American Journal of Operations Research, **2013, 3, 196-206**
http://dx.doi.org/10.4236/ajor.2013.31A019 Published Online January 2013 (http://www.scirp.org/journal/ajor)

Smart Grid and Optimization

Murat Ahat[1,2], Soufian Ben Amor[1], Marc Bui[3], Alain Bui[1], Guillaume Guérard[1], Coralie Petermann[1]
[1]Laboratory of PRiSM, University of Versailles SQY, Versailles, France
[2]Laboratory of Econoving, University of Versailles SQY, Versailles, France
[3]Laboratory of Chart, Ecole Pratique Des Hautes Etudes, Paris, France
Email: murat.ahat@prism.uvsq.fr, guillaume.guerard@prism.uvsq.fr, coralie.petermann@prism.uvsq.fr, soufian.benamor@uvsq.fr, alain.bui@uvsq.fr, marc.bui@ephe.sorbonne.fr

Received December 1, 2012; revised January 5, 2013; accepted January 17, 2013

ABSTRACT

With urging problem of energy and pollution, smart grid is becoming ever important. By gradually changing the actual power grid system, smart grid may evolve into different systems by means of size, elements and strategies, but its fundamental requirements and objectives will not change such as optimizing production, transmission and consumption. Studying the smart grid through modeling and simulation provides us with valuable results which can not be obtained in real world due to time and cost related constraints. However, due to the complexity of the smart grid, achieving optimization is not an easy task, even using computer models. In this paper, we propose a complex system based approach to the smart grid modeling, accentuating on the optimization by combining game theoretical and classical methods in different levels. Thanks to this combination, the optimization can be achieved with flexibility and scalability, while keeping its generality.

Keywords: Smart Grid; Optimization; Complex System

1. Introduction

Energy technologies are vital for social and economical development of our society. Electrical grids providing electricity to households, businesses and industries, our society has become dependent on electricity at every level. With the pressure from ever increasing energy demand and climate change, finding new energy resources and enhancing energy efficiency have become priority of many nations in the 21st century. For instance, in 2007 the US department of energy estimated that that increasing energy efficiency could reduce national energy use by 20% or more in 2020, with net economic benefits for consumers and businesses as a result [1].

The concept of an efficient power grid has taken a global concern and the expression "Smart Grid" has expended into different dimensions: some see it as a numerical solution for downstream counter and mostly residential customers, while others believe that it is a global system vision that transcends the current structure of the energy market to generate economical, environmental and social benefits for everyone. However, a view accepted by the most is that smart grid is to improve the current power grid and to achieve goals of green energy and reducing greenhouse pollution.

Research works are being conducted to attain the objectives, but many problems of modeling and coordination hamper advancements. But each offers its own vision of the smart grid, putting aside theoretical and technological advancement of others. Cooperation between smart technologies and existing infrastructure is often neglected in scientific and industrial studies [2]. In [3], authors argued that an electrical grid which allows the adjustments on both supply and demand will improve efficiency, reduce costs on both sides and will be beneficial for the environment.

In this paper, we illustrate our approach through the modeling of smart grid in terms of optimization. Contribution of our approach consists in treating the smart grid as a complex system, locating the problems at local as well as global levels, and solving them with coordinated methods. In other words, through studying and analyzing smart grid, we isolate homogeneous parts with similar behaviors or objectives, and apply classical optimization algorithms at different levels with coordination. Thanks to combining those interdependent methods, our approach guarantees the flexibility in terms of system size. Besides, generality of our approach allows its applicability in different scenarios and models, as well.

This paper is organized as the following: in the next section, smart grid and smart grid technologies, complex system and its relationship with smart grid are introduced; in Section 3, we discuss the theoretical approaches in modeling smart grid as a complex system; and in Section 4, we present the details of our approach with the help of diagrams; we conclude the article in the last section. At present, we are actively developing our model and integrating algorithms. Preliminary tests are showing promises and potentials. In the last section, we will also discuss our perspectives and possible collaboration with smart grid projects.

2. Smart Grid and Complex Systems

As we stated in the introduction, smart grid is an evolution of the current power grid systems to provide solutions to future energy requirements. Computer modeling and simulation have proven to be a useful, if not indispensable, tool for help decision making in studying and designing complex artificial systems [4]. However before modeling, a deep understanding of modeled system is more than necessary. Thus, in this section we firstly introduce smart grid and smart grid technologies, then we discuss complex system and smart grid. This section will pave the way to discuss theoretical approaches in the next section.

2.1. Smart Grid

The term smart grid is coined by Amin in 2005 [5]. 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 [6]. 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 in the electrical network. It is not intended to replace the current power grid system but only to improve it.

A Smart Grid integrates advanced sensing technologies, control methods and integrated communications into current electricity grid both in transmission and distribution levels [7,8]. The Smart Grid should have following key characteristics: 1) self-healing; 2) consumers motivation and participation; 3) attack resistance; 4) Higher quality power; 5) different generation and storage options; 6) flourished markets; 7) efficiency and 8) higher penetration of intermittent power generation sources.

Smart grids are composed of an enormous number of devices of various types, from smart meters and solar inverters to electrical substation equipment and sensors on power lines. Electricity can be produced by multiple processes: from the stable production of a nuclear plant, to the storage via electric vehicles, and integration of renewable energy which production may depend on environmental factors. A huge distribution and energy transport network has been created over the years but it is not mastered nor optimized. The goal is to make power grids more efficient by integrating renewable energies and taking advantages of information and communication technologies.

