Demand-Side Behavior in the Smart Grid Environment

A. Moshari, G. R. Yousefi, A. Ebrahimi, and S. Haghbin

Abstract—Recent developments in traditional power systems which involve emerging smart technologies and widely employing of communication will convert the present electricity grids into the smart grids. The future smart and efficient power systems will treat completely different compare with the existing power systems. This paper discusses the effect of emerging smart grids on the consumer’s behavior. It investigates the responses of different types of consumers to the spot electricity price and the price elasticity of demand in the smart grid environment. Smart technologies could bring all of the consumers with any level of demand to the market actively, and results in increasing the efficiency of the market in a fully competitive electricity market.

This paper also describes the effect of Demand Response (DR) on some electricity market issues like short-term load forecasting, generation expansion, and imperfect competition, in the smart grid environment. The qualitative discussions show that by emerging the smart grids the market efficiency, consumer’s benefits, and Demand Response of the power system are improved and the ability of strategic players to exert market power will be reduced.

Index Terms—Advanced Metering Infrastructure (AMI), Demand Response (DR), generation expansion, imperfect competition, short-term load forecasting, short-term price forecasting, smart grid.

I. INTRODUCTION

Reducing the electrical energy price paid by consumers has always been one of the first reasons given for introducing competitive electricity markets. In most present electricity markets, however, consumers (especially small consumers) have the least influence on the market decisions and design. Because in the present structure of these markets most consumers, except the large ones, do not have the financial incentive and enough expertise required to participate actively in such a complex and time-consuming activity. Therefore these consumers are treated as the loads which need to be served under all conditions. Generally, in these electricity markets consumers do not face with spot prices. Retailers or aggregators attend in the wholesale electricity market, as the consumers’ representatives, and purchase required electricity energy [1]. However, experiences in California showed that introducing competition on the supply side while shielding the demand from liberalized prices distorts the market seriously [2].

There are a variety of researches which show that more active participation in the market by the demand side could have significant benefits for the whole market. In particular [3]–[9]:
- Reduction in the energy cost for consumers who shift their demand from periods of high prices to periods of lower prices;
- Reduction in the overall generation cost of the system because this demand shifting will flatten the overall demand profile;
- Even consumers who do not adjust their demand will make a profit if this reduction in cost translates into a reduction in prices;
- Avoiding price spikes (i.e. very large increases in price over short periods of time);
- Reduction in the ability of generating companies to exert market power.

However a more elastic demand will generally reduce the profits of the generating companies [10], [11], but it will increase the social welfare and the efficiency of the electricity market.

By emerging the smart grids, consumers will play more important roles in the electricity markets. Advanced metering systems and monitors which show the spot prices of the electricity market, will increase the sensitivity of consumers to the variations in market prices. Moreover, by developing the technology of demand management advanced controllers which can automatically shift a portion of the consumer’s demand from periods of high prices to periods of lower prices, the Demand-Response (DR) of the electricity market will be improved. Therefore, one of the most important results of emerging smart grids is the increase in short-run price elasticity of demand. This increase, as discussed above, can yield to several benefits for consumers and the electricity market. This paper investigates the effect of emerging smart grids on consumers’ demand response and its consequent results in some of the electricity market issues. This paper is organized as follows. Section II proposes some of the main features of smart grid in brief. Section III, at first, discusses the effects of demand response on the market operation and spot prices. Then, demand response is investigated in the smart grid environment for different kinds of consumers (industrial, commercial, and residential). Finally, this section will review issues like short-term price and load forecasting, generation expansion planning strategy in the electricity market.

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1 We simply call them “smart monitors” in this paper
2 We simply call them “smart controllers” in this paper
market, and imperfect competition in the smart grid environment. Conclusions will be drawn in Section IV.

II. SMART GRID CONCEPT

The concept of smart grid started with the idea of Advanced Metering Infrastructure (AMI) and its initial goal was improving the demand-side management, energy efficiency, and developing a self-healing electrical grid to improve the power system reliability. However, some issues have expanded this initial concept and shaped the new face of the electricity industry. Some of these issues are: emphasis on environmental protection which supports the development of renewable generation (wind, solar, etc.) and demand response (DR); the need for better asset utilization and better operating of power system; and the need to provide more and better options for customers [12]. Fig. 1 schematically shows these factors in relation to the new emerging smart grid paradigm [12].

