# Effects of Supply Voltage non-Idealities on the Behavior of an Active Power Conditioner for Cogeneration Systems

Domenico Casadei, Gabriele Grandi, Claudio Rossi
Dept. of Electrical Engineering
University of Bologna
Bologna, 40136 - ITALY

**Abstract – The use of a Power Conditioning System (PCS) connecting a cogeneration plant to the electrical network, makes it possible to employ high-speed turbines directly coupled to permanent magnet synchronous generators. This solution leads to a very compact arrangement, characterized by high reliability and efficiency. Furthermore, the PCS is able to deliver not only the rated active power to the mains, but reactive power and current harmonics as well. In this way, the PCS can operate as active filter when non-linear loads are connected to the same network. Nevertheless, undesired behavior may occur when the supply voltages are non-ideal, such as in presence of unbalance, harmonics, flicker, or when the line impedance is not negligible. This paper presents a new control strategy that allows good performance to be achieved under ideal and non-ideal supply voltages. The stability and the dynamic behavior of the overall system has been analyzed by introducing suitable transfer functions. The analytical developments have been confirmed by performing numerical simulations on a realistic circuit model implemented with PSpice.**

## I. INTRODUCTION

Industrial plants often provide different types of energy that can be partially converted into electric energy by means of cogeneration systems. These solutions allow, in general, the improvement of the overall efficiency of the plant. If low-pressure steam is available, an efficient utilization of the related energy is achieved employing a high-speed turbine. In order to avoid the need of a reduction gear, the use of high-speed synchronous generators directly coupled to the turbine shaft is considered a valid solution [1]. The electric energy produced by the generator is rectified and delivered to the mains by a dc/ac converter having a structure very similar to that of a standard shunt active filter [2]-[5]. Using a suitable control technique, the PCS can operate as active ac line conditioner [6], [7]. In this way, additional tasks, such as compensation of reactive power and current harmonics of non-linear loads, can be performed.

A control strategy for the PCS, which can be implemented on a DSP based controller, has been presented in [8], [9]. The control method performs the direct regulation of the source currents, which are forced to be sinusoidal and in phase with the corresponding line-to-neutral voltages, as in active power filters [10]-[12]. Nevertheless, undesired behavior may occur when the supply voltages are non-ideal, such in presence of unbalance, harmonics, flicker, or when the line impedance is not negligible. In order to achieve a good performance of the PCS even in these non-ideal conditions, a new control strategy has been analyzed. The behavior of the cogeneration system has been verified by PSpice in several steady-state and transient non-ideal operating conditions.

## II. DESCRIPTION OF THE COGENERATION SYSTEM

A simplified block diagram of the whole system is shown in Fig. 1. The generator (*G*) is a 4-pole, three-phase, PM synchronous machine, operating at 400 Hz. The rated power of the turbine (*T*) is 20 kW at the rated mechanical speed of 12,000 rpm.

As a result of using rare-earth PM, the armature reaction effect in the generator is quite low, thus the synchronous inductance of the machine is reduced as compared to that of machines with traditional construction. However, due to the high stator frequency, the synchronous impedance ($Z_G$) is still high. In order to avoid a limitation of the output power, the capacitor ($C_G$) has been inserted for the compensation of the synchronous impedance. The series connection has been preferred to the shunt connection in order to achieve a compensation independent of the load . Assuming $C_r$ as the value of the series capacitance that gives resonance with the synchro-

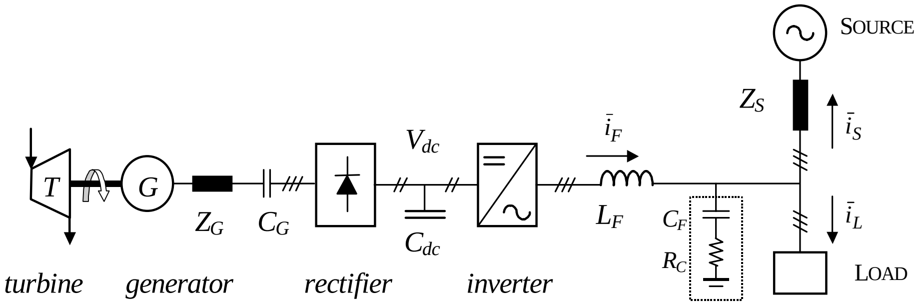


Fig. 1. Block diagram of the cogeneration system.

