Reactive and Harmonics Compensation in a Medium Voltage Distribution Network With Active Filters

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Abstract— **This paper presents the design of a shunt active filter to compensate reactive power and harmonics in the medium voltage level of a power distribution system. Reconfiguration of the power delivery network imposes new constraints in a distribution substation so that the reactive compensation should be increased. The alternative of shunt active filter compensation connected to the 13.8 kV level is analyzed. Two alternatives are proposed, the first one considers full compensation with the active filter while the second one uses the existing capacitor bank and builds the complementary compensation with the active filter. In the last case, the capacitor bank is modified to make a 5th harmonic filter to avoid system resonances. Both proposals show very good performance.**

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, has become a major problem for the utilities at distribution levels. Utilities frequently encounter harmonic related problems, such as higher transformers and line losses, reactive power, and resonance problems, de-rating of distribution equipment, harmonic interactions between the utility and loads, reduced system stability and reduced safe operating margins [1] [2].

The use of traditional compensation with capacitor banks and passive filters gives rise to harmonic propagation. That is harmonic voltage amplification due to resonance between line inductances and shunt capacitors. So, alternative active solutions have been continuously analyzed in the last years. One of the most popular topologies employed in harmonic compensation is Shunt Active Power Filter (SAPF) [2] [3]. It basically functions as a harmonic current generator feeding the needed harmonics and/or reactive currents at a certain point of the network. Several control strategies have been proposed for the SAPF, being those based on the generalized theory of the instantaneous reactive power the most popular [4-6].

The particular problem of a power distribution network is considered in this paper. Reconfiguration of the network imposes new constraints in different distribution substations (DS). Harmonic studies were performed considering the future configuration of the network. Voltage distortions in different points of the network and the working conditions of the capacitor banks were verified by means of harmonic flows [7]. A preliminary proposal suggested increasing the existing passive compensation with capacitor banks from 3 MVAr to 6 MVAr, but this solution introduced resonances near the 5th and 7th harmonics resulting in unacceptable distortion levels. So, the alternative of an active compensation is proposed here.

The paper is organized as follows. The network configuration and the harmonic problems are described in section II. The shunt active power filter is analyzed in section III. Section IV presents two compensation alternatives. Finally conclusions are drawn in Section V.

II. NETWORK DESCRIPTION

Fig. 1 shows a map of the transmission network of the electric distribution utility. The 132 kV network, where the DS under study are connected, works meshed and connected to the 500 kV high voltage transmission system through two points. In the future, it will be necessary to work in a radial network only connected to one 500 kV point of the system. The requirement to enhance the voltage profile at 132 kV level demands for new compensation in the different substations [7].

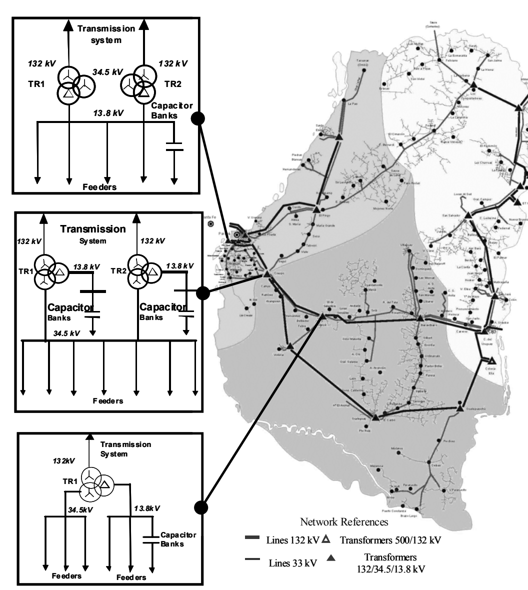

Fig. 1. Electric distribution utility power network.

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Fig. 2 shows the one line diagram of the network model adopted for the distribution substation (DS) under test. A digital three-phase model of the network is constructed using MATLAB/Simulink Power System Blockset (PSB). The system is represented as an ideal voltage source of 132 kV connected to two transformers of similar characteristics, 132/34.5/13.8 kV and 15/10/15 MVA. There are no loads at the 34.5 level. Both transformers are connected in parallel to 13.8 kV where the capacitor banks are placed. The short circuit power at 13.8 kV is approximately 150 MVA. Based on the power flow and harmonics studies performed on the network [7], the power demand considered in this model is 23 MVA with a cos φ = 0.8 and harmonics peak currents of $I_5 = 69$ A, $I_7 = 55$ A, $I_{11} = 31$ A e $I_{13} = 26.5$ A; resulting in a total harmonic distortion of THDi = 7 %. A reactive compensation of 6 MVAr will result in cos φ = 0.92 at 13.8 kV which is the goal for the proposed compensator.

