A Complex System Approach for Smart Grid Analysis and Modeling

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Abstract. Smart Grid is a vague concept with little theoretical studies. We propose in this paper a state of the art on Smart Grids to clarify the concept and identify the important issues.
This term refers to an electrical network integrating the behavior and actions of users. It uses new information and communication technologies and new services combining: monitoring, control, communication and self-healing.
Current simulations are done on specific, preset cases and with a limited evolution. A better knowledge of the smart grid structure and characteristics would give a more effective and more efficient, global modeling. Smart Grids have many characteristics corresponding to complex systems. We propose to analyze these similarities to reach a better understanding and a holistic view of smart grid's concept.
The objective of this paper is to provide theoretical research themes that could help the design of a reliable and efficient Smart Grid.

Keywords: Smart Grid; Complex System; Emergence; Self-organization; Game Theory

1 Introduction

The classical electric power infrastructure that has served us sufficiently to a certain extent, also known as *the grid*, is rapidly running up against its limitations. Our lights may be on, but systematically, the risks associated with relying on an often overtaxed grid grow in size, scale and complexity every day. The Power Grid is evolving into a Smart Grid, where power systems, information and communication technologies meet in order to generate, transport, distribute and consume energy in a more efficient manner. Distributed generation and storage, smart meters and electric vehicles are examples of influencing technologies.

Smart Grid is a type of electrical grid which attempts to predict and intelligently respond to the behavior and actions of all electric power users connected to it - suppliers, consumers and those that do both - in order to efficiently deliver reliable, economic, and sustainable electricity services. In Europe, Smart Grid is conceived using innovative products and services together with intelligent monitoring, control, communication, and self-healing technologies. Smart Grid have three economic goals: to enhance the reliability, to reduce peak demand and to reduce total energy consumption. To achieve these goals, various technologies have been developed and integrated in the electrical network. It is not intended to replace the current system of Power Grid, but only to improve it.

The Smart Grid concept is still fuzzy and no unifying definition exist. We analysed the concept and tried to find common properties in order to give a coherent definition of Smart Grid. Then, we tried to identify the suited theories to model an efficient Smart Grid. Actually, we design adapted architecture of algorithms to garantee an effective energy distribution and management.

The rest of the paper is organized as follows: in section 2, we present a definition of Smart Grid, in order to precise the demand, the goals and the evolution of Power Grid to Smart Grid. This point of view aims to understand the expectations and principles of the future grid. Modeling and simulation of Smart Grid are also resumed. We analyze the advantages and drawbacks of these models. In section 3 we study Smart Grid as a complex system taking into account the state of the art and models to identify adapted theories to model efficient Smart Grid.

2 Introduction on Smart Grids: industrial point of view

2.1 Power Grid defects

Today's alternating Power Grid, based partially on Nikola Tesla's design published in 1888, has evolved since 1896. Many implementation decisions that are still in use today were made for the first time using the limited emerging technology available 120 years ago. Specific obsolete Power Grid assumptions and features as centralized unidirectional electric power transmission, electricity distribution, and demand-driven control; represent a vision of what was thought possible in the 19th century. Over the past 50 years, electricity networks have not kept pace with modern challenges. This is due, in particular, to an institutional risk aversion that utilities naturally feel regarding use of untested technologies on a critical infrastructure.

Today, Power Grid presents any structural defects such as security from scale-free unidirectional structure and intermittent supplies from the alternative power generation sources.

The structural defaults have a significant cost. The lack of critical infrastructure investment and the growing demand for high quality, digital-grade electricity has pushed the electrical infrastructure to its limit. The current system is obsolete and make harder the integration of new technologies. The supply and demand are based on statistics and prognostics. Production is always greater than the demand which creates a considerable loss. This has led to unprecedented electricity reliability problems, as well as inadequate power quality responsible for tens of billions of dollars in losses to industry and society annually [1]. In addition, a large part of energy producted is lost along the way between the primary energy production and the final consumer, through its transport and distribution. Morever, energy generation is the largest emitter of CO_2 [7].