0-7803-5695-0/00/$10.00 (c) 2000 IEEE

nous inductance at 400 Hz, it has been verified that choosing $C_G$ equal to $C_r$ leads to current overshoots during load transients. This drawback has been overcame assuming $C_G = 0.8\, C_r$. With this capacitance value the dynamic behavior of the co-generation system is quite good, and the residual voltage drop due to the partial synchronous reactance compensation at 400 Hz is still acceptable.

The control structure of the whole system is based on two main regulators. The former is a mechanical regulator that keeps the outlet steam pressure of the turbine close to its reference value. The latter is the intermediate dc-link voltage regulator that provides the indirect control of the speed, being the dc-link voltage almost proportional to the mechanical speed. This regulator generates also the reference currents that should be injected into the mains by the PCS. The control strategy of this regulator will be analyzed in details in the next Sections.

The principle of operation of the PCS may be summarized as follow. When the load is not connected to the mains, the cogeneration system will supply the rated active power. As the load is switched on, the source will supply the difference between the active power required by the load and the active power delivered by the cogeneration system. In general, the reactive power of the load is compensated by the PCS. If the reactive power exceeds the converter ratings, the difference will be supplied by the source.

## III. PCS CONTROL STRATEGY

The aim of the PCS is to control the active power flow from the generator to the mains, and to compensate the reactive power and the current harmonics of non-linear loads connected to the same network. These requirements can be obtained forcing the total source currents to track the waveforms of the corresponding line-to-neutral source voltages, and controlling the amplitude of these currents through the dc-link voltage regulator according to the power balance equation [9]. This control technique performs correctly in presence of balanced and sinusoidal supply voltages, whereas some problem may occur when the supply voltages are affected by perturbations. In order to overcome these problems a solution is to synchronize the source currents with the fundamental positive sequence component of the source voltages, leaving the task of determining the current amplitude to the dc-link voltage regulator.

In this way a balanced and sinusoidal system of source currents is achieved, even in presence of voltage perturbation coming from the mains.

The analytical developments have been carried out using the space vector representation of three-phase quantities in a d-q stationary reference frame.

### A. DC-link voltage controller

The control strategy proposed for the regulation of the dc-link voltage is summarized by the scheme shown in Fig. 2.

The reference source current $\bar{i}_S^*$ is obtained by multiplying the unity vector $\hat{v}_S^{+1}$, which is in phase with the positive sequence fundamental component of the line voltage $\bar{v}_S$, by the reference source current magnitude $I_S^*$. This last is generated by the regulator $R(s)$, which operates on the instantaneous error between the reference value $V_{dc}^*$ and the actual value $V_{dc}$ of the dc-link voltage. It is known that in presence of unbalanced either in the source voltages or in the load, the instantaneous power flow is characterized by fluctuations at a frequency of 100 Hz. The power conditioning system that is connected in parallel with the load will be affected by these power fluctuations. As a consequence a 100Hz oscillation can be observed in the dc-link voltage of the PCS.

This voltage oscillation determines a perturbation on the reference value of the source current magnitude $I_S^*$, which is reflected on the instantaneous value of the source currents determining current harmonics. To avoid this drawback, an explicit filtering action should be introduced in the regulator $R(s)$ to smooth the 100 Hz component.

In this paper a standard PI regulator combined with a first order low pass filter has been chosen for $R(s)$. The behavior of the regulator is represented by the following equation, where s is the Laplace operator

$$R(s) = \frac{1}{1 + s\tau_c}\left(K_P + \frac{K_I}{s}\right). \tag{1}$$

The regulator parameter are: $K_I = 2$, $K_P = 10$, $\tau_c = 20$ ms.

