Survey on smart grid modelling

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Guillaume Guérard*, Soufian Ben Amor and
Alain Bui

Laboratory PRiSM CaRO,
45, Avenue des États-Unis,
Versailles, 78000, France
E-mail: guillaume.guerard@ens.uvsq.fr
E-mail: soufian.ben-amor@uvsq.fr
E-mail: alain.bui@prism.uvsq.fr
*Corresponding author

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. We analyse different visions to bring out the characteristics of smart grids.

This term refers to an electrical optimised network integrating the behaviour and actions of users (generators, consumers, consume-actors, etc.). These power grid's upgrades aim: to improve quality and security, to reduce environmental impact, and allow consumers to play a regulation role in the system.

Current simulations are done on specific 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 modelling. Smart grids have many characteristics corresponding to complex systems. We propose to analyse these similarities to reach a better understanding and a holistic view of smart grid's concept.

Keywords: smart grid; complex system; multi-agent system; MAS; emergence; self-organisation; survey; systems; control; communications.

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Biographical notes: Guillaume Guérard is a PhD student at the University of Versailles Saint-Quentin-en-Yvelines, France.

Soufian Ben Amor received his PhD in Computer Science in 2008 from Ecole Pratique des Hautes Etudes. His PhD was performed at the European Organisation for the Safety of Air Navigation (EUROCONTROL). He is currently an Associate Professor at University of Versailles Saint-Quentin-en-Yvelines, France. He is an author and co-author of more than 30 papers and conference papers on the topics complex systems modelling and operation research.

Alain Bui is a Full Professor of Computer Science PRiSM-CNRS Laboratory at the University of Versailles Saint-Quentin-en-Yvelines, France. He received his PhD in Computer Science in 1994 from University Paris 7 and INRIA. His interests include distributed algorithms and operations research.

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 systemically, 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.

Smart grid is a type of electrical grid which attempts to predict and intelligently respond to the behaviour 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. Smart grid has 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 to the electrical network.

From 1980s, many technologies have emerged. Automatic meter reading was used for monitoring loads from important customers, and evolved into the advanced metering infrastructure, whose meters could store how electricity was used at different times of the day. Monitoring and synchronisation of wide area networks were revolutionised in the early 1990s when the Bonneville Power Administration expanded its smart grid research with prototype sensors that are capable of very rapid analysis of anomalies in electricity quality over very large geographic areas. The culmination of this work was the first operational wide area measurement system (WAMS) in 2000. By the late 1990s, home automation was commonly used. Automation describe any system in which informatics and telematics were combined to support activities at home. Security, privacy, reliability and robustness are important aspects concerning power grid operations. The deployment of smart grid technologies can give benefits in these areas (Vyatkin et al., 2010). Fault detection and restoration can be automated, leading to faster response time and less risk of human operator errors.

The rest of the paper is organised 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. Section 3 concerns the complex system approach. Indeed, smart grid has many features and properties similar to complex systems. Modelling and simulation of smart grid are resumed in Section 4. We analyse the advantages and drawbacks of these models. In Section 5, 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 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 centralised 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 some structural defects such as:

- Security threats, from either energy suppliers or cyber attack. Scale-free centralised architecture are weak against targeted attacks.
- National goals to employ alternative power generation sources whose intermittent supply makes maintaining stable power significantly more complex.
- Conservation goals that seek to lessen peak demand surges during the day so that less energy is wasted in order to ensure adequate reserves.
- High demand for an electricity supply that is uninterruptible.
- Digitally controlled devices that can alter the nature of the electrical load. and result in electricity demand that is incompatible with a power system.

The increased use of such devices lead to electric service reliability problems, power quality disturbances, blackouts, and brownouts. 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 (http://www.energyfuturecoalition.org/resources).

