ATEE - 2004

DIGITAL-CONTROLLED SINGLE-PHASE UNIFIED POWER QUALITY CONDITIONER FOR NON-LINEAR AND VOLTAGE SENSITIVE LOAD

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Abstract – Power quality has become an important factor in power systems, for consumer and household appliances with proliferation of various electric/electronic equipment and computer systems. The main causes of a 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 highlighted too. To reduce the total cost, but to increase the performance, the system is fully digital-controlled using the fixed-point TMS320F240 digital signal processor. The performances of UPQC that is composed by shunt and series PWM controlled-converters have been verified on a laboratory prototype.

I. INTRODUCTION

The power quality has become an issue recently, but this does not mean that it was not important in the past. Utilities all over the word have for many years ago 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 are summarised below. Anyway, it is difficult to say which of these should be the first. In the last decade, there were an increased number of publications on this subject

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

The increased use of converter-driven equipment, such as consumer electronics, up to adjustable-speed drives has led to a large growth of 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 for a number of decades. These kinds of currents that are flowing especially from finite impedance of the supply-source cause the 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, power factor of the load equals unity, and the reactive power consumption is zero; this situation enables the most efficient transport of the active power, leading of the cheapest distribution system.

Relating to power quality issues, the designers of 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 -recommended practice and requirements for harmonic control in electric power systems [1], [2], [3].

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

- the disturbances like rms voltage sag or swell occurs at the Point of Common Coupling then at the utility distribution system or at the substation;
- the most of the voltage events are 10-20% voltage sags/swells; the occurrence of more severe

sag events are less frequent;

- some electric-drives equipment can cause under or over voltage especially at Point of Common Coupling of a high impedance supply source;
- the weather events, as thunderstorms can cause low rms voltage;
- depending on the loads, the poor factor operation leads to the restriction on the total load-equipment that can be connected to the customer that is responsible for limiting effects of reactive power consumption and also for limiting harmonic currents injected onto power system.

Even if the cost of semiconductor power devices is getting lower, still this cost is the main factor, which make Power Conditioning equipment very costly. In search of low-cost Power Conditioning equipment, by reducing the equipment rating, making them a multi-functional system, 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 performed. To reduce the total cost, but to increase the performance, the system is fully digital-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 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 shunt-converter.
- obtaining an input current with low harmonic content.

II. 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 transformer. The series-connected converter inject/extract 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. Shunt-converter acts not only as an active filter, but assures the necessary active power for series-converter, as well.

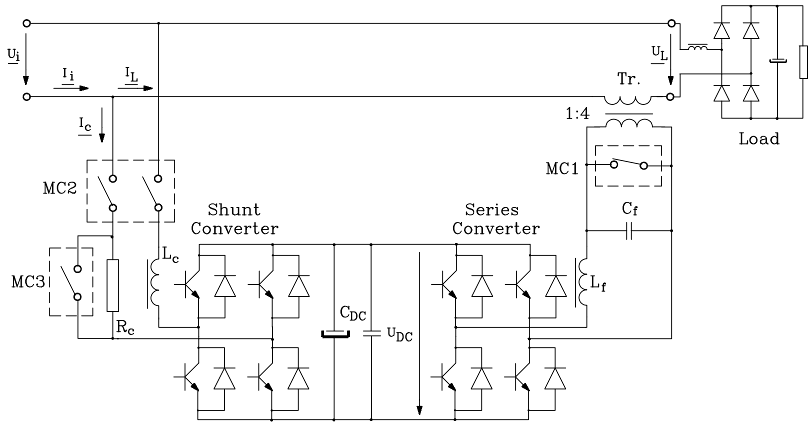
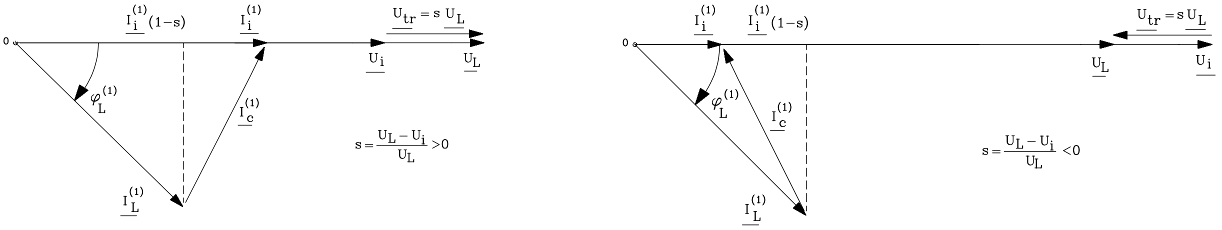


