Towards an Energy Internet: A Game-Theoretic Approach to Price-Directed Energy Utilization

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Abstract. The growing interest towards internet-inspired research for power transmission and distribution invariably encounters the barrier of energy storage. Limitations of energy storage can be offset, to a degree, by reliable forecasting of granular demand leading to judicious scheduling involved and incentivized by appropriate pricing signals. The anticipation of energy demand and future system state is of great benefit in scheduling capacities offsetting storage limitations. In this paper, a game is formulated that shows the effect of the synergy between anticipation and price elasticity to achieve lower Peak-to-Average Ratios and minimize waste of energy. The results demonstrate that the final demand signal can be smoother and energy efficiency increased.

Keywords: Energy Internet, intelligent meters, energy anticipation, decision-making.

1 Introduction

Although modern civilization is characterized by ever increasing per-capita energy consumption, energy security, resource limitations, environmental constraints, call for systematic energy efficiency gains and appropriate technological advancements towards sustainability. Electric power is emblematic of modernity and of paramount importance for human progress and economic development. Electricity generation, distribution and utilization are obviously of great significance to both the industrialized and the developing world. A typical and complete path of energy flow rooted in power plant generation from where power is transported at the speed of light through the electric power grid (or simply "the grid") to devices and machinery of all types (the consumers) is often viewed as a gigantic machine in itself.

The electric power grid is the essential and primary medium for power distribution. It is a system of high complexity with evolved characteristics – often resulting in significant deviations from design specifications and hence vulnerable to instabilities which may result in brownouts or even blackouts. Instabilities are common in highly complex systems and need to be countered effectively and cautiously. If the time of failure (blackout) is long then the consequences in various aspects of social and economic life can be very severe. To avoid that, it is desirable to have "self-healing"

N. Hatziargyriou et al. (Eds.): E-Energy 2010, LNICST 54, pp. 3–11, 2011.

capacities where restorative action following a disturbance can be taken effectively before a brownout or a blackout [1]. Hence, accurate prediction and prognosis of destabilizing events is of great importance in managing disturbances and preventing destructive effects and their cascade-type or domino propagation through the network.

Usually, widespread failures in power networks require significant amount of human resources that may entail high cost. On the other hand, prognosis of non normal states is preferable since it reduces the cost of restorative activities and maintains overall network availability. Because of the importance of this system, regulation of the power grid necessitates short term forecasting of the load and when possible forecasting at the nodal level of individual devices and machines [2] [3]. Indeed, anticipation of nodal energy demand helps in scheduling proper actions so as to prevent the grid from failure. Towards that goal, several models and systems have been proposed for predicting load patterns and managing the grid.

The term *Energy Internet* [4] is found in efforts to embed information and automation technologies in the power grid to achieve intelligent energy distribution [5] and management [6]. Many techniques and protocols utilized by the information Internet may also be adopted in an Energy Internet [7]. However, the lack of satisfactory energy storage makes it difficult (if not impossible) to develop such approaches. In that direction, the notion of virtual buffers [8] is applied to the Energy Internet to compensate for this shortcoming. Virtual buffers are entities that exploit load anticipation capabilities within the grid so as to balance, as much as possible, the generated and the consumed energy. The difference in these two quantities comprises a crucial, but unstable, factor for the distribution network and, as such, needs to be carefully monitored and computed.

In this paper, a new algorithm is introduced with the aim of extending an Energy Internet's capabilities. The proposed methodology is coupled with the anticipated module of an intelligent meter in order to enhance intelligent decision-making. The overall goal is to incentivize a customer's financial benefit through pricing signals, a smart schema of anticipation and sequential placing of orders to the supplier.

In the next section, a brief introduction to the proposed concept of Energy Internet is presented and the role of energy anticipation is described. Also, related work by the Consortium for the Intelligent Management of the Electric power Grid (CIMEG) is presented. Section 3 presents the game-based approach used to show the role of anticipation. Additionally, anticipation is demonstrated through a simulated example and the advantage presented by its use is clarified. Lastly, the paper is summarized and the main directions derived from the game-based approach are outlined.

