

# Voltage Source Active Power Filter, Based on Multi-Stage Converter and Ultracapacitor DC-Link.

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**Abstract.** A multi-stage inverter using three-state converters is being analyzed for active filter and static var compensator applications. Each phase of the converter is composed of four three-state converters, all of them connected to the same DC link and its output connected thorough output transformers scaled in powers of three. The Filter can compensate load currents with high harmonic content and low power factor, obtaining sinusoidal currents from the source. A 1F Ultracapacitor is used in the DC link, making it possible to obtain a very stable voltage at the DC bus, even with highly contaminated currents. This high capacity also makes it possible to continue feeding the contaminating load during a Voltage Dip. The capacitor voltage is controlled simply by changing the phase angle of the converter, and thus changing the amount of active current flowing to and from the converter. The control is implemented with a non-linear PI gain and a modulation control to maintain a stable AC voltage during DC voltage drops. The great advantage of this kind of converter is the minimum harmonic distortion obtained. Simulation results for this application are shown and compared with similar results obtained with conventional PWM converters.

## I. INTRODUCTION

Power Electronics devices contribute with important part of harmonics in all kind of applications, such as power rectifiers, thyristor converters, and static var compensators (SVC). On the other hand, the PWM techniques used today to control modern static converters such as machine drives, power factor compensators or active power filters, do not give perfect waveforms, which strongly depend on switching frequency of the power semiconductors. Normally, voltage (or current in dual devices) moves to discrete values, forcing the design of machines with good isolation, and sometimes loads with inductances in excess of the required value. In other words, neither voltage nor current are as expected. This also means harmonic contamination, additional power losses, and high frequency noise that can affect the controllers. All these reasons have generated many research works on the topic of PWM modulation [1-4].

Multi-stage converters [5-7] work more like amplitude modulation rather than pulse modulation, and this fact makes the outputs of the converter very much cleaner. This way of operation allows having almost perfect currents, and very good voltage waveforms, eliminating most of the undesirable harmonics. And even better, the bridges of each converter work at a very low switching frequency, which gives the possibility to work with low speed semiconductors, and to generate low switching frequency losses.

The objective of this paper is to show the performance advantages of a multi-stage converter used as an active filter and VAR compensator. The filter is used to compensate a contaminated load with small power factor and to feed the load during voltage Dips. The results are compared with conventional PWM modulators working at a switching frequency of 10 kHz. All the load parameters of both types of converters are set at the same values.

## II. BASICS OF MULTI-STAGE CONVERTERS

### A. Basic Principle

The circuit of fig.1 shows the basic topology of one converter used for the implementation of multi-stage converters. It is based on the simple, four switches device, used for single phase inverters. These converters are able to produce three levels of voltage in the load: +Vdc, -Vdc, and Zero.

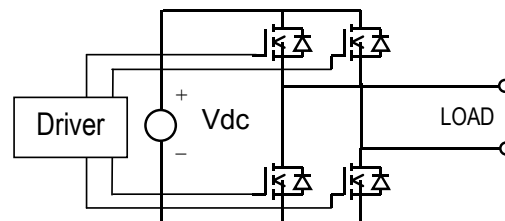


Fig. 1. Three-level module for building multiconverters

References [8-10] have proposed a per phase power conversion scheme for synthesizing multilevel waveforms, connecting many converters like the one shown in figure 1 in series, but with all the dc voltages equal to "Vdc". Such a multilevel inverter with 'n' equal dc voltage levels can offer only 2n+1 distinct voltage levels at the phase output. The references [11, 12] go one step ahead with dc voltages varying in binary fashion, which gives an exponential increase in the number of levels. For 'n' such cascaded inverters, with dc voltage levels varying in binary fashion, one can achieve  $2^{n+1} - 1$  distinct voltage levels. In this paper, the outputs of the modules are connected thorough transformers whose voltage ratios are scaled in power of three, allowing  $3^n$  levels of voltage. Then, with only four converters (n=4), 81 different levels of voltage are obtained: 40 levels of positive values, 40 levels of negative values, and zero. As a comparison, the first

topology only achieves 9 levels with four converters, and the second topology just 31 levels.

Fig. 2 displays the main components of the four-stage converter which is being used in this paper as an active filter. The figure only shows one of the three phases of the complete system. As can be seen, an Ultracapacitor of 1F is used in the DC link. The transformer located at the bottom of the figure has the highest voltage ratio, and will be called Master. The rest of the modules will be the Slaves. The Master works at the lowest switching frequency, which is an additional advantage of this topology.

