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Digital-Controlled Single-Phase Unified Power Quality Conditioner for Non-linear and Voltage Sensitive Loads

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Abstract - The ability to provide quality power has become a significant issue in power systems. The main causes of poor power quality are harmonic currents, poor power factor, supply-voltage variations, etc. A technique of achieving both active current distortion compensation, power factor correction and also mitigating the supply-voltage variation (sag or swell) at the load side is presented in this paper. The operation and rating issues of the proposed Single-phase Unified Power Quality Conditioner are also highlighted. To reduce the total cost while simultaneously increasing the performance, the system is fully digitally controlled using the fixed-point TMS320F240 digital signal processor. The performances of the UPQC, which is composed by shunt and series PWM controlled-converters, have been verified on a laboratory prototype.

Keywords: Power quality, Unified power quality conditioner, Voltage sag/swell, Wave-shaping

1. Introduction

Power quality has become a significant issue recently, but this does not mean that it was not important in the past. Utilities all over the word have for many years worked on the improvement of what is known nowadays as "power quality".

The recent increased interest in power quality can be explained in a number of ways and these are summarized below. Over the last decade, there have been an increased number of publications on this subject.

In particular, power electronic equipment has become much more sensitive then its counterparts of ten or twenty years ago. Also, companies have become more sensitive to loss of production time due to their reduced profit margins. In the domestic market, electricity is more and more considered to be a basic right, which should simply always be available to the consumer.

The increased use of converter-driven equipment, such as consumer electronics up to adjustable-speed drives, has led to a significant growth in voltage disturbances. The main cause here is the non-sinusoidal current of rectifiers and inverters.

The harmonic distortion of the current leads to harmonic distortion. These kinds of currents that are flowing chiefly from finite impedance of the supply-source cause voltage distortion at the Point of Common Coupling.

Another aspect of the power quality parameters is related to the current phase variation. Ideally, voltage and current waveforms are in phase, with power factor of the load equal to unity and reactive power consumption at zero; this situation enables the most efficient transport of the active power, leading to the most economical type of distribution system.

Relating to power quality issues, designers of the Power Quality Conditioner systems are required to follow the recommendations of some world-wide accepted standards like IEEE-519-1992, IEC 1000-3-2, IEC 1000-3-4 and recommended practice and requirements for harmonic control in electric power systems [1-3].

In order to emphasise the importance of a Unified Power Quality Conditioner some observation of Power Quality must be done [1]:

- the disturbances like rms voltage sag or swell initially occurs at the Point of Common Coupling, then at the utility distribution system or at the substation;
- most of the voltage events are 10-20% voltage sags/ swells; the occurrence of more severe sag events are less frequent;
- some electrically operated equipment can cause under or over voltage especially at the Point of Common Coupling of a high impedance supply source;
- weather events, such as thunderstorms can cause low rms voltage;
- depending on the loads, poor factor operation leads to the restriction on the total load-equipment that can be connected to the customer, which is in turn responsible for the limiting effects of reactive power consumption and also for limiting harmonic currents injected into the power system.

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Nowadays many researchers study active filters and power conditioners to overcome the drawbacks mentioned above and to perform improved harmonic current compensation. Even if the cost of semiconductor power devices is getting lower, it still remains the main factor, and is what causes Power Conditioning equipment to be so costly. In search of low-cost Power Conditioning equipment, by reducing the equipment rating and making them multi-functional, the present paper points out a new multi-purpose digital-controlled single-phase Unified Power Quality Conditioner for non-linear and voltage sensitive loads.

To verify and validate the proposed Power Conditioning equipment and control methods, a laboratory prototype was created. To reduce the total cost while increasing the performance, the system is completely digitally-controlled using the fixed-point TMS320F240 digital signal processor.

The proposed Unified Power Quality Conditioner has the following goals:

- maintains the load voltage at the rated value even for supply voltage sag/swell; the compensating voltage by series converter is taken from the same dc-link voltage controlled at a fixed level ($400V_{DC}$) by shunt-converter, being in the same phase or in opposite phase with the load voltage, depending on sag or swell of the supply-voltage;
- assures the power factor at supply side equals unity, the supply-voltage and input current being always in phase, independent of the load power factor, by controlling the current of the shunt-converter, that is in quadrature advance relationship with the supply-voltage; in steady-state operation, at the rated supply-voltage, no active power is consumed by the shunt-converter;
- obtaining an input current with low harmonic content that meets the regulation of the above mentioned standards.