2 Energy Internet

This section is devoted in the concept of the Energy Internet. Specifically, there are two sections: the first summarizes the fundamentals of the principle idea, and, the second briefly describes work done in that direction by CIMEG [9].

2.1 The Concept of the Energy Internet

The notion of an Energy Internet is a novel idea that is an implementation of a more advanced smart grid [10]. It possesses features of conventional smart grids have such as quick detection of abnormal states and self healing. Its principle perspective considers energy flows through the grid in a way analogous to data packets in data networks.

The main concern addressed by the Energy Internet is the lack of energy storage. Due to this, the contribution of energy anticipation [10] and virtual buffering are of great significance. Initially, consumers predict their short term energy demand pattern [11] and then forward an order to the supplier's site. Through its infrastructure the supplier will provide the customer the amount of requested energy. After the order is approved by the supplier, the requested energy can be considered as stored or buffered. It should be mentioned that physically the energy has not been generated yet. Towards that, this hypothetical stored energy defines a virtual buffer as it is presented in figure 1.

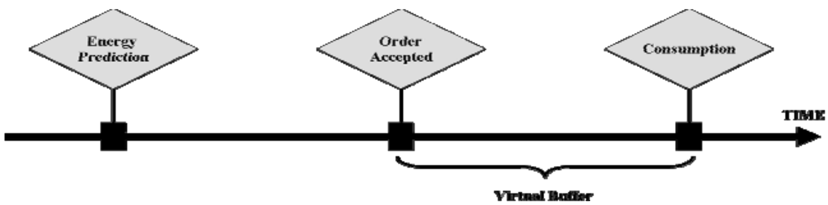

Fig. 1. The notion of Virtual Buffer

The scheme of collecting and accumulating energy orders makes possible the utilization of dynamic power generation level. The latter means that power generation is adjusted to the power needs and the wasted amount of energy is reduced significantly compared to that of a fixed generation level (figure 2).

The basis for the efficient function of the Energy Internet is the use of intelligent meters. Each intelligent meter stands for one customer of the electric grid. Its role is to perform a variety of functions including purchases of the required energy. In doing that, such a meter possesses intelligence capabilities in the sense that it processes data and makes predictions. In fact, such meters are software agents since they have their own agenda, seek their own goal, react to and communicate with their environment.

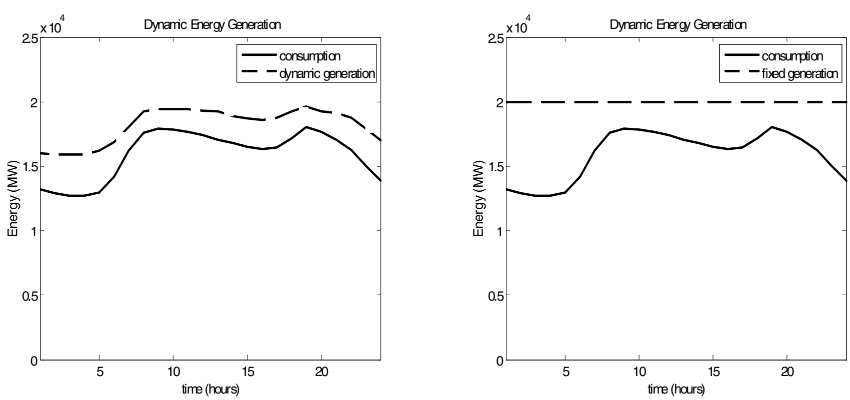

Fig. 2. Schemes for Dynamic and Fixed Generation of Energy

A crucial part of an intelligent meter is its anticipation module. In that subsystem, algorithms for prediction of customers energy need are implemented. Specifically, the meter uses previous energy profiles in order to come up with a prediction. The result of the prediction is submitted to the power supplier as energy that is pre-ordered. The latter necessitates the need for a type of identification for the meter. In that direction the meters are supplied with a unique IP address which is assigned to them upon registration to the network. Overall, Energy Internet can be considered as one step ahead in evolution of smart energy grids and as a good mimic of the data networks.