Initial vision of smart grid started with the idea of advanced metering infrastructure, but with the growing requirements and technologies the smart grid vision is also evolved. In 2010, the US National Institute of Standards and Technology (NIST) gathered and formalized smart grid requirements and vision in their report [9]. In a smart grid survey [10], Fang *et al.* divided smart grid into three major systems: smart infrastructure, smart management and smart protection systems. The smart infrastructure system is the energy, information, and communication infrastructure underlying the smart gird. Smart management and protection systems are build on the smart infrastructure system, and their realization depends on it. The smart management system takes advantage of the smart infrastructure to pursue various advanced management objectives. Thus far, most of such objectives are related to energy efficiency improvement, supply and demand balance, emission control, operation cost reduction, and utility maximization. The smart protection system is the subsystem in smart grid that provides advanced grid reliability analysis, failure protection, and security and privacy protection services. Thus our approach is based on the hypothesis that there exists a smart infrastructure system, attacks the optimization problems in smart management system.

Before attacking the optimization problems in smart management system, we should carefully consider the complexity of the smart grid infrastructure system. In the following subsection, we discuss complex system and its relationship with smart grid.

2.2. Complex System

A system which consists of large populations of connected agents (or collections of interacting elements), is said to be complex if there exists an emergent global dynamics resulting from the actions of its parts rather than being imposed by a central controller. That is a self-organizing collective behavior difficult to anticipate from the knowledge of local behavior [11]. Complex system study embraces not only traditional disciplines of science, but also engineering, management, and medicine as well.

Many natural and artificial systems manifest the characteristics of complex systems. When studying them, classical methods fail most of the time. For example, optimization as in operational research seeks to solve an objective function, often with multi-variables and constraints [12]. Applying the optimization method in complex systems in a global manner is almost an impossible task, if not impossible at all. Because, 1) complex systems are composed of heterogeneous parts; 2) it is hard to find all the variables that matters; 3) even if all variables are included, the complexity of the objective function will become beyond the computation powers of computers [12].

The attempts to understand complex systems include the structural studies. Those structures are often represented as networks. Those networks manifested complex characteristics which are not found in simple networks, and thus called complex networks. Complex networks theory has become a major interest area in complex system study and provides mathematical tools to model the structures of complex systems [13]. We will discuss more about complex networks in the next section.

The study of complex systems also influenced the classical modeling and simulation approaches. In classical modeling approaches, the model is developed in a top-down manner, while modeling complex systems, we model the system from the bottom, and this is called bottom-up approach, contrary to the top down approach [14,15]. Complex systems, as definition, contain multiple parts which interact with each other. In bottom-up approach, those parts are modeled as agents and interactions as agent interactions. After abstracting and adding the environment in which complex system exists, the model become agent based model of the complex system, which will enable the simulation of the complex system with flexibility and parameters. In agent based models, the validity of the model depends largely on the abstraction of agents, interactions and environment around the agents, during which mathematical tools, such as complex network theory, game theory, etc., provide abstraction methods. There are even development of modeling methodologies concerning agent based models, such as ASPECS [16], to facilitate the model development and collaboration. Though this is a new modeling paradigm, bottom-up approach has gained popularity in different domains and found its way into modeling and simulation of many complex systems.

2.3. Smart Grid and Complex System

As we have seen earlier in this section, smart grid can be qualified as a complex system [17], due to its heterogeneous actors, dynamic, complex interactions among them, and global behaviors such self healing, self organizing characters, etc. Hence, while studying smart grid, we should consult complex system approaches.

Based on this observation, we will analyze the smart grid methodologically in order to understand the mechanisms and internal components as well as the needs of every sub-components. Once sub-components are defined, we must standardize internal constraints and objectives in order to use an efficient and fast optimization method. The sub-components being connected, a communication system provides an exchange of input data and output of each sub-component. This system ensures feedback optimality at any scale. In addition, the overall system is subject to external or internal general rules, it is likely that certain constraints or objectives exist at any level—such as congestion or supply and demand. These constraints will be verified by both the feedback system at any scale, but the vision and overall system.

The task of optimizing a complex system has at least two levels of problems for the system designer. First, a class of optimization algorithms to be selected which is suitable for application to the system. Second, the various parameters of the optimization algorithm must be granted to the effectiveness [18]. Smart grid aims to smooth the curve of consumption, reduce overall consumption, balance supply and demand, and integrate new technologies. The next chapter will explore the Smart Grid to extract the different sub-components in order to provide an approach to ensure optimization of the complex system.

3. Complex System Approach towards Smart Grid Optimization

In the previous section we have discussed the smart grid and complex system, and optimization difficulties in complex systems. In this section, we will discuss the complex system approach on which we have embarked to provide a solution to optimization problems in smart grid.

The problems of electrical networks have been known for long, and research as well as industrial works has been carried out to find effective and competitive solutions. Nevertheless the efforts are often concentrated on specific cases, and solutions are, too, specific without any room for evolution. Among the proposed solutions we can mention:

- Distributed generation/microgrids: since a centralized optimization is very costly in terms of time and memory, optimization should be done at all levels. The microgrids can change the centralized interface into a distributed interface, therefore optimization can be carried out in a distributed manner. Consequently calculation benefits in terms of time and memory are significant, while ensuring optimal at different scales.
- Design of intelligent network (home automation): domotics or smart devices can better understand the real needs of consumers. While optimizing local consumption, they optimize overall consumption as a result.
- Energy storage device: the energy storage coupled with energy optimization from beginning to end, regulates consumption and clears consumption peaks.
- Reduction of Transmission and Distribution T&D

network losses by automated distribution: One of the strong points of our model is the distribution optimization by local and global algorithms which reduce the loss of congestion or routing errors.
- Intelligent control of price: when the network becomes intelligent, it is necessary that the consumer prices may also change in order to follow the new consumer behavior.