2. Unified Power Quality Conditioner Model

The proposed system presented in Fig. 1 consists of two single-phase PWM controlled converters and a series low-impedance transformers. The series-connected converter injects/extracts the necessary voltage to compensate the supply-voltage sag/swell. The compensating voltage is in the same phase or opposite phase, depending on the supply-voltage event. The shunt-converter, connected in parallel with the load takes a current from the supply to compensate the reactive power requested by the load, to reduce the harmonics and to control the dc-link voltage at a desired value. The shunt-converter acts not only as an active filter, but assures the necessary active power for the series-converter as well.

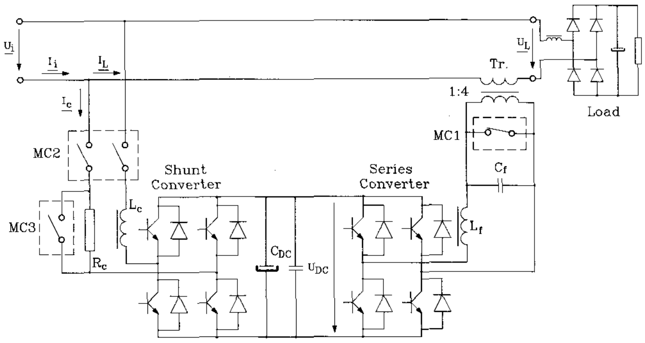

Fig. 1 Single-phase Unified Power Quality Conditioner System

The system parameters are described in Table 1.

Table 1 System Rating and Circuit Parameters

Rated load power	20 kVA
Transformer turn ratio	1:4
Rated UPQC power	10 kVA
Shunt-converter inductance	2 mH
Charge resistor	500 Ω/100W
dc-link capacitors	4000 μF
	5 μF
Series-converter filter inductance	0.5 mH
Series-converter filter capacitor	15 μF
Switching frequency	10 kHz

The main advantage of the shunt-series controller is that it does not require any energy storage. It is designed to mitigate any supply-voltage variation of a certain magnitude independent of its duration. The shunt-converter of the Unified Power Quality Conditioner is used to mitigate current quality problems, as mentioned above, with later discussion of the shunt-converter.

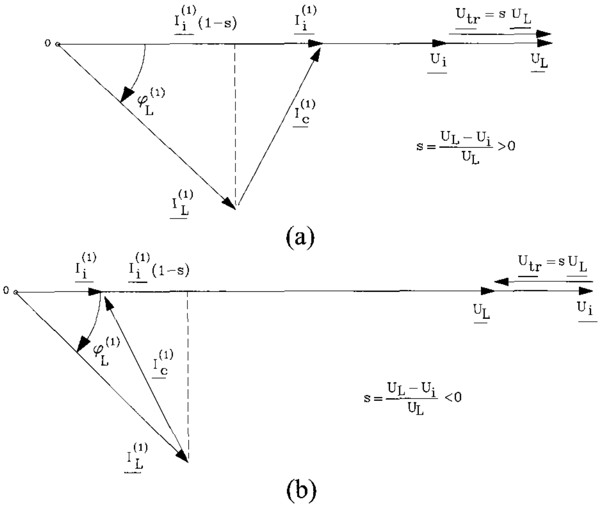

Fig. 2 Phasor diagram of UPQC: (a) supply-voltage sag; (b) supply-voltage swell

The operation of the proposed UPQC is based on the phasor diagram from Fig. 2 related to the first-harmonic components.

When the supply-voltage U_i falls (a sag in the supply), the series-converter adds through the transformer U_{tr}, so that the magnitude of the load voltage is maintained constant at the rated value (the added voltage has the same phase as the supply-voltage). When a swell is detected in the supply-voltage, the series-converter subtracts the voltage U_{tr} (the transformer voltage being in opposite phase with the supply-voltage).

Depending on the transformer ratio, the series-converter can mitigate larger swells (greater then 25%) but, for this case, the rating of the shunt-converter must be increased.

Taking into account the phasor diagram, it can be seen that the shunt-converter compensates the reactive component I_c of the load (that has the Displacement Power Factor angle $\varphi_L^{(1)}$). The input current is always in phase with the supply-voltage, which implies a better use of the volt-ampere rating of the utility equipment (i.e. transformers, generators, distribution line), this being one of the goals of the proposed UPQC.

The current rating of the shunt-converter, being one of the parameters that make the UPQC so costly, can be obtained taking into account that the active power consumed by the load remains the same even for input voltage sag or swell.