### B. Positive sequence detection

The source voltage vector can be expressed in terms of fundamental sequence components and harmonic components as

$$\begin{aligned}\bar{v}_S &= \bar{v}_S^{+1} + \bar{v}_S^{-1} + \sum_{k=\pm 2}^{\pm\infty} \bar{v}_S^k = \\ &= \bar{V}_S^{+1} e^{j\omega t} + \bar{V}_S^{-1} e^{-j\omega t} + \sum_{k=\pm 2}^{\pm\infty} \bar{V}_S^k e^{jk\omega t} .\end{aligned} \tag{2}$$

Writing (2) with respect to a synchronous positive rotating frame yields:

$$\bar{v}_S^{\omega} = \bar{v}_S\, e^{-j\omega t} = \bar{V}_S^{+1} + \bar{V}_S^{-1} e^{-j2\omega t} + \sum_{k=\pm 2}^{\pm\infty} \bar{V}_S^k e^{j(k-1)\omega t} \tag{3}$$

It can be noted that the negative sequence fundamental component $\bar{v}_S^{-1}$ and the harmonic components have zero dc value. Then, by applying an opportune low-pass filter, it is possible to extract the phasor of the positive sequence fundamental component $\bar{V}_S^{+1}$. For this purpose a second order low-pass filter has been applied to the source voltage vector, according to the following equation

$$\bar{v}_S^{+1} = \bar{V}_S^{+1} e^{j\omega t} = \frac{1}{(1+\tau s - j\omega\tau)^2}\bar{v}_S \, . \tag{4}$$

Once $\bar{v}_S^{+1}$ is estimated, the unity space vector $\hat{v}_S^{+1}$ can be readily calculated and utilized to modulate the output of *R*, as shown in Fig. 2.

### *C. AC current controller*

The ac current regulator must operate in order to keep the source current $\bar{i}_S$ close to its reference value $\bar{i}_S^*$. As a first step, the reference filter current $\bar{i}_F^*$ must be determined since the VSI acts directly on the filter current $\bar{i}_F$. The filter current is given by

$$\bar{i}_F^* = \bar{i}_S^* + \bar{i}_L \, , \tag{5}$$

where the load current $\bar{i}_L$ is a measured quantity. The reference voltage $\bar{v}_F^*$ for the PWM-VSI can be calculated by using a regulator in which the input variable is the difference between the reference and the actual value of the filter current

$$\Delta\bar{i}_F = \bar{i}_F^* - \bar{i}_F \, . \tag{6}$$

The equation of the current controller can be expressed as follows

$$\bar{v}_F^* = \bar{v}_S + L_F \frac{\Delta\bar{i}_F}{\Delta t} = \bar{v}_S + K\Delta\bar{i}_F \, . \tag{7}$$

This equation shows that the current controller behaves as a proportional controller having gain *K*, with an additional term for the source voltage compensation. On the basis of (5), (6) and (7), the block diagram shown in Fig. 3 can be derived. It can be noted that the filter current is regulated through a closed loop control scheme.

Assuming that the VSI can generate the reference voltage at each cycle period, i.e. $\bar{v}_F = \bar{v}_F^*$, the following transfer function for the filter current can be obtained

$$\bar{i}_F = \frac{1}{1+\frac{L_F}{K}s}\bar{i}_F^* \, . \tag{8}$$

Eq. 8 shows that the response of the ac current controller is represented by a first order low-pass filter with a time constant $\tau = L_F/K$. The PCS behavior as active filter is mainly determined by the dynamic response of this current regulator.

Low values of $L_F$ will determine fast current variations, and then a wide filter bandwidth. On the other hand, high values of $L_F$ reduce the HF harmonics of the currents injected into the mains by the PCS, improving the voltage quality at the point of common coupling. According to (7), by increasing *K* it is possible to compensate high values of $L_F$. However, this possibility is limited by the maximum output voltage capability of the VSI, which is defined by the value of the dc-link voltage $V_{dc}$.

