

# Three-phase Active Power Filter for Power Quality: Compensation and Balancing

C. G. Bianchin, *Electronic System Division, LACTEC*, R. Demonti, *Electronic System Division, LACTEC* and J. S. Omori, *Paranaense Electric Company, COPEL*

**Abstract--** Present paper deals with the implementation of parallel three-phase active power filter used to compensate current harmonics, to correct the imbalance between voltage and current generated for capacitive or inductive loads and, the implementation of the control strategy, to carry through the balancing of currents for three phases, being minimized the current of neutral. The justifications for the choice of this topology and the strategy of control are presented adopted beyond the mathematical analysis, procedures of calculation, results of simulation and laboratory a time that, as final stage of the developing, was constructed a prototype with 10 kW.

**Index Terms—**Harmonic distortion, active filter, voltage control, inverters, digital control.

## I. INTRODUCTION

Active filter technology consist of measuring harmonic currents of one or more phases of the power grid and generate all harmonic currents components in opposition of phase in relation to those measures. Active power filters already are used with success for consumers and suppliers of electric energy in many countries. In [1] is shown about use of incorporated active power filters, for the proper manufacturers, the equipment that traditionally originates great harmonic currents. The active power filters can be parallel or series [2, 3, 4]. Filters series are voltage restorers, have the function to eliminate distortions in the voltages of the electrical system. Parallel active filters are current restorers, have the function to eliminate the harmonic currents components. The hybrid filters still exist, that combine the two functions [2, 3]. This work deals with solely the parallel filters, which operate as currents sources in derivation with the electrical system. Its function is to inject in the point of connection of the electrical system with the load (PAC), currents of compensation capable to attenuate or to eliminate harmonic currents originated by not linear loads.

In the described configuration in this paper the parallel active power filter is capable to inject current in the PAC or to remove current for load of the capacitive bank, since the structure is bidirectional.

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Carlos Gabriel Bianchin ([bianchin@lactec.org.br](mailto:bianchin@lactec.org.br)) and Rogers Demonti ([rogers@lactec.org.br](mailto:rogers@lactec.org.br)) are with LACTEC – Instituto de Tecnologia para o Desenvolvimento.

Julio Shigeaki Omori is with COPEL (<mailto:julio.omori@copel.com>).

## II. CONVERTER TOPOLOGY

The inverter used in this project is voltage fed inverter. Considering the possible topologies for the voltage inverter meet the inverter of three legs and the inverter of four legs. Fig. 1 illustrates as the second type.

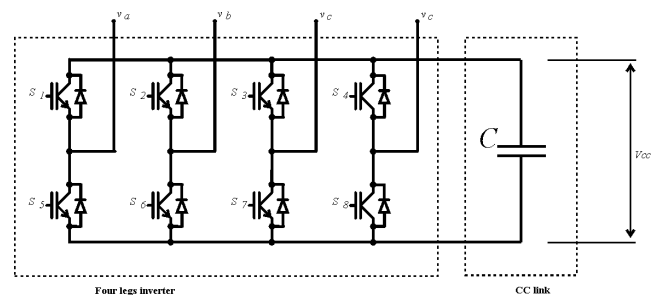


Fig. 1. Voltage inverter with four legs

In [5] can be found a lot of techniques of modulation for these structures. Inverter of three legs is appropriate for balanced three-phase systems, where the voltages supplied for the inverter and currents demanded for the load are balanced. Is possible to use this topology in systems unbalanced through the addition of a neutral conductor to the center of the continuous voltage side (CC link in Fig. 1), however this can cause problems of control and stability, a time that is necessary to carry through the balancing of the voltages over the two capacitors in CC link. Moreover, the neutral currents are drained or injected directly in the capacitors, what it requires high values of capacitances. Another disadvantage of this converter, when used with the neutral conductor, is the poor use of the voltage in CC link [6]. The inverters with four legs are not so known, however comes being pointed as the topology most appropriate with respect to applications in unbalanced systems [7]. The existence of an exclusive leg for the neutral conductor becomes possible the independent control of the current of neutral supplied by the inverter. Moreover, the inverter does not require the addition of a conductor to the CC link (continuous voltage), what it means that the capacitor will not be connected directly to the neutral conductor. This becomes possible to reduce the value of the capacitance and still it excuses the necessity of a controller to carry through the balancing of the voltages. A system of current control with this inverter is more robust of what its competitor with three legs.