Because the UPQC assures the input power factor unity, and input THD_i within the permissible limits recommended by IEEE-519, IEC 1000-3-4, the input active power is:

$$P_i = U_i I_i^{(1)} = U_L(1-s)I_i^{(1)} \approx U_L(1-s)I_i . \qquad (1)$$

where:

$I_i^{(1)}$ is the fundamental rms value of the input current,

I_i is the rms value of the input current,

$s = 1 - U_i / U_L$ is the percent sag/swell of the supply-voltage (U_L being the rated voltage).

The active power requested by the load is:

$$P_L = U_L I_L^{(1)} \cos\varphi_L^{(1)} . \qquad (2)$$

To have a constant active power ($P_i = P_L$), the rms value of the input current can be expressed in terms of load parameters:

$$I_i^{(1)} = I_L^{(1)} \frac{\cos\varphi_L^{(1)}}{1-s} . \qquad (3)$$

and the fundamental component of the shunt-converter current can be obtained taking into account the above equation and the phasor diagram from Fig. 2:

$$I_c^{(1)} = \frac{I_L^{(1)}}{1-s}\sqrt{s^2 + \sin^2\varphi_L^{(1)}(1-2s)} . \qquad (4)$$

Using the fundamental component of the shunt-converter current, the apparent power of the shunt-converter is:

$$\begin{aligned} S_{sh} &= U_i I_c = U_L(1-s)I_c = U_L(1-s)I_c^{(1)}\sqrt{1+THD_{sh}^2} = \\ &= U_L I_L^{(1)}\sqrt{s^2+\sin^2\varphi_L^{(1)}(1-2s)}\sqrt{1+THD_{sh}^2} \end{aligned} , \qquad (5)$$

where:

total harmonic distortion index is defined as:

$$THD = \sqrt{I^2 - I^{(1)2}} / I^{(1)} . \qquad (6)$$

Since, in the ideal situation the shunt-converter cancels the distortion component from the load current, the distortion component from the shunt-converter current related to the fundamental current is the same as in the load current.

$$THD_{sh} = \sqrt{I_c^2 - I_c^{(1)2}} / I_c^{(1)} \approx \sqrt{I_L^2 - I_L^{(1)2}} / I_L^{(1)} \qquad (7)$$

From relationships (5) and (7), the apparent power of the shunt-converter in terms of load parameters becomes:

$$S_{sh} \approx U_L I_L^{(1)}\sqrt{s^2+\sin^2\varphi_L^{(1)}(1-2s)}\sqrt{1+THD_L^2} \qquad (8)$$

The apparent power of the series-converter is the following:

$$S_{ser} = U_{tr} I_L = |s| U_L I_L^{(1)}\sqrt{1+THD_L^2} \qquad (9)$$

Adding relationship (8) to (9), the total apparent power of the UPQC is evaluated as:

$$S_{UPQC} \approx U_L I_L^{(1)}\left(\sqrt{s^2+\sin^2\varphi_L^{(1)}(1-2s)} + |s|\right)\sqrt{1+THD_L^2} \qquad (10)$$

Assuming a $THD_{L\max} = 0.8$ of the rated load current, the following four figures present: apparent power for shunt-converter and series-converter, input current and fundamental current of the shunt-converter for different supply-voltage sag/swell and different load displacement power factors ($\cos\varphi_L^{(1)}$).