In addition to structural defects, the current grid has many consumption gaps:

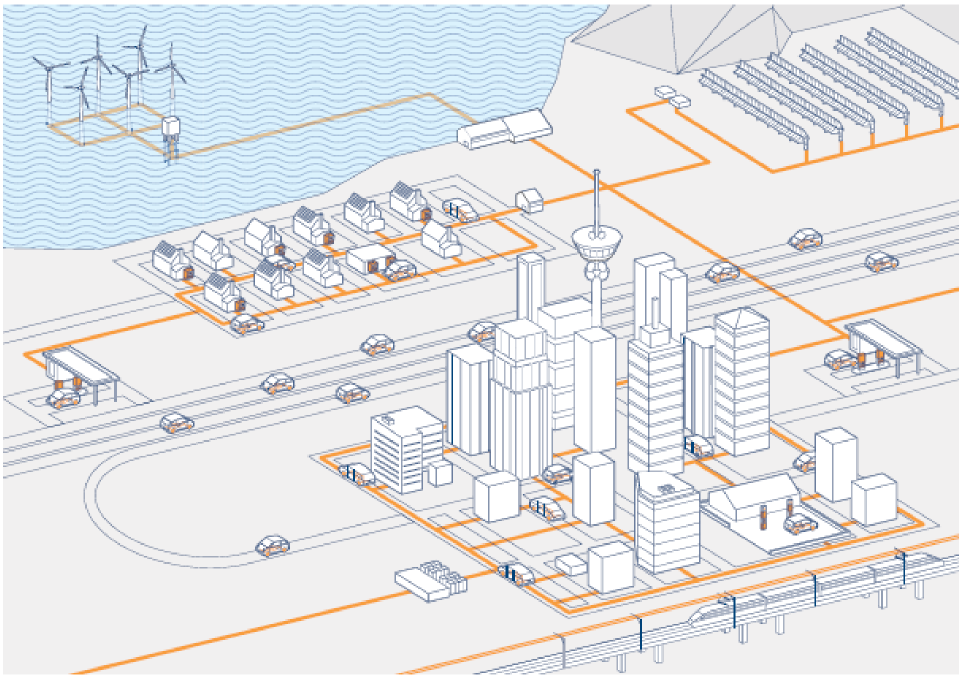
- 80% of the energy is lost along the way between the primary energy production and the final consumer, through its transport and distribution.
- 40% of world energy production comes from coal, energy generation is the largest emitter of CO_2. The USA power system alone produces 40% of all nationwide carbon emissions.
- Micro-cuts cost 80 billion dollars per year (data: 2009, USA).
- Additional cost due to network latency, demand and response are not simultaneous.

The power grid is unable to meet suppliers, distributors and users' demands (QoS 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

The main goal of manufacturers is to minimise adverse impacts on electricity grids and maximise consumer savings.

Figure 1 Example of smart grid city



According to the DOEs modern grid initiative (NETL Modern Grid Initiative, 2008), a smart grid integrates advanced sensing technologies, control methods and integrated communications into current electricity grid both at transmission and distribution levels. The smart grid must have the following key characteristics:

- 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.
- To motivate consumers to actively participate in operations of the grid. The grid will enable consumers to better control the appliances and equipment in their homes and businesses.
- To be more secure from physical and cyber threats.
- To provide higher quality power that will save money wasted from outages.
- To accommodate all generation and storage options.
- To enable electricity markets to flourish. The grid will achieve greater throughput, thus lowering power costs.

- To run more efficiently.
- To enable higher penetration of intermittent power generation sources.

For this, manufacturers have developed smart energy demand mechanisms and tactics that include: smart meters, dynamic pricing, smart thermostats and smart appliances, automated control of equipment, real-time and next day energy information feedback to electricity users, usage by appliance data, and scheduling and control of loads such as electric vehicle chargers, home area networks (HANs), and others. But adding new appliances into customer's houses and buildings gives more instability to the current power grid.

Smart grid is designed to integrate advanced communication/networking technologies into electrical power grids to make them smarter. The design and implementation of a new communication infrastructure for the grid are two important fields of research. The smart grid is expected to affect all fields of the current electrical grid system, from generation, to transmission, and to distribution. Smart grid can be defined as "a complex system of systems" (Gao et al., 2012). Requirements and improvements needed to change all the conceptions of the current grid.

