# A Supercapacitor-Based Power Conditioning System for Power Quality Improvement and Uninterruptible Power Supply

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*Abstract* - **A Power Conditioning System (PCS) which uses a supercapacitor bank as energy storage device is proposed as a viable solution for improving the quality and the reliability of the electric energy supply. Several tasks can be performed at the same time, such as reactive power compensation, current harmonic reduction, and smoothing of pulsating loads. Moreover, the PCS can operate as Uninterruptible Power Supply (UPS) during short time interruptions of the grid supply.**

## I. INTRODUCTION

In practical applications a high reliability power supply is required for critical loads. In general, this requirement is fulfilled by a standard UPS configuration. The energy is usually stored in a lead acid battery bank shunt connected to the intermediate dc-link. However, most of grid faults are very short ($\leq$ 1 s), therefore, high-power and low-energy storage devices should be employed. The use of batteries for these applications requires oversized banks, paying an extra cost for an energy reserve that will be never used.

Nowadays supercapacitors represent an emerging technology of electrochemical devices with very high capacitance values, that allows reaching specific energy density of 4.5 Wh/kg and specific power density of about 3500 W/kg. Using these new types of supercapacitors that are suitable for high power and low energy applications, it is possible to better exploit the energy reserve for applications such as UPS and smoothing of source power fluctuations due to pulsating loads [1].

With the same hardware structure required for the UPS operation, the proposed system is able to perform additional tasks such as reactive power compensation, current harmonic reduction, load unbalance compensation, and smoothing of pulsating loads. In this way, the UPS behaves as a power conditioning system when the grid supply is present, improving significantly the power quality in the grid section next to the Point of Common Coupling (PCC).

In order to utilize the stored energy when the system operates as either UPS or smoother of load power fluctuations, a suitable design of the supercapacitor bank is required.

The scheme of the proposed PCS is shown in Fig. 1. The bank of supercapacitors is connected to a dc/dc boost converter, which allows the bi-directional energy flow with the dc-link bus. The three-phase Voltage Source Inverter (VSI) is shunt connected to the PCC through a three-phase transformer. The PCC is connected to the mains through a static switch that must be turned off during the operation of the power conditioning system as UPS. When the grid supply is present, the stored energy can be used to compensate flicker phenomena due to switching-on and -off of the load. During these transients the PCS exchanges a given quantity of the stored energy in order to deliver the difference between the instantaneous load power and its average value, which is supplied by the source.

From Fig. 1 it is clear that the dc/ac section of the PCS has the same topology of a shunt active power filter [2]-[4]. Therefore, by means of a suitable control of the PCS it is also possible to compensate the load reactive power, to reduce the current harmonics of non-linear loads, and to compensate unbalanced loads. These features are achieved by the direct control of the currents through the transformer in order to force the source currents to be balanced and sinusoidal for any operating condition. The source currents are synchronized with the fundamental positive sequence component of the source voltages. As a consequence, balanced and sinusoidal source currents with unity power factor can be obtained, even in presence of voltage perturbations coming from the mains [5], [6].

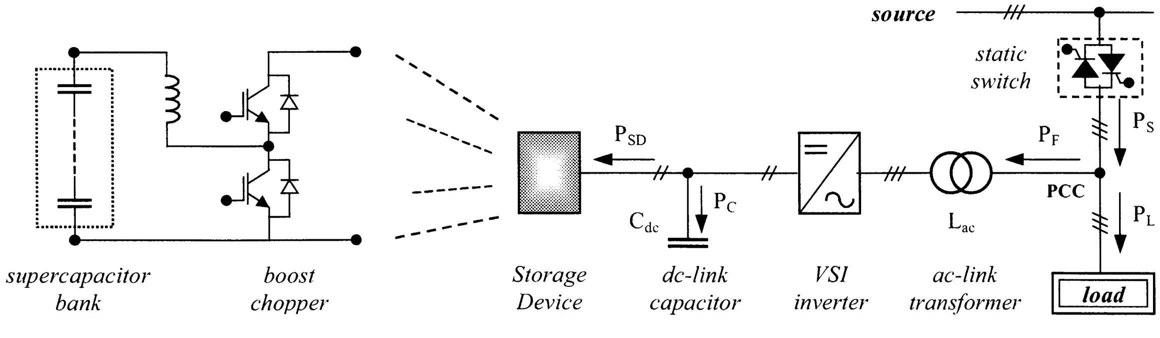

Fig. 1. Schematic drawing of the PCS structure

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The flicker compensation and the active filter operation are both achieved operating the PCS in "current source mode". When a perturbation of the mains is detected, the control system commutates the operating status from "current source mode" to "voltage source mode" and the PCS behaves as UPS. This commutation should be carried out without discontinuity in the voltage applied to the load.