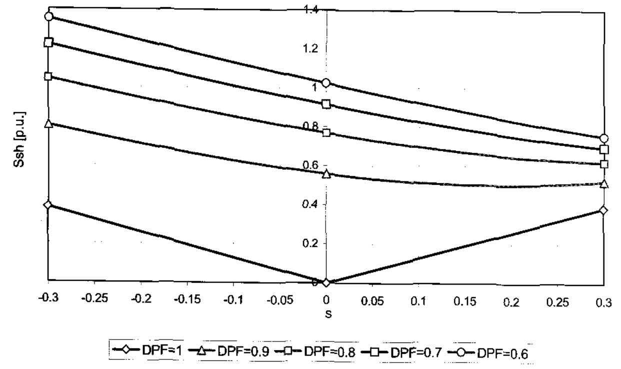

Fig. 3 Apparent Power of Shunt-converter for $THD_L=0.8$

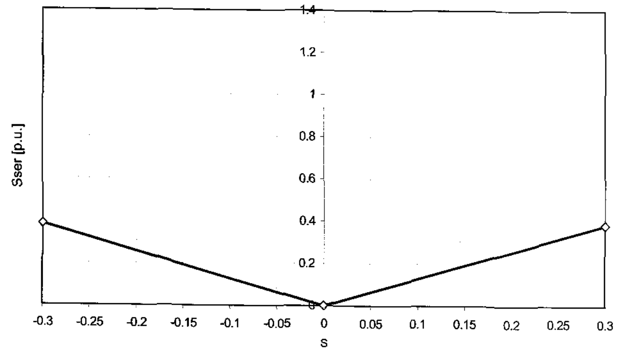

Fig. 4 Apparent Power of Series-converter for $THD_L=0.8$

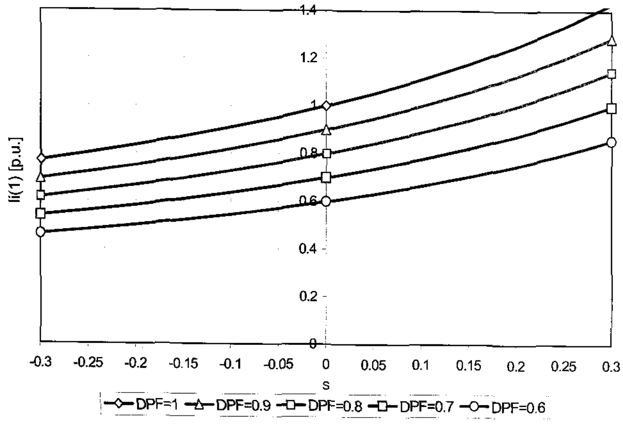

Fig. 5 Input Current

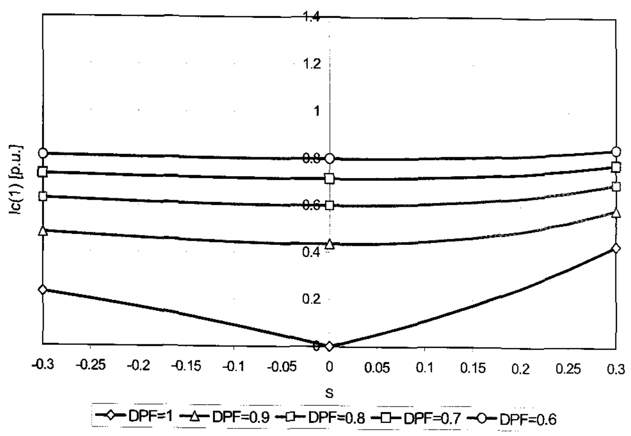

Fig. 6 Fundamental Current of Shunt-converter

One can observe that shunt-converter VA loading is decreasing for supply-voltage sag, which is the most frequent comparing to supply-voltage swell. The VA loading of the series-converter is independent of the load displacement power factor, being lower than VA loading of the shunt-converter. For this reason the rating of the series converter can be reduced. The UPQC VA loading is balanced on the shunt-converter, being greater than the series-converter.

3. Control strategy

The UPQC control strategy is digital, and is implemented using the fixed-point digital signal processor TMS320F240. The sampling period for the control algorithm is $100\mu s$, being the same as the switching period of the IGBT shunt and series converters. For monitoring different quantities of the control-system, a Windows based Program-Monitor was installed. The hardware configuration of the DSP system is shown in Fig. 7.

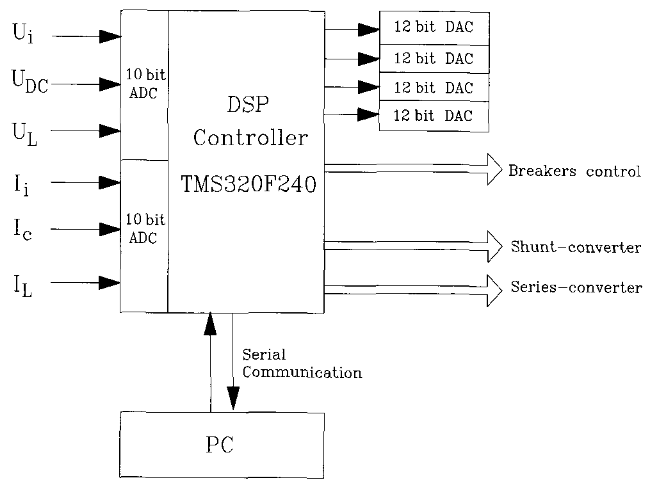

Fig. 7 DSP Controller

To control the single-phase UPQC system there are four quantities (dc-link voltage - U_{DC}, input current - I_i, shunt converter current - I_c and load current I_L) to control the shunt-converter, load voltage - U_L to control the series-converter, and supply-voltage - U_i to synchronise both shunt and series converters control-algorithms, by detecting the fundamental zero-crossing.