## IV. EFFECTS OF THE SUPPLY VOLTAGE NON-IDEALITIES

As a first example, a switching-on of a 40 KW load under sinusoidal and balanced supply voltages has been considered. The results obtained are shown in Fig. 4. Before the switching-on of the load, the power of the cogeneration system is completely delivered to the source. After the switching-on, being the load power higher than the rated power of the cogeneration system, a reversal of the source power flow occurs (Fig. 4b). From Figs. 4a and 4b, it is evident the capability of the PCS to smooth the variation of the source current amplitude during load changes. This feature is achieved against an increase of the generator current (Fig. 4c). It is possible to reduce the generator over-current by adjusting the parameters of the dc-voltage regulator. The performance of the cogeneration system for various supply voltage non-idealities is analyzed in the following examples.

### *A. Line impedance*

The effects produced by the switch commutations of the inverter are reflected on the voltage in the point of common coupling, introducing a HF voltage ripple. The amplitude of the voltage ripple is related to the ratio between the source inductance ($L_S$) and the link inductance ($L_F$). Figs. 5a and 5b show the voltage and current waveforms in the point of common coupling for different values of $L_F$. The voltage ripple is acceptable when using a large value of the link inductance ($L_F$ = 2 mH, Fig. 5a), whereas it is unacceptable when reducing this value ($L_F$ = 0.5 mH, Fig. 5b). In this case, the voltage quality can be improved by introducing a parallel capacitive filter ($C_F$ = 50 μF, damping resistance $R_C$ = 1.3 Ω).

The results obtained are shown in Fig. 5c. It can be noted that the use of a small link inductance it is advisable to increases the PCS bandwidth when operating as active filter.

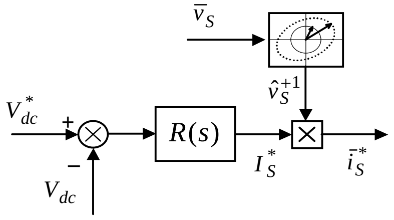


Fig. 2. DC-link voltage controller.

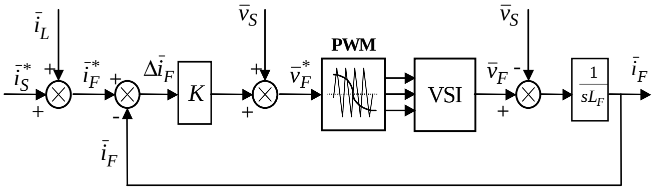
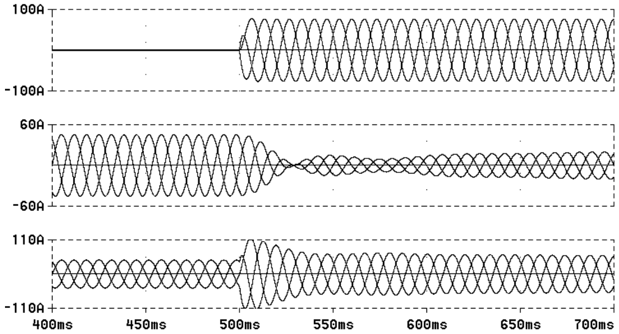
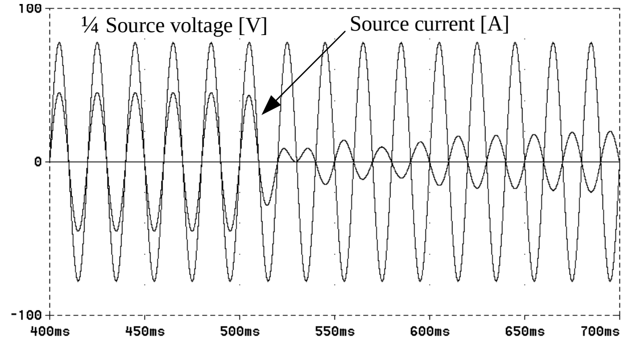


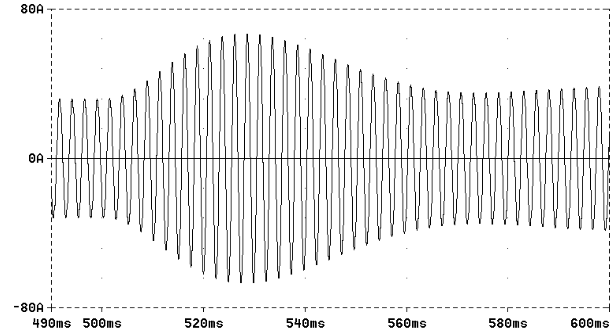
Fig. 3. AC current controller.