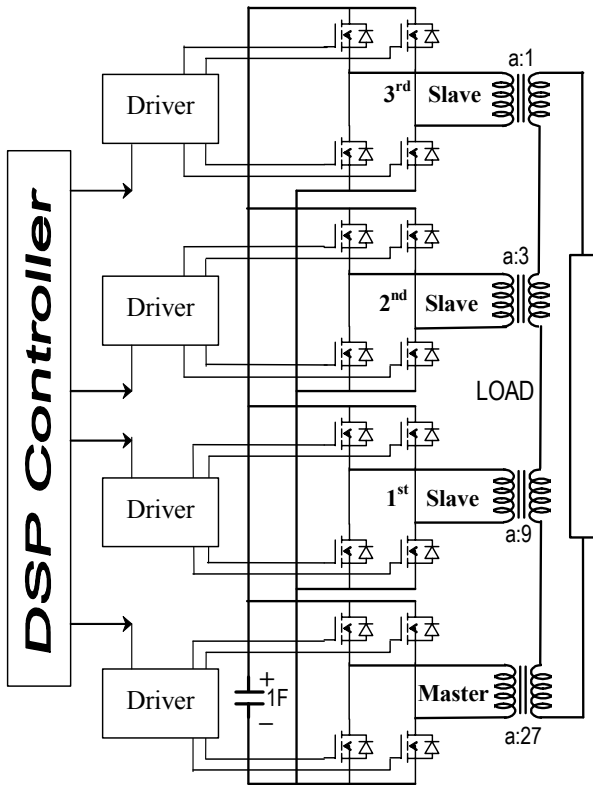


Fig. 2. Main components of the four-stage multiconverter.

With 81 levels of voltage, a four-stage converter can follow a sinusoidal waveform in a very precise way, as shown in Fig. 3. It can control the load voltage as an AM device (Amplitude Modulation) or, if the DC voltage varies, it can maintain a constant sinusoidal voltage at the load, compensating the DC variations by changing the amplitude modulation. This change in the modulation is easily done by changing the amplitude of the sinusoidal reference by the ratio of the actual DC voltage to the ideal voltage. Fig. 3 shows how the same amplitude voltage wave can be achieved with different voltages at the DC Ultracapacitor, which are obtained through the control of the gates of the power transistors in each one of the four converters. This allows using the energy stored at the Ultracapacitor to feed the load during voltage Dips. All the AM control of the voltage is easily done by using DSP control.

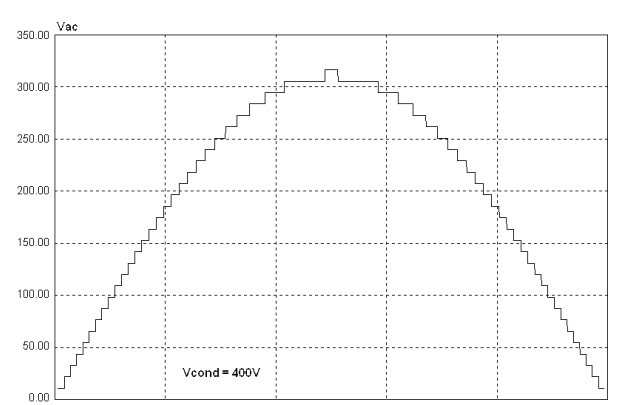
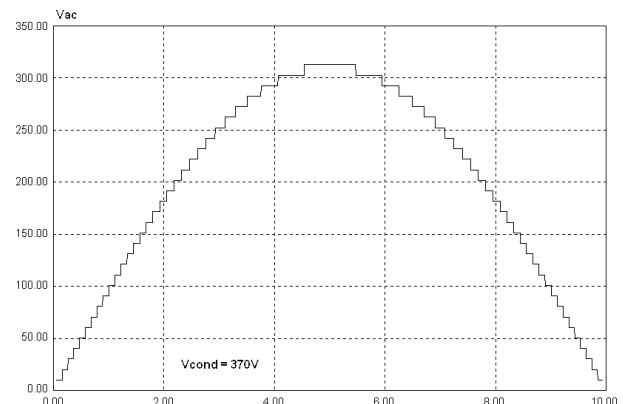
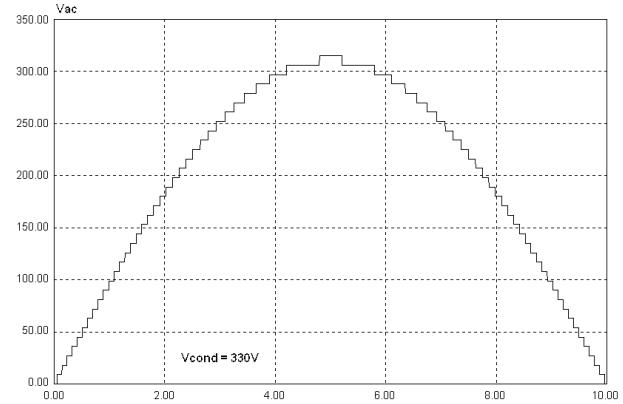
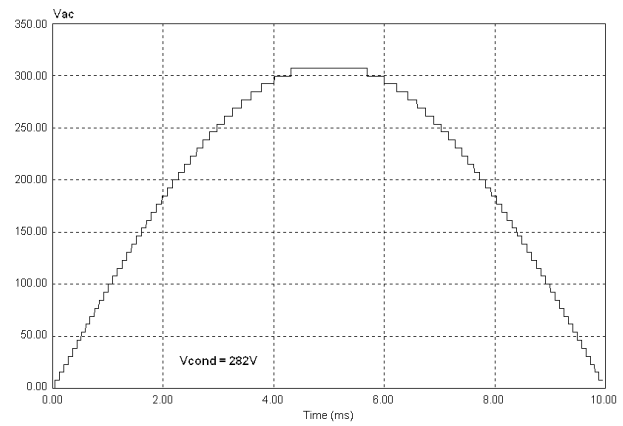