The interpretation of the future smart grid nevertheless has a defect: the division of zones is based on technological developments and not according to the homogeneity of the sub-components. Therefore, there should be a new subsystem for each advanced technology, which only complicates the existing power grid problems. That is why we propose in this paper an analysis of the smart grid as a complex system.

Like any complex system, the Smart Grid has a large number of heterogeneous entities interact in a complex network. In order to optimize the entire system, we must observe and study the complex system in order to discern the sub-components. Each sub-component is defined by common criteria: interacting elements, greater homogeneity, common or compatible interest and purpose. For example, in a residential area, the various devices of every house want to receive a certain amount of energy. All units are consumer or prosumer, possessing many common characteristics, thus they can be applied in a single optimization algorithm.

Local optima are used in the overall system for a communication system that integrates a formalism for data exchange between the different components. These standardized data provide transparency between the sub-components, while ensuring the anonymity of the internal calculation. Influences are then reduced to a feedback system to balance the components interactions. This self-regulation provides an optimal global optimum at any scale.

3.1. Electric Grid and Complex Network

Networks are representations of relation or interaction structure among entities. To study real world networks, different models have been proposed and studied thoroughly. Erdös and Rényi (1959) suggested the modeling of networks as random graphs [19]. In a random graph two pair of nodes are connected with probability *P*. This leads to a Poisson distribution when considering the numbers of connections of the nodes. However, the study of real world networks has shown that the degree distribution actually follows a power law [20]. Those networks are called scale free networks. For example, airline networks, metabolic networks, citation networks and even power grid networks are scale free networks. In [21], the authors demonstrated that the real world power grid networks follow a exponential degree distribution. In [22,23], the authors discussed the other applications of complex networks in smart grid systems, such as vulnerability analysis, data streaming mining, fault detection and early warning.

Studies conducted by Barabasi [24] and Watts [25] raise four general principles in distributed adaptive systems more generally in complex systems:

1) Global information is encoded as statistics and dynamic patterns in the components of the system.

2) Chance and probabilities are essential.

3) The system performs a parallel search of opportunities.

4) The system has a continuous interaction with bottom-up or top-down [26].

In [27], Segel and Cohen states that the autonomous distributed networks that process information in a adaptive manner are more effective for describing the immune system and cellular metabolism. Segel and Cohen's remark can be taken into account by the majority of complex systems to manage common resources, especially for the Smart Grid. Although studies tend to make the existing power grid autonomous and distributed, most studies are only in specific cases of microgrids. However, the microgrid is only part of the Smart Grid, the entropy of complex systems does not consider only the sub-parts of the system. Because the overall complexity is greater than the sum of its sub-parts, smart grid must be studied at all scale and local and global solutions should be proposed for a better distribution of energy in the network.

In particular, Albert *et al.* [28] studied the ability of the North American power grid to resist cascading failures. The results indicate that if 4% of nodes possessing a very high load are disrupted, then the overall system loses 60% of its performance. We note that the geodesic distance (the shortest path, or one of the shortest paths if there are several), used in the metric of complex networks, can be generalized to account for the flow capacity between nodes.

The structure of the graph is essential to study the behavior of a complex network. The power grid receives much attention in the literature on the science of networks and complex systems due to its size, complexity and scope of potential economical benefits. Watts and Strogatz [29] measured the length characteristic paths and clustering in electrical networks, and found similarities with the small-world networks. Many other works found characteristics of scale free networks in power grids [30]. These studies are performed on different criteria in different countries and regions, it is not surprising to see so much variance in the results. And even on the same network it is possible to obtain different results [28, 30].

Although they give an overview of the grid structure, these studies focus on the global topology of the grid, while it does not have the same structure according to the needs or local objectives. Indeed, studying many structures such as European and American power grids, we have been able to extract three major structures with their own particularity:

- The network of transmission and distribution (T&D): in the production zone, particularly at national power centers, we observe a lattice structure. The produced energy must provide all national or international network, which is why it takes at least a backup line in case of congestion. The network is double connected, *i.e.* there are at least two routes from one point to another point. In case of disturbance, energy can be rerouted to repair the defect without jeopardizing the energy supply to the grid.
- The subtransmission network: the network connects great distance to deliver energy from T&D network to cities, industrial parks and other consumers. Not being subject to the constraint of congestion or multidirectional flows, the network is generally linear or with loops.
- Distribution network: once the energy delivered to the consumption points, it should be distributed. This network has a tree structure. From a source post, which itself is fed by the subtransmission network, electricity is connected directly to the branches of derivation, in which we can find similar patterns until arriving at final consumer. These networks are in the form of tree, or more generally scale-free.

Since these differentiations in terms of the structure are not sufficient to distinguish the sub-components of the system, we must consider the entities present in each section to understand their behavior and their goal.

3.2. Behaviors and Local Objectives

While historically only conventional power plants offered energy, increasing penetration of intermittent energy requires interfacing new sources of production, storage and consumers willing to synchronize their energy demand, which is a key theme of smart grids. Therefore migration from power grids to smart grids requires a significant overhaul of the real-time information systems with new challenges related to the integration of large volumes of data—these data will potentially be derived from each consumer—and new visualization technologies to help decision making.

With the advent of smart meters that can monitor and control the home appliances, it is now possible to consider that the integrated software will be able to optimize the usage and storage profile of the house using the information from various sources (e.g. weather data, energy rates, statistics and consumption time of devices).