2.2 Consortium for Intelligent Management of Electric-Power Grid (CIMEG)

In 1999, CIMEG was funded by EPRI and DOD with the aim to develop intelligent methodologies for the management of the electric grid. Its principle objective was to develop new tools for mitigating potential threats for the normal operation of the grid. Led by Purdue researchers CIMEG involved several partners from The University of Tennessee, Fisk University, TVA and ComEd (Exelon).

CIMEG's approach models the grid as a demand-driven system. A bottom up approach is followed in order to determine the health of the system at higher levels and ultimately its global state of health. The latter necessitated the introduction of the notion of a Local Area Grid (LAG). A LAG can be characterized as the clustering of several different customers and is responsible for keeping its own stability by taking appropriate actions when necessary. The implementation of LAGs was based on development of on a multi-agent system named Transmission Entities with Learning-capabilities and On-line Self-healing (TELOS). In TELOS, intelligent agents perform the anticipation process for the LAG and might act to prevent possible future faults.

The ultimate vision of CIMEG was the creation of a platform that controls the power grid in an autonomous and intelligent way. More specifically, intelligent meters are given the responsibility to negotiate with suppliers and place orders. On the other hand, suppliers and generators intend to maximize gain by keeping demand below optimal generation levels. The latter can be accomplished via elasticity models which can affect demand by generating appropriate pricing signals.

3 Regulation of Power Market

This section is devoted to description of the approach followed for regulation of the power demand curve through price elasticity. Specifically, a game is set up [12], in which players aim in achieving regulation by achieving an agreement beneficial to all parts.

3.1 Description of Game

An important goal in the power system is to harmonize the power generation-demand equilibrium; implicitly, by smoothing out demand signals the electric power grid becomes more stable thus assuring effective distribution of energy. In order to illustrate that let us consider a game in which short term pricing is determined through a series of negotiations between players [13].

As expected, players in the game are identified either as a) *energy consumers*, or b) *electricity suppliers*. Specifically:

- ***Consumers*** can be classified as *residential* or *industrial*. The distinction is based on the energy consumption profiles, which appear to have significant differences and possess specific characteristics. For the purposes of the game in this work, no distinction is made between the various customers. Moreover, their individual demand curves are aggregated to yield a global demand profile (D_p). Generally speaking, a global demand profile is created by registered customers of a specific geographical area.
- ***Suppliers***, who are also the electricity generators in order to simplify the presented approach, have an upper limit in energy production and distribution (G_{max}). The latter constraint once exceeded by uncontrolled demand, can result in destabilization of the power grid and subsequent failure of providing power to all consumers. In other words, the grid may collapse. It should be emphasized that in the current work, it is considered that there is only one electricity supplier. In addition to that, it should be stated that the supplier's generation capacity is assumed to be above the electricity demand at all times, that is,

$$G_{max} > D_p \; . \tag{1}$$

In this paper, the presented game adopts the principles of the Energy Internet. So it is considered that the power demand is predicted for a horizon of an hour ahead. Exploiting the anticipation information, the purpose of applying the game approach is to drive all players into a kind of agreement called equilibrium. To be more specific, equilibrium includes:

- Smoothening of power demand (reduce PAR) – consumers change their consumption schedule,
- Keeping the profit of suppliers as high as possible.

The methodology followed for regulating the power demand curve is variation of the price of electricity. Accomplishing that, the concept of price elasticity (see (2)) is applied as the mechanism to determine a suitable price that might drive customers to reduce consumption or alter their schedules. The latter will lead the overall demand towards the predetermined goal.

$$E = \frac{\Delta Q_d / Q_0}{\Delta P / P_0} = \frac{\%\_change\_in\_demand}{\%\_change\_in\_price} \tag{2}$$

More specific, the game is based on initial demand prediction and subsequent adjustment of price through price elasticity. It should be emphasized that the initial goal might not be achieved with the first iteration and more adjustments of price might be needed. Although there are several models developed for estimation of elasticity, in the current game use is made of a constant value for elasticity and specifically one of those provided in [14].