(a) Top to bottom: Load, Source, and PCS currents.

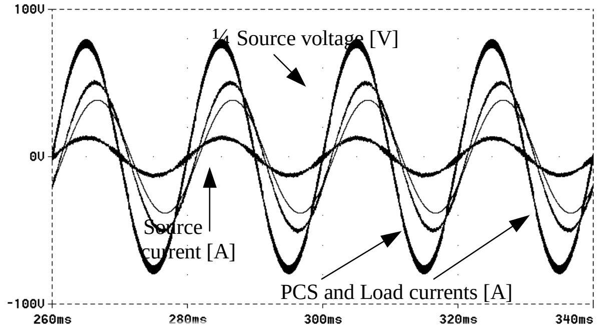


(b) Details of the source voltage and current.

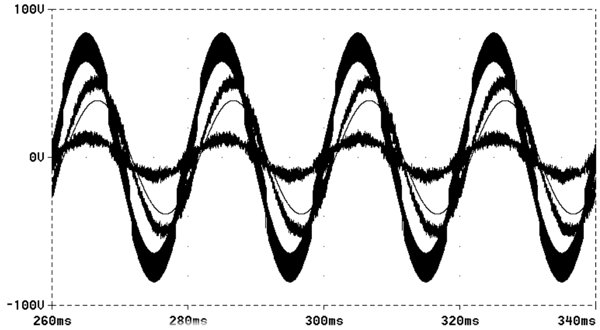


(c) Generator phase current during the load change.

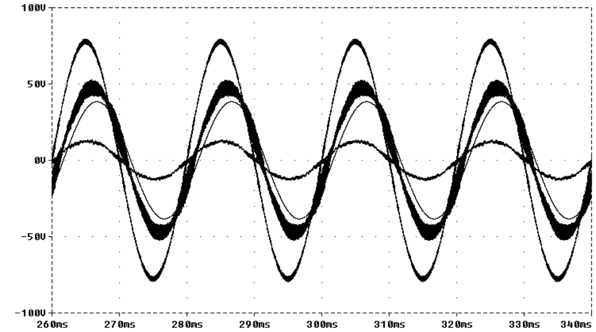
Fig. 4. Switch-on of a load in ideal source conditions.



(a) $L_S$ =100μH, $L_F$ =2mH, no passive filters.



(b) $L_S$ =100μH, $L_F$ =0.5 mH, no passive filters.



(c) $L_S$ =100μH, $L_F$ =0.5 mH, with a parallel capacitive filter ($C$ =50μF, $R_C$ =1.3 Ω).