The Power Grid is unable to meet suppliers, distributors and users' demands (Quality of Service included). Manufacturers have provided applications for research and development to overcome its shortcomings. More voltage sags, blackouts, and overloads have occurred in the past decade than over the past 40 years. Most of the blackouts and brownouts are occurring due to the slow response times of devices over the grid.

2.2 Industrial point of view

According to the Department Of Energy's (DOE) Modern Grid Initiative[1], a Smart Grid should integrate advanced sensing technologies, control methods and integrated communications into current electricity grid into both in transmission and distribution levels. Smart Grid not only requires communication to be real-time, reliable, scalable, manageable, and extensible, but also should be inter-operable, secure, future-proof, and cost effective [2].

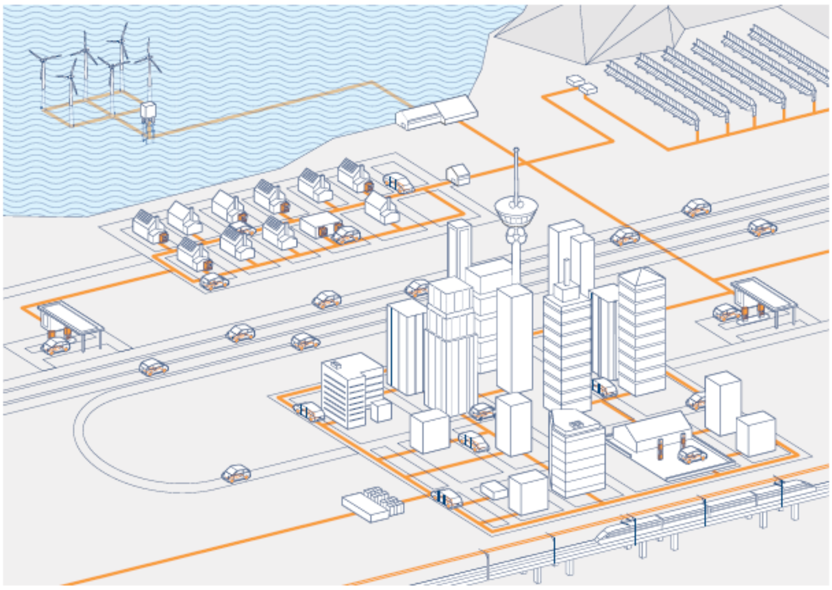

Fig. 1. Example of Smart Grid City.

The Smart Grid must have the following key characteristics:

[1] http://www.netl.doe.gov/smartgrid/

1. To be self-healing. Sophisticated grid monitors and controls will anticipate and instantly respond to system problems in order to avoid or mitigate power outages and power quality problems.
2. To motivate consumers to actively participate in the operations of the grid. The grid will enable consumers to better control the appliances and equipment in their homes and businesses.
3. To be more secure from physical and cyber threats. New technologies such as smart meters or smart appliances have private data on users or on the local energy distribution.
4. To provide higher quality power that will save money wasted from outages.
5. To accommodate all generations and storage options (vehicles to grid, renewable energy Etc.)
6. To enable electricity markets to flourish. The grid will achieve greater throughput, thus lowering power costs.
7. To run more efficiently. Smart Grid relies greatly on the design, development, and deployment of dedicated information networks that enable information communication between devices, applications, consumers and grid operators. For the desired Smart Grid, communication/networking is a key technology for achieving automation and interactivity.
8. To enable higher penetration of intermittent power generation sources (mainly local renewable energy).

We notice that these properties are also established by active research in complex systems. According to the New England Complex System Institute, complex systems is a new field of science studying how parts of a system give rise to the collective behavior of the system, and how the system interacts with its environment[2]. Thus, we have to understand the collective behavior to model an efficient Smart Grid.

