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Power Quality Indexes in an Agent-Based Reconfiguration Strategy for Ship Power Systems

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***Summary*: This paper presents an analysis of the introduction of power quality assessment through power quality indexes within the framework of an agent-based power system control. The objective is to account for power quality in the power management of systems where the total power of the loads significantly exceeds the power available from generation. This is typically the case of next generation all-electric warships.**

1. INTRODUCTION

In recent years the aerospace industry and the ship industry started looking at new solutions heavily based on electrical systems. Basically, the main trend has been the progressive substitution of pneumatic and hydraulic actuators with electrical actuators mostly in consideration of the evolution of the electrical drive and power electronic technology. The expected outcome of this transformation is increased flexibility, efficiency and power density, reduced maintenance, volume and manpower.

Focusing on the ship technology and in particular on the future generation of combat ships envisioned by the US Navy, we face the interesting challenge of managing a complex plant where the total generated power is far lower than the total installed power, due to the presence of very large loads characterized by discontinuous operation, such as aircraft launchers, and weapons. Furthermore, the power management technology should allow for flexibility of power distribution for increased survivability in case of damage.

This situation calls for new approaches to the management of power and in a new concept of plant reconfiguration. It is very likely, in fact, that the system may trend to operate in configurations where the requested power exceeds the acceptable limit. This type of operation must be prevented and it is advisable to do so through smooth transitions whenever possible.

The traditional corrective measure is load shedding, i.e. identification and disconnection of loads that can be removed from the system to keep the total delivered power under boundaries.

Thanks to a massive use of power electronics though, it is possible to move towards more sophisticated solutions, adopting load performance degradation instead of shedding.

The definition of strategies to the achieve what we could define as an optimal power flow is anyhow quite complicated, due to interactions system level as well as local level and is still under investigation.

In this paper we present the analysis of a possible approach based on the use of distributed intelligence through the use of agents.

The adoption of an agent-based approach to power management should be beneficial for a number of reasons:

- robustness: avoiding a fully hierarchical approach with single point control and decision making the system less sensitive to failures;
- limitation of the information traffic: the more the information is processed locally the more the band of the communicational channels is available for other types of communication.

Multi-agent systems have been increasingly analysed and in few cases experimentally introduced in power system applications. In particular, its application to control of micro-grids, [2], management of large amount of fault data in SCADA systems, [4] and diagnostic of power components, [5], highlights the two major features of agent system listed above. Within this paradigm, we propose to introduce the power quality as an important figure of merit to define the operative structure of the power system.

In the following, we introduce the notional structure of the future power system on board of future all-electric warships, as well as the concept of agent-based control.

Then we investigate a possible approach to introduction of power quality indexes as elements of the decision making process. The topic is discussed with reference to a simulation scenario and to the hardware (HW) set-up that is going to be used in the near future to evaluate the feasibility of this proposal.

2. THE STRUCTURE OF THE POWER SYSTEM

Figure 1 presents a diagram of the notional power system to be adopted for future generation ships.

This system is based on a two-level distribution setting: an AC bus-bar connects the generators directly to the main propulsion drives and to a set of converters each feeding one DC Zonal System. Each zone then has a set of local converter-fed DC loads connected to it [6].

As result of this architecture the AC distribution system interacts with a set of DC distribution systems. A notional representation of the AC-DC system is provided in Figure 1, where the voltage source elements named G to the far left and right, are the AC generators, feeding three-phase