### A. Control Strategy

Great part of technical literature about active filters deals with solely its application in balanced three-phase systems. However, the number of electric installations that have a neutral conductor with current phases unbalanced is increasing, which are mainly caused by the significant single-phase load presence [1]. The filter is connected to the electric installation through coupling inductors, for which they circulate currents synthesized for the current controllers, characterizing the active filter as controlled current source. The strategy to produce the correct control is composed two-piece basic: a system of identification of the references and a system of current control (Fig. 2).

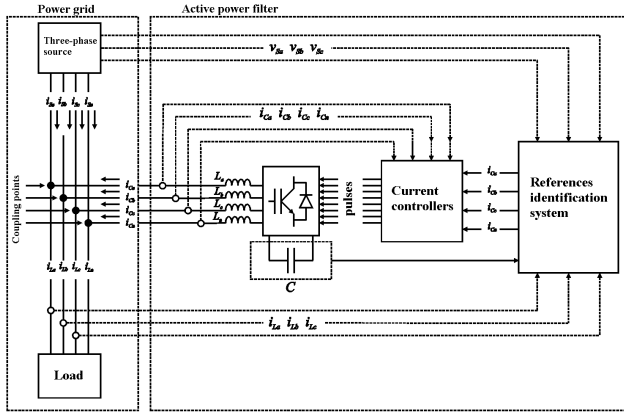


Fig. 2: Strategy of control for active filter.

The function of the references identification system is to determine the compensation currents that must be injected by the active filter in the electrical system. When the active filter is used in systems unbalanced with neutral, the compensator has still the function to determine the compensation currents that become possible the balancing of the phases and the elimination of the neutral current. To get these objectives the strategy of compensation based on the sinusoidal currents synthesis will be used, balanced and in phase with the basic source voltages. This will guarantee a current in the PAC with low distortion harmonic and high power factor, beyond minimizing the neutral current. The synthesis of currents of the filter is carried through with using of proportional and integral controllers (PI) that they act in set with a modulator of pulse width. Fig. 3 shows the simplified block diagram of a system of current control. Rigorously each one of the proportional and integral regulators receives the name from controller, but the name of current controller will be given to the complete system, simplifying the adopted nomenclature.

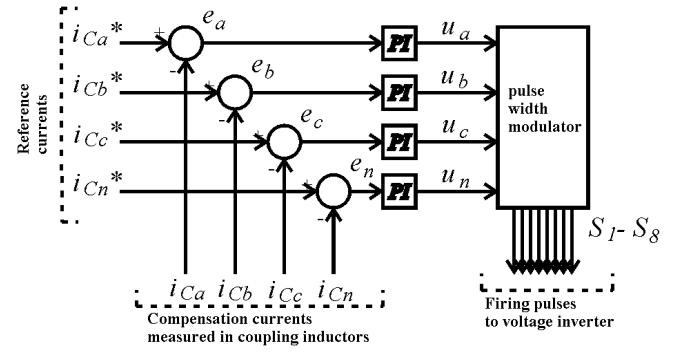


Fig. 3: Current controller of the active filter.

In the block diagram of Fig. 3 four controllers PI exist which generate references currents for a pulse width modulator. This modulator generates the pulses for inverter firing used for the synthesis of current compensation. The voltages signals are generated by controllers PI basing on the errors between measured and reference currents.

