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From Smart Grids to an Energy Internet: Assumptions, Architectures and Requirements

ABSTRACT

Secure and reliable delivery of energy is essential to modern society. Achieving this goal is becoming more challenging with increasing demand and declining resources. The ongoing restructuring of the rather old delivery infrastructure is an attempt to improve its performance so that energy can be utilized with higher efficiency. Smart grids are an advanced concept with a number of unique features compared to their precedents, including early detection and self healing capabilities. An implementation of smart grids is an energy internet where energy flows from suppliers to customers like data packets do in the Internet. Apparent benefits from an energy internet are its openness, robustness and reliability. This paper uses electricity as an example to present some key assumptions and requirements for building the energy internet. An example is presented.

Keywords: *Energy Internet, Smart Grids, Anticipatory System, Price Elasticity, Online Learning*

1. Introduction

The importance of energy and its delivery infrastructure for humanity can never be overstated. The availability of resources determines that massive generation of energy, such as electricity, has to be centralized. While customers are highly distributed, an extremely sophisticated transmission and distribution network is needed for energy delivery. As an example, the electric power grid of the United State of America consists of more than 3,100 electric utilities operating more about 10,000 power plants, and 131 million customers consuming more than 3,500 billion kwh every day. In the middle, there are about 157,000 miles of high voltage electric transmission lines. And on top of it, there are policy makers and regulatory agencies. The top priority of this massive and super complicated infrastructure is to make sure that electricity is available whenever it is needed. Because its service is socritical the grid was highly regulated for nearly a century.

The dilemma is that our current knowledge about complex systems like the electric power grid does not enable us to regulate it efficiently and reliably. Often a compromise has to be made between efficiency and reliability. And when it happens, reliability always has the priority. Even with this assumption, reliability is not always guaranteed. It has been estimated that annual loss due to service interruption is about $80 billion for the US alone. [1] The Summer 2003 blackout in Northeastern US was an example. The cause for each interruption might be different. But the principal reason is that generation and delivery capacity fails to provide sufficient safety margins, which may be further reduced due to poor management and regulation. Investing on more generators and better delivery systems (transmission and distribution) is an answer with some severe limitations. There is an unavoidable and unprecedented increase on energy demand. Consumers will have higher expectations for the service, both on quality and quantity. On the other hand, resources are limited and the investment on exploiting them is a lengthy and expensive process. In this picture, undoubtedly the safety margin will be greatly reduced in the future and more service interruptions will occur. An alternative approach is the so called "generating through saving", which is inspired by the observation that a large portion of the energy was lost due to the inefficiency in operations.

Viewed from another angle, an energy infrastructure as a complex system is in a healthy and stable state only when all its components (10,000 power plants, 131 million customers, 157,000 miles of transmission lines, and more) are appropriately configured. This is an extremely difficult optimization problem without any analytical so-

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lution. The best tool available is the multi-agent (or intelligent agents) approach, where the search for solutions, rather than the solutions themselves, is explicitly formulated. A framework (agent environment) is developed for components to interact with each other and some protocols are imposed on their interactions. With an effective agent environment and the right set of protocols, components can reconfigure themselves adaptively in order to survive in the system. The system then acquires a very desirable characteristic, that is, self healing. Whenever the system deviates from its optimal operating point, its components automatically reconfigure themselves to correct the problem. The Internet is one example where all these things take place. In this sense, an Internet-type network is a favorable option for the next generation energy infrastructure. The new system can provide an unprecedented degree of flexibility to users, services providers, marketers, and regulators. Customers will be able to choose the service package that fits their budget and preferences thanks to competition. Service providers will see more profits through organized production, a result of real-time interactions with customers. Marketers or brokers will have more information to plan more user-oriented marketing strategy. The regulation agency can operate to its maximal capacity by focusing effectively on mostly on regulating issues. Best of all, it will be a more reliable and more efficient energy infrastructure.

Unfortunately, the existing energy infrastructure is not immediately ready for upgrading to an energy internet. For example, most components, including millions of electricity meters, in the current electric power grid are passive with very limited communication and reconfiguration capability. Furthermore, necessary regulations are not in place for opening up the whole infrastructure.

Researchers have recognized the gap and tremendous progress has been made on smart grids. [2] Smart grids are an advanced concept with a number of unique features compared to their precedents, (1) detecting and correcting incipient problems at their very early stage; (2) receiving and responding broader range of information; (3) possessing rapid recovery capability; (4) adapting to changes and reconfiguring accordingly; (4) building in reliability and security from design, and (5) providing operators advanced visualization aids. [3]

Progress made on smart grids has enabled new and meaningful discussions on a full scale energy internet. Building such a network requires substantial amount of effort from diverse sectors such as technology, social science, and legislation. Even though the Internet is a full-fledged technology, some key differences between energy (especially electricity) and electric data, which is transmitted on the Internet, prevent a direct copy. They are as follows:

1) Compared to electric data, electricity is mainly generated centrally and consumed locally. Long distance transmission is critical and traffic control becomes important since routing options are usually limited. Bottlenecks are more likely created.