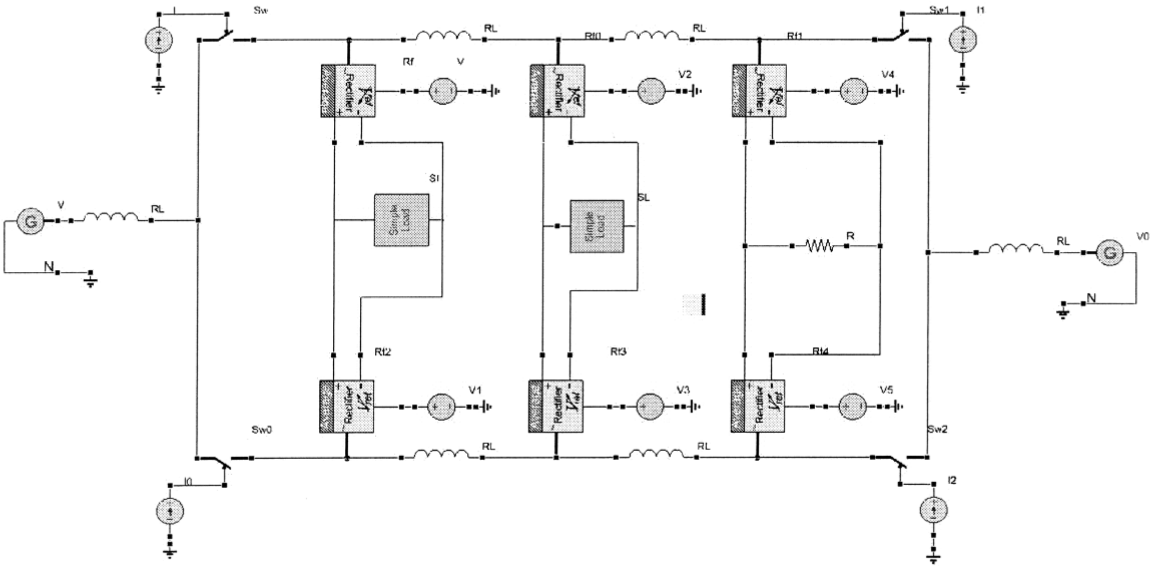

Fig. 1. The notional power system structure

distribution lines, while the three shunt branches, fed by the blocks Rectifier, represent the DC zones.

In previous papers [7, 9] the authors focused on the DC distribution part, providing introductory strategies for agent-based reconfiguration.

In this paper vice versa we start analyzing the AC side of the problem introducing power quality as an important element of the decision making process. A further step in our research is the integration of power management of the two interconnected AC and DC systems.

A notional representation of the AC-DC system is provided in Figure 1, where the voltage source elements named G to the far left and right, are the AC generators, feeding three-phase distribution lines, while the three shunt branches, fed by the blocks Rectifier, represent the DC zones.

3. THE AGENT-BASED APPROACH

A flexible and intelligent measurement system is the key to successful coordination of loads and power distribution in the envisioned scenario. Multi-agent systems provide the framework for the implementation of such a system, allowing for fine granularity in delocalization (local vs central) and hierarchy (top-down vs peer-to-peer).

An overview of multi-agent systems in power applications is given in [3], while more detailed applications are described in [1] and [2]. An application of monitoring and diagnostic based on multi-agent technology has been described in [7] and [9].

In a flexible and reconfigurable system the individual agents must be capable of handling communication with other agents and to perform their own functionality possibly interacting with other environments. For example, in the monitoring and diagnostics systems presented in [9] the capabilities of the measurement agent are implemented in LabVIEW.

The agent system presented in this work is implemented in JADE. The interface between the agents and the data acquisition and control environments is implemented through the JADE-COM interface libraries of the Jacob Project [11]. The communication between agents is compliant with Agent Communication Language (ACL) defined in the IEEE Foundation for Intelligent Physical Agents (FIPA) standard. FIPA defines many standard interaction protocols for Agent communication. In particular the agents in our system use the FIPA-QUERY and FIPA-REQUEST interaction protocol [8]. Some conversations and messages exchanges between agents in our system do not use the standardized FIPA interaction protocols implemented in JADE but still strictly adhere to the ACL (Agent Communication Language) standard defined in FIPA. This standard allows adding many auxiliary parts in addition to the content of a message like the intended recipients, the sender and the message type. JADE also allows users to develop Ontologies that define the concepts and the language that the agents would use for communication.

