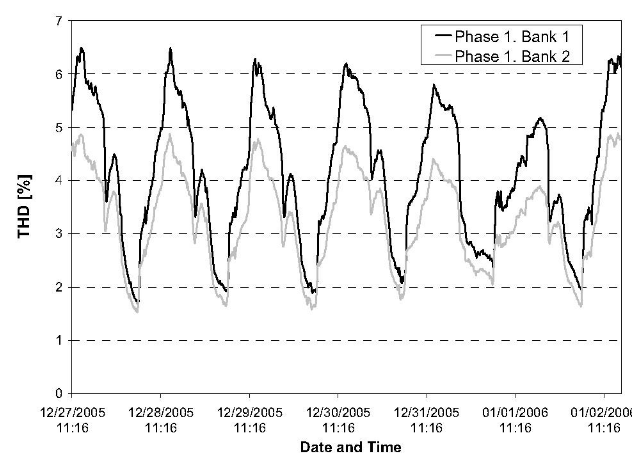

Fig. 8. DS2 voltage THD profile in one phase of capacitor bank 1 and 2.

Table III presents the summary of the 13.2 kV voltage harmonic distortion, mean , P_{95} and maximum values. Also limit values imposed by ENRE [5] are shown.

TABLE III
DS2 VOLTAGE HARMONIC DISTORTION IN 13.2 KV BUSBAR.

	THD [%]	h_3 [%]	H_5 [%]	h_7 [%]	h_9 [%]	h_{11} [%]	h_{13} [%]	h_{15} [%]	h_{17} [%]	h_{19} [%]
ENRE Limits	*8*	*5*	*6*	*5*	*1.5*	*3.5*	*3*	*0.3*	*2*	*1.5*
Phase 1 Tr 1										
Mean	4.16	0.15	4.01	0.77	0.00	0.00	0.00	0.00	0.00	0.00
P_{95}	6.14	0.27	6.01	1.20	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	6.48	0.27	6.31	1.35	0.00	0.00	0.00	0.00	0.00	0.00
Phase 1 Tr 2										
Mean	3.27	0.06	3.24	0.47	0.03	0.06	0.01	0.01	0.01	0.00
P_{95}	4.68	0.10	4.64	0.68	0.04	0.09	0.02	0.01	0.02	0.01
Maximum	4.88	0.18	4.85	0.75	0.05	0.11	0.03	0.01	0.02	0.01

2) Current harmonics in steady state

Fig. 9 shows the THD profile in one phase current of the 13.2 kV winding in both transformers, Tr 1 and Tr 2. They correspond to currents of capacitor banks 1 and 2.

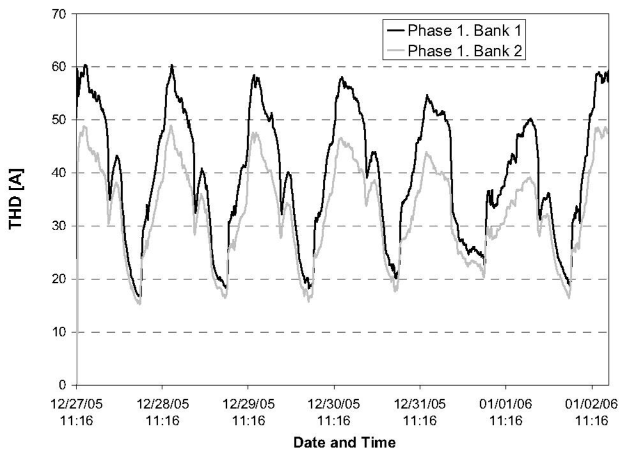

Fig. 9. DS2 THD current profile of both capacitor banks

Table IV, presents the harmonic distortion summary of current in one phase of the 13.2 kV winding: mean, P_{95} and maximum values.

TABLE IV
DS2 CURRENT HARMONIC DISTORTION AT 13.2 KV.

	THD [A]	h_3 [A]	h_5 [A]	h_7 [A]	h_9 [A]	h_{11} [A]	H_{13} [A]	h_{15} [A]	h_{17} [A]	h_{19} [A]
Phase 1 Tr 1										
Mean	39.93	0.85	38.33	10.9	0.83	0.45	0.39	0.29	0.35	0.24
P_{95}	57.75	1.27	55.62	15.6	1.93	1.14	1.42	1.27	1.24	0.98
Maximum	60.42	2.33	58.32	16.8	2.64	1.74	1.99	1.63	1.50	1.19
Phase 1 Tr 2										
Mean	32.70	0.74	32.00	6.58	0.51	1.28	0.27	0.06	0.24	0.05
P_{95}	46.90	1.03	46.15	9.53	0.74	1.82	0.49	0.09	0.39	0.08
Maximum	48.92	1.40	48.04	10.4	0.97	2.25	0.73	0.11	0.56	0.10

3) Transient behavior

In this case there are no transient measurements.

