Demand Response Management in the Presence of Renewable Energy Sources using Stackelberg Game Theory

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Abstract. A demand response algorithm for electricity trading using renewable energy sources using stackelberg game methodology. Energy consumption is rapidly increasing day by day and to maintain the balance between energy consumption and generation needs solution to generate electricity from renewable energy sources and demand response methodology is essential. Demand response (DR) algorithm maintain the balance and reduce the peak to average energy consumption ratio. Large number of constraints (i.e. number of appliance at consumer end, different consumers, renewable energy sources, electric vehicles, etc.) interface make the DR algorithm complex. Stackelberg game theory is provided the solution based on one leader N follower strategy where leader first decide their best response and followers select their best response on the basis of leaders strategy and then leader again optimize the new strategy. Process is repeat again and again to find nash equilibrium between consumers and utilities. Proposed methodology increase the generation from renewable energy sources and manage the appliances. Simulation results showed that stackelberg game with demand response algorithm is effective for optimal energy consumption control of appliances.

Keywords- Stackelberg game theory; energy management center; renewable energy sources; electricity trading.

1. Introduction

Energy consumption pattern varies with respect to time, energy demand is higher during peak hours and low during normal hours. Demand response is providing promising solution for energy management [1-2]. Incentive based mechanism attracting consumers for DR. It convinces consumers to consume less energy during peak hours and manage their energy demand from peak hours to normal hours [3]. A large amount of energy is generated through fossil fuels they harm the environment drastically [4-5]. Renewable energy sources (RES) near load centers provide probable solution and reduce the dependency of consumers on fossil fuels. Energy generation through RES are random in character and reliability of generation is very low. Introduction of electric vehicles (EV’s) increase the reliability of the renewable energy sources by providing availability of electricity during off generation period [6-7]. For long term investigation real time pricing is expected to provide better results. An Energy management center (EMC) is established between utility and consumers. Prime objective of the EMC is to minimize the dependency of consumers on grid and provide maximum amount of energy through RES [8-10]. By the introduction of RES, EV’s, DR, real time pricing make the system complex and
need the solution for optimization [11]. Game theory providing the solution for optimization demand response.

Game theory is mathematical tool based on desired rules to find the win-win situation between all the agents. Different agents compete to maximize their benefits. Demand response algorithm is classified agents in utility of consumers [12-13]. On the basis of different agents participated game theory is classified in two categories, the game played between different consumers and providing nash equilibrium between consumers e.g. day ahead price, real time price, incentive based games etc. Second game is played between consumer and utility to provide benefits to utilities and on the basis of their strategy consumer updated their strategy to find nash equilibrium is classified as stackelberg game [14-15].

Stackelberg game is played between consumer and utility, utility is participated as leader and they first select the best strategy amongst their strategy set. Consumers participated as followers and they select their best strategy based on utility best response and again by considering the response of followers leader update their response. This process repeat again and again till the both leader and follower get their combined best response. Best response of utility and consumer is achieved at a particular condition is known as nash equilibrium where consumer as well as utility both are satisfied.

Main Contribution of this paper are as follows.
1. To reduce the dependency on fossil fuels generate electricity through renewable energy sources near load centers.
2. By introduction of electric vehicles with RES increase the reliability of the system.
3. A one leader N- follower methodology for demand response is proposed using stackelberg game for residential consumers.
4. A dissatisfaction function is defined for different appliances and a stackelberg equilibrium is obtained which define the coalitions of different players.

Rest of the paper is organized as follow. Section 2 introduced the stackelberg model in demand response methodology with mathematical modeling include the energy consumption model, utility model and renewable energy generation model. Section 3 elaborate the process of stackelberg game and nash equilibrium of stackelberg game. Simulation results of residential consumers equipped with smart appliance is discussed in section 4 and section 5 conclude the paper with research finding and outcomes.

2. Stackelberg Game Model

Stackelberg game is played between consumers and utility where utility is participated as leader and consumers are participated as followers [16-17]. Some assumptions are taken as following:
1. All active consumers equipped with Energy management center for their energy management.
2. Each consumer having two category of appliances first in interruptible appliances (i.e. electric vehicles, dishwasher, washing machine, AC’s etc.) and second are uninterruptible appliances (i.e. lightning, refrigerators etc.).
3. Energy management center is equipped with renewable energy sources as primary energy supplier for consumers.

2.1 Consumer Model

The energy management center receives the real time energy price few minutes ahead e.g. 15 to 20 minutes [18-19], and manage the energy consumption of all connected appliances as per the response received from utility.

