Strategic Bidding in A Deregulated Electricity Market Environment

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Summary

Many countries worldwide have initiated the privatisation of electricity assets, the restructuring of electricity industries. The traditional vertically integrated electric utility structure has been deregulated and replaced by a competitive market scheme. This activity is called deregulation, restructuring or unbundling in different applications. The objective of this activity has been to create a competitive environment for trade in electricity that ultimately improves social welfare. In today's competitive electricity market, the formation of electricity prices is determined primarily based on auction mechanism. The market participants tender the supply bid curves for the day-ahead and hour-ahead energy markets.

An ideal electricity market is a perfectly competitive market where no market participants can deliberately affect the market prices and the social welfare is maximized. In reality, however, the electricity market appears closer to an oligopolistic market with fewer power suppliers/generators. As a result, a power generation company (GENCO) can increase profits through strategic bidding (bidding in an effort to exploit imperfections in the market to increase profits), or in other words, through exercising market power (the ability of a single seller or a group of sellers to influence the price of product or service in which it is trading). Thus, the realisation of improving social welfare depends on the unfettered development and efficient operation of markets, which includes limiting the opportunities for participants to exercise market power.

The exercise of market power creates productive and allocative inefficiencies. Market power may also create dynamic inefficiencies if it distorts price signals for new investment. As a result, the effects of market power may erode the benefits that would otherwise arise from a fully competitive market. Thus, for the power system regulators and policy makers, it is necessary to study the market behaviors to recognize the potential market power and to find ways to mitigate the strategic bidding and market power. As the nature of electricity production and consumption make it particularly susceptible to market power, the electricity industry requires more special remedial treatment as compared to other industries. Thus, regulations for controlling the abuse of market power are required. However, there is a trade-off between regulation and competition. In some cases, the costs caused directly or indirectly by regulation may approach or outweigh the potential gain in social welfare. How to successfully mix regulation and competition is more a problem of art rather than science. As a result, the appropriate standard to be aiming at is a competitive standard with an acceptable level of market power rather than a perfect competition.

One major objective of this research work is to study a way to detect the strategic bidding behavior and potential market power. There are a variety of techniques and methods for strategic bidding and monitoring the market power. Among these methods, the game theory based strategic bidding method is most suitable to analyze the behavior in an oligopolistic electricity market. Meanwhile, oligopoly simulation model method is perhaps one of the most powerful tools in exploring market power. In this method, by explicitly simulating one oligopoly model with many of the structural, behavioral and market design factors, the market power related to this model could be analyzed. This thesis presents a conjectural variation based analysis method, which could be designated as one of oligopoly simulation model methods, to investigate the strategic behaviors of GENCOs and detect the underlying market power in game-theoretic context. The conjecture variation (CV) of a GENCO, which is the GENCO's belief or expectation on its rivals' reaction to its output changes, is used as an index to analyze the strategic behavior. The Australia National Electricity Market (NEM) has been investigated by the proposed method. From the available historical data including bidding curves of GENCOs and market clearing price, an empirical methodology has been proposed to estimate the values of conjectural variation. Based on the estimate of conjectural variation, several classical oligopoly models like Cournot, Bertrand and so on are used as benchmarks to analyze the strategic behaviors of GENCOs through comparing the estimate with these benchmark models. At first, the static behaviors of GENCOs in a given period are investigated. However, in the actual electricity market, each GENCO must provide bidding for each period everyday and the market will be accordingly cleared for each period. It means the electricity market is a repeated market, where each GENCO will continuously repeat its bidding process over time. Meanwhile, each GENCO will develop its strategies by learning the behaviors of its rivals, i.e., all GENCOs play a repeated game. Dynamic strategic interaction could be a more important aspect of strategic bidding study in the oligopolistic electricity market. Then the dynamic interaction among GENCOs in the actual electricity market has been also studied via a proposed empirical dynamic analysis method.

Another major objective is to find a way to curb strategic bidding and mitigate market power. Vesting contract, which is a form of bilateral contract, or it is known as Contract for Difference (CfD), vested on GENCOs by the market regulator, is used to limit the potential opportunity for exercising market power. By appropriately setting the strike price and amount covered, vesting contract not only could control the incentive to use market power at an acceptable level, but also hedge the price volatility in electricity market for both GENCOs and retailers. To analyze the impact of the vesting contracts on market power, an electricity market with both a bid-based spot market and a transparent future market is analyzed. Equilibria on the spot market and the future market under vesting contract are theoretically analyzed through supply function and conjectural variation respectively. After that, formulations for the regulators are also derived to compute the proper vesting contract amount so that the existing market power can be reduced and the expected market competitiveness can be obtained.

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1) Symbols in Chapter 4

π_i	Profit of GENCO *i*
p	Price cleared in the spot market ($/MWh)
q_i	Amount cleared under the price *p* for GENCO *i* in the spot market (MW)
D	Demand amount cleared in the spot market (MW)
Q	Total amount cleared under the price p in the spot market (MW)
a_i	Constant in the cost function for GENCO *i*
b_i	First order parameter in the cost function for GENCO *i*
c_i	Second order parameter in the cost function for GENCO *i*
e	Constant in the demand function
f	First order parameter in the demand function
$R_i(\ )$	Revenue function for GENCO *i*
$C_i(\ )$	Cost function for GENCO *i*
$MR_i(\ )$	Marginal revenue function for GENCO *i*
$MC_i(\ )$	Marginal cost function for GENCO *i*
$c_i(\ )$	Marginal cost function for GENCO *i*
CV_i	Conjectural variation of GENCO *i*
N	Number of GENCOs
α	Price elasticity of demand of the market
s_i	Market share for GENCO *i*
$SO_i(p)$	Amount of capacity bid by all other GENCOs except GENCO *i* as a function of the market price *p*
$DR_i(p)$	Residual demand faced by GENCO *i*, specifying the demand faced by GENCO *i* as a function of the market price *p*
$S_i(p)$	Bid function of GENCO *i* giving the amount it is willing to supply as a function of the market price *p*
CV_{ic}	Conjectural variation of GENCO *i* in collusion periods

CV_{in}	Conjectural variation of GENCO *i* in non-collusion periods
CV_{it}	Conjectural variation of GENCO *i* in period *t*
MS_t	Market share of marginal GENCOs
CV_{ir}	Regime value of conjectural variation of GENCO *i*
β_i	Coefficient of the regression equation
μ_{it}	random independently and identically distributed (iid) error

2) Symbols in Chapter 5

A	Constant in the demand function
f	First order parameter in the demand function
$C_i(\ )$	Cost function for GENCO *i*
a_i	Constant in the cost function for GENCO *i*
b_i	First order parameter in the cost function for GENCO *i*
c_i	Second order parameter in the cost function for GENCO *i*
a	Uniform constant in the cost function for GENCO *i*
b	Uniform first order parameter in the cost function
c	Uniform second order parameter in the cost function
α_i	Constant in the supply function for GENCO *i*
β_i	First order parameter in the supply function for GENCO *i*
β_{-i}	Sum of the first order parameter in the supply functions for GENCOs other than GENCO *i*
β	Uniform first order parameter in the supply function
p	Price cleared in the spot market ($/MWh)
p_c	Price for CfD ($/MWh)
p_v	Price for the vesting contract ($/MWh)
p_B	Market clearing price under full competition ($/MWh)
Q	Demand amount cleared in the spot market (MW)
$q_i(p)$	Amount cleared under the price *p* for GENCO *i* in the spot market (MW)
$q_{-i}(p)$	Sum of the quantities cleared under price *p* for other than GENCO *i* in the spot market (MW)
q_B	Market clearing quantity under the full competition (MW)

x_i	Amount in CfD for GENCO *i* (MW)
x_{iv}	Amount in the vesting contract for GENCO *i* (MW)
N	Number of GENCOs
π_i	Net profit of GENCO *i* ($)
k	The projected quantity index, i.e., the ratio of expected market clearing quantity over the full competition quantity.
m	Conjectural variation index in the CfD market considering the impact of conjectural variations
φ	Expected price ratio, i.e. the ratio of the expected clearing price over the fully competitive price

Chapter 1 Introduction

1.1 Motivation

1.1.1 Deregulated Electricity Market Environment

For many decades, in nearly all the countries vertically integrated electric utilities monopolized the way they controlled, sold and distributed electricity to customers in their service territories. In this monopoly, each utility managed three main components of the electric system: generation, transmission and distribution. Any customer who wanted power had to buy it from the local utility. The prices were set in accordance with government regulatory rules and the utility is assured a fair return on its investment.

The success of privatization of the airline, telecommunications industries has motivated the deregulation and restructuring of the electricity industry. Since the 1980s, drastic change and restructuring in the electricity industry have occurred, with the traditional vertically integrated electric utility structure being replaced by a deregulated electricity market structure. In 1989, the UK became one of the pioneers in privatising its vertically integrated electricity industry. Norway and California followed in 1990 and 1996 respectively. The success of energy privatisation in the UK and Norway has encouraged other countries worldwide to follow the trend [1].

In the deregulated electricity market, one traditional utility is separated into generation companies, transmission and distribution companies, and retail companies. This process of commercial rearrangements for trading energy is called restructuring or deregulation. The forces that lead to the deregulation and restructuring are not uniform across different countries and states, and vary according to different needs. However, the main goals are to introduce competition and incentives in electricity industry.

Deregulation and Restructuring of the electric industry are occurring in many nations or states throughout the world, not always for the same reasons and often with unique local interpretations of how competition will be accomplished. However, the most popular method used to achieve this goal is open access to power delivery. In the deregulated industry, generation companies will produce and sell power, vying for the business of electric consumers, but these different generations will deliver their power to their customers over a common set of transmission and distribution (T & D) “wires”- a single T & D system. In the open access environment, all the qualified parties have access to transmission and distribution on an equitable basis. The T & D system operator must operate the system at high efficiency and as economically as possible. In addition, in order that the T & D system operator does not have a bias towards its own competing interest over other qualified users, it cannot be a competitive power seller or producer. As a result, the T & D operator must be objective. Competition is introduced among power producers (competition on wholesale level) and in many cases also among power sellers (retail companies).

A major restructuring model is PoolCo model. A PoolCo is defined as a centralized marketplace that clears the market for buyers and sellers where electric power sellers/buyers must submit bids and prices into the pool for the amounts of energy that they are willing to sell/buy. In many countries, an independent entity, called the Independent System Operator (ISO), is organized to operate the transmission system and take charge of accepting the offers from the generation companies (GENCOs) and demands from customers and determining the market price. In some countries, Power Exchange (PX) is a trading exchange for electric power that operates the electricity market. It accepts the bids from buyers and sellers and determines a market-clearing price in a way similar to that in a stock or commodity market. It submits the balanced schedules to the ISO and the ISO operates the power system. In another restructuring model, the market participants can trade power through making bilateral contracts directly between power producers and customers as well as by submitting offers and bids to the market.

Generally, the wholesale electricity market operates in much a common way: power producers submit bids (prices and quantities) to the ISO or PX. For buyers, in some markets such as the Ontario, Alberta, Norway, and Spain market, they submit bids with prices and quantities to the ISO or PX and in some other markets such as the Singapore and New England market, they just provide estimated load quantities. Normally, the power prices are determined as the intersection point of the aggregated producers' bidding curves and the aggregated buyers' bidding curves. Generally all the power producers are paid the market-clearing price. In addition, in most electricity markets, power producers are allowed to directly make contract with buyers in certain ways.

Deregulation and restructuring have brought forth an innovation in the electric industry, which has led to very significant changes in power system operation, planning, transactions and so on. At the same time, many new topics after deregulation are brought forward for study. The main objective of deregulation is to introduce fair competition and improve social welfare. After deregulation is introduced, electricity industry performance improves significantly with evidence like improvements in labor productivity and service quality, falling wholesale electricity price, and so on. However, electricity restructuring has also exhibited to a number of performance disappointments and problems, making ongoing reforms necessary. Within these problems, market power via strategic bidding, which will badly damage the competitiveness and reduce the social welfare, is the most important one. As a result, after the creation of the electricity market, the study of market power and the behaviors (strategic bidding) of the market participants has naturally become one of the most important topics, which is the major subject of this thesis.

1.1.2 Importance of Strategic Bidding and Market Power Study

As mentioned in the previous section, the basic purpose of deregulation is to set up a fairly competitive environment for power producers. Ideally, a perfectly competitive power market is the most desirable market structure. Perfect competition is a market structure characterized most notably by a situation in which all firms in the industry are pricetakers and there is freedom for entry into and exit from the industry. In a perfectly competitive power market, all the power producers bid the production costs (or short-run marginal costs) of their generating units. There are no market participants that can deliberately affect the market prices. Therefore, the competitive market prices are obtained and the real maximization of social benefits is achieved.

However, the emergent electricity market structure is more akin to oligopoly than perfect market competition [2]. An oligopoly is a market structure with a few producers of significant size and the action of one producer has an influence on the overall market, and prices and payoffs are influenced by the behavior of the producers; or in other words, the payoffs received by producers are interdependent. In reality, the electricity market behaves more like an oligopoly than the ideal perfectly competitive market due to its special features. As a result, the market participants could always improve their profit by strategic bidding and exercising market power in spot wholesale power and reserve markets. Strategic bidding is the behavior in which a power producer bids other than the marginal cost with the aim of exploiting imperfections in the market to increase its benefits. Market power, as a kind of market behavior exercised by the market participants, is the ability of a single seller or a group of sellers to influence the price of the product or service in which it is trading [3].

In reality, a certain degree of market power always exists in a practical market, especially since electricity in many ways is a very special product. The following features of the electricity make it markedly different from other products in other markets and also make it relatively easier for generation of electricity to exercise market power:

- Electricity cannot be stored in large quantities in most electric systems.
- Electricity cannot be readily substituted, especially in the short term.
- Electricity can only be transported through existing transmission lines and new transmission lines require long periods of time and are expensive to build.
- Large capital is required to build new generating units, which increases the risk for new entrants in the electricity market.

The exercise of market power by market participants in the deregulated power market may lead to inefficient dispatch and other productive inefficiency, high consumer costs and inefficient signals for new investment, etc [4]. Although it is expected that deregulation of the electricity generating industry will yield economic efficiency as a result of the introduction of the competition, in practice there are such well-recognized aspects of market behavior to damage the market efficiency that it is not easy to set up an efficiently competitive power market. As a result, it is crucial for the power system regulators to recognize the potential market power by studying the market strategic behaviors and to find ways to mitigate the market power. Thus, the major topics of this thesis include: (i) monitoring the strategic behavior and market power; and (ii) controlling strategic bidding and curbing market power.

1.2 Objectives

The broad objective of this research work is to study the strategic bidding behavior in the deregulated electricity market environment. The studies are carried out in two categories: (i) To investigate the possible market power made by GENCOs through analyzing the strategic behavior of GENCOs. (ii) To develop an effective way for the market regulator to mitigate market power. The detailed objectives of this research work are concisely stated as follows.

1.2.1 The Monitoring of Market Power Associated with Strategic Bidding

Evidence of market power existing in the electricity markets has been empirically revealed, but the understanding of the market structure and GENCOs' strategic behaviors underlying the market power is far from satisfactory. There are various research papers on analyzing market power, but most of them only show evidence of market power existing in the electricity markets. Few of them attempt to investigate what underlying GENCOs behaviors and oligopoly market structures caused the market prices to deviate from competitive levels, i.e., market power. In this thesis, a conjectural variation based method will be used to analyze GENCOs' strategic behavior and the market structure, as well as the market power associated with the oligopoly model. A theory and method for the empirical estimation of the conjectural variation will be presented. An actual PoolCo electricity market will be used as the simulation study case. A variety of historical market data, including bidding curve of all GENCOs, market clearing price and so on, are collected for empirical analysis. By investigating the estimated conjectural variation, the market structures and GENCOs' static behaviors in a given period will be analyzed by comparing with the classical oligopoly models like Cournot, Bertrand and so on. As a result, the understanding of the nature and root of market power can be obtained.

In the actual electricity market, each GENCO learns from other GENCOs' behaviors and modifies its behavior over time. It means all GENCOs play a repeated game. There is great chance for all GENCOs to collude tacitly in this case. Dynamic behavior analysis based on conjectural variation in a series of periods can also be used to produce a profile of strategic behavior series and examine whether GENCO's behavior is more consistent with unilateral market power or tacit collusion.

1.2.2 The Mitigation of Strategic Bidding and Market Power

As most economists argue, the electricity industry needs more specific regulation than other industries to curb market power, for the electricity industry is particularly easier to exercise market power. However, the mitigation techniques and methods should be carefully accomplished to get the desirable result. In some cases, the mitigation regulations may give rise to unexpected result. For example, if price caps lead to plants only covering their marginal costs, there will not be enough revenue to cover the fixed costs of the plant. However, as most people agree, regulations for controlling the abuse of market power are required. As a result, a problem arises: how does one successfully mix regulation and competition? Regulation of market power implies benefits and costs. In some cases, the direct administrative costs of regulation may approach or outweigh the potential benefits in social welfare. Thus, the objective of regulation should be to set up a workable electricity market rather than a perfectly competitive one.

In this thesis, vesting contracts will be used as the mitigation method to curb strategic bidding and control market power. With an appropriately set strike price and amount, vesting contracts can perform the function of stabilizing the price and also limit the potential market power to a desirable level. To analyze the impact of the vesting contracts on market power and the strategic behavior of generators, an oligopoly electricity market comprising a spot market and a future market is studied. A way to determinate the optimal vesting contract amount will also be presented. Through the adjustment of the vesting amount, the regulator can curb the market power by maintaining the market clearing price and the total cleared amount at a reasonable level.

1.3 Major Contributions

1.3.1 Study of Monitoring Market Power Associated with Strategic Bidding

1) Method for estimating conjectural variation

A method for estimating conjectural variation is proposed. By this method, the conjectural variation of GENCOs in actual electricity markets could be estimated based on the historical data in the pool market, which includes bidding curve, market clearing price and so on. The NEM is used as the simulation study case. All the historical data are obtained from the NEM official website. The useful market data are carefully extracted from the historical market data package. A method also is presented to estimate the marginal cost of GENCOs based on this historical data. All the parameters needed to calculate the conjectural variation, the values of the marginal cost, the price elasticity, the market clearing price and the market share are estimated based on the actual data. With these estimate of parameters, the conjectural variation of GENCOs could be calculated by the proposed formulation. These conjectural variations will be used as indices to analyze the strategic behavior of GENCOs.

2) Static strategic bidding behavior analysis based on conjectural variation

A method for calculating the conjectural variations of GENCOs in classical models like Cournot, Bertrand and Monopoly is also introduced. All parameters needed to calculate the conjectural variation are estimated based on the historical data as it was mentioned in the previous section. In static strategic behavior investigation, a fixed period is given for research and all parameters estimated are mean values in this given period. Then the conjectural variations of GENCOs in these three classical models are calculated as benchmarks to analyze the strategic behavior. Through comparing the estimate of conjectural variation in real market with these benchmarks, the static market behavior of GENCOs could be investigated. That is to draw inferences about whether Bertrand, Cournot, or Monopoly is supported by the mean estimated conjectural variations. After the GENCO behaviors are estimated the competitiveness of a set of GENCOs and market power in the market could be analyzed accordingly.

3) Dynamic strategic bidding behavior analysis based on conjectural variation

In reality, GENCOs play a repeated game. A GENCO can develop its behaviors by learning the behaviors of its rivals. Thus, the dynamic strategic interaction is a very important aspect of strategic bidding study in the oligopolistic electricity market. An empirical and statistical methodology of dynamic behavior analysis is presented to fulfil this objective. The dynamic interaction among GENCOs in the actual electricity market is investigated using time series historical data in this thesis. By empirically estimating a time series of conjectural variations, one is able to investigate whether repeated Bertrand, Cournot, Monopoly or the Cournot based Regime-switching (RS) model is supported by the estimated conjectural variations series. Based on this investigation, one can also test whether GENCO performs unilateral market power or tacit collusion.

1.3.2 Study of Mitigating Market Power

1) Equilibria in the spot and future market with vesting contract

To mitigate market power, vesting contracts are introduced. The impact of vesting contracts on market power and the strategic behavior of GENCOs is analyzed through an electricity market with a spot market and future market. The future market and spot market equilibrium under vesting contract is theoretically analyzed through supply function and conjecture variation respectively. From these equilibria result, it shows the implementation of the vesting contract can change the market equilibrium. The increase of the total mount of vesting contract and CfD would result in the increase of the cleared quantity in the spot market. The market clearing price will reduce accordingly, which means the decrease of market power level. It proves the implementation of vesting contract could reduce the incentive of GENCO to bid strategically and limit the ability of GENCO to exercise market power.