C. DS3

1) Voltage harmonics in steady state.

Fig. 10 shows the THD profile in two phase voltages of the 13.2 kV busbar.

Table V presents the summary of the 13.2 kV voltage harmonic distortion, mean , P_{95} and maximum values. Also limit values imposed by ENRE [5] are shown.

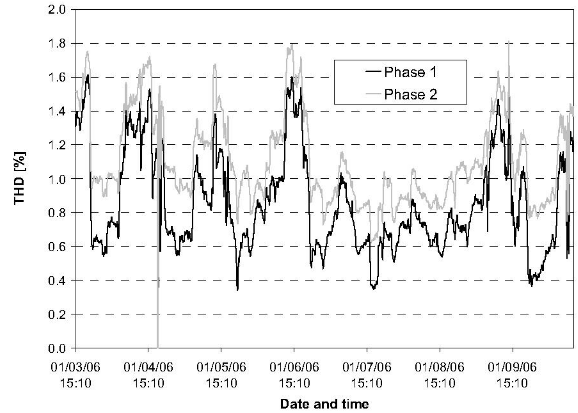

Fig. 10. DS3 voltage THD profile in two phases of 13.2 kV busbar.

TABLE V
DS3 VOLTAGE HARMONIC DISTORTION IN 13.2 KV BUSBAR.

	THD [%]	h_3 [%]	h_5 [%]	h_7 [%]	h_9 [%]	h_{11} [%]	h_{13} [%]	h_{15} [%]	h_{17} [%]	h_{19} [%]
ENRE Limits	*8*	*5*	*6*	*5*	*1.5*	*3.5*	*3*	*0.3*	*2*	*1.5*
Phase 1										
Mean	0.85	0.07	0.79	0.21	0.09	0.09	0.08	0.02	0.03	0.04
P_{95}	1.41	0.13	1.38	0.35	0.11	0.19	0.18	0.03	0.09	0.12
Maximum	1.62	0.21	1.59	0.42	0.13	0.22	0.21	0.04	0.14	0.19
Phase 2										
Mean	1.11	0.53	0.89	0.26	0.08	0.11	0.09	0.01	0.04	0.04
P_{95}	1.63	0.65	1.51	0.41	0.12	0.23	0.17	0.02	0.11	0.14
Maximum	1.81	0.74	1.68	0.47	0.14	0.29	0.21	0.03	0.18	0.19

2) Current harmonics in steady state

Fig. 11 shows the THD profile of one phase current in the 13.2 kV winding.

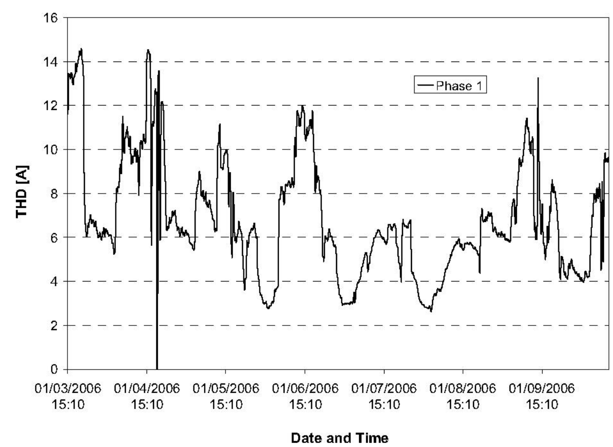

Fig. 11. DS3 THD current profile of one phase current in the 13.2 kV busbar

Table VI, presents the harmonic distortion summary of current in one phase of the 13.2 kV winding: mean, P_{95} and maximum values.

TABLE VI
DS3 CURRENT HARMONIC DISTORTION AT 13.2 KV.