In stackelberg game model shown in figure 1 utility with the help of EMC behave as a leader upload the strategy of energy price to the consumers, on the basis of energy consumption each and every consumer define its strategy of consumption and after taking in consideration of consumer best strategy utility update their own strategy. The process run again and again to find nash equilibrium between consumer and utility.
2.1.1. Regulatory cost

Utilities are investing on infrastructure, generating, transmission and distribution of energy to provide reliable energy to consumers. Utilities charged in terms of tariff for recovery of their investments. Energy management centers for providing benefits to consumers providing best suitable strategy of consumption. Consumer payoffs are based on two factors first is constraints wattage and second is probability of the constraint to maximize the payoff of the consumer. Conditional probability of \( m_i \in M_i \) is defined in (1) where \( m_i = (m_1, \ldots, m_{i-1}, m_{i+1}, \ldots, M_i) \) is the combination of all consumers except \( i^{th} \) consumer.

\[
p(m_i|m_i) = \frac{p(m_{-i}|m_i)}{\sum p(m_i)}
\]  

Payoff function of consumer \( i \) for category \( m_i \) can be expressed as \( EPi (mi) \) in (2):

\[
EPi (mi) = \sum_{m_i \in M_i} \left( p(m_i | m_{-i}, x_c(m_i)) p(m_i | m_i) \right)
\]  

Where, \( x_c(m_i) \) denotes the wattage of constraint \( c \) for category \( m_i \).

2.1.2. Dissatisfaction cost function

Dissatisfaction cost function denoted the consumer satisfaction at a particular time to use the appliances based on total energy consumption. Dissatisfaction cost function is varied from positive to negative by comparing with median of total energy consumption denoted as \( K_j \). If energy consumption at a particular time is less than median energy consumption, dissatisfaction cost function denotes positive value. Positive dissatisfaction function meaning is that the current strategy is dissatisfied to consumers. If the energy consumption at a particular time is higher as compared to median energy sources, dissatisfaction function is denoted negative and the meaning is that consumers are satisfied with the strategy provided by EMC based on DR algorithm. Dissatisfaction cost function is calculated by (3).

\[
\Phi_j(x_j) = e^{y_j \left(1 - \frac{x_j}{k_j}\right)} - 1, \quad y_j > 0
\]  

In (3), \( Y_j \) is denoted as priority factor of appliances \( j \) (\( \forall j \in J \)) based on their utilization. Value of \( Y_j \) is higher for higher priority and lower for lower priority of appliances. To minimize the energy consumption, the utility function of an appliance is denoted as \( U_j(c, x_j) \) have the summation of regulatory cost function and dissatisfaction cost function in (4).

\[
U_j(c, x_j) = EPi (mi) + \omega \cdot \Phi_j(x_j), \quad \omega > 0
\]  

In (4), \( \omega \) is defined as the satisfaction over the given period. Energy consumption period is divided in three different durations e.g. peak energy consumption duration, modest energy consumption duration, and real time pricing.
and least energy consumption duration. The value of $\omega$ is higher indicates that consumer is concern about reducing dissatisfaction. In energy consumption cost model, need to obtain an optimal strategy $x_j$ foe each appliance with respect to defined strategy of utility. The appliance aims to minimize the cost, the problem is formulated as in (5):

$$\min_{s.t. \ x_j^{\min} \leq x_j \leq x_j^{\max}} U_j(c, x_j) \quad (5)$$

$$2.1.3. \text{Renewable Generation Cost}$$

RES generation random characteristics make it complex to design the generation from renewable energy sources. RES are the main source of energy and consider satisfaction function to supply energy to utility company [20]. Renewable generation cost model is denoted by $U_R$ in (7):

$$U_R = [R_R + C_R]X_R \quad (7)$$

Where, $R_R$ denoted as the revenue invested on energy generation through RES in EMC and $C_R$ is denoted as the cost of energy brought by utility and $X_R$ is the satisfaction parameter of RES generation.

$$2.2. \text{Utility Model}$$

The objective of utility is to get maximum benefit by charging suitable tariff from consumers. Conventional energy tariff models are particularly based on energy consumption all the time. Proposed model with stackelberg game provide an opportunity to the utilities to update their strategy based on consumers strategy. The objective of the consumer is to minimize the dissatisfaction cost function by updating their own strategy and reduce the tariff cost by adding low cost generation from renewable energy sources is defined in (8).

$$U_{\text{utility}} = \sum_{i=1}^{I} EPi(m_i) + U_R - \sum_{j=1}^{J} \omega \cdot \Phi_j(x_j) \quad (8)$$

