The Role of Smart Sensor Networks for Voltage Monitoring in Smart Grids

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Abstract— The large-scale deployment of the Smart Grid paradigm will support the evolution of conventional electrical power systems toward active, flexible and self-healing web energy networks composed of distributed and cooperative energy resources. In a Smart Grid platform, distributed voltage monitoring is one of the main issues to address. In this field, the application of traditional hierarchical monitoring paradigms has some disadvantages that could hinder their application in Smart Grids where the constant growth of grid complexity and the need for massive pervasion of Distribution Generation Systems (DGS) require more scalable, more flexible control and regulation paradigms. To try to overcome these challenges, this paper proposes the concept of a decentralized non-hierarchal voltage monitoring architecture based on intelligent and cooperative smart entities. These devices employ traditional sensors to acquire local bus variables and mutually coupled oscillators to assess the main variables describing the global grid state.

Index Terms—Distributed Generation, Voltage Monitoring, Smart Grids, Sensors.

I. INTRODUCTION

VOLTAGE monitoring is assuming a major role in the context of future Smart Grids, where a malfunctioning power system could be responsible for serious damages to a large number of system operators (i.e. distributed power producers, transmission systems operators, power distributors, users) having access to the shared energy resources.At the same time the constant growth of the market participants and the number of DMS/EMS systems operating on the Smart Grids will raise the interdependency between the operation of the electric networks and the electric markets and, consequently, the intrinsic complexity of Smart Grid monitoring [1].

The main difficulties arising in developing an effective, wide area Smart Grid monitoring is mainly due to the upgrade and interoperability of existing EMS/DMS that are typically based on client server based platforms integrating different information technologies and standards for the data exchange. In these systems a large volume of raw data is collected by distributed sensors and sent to a central server for post processing activities [2].

The large scale deployment of this hierarchical paradigm in a Smart Grid environment is causing designers of high performance monitoring systems to revisit numerous design issues and assumptions pertaining to scale, reliability, heterogeneity, manageability, and system evolution over time [3,4]. With dispersed generators now the "de facto" building block for Smart Grids, scale and reliability have become key issues as many independently failing and unreliable components need to be continuously accounted for and managed over time. Power components heterogeneity, a non-issue in traditional electricity distribution systems, must now be addressed since measurement systems that grow over time are unlikely to scale with the same hardware and software base. Manageability also becomes of paramount importance, since Smart Grids could integrate hundreds or even thousands of power nodes. Finally, as Smart Grids evolve to accommodate growth, monitoring system configurations inevitably need to adapt.

In this connection, the recent advances on collaborative and cooperative computing has opened the door for decentralised non hierarchical monitoring architectures based on reliable and high scalable information processing paradigms [10]. In particular, the work in [5] proposes and prototypes a novel voltage monitoring system based on a web based sensor network. The sensors are realized by a micro-controller based architecture and they can be remotely managed by a web based interface. In [3], 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 reconfigure. In [2], 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.

In [6], a web-enabled measurement and control system for electricity utilities is designed and different implementation strategies are discussed. The proposed system architecture is composed of a network of intelligent field devices, connected to field buses, remotely managed by a Web-browser and interfaced with the factory database systems by JAVA applets using JDBC-software interface (Java Data Base Connectivity). In [7], the development of distributed adaptive units for diffused on line power equipment monitoring is proposed. The proposed units are implemented on hardware microcontrollers with web based functionalities. These microcontrollers lead to the development of a JAVA® based client/server architecture composed of a network of intelligent units remotely controlled by advanced TCP/IP based communication services. The units, installed in the most critical sections of the electrical network, monitor continuously the thermal state of power components (e-monitoring) and communicate the corresponding results to central servers for further post processing activities.

According to the scientific trends outlined by these works, this paper intends to give a further contribution toward the definition of a fully decentralized 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

II. VOLTAGE MONITORING BY COOPERATIVE SENSOR NETWORKS

The proposed solution is based on a challenging idea, proposed in [8,9], that borrows the dynamical model of populations of mutually coupled oscillators, where the self-synchronization of the network 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 set of sensors for directly measuring the main bus variables, and a dynamical system, initialized by these measurements. After a short transient, the dynamical system converges to the actual value of the main variables characterising the monitored grid section (i.e. mean and standard deviation of the grid voltage, power losses, number of undervoltages/overvoltages, total reactive power costs) making available, at each node, both local and global grid performances.