However, current approaches do not take into account the individual preferences of each house and do not allow modeled agents to adapt to the constraints imposed by the system at any time. Thereby an approach that focuses on the dynamics where all agents in the system can buy or sell electricity to one another would be able to respond to local constraints.

Local production of renewable energy are directly integrated into local consumption, we do not consider the case where the energy is sold to the dealer because it comes down to a dynamic price for each regulation. Management device, including home automation, is a fundamental pillar of energy management. These devices are part of an overall plan to control the consumption with the help of smart meters. In a general perspective, we assume that all devices can be managed whether it is simple home appliance or motorized system such as air conditioner.

As part of the energy distribution, stations influence the routing of energy. In order to better distribute energy among all consumers, we considered the following problem: we must route the energy from producers to consumers, balancing the demand and supply. This can lead to a simple rule on stations, there is as such much in and out energy on a post. Therefore these entities are nodes which belong to a network with flow problem.

Game theory [31,32] is a mathematical tool, which is worth mentioning, to study conflict and cooperation among decision makers. In smart grid different consumers are bound by the distribution network, and there is competition in the energy sharing in a distribution branch. In order not to create conflict or congestion in sharing common resource, we use game theory. Each player is an entity or group of local consumers entities aiming to meet their energy demand. Different players should receive the energy as a result of their strategy.

Saad *et al.* in [33] provided a comprehensive account of game theory application in smart grid systems, tailored to the interdisciplinary characteristics of these systems that integrate components from power systems, networking, communications and control. Authors overviewed the potential of applying game theory for addressing relevant and timely open problems in three emerging areas that pertain to smart grid: micro-grid systems, demand-side management, and communications.

3.3. A Global Direction

3.3.1. Regulating the Consumption Curve

Nowadays, electricity consumed by residential areas are from central power plants. However, the production efficiency of these plants are about 55% due to the inefficiency in generation. This low efficiency is greatly caused by the bi-directional production and strong fluctuations in demand [2].

Management on the consumer side, called Demand Side Load Management aims to increase the efficiency of generation by shifting consumption into low consumption time periods [34]. Many devices can temporarily go into standby mode (heating) or consumption can be postponed. Some devices are also able to stop using energy during operation (preemption). Approximately 50% of the consumption of residential areas can be controlled without reducing the comfort [35].

To increase the effectiveness of this method, it is assumed that the front part of the infrastructure is home automation and every device can be controlled separately by the user and regulation algorithms.

We can discern three types of regulation:

- Mathematical regulations: mathematical tools are introduced to smooth the consumption curve (standard, planning according to the derivative, gradient and barycenter, etc.).
- Regulation by self-stabilization: the criteria for regulation of the curve are done at any point of the smart grid. Some technologies are already in effect, such as dynamic pricing systems or consumer subscriptions.
- Hybrid regulation: This type of regulation is based on both mathematical and self-stabilizing approach. Its main advantage is to minimize the risks associated with either method.

Global regulation must be done both at consumer and producer level, taking into account the difficulties of routing. A feedback system between system components must reflect a balance at all levels.

3.3.2. Data Synchronization

In computer systems, synchronization is desirable for effective performance of distributed systems. The purpose of the distributed system is to reach a common global state (consensus). Today, these systems are becoming larger in size and more complex in topology. On the other hand, some engineering problems are faced with the need to maintain coordination in large networks, such as dissemination problem of information, energy or materials [36]. In [37], the authors defined the problems of consensus on general graphs.

Principles of electricity generation and distribution are well known. Synchronization of the system is recognized that each station and each piece of equipment runs on the same clock, which is crucial for its proper functioning. Cascading failures related desynchronization can lead to massive power outages. In smart grid, a technical control automates the management of energy. Real-time data must be converted into information quickly enough so that errors are diagnosed in time, corrective actions are identified and executed dynamically in the network, and feedback loops provide measures to ensure that the performed actions and production are consistent [38].

4. A Smart Grid Model for Optimization

In previous sections, after familiarizing with smart grid and complex system, we approached smart grid with complex system point of view. Our observation and discussions prepared us to present the model in this section for smart grid optimization.

4.1. Global View

We analyzed the network structure, parameters and behavior of the smart grid entities. From these data, we defined three sub-components or layers having their own properties and objectives.

The three layers are, which are shown in **Figure 1**:

- Local layer: This sub-component manage consumer aspects of smart grid. Domotics equipped with a smart control of consumption can better provide and distribute energy according to the current configuration.
- Microgrid layer: the microgrids form the junction between consumers and production. As sharing a resource involves competition among consumers, microgrid is in charge to manage sets auction. Consumers bid on an amount of energy depending on energy that can be supplied, then the Microgrid reward or punish players until a global consensus.
- Transmission and Distribution layer: the transmission and distribution network manage energy from producers to consumers areas defined by microgrids (which can be represented as smart stations). This sub-component aims to better distribute energy in the entire network, by controlling supply and demand.

Objectives, roles and needs of each sub-component is described below in more detail.