Where, $EPi(m_i)$ denotes the gross benefit gained by consumer by managing the demand of each appliances and $U_R$ denotes as the energy brought cost from RES. $\sum_{j=1}^{J} \omega \cdot \Phi_j(x_j)$ is dissatisfaction function will reduce overall cast with increasing satisfactory factor.

$$3. \text{Stackelberg Game Analysis}$$

SNE is obtained by maximize the utility strategy based on best response of consumers strategy [3-5]. Energy consumers are able to minimize their energy consumption by applying best strategy on the basis of utilities strategy and utilities update their strategy on the basis of consumers strategy is called SNE and all categorized consumers and utility are agreed on coalitions. The SNE is defined as $(c^*, x^*)$ for the best strategy of consumers $x^* = [x_1^*, x_2^*, ....., x_N^*]$ and $c^*$ denotes the best response of utility are define by (9-10):

$$\begin{align*}
(c^*, x^*) & = \max_{c, x} U_{\text{utility}}(c, x) \\
& s.t. \ \min_{x} U_j(c, x_j) \quad \forall j \in J
\end{align*} \quad (9)$$

$$4. \text{Simulation Results:}$$

Household consumers are equipped with interruptible and uninterruptable appliances, interruptible appliances are one washing machines denoted as WM, one dish washers denoted as DW, one air conditioners denoted as AC and one electric vehicle denoted as EV. Uninterruptible appliances are two
lights denoted as L1 and L2, and one refrigerators RF. Appliance characteristics are listed in Table-1, each appliance have significant value of \( Y_j \) denotes the probability of operation [21-22].

**Table 1. Appliance Characteristics**

| Appliance Type | Interruptible Appliances | Uninterruptible Appliances |
|----------------|--------------------------|---------------------------|
| Appliance      | AC  | EV  | DW | WM | L1 | L2 | RF |
| \( Y_j \)      | 4.5 | 3.5 | 5  | 4  | 2  | 2.5| 1.5|
| Power Rating (kWh) | 1.5-3 | 1.5-3 | 2  | 1-3 | 0.5-1.5 | 0.5-1.5 | 1.5-3 |
| Duration of Operation (hr.) | 8-10 | 2-4 | 2  | 2  | 8-10 | 8-10 | 24 |

Appliance probability is defined that RF, L1 and L2 have lowest priority of operation means they operate on priority. A satisfaction factor \( \omega \) is denoted by dividing a day in three different energy consumption durations listed in Table-2. Satisfaction factor is higher in off-peak period and less in peak period where utility expect less energy consumption from each appliances [7].

**Table 2. Satisfied Weight Factor for Different Time Durations**

| Duration | Off-peak duration (1:00 am to 7:00 am & 12:00 pm to 1:00 am) | Mid-peak duration (10:00 am to 5:00 pm & 11:00 pm to 12:00 pm) | Peak duration (8:00 am to 10:00 am & 6:00 pm to 10:00 pm) |
|----------|---------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|
| \( \omega \) | 0.18 | 0.1 | 0.07 |

For the real time pricing, we adopted the on-line data of energy consumption price from ComEd (Commonwealth Edison Company) for the date may 11, 2019 [23-24]. Figure 2 represent the energy price of appliances as per the priority and provide stackelberg nash equilibrium between consumer and utility for interruptible and uninterruptible appliances respectively in (a) & (b) prices are higher for interruptible appliances as their energy consumption priority is higher.
Figure 2. Hourly Energy Consumption for Residential Consumers (a) Interruptible Appliances (b) Uninterruptible Appliances

Figure 3. Comparative Analysis of Real Time Price and Day Ahead Price

Real time price model is compared to day ahead energy price model produced by same ComEd company for the date May 11, 2019. Figure 4 shows the comparison between RTP and day ahead price for the proposed Stackelberg Nash equilibrium for residential consumers. Results shows that total energy
price reduced from 259.35 ¢ to 249.91 ¢ when using RTP instead of day ahead price. Average hourly price reduced from 10.80 ¢/hour to 10.37 ¢/hour.

5. Conclusion
A novel real time price based demand response approach using stackelberg game theory is used for retail electricity market with energy management center to control the consumption from renewable energy sources. Proposed stackelberg game based demand response model is able to manage the energy consumption for less energy consumption during high price range and higher during low consumption range and providing nash equilibrium where utility and consumer both get benefitted. Energy consumption patterns are also compared with day ahead energy consumption and providing better results. RES are connected at consumer manage the RTP and maintain lesser compared to day ahead price. In future the practically investigated the probability of appliances on existing smart grids.

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