A power conditioning system having all the described features has been analyzed in this paper. The performance of the PCS has been verified by simulation and experimental tests. Good results have been achieved both in active power filter operation and UPS operation.

## II. ANALYSIS OF THE ENERGY CONTROL SYSTEM

The control system consists of two sections that allow the operation of the PCS in "current source mode" when the grid supply is present, and in "voltage source mode" when a grid fault occurs. A commutation strategy based on the monitoring of the source voltage vector $\overline{e}_S$ allows the commutation between the two control modes, without discontinuity in the voltage applied to the load.

### *A. Current Source Mode*

During the operation of the PCS as current source the transfer of energy among the Storage Device (SD), the dc-link capacitor and the ac network is performed by the Energy Control System (ECS). The analysis of the ECS can be usefully carried out in terms of power flows and energy balance [9], [10].

In order to explain the principle of operation of the ECS, reference is made to a load power perturbation. Any load power change determines a variation of the power supplied by the PCS, and then a variation of the energy stored in the dc-link capacitor. This energy should be quickly restored to its reference value using energy coming from the SD.

In this way, it is possible to avoid large voltage variations even using a small dc-link capacitor, ensuring correct inverter operations.

The ECS behavior can be analyzed in terms of Laplace transform by the control scheme shown in Fig. 2. The input control variables are the energy in the dc-link capacitor $E^*_C$, and the energy in the storage device $E^*_{SD}$. The regulator $R_1$ generates the reference source power $P_S$ on the basis of the dc-link capacitor energy error. The inverter power $P_F$ that should be exchanged with the mains, is obtained by subtracting the load power to the source power ($P_F = P_S - P_L$). The regulator $R_3$ varies the reference value of the SD energy on the basis of the error in the dc-link capacitor energy. The regulator $R_2$ keeps the SD energy close to its reference value by exchanging power with the dc-link.

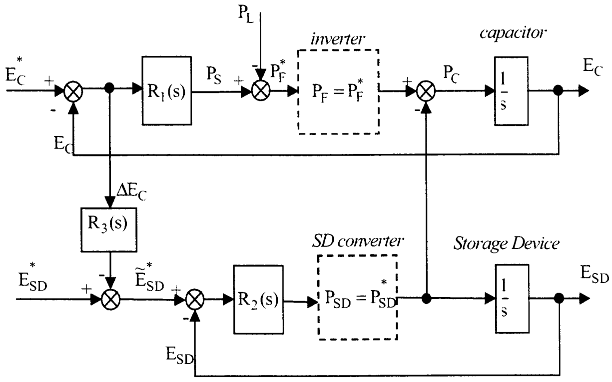

Fig. 2. Block diagram of the Energy Control System

In order to analyze the compensation of flicker phenomena, it is useful to rearrange the block diagram of Fig. 2, determining the transfer function linking the source power to the load power [6].

Assuming for three regulators the following expressions:

$$R_1(s) = K_1, \quad R_2(s) = K_2, \quad R_3(s) = K_3, \tag{1}$$

the open-loop transfer function F(s) between the source power $P_S$ and the load power $P_L$ can be expressed by

$$F(s) = \frac{K_1(s + K_2)}{s(s + K_3 K_2)}. \tag{2}$$

It can be verified that this transfer function ensures a stable operation of the PCS for any load perturbation [6]. A smooth variation of the source power in response to a step change of the load power can be obtained by a proper tuning of the parameters $K_1$, $K_2$ and $K_3$.