4.2. Local Layer

Local level models consumers, *i.e*. a group of consuming

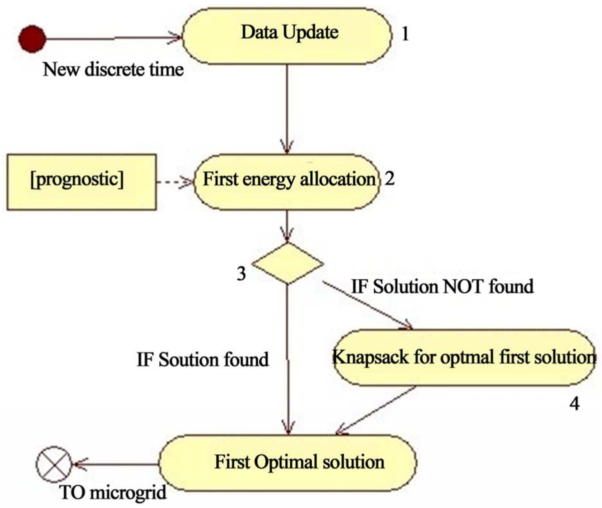

Figure 1. Global structure.

devices, local renewables or electric vehicle requesting or providing a measurable amount of energy. The following diagram shows the progress of algorithms concerning that level and interactions with other levels. The local level includes a panel of consuming devices. The raw information is not useful in Smart Grid management, but implementing a concept of operational priority will regulate consumption peaks and leveled recesses. This priority is specific to each device and is coupled to a priority coefficient for the device. This coefficient is based on the device importance at local level, on its maximum consumption and on its running time. The coefficient influence the device priority by default, some device operates from the start, while other will wait for the suitable moment in order not to jeopardize microgrid and smart grid. A device with a maximum priority is guaranteed to be provided with energy. A device which is fully provided in energy, is—or become—highest priority.

Future consumption has a major impact on the running of smart grid. Indeed, Smart Grid aims to smooth consumption curve while ensuring energy supply. To prevent brownout and blackouts, it is important to know the users behavior.

Functions that are not based on real time include the integration of existing databases and the moment to calculate future operations among: operational optimization, drawing usages, computing consumption cycle, planning or replacing future consumption patterns, maximizing flows, optimizing performance systems.

In **Figure 2**, the conduct of local algorithms is shown:

- Data Update: at the beginning of a new iteration, all data on the smart grid are updated, as well as prognostic and network topology.
- First energy allocation: we compare consumption data with prognosis. A function attributes for each device a gain according to its priority and consumption. The higher the priority, or the smaller its consumption, the larger the gain is.
- Decision: if consumption and prognostic match, we send consumption data at the second level, the microgrid. Otherwise, we move to the fourth step to find the optimal solution. This solution is then returned to the microgrid.
- Knapsack: to obtain a solution consuming the most energy possible, based on received energy, and maximizing the utility of consuming devices, (so maximizing gain), we perform a knapsack algorithm. The size of the bag is the energy received, the objects are devices and utility is the gain function.

The calculation of the First Optimal solution is important and provides a first approximation of the final solution.

4.3. Microgrid Layer

The microgrid is a group of local levels of consumactors. It can be represented by the station serving those consumers. It is charged to find a compromise, a consensus between production and energy consumption at current time.

The microgrid is a group of several local levels, the problem is then to define border of microgrids. Game networks are a formalism for game theory to enable players to play several games simultaneously. In this case, it raises the question of how to determine games, players, and overall balance. The microgrid receives consumption vectors of local levels under its responsibility. At this stage of the model, players are part of a single microgrid, defined by the tree configuration of the network. If we were in presence of loop, interactions between players and microgrid would be disturbed. In addition, each player is associated with a single microgrid. At this point, game theory, in particular, game networks can be applied

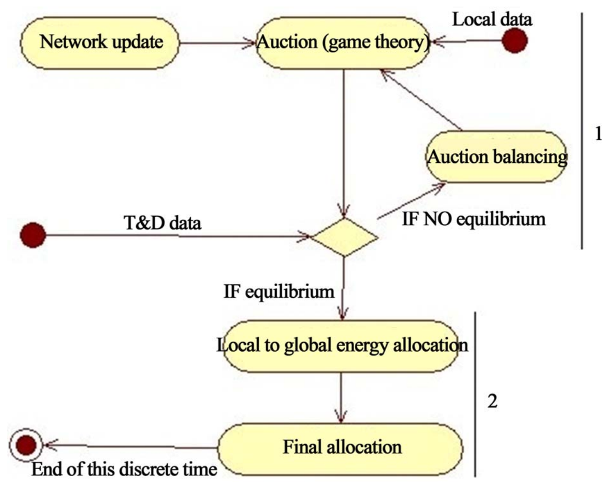

Figure 2. Local layer.

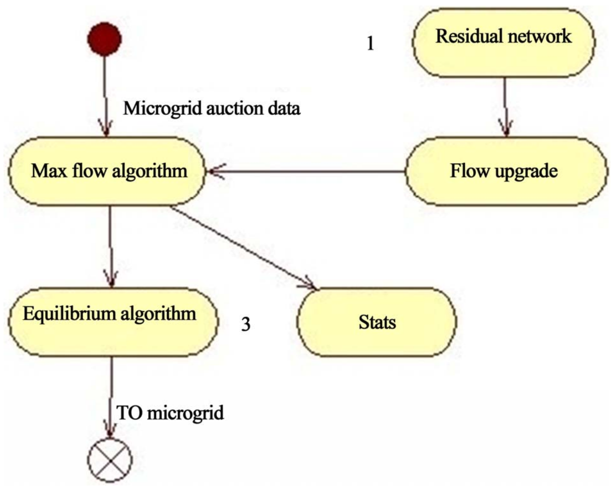

Figure 3. Microgrid layer.

to this case.

