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Gossip Sensor Networks for Power Quality Monitoring in Smart Grids

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Abstract. This paper intends to give a contribution toward the definition of a fully decentralized power quality monitoring architecture by proposing the employment of Gossip 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. Moreover, thanks to this feature each node could automatically detect local power quality anomalies. System operators can assess the system power quality index for each grid section by inquiring any node of the corresponding sensor network without the need of a fusion center acquiring and processing all node acquisitions. This makes the overall monitoring architecture highly scalable, self-organizing and distributed.

Key words
Smart grids, power quality, monitoring techniques, sensor networks, Gossiping.

1. Introduction

Distributed power quality monitoring systems have been traditionally deployed according to a client/server paradigm, where sensors, located across the grid to be monitored, formed a network of remote acquisition units equipped by specifically routines for data gathering, data preprocessing and data exchange. Tipically a fusion centre was in charge for detailed data processing and information dissemination while a database management system played the role of information storage.

Over time new paradigms have become necessary to be employed because of rising demands and expectations for reliability. Advanced functions must ensure high performances of power systems when they operate at or near their limits and under frequently changing operating conditions [1]. In this complex scenario the deployment of Smart Grids paradigm, that is the convergence of information and operational technology applied to the electric grid in order to allow sustainable options to customers and improve security, plays a strategic role in enhancing the efficiency of power systems and the use of cleaner energy resources [2].

However in Smart Grids, hierarchical monitoring architectures have shown to suffer for intrinsic disadvantages [3], [4], while self–organizing sensor networks have proved to be applied successfully to fully decentralized quality monitoring architectures based on a peer–to–peer (P2P) paradigm where intelligent devices (smart sensors) are adopted for a more efficient tasks distribution. Moreover, the P2P model exhibits several advantages also in terms of less network bandwidth requirement and computation time. Therefore, when Smart Grids evolve to accommodate growth (they must integrate hundreds or even thousands of power nodes), monitoring system configurations inevitably need to adapt and to move on toward a decentralized non–hierarchical architecture based on reliable and high scalable information processing paradigms. In recent years an extended work appears in literature. In particular, in [5] a novel voltage monitoring system relayed on a web based sensor network is proposed and prototyped. The sensors are realized by a microcontroller based architecture and they can be remotely managed by a web based interface. In [6] a Power Quality (PQ) monitoring system, based on intelligent, adaptive and reconfigurable multi–agent system, is conceptualized and it exhibits several advantages over traditional client/server systems. 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. In [8] 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 [9] the development of distributed adaptive units for diffused on line power equipments 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 architecture composed of a network of intelligent units remotely controlled by advanced TCP/IP based communication services. In [10] and [11], a IEEE802.15.4 based wireless sensor network (WSN) has been analyzed in order to assess its performance for an urban-scale Smart Grid environment. The obtained results show that the application of WSN based services exhibits a set of intrinsic advantages, particularly useful in Smart Grid monitoring. These advantages have also been confirmed in papers [12] and [13] where a cooperative and decentralized architecture has been proposed for voltage quality monitoring. According to the scientific trends outlined by these works, this paper intends to give a further contribution toward the definition of a fully decentralized power quality monitoring architecture. The idea started from the theory of Gossip algorithms for designing high pervasive and self organizing sensor networks. The application of these algorithms is expected to be highly beneficial for power quality monitoring in smart grids since they allow remote sensors to compute a function of the measured data according to a totally distributed paradigm. This feature can be used to carry out the monitoring computations within the sensor network so that, instead of transmitting raw data to a fusion center, only the results of the computation are transmitted to the smart grid operators. In order to prove the effectiveness of the proposed architecture simulation results obtained on the 300 bus IEEE test network are presented and discussed.

2. Power Quality Monitoring by Gossip Sensor Network

The proposed solution is based on the challenging idea that borrows the theory of information spreading in pervasive sensor networks, 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 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 power quality index of the grid section, making available, at each node, both local and global performances.

A. Theory of Operation

In our specific case of interest we have focused our attention on "Aggregate computation" algorithms among all the Gossiping algorithms. Actually, in wide scale applications, above all in the specific case of Smart Grids applied to Power Systems, decentralized Gossiping based protocols represent the right approach to maintaining simplicity and scalability, while achieving fault–tolerant information dissemination, and moreover they show to converge exponentially fast through the network for the computations of sums, averages, random samples and other aggregate functions. The reader can refer to [14] for more details. Specifically, we have referred to the algorithm presented by Boyd and others [15] who presented a particular Gossiping algorithm where the network is modelled through a connected graph (see Appendix A). The Boyd algorithm has the advantages to be fully distributed and to not need a centralized management. Moreover, it's also asynchronous, that means no synchronization among the several nodes is necessary. An asynchronous time model is based on the assumption that a node performs an operation only when its clock ticks and two clocks cannot tick at the same time. For each $i \in \{1, ...N\}$, $x_i(t_k)$ represents the value measured from the node i at a given instant t_k and the hypothesis is that at $t_k = 0$ each node has got an initial measure $x_i(0)$.