### *B. Voltage Source Mode*

During grid faults, the operation of the PCS as voltage source is obtained by a simple control system which uses the energy stored in the SD. The dc/dc boost converter discharges the storage device determining a power flow toward the dc-link, in order to keep the dc voltage close to its reference value. The block diagram of the ECS employed in the "voltage source mode" is shown in Fig. 3. The inverter is controlled by a Space Vector Modulation (SVM) technique, and supplies the load with three-phase system of sinusoidal voltages, corresponding to the grid rated voltages.

## III. SUPERCAPACITOR MODEL

In order to determine the behavior of the energy control system when the PCS operates either as current source or as voltage source, it is necessary to characterize the energy storage device.

As it is known, the behavior of a conventional capacitor is represented by the linear relationship between current and voltage derivative: i = C dv/dt. This simple model is not applicable to a supercapacitor, which must be modeled assuming a capacitance value depending on the state of charge of the supercapacitor, and then, on the voltage across the capacitor itself [7]. The scheme of Fig. 4 represents the electrical circuit used to model the supercapacitor.

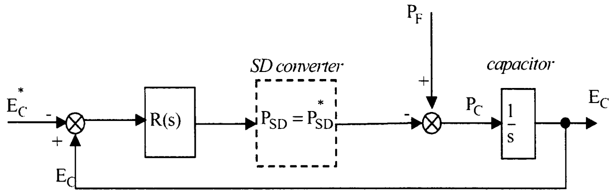

Fig. 3. Block diagram of the Energy Control System (voltage source mode)

In this circuit, the external capacitance $C_U$ is given by the expression

$$C_U = C_0 + kU_C, \tag{3}$$

where $C_0$ is a constant value capacitance, $U_C$ is the voltage across the capacitance and k is a constant depending the supercapacitor type. Using (3), the relationship between current and voltage is given by

$$i = \frac{d(C_U U_C)}{dt} = \frac{d\left(C_0 U_C + kU_C^2\right)}{dt} = (C_0 + 2kU_C)\frac{dU_C}{dt}, \tag{4}$$

then, the energy stored in the capacitor is a function of voltage $U_C$:

$$E(U_C) = \int_0^{t^*} i(t) u_c(t) dt = \int_0^{U_C} (C_0 + 2k\,u_c) u_c du_c = \\ = \frac{1}{2} C_0 U_C^2 + \frac{2}{3} kU_C^3. \tag{5}$$

The supercapacitor considered in this paper is the Montena BCAP0010, having the parameters given in Table I.

Fig. 5 shows the behavior of the supercapacitor voltage when a charge-discharge cycle with a constant current equal to the rated current ($I_C$ = 100A) is considered. The results of Fig. 5 define the maximum slope of the charge-discharge curve.

During the operation of system as UPS, the dc/dc converter allows the supercapacitor to be discharged down to 50% of the rated voltage. The corresponding energy ΔE transferred to the dc-link is given by:

$$\Delta E = \int_{U_C/2}^{U_C} (C_0 + 2k\,u_c) u_c du_c\,. \tag{6}$$

ΔE can be expressed as function of the energy $E(U_C)$ stored at the rated voltage $U_C$

$$\Delta E = \frac{3}{4} E(U_c) + \frac{1}{12} kU_c^3\,. \tag{7}$$

With reference to the supercapacitor BCAP0010, it is possible to utilize the 79% of the stored energy $E(U_C)$ by discharging the supercapacitor down to the 50% of its rated voltage.

It can be noted that during UPS operation a constant power discharge should be considered instead of a constant current discharge. The constant power value corresponds to the power that can be supplied at the end of the discharge. Assuming a discharge down to $U_C/2$, the supercapacitor can supply a constant power $P_M = P_C/2$. The discharging time can be calculated by

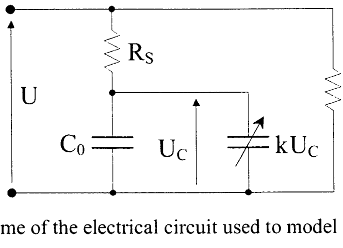

Fig. 4. Scheme of the electrical circuit used to model the supercapacitor

TABLE I
PARAMETERS OF SUPERCAPACITOR MONTENA BCAP0010

| | |
|---|---|
| rated capacitance: | 2600 F |
| rated voltage: | 2,5 V |
| rated current | 100 A |
| maximum voltage | 3 V |
| weight | 0,52 kg |
| volume: | 0.42 dm$^3$ |
| fixed capacitance | $C_0$ = 1800 F |
| capacitance constant | k = 340 F/V |
| internal series resistance | $R_S$ = 0.8 mΩ |
| internal shunt resistance | $R_P$ = 3000 Ω |
| stray inductance | 50 nH |