2) Determination of the optimal vesting amount

As mentioned previously, the objective of regulation is to set up a workable electricity market rather than a perfectly competitive one. The power industry needs to get enough revenue to cover the fixed costs of the plant and to sustain its development. A proper vesting quantity is also obtained aiming at driving the anticipated market clearing price to a predetermined level. Thus, formulations for the regulators are also derived to compute the proper vesting contract amount so that the existing market power can be reduced and expected market competitive situations can be obtained. The impact of factors, such as number of GENCOs, system demand function and conjecture variation attitude in the market, on the vesting contract amount and the market equlibira is also investigated.

1.4 Thesis Organization

Chapter 1 described the motivation, objectives and major contributions of the thesis.

In Chapter 2, the basic concepts on deregulation in the electric industry are briefly introduced. Various aspects of the deregulated electricity market are outlined.

In Chapter 3, a brief introduction to the basic concepts of strategic bidding and market power is presented and a review of the relevant literature on monitoring and mitigating strategic bidding and market power study is summarized.

Chapter 4, one of the main parts of the thesis, discusses the method to empirically analyze the strategic behavior and detect market power. Basic concepts on game theory and conjectural variation method are introduced first. An empirical methodology for estimating the conjectural variation in actual electricity markets is presented. Based on the estimation of conjectural variation, the static and dynamic strategic behaviors of GENCOs are investigated. The Australia National Electricity Market (NEM) is used as the example to validate the proposed method.

In Chapter 5, another main part of the thesis, vesting contract is introduced as a way to mitigate the market power. An oligopoly electricity market comprising a spot market and a future market is studied to analyze the impact of the vesting on market power. Equilibria on both markets are obtained. A way to determinate the optimal vesting contract amount is also presented. A simulation study case is analyzed by the proposed method.

Finally, conclusions of the research work and the recommendations for further study are presented in Chapter 6.

Chapter 2 Background of Deregulated Electricity Market Environment

2.1 Introduction

In this Chapter, the deregulated electricity market environment occurring in many countries worldwide is briefly reviewed. Some basic concepts and topics related to the studies in deregulation of power industry are explained. The market structure and power trading rules, which will be the basis for strategic bidding and market power in practice, is also reviewed. A review of deregulation around the world is presented focusing on the power trading process at the wholesale level in countries where the electricity industries are deregulated. After that, improved performances of the electricity industry after the introduction of deregulation are reviewed and a number of performance disappointments and problems are summarized.

2.2 Deregulated Electricity Market

For nearly a hundred years, from the late 19th to the end of the 20th century, the electric power industry operated as a regulated monopoly. As we enter the 21st century, in many parts of the world including England and Wales, Columbia, Australia, Singapore, the United States and many more countries, the electric power industry is being "deregulated". Deregulation is a restructuring of the rules and economic incentives that governments set up to control and drive the electric power industry [5]. Under deregulation, governments are changing the utility environment and regulations to foster competition. The basic goal of the restructuring is to increase this competition by providing a choice of suppliers to all users of electricity [6]. The terms "re-regulation" and "restructuring" have the same meaning as deregulation in this study. Figure 2-1 graphically shows the differences between the structures of electric utility before and after deregulation.

Before deregulation, vertically integrated electric utilities monopolized the way they controlled, sold and distributed electricity to customers in their service territories. In this monopoly, each utility managed three main components of the system: generation, transmission and distribution. In addition, such companies receive a single bill for the services of generation, transmission, distribution and retail sales at a single price without making any distinction between the costs of difference services. This is shown in Figure 2-1.

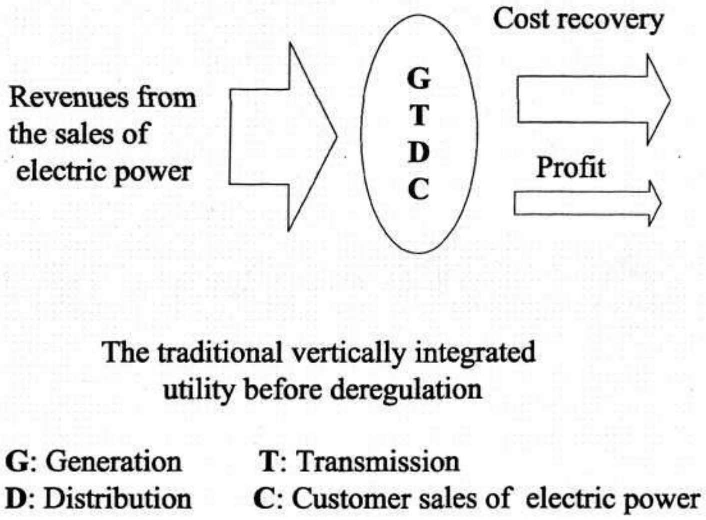

Figure 2-1 Structures of electric utilities before deregulation

Some features of regulation are briefly introduced as follows:

1) **Monopoly franchise**: The government grants one, and only one, company the right to sell electricity to consumers in a certain area, the franchise territory. Within this service territory, no other company can produce and commercially sell electric power.

2) **Obligation to serve**: This local power company must provide for the needs of all electric consumers in the region.

3) **Guaranteed rate of return**: The government guarantees the utility that its regulated rates will provide it with a reasonable profit margin above its costs.

4) **Prescribed operating and business practices**: The government may put stringent limitations on what and how the local power company functions. These could be anything from a requirement on how it builds its system, or the way it does its planning, to strict definitions on how it finances its operation.

5) **Least cost operation**: The government will define how the utility computers costs and sets its prices. Usually, it requires that the utility operates in a lowest cost manner, and defines specific ways that it should and should not finance its operations.

From these features of regulation, it can be seen that government granted each electricity utility a vertically-integrated franchise monopoly for electricity production, delivery, and sales in its service territory and the utility had to operate in a regulated environment with cost-based pricing of its product. However, after deregulation, vertically integrated utilities will disaggregate themselves by functions into separate companies. Of the four functions (generation, transmission, distribution and retail sales), generation and retail sales are expected to be competitive and transmission and distribution are generally still regulated. Consequently, the revenues for different services are also separated. It should be noted that some utilities like to split their T&D company as shown in Figure 2-2 into two separate companies.

Both government and business favored utility regulation during the early history of the industry. From the perspective of the businessmen running the early utilities, regulation brought several important benefits including that it legitimized the electric utility business; it assured a return on investment and it established a local monopoly. Municipal leaders wanted regulation, too. Monopoly franchise simplified the buying process, which is important for early consumers. Beyond the reasons given above, and perhaps most important for both government and business, regulation offered an acceptable, risk-free way to finance the creation of an electric industry. However, in recent years, for a variety of reasons, government and society in general have decided that the rules governing the electric power industry should change. The forces that lead to the deregulation and restructuring are not uniform across different countries and states, and vary according to different needs. The general reasons for electric industry de-regulation are presented as follows:

1) **The need for regulation changed**: The original need for regulation, which was to provide relatively risk-free financing of electric system development, passed into unimportance decades ago.

2) **Privatization**: In many of the countries where electric utility deregulation first occurred, the government was also privatizing the industry. Privatization means the government sells its state-owned electric utility business to private investors. Usually the governments like England and so on strongly believe that private investors could do a better job of running the power industry, because the private investors have more motives to reduce their cost and improve their efficiency. This firm conviction always led to favoring deregulation.

3) **Cost is expected to drop**: Competition breeds innovation, efficiency and lower costs. People believe that competition will bring about significant decreased in cost.

4) **Regulation provided no incentives for innovation**: The regulatory process and the lack of competition gave electric utilities no incentive to improve on yesterday's performance or to take risks on new ideas that might increase customer value.

5) **Competition will improve customer focus**: Many of the technological advances that will be applied under deregulation address customer service, i.e., providing better reliability and value, or giving customers more options or increased control over their energy usage. This is another theme of deregulation: It promotes customer focus on the part of suppliers, and increases customer choice.

In response to these reasons, it is expected that the competition caused by deregulation might be a better way to reduce the price, to encourage private investment in operation of an electricity market, to improve the investment decisions, to better use the existing plant and to enhance the choices for customers.

Deregulation and restructuring of the electric industry are occurring in many nations or states throughout the world since the 1980s. However, restructuring of the electricity supply industries is a very complex exercise based on national energy strategies and policies, macroeconomic developments and national conditions, and its application varies from country to country. It is important to point out that there is no single solution applicable to all countries and there is a broad range of diverse trends [1]. Regardless, after deregulation, the former integrated organizations have been replaced by more complex and unbundled ones. As a result of deregulation, utilities typically disaggregate, breaking apart into several companies, as shown in Figure 2-1 where the vertically integrated utility in Figure 2-2 has changed into different elements.

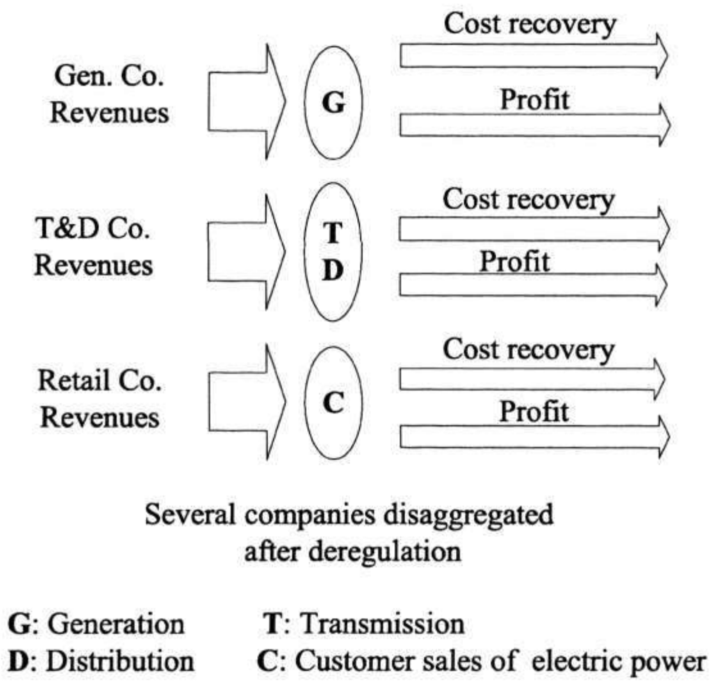

Figure 2-2 Structures of electric utilities after deregulation

The basic structure of a deregulated electricity market comprises:

1) **Competitive power generator**: An open market exists in which any entity that is qualified, competent, solvent, able to meet standards and become licensed, can produce

and sell power. Usually, there are many dozens of generation companies competing to produce and sell electric power on a wholesale basis.

2) **Monopoly franchise "wire company"**: Some organization is given responsibility to operate the sole transmission and distribution system in an area for the benefit of everyone who wants to move electricity. An important point in the deregulated industry is that these wire companies are not allowed to play favorites. They must provide equal access to all potential users of the T&D system and cannot favor any one generation company. Sometimes, for business reasons, the T&D functions are split into two separate companies.

3) **Competitive retailers**: They buy power in bulk at the wholesale level and sell it to consumers. Homeowners and businesses are offered power from these retail companies. All these companies rent space on the T&D systems from the "wire companies" in order to move their power so that it can be delivered to consumers.

From above, the key concept of deregulation in nearly every nation is that no one company should have a monopoly on either the production, the wholesale sale, or the retail sale of electricity and electricity-related services. Thus, unbundling of power generation from delivery, and of delivery from retail sales, is the main theme of deregulation. As a result of deregulation, the major types of players in the electric utility industry are:

1) **Generation companies (GENCOs)**: They are electric power manufacturers. They own generation units and produce electric power.

2) **Transmission companies (TRANSCOs)**: They move power in bulk quantities from where it is produced to where it is wanted.

3) **Distribution companies (DISCOs)**: They are companies that deliver electricity locally. In some places, the local distribution and retail functions are combined in a local

distribution company (LDC). Mostly, they only own and operate the local distribution system, but not sell power.

4) **Retail energy service companies (RESCOs)**: They are retailers of electric power, perhaps other forms of energy like gas, and various services such as backup power supplies.

5) **Independent system operator (ISO)**: It is a non-partisan organization that actually operates the power system in a region. Its duties are to operate the system in a reliable and economical manner, and to assure all who need to use the transmission system of equitable treatment.

6) **Power exchange (PX)**: It is an organization, somewhat like a stock exchange, that permits buyers and sellers of wholesale electricity to buy and sell electric power as a commodity.

In most cases, competition is introduced gradually from the wholesale market to the retail market. Regardless, the basic method used under deregulation to promote competition is ***open access*** to power delivery. In the open access environment, all the qualified parties have access to transmission and distribution on an equitable basis. The T & D (transmission and distribution) system operator must operate the system at high efficiency and as economically as possible. In addition, in order that the T & D system operator does not have a bias towards its own competing interest over other qualified users, it cannot be a competitive power seller or producer and must be objective as it is an impossible task if the same company is operating the delivery lines and at the same time trying to compete as a generator and retailer.

2.3 Deregulated Electricity Market Structure and Trading Rules

Each deregulated electricity market is structured differently and continues to go through different phases of restructuring in different nations. There are no one market model and trading rules that can represent the situations of all the countries and states. To better understand the features of the power trading processes, this section aims at classifying the categories of market structure or trading protocols according to different aspects. It can also be regarded as a summary of the power trading processes in different countries.

2.3.1 Electricity Market Models

There are three major market models as alternatives to the vertically integrated monopoly. They are outlined as follows [7]:

1) PoolCo model

A PoolCo is defined as a centralized marketplace that clears the market for buyers and sellers where electric power sellers/buyers submit bids and prices into the pool for the amounts of energy that the are willing to sell/buy. The ISO or PX will forecast the demand for the following day and receive bids that will satisfy the demand at the lowest cost and prices for electricity on the basis of the most expensive generator in operation (marginal generator).

The main characteristic of the PoolCo model is the establishment of independently owned wholesale power pools served by interconnected transmission systems. This pool becomes a centralized clearing market for trading electricity which would implement competition by forcing distribution utilities to purchase their power from the PoolCo instead of trading with generation companies. These companies sell power at a market-clearing price (MCP) defined by the PoolCo, instead of a price which is based on generation cost (as in the case in a vertically integrated monopoly). MCP could be defined differently, but the most widely used definition is “the price of highest selected bid”. The final price for the spot market power may exceed MCP to account for charges that the ISO could obligate customers to pay for the associated ancillary services and to cover ISO’s overhead costs.

2) Bilateral contracts model

This model, which is based on bilateral contracts, may also be referred to as Direct Access Model. This model has two main characteristics that would distinguish it from he PoolCo model. These two characteristics are: the ISO's role is more limited; and buyers and sellers could negotiate directly in the marketplace. Under this model, a single centrally dispatched regional power pool is not obligatory as under the PoolCo model.

This model permits direct contracts between customers and generators without entering into pooling arrangements. Any two contracted parties would agree on contract terms such as price, quantity and locations, and generation providers would inform the ISO on how its hourly generators would be dispatched.

3) Hybrid model

This model combined various features of the pervious two models. The hybrid model differs from the PoolCo model in that the ISO or PX is not obligatory and customers are allowed to sign bilateral contracts and choose suppliers from the pool. The pool would serve all participants (buyers and sellers) who choose not to sign bilateral contracts. This structure has advantages over a mandatory pool as it provides end-users with the maximum flexibility to purchase from either the pool or directly from suppliers. This model would enable market participants to choose between the two options based on provided prices and services. Most of the existing electricity markets are using this model such as California.

2.3.2 Power Market Types

Based on trading, the market types include the energy market, ancillary services market, and transmission market. Furthermore, markets are classified as future markets and spot markets based on the trading time horizon. It is important to note that markets are not independent but interrelated. In the following, we will learn how these market types are organized.

A. Energy, Ancillary Services, and Transmission Markets

1) **Energy Market**: The energy market is where the competitive trading of electricity occurs. The energy market is a centralized mechanism that facilitates energy trading between buyers and sellers. The energy market has a neutral and independent clearing and settlement function. In general, the ISO or the PX operates the energy market. The ISO (or PX) accepts demand and generation bids (a price and quantity pair) from the market participants, and determines the market-clearing price (MCP) at which energy is bought and sold. In general, the way to determine the MCP is as follows: Aggregate the supply bids into a supply curve and aggregate the demand bids into a demand curve. The intersection point of the supply curve and demand curve is the MCP. In time periods of congestion, a corresponding adjustment would be made.

2) **Ancillary Services Market**: Ancillary services are needed for the power system to operate reliably. In the regulated industry, ancillary services are bundled with energy. In the restructured industry, ancillary services are mandated to be unbundled from energy. Ancillary services are procured through the market competitively. In general, ancillary services bids submitted by market participants consist of two parts: a capacity bid and an energy bid. Usually, ancillary services bids are cleared in terms of capacity bids. The energy bid represents the participants' willingness to be paid if the energy is actually delivered. Different ancillary services in the market could be cleared sequentially or simultaneously.

3) **Transmission Market:** In a restructured power system, the transmission network is where competition occurs among suppliers in meeting the demands of large users and distribution companies. The commodity traded in the transmission market is a transmission right. This may be the right to transfer power, the right to inject power into the network, or the right to extract power from the network. The holder of a transmission right can either physically exercise the right by transferring power or be compensated financially for transferring the right for using the transmission network to others. The importance of the transmission right is mostly observed when congestion occurs in the

transmission market. In holding certain transmission rights, participants can hedge congestion charges through congestion credits. The transmission right auction would represent a centralized auction in which market participants submit their bids for purchase and sale of transmission right. The auction is conducted by the ISO or an auctioneer appointed by the ISO, and its objective is to determine bids that would be feasible in terms of transmission constraints and that would maximize revenues for the transmission network use.

B. Future and Spot Markets

1) **Future Market:** It is a purely financial market for price hedging, risk management and trade in forward or future power contracts. A forward or futures contract would include an obligation to buy or sell a specified quantity of an asset at a certain future time for a certain price. The trading time horizon could be up to years and contracts are divided into days, weeks, blocks, seasons and years. None of these contracts entails physical delivery. They are all settled in cash against the market-clearing price in the spot market. These contracts refer to a base MW load during every hour for a given delivery period of one day, one week, one block, one season, and one year that may be available for trading depending on the type of contracts.

2) **Spot Market**: In a spot market, electricity is traded for actual physical delivery to the transmission grid. The market is in charge of accepting the offers from the generation companies and demands from customers, and in determining the market-clearing price. Such organization will be operated by the ISO or PX. Day-ahead or hour-ahead electricity power contracts are traded in the spot market for physical delivery for each hour during the following day or hour.

2.3.3 Market Trading Rules

To better understand the features of the power trading processes, the categories of trading rules according to different aspects are presented as follows:

1) Simple and multi-part bids

In simple-bids auction, market participants only submit the offered power quantity and its unitary price. In multi-part bids auction, bidders submit both a startup and variable cost coefficient. The two kinds of auction rules are discussed in [8]. In UK, multi-part bid is typically adopted. Simple bid is applied in Norway, California, etc.

2) Static and dynamic repetition bids

Based on whether the repetitive bid is allowed, bidding protocols are classified into static and dynamic bids. In a static bid, there is one single bid daily. In a dynamic bid, a more responsive feedback mechanism is included such that the market participants are allowed to modify their bids upon receiving their generation levels. Static bid is adopted in most deregulated electricity markets. Many studies on dynamic bid have been reported. In [9], the authors examine the effects of including a feedback mechanism such that upon receiving generation levels from the ISO, independent generators be allowed to modify their bid if they so desire. In [10], the electricity market is modeled as a dynamic process in which generators learn market opportunities on daily and hourly basis, and evaluate their subsequent bids based on the assumed strategies to adjust the chosen strategy using the available information about power prices and their own cost functions. Using the dynamic model, it is shown that the repetition of bidding actually plays a significant role in the market dynamics. In addition, several critical factors in determining the level of market power exercised are also explored in this paper.

3) Single-side bid and double-side bid

Single-side bid means that only power producers submit bids to the spot market and power buyers are not allowed to submit bids, that is, the elasticity of demand is zero. In double-side bids, Demand Side Bidding (DSB) is included, that is, both power producers and buyers are allowed to bid in the spot market. In the Norway and Sweden, Alberta, New Zealand, Australia and California market, double-side bidding is adopted, i.e., demand side bidding is allowed. In New England and Singapore, power producers are allowed to bid and buyers can submit the estimated load requirements and the system schedule and dispatch are based on the forecasted load requirements. However, demand side bidding will be allowed with the further development of deregulation.