2.3 A complex system of systems

Smart grid not only requires communication to be real-time, reliable, scalable, manageability, and extensible, but also should be inter-operable, secure, future-proof, and cost effective (NETL Modern Grid Initiative, 2007). Most organisations, companies, and researchers have proposed their flown underlying strategies and applications of legacy communications for electrical grid systems. There are many research in networking (Lin et al., 2009) that can be applied into smart grid communications. The National Energy Technology Laboratory synthesised requirements of the desired smart grid with five key technology areas (NETL Modern Grid Initiative, 2007):

1. integrated communications: fully integrated, two-way communication, open plug-and-play environment that allows the networks' grid components to talk, listen, and interact securely
2. sensing and measurement: enable the transformation of data into information
3. advanced components: these will produce higher power densities, greater reliability and power quality, enhanced electrical efficiency which produces major environmental gains, and improved teal-time diagnostics
4. advances control methods: new methods will be applied to monitor essential components, enabling a rapid diagnosis of and timely, appropriate response to any event
5. improved interfaces and decision support: the time available for operators to make decisions is only seconds. The modern grid will require wide, seamless, real-time use of applications and tools that enable grid operators and managers to make decisions quickly.

We notice that all these news properties refer to the known properties of active researches in complex system. 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 behaviour of the system, and how the system interacts with its environment (http://necsi.org).

3 Complex system overview

3.1 Definition of complex system

Research is currently facing the notion of complex system in different disciplines and fields. A major problem in these systems is to understand how a set of objects that interact according to local rules generate a specific global behaviour. In other words, the problem is to explain why and how systems can have a microscopic behaviour easy to describe and a macroscopic behaviour more complicated (Nguyen, 2006).

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 (Amor et al., 2007). Both aspects contribute to the emergence of new properties in the system. Every organised 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 (Amor et al., 2006).

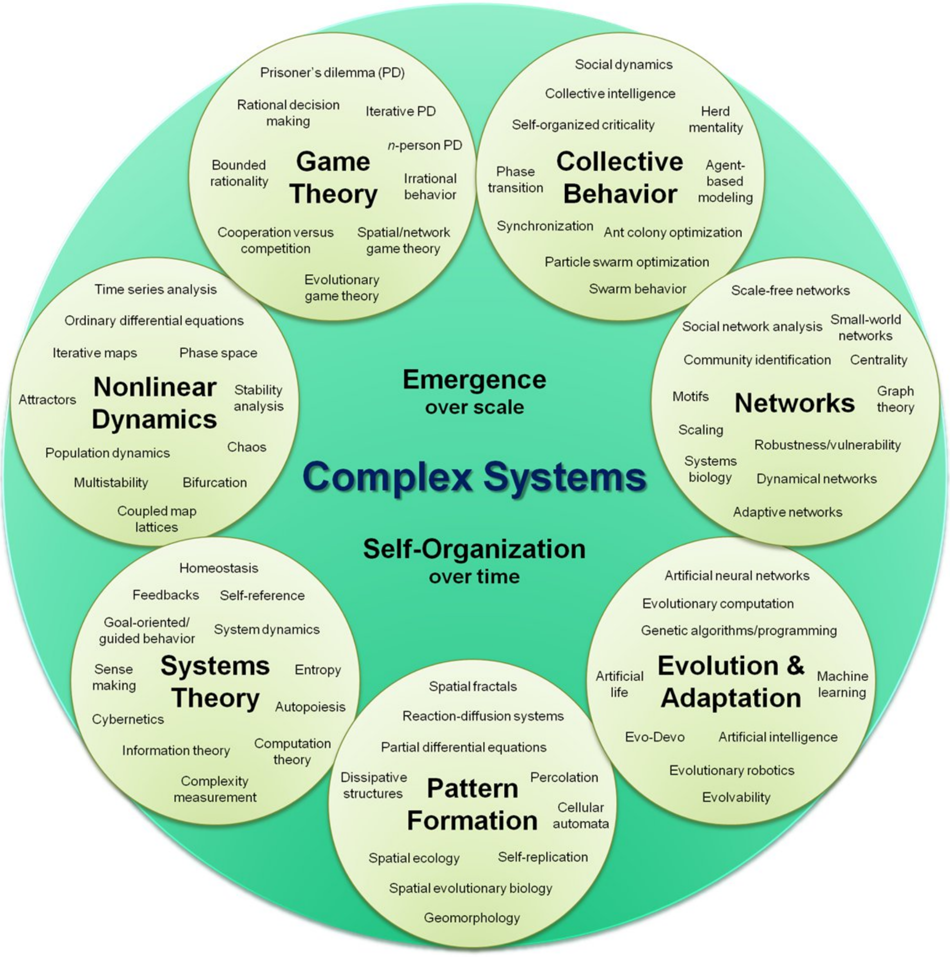
Sometimes the notion of self-organisation and emergence are confused. Properly defined, however, there may be instances of self-organisation without emergence and emergence without self-organisation, and it is clear from the literature that these phenomenas are not the same (Heylighen, 1989). The link between emergence and self-organisation remains an active research question. It is important to note that emergence is the effect of internal interactions and self-organisation is the effect of external interactions to the system.

