Load Profile Reformation through Demand Response Programs Using Smart Grid

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Abstract- **Smart Grid is the means to reach the highest demand side management goals which are inaccessible through today's demand side management methods. Smart Grid has been introduced in this paper but the focus is on improving Time of Use (TOU) programs using smart grid. In the Smart Grid environment, Real Time pricing method has been analyzed using multi period load model. Also, reaching market equilibrium and the effect of Smart Grid on demand curve has been simulated. Finally an example day of Iran's grid has been chosen to analyze the effect of real time pricing in Smart Grid environment on load curve. For better understanding the results have been compared with normal TOU programs which were also simulated on the same initial load curve.**

Keywords - *Demand Response, Smart Grid, Real Time Pricing, Demand Response Model, Time of use programs*

I. Introduction

In 1980s Electric Power Research Institute (EPRI) introduced a concept called Demand Side Management (DSM), which consists of series of activities which government and utilities perform to increase social welfare and decrease the needed investment in electricity industry [1].

Demand Response (DR) as a part of DSM is introduced by Department of Energy (DOE) as: "Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" . DR programs are being conducted to reach flatter load and price profiles [2].

DR is able to change the amount and time in which electricity consumption takes place in order to increase efficiency and decrease market spot price [3].

In this paper, Smart Grid as a new tool for better execution of DR has been introduced, modeled and analyzed. The impact of Smart grid on DR has been discussed and the aim is to prove that using smart grid, Demand response would be executed more effectively. DR has been modeled using Elasticity model and the effect of Smart Grid on time based DR programs has been simulated.

II. Demand Response Programs

In the traditional electricity market, customers have no participation in power market; in fact market is managed by Independent Power Producers (IPPs), Regional Transmission Organizations (RTOs) and Regulatory entities. In this situation, customers have not enough information and hardware to participate in power market and be a part of active players; on the other hand it is necessary for some customers to avoid price volatility. This paradoxical behavior of customers, leads to price crisis in market (price spikes, line congestion, etc) [4]

Figure 1 shows how DR programs can affect market price. [5]

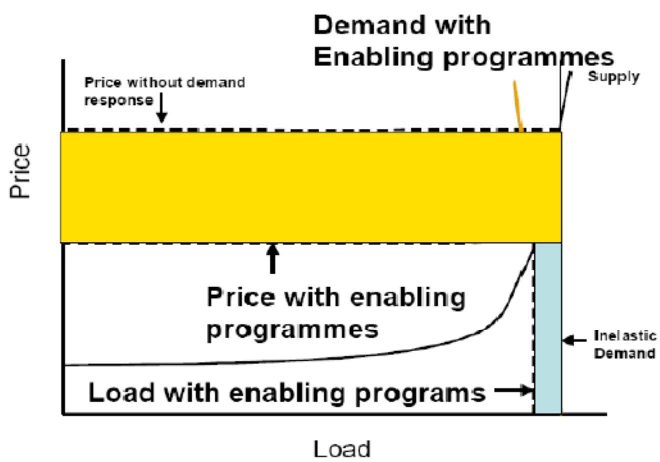

Fig 1. Effect of demand variation on electricity price.

DOE has divided DR programs into two major categories and each category contains several programs, these programs are listed below: [2]

1 – Incentive Based Programs:
1-1- Direct Load Control (DLC)
1-2- Interruptible/curtail able service (I/C)
1-3- Demand Bidding/Buy Back

1-4- Emergency Demand Response Program (EDRP)
1-5- Capacity Market Program (CAP)
1-6- Ancillary Service Markets (A/S)

2- Time-based programs:
2-1- Time-of-Use (TOU) program
2-2- Real Time Pricing (RTP) program
2-3- Critical Peak Pricing (CCP) Program

This paper has focused on Time Based Programs.

III. Problem Facing DR

Time Based Programs are based on the customer's choice to consume energy at times which it's cheaper; hence successful execution of DR programs deeply depends on the market situation, such as electricity price and customer behavior.

For obtaining results from Time-based-DR programs, it's necessary that customers respond to changes in energy price during a day.

Variations in electricity price during a day, is followed by two reactions in demand:

1- A portion of loads can't be shifted to other time intervals (such as illumination and air conditioning loads), so the only option for this portion of loads is to decrease by price increase.
2- There exists another portion of loads which are able to be shifted to other time intervals (such as washing machines and hybrid and electric vehicles)

The first reaction requires the customers to sacrifice a part of their welfare, and the second reaction would happen if customers change their lifestyle which would also lead to losing part of their welfare. This prevents the customers to respond to DR programs as expected and the reason is customers are not willing to lose part of their welfare easily.