4) Single energy and energy-reserve market

In the single energy market, the only product in the market is energy, and power reserve that is necessary for maintaining the security of the power system is not paid but is mandatory, such as the electricity market in Australia [11]. In an energy-reserve market, both the requirements of the energy and reserve are considered simultaneously and paid, such as the electricity market in the UK. Another kind is that the energy and reserve are traded in two different markets, such as in the California Power Exchange. Energy is traded in a spot market (power exchange) while reserve is traded as a kind of ancillary service in an ancillary service auction.

5) Spot market and bilateral contract

The approaches for power trading generally include submitting offers to the spot market and making bilateral contracts with customers. The spot market is in charge of accepting the offers from the generation companies and demands from customers, and in determining the market price. Bilateral contracts are direct long-term or mid-term ones between any two participants. Generally the two trading approaches are allowed in an electricity market. Power producers can choose to bid in a day-ahead market or make long-term or mid-term contracts with customers to sell energy of certain quantity at a certain price, or both. Most of the existing electricity markets allow both trading ways, such as Norway, California Power Exchange, New Zealand, Australia, Singapore, etc.

6) Centralized and decentralized schedules

There are centralized and decentralized unit commitment and economic dispatch in a deregulated environment. In a centralized market, power producers provide the bidding curves and operational parameters of all its units to the Independent System Operator (ISO) and the unit commitment and dispatch are determined by the ISO, such as in the

UK. In a decentralized market, power producers have to make the decisions about the unit commitment and dispatch of their generators themselves. They only provide their quantity-price bidding curve, such as California Power Exchange, Nordic Pool, etc.

2.4 A Review of Deregulated Electricity Market around the World

Deregulation and restructuring of the electric power industry are occurring in many nations throughout the world. In this section, a review of deregulation around the world is presented focusing on the power trading process at the wholesale level in countries where the electricity industries are deregulated.

2.4.1 Latin America

In many ways, South America was the pioneer in privatization to drive restructuring [12]. From 1978, a major restructuring took place throughout the electric power industry in South America. Chile started its deregulation process in 1978 and Argentina followed with an aggressive process in 1991 [13]. Both Argentina and Chile wholesale electricity markets include a spot market operated through a pool and a long-term market involving agreements freely made by the market participants. An ISO or PoolCo independently operates its members and their contracts. Both models started with an optimum economic dispatch. In Chile, GENCOs are dispatched depending on audited generation costs and water availability information. The global demand is forecasted and the values are updated monthly. The variable cost of the last unit dispatched to fulfill the demand determines the Short Term Marginal (Energy) Cost (STMC). Unit commitment is not important in the dispatch function of the Chilean predominantly hydro system. In Argentina, a bidding scheme similar to that in the UK was adopted. Variable costs of the thermal generators are quoted and declared twice a year on a weekly basis. Hydro GENCOs declare a price that is a function of the reservoir's level. DISCOs submit their forecasted demand for the seasonal schedule in advance, stating a maximum load not to be exceeded. The variable cost of the last unit dispatched to fulfill the demand determines the Market Clearing (Spot) Price (MCP). In Argentina, economic dispatch considers the physical location of each unit along the grid related to the system' load center so as to take into consideration the losses. Chile includes approximate locational differences in prices. Both pools perform yearly, monthly, weekly and daily operation schedules. However, final dispatch occurs within real time and the whole tariff regime is based on the system's actual hourly spot price. Dispatched GENCOs, paid by supplied energy and capacity, receive an ex-post payment based on hourly price at every network location. DISCOs in Argentina pay a seasonal stabilized wholesale price and will be compensated in the next section should the price deviations exist. In Chile, DISCOs are paid as nodal prices and the prices are adjusted if they deviate more than 10% from average wholesale prices. In addition, large users (more than 1 MW in Argentina and 2 MW in Chile) may contract directly with GENCOs in the long-term market or buy in the spot market.

2.4.2 England and Wales

The UK electrical industry seems to be a most widely quoted example of deregulation. In some ways the UK led the world in electric industry deregulation [14]. The process of privatization in the UK began in Feb. 1988 and a national wholesale electricity market was created in March 1990.

The England and Wales Electricity Pool facilitates a competitive bidding process between generators by setting the price of electricity each half-hour of the day and establishing which generators will run to meet forecast demand. It is a mandatory pool that acts like a uniform price single-sided auction (only a very small number of demand side participants are allowed to bid) and adapts *ex ante* pricing combined with *ex post* mechanisms for power imbalances. The ISO in the UK is the National Grid Company (NGC). It operates the mandatory power pool as well as owns and operates the transmission system. The UK includes future market, day-ahead, hour-ahead and real-time markets. In the day-ahead market, the Regional Electricity Companies (RECs), as power buyers, submit load forecasts ahead of time and GENCOs submit a 24-hour production and price schedule for the next day to the pool. The GENCO offer includes price-quantity curve and a set of scheduling and dispatch parameters (run-up and run-down rates, synchronizing generation, minimum generation, inflexibility, spinning reserve level, merit order availability) [15]

[16]. Based on these bids and forecasts, first an unconstrained schedule is derived, which minimizes the cost (in terms of the offered prices). The offer price of the marginal generator set determines the System Marginal Price (SMP) for every half hour. Then the Power Purchase Price (PPP) is obtained by adding an element related to the expected degree of capacity surplus on the system to the SMP. On the operating day, when there is a deviation of the actual output from the unconstrained output, the change of the output is bought or sold in terms of its offer prices. After all the transactions have been completed, the Power Selling Price (PSP) is calculated by adding a uplift related to the ancillary services cost to the PSP. Consumers buy the energy in terms of the PSP. The optional bilateral agreements can be made outside the pool through Contracts for Differences (CfDs).

From its beginning, the UK's Poolco market system has exhibited some problems: (i) wholesale prices have been excessive, associated with market power being exerted by the two largest generation companies; (ii) too few benefits have reached customers in the form of lower prices. To make the market more functional and competitive to avoid market power, the New Electricity Trading Arrangements (NETA) replaced the pool on March 27, 2001. Under NETA, the pool has been replaced by a series of forward markets and a short-term balancing market. Market participants are now expected to transact voluntarily, primarily through forwards and futures contracts for the exchange of energy in advance of actual production. The balancing market allows traders to fine tune their positions and the System Operator to change traders' plans if this is necessary to match overall supply and demand over the day. In contrast to the formerly used uniform-auction, the auction format used in the balancing market is of the discriminatory or "pay-your bid" type. The British regulatory authority, Ofgem, has recently reported that the month ahead base-load prices fell by a 40% since the Government accepted the reforms in 1998 up to March 2002, i.e., one year after the "go-live" of NETA. Following the success of NETA, Ofgem worked to extend these benefits to customers in Scotland. This led to the creation of a Great Britain-wide Electricity Trading and Transmission Arrangements in April 2005. By providing a larger electricity market for Scottish electricity, the new GB-wide wholesale market will increase the competitive pressure on prices across Britain. It will also help to reduce the costs of transmitting electricity to homes and businesses in

Scotland. This will mean that Scottish customers should see an average cut in their electricity bills of £20 each year [17].

2.4.3 Nordic Electricity Market

The market operation in Norway started in May 1992 [18] [19]. Sweden became part of the power exchange area in 1996 to reduce market power considering that Vattenfall would have had market power in a Sweden-only market. Finland joined in 1998, Western Denmark in 1999 and eastern Denmark in 2000. Today the Nordic power market is recognized as the world's most liquid and best-functioning power market. The new Nordic wholesale electricity market combines both over the counter bilateral contracting and trading via the Nordic Power Exchange, Nord Pool ASA. Basically, Nord Pool organizes two markets, a "physical market" (Elspot) [20] and a "financial market" (Eltermin and Eloption) [21], and also provides with clearing services.

The ISOs (Norway: Statnett, Sweden: Svenka Kraftnat, Finland: Fingrid) operate the transmission systems. Nord Pool operates two markets, a spot market and an open, bilateral-contract market (future market). The spot market accepts bids for all 24 hours of each day. Both generators and loads bid in the form of linear segment price versus quantity curves. Different from those in the UK, the energy bids must not relate to individual physical generating units. The generating units take the task of self-scheduling.

The bids are aggregated into separated price versus quantity curves for supply and demand. The system price is the equilibrium point where the aggregate demand curve meets the aggregate supply curve. The Nord Pool facilitates a uniform price auction by paying all generators the last accepted bid. Norway's spot market also operates a supplementary market (long-term supply market), where generators and buyers may reserve commitments on sales and purchases further ahead. The spot market is optional. In the Norwegian market, the majority of electric sales (about 70 percent) are made through bilateral contracts between the generator and the buyer. The futures market permit trade of weekly base or peak load contracts for up to three years ahead for generators and loads to hedge price risk. Originally, the market contracts were settled by physical electric delivery. Since Oct. 1995, the settlement has become financial, the market contracts are all settled in cash against the system price in the spot market. The market contracts refer to a base load of 1 MW during every hour for a given delivery period of one day, one week, one block (four weeks), one season, and one year that may be available for trading depending on the type of contracts [22].

2.4.4 USA

In USA, the Federal Energy Regulation Commission (FERC) deregulated the wholesale generation and bulk transmission to open access with its Order 888 in April 1996 [23]. Within the FERC guidelines, the individual states are free to pursue different approaches to implement and operate the electric power industry in their state [24].

The California electricity market opened on May 31, 1998. The structure of California electricity market is shown in Figure 2-3. The main players that compose the California market structure include the ISO (provides grid dispatch and transmission access services), Scheduling Coordinators (SCs which submit balanced schedules to the ISO), Power Exchange (PX which creates a spot market for electricity, schedules and settles trades in its markets), Utility Distribution Companies(UDCs which distribute or deliver electricity), Retail Marketers that include Electricity Service Providers (ESPs which provide competitive energy services), Retail Customers (which acquire and consume electricity), Customers (which acquire and consume electricity) and Generators (which generate electricity).

The California Power Exchange is a wholesale spot market where both buyers and sellers bid in the short-term (real time, hour ahead and day ahead). In a day-ahead spot market, both buyers and sellers submit bids (amounts and prices) and the PX matches buyers and sellers in a non-discriminant auction method which results in a market clearing price every half hour. Besides the California Power Exchange, other power exchanges (also named scheduling coordinators) are allowed and have been set up. These scheduling coordinators can operate a market over a longer forward period than just one day. Similar to the PX, they must match sellers and buyers and submit portfolio requests to the ISO for power transmission. Bilateral trading of power over short or long periods is not only allowed but encouraged, which allows sellers and buyers to make their own deals outside of the power exchange.

The California ISO (Independent System Operator) controls power dispatch to keep the system operating in a secure and stable state; manages the transmission system reliability; provides equitable open access to transmission system although it does not own transmission system; procures ancillary services; coordinates day-ahead, hour-ahead schedules and performs real time balancing of supply and demand. In addition, the ISO also administers congestion management protocols for the transmission system.

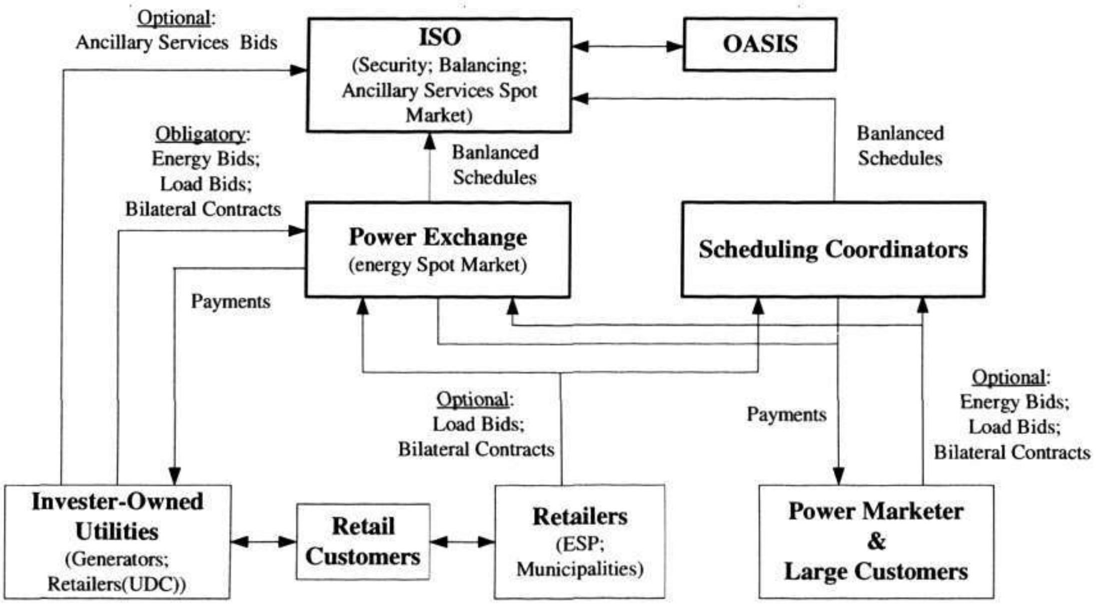

Figure 2-3 Structure of California market

In New England, ISO-New England which took over operation of the New England grid in July 1997 [25], is a single entity that both operates the system and controls commitment of wholesale generation connected to the grid, i.e., it performs both ISO and PX functions. In New England PoolCo, buyers do not bid price, only submit demand needs to the system. Bilateral trading is permitted. The New York ISO (NYISO) was formed in 1998 with the missions to operate the State's major transmission system and to administer an open, competitive and nondiscriminatory wholesale market. The Pennsylvia-Jersey-Maryland Pool (PJM) is the oldest and largest centrally dispatched power pool in the United States [26]. It runs both ISO and PX functions with both buyers and sellers submitting bids.

2.4.5 Canada

The Power Pool of Alberta began operations in 1996 [27] [28]. The electricity market is run by the Power Pool Administrator. The structure of the Power Pool of Alberta is shown in Figure 2-4.

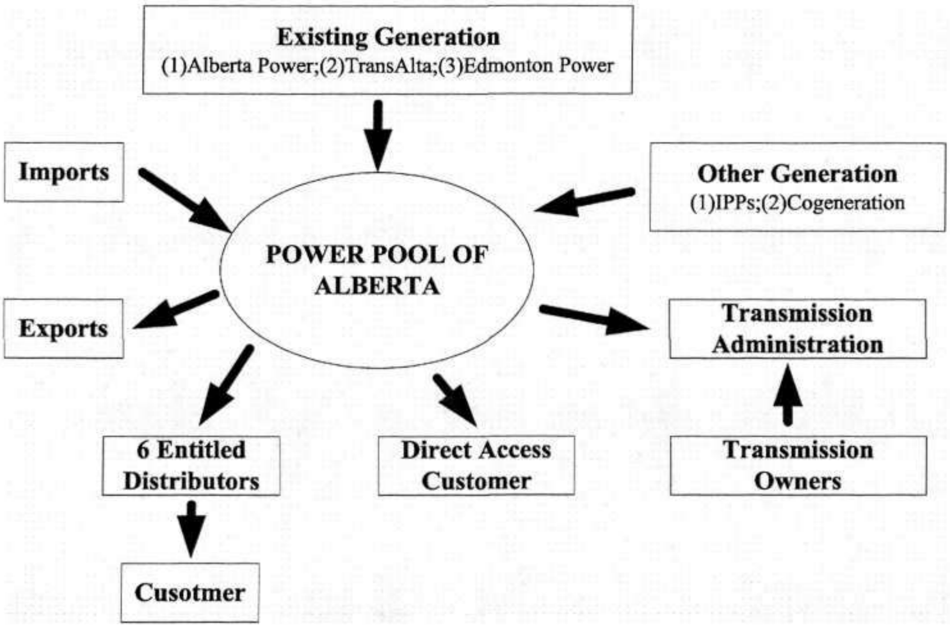

Figure 2-4 Power pool of Alberta

The Power Pool is responsible for the safe and reliable operation of Alberta's electric system. In addition, it is also responsible for market surveillance to oversee market activities to discourage non-competitive practices and to ensure that market participants comply with the related rules and regulations. On a day-ahead basis, both generation companies and electricity purchasers submit offers to supply/buy hourly blocks of energy at specific prices. Offers are submitted for a seven-day period and offer prices for the first trading day cannot be changed. Operating much like a commodity exchange, the Pool ranks offers and bids from least expensive to most expensive, and publishes a schedule for the next trading day. In real-time, the Pool dispatches the required generation, import offers and demand bids to serve the actual system demand and exports. The hourly Pool Price is calculated from the actual dispatch orders and the Pool settles with buyers and sellers each month. All power producers receive the hourly Pool Price for the power generated and all purchasers pay the Pool Price for the power received.

2.4.6 Australian

Since 1991, successive Australian governments have introduced reforms to improve the performance of the electricity supply industry [29]. The National Electricity Market (NEM), which started in December 1998, is a wholesale market for trading electricity in the Australian Capital Territory and the four states, New South Wales, Queensland, South Australia and Victoria. NEM is operated by the National Electricity Market Management Company (NEMMCO) with the functions of managing the operation of the wholesale electricity market and security of the power system. The NEMMCO's market structure is shown in Figure 2-5. Generators provide offers containing the prices and associated quantity of electricity. Generators can self-commit. Retailers and any large consumers submit bids containing prices and associated quantity of demand. NEMMCO dispatches the scheduled generation and demand with the objective of minimizing the cost of meeting the electricity demand. A spot price for each half hour interval for the wholesale electricity is calculated independently of all the other intervals. In NEM, market participants can also engage in financial instrument trading to hedge risks by means of specialized contracts, over-the-counter instruments and exchange-based trading.

In NEM, the approximate nodal spot market is implemented. Each region has a regional reference node at which the regional reference price is calculated. The prices at other nodes within a region are determined by a fixed ratio to the regional reference price. The ratio is the node's reference loss factor and equal to the average of the estimated marginal loss factor over a defined period (usually one year). The simplified models of regulated interconnection lines between regions are also embedded in the market auction algorithm. Deregulation has provided customers with the ability to choose their retailer, which is being introduced in stages [30]. Each jurisdiction's program of retail competition has nominated the deregulation of customer groups in terms of their annual energy consumption. At some stage all customers in each jurisdiction will be able to select their energy retailer.

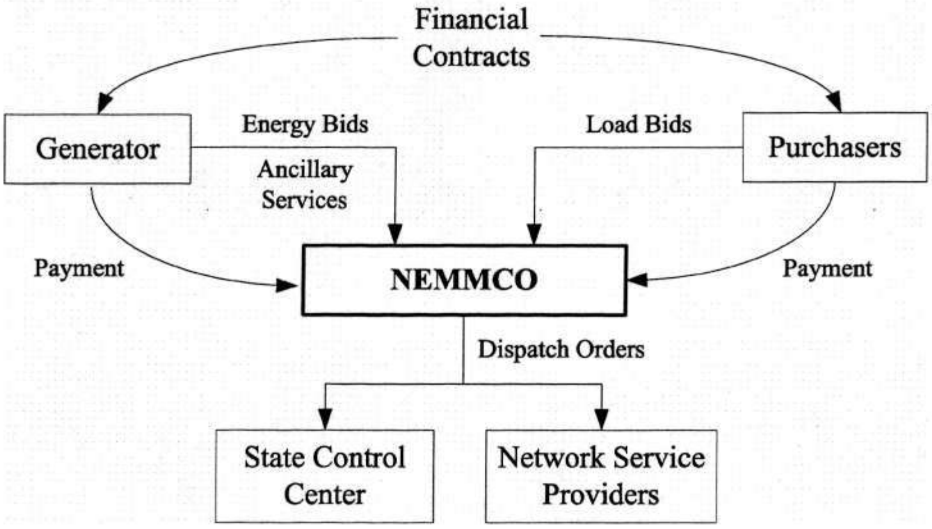

Figure 2-5 NEMMCO's market structure

2.4.7 New Zealand

The electrical industry reforms in New Zealand began in the late 1980s. During the 1990s the electricity industry experienced massive change through extensive reform. The wholesale electricity market, New Zealand Electricity Market (NZEM), was established and operated by Marketplace Company Ltd (M-co) in 1996 [31].