These signals are applied the switch of the inverter, in this in case that, IGBT transistors. The system operates in closed loop looking for to do with that the currents in the inductors are next possible to reference currents. Controllers PI operate in the intention to minimize the errors between the references and effectively synthesized currents in the  $L_a$  inductors until  $L_n$  (Fig.2). In this paper the control of the filter was implemented digitally in processor DSP TMS320F2812, manufactured for the Texas Instruments. Fig. 4 shows more detailed strategy of implemented control in the DSP. The control strategy must synthesize a current ( $i_f$ ) in the output of the filter, that assures low distortion the current ( $i_s$ ) in the PAC, considering that the load current ( $i_c$ ) has distortion of up to 50%. To keep high factor of power, the voltage signal in the PAC is used as reference. The voltage in capacitor C of the inverter is monitored to guarantee the system power balancing.

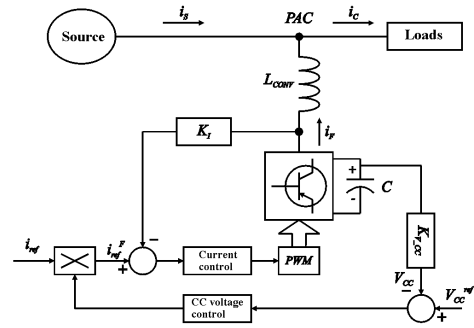


Fig. 4: Block diagram to use in voltage and current controller design

### B. Mathematical Analysis

Mathematical analysis contemplated all the procedures for implementation of the control of the three-phase inverter of four legs operating as active filter of harmonics. The requirements of harmonics attenuation until 21<sup>a</sup> order, reduction of the neutral current (unbalance between the

phases) and reduction of the displacement between voltage and current in the three phases had been the main considerations in the design. In the filter, two controllers PI are used: current controller PI of fast response and controller PI of CC link, of slower response. Controller PI of link CC was calculated in function of the described parameters below:

- Value of the CC link capacitor;
- Value of the rms phase voltage;
- End of scale of the sensors of CC link voltage and alternated voltages;
- Value of voltage desired in CC link;
- Analogical-digital converter gain;

Considering the bidirectional inverter for balanced loads, the CC link voltage it must be bigger than the value of line voltage peak. In such a way, to assure the synthesis of the current in the filter, the CC link voltage ( $V_{cc}$ ) must be 3/2 greater than the peak of the maximum rms phase voltage ( $V_a$ ) [8], that is:

$$V_{cc} \geq \frac{3}{2} V_a \sqrt{2} \sqrt{3} \quad (1)$$

The CC link capacitor is responsible for some specific characteristics, such as: to assist in the balance of energy in conditions of transitory in the load, to guarantee one high tax of variation of the output current inverter and, to make possible the current circulation of negative sequence for the inverter. In the case of the topology adopted for the inverter (4 legs), the currents of zero sequence are manipulated by the fourth arm, making that the CC link voltage will be influenced only from the harmonics and components of negative sequence, especially in the basic frequency (bigger power). It is considered that the voltages of the three-phase power grid are balanced and that the fluctuation of CC voltage ( $\Delta V_{cc}$ ) is lesser than the total value of CC link voltage ( $\Delta V_{cc} \ll V_{cc}$ ), where  $\Delta V_{cc}$  is peak of the CC voltage ripple. The parcel most significant of this ripple is proportional to the oscillation of power in the inverter, which had to currents of negative sequence:

$$P_{neg} = [v_{an} v_{bn} v_{cn}]^* [i_{aneg} i_{bneg} i_{cneg}] \cong \tilde{P}_{cc} \quad (2)$$

From (2) it is possible to show that the power of negative sequence has oscillatory characteristic in  $2\omega$  and can be written as:

$$P_{neg} = \frac{3}{2} V_a \sqrt{2} I_{neg\_pk} \cos(2\omega t + \phi) \quad (3)$$

where:  $I_{neg\_pk}$  is the peak value of negative sequence current, which if desires that to the active filter support. Therefore, the fluctuation of energy peak-peak ( $\Delta E_{pp}$ ) provoked by the load is:

$$\Delta E_{pp} = \frac{3V_a \sqrt{2} I_{neg\_pk}}{2\omega} = \frac{1}{2} C (V_{cc} + \Delta V_{cc})^2 - \frac{1}{2} C (V_{cc} - \Delta V_{cc})^2 = 2CV_{cc} \Delta V_{cc} \quad (4)$$

