COOPERATIVE CONTROL OF ELECTRONIC POWER PROCESSORS IN MICRO-GRIDS

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***Abstract* – Micro-grids offer a new challenging domain for power electronics, since they include a variety of power sources and electronic power processors (*EPP*) interacting each other. In micro-grids, energy efficiency requires smart control of power flow, and power quality calls for voltage support by reactive power regulation, suppression of voltage distortion at load terminals and limitation of current harmonics at utility interface. Pursuing such complex duties requires *EPP* to perform cooperatively, irrespective of type and power rating. This paper provides a background to cooperative control of distributed *EPP* in micro-grids, where power capability is limited, voltage supply is often distorted and distribution line impedances play a significant role.**

***Keywords* – Micro-grids, electronic power processing, cooperative control, distributed compensation.**

I. INTRODUCTION

In recent years, electrical networks have been experiencing an increasing concentration of distorting loads, causing harmonic currents and voltage distortion. Obviously, the impact of distorting loads grows as their power rating approaches the power capability of the grid.

On the other hand, the adoption of "green energy" policies in several countries encouraged installation of small- or medium-power units based on renewable energy sources in support of conventional power sources. Since every "green power" source is equipped with a controllable Power Switching Interface (*PSI*), we assist to the proliferation of "intelligent power sources".

The above trends create a new scenario with a growing role for *micro-grids*, where intelligent power sources cooperate to support energy demand by exploiting renewable energy sources at the maximum possible extent.

This scenario offers new opportunities, problems and challenges to power electronics. On one side, in fact, micro-grids are characterized by limited power capability, and are therefore affected by voltage regulation problems and distortion; on the other side, however, they can take advantage of cooperative operation of distributed *EPP* to ensure energy efficiency and power quality.

The *micro-grid paradigm* is therefore different from the traditional one, based on the assumption of few power sources of large capacity. While traditionally every apparatus connected to the grid is devised to suit local needs, assuming no interaction with the rest of the network, in micro-grids the local and global performances must be accounted as a whole, because any equipment interacts with the entire network. In particular, every action to improve micro-grid operation (power flow control, voltage support, unbalance compensation, harmonic suppression) must be coordinated among all *EPP* acting in network: *PSI*, *SVC* (Static VAR Compensators) and *APF* (Active Power Filters).

In approaching the control problem, consider that *EPP* tend to interact through distribution lines, possibly causing control instabilities. Moreover, they are normally designed for sinusoidal supply and their operation can be affected by voltage distortion.

From the above considerations it follows that facing the problems of micro-grids requires a comprehensive approach to cooperative operation of *EPP*. A revision of *EPP* control strategy is needed, since they must operate under non-sinusoidal conditions and perform local and global duties at the same time, by interacting with each other and remote network controllers. The control architecture must support global and local optimization algorithms, allowing full exploitation of distributed intelligent power sources.

This paper presents an approach to cooperative control of *EPP* acting in micro-grids. The approach makes use of instantaneous complex power as the basic control variable, and aims at the optimization of local and global performance indexes by proper sharing of control duties among *EPP*.

II. THEORETICAL BACKGROUND

The problem of defining power and current terms under non-sinusoidal conditions dates back some eighty years [1]. While definition of active power and current terms was developed in early 30's [2], definition of power and current terms related to "reactive" and "harmonic" phenomena is still under discussion and different solutions are proposed depending on application field [2-10]. In fact, this is the basis for design and operation of *SVC* [11-14] and passive filters [15]. More recently, availability of *APF* made feasible the concept of "instantaneous compensation", based on suitable definitions of instantaneous power and current terms [16-27]. Coordination of multiple compensation devices acting in the same network has been addressed lastly [28-38]. All these issues merge together when dealing with cooperative control of *EPP* in micro-grids.

Before entering control issues, let's remember that *EPP* can be subdivided in two main categories:

- *Static VAR Compensators* (*SVC*), i.e., Thyristor Switched Capacitors (*TSC*), Thyristor-Controlled Reactors (*TCR*), and STATCOM, which are called *quasi-stationary EPP* because their response time is larger than line period.

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- *Switching Power Compensators (SPC)*, i.e., *SPI* and *APF*, which are called *dynamic EPP* because their response time is less than line period.

The control approaches for the two types of *EPP* are obviously different. In fact, *SVC* handle electrical quantities averaged over one or more line cycles, while *SPC* perform control within a switching cycle. However, the two approaches can be unified by making use of the control quantities described hereafter.