The NZEM is a voluntary multi-lateral trading contract where most New Zealand wholesale electricity sales are transacted. The national transmission grid was owned and operated by Transpower formed as a separate company. It is a voluntary market for centralized clearing of energy generation and demand and for determining reserve requirements and prices. Electricity generators offer electricity and then retailers buy electricity from a pool. By adopting a nodal pricing model, M-co publishes the wholesale price of electricity at each grid point for each half-hour trading period. Electricity is priced at market clearing levels and the price is not capped. This is called a physical "spot" market and is supplemented by trading a range of forward contracts. Companies can also use bilateral contracts to transact electricity off-market.

2.4.8 Singapore

On 1 October 1995, Singapore government began to corporatize and reconstruct the electricity utility [32]. The competition was gradually introduced in power generation and retail to form an electricity market. The Singapore Electricity Pool (SEP) was set up on April 1, 1998 with the purpose of encouraging generation companies (GENCOs) to be more efficient and thereby reducing the cost of electricity [33]. The next phase of the liberation process was started in 1999 when the ministry of Trade and Industry initiated a comprehensive review of electricity. The key point of the review was to implement an electricity market structured and regulatory framework that would support a competitive electricity industry in Singapore, while ensuring that the system reliability and security were maintained. On April 1, 2001, the EMA (Energy Market Authority) was created to regulate the electricity and operate the electricity system. The new company, EMC (Energy Market Company Pte Ltd, an EMA subsidiary company) will operate the new electricity wholesale market. Finally, after the further liberalization of the electricity retail market, the new electricity wholesale market commenced on 1 Jan 2003. The structure of the NEM is shown in Figure 2-6.

In the new wholesale electricity market, NEM, a spot electricity market is operated for the dispatch of generating units. GENCOs offer their price/quantity pairs biddings into the spot market and retail companies only offer their demand. The NEM also has reserve and regulation markets into which GENCOs can offer reserve and Retail companies can offer interruptible load and for which they will be compensated. Based on the biddings, the market operator, i.e., Energy Market Company (EMC), determinates the least-cost dispatch quantities and the corresponding market clearing prices by co-optimized energy, reserve and regulation markets. The system operator, i.e., Power System Operator (PSO) will provide network status and load forecast to EMC and dispatch generating units according to EMC's schedule. The NEM is mandatory for all trading of electricity. However, Contracts for Differences (CfDs) can be utilized by the generation and retail companies to hedge against the volatility of prices. In order to limit the potential for misuse of market power by the GENCOs, in January 2004, the EMA imposed vesting contracts on the NEM. With an appropriately set strike price, vesting contract an also perform the function of stabilizing the price to consumers. GENCOs are required to enter into vesting contracts and the contract quantity and price are determined by EMA. The contract quantity will be set to keep the market power of GENCOs at an acceptable lever. The coverage for the peak load is 65% and 55% for the valley load. The contract price is set at about long-run marginal cost (LRMC) of the most economical generator.

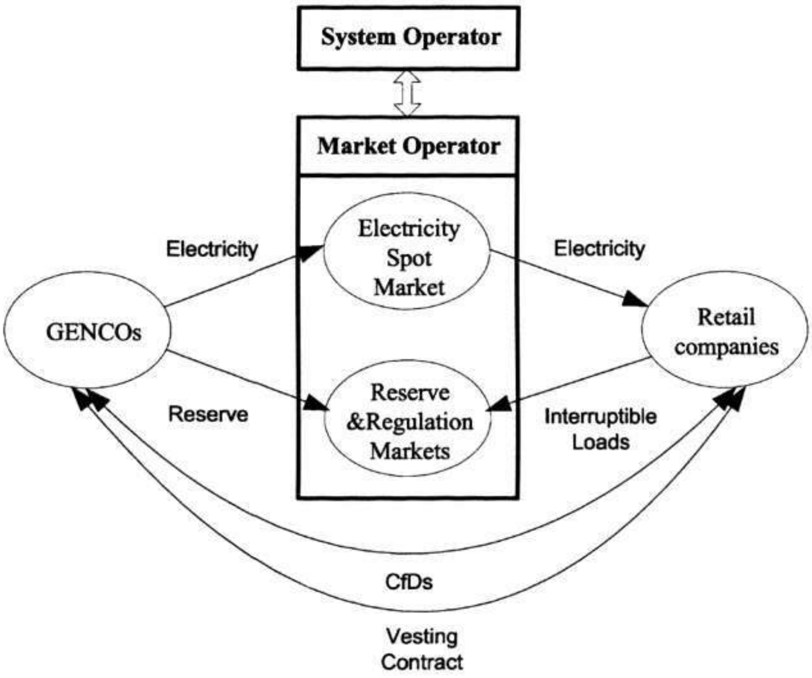

Figure 2-6 New electricity wholesale market of Singapore

2.5 Effect and Performance of Deregulation

2.5.1 Improved Performance

When electricity restructuring and competition programs are designed and implemented well, electricity industry performance can improve significantly. The performance improvements come from a combination of institutional reforms: privatization of state-owned enterprises, vertical and horizontal restructuring to facilitate competition and mitigate potential self-dealing and cross-subsidization problems, performance-based regulatory (PBR) regulation applied to the regulated transmission and distribution segments, good wholesale market designs that facilitate efficient competition among existing generators, competitive entry of new generators, and retail competition, at least for industrial customers [34]. The evidence is compelling, which is shown as below:

1) Privatization and the application of high-powered regulatory mechanisms has led to improvements in labor productivity and service quality in electric distribution systems in England and Wales, Argentina, Chile, Brazil, Peru, New Zealand and other countries [35-37]. An electrical power system that had experienced physical distribution losses due to poor maintenance and antiquated equipment has generally experienced significant reductions in this type of losses. Distribution and transmission network outages have declined. Improved performance of regulated distribution (and sometimes transmission) systems has accompanied privatization and the application of high-powered performance-based regulatory mechanisms has been implemented almost everywhere.

2) The performance of existing generating plants that have been privatized and required to operate in competitive wholesale markets has generally improved dramatically. Old inefficient and uneconomic generating facilities have been retired. Costly political preferences for using domestic fuels and equipment have been undercut by the need for private generation companies to reduce costs to compete successfully.

3) Substantial amounts of capital have been mobilized to support construction of new efficient generating capacity in many countries that have implemented reforms. In the U.S., about 150,000 MW of new generating capacity, most of it merchant capacity, has

begun operating in the last five years. About 40% of the stock of generating plants in service in England and Wales has been replaced with modern efficient combined-cycle gas turbine (CCGT) technology as old coal-burning generators have been closed and expensive dirty coal plants have been displaced by cheaper and cleaner CCGT capacity [35]. Many other countries implementing reforms have also attracted significant investment in both distribution infrastructure and existing and new generating capacity [38].

4) Wholesale electricity prices in England and Wales, in much of Europe [39], in Australia, and in several Latin American countries have fallen (controlling for fuel price changes) as competitive wholesale markets have developed and entry of new generation capacity has expanded supplies and increased competition.

5) Retail electricity prices have become better aligned with electricity supply costs as a consequence of better regulation of distribution and transmission charges and the diffusion of retail competition, especially for larger industrial customers. In some countries this has meant increasing retail prices that previously had been too low, but especially developed countries, retail prices have generally fallen to reflect reductions in costs.

2.5.2 Performance Problems

Electricity restructuring and competition initiatives have also exhibited to a number of performance disappointments and problems, making ongoing reforms necessary. These problems include:

1) The new electricity markets are certainly not perfectly competitive, and as a result, suppliers can increase profits through strategic bidding, or in other words, through exercising market power in spot wholesale power and reserve markets. Significant wholesale market power problems have been identified empirically in a number of countries using both ex post empirical evidence and ex ante simulation models [40, 41]. The problems can be attributed to the interactions between the attributes of electricity

networks noted above, too few competing generation companies, wholesale market design flaws, vertical integration between transmission and generation that creates the incentive and opportunity for exclusionary behavior, excessive reliance on spot markets rather than forward contracts, and limited diffusion of real time prices and associated communications and control technology that facilitates the participant of demand in wholesale spot markets. As a result, market power mitigation strategies have become an important component of wholesale market reforms. However, efforts to mitigate market power with restrictions on bidding behavior and price caps, rather than with structural remedies (e.g. divestiture of generating plants by firms with market power, mandatory forward contracts, and market design improvements), may have caused more harm than good and adversely affected investments in new generating capacity.

2) The most efficient design of spot wholesale energy markets continues to be a subject of dispute among interest groups and independent experts [42-44]. Should the market be built around a pool or rely on bilateral contracts? Should there be locational pricing of energy and operating reserves? How should scarce transmission capacity be allocated? Should transmission rights be physical or financial [45, 46]? Several basic wholesale market design features include the creation of voluntary public spot markets for energy and ancillary services (day-ahead and real time balancing) that accommodate bilateral contracts and self-scheduling of generation; locational pricing reflecting the marginal cost of congestion and losses at each location; the integration of spot wholesale markets for energy with the efficient allocation of scarce transmission capacity; auctioning of (physical or financial) contingent transmission rights that are simultaneously feasible under alternative system conditions to hedge congestion, serve as a basis for incentives for good performance by system operators and transmission owners, and partially to support new transmission investment; an active demand side that can respond to spot market price signals [47]. The allocation of transmission rights can affect the incentives of firms to exercise market power and this should be taken into account in the design of rights allocation mechanisms and restrictions on the entities that can purchase these rights [48].

3) No market design will work well if there are no adequate number of competitive suppliers of generation service or the market power of dominant firms has not been mitigated in some way (i.e., with regulated forward contracts). There should be a large number of competing suppliers of generation service and deep liquid bilateral forward wholesale markets for physical and financial contracts for power.

4) Independent market monitors are necessary to identify behavior by market participants that distorts market prices from competitive levels and market design flaws that create opportunities for market participants to profit from inefficient strategic behavior.

5) Retail competition initiatives have often worked well for large industrial and commercial customers. But the benefits for residential and small commercial customers are yet to be demonstrated compared to alternative procurement arrangements that retain distribution company responsibilities for supplying smaller customers by procuring power in competitive wholesale markets [49]. Providing electricity supplies competitively to small customers is relatively costly and these customers have proven to be quite "sticky", creating potential market power problems. Developing and applying viable models to deliver the benefits of wholesale market competition to smaller customers is an ongoing reform challenge.

6) Stimulating performance improvements in the operation of transmission networks and, especially, attracting adequate investment to reduce congestion and to increase the geographic expanse of competition to reduce market power and the associated need to regulate wholesale markets to mitigate it, has been a challenge. The transmission systems that have exhibited the best performance are organized with a single independent transmission company that spans a large geographic area, integrates system dispatch, congestion management, network maintenance and investment under PBR regulation (e.g. NGC in England and Wales). Fragmented transmission ownership, separation of system operations from transmission maintenance and investment, and poorly designed incentive regulation mechanisms reduce performance [42].

7) Creating appropriate investment incentives for new generating capacity is a growing problem in many countries. The environment for financing new generating investments has changed dramatically in the last two years as a result of financial problems for merchant trading and generation companies in Europe, the U.S. and Latin America as well as macroeconomic instability [38]. Investors are looking for stable market rules and longer term contractual commitments, before they will commit capital. Financing investments in peaking capacity, which relies heavily on wholesale market prices creating "rents" to support fixed investment costs in a relatively small number of hours is especially problematic.

8) Regulatory institutions that are independent, are well staffed and have access to necessary information about costs, prices, and service quality continue to be an important linchpin of successful electricity reform programs. Inadequate attention has been paid to create good regulatory institutions in many countries, especially developing countries.

2.6 Concluding Remarks

In this chapter, the concept of deregulation in the electricity industry is first explained. The background of deregulated electricity market, including the general reasons for electric industry deregulation, the features of deregulation and the major players of electricity markets, is reviewed. After that, the Market Structure and Trading Rules that are closely related to the strategic bidding study are stated. Then the market environment and power trading processes in different countries are reviewed. As there is no common market structure and no common set of trading rules that suit all the situations in different electricity markets, the study of strategic bidding and market power has to be based on certain market structures and trading rules. The effect and performance of deregulation based on the experience of restructuring worldwide are concluded. Significant performance improvements have been observed in many countries as a result of deregulation. Wholesale markets have stimulated improved performance from existing generators and helped to mobilize significant investments in new generating capacity in several countries. However, a number of performance disappointments and problems are still exhibited in electricity restructuring and deregulation. As a result, efforts to create well functioning competitive wholesale and retail markets have also revealed many significant challenges and the restructuring and competition reforms still remain a work in progress in most countries. In all these performance problems, strategic bidding and market power are two of the most significant problems. The exercise of market power by market participants in the deregulated power market may lead to productive and allocative inefficiencies and inefficient signals for new investment, which will badly undermine the benefit and social welfare caused by deregulation. Hence, a strategic bidding study is important for system regulator to recognize market power and improve social welfare. One of the study objectives of this thesis is to empirically analyze the market power in the real electricity market to investigate the strategic behavior of GENCOs. Meanwhile, market power mitigation strategy is also an important component of wholesale market reforms, which will be another study objective of this thesis. The review of the research literature on strategic bidding study and market power in the deregulated electricity market will be summarized in the next chapter.

Chapter 3 A Review of Strategic Bidding and Market Power

3.1 Introduction

In this Chapter, the basic concepts and various aspects of strategic bidding and market power are briefly introduced. A summary of the research work on strategic bidding and market power is given in the following sections with the attempt to classify the research publications related in different ways. The approaches to analyze strategic bidding and detecting market power are outlined. Finally, a review of approaches to curb and mitigate market power is presented.

3.2 Strategic Bidding and Market Power

3.2.1 Defining Strategic Bidding and Market Power

As mentioned before, since the 1980's much effort has been made to restructure the traditional monopoly power industry with the objectives of introducing fair competition and improving economic efficiency. The creation of mechanisms for power suppliers, and sometimes for large consumers, to openly trade electricity is at the core of this change. In a deregulated electricity market, there will be many generation companies competing with each other. In a decentralized electricity market, the power producers make their own generation planning and their financial decisions guided by the objective of maximizing their own benefits. Ideally, the market structure and management mechanisms or rules in an electricity market are sufficiently well designed and competition among participants is sufficiently vigorous to direct the operation of the market towards maximizing social welfare. Social welfare is a combination of the cost of a commodity, in this case energy, and the benefit of the commodity to society as measured by society's willingness to pay for it. A perfect market maximizes social welfare. However, the emergent electricity market structure is more similar to oligopoly than perfect market competition. This is due to special features of the electricity supply industry such as, a limited number of producers, large investments size (barrier to entry), transmission constraints which isolate consumers from effective reach of many generators, and transmission losses which discourage consumers from purchasing power from distant suppliers. All these make it practicable for only a few generation companies to service a given geographic region and in this setting each supplier can maximize profit through strategic bidding, or exercising market power. Strategic bidding, which is the process by which participants in a market develop bids that are aimed at achieving their performance goals [50], has received much attention in recent years. Corresponding to this new emerging competitive environment in the electricity industry, a lot of research works about strategic bidding for power producers/customers in power markets have been carried out. The exercise of market power by market participants in the deregulated power market may lead to inefficient dispatch and other productive inefficiency, high consumer costs and inefficient signals for new investment, etc [4]. In [51], the authors conducted a survey on the study of strategic bidding based on a great number of research publications. It is pointed out in this reference that the study of strategic bidding in competitive power markets is necessary both for the market participants to develop bidding strategies to maximize their own benefits and for market regulators to investigate strategic bidding behavior in order to identify possible market power abuse and to take measures to limit such abuse for building a fair and efficient competitive environment. The focus of this thesis is (i) detecting the market power and analyzing strategic biding behavior and; (ii) curbing and mitigating market power and strategic biding.

In another definition, strategic bidding is the behavior in which a power producer bids other than the marginal cost with the aim of exploiting imperfections in the market to increase its benefits. If the power producer can succeed in increasing its benefits by strategic bidding or by any means other than reducing its costs, it is said to have market power [50]. Market power is typically defined as the ability to profitably alter prices away from competitive levels [43]. In essence, strategic bidding is inherently related to the market power. In practice, the emerging electricity markets are not perfectly competitive and some degree of market power always exists in a practical market. Therefore a power producer can generally increase its benefit using strategic bidding. Based on the above definitions, all the strategic bidding behaviors are about market power.

A distinction should be made with respect to the industry structure to which the concept of market power is being applied. Horizontal market power concerns company behavior in a single market activity (e.g. generation) and is often exercised via control of a significant market share. Vertical market power concerns companies involved in two or more related activities, such as electricity generation and transmission, where dominance in one area is used to raise prices and increase profits in the other activities. Concerns related to vertical market power in the electricity sector are commonly understood and will not be discussed here. The mechanisms for addressing them, such as requirements for independent operation of the transmission system and non-discriminatory access to it are now becoming more widely accepted.

There is also an important relationship between the various electricity energy markets including the spot, day-ahead and forward markets. As noted by [52], in a simple two-period model, generators that have contracted all their energy in the forward market have no incentive to distort the spot price, and will therefore bid competitively. That is, the forward market is a powerful means of mitigating market power in the spot market. In [53], this theory was confirmed by its observation that "the one supplier for which we do not find any significant evidence of withholding had apparently contracted most of the output of its capacity forward.

Another common distinction of relevance is the separation of system-wide market power from local market power. The former refers to market power occurring at the broad market level, typically due to the existence of dominant generators and/or tight supply conditions. Local market power arises when transmission constraints create isolated geographic markets in which the broader market players can only minimally participate. In this thesis, only system-wide market power will be investigated and the impact of transmission capacity is not taken into consideration.

Finally, there is an important distinction between the *potential* for market power and the *actual exercise* of market power. Interest in detecting the actual exercise of market power is deemed by most market regulators as just as important a tool as detecting potential market power. The actual exercise of market power will be detected and analyzed in this thesis.

3.2.2 Sources of Market Power

Broadly speaking, the potential for market power abuse in the restructured power industry appears in two main forms [2, 54].

1) Market Dominance

If one power supplier is large enough to affect price, it has an incentive to restrict output or raise its offer price on marginal units in order to raise the market price on all units in a pool market. Market rules governing the operation of an electricity market and the structure of the market can have a substantial impact on the ability of suppliers to exercise horizontal market power [55]. An example is the England and Wales (E&W) pool where a highly concentrated market may have allowed the two dominant suppliers, National Power and PowerGen, to selectively withdraw capacity during peak periods and increase profit.

Market power can be created or strengthened by the elimination of competitors and potential competitors through horizontal mergers or by collusion. For collusion of suppliers to be successful, suppliers must be able to reach terms that are mutually profitable and also be able to detect and punish deviants who undermine the coordinated action. Factors that tend to facilitate collusion are: 1) a frequently repeated auction for a homogeneous product under similar demand and supply conditions; 2) intimate knowledge of a rival's operating costs; and 3) almost immediate knowledge of a rival's actions.

Generally, several aspects of electricity markets discourage collusive behavior. First, demand conditions vary considerably throughout the day and the actual demand level experienced can vary significantly from the forecast. The uncertainty associated with these variables is compounded by the uncertainty associated with predicting the amount and prices offered by all rivals, given forced outages and system operating constraints. Second, while information regarding power suppliers' operating costs in the past has been publicly available, this historical information is not necessarily indicative of suppliers' likely bid prices, since these operating costs do not reflect startup costs, and are, in many instances, average costs for an entire power plant.

2) Transmission Constraints

The existence of transmission constraints or congestion introduces local or locational market power. A supplier in a region, which has limited ability to import less expensive energy from elsewhere, will be able to exercise market power. Furthermore, transmission constraints make possible the creation of market power in unconventional ways. A supplier can even profit from increasing, rather than decreasing, production at strategic points in the network to intentionally create congestion and limit the access of competitors. In this way, a local submarket will be formed, and the supplier will be at the position of monopoly. There are two ways in which this occurs: radial congestion and the exploitation of network externalities. Radial congestion refers to a simple configuration in which one transmission line (or a set of lines in a "corridor") can be filled to its limit by exporting generation through a rival's low-cost region into a high-cost region. This results in a separation of the markets. Network externalities arise due to interactions in networks with "loops" of various kinds when the actions of one participant at one node foreclose the opportunities of rivals at other nodes. The former is much simpler to model than the latter.

3.2.3 Techniques of Strategic Bidding and Excising Market Power

Based on the methods adopted to study strategic bidding, the approaches can broadly be classified into the following categories, which is similar to the classification on the ways of strategic bidding study reported in [51].