A. Theory of Operation

The dynamical model of evolution in a system of N mutually coupled oscillators, carefully discussed in [8], is given by a system of differential equations:

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

where $\theta_i(t)$ describes the evolution of a state function 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. 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. It has been shown in [8,9] that the synchronization is possible if a proper choice of the control loop gain K is made, according to a lower and upper bound whose values depend on the network topology. It is also simple to show that, if the system synchronizes, the solution is

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

such 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 centre.

B. Proposed Architecture

According to the above theoretical model, an innovative approach can be designed for a decentralized/ non-hierarchal monitoring architecture. We consider a cluster of sensor networks, each one monitoring a specific electrical grid section. Each sensor node is equipped with four basic components:

- a set of transducers measuring the available set of local electrical variables (i.e. voltage magnitude, active and reactive bus power);
- a programmable unit (i.e. Digital Signal Processing, microcontroller) for data processing;
- a dynamical system, whose state is initialized with the vector of the sensor measurements and it evolves interactively with the states of nearby sensors according to equation (1);
- a radio interface ensuring the interaction among the nodes by transmitting the state of the dynamical system and receiving the state transmitted by the other nodes.

As shown in the previous section, if the sensor network synchronizes, all the dynamical systems converge to a weighted average of the sensed variables from all the nodes in the network. Thus, it is possible to assess, in a totally decentralized way, many important variables characterizing power systems operation. In particular, if the sensor nodes sense the bus voltage, the following vector of observations could be adopted to initialize the dynamical systems:

$$\Theta_i = \left(V_i, \left|V_i - V_i^*\right|\right) \tag{3}$$

where

V_i and V_i^* are the current and the nameplate voltage at the node

i respectively,

and n is the number of nodes.

In this case it is easy to show that the dynamical systems synchronize to the mean grid voltage and the average voltage deviation:

$$\dot{\Theta} = \left(\frac{\sum_{i=1}^{n} V_i}{n}, \frac{\sum_{i=1}^{n} \left|V_i - V_i^*\right|}{n} \right) \tag{4}$$

Other variables of interest (i.e. power quality indexes) could be easily accessed by a proper selection of the vector of observations. In particular if the sensor nodes sense the active and reactive bus power, the following vector of observations could be adopted to initialize the dynamical systems:

$$\Theta_i = \left(n \cdot (P_{Gi} - P_{Li}), n \cdot c_{pi}(P_{Gi}) \cdot P_{Gi}, n \cdot c_{qi}(Q_{Gi}) \cdot Q_{Gi}\right) \tag{5}$$

where

P_{Gi} and P_{Li} are the active power generated and absorbed at bus i;

Q_{gi} is the reactive power generated at bus i;

$c_{pi}(P_{Gi})$ and $c_{qi}(Q_{Gi})$ are cost of the active and reactive power generated at bus i;

In this case the dynamical systems synchronize to the active system losses and to the total cost of the active and reactive power :

$$\dot{\Theta} = \left(\sum_{i=1}^{n} (P_{Gi} - P_{Li}), \sum_{i=1}^{n} \left(c_{pi}(P_{Gi}) \cdot P_{Gi}\right), \sum_{i=1}^{n} \left(c_{qi}(Q_{Gi}) \cdot Q_{Gi}\right) \right) \tag{6}$$

With the employment of this biologically inspired processing paradigm, each node knows both the local variables characterising the monitored node and the global variables describing the global performances of the monitored grid section. Thus a comparison between local and global quantities can be made at any time, for any node, and subsequent actions can be taken in the case that the node parameters strongly deviates from the actual grid performances.

C. Compared to the Traditional Approach

Compared to the approach used in most control centers, utilizing power system component data, load flow equations and state estimation techniques, there are advantages and disadvantages. The proposed approach does not need to collect and maintain power system data from the whole network section and be updated on the system configuration. It relies solely on the sensor values available locally and from the connected neighboring nodes. State estimation techniques usually need a central data collection point and more processing power. The functionality required and the accuracy needed determines what would be the best approach, but it can be argued that the Cooperative Sensor Network approach is simpler and more robust while still being able to deliver most of the functionality needed in distribution systems.