In such a way, the minimum capacitor to get value for  $\Delta V_{cc}$ , is:

$$C_{min} = \frac{3V_a \sqrt{2} I_{neg\_pk}}{4\omega V_{cc} \Delta V_{cc}} \quad (5)$$

Coupling inductors, between the inverter and the power grid, must operate in a big band of frequencies, what it must be considered in the design for definition of the constructive characteristics of the inductor and the core material. The specification of the inductance value is made to satisfy criteria and specific functions, such as: to limit the current ripple in the output of the converter, being operated as first-class filter pass-low, without provoking a drop of voltage exaggerated on its terminals. Additionally the inductor does not have to limit the tax of variation of the converter current, what it would limit the performance of the active filter for compensation of harmonic currents of higher order. It must have a commitment between the CC link voltage and the value of the inductor. High values of voltage make possible to get high di/dt to cancel the harmonics completely, however this also causes values raised for the current ripple. A chosen time the voltage, must be proceeded to the calculation of the coupling inductors. Diverse papers as [9, 10, 11], establish criteria for the calculation. Thus according [12], the tax of rising (di/dt) of the current generated for the active filter must be bigger than the tax of harmonic currents rising of the load. Considering the Kirchhoff's Voltages Law, for one of the phases of the system (Fig. 2 and 3), it results:

$$-\sqrt{2}\sqrt{3}V_a - 2L_a \left( \frac{di}{dt} \right) + V_{cc} = 0 \quad (6)$$

Soon, a time that if desires that the inductance value allows that the tax of variation of the current of the active filter (di/dt), either bigger than the tax of variation of harmonic currents of the load, becomes:

$$L_a = \frac{V_{cc} - \sqrt{2}\sqrt{3}V_a}{2 \frac{di}{dt}} \quad (7)$$

As much for the project of the current controller, how much for the one of voltage, the system is considered according Fig. 4. As it does not have power plant in capacitor C, the system must observe and keep constant this voltage. It is necessary also that the output current of the filter synthesizes the references defined for the compensation strategy. Thus the system can be configured as two subsystems of control: one for the voltage in C and another one for output harmonic currents. It is noticed that the controller of the voltage of capacitor C is responsible for modulating the value of the current reference of the active filter, to keep fixed this voltage. In such a way, the transfer function of the physical system of the voltage control can be represented by the capacitive function  $\frac{1}{sC}$ , while the transfer function of the system of control of the output current is given by the function

$\frac{1}{sL_{conv}}$  [13]. Additionally the gains of the voltage sensors and current must be considered. Finally, depending on the technique of adopted modulation the gain of converter PWM is defined. In the case of the used three-phase inverter, modulating set PWM - converting it is understood, of the point of view of control, as a voltage gain equal to:

$$K_{PWM} = \frac{V_{cc}}{2} = 250 \quad (8)$$

Fig. 5 illustrates the used basic project for the design of the current controller. It is observed that the current in the output of the active filter is converted in voltage and scaled through the current sensor (block  $K_{si}$ ) and the conditioning board. To follow then it is converted by A/D converter (block  $K_{DSP}$ ) into p.u. (per unit) scale.

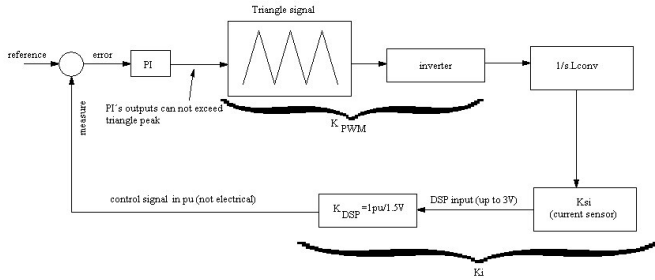


Fig. 5. Diagram of blocks of the plant with the current controller.