2) Electricity cannot be stored at a large scale, which is unique compared to the Internet where data are stored and retransmitted. Storage, served as buffers, is an important stabling factor in a complex system. The lack of storage in the electric power grid makes it vulnerable to all kinds of instabilities.

3) The Internet uses a “Best-Effort” service model and the quality of service (QoS) is a secondary consideration. The energy network, however, assumes the opposite. The top priority for the service network is to satisfy customers’ demand anytime. Therefore, for the Internet the problem is how to allocate the bandwidth so that data packets can be delivered efficiently. On the other hand, in energy networks, customers’ peak demand, which can occur at any time, will be closely monitored and forecasted so that generation/transmission/distribution can be scheduled to meet this demand.

Recognition of the differences is a necessary step towards a feasible energy internet. Of many possible solutions to address these differences, the anticipatory control methodology appears very promising. Anticipatory control is a set of tools that make control actions based on system’s projected states.

The power of this paradigm comes from its farther future vision as compare to conventional approaches which use only current-state information to affect change. Anticipatory control consists of two parts, anticipation of future states and intelligent decision-making based on the anticipation. These two components, as discussed later, are the key to fill the gap.

The rest of the paper will discuss an approach for building the energy internet. The discussions include key assumptions, critical requirements and candidate architecture.

2. Assumptions

2.1 Intelligent Management and Sharing of Information Achieve Virtual Energy Storage

As we have discussed before, the biggest obstacle for the energy internet is the lack of significant energy storage capacity inside the network. Without any feasible solution in the horizon, some researchers argue that it can be virtually achieved via intelligent information management and sharing. [4] The idea is to create a virtual energy buffer between customers and suppliers.

A virtual buffer is implemented through a demand side management strategy which is build upon the practice of dynamic data driven paradigms. With the emergence of intelligent meters, it is possible to dynamically schedule the use of electricity of every customer. This dynamic scheduling will create a sheet of virtual buffer between generation and consumption as we argue here, as shown in Figure 1.

Under the new paradigm, the consumption of electricity of every customer is intelligently managed. Customers don't power up their electricity-hungry machines at will. Rather, they make smart decisions after balancing the costs and benefits. For example, some non-urgent activities, such as laundry, can be scheduled for sometime during the day or night when electricity is abundant and cheap. The costs of the electricity are determined by the supply-to-demand ratio and the capacity of the network to transfer the resources. This managed use of resources is analogous to the access control widely used in the Internet. A buffer between generation and consumption is therefore created, virtually. No physic laws are broken. The electricity is still actually consumed when generated. However, from the customer point of view, with dynamic consumption scheduling the resources (electricity) are created and then stored somewhere in the power grid before they are used. The analogy is shown in Figure 2. The virtual buffer may greatly increase the stability of the power grid.

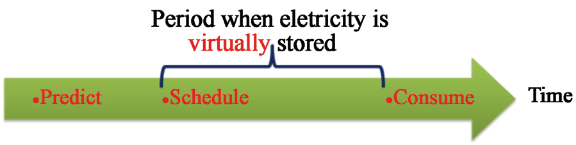


Figure 1. Virtual storage of energy

Dynamic scheduling has to be carried out by software agents or intelligent agents. The intelligent agents will act on behalf of their clients; making reasonable decision based the analysis of the situation. One of the most important analysis powers an agent has to possess is the anticipation capability. The intelligent agent needs to predict its client's future consumption pattern to make scheduling possible. In other words, load forecasting capability is the central piece for such a system.

2.2 Price Elasticity Can Effectively Manage the Uncertainty

As presented earlier, prediction is the cornerstone of the energy internet. However, accuracy is one of the major concerns for using prediction data as the basis for generation. Uncertainty is always associated with predictions and uncertainty may grow to an unacceptable level when millions of predictions are summed up. To circumvent this problem, a second assumption is presented, which is that price elasticity can be used to effectively manage uncertainty.

This assumption is analogous to the one used in feedback controls systems. Measurements are fed back as references, which the controller can use to adjust its outputs adaptively. As a result the controller itself needs not to be very accurate. Similar conclusion can be drawn here. Provided a feedback loop between customers and suppliers, prediction errors will be corrected adaptively. The best feedback mechanism is provided by price elasticity, particularly short-term elasticity. The mechanism of short-term price elasticity will be discussed in more details in the following sections. A good short-term price elasticity model provides an estimate on the customer's purchasing willingness with respect to the change of the price. Through this tool, customers and suppliers can perform dynamical negotiations to achieve a delicate balance between generation and consumption, even with less accurate load forecasting.