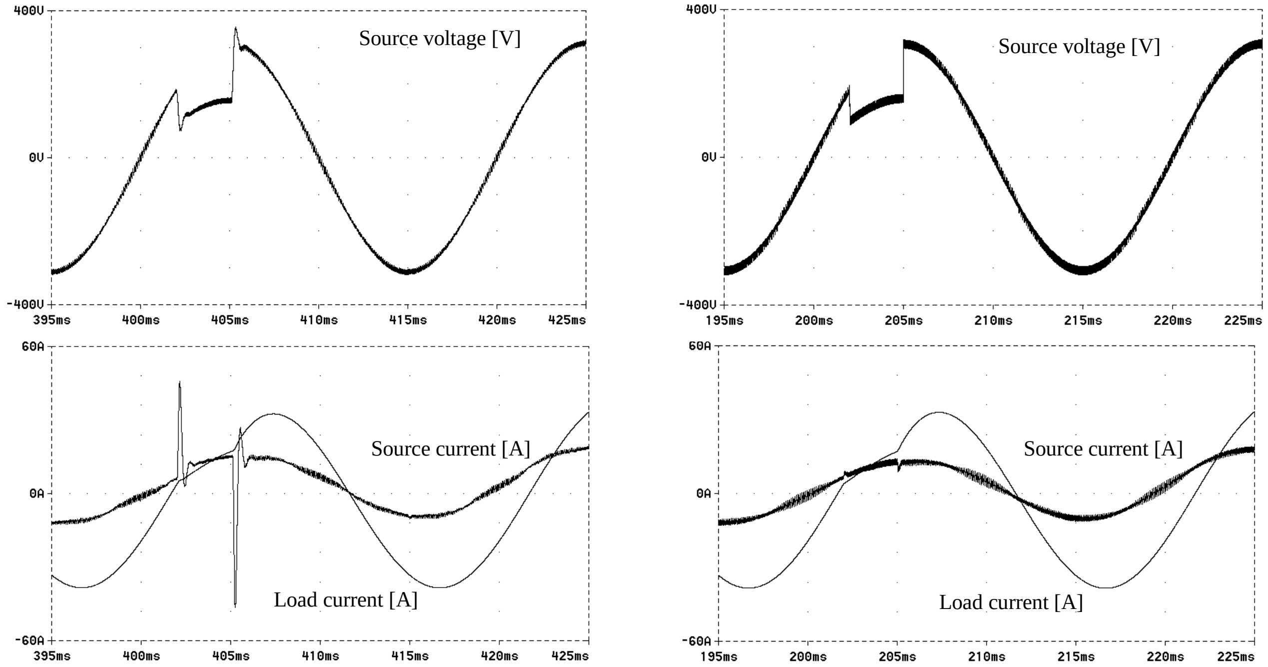
Fig. 5. Voltage and current waveforms in the point of common coupling.

The system behavior has been verified even in the case of voltage sags. If a capacitive filter is used to smooth the voltage ripple, the presence of a high voltage derivative, i.e. high $dv/dt$, produces undesired current spikes. Fig. 6a shows a typical voltage sag (50%, 5 ms) and the corresponding current spikes on the capacitive filter. As shown in Fig. 6b, the same voltage sag does not determine relevant over currents if the filter inductance is increased and the capacitive filter is not used.

### *B. Source voltage unbalance*

Unbalanced supply voltages determine a space voltage vector rotating with a variable angular speed and describing an elliptical locus. The synchronization of the source reference currents to this vector causes the generation of unbalanced or non-sinusoidal currents, which can further decrease the quality of the supply voltages. The control algorithm proposed in this paper avoids this problem. Fig. 7 shows the steady state and the dynamic behavior of the cogeneration system during the switching on of a linear load under unbalanced supply voltages.

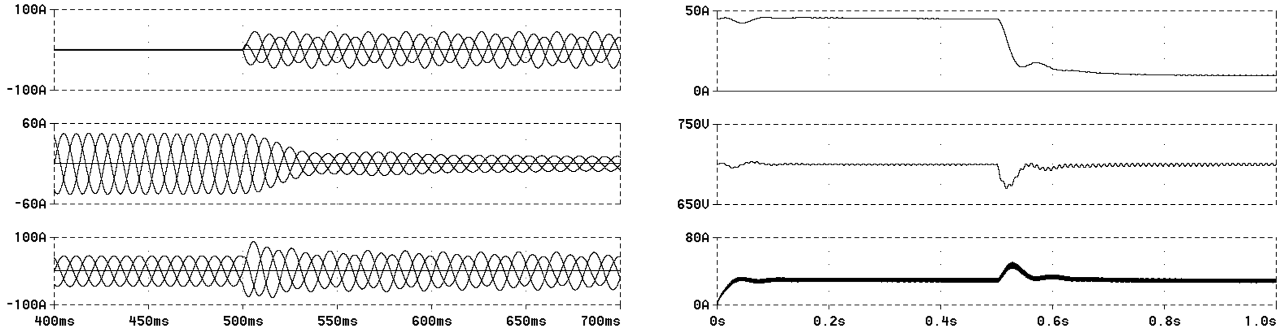
In Fig. 7a the source currents are still sinusoidal with a smooth amplitude variation. In this condition, the PCS delivers unbalanced currents that compensate the load current unbalance due to the supply voltage unbalance. Fig. 7b shows the fast time response of the dc-link regulator during transient conditions, even in presence of unbalanced source voltages.