The agent structure that we propose for this application comprises one Measurement Agent, one Diagnostic Agent and one Load Agent with control capabilities for each load, so a total of three Load Agents. The Measurement Agent coordinates data acquisition and manipulation of the measurement sections, one per load, and is capable of sending data to any other specific agent. In this way, for example, each Load Agent can have knowledge of its own condition. The Diagnostic Agent is capable of data elaboration, in this application is capable of computing a power quality pollution index for each load. It can receive data from the Measurement Agent and can send data to the Load Agents. In this way each load can have deeper knowledge of its own condition, for example with reference to its own contribution to polluting the network.

The decision making process, for the purpose of reconfiguration, is deferred to the negotiation between Load Agents. For example, suppose that the reconfiguration calls for shedding one load and suppose the criterion, for sake of simplicity, does not depend on current state of the load or of the system, but is strictly based on pre-assigned priority levels. Suppose also that each Load Agent knows its own priority level and does not know the priority level of the other loads. Negotiation will be engaged among the Load Agents to establish which is the load with the lowest priority. The outcome of the negotiation is the identification of the load with the lowest priority. Once the lowest priority Load Agent becomes aware its priority condition, since it knows that a reconfiguration process is ongoing, it will take action to control its corresponding load to cut it off. This structure allows load agents to connect or disconnect loads from the system with no need to propagate all load information to a central unit.

This totally distributed structure helps reducing the amount of information that is to be transferred to all the intelligent units in the system, it leads to the solution of many smaller problems rather a very complex one (local negotiation *vs* system level decision), improves survivability in case parts of the system are unavailable (for example because the ship has been hit).

Within this framework, many open problems remain, among which the "right" level of delocalization and the analysis of the system-level impact of this approach.

4. POWER QUALITY INDEXES AND THEIR POSSIBLE ROLE IN A RECONFIGURATION STRATEGY

In a previous work [7], an experimental test of the proposed approach based on load priority only has been presented. It is assumed that each load is aware of its own priority level because it received it from an operator or from an automatic system (for example based on the current mission of the ship). The negotiation consists in the comparison of priority at load agent level. Normally though, the scenario is more complex and many criteria have to be considered at the same time, base on current load state and other information.

With reference to the AC power system described in Paragraph 2, one parameter that is very influential on the correct operation of the power distribution system is power quality. It is up to the converters that interface the AC power system with the DC Zonal Systems to provide a stable DC bus. Nonetheless there are limits to the effectiveness and efficiency of their action depending on the power quality at the AC system level. For this reason the decisions regarding load shedding or load performance degradation for reconfiguration purpose must account for responsibility in power quality degradation as well as priority level. In particular, in the simple case considered in this work, we assume that out of the three loads fed by the AC system, two of them end up with the same priority level during a reconfiguration negotiation. The further step in negotiation involves the comparison of power quality pollution of each load. Within this framework the power quality assessment needs to be local. What needs to be assessed in this context is not much the overall pollution level of the distribution system but rather the single load responsibility. In this sense rather that opting for global harmonic pollution indices, we need local indices.

A lot of work has been done for the identification of meaningful load level pollution assessment, in particular indexes readily applicable in this case study have been introduced, documented and theoretically justified in [12]. These power quality indexes are able to identify from voltage and current measurement at the load terminals whether the load is polluting the network, even in presence of distorted line voltage and furthermore to identify whether the pollution originates from load unbalance or non-linear and/or time varying behavior. This result is achieved through the analysis of harmonic active powers associated with three phase components and obtained from frequency-domain components of voltage and current Park vectors.

In particular, Park transformation is a linear transformation and for this reason is possible, starting from the component of the complex Fourier series of a generic Park Vector, to express a generic Park vector ***w(t)*** as:

$$w(t) = \sum_{k=-\infty}^{k=+\infty} \mathbf{W}_k \cdot e^{jk\omega t} \tag{1}$$

The previous equation shows that the components of the complex Fourier series are Park vectors with amplitude $W_k=|\mathbf{W}_k|$ and angular frequency $k\omega$.

