Shunt Active Power Filter Synthesizing Resistive Loads

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Abstract — The paper discuss use of shunt Active Power Filters to compensate the line current distortion and to improve the power factor. The advantages of the Resistive Load Synthesis over the Sinusoidal Current Synthesis when the filter is used in a system in which the voltage is not perfectly sinusoidal. The control circuit is based on multipliers, and the currents follow the same waveform of the respective line voltages. Experimental results of a three-phase active power filter connected to a non-sinusoidal grid are presented.

I. INTRODUCTION

The use of shunt Active Power Filters (APF) to compensate the line current distortion and to improve the power factor has been deeply studied in the last years [1-5]. This interest is due to many factors as, for example, international standards regarding current distortion limits [6], national rules concerning the power factor [7], social and economical interest in using the energy in a more efficient way [8], etc.

The paper discusses the advantages of the Resistive Load Synthesis (RLS) over the Sinusoidal Current Synthesis (SCS) if the APF is used in a system in which the voltage is not perfectly sinusoidal. Additionally, presents some design guidelines and experimental results of a three-phase APF connected to such kind of utility grid.

Nowadays the presence voltage distortion in the utility is a common fact. The distortion level at the Common Coupling Point (CCP) strongly depends on the load current associated with the line impedance together with the voltage distortion present at the bus. Specially if the load consumes a distorted current, the effect on the CCP voltage distortion can be important, affecting the behavior of other appliances connected to the same point.

The IEEE [9] establishes as acceptable a Total Harmonic Distortion (THD) of 5% in a low-voltage grid, limiting each harmonic to 3% of the fundamental component. This value can easily be surpassed , especially if the line feeds highly current distorted non-linear loads as rectifiers with capacitive filters, typically used in electronic apparatus.

The action of the shunt APF does not change the load current, once it dos not affect the voltage at the CCP. The APF delivers to the load all the non-active components of its current, as defined in [2]. From the line will be consumed just the current related to the active power. This fact maximizes the power factor, thus minimizes the transmission losses, once this is the minimum RMS current that needs to flows through the line to deliver the necessary active power to the load.

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II. SINUSOIDAL CURRENT AND RESISTIVE LOAD SYNTHESIS

It is well known the merits of the Instantaneous Power Theory (IPT) [1] to treat distorted and unbalanced loads, and to generate signals to adequately control a shunt APF. The APF produces compensating currents that, after injection into the grid, result in sinusoidal line currents in phase with the respective voltages.

However this theory does not provide good results if the line voltage is not sinusoidal. In fact, the theory allows to determine a compensating current that, after injection into the grid results in a constant instantaneous power absorbed from the source. If the voltages are sinusoidal and balanced, this results in sinusoidal and balanced final currents. Otherwise the final line currents will be distorted with a harmonic content different from the voltage one. The power factor will not be unitary. Fig. 1 shows some waveforms displaying this situation. A 5th harmonic with amplitude of 10% the fundamental is present at the voltage. The final current (after compensation) has a different waveform, producing a power factor of 0.99.

Under this situation, some modifications in the Instantaneous Power Theory can be made [10] in order to generate in a different way the current produced by the APF, which results in a sinusoidal line current. However, if the voltage is distorted, this solution does not allow to have unitary power factor, once the voltage harmonic content does not contributes to the active load, while increases the apparent power. Nevertheless, this solution improves the power factor respect the previous theory. Fig. 2 shows some waveforms displaying this situation. The calculated power factor is 0,995.

Resonance phenomena due to the presence of resonant circuits in a voltage distorted grid are known for a long time [11]. In such situations the damping effect is provided by the resistive part of the circuit, complying not only the physical resistance (cable, wiring, etc.), but also the equivalent resistive load (associated with the active power consumed) at that specific grid. Once the physical resistance usually is low, the effective damping is due the load.

