B.Sc. in Computer Science and Engineering Thesis

A Game Theoretic Approach on Peer-to-Peer (P2P) Demand Response of a Smart Grid

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CANDIDATES' DECLARATION

This is to certify that the work presented in this thesis, titled, "A Game Theoretic Approach on Peer-to-Peer (P2P) Demand Response of a Smart Grid", is the outcome of the investigation and research carried out by us under the supervision of Dr. Rifat Shahriyar.

It is also declared that neither this thesis nor any part thereof has been submitted anywhere else for the award of any degree, diploma or other qualifications.

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CERTIFICATION

This thesis titled, **"A Game Theoretic Approach on Peer-to-Peer (P2P) Demand Response of a Smart Grid"**, submitted by the group as mentioned below has been accepted as satisfactory in partial fulfillment of the requirements for the degree B.Sc. in Computer Science and Engineering in October 2018.

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ABSTRACT

Smart grid energy distribution system is a recent development in the history of energy management. It allows two way flows of energy between the main grid and end-users and also creates an automated system to maintain it efficiently. It is based on a demand response support. The main issue of this system was that it had become too costly for the end-users to exchange energy with the grid. Some works related to game theory has been done on this matter. Game theory in this field can be used as a model where both sides try to maximize their benefits by planning different strategies. Besides, Peer to Peer (P2P) energy trading was introduced to tackle this issue. But, the grid seems to suffer losses in certain cases while allowing P2P trading. Though game theoretical approach has been attempted in smart grid but very few works has been done regarding P2P energy trading. We want to propose a new model/modify an existing model which can contribute to the grids benefit as well as the users, even in P2P system. In this paper, we plan to use Stackelberg game theory to create a relation between the grid and the users so that both can benefit and balance the energy exchange.

Chapter 1

Introduction

Energy has always been the core object that drives our world. Using energy in a more efficient way is one of the conquests that humans have been trying to conquer for years. In recent world, smart grid energy trading has paved a way which may be followed to go ahead on this journey. Smart grid energy trading is a system that introduces automatic interaction between micro grids and end users which takes off load from the macro grid and helps to distribute energy efficiently. It even allows two-way communication and transfer between micro grids and end users which enables the end users to contribute surplus energy in time of need. Some works have been done on improving the trading and the price related to it. But problems remain as the selling price of the grid is much higher than the buying one. Peer to Peer (P2P) energy trading has been introduced to deal with this matter. Generally, to reach an equilibrium state on pricing between the grid and the users, game theory is applied. Some game theoretic approaches have been used to improve the pricing model in smart grid, but there hasn't been much work which includes game theory regarding P2P trading system. In this paper, we are targeting to have a game theoretic approach to propose a new price and trading model between the micro grids and end users so that both can be beneficial from this.

1.1 Motivation

Smart grid introduces a better way of using energy efficiently and reducing transmission related costs. Direct trading of energy has been introduced recently. The automation of micro grids with the end-users alleviate the load from the macro grid. Previously, the micro grids used the macro grid to distribute energy to the users. But now the macro grid determines how the micro grids should interact with the end-users and the micro grids act autonomously. This idea reduced the overall transmission cost and ensured efficiency.

This system has been established using some core concepts of several cooperative and non-cooperative games. The main idea behind this is to use cooperative/non-cooperative game theory to reach equilibrium between the users and the micro grids, so that energy can be distributed in an efficient way. If some micro grids have surplus energy, then it has to be decided whether they will transfer it to some other grids which are in need of energy or send it to the macro grid. Usually, cooperative game theory is used in this process.

Another feature of smart grid is demand response. The demand in energy trading is not constant. It fluctuates with time. If proper measures are not taken, then in the peak hours, when the demand of energy is quite high, it becomes difficult to supply the required energy as the demand surpasses the available energy. Demand response is a program which helps to mitigate this situation. When the demand goes high, the grids increase the price rate of energy so that the users are compelled to reduce heavy usage of electricity, and thus the overall demand per unit time remains stable. Another possible way to achieve this is load balancing.

Energy selling and buying between micro grid and users has come across a concerning matter. The grid sells energy to the users at a high price but when the users sell surplus energy, the grid buys it at a very low price if compared. Thus the grid profits a lot and the users suffer loss. To handle this situation, a peer to peer energy trading can be introduced. Peer to peer trading has been used in several other fields. The main idea is transferring energy among the end-users directly without going through the micro grid. The price rate of transferring in this way is somewhere between the buying and selling price of the grid so that both buyers and sellers can benefit from it. It also reduces the load of the grid to manage this varying demand.