III. CASE STUDY

This section discusses the application of the proposed methodology in the task of grid monitoring for the IEEE 14-bus test system depicted in Fig.1.a. The adopted sensor network is composed by 14 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. The corresponding topology is depicted in Fig.1.b.

Each node sensor senses the following bus variables: voltage magnitude, active and reactive bus power. The corresponding vector of local observations is organized as follow:

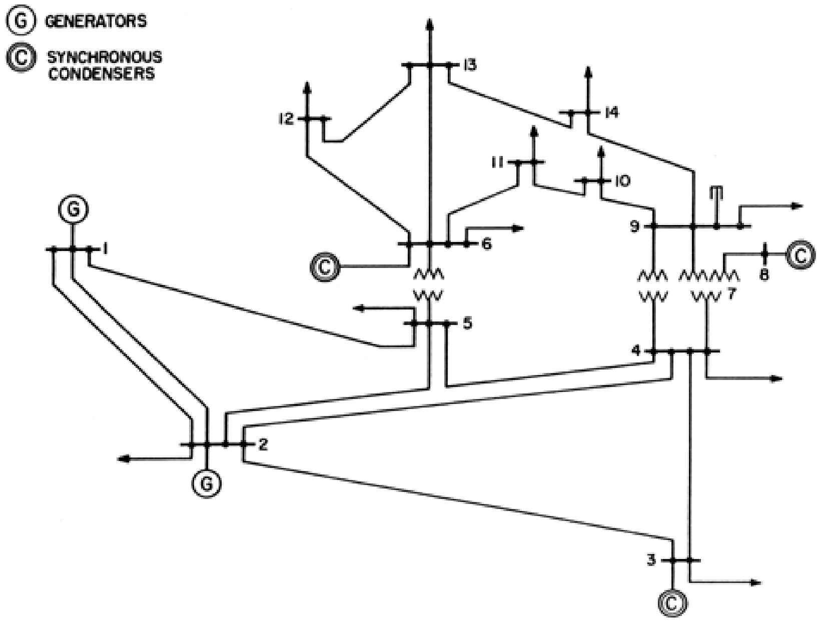
$$\Theta_i = (\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6) = \left(V_i, n \cdot c_{pi}(P_{Gi}) \cdot P_{Gi}, n \cdot c_{qi}(Q_{Gi}) \cdot Q_{Gi}, n \cdot (P_{Gi} - P_{Li}), \left|V_i - V_i^*\right|, 1\right) \tag{7}$$

It allows the dynamic systems to synchronize to the following values:

$$\dot{\Theta} = \left(\sum_{i=1}^{n} \frac{V_i}{n}, \sum_{i=1}^{n} \left(c_{pi}(P_{Gi}) \cdot P_{Gi} \right), \sum_{i=1}^{n} \left(c_{qi}(Q_{Gi}) \cdot Q_{Gi} \right), \sum_{i=1}^{n} \left(P_{Gi} - P_{Li} \right), \sum_{i=1}^{n} \frac{\left| V_i - V_i^* \right|}{n}, \sum_{i=1}^{n} \gamma_i c_i \right) \tag{8}$$

Representing the mean grid voltage, the total active and reactive generation costs, the active system losses, the average voltage deviation and an estimation of the channel latency (useful to compute the unbiased estimates as illustrated in the previous section). 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.

As far as the sensor network communication protocol is concerned, the IEEE 802.15.4 has been adopted as reference in our research activities. The corresponding IEEE 802.15.4 based data exchange have been simulated by an advanced network emulator developed in the Matlab environment. The employment of this simulation platform allows us to integrate in the sensor network synchronization process also the effect of data latencies. A Newton Raphson based algorithm for power system state equations solution has been integrated in this simulation environment in order to describe the electrical network evolution.