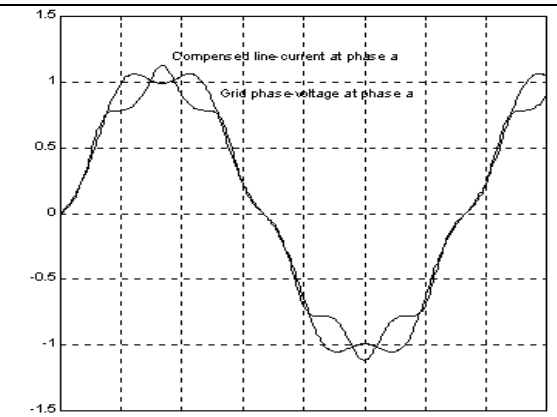


Fig. 1 Resulting line current using IPT under non-sinusoidal voltage.

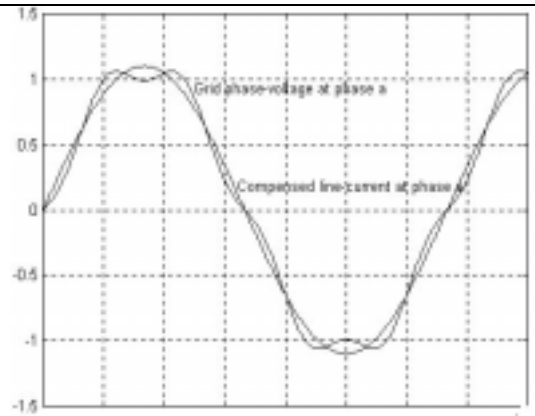


Fig. 2 Resulting line current using extended - IPT under non-sinusoidal voltage.

If an APF acts synthesizing a sinusoidal current in a distorted systems, this means that, in the frequency domain, the supply will see a load only in the fundamental frequency. In the harmonic frequencies the load will be open, once no current will flow in these frequencies.

Considering the damping role played by the load, this means that the system will lose its ability to damp any eventual resonance, that could, in this case, produce a severe voltage distortion at the CCP.

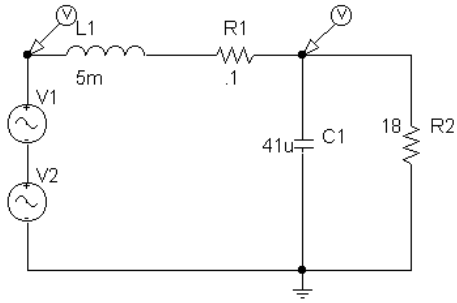
On the other hand, if the APF works synthesizing a resistive load, what means, the final line current will present the same waveform of the voltage, the damping effect remains unchanged and additionally the power factor is unitary, what implies the RMS current is the minimum one, considering a constant load active power.

Fig. 3 shows a comparative situation in which the same system (with 7th harmonic voltage 1%) is connect to APFs operating with resistive load or sinusoidal synthesis. The lost of the damping effect is clear in the second situation. In the first one the voltage waveform at CCP is practically not affected by the APF operation. It is important to observe that a 1% THD at the source implies in more than 10% at the CCP.

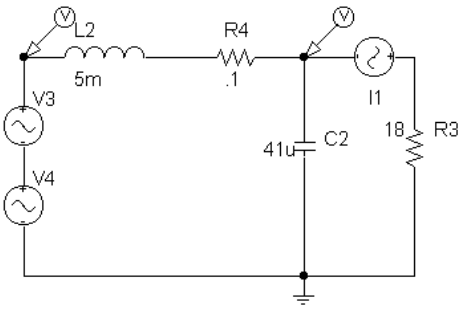
At the limit, if all the loads connected to the system were resistive, the voltage distortion induced by the loads would disappear, and the voltage at the CCP would become sinusoidal.

This shows that the use of RLS is more convenient to control APFs in distorted voltage grids. The drawback of this solution is that there is not a simple and fast analytical treatment that allows instantaneous current reference synthesis, while maintaining the system power balance. Few references compares the behavior of both control strategies [12], indicating a slower transient response of the RLS. However, by using modern non-linear control techniques, like sliding-mode control, certainly this response can be improved.