Even after all these approaches, peer to peer energy trading has limitations. The grid cannot participate in peer to peer trading in a way that is fully beneficial to it. Here our proposal comes in. We want to introduce a pricing model that deals with this issue and try to resolve these obstacles for the grid.

1.2 Research Problem

Some works have been done on peer to peer transfer. And some ideas have been introduced regarding the pricing model in case of energy trading. Generally it seems that peer to peer trading is quite beneficial and resolves many problems. But if the grid always allows peer to peer trading without any condition, then the users may not cooperate with the grid at certain times. Given the chance, the users will always try to avoid transfer with the grid except in emergency conditions and this can be a huge problem for the grid. The grid should have some control over the peer to peer trading by enforcing some necessary conditions. And we are planning to work on resolving this problem.

1.3 Idea of Proposed Model

The main purpose of our thesis is that, we will propose a model which will address this issue and try to find a solution to the problem regarding the participation of the grid. Our model provides a possible approach which makes the users interact with the grid in such a way that fulfills both sides demands. The model is designed in a way so that the users feel interested in dealing with the grid under specific conditions.

1.4 Organization

In chapter 2 works related to smart grid have been discussed.Our approach to solve the problem and our proposed model have been discussed in chapter 3. In chapter 4, various property of peer to peer trading and proof of these properties have been discussed. In chapter 5 a small simulation on public data has been shown. Conclusion and future work are in 6

Chapter 2

Literature Review

Smart grid is the future power grid that supports environmentally friendly electricity generation, efficient electricity distribution that uses two way communications for this purpose. Traditional power grid is unidirectional [1] . Usually centre power plants generate energy. The energy is then transmitted to end users via distribution grids. The idea of smart grid is that the distribution grids will have small scale power generator (solar panels, wind turbines etc.). So energy transmission in smart grid is more complicated. Demand response management is another feature of smart grid. It is defined as changes in electric usage by end-users from their normal consumption patterns in response to changes in the price of electricity over time. There are many literature that have been discussed about smart grid and apply game theory in energy trading and demand response management. Works on energy trading and demand response in smart grid are discussed in section section 2.1 and section 2.2. Works on peer to peer system are discussed in section section 2.3.

2.1 Energy Trading in Smart Grid

Renewable energy sources of micro grids sometimes create surplus of energy and sometimes lack of energy in the distribution lines. So direct energy trading among the micro grids has been introduced. This improves economic efficiency and reduces energy loss, cost. Cooperative and non-cooperative game theoretic idea is applied in many literature.

2.1.1 Cooperative Game

The authors in [2–4] apply cooperative game in energy trading of smart grid. Walid Saad et al. [2] proposed a novel cooperative strategies between the micro grids (e.g., solar panels, wind farms, PHEVs, etc.) of a distribution network, allowing them to trade power, reduce the load on the main macro-grid, and minimize the losses of power over the distribution lines. Each coalition consists of two sets of MGs (One set has surplus of energy or wants to sell energy; another set is in need of energy or wants to buy energy). The authors claimed that coalitional game is first used in this paper. The simulation result of this approach shows that average pay off (power loss) decreases as with the increasing number of micro grids.

Jianmo et al. [3] focuses on power transaction between multiple MGs with multi agent system. They proposed a coalitional game strategy based on three stage algorithm (request exchange stage, merge and split stage, cooperative transaction stage). This minimise expenditures comprising the generation costs, transmission costs, power losses and load shedding compensation. The future work of this paper is to implement a pricing policy for the micro grids.

Small scale electricity suppliers (SESs) have entered in the electricity market as distributed energy generators. SESs enable direct trading of electricity between SESs and end users without going through the retailers. This scheme helps both parties to get benefit. The authors of [4] used coalitional game in the direct trading of electricity between SESs and end users and proposed an idea to divide the revenue among them by using the asymptotic Shapely value. They also proposed a pricing scheme that can determine the price of electricity instantaneously based on the number of participant in the direct trading and statistical information about electricity supply and demand.

2.1.2 Non-Cooperative Game

There are several literature that apply non-cooperative game in energy trading. Park et al. [5] proposed a contribution based energy-trading system among micro grids where they formulated a non-cooperative game. The authors of [6] used a non-cooperative stackelberg game for a community consisting of a large number of residential units (RUs) and a shared facility controller (SFC) to determine how both entities can benefit.