1) Forecasted Market Clearing Price (MCP)

This approach is simple in principle and it relays on estimations of the MCP in the next trading period. Predicting the MCP on a deregulated market is one of the essential daily tasks for a generation company and is the basis for other decision-makings, such as optimizing the bidding strategies. In [56], a new method is developed for time series prediction by combining a Bayesian-based classifier and an auto-regression model. The basic idea is to form a number of classes by discretizing the output and thus converts the time series prediction problem into a pattern classification problem. In [57], a two-level optimization problem is presented for an individual to maximize its benefits. The dispatch and price are determined by the Optimal Power Flow (OPF) and are regarded as the constraint of the problem to determine how a market participant should vary its bid portfolio to maximize its benefit. In [58], the model of energy trading with two-level optimization, a top level of a centralized economic dispatch at which the market price is obtained and a lower level of a set of decentralized bidding subproblems, is considered. The authors present an algorithm to solve the revenue adequacy problem for marginal units with the objective of maximizing revenue.

2) Estimated Competitor's Behavior

Among the methods published so far, probability analysis and fuzzy sets are utilized for estimation. In [59], a model and method for optimization-based bidding and self-scheduling where a utility bids part of its energy and self-schedules the rest as in New England was presented. The model considers Independent System Operator (ISO) bid selections and uncertain bidding information of other market participants.

3) Simulation and Experimental Methods

Bidding behavior of market participants is determined by several factors, such as bilateral contracts, predicted demand, generation reserve and experience from the past. Australia has a significant experience in designing of electricity market structures and construction of market simulators. In [60], a typical bidding behavior of power generators in the Victorian and Australian National Markets was analyzed. In [61], based on the genetic algorithm, a framework is presented in which bidding strategies may be tested and modified as GENCOs and DISCOs trade power. It is pointed out that the simulated electric commodity exchange can be used both to predict whether bid strategies will be profitable and successful off-line and to experimentally verify how bidding behavior affects the competitive electric marketplace.

4) Game Theory

Game theory is a discipline that is used to analyze problems of conflict among interaction decision makers. It may be considered as a generalization of decision theory to include multiple players or decision makers [62]. To put it simply, it's a study of ways to win in a situation given the conditions of the situation of other players. Game theory can be used to predict important trends and it has been widely applied to carry out bidding strategy studies in the electricity market. Game theory can be classified into two areas: cooperative and non-cooperative. Beginning from some earlier models used in games, such as Cournot, Bertrand and Stackelberg, many of the important developments in the field has taken place during the past decades. The best known among these is the concept of Nash equilibrium. Nash equilibrium can be used in both cooperative and non-cooperative games. In cooperative games, [63] describes an open access transmission method for maximizing profits in a power system. The proposed method in [63] is based on the Nash bargaining game for power flow analysis in which each transaction and its optimal price are determined to optimize the interests of individual parties and in [64], this approach was also used to simulate the decision making process for defining offered prices in a deregulated environment which is used by the system regulators to discourage unfair coalitions. [65] is an example that Nash equilibrium is used in a non-cooperative game. In [65], the competition among pool participants is modeled as a non-cooperative game with incomplete information. Under the assumption, the game with incomplete information is transformed into a game with complete, but imperfect information and solved using the Nash equilibrium idea.

Among the techniques mentioned above, the game theory based method is most suitable to analyze the behavior in an oligopolistic electricity market. The game theory based method can offer sufficient flexibility for representing the market and institutional features of oligopoly such as the number of firms in the market, the nature of interaction among these firms, the legal and regulatory frameworks that determine the organisation and operation of the market and so on. Computable equilibrium models enable the analyst to build a model, such that deviations from the perfectly competitive market to imperfectly competitive market are captured by parameters in the model. The methodology of game theory will be used in this thesis to analyze the strategic behavior and market power.

As for market power, how market power is exercised depends on the exact structure of the market, and in particular the price-setting mechanism. However, the primary methods of exercising market power are:

1) **Physical or quantity withholding:** which involves deliberately reducing the output that is bid into the market even though such output could still be sold at prices above marginal cost. Withholding can be done through not bidding, de-rating, or declaring unit outages.

2) **Financial or economic withholding:** which involves bidding in prices higher than the competitive bid for the particular unit.

3) **Transmission related strategies:** which involves creating or aggravating transmission congestion in order to raise prices in a particular zone or node. Insufficiently unbundled generators can achieve this through outages of transmission, understating transmission ratings/capacity, and dispatch of generation deviating from marginal cost.

From an analytical perspective these strategies (especially the first two) are often equivalent. For example, a shift in the supply curve could be a leftward shift due to reduced output or an upward shift due to increased price depending on which company has withdrawn output or raised their bid price [43].

3.3 Approaches to Analyze Strategic Bidding and Detect Market Power

Analyzing strategic bidding and detecting market power is never an easy task and doing so in electricity markets is no exception. However, there are features of electricity markets that assist in the detection of market power that are not present in most other markets. For example, in electricity pools, most spot-markets generators bid their willingness to provide output for their entire range of market prices (whereas in other markets we typically only observe the market clearing price and quantity data). One useful consequence is that it is possible to construct actual residual demand curves for individual market participants. The elasticity of this residual demand curve provides a direct measure of potential market power, as discussed below. Another feature of most electricity markets is that technological data such as generation heat rates and capacity are often available to monitors because many generation units were formerly state-owned or under a cost-regulation regime or are technologically standard units for which there is publicly available cost data. Thus forming estimates of costs is perhaps more precise than in other industries. Another useful feature of the electricity industry is that the overwhelming contribution to short-run variable costs is the cost of fuel, for which prices are usually readily available.

A considerable amount of literature has presented various indices and models to detect market power. An ideal index of market power is one that provides in a simple number a measure of the ability to exercise market power. The test of its suitability is its ability to predict the exercise of market power, or its correlation with the excess of the market price above a reference benchmark competitive level. The indices and models of detecting market power will be reviewed in the following sections [2, 12, 43, 51, 54, 66, 67].

3.3.1 Structural Indices

A natural starting point in discussing measures of market power is the structural indices of traditional industrial organization theory. Some of the earliest work in market power in electricity markets [68] was based on analyzing the market share and the Herfindahl-Hirschmann Index. Criticisms of these measures, in particularly the appropriateness of these static measures in a dynamic market such as electricity, has led to the development of other indices which take into account demand conditions and not just the supply side (e.g. the pivotal supply index). The aim of this section is to briefly review the features and applications of these indices.

1) Market Share

Concentration indices are usually simple scalar metrics that measure the supplier concentration of a market. The motivation behind these indices is that the more concentrated a market, the more likely is the ability of its participants to exercise market power. The two most commonly used concentration indices are market share and Herfindahl-Hirschman Index (HHI).

The market share concentration ratio is the percentage of market share of the largest n companies in the industry. In order to calculate this index, some preliminary definitions need to be made. Firstly, the relevant product needs to be identified. In electricity markets the choices can include energy production, energy plus reserves, short-term capacity or long-term capacity. Normally, electricity in different half-hours may not be readily substitutable, so a time dimension (e.g. month winter peak-hours) may also be needed. The second preliminary definition concerns the geographic boundaries of the market: who should be considered competitors of a company? Once the product and market boundaries have been determined, the index is easy to calculate and can be used in long term studies as well as close-to-real-time screening. Market share is easy to understand and only require sales or capacity data to calculate. However, most users of this index are aware that it has serious limitations: i) it ignores demand side, strategic incentives and often congestion issues, ii) it does not fit well to dynamic market conditions and iii) it has difficulties determining appropriate geographic region.

2) Herfindahl-Hirschman Index (HHI)

One of the criticisms of the market share index is that the ability of a company with a 20% market share to exercise market power may be different when that company is the largest player in a largely deconcentrated market, versus being the second or third largest player in a highly concentrated market. An attempt to address this systems aspect of market power is the Herfindahl-Hirschman Index (HHI). The HHI is calculated by taking the sum of the squares of the respective market participant's market shares:

$$HHI = \sum S_i^2 \qquad \sum S_i = 100\%$$

where S_i is the percentage market share of company *i*. As the HHI is composed of company level market shares, the same issues of product and market size definitions obviously have to be addressed here as well.

In evaluating the significance of a particular HHI, the results can be broadly characterized into three regions:

- unconcentrated (HHI below 1000),
- moderately concentrated (HHI between 1000 and 1800),
- highly concentrated (HHI above 1800).

A major criticism of market share and HHI analysis for electricity markets is that even where the most dominant net seller has a relatively small market share (say less than 10%), they may still be able to exercise market power. This is seen as a consequence of being a static measure and examining only the supply side of the market. Electricity market conditions change hour by hour due to changing demands levels, generation outages, transmission failures, etc. Most significantly, during periods when the system demand is close to capacity, a supply can become 'pivotal' and exercise market power even with a relatively small market share. [69] points out that under certain definitions of the relevant market, no single supplier in California had a 20% market share during the California crises, yet many would argue that the market was not workably competitive.

3) Pivotal Supplier Indicator

The pivotal supplier indicator is an attempt to incorporate demand conditions, in addition to supply conditions, in a measure of potential market power. This indicator examines whether a given generator is necessary (or 'pivotal') in serving demand. In particular, it asks whether the capacity of a generator is larger than the surplus supply (the difference between total supply and demand) in the wholesale market. Reference [70] defined the Pivotal Supplier Index (PSI) as a binary indicator for a supplier at a point in time which is set equal to one if the supplier is pivotal, and zero if the supplier is not pivotal. The PSI from each hour over a period of time (e.g. one year) can then be aggregated to determine the percentage of time for which a company achieves pivotal status. The Supply Margin Assessment (SMA) is the name of the pivotal supplier indicator adopted by FERC in 2001 as a market power screen to replace the 20% market share screen. Many of these criticisms, however, are not of the concept of the pivotal supplier index but of its implementation.

4) Residual Supply Index

The Residual Supply Index (RSI) is similar to the PSI but is measured on a continuous scale rather than a binary scale. As such the index addresses the criticism of the PSI in that it may be possible for a company to exercise market power when it is nearly, but (as the PSI shows) it is not actually pivotal. The RSI was developed by the California Independent System Operator (CAISO). The residual supply index for a company *i* measures the percent of supply capacity remaining in the market after subtracting company *i*'s capacity of supply.

5) Residual Demand Analysis

Residual demand analysis is a more sophisticated measure of the incentive of a company to exercise market power that is derived from examining the residual demand curve faced by a company. The residual demand curve is calculated by subtracting from the total demand curve all the offer curves bid into the market by other participants. Of course, in real time the company does not know exactly the residual demand curve it faces. However, it can be constructed ex-post. As mentioned earlier, one of the advantages of electricity markets is that such data for constructing residual demand curves actually exists.

In a competitive market, a company will face a highly elastic residual demand curve and will have no ability to raise prices above the competitive level via any amount of withholding. At the other extreme, if a company is pivotal (as defined above), then it faces a highly inelastic residual demand curve and will suffer little loss in sales by charging a high price. In the intermediate cases, a company may not be strictly pivotal (in terms of total market capacity) but may still face a range of prices for which it may be able to exercise some market power depending of the degrees of residual demand elasticity. In electricity markets, the empirical work employing residual demand analysis has been conducted to measure the incentives of the five largest electricity suppliers in California to exercise power in the state's wholesale market during 1998-2000 [71].

A limitation of this analysis is that it has, so far, not taken into account transmission constraints in constructing the residual demand curves. Such constraints would have the effect of decreasing the residual demand elasticity and thus increasing the potential to exercise market power.

3.3.2 Behavioral Indices and Analysis

Whereas structural indices look to find the potential for market power, behavioral indices typically examine the actual conduct of companies, looking for evidence of the exercise of market power. This often involves examining individual bid prices and quantities. Normally, high prices (or low quantities offered) are not, in and of themselves, evidence of market power. The challenge therefore is to develop meaningful indices and analyses that can discriminate between high prices resulting from genuine scarcity as opposed to the exercise of market power. The problem that often arises, however, is that such analysis often requires detailed data for which there are issues of availability, access and confidentiality.

1) Bid-Cost Margins

In a competitive market, price-taking companies should bid at marginal cost. Therefore, the comparison of a generator's bid with its marginal cost is an important measure in determining the exercise of market power in electricity markets. If a company is frequently bidding in prices well in excess of marginal cost (whether it is setting the system price or not), it may well be exercising market power. Therefore there have been a number of empirical studies examining bid and cost data seeking to determine the extent to which market power has been exercised. The results of these studies are usually expressed in terms of the Lerner Index (LI) or Price-Cost Margin Index (PCMI):

$$LI = \frac{P - MC}{P}$$

$$PCMI = \frac{P - MC}{MC}$$

where P is the market clearing price and MC is the marginal cost of a GENCO.

A perfectly competitive market is presumed to offer no margin above marginal cost, and hence the LI and PCMI are zero.

One of the earliest examples of price-cost margin analysis was [72] which analyzed bid and marginal cost data for the two large conventional generation companies in the England and Wales pool from May 1990 to April 1991, using the electricity pool bid data and generator cost estimates derived from published thermal efficiencies and fuel prices. Their evidence showed that for the first 7-9 months of the market's operation, both National Power and PowerGen bid very close to their (estimated) marginal costs in most periods. By early 1991 however, bidding behaviour had changed and both of the generators were increasingly bidding above their costs. More recent studies include [73] and [74], where the authors not only try to demonstrate the existence of market power but also attempt to explain the variations in the Lerner Index with reference to structural and other factors.

One of the great difficulties of this empirical work is determining the appropriate marginal cost. The approximation most commonly used is the variable fuel cost of the generator, calculated from fuel prices and thermal efficiencies (heat rates). However there are problems with this approach:

- There are other variable costs that are difficult to quantity, such as commitment decisions and increased cost of equipment degradation if used outside of designated parameters.
- Variable costs do not necessarily approximate marginal costs for units with substantial opportunity costs (e.g. hydro electricity resources, generation with significant environmental restrictions, export market alternatives) [75].
- Variable costs data may be confidential and difficult to obtain and audit.
- Questions remain over whether the appropriate measure is long run marginal cost rather than short run marginal cost.

Thus given all these issues, even if a study uncovers a large price-cost margin, it is still difficult to say conclusively whether this is due to abuse of market power or estimation error.

An alternative to comparing bids with estimates of marginal costs is to compare bids with prior bids submitted by the same company when the market was assessed to be competitive. However, variations in bids are still possible, given changes in costs, even in a competitive market, so prior bids or "reference" bids are usually indexed to fuel and other costs, thus reintroducing most of the previous criticisms of estimating marginal costs. Nevertheless, screening tools using such approximated reference bids can be used to identify changes in bidding patterns that fall outside of established thresholds.

2) Net Revenue Benchmark Analysis

Another type of analysis employing cost data is net revenue benchmark analysis. As well as indicating the possibility of abnormal profits due to market power, tracking net revenue in markets with price-cap mitigation may also useful to determine if peak generation earns enough revenue to cover fixed costs.

In the long run, the revenues from the energy, capacity, and ancillary services markets should cover the costs of a new generating plant, including a competitive return on investment. Revenues consistently below this level would discourage entry into the market, eventually putting upward pressure on prices. On the other hand, revenues above this level should lead to new entrants and exert downward pressure on prices. The margin between a plant's market revenues and its variable costs (primarily fuel for fossil units) contributes to the recovery of its fixed costs, including non-variable operating and maintenance expenses and capital costs. This margin can be estimated, given the variable costs of a typical new generating unit, hourly energy-clearing prices in the region, and estimates of capacity and ancillary services revenue. In a competitive market without market failures competitive entry would occur with the most cost effective technology. This suggests that net-revenue does not need to cover fixed costs of existing technologies.

In a recent study of the New England electricity markets, in [42] the author used a form of net revenue benchmark analysis to demonstrate that energy markets do not provide sufficient scarcity rents to recover the annualized fixed costs (defined as amortized capital costs plus fixed operating and maintenance costs) of a unit operating only during periods of scarcity. The author concludes that, without enhancements, the existing New England energy and reserves markets are unlikely to provide the necessary incentives for investment in new generating capacity to maintain existing reliability levels.

3) Economic Withholding

In [43], the author has argued that the most basic approach to detecting market power is to look for "missed opportunities": If a generator would profit (in expectation) from the sale of an additional unit of electricity, assuming the market price would not change, and the generator chooses not to sell, it has exercised market power. Thus, according to this view, the focus on assessment of market power in electricity should not be on price but on output, looking for generation capacity that would have been profitable to run at prevailing market prices, but was not.

The aim of "withholding analysis" is to identify generation capacity that would have been profitable at prevailing market prices but was withheld from sale. As mentioned earlier, there are two types of withholding – economic withholding, where output is reduced because it is bid into the market above competitive prices, and physical withholding, where output is not bid into the market at all. Economic withholding is examined here and physical withholding is discussed in the next section.

Economic withholding is measured by estimating an "output gap", which is defined as the difference between the unit's capacity that is economic at the prevailing market price and amount that is actually produced by the unit. This measure was introduced by [53] in an analysis of market power in the California electricity market.

The simplest definition of the output gap is: $Q_i^{econ} = Q_i^{prod}$ where Q_i^{econ} is the economic level of output for unit *i* given the market price and competitive bid for the unit, and Q_i^{prod} is the actual production of unit *i*.

A positive value of an estimate of the output gap implies the existence of economic withholding, to the extent that there is no other explanation for the gap. Where this gap is small (e.g. less than 1% of capacity) it may provide some comfort that economic withholding is not a serious problem. However, as with price-cost margins, the margin of error in estimating a number of inputs to this index leaves open to question the significance of any particular result. What may be more useful is relating the output gap to incentives to exploit market power.

4) Physical Withholding

With physical withholding, the generator's resources are not bid into the market (physically withdrawn) by declaring a "derating" of the generating unit, i.e., lowering the unit's high operating limit.

The derating quantities analyzed usually exclude planned outages and long-term forced outages because they are much less likely to constitute strategic physical withholding and including them could mask true physical withholding.

Using derating data to determine the exercise of market power faces very similar issues to output gap analysis: unit outages and other deration occur under perfectly competitive conditions as well as noncompetitive condition. The evidence of deration alone cannot provide evidence for the exercise of market power. However, similar statistical methods to those described in output analysis can be used to evaluate the pattern of deratings that may signal a physical withholding concern.

3.3.3 Simulation Models

Most of the above indices are constructed as simple ratios or differences using market or structural data. In this section we look at more sophisticated modelling exercises which attempt to simulate some aspects of the market for the purposes of ex-post comparison with actual market outcomes or ex-ante simulations of possible market outcomes given a particular market structure and design.

1) Competitive Benchmark Analysis

The basic idea of competitive benchmark analysis is to develop an estimate of the market price that would result if all companies behaved as price-takers (i.e. if no company attempted to exercise market power) and to compare that price to the observed market price. Compared to the simple application of the Lerner Index to the actual price-setting (marginal) producer (as discussed above with bid-cost margins), this form of analysis does not assume that the marginal producer in reality is the same as the marginal producer under competitive conditions. As with simple bid-cost margin indices, the determination of an appropriate competitive benchmark is not uncontroversial.

The most common form of competitive benchmark analysis involves estimating the marginal cost of production of the marginal generator by simulating a hypothetical competitive market. This is done by collecting data on the generation technologies that are present in the market and then estimating a supply curve for each trading period by stacking generators from the least expensive to most expensive.

Applied to the U.K electricity market in [40], this approach was refined to include detailed production data [41] as well as environmental costs [53] in studies of the California market. In [76], the authors adapt this approach to the PJM market.

As with the use of simple bid-cost margin, the major concern with this type of analysis is the simplifications that are typically required in order to construct the marginal costs estimates. Examples of these simplifications include modeling in a static setting, not incorporating start-up costs or minimum load effects, and condensing the market into a single location with a single price. The danger is that these simplifications may in fact underestimate marginal cost by not correctly incorporating the complexities of the real electricity market [77]. Thus in a review of a number of competitive benchmark market simulation models, [78] concludes: Drawing inferences regarding competition based on comparisons between actual prices and those simulated in these simple models could produce substantial errors. The difference between the actual and simulated prices could arise from the real-world constraints omitted from the model in conjunction with purely competitive behavior, or the difference could arise from the exercise of market power by sellers that are able to raise prices because of constraints omitted from the model. One simply cannot tell from these simulations. The error is larger than the effect being estimated.

2) Oligopoly Simulation Models

Oligopoly simulation models are perhaps one of the most powerful tools in exploring market power by explicitly incorporating into one model many of the structural, behavioral and market design factors that are related to market power, including concentration, demand elasticity, supply curve bidding, forward contracting, and in some cases transmission constraints. Using a game theoretic framework these models can be calibrated with cost data to predict the market prices or Lerner Index of a market with a given structure and design.