Starting from this assumption it is possible to analyze the Park power vector by using the frequency-domain components of the Park vectors of voltages and currents:

$$\begin{aligned} P_k &= Re\left(\mathbf{V}_k \mathbf{I}_k^{*}\right) \quad \text{for } k \geq 0 \\ P_k &= Re\left(\mathbf{V}_k^{*} \mathbf{I}_k\right) \quad \text{for } k < 0 \end{aligned} \tag{2}$$

where k is the harmonic index, $\boldsymbol{V}_k$ is the k-th harmonic component of the voltage Park vector and $\boldsymbol{I}_k$ is the k-th harmonic component of the current Park vector.

The total harmonic active power flowing out of the load branch is an index of the polluting effect of the load on power quality. Following up from these considerations, the harmonic indexes k corresponding to $P_k>0$ can be grouped in sets.

Set K_l of harmonic indexes at which the load has a linear, balanced behavior:

$$K_l = \left\{k \middle| \left(P_k > 0\right) \wedge \left(P_{-k} > 0\right)\right\} \tag{3}$$

Set K_u of harmonic indexes at which the load has an unbalanced behavior:

$$K_u = \left\{k \middle| \left(P_k < 0\right) \wedge \left(P_{-k} > 0\right)\right\} \tag{4}$$

Set K_{nl} of harmonic indexes at which the load has a distorting non-linear or time-varying behavior:

$$K_{nl} = \left\{k \middle| \left(P_k < 0\right) \wedge \left(P_{-k} < 0\right)\right\} \tag{5}$$

The resulting active power P_u, which is the sum of all the power terms related to the K_u harmonic indeces, flows out of the load branch and represents the effect of an unbalanced load on power quality. The resulting active power P_{nl}, which is the sum of all the power terms related to the K_{nl} harmonic indeces, flows out of the load branch and represents the effect of distortion on power quality.

The value of these active powers is used as a criterion to determine the level of adverse effect of the load on network power quality.

Suppose the AC bus-bars feed three loads and suppose that the system needs to be reconfigured, as a consequence of a request to accommodate a load change that would push the system beyond the maximum allowable power. One of the three loads has to be reduced/shed. The Measurement Agent, through LabVIEW, acquires voltage and current at each load terminals, performs Park decomposition of the instantaneous values, evaluates the frequency domain components of the Park vectors, determines the sets K_l, K_u and K_{nl} and the related active powers, sends each load information set to the related load. The loads at this point possess two pieces of information: their own priority level and their own pollutant impact, plus the awareness that they need to negotiate for reconfiguration. The negotiation starts resulting in a first conclusion based on priority levels only. In case this information is conclusive, meaning one load results in possessing the strictly lowest priority of all, then that load is shed/reduced. In case multiple loads end up with the same priority level, the first negotiation is inconclusive, and the next step is comparing the power quality pollution impact. A second round of negotiation starts at this point using as a parameter the pollution indicators introduced above. At the end of this negotiation the load which pollutes the most is shed/reduced.

The first level negotiation can be implemented in various ways and the authors are carrying out a systematic comparison. In this application, the Diagnostic Agent compares priority levels and finds conflicts, if any. The Load Agents are informed of the existing conflict thus infer they have to provide a second level priority level. Notice that the Load Agents have memory of what has happened before (first priority level provided), and know that second priority level must be based on measurements. In previous experiments, the first level negotiation was carried out by exchanging the priority levels among all loads, so each Load Agent could figure on its own if its priority level was the lowest. In that case to conflict was considered. The present and past examples show the two extreme strategies, with pros and cons. The strategies conceptually in between are under investigation. In particular, the negotiation based on neighbor to neighbor sub-negotiations. Figures of merit in this investigation are amount of data exchange, survivability.