2.2 Demand response management in smart grid

Demand response management is a program that balance the demand and electricity supply of grid. Demand response management is divided into two types (utility company oriented and end user oriented). Sabita et al [7] proposed an idea on demand response management that is beneficial to both utility company and end users. Here they used Stackelberg game for multiple utility companies and multiple end users.

Demand side management is efficient use of available energy. One way is shifting high power appliance to off peak hours. But it is not an efficient approach. Efficient approach is to try to balance the total load at each hour. The authors in [8] paper proposed an incentive-based energy consumption scheduling scheme for the future smart grid.

2.3 Peer to Peer System

In P2P system participants act both as consumers and providers by routing packet for each other. But some participants do not cooperate in routing packet. These participants are called free loaders. Alberto et al. [9] discussed on different ways of incentive design to reduce this problem of free loaders. A simple reputation system is introduced that provides incentive for good behaviour. The authors used a random-matching game to model routing in peer-to-peer networks.

The advantages of P2P system is scalability (when a new participant joins a P2P system, not only the load on the system increases but at the same time the resources of the system increase), robustness. P2P system is less vulnerable than centralized system as each node of P2P has small portion of total resources. Teemu [10] described the main problem of P2P system (free riding) and try to solve the problem with the concept of game theory.

The authors in [11] discussed the pros and cons of various peer to peer architectures (Gnutella, bit torrent) and proposed a novel game theory based peer to peer file sharing mechanism.

Chapter 3

Proposed Peer to Peer Model

As we have seen, there is a system that manages the transfer or energy between the grid and the end users. But the end users are not fully satisfied with the system. They take part in the exchange with the grid and suffer loss which they want to avoid. To tackle this issue Peer to Peer (**P2P**) energy transfer was introduced. But even in this system, some problems remained regarding the participation of the grid in the exchange. The main purpose of this thesis is to propose a model that can possibly ensure the participation of the grid in **P2P** trading and introduce a system that benefits both the grid and the users. Our model proposes a pricing scheme that puts a balance between the profits and losses.

3.1 Challenges

In most existing models, while exchanging energy, the buying price for the grid is $\mathbf{P_{BG}}$ and the selling price is $\mathbf{P_{SG}}$. And generally, $\mathbf{P_{BG}} << \mathbf{P_{SG}}$. Which is why the users suffer a great loss when they sell their surplus energy to the grid. And later they have to buy the energy at a much higher rate. Peer to Peer (**P2P**) energy trading was introduced in this regard, which introduced the idea of sharing energy among the end users without the direct participation of the grid. A price $\mathbf{P_{P2P}}$ was determined for buying and selling among the users. When in need, a user will request for energy to other neighbor end users and those end users who have surplus energy will provide energy to the ones in need. And this exchange will take place on price **P2P**, and it holds the condition $\mathbf{P_{BG}} < \mathbf{P_{P2P}} < \mathbf{P_{SG}}$ because otherwise the users wont be interested in this model. In this case, the users dont suffer loss rather they make profit. But, the grid can be dissatisfied by this system because the users will always try to keep the grid out of this transfer and always try to make profit for themselves. If the grid allows the users to take part in **P2P** trading without any condition any time, then the grid cannot make profit as it cant buy energy from the users as before.

3.2 System Model

We want to introduce a model that will use the **P2P** trading model but also is modified in such a way that the grid can make profit from it and thus the system is balanced. In our proposal, the grid makes certain conditions for the users to take part in the **P2P** trading. We have created an initial system model for our proposal which is explained from here on:

- Let $\mathbf{D_i}$ be the demand of energy for a user i. The grid will allow peer to peer energy trading only when the total demand of the users cross a certain threshold, D_{CAP}, which is the capacity of supply of the grid at that moment. So the condition for P2P trading to be initiated is:
$$\sum D_i > D_{CAP}$$
- Suppose the grid buys and sells energy at $\mathbf{P_{BG}}$ and $\mathbf{P_{SG}}$ and $\mathbf{P_{BG}} << \mathbf{P_{SG}}$. So the users suffer a loss because they sell at a lower price than the one they buy at. In peer to peer trading there will be an intermediate price, $\mathbf{P_{P2P}}$ which will maintain the condition $\mathbf{P_{BG}} < \mathbf{P_{P2P}} < \mathbf{P_{SG}}$. So the users will be interested in the system because both buyer and seller will have profit in this case. Our initial estimate for the value $\mathbf{P_{P2P}}$ is
$$\frac{\mathbf{(P_{BG} + P_{SG})}}{\mathbf{2}}$$
- We can group the users in three groups: Buyer, Seller, Neutral. The seller group will have surplus in their supply energy which they can contribute to other users who are in demand of energy (the buyer group). The sellers will try to fulfill the demand if they have sufficient energy. But when they cant fulfill it, the role of the neutral group comes along. The neutral group will have members who neither have a demand nor a surplus. They have the amount of energy which is necessary for them and not more. Generally they dont want to buy or sell energy.
- Let $\mathbf{D_i}$ and $\mathbf{S_i}$ be the demand and surplus of energy for a user **i**, respectively. In usual case, the sellers will always sell to the buyers in the rate $\mathbf{P_{P2P}}$. But in some special cases, the total demand of the buyers will exceed the total surplus of the sellers. That is:
$$\sum \mathbf{D_i} > \sum \mathbf{S_i}$$

  In this case, the neural group will step in. Some of them will sell energy to the buyers even if they do not have surplus. They will limit their usage for a certain period and sell this unused energy. But as they dont have surplus, they will not consider selling unless they have some profit from it as they are limiting their own usage and giving it to others. They will charge a higher rate, $\mathbf{P_{NEU}}$, so that they can have profit even if they are contributing

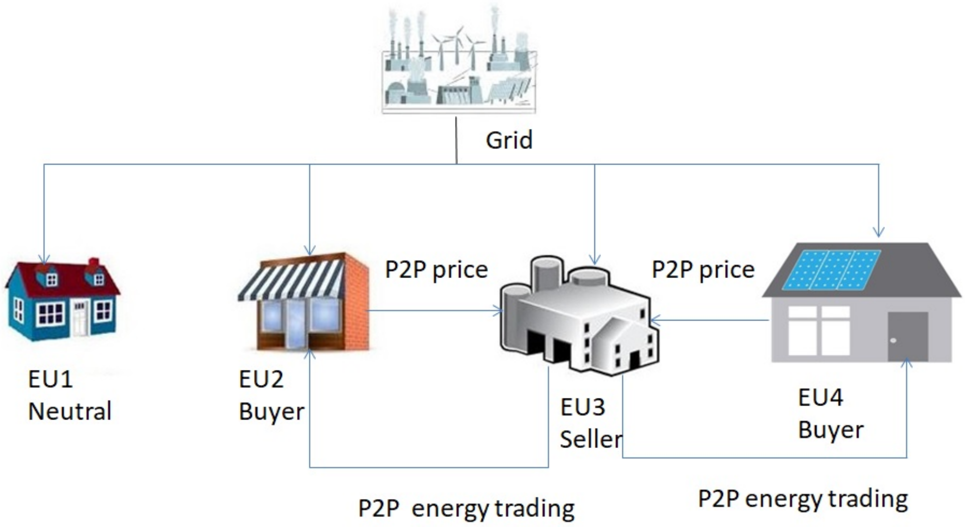

Figure 3.1: Modified P2P trading for our approach

having less energy. Our initial estimate for the value $\mathbf{P_{NEU}}$ is

$$\frac{(\mathbf{P_{P2P}} + \mathbf{P_{SG}})}{\mathbf{2}}$$

.

- But if the grid always allows this system in all situations, then it will be not good for it because then the users will always transfer energy bypassing the grid. Thats why its not feasible for the grid to always allow peer to peer trading. If the exchange price between users is always lower than $\mathbf{P_{SG}}$, then the grid will suffer a huge loss. So, the grid will introduce some more conditions. If the total demand is greater than total surplus or a certain amount then the grid will have a new proposal. Normally, it will allow **P2P** trading but the grid will stop **P2P** service in these two cases:

  1. When the traded energy in P2P system has exceeded a certain amount.
  2. When the peak demand hour is over (if P2P is allowed in a peak demand hour).

  When the grid takes over, it will lower its selling price $\mathbf{P_{SG}}$ to compete with the neutral groups price $\mathbf{P_{NEU}}$. The new proposed price will be $\mathbf{P'_{SG}}$ and it will hold the condition:

$$\mathbf{P'_{SG}} < \mathbf{P_{NEU}} < \mathbf{P_{SG}}$$

We are planning to mathematically proof the advantage of this model and also simulate some systems so that we can compare the outcomes and calculate the performance. We will use Stackelberg game theory and its properties to execute our plan.