![Driver factors of emerging smart grid](image1)

Fig. 1. Driver factors of emerging smart grid [12]

Present power systems have numerous problems which resolving them in the current structure is very difficult or even impossible. For example in the area of power systems operation, only one-third of fuel energy is converted into the electricity, without recovering the waste heat. Almost 8% of the power system output is lost along its transmission to loads, while typically 20% of its generation capacity exists to meet peak demand only (i.e. only for 5% of the time). It is clear that such critical issues cannot be addressed within the limitations of the existing electricity grid [13].

The future electricity grids, known as the “smart grids”, should provide a solution for these problems. They must have more observability than conventional grids to improve the ability of control the operation of the power system. Also they should have the ability to employ the distributed generation (DGs) sources widely and resolve the problems which limit implementing of micro grids like protection, synchronization, fault detection, and self-healing and islanding operation mode issues. The features of smart grid which are related to the demand-side are concerned more than its other features by the public. AMI systems, smart monitors, and smart controllers are some of these demand-side features. By using advanced metering systems the real electricity consumption of each consumer is available for all the time. Therefore, unlike the present electricity markets, customers who did not consume in the periods of high prices will not pay an extra cost because of the consumption of other customers. This procedure will encourage consumers to adjust their demand and lead them to a more desirable behavior in response to the spot price variations. As mentioned before, smart monitors show the spot prices of electricity in their zone. This technology needs a continuous communication between the market manager and consumers. This technology in conjunction with AMI systems can improve the demand response of the electricity markets. When consumers are informed about the price of their electricity energy consumption, they are more likely to conserve a portion of their demand or shift it to the periods of low prices. Development of low-price smart sensors will smooth the path for smart controllers. These controllers can manage the demand of consumers based on the spot prices of the electricity market and their settings. In the local mode these controllers can be set based on the consumer’s decision and desire. In the global mode, smart controllers communicate with each other and are controlled by a hierarchical scheme. In the second mode, retailers may control the smart controllers to manage their risk; or even System Operator (SO) may use this scheme to increase the security of the power system. However, this scheme can endanger the consumers’ privacy.

The concept of smart grid, however, is much more extensive than these limited features. In fact, smart grid is generally the digitalization process of the power system. In other words, the smart grid is emerging as a convergence of information and communication technologies with power system engineering [13]. Fig. 2 shows the way of flowing power and information in the traditional power system environment. Power flow is almost unidirectional from centralized supply sources (power plants) to demand, and information flow is from lower voltages to the grid operational centers. By emerging the smart grid both of these flows will be bidirectional as shown in Fig. 3 [12]. Also Table I illustrates the basic differences between smart grid and the existing grid [13].

![Power and information flow in the traditional power system environment](image2)

Fig. 2. Power and information flow in the traditional power system environment [13]

![Power and information flow under the smart grid environment](image3)

Fig. 3. Power and information flow under the smart grid environment [13]

Smart grid can also affect power systems operation and control, the penetration level and the way of using distributed generations in the power grid, and the security issues of the
power systems. However, this paper focuses on the effects of emerging smart grid on consumers’ behavior and its consequent results in power market issues. Currently, several researches and projects are being conducted around the world in the area of developing the smart grid technologies. For more information about them, readers are encouraged to study related references [12]-[14].

**TABLE I**

**BASIC DIFFERENCES BETWEEN SMART GRID AND THE EXISTING GRID [13]**

<table>
<thead>
<tr>
<th>Existing Grid</th>
<th>Intelligent Grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromechanical</td>
<td>Digital</td>
</tr>
<tr>
<td>One-Way Communication</td>
<td>Two-Way Communication</td>
</tr>
<tr>
<td>Centralized Generation</td>
<td>Distributed Generation</td>
</tr>
<tr>
<td>Hierarchical</td>
<td>Network</td>
</tr>
<tr>
<td>Few Sensors</td>
<td>Sensors Throughout</td>
</tr>
<tr>
<td>Blind</td>
<td>Self-Monitoring</td>
</tr>
<tr>
<td>Manual Restoration</td>
<td>Self-Healing</td>
</tr>
<tr>
<td>Failures and Blackouts</td>
<td>Adaptive and Islanding</td>
</tr>
<tr>
<td>Manual Check/Test</td>
<td>Remote Check/Test</td>
</tr>
<tr>
<td>Limited Control</td>
<td>Pervasive Control</td>
</tr>
<tr>
<td>Few Customer Choices</td>
<td>Many Customer Choices</td>
</tr>
</tbody>
</table>