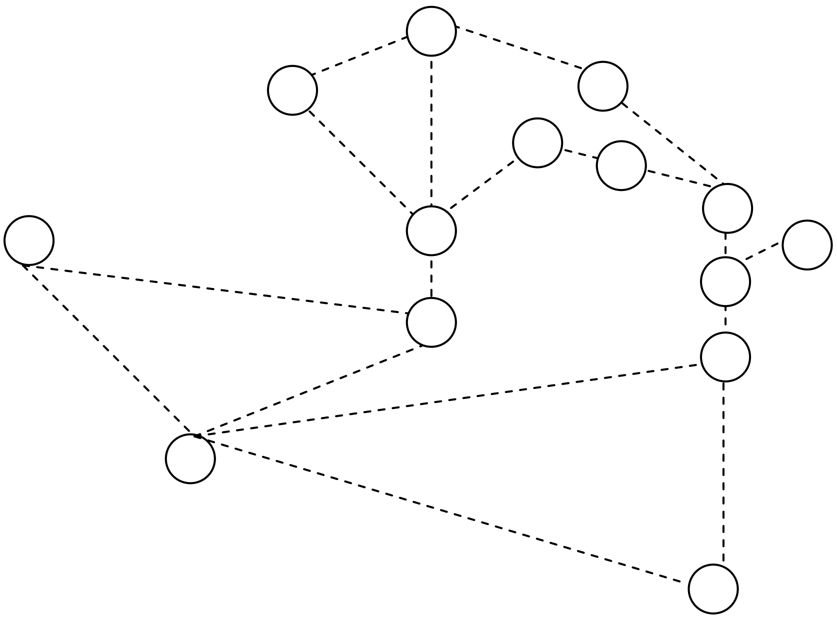


Fig.1 :The test case analyzed:

(a) The 14 bus power system. (b) The sensor network topology

With the adoption of this integrated simulation platform, we applied the proposed cooperative based computing paradigm obtaining the results reported in fig.2-7.

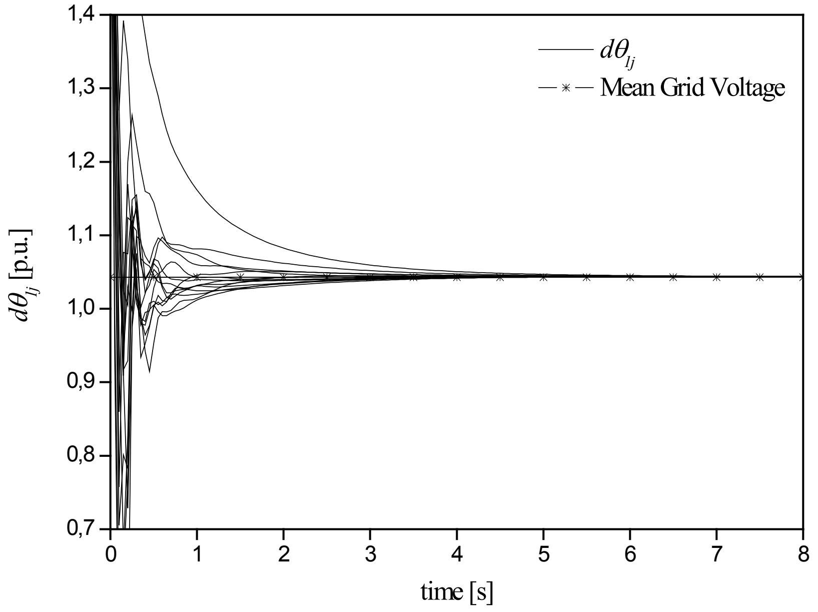


Fig. 2. Sensor oscillators’ evolution (first component of the vector of the local observations)