3.3 Utility Functions and Constraints

Let us assume that the i th prosumer generates energy $\mathbf{Gen_i}$ and minimum energy need for the i th prosumer is $\mathbf{Need_i}$. When $\mathbf{Gen_i} > \mathbf{Need_i}$, i th prosumer has surplus energy $\mathbf{S_i} = \mathbf{Gen_i} - \mathbf{Need_i}$. When $\mathbf{Gen_i} < \mathbf{Need_i}$, i th prosumer has demand for energy $\mathbf{D_i} = \mathbf{Need_i} - \mathbf{Gen_i}$.

The seller group will sell minimum of D_{avg_i} and S_i energy at P_{P2P} price to the buyer group and if the remaining surplus energy (if any) will be sold to the grid at P_{BG} price. So the total utility for the i th seller is,

$$U_i = min(D_{avg_i}, S_i) * P_{P2P} + max(0, S_i - D_{avg_i}) * P_{BG} + k * W_i \tag{3.1}$$

Here D_{avg_i} is the weighted demand of i th buyer. As the buyer with higher demand will get higher portion of the surplus energy.

$$D_{avg_i} = \frac{\sum D_i}{\sum S_i} * S_i = D' * S_i$$

W_i is the willingness of the i th user to participate in the game as seller.

$$W_i = \log_x(1 + S_i - D_{avg_i}) \tag{3.2}$$

This is because the willingness will change faster when S_i is slightly greater than D_{avg_i} , but once it gets too high the willingness will be saturated. So we have to finalize the base x of the logarithm according to the quantity of energy.

The neutral group will sell at most E_{thres} energy at P_{NEU} price. So the utility for the i th neural is,

$$U_i = min(D_{avg_i}, E_{Thres_i}) * P_{NEU} * W_i \tag{3.3}$$

W_i is the willingness for the i th neutral.

$$W_i = \log_x(1 + \sum D_i - \sum S_i) \tag{3.4}$$

The neutral user will only be interested in selling when $\sum D_i$ is greater than $\sum S_i$ and the more the difference, the more willing they will be.

The buyer group will first try to buy energy at P_{P2P} price. let i'th buyer buys D_{i_1} energy at P_{P2P} price. If D_{i_1} is less than D_i then the buyer buys rest of the energy from neutral and the grid. So the utility for buyer is,

$$U_i = D_{i_1} * P_{P2P} + D_{i_2} * P_{NEU} - (D_i - D_{i_1} - D_{i_2}) * P_{SG} \tag{3.5}$$

The utility function for the grid is,

$$\begin{aligned} U_i = max(0, \sum D_i - \sum S_i) * P_{SG} - \\ max(0, \sum S_i - \sum D_i) * P_{BG} - \\ GenerationCost \end{aligned} \tag{3.6}$$

As $P_{NEU} > P_{P2P}$ most followers will try to participate the game as neural though they have enough surplus energy. So we need some boundary conditions.

Minimize the willingness W_i for the seller with respect to the surplus energy S_i and subject to the condition

$$Gen_i = Need_i + S_i$$

Using Lagrange multiplier and equation (3.2),

$$L_i = \log_x(1 + S_i - D_{avg_i}) - \lambda(Need_i + S_i - Gen_i)$$

Now differentiate this with respect to S_i,

$$\frac{\partial L_i}{\partial S_i} = \frac{1 - D'}{1 + S_i - D_{avg_i}} - \lambda = 0$$

Rearranging this equation, we get

$$S_i = \frac{1 - D'}{\lambda} - 1 + D_{avg_i} \tag{3.7}$$

This is the minimum surplus energy need to be a seller.

The neutral participant is allowed to sell at most E_{thres} energy at P_{NEU} price when the demand is high enough than the surplus energy. So for neutral constrain is,

$$S_i \leq E_{thres}$$

Using Lagrange multiplier equation (3.4) can be written as,

$$L_i \leq \log_x(1 + \sum D_i - \sum S_i) - \lambda(S_i - E_{thres})$$

Now differentiate this with respect to S_i,

$$\frac{\partial L_i}{\partial S_i} \leq \frac{1}{1 + \sum D_i - \sum S_i} - \lambda \leq 0$$

Rearranging this equation, we get

$$\sum D_i - \sum S_i \geq \frac{1}{\lambda} - 1 \tag{3.8}$$

So neutral can sell at most E_{thres} energy when the difference between total demand and total surplus is at least $\frac{1}{\lambda} - 1$.

