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Experimental characterization of consensus protocol for decentralized smart grid metering

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A B S T R A C T

The availability of intelligence at substation level, combined with the adoption of pervasive communication networks, offers technologies and opportunities to decentralized smart grid metering and control. In this domain self-organizing sensor networks equipped by distributed consensus protocols have been recognized as an effective enabling paradigm.

The performance of these protocols is usually evaluated in simulation environments without considering the effects of real measurement transducers, data acquisition systems and communication systems. Attention is rarely paid to the influence of factors such as: the measurement uncertainty of the transducers, the effect of the limited bandwidth available on real radio systems, and the change of performance when real nodes enter and exit from the network during or among consensus procedure. The large scale deployment of this paradigm asks for comprehensive analysis aimed at assessing the impact of the non-idealities characterizing the real power system environment on the cooperative protocols performance. Armed with such a vision this paper aims at characterizing the performance of distributed consensus protocols in presence of uncertainty and non-ideality of the measurement instruments, of the measurement process and of the communication channel in a smart grid environment. Results obtained in simulation and real scenarios might be helpful hints in the implementation and use of this protocol in real networks.

1. Introduction

Electrical power systems were traditionally characterized by the presence of numerous utilities, heterogeneous standards, overlapping territories and a general lack of integration. Recently, under pressure from deregulated electricity markets and the new environmental policies, the main limitations intrinsic to this environment have become clear and the structures of modern power systems are evolving to accommodate large changes induced by these new energy policy trends.

In this emerging scenario, the large scale deployment of the Smart Grid (SG) paradigm could play a strategic role in supporting the evolution of conventional electrical grids toward active, flexible and self-healing web energy networks composed of distributed and cooperative energy resources [1].

SG technologies include advanced sensing systems, two way high-speed communications, monitoring and enterprise analysis software and related services to get location-specific and real-time actionable data in order to

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provide enhanced services for both system operators (i.e. Distribution Automation, Asset Management, Advanced Metering Infrastructure) and end-users (i.e. Demand Side Management, Demand Response) [2,3]. The large scale deployment of these technologies on existing power distribution systems is expected to increase the current data acquisition in about 4 orders of magnitude leading traditional hierarchical centralized control architectures to becoming rapidly saturated [4,5].

As a consequence, researchers and designers of high performance monitoring and control systems are revisiting numerous design issues and assumptions pertaining to scale, reliability, heterogeneity, manageability, and system evolution over time [6,7]. These research works conjectured that hierarchical metering paradigm could be not affordable in addressing the increasing network complexity and the massive pervasion of distributed generators characterizing modern smart grids. Unaffordable complexity, hardware redundancy, network bandwidth and data storage resources are the main barriers imposed by technology and costs [8,9].

To address this complex issue the SG community has identified the deployment of cooperative smart sensor networks as the most promising enabling technology [10,11] to realize wide area monitoring systems (WAMS). This is mainly due to broad application of distributed decision making in coordinating networks of dynamic agents aimed at enhancing operational effectiveness in networked autonomous systems [12].

In particular, several papers clearly outlined the important role of self-organizing sensor networks equipped by distributed consensus protocols for smart grid monitoring and control [13–15]. The application of consensus protocols allows distributed sensors reaching an agreement on key pieces of information or on a common value that enable them to cooperate in a coordinate fashion. This decentralized paradigm does not require neither explicit point-to-point message passing nor routing protocols. It spreads information across the network by updating each sensor state by a weighted average of its neighbors states. At each step, every sensor computes a local weighted least-squares estimate, which converges to the global maximum-likelihood solution.

Thanks to this feature the sensors network may assess, in a completely decentralized way, the many important variables characterizing the power system operation (i.e., mean grid voltage magnitude, power losses, regulation costs) without the need for a central fusion centre acquiring and processing all the power systems measurements. These global variables are then amalgamated with local measurements and processed by each smart sensor in order to improve the grid performance.

The recent advances on cooperative smart sensors networks has opened the door for decentralized non-hierarchical monitoring architectures based on reliable and high scalable information spreading algorithms. Thanks to adoption of these paradigms the grid sensor acquisitions can be time synchronized and each sensor can compute the most important variables characterizing the global SG operation without the need for a fusion centre. Consequently all the basic monitoring functions can be implemented according to a totally decentralized/non-hierarchical paradigm.

Armed with such a vision in paper [16] the authors advocate the role of self-organizing sensor networks equipped by decentralized consensus protocols in synchronized wide are smart grid monitoring. In details they demonstrate as the application of consensus protocols allows distributed Phase Measurement Units (PMUs) to be synchronized and to assess, in a completely decentralized way, the many important variables characterizing the smart grid operation without the need for a central fusion centre acquiring and processing all the power systems measurements. These global variables are then amalgamated with local measurements and processed by each PMU in order to improve the grid performance.

In paper [17] the authors propose a fully decentralized adaptive re-weighted state estimation scheme for multi area power systems via network gossiping. The proposed paradigm is based on the Gossip-based Gauss–Newton algorithm, which allows to harness the computation capability of each system area to collaboratively solve for an accurate global state. The proposed estimation scheme mitigates the influence of bad data by updating their error variances online and re-weighting their contributions adaptively for state estimation. As a consequence, the state of the entire power system can be estimated and tracked robustly using near-neighbor communications in each area.

Self-organizing sensor networks have been recently applied also in the task of solving many critical SG control problems. In particular, in papers [18] a decentralized non-hierarchal voltage regulation architecture based on intelligent and cooperative dynamic agents has been proposed. This architecture aims at computing the actual value of the cost function describing the grid control objectives by deploying a bio inspired processing paradigm based on the consensus theory. Starting from this value the dynamic agents implement a distributed and cooperative optimization strategy aimed at identifying the optimal asset of the voltage controllers. In papers [19] the same problem has been solved by deploying a decentralized fuzzy based programming paradigm on a network of cooperative smart controllers equipped by consensus protocols. These papers demonstrate as distributed fuzzy controllers based on consensus protocols could play an important role in improving the effectiveness of traditional voltage control paradigms by reducing dependencies and enhancing the system ability to remain in operation after disturbances and/or loss of equipment [20]. Besides, if properly designed, they are characterized by stabilizing and self-healing proprieties.

These benefits have been confirmed by others studies addressing the economic dispatch analysis in a distributed scenario. These papers demonstrate that, under some hypothesis, the solution of this problem can be obtained by a network of cooperative dynamic agents solving distributed average consensus problems. Thanks to this decentralized/non-hierarchical paradigm, all the basic operations needed to solve the economic dispatch problem could be easily processed by the agents. This computing architecture exhibits several advantages over traditional client server-based paradigms (as far as less network