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Cooperative Sensor Networks for Voltage Quality Monitoring in Smart Grids

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Abstract-- **The paper intends to give a contribution toward the definition of a fully decentralized voltage quality monitoring architecture by proposing the employment of self organizing sensor networks. According to this paradigm each node can assess both the performances of the monitored site, computed by acquiring local information, and the global performances of the monitored grid section, computed by local exchanges of information with its neighbors nodes.**

Thanks to this feature each node could automatically detect local voltage quality anomalies. Moreover system operator can assess the system voltage quality index for each grid section by inquiring any node of the corresponding sensors network without the need of a central fusion center acquiring and processing all the node acquisitions. This makes the overall monitoring architecture highly scalable, self-organizing and distributed.

Index Terms-- **Sensor networks, decentralized architectures, power systems monitoring.**

I. INTRODUCTION

Voltage quality issues are assuming a key role in modern electrical distribution systems where the continuous growth of non linear time variant loads in both household and industrial applications [1] and the raising penetration of dispersed generation connected to LV/MV networks [2] are leading to an increase of distortion and disturbances on the voltage signals.

This has forced international standard organizations to issue recommendations defining both the characteristic of the voltage supplied by public networks and the procedures to assess its quality (i.e. to compute the voltage quality indices) [3,4].

The fully accomplishment of these recommendations requires an increasing pervasion of distributed monitoring systems that, if integrated with advanced information and communications technologies, could allow system operators to identify and mitigate system-wide voltage quality problems by assessing the quality indices on more points of the distribution systems also located on wide geographical areas [5].

Distributed voltage quality monitoring systems have been traditionally deployed according to client/server based architectures. In details, they employ monitoring platforms basically composed by (1) a network of re-mote acquisition units equipped by specifically routines for data gathering, data preprocessing (e.g. FFT and voltage quality index calculation) and data ex-change, (2) a central processing platform for detailed data processing and information dissemination, and (3) a data base management system for historical information storing [6].

As outlined by many papers [5-8], this hierarchical monitoring architecture exhibits some intrinsic disadvantages that could hinder its application in distribution systems where the constant growth of the electrical network complexity and the need for pervasive monitoring ask for more scalable, more flexible monitoring paradigms.

In this connection the paper intends to give a further contribution toward the definition of a fully decentralized voltage quality monitoring architecture.

The idea is to start from the mathematics of populations of mutually coupled oscillators for designing high pervasive/self organizing sensor networks for voltage quality monitoring in electricity distribution systems [11,12]. Specifically, we propose the employment of a cluster of sensor networks each one monitoring a specific electrical grid section. Each network node is com-posed by a sensor, that acquires the voltage waveforms and computes the corresponding quality index (i.e. node index), and of a dynamical system (oscillator) initialized by the sensor computation. We show that if the oscillators of nearby nodes of the same sensors network are mutually coupled by proper local coupling strategies, then each dynamic system on each node converges to the global voltage quality index of the monitored grid section.

This feature allow system operators to assess the sys-tem voltage quality index for each grid section by inquiring any node of the corresponding sensors network without the need of a central fusion center acquiring and processing all the node acquisitions. This makes the overall monitoring architecture highly scalable, self-organizing and distributed.

In order to prove the effectiveness of the proposed architecture simulation results obtained on the 300 bus IEEE test network are presented and discussed.

II. MODERN TRENDS IN VOLTAGE QUALITY MONITORING

Voltage quality could be defined as “the characteristics of the supply voltage concerning magnitude, wave-form and symmetry of the phases”. This definition leads to consider a variety of concepts such as frequency, voltage magnitude, voltage dips and harmonic distortion. The corresponding parameters to consider are listed and defined in the European

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standard EN 50160 which is applicable in all European countries for low and medium voltage networks (up to 35 kV).