Fig.1 Single-phase Unified Power Quality Conditioner system

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



(a) (b)

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

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 is detected a swell 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 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, that 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 shunt-converter, being one of the parameters that makes UPQC costly, can be obtained tacking into account that the active power consumed by 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:

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

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 is the rated voltage). The active power requested by the load is:

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

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:

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

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

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

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

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

where, the total harmonic distortion index is defined as:

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

Because, in the ideal case the shunt-converter is cancelling 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.

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

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

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

The apparent power of series-converter is the following:

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

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

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

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

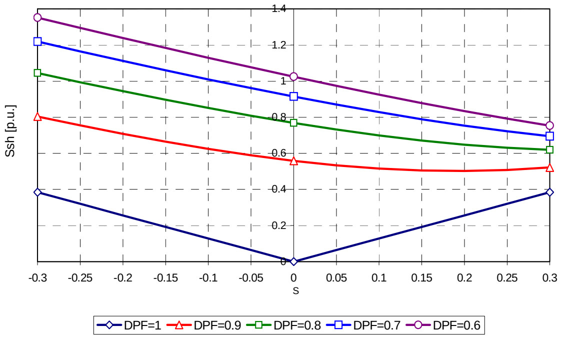


Fig.3 Apparent Power of shunt-converter

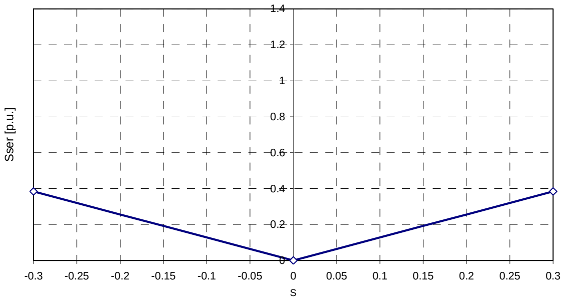


Fig.4 Apparent Power of series-converter

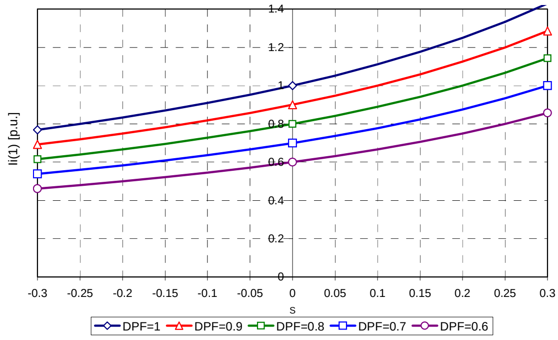


Fig.5 Input current

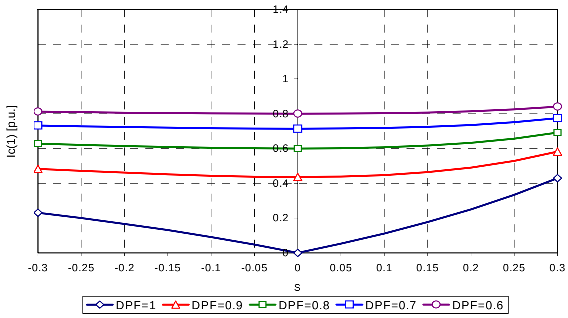


Fig.6 Fundamental current of shunt-converter

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

III. CONTROL STRATEGY

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

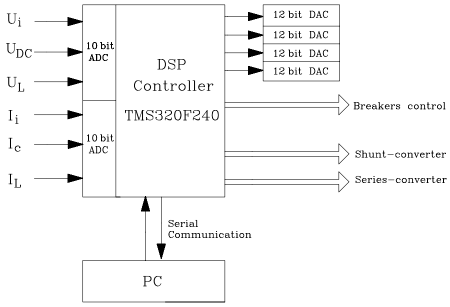


Fig.7 DSP Controller

To control the single-phase UPQC system there are acquired 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 control for starting/stopping operation.