Considering this design, the transfer functions without ( $G_{SC}$ ) and with ( $G_{CC}$ ) controller PI, are express, respectively for:

$$G_{SC}(s) = K_i K_{PWM} \frac{1}{sL_{conv}} = \frac{\omega_{SC}}{s} \quad (9)$$

$$G_{CC}(s) = G_{SC}(s)PI(s) = \frac{\omega_{CC}}{s} \quad (10)$$

Soon it is possible to calculate the proportional gain ( $K_p$ ) and integral gain ( $K_i$ ) of regulators PI through [14]:

$$K_p = \frac{\omega_{CC}}{\omega_{SC}} = \frac{f_{CC}}{f_{SC}} \quad (11)$$

$$K_i = \frac{K_p \omega_{CC}}{\tan(mf)} T_a \quad (12)$$

where  $f_{cc}$  is the frequency of the broadband in Hz and  $mf$  is the phase margin stipulated for the system in closed loop with regulator PI.  $T_a$  is the period of sampling of the digital system. In general, the band-pass of the current controller of an active filter cannot be low to disable the synthesis of harmonic currents necessary, nor high to become the unstable system or to exceed the criteria of Nyquist stability. How much to the phase margin values between  $70^\circ$  and  $85^\circ$  had been kept.

Considering that the dynamics of the voltage of CC link of the inverter is sufficiently slow, it is relatively easy to get a controller PI who satisfies the conditions of dynamics and stability. The calculation of the gain of the converter seen for the voltage controller is made by the balance of power of the converter. Operating as parallel active filter in condition of

steady state the converter does not have to absorb nor to deliver active power. That is the calculated active power in side AC of the converter must be the same one of that one calculated of side CC. In such a way the gains of the PI can be calculated by similar expressions to those used for the current control.

### III. PROJECT PROCEDURES

In this section the basic criteria for the dimensioning of the components of the parallel active filter are exposed. The conditions where the active filter is used and that type of load the same is capable to compensate are described. The system is three-phase with neutral conductor. The voltage of phase  $V_a = 127$  V and 60 Hz frequency. The nonlinear loads produce currents with up to 50% of harmonic distortion and unbalance of negative sequence. The loads present a power about 10 kVA, what it results in a current of the order of 26 A. Voltage of CC link is defined in agreement (1) in 500 V, with  $V_a = 127$  V + 5%. The capacitor of CC link is calculated according (5), in 3,6 mF, being  $I_{neg\_pk} = 50$  A and  $\Delta V_{cc} = 10$  V. Considering a derivative of current as 50 kA/s and a CC voltage in 500 V, is gotten, using (7), a value of 1,9 mH.

### IV. SIMULATION RESULTS

Diverse simulations had been carried through to test the control strategy and to verify the static and dynamic conditions of the parameters of the filter. To follow the results of a simulation are presented where some problematic situations are considered that can occur with the electric power grid and its loads, also the presence of distorted voltage for the fifth harmonic in the input. The load is composed for a three-phase rectifier without capacitor, a single-phase rectifier with capacitor in the phase A, and an electrical resistance in phase B, representing an unbalanced situation for phase currents. The switching frequency is 12 kHz, the output inductors are of 2 mH and the CC link voltage is 500 V.

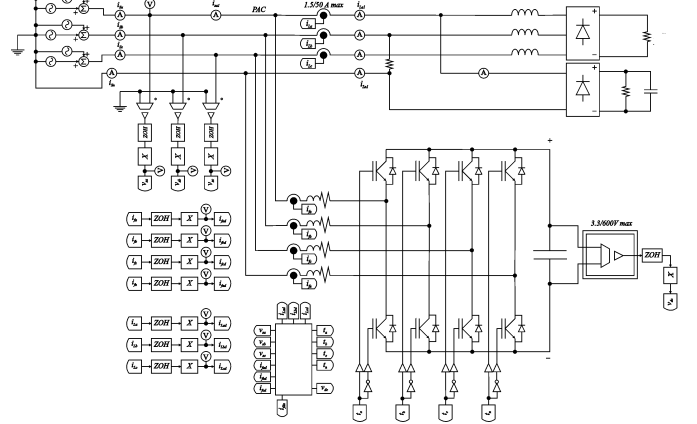


Fig. 6. Simulated circuit showing a set of adverse situations of the load and the power grid.