Power terms under non-sinusoidal conditions

We make reference to *instantaneous complex power* [9], which is defined, at a generic port of a N-phase network, by:

$$\dot{s} = p + j\,q = \underline{u} \circ \underline{i} + j\,\underline{\hat{u}} \circ \underline{i} \tag{1}$$

Term p represents *instantaneous (real) power* absorbed by the network, q represents *instantaneous imaginary power*, $\underline{u}$ is vector of port voltages and $\underline{i}$ is vector of port currents. Operator "*dot*" means scalar product, i.e.:

$$p = \underline{u} \circ \underline{i} = \sum_{n=1}^{N} u_n i_n \qquad q = \underline{\hat{u}} \circ \underline{i} = \sum_{n=1}^{N} \hat{u}_n i_n \tag{2}$$

Operator "*hat*" means *normalized integral*, i.e. unbiased voltage integral times angular frequency $\omega = 2\pi/T$ (T is line period). Quantity $\hat{u}$ is homogeneous to u; moreover, if u is sinusoidal, its rms value U equals rms value $\hat{U}$ of normalized integral $\hat{u}$.

All power terms p, q, $\dot{s}$ are conservative in every electrical network [9,36].

By averaging (1) over period T we get:

$$\dot{S} = \overline{\dot{s}} = \overline{p} + j\,\overline{q} = \langle \underline{u}, \underline{i} \rangle + j \langle \underline{\hat{u}}, \underline{i} \rangle = P + j\,Q \tag{3}$$

Chevrons refer to internal product, i.e.:

$$P = \langle \underline{u}, \underline{i} \rangle = \frac{1}{T}\int_0^T \underline{u} \circ \underline{i}\, dt = \frac{1}{T}\sum_{n=1}^{N}\int_0^T u_n i_n\, dt = \sum_{n=1}^{N} P_n \tag{3.a}$$

$$Q = \langle \underline{\hat{u}}, \underline{i} \rangle = \frac{1}{T}\int_0^T \underline{\hat{u}} \circ \underline{i}\, dt = \frac{1}{T}\sum_{n=1}^{N}\int_0^T \hat{u}_n i_n\, dt = \sum_{n=1}^{N} Q_n \tag{3.b}$$

Definitions (3) are valid also for non-sinusoidal operation and extend those used in the sinusoidal domain. In particular, $\dot{S}$ is *complex power*, P is *active power* and accounts for *average power* absorbed by the network, Q is *reactive power* and relates to *average energy* stored in the network. In [9,36] it was demonstrated that, in a passive network with K_L inductors and K_C capacitors, reactive power Q is:

$$\begin{aligned} Q &= 2\,\omega\left(W_L - W_C\right) = 2\,\omega\left(\sum_{k=1}^{K_L}\overline{w}_{L\,k} - \sum_{k=1}^{K_C}\overline{w}_{C\,k}\right) = \\ &= \sum_{k=1}^{K_L}\omega\, L_k I_{Lk}^2 - \sum_{k=1}^{K_C}\omega\, C_k U_{Ck}^2 \end{aligned} \tag{4}$$

where W_L is *total (average) inductive energy*, W_C is *total (average) capacitive energy*, I_{Lk} is rms current in generic inductor, and U_{Ck} is rms voltage on generic capacitor.

The *apparent power* is defined by:

$$A = \boldsymbol{U}\,\boldsymbol{I} \tag{5}$$

where bold variables represent the *norm*, i.e.:

$$\begin{aligned} \boldsymbol{U} &= \sqrt{\langle \underline{u}, \underline{u} \rangle} = \sqrt{\frac{1}{T}\sum_{n=1}^{N}\int_0^T u_n^2\, dt} = \sqrt{\sum_{n=1}^{N} U_n^2} \\ \boldsymbol{I} &= \sqrt{\langle \underline{i}, \underline{i} \rangle} = \sqrt{\frac{1}{T}\sum_{n=1}^{N}\int_0^T i_n^2\, dt} = \sqrt{\sum_{n=1}^{N} I_n^2} \end{aligned} \tag{6}$$

For single-phase quantities the norm coincides with rms value. The Cauchy-Schwartz inequality states that:

$$\left|\langle \underline{u}, \underline{i} \rangle\right| \le \boldsymbol{U}\,\boldsymbol{I} \qquad \Leftrightarrow \qquad |P| \le A \tag{7}$$

The ratio between P and A is *power factor* λ.