Fig. 3. Voltage AM using a four-stage converter

Fig. 4 shows the voltage modulation of each one of the four converters of the chain of Fig. 2 when full modulation is used.

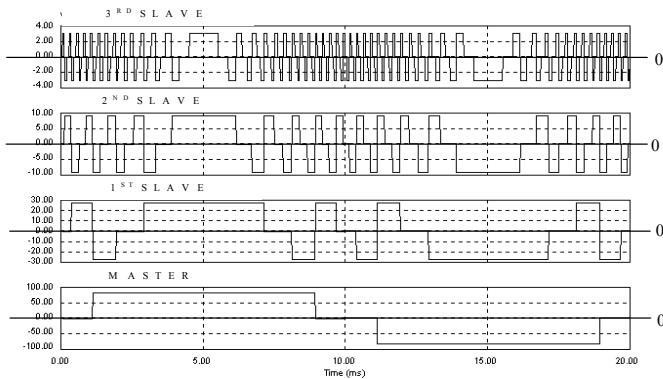


Fig. 4. Voltage modulation in each converter

### B. Power Distribution

One of the good advantages of the strategy described here for multiconverters is that most of the power delivered comes from the Master. The example of Fig. 5 shows the power distribution in one phase of the four-stage converter, feeding a pure resistive load with sinusoidal voltage. A little more than 80% of the real power is delivered by the Master converter, and only 20% for the Slaves. Even more, the second and third slave only deliver 5% of the total power. This means that the output transformers and the semiconductors needed by the Slave modules are small.

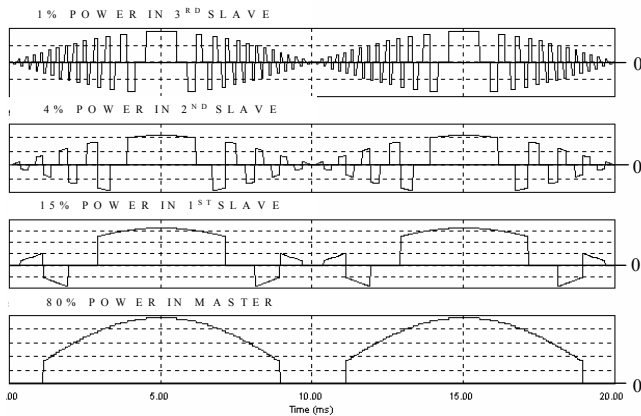


Fig. 5. Active power distribution in a four-stage converter.

Another attribute of this configuration, which is possible to see in Figs. 4 and 5, is the very low switching frequency of each converter. But even better, the Master, which carries most of the power, operates at the lower switching frequency. Then, the larger the power of the unit, the lower its switching frequency. In large power applications, the Master can be implemented with GTOs, and the Slaves with IGBTs.