This article presents a control structure, based on multipliers, like in power factor corrector topologies, in order to generate the necessary compensating current.



Resistive Load Synthesis



Sinusoidal Current Synthesis

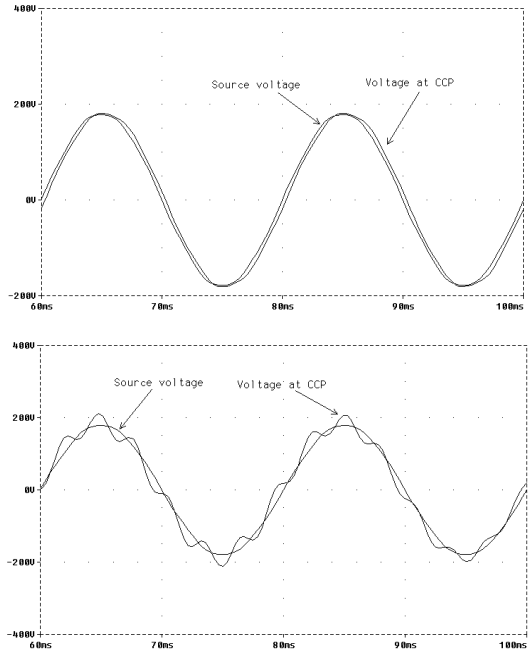


Fig. 3 Comparison of RLS and CSC effect in a distorted voltage system.

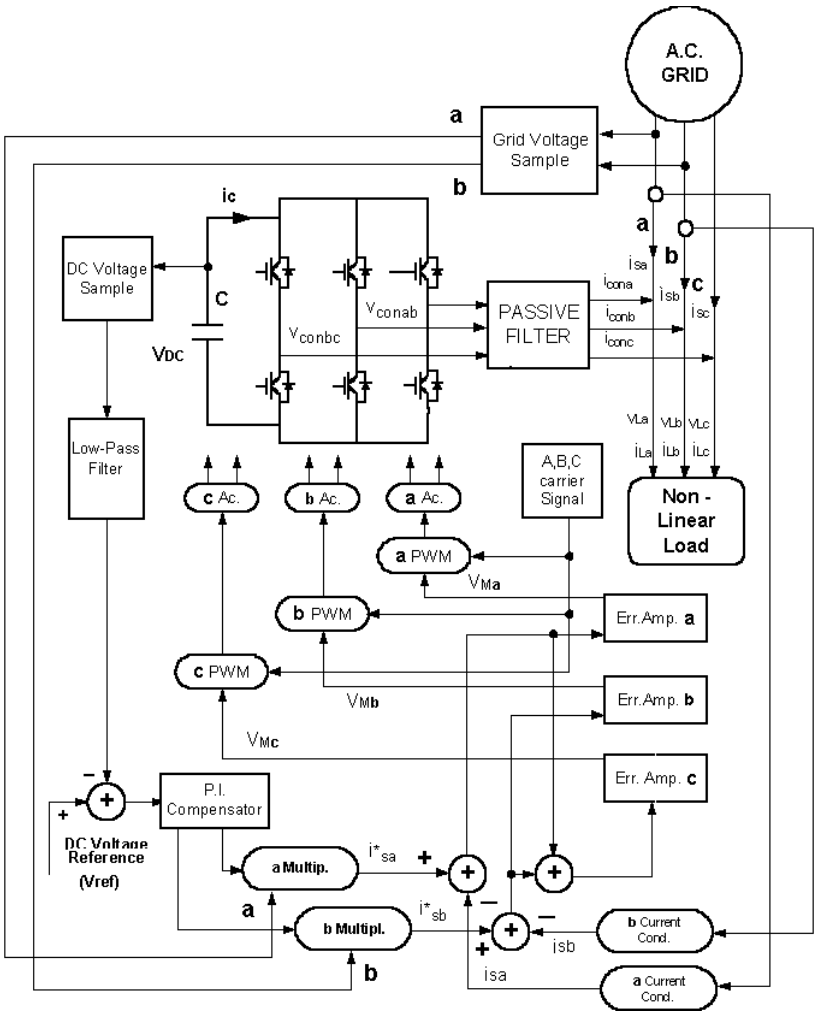


Fig. 4 Block diagram of a three-phase shunt active filter using Resistive Load Synthesis control.