Complexity is often associated to the concept of emergence. A system is known as complex if it presents phenomena of emergence, i.e., it has a potential richness higher than the sum of its subsystems. This function is called in statistical physics the entropy of the system (Ricard, 2003). 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-organisation may be defined as a spontaneous, i.e., not steered or directed by an external system, process of organisation, i.e., of the development of an organised structure (Heylighen, 1989). Systems in thermal equilibrium can show certain transitions between their states when we change a parameter like temperature. For instance, when we heat ice it will melt and form new state of a liquid. When we heat water up more and more, it will boil at a certain temperature and form vapour. Thus, the same microscopic elements, molecules, may give rise to quite different macroscopic states which change abruptly from one state to another. At the same time new qualities emerge, for example ice has quite different mechanical properties from those of a gas (Haken, 2006).

Both axes will be studied in Section 5 to identify the important factors and properties in the context of smart grids. On the following subsection we try to answer to: What is a model? What tools are used for complex system modelling?

Figure 2 Scheme presenting the different theories dealing with complex system modelling (see online version for colours)



3.2 Complex system modelling

A model is a simplified, often mathematical, system. In real system, several parameters with different natures exist. But only some of these parameters are taken into account in the model, depending of their relevance and their degree of influence. Typically, in complex system, few factors are the origin of the observed phenomena. A model is adapted to a question and, for the same purpose and the same question there may have several models. A model can be built to answer different questions and thus constitute a research tool, and forecasting tool. In general, numerical models are associated with measurable physical quantities in space and time and affect the forecast. The qualitative models analyse the intelligibility of studied phenomena. The conventional quantitative approach is inadequate to represent complex systems. Indeed, any quantitative global assessment is imprecise. Complex system are very sensitive to initial conditions and a little measurement error entails an impossibility to predict, at least quantitatively.

We often forget that the main objective of complex system models is to describe their behaviour. Modelling a complex phenomenon is basically qualitative rather than quantitative (Bar-Yam, 2003). The modelling approach of a complex system focuses on its holistic properties and organisational principles. Simulation as a scientific method is not limited to the prediction aspect. It is also interested in exploration and discovery of properties and organising principles of the studied phenomena. An exploratory simulation is at least as important as predictive simulation (Conte et al., 1997).

Interactions between components of a complex system is essential for understanding their behaviour but data at local level is not sufficient. It is important to consider the system as a whole and focus on qualitative aspects, looking for emergent properties and the context of their appearance. Understanding properties' alterations or variations and relationships between these properties enables us to use practical applications to control and optimise complex systems (Amor et al., 2006). Conventional analytical approaches are essentially quantitative studies using differential equations to describe the behaviour of the studied phenomena. These equations are based on the assumption of uniformity, a system is uniform and the local behaviour does not affect the global behaviour. These considerations are not true in the case of complex systems where heterogeneity of the components is one of the factors generating the global behaviour (Bar-Yam, 2003).

Recent development of computer technologies has enabled the development of concepts and tools to study the dynamics of complex system. This modelling has opened new approaches such as cellular automata, or multi-agent systems (MASs) (Boccara, 2004). Computers simulate several scenarios by combining the effect of different parameters in order to identify the most important among them. It also allows testing non-real situations, to exhibit new properties that contribute to the understanding of some complex mechanisms and the discovery of others.

4 Smart grid modelling

4.1 MAS modelling

Designing a communication system architecture that meets these complex requirements is 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. Chen et al. (2010) argued that successful smart grids should be able to collect all kinds of information regarding electricity generation – centralised or distributed –, consumption – instantaneous or predictive –, storage – or conversion of energy into other forms –, and distribution through this communication infrastructure.