$$i = \frac{P_M}{u_c} = \frac{dQ}{dt} \Rightarrow \frac{P_M}{u_c} = \frac{d}{du_c}(C_u.u_c)\frac{du_c}{dt},$$

$$dt = \frac{u_c}{P_M}\left[\frac{d}{du_c}\left(C_0 u_c + k\,u_c^2\right)\right]du_c = \frac{u_c}{P_M}(C_0 + 2k\,u_c)du_c\,.$$

Integrating the previous equation gives:

$$t = \int_{U_C/2}^{U_C} \frac{u_c}{P_M}(C_0 + 2k\,u_c)du_c = \frac{1}{P_M}\left(\frac{3}{2}U_C^2 C_0 - \frac{7}{12}kU_C^3\right). \tag{8}$$

The voltage and current behavior of the BCAP0010 during constant power discharge is shown in Fig. 6. For this supercapacitor the maximum constant power that can be supplied during discharge is $P_M$ = 125 W, and the corresponding discharging time is 58.6 s.

With reference to a bank with n series connected supercapacitors, the voltage across the equivalent series capacitance $C_T = C_U/n$ is $U_T = n\ U_C$. Then, by using (4), the relationship between the current and the voltage becomes:

$$i = \left(\frac{C_0}{n} + \frac{k}{n^2} 2U_T\right)\frac{dU_T}{dt}. \tag{9}$$

The stored energy at voltage $U_T$ is given by

$$E(U_T) = \frac{1}{n}\left(\frac{1}{2}C_0 U_T^2 + \frac{2}{3}\frac{k}{n}U_T^3\right). \tag{10}$$

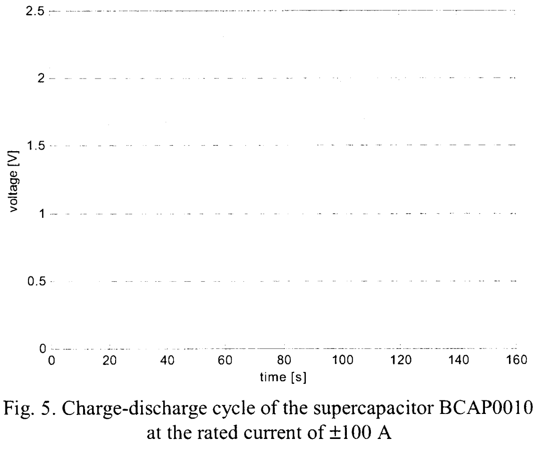

Fig. 5. Charge-discharge cycle of the supercapacitor BCAP0010 at the rated current of ±100 A

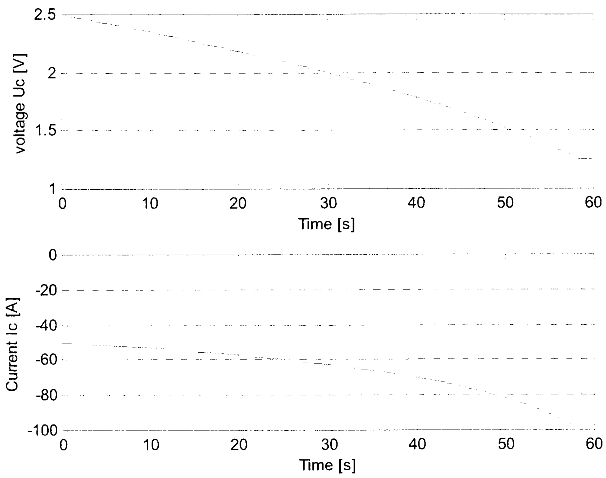

Fig. 6. Voltage and current across a capacitor BCAP0010 during a constant power discharge

The control of the energy stored in the supercapacitor bank can be achieved by regulating the bank voltage, according to (10). The voltage $U_T$ cannot be directly measured because of the voltage drop across the series resistance n $R_S$. Therefore, $U_T$ can be calculated by $U_T = U_{SD} - n\ R_S I$, where $U_{SD}$ is the voltage at the terminals of the supercapacitor bank.