Voltage quality monitoring is the process of gathering voltage data, transporting the data to a remote server, and processing it into decision making information [6]. This is traditionally addressed by adopting wide power quality monitoring systems that collect voltage data and transfer them to a data characterizer for:

- the identification of the event (a.k.a. single-event indices calculation),
- the calculation of the site indices from the single-event indices of all events measured during a certain period of time,
- the calculation of system indices from the site in-dices for all sites within a certain power system

To address these issues client server based architectures are traditionally adopted. In these scheme a large volume of raw data is collected by distributed sensors and sent to a central server for post processing activities (i.e. site/system indices calculation) [7].

As outlined by many papers, this hierarchical monitoring paradigm exhibits some intrinsic disadvantages as far as low scalability levels (i.e. the increasing of the monitoring points leads to a sensible costs rise) and the need of hardware redundancy for the central processing resources (since they represent critical failure points). It requires, moreover, high network bandwidth and extremely large data storage and computation time [5,8].

According to these argumentations many research papers propose the employment of advanced voltage monitoring architectures that move away from the older centralized paradigm to system distributed in the field with an increasing pervasion of intelligence devices (smart sensors) where central controllers play a smaller role [7,9]. The adoption of smart sensors leads to a more efficient tasks distribution amongst the monitoring system resources and, consequently, to a sensible lightening of the centralized computing resources. This decreases the total cost of the voltage monitoring sys-tem making straightforward its upgrade [7].

In particular, the work [10] proposes and prototypes a novel voltage monitoring system based on a web based sensor network. The sensors are realized by a microcontroller based architecture and they can be remotely managed by a web based interface.

In [5] a PQ monitoring system based on intelligent, adaptive and reconfigurable multi agent system is conceptualized. The proposed architecture exhibits several advantages over traditional client server systems. In details, it requires less network bandwidth and computation time and it is easy to extend and to recon-figure.

In [7] a distributed measurement system deployed according to a non hierarchical architecture is proposed for power quality applications. The proposed architecture is integrated by a collaborative network of low cost smart sensors realized according to the mobile agents paradigm.

According to the scientific trends outlined by these works, the paper intends to give a contribution toward the definition of a fully decentralized voltage quality monitoring architecture by proposing the employment of self organizing sensor networks in which the spreading of information occurs as a result of the local coupling between adjacent nodes which act as mutually coupled adaptive oscillators.

III. Voltage Quality Monitoring by Self Organizing Sensor Networks

The proposed solution is based on a challenging idea, originated from papers [11,12], that borrows the dynamical model of populations of mutually coupled oscillators, where the self-synchronization of the net-work is ensured without the need of a fusion center, but only with proper local coupling of nodes. We consider a complex system consisting of different sensor networks, each monitoring a specific electrical grid section, where nodes include a sensor for deriving the node quality index, and a dynamical system, initialized by the sensor computation. After a short transient, the dynamical system converges to the global voltage quality index of the grid section, making available, at each node, both local and global performances.

A. Theory of operation

The dynamical model of evolution in a system of N mutually coupled oscillators, carefully discussed in [12], is given by a system of differential equations:

$$\dot{\theta}_i(t) = \omega_i + \frac{K}{c_i}\sum_{j=1}^{N} a_{ij} F\left[\theta_j(t) - \theta_i(t)\right] \quad i = 1,..,N \qquad (1)$$

that describes the evolution of a state function $\theta_i(t)$ for each node of the network, starting from the initial condition ω_i, that is related to the variable of interest acquired from the i-th sensor. $F(.)$ is a monotonically increasing, nonlinear, odd function and the coefficients a_{ij} indicate the coupling between the i-th and the j-th sensor, with $a_{ij} = 0$ when nodes i and j are not coupled. The above model also takes account of a control loop gain, through the parameter K, and of the attitude of the i-th sensor to adapt itself to the state variations of the coupled sensors, through the coefficients c_i. To understand the system behavior, it is worth to note that, due to the properties of the function $F(.)$, when most of the neighboring states $\theta_j(t)$ are greater than $\theta_i(t)$, then $\theta_i(t)$ tends to increase, otherwise when most of the neighboring states $\theta_j(t)$ are smaller than $\theta_i(t)$, then $\theta_i(t)$ tends to decrease. In this way the evolution of $\theta_i(t)$ follows the variations of the coupled sensors and it is reasonable that the system tends to synchronize, i.e. to reach the condition $\dot{\theta}_i(t) = \dot{\theta}^*(t)$ for each node. It has been shown in [12, 13] that the synchronized state exists and is globally asymptotically stable if the control loop gain K is greater than an upper bound K_U, whose value depends on the network topology, precisely on the algebraic connectivity of the graph, and on the function $F(.)$. It is also simple to show that, if the system synchronizes, the solution is