Chapter 4

Property of the P2P Trading Plan

The trading scheme we have proposed must have some specific properties to lead to a stable situation where the grid and the users will be interested in taking part in the plan.

If our planned model is superadditive, and also if we can show that the pricing scheme satisfies the property that if the **P2P** price is between the selling and buying price of the grid, meaning if the relation,

$$\mathbf{P_{BG}} < \mathbf{P_{P2P}} < \mathbf{P_{SG}}$$

is true, then users will be interested to join the coalition, then it can be said that the model has stable condition.

4.1 Superadditivity

Almost all the utility functions in our proposed model have a logarithmic function involved, such as the utility functions for buyer, seller and neutral group. So they are concave in nature. Also, the utility function for the grid is concave. So, all the utility functions are concave.

We will use *Jensen's inequality* to prove that our model satisfies superadditivity. It states that:

Let a real-valued function ***f*** be concave on the interval ***I***. Let $x_1, x_2, ..., x_n \in \boldsymbol{I}$ and $w_1, w_2, ...w_n \geq 0$, then we have

$$\frac{w_1 f(x_1) + ... + w_n f(x_n)}{w_1 + ... + w_n} \leq f(\frac{w_1 x_1 + ... + w_n x_n}{w_1 + ... + w_n})$$

Let's assume that the group of buyers and sellers divide into two parts in order to gain more utility. And let the contribution factor of these two groups be c_1 and c_2, such as $c_1 + c_2 = 1$. Now for example, if we take the microgrid's utility function, it will be,

$$
\begin{aligned}
c_1 \cdot \Big[P_{BG} \cdot max(0, \sum D_{i_1} - \sum S_{i_1}) -& \\
P_{SG} \cdot max(0, \sum S_{i_1} - \sum D_{i_1})\Big] +& \\
c_2 \cdot \Big[P_{BG} \cdot max(0, \sum D_{i_2} - \sum S_{i_2}) -& \\
P_{SG} \cdot max(0, \sum S_{i_2} - \sum D_{i_2})\Big]& \\
- \, Generation \; Cost&
\end{aligned}
\tag{4.1}
$$

where S_{i_1}, S_{i_2}, D_{i_1} and D_{i_2} are the surpluses and demands of sellers and buyers from the two groups, respectively.

But according to *Jensen's Inequality*, the following relation holds,

$$
\begin{aligned}
c_1 \cdot \Big[P_{BG} \cdot max\Big(0, \; \sum D_{i_1} - \sum S_{i_1}\Big) \; -& \\
P_{SG} \cdot max\Big(0, \; \sum S_{i_1} - \sum D_{i_1}\Big)\Big] \; +& \\
c_2 \cdot \Big[P_{BG} \cdot max\Big(0, \; \sum D_{i_2} - \sum S_{i_2}\Big) \; -& \\
P_{SG} \cdot max\Big(0, \; \sum S_{i_2} - \sum D_{i_2}\Big)\Big] \; -& \\
Generation \; Cost \; \leq& \\
P_{BG} \cdot max\Big(0, \; c_1 \cdot \Big[\sum D_{i_1} - \sum S_{i_1}\Big] \; +& \\
c_2 \cdot \Big[\sum D_{i_2} - \sum S_{i_2}\Big]\Big) \; -& \\
P_{SG} \cdot max\Big(0, \; c_1 \cdot \Big[\sum S_{i_1} - \sum D_{i_1}\Big] \; +& \\
c_2 \cdot \Big[\sum S_{i_2} - \sum D_{i_2}\Big]\Big) \; -& \\
Generation \; Cost&
\end{aligned}
\tag{4.2}
$$

The right hand side of the equation denotes the utility if the sellers and buyers from the two different groups make a coalition and co-operate with each other. Which proves that this utility function is superadditive, in other words, it is beneficiary for everyone if they make a large group rather than smaller ones. As all the utility functions are concave in nature, a similar proof can be shown for them also. Hence, the model is superadditive.