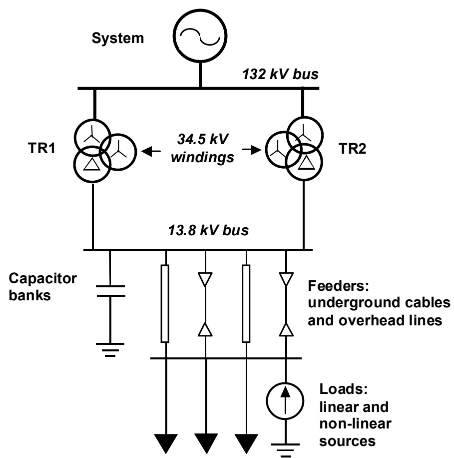

Fig. 2. One line diagram of network model.

A. Harmonics

The interaction between the capacitance of the compensator and the short circuit inductance of the network gives rise to resonances at a frequency

$$f_r = f\sqrt{\frac{S_{cc}}{Q_c}} \tag{1}$$

where f = 50 Hz is the nominal frequency of the network, S_{cc} is the short circuit power at the Point of Common Connection (PCC) and Q_c is the reactive power of the capacitor bank at PCC. Considering Q_c = 3 MVAr and Q_c = 6 MVAr the resulting resonance frequencies are shown in Table I.

TABLE I
RESONANCES IN 13.8 KV BUSBAR

Compensation (MVAr)	f_r (Hz)	Harmonic (order)
3	353	7
6	250	5

These values are confirmed obtaining the frequency response of the simplified model proposed for the simulations as shown in Fig. 3. It is evident that in both cases the resonance frequencies are very near the most important current harmonics such as 5th (250 Hz) and 7th (350 Hz).

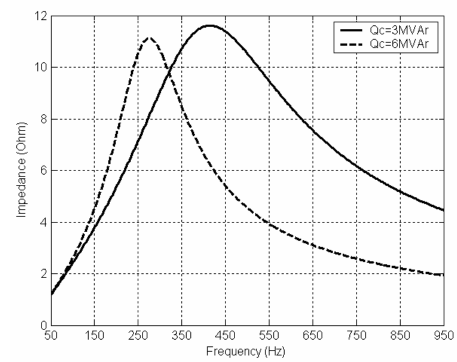

Fig. 3. Frequency response in 13.8 kV busbar.

Considering the load characteristics mentioned above, harmonics flows were performed for both alternatives of capacitor banks (present and future). Figs. 4 a) and b) show the current and voltage harmonics expressed as a percent of the fundamental value.

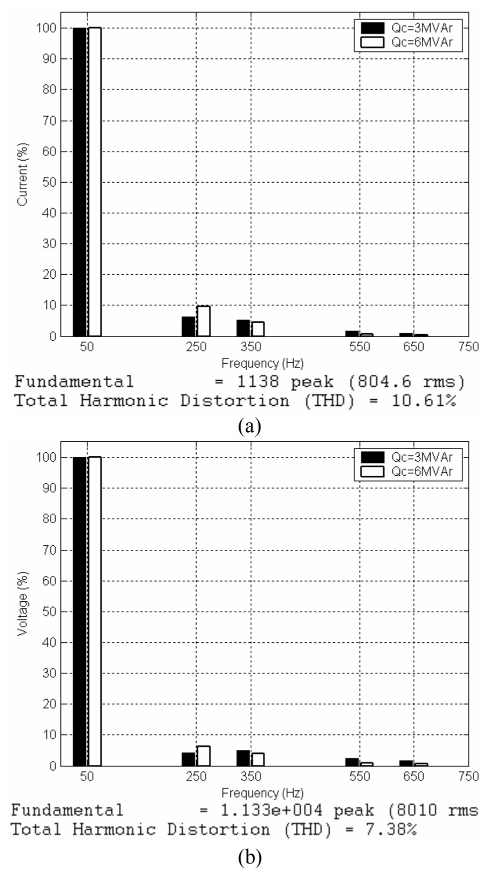

Fig. 4. Frequency spectrum magnitude (%) (a) Current. (b) Voltage.