One of the major benefits of MAS is to view the complex systemic issue of simultaneous activity of different agents. Smart grid present a shared resource among multiple actors, with divergent interests. A MAS modelling presents the global dynamic of the system from individual components and explores emergent properties associated with this dynamic. MAS enables to include the following items that are difficult or impossible to integrate analytically (Amor et al., 2006):

- competitive and simultaneous action of a large number of entities
- management of access to a shared resource

- constraints' relaxation and individualisation of entities' behaviour
- opportunity to express heterogeneity and diversification in the nature of entities
- intervention in real time during the simulation by changing some parameters.

We insist on the importance of the following two properties of MAS: the ability to simulate parallel action of various entities in the system and intervention in real time during the simulation. This is very important for understanding the complex dynamics particularly near the threshold of transition. 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.

4.1.1 Modelling the management of renewable resources

Bousquet et al. (1999) expose modelling and simulation of renewable resource management. Simulating the management of common resources raises the problem of the interaction between sets of agents and dynamic resources. Empirically, several different methods for modelling these interactions can be distinguished:

1. The first modelling method places emphasis on the cognitive processes or representations which determine the interaction between agents and resources. Each agent makes his flown representation of the resource and acts upon it accordingly. By doing so, he transforms this resource for others. We can speak of coordination by the environment.
2. A second method focuses on the simulation of management in social network. The relationships between agents and resources are formulated as relationships between agents with respect to resources. MAS simulate exchanges of information, services, contracts and agreements between agents.
3. Third method propose to represent 'mediator' objects or 'common referents'. These are objects which are both an individual and a shared representation, which tend both to create the social group and to be the expression of its existence. Through the perception of these objects, each agent sees himself as a member of the whole and thus contributes to the creation or continuation or modification of this whole. This has been conceptualised by Gilbert (1995) as second-order emergence.

MASs offer formulations which are capable of taking into account several thought models for collective management of renewable common resources. MASs, which provide the possibility of modelling representations, modes of communication within network, individual or social controls, imposed or constructed controls and interactions, provide a good means to simulate forms of coordination observable in the field.

4.2 Smart grid modelling

Smart grid models and simulations are very few. There are three major sources of smart grid architecture proposals:

- government and organisations: provisioned requirements and blueprints of smart grid
- industrial: proposals of communication infrastructure implementations
- academia: greater focus on defining communication architecture requirements and solutions.

However, several conceptual architectures of the smart grid have now been proposed by national organisations and companies, such as the DOE US, the State of West Virginia (Pullins, 2010), NIST (Framework, 2010), etc. We conclude that a smart grid architecture must address the following critical issues (http://www.cisco.com/web/strategy/docs/energy):

1 transmitting data over multiple media
2 collecting and analysing 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
8 maximising return on investment.

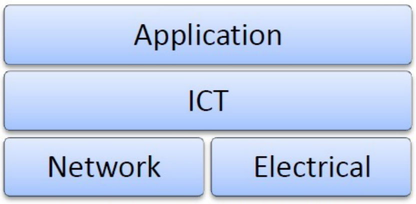
Most of models are based on MAS and present the following characteristics for architecture and agents implementation.

4.2.1 Layered architecture

In Kramer and Magee (2007), they describe self-management at the architectural level, where a self-managed software architecture is one in which components automatically configure their interaction in a way that is compatible with an overall architectural specification and achieves the goals of the system. They have defined a three layer reference model: component control, change management and goal management. At the component layer, the main challenge is to provide change management which reconfigures the software components, ensures application consistency and avoids undesirable transient behaviour. At the change management layer, decentralised configuration management is required which can tolerate inconsistent views of the system state, but still converge to a satisfactory stable state. Finally, some form of online (perhaps constraint-based) planning is required at the goal management layer.

Mets et al. (2010) 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 and communications technologies (ICT) and support layers. Support layers are composed of: the network and electrical components.