The DSP controller assures the gate-signals for shunt and series converters, and also the breakers for control of the starting/stopping operation. The four 12 bit DACs are used for monitoring of different system-quantities. Serial-communication between the DSP controller and a PC is supervised by the Program-Monitor.

Fig. 8 illustrates the control-block diagram of the shunt-converter. The control algorithm has three goals:

- to assure the desired dc-link voltage (in this case 400V_{DC}) for the series-converter that mitigates (through the series transformer) the supply-voltage variations (sag or swell);
- to assure a unity displacement factor at the input side;
- to shape the input current as a sine-wave (to reduce the THD_i below the limits recommended by IEEE-519-1992, IEC 1000-3-2, IEC 1000-3-4 standards).

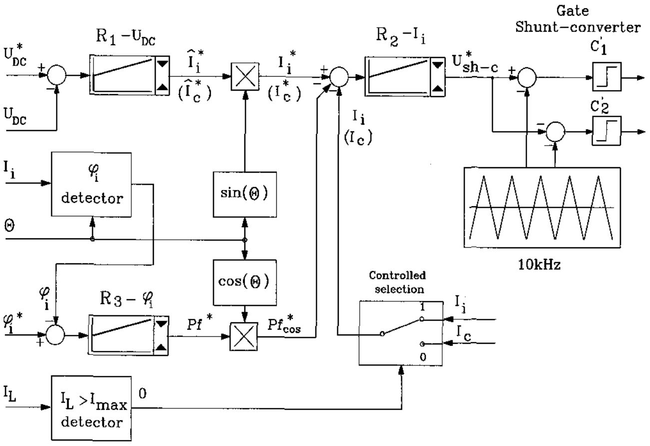

Fig. 8 Control-block Diagram of Shunt-converter

The U^*_{DC} reference is selected as a constant value to control dc-link voltage at the desired value. The error in dc-link voltage is a measure of the active power required by load and UPQC from the supply. This error is processed by the numerical PI controller (R_1-U_{DC}). The output that, in a normal case produces the magnitude of the supply-current is multiplied by the sinusoidal template to produce the reference current for the supply (I^*_i). The supply-current error is applied to the input of the PI current controller (R_2-I_i) that controls the shunt-converter voltage (in a PWM mode) to assure a sine-wave shape of the supply-current. Additionally, the output of the power-factor PI controller (R_3- φ_i) is applied to the input of PI current controller, which is multiplied by a cosine-wave template to assure the desired input power-factor. From the measured supply-current, the phase-angle φ_i (related to the supply-voltage) is computed, which represents the feedback of the power-factor controller. The main goal of this controller is to maintain constant the input power-factor, even for leading or lagging operation. In the case of UPQC operation, the power factor is unity.

Sine-wave and cosine-wave templates are calculated using a lookup-table of 256 points that are synchronized with zero crossing of the supply-voltage fundamental.

To avoid the over-charging of the shunt-converter when the load current amplitude is increased over a certain value, the current feedback of the PI current controller is changed as shunt-converter current. In this situation, sine-wave shaping of the supply-current is aborted, keeping only the displacement power factor unity at the input side. Even in this case, the supply-voltage variation is mitigating by series-converter, with the dc-link voltage being continuously controlled. For the series-converter, the control-block diagram is shown in Fig. 9.

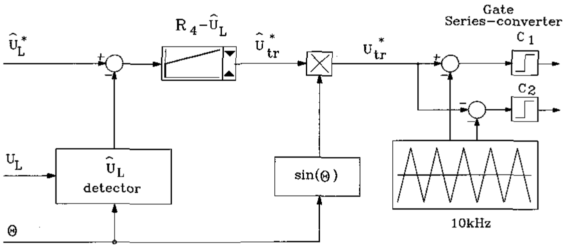

Fig. 9 Control-block diagram of series-converter

The control system of the series-converter uses as feedback the peak value of the load voltage. The output of the load-voltage PI controller (R_4-U_L) represents magnitude of the transformer voltage, which is controlled by the series-converter through the series transformer. A sine-wave template, in phase with the supply-voltage assures the same phase or the opposite phase of the transformer voltage for mitigating the supply-voltage sag or swell. There are several alternative ways that can be used for qualifying the voltage level. The information concerning voltage sag/swell can be obtained from:

- the rms supply-voltage;
- the magnitude of load voltage fundamental component;
- the peak voltage over each cycle or half-cycle.