The overall process can be in fact much more sophisticated and this basic operation raises a number of issues that need to be answered, from the point of view of agents operation (timing, capabilities,…), of the system operation (overall stability, mission-based reconfiguration,…), of communication, of load performance degradation criteria. Nonetheless this basic example shows some of the strengths of the agent based approach. These strengths originate from the distributed structure and from the peculiarities. A distributed structure makes the overall system less vulnerable, in fact while a fault in the centralized intelligence leads to total loss of control and some monitoring capabilities, fault of one agent leaves the rest of the agent system active. This is of particular interest in applications, such as warships, in which survivability is a design priority. The peculiarity of multi-agent systems lie in the emerging behavior they can present thanks to their autonomy. This implies that the agents react locally to changes in the environment, thus avoiding

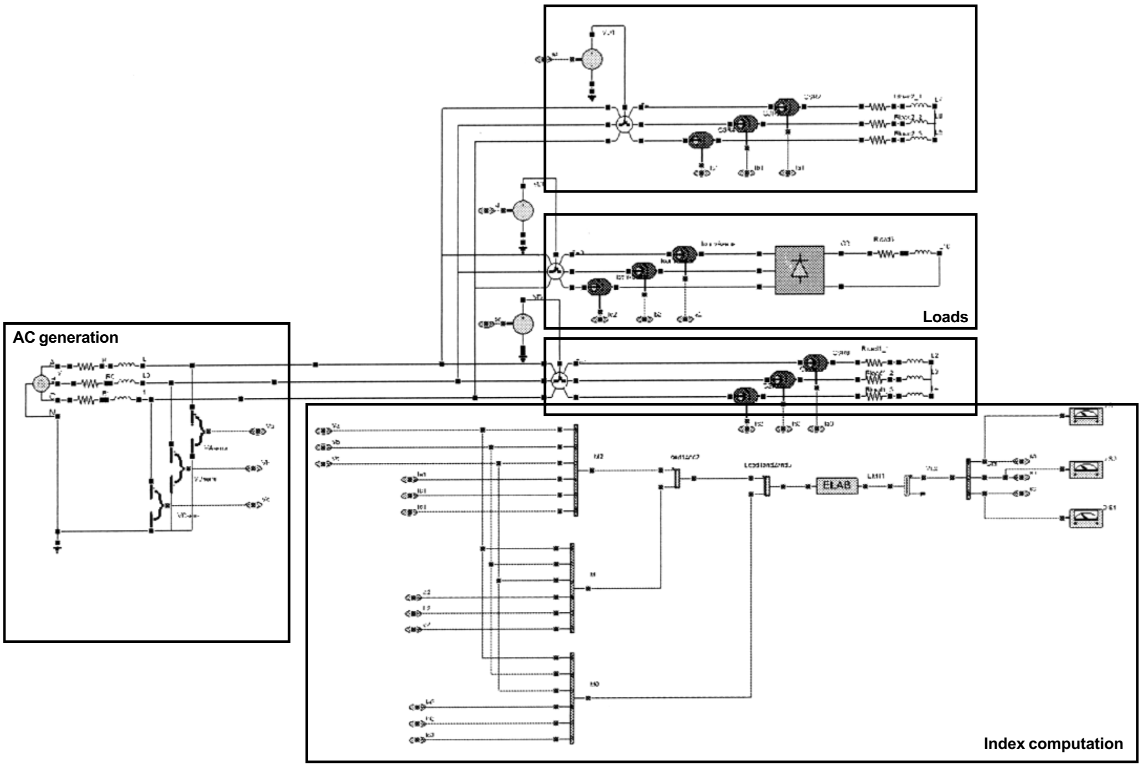

Fig. 2. The VTB schematic used for the testing

the need to send large amount of information to a central intelligent unit. If the goal is a soft continuous reconfiguration of monitoring and control for maximally flexible power usage in limited power systems, such as a military ship, then some decisions are to taken locally and continuously.

5. SIMULATION TEST

A preliminary analysis of the impact of this approach has been performed by means of simulation testing.

A Virtual Test Bed [13] schematic has been developed where three loads are connected on a shared bus.

One load is linear and balanced, one is linear unbalanced and one is non-linear because of the presence of a diode bridge rectifier (Figure 2).

The purpose of the simulation test is to verify if it is possible to extract a power quality index calculated locally by each load that can be used for negotiation purpose.

For this reason the schematic adopted is simply notional and it has been designed with the idea of including at least one load for each category: non-polluting, non linear, unbalanced.