Figure 3 Simulation framework layers (see online version for colours)



High level applications and services are implemented in the application layer. Examples of such services are real time energy monitoring, demand side management or billing. These applications use the functions provided by the ICT layer, which provides generic functionalities that can be used by any service. These include communication features that work independent of the underlying physical medium (e.g., ZigBee), discovery of devices or energy management services, etc. The support layer, composed of the network and electrical components, provides support functions for the layers above. Communication between services is made possible by the network layer that provides communication modules for multiple physical media and makes simulation of communication using a variety of technologies possible. The electrical layer not only models individual appliances, but the whole power grid. It provides functionality to determine the topology and status of the power grid, enabling users to calculate for example bidirectional power flows. The power grid as well as the communication network and coordination services can be simulated simultaneously, supporting, e.g., the assessment of the interdependencies between them.

4.2.2 Agents implementation

Pipattanasomporn et al. (2009) focus on implementing the concept of agents in an intelligent distributed autonomous power system (IDAPS) environment. IDAPS is a distributed smart grid concept proposed by Advanced Research Institute of Virginia Tech (Rahman et al., 2007). Having a built-in multi-agent functionality, IDAPS can be perceived as a microgrid that is intelligent. The agents in the IDAPS MAS work in collaboration to detect upstream outages and react accordingly to allow the microgrid to operate autonomously in a microgrid. This capability can be perceived as a software alternative to a traditional hardware-based zonal protection system for isolating a microgrid.

In the IDAPS MAS, 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. Agents are implemented for various tasks:

1 control agent puts forth responsibilities that include monitoring system voltage and frequency to detect contingency situations or grid failures

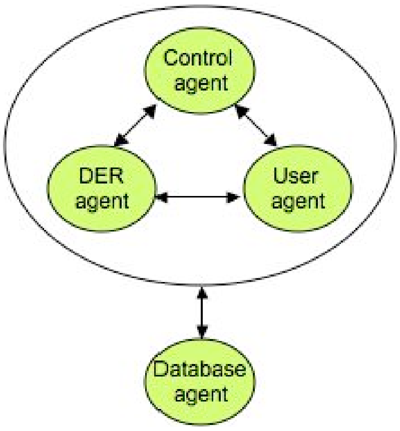
2 distributed energy resources (DER) agent is responsible for storing associated DER information, as well as monitoring and controlling DER power levels and its connect/disconnect status

3 user agent acts as a customer gateway that makes features of a microgrid accessible to users

4 database agent serves as a data access point for other agents, as well as users.

The application design step involves a process of modelling knowledge that will be used by each agent. In this step, Facts are defined for the application. Facts represent statements that an agent believes to be true, either about itself or its external environment.

Figure 4 IDAPS multi-agent architecture (see online version for colours)



4.3 MAS gaps for smart grid simulation

Conclusion of Mets et al. (2010) presents the main gap of MAS simulation: “We will continue the development of the framework, which includes adding new models to the simulator and enhancing existing ones”. Or from Karnouskos and de Holanda (2009): “The motivation was to create a dynamic infrastructure that can partially simulate the behavior of the future smart grid city [...]. To demonstrate and validate the simulator, we have run several scenarios”. For 3,840 appliances and 24 hours, the scenario run generated $63 * 10^6$ appliance consumption events, $8 * 10^6$ vehicle consumption events and $480 * 10^3$ power station generation events. Taking into account the number of appliances this makes an approximate average of $16 * 10^3$ events per device.

Agent-based models complement traditional analytic methods. Where analytic methods enable humans to characterise the equilibrium of a system, agent-based models allow the possibility of generating those equilibria.

The MAS simulate the behaviour 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/add/remove a setting you have to create a new model. Scenarios are known, MAS cannot create a global model. It is therefore necessary to study properties, structure and behaviour of smart grids.

To ensure an effective modelling and optimisation of smart grids, we have to study systemically in order to highlight the main characteristics and behaviours of different components of the overall system.

5 Complex system: a new way to understand smart grid

Smart grid has many properties similar to complex systems, among which we cited:

- heterogeneity of elements
- external and internal factors leading to local and global behaviour
- sensors and measurement tools for the good execution of the system
- a local decision for an overall balance.

The list includes other similarities that we will see in the two following subsections. The first deals with the structural properties: emergence. The internal factors of the system are regulated independently and locally to bring an optimised balanced system. The second subsection examines the dynamic aspect of the system. Under external constraints, the smart grid must evolve to ensure network stability while maintaining its QoS at any time.