Current terms under non-sinusoidal conditions

In poly-phase circuits the generic phase current i_n can be decomposed as follows:

$$i_n = i_{a\,n} + i_{r\,n} + i_{v\,n} \tag{8}$$

Term $i_{a\,n}$ is *active current*, given by:

$$i_{a\,n} = G_n\, u_n = \frac{P_n}{U_n^2} u_n \tag{8.a}$$

where P_n is active power and G_n is *equivalent conductance* of phase n. Term $i_{r\,n}$ is *reactive current*, given by:

$$i_{r\,n} = B_n\, \hat{u}_n = \frac{Q_n}{\hat{U}_n^2}\hat{u}_n \tag{8.b}$$

where Q_n is reactive power and B_n, is *equivalent susceptance* of phase n. *Void current* $i_{v\,n}$ is defined by difference:

$$i_{v\,n} = i_n - i_{a\,n} - i_{r\,n} \tag{8.c}$$

It is noticeable that active current $i_{a\,n}$ conveys entire active power P_n and no reactive power; reactive current $i_{r\,n}$ conveys entire reactive power Q_n and no active power; void current $i_{v\,n}$ conveys neither active nor reactive power.

The meaning of void current was explained in [33]. It includes *scattered current terms*, due to different values of the equivalent admittance at different harmonics, and *generated current terms*, i.e., harmonic terms that exist in currents only, not in voltages.

All current terms are orthogonal, thus their rms values satisfy the condition:

$$I_n^2 = I_{a\,n}^2 + I_{r\,n}^2 + I_{v\,n}^2 \tag{8.d}$$

Extending the above definitions to all phases, we set the vectors of active, reactive and void currents as follows:

$$\underline{i}_a = \begin{vmatrix} i_{a\,1} \\ \cdots \\ i_{a\,N} \end{vmatrix} = \begin{vmatrix} G_1 u_1 \\ \cdots \\ G_N u_N \end{vmatrix} \tag{9.a}$$

$$\underline{i}_r = \begin{vmatrix} i_{r1} \\ \cdots \\ i_{r\,N} \end{vmatrix} = \begin{vmatrix} B_1 u_1 \\ \cdots \\ B_N u_N \end{vmatrix} \tag{9.b}$$

$$\underline{i}_v = \underline{i} - \underline{i}_a - \underline{i}_r \tag{9.c}$$

In general, the active and reactive currents can further be split into *balanced* and *unbalanced* terms. The *balanced* *currents* refer to an equivalent symmetrical circuit which takes entire active and reactive power. They are expressed by:

$$\underline{i}_a^b = G_b\,\underline{u} \tag{10.a}$$

$$\underline{i}_r^b = B_b\,\underline{\hat{u}} \tag{10.b}$$

Equivalent admittances G_b and B_b correspond to full active and reactive power absorption, thus:

$$\left\langle \underline{i}_a^b, \underline{u} \right\rangle = P \quad \Rightarrow \quad G_b = \frac{P}{\boldsymbol{U}^2}, \quad \boldsymbol{I}_a^b = G_b\,\boldsymbol{U} = \frac{P}{\boldsymbol{U}} \tag{11.a}$$

$$\left\langle \underline{i}_r^b, \underline{\hat{u}} \right\rangle = Q \quad \Rightarrow \quad B_b = \frac{Q}{\hat{\boldsymbol{U}}^2}, \quad \boldsymbol{I}_r^b = B_b\,\hat{\boldsymbol{U}} = \frac{Q}{\hat{\boldsymbol{U}}} \tag{11.b}$$

The remaining active and reactive phase currents are the *unbalanced components*, which account for the asymmetrical behavior of the various phases:

$$\underline{i}_a^u = \underline{i}_a - \underline{i}_a^b = \begin{vmatrix} (G_1 - G_b)u_1 \\ \ldots \\ (G_N - G_b)u_N \end{vmatrix} \tag{12.a}$$

$$\underline{i}_r^u = \underline{i}_r - \underline{i}_r^b = \begin{vmatrix} (B_1 - B_b)\hat{u}_1 \\ \ldots \\ (B_N - B_b)\hat{u}_N \end{vmatrix} \tag{12.b}$$

In conclusion, we can split the total currents as:

$$\underline{i} = \underline{i}_a^b + \underline{i}_r^b + \underline{i}_a^u + \underline{i}_r^u + \underline{i}_v \tag{13.a}$$

All terms are orthogonal, thus:

$$\boldsymbol{I} = \sqrt{\boldsymbol{I}_a^{b\,2} + \boldsymbol{I}_r^{b\,2} + \boldsymbol{I}_a^{u\,2} + \boldsymbol{I}_r^{u\,2} + \boldsymbol{I}_v^{\,2}} \tag{13.b}$$

<u>*Apparent power decomposition*</u>

From (11) we express the active and reactive power as:

$P = \boldsymbol{U}\,\boldsymbol{I}_a^b$ *(balanced) active power* (14.a)

$Q = \hat{\boldsymbol{U}}\,\boldsymbol{I}_r^b$ *(balanced) reactive power* (14.b)

By similarity, we define the *unbalance power terms* as:

$N_a = \boldsymbol{U}\,\boldsymbol{I}_a^u$ *unbalanced active power* (14.a)

$N_r = \hat{\boldsymbol{U}}\,\boldsymbol{I}_r^u$ *unbalanced reactive power* (14.b)

The apparent power can now be expressed as:

$$A = \boldsymbol{U}\,\boldsymbol{I} = \sqrt{P^2 + Q^2 + N^2 + D^2} \tag{15}$$

where N is *unbalance power*, given by:

$$N = \sqrt{N_a^2 + N_r^2} \tag{16}$$

and D is *distortion power*, given by:

$$D = \sqrt{D_s^2 + D_l^2} \tag{17}$$

Term D_s is *source distortion power* and depends on voltage distortion. It is given by:

$$D_s = \sqrt{\left(Q^2 + N_r^2\right)\left(\frac{\boldsymbol{U}^2}{\hat{\boldsymbol{U}}^2} - 1\right)} \tag{17.a}$$

and vanishes if supply voltages are sinusoidal ($\boldsymbol{U} = \hat{\boldsymbol{U}}$) or in absence of reactive power terms.

Term D_l is *load distortion power*. It is given by:

$$D_l = \boldsymbol{U}\,\boldsymbol{I}_v \tag{17.b}$$

and vanishes only in absence of void currents.

Achieving unity power factor requires compensation of reactive, unbalance and distortion power terms. This can be achieved by cooperative control of *EPP* acting in the network. In fact *SVC*, as a whole, can compensate for reactive and unbalance power, while *SPC* do the rest of compensation and eliminate distortion power [39].

III. CONTROL OF ELECTRONIC POWER PROCESSORS BASED ON COMPLEX POWER COMMAND

At a generic port of a 3-phase 4-wire system the absorbed real and imaginary power are:

$$p = \sum_{n=0}^{3} u_n i_n \qquad q = \sum_{n=0}^{3} \hat{u}_n i_n$$

Since p and q do not depend on voltage reference, we assume neutral voltage u_o as the voltage reference. Let:

$$u_{no} = u_n - u_o \qquad \hat{u}_{no} = \hat{u}_n - \hat{u}_o$$

we have:

$$p = \sum_{n=1}^{3} u_{no} i_n \qquad q = \sum_{n=1}^{3} \hat{u}_{no} i_n \tag{18}$$

With this voltage reference, neutral current i_o does not contribute to real and imaginary power. Defining now, for the sake of commodity:

$$\chi = \sqrt{\sum_{n=1}^{3} u_n^2} \qquad \hat{\chi} = \sqrt{\sum_{n=1}^{3} \hat{u}_n^2}$$

$$i_p = \frac{p}{\chi} \qquad i_q = \frac{q}{\hat{\chi}} \tag{19}$$

$$\nu_n = \frac{u_{no}}{\chi} \qquad \hat{\nu}_n = \frac{\hat{u}_{no}}{\hat{\chi}}$$

from (18) and (19) we obtain:

$$\begin{vmatrix} i_p \\ i_q \\ i_o \end{vmatrix} = \begin{vmatrix} \nu_1 & \nu_2 & \nu_3 \\ \hat{\nu}_1 & \hat{\nu}_2 & \hat{\nu}_3 \\ -1 & -1 & -1 \end{vmatrix} \begin{vmatrix} i_1 \\ i_2 \\ i_3 \end{vmatrix} \tag{20}$$

Since this equation system is always invertible, we can state that instantaneous complex power and instantaneous currents are related by a bi-univocal transformation.

Equation (20) is the basis for *EPP* control by power command. In fact, given complex power command $\dot{s}^*$ and *EPP* supply voltages $\underline{u}$, variables (19) can be computed. Then, current references are derived by inverting (20):

$$\begin{vmatrix} i_1^* \\ i_2^* \\ i_3^* \end{vmatrix} = \begin{vmatrix} \nu_1 & \nu_2 & \nu_3 \\ \hat{\nu}_1 & \hat{\nu}_2 & \hat{\nu}_3 \\ -1 & -1 & -1 \end{vmatrix}^{-1} \begin{vmatrix} i_p^* \\ i_q^* \\ i_o^* \end{vmatrix} \tag{21}$$

Since i_o does not contribute to instantaneous complex power, it can be set to zero or chosen to suit local needs.

Note that for sinusoidal voltages equations (20) closely approach *dq0* transformation and keep similar properties.

Power control versus current control

The above equations show that, in theory, compensators can be indifferently driven by current command or power command. In practice, there are significant differences between the two approaches.

In fact, current command cannot be used to drive a set of distributed compensators from a central controller if the network includes phase-shifting transformers. The current references should be corrected to compensate the phase shift, but this would require knowledge of the network that is not always available.