$$\dot{\theta}^*(t) = \omega^* = \frac{\sum_{i=1}^{N} c_i \omega_i}{\sum_{i=1}^{N} c_i} \qquad (2)$$

so that at each node a weighted average of the sensed variables from all the nodes in the network is available, without the need of a fusion center.

B. *Proposed architecture*

According to the above theoretical model, an innovative approach can be designed for a decentralized voltage quality monitoring architecture. We consider a cluster of sensor networks, each one monitoring a specific electrical grid section, where the different nodes acquire the local voltage waveform and evaluate a specific site quality index, for example a Sag Energy Index, a voltage or a phase index. This site index is the initial value ω_i in the evolution equation (1) of the state function of the i-th node.

The network topology is crucial for the system synchronization and, specifically, an important condition is required: that the network graph is connected. Then, the coupling coefficients a_{ij}, assumed nonnegative, take account of the reliability of the link between nodes, as they depend on the propagation and radio interface. At this stage we refer to the simplest choice that the coefficients a_{ij} are just the binary values of the connectivity matrix of the electrical network, corresponding to the hypothesis of ideal link, without loss. Finally, the control loop gain K can be chosen according to the algebraic connectivity of the graph, as specified in [13].

Another system characteristic that can be introduced in the proposed model is the reliability of the sensor measurement: since the coefficient c_i regulates the attitude of the i-th node to modify its state according to the variation of the coupled nodes, it can be chosen equal to an SNR value representative of the measurement quality. In this case, the higher the SNR value, the less the change of the state function, because the initial sensor measurement can be considered reliable.

Following the above requirements, a dynamic component is defined for each node of the network and, when the overall system is let to evolve according to the equation (1), exchanging the information about state among connected nodes, the system synchronizes making available the following system quality index

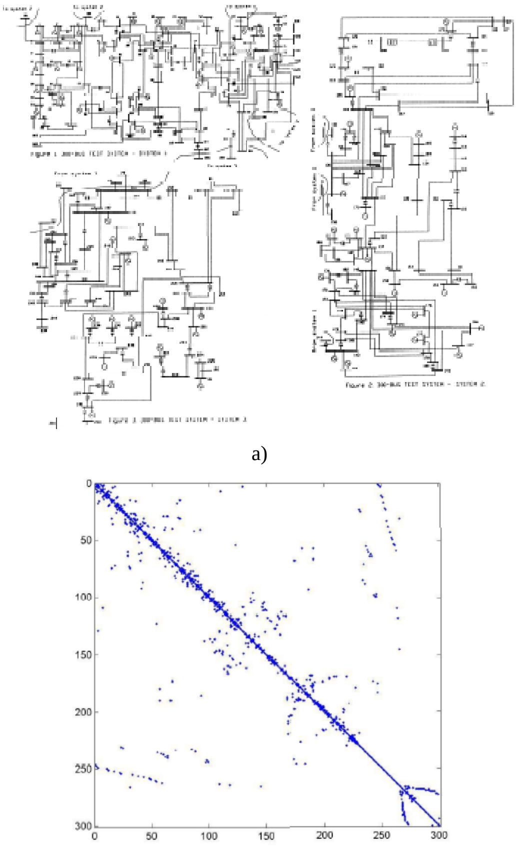
$$\omega^* = \frac{\sum_{i=1}^{N} SNR_i \omega_i}{\sum_{i=1}^{N} SNR_i} \qquad (3)$$

at each node as an average of all the site indices in the monitored grid section, weighted through the SNR values of the sensors. It is interesting to note that each node knows both the local quality of the monitored site and the global quality of the monitored grid section, so that a comparison between local and global indices can be made at any time, for any node, and subsequent actions can be taken in the case that the site index strongly deviates from the system index.