In other word, electricity's elasticity of demand remains very low compared to other products.

Elasticity is defined as changes in demand with respect to changes in price: [6]

$$\in = \frac{\partial q}{\partial p} = \frac{dq}{dp} . \frac{p_0}{d_0} \qquad (1)$$

Where:
E =Elasticity of the demand
q = The demand value (MWh)
ρ = Electricity energy price ($/MWh)
ρ0 = Initial electricity energy price ($/MWh)
q0 = Initial demand value (MWh)

Since DR programs depend deeply on elasticity, this problem prevents the DR programs to yield the expected response.

The source of inelasticity in electrical energy demand may vary depending on region. Considering the fact that a more elastic demand requires customers who are shifting or reducing their consumption in periods of higher energy price, the roots of inelasticity generally are:

1- A large portion of electricity demand cannot be shifted to other periods of time.
2- People are not able or willing to change their lifestyle.
3- Industries are not able to change their manufacturing routine.

Finding a way to increase the demand's elasticity, would improve the result of Time-Based-programs, which leads to controlling the market price and load profile more effectively.

IV. Smart Grid

Smart Grid refers to a modern and intelligent power system, which would have a wide range of advantages for electrical power industry. U.S. Department of energy defines Smart grid as today's grid joined by advanced metering and control devices such as:

1- Information Technology
2- Sensors
3- High speed, Real-time two way communications
4- Energy Storages
5- Distributed Generation
6- In-home Energy controllers
7- Automated home energy use

Enabled by smart infrastructures, each customer will pay the instantaneous market price (depending on market, price will be determined every hour, half an hour or every quarter).

Smart grid enables the use of distributed generation in all voltage levels and with real time pricing and smart meters, even domestic customers would be able to install their own distributed generator. Domestic generators such as wind turbines or photovoltaic cells would help customers to reduce their energy bills and even sell extra to demand electricity to the grid.

Hybrid cars would be able to act as distributed storages, storing the energy at times of low electricity price and discharging the stored energy at times of high price.

An in-home controller would be needed to control all of these actions. The controller receives energy spot price trough high speed connections and controls home appliances. In other words, it makes it possible for customers to use electricity as flexible as possible. For example the controller can be set to increase room temperature at times of high spot price, or to turn on washing machines at times of low spot price (2 or 3 am).

Some of Smart Grid's characteristics can be summarized as:

1- Real time pricing would be practical.
2- Smart Grid accommodates all distributed generation and storage technologies.
3- Customer participation would be at its highest level.
4- Smart Grid optimizes assets and operates efficiently.
5- System would be more economic.
6- It anticipates and responds to system disturbance (self healing).
7- The system would be more environmentally friendly.
8- It enables new products and market services.
[7], [8], [9]

V. Modeling Demand Response

For analyzing DR on electricity demand and power market having a model is necessary.

According to equ.1, two kinds of elasticity can be defined;

Self elasticity (E_{aa}): changes in demand in a time interval with respect to changes in price of the same time interval (which is negative). [6]

$$E_{aa} = \frac{\Delta D_a}{\Delta \rho_a} = \leq 0 \qquad (2)$$

Cross elasticity (E_{ab}) : changes in demand in a time interval with respect to changes in price of a different time interval (which is positive).

$$E_{ab} = \frac{\Delta D_a}{\Delta \rho_b} = \geq 0 \qquad (3)$$

Where:
ΔD_a: Demand changes in period "a"
$\Delta \rho_a$: Price changes in period "a"
ΔD_b: Demand changes in period "b"

Here each time interval is supposed to be one hour.

Suppose that:
d(i) = Customer demand in i-th hour (MWh).
ρ(i) = Spot electricity price in i-th hour ($/MWh).
B(d(i)) = Customer's income in i-th hour ($).

It is supposed that customer's demand has the initial value of $d_0(i)$ which changes to d(i) after executing DR programs, so:

$$\Delta d(i) = d_0(i) - d(i) \quad \text{(MWh)} \qquad (4)$$

Customer's benefit, S ($), for i-th hour would be as follow:

$$S\big(d(i)\big) = B\big(d(i)\big) - d(i).\rho(i) \ \ (\$) \quad (5)$$

To maximize customer's income, $\frac{\partial S}{\partial d(i)}$ must equal to zero, so:

$$\frac{\partial S}{\partial d(i)} = \frac{\partial B\big(d(i)\big)}{\partial d(i)} - \rho(i) = 0 \qquad (6)$$

$$\frac{\partial B\big(d(i)\big)}{\partial d(i)} = \rho(i) \qquad (7)$$

Considering quadratic benefit function:

$$B(d(i) = B_0(i) + \rho_0(i)[d(i) - d_0(i)]. \left\{1 + \frac{d(i) - d_0(i)}{2E(i).d_0(i)}\right\} \quad (8)$$