5.1 Structural properties

Emergence is the process of complex systems and patterns that arise out of a multiplicity of relatively simple interactions. An emergent behaviour or emergent property can appear when a number of simple entities named agents operate in an environment, forming more complex/collective behaviours. If emergence happens over disparate scales, then the reason is usually a causal relation across different scales. In other words there is often a form of top-down feedback in systems with emergent properties. Emergence regroup the following theories: non-linear dynamics, chaos, collective behaviour, and networks.

Group dynamics in non-linear 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 (Forsyth, 2009). Because they interact and influence each other, groups develop a number of dynamic processes that separate them from a random collection of individuals. These processes include norms, roles, relations, development, need to belong, social influence, and effects on behaviour. Non-linear dynamics is critical in modelling and simulation of smart grids. It brings out the different behaviours (chaotic or not) of the network. In addition, the system evolution can be partially predicted.

Local behaviour obtained by game theory, also enter in upper scale equilibrium. Game theory reflects calculated circumstances (games) where a person’s success is based upon the choices of others (Myerson, 1997). Emergence of a behaviour is often the effect of a local or global equilibrium. Game theory helps to understand and predict these balances. Network theory models complex systems with local interactions: it is based on strategic games. Players participate simultaneously in several games, this model is based on the definition of games basic regulation (activation or inhibition) (Manceny, 2006). We can consider smart grid as a grid of games. Game in microgrid defines the variables at another scale. The goals defined by manufacturers are the following: to minimise the price, the energy cost and the time between demand and response. At a macroscopic scale, goals are: enhancement of reliability, reduce peak demand. And at a microscopic scale, goals are: lower total energy consumption, actively manage electric vehicle charging, actively manage other usage to respond to solar, wind, and other renewable resources.

In addition to the equilibrium, actors in smart grid react at same time, they have collective interactions and actions. Game theory suggests that even during a panic in a burning theatre actors may conduct themselves rationally: this is a collective behaviour (Blumer, 1951). Collective behaviour might also be defined as action which is neither conforming – in which actors follow prevailing norms – nor deviant, in which actors violate those norms. It refers to social processes and events which do not reflect existing social structure like laws, conventions, and institutions; but which emerge in a spontaneous way. The collective behaviour of the smart grid aims to reduce energy loss and reduce peak consumption. We must find the rules for the proper functioning of the network but also to meet the demands of local production, consumption and cost (time, money, energy).

To send information between different levels, we need a way to spread them. In the case of smart grid, electricity distribution in a random structure is named percolation. In mathematics, percolation theory describes the behaviour of connected clusters in a graph. More generally, percolation theory studies the deterministic propagation of a fluid on a random medium. It offers a good theoretical framework to study the behaviour of complex systems and their characteristic phase transition phenomenon. 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.

Pretopology theory, a generalisation of topology theory which expresses structural transformation of sets of interacting elements. It allows an efficient modelling of dynamic discrete structures thanks to the general concept of proximity. The functional distance between actors requires a more detailed graph to balance the system at any scale, we propose to study pretopology. 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 is not the only factor of Euclidean distance/Chebyshev distance, we also take into account the energy loss, transport costs and the current direction of energy.

We cannot change the current structure of power grid, a centralised unidirectional architecture scale-free network. Network theory concerns the study of graphs as a representation of either symmetric relations or, more generally, of asymmetric relations between discrete objects. A specific properties from network is resilience. Resilience is the ability of the network to provide and maintain an acceptable level of service in the face of various faults and challenges to normal operation. When a critical fraction of nodes is removed the network becomes fragmented into small clusters. In the case of smart grid, scale-free architecture is strong versus random errors but weak against aimed attack. A migration to bidirectional network with derivable connections reduces weakness of current power grid.

5.2 Dynamic properties

Smart grid is a data communications network integrated in the electrical grid that collects and analyses data captured in near-real-time about power transmission, distribution, and consumption. 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 (Gao et al., 2012).