Microgrid level occurs in two steps: a first step look at the balance between consumers and producers and the second step will provide the energy level according to their local application and available energy. Those steps are shown in **Figure 3**, and here are the corresponding details:

1) Auction: the microgrid knows the first allocation of energy at local levels. An auction system allows each local level to bid on an energy quantity close to the first allocation. In response to these requests, the microgrid sum auctions. This sum is the total consumption of the microgrid or the energy to be provided via the microgrid routing of energy. The total energy consumed must be sent at T&D to determine if it can be provided or should be adjusted. Once the decision is returned to the routing microgrid, it punishes or reward each local level to make a new bid. The purpose of feedback system is to balance supply and demand without using deterministic mathematical system, allowing flexibility network.

2) Final allocation: once the supply and demand are balanced perfectly, we must distribute the energy obtained among local levels. Each level performs a local knapsack problem with energy obtained by auction. Then the remaining energy of each knapsack is better distributed in the level adjacent premises. This means that we make a knapsack problem with energy remaining throughout the microgrid.

Algorithms for each level has an optimal solution, it marks the end of the iteration. The input and output of each level provide statistics to predict the next iterations.

During an auction, it is likely that energy required does not correspond to any new consumption strategy, *i.e.* local level consume as much with that or without. In addition, it is possible to search the nearest consumer at lowest cost. The number of possible strategies is infinite, we must look at the impact of each of them on the microgrid and on the final decision.

4.4. T&D Layer

Once auctions have been completed, the network must deliver energy reserved from producers to points of consumption. Energy flows on electric cables with various criteria and technical constraints limiting the amount of energy that can circulate on each. The algorithm at T&D level should be able to limit the effects of congestion n due to the widespread use of a few lines, while limiting the cost of routing energy. Production and consumption must match as better as possible, in order to achieve this, we must deliver most of energy while satisfying most of consumers. If the supply and demand does not match, the algorithm must analyze bottlenecks to adjust the results in a system of feedback. A maximum flow problem is fully consistent with the criteria.

The procedure is illustrated in **Figure 4**. T&D level receives energy requested by microgrid level. It must route energy to microgrids while avoiding congestion:

1) Residual Network: routing of energy based on the routing previous step. Indeed, there may change between the previous iteration and the current iteration. That is why we are working on a differential graph representing production deficits and consumption as well as new flows to satisfy.

2) Max flow algorithm: the max flow problem is known in electric networks. In the context of our simulation, we use a Ford-Fulkerson problem in order to obtain an optimal solution on the residual network. This solution is then added to the optimal solution of the previous iteration. Data are recorded to predict possible variations of next iterations of the Smart Grid.

3) Equilibrium algorithm: it is likely that the sources (producers) do not provide all the available energy, or sinks (microgrid) don't receive all the energy needed. The equilibrium algorithm aims to analyze differences in these two levels to send to microgrids punishments and rewards. This feedback system aims to balance supply and demand.

T&D level is probably the most important level in the Smart Grid. Indeed, it is at this level that the production and consumption will balance each other while avoiding congestion or routing problems. In addition, the feedback helps to predict future consumption and production, delivering at the next time a result already close to optimal.

4.5. Discussion

Our model allows to take into account different objectives and various constraints of the smart grid, without imposing any special technology. In other words, it is flexible and can incorporate any device or technology.

However, our model does not present all aspects intrinsic to certain network, for instance an economic model of energy prices or management of storage systems or electric vehicles. Because these constraints vary depending on the network management of a country. Furthermore, our grid does not currently address the problems of parallel flows or competitive producers.

5. Conclusions and Perspectives

In this paper, we addressed the optimization problem in power grids, especially in smart grids. As smart grid can be qualified as a complex system, classical optimization methods cannot be applied directly, due to the computational complexity in terms of time and memory. Since it is complex system, we studied the smart grid from global and local views, and were able to find sub-components with homogeneous objectives and behaviors. Numerous studies have provided us with valuable materials in