In the first case, the voltage sags are recorded as sampled points in time and the rms voltage will have to be calculated from the sampled time-domain voltages (in one-cycle or half-cycle), using the following equation:

$$U_{rms} = \sqrt{\sum_{i=1}^{N} u_i^2 / N} \cdot \qquad (11)$$

where:

N is the number of samples per cycle (or per half-cycle),
u_i are the sampled voltages in time domain.

The second case uses the Fast-Fourier Transform algorithm to calculate the fundamental component of the supply-voltage.

The third method calculates the peak voltage as a function of time:

$$U_{peak} = \max\left|u(t-\tau)\right|; \quad 0 < \tau < T \, . \qquad (12)$$

where:

$u(t)$ is the sampled voltage waveform,

T is an integer multiple of one half-cycle.

The third method was chosen taking into account that the DSP is a fixed-point one. The other two methods can be used too, but are time-consuming, and the results, from point of view of control, are comparable with the third one.

4. Experimental results

This section presents some experimental results that have been carried out on the proposed single-phase UPQC system, taking into account the previously explained control methods. The experimental results for the non-linear diode bridge rectifier are presented. Fig. 10, Fig. 11 and Fig. 12 show from top to bottom supply-voltage, load current, supply current and compensating current (the input current of the shunt-converter). In Fig. 10, the non-linear load is assured by an inductance (5mH) at the input-side of the diode bridge rectifier and a resistor at the dc side. In Fig. 11 and Fig. 12, the non-linear load is assured by the same inductance at the input-side of the diode bridge rectifier and a parallel RC load at the dc side (capacitor value is 2000μF).

The load current distortion and the load displacement power factor that are not unity, are evident in all cases.

The THD_L of load current from Fig. 10, taking into account frequencies up to 1020Hz, is 26.3% and load power factor is 0.779. After compensation, the THD_i of input current is 2.17% and the input power factor is 0.9998. For the case presented in Fig. 12, the THD_L of load current is 45.7%, with the load power factor being 0.62. After compensation, the input THD_i is 4.95% and the input power factor is 0.9987. For this case, in Fig. 13 and Fig. 14 there are the plotted fundamental and third harmonic of load and input current respectively (third harmonic being the most important from the higher harmonics).

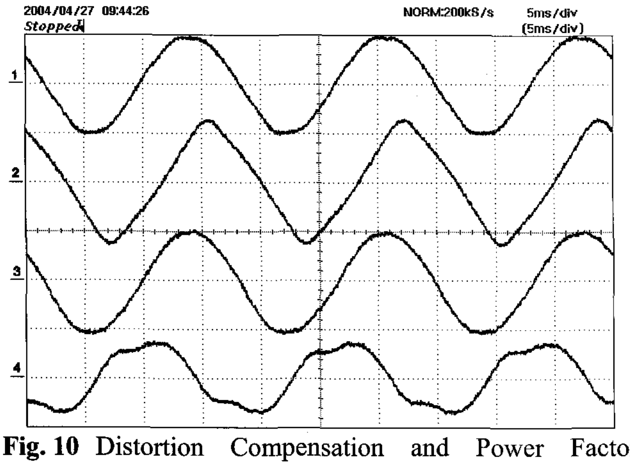

Fig. 10 Distortion Compensation and Power Factor Correction: 1 - Supply-voltage; 2 - Load current; 3 - Input current; and, 4 - Compensating current. (302V/div; 62A/div; time - 5ms/div)

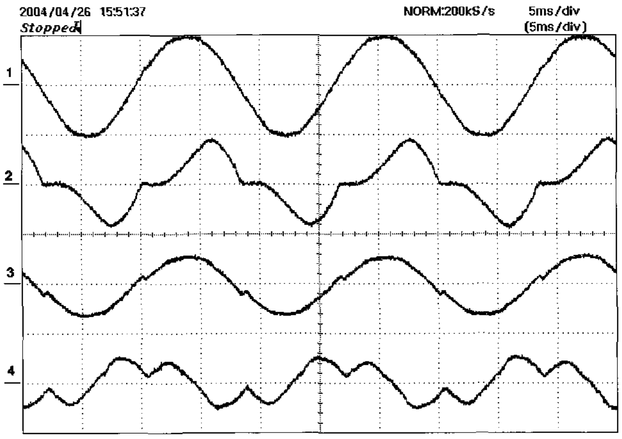

Fig. 11 Distortion compensation and power factor correction: 1- Supply-voltage; 2 - Load current; 3 - Input current; and, 4 - Compensating current. (302V/div; 62A/div; time - 5ms/div)