III. CONSUMERS BEHAVIOR IN THE SMART GRID ENVIRONMENT

The basis of electricity markets is on the premise that electrical energy can be treated as a commodity and therefore can be traded in a competitive market. So, it is expected that in the electricity market consumers increase their demand up to the point that the marginal value of the electricity is equal to the cost they pay for it. If the customers pay a flat rate per kWh for the electricity they consume, they are not likely to respond to the variations in market prices. In fact, in this case they are isolated from the spot prices of the electricity. In the present electricity markets, even when consumers face with the spot prices, decreasing of their demand in response to a short-term increase in electricity price is small [15], [16]. In other words, the short run price elasticity of the demand for electricity is small in the existing electricity markets. This weak elasticity can be explained by economic and social factors [3].

This very low elasticity of the demand causes two major problems in the electricity markets. It causes large price spikes which facilitates exerting market power by generating companies [2], [17], [18]. A typical supply function can be represented by a three-segment, piecewise linear curve [3]. The first segment represents the bulk of the generating units in a reasonably competitive market. The second segment, which has a much steeper slope, represents the peaking units which will be called infrequently. The third segment is vertical and represents the supply function when all the existing generation capacity is in use. The nature of demand in the present electricity markets can be represented by an almost vertical line. Fig. 4, shows two scenarios for demand. One of them is related to a low demand period and the other is related to a peak demand period [3]. The intersections of these curves with the supply function determine the electricity prices for these scenarios. As shown in Fig. 4, in the peak demand periods because the marginal producer is a peak load generating unit, the price rises sharply. Fig 5, shows the state when there is a problem in the generating-side and the whole reserve capacity is in use (e.g. due to an unplanned outage of a major unit or an unexpected demand growth) [3]. In this case the electricity price can rise extremely and yields to a price spike. As a result, such a weak elasticity allows generating companies to exert market power by deliberately reduction in their generation.

![Fig. 4. Electricity price for low demand and peak demand scenarios [3]](image)

Now let’s see what happens if a part of demand-side has the ability to response to the price variations. This state has been shown in Fig. 6. In this case, the demand curve has two parts [4]. The first one is that which cannot response to the electricity price variations (price taking part). This part is shown as a vertical line. The second part is related to the price responsive part of demand and has a minus slope in Fig.6. In fact, this part represents the Demand Response (DR) of the system. As can be seen in Fig. 6, proper DR in the system can protect the demand-side from price spikes. Therefore the price taking part of the demand will also benefits from the DR of the system.

![Fig. 5. The mechanism which leads to price spikes in the markets due to insufficient electricity generation [3]](image)
Fig. 6. The effect of DR on price spikes in the electricity markets.

In the most of the existing electricity markets the price responsive part of demand is very small. In these markets only the large consumers are usually either obliged or given the opportunity to participate directly in the wholesale electricity market. Small consumers cannot directly participate in the competitive electricity market (wholesale market) because of two practical reasons [19]. First, for participating in such market the real-time consumption of consumer must be measured continuously. Also consumer should be informed in advanced from the electricity prices of different periods. Implementation of these advanced metering and communicating systems involves high costs in the existing conditions. These extra costs may not be recovered by the benefits that small consumers earn by attending in a competitive electricity market. The second problem is that there are a very large number of small consumers in a power system which leads to an unimaginable amount of data which should be received and sent by the market operators. As mentioned in section II, developing of the AMI and smart monitors technologies could solved these problems in the smart grid infrastructure.