	THD [A]	h_3 [A]	h_5 [A]	h_7 [A]	h_9 [A]	h_{11} [A]	h_{13} [A]	h_{15} [A]	h_{17} [A]	h_{19} [A]
Phase 1										
Mean	6.84	1.53	5.78	2.79	0.32	0.54	0.34	0.08	0.12	0.14
P_{95}	11.94	2.57	11.11	3.74	0.54	0.90	0.56	0.10	0.23	0.26
Maximum	14.61	2.93	14.05	4.39	0.69	1.04	0.69	0.12	0.38	0.33

3) Transient behavior

Fig.12 shows the energizing transient of the capacitor bank.

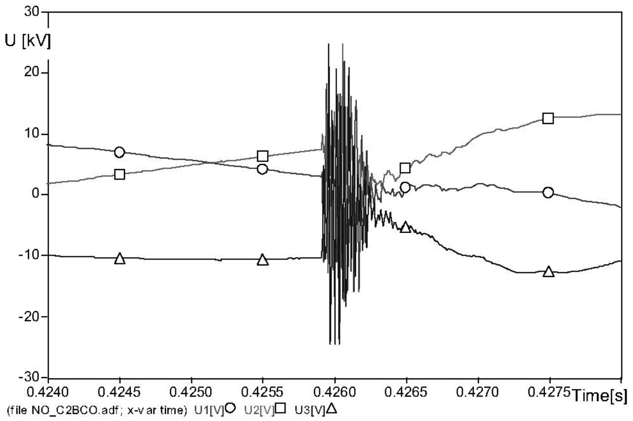

Fig. 12. DS3 Phase to ground voltage during energization transient of the capacitor bank.

V. Measurement Analysis

An analysis of the characteristics of voltages and currents measured in the three distribution substations is presented in this section.

A. Steady State

The analysis of Figs. 5, 8 and 10, and Tables I, III and V corresponding to voltage measurements shows similar characteristics to that of the current measurements shown in Figs. 6, 9 and 11 and Tables II, IV and VI. The main aspects are summarized herein:

- Depending on the DS, there are similar or different levels of total and individual voltage distortion in the different phases.
- Odd harmonics of order 6k+/-1 prevail.
- There is a low level of triple harmonics (3, 9, 15, 21...).
- The 5th harmonic distortion is similar to THD, then it constitutes the most harmful harmonic.
- There are no significant values of high frequency harmonics.
- There are significant differences between Mean value, P_{95} value and Maximum value.

The active filter rating will depend on whether it is used to supply the reactive at industrial frequency or the current harmonics that should be eliminated from the network.

B. Transients State

Due to the possible coexistence of the traditional compensation and that of an active filter, the latter is subjected to voltage transients produced by connection and disconnection of traditional capacitor banks installed in the same busbar or in a different one. [3]-[4]. Fig. 12 shows that the magnitude reached by the phase to ground voltage in DS3 during transient was ≅ 2 p.u.. Then, this requirement should be taken into account when designing the active filter [4].

VI. Studies of Future Compensation

In the future, it will be necessary to work in a radial network connected only to one 500kV point of the system, as shown in Fig. 13.

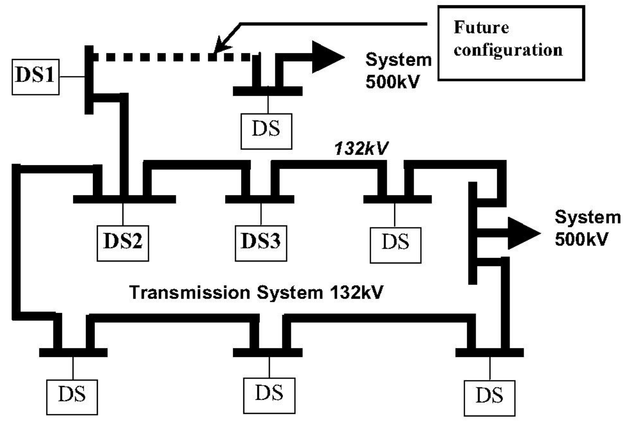

Fig. 13. One line diagram of future network distribution utility.

The requirement to enhance the voltage profile at 132 kV level results from the load flow studies for the configuration shown in Fig. 13. Also an annual demand increase of 7.5 % is taken into account. Then, it is suggested to increase the reactive compensation through capacitor banks connected to the 13.2 kV windings in the 3 distribution substations. [2].

It is also necessary to carry out harmonic studies to determine the effects of the future capacitor banks in voltage distortions at different points of the network [5] and verify the operating conditions of the capacitor banks [6]. It is supposed that harmonic pollution increases in the same percentage as load demand over the present measured harmonics.