IV. CASE STUDY

In order to prove the effectiveness of the proposed approach, a case study concerning the voltage quality assessment of the IEEE 300 bus power system will be presented and discussed.

The topology and the sparsity pattern of the nodal admittance matrix for the analyzed power system are reported in fig. 1a and 1b respectively. The evolution of the node's voltage was simulated by solving the power system state equations.



a)

b)

Figure 1: The analyzed power system.
a) The power system topology
b) The sparsity pattern of the nodal admittance matrix

The adopted sensor network is composed by 300 cooperative sensors distributed along the power system (one for each node). The coupling coefficients a_{ij} are obtained starting from the connection matrix of the electrical network.

For the purpose of this study, in assessing voltage quality for each node we referred to the Voltage RMS variations ΔV_i, defined as the difference between V_i (i.e. the current RMS voltage of the $i-th$ node) and the corresponding nominal value V_N.

$$\Delta V_i = \frac{V_i - V_N}{V_N} \qquad (4)$$

To characterize the voltage quality of the entire power system (a.k.a. system index), or of a set of nodes located in a particular geographical area, we referred to the following global index (a.k.a. mean grid/section voltage module):

$$I = \frac{1}{N}\sum_{k=0}^{N} w_k V_k \qquad (5)$$

Which represent a weighted sum of the local voltage quality index. Obviously more complex index could be considered and integrated in the sensor dynamic evolution. This choice does not affect the validity of the proposed monitoring architecture.

To compute the system and the site index we applied the proposed cooperative based computing paradigm. The main results are reported in fig.2-3.

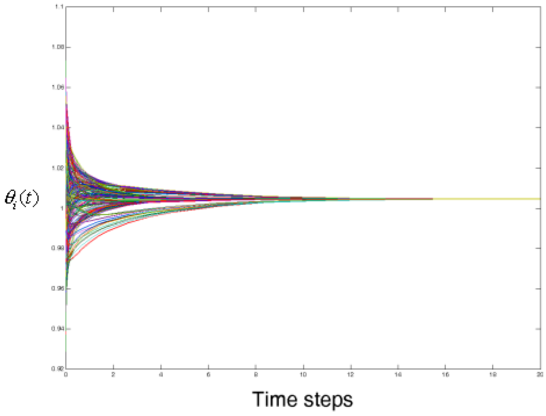


Fig. 2: Sensor oscillators evolution (one sensor clusters)

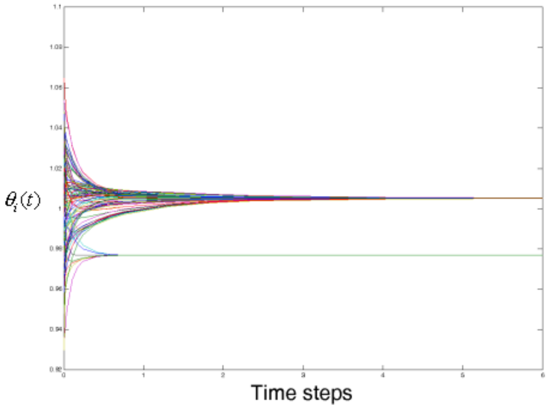


Fig. 3: Sensor oscillator evolution (case 2: two sensor clusters)

In details, fig.2 reports the evolution of the oscillator state variables $\theta_i(t)$ considering a single sensor network distributed on the power system. In this case all sensor oscillators (whose initial values are chosen randomly) rapidly converge to the mean grid voltage module.

The proposed sensor network could also be organized in sensor clusters each one monitoring a particular grid section. The intrinsic adaptation and the self-organizing properties of the cooperative sensor networks makes them potentially suitable for pervasive monitoring of both small (i.e. substation level) and large (i.e. sensors distributed along line routes [14]) grid sections.

In this case each oscillator of the same sensor cluster converges to the mean voltage module of the monitored grid section (a.k.a. site indexes). In order to asses this feature it is possible to analyze fig.3 where the specific case of two sensor clusters is considered.