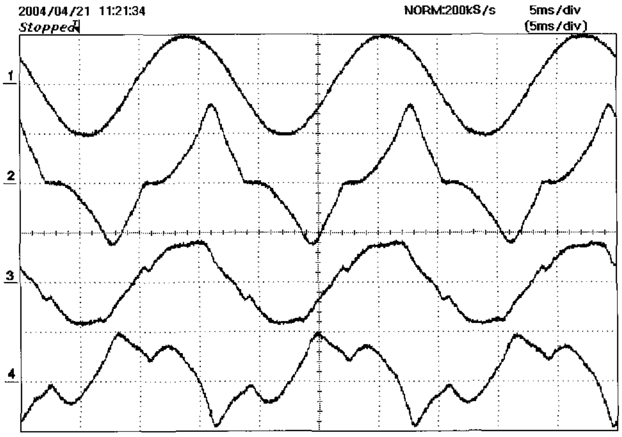

Fig. 12 Distortion compensation and power factor correction: 1- Supply-voltage; 2 - Load current; 3 - Input current; and, 4 - Compensating current. (302V/div; 62A/div; time - 5ms/div)

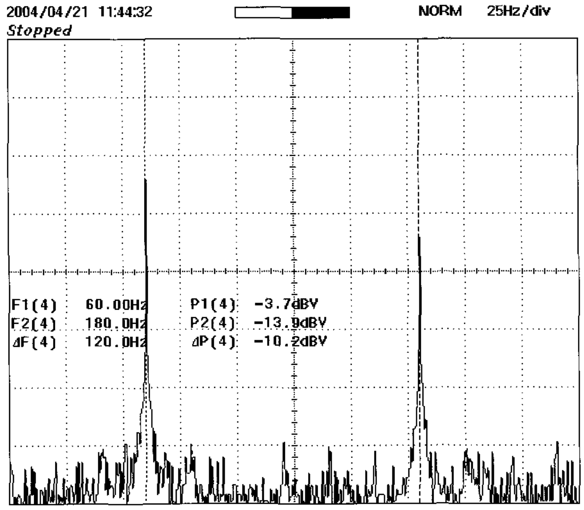

Fig. 13 First and Third Harmonic of Load Current (case of Fig. 12)

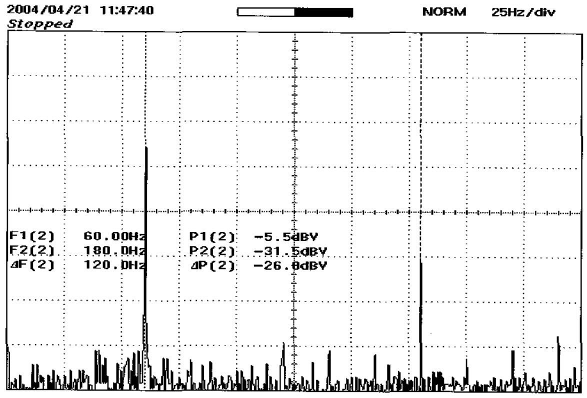

Fig. 14 First and Third Harmonic of Input Current (case of Fig. 12)

The rms values of fundamental and third harmonic are calculated with the following relationship:

$$I^{(h)} = 10^{dBV/20} \cdot 62[A]. \tag{13}$$

From Fig. 13, it can be seen that the third harmonic component of load current is very high, being 30.9% from the fundamental one. After compensation, as Fig. 14 shows, the third harmonic component has been reduced to 5% from the fundamental input current, being in the limits stipulated by the above mentioned standards.

Fig. 15 indicates the experimental power factor characteristics of the UPQC for different non-linear loads (as presented before), with the base load current being 90A.

For the case of diode bridge rectifier with L at the input side and parallel RC load at the dc side, the increase of load current (over 50A rms value) leads to a high crest value. Because the crest value can exceed the chosen ratings of the shunt-converter, starting from a certain value of the load current magnitude (i.e. 150A) the wave-shaping is aborted but, the input displacement power factor is continously maintained at unity. One can see that, for load currents greater then $0.5i_L$ (for the case of diode bridge rectifier with L at input side and parallel RC load at dc side), even if the sine-wave shaping is aborted the input power factor is greater than 0.9.