The index calculation and load negotiation has been implemented in Matlab.

The evaluation of the distortion factor is implemented as a separate function file with the purpose to adopt the same code also in the experimental set-up described later (this solution removes error-prone coding procedures).

A monitoring unit is supposed to be connected in each load location. These units sample voltages and currents with a sampling frequency of 12.8 kHz and calculates the indexes every 512 samples.

The frequency components of the power in the Park domain and the total distortion power are evaluated. The load with the highest values is selected for shedding.

The shedding is performed opening the power switches controlled by the outputs of the Matlab negotiation.

One important difference with respect to the approach proposed in [12] is the fact that in this case the loads calculate the power as absolute values.

The idea behind this approach is the fact that the purpose of the negotiation is to optimize the whole power flow from the generators standpoint. In this respect, assuming the loads have the same priority, the best decision in the direction of improving the power quality on board is to remove the load with the highest absolute value of pollution.

It must be underlined that the policy, as already mentioned before, could be improved moving towards load degradation instead of simple shedding.

Another possible improvement for this proposed policy is based on the possibility to take advantage of the calculation of the distortion power for non-linear/time-variant loads as a separate value from the distorted power related to unbalanced loads.

Depending on operating condition the strategy could privilege one term with respect to the other. Currently the total value is the only index adopted in the negotiation.

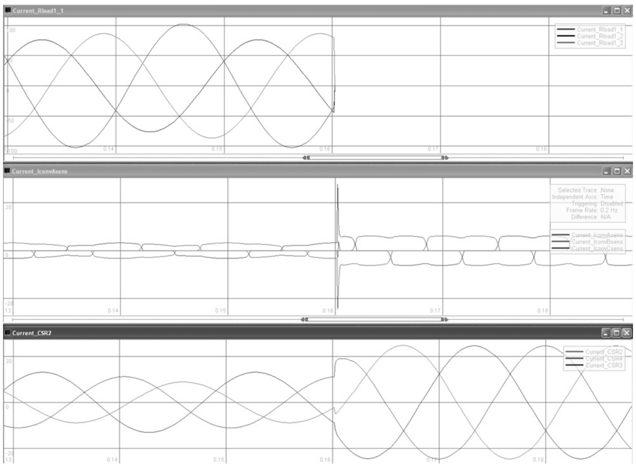

Fig. 3. A first example of load shedding (upper trace is the current in the unbalance load, middle trace the current in the non linear load, lower trace current in the linear balanced load); x-axis, 10ms per division; y-axis: 40A per division in top figure, 20A per division in middle and bottom figure

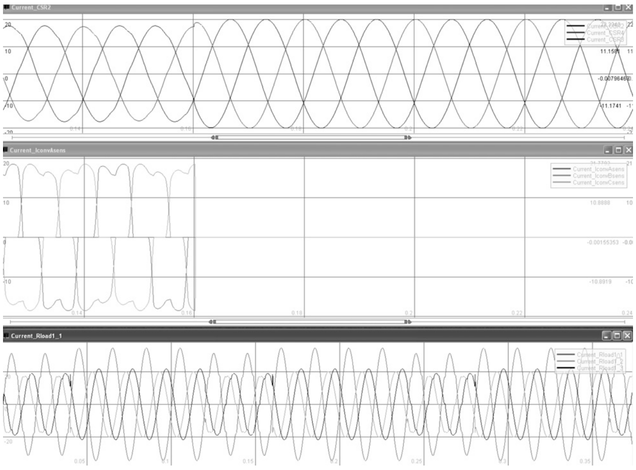

Fig. 4. A second example of load shedding (upper trace is the current in the linear balanced load, middle trace the current in the non linear load, lower trace current in the linear unbalanced load); x-axis, 10ms per division; y-axis: 20A per division

A very simple approach could be given by a linear combination of the two terms with coefficients dependent on the load priority and operating condition, as reported in the following formula:

$$P_i = \alpha P_{nl} + \beta P_u$$

where:

— distortion power related to non-linear loads;

— distortion power related to unbalanced loads;

— suitable coefficients to be defined depending on load priority and operating conditions.