The initial price is sent to all registered users. Each one of them replies back with the anticipation of its demand. Aggregation of all demand signals yields the total demand. In the next step, the supplier using the formula shown in (2) computes the new price and broadcasts it to the customers waiting for their updated anticipation response. In case the updated demand signal reaches the predetermined goal then the current price is used for the transactions of the next half hour.

Customer reactions are limited to three choices; increase their demand, stay at the same level, or, reduce it. Following a rationale approach, if the price changes upwards then the demand will decrease since customers do not want to pay more than their initial budget allows. In order to model the behavior of the consumers we use a probability distribution schema:

$$\begin{aligned} P_{in} &= \text{increase demand} \\ P_{dec} &= \text{decrease demand} \\ P_{same} &= \text{same demand} \end{aligned} \tag{3}$$

Getting into more details, each of the three expected reactions is assigned a values which stands for the probability that the customers might reach respectively. As a result, an action is selected randomly according to the probability distributions in each pass. Moreover, probabilities are not constant but are rather updated in each iteration according to:

$$P_{xi} = P_{x(i-1)} + k_{xi} \tag{4}$$

where, x denotes the type of action, i is the iteration number, and k is a constant of update. In all cases probabilities should the follow Kolmogorov's axioms. Hence:

$$P_{ini} + P_{deci} + P_{samei} = 1 \tag{5}$$

which implies that

$$k_{ini} + k_{samei} = k_{deci} \tag{6}$$

Updated probabilities stand for the rational change of customers' response to market changes. The more one has to pay the more willing is to alter his schedule of power consumption. Once an action is chosen then the consumption should change. In the current work either increase or decrease is done by an amount which is equal to:

$$(demand - regulated)/\#customers \tag{7}$$

From the supplier point of view the maximum profit is obtained by shaping the demand curve to the maximum value which regulates the market and assures stability of the power grid. In other words the predetermined goal demand is put by supplier to the maximum possible in each case.

3.2 Application of the Game and Results

Application of the game will show the efficiency of the model for regulation of the power market via price elasticity. For this reason, some simple assumptions are made to simplify the game. Specifically, reaction probabilities are given random values in the beginning, through the rationale that once prices go up it is more likely that a consumer will reduce his demand, less that he will ask for the same amount and even less that he might increase it. The constants k_x take the values 0.04, -0.015 and -0.025 for decreasing, ask for the same and increase the demand respectively. Demand data and prices signals are taken from [15]. To simplify for the purposes of the paper, it is assumed that the registered customers are 6,500,000 and all of them share the same probability distributions for reaction.

Furthermore, a fixed elasticity value is adopted for the current game and is equal to -0.88 as shown in [14]. It should be mentioned that the fixed value allows little space for flexibility and might lead to high variations. In addition to that, we set for some a higher boundary for approaching the desired curve smoothening. To be more specific, it is difficult to reach the exact predetermined demand values and as a result a margin of +/- 10 MW is set. For the purposes of the game it is assumed that the module is not aware of the demand and price signal so as to have a virtual real time demonstration. Figure 3 shows the initial demand curve, the desired regulated signal and the prices before changes based on elasticity. Observation of figure 3 provides that the peak of the demand to be smoothed is the time between 17:00 and 21:00.

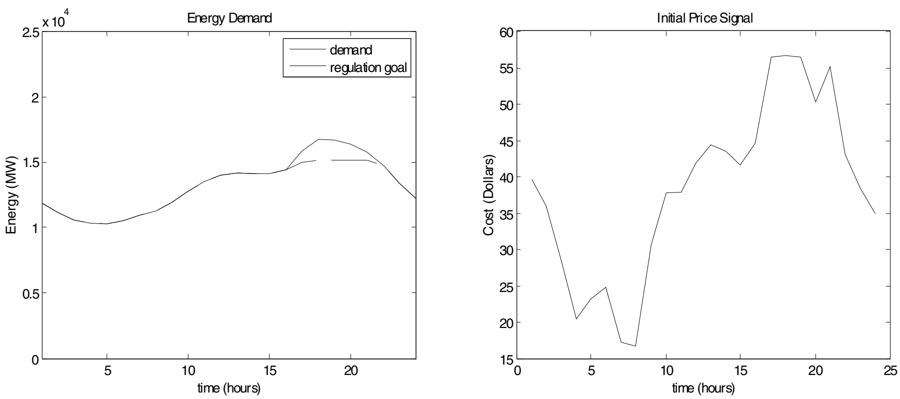

Fig. 3. Curves for Energy demand, regulation of its peak and price signal over a period of one day (source NE ISO)