On the other side, the current command is preferable in absence of phase-shifting transformers, when the voltage difference between control section and *EPP* is only due to voltage drop on line impedances. In this case, the power command is less accurate, because it introduces a control delay which is higher than for current control. This can easily be verified for the simple two-port single-phase network shown in figure1, where voltage u_1 is impressed by a voltage source (ac supply) and current i_2 is impressed by a current source (*EPP*).

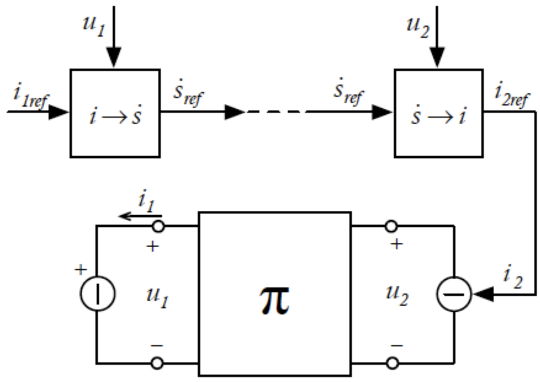

Fig. 1. Principle of complex power control.

Assuming sinusoidal quantities and let $\dot{U}_1, \dot{I}_1$ and $\dot{U}_2, \dot{I}_2$ be the phasors of port quantities, the *reciprocity theorem* says that:

$$\left.\frac{\dot{U}_2}{\dot{U}_1}\right]_{I_2=0} = \left.\frac{\dot{I}_1}{\dot{I}_2}\right]_{U_1=0} = K\, e^{j\delta} \qquad (22.a)$$

This means that a current injected at port *2* reflects at port *1* with same gain K and phase shift δ shown by no-load voltage $\dot{U}_2$ compared to source voltage $\dot{U}_1$. Let $\dot{I}_{1ref}$ be current reference at port *1* and $\dot{S}_{ref}$ be the corresponding complex power reference, current reference $\dot{I}_{2ref}$ at port *2* is chosen to meet the power reference. Thus:

$$\dot{U}_1 \dot{I}_{1ref}^{cnj} = \dot{S}_{ref} = \dot{U}_2 \dot{I}_{2ref}^{cnj} \quad \Rightarrow \quad \frac{\dot{I}_{2ref}}{\dot{I}_{1ref}} = \left(\frac{\dot{U}_1}{\dot{U}_2}\right)^{cnj} = \frac{1}{K} e^{j\delta} \quad (22.b)$$

where apex *cnj* means complex conjugate. Assuming now that current $\dot{I}_2$ tracks reference $\dot{I}_{2ref}$, the corresponding current at port *1* becomes:

$$\dot{I}_1 = K\, e^{j\delta} \dot{I}_2 = K\, e^{j\delta} \frac{1}{K} e^{j\delta} \dot{I}_{1ref} = e^{j2\delta} \dot{I}_{1ref} \qquad (22.c)$$

Therefore, the open-loop transfer function introduces a phase shift equal to 2δ. Instead, if we apply current reference $\dot{I}_{1ref}$ directly at port *2*, the phase shift is only δ.

Control of EPP units

Power and current references are handled differently by *SVC* and *SPC*. In fact, *SPC* execute directly the current command, while *SVC* need further processing [39].

SVC units appear as controllable reactances connected to the grid. Under the assumption of sinusoidal operation, they can therefore be controlled to compensate for load unbalance and reactive power according to the approach developed by C.P.Steinmetz in the early 20th century [41]. Under non sinusoidal operation the *Steinmetz circuit* can still be used, however its operation is affected and compensation is not fully achieved. Moreover, *SVC* operation inherently causes distortion, which must be suppressed by passive filters or *SPC*.

If *SVC* and *SPC* units coexist in the same network, the approach described in [39] can be applied, where *SVC* are controlled to compensate only for unbalance and reactive power associated to fundamental positive-sequence voltages, while *SPC* take care of the remaining compensation needs.

IV. COOPERATIVE CONTROL OF DISTRIBUTED ELECTRONIC POWER PROCESSORS

Figure 2 shows a general representation of networks with distributed *EPP* (*TSC*, *TCR* and *SPC*). *EPP* are shown separately, while the rest of the network (power sources, transformers, transmission lines, loads and passive filters) is included in block π. *PCC* is the point of common coupling with public utility.

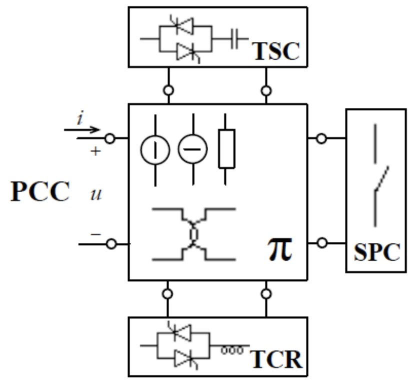

Fig. 2. Network with distributed compensators.