In Boyd algorithm at each round, one of the N sensor, say i, becomes active at random and contact one of its neighbor, say j, with probability $f_{i\to j}$, that in general varies with j and over time. Both nodes, i and j, update their measurement to a new value given from the average between their own initial measurements accordingly to the relation

$$x_i(t_k) = x_j(t_k) = \frac{1}{2}(x_i(t_{k-1}) + x_j(t_{k-1})) \qquad (1)$$

The goal is to get through the Gossiping algorithm, in a distributed and asynchronous manner, the quantity:

$$x_{ave} = \frac{1}{N}\sum_i x_i(0) \qquad (2)$$

This average represents the consensus to reach. The quantity of interest is the time necessary to let all nodes converge to the value given by (2) and is represented with T_{ave}, the *averaging time*. It's crucial to our aims to find the dependence of the *averaging time* on network properties such as topology (connection degree, betweenness, clustering coefficient, etc.), quality (congestion, failure of nodes, etc.) or size. Over the graph G = (V, E), it's possible to define a *random walk* or equivalently a Markov chain with its states represented by V and transitions represented by E. The Markov chain is characterized by a $n \times n$ non–negative valued probability transition matrix $\mathbf{P} = [P_{ij}]$, with P_{ij} the probability of transition from state or node *i* to *j*, in one time step, thus in general depends on t_k. The probabilities of transition must satisfy the condition:

$$\sum_{j=1}^{N} P_{ij} = 1, \qquad \forall i \in V \qquad (3)$$

On the basis of adjacency matrix entries a_{ij} and node degree d_i (see Appendix A), a straightforward result is

$$P_{ij} = \frac{a_{ij} f_{i\to j}}{\sum_j a_{ij} f_{i\to j}} \qquad (4)$$

and if all the probabilities $f_{i\to j}$ are equal

$$P_{ij} \equiv f_{i\to j} = \frac{a_{ij}}{d_i}, \qquad \forall i \in V \qquad (5)$$

where in (5) actually should be $P_{ij} = \frac{1}{d_i}$ but since the result works only for $a_{ij} \neq 0$, a_{ij} is left.

Many considerations can be made about the transition matrix **P**; it may be called *irreducible*; it may be said to have a *period* and to have a *stationary distribution*; it may be called *aperiodic*; *reversible* and *non–reversible*. The reader can refer to [16] for more details.

We refer to a matrix **P** that is *irreducible* and *aperiodic* unless specified otherwise. Let $x(t_k)$ denote the vector of values at the end of time round k. We can write

$$x(t_k) = W(t_k)x(t_{k-1}) \tag{6}$$

with the matrix **W** a random matrix given with probability $\frac{1}{N}P_{ij}$ by the following equation

$$W_{ij} = I - \frac{(e_i - e_j)(e_i - e_j)^T}{2} \tag{7}$$

where $e_i = [0 \ldots 010 \ldots 0]^T$ is an $N \times 1$ unit vector with the *i*th component equal to 1 [15].

Our interest is to determine the time it takes for all nodes to converge to x_{ave} that is equivalent for matrix **P** to reach its stationary distribution. Boyd has proved that the averaging time $T_{ave}(\epsilon, P)$ necessary to reach consensus is bounded as follows

$$T_{ave}(\epsilon, P) \leq \frac{3log\epsilon^{-1}}{log\lambda_2^{-1}} \tag{8}$$

and

$$T_{ave}(\epsilon, P) \geq \frac{0.5log\epsilon^{-1}}{log\lambda_2^{-1}} \tag{9}$$

and in this case

$$W \triangleq I - \frac{1}{2N}D + \frac{P + P^T}{2N} \tag{10}$$

with D a diagonal matrix with entries

$$D_i = \sum_{j=1}^{N}[P_{ij} + P_{ji}] \tag{11}$$

For the assumptions on **P**, W is a symmetric positive–semidefinite doubly stochastic matrix with non–negative real eigenvalues

$$1 = \lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_N \geq 0 \tag{12}$$

It exists a relation between the *averaging time* T_{ave} of the consensus algorithm, the second largest eigenvalue λ_2 of W and the *mixing time* T_{mix} of the random walk based on **P**, that is the mixing time of the Markov chain with transition matrix **P** [15], [17], [16].

Practically, λ_2 governs the algorithm convergence: the lowest is this eigenvalue the fastest the algorithm converges.

B. Proposed Architecture

According to the above theoretical models, an innovative approach can be designed for a decentralized/ non-hierarchical power quality 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: i) a set of transducers measuring the available set of local electrical variables (i.e. voltage magnitude, active and reactive bus power); ii) a programmable unit (i.e. Digital Signal Processing, microcontroller) for data processing; iii)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 the previous described information spreading algorithm; iv) a communication 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. Thanks to this feature it is possible to assess, in a totally decentralized way, many important variables characterising 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:

$$\dot{\Theta} = (V_i, |V_i - V_i^*|) \tag{13}$$

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:

$$\dot{\Theta} = \left(\frac{\sum_{i=1}^{N} V_i}{N}, \frac{\sum_{i=1}^{N}|V_i - V_i^*|}{N} \right) \tag{14}$$

Other variables of interest (i.e. power quality indexes) could be easily assessed by a proper selection of the vector of observations. Thanks to the employment of information spreading algorithms 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.