2.3 Smart Grid modeling

Designing a communication system architecture that meets these complex requirements are the key to the successful implementation of a Smart Grid in the future. Based on these requirements, it initially implies a need for bidirectional, real-time communication networks for data collection and processing. In [8], Chen et al. argued that successful Smart Grids should be able to collect all kinds of information regarding electricity generation (centralized or distributed), instantaneous or predictive consumption, storage or conversion of energy into other forms, and distribution through this communication infrastructure.

Smart Grid presents a shared resource among multiple actors, with divergent interests. A multi-agent system (MAS) modeling presents the global dynamic of the system from individual components and explores emergent properties associated with this dynamic. However, it should be noted that MAS have a major drawback: one model run does not allow to conclude about the relationship between model and results [21].

[2] http://necsi.org

Smart Grid models and simulations are very few. However, several conceptual architectures of the Smart Grid have now been proposed by national organizations and companies, such as the DOE, the State of West Virginia [19], NIST [10], etc. We conclude that a Smart Grid architecture must address the following critical issues[3] : (1) transmitting data over multiple media; (2) collecting and analyzing massive amounts of data rapidly; (3) changing and growing with the industry; (4) connecting large numbers of devices; (5) maintaining reliability; (6) connecting multiple types of systems; (7) ensuring security; and (8) maximizing return on investment.

Most of the models are based on multi-agent system and present the following characteristics:

1. Layered architecture: in [15], Mets et al. use a similar architecture for Smart Grid. The simulation framework allows simulating the management and control strategies, the communication network and the Power Grid. In order to do this, the Smart Grid simulator defines a layered architecture. The layered architecture supports decomposing the system and similar responsibilities groups. We identify three main layers: application, information with communications technologies (ICT) and support layers. Support layers are composed of: the network and electrical components.
2. Agents implementation: in [18], Pipattanasomporn et al. focus on implementing the concept of agents in an Intelligent Distributed Autonomous Power System (IDAPS) environment. In the IDAPS multi-agent system, each agent has unique objectives and responsibilities. When working in collaboration, four agents will work toward achieving the overall goal of an IDAPS microgrid, which is to secure critical loads within the microgrid during outages (Control agent, Distributed Energy Resources agent, User agent, Database agent).

The multi-agent system simulate the behavior of Smart Grids. But simulations are preconceived and specific cases and cannot be accommodated to integrate new technologies. The model is for single use. If you want to modify, to add or to remove a setting you have to create a new model. Scenarios are known, multi-agent system cannot create a global model. It is, therefore, necessary to study properties, structure and behavior of Smart Grids.

To ensure an effective modeling and optimization of Smart Grids, we have to study systemically in order to highlight the main characteristics and behaviors of different components of the overall system.

3 Complex system: a new way to understand Smart Grid

Smart Grids have many properties similar to complex systems, among which we cited:

- Heterogeneity of elements.

[3] http://www.cisco.com/web/strategy/docs/energy/

- External and internal factors leading to local and global behavior.
- Sensors and measurement tools for the good execution of the system.
- A local decision for an overall balance.

The current Power Grid is scale-free and have a centralized unidirectional architecture. The future bidirectional distributed structure of Smart Grid generates many modeling problems. We rely on the properties of complex system to find suitable theories to model an efficient global Smart Grid. The first subsection presents a definition of complex system. The second one deals with the structural properties: emergence. The internal factors of the system are regulated independently and locally to bring an optimized balanced system. The third subsection examines the dynamic aspect of the system. Under external constraints, the Smart Grid must evolve to ensure network stability while maintaining its Quality of Service at any time.

3.1 Definition of complex system

A complex system is generally regarded as being a network of elements in mutual interactions, which behaviors and properties cannot be deduced from a part. A complex system adapts to external or internal pressures to maintain its functionality. The complexity of the system depends on two factors: the effectiveness of the structure according to the scale and topology, and the dynamics over time and determined by interactions; in order to accomplish the global mission [6]. Both aspects contribute to the emergence of new properties in the system. Every organized activity shows an opposition between two basic requirements: the division of resources into different tasks to be performed, and the coordination of these tasks to accomplish the mission. Thus, the study of a complex phenomenon requires a holistic approach considering the system in its totality [5].