The goal of cooperative control is to drive every *EPP* so as to optimize suitable performance indexes, both local and global. The cooperative control architecture generally includes a *Central Control Unit* (*CCU*) and a set of *Local Control Units* (*LCU*), one per *EPP*.

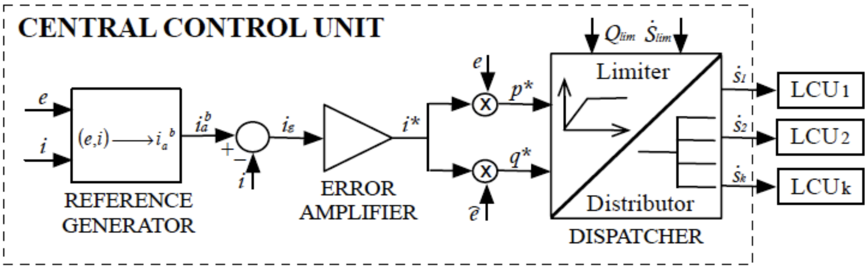

Fig. 3. Cooperative Control Architecture

The *CCU* is responsible for global performance index optimization. It processes system-level measurements, done in the network and at *PCC*, and determines the references for global control variables. Then, based on suitable duty-sharing criteria (accounting for transmission losses, incidence of *EPP* on performance indexes, available power capability etc.), it assigns the control task to every *EPP* by means of an instantaneous complex power command. Every *LCU* performs its local control duty (optimization of local performance index) and keeps the *CCU* informed about the power capability, which is available for system-level needs. Within this power capability, the *LCU* executes the power command sent by the *CCU*, thus cooperating to optimization of global performance indexes.

An example of control architecture is shown in figure 3, which refers to the simple, but common, situation where the goal of cooperative control is to optimize network behavior at *PCC* by pursing unity power factor [39]. This requires elimination of unwanted current components at *PCC*, i.e., compensation of reactive, unbalance and void currents. The *CCU* includes three main elements:

- *Reference generator* which, based on measurement at *PCC*, determines balanced active currents $\underline{i}_a^b$ according to (10.a). These are set as input current references.
- *Error amplifier*, which processes the error signal obtained by comparing actual currents $\underline{i}$ at *PCC* with references $\underline{i}_a^b$ and generates internal current references $\underline{i}^*$ and corresponding complex power command $\dot{s}^*$.
- *Dispatcher*, which distributes the compensation duty among *EPP*. The dispatcher assigns a proper power reference to each *EPP* based on its actual compensation capability (reactive power for *SVC*, apparent power for *SPC*) with the goal to minimize a global cost function which accounts for cost and effectiveness of the duty performed by every compensation unit.
  The dispatcher includes two main functional blocks: the *limiter*, which sets the actual compensation goals based on available reactive power (*SVC*) and apparent power (*SPC*); the *distributor*, which shares the compensation effort among compensators, according to suitable duty-sharing criteria.

V. APPLICATION EXAMPLE

As an example of cooperative control the network of figure 4 was simulated. It includes unbalance and distorting loads, transmission lines, transformers, various compensation units (fixed capacitor bank, *TCR*, *APF*) and is fed by distorted and asymmetrical voltages. The central and local control units are implemented according to Fig.3, with the goal to optimize the power factor at *PCC*.

The *TCR* is switched on at time t_1 (0.2 s) and the *APF* at time t_2 (0.6 s). At time t_3 (1.2 s) a sudden load change (control angles of thyristor rectifier delayed by 50°) is introduced, so as to test the dynamic response of control.

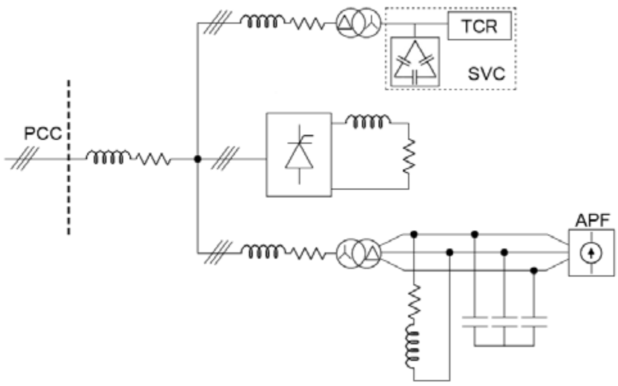

Fig. 4. Simulated Network

Figure 5 shows the voltages at *PCC*. They exhibit considerable asymmetry (unbalance factor: 10%) and distortion (5th harmonic: 5.0%; 7th harmonic: 5.0%).