## IV. CONTROL SYSTEM IMPLEMENTATION

The energy control system required for operating the PCS in the current source mode has been implemented introducing some changes with respect to the basic scheme of Fig. 2.

The energy level in the dc-link capacitor is kept under control using the capacitor voltage $V_C$ as control variable. The source power is regulated using the source current $\bar{i}_S$ as control variable [5]. Figs. 6 and 7 show the control system modified according to these considerations.

The reference source current $\bar{i}_S^*$ is obtained by multiplying the unity vector $\hat{v}_S^{+1}$, by the reference source current magnitude $I_S^*$, where:

- the unity vector $\hat{v}_S^{+1}$ is in phase with the positive sequence fundamental component of the line to neutral voltage $\hat{v}_S$, and it is generated by a Three Phase Locked Loop algorithm [4]. This algorithm operates correctly even in the case of unbalanced and non-sinusoidal voltages [5].
- the reference source current magnitude $I_S^*$ is generated by the regulator $R_1(s)$, which operates on the instantaneous error between the reference value $V_C^*$ and the actual value $V_C$ of the dc-link voltage.

The ac current regulator operates in order to keep the source current $\bar{i}_S$ close to its reference value $\bar{i}_S^*$ [3].

The regulator $R_2(s)$ of the energy control system shown in Fig.2 keeps under control the energy level in the storage device. In the implemented control system this has been achieved controlling the voltage across the supercapacitors. This control is performed using the dc/dc converter between the dc-link and the storage device.

The commutation between "current source mode" and "voltage source mode" is implemented by monitoring the source voltages. Assuming balanced and sinusoidal supply voltages, the voltage vector $\bar{v}_S$ rotates at constant speed describing a circular locus. In case of unbalanced or non-sinusoidal supply voltages, the trajectory described by the voltage vector $\bar{v}_S$ deviates from the circular locus, causing variations of its magnitude and angular speed. Perturbations of the supply voltages, such as voltage sags, large voltage drops, and zero voltage conditions, cause large deviations of the voltage vector trajectory. A critical circular region has been defined in order to detect these perturbations and to start the commutation sequence. If the voltage vector lays in the critical region for a time interval greater than a given value, the control algorithm disables the "current source mode", drives the static switch to the off-state and, when the source currents are almost zero, enables the operation of the PCS in "voltage source mode". During the commutation sequence, the phase angle of the source voltage is continuously estimated allowing the PCS to supply the load without appreciable voltage discontinuities. When the source voltage vector leaves the critical region for a time large enough, the control system commutates back from the "voltage source mode" to the "current source mode". During this commutation, a PLL algorithm allows the synchronization of the voltage vector applied to the load with the restored source voltages. In this way, the commutation is performed without discontinuities on the voltages applied to the load.

The energy storage device considered in this paper is a bank of 35 series connected supercapacitors of the type described in Section III. The supercapacitor bank has the following electrical characteristics: rated voltage $U_{SD}$ = 87,5 V, rated power $P_{SD}$ = 8750 W, stored energy at rated voltage $E_{SD}$ = 321 kJ.