(a) $L_F$ =0.5 mH, parallel capacitive filter

(b) $L_F$ =2mH, no passive filter

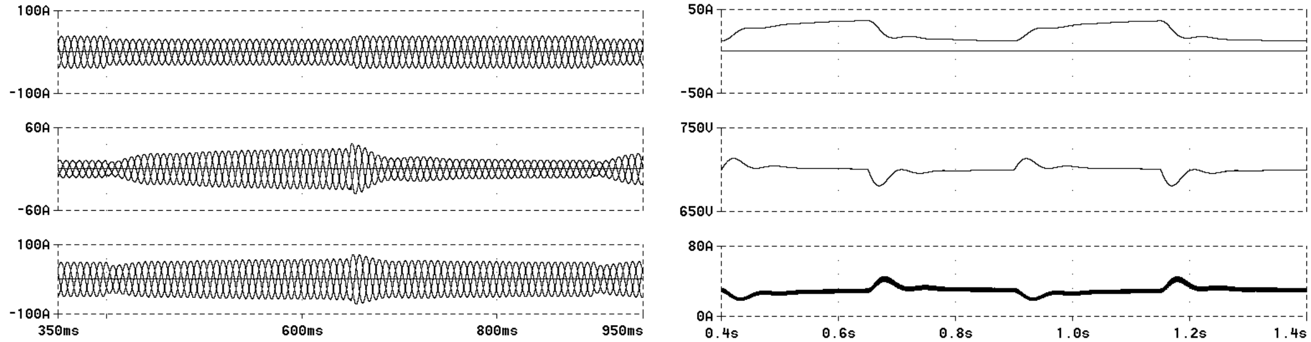
Fig. 6. Effects of a source voltage sag.



(a) Top to bottom: Load, Source, and PCS currents.

(b) Top to bottom: reference source current magnitude,
dc-link voltage, and dc-link current.

Fig. 7. Switch-on of a balanced load with 20% unbalance degree of the  source voltages.



(a) Top to bottom: Load, Source, and PCS currents.

(b) Top to bottom: reference source current magnitude,
dc-link voltage, dc-link current.

Fig. 8. Source voltage flicker (±10%, 2 Hz).

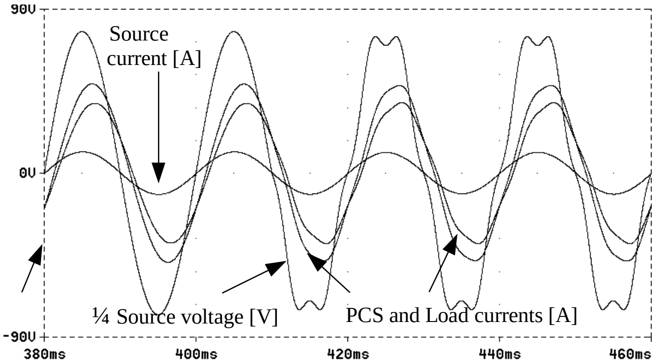


Fig. 9. Effects of a 5th harmonic in the source voltage.

### C. Source voltage flicker

To verify the PCS performance during the flicker phenomena, a pulsed variation of the supply voltages has been considered (±10%, 2 Hz). The numerical results are given in Fig. 8. Fig. 8a shows the waveforms of load, source, and PCS currents. In response to the supply variations, the dc-voltage regulator changes the amplitude of the reference source currents in order to deliver the rated active power (Fig. 8b).

### D. Source voltage harmonics

As it is known, non-linear loads connected to the network determine the presence of low-order harmonics in the supply voltages owing to the non-negligible line impedance. A numerical simulation has been carried out considering a voltage distortion caused by a 5th harmonic component having amplitude of 0.1 p.u.