4.2 Effective P2P Trading Price

As the P2P trading starts taking place, the effective P2P price actually varies from the buyer side to the seller side. It depends on the amount of generation of energy from the users. Let the effective P2P price for buyers and sellers be $\mathbf{P_{P2P_B}}$ and $\mathbf{P_{P2P_S}}$, respectively. Four situations can possibly occur, which are stated below:

4.2.1 Surplus is equal to demand

When the total surplus from the sellers will be equal to the total demand of the buyers, only then the P2P trading price on both sides will be equal. The buyers will only buy from sellers, so

$$P_{P2P_B} = P_{P2P_S} = \frac{P_{BG} + P_{SG}}{2}$$

4.2.2 Surplus is higher than demand

When the total surplus is more than the amount of the need of the buyers, then the sellers sell that extra energy to the grid as the grid may have need for it to use elsewhere. So, in this case, the effective selling price of the sellers will change. If the sellers sell the extra energy to the grid in the price P_{BG}, then

$$P_{P2P_S} = \frac{\sum D_i \cdot P_{P2P} + \left(\sum S_i - \sum D_i\right) \cdot P_{BG}}{\sum S_i}$$

This is the effective selling price for the sellers as it denotes the weighted average of the price they are selling the total energy.

4.2.3 Surplus is slightly lower than demand

When the total surplus is slightly less than the amount of the need of the buyers, then the neutral group steps in to help resolve the matter. They will sell their little surplus energy to the buyers to meet the demand. And their selling price will be,

$$P_{NEU} = \frac{P_{SG} + P_{P2P}}{2}$$

So, in this case the effective price of the buyers will change. It will convert to,

$$P_{P2P_B} = \frac{\sum S_i \cdot P_{P2P} + \left(\sum D_i - \sum S_i\right) \cdot P_{NEU}}{\sum D_i}$$

This is the effective buying price for the buyers as it denotes the weighted average of the price they are buying the total amount of energy they demand.

4.2.4 Surplus is much lower than demand

When the total surplus is much less than the amount of the need of the buyers, then only the neutral group cannot manage to uphold the situation. So, the buyers have to buy the rest of the energy from the grid in the price P_{SG}. And so the effective buying price again changes to,

$$P_{P2P_B} = \frac{\sum S_i \cdot P_{P2P} + \left(\sum E_{Thres_i}\right) \cdot P_{NEU} + \left(\sum D_i - \sum S_i - \sum E_{Thres_i}\right) \cdot P_{SG}}{\sum D_i}$$

Here $\sum E_{Thres_i}$ is the maximum amount of energy that the neutral group can contribute.

4.3 Range of the Effective P2P trading price

As the buying and selling price of the P2P trading price varies with the surplus of the users, both the selling and buying price must be in the range $[P_{BG}, P_{SG}]$. For the case in 4.2.4, we have proved that the price will be in desired range.

Let,

$$\frac{\sum S_i}{\sum D_i} = r, \quad r < 1$$

and

$$\frac{\sum E_{Thres_i}}{\sum D_i} = r', \quad r' < r < 1$$

Then the equation in 4.2.4 turns out like this,

$$P_{P2P_B} \leq r \cdot P_{P2P} + r' \cdot P_{NEU} + \left(1 - r - r'\right) \cdot P_{SG}$$

Now, if P_{P2P_B} became greater than P_{SG} during the varying phase, this equation would not hold because it would imply that, either

$$P_{P2P} \geq P_{SG} \quad or \quad P_{NEU} \geq P_{SG}$$

none of which is true. So, $P_{P2P_B} \leq P_{SG}$.

In a similar manner if P_{P2P_B} became smaller than P_{BG} during the varying phase, this equation would not hold because it would imply that, either

$$P_{P2P} \leq P_{BG} \quad or \quad P_{NEU} \leq P_{BG}$$

none of which is true again. So, $P_{P2P_B} \geq P_{BG}$.

Combining these two outcomes, we can deduce that, even after following our proposed model, the trading price stays in desired range, meaning,

$$P_{BG} \leq P_{P2P_B} \leq P_{SG}$$

And, for the cases in 4.2.2 and 4.2.3, a similar approach can be taken and deduce that,

$$P_{BG} \leq P_{P2P_S} \leq P_{SG}$$

.