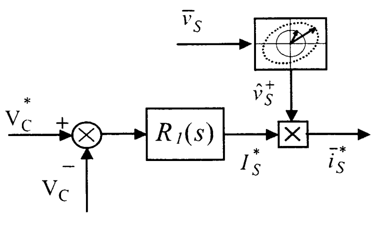

Fig. 7. dc-link voltage controller

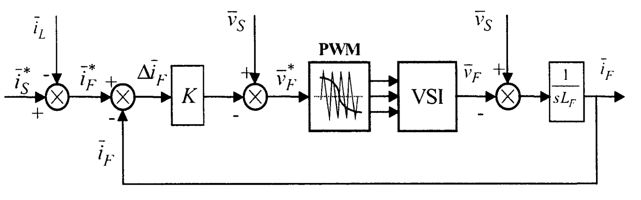

Fig. 8. ac current controller

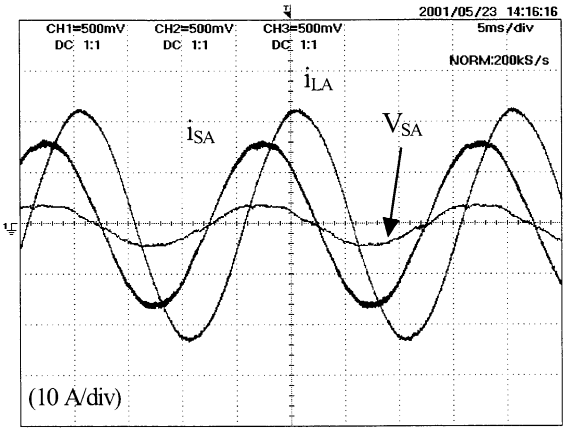

Fig. 9. Compensation of reactive power

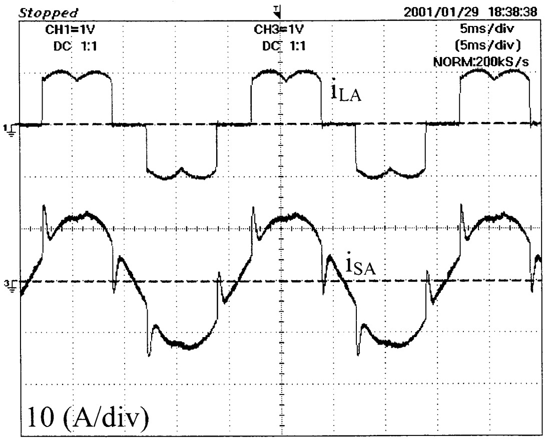

Fig. 10. Compensation of current harmonics

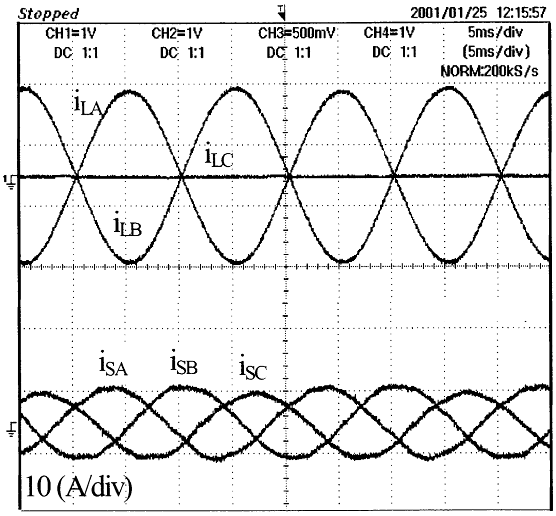

Fig. 11. Compensation load unbalance

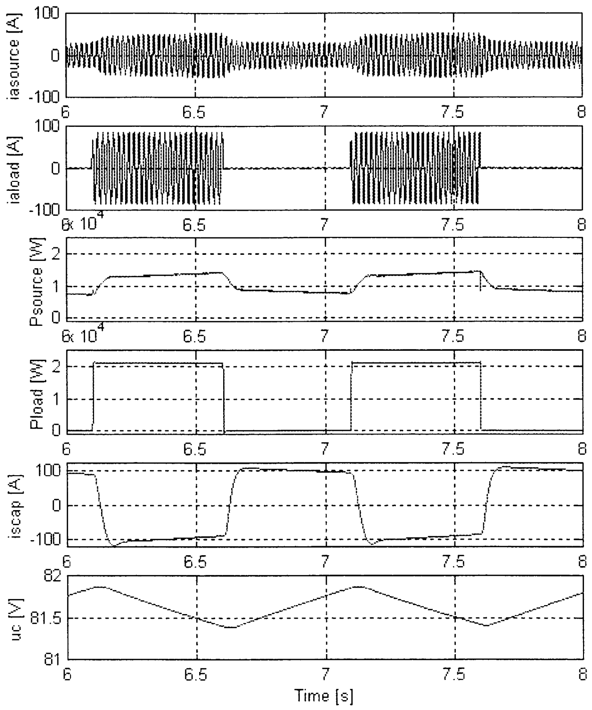

Fig. 12. Compensation of a pulsating load $f_P$=1Hz, $P_L$= 20 kW, duty-cycle 50%