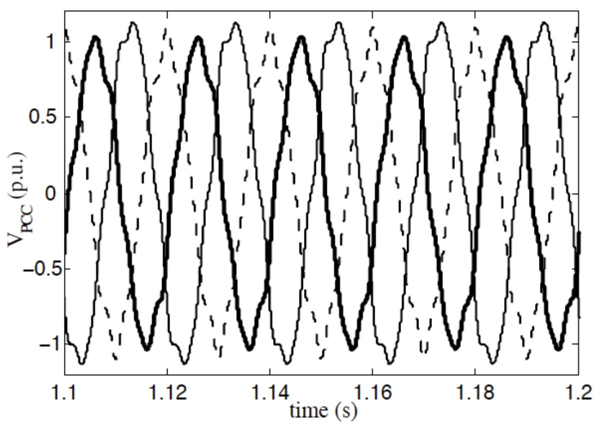

Fig. 5. Voltages at *PCC*

Figure 6 shows the currents at PCC when the compensation units are off. The high distortion is due not only to distorting load, but also to the capacitor bank located next to the *TCR*. The current asymmetry is due to load unbalance and voltage asymmetry.

Figure 7 shows the currents at *PCC* after time t_1 when the *SVC* is turned on. Although distorted, the fundamental components of the currents are now reasonably balanced and in phase with line voltages.

Figure 8 shows the currents at *PCC* after time t_2, when also the *APF* is turned on. Within the control bandwidth, the input currents now track active current references with good accuracy.

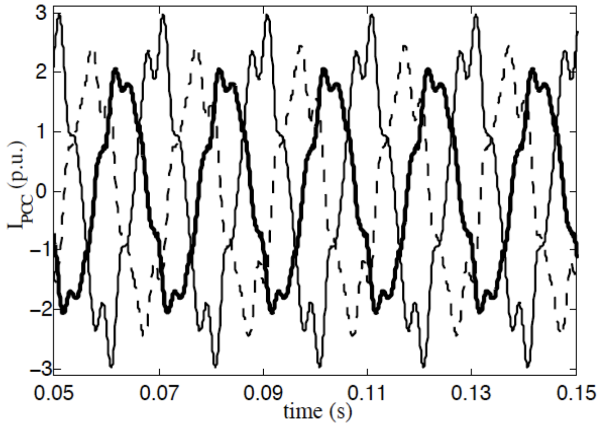

Fig. 6. Currents at *PCC* without compensation

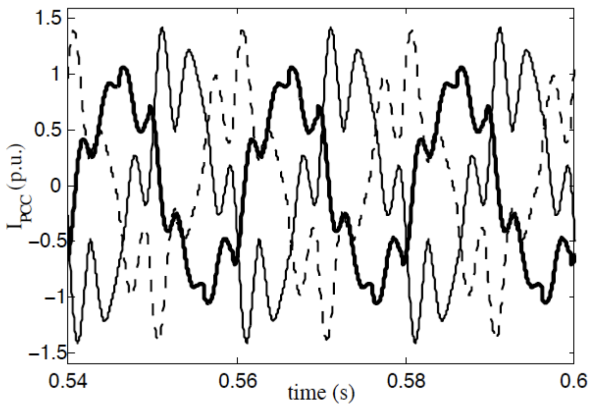

Fig. 7. Currents at *PCC* with *SVC* turned on

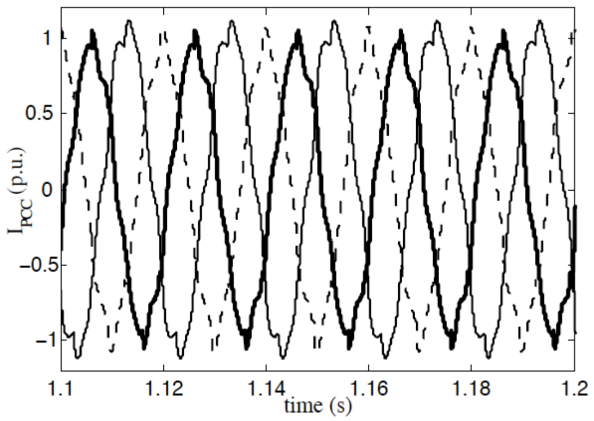

Fig. 8. Currents at *PCC* with *SVC* and *APF* turned on

Figure 9 shows the relative current error on a logarithmic scale. The error is initially very high (150%), then drops to 32% after *SVC* intervention and to 2.2% when the *APF* is switched on. The load transient causes a temporary error increase to 15%, which is recovered in 150 ms.