Table II summarises the voltage harmonics for both cases together with the allowable limits fixed by IEEE [8] and the Argentinean regulation [9]. In both cases, the individual voltage harmonics for the 5th and the 7th harmonics are above the allowable limits, so a different compensation should be considered.

TABLE II
RESULTS AND VERIFICATIONS

Harmonic voltages	Q_c = 3 MVAr	Q_c = 6 MVAr	ENRE limits	IEEE limits
V_5 (%)	4.24	6.15	6	3
V_7 (%)	5.03	3.91	5	3
V_{11} (%)	2.42	0.99	3.5	3
V_{13} (%)	1.61	0.65	3	3
THD (%)	7.2	7.38	8	5

III. SHUNT ACTIVE FILTER COMPENSATION

A general structure of the shunt active power filter (SAPF) is presented in Fig.5. It consists of a three phase current controlled voltage source inverter (CCVSI) connected to the grid through a coupling inductor and transformer. The coupling inductor may be avoided if the leakage inductance of the transformer is enough to limit the current ripple to acceptable levels. The current references for the CCVSI are generated by the control system based on the instantaneous reactive power theory [4]. So, the analysis of the SAPF is divided in two main sections: the CCVSI and the control block to obtain the desired currents and maintain the DC voltage of the CCVSI.

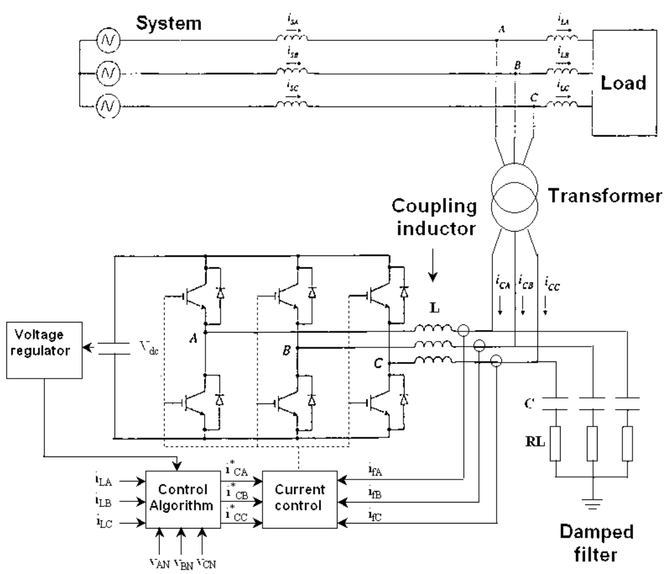

Fig. 5. General structure of the SAPF.

A. *Current Controlled Voltage Source Inverter*

The CCVSI is a standard two level three phase voltage source inverter with IGBTs [2] [10] [11]. The current loops are closed with hysteresis band controllers. The output current through the coupling inductor is sampled at a fixed frequency in order to limit the switching frequency of the inverter.

The inverter is connected to the PCC through a coupling inductor. The value of the inductance results from a trade off between filtering the high frequencies produced by switching the converter and allowing high di/dt on the inductor to follow the harmonic currents that should be damped [12]. The switching frequencies are further filtered with a second order parallel filter which takes the high frequency currents away from the PCC [1].

The DC side of the converter is built only with a capacitor of proper value. The capacitance is selected in order to keep the voltage ripple below 1 %. The DC value is chosen so that the converter can supply the current time derivatives demanded by the harmonics to be compensated. So, when higher harmonics are required to the SAPF, higher are the voltage level in the DC side, the voltage rating for the power IGBTs and the switching frequency required to follow the reference currents. The DC voltage level is controlled with a proportional controller which modifies the active power reference to the converter as it will be analyzed in the next subsection.

Finally the coupling transformer adapts the voltage level of the power network (13.8 kV) to AC voltage obtained from the CCVSI with a 6.5 kV on the DC side. This transformer provides extra filtering of the switching frequencies.