III. IMPLEMENTATION OF AN APF USING RLS CONTROL TECHNIQUE

The block diagram of a three-phase shunt APF, including the proposed control system, is shown in Fig. 4. The APF is intend to be used in a balanced three-wire grid, in which the voltage can be distorted.

This structure allows the control of the three-phase system by sensing only two currents and three voltages (the inverter DC bus and two phase voltages).

The current references for phase *a* and *b* are obtained by sampling the grid voltage (phase-neutral). This signal is multiplied by a DC signal, given the desired waveform and amplitude to the references. Phase *c* reference is obtained by inverting the sum of the other two references.

The other input of the multipliers comes from the DC link control circuit, like in PFC circuits. If the DC voltage is at the desired level, the PI controller does not change its output, and the references amplitude remain constant. Otherwise they are increased (if the DC link voltage decreases) and vice-versa.

The DC link voltage must be higher than the peak line-to-line voltage in order to allow the injection of the desired current through the passive filter that connects the inverter with the grid. This low-pass filter is composed at minimum by inductances, but can be made of superior order improving its filtering capacity.

Such a high DC voltage is obtained during APF start-up by consuming a current higher than the load one. The additional energy is stored in the DC capacitor, up to reach the desired level. At this point the PI controller reduces the current reference amplitude and the line current becomes exactly the necessary to supply the load active power plus the APF losses. All the harmonics and reactive energy are provided by the APF.

The switching strategy is based on a PWM modulator. This choice was made due to the well known spectrum of this technique. This knowledge helps the design of the output passive filter, allowing to choose correctly the passive components to avoid undesirable resonance between the high-frequency components and the passive filter.

Hysteresis control is also possible, but using a simple first order inductive filter, which would have a high value if would be necessary to reduce the high-frequency components injected into the line.

Considering the PWM control, a reduced current error will be obtained if the inner current loop presents a high enough gain. This gain must be adequately limited to avoid instabilities induced by the passive filter resonances [13].

The overall system stability also depends on the line current signal processing. The circuit must have a low-pass characteristic, to effectively damp the passive filter resonance. On the other hand, has to have a flat response (in gain and phase) in the harmonic range (approximately up to 2500 Hz). This means that if the line current presents an harmonic content out of this range, full compensation will not be possible.

IV. EXPERIMENTAL RESULTS

A 1 kVA, 220V prototype was built, allowing to evaluate the APF behavior. The grid voltage is typically distorted, with significant 5th and 7th harmonics. The voltage THD is less than 3%, as shown in Fig. 5.

Fig. 6 shows the case of a non-linear three-phase balanced load (six-pulse rectifier). After compensation, the line currents are similar to the respective voltages, including the distortions. The fast transitions are not fully compensated due to the frequency limitation of the current loop response.

The load current spectrum is shown in Fig. 7. The THD is 25%. After the APF action the line current distortion is significantly reduced, producing a THD of 5.2%, as shown in Fig 8. Note that the active filter is not able to attenuate the harmonics in the range above 2kHz, due to the limited system frequency response.

Fig. 9 shows the case of an unbalanced non-linear load (single-phase rectifier). Also in this case the APF is able to compensate the load, reflecting to the grid a resistive and balanced load.

Fig.10 shows the voltage spectrum before the APF action. In this case the THD is significantly higher due to the use of a feeder with a lower short-circuit level (higher line impedance). The voltage distortion is evident and the THD is 4.2%, including an important 3rd harmonic.

After the compensation, the THD is reduced to 2.8%, approximately the normal value at the local grid, as shown in Fig. 11.

The measured power factor is 0.995. The measured APF efficiency is 0.965.