Where:
$B_0(i)$ =Benefit during nominal demand ($d_0(i)$)
$\rho_0(i)$ =Nominal electricity price when demand is nominal.

$$\rho(i) = \rho_0(i)\left\{1 + \frac{d(i) - d_0(i)}{E(i).d_0(i)}\right\} \qquad (9)$$

Considering (8) and (9):

$$\rho(i) - \rho_0(i) = \rho_0(i)\left\{\frac{d(i) - d_0(i)}{E(i).d_0(i)}\right\} \qquad (10)$$

So, customer's demand would become:

$$d(i) = d_0(i).\left\{1 + \frac{E(i)[\rho(i) - \rho_0(i)]}{\rho_0(i)}\right\} \qquad (11)$$

The cross elasticity between i-th and j-th interval is defined as:

$$E_0(i,j) = \frac{\rho_0(j)}{d_0(i)}.\frac{\partial d(i)}{\partial \rho(j)} \qquad (12)$$

$$\begin{cases} E_0(i,j) \leq 0 \ \ if \ i = j \\ E_0(i,j) \geq 0 \ \ if \ i \neq j \end{cases}$$

If $\frac{\partial d(i)}{\partial \rho(j)}$ is supposed to be constant, the demand response to price variations could be written as:

$$d(i) = d_0(i) + \sum_{j=1}^{24} E_0(i,j).\frac{d_0(i)}{\rho_0(j)}.[\rho(j) - \rho_0(j)]$$

$$i = 1,2,3,\ldots,24 \qquad (13)$$

Combining (11) and (13) the final model will be achieved:

$$d(i) = \left\{ d_0(i) + \sum_{j=1}^{24} E_0(i,j).\frac{d_0(i)}{\rho_0(j)}.[\rho(j) - \rho_0(j)] \right\}.$$

$$\left\{ 1 + \frac{E(i)[\rho(i) - \rho_0(i)]}{\rho_0(i)} \right\} \quad i = 1,2,3,\dots,24 \quad (14)$$

Equation (14) shows the customer's consumption to reach the maximum benefit in a 24 hours interval. [10]

VI. TOU SENARIO

Iran's Grid peak day in year 2009 has been chosen to analyze the effect of Smart Grid.

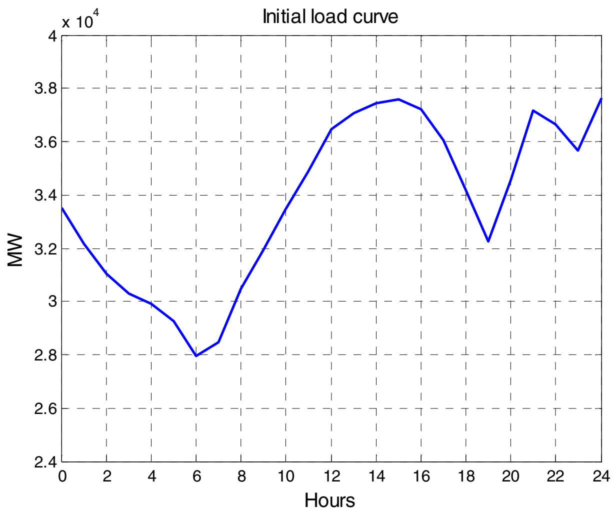

Fig. 2. Load curve of Iran's grid (19-July-2009) [11]

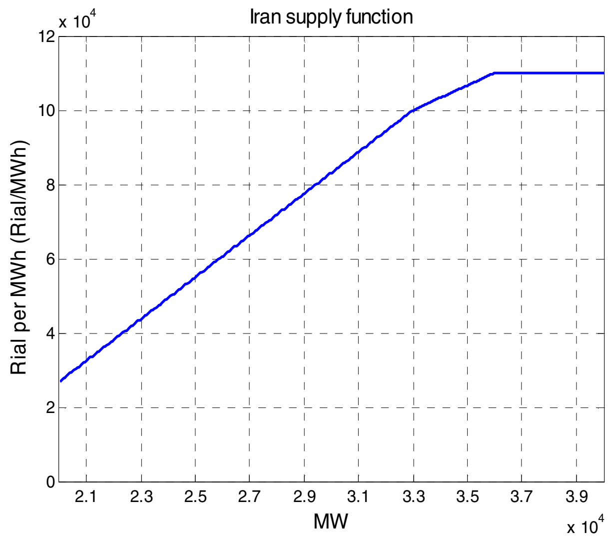

Fig. 3. Iran's supply curve

By estimating the supply curve for electrical energy in Iran, Market price curve can be derived from demand curve. [11]

Iran's supply curve has an extraordinary shape due to its limit for maximum electricity price at 110'000 Rial/MWh which is visible in figure 3. This fact makes the Gencos to bid at higher prices because they know soon the price limit will be reached, especially during peak days of summer in which price has its maximum value for 3 to 4 hour during the day. On the other hand because of the lack of high efficiency power plants in Iran, Iran's supply curve grows at a higher rate and have a relatively high gradient even in low demands.