B. *Control System, Reference Currents Generator*

The control system mainly measures the network phase voltages (v_a v_b v_c) and the load phase currents (i_a i_b i_c) and builds the reference currents for the CCVSI.

First, the measured variables are transformed to the stationary $\alpha\beta o$ frame using the stationary transformation as shown in (2)

$$\begin{bmatrix} x_o \\ x_\alpha \\ x_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \qquad (2)$$

where x_i are the phase voltages v_i or currents i_i.

Then instantaneous powers are calculated

$$\begin{bmatrix} p_o \\ p \\ q \end{bmatrix} = \begin{bmatrix} \bar{p}_o \\ \bar{p} \\ \bar{q} \end{bmatrix} + \begin{bmatrix} \tilde{p}_o \\ \tilde{p} \\ \tilde{q} \end{bmatrix} = \begin{bmatrix} v_o & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_o \\ i_\alpha \\ i_\beta \end{bmatrix} \qquad (3)$$

where p is the real power, q the imaginary power and p_o the zero sequence power.

The system under study is a three-wire system where the zero sequence may be neglected so in the sequel only p and q are considered. In the general case of nonlinear loads, p and q have both DC and AC components. The mean value of the instantaneous real power ($\bar{p}$) equals three times the active power per phase, while the mean value of the instantaneous imaginary power ($\bar{q}$) equals three times the reactive power per phase. The AC components of both instantaneous powers correspond to the contribution of the harmonics.

In the general case, the network will supply the DC value of the real power while its AC component as well as the whole imaginary power should be supplied by the SAPF. Then, the instantaneous real power is filtered in order to separate both components and to calculate the reference values p^* q^*. Then the reference currents in the $\alpha\beta$ frame are:

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} p^* \\ q^* \end{bmatrix} \quad (4)$$

and the phase currents of the CCVSI should be:

$$\begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} \quad (5)$$

When the network voltages are distorted, the currents calculated with the previous equation will not exactly compensate the harmonics. Then, it is desirable to obtain pure sinusoidal voltages instead of those directly measured. This is done by a Phase Locked Loop (PLL) synchronous with the positive sequence of the sinusoidal phase voltages [13-15]. The outputs of the PLL are pure sinusoidal phase voltages ($v_a' v_b' v_c'$) which are used to synchronize the filter currents and also to calculate the instantaneous powers.

A complete block diagram of the proposed control is presented in Fig. 6.

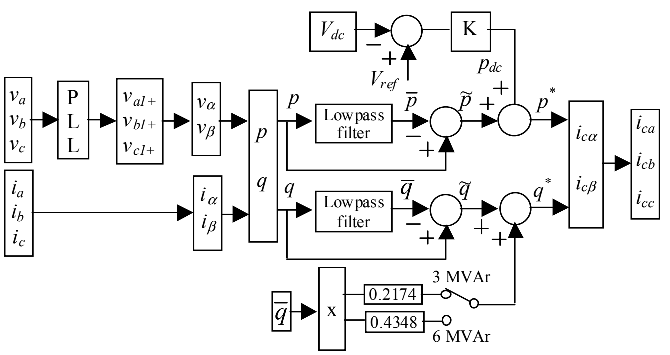

Fig. 6. Control block diagram of the SAPF.

IV. Compensation Alternatives

In this Section, two different alternatives for the SAPF compensation are considered. In the first one, the whole compensation is performed by the SAPF. In this case, the current harmonics are completed provided by the SAPF, while the reactive compensation is limited to 6 MVAr which allows obtaining an acceptable cos φ and limits the current delivered by the SAPF.

The second alternative takes advantage of the capacitor bank already installed in the DS under study. Then, the 3 MVAr are compensated by the capacitor bank and less current is provided by the SAPF or a higher cos φ can be obtained with the same SAPF. Again the current harmonics are completed provided by the SAPF. In order to avoid possible resonances with the capacitor bank, this is modified to make a passive filter for the 5th harmonics [1]. The design parameters for both filters are summarized in Table III. In the following subsections the results obtained with both alternatives are presented.