The consumers can be generally divided into three main groups: industrial, commercial, and residential. In electricity markets which small consumers pay at flat rates, as discussed before, they do not have enough motivation to respond properly to the electricity price variations. Emerging smart grid in the grids where the electricity market is run based on this method will not effectively improve the DR. In this case, a retailer may encourage its customers by lower cost electricity bills for employing smart controllers. This retailer can reduce its risk when facing with the high prices scenarios using a proper scheme for managing these smart controllers. In the existing electricity markets, retailers also use similar strategies by offering “Interruptible load contracts” to their customers which allow them to interrupt supplying electricity to these consumers in critical conditions (i.e. high electricity prices scenarios). However, smart controllers are more flexible than these contracts and probably costumers are more satisfied with them. Also in this kind of electricity markets, by informing consumers about the spot prices using smart monitor technologies, they can decide on different choices to optimize their benefit. This decision making process will consider different kinds of contracts which retailer could offer (e.g. flat rate contracts, time of use contracts, interruptible load contracts, etc. [1]) and probable options of using personal DGs, which will be facilitated in the smart grid environment. In the electricity markets with flat rate pays, there is not a considerable difference between the responses of three major groups of consumers to market prices.

In the second form of the electricity market which will be discussed here, consumers face with the spot electricity prices and therefore there is a powerful motivation to improve their responce. Emerging the smart grid will have the most effect on the consumer’s behaviors in such markets. All of the consumers will pay at spot prices based on the measurements of installed AMI systems. In this case two groups of price responsive consumers may exist. First, consumers that manage their demand manually based on the price signals which their installed smart monitors show. Second, consumers which their smart controllers manage their demand automatically. It seems logical that the smart controller works based on its owner desires and settings. But since these controllers can play an important role in the power system security, perhaps they should communicate with each other or even be controlled by the System Operator (SO) for some conditions in a hierarchical manner. Since these technologies can operate automatically and in an intelligent manner, they probably result in a higher efficiency compare with the manually demand management employed by the first consumers group.

It should be noted that enhancing demand response to price signals requires not only some communication and control schemes, but also it needs a form of storage. For example, residential consumers in some countries take advantage of lower nighttime tariffs by waiting until later in the evening to wash clothes or heat hot water. This form of demand shifting is possible only if the consumer is able to store one of the factors of production i.e. heat, or dirty clothes in these cases [1]. Therefore, the industrial consumers are likely to have more active responses to the electricity price variations because their ability to store their productions is more than two other types of customers. Commercial customers will have the weakest responses to the price variations because they usually need a certain amount of electrical energy in a certain time and they infrequently can shift or conserve their demand. For residential consumers we can divide their demand into two major parts. The larger portion of their demand like lighting, air conditioning, etc. could not be shifted to other periods but may be conserved, whereas the other portion of their demand like washing, water heating, etc. could be shifted. Contracts which are offered in flat rate paying markets, especially the interruptible contracts, are not logical in this case but may be used for security issues. Smart grid is more compatible with this kind of electricity market (i.e. the spot price paying market) and can improve the DR of system which will yield to increase in market efficiency. At following parts, the effects of emerging smart grid in this kind of electricity market and the consequent behaviors of consumers will be investigated in the issues like short-term load and price forecasting, generation expansion, and
imperfect competition.

A. Short-Term Load and Price Forecasting

Short-term load forecasting and short-term price forecasting have vital values for the operation of electricity markets and their participants [20]. In the traditional electricity markets these two operations are usually performed separately, because as discussed before in the present structure of electricity grids, the variation of electricity price has a negligible effect on the electricity demand. In a conventional load forecasting system, only the historical load and climatic data are employed as the inputs to forecast the short-term future demand of the power system.

As mentioned before, by emerging the smart grids the response of consumers to the price signals of the electricity market will not be weak and the spot electricity price and demand will mutually affect each other. Therefore in this new electricity grid, load forecasting and price forecasting cannot be implemented independently. On the other hand, the penetration level of smart grid technologies like AMI systems, smart monitors and smart controllers and also the arrangement of different kinds of consumers (i.e. the ratio of industrial, commercial, and residential consumers) will affect the overall response of the demand-side to the price signals. Although, in long-term these factors will become fixed and the overall response of the demand-side will be stable, but they have great effect on DR in the transition period. The structure of the forecaster is also likely to be changed due to the dynamic relation between load and price. Although, in long-term these factors will become fixed and the overall response of the demand-side will be stable, but they have great effect on DR in the transition period. The structure of the forecaster is also likely to be changed due to the dynamic relation between load and price. Fig 7, schematically shows possible inputs and outputs of the future load and price forecasting systems.