3. Case Study

This section discusses the application of the proposed methodology in the task of voltage monitoring for the IEEE 300-bus test system. 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. Each node senses the following bus variables: voltage magnitude V_i, active power P_i. The corresponding vector of local observations is organized as follow:

$$\dot{\Theta} = (\theta_1, \theta_2) = (V_i, NP_i) \tag{15}$$

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

$$\dot{\Theta} = \left(\frac{1}{N} \sum_{i=1}^{N} V_i, \sum_{i=1}^{N} P_i \right) \qquad (16)$$

representing the mean grid voltage and the active power losses.

Obviously more complex indexes could be considered and integrated in the sensor dynamic evolution. This choice does not affect the validity of the proposed monitoring architecture. 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. Thanks to the adoption of this integrated simulation platform, we applied the proposed information spreading algorithms obtaining the results that are reported in Figures 1 and 2.

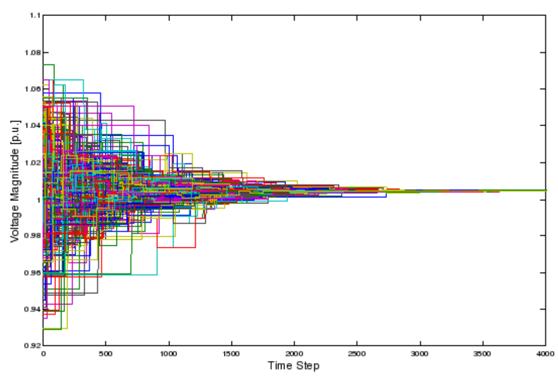

Fig. 1. Sensor oscillators evolution (first component of the vector of the local observations)

The analysis of the obtained results demonstrate that all sensor oscillators converge to the actual value of the mean grid voltage and to the active system losses. Thanks to the employment of this monitoring paradigm each sensor knows both the performances of the monitored node (i.e. the node 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 main variables characterizing the actual grid operation by inquiring any node of the sensor network 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.
A crucial point remains the time for the algorithms to converge. A further application has utilized *geographic Gossip algorithms* instead of basic one–hop Gossip algorithms: the main improvement has been the possibility of routing local information on long paths in the network. Differently from the Gossip algorithm described in 2, the *geographic Gossip algorithms* allow all nodes in the routed path to be averaged jointly. This is easily performed by aggregating the sum and the hop length while routing. As long as the information of the average can be routed back on the same path, all the intermediate nodes can replace their estimates with new updated values. The modified algorithm is also called *geographic gossip with path averaging* and it was recently shown that it converges much faster if compared to normal Gossiping algoritms [18]. Also in our applications, this choise appears to be more appropriate and efficient in terms of average time for reaching consensus among all nodes in the grid.

Appendix A

A connected undirected graph with N nodes and h (bidirectional) links is denoted by G = (V, E), where V = $\{1, ...N\}$ is the set of the graph vertexes and E $\subset$ V $\times$ V is the set of the pair (i,j) where (i,j) $\in$ E if and only if nodes i and j ($\in$ V) can communicate with each other. The graph is assumed to be indirected if (i,j) $\in$ E then (j,i) $\in$ E as well. A node i has neighbors $\mathcal{N}(i) \stackrel{\triangle}{=} \{j \in V : (i, j) \in E\}$ and for each node i, d_i is the connection degree of i in G, that is $d_i = \mid \mathcal{N}(i) \mid$, the cardinalship of $\mathcal{N}(i)$. The most natural matrix to associate with a graph G is its adjacency matrix A, whose entries a_{ij} are given by $a_{ij} = 1$ if $(i, j) \in E$ and 0 otherwise.

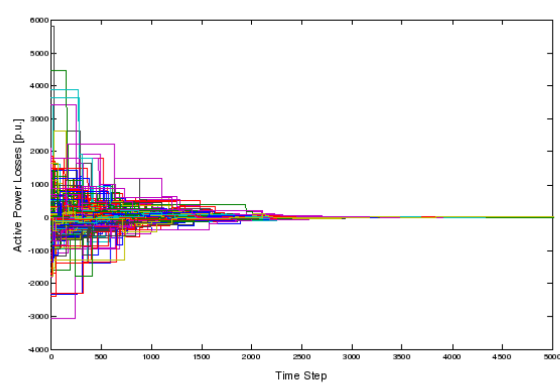

Fig. 2. Sensor oscillators evolution (second component of the vector of the local observations)

4. Conclusion

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 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 assess the main variables characterizing the actual grid operation without the need of a central server acquiring and processing all the sensors data. The convergence of this process corresponds well with the time constraints characterizing the monitoring process in Smart Grids above all if *geographic Gossip algorithms* are preferred to the basic one–hop Gossip algorithms.

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