A. DS1

The substation DS1 will be far away from the connection point to HV system. Then, an increase of 9.6 MVAr in the reactive compensation connected to the 13.2 kV busbar will be required. This may be implemented with 2 modules of 4.8 MVAr shunt connected to capacitor banks 1 and 2. Harmonic studies indicate that voltage distortions would meet the limits imposed by ENRE [5] and that the capacitor banks would not be overloaded by harmonics, according to IEC 60871-1 [6]. Then, it is not necessary to design the capacitor banks as passive filters. Possible resonance conditions were not found near the harmonics of interest.

B. DS2

Load flow studies for DS2 indicate a necessary increase of 19.2 MVAr of reactive compensation, additional to the present 9.6 MVAr compensation corresponding to capacitor banks connected in Tr 1 and Tr 2. This will be implemented with modules of 4.8 MVAr. Different alternatives of capacitor bank modules connected to each transformer are analyzed. This results in alternatives A and B shown in Table VII.

TABLE VII
ALTERNATIVES FOR PRESENT AND FUTURE COMPENSATION.

A			B		
Tr (13.2 kV)	**Present (MVAr)**	**Future (MVAr)**	**Tr (13.2 kV)**	**Present (MVAr)**	**Future (MVAr)**
Tr 1	1 x 4.8	2 x 4.8	Tr 1	1 x 4.8	1 x 4.8
Tr 2	1 x 4.8	4 x 4.8	Tr 2	1 x 4.8	5 x 4.8

Harmonic studies show that both alternatives are comparable regarding distortions and possible overloads. But both of them present possible resonance problems. When alternative B is considered, the connection of 5 capacitor banks in Tr 2 13.2 kV winding, produces a resonance in the 7th harmonic in Tr 1 13.2 kV winding. In this case the harmonics in the network exceeds the limit imposed by ENRE [5] for all the capacitor banks connected in each transformer. Fig. 14 shows the impedance as a function of the frequency in that connection point of the capacitor bank for the present and future condition. A parallel resonance in 350 Hz is clearly observed in the figure.

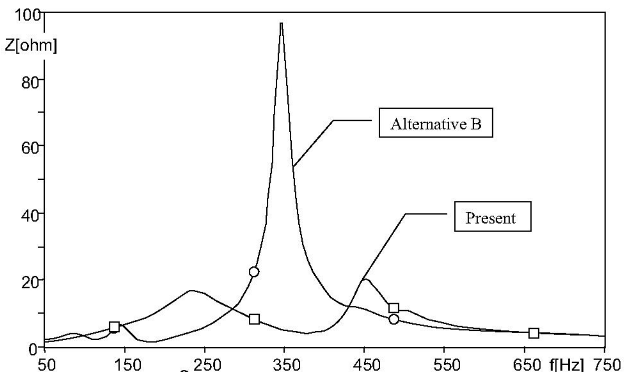

Fig. 14. DS2 frequency response at 13.2 kV busbar of Tr 1. Present and alternative B..

The sensitivity study for alternative A determines possible resonance conditions also at the connection point of capacitor banks in Tr 1. The resonance appears near the 5th harmonics for all the capacitor banks connected in each transformer. Fig. 15 shows the impedance as function of frequency in such connection point of the capacitor bank for the present and future condition for alternative A. A parallel resonance near 250 Hz is clearly observed in the figure. Nevertheless the impedance magnitude is almost half of that of alternative B, its resonance near the 5th harmonic is more harmful than the first alternative.

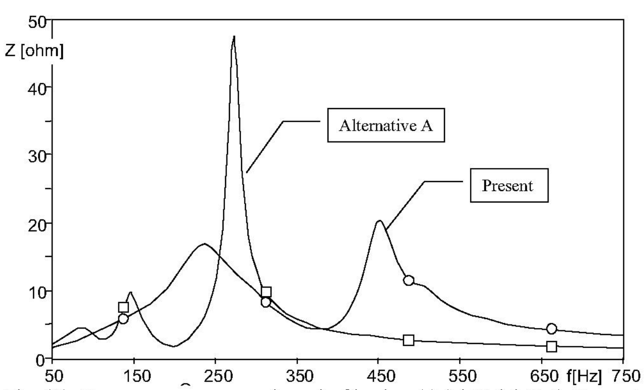

Fig. 15. Frequency response viewed of busbar 13.2 kV del Tr 1. Present and alternative A. DS 2.