Two different simulation scenarios are here considered.

In Figure 3 the non-linear load is connected to a light load so that the impact is quite limited. As result of that the negotiation results in the shedding of the unbalanced load as most significant actor of pollution.

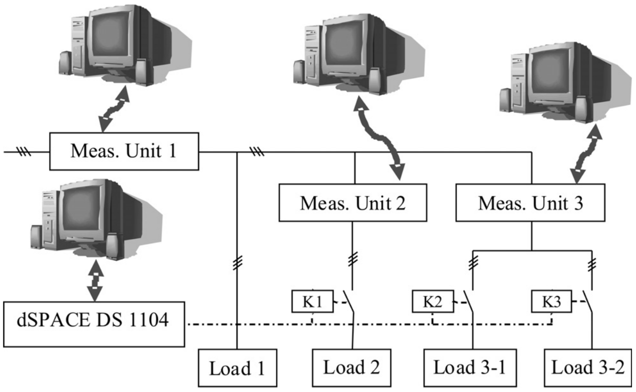

Fig. 5. Hardware experimental set-up

In the second situation, vice versa, see Figure 4, the non-linear load impact is more significant and the negotiation results in the shedding of the diode bridge.

It is interesting to notice that the different outcome of these two negotiations are strictly related to the fact that the absolute values of power are used.

Looking at relative values, in effect, the second scenario will result in the same decision, considering that the p.u. spectra of the diode bridge would be only slightly influenced by the change of the load resistance.

Notice that in both cases, being the line impedance significant in p.u., the shedding of one load means a significant change of power available for the other loads.

This remark is one more reason to consider the performance degradation: being the distribution system so sensitive, a small change can sometime have a significant beneficial impact on the rest of the system.

6. DESIGN AND IMPLEMENTATION OF A HW SETUP

In order to verify the effectiveness of the agent-agency strategy an hardware platform has been realized (Fig. 5). The experimental set-up comprises three loads supplied by the same three-phase power line. The load number one is a three phase induction motor (4 kVA) fed by a six step inverter. The load number two is a balanced three phase resistive load, which nominal value is 50Ω. The load number three is three phase resistive load too. This last load is composed of two section, load 3-1 and load 3-2, which nominal values are 30Ω and 4Ω respectively. In order to obtain a distortion of the absorbed power, necessary to verify the effectiveness of the index, the load number three has been unbalanced modifying the resistive value of a phase. Notice that this schematic is not the exact replica of the simulation scenario. In effect this second set-up represents a first evolution where performance degradation is possible for each load. The AC drives can smoothly be controlled virtually at every level of power while the R–L is able to switch between two configurations.

The on–off state of the loads is determined by the acknowledgment of the Load Agent to the dSpace agent that turns on or off the load. The dSpace agent is an interface between the Java agent system and a DS 1104 board based on a 250MHz PowerPC from dSpace,. Load Agents are hosted in dedicated PC connected to internet. Data visualization in numerical and graphical form, connection error detection, plus some ancillary indicators are implemented in a LabView environment as VI. Each Load Agent includes also the measurement section; a DSP-based system acquires the field signals and calculates the power quality indexes. The line voltage and current are acquired by an Analog-to-Digital conversion board (ADC), 8 input channels with simultaneous sampling up to 500 kHz sampling rate on a single channel, ±10V range, 12-bit resolution and offset, gain and non-linearity error in the range ± ½ LSB.

Voltage and current transducers have been specially realized in order to ensure both a high accuracy level over a wide band and a proper insulation level between channels and between the supply and measuring devices. According to the input signal range (380 V rms) for the voltages and up to 63 A rms for the currents a non-inductive, resistive voltage divider followed by an isolation amplifier has been used as voltage transducer and a closed-loop Hall effect transducers have been used as current transducers. Characterization of the transducer system has been performed as reported in [10].