Fig. 12 shows the transient response of the DC voltage loop. After a 50% load step variation, the DC voltage initially decreases, once the inverter delivers energy to the load. After the DC voltage sag is detected, the current reference is increased, allowing to absorb from the mains the necessary amount of power to supply the load. When the load decreases an reverse situation occurs.

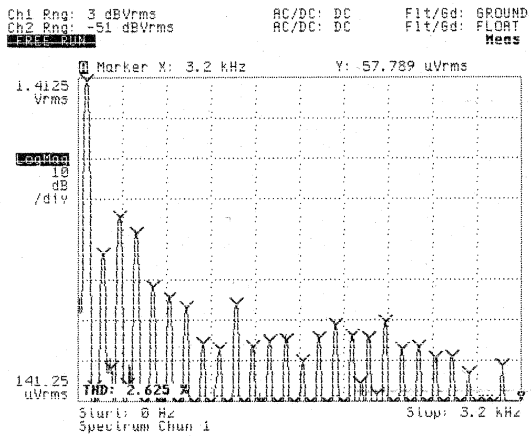


Fig. 5 Frequency spectrum of phase a grid voltage without load .

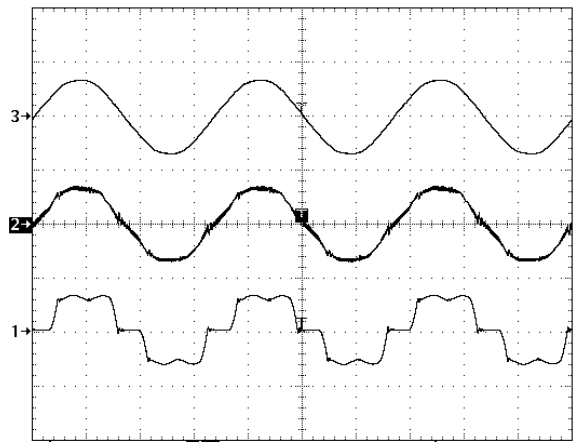


Fig. 6 Three-phase non-linear balanced load:
Top: Voltage (500V/div.);
Middle: Line current (5 A/div.);
Bottom: Load current (5 A/div).

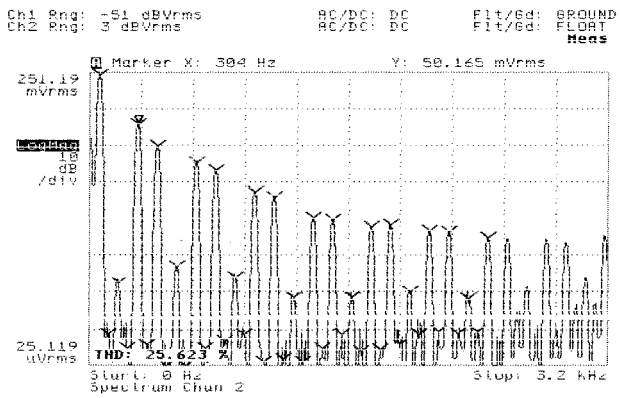


Fig. 7 Phase a current load frequency spectrum , before APF acting.