For demonstration purposes, it is assumed that at 16:00 the customers report their anticipated demand to the supplier. The demand is as shown in figure 3 at 16:00. The supplier observes the rise in the demand and tries to suppress the demand by changing the price of the electricity. Accomplishing that, a fixed elasticity model is adopted and a new price is computed.

Customers react to the new price according to their probability distributions. It should be said that in the first each customer decides whether to reduce consumption, ask for the same, or to increase with probabilities of 0.5, 0.35 and 0.15 respectively. From the latter values, it is obvious that the rational behavior of reducing consumption if cost goes up is modeled. Table 1 shows the negotiations among supplier and customers for energy consumption at 18:00. Specifically, the evolution of price and demand through a fixed elasticity for achieving the desired smoothing goal is presented.

Table 1. Price and Demand Evolution during game negotiations for energy needs at 18:00

	Initial	*Round 1*	*Round 2*	*Round 3*	*Round 4*	*Round 5*	*Round 6*	*Round 7*
Price - LMP($)	56.61	62.64	65.32	66.31	66.62	66.69	66.71	66.72
Demand (MW)	15826	16146	15711	15448	15307	15240	15213	15203

Following the same process at times 18:00, 19:00, 20:00 and 21:00, the energy demand is reduced to the desired level and the peak is eroded. This is observed in figure 4, in which the initial demand has been reduced to the desired levels. Precisely, the energy demand after the game is almost the same as the initial desired regulated curve. To be more specific, the regulation goal was achieved with high accuracy for the interval 18:00 to 21:00 and with less as 17:00. Therefore, figure 4 shows the flattening of the demand curve.

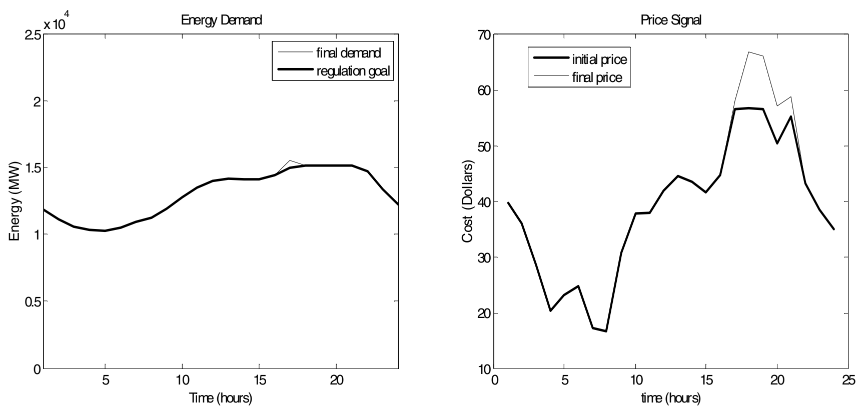

Fig. 4. Final demand and price signal at the end of the game superimposed to initial signals

4 Conclusions

In this paper, a new model of control (regulation) of the power market based on negotiations and change of the cost of electricity is discussed. More specifically, the underlying idea states that the power grid could become more intelligent once coupled with information services such as anticipation of energy consumption. For that reason, the proposed concept of an Energy Internet and the research work done in that direction by CIMEG was briefly presented.

Furthermore the idea of suppressing the energy demand, which is anticipated ahead of time, through price elasticity models was demonstrated by a game based approach. The game described in this work assumed as players the registered customers and one supplier. Behavior of customers in the market was modeled by probability distribution. The case presented used data from NE ISO and showed that regulation of market can be achieved by alteration of the price electricity. The example examined illustrated how the erosion of peak demand may be achieved through increase of the cost of electricity supplied.

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