The capacitor banks were not overloaded by harmonics neither for alternative A, nor for alternative B, considering the original capacity and inductance parameters of the circuit.

C. DS3

Load flow studies for DS3 indicates a necessary increase of 4.8 MVAr of reactive compensation, additional to the present 4.8 MVAr compensation corresponding to the capacitor banks connected in 13.2 kV winding. Harmonic studies determined that voltage distortions would meet ENRE requirements [5] and that the capacitor banks would not be overloaded by harmonics [6]. Possible resonance conditions were not found near the harmonics of interest.

VII. Analysis of an Active Filter Incorporation

The possibility of implementing future compensation with an active filter or a combination of active and passive compensation is evaluated in this section.

A. DS1 and DS3

The results of harmonic studies for these distribution substations determined that there are no possible resonance conditions when the future compensation is incorporated by means of capacitor banks. Besides, the voltage distortions would also meet the limits and the banks would not be overloaded by harmonics. Then it is possible to implement future compensation in the traditional way with capacitor banks.

B. DS2

The results of harmonic studies for this substation determined that there are possible resonance conditions if the future compensation is incorporated by means of capacitor banks even with different configurations of the passive compensation. Since the active equipment does not establish interaction with the rest of the system producing resonance, future compensation may be implemented with an active filter. This filter should supply the reactive at industrial frequency and eliminate or attenuate harmonic currents from the network [7].

VIII. Conclusions

The harmonic studies carried out with the actual load measurements, determined which type of equipment is more convenient for the compensation in each substation.

Based on possible resonances and harmonic currents existing in the network, it is concluded that compensation with passive traditional capacitor banks is sufficient, for DS1 and DS3; while it is necessary to analyze the solution with active filters for DS2 where some resonances appear around the 5th and 7th harmonic.

The requirements for an active filter depend on the reactive supply needed at fundamental frequency and on the attenuation of the current harmonics of the network. Since 5th and 7th are the dominant harmonics, it is possible to implement an active filter with relatively low switching frequency. This is important in the design of high power and medium voltage active filters.

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X. Biographies

F. Corasaniti was born in Necochea, Argentina, on October 30, 1973. He got his degree in Electrical Engineering from La Plata National University (UNLP), Buenos Aires, Argentina, in 1999. His special field of interest includes power systems operation and control and power quality. He has been working for the IITREE-FI-UNLP studying normal and transient conditions of electrical systems and technical planning since 1999. As a researcher of the IITREE he has made technical works for public and private companies of electrical service and industry in Argentine. He is an assistant professor at the Electrical and Electronic Engineering Department, UNLP. At present he is graduate student at UNLP.

M. Beatriz Barbieri was born in Laprida, Argentina, on July 5, 1960. She got her degree in Telecommunications Engineering (with honors) from UNLP in 1984. Her special field of interest includes Electrical Power Systems. She has been working for the IITREE-FI-UNLP studying normal and transient conditions of electrical systems and in economic and technical planning since 1983. As a researcher of the IITREE she has made technical works for public and private companies of electrical service and industry in Argentine. She is Professor of Electricity and Magnetism at the EE Dept., School of Engineering , UNLP. She is IEEE member of Power Electric Society.

Patricia L. Arnera was born in Buenos Aires, Argentina, on April 27, 1958. She got her degree in Electrical Engineering from the UNLP in 1981. Her special field of interest includes Electrical Power Systems. She works for the IITREE-FI-UNLP studying transient conditions of electrical systems and working in Electromagnetic Fields and health. As a researcher of the IITREE she has made technical works for public and private companies of electrical service and industry in Argentine. She is Full Professor of Power System at the EE Dept., School of Engineering, UNLP. She has been IITREE director since 1998. She was Argentina PES Chapter Chairman in 2001-2002.

María Inés Valla was born in Paraná Argentina, on April 3, 1956. She received the Electronics Engineering and Doctor in Engineering degrees from UNLP, in 1980 and 1994, respectively. She is currently a Full Professor in the EE Department, School of Engineering, UNLP. She is also with the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET). She is engaged in teaching and research in the area of power converters and ac motor drives. Dr. Valla is a Member of the IEEE Ethics and Memebership Conduct Committee, a Senior Member of the Administrative Committee of the IEEE Industrial Electronics Society (IES) and the IES Coordinator of Membership for Region 9. She has been a member of the organizing committees of several international conferences. She is also member of the Automatic Control Association of Argentina.