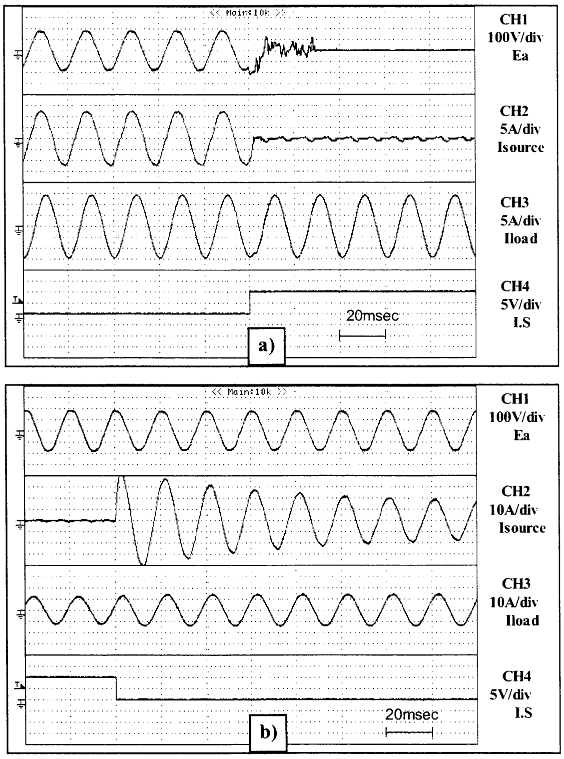

Fig. 13. UPS operation: detailed view of the commutation:
a) *current source mode → voltage source mode*
b) *voltage source mode → current source mode*

The bank is connected through a dc/dc boost converter to the dc-link bus at a voltage of $V_{dc}$= 170 V. The inverter is connected to the grid through a transformer that allows the operation of the inverter at the output voltage value of 90 V rms. The leakage inductance of the transformer behaves as an ac-link inductance for the connection of the PCS to the grid.

## V. RESULTS

A prototype of the proposed PCS with a rated power of 30 kVA has been realized in laboratory. The system configuration is the same as in Fig. 1, and it is designed to utilize the supercapacitor bank described in Section III. The PCS is able to compensate flicker phenomena, to behave as active power filter, and to ensure the continuity of the load supply during short time interruption of the grid.

The control system has been implemented on a PPC 333 MHz DSP based board, including A/D converters. The board includes also a second DSP (TMS320F240) to generate the PWM signals for both the converters. As a first step, the capability of the PCS to operate as active filter has been verified. Fig. 9 shows the compensation of the reactive power of a R-L linear load.

Fig. 10 shows the compensation of the current harmonics of a non-linear load represented by a three-phase diode rectifier.

A single-phase load has been connected to the PCC to represent an unbalanced load. The results obtained, showing the effectiveness of the compensation are illustrated in Fig.11.

At this stage of the research project the supercapacitor bank is not yet available. Therefore, the operation of the system as smoother of pulsating loads has been verified only by simulations, carried out in the Simulink environment of Matlab.

Fig. 12 shows the transient response caused by a load pulsating at a frequency of 1 Hz, with a duty cycle of 50%. The effect of the PCS is to keep the source current amplitude almost constant and equal to the mean value of the load current. This is achieved exchanging a fraction of the energy stored in the supercapacitor bank.

The details of the commutation between the two operating modes, i.e. "current source" and "voltage source", are represented in Fig. 13. Both the commutations are carried out without significant discontinuities in the load current, ensuring continuity of service for critical loads.

## VI. CONCLUSION

The performance a PCS with the capability to meet several power quality requirements has been analyzed and verified by experimental tests. An analytical approach has been used to determine the parameters of the three regulators. A PCS prototype has been realized in laboratory. Several tests have been carried out in different operating conditions. It has been verified that this system is able to compensate reactive power and current harmonics due to non-linear loads. Furthermore, the results obtained have shown that the presence of an energy storage device makes it possible to reduce the source current variations due to pulsating loads, and to ensure the continuity of the supply during short time utility faults.

The experimental results are quite satisfactory, showing the effectiveness of the proposed PCS in improving the power quality and the reliability of the power supply.

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