Sometimes the notion of self-organization and emergence are confused. Properly defined, however, there may be instances of self-organization without emergence and emergence without self-organization, and it is clear from the literature that these phenomena are not identical [13]. The link between emergence and self-organization remains an active research question. It is important to note that emergence is the effect of internal interactions and self-organization is the effect of external interactions to the system.

The concept of emergence is very present in complex systems and is expressed through the appearance of a new property in the system when a key parameter reaches a critical value (threshold). Self-organization may be defined as a spontaneous, i.e. not steered or directed by an external system, process of organization, i.e. of the development of an organized structure [13].

3.2 Structural properties

Emergence is one of the most important properties of complex systems. Emergence occurs when appears a new property in the system often after a phase transition phenomenom[4]. An emergent behavior or emergent property can appear when a number of simple entities named agents operate in an environment, forming more complex/collective behaviors. If emergence happens over disparate scales, then the reason is usually a causal relation across different scales [14].

Smart Grid has a scale-free network whose nodes or elements differ in their properties, their objectives and actions which can be made. Moreover, the network consists of multiple microgrids with a local behavior in interactions with each other. We propose to study group dynamics to analyse and understand the global behavior of the Smart Grid. Group dynamics is the study of groups, and also a general term for group processes. A group is two or more individuals who are connected to each other by social relationships [9]. Because they interact and influence each other, groups develop a number of dynamic processes that separate them from a random collection of individuals [12].

We can consider the Smart Grid as a grid of games. Game in microgrid defines the variables at another scale. Local behavior obtained by game theory, also enter in upper scale equilibrium. Game theory reflects calculated circumstances where a person's success is based upon the choices of others [17]. The emergence of a behavior has been often the effect of a local or global equilibrium. Game theory helps understand and predict these balances. Each game is based on various factors; the goals defined by manufacturers are the following: to minimize the price, the energy cost and the time between demand and response. At a macroscopic scale, the goals are: enhancement of reliability, reduce peak demand, lower total energy consumption, actively manage electric vehicle charging, actively manage other usage to respond to solar, wind, and other renewable resources.

To send microgrids and production's datas between different levels, we need a way to spread them. In the case of Smart Grid, data distribution in a random structure is named percolation. In mathematics, percolation theory describes the behavior of connected clusters in a graph. More generally, percolation theory studies the deterministic propagation of a fluid on a random medium. We can compute the critical thresholds and study the evolution of the system related to the variation of characteristic quantities such as the clustering coefficient, the average size of the clusters and its distribution using the mathematical methods developed in percolation theory [3].

The functional distance between actors requires a more detailed graph to balance the system at any scale, we propose to study pretopology. Pretopology theory, a generalization of topology theory which expresses structural transformation of sets of interacting elements [4]. It allows an efficient modeling of dynamic discrete structures thanks to the general concept of proximity. Axiomatic requirements of topology are such that they are often incompatible with real properties of the model. Hence the idea to consider the construction of a less restrictive axiomatic theory: this is what provides the pretopology. The distance

[4] Abrupt change in the state of the system when a key parameter reaches critical value.

is not the only factor of Euclidean distance or Chebyshev distance, we also take into account the energy loss, transport costs and the current direction of energy.

Structural properties like self-similarities in scale-free network is only structural properties and do not mean that the system can be studied at any scale.

3.3 Dynamic properties

The importance of the system's environment should not be underestimated. Inputs, output, and adaptation are all explicitly dependent on the particularities of the environment of the system. The environmental factor is present at any scale on a Smart Grid. The network must be able to adapt in real-time to weather, users and any internal problem. Smart Grid should be composed of a data communications network integrated in the electrical grid that collects and analyzes data about power transmission, distribution, and consumption.