Self-organisation is the process where a structure or pattern appears in a system without a central authority or external schemes influence. This global coherent pattern appears from the local and parallel interactions between the elements that make up the system. This definition of self-organisation can be enumerated into a list of features: the system is composed of units which may individually respond to local stimuli; the units act together to achieve a division of labour; the overall system adapts to achieve a goal or goals more efficiently. For these features to hold, the following are some of the conditions that must be met:

1 the system must have inputs and some measurable output

2 the system must have a goal or goals

3 the units must change internal state based on their inputs and the states of other units

4 no single unit or non-communicative subset of units can achieve the system's goal as well as the collection can

5 as it gains experience in a specified environment, the system achieves its goals more efficiently and/or accurately, on average (Collier and Taylor, 2004).

Self-organisation regroup the following theories: systems theory, pattern formation, evolution and adaptation.

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 problems. The evolution is 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 behaviour of the interactions among the control elements over the adaptation process, to guarantee system properties at run-time.

Feedback describes the situation when output from an event or phenomenon in the past will influence an occurrence or occurrences of the same event in the present or future. Integrating sensor networks and grid computing in sensor-grid computing is like giving *eyes and ears* to the computational grid. 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 (NETL Modern Grid Initiative, 2007). Real-time information about phenomena in the physical world can be processed, modelled, correlated and mined to permit on-the-y decisions and actions to be taken on a large scale (Tham and Buyya, 2005). Real-time is an instant response, but smart grid have to learn and evolve to meet the internal and external constraints.

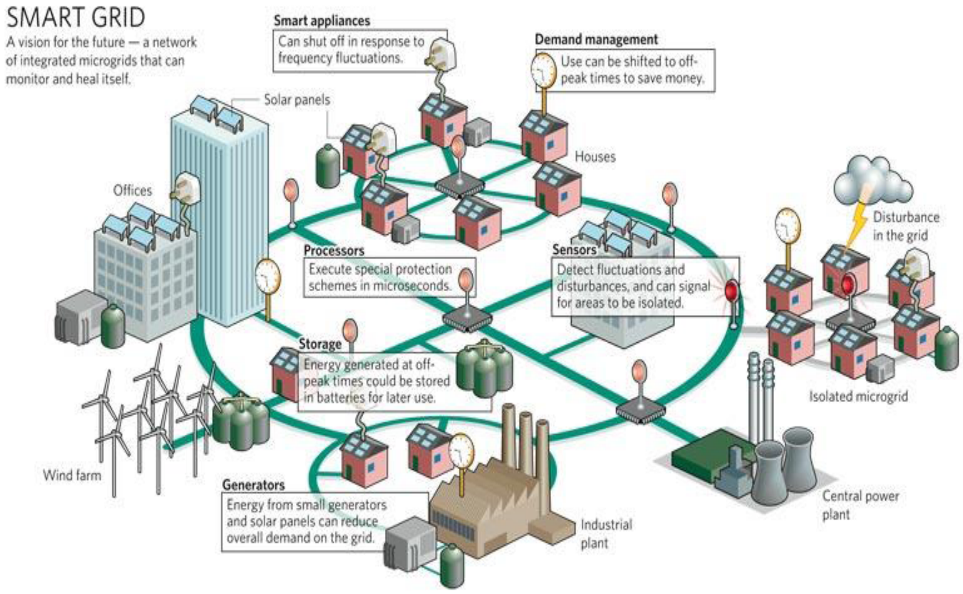
Machine learning, a branch of artificial intelligence, is a scientific discipline concerned with the design and development of algorithms that allow computers to evolve behaviours based on empirical data, such as from sensor data or databases. Machine Learning is concerned with the development of algorithms allowing the machine to learn via inductive inference based on observing data that represents 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 recognise complex patterns, to distinguish between exemplars based on their different patterns, and to make intelligent decisions (Mitchell, 1997). 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.

6 Conclusions and future work

Smart grid, like complex system, evolves according to scale and time. The current power grid is outdated, it cannot satisfy demand-response, security and to integrated new technologies.

Figure 5 Smart grid: vision of the future



In conclusion, Smart grid concept has few theoretical studies that only include known technologies. Modelling and simulation deal only with microgrids, and cannot represent efficient global smart grid. Smart grid as a complex system opens new perspectives, especially concerning scales and behaviours at different level of the grid. Adapted theories such as pretopology and percolation theory may be used to route energy deterministically over a random structure while using a functional neighbourhood.

Future development of our work aims to conceive an efficient model of smart grid taking into account its basic properties and using the exposed theories.

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