Chapter 5

Experiment

5.1 Case Study

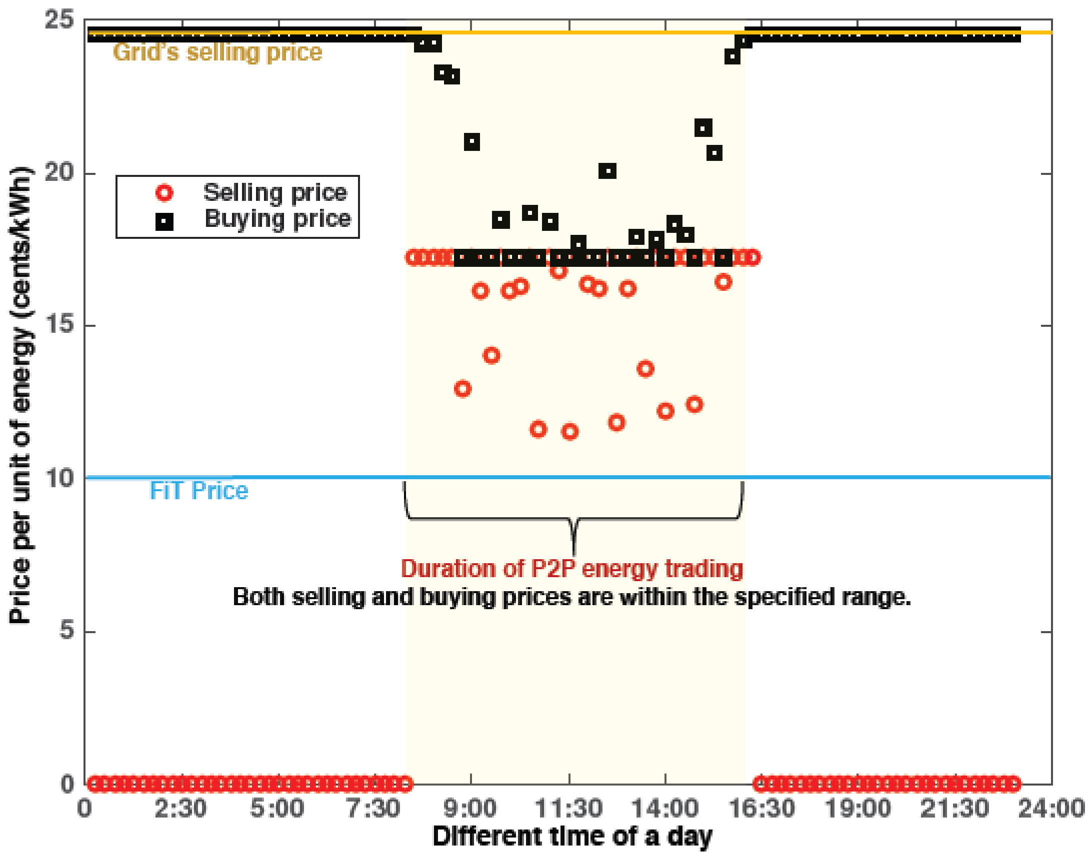

Figure 5.1: Buying and selling price per unit of energy at different time slots of the day

As not much work has been done on this topic, and also, very few public data are available online regarding this type of energy generation and simulation, we couldn't work with large scale user data yet. Our collaborator, Wayes Tushar and his team conducted a small scale experiment on some publicly available data. The figure is the result of a numerical study, in which publicly available real-data on solar generation [6] and household energy demand of residential consumers was used. They considered residential houses as prosumers, each of which is equipped with a 3kWp solar panel. They used 15 minute resolution data to validate the model, and the data used for this case study was recorded in December 2013. The values of grids selling price (p_{sg}) and buying price (p_{bg}) are assumed to be 24.6 and 10 cents/kWh respectively according to the electricity price in Brisbane, Australia.

Chapter 6

Conclusion

In this thesis, we have introduced a new novel peer to peer technique for the demand response management of smart grid. We have proposed a game theoretic approach for this purpose and proved the stability of the game.

We have divided the end users in three groups; buyer, seller and neutral group for the purpose of peer to peer energy transfer technique. The neutral group will step in only when the demand is much larger than the surplus energy.

We have showed that the pricing will vary but it will not exceed the desired threshold in any way. We've tried to create a better model that will attract both the grid and the end users in the coalition in order to reduce their loss and be benefited from the new pricing model.

Due to insufficiency of data available online, we haven't been able to run diagnostics on large scale data yet. But we've addressed a possible solution to the problem and tried to prove the stability of it. In future, we hope to test this in large scale and also propose a better model for more complex situations.

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