### III. ACTIVE FILTER CONFIGURATION

Fig. 6 shows a typical configuration for a shunt active power filter, using PWM strategy. The source is feeding a contaminating load, such as a power rectifier, and the active filter, connected in parallel, injects the harmonics to the load needs, and the power system sees a cleaner sinusoidal current

waveform. Nevertheless this filter produces significant switching losses, electromagnetic noise and its output voltage has a high frequency noise content.

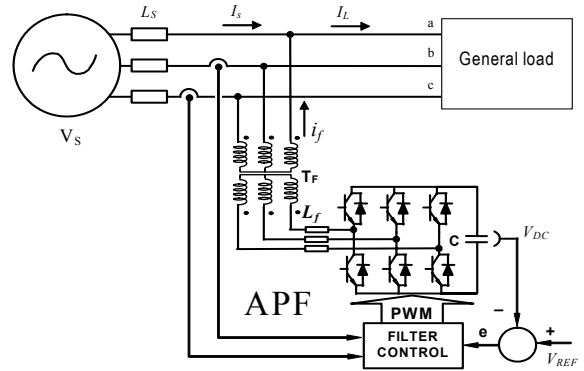


Fig. 6. Shunt active filter using PWM techniques

The same filter can be constructed replacing the classic PWM-driven converter by a multiconverter like the one mentioned before, achieving low switching losses and low electromagnetic noise. Fig 7 shows this topology and its main components.

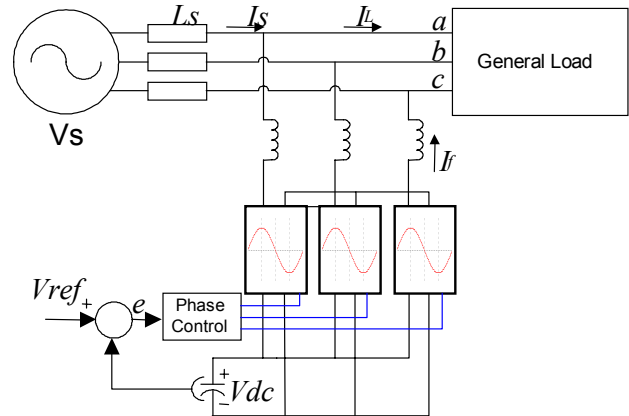


Fig. 7. Shunt active filter using the four-stage converter.

Three converters, like the one shown in Fig. 2, are connected to the same capacitor at the DC side and in star at the AC side. The capacitor voltage is simply controlled by shifting the angle of the voltage wave at the filter's output. The output voltage is practically sinusoidal; therefore all harmonic currents consumed by the load are fed by the filter.

Fig. 8 shows a single phase equivalent of the circuit formed by the source, the filter and the contaminating load.

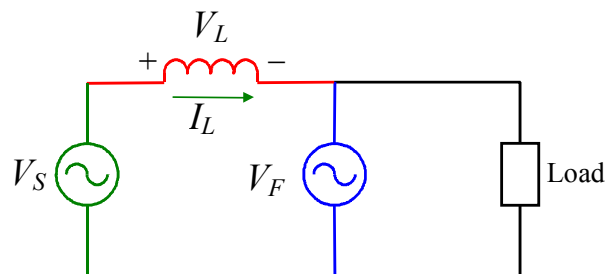


Fig. 8. Single phase equivalent circuit.

Fig. 9 shows phase diagrams of source voltage, filter voltage and line current for different angles and amplitudes of the filter's voltage; with colours matching those of Fig. 8. The line impedance is assumed highly inductive, which is the key to achieve power flow control without changing the filter's voltage amplitude.