Probably the most popular model of behavior is Cournot competition under which companies choose their levels of output knowing that their strategy and the strategies of other companies will affect the market equilibrium. However, it is not clear whether it is the best model of the behavior of electricity generators, as generally companies can also choose the prices at which they offer electricity. The well known alternative is the Bertrand model of oligopoly in which participants choose prices to sell their output. However, in [79], the author contends that Bertrand competition is inappropriate because it assumes that each company can expand output sufficiently to serve the entire market, which is unlikely to be the case in electricity markets. Indeed, [80] has shown that models of Bertrand competition with capacity constraints may have equilibria that are closer to the Cournot outcome. In [81], the author provides a solution to a model of oligopoly in which companies choose a "supply function" relating their quantity of output to the market price, which is close approximation of what usually happens in electricity marketplace. However, a drawback of this method is that there may be a wide range of possible equilibria.

The cost of such flexibility in modelling market power is the difficulty associated with determining a number of inputs into the model. For example, the level of forward contracting or demand elasticity is often an educated guess and unfortunately the results are often sensitive to these assumptions. However, to the extent that these assumptions remain constant under comparative analysis (e.g. how will the competitiveness of the market change if the number of market participants increase from 2 to 4) the analysis is still valuable.

In an interesting line of research, some researchers have used detailed data on demand and generator bids and marginal costs to compare actual bid curves to the theoretical benchmark ex-post optimal bids. In an analysis of the Texas balancing market, [82] found, for large companies, a close fit between the actual bid schedule and the ex-post optimal bid schedule. The authors believe that this is a confirmation that strategic equilibrium models such as the supply function equilibria (SFE) models are accurate descriptors of strategic agents.

Transmission constraints can isolate markets and enhance market power. Several models of strategic interaction on networks have been developed [83, 84]. Most models of generator competition take a general approach of defining a market equilibrium as a set of prices, generation amounts, transmission flows, and consumption that satisfy each market participant's first-order conditions for maximizing their net benefits while clearing the market. If a market solution exists that satisfies this set of conditions, it will have the property that no participant will want to alter their decisions unilaterally (as in a Nash equilibrium). Although it is recognized that no modeling approach can precisely predict prices in oligopolistic markets, there appears to be agreement that equilibrium models are valuable for gaining insights on modes of behavior and relative differences in efficiency, prices, and other outcomes of different market structures and designs. Equilibrium market models differ in many ways, including the market mechanisms modeled, the type of game assumed, fidelity to the physics of power transmission, and computational methods. Regarding market clearing mechanisms, most studies of generation markets implicitly or explicitly assume a single buyer or "pool"-type centralized bidding process supervised by an Independent System Operator (ISO). This process results in a set of publicly disclosed market clearing prices. The method used in this thesis could be ranged in the oligopoly simulation models. These assumptions will also be made in this research work.

3.3.4 Transmission Related Issues

Transmission constraints can allow for the exercise of market power along different categories.

First, if transmission constraints are explicitly addressed in the market design, either using nodal or zonal pricing or using physical transmission contracts, then bids that create constraints change the price received by all local generators. This can make an import constraint even more profitable for the generators affected by it, since all of their output, rather than just the (perhaps relatively small) amount needed to relieve the constraint, gets a high price. In contrast, it is no longer profitable to create export constraints, as they reduce local spot prices and therefore revenue, rather than increasing revenue in re-dispatch. [85] shows for explicit treatment of transmission constraints that it can be profitable for generators to withhold output in order to constrain a transmission line into the location of the generator that would not have been constrained under perfect competition.

Second, transmission contracts, both physical and financial, can enhance the market power of generators and provide financial incentives to change output decisions of generators even as transmission constraints are and remain constrained. This was first addressed by Hogan in [86]. It was shown in [45, 46] that physical and financial transmission rights have almost identical properties.

Finally, particular opportunities to exploit market power might arise in settings with physical transmission contracts, as for example between Germany and the Netherlands. Market participants might, for example, participate in the transmission auction but subsequently not use their transmission contracts to earn extra profit.

3.4 Approaches to Control Strategic Bidding and Mitigate Market Power

As mentioned previously, some special factors of electricity production and consumption make it particularly susceptible to market power. The two most important factors are: i) Electricity cannot be stored cheaply (except in hydro facilities), which, along with binding, short-run capacity constraints, makes the supply response relatively inelastic; and ii) Demand price-responsiveness of electricity customers is limited and therefore very inelastic. The combination of inelastic supply and demand facilitates the exercise of market power when total demand moves closer to total supply capacity during peak demand periods. The electricity industry also has characteristics that tend to assist in tacit collusion among its participants. As a result, the electricity industry requires special remedial treatment as compared to other industries. Market mitigation methods can be loosely collected into three main categories, which are outlined below.

3.4.1 Structural Solutions

1) The divestiture of the dominant generator

The classical structural solution to the problem of market power is to mandate or encourage the divestiture of the dominant generator or generators. This will reduce the market share of dominant suppliers, and move the market closer toward competition. One of the earliest examples of this was in the UK, where the conventional generation units of the formerly state-owned monopoly were split into two new companies, which in turn were later encouraged to further divest their assets. Divestiture has also been used to enhance competitiveness in California, Australia, New Zealand and Argentina.

2) Ease of Entry

The regulator can mitigate market power by encouraging more suppliers to enter the market since the threat of entry is an effective deterrent to the exercise of market power. Barriers may include licence conditions, generation site permits, and non-discriminatory access to the transmission network. To this end, entry must be "easy" and would be if: 1) timely, i.e., within a sufficiently short period; 2) likely, i.e., profitable; and 3) sufficient, i.e., of large enough magnitude.

3) Expansion of Transmission Network

When transmission congestion is the driver of market power abuse, changing or expanding the network may be appropriate since network enhancement can eliminate this type of local market power. However, since expansion of the network can induce significant changes to the power flow in other parts of the system as well, this approach may not always be popular since some market participants may dispute the right of the system operator to dramatically change the market in this way.

4) Demand Side Bidding

The importance of price-response demand in an electricity market in mitigating market power has been well recognized, and much research work has shown that the lack of real-time price responsiveness on the part of most electricity customers in the E&W [87] and California [79] markets exacerbated the potential for market power abuse in peak load hours. Hence, policies that promote the responsiveness of consumers of electricity to short-term price fluctuations can have a significant effect on reducing market power problems.

3.4.2 Regulatory Solutions

1) Price Cap

A price cap provides an upper limit to the pool price. Proponents of price caps claim that caps can reduce market power. Opponents point to the artificial nature of price caps, and claim that very high prices are not necessarily a sign of market power abuse. Instead, the high prices can be considered a signal to the market of the need to build new generation and/or eliminate transmission congestion. If the price cap is set too low, it can artificially depress prices and interfere with price signals for new entrants. Hence, price caps may be more appropriate as a short-term measure.

2) Contract Based Methods

Intuitively, long-term contracts, physically or financially, play a significant role in reducing the incentives of the dominant suppliers to exercise market power. This is because the more of a supplier's output that is covered by contract(s), the less of an incentive it will have to participate in the spot market.

The effect of long-term contracts on mitigating market power has been examined for the E&W market [88]. In the initial operation stage, the existence of Contracts for Difference (CfD) which covered a very high percentage of the two dominant power suppliers' combined capacities reduced significantly the incentives to bid strategically into the pool. The pool price in 1991 was 25 percent below the government's expectation at the time of privatization. The first trenche of CfD expired in March 1992. Pool prices in August 1992 were some 17% above those in August 1991. It is believed that the large portfolio of CfDs has led to low and volatile pool pricing in 1991, and that the pool prices rose after a significant CfDs expired in 1992. These phenomena explain the role of contracts in mitigating market power. Similar evidence is observed in the former Victoria Pool and the current National Electricity Market of Australia [89], in which the vesting contracts and hedge contracts contribute to the reduction of electricity price in the spot market.

Another regulatory tool is to require dominant generators to sell a certain amount of their capacity under long-term contracts at a pre-negotiated or regulated rate. Where governments have privatized generation companies they have frequently provided them with so-called "vesting contracts" as a transitional tool in the development of competitive electricity markets. In the markets where the vesting contracts were imposed, the reduction in the market clearing price was observed. For example, in January 2004, the Energy Market Authority of Singapore (EMA) imposed vesting contracts on the Singapore Electricity Market. The coverage is 65% and 55% for the peak load and valley load respectively [9]. The Singapore Electricity market observed about a 10% drop in energy price after installing a vesting contract.

In other cases, governments may provide private generation companies with Competition Transition Contracts to allow them to recover stranded costs incurred under a previous cost-based regulatory regime (as in Spain and California).

In cases where local reliability considerations require a generator at a specific location to be on-line in some hours, the related localized market power can be dealt with by signing Reliability Must Run (RMR) contracts with the supplier [62], as is the case in California.

3.4.3 Market Rules Solutions

This type of market mitigation methods are those market rules or behavioral regulations aimed at the actual operations or decisions of the generators in electricity markets. The most important of these include caps on unit-specific bidding. These are often regarded as the most heavy-handed form of regulation and most liable to have unintended undesirable side effects. They also often require specific company related information that may be difficult to acquire. Most economists would argue that the market rules mitigation solutions should be used as transitional devices on the road to fully competitive markets or only under rare market conditions, rather than a foundation upon which to operate the market.

3.5 Concluding Remarks

There is a growing consensus that the market monitoring process is an essential part of a well functioning electricity market. There are sound theoretical reasons and supporting evidence for suspecting that electricity markets may be unusually susceptible at times to the exercise of market power, compared to other markets. The sources of market power could be market dominance and transmission constraints. As new electricity markets are more similar to oligopoly markets, GENCOs could improve their profit by strategic bidding. There are various techniques to perform strategic behavior. The game theory application will be the strategic bidding model to study in this thesis, for the game theory based method is the best way to analyze the strategic behavior in an oligopolistic electricity market.

A considerable amount of literature has presented various indices and models to detect market power. Within these ways, the oligopoly simulation model method is perhaps one of the most powerful tools. This method explicitly incorporates many of the structural, behavioral and market design factors, which are related to market power, into one oligopoly model to explore market power. This thesis will empirically analyze GENCOs strategic behavior based on the historical data in the electricity market. Several classical oligopoly models like Cournot, Bertrand and so on will be used as the benchmark to analyze the potential market power.

As mentioned in the previous section, because of some special features of the new electricity market, GENCOs will find relatively easier to exercise market power. As a result, more special remedial treatment to mitigate market power would be required as compared to other industries. Theoretically, perfect competition, where no market participants can deliberately exercise market power to affect the market prices, should be the most desirable objective to be aiming at. However, most economists would agree that it is far more costly to eliminate all market power for perfect competition than to allow some market power to exist. For example, even though there are potential market power consequences, there are efficiency benefits of providing flexibility to supply bids as well. Similarly, price caps could control market power, but the use of price caps has created an enormous debate regarding their effect on revenue sufficiency for peaking plants. As a result, perfect competition is not necessarily the appropriate standard to be aiming at. Economists generally refer to "workable competition" as a competitive standard with an acceptable level of market power. In this thesis, vesting contract, which is one of contract based methods, is used to mitigate market power. With an appropriately set strike price and amount, Vesting Contracts can perform the function of stabilizing the price and also limit the potential market power to a desirable level.

Chapter 4 Strategic Bidding and Market Power Analysis Based on Conjectural Variation

4.1 Introduction

As mentioned previously, because the new electricity markets are more similar to oligopoly markets than a perfectly competitive market, strategic bidding and market power exercising by GENCOs could seriously undermine the competition and market efficiency, which is the major objective of deregulation. Therefore, it is very important for a system regulator to analyze the competitiveness of a set of GENCOs and to recognize strategic bidding behavior and curb market power.

Three main approaches are often used for generation firm strategic bidding. They are market clearing price (MCP) forecasting, rivals' bidding curve modeling and rivals' strategic behavior simulation in game-theoretic contexts. The third approach of game theory applications is suggested for generation firms to make strategic bidding based on rivals' strategic behavior. The study in this chapter will be based upon the game theory application on strategic bidding for its suitability to analyze the strategic behavior in an oligopoly market.

Recently, the conjectural variation (CV) method is proposed to estimate the strategic behavior in the game-theoretic context in terms of imperfect information available in actual electricity market. The concept of conjectural variation was brought forward by Bowley in 1924, but named as 'conjectural variation' by Frisch in 1933. The conjecture of a firm is defined as its belief or expectation of how its rivals will react to the change of its output. The CV based bidding strategy (CVBS) method can help generation firms to improve their strategic bidding and maximize their profits in actual electricity spot markets with imperfect information. It is shown in [90] that classical game theoretical bidding strategies (GTBS) including Cournot, Bertrand, and Monopoly and so on, are special cases of CVBS families, and the system equilibrium reached via CVBS is a Nash equilibrium. This chapter presents a theory and method for the empirical estimation of the conjectural variation. By investigating the estimated conjectural variation, the market structures and static GENCOs' behaviors can be analyzed. As a result, the understanding of the nature and root of market power can be obtained. However, in the electricity market, each GENCO learns from other GENCOs' behaviors and modifies its behavior over time. An empirical dynamic behavior analysis based on conjectural variation is also introduced to examine the dynamic strategic interaction between GENCOs. The Australia National Electricity Market (NEM) is utilized as an example test system to validate the proposed method.

This chapter is arranged as follows. A review of strategic bidding behavior and market power analysis methodology based on conjectural variation is introduced in Section 4.2. Section 4.3 introduced the basic game theory concepts. Perfect competition and several classical oligopoly models are presented in Section 4.4. The concept of conjectural variation (CV) and its applications in electricity spot markets are introduced in Section 4.5. In this section, the relations between CVBS and GTBS are also presented. Section 4.6 presents the theoretical framework of measurement method for estimating conjectural variations. The proposed method is used to empirically analyze the static strategic behavior of GENCOs in the Australia National Electricity Market (NEM). Section 4.7 shows an empirical and statistical methodology to analyze the dynamic interaction between GENCOs. The market dynamic behavior of GENCOs in the NEM is analyzed and discussed in the same section based on the proposed method. Section 4.8 presents the conclusions.

4.2 A Review of Strategic Behavior Analysis Methodology Based on Conjectural Variation in the Electricity Market

Market power can result from a number of factors such as strategic bidding, topology, congestion, and so on. In [91], market power could also appear as a consequence of the operation of the reservoir in hydrothermal systems. However, in the decentralized electricity markets, which are carried out in many countries worldwide, GENCOs have to make their own decisions about the unit commitment and only provide their quantity-price bidding curve. Under such circumstances, the most straightforward way for a GENCO to exercise market power is to perform strategic bidding. One of the easiest ways is to bid high. However, as the regulator approximately knows the cost of specific unit, this strategy cannot be realized. Another way to exercise market power is by withholding capacity, which can cause more expensive units to operate and raise the market clearing price. In [92], the authors have observed that in the England & Wales Electricity Market GENCOs exercise a strategy of withholding capacity during peak loads to let high-cost units set market price. In addition, various academic studies and government agencies have examined and investigated how to analyze the potential for market power in the electricity market. Traditionally, estimation and prediction of market power has relied heavily on market share and other concentration measures such as the Herfindahl-Hirschman Index (the sum of the squared market shares for each firm in the industry). The first efforts by the Federal Energy Regulatory Commission (FERC) in USA to analyze the potential of market power have focused primarily on this way. The FERC has proposed that market concentration measures should be used as the foundation of screening the horizontal market power [93]. In [94], the authors have doubted the approach taken by FERC using market share and other concentration measures as an indicator of possible market power. It was pointed out that these types of measures fail to account for inelastic electricity demand, the GENCOs' incentives, and the possibility of entry by competitors. Alternatively, a number of papers have focused on simulating the deviation of actual prices from competitive prices by estimating generators' marginal costs. In [41], a perfectly competitive market is simulated using data from June 1998 to October 2000 in the California electricity market. By comparing the simulating perfectly competitive price with the actual price in the market, significant departures from competitive pricing were found, particularly during the high-demand summer months. Meanwhile, a common way of measuring this deviation above was by constructing a price-marginal cost margin (or Lerner index) calculated as $(p - MC)/p$. Green and Newbery [95] use actual demand data from the England and Wales market along with the marginal cost estimates to simulate the spot price. Depending on the demand elasticity assumptions, the implied Lerner index markups range from 28% up to 65% for the existing duopoly GENCOs in the market. Although studies mentioned above show evidence of market power existing in the electricity markets, there has been no clear understanding about the GENCO's behavior and market framework underlying these electricity prices, which notably deviate from the perfectly competitive prices. For example, the price-cost margins could have resulted from GENCOs behaving less competitively on a highly elastic demand function or GENCOs behaving competitively on a less elastic demand function. Therefore, a natural question to ask is what kind of oligopoly behavior and market structure the price-cost margins should be based on. Several oligopoly equilibrium models such as Cournot, monopoly and Bertrand models, which are three most classical oligopoly models, are used to analyze the market power in electricity market. For instance, the Cournot model provides a general approach to analyze the market behavior in the oligopolistic electricity market when GENCOs make decisions independently and simultaneously and in non-cooperating case. In [79], the authors have analyzed the electricity market power issue in California using the Cournot models based on historical data.

When market power is suspected to be present based on estimating the index like Lerner index, the regulator can exercise one or two options. A common option is the capping of bidding price to less than several times, say four times, the average price of electricity. However, this has a direct effect on the day to day electricity price and could distort the system marginal price. Alternatively, when power companies make excessive profits, the regulator could suggest to the government to exercise a 'wind fall' tax on those excess profits. However those approaches are not ideal as they could mask the real market trading situation. It would greatly strengthen any suggested actions by the regulator if he could identify which particular generators are exercising market power individually. The use of conjectural variation method is suitable for such an analysis. The conjectural variations model attempts to understand pricing behavior by generalizing how GENCOs react to changes in the strategic decisions of other GENCOs. The magnitude of this strategic reaction influences the competitiveness of an industry and the oligopoly behavior of each GENCO. In the conjectural variation model, each GENCO in the oligopolistic electricity market strategically maximizes its profit while taking reactions of its rivals into account. Conjectural variation of GENCOs may have various values, which shows different market behaviors performed by GENCOs. For instance, in Bertrand, Cournot, or Monopoly models, each GENCO has its corresponding value of conjectural variation respectively, which could be used as the benchmark for analyzing the market structure and the behavior of GENCOs. By empirically comparing estimates of conjectural variation in real markets with these benchmarks, the market structure and strategic behavior of each GENCO could be analyzed. This chapter proposes a methodology to estimate the conjectural variation and investigate the strategic behavior of the GENCOs.

The conjectural variation based method has been introduced to manage strategic bidding and analyze the market power in actual electricity markets. The conjectural supply function is proposed to simulate the electricity market of Spain effectively [96]. In [90], the concept of conjectural variation (CV) and its application in electricity spot markets are introduced. It presents CV based bidding strategy (CVBS) method, which can help GENCOs to improve their strategic bidding and maximize their profits in actual electricity spot markets with imperfect information. The three classic oligopoly models mentioned above are special cases of CVBS families. The values of CV of GENCOs in these three classical oligopoly models are also given in [90]. All values of conjectural variation in [90] are assumed as given. In [97], a theory and method for empirical estimation of the conjectural variations of GENCOs are presented. As a result, the values of conjectural variation of GENCOs can be estimated based on the historical market data in the real electricity market. Then the conjectural variation of GENCOs can be used to analyze the static market behavior of oligopolists. That is to analyze whether Bertrand, Cournot, or Monopoly is supported by the mean estimated conjectural variations via comparing the estimations with these three benchmark models. These three classical models of oligopoly result from postulating how GENCOs make this profit maximizing output choice. In economic terms, the central question of the maximum problem concerns how one GENCO assumes other GENCOs react to its decisions. In Bertrand model, as in the case under perfect competition, each GENCO is assumed to be a price taker. Cournot model assumes that each GENCO recognizes that its own decisions about its output affect price, but that its output decisions do not affect the output of other GENCOs, i.e. each GENCO treats the output level of its competitors as fixed. The monopoly model assumes that GENCOs as a group recognize that they can affect the market price. It also assumes that they collude and manage to coordinate their decisions. Generally, different oligopoly models mean that the intensity of competition of these solutions is different. At one extreme is Bertrand (Perfect competition), characterized by price-taking behavior by participants. Profit-maximizing behavior of firm results in producing the output level at which price equals marginal cost. The degree of competition in this case is most intense. At the opposite extreme, a Monopoly consists of a single producer that faces the entire market demands of a product. There is no competition existing in this case. The monopolist maximizes its profit by producing the output level at which its marginal revenue equals marginal cost and charging a price above the socially optimal price, which is marginal cost. The output of monopoly is much less than the output in the perfect competition market. The degrees of competition of Cournot lie between these two extremes. So it can be seen that if the GENCO behaviors could be estimated, the competitiveness of a set of GENCOs and market power in the market could be analyzed accordingly.