Finally, figures 10 and 11 show the time behavior of power factor (active power divided by apparent power) and unbalance factor at *PCC* (negative-sequence component of the input currents divided by the positive-sequence component). Both values are averaged over line period. The power factor is initially very low (0.58) due to unbalance, distortion and reactive current components. The intervention of the *SVC* almost suppresses reactive and unbalance currents, thus the power factor increases to 0.94. A power factor close to unity is reached after intervention of the *APF*, which removes residual reactive and unbalance currents together with the void currents, including those generated by the *SVC*. The effect of load transient on this parameter is temporary and small.

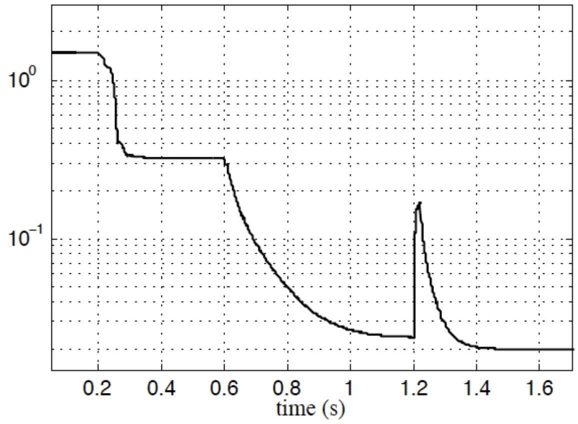

Fig. 9. Current error at *PCC* (p.u., logaritmic scale)

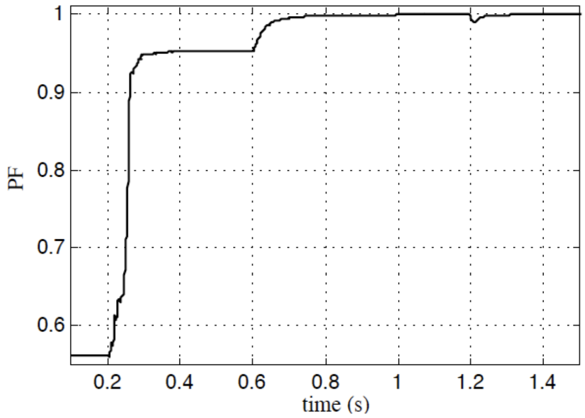

Fig. 10. Time behavior of Power Factor

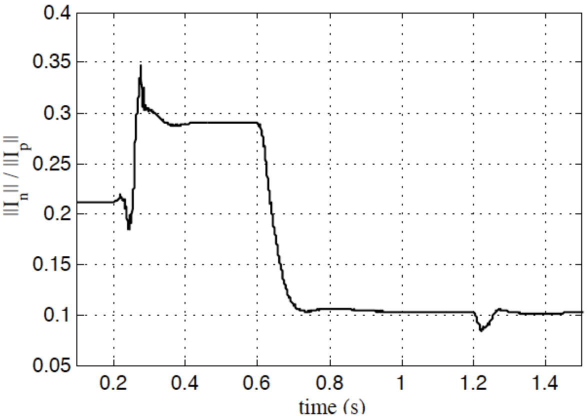

Fig. 11. Time behavior of Unbalance Factor

The unbalance factor is initially high (0.21) due to load asymmetry. The *SVC* intervention causes further increase of the unbalance factor. In fact, compensation of reactive power reduces positive-sequence currents (i.e., denominator of unbalance factor), while compensation of unbalance reduces negative-sequence currents (i.e., numerator of unbalance factor). Since the first effect is higher than the second, the result is an increase of the unbalance factor.

When the *APF* is turned on the unbalance factor drops to 0.1, because the void currents vanish. Such residual unbalance is due to voltage asymmetry. The effect of the load transient on this parameter is also small.

Figures 9, 10, 11 demonstrate the good static and dynamic performance of the proposed cooperative control of distributed *EPP*.

VI. CONCLUSIONS

A general approach to cooperative control of electronic power processors distributed in electrical grids has been presented, which allows synergistic and effective use of every type of power electronic units.

The theoretical background of the approach lies on the definition of instantaneous complex power, a conservative quantity which allows remote control of power processors irrespective of phase shifts and voltage changes introduced by transformers and voltage drops on transmission lines.

The definitions of active, reactive, unbalance and distortion power terms have also been revised and extended to non-sinusoidal operation, setting the basis for design and control of *EPP* as compensation units in the perspective of optimizing network performance at local- and system-level.

The proposed approach has been tested on a significant case study by simulation, showing excellent static and dynamic performance even in presence of severe distortion and unbalance in voltage supply and load currents.

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