TABLE III
SAPF and Passive filter design parameters

Alternative 1					
Inverter		Damped filter		Transformer	
Vdc (V)	6500	R (ohm)	30	S (MVA)	10
C (uF)	5000	C (uF)	1.51	U_1 / U_2 (kV)	2.3 / 13.8
L (mH)	0.5	L (mH)	1.36	X (%)	10

Alternative 2										
Inverter		Damped filter		Transformer		Passive filter				
Vdc (V)	6500	R (ohm)	30	S (MVA)	**5**	Q_c (MVAr)	3	C (uF)	50.14
C (uF)	**3500**	C (uF)	1.51	U_1 / U_2 (kV)	2.3/ 13.8	f_s (Hz)	250	L (mH)	8.08
L (mH)	0.5	L (mH)	1.36	X (%)	10	R (ohm)	0.42		

A. *Alternative 1- Only Shunt Active Power Filter*

Current and voltage of one phase at the 13.8 kV level upstream the SAPF are presented in Fig. 7.

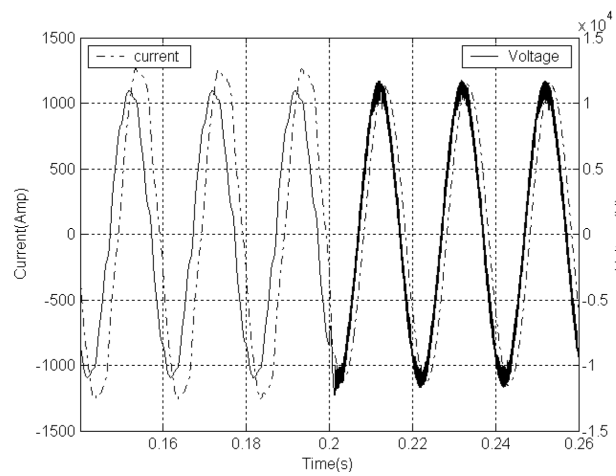

Fig. 7. Current and voltage in 13.8 kV busbar when connecting SAPF.

The SAPF is connected at t = 0.2 s. Fig. 7 shows how the distorted currents become sinusoidal and almost in phase with the voltage, after the SAPF is connected. It also shows that a small high frequency ripple appears in the phase voltages. It is difficult to filter this ripple without affecting the compensation currents since the harmonics to be compensated are near the switching frequency which has a mean value of 2 kHz.

Fig. 8 shows the instantaneous values of the real and imaginary powers. An increase in the active power is observed due to an increase in voltage at the PCC since a lower current flows through the network. The reactive compensation is presented in the imaginary power. At t = 0.2 s, the DC component reduces 6 MVAr while the AC component is almost cancelled.

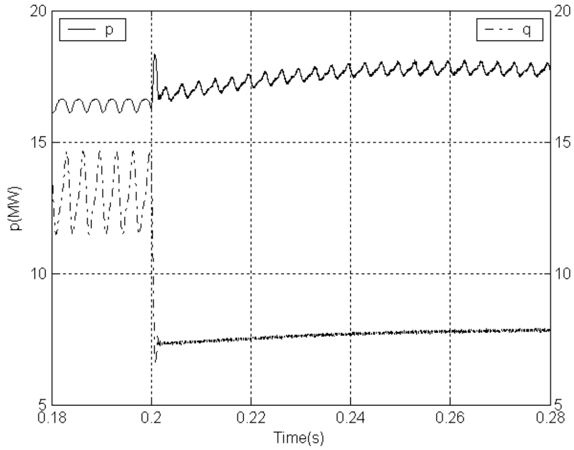

Fig. 8. Real and imaginary power in 13.8 kV when connecting SAPF.

The individual harmonics of phase current and voltage are shown in Fig. 9. The THD of current harmonics has been reduced from the original 10.6 % to 0.79 % with a fundamental value of I_{1rms} = 806.7 A. Regarding the voltage harmonics, the THD has been reduced from the original 7.4 % to 0.87 % with a fundamental rms. value of V_{1rms} = 7973 V.