The market power exercising by GENCOs can be analyzed based on the market behaviors. A number of papers have investigated the static behavior of firms [98]. However, in real life, GENCOs play a repeated game. It can be imagined that a GENCO can develop its behaviors by learning the behaviors of its rivals. As a result, tacit collusion may be facilitated by the daily repetition of the bidding game between a set of GENCOs with information about their rivals' behaviors. Thus, the dynamic strategic interaction is a very important aspect of strategic bidding study in the oligopolistic electricity market. The dynamic interaction among GENCOs in the actual electricity market will be investigated using time series historical data in this paper. Based on this investigation, one can also test whether GENCO behavior is more consistent with unilateral market power or tacit collusion.

The simplest way to approximate the dynamic behavior is the repetition of static snapshot of Bertrand, Cournot, or Monopoly. That is a GENCO performs any one of these three classical types in each period through the periods. Alternatively, GENCOs may switch their behavior in periods depending on the actions of GENCOs in the previous periods. There may be several ways to act in this dynamic interaction. One way is that firms use a grim trigger strategy to keep the Monopoly outcome. A firm begins by cooperating in the first period and continues to cooperate until a single defection by its opponent, following which the firm performs punishment behavior forever [99]. More complex dynamic model is a regime-switching model proposed by [100]. In this model, GENCOs switch between periods of punishment such as Cournot outcome and periods of tacit collusion. But in this model, punishment lasting for a particular number of periods will be required. In this chapter, empirical investigation whether GENCOs switch back and forth between two particular regimes, i.e. collusion and non-collusion (price war) will be carried on. The dynamic market behaviors of GENCOs can be understood through a thorough investigation.

4.3 Basic Game Theory Concepts

Game theory is the study of multi-person or multi-firm decision-making problems [101]. In the field of industrial organisation in economics, game theory is used extensively to study auction behaviour, bargaining, principal-agent relationships, product differentiation, and strategic behaviour by firms.

The strategic (or normal) form representation of a game includes three components [102]:

- the set of players, $i \in \{1, \cdots I\}$, in the game, which is assumed finite;
- the pure strategy space, S_i, which contains the individual strategies available to player *i*, $s_i \in S_i$, where s_i is an arbitrary strategy;
- the pay-off function for each player *i*, $\pi_i(s)$, which gives player *i*'s payoff for each strategy profile or play of the game, $s = (s_1, s_2, \cdots s_I)$, where s_i ($s_i \in S_i$) is the action taken by player *i*.

It is useful to classify games on the basis of (i) the timing of moves and (ii) uncertainty about the payoffs of rivals [103]. In a static game each player moves once, and when a player moves she does so not knowing the action of her rivals. In a dynamic game, players move sequentially and have some idea, perhaps imperfect, about what their rivals have done; that is, players are at least partially aware of the actions taken by others so far. In a game of complete information, players know not only their own payoffs, but also the payoffs of all the other players. In a game of incomplete information, players know their own payoffs, but there are some players who do not know the payoffs of some of the other players. Therefore, four types of games are distinguished:

- Static games of complete information
- Dynamic games of complete information
- Static games of incomplete information
- Dynamic games of incomplete information

The games that firms play can be either *cooperative* or *noncooperative*. A game is *cooperative* if the players can negotiate binding contracts that allow them to plan joint strategies. A game is *nocooperative* if negotiation and enforcement of a binding contract are not possible.

Game theoretic analysis is built on two fundamental assumptions:

- **Rationality:** In a game, a player often takes the form of a rational individual or a profit-maximising firm. Each player's objective is not to "defeat" the other players (denoted –*i*), i.e. its rivals, but to maximise its pay-off function from playing the game. Playing the game to achieve this objective may 'benefit' or 'harm' other players in the game.
- **Common Knowledge:** Common knowledge means that all players know the structure of the game and that their opponents are rational, that all players know the structure of the game and that their opponents are rational, and so on.

In essence, the gaming and strategic decision making are all about the following question: *if I believe that my competitors are rational and act to maximize their own profits, how should I take their behavior into account when making my own profit-maximizing decision?*

To determine the likely outcome of a game, an equilibrium must be available. An equilibrium concept is a solution to a game. The equilibrium concept identifies, out of the set of all possible strategies, the strategies that players are actually likely to play. The most common equilibrium concept used is Nash Equilibrium. A Nash equilibrium is a set of strategies such that given the action of its opponents each player is doing the best it can. In another word, a Nash equilibrium is a 'best response', in the sense that no player has an incentive to deviate from its strategy choice, given all other players' strategy choices. In a Nash equilibrium, each player will decrease its pay-off if it deviates from its Nash equilibrium strategy, assuming all other players continue to play their existing strategies.

A formal definition of Nash equilibrium is given as [101]:

Definition: In the n-player strategic form game, $G=\{S_1,\cdots,S_n;\pi_1,\cdots\pi_n\}$, the strategies ($s_1^*,\cdots,s_n^*$) are a Nash equilibrium if, for each player *i*, s_i^* is player *i*'s best response to the strategies specified for the other (n-1) players, $(s_1^*,\cdots,s_{i-1}^*,s_{i+1}^*,\cdots,s_n^*)$, such that $\pi_i(s_1^*,\cdots,s_{i-1}^*,s_i^*,s_{i+1}^*,\cdots,s_n^*)\geq\pi_i(s_1^*,\cdots,s_{i-1}^*,s_i,s_{i+1}^*,\cdots,s_n^*)$, for every feasible strategy $s_i\in S_i$.

4.4 Perfect Competition and Oligopoly Market Models

In the deregulated environment, the market model on which the strategic bidding study is based can generally include two types: Perfectly competitive and oligopoly models. In a perfectly competitive market, no participant holds significant market power in equilibrium. For example, in a perfectly competitive electricity market, all the power producers bid their unit variable production costs, the resulting market clearing price of electricity is the value given by the short-term marginal cost of electricity generation. In practice, the market is not perfectly competitive but some degree of market power always exists. Another kind of model is oligopolistic. Oligopoly exists when there are a small number of participants selling in a single market. The situation differs from perfect competition because each firm is large enough to have a significant effect on the market price. In the oligopolistic model, the outcome of one market participant's decision depends on its rivals' choices and each market participant takes into account its competitor's probable choice when it takes an action itself. For each participant, a dominant strategy exists if its choice is the best one irrespective of its rivals' choice based on the analysis through game theory. There are three classical oligopoly models, which will be introduced below.

The general formulation of the imperfectly competitive model is as follows. Each firm's decision problem is to maximize its own profit (π_i), given a market clearing price $P = P(Q) = P(q_1 + q_2 + \cdots + q_N)$ and the firm's total costs $C_i(q_i)$. The profit will be

$$\pi_i = P(Q)q_i - C_i(q_i) \tag{4.1}$$

where i = 1, 2, ... , N refers to individual firms and non-subscripted terms refer to the parameters of market [104].

The models of oligopoly result from assuming how firms make this profit maximizing output choice considering other firms' reaction to its own decisions. A popular approach about how to capture these strategic considerations relies on the tools of game theory to examine strategic choices in a simplified setting. According to game theory, a market is said to have achieved a Nash equilibrium if, given the equilibrium price and quantity, no market participant has any incentive to change its behavior.

Models in common use are discussed in detail as follows [104]:

- **Betrand Model**

As in the case under perfect competition, each firm in a Betrand model is assumed to be a price taker. The Bertrand model assumes each firm to maximize profits on the presumption that the other firm will not change its price. In this case the first order condition for profit maximization is that

$$\begin{gathered} \frac{d\pi_i}{dq_i} = P - \frac{dC_i}{dq_i} = 0 \\ or \\ P = MC_i(q_i) \end{gathered} \tag{4.2}$$

As a result, even though *N*, the number of firms, may be small, the assumption of price-taking behavior results in a perfectly competitive outcome.

- **Monopoly (Collusion) Model**

The monopoly model assumes that firms as a group recognize that they can affect the market price. It also assumes that they collude and manage to coordinate their decisions. In this case the collusion group acts like a multi-plant monopoly and chooses the total market output ($q_1 + q_2 + \dots + q_N$) so as to maximize the total monopoly profits Π.

$$\begin{aligned}\Pi &= \sum_{i=1}^{N} \pi_i = P(Q)Q - \sum_{i=1}^{N} C_i(q_i) \\ &= P(q_1 + q_2 + \cdots + q_N)(q_1 + q_2 + \cdots + q_N) - \sum_{i=1}^{N} C_i(q_i)\end{aligned} \tag{4.3}$$

The first order conditions for maximum total profit $\Pi = \sum_{i=1}^{N} \pi_i$ are

$$\begin{aligned}\frac{d\Pi}{dq_i} &= P + (q_1 + q_2 + \cdots + q_N)\frac{dP}{dq_i} - MC_i(q_i) \\ &= P + Q\frac{dP}{dQ}\frac{dQ}{dq_i} - MC_i(q_i) = P + Q\frac{dP}{dQ} - MC_i(q_i) \\ &= MR(Q) - MC_i(q_i) = 0\end{aligned} \tag{4.4}$$

where $\frac{dQ}{dq_i} = 1$ as $Q = q_1 + q_2 + \cdots + q_N$. Equation (4.4) holds because the total revenue depends on the sum of all collusion members' output levels, and the marginal revenue is the same no matter whose output level is changed. Because this coordinated plan requires a specific output level for each firm, the plan will also dictate how monopoly profits earned by the monopoly are to be shared.

- **Cournot Model**

Cournot model assumes that each firm recognizes that its own decisions about its output q_i affect price, but that its output decisions do not affect the output of other firms, i.e. each firm treats the output level of its competitor as fixed. That is, each firm recognizes that $(\frac{dP}{dq_i} \neq 0)$ but assumes $(\frac{dq_j}{dq_i} = 0)$ for all *j* not equal to *i*. Using these assumptions, the first order conditions for a profit maximum can be derived as follows:

$$\frac{\partial \pi_i}{\partial q_i} = P + q_i \frac{\partial P}{\partial q_i} - MC_i(q_i) = 0 \tag{4.5}$$

The firm assumes that changes in its output level q_i affect its profits only through their direct effect on the market price. The above equation together with the market clearing demand equation $P = P(Q) = P(q_1 + q_2 + \cdots + q_N)$, will permit an equilibrium solution for the production levels $(q_1, q_2, \cdots, q_N)$. Note that the market price *P*, from the profit maximizing condition $P = MC_i(q_i) - q_i \frac{dP}{dq_i}$, is greater than the marginal cost $MC_i(q_i)$, since the term $\frac{dP}{dq_i}$ is negative.

Specially, market equilibrium under an oligopoly can occur at many points on the demand curve. In Figure 4-1, the Bertrand (Perfect competition) equilibrium occurs at point C, the Cournot equilibrium at point B, and the monopoly (collusion) equilibrium at point A. In general, the Bertrand (Perfect competition) equilibrium and the monopoly (collusion) equilibrium will provide the limits within which equilibrium will occur. The Cournot equilibrium represents an interior point. Many other solutions may occur between points A and C, depending on the specific assumption made about firms' strategic interrelationships.

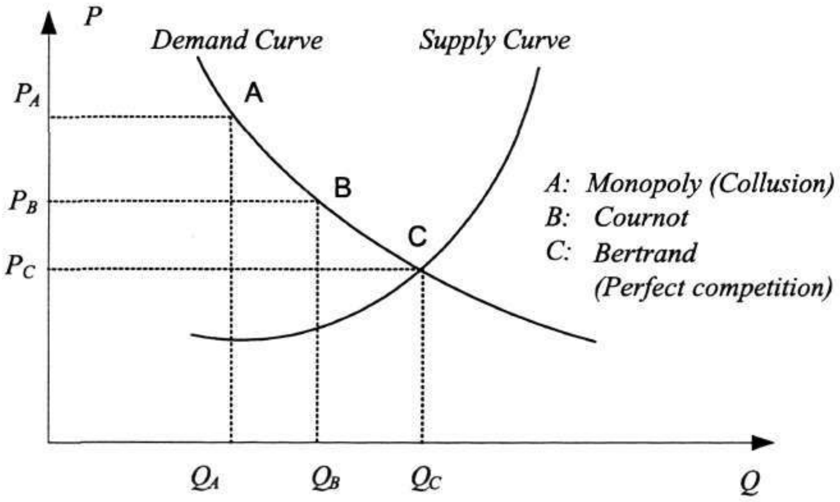

Figure 4-1 Alternative solutions to the classical oligopoly models

At the same time, different solutions between points A and C mean that the intensity of competition of these solutions is different. Figure 4-2 illustrates the relationship between the level of competition and market type. At one extreme is Bertrand (Perfect competition), in which all participants are price takers. There will be the most intense degree of competition in this case. The opposite extreme is a monopoly market, where a single producer provides the entire market demand. No competition exists in this case. The degree of competition of Cournot and other oligopoly models lies between these two extremes.

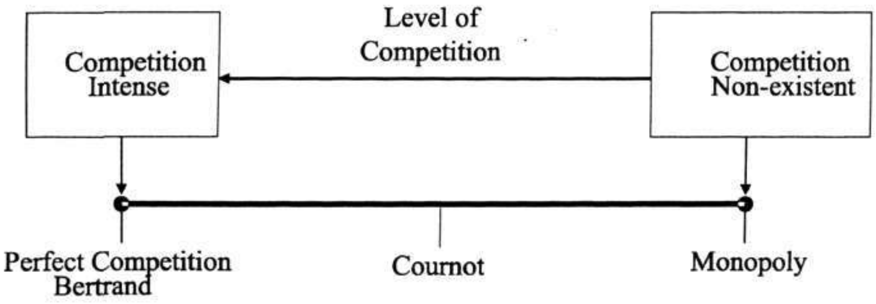

Figure 4-2 The degree of competition in oligopoly

For a typical electricity market, it can be assumed that the market participants are composed of several big power producers with relatively large market shares (such as big generation utilities) and a lot of small producers (such as Independent Power Producers and small utilities). The behavior of big producers may affect the price in the power market and thus the decision of the big producers depends on their rival's behaviors. Therefore, it will be appropriate to apply oligopoly model to study the strategic behaviors of the big producers. On the contrary, the effect of a small producer's behavior on the power price is relatively small and can generally be ignored. Therefore, the small producers can reasonably be regarded as price-takers in the study and the effect of their behaviors on the power price is ignored.

4.5 Methodology of Conjectural Variation Based Bidding Strategy

In this section, the concept of conjectural variation (CV) which has been discussed in [105-108] and its applications in electricity spot markets are introduced as follows.

4.5.1 Mathematical Model for CV Based Bidding in N-player Spot Market

Let's consider a N-GENCO market with homogeneous product. Assume the market price p is

$$p = p(D) = p(Q) \tag{4.6}$$

Meanwhile, Q is the total product quantity of all GENCOs and D is the total demand of the whole market

$$D = Q = q_1 + q_2 + \ldots + q_N = \sum_{i=1}^{N} q_i \tag{4.7}$$

where q_i $(i = 1, \cdots, N)$ is the individual product quantity of GENCO i.

Assuming that each GENCO is rationally aiming at maximizing its profit via optimizing q_i, then the corresponding optimization problem for GENCO i $(i=1,\cdots,N)$ can be defined as:

$$\begin{aligned} &\max_{q_i} \pi_i = R_i(q_i) - C_i(q_i) = p(Q)q_i - C_i(q_i) \qquad (i=1,\cdots,N) \\ &s.t. \quad \begin{cases} Q = \sum_{i=1}^{N} q_i \\ q_{i\min} \le q_i \le q_{i\max} \end{cases} \end{aligned} \tag{4.8}$$

where $R_i(q_i)$ and $C_i(q_i)$ are the revenue and cost function of GENCO i respectively. From the first order condition

$$\frac{d\pi_i}{dq_i} = 0 \tag{4.9}$$

(4.10) is obtained:

$$\begin{aligned} MR_i(q_i) - MC_i(q_i) &= \frac{d(p(Q)q_i)}{dq_i} - c_i(q_i) \\ &= \frac{dp}{dQ}\left(1 + \sum_{j=1, j\neq i}^{N} \frac{dq_j}{dq_i}\right)q_i + p - c_i(q_i) = 0 \end{aligned} \tag{4.10}$$

where $MR_i(q_i)$ is the marginal revenue and the marginal cost of GENCO i is $MC_i(q_i) = c_i(q_i) = \frac{dC_i(q_i)}{dq_i}$.

For simplicity, assume the inverse demand curve i.e. the price function is $p(Q) = e - fQ$, where e and f are known constants and every GENCO has quadratic cost function $C_i(q_i) = a_i + b_i q_i + 0.5 c_i q_i^2$, where a_i, b_i *and* c_i are coefficients of the cost function of GENCO i.

Then, derived from (4.10), the strategic bidding for GENCO i can be obtained as follows:

$$q_i = \frac{e - f\sum_{j=1, j\neq i}^{N} q_j - b_i}{f(2 + \sum_{j=1, j\neq i}^{N} \frac{dq_j}{dq_i}) + c_i} \tag{4.11}$$

$p(q_1, \cdots, q_N)$ is assumed to be known by all GENCOs based on historical data, i.e. for a linear inverse demand function $p= e\text{-}fQ$, (e, f) are known, while $C_i(q_i)$ is only known by GENCO i itself. It is clear from (4.11) that GENCO i can make optimal decision q_i if and only if it can estimate q_j and $\frac{dq_j}{dq_i}$ for all individual $j = 1, \cdots, N(j \neq i)$ correctly; and that there is no need for GENCO i to know its rivals' cost functions.

However, it is very difficult for GENCO i to estimate individual q_j and $\frac{dq_j}{dq_i}$ for all $j = 1, \cdots, N(j \neq i)$ without knowing their individual production cost functions. A practical approach can be worked out via aggregating all $j = 1, \cdots, N(j \neq i)$ into one pseudo-competitor denoted as (-i), i.e.

$$q_{-i} = \sum_{j=1, j\neq i}^{N} q_j = Q - q_i \tag{4.12}$$

$$CV_i = \frac{\partial q_{-i}}{\partial q_i} = \sum_{j=1, j\neq i}^{N} \frac{\partial q_j}{\partial q_i} \tag{4.13}$$

From (4.13), *the conjecture variation (CV_i) of a firm is defined as the conjecture or belief of how its rivals will change their output responding to its output change,* which is known from industrial organization theory [80]

Therefore, (4.11) can be rewritten as follows:

$$q_i = \frac{e - fq_{-i} - b_i}{f(2+CV_i)+c_i} \qquad (i=1,\cdots,N) \tag{4.14}$$

From (4.14), it can be seen that if and only if GENCO *i* can estimate the aggregate information of q_{-i} and $CV_i = \frac{dq_{-i}}{dq_i}$, it can make optimal decision q_i according to (4.14) without difficulty, which means that only the group (-*i*) behavior ($CV_i = \frac{dq_{-i}}{dq_i}$, q_{-i}) is useful for GENCO *i* to make optimal decision although other GENCOs may have totally different market positions (leader, follower, price-taker etc.) and bidding strategies. This feature can significantly reduce the difficulties for individual GENCOs to make optimal decisions. In this section, CV_i is treated as a "static" value as it is given.

4.5.2 Nash Equilibrium via CVBS

When individual GENCOs hold different conjectures CV_i, different equilibria will be generated in the market (see (4.11) and (4.14)), one of the most significant characteristics of CVBS method is that the equilibria through CVBS are Nash equilibria [90].

Proposition: When time goes to infinite and after infinite times of repeated bidding, if every GENCO *i* (*i* =1, ..., *N*) tends to have constant CV_i, denoted as CV_i* and each GENCO is rational and makes decision according to (4.14), and if the market can reach an equilibrium, then the equilibrium is a stable equilibrium, and the corresponding bidding strategies $q^* = [q_1^*, q_2^*, \cdots, q_N^*]^T$ is also a Nash equilibrium, which satisfies

$$Aq^* = B \tag{4.15}$$

where

$$A = \begin{bmatrix} f(2+CV_1^*)+c_1 & f & \cdots & f \\ f & f(2+CV_2^*)+c_2 & \cdots & f \\ & & \cdots & \\ f & f & \cdots & f(2+CV_N^*)+c_N \end{bmatrix}$$

$$B = \begin{bmatrix} e-b_1 \\ e-b_2 \\ \vdots \\ e-b_N \end{bmatrix}$$

and b_i and c_i $(i=1,\dots,N)$, e and f have the same meanings as before; and CV_i $(i=1,\dots,N)$ is the constant belief held by GENCO i on its pseudo-competitor's reaction when time goes to infinite. The proof is presented fully in APPENDIX A.