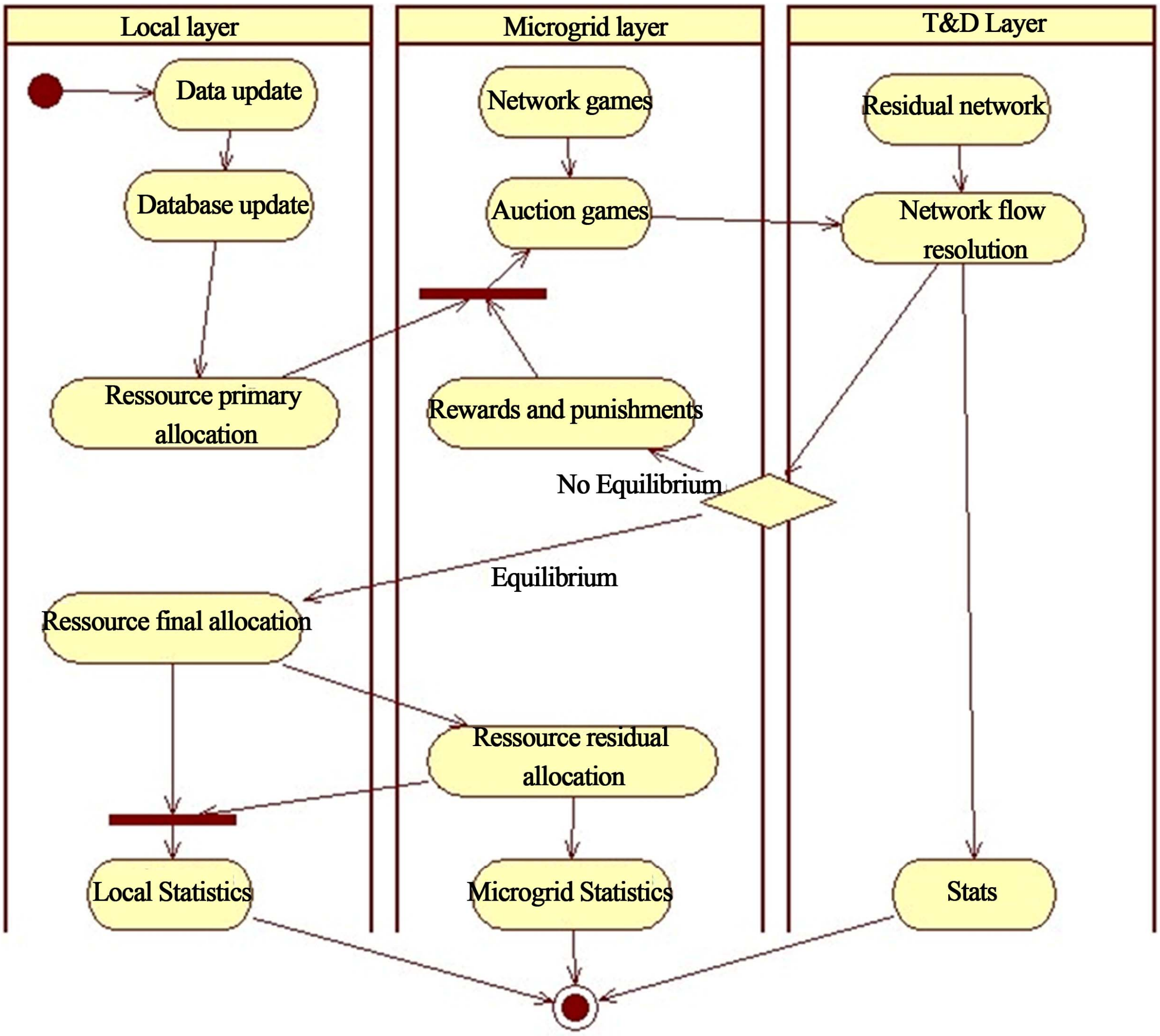

Figure 4. T&D layer

finding those sub-components. Since each sub-component consists of homogeneous actors concerning the optimization problem, we were able to apply algorithms to achieve the optimization goal. It should be noted that those algorithms work together in different sub-components toachieve the global optimization.

Our approach applies different algorithms and coordinates between them to achieve optimization in smart grid. The sub-component approach enabled us to divide the problem into sub-problems, and as a consequence the complexity of the problem decreased considerably. In addition, it also resulted an approach with flexibility and generality.

More generally, we also demonstrated how to solve optimization problems in complex systems. While applying optimization algorithms directly in complex systems is nearly impossible, we should analyze the system and divide them into sub-systems with homogeneous characteristics, then we should apply specific algorithms and coordinate them to achieve global optimization.

A general model of smart grid is being developed, which integrates those algorithms. Preliminary tests have shown promises and potential of our approach. Once it is finished, we will validate the model with real world data. Two smart grid oriented projects EPIT and GARE, in which laboratory of PRiSM participate, are in our perspectives to collaborate in validating, testing and simulating the model with real world scenarios.

REFERENCES

[1] ABB Inc., "Energy Efficiency in the Power Grid," ABB Inc., Fort Smith, 2007.

[2] A. Molderink, M. G. C. Bosman, V. Bakker, J. L. Hurink and G. J. M. Smit, "Simulating the Effect on the Energy Efficiency of Smart Grid Technologies," *Proceedings of*

the 2009 *Winter Simulation Conference* (*WSC*), Austin, 13-16 December 2009, pp. 1530-1541. doi:10.1109/WSC.2009.5429305

[3] S. Borenstein, M. Jaske and A. Rosenfeld, "Dynamic Pricing, Advanced Metering, and Demand Response in Electricity Markets," *Journal of the American Chemical Society*, Vol. 128, No. 12, 2002, pp. 4136-4145.

[4] S. Robinson, "Simulation: The Practice of Model Development and Use," John Wiley & Sons, Hoboken, 2003.

[5] M. Amin and B. F. Wollenberg, "Toward a Smart Grid," *IEEE Power and Energy Magazine*, Vol. 3, No. 5, 2005, pp. 34-38. doi:10.1109/MPAE.2005.1507024

[6] A. Keyhani, "Chpater 1: Smart Power Grids, Smart Power Grids," Springer, Berlin, Heidelberg, 2011, pp. 1-25.

[7] "A Vision for the Modern Grid," Technical Report, National Energy Technology Laboratory, Morgantown, 2008.

[8] M. Amin and J. Stringer, "The Electric Power Grid: Today and Tomorrow," *MRS Bulletin*, Vol. 33, No. 4, 2008, pp. 399-407. doi:10.1557/mrs2008.80

[9] National Institute of Standards and Technology, "NIST Framework and Roadmap for Smart Grid Interoperability Standards," National Institute of Standards and Technology, Gaithersburg, 2010.

[10] X. Fang, S. Misra, G. Xue and D. Yang, "Smart Grid—The New and Improved Power Grid: A Survey," *IEEE Communications Surveys and Tutorials* (*COMST*), Vol. 14, No. 4, 2012, pp. 944-980. doi:10.1109/SURV.2011.101911.00087

[11] N. Boccara, "Modeling Complex Systems. Graduate Texts in Contemporary Physics series," Springer-Verlag, Berlin, Heidelberg, 2004.