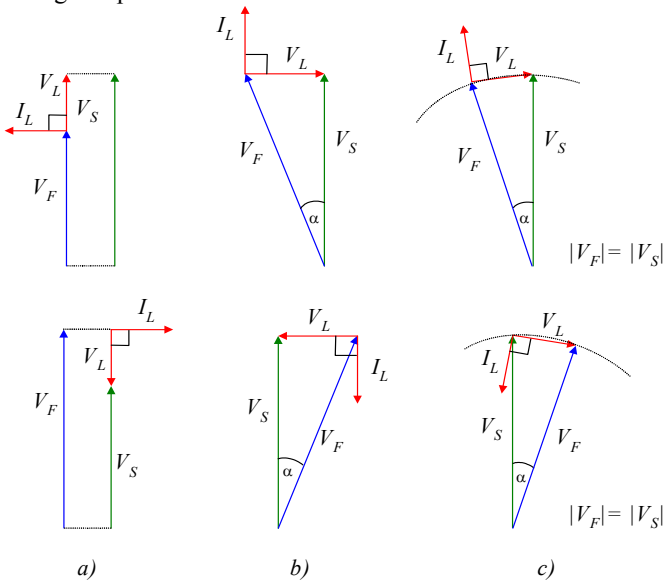


Fig. 9. Phase diagrams of voltages and currents.

As can be seen in diagram a), when the filter's voltage angle is 0 there's only reactive power flows through the line, which's amount depends on the voltages amplitudes, leaving the filter supplying by itself the load's active power. This would lead to discharge the filter's DC link capacitor. Diagram b) shows that if the line's voltage is in  $90^\circ$  with the source voltage then only active power will flow from the source; and the amount of active current will depend on the angle's sine and the line's impedance. Then, as it can be seen in diagram c), if the angle  $\alpha$  is small enough (less than  $10^\circ$  for example) the amplitude of the filter's voltage can be maintained at the nominal value, because the angle between the source's voltage and the line's voltage will be close to  $90^\circ$ , therefore the amount of active current will also depend on the angle's sine, which is almost linear when the angle is close to 0. Then the filter's DC voltage can be easily controlled (by manipulating the angle  $\alpha$  and thus the active current flowing through the line) if the angle  $\alpha$  is close to  $0^\circ$  and the filter's AC voltage amplitude is close to the source's voltage amplitude.

#### IV. COMPARISON BETWEEN PWM MODULATION AND MULTILEVEL APPROACH

The following results show a comparison between PWM and multilevel converter methodologies. These results have been obtained using a software called PSIM [13], which has demonstrated its reliability for almost 10 years of simulations, which have been corroborated with real experimental results. Shunt active power filters, sinusoidal voltage power supplies, and machine drives for brushless dc motors, are compared.

Fig. 10 compares the current quality obtained with a shunt active power filter implemented with a PWM converter working at 10 kHz switching frequency, and with the four-stage converter described in this paper (at maximum modulation). Both the figures show the load current (a three-phase diode rectifier), the source current, and the filter current. The parameters are the same for both the systems:  $V_{source}=120$  Vff, line impedance  $Z_L = 0.01+j0.314 \Omega$ , rectifier input impedance  $Z_R = 0.1+j0.157 \Omega$ , rectifier output dc load  $R_D = 5 \Omega$  plus a smoothing reactor  $L_S = 20$  mH. The more sinusoidal current correspond to the source. The quasi-square current is from the rectifier, and the more distorted current is the compensating current coming from the active power filter. There is an evident difference between the bad quality of the currents when PWM techniques are used and the excellent quality of the currents when multi-converters are used.

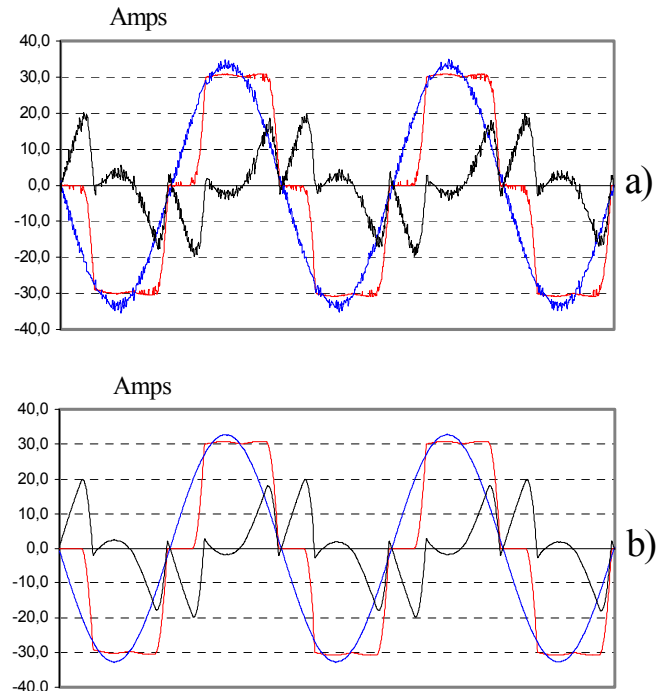


Fig. 10. Active power filter waveforms.  
a) PWM technique  
b) Proposed technique

Figs. 11a) and b) show in more detail the current waveforms of the active power filter. Now is more evident the quality of the current generated by the active filter implemented with the four-stage converter. In fact, the more levels has the converter, the better the current, but with only four converters the source current is almost a perfect sinusoidal waveform, because the active filter has 81 levels of voltage.