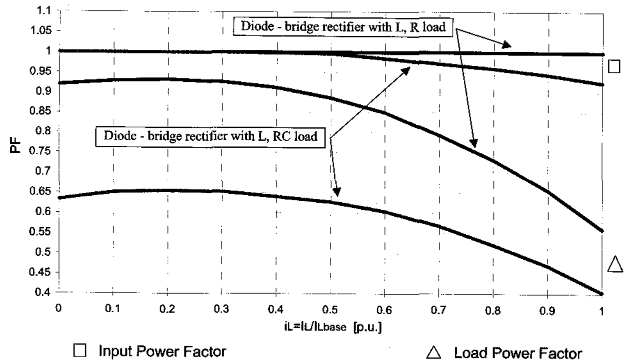

Fig. 15 Power Factor for Different Non-linear Loads ($DPF_i = 1$)

Fig. 16 and Fig. 17 indicate the operation of the series-converter for load voltage compensation in two cases: supply-voltage sag from 212V to 180V and supply-voltage swell from 180V to 255V. The experimental results denote a good dynamic performance, the load voltage being controlled in a maximum two cycles, depending on the moment when the load voltage sag/swell is detected.

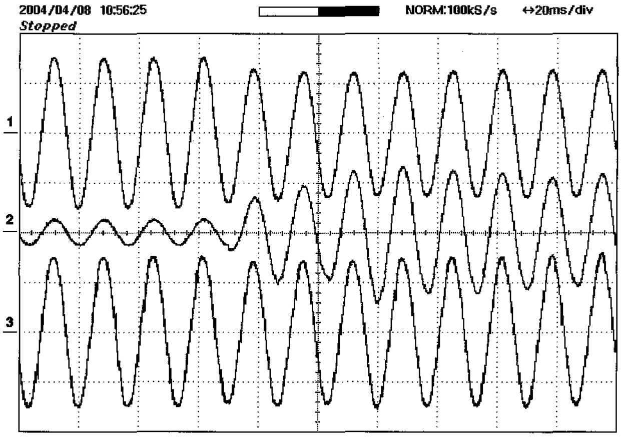

Fig. 16 Load Voltage Compensation supply-voltage sag from 212V to 180V; 200V/div, 20ms/div 1-Supply-voltage; 2-Injected voltage (series-converter); 3-Load voltage

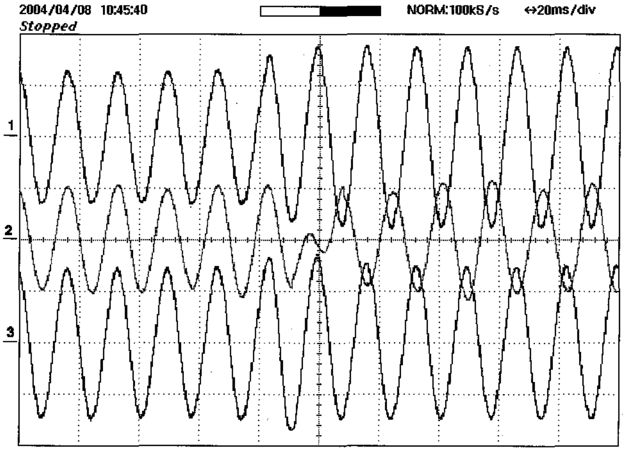

Fig. 17 Load Voltage Compensation supply-voltage swell from 180V to 255V; 200V/div, 20ms/div. 1-Supply-voltage; 2-Injected voltage (series-converter); 3-Load voltage

5. Conclusion

It was shown that the UPQC can maintain at very low limits the harmonic currents (the THD_i is less then 5%) and also that the power factor is improved at unity by compensation. The voltage compensation method also demonstrates a good performance. The load voltage is maintained at its reference value. From the experimental results, one can say that the proposed control methods have good compensation characteristics and the UPCQ system can play an important role in power quality improvement.

Acknowledgements

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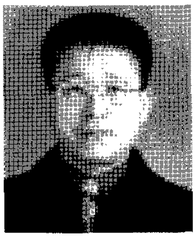

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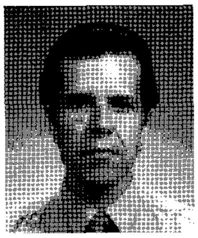

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