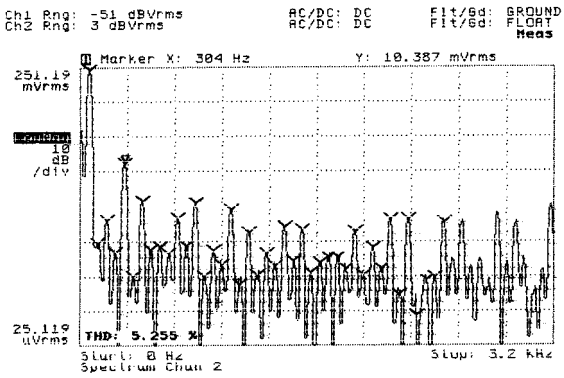


Fig. 8 Phase a current load frequency spectrum , after APF acting

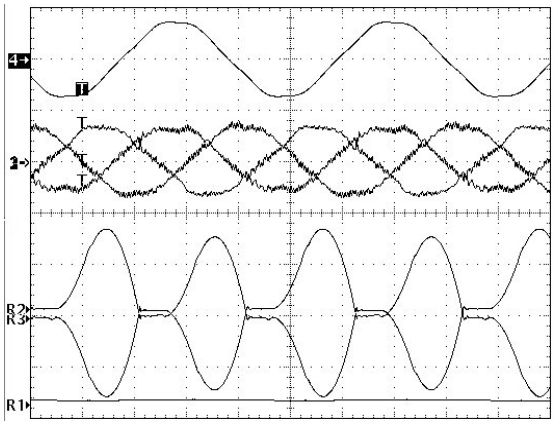


Fig. 9 Single-phase, non-linear load:
Top: Voltage (500V/div.); Middle: Line currents (1 A/div.);
Bottom: Load current (1 A/div)

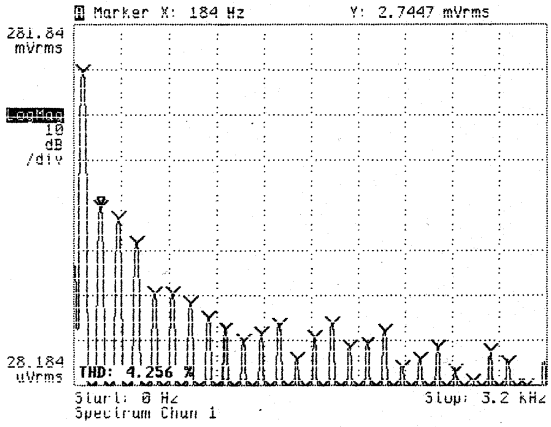


Fig.10 Frequency spectrum of phase a grid voltage with single-phase non-linear load.

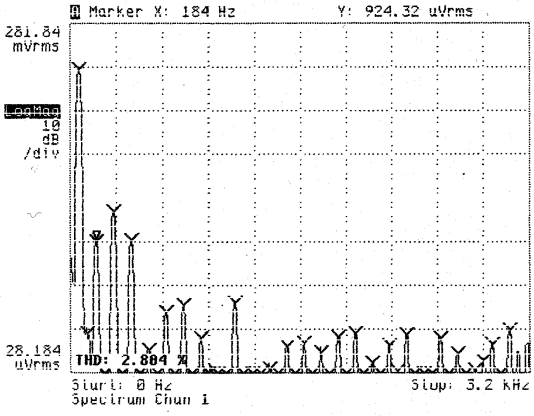


Fig. 11. Frequency spectrum of phase a grid voltage after APF acting.

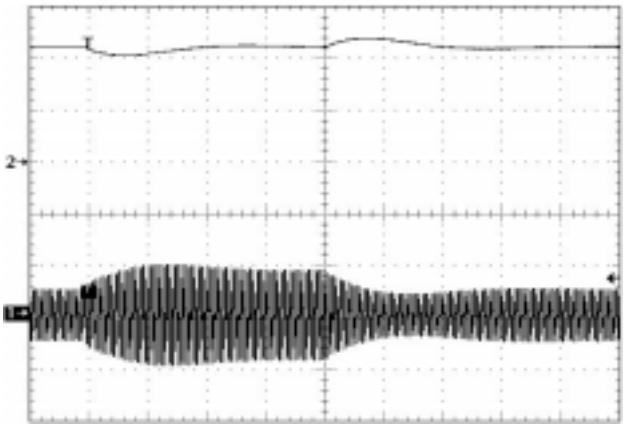


Fig. 12 Voltage range at the CC bus
Top: DC voltage (100V/div) Bottom: Line current (2A/div)

V. CONCLUSIONS

The paper shows that in a distorted voltage system the use of an Active Power Filter based on the Resistive Load Synthesis Method to generate the current references is better than the Sinusoidal Current Synthesis. The main reason is the maintenance of the damping capacity provided by the load against induced resonances. This characteristic is lost if the SCS is used. An APF was built and experimental results were shown, considering different load behaviors. The results confirm the theoretical expectation.

VII. REFERENCES

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