Fig.8 and Fig. 9 show the control-block diagram of the shunt-converter and series-converter.

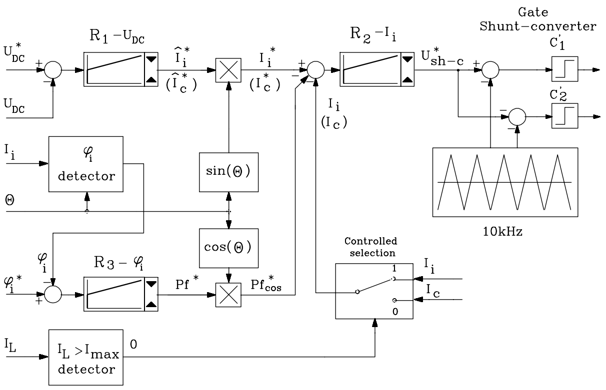


Fig.8 Control-block diagram of shunt-converter

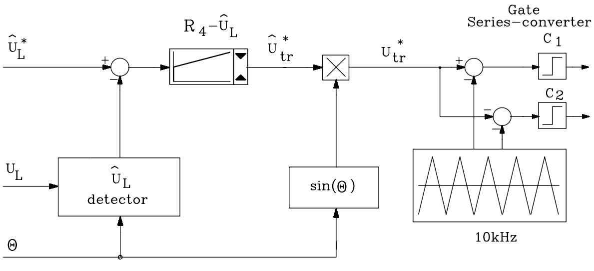


Fig.9 Control-block diagram of series-converter

IV. EXPERIMENTAL RESULTS

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

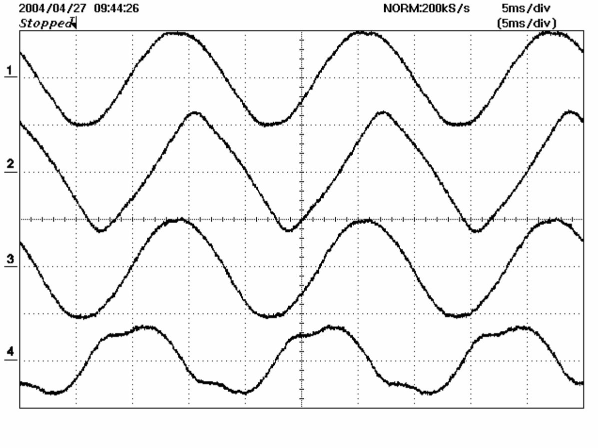


Fig.10

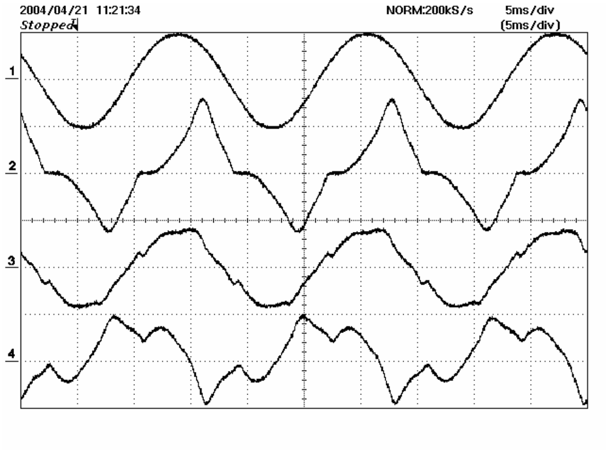


Fig.11

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

The load current distorsion and the load displacement power factor that is 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%, the load power factor being 0.62. After compensation, the input THD_i is 4.95% and the input power factor is 0.9987.

V. 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 the power factor is improved at unity by compensation. Voltage compensation method also shows 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 have an important role for power quality improvement.

VI. REFERENCES

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