The evolution of the system will be done locally by a system of sensors and simple rules. Sensors at local scale provide generic mechanisms for controlling the running, maintenance, and evolution. They define the behavior of the interactions among the control elements over the adaptation process, to guarantee system properties at run-time. Based on these data, Smart Grid technology then provides predictive information and recommendations to utilities, to their suppliers, and to their customers on how best to manage power [11].

Integrating sensor networks and grid computing in sensor-grid computing is like giving "eyes", "ears" and feedback to the computational grid. Feedback describes the situation when output from, or information about the result of, an event (or phenomenon) in the past will influence an occurrence or occurrences of the same event (or phenomenon) in the present or future. They evaluate the health of equipment and the integrity of the grid and support advanced protective relaying; they eliminate meter estimations and prevent energy theft [2]. Real-time information about phenomena in the physical world can be processed, modeled, correlated and mined to permit on-the-fly decisions and actions to be taken on a large scale [20]. Real-time is an instant response, but Smart Grid has to learn and evolve to meet the internal and external constraints.

Machine learning in Smart Grid should be a major part of the system regulation and self-healing. Machine learning is concerned with the development of algorithms allowing the machine to learn via inductive inference based on observing data that represent incomplete information about statistical phenomenon. Classification which is also referred to as pattern recognition, is an important task in machine learning, by which machines learn to automatically recognize complex patterns, to distinguish between exemplars based on their different patterns, and to make intelligent decisions [16]. This process of adaptation is made possible by a set of internal mechanisms called sensors or effectors.

When external pressure exceeds the critical values beyond the tolerance levels of learning mechanisms, the system is forced to migrate to a new stage of evolution.

4 Conclusions and future work

In this paper, we clarified the concept of Smart Grid. There isn't a single definition but a multitude of perspectives. After an analysis of both theoretical state of the art, and industrial point of view, our work has extracted common and essential behavior and properties. Following this work, we proposed appropriated theories to design and model an efficient Smart Grid at any scale (microgrid, transmission and distribution, Etc.).

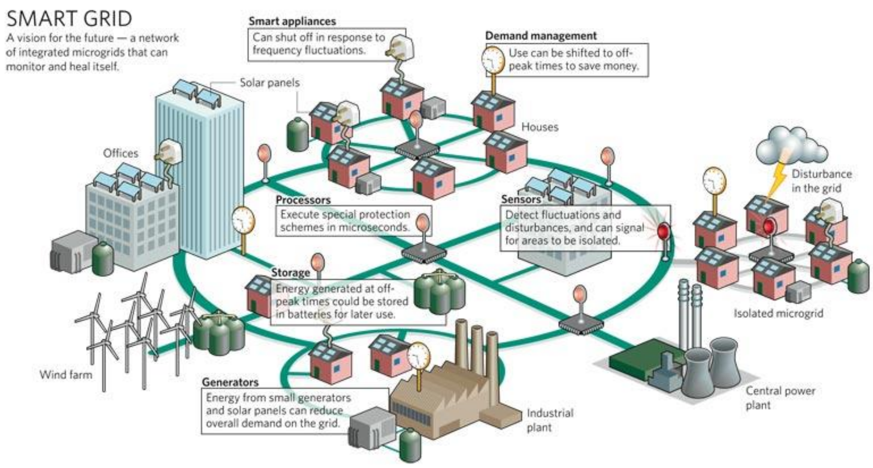

Fig. 2. Smart Grid: Vision of the future.

Our work belongs to a research program including scientific and industrial projects such as GARE, an industrial project with Alstom, SNCF and EDF, which consist in modeling and simulating an optimized smart district. We develop algorithms to manage the energy's distribution among consumers and we will provide results in future publications.

Our current work aims to finish the conception and the implementation of the designed algorithms and to validate our exposed approach.

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