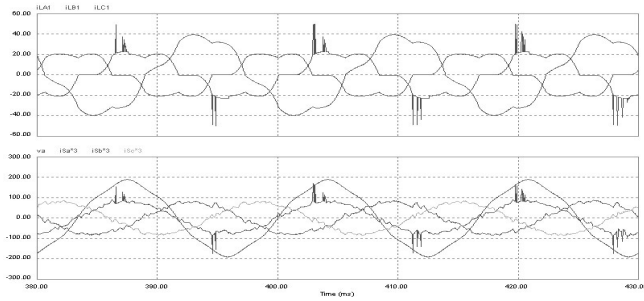


Fig. 7. Loads currents (superior) and source currents with voltage in the phase A (inferior).

It is observed that, exactly for this extreme situation that combines harmonic distortion of currents, unbalance and distortion of the input voltage; the output currents are balanced and with reduced harmonic content.

### V. EXPERIMENTAL RESULTS

To follow the results of the operation in laboratory of the active filter for compensation of six loads that compose a sufficiently severe situation of generation of harmonics and unbalanced currents meet. Total load is 11,2 kVA and the diagram of connections is presented in Fig. 8. This loading value got the filter to next to the limits to current protections in the legs of the inverter. The design power of this filter is of 10 kVA

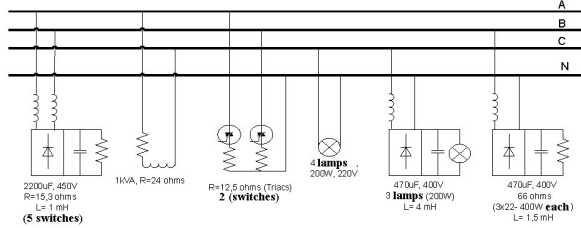


Fig. 8: Diagram of loads used for one of the laboratory tests. Nonlinear and unbalanced load – 11,2 KVA.

The measurements had been carried through with a power quality analyzer and an oscilloscope of 4 channels.

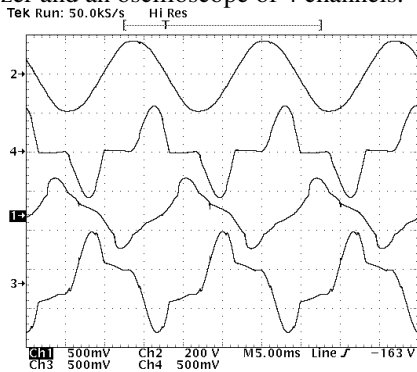


Fig. 9: Voltage of the phase A, the currents of the load in the phases A, B, C (10mV/A).

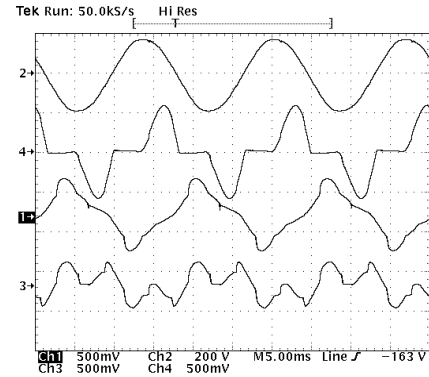


Fig. 10: Voltage of the phase A, the currents of the load in the phases A, B and in neutral one (10mV/A).

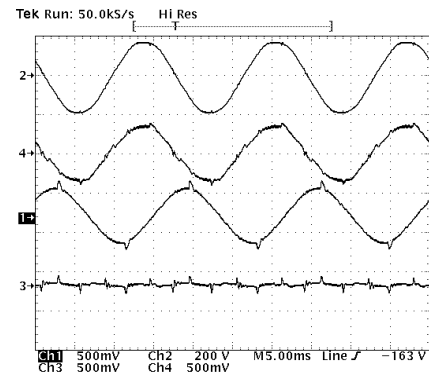


Fig. 11: Voltage of the phase A, the currents of the source in the phases A, B and in the neutral one (10mV/A) with the filter in operation.