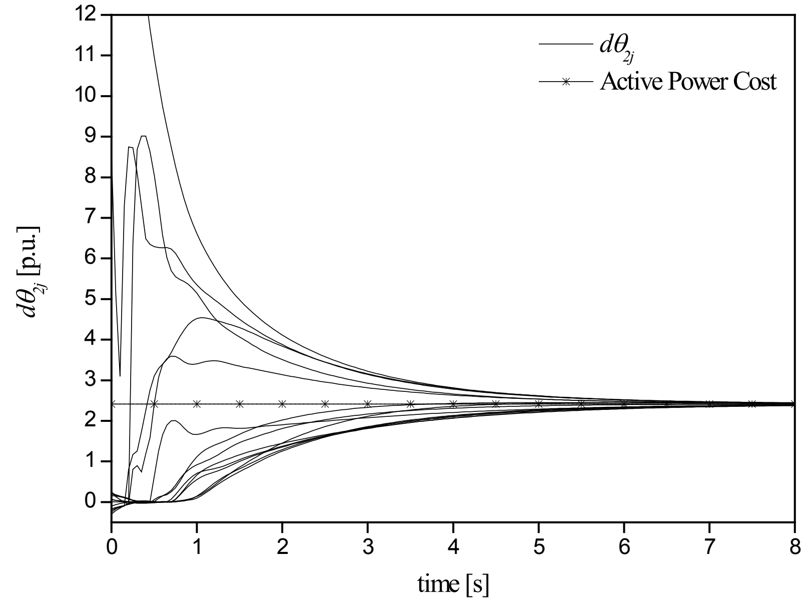


Fig. 3. Sensor oscillators’ evolution (second component of the vector of the local observations)

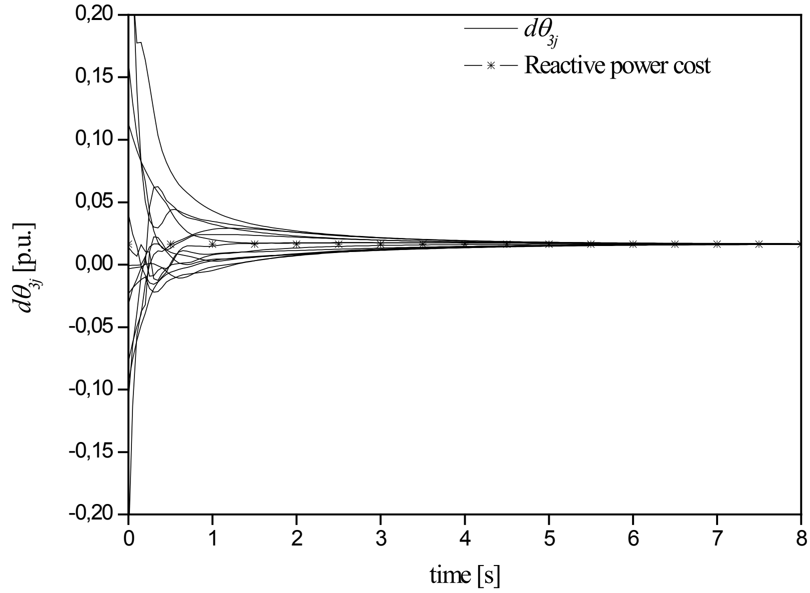


Fig. 4. Sensor oscillators evolution (third component of the vector of the local observations)

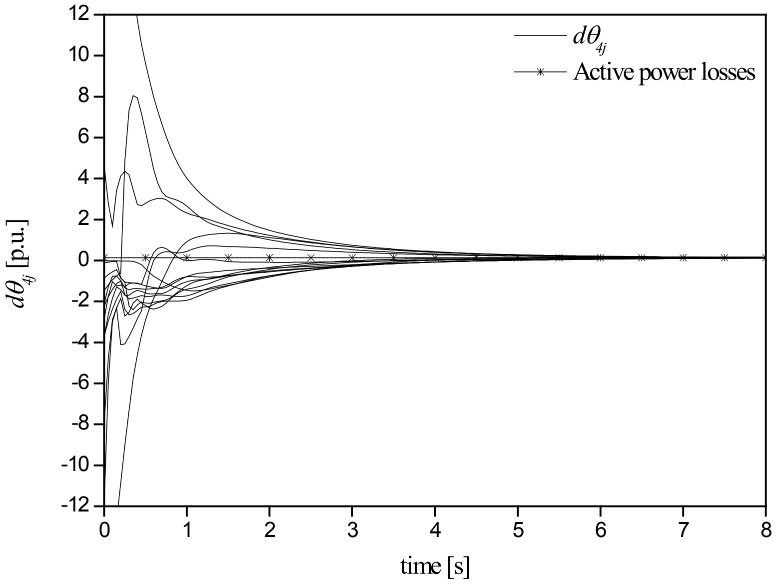


Fig. 5. Sensor oscillators evolution (fourth component of the vector of the local observations)