The objective of this experiment is to verify the functionality of the proposed agent-based control system. In particular, a deadlock situation after load negotiation based on first level priority criteria (absolute priority imposed by the user or some other external entity) is artificially created. The system should react resuming to other, state-dependant criteria to assess actual priority. The state dependant criterion used here is based on the power quality impact of the loads, that is not normally assessed during system operation. The agents must take the initiative and the Measurement Agent must act to provide the necessary pollution indexes.

Each experiment is initiated with the following two steps:

1. The user assigns the first level of priority to each load.
2. The user assigns the levels and steps for gentle degradation of each load.

The description provided below shows how the agency operates and how information is propagated among the agents.

The agency is started, so each agent is running and ready for action. The user, or some external automatic system, requests the starting of the motor with given reference speed ω. This request, in the current agency set-up, is entered directly to the load agent that controls the motor that must start.

a. The Diagnostic Agent requests that the Load Agents send their respective priority levels; all priority levels are received and compared by the Diagnostic Agent. In case of a conflict (loads with same priority), the Diagnostic Agent requests the Load Agents to send a second level of priority levels.

The second level priority levels are based on the power quality index, so that the load that is polluting the most will be sacrificed. The Load Agents are aware that they do not already possess the information of their second level priority level but they need to get it from measurements. Notice that the Load Agents have memory of what has happened, that is, they know this is the second time they receive a request for priority levels. Also, the power quality indexes are scaled so that the value of the power quality index matches the value of the corresponding priority level.

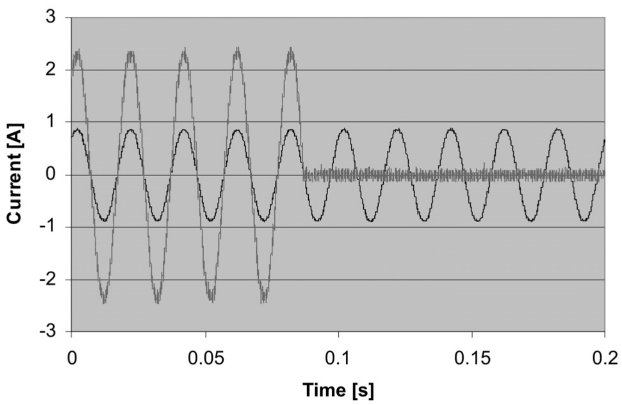

Fig. 6. current in one phase each of two loads; low priority load is switched off at the end of negotiation

b. The Load Agents request the Measurement Agents associated with their respective loads to calculate a new set of priority levels.
c. The Measurement Agent reconfigures the measurement system and execute the appropriate VIs to calculate the power quality indexes of each load. Depending on these pollution indexes the loads are assigned a new level of priorities. The load polluting the most is assigned the least priority level.
d. The Load Agents then send these levels again to the Diagnostic Agent. The Diagnostic Agent selects the one with the least priority and then instructs the corresponding Load Agent to subject it to gentle degradation.

In his specific experiment, the load that must be subject to degradation, can only be switched between two levels. The objective of future work is that of achieving virtually infinite flexibility through power converter fed load.

e. The Load Agent implements the gentle degradation through a Jade Agent-Matlab/DSpace interface. In this application a digital on/off switch signal, that switches the load between levels.
f. The same gentle performance setting is sent to the Simulation Agent that runs the simulation again, under new conditions, to check for overload.
g. The system keeps iterating until the solution converges.

Figure 6 shows one phase in a surviving load and one phase in a shed load at the end of negotiation.

7. CONCLUSIONS

In this paper an agent-based power system control has been implemented. The simulations performed to verify the adopted load shedding strategy, based on power quality index evaluation, have verified the paradigm of robustness, flexibility and reconfigurability required.

An hardware platform, implementing the agent-agency strategy is currently under test.

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Another major field of interest for Dr. Ponci is the innovative approach based on Polynomial Chaos for measurement uncertainty propagation in measurement and signal processing algorithms and for the modeling and simulation of uncertain systems with stochastic approach.

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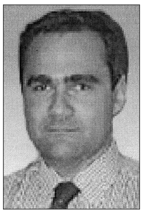

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