Another point of comparison is cost. As was shown in Fig. 5, the Slaves are very small power converters and hence they do not contribute to increase drastically the cost of this method. In fact, it is possible that the cost could result lower than with conventional PWM techniques, because this system uses components that may be cheaper for their lower power ratings.

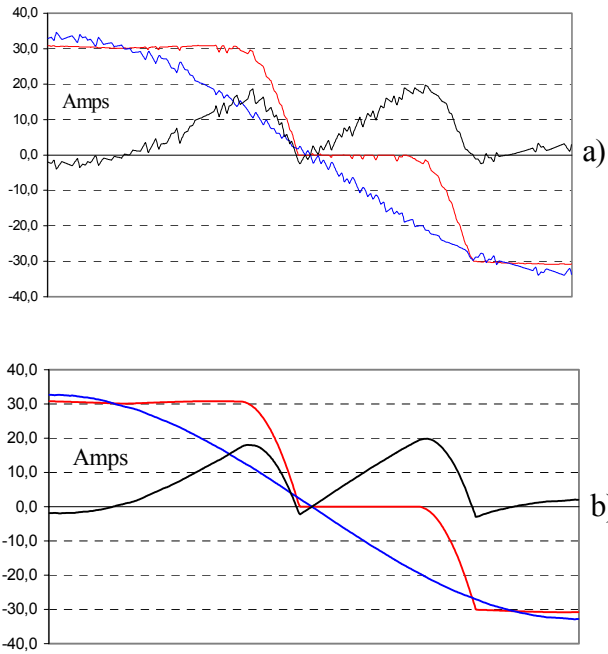


Fig. 11. A detail of currents from Fig. 10  
a) PWM technique  
b) Proposed technique

## V. SIMULATION RESULTS

An example of the aforementioned filter was simulated using the software PSIM. The parameters of the system are:  $V_{source}=380$  Vff, line impedance  $Z_L = 0.1+j0.569 \Omega$ , diode rectifier input impedance  $Z_R = 0.1+j0.157 \Omega$ , rectifier output dc load  $R_D = 5 \Omega$  plus a smoothing reactor  $L_S = 40$  mH. This represents a load of approximately 60 kVA.

A voltage Dip is simulated at  $T=0.4$  sec, with a duration of 0.2 sec. During this time the load is fed from the filter's capacitor and a sinusoidal voltage of nominal amplitude is maintained at the filter's output. In real life, for a case like this, an automatic isolating device would have to be implemented between the source and the load, in order to feed the load from the filter without feeding the rest of the system.

Fig. 12 shows a plot of the line, load and filter currents during the simulation. Also the filter's output voltage and the DC Ultracapacitor's voltage are shown.

The Ultracapacitor's voltage drop represents the energy supplied by the capacitor during the Voltage Dip. After the voltage from the source is re-established, the control modifies the filter's voltage angle to inject active current to the filter and recover the capacitor's voltage level.

As can be seen in Fig. 12, the source currents are perfectly sinusoidal, and with unity power factor. Also, the load currents are completely fed by the filter during the voltage Dip. This demonstrates that this kind of multiconverter works perfectly as Voltage-Dip-proof filter and VAR compensator, delivering quasi-sinusoidal voltages. Finally, The figures 13 and 14 show details of figure 12.