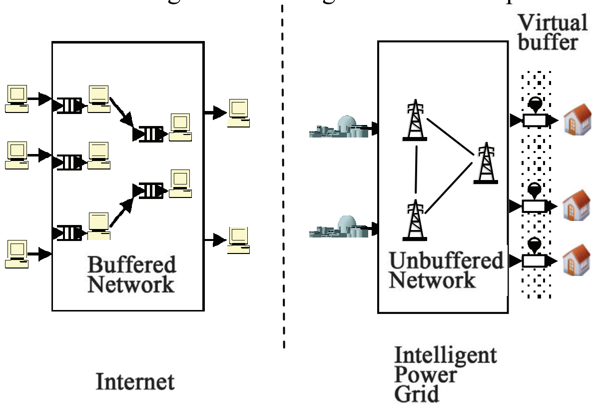


Figure 2. Internet and power grid with virtual buffers

3. Architectures

There are many possible architectural candidates for the energy internet as long as they satisfy the abovementioned assumptions. In this paper example architecture will be delineated and discussed. The work presented here was conducted mostly the Consortium for Intelligent Management of Electric-power Grid (CIMEG).

In 1999, EPRI and DOD funded the Consortium for the Intelligent Management of the Electric Power Grid (CIMEG) to develop intelligent approaches to defend power systems against potential threats [5]. CIMEG was led by Purdue University and included partners from The University of Tennessee, Fisk University, TVA and ComEd (now Exelon). CIMEG advanced an anticipatory control paradigm with which power systems can act proactively based on early perceptions of potential threats. It uses a bottom-up approach to circumvent the technical difficulty of defining the global health of a power system at the top level, as shown in Figure 3. The concept of Local Area Grid (LAG) is extremely important in CIMEG. A LAG is a demand-based autonomous entity consisting of an appropriated mixture of different customers, charged with the necessary authority to maintain its own health by regulating or curtailing the power consumption of its members. Once all LAGs have achieved security, the whole grid, which is constructed by a number of LAGs in a hierarchical manner, achieves security as well. To pursue the health of a LAG, intelligent agents are used. Intelligent agents monitor every load within the LAG, forecasting the power consumption of each individual load and taking anticipatory actions to prevent potential cascade of faults. A prototypical system called the Trans-

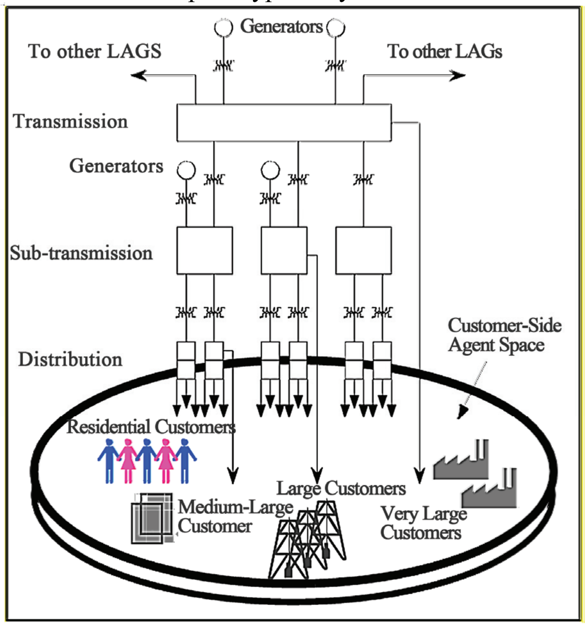


Figure 3. CIMEG's implementation of an energy internet

mission Entities with Learning-capabilities and On-line Self-healing (TELOS) has been developed and implemented in the service area of Exelon-Chicago and Argonne National Laboratory. [6]

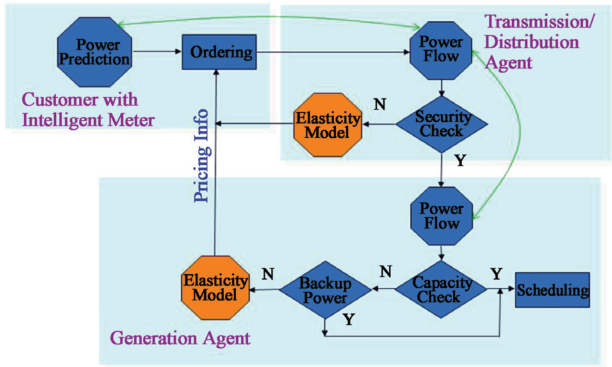
CIMEG's mission was to create a platform for managing the power grid intelligently. In CIMEG's vision, customers play more active role than in current power system infrastructure. Lots of solicitation and negotiations are involved, as shown in Figuer 4. The customer, who is represented by an intelligent meter in Figure 4, predicts a future need for electricity and places an order in the market. The amount of the order is influenced by the market price of the electricity, which is further determined by the difference of the demand and supply and also the capacity of the network. Economic models with price elasticity are used in the process. [7] The active interaction between customers and suppliers create a virtual buffer between consumption and generation as discussed earlier.