Through the estimated supply curve of Iran, energy price curve during this day would be as follows:

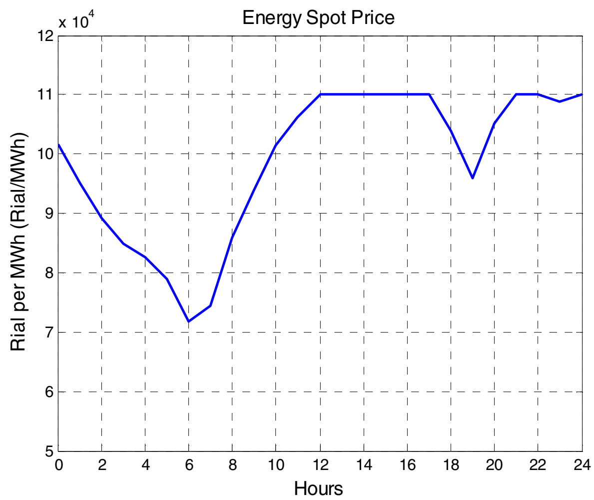

Fig. 4. Market price curve

For better comparison, a typical TOU program which is being used by today's electric utilities has been analyzed in this paper. This TOU program consists of 3 different time periods with different energy prices, low interval (0 to 9), Off-Peak interval (9 to 19) and Peak interval (19 to 24) [10]. It has been considered that in each period, electrical energy costs equal to the mean value of the energy spot price curve during that period of time which yields 85000 Rial/MWh during low period, 106000 Rial/MWh during Off-Peak period and 108000 Rial/MWh during peak period.

It has also been considered that 30% of customers would respond to TOU programs and elasticities have the following values [10]:

	Peak	Off-Peak	Low
Peak	-0.1	0.016	0.012
Off-Peak	0.016	-0.1	0.01
Low	0.012	0.01	-0.1

Enabled through smart infrastructures, real time pricing is achievable instead of today's TOU programs. Electrical energy has it's real price in every hour. The price curve considered for real time pricing is shown in figure 4.

VII. SMART GRID'S INFLUENCE; ADAPTIVE ELASTICITIES

In this section, the influence of using smart grid on time-based-rate DR programs has been evaluated.

In real-time pricing (RTP) program, every two different time periods (each period is an hour in this paper), would have their own cross elasticity and also every time period would have a different self elasticity. For simplicity, hours of a day have been divided to 3 categories, Peak, Off-Peak and Low periods. But for modeling RTP program, these time intervals could not be assumed to be fixed during a day but they change depending on the load and energy price at that hour.

The technique used here is based on defining Peak, Off-Peak and Low periods depending on how high the electricity demand and relatively its price is. As it is obvious, hours with higher demand are Peak periods and the ones with lower electricity demands must be Low periods. In this paper these periods have been considered as:

Peak period	Demand is between 70% and 100% of its range.
Off-Peak period	Demand is between 30% and 70% of its range.
Low period	Demand is between 0% and 30% of its range.

Smart Grid's characteristics defined in section IV will help customers to respond to changes in electricity price and vary their energy consumption during the day more effectively. In this new situation, even smallest customers would have the ability to participate in power market and to adjust their consumption with electricity price to reach the highest welfare. Enabled by Smart Grid infrastructures, each customer would be able to install his own electric plant and appear as a producer who sells power to the grid at times of extra production.[7]

This means, customers are able to buy less energy from grid at times of high price, by shifting loads, using their own DG plant or even through discharging batteries of their hybrid vehicle charged during the last night.

So Smart Grid's characteristics can be added to DR model as an increase in self and cross elasticities of demand between different time periods.

It has been assumed that in Smart Grid environment, customer's participation increases for 10% and reaches a portion of 40%.

Elasticities between different time intervals have been increased comparing to the normal TOU programs. The increase is 10% for self elasticities and 100% for cross elasticities:

	Peak	Off-Peak	Low
Peak	-0.11	0.032	0.024
Off-Peak	0.032	-0.11	0.02
Low	0.024	0.02	-0.11

The great increase in cross elasticity is due to smart grid's ability to effectively shift loads, also the influence of DG plants and distributed storages, lies inside this increase.