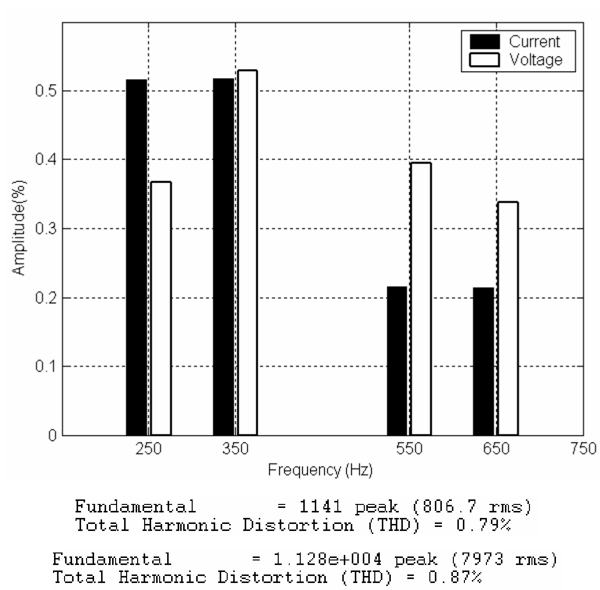

Fig. 9. Frequency spectrum amplitude (%) of voltage and current in 13.8 kV.

Regarding the performance of the CCVSI, Fig. 10 show the current delivered by the converter and the DC voltage.

The upper trace shows the current of one phase entering the PCC. Its fundamental value corresponds to the 6 MVAr reactive compensation, the harmonics are those required by the load and there is a low ripple due to the switching frequency of the converter. The bottom trace shows that the DC voltage suffers a transient behavior immediately after the SAPF connection and reestablished its mean value around 6.5 kV with a 6th harmonic oscillation due to the AC component of the instantaneous active power.

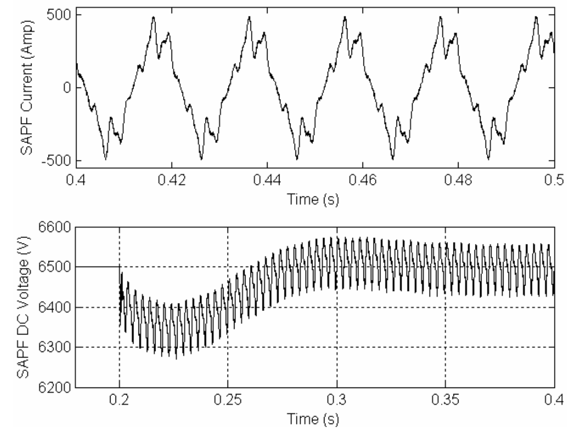

Fig. 10. Current into the PCC and DC Voltage of the CCVSI.

B. *Alternative 2- Shunt Passive and Active Power Filter*

Current and voltage of one phase at 13.8 kV level upstream the passive filter and SAPF are presented in Fig. 11.

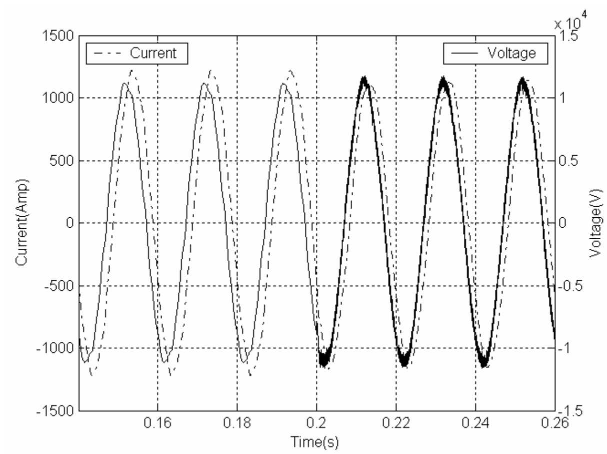

Fig. 11. Current and voltage in 13.8 kV busbar when connecting SAPF.

The passive filter is always connected. The SAPF was connected at t = 0.2 s. Fig. 11 shows how the distorted currents become sinusoidal and almost in phase with the voltage, after the SAPF was connected. It also shows that a small high frequency ripple appears in the phase voltages.

Fig. 12 shows the instantaneous values of the real and imaginary powers.

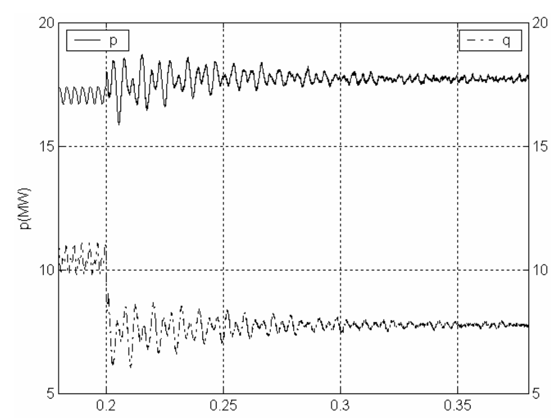

Fig. 12. Real and imaginary power in 13.8 kV when connecting SAPF.