It should be mentioned that the height of peaks and depth of valleys in the load profiles will be reduced, because the load management due to the smart grid technologies will flatten load profiles. Also small variations of demand will likely to be reduced, i.e. the load profiles may become smoother than today’s load profiles. All of these possibilities can result in more precise forecasts of the future load and price forecasting system.

B. Generation Expansion

Some power system economists argue that electrical energy should be treated like any other commodity [10]. Therefore if electrical energy is traded on a free market, there should be no centralized mechanism for controlling or encouraging investments in generating plants [3]. This method, called in [3] as “expansion driven by the market for electrical energy”, is an ideal generation expansion method in the fully competitive markets. In this method, the expansion process is done by independent generating companies and based on the electricity price spikes. In other words, the electricity price spikes represent the need of creating new capacities in the electricity market and show an opportunity of earning new benefits to the generating companies. These price spikes also encourage consumers to manage their demand to prevent unreasonable electricity costs.

According to a theory, which is supported by quite sophisticated mathematical models [21], there is an equilibrium at which, the balance between investments in generation capacity and investments in load control equipment is optimal and the global welfare is maximum. However, implementing this method of generation expansion in the existing electricity grids suffers from several problems. As mentioned before, small consumers in most of the electricity markets do not face with the spot prices and pay at flat rates. Also, required technology to make a sufficient portion of the demand responsive to short-term price signals is not available yet. As a result, the system operator may have to disconnect loads to keep the system in balance during periods of peak demand which is extremely undesirable in the competitive electricity markets. As discussed before, emerging the smart grid will meet the requirements for running the electricity market based on spot prices and also will improve DR of the system. Therefore this economically desirable expansion method will be facilitated in the smart grid environment.

C. Imperfect Competition

When competition is less than perfect, some strategic players are able to influence the market price through their actions. It is quite common for an electricity market to consist of a few strategic players and a number of price takers [3]. This condition is known as the imperfect competition. The models which have been introduced for the imperfect competition illustrate the effect of decisions of the strategic players on the market status, i.e. the electricity price and the amount of electrical energy sale. However, because of the low price elasticity of demand in the existing electricity markets, the proposed models do not take into account the role of DR in the market interactions. But in the smart grid environment due to the different behavior of demand-side, all of these models should be revised. For example in the “Bertrand model”, the amount of energy which is sold is not determined only by the most efficient generating units anymore. Similarly in the “Carnot model” and “Supply function equilibria method” the role of DR should be accounted in the player’s decisions.

But the main point in this area is that by emerging smart
grid, the options of consumers for providing their required energy will be increased, e.g. by expanding the use of DG technologies in the distribution networks. Therefore the power of strategic players on the current electricity market will be weakened in the smart grid environment. Moreover by developing of the communication transactions and increasing the observability of the power system due to emerging of the smart grid, the administrative role of system operator will be increased and the probability of exerting market power will be decreased.

IV. CONCLUSION

In this paper the effect of emerging smart grids on the consumer’s behavior has been investigated. Especially, the way that the AMI systems, smart monitors, and smart demand management controller will affect the response of different types of consumers to the spot electricity prices of the competitive markets, was discussed. It showed that by developing of these smart technologies in the power systems all of the consumers with any type of electricity demand can actively participate in the electricity markets and trade electricity at the spot prices. This will increase the efficiency of the markets and the benefits of the consumers.

Also the effect of DR on some electricity market issues like short-term load and price forecasting, generation expansion, and imperfect competition, in the smart grid environment has been discussed in the paper. Unlike the present forecasting systems, load forecasting and price forecasting should be implemented in a same model and some new inputs may be added to the forecaster structure. In the generation expansion area, smart grid could meet the requirements of liberalized generation expansion which is not possible in the current structure of the power systems. And finally by emerging the smart grids the models which illustrate imperfect competition should be modified and must take into account the effect of consumer’s responses to the market events. Emerging the smart grid reduces the power of strategic players and also the probability of exerting market power.

V. REFERENCES


VI. BIOGRAPHIES

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