In an actual market, changes in load, leads to changes in market price; Therefore for analyzing the effect of smart grid on load and price curve during one day, it must be noted that in RTP program unlike TOU programs in which only price affects demand, demand would affect price curve too. That's because consumers have the ability to change their load in response to price, and this happens through interactions between demand and supply side in real time.

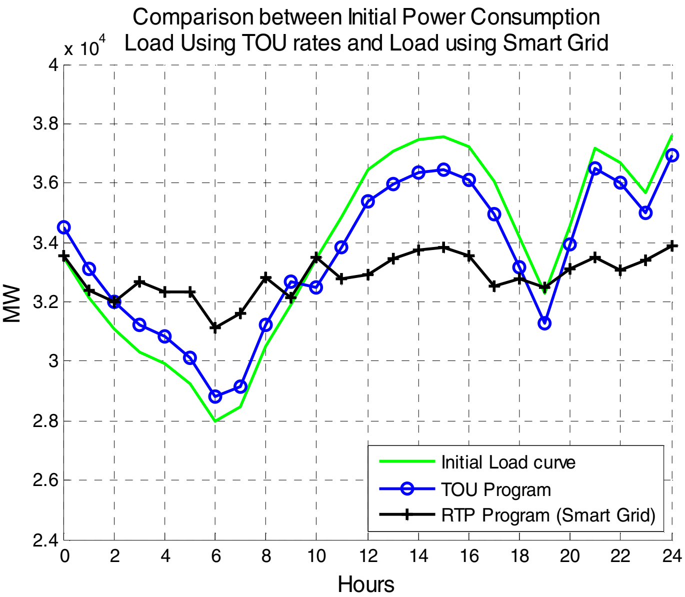

Fig. 5. Comparison between initial load curve, load curve using TOU and load curve using Smart Grid

After deriving load curve through elasticity model, a new price curve could be obtained through supply curve and if this new price curve is used to derive a new demand curve using elasticity model again, the demand considering smart grid's effect has been obtained which shows the interactions between demand and supply side. This demand curve has been shown in figure 5.

Figure 5 shows the initial load curve, the load curve during TOU program and the load curve during RTP program enabled by Smart Grid after 4 iterations.

It can be seen that using smart grid, a much better customer's participation would be achieved and load would respond to price changes more effectively. The price curve would also become smoother and energy would have a cheaper price during the day also in contrast with initial price curve, electricity price doesn't reach its limit (110'000 Rial/MWh). Price curve using smart grid can be seen in figure 6.

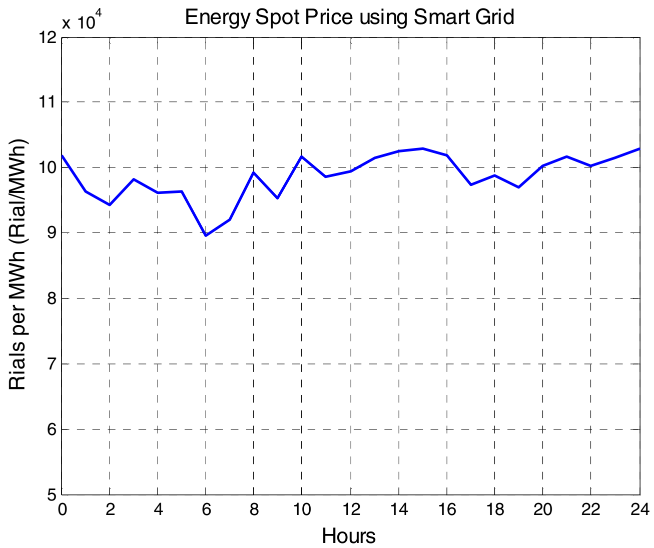

Fig. 6. Energy price using Smart Grid and RTP program

VIII. CONCLUSION

In this paper, time based demand response programs have been reviewed and the problems which are avoiding these programs to reach their highest efficiency have been identified. As a solution, Smart Grid has been introduced and the DR model has been upgraded to DR model in Smart Grid environment.

The peak day in Iran's grid was chosen to simulate the new DR program. Real time pricing and Critical peak pricing have been simulated, analyzed and compared also the effect of smart grid on time based rate DR programs have been evaluated. It has been shown in this paper that using smart grid, higher demand side participation, increased elasticity of demand, more effective TOU programs and therefore a smoother and lower demand curve plus cheaper energy price could be achieved.

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