An increase in the active power is observed due to an increase of voltage at the PCC since lower current flows through the network. The reactive compensation is presented in the imaginary power. An initial lower value in the imaginary powers is observed due to 3 MVAr compensated by the passive filter. At t = 0.2 s, the DC component reduces 3 MVAr while the AC component is almost cancelled by the SAFS. Comparing Fig. 8 and Fig. 12, it is evident that the presence of the shunt capacitors affects the transient behavior of the SAPF connection.

Fig. 13 shows the current and voltage harmonics. The THD has been reduced from the original 10.6 % to 0.34 % in the current with a fundamental rms. value of I_{1rms} = 805.9 A. Regarding voltage harmonics, the THD has been reduced from the original 7.4 % to 0.45 % with a fundamental rms. value of V_{1rms} = 8001 V.

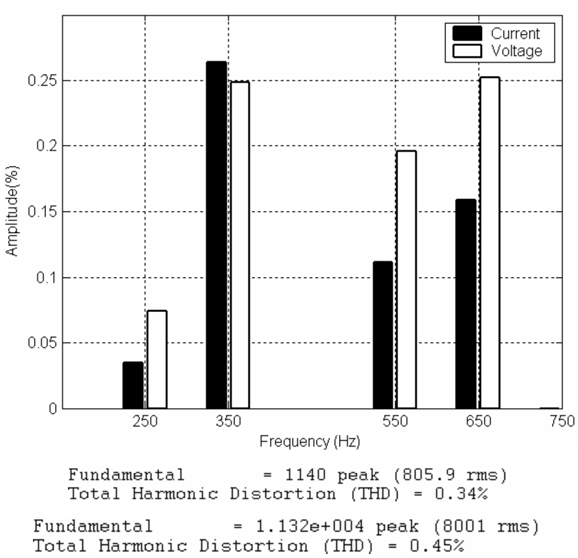

Fig. 13.Frequency spectrum amplitude(%) of voltage and current in 13.8kV.

The performance of the CCVSI is presented in Figs. 14, showing the current delivered by the converter and the DC voltage.

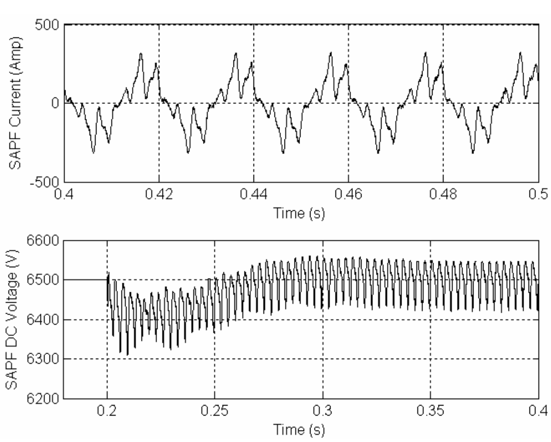

Fig. 14. Current into the PCC and DC Voltage of the CCVSI.

The upper trace shows the current of one phase entering the PCC. Its fundamental value corresponds to the 3 MVAr reactive compensation, the harmonics are those required by the load and there is a low ripple due to the switching frequency of the converter. The bottom trace shows that the DC voltage suffered a transient behavior immediately after the SAPF connection and recovered its mean value around 6.5 kV with a 6^{th} harmonics oscillation due to the AC component of the instantaneous active power.

V. Conclusions

The design of a shunt active filter to compensate reactive power and harmonics in the medium voltage level of a power distribution system was presented in this paper. Two alternatives were proposed, the first one considered full compensation with the active filter while the second one used the existing capacitor bank and built the complementary compensation with the active filter. In the last case, the capacitor bank was modified to make a 5^{th} harmonic filter to avoid system resonances. Both proposals show very good performance. The second one may be more economic but presents the problem of possible resonances due to the interaction of the shunt capacitor and the line inductance.

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