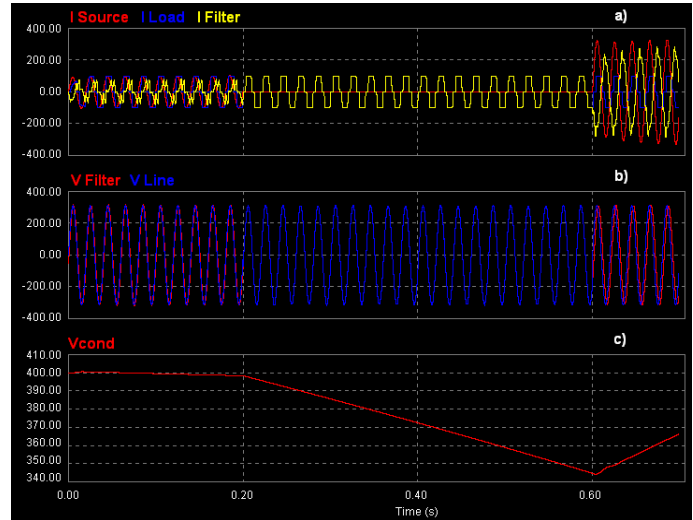


Fig. 12. Results from simulation.  
a) Source, load and filter currents.  
b) Filter (load) and line voltages.  
c) Ultracapacitor voltage.

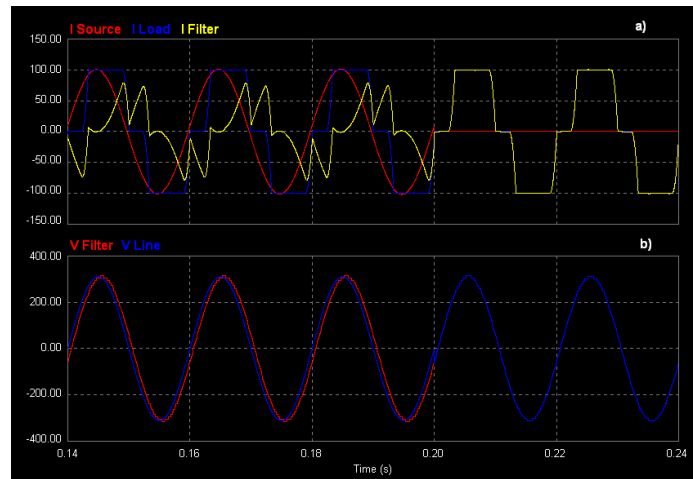


Fig. 13. A detail of figure 12 a) and b) before the voltage dip

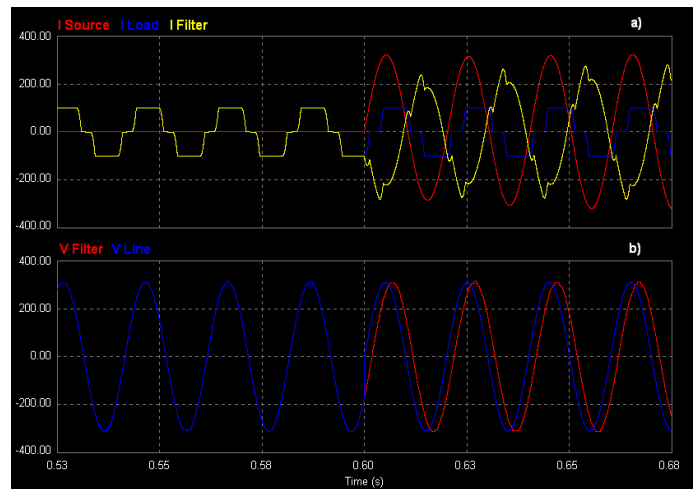


Fig. 14. A detail of figure 12 a) and b) after the voltage dip

## VI. CONCLUSIONS

A four-stage inverter, using three-state “H” converters, has been analyzed and simulated for use as a Voltage-Dip-proof active filter and VAR compensator. The advantages of this kind of converter have been displayed and compared with conventional PWM converter performance. A simple control scheme has been proposed, which consists of modifying the filter’s voltage angle, while maintaining the nominal voltage amplitude. This control scheme allows to easily modify the amount of active power being transferred to or from the filter and thus control the DC capacitor voltage. A filter like the one proposed in this paper is perfect for “weak” systems, because it profits from the high line impedance for control purposes, but the source’s voltage signal has to be accessible to calculate the phase angle that controls the filter.

Finally, the proposed filter, compensating a contaminating load was simulated, including a voltage Dip during the experiment. Simulation waveforms showed that source currents were always sinusoidal and with unity power factor, while the voltage at the load terminals were also sinusoidal at all time.

This experiment demonstrated that the proposed multilevel converter can work perfectly as an active filter, even if the DC capacitor voltage varies (over certain limits), maintaining perfect sinusoidal voltages at the load terminals and currents at the source; with the possibility of using the unit as a voltage Dip protection if a relatively high capacitance condenser, like an ultracapacitor, is used.

## VI. ACKNOWLEDGEMENTS

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