Thanks to the employment of this monitoring paradigm each sensor knows both the performances of the monitored site (i.e. the site index), computed by acquiring local information, and the global performances of the monitored grid section (i.e. the grid section index), computed by local exchanges of information with its neighbors nodes. This allows system operator to assess the system voltage quality index for each grid section by inquiring any node of the corresponding sensor cluster without the need of a central fusion center acquiring and processing all the sensor acquisitions. This makes the overall monitoring architecture highly scalable, self-organizing and distributed.

V. HARDWARE IMPLEMENTATION ISSUES

A prototype version of the proposed sensor network architecture is under development. It employs smart sensors equipped by a 16 bit Digital Signal Processor (dsPIC33F), a three phase voltage transducer, a monolithic true rms-to-dc converter (AD736) and a medium/long range radio communication unit working at 2.4 GHz and employing the ZigBee/IEEE 802.15.4 protocol (Xbee Pro modem).

The IEEE 802.15.4 based communication architecture identifies three kinds of devices:

- A coordinator, which organizes the sensor network and maintains routing tables.
- Routers, which can talk to the coordinator, to other routers and to reduced-function end devices.
- End devices, which can talk to routers and the coordinator, but not to each other.

The expected benefits deriving by the application of this communication architecture are:

- Low cost: a typical IEEE 802.15.4 modem can be as low as $12 each in quantities as few as 100 pieces. This pricing provides an economic justification for extending wireless networking to even the simplest of devices.
- Range and obstruction issues avoidance: The routers double as input devices and repeaters to create a form of mesh network. If two network points are unable to communicate as intended, transmission is dynamically routed from the blocked node to a router with a clear path to the data's destination. This happens automatically, so that communications continue even when a link fails unexpectedly. The use of low-cost routers can also extend the network's effective reach. When the distance between the base station and a

remote node exceeds the devices' range, an intermediate node or nodes can relay transmission, eliminating the need for separate repeaters without stopping the system operation. This long-term reliability is critical for many power automation systems that are expected to last 20–30 years once installed.

- Multisource products: As an open standard, ZigBee provides customers with the ability to choose vendors as needed. A ZigBee-certified modem will interoperate with any other ZigBee-certified radio adhering to the same profile.
- High level of network scalability and reliability: Networks can scale to hundreds and thousands of devices and all will communicate using the best available path for reliable message delivery.

An intense experimental activity aimed at characterizing the real performances of the proposed solution on a realistic power systems are currently under development.

VI. CONCLUSIONS

In recent years, as a consequence of a growing occurrence of problems related to power quality, the demand of wide area voltage monitoring systems is becoming more pressing. In this connection modern trends are oriented toward the employment of advanced voltage monitoring architectures that hat move away from the traditional centralized paradigm to system distributed in the field with an increasing use of more intelligence devices where central controllers play a smaller role.

According to these considerations, the paper proposed a fully decentralized voltage quality monitoring architecture. The proposed solution is based on the employment of self organizing sensor networks in which the spreading of information occurs as a result of the local coupling between adjacent nodes which act as mutually coupled adaptive oscillators.

The obtained results show as this paradigm allows the sensor node to automatically detect local voltage quality anomalies since it know both the performances of the monitored site, computed by acquiring local information, and the global performances of the monitored grid section, computed by local exchanges of information with its neighbors nodes.

Thanks to this feature system operator can assess the system voltage quality index for each grid section by inquiring any node of the corresponding sensors network without the need of a central fusion center acquiring and processing all the node acquisitions. This makes the overall monitoring architecture highly scalable, self-organizing and distributed.

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VIII. BIOGRAPHIES

Maurizio di Bisceglie (M’91) received the Dr.Eng. in Electronic Engineering and the PhD in Electronics and Telecommunications from Università degli Studi di Napoli, Naples, Italy.

In 1997, he was a Research Fellow with the University College of London, London, U.K. Since 1998, he has been with the Facoltà di Ingegneria, Università degli Studi del Sannio, Benevento, Italy, as a Professor of telecommunications.

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