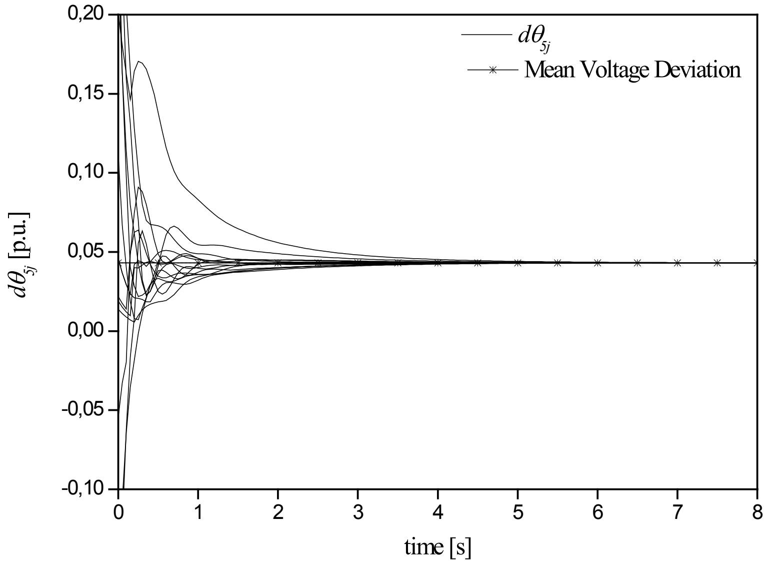


Fig. 6. Sensor oscillators evolution (fifth component of the vector of the local observations)

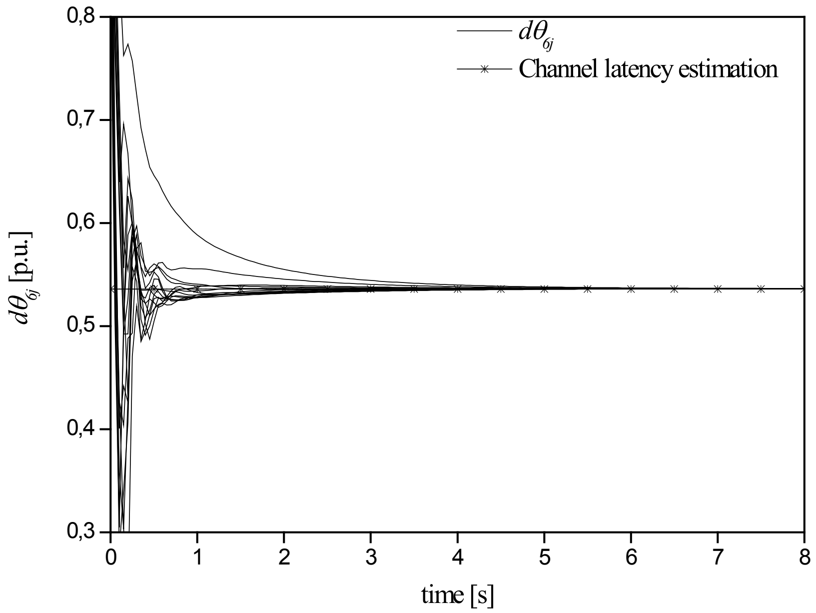


Fig. 7. Sensor oscillators evolution (sixth component of the vector of the local observations)

The analysis of the obtained results demonstrate as all sensor oscillators (whose initial values are chosen randomly) rapidly converge to the actual value of the mean grid voltage, the total active and reactive generation costs, the active system losses, the average voltage deviation and an estimation of the channel latency. In particular the synchronization time (which includes the effect of data latency, data retransmission, bad data reception etc.) is of the order of few seconds. The results therefore are suitable to address many important monitoring functions.

IV. CONCLUSIONS

Modern trends in Smart Grids are oriented toward the employment of advanced monitoring architectures that move away from the older centralized paradigm to a system distributed in the field with an increasing pervasion of smart sensors where central controllers play a smaller role. In supporting this complex task, this paper proposes the concept of a decentralized non-hierarchal voltage monitoring architecture based on intelligent and cooperative smart entities. The results obtained on a test power grid show that this monitoring paradigm allows smart sensors to detect local voltage anomalies since they know both the performances of the monitored buses, computed from locally acquired information, and the global performance of the entire grid, computed by local exchanges of information with neighboring nodes. The convergence of this process corresponds well with the time constraints characterizing the voltage monitoring process in Smart Grids. An interesting area for further studies are how this approach could make use of power system parameters to increase accuracy if needed for advanced system functionality.

V. REFERENCES

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