Fig. 9 shows that the source current maintains a sinusoidal waveform despite the harmonic distortion in the supply voltages.

## V. CONCLUSIONS

An effective control scheme for the power conditioning system of a cogeneration plant has been proposed in this paper. The principle of operation is based on keeping the dc-link voltage close to the reference value. This ensures a practically constant angular speed for the turbine-generator set and, for a given value of the outlet steam pressure, a constant active power injected into the mains.

With standard control algorithms, the PCS behavior is affected by the voltage perturbations coming from the mains, such as voltage unbalance and voltage distortion, leading to system instability and/or line current harmonics.

In order to avoid these drawbacks, a new control algorithm is proposed and the behavior of the control system has been analyzed in several operating conditions characterized by different supply voltage perturbations. It has been verified by numerical simulations that in all cases the PCS operation is stable and the source currents are balanced and sinusoidal.

## REFERENCES

[1] R.K. Jardan "Generation of Electric Energy by High-Speed Turbine - Generator Sets," *Proceedings of Intelec'95 Conference*, The Hague, The Netherlands, Oct. 29 - Nov. 1, pp. 664-670.

[2] H. Akagi, Y. Kanazawa, A. Nabae, "Instantaneous Reactive Power Compensators Comprising Switching Devices without Energy Storage Components," *IEEE Trans. on IA*, Vol. 20, 1984.

[3] H. Akagi, A. Nabae, S. Atoh, "Control Strategy of Active Power Filters Using Multipole voltage-source PWM Converters," *IEEE Trans. on IA*, Vol. 22, May/June 1986, pp. 460-465.

[4] L. Malesani, L. Rossetto, P. Tenti, "Active Filters for Reactive Power and Harmonic Compensation," *Proc. IEEE-PESC*, June 1986, p. 321.

[5] H. Fujita, H. Akagi, "The Unified Power Quality Conditioner: The Integration of Series Active Filter and Shunt Active Filters," *Proc. IEEE-PESC*, Baveno (IT), June 1996, pp. 494-501.

[6] E. Raaijen et. al. "An Efficient and Economical Active AC Line Conditioner," *Proc. of IEEE-INTELEC*, The Hague, The Netherlands, Oct 29-Nov 1, 1995, pp. 664-670.

[7] L. Gyugyi, E.C. Strycula, "Active AC Power Filter," *Proc. IEEE-IAS Annual Meeting*, 1976, p. 529.

[8] D. Casadei, G. Grandi, R.K. Jardan, F. Profumo, "Control Strategy of a Power Line Conditioner for Cogeneration Plants," *Proc. of IEEE-PESC Conference*, Charleston-SC (USA), June 27- July 1, 1999.

[9] D. Casadei, G. Grandi, U. Reggiani, C. Rossi, "Active AC Line Conditioner for a Cogeneration System," *European Confer. on Power Electronics and Applications, EPE*, Lausanne (CH), September 7-9, 1999.

[10] P. Delarue, R. Bausierre, "New Control Methods for Active Power Filter Needing Line Current Measurements only," *Proc. EPE*, Sevilla (SP), Vol. 1, 1995, pp. 914-919.

[11] L.A. Moran, J.W. Dixon, R.R. Wallace, "A three- phase active power filter operating with fixed switching frequency for reactive power and current harmonic compensation," *IEEE Trans. on IE*, Vol. 42, No.4, 1996, pp.402-408.

[12] D. Casadei, G. Grandi, U. Reggiani, C.Rossi, "Control methods for active power filters with minimum measurement requirements," *Proc. of IEEE-APEC*, Dallas-TX (USA), March 1999, Vol. 2, pp.1153-1158.

[13] D. Casadei, G. Grandi, U. Reggiani, G. Serra, A. Tani, "Behavior of a Power Conditioner for µ-SMES Systems under Unbalanced Supply Voltages and Unbalanced Loads," *Proc. of IEEE International Symposium on Industrial Electronics, ISIE*, Bled (SI), July 12-16, 1999.