4. Requirements

There are many possibilities to build an energy internet. However, to make it successful, some requirements have to be satisfied. It is out of the scope of this paper to enumerate the whole list. Instead, only some of the most important ones are discussed here.

4.1 Smart Meter with Unique Address and Communication Capability

This is probably the most fundamental requirement on the side of hardware. Everything will start from a meter installed on the customer side. The interactions between customers and suppliers (including any middlemen, such



Figuer 4. Interactions among agents

as retailers) occur in such a high rate that manual operation is impossible. Basic hardware support is needed for automatic and real-time communication between customers and suppliers. That necessitates a smart meter with a unique and addressable identifier and two-way communication capability.

4.2 Forecasting Capability

Prediction and anticipation are the essential stabling forces in a complex system. The more information about the future is known, the better planning can be made. For an energy internet, it is crucial that customers' energy usage patterns can be predicted with a degree of certainty. There are plenty of tools available for this purpose thanks to extensive research efforts in the past. Using parametric (statistical) or non-parametric (neural networks) or hybrid (fuzzy logic) methods, these tool can predict very accurately a customer's short-term demand. [8]

4.3 Multi-Resolution Agents

The real time operation in an energy internet requires the application of intelligent agents. Intelligent agents act on behalf of their clients, who can be actual customers, power grid operators, electricity brokers, or non-human entities such as transformers, generators, transmission lines. Intelligent agents are equipped with sufficient knowledge so that they can act rationally. Conventional wisdom suggests that each intelligent agent should take actions to pursue maximal benefit for itself. This assumption made to simplify the operation of intelligent agents. However, it may result in some unwanted side effects that have been identified by many researchers especially in game theory. These side effects are harmful to the health of the whole system and appropriate actions should be taken to avoid that.

In classic game theory, an agent is given access to all information if available, such as the possible actions and outcomes of other agents. We argue that this is an unrealistic condition. In classic game theory, an agent is able to choose the best strategy (i.e., act rationally) if it can examine all possible scenarios. Experimental data contradicts such conclusions (see Prisoner's Dilemma). Human beings sometimes act irrationally according to game theory. A human being does anticipatory reasoning, which means that when making a decision the consequence has been taken into consideration. The major difference with classic theory is that human being does not have an accurate prediction for things in very far future, which in part explains why a human being sometimes acts irrationally according to classic theory. A human being sees the future in two different time scales, short term and long term. In the short term scope, we can make very accurate estimations. In long term scope, we have to make estimations with increasing degree of uncertainty. Therefore, a more realistic agent must possess a multi-resolution vision. We propose it as a second principle (assumption) for agents. We shall show that this is not only a reality but also a stabling factor for complex systems.

In classical game theory, agents compete for their maximal benefits (payoffs). This assumption excludes them from collaboration in many situations (such as Prisoner's Dilemma). For agents with multi-resolution vision, collaborations are possible because the future is not clearly mathematically defined. For example, in the Centipede game, if both players know exactly what the other player's move (future), the first player is likely to choose to defect on the first play because this is Nash equilibrium and he has no incentive to choose the other option (cooperation). However, in reality, the future that players can see is not a clear picture. But the most important information a player can read from this fuzzy picture is that the payoffs would be much better in the future. A player is likely to choose to cooperate if he knows he can gain more by passing the piles. Then he would be very likely to choose cooperate in order to maximize the personal gain.

4.4 Short-Term Price Elasticity Model

Price elasticity is used to characterize the sensitivity of customers to the change of the price. In the case of electricity, the price elasticity measures how the price change impacts the customers' willingness to consume power. A good short-term price elasticity model provides the basis for interactions between customers and suppliers.

5. Conclusions

Building an internet type of energy network for the future may be the answer to some of the pressing energy challenges. Advancements in information technology and ongoing research on power infrastructure and complex system has made this goal reachable. The paper summarized some of the fundamental assumptions and requirements and presented an example architecture as well. The discussion was focused on technical and marketing issues. It is noteworthy that the subject requires inclusion of work from several other areas including, economics, regulation, resource management, and market structures for and capital allocation and risk management.

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