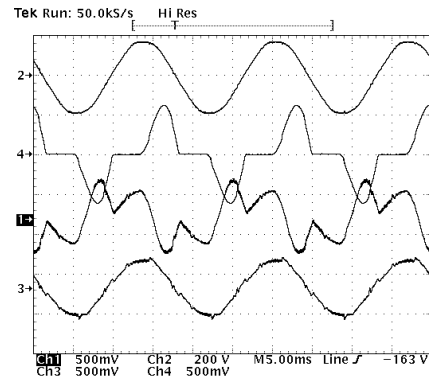


Fig. 12: Voltage of the phase A, load current, current of compensation (filter) and current compensated for source.

TABLE I  
SUMMARY OF EXPERIMENTAL RESULTS

Phases	S (kVA)	PF	I <sub>rms</sub> (A)	I <sub>peak</sub> (A)	DHT (%)
A – load	3,7	0,59	28,4	55,4	50,1
A – grid	3,0	0,99	23,2	34,6	7,2
B – load	3,1	0,77	24,1	43,3	27,8
B – grid	3,0	0,99	23,5	40,2	7,4
C – load	4,4	0,87	33,8	62,6	38,2
C – grid	3,0	0,99	23,4	35,2	7,8
N – load			16,2	27,4	
N – grid			2,2	7,6	

The table indicates the apparent power (S), power factor (PF), current (rms), peak current and the current distortion for each one of the conductors of phase and neutral, considering only the load and later the grid (PAC) with the active filter operating. Notice that kVA of the load diminishes in function of the improvement in the power factor (0,99). The current distortion with filter power on, is less than 8%. As much the efficient values, how much the peak are balanced with the compensation. The current of neutral sufficiently is attenuated by the operation of the filter. Notice that the power and consequently, the currents, are distributed between the three phases. Notice that the distortion is too reduced, being below of 15%, exactly considering distortions of up to 76% (Phase A). Errors in the scales of the sensors, as well as low the digital resolution must be considered.

## VI. CONCLUSIONS

This paper presented the design, simulation and practical implementation of an active filter for compensation of harmonics currents, with balancing of the phases and compensation of reactive power. An observed important point during the tests in laboratory is that the result of the compensation is directly proportional to the operational conditions of the load, a time that the filter designed for one is determined nominal condition. Thus the study of the type of load to be compensated it is basic for the correct dimensioning of this filter and its optimization. It is possible to design a filter for all characteristic of load, but if it will be possible design for only one, the results will be more expressive.

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## VIII. BIOGRAPHIES



**Carlos Gabriel Bianchin** was born in Palmeira D'Oeste, Brasil, on August 9, 1972. He graduated from the UNESP – Universidade Estadual Paulista, Guaratinguetá, and had Master of Science at the UNICAMP.

His employment experience include the LACTEC – Institute for Development Technology (where works nowadays) and SUNNYVALE – Import. and Maintenance. His special fields of interest include power electronics for power quality, distribution energy (medium voltage), public street lighting and

power supplies.



**Rogers Demonti** was born in Brusque, Brasil, on May 27, 1971. He graduated from the UFSC – Universidade Federal de Santa Catarina, where he had Master of Science and Doctor of Science.

He works in LACTEC - Institute for Development Technology. His special fields of interest include active harmonic filtering, solar energy processing and electronic energy metering.



**Júlio Shigeaki Omori**, was born in São Mateus do Sul, Brasil, on January 9, 1977. He graduated from CEFET-PR – Centro Federal de Tecnologia.

He works in COPEL – Companhia Paranaense de Energia since 2002, and CEFET-PR as teacher. His special fields of interest include development of power systems, planning and power quality.