[12] S. Kirkpatrick, C. D. Gelatt and M. P. Vecchi, "Optimization by Simmulated Annealing," *Science*, Vol. 220, No. 4598, 1983, pp. 671-680. doi:10.1126/science.220.4598.671

[13] M. E. J. Newman, "The Structure and Function of Complex Networks," *SIAM Review*, Vol. 45, No. 2, 2003, pp. 167-256. doi:10.1137/S003614450342480

[14] C. M. Macal and M. J. North, "Tutorial on Agent-Based Modelling and Simulation," *Journal of Simulation*, Vol. 4, No. 3, 2010, pp. 151-162. doi:10.1057/jos.2010.3

[15] A. Borshchev and A. Filippov, "From System Dynamics and Discrete Event to Practical Agent Based Modeling: Reasons, Techniques, Tools," *Proceedings of System Dynamics Conference*, Oxford, 25-29 July 2004.

[16] M. Cossentino, N. Gaud, V. Hilaire, S. Galland and A. Koukam, "Aspecs: An Agent-Oriented Software Process for Engineering Complex Systems," *Autonomous Agents and Multi-Agent Systems*, Vol. 20, No. 2, 2012, pp. 260-304. doi:10.1007/s10458-009-9099-4

[17] G. Guérard, S. Ben Amor and A. Bui, "Survey on Smart Grid Modelling," *International Journal of Systems, Control and Communications*, Vol. 4, No. 4, 2012, pp. 262-279.

[18] J. J. Grefenstette, "Optimization of Control Parameters for Genetic Algorithms," *Systems, Man and Cybernetics, IEEE Transactions*, Vol. 16, No. 1, 1986, pp. 122-128. doi:10.1109/TSMC.1986.289288

[19] P. Erdös and A. Rényi, "On Random Graphs," *Publicationes Mathematicae* (*Debrecen*), Vol. 6, 1959, pp. 290-297.

[20] A. L. Barabási and R. Albert, "Statistical Mechanics Complex Networks," *Reviews of Modern Physics*, Vol. 74. No. 1, 2002, pp. 47-97.

[21] R. V. Solé, M. Rosas-Casals, B. Corominas-Murtra and S. Valverde, "Robustness of the European Power Grids under Intentional Attack," *Physics and Society*, November, 2007.

[22] X. Yu, "Smart Grids: A Complex Network View," *IECON* 2011, Melbourne, 7-10 November 2011.

[23] G. A. Pagani and M. Aiello, "The Power Grid as a Complex Network: A Survey," *Physics and Society*, Vol. 97, No. 6, 2012.

[24] A. L. Barabasi and R. E. Crandall, "Linked: The New Science of Networks," *American Journal of Physics*, Vol. 71, No. 4, 2003, pp. 409-410. doi:10.1119/1.1538577

[25] D. J. Watts, "Six Degrees: The Science of a Connected Age," W. W. Norton & Company, New York, 2004.

[26] M. Mitchell, "Complex Systems: Network Thinking," *Artificial Intelligence*, Vol. 170, No. 18, 2006, pp. 1194-1212. doi:10.1016/j.artint.2006.10.002

[27] L. A. Segel and I. R. Cohen, "Design Principles for the Immune System and Other Distributed Autonomous Systems," Oxford University Press, Oxford, 2001.

[28] R. Albert, I. Albert and G. L. Nakarado, "Structural Vulnerability of the North American Power Grid," *Physical Review E*, Vol. 69, No. 2, 2004. doi:10.1103/PhysRevE.69.025103

[29] D. J. Watts and S. H. Strogatz, "Collective Dynamics of Small-World Networks," *Nature*, Vol. 393, No. 6684, 1998, pp. 440-442. doi:10.1038/30918

[30] D. P. Chassin and C. Posse, "Evaluating North American Electric Grid Reliability Using the Barabasi-Albert Network Model," *Physica A*: *Statistical Mechanics and Its Applications*, Vol. 355, No. 2-4, 2005, pp. 667-677.

[31] A. D. Peacock and M. Newborough, "Controlling Micro-CHP Systems to Modulate Electrical Load Profiles," *Energy*, Vol. 32, No. 7, 2007, pp. 1093-1103. doi:10.1016/j.energy.2006.07.018

[32] R. J. Aumann and S. Hart, "Handbook of Game Theory," North-Holland, Amsterdam, 1992.

[33] M. J. Osborne and A. Rubinstein, "A Course in Game Theory," The MIT Press, Cambridge, 1994.

[34] W. Saad, Z. Han, H. V. Poor and T. Basar, "Game Theoretic Methods for the Smart Grid," *Information Theory*, Vol. 8, No. 1-2, 2012, pp. 1-177.

[35] C. Block, D. Neumann and C. Weinhardt, "A Market Mechanism for Energy Allocation in Micro-CHP Grids," *Proceedings of the* 41*st Annual Hawaii International Conference on System Sciences*, Waikoloa, 7-10 January 2008, pp. 172-182. doi:10.1109/HICSS.2008.27

[36] A. Arenas, A. Diaz-Guilera, J. Kurths, Y. Moreno and C. Zhou, "Synchronization in Complex Networks," *Physics*

Reports, Vol. 469, No. 3, 2008, pp. 93-153. doi:10.1016/j.physrep.2008.09.002

[37] R. Olfati-Saber and R. M. Murray, "Consensus Problems in Networks of Agents with Switching Topology and Time-Delays," *IEEE Transactions on Automatic Control*, Vol. 49, No. 9, 2004, pp. 1520-1533. doi:10.1109/TAC.2004.834113

[38] R. N. Anderson, A. Boulanger, W. B. Powell and W. Scott, "Adaptive Stochastic Control for the Smart Grid," *Proceedings of the IEEE*, Vol. 99, No. 6, 2001, pp. 1098-1115. doi:10.1109/JPROC.2011.2109671