4.5.3 Comparison of CVBS with Classical Game Theoretical Bidding Strategies

4.5.3.1 Duopoly Case

Classical game theoretical bidding strategies (GTBS) are widely used in various market structures. Three dominant market structures, i.e. monopoly (or collusion), Cournot, and Bertrand (or perfect competition), are used to demonstrate the relation of CVBS w. r. t. classical GTBS approaches.

Let us consider a classical duopoly with identical cost functions: $C_i(q_i) = a_i + b_i q_i + 0.5 c_i q_i^2$, where $a_i = c_i = 0,\ b_i = b (i = 1, 2)$, and the inverse demand is $p = e - f(q_1+q_2)$ with $f = 1$.

1) Monopoly:

Both GENCOs incorporate (collude) to each other, and make decision to optimize their total profit of them. Therefore, their objective function becomes

$$\pi = \max\ p(q_1 + q_2) - \sum_{i=1}^{2} C_i(q_i) \tag{4.16}$$

According to (4.16), the optimal solutions for both GENCOs can be expressed as follows:

$$q_1^* = q_2^* = \frac{e-b}{4} \tag{4.17}$$

If both GENCOs take their CVs as 1, the same optimal solution can be derived from (4.14) of CVBS model,

$$\begin{cases} q_1^* = \dfrac{e - q_2^* - b_i}{2 + CV_1} = \dfrac{e - q_2^* - b}{3} \\ q_2^* = \dfrac{e - q_1^* - b}{2 + CV_2} = \dfrac{e - q_1^* - b}{3} \end{cases} \Rightarrow q_1^* = q_2^* = \frac{e-b}{4} \tag{4.18}$$

which means that the tacit collusive case by GTBS is a special case of the CVBS approach.

2) Cournot, and Bertrand (Perfect competition):

It is easy to prove that when $CV_i = 0$ ($i = 1,2$), the market is indeed Cournot competitive with $q_1^* = (e-b)/3$; and when $CV_i = -1$ ($i = 1, 2$), the market becomes Bertrand competitive with $q_1^* = q_2^* = (e-b)/2$.

The optimal (q_i^* and Q^*) by GTBS and the optimal (CV_i, q_i^* and Q^*) by CVBS for different market structures are listed in Table 4-1 and plotted in Figure 4-3. It can be seen that the optimal solutions from GTBS for various typical market structures are within the CVBS solution family of line segment AC, since it is well known that the real market will be settled at a point between monopoly and perfect competition solutions, i.e. $(e-b)/2 \leqslant Q \leqslant (e-b)$ (see Figure 4-3).

Table 4-1 CV Method vs. Classical Market Structure (Duopoly case)

Market Structure	GTBS		CVBS		
	q_i^*	Q^*	CV_i^*	q_i^*	Q^*
Monopoly (A)	$(e-b)/4$	$(e-b)/2$	1	$(e-b)/4$	$(e-b)/2$
Cournot (B)	$(e-b)/3$	$2(e-b)/3$	0	$(e-b)/3$	$2(e-b)/3$
Perfect Competition (C)	$(e-b)/2$	$(e-b)$	-1	$(e-b)/2$	$(e-b)$

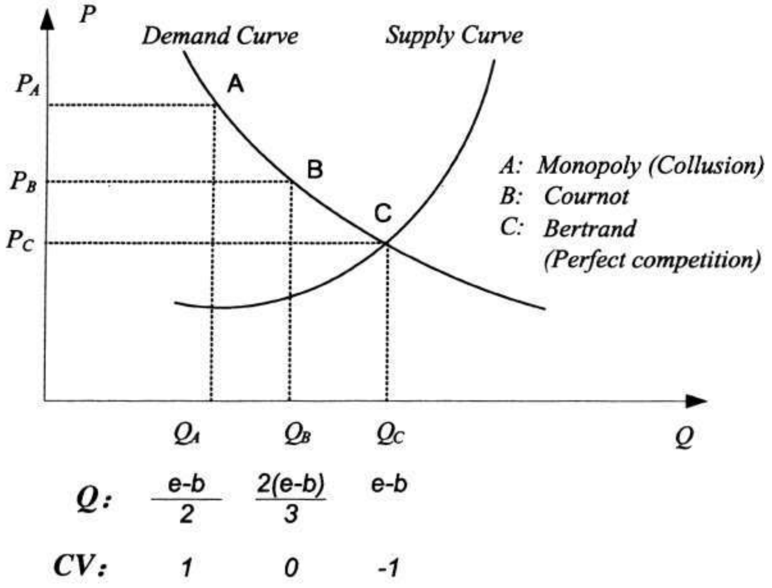

Figure 4-3 CVs in classical market structures (Duopoly case)

4.5.3.2 Multi-player Case

Let us consider multi-player case with cost functions: $C_i(q_i) = a_i + b_i q_i + 0.5 c_i q_i^2$, where the inverse demand is

$$p = e - fQ = e - f\sum_{i=1}^{N} q_i \tag{4.19}$$

where $Q = \sum_{i=1}^{N} q_i$

1) Monopoly:

All GENCOs collude to each other, and make decision to optimize their total profit. So their objective is to maximize the total benefit of the monopoly.

$$\max_{q_i} \pi_i = pQ - \sum_{i=1}^{N} C_i(q_i) = p\sum_{i=1}^{N} q_i - \sum_{i=1}^{N} C_i(q_i) \tag{4.20}$$

From the first order condition: $\frac{d\pi_i}{dq_i} = 0$, then (4.21) could be obtained.

$$MR(Q) = p + \frac{dp}{dQ}Q = MC_i(q_i) = c_i(q_i) \tag{4.21}$$

(4.21) holds because the total revenue depends on the sum of all collusive GENCOs' output level, and the marginal revenue is the same no matter whose output level is changed.

It means that to maximize the total benefit, it must satisfy:

$$MR(Q) = c_i(q_i) = c_j(q_j) \qquad (i \neq j) \tag{4.22}$$

From the cost function,

$$c_i(q_i) = b_i + c_i q_i ; c_j(q_j) = b_j + c_j q_j \tag{4.23}$$

Then the following can be obtained

$$\frac{\partial q_j}{\partial q_i} = \frac{c_i}{c_j} \tag{4.24}$$

Therefore, the conjectural variation is obtained as follows:

$$CV_i = \sum_{j=1,j\neq i}^{N} \frac{\partial q_j}{\partial q_i} = c_i \sum_{j=1,j\neq i}^{N} \frac{1}{c_j} \tag{4.25}$$

2) Cournot, and Bertrand (Perfect competition):

It is easy to prove that in the Cournot case $CV_i = 0$ ($i=1,\cdots,N$), and in perfect competition case $CV_i=-1$ ($i=1,\cdots,N$), then the detail proofs are omitted.

In multi-player case, the relation between CVBS model and GTBS models is depicted in Table 4-2. It also implies that GTBS models are special cases in the CVBS families when assigning appropriate *CV* values to GENCOs.

Table 4-2 Relations between CVBS and GTBS ($p(Q)=e-fQ$)

GTBS	CV_i (CVBS)
Monopoly	$c_i \sum_{j\neq i} \frac{1}{c_j}$
Cournot	0
Perfect Competition	-1

4.6 Static Strategic Behavior Analysis Based on Conjectural Variation

In the last section, the conjectural variation of GENCO is considered as given. Various values have been assumed for the value of conjectural variation, but few attempts to measure it empirically have been made. The conjectural variation of GENCO cannot be detected directly from the electricity market. In this section, the theory and method for the statistical estimation of the conjectural variation are developed. This proposed method is applied to the Australia National Electricity Market (NEM). Then the market behavior of the NEM is empirically investigated with the measured conjectural variation.

4.6.1 A Theoretical Framework Of Estimating Conjectural Variation

Suppose there is an oligopolistic electricity market. Let the number of GENCOs be N and the supply of the ith GENCO be q_i. Then the total supply $Q = q_1 + q_2 + \ldots + q_N$ must be equal to the total demand D:

$$D = Q = q_1 + q_2 + \ldots + q_N \tag{4.26}$$

Let the price be p, then the inverse market demand function will be as follows:

$$p = p(D) = p(Q) \tag{4.27}$$

The derivative of this inverse market demand function is to be negative for any positive D.

Assume that each GENCO is rationally aiming at maximizing its profit. Define profit as

$$\pi_i(q_i) = R_i(q_i) - C_i(q_i) = pq_i - C_i(q_i) \tag{4.28}$$

where $R_i(q_i)$ and $C_i(q_i)$ are total revenue and cost function respectively.

The marginal revenue can be expressed as follows:

$$\begin{aligned} MR_i(q_i) &= \frac{dR_i}{dq_i} = \frac{d(pq_i)}{dq_i} \\ &= \frac{dp}{dD}\frac{dD}{dq_i}q_i + p \\ &= \frac{dp}{dD}(1 + CV_i)q_i + p \end{aligned} \tag{4.29}$$

where

$$CV_i = \sum_{j=1, j\neq i}^{N} \frac{dq_j}{dq_i} \tag{4.30}$$

As mentioned above, CV_i is the conjectural variation of GENCO i, which is its belief or expectation on its rivals' reaction to its output changes. In industrial organization theory, the oligopoly models result from postulating how GENCOs make its profit maximizing output decision together with how one GENCO assumes other GENCOs react to its decisions. Conjectural variation is such an index to measure the reactions in which output is used as the decision variable. Different strategic considerations such as different conjectural variations here will result in different oligopoly models. Conjectural variation of a GENCO can be numerous values depending on its strategic considerations. The higher the level of conjectural variation, the greater the price-cost margin and hence the less the degree of competition in an electricity market. However, the value of conjectural variation must be in two extreme bounds, which are the values of conjectural variations in Bertrand model and monopoly (collusion) model. The degrees of competition of other cases lie between these two extremes while the values of conjectural variation will then be within the extreme values in these two models. For instance, the value of CV of each GENCO in classical duopoly Cournot model with identical cost function is 0, which is within the extreme bounds of -1 (Bertrand) and 1 (monopoly). It means each GENCO in this model believes that its rival will not change its output level in response to its own output change, i.e. the output level of its rival is fixed. In general, the value of conjectural variation of GENCO may take any value within the reasonable ranges.

The first order condition for profit maximization is

$$\frac{d\pi_i}{dq_i} = \frac{dp}{dD}(1+CV_i)q_i + p - MC_i = 0 \tag{4.31}$$

where the marginal cost $MC_i = dC_i/dq_i$.

The price elasticity of electricity demand is defined as the percentage change in the quantity of electricity demand in response to a percentage change in the price of electricity. The price elasticity of demand is denoted by α (<0):

$$\alpha = \frac{dD/D}{dp/p} \tag{4.32}$$

Then (4.31) can be expressed as follows:

$$\frac{1}{\alpha}\frac{p}{D}(1+CV_i)q_i + p - MC_i = 0 \tag{4.33}$$

Define the market share of GENCO *i* as follows:

$$s_i = \frac{q_i}{D} \tag{4.34}$$

Then the conjectural variation CV_i is derived as follows:

$$CV_i = \alpha\frac{MC_i - p}{p}\frac{1}{s_i} - 1 \tag{4.35}$$

Thus the conjectural variation CV_i can be calculated if the values of the price elasticity α, the marginal cost MC_i, the market clearing price p and the market share s_i are known. These parameters can be estimated for each GENCO from the historical data of actual electricity market.

As mentioned before, consider the *N*-GENCO electricity market with a linear inverse demand curve and quadratic cost functions: $C_i(q_i) = a_i + b_i q_i + 0.5c_i q_i^2$. Then if the GENCOs can be described by Bertrand, Cournot, and Monopoly model, then the conjectural variation of GENCOs are -1, 0, $c_i \sum_{j=1, j\neq i}^{N} \frac{1}{c_j}$, respectively. These results are empirical independent of the estimation of the conjectural variation. Therefore, these conjectural variations can be considered as indicators for analyzing the market behavior of GENCOs in actual electricity markets. Whether Bertrand, Cournot, or Monopoly is supported by the estimated conjectural variations could be inferred. All aspects of these three classical oligopoly models have been well investigated and researched for years. If GENCOs in a real market act as any one of these three behaviors, the performance of the market including the degree of competition and market power of any GENCO can be observed. Then the regulator can take suitable action to curb market power and improve efficiency of electricity markets.

4.6.2 Methodology of Estimation of Marginal Cost

Let GENCO i denote the GENCO whose bidding strategy is being computed.

Define:

D: Total market demand

$SO_i(p)$: Amount of capacity bid by all other GENCOs except GENCO i as a function of the market price p

$DR_i(p) = D - SO_i(p)$: Residual demand faced by GENCO i, specifying the demand faced by GENCO i as a function of the market price p

$\pi_i(p)$: Profit of GENCO i at price p

$C_i(p)$: Total cost of GENCO i

$MC_i(q_i)$: Marginal cost of GENCO i

$S_i(p)$: Bid function of GENCO i giving the amount it is willing to supply as a function of the market price p

Assume that GENCO i is able to observe the market demand and bids submitted by all other market participants from the historical data. It can construct its residual demand function implied by the market demand and these bids. Then GENCO i selects the profit maximizing price associated with this residual demand. Assume that the market clearing price p is determined by solving the smallest price such that the equation $S_i(p) = DR_i(p)$ holds for GENCO i.

Then, the profit function of GENCO i can be expressed as follows:

$$\pi_i(p) = S_i(p)p - C_i(S_i(p)) = DR_i(p)p - C_i(DR_i(p)) \tag{4.36}$$

To compute the optimal price associated with the residual demand function, $DR_i(p)$, differentiate the profit function with respect to p and set the result equal to zero:

$$\frac{d\pi_i(p)}{dp} = \frac{dDR_i(p)}{dp} p + DR_i(p) - \frac{dC_i(DR_i(p))}{dDR_i(p)} \frac{dDR_i(p)}{dp} = 0 \tag{4.37}$$

This first-order condition as shown in (4.37) can be used to estimate of the marginal cost at the observed market clearing price, p^*, as follows:

$$MC_i(DR_i(p^*)) = \frac{dC_i(DR_i(p^*))}{dDR_i(p)} = p^* + DR_i(p^*) / DR_i^{'}(p^*) \tag{4.38}$$

$DR_i(p^*)$ and $DR_i{}'(p^*)$ can be computed using the actual market demand and bid functions submitted by all other market participants except GENCO i. The market clearing price, p^*, can be directly observed.

Now the proposed technique mentioned above will be applied to the real electricity market. This requires collecting data on GENCOs bids and market outcomes for a time period.

Firstly, compute implied marginal cost estimations using bid data submitted by all GENCOs, actual market prices and total market demand. The mean marginal costs of all GENCOs could be obtained.

From the historical data, one can get a series of the marginal cost and associated output pairs, $(C_i'(DR_i(p^*)), DR_i(p^*))$, for all values of the half-hourly market clearing price p^*.

Assume GENCOs have quadratic cost functions: $C_i(q_i) = a_i + b_i q_i + 0.5 c_i q_i^2$. Using the regression analysis method, one can get the linear regression of the implied marginal cost, $C_i'(q_i)$, on q, the associated implied output of GENCO *i*:

$$C_i'(q_i) = b_i + c_i q_i \tag{4.39}$$

The value of c_i can be used in calculating the conjectural variations of GENCOs in the Monopoly case shown as above.

4.6.3 The Simulation Study

The proposed method is used to analyze the Australia National Electricity Market (NEM). The data used in this study are obtained from the website of NEM [109]. It means all these data including bidding data of all generation companies (GENCOs), market clearing price and demand are the actual historical market data of NEM.

4.6.3.1 The Introduction of NEM

The Australia NEM was initiated in December 1998 to represent the wholesale market for the supply and purchase of electricity in several Australian states and territories. It was also an administration of open access to transmission and distribution networks in those states and territories.

The National Electricity Market Management Company Limited (NEMMCO) manages and facilitates the wholesale electricity market. The main functions of NEMMCO include managing the power system to keep supply and demand in balance based on the generating capacity available to the wholesale market, keeping security of power system, administering the spot market including calculation of spot prices.

In the wholesale electricity market, generators decide their own unit commitment respectively and provide dispatch offers (prices for different levels of generation) to NEMMCO. The electricity outputs from all generators are centrally pooled and scheduled to meet the electricity demand. A spot price for wholesale electricity is calculated for each half-hour period during the day and is the clearing price to match supply and demand. The price is determined as the highest price of the power producers that satisfies the load requirement.

4.6.3.2 Background of Empirical Analysis

The period of analysis is confined from April 2002 to October 2003, because the bidding data of GENCOs are only available in this period.

Normally, every GENCO has several power stations, and each of them submits its own bidding curve everyday to the NEM. Assuming the objective of these units' bidding strategies is maximizing profit for the whole GENCO owning these units. It means that the market behavior of GENCO is considered as a whole. In general, there are more than 160 units, which are owned by about 58 GENCOs, offering their bidding data everyday in the NEM. 69.86% of the total demand is supplied by 11 GENCOs. The minimal share of each of these 11 GENCOs is 4.13 % and the maximal share is 8.33 %. For simplicity, only the conjectural variations of these 11 GENCOs are estimated. Their market behavior is analyzed as dominant GENCOs while the total supply of fringe GENCOs is considered as the marginal supply. Assuming that each of dominant GENCO only takes the behaviors of these dominant GENCOs into account, the marginal supply will be simply taken as an exogenous variable. Then the output of marginal GENCOs can be removed from total demand. The values of market share used for calculating the conjectural variation are proportionally more than the values without considering marginal supply.

The pool operation of NEM, managed by NEMMCO, mainly covers an interconnected power system including New South Wales, Queensland, South Australia, SNOWY, and Victoria. There is some little difference in clearing prices among these different areas for the transmission loss and transmission constraint. Every area has its own demand respectively. As the difference between these areas is very slight, the mean of prices and the aggregation of demands are used as the final clearing price and total demand of every period respectively.

4.6.3.3 Estimates of Parameters for Calculating Conjectural Variation

From the historical data, the mean market clearing price of NEM from April 2002 to October 2003 can be calculated, which is 23.81 ($/MWh).

Meanwhile, the bidding curve of every GENCO in every half-hour period can be obtained. Then the market share of GENCO's supply can be calculated. The mean estimated market share of 11 GENCOs from April 2002 to October 2003 are shown in Table 4-3.

Table 4-3 Estimated Market Shares of GENCOs from April 2002 to October 2003

No.	GENCOID	Market share
1	BW	8.33%
2	ER	6.36%
3	GSTONE	5.36%
4	HWPS	6.44%
5	LD	6.81%
6	LOYY	4.13%
7	LY	8.15%
8	MP	7.76%
9	STAN	4.96%
10	TARONG	5.63%
11	YWPS	5.93%

Estimation of conjectural variation calls for the elasticity of demand, which requires that some elasticity estimation should be obtained. The elasticity of demand of NEM is obtained from a report for the National Electricity Market Management Company [110], which is about the price elasticity of demand for electricity in the NEM regions. In real markets, the single-period demand function is nearly vertical. The majority of the demand is price-insensitive. This is to be expected because demand really is highly inelastic in the short run. Arguably demand is more elastic over longer periods. The conjectural variation is estimated with long run historical data and is considered as a constant value for each GENCO in a relative long period. Hence it may be appropriate to use the elasticity of demand over longer periods e.g. a monthly or annual horizon. Empirical estimates of price elasticity of demand represent the average relationship over time between quantity and price. In this report, the demand for electricity is still price inelastic but not so inelastic in the long run. This means that a 1.0 per cent change in the electricity price will lead to less than a 1.0 per cent change in the quantity of electricity demanded.

The estimated long run own price elasticities of electricity demand by the states are shown in Table 4-4. Both a range and a mean value are provided for each region.

Table 4-4 Estimated Long Run Price Elasticity of Electricity Demand of NEM

	Range	Mean
New South Wales	-0.22 to -0.52	-0.37
Victoria	-0.23 to -0.53	-0.38
Queensland	-0.14 to -0.44	-0.29
South Australia	-0.17 to -0.47	-0.32
NEM	-0.20 to -0.50	-0.35

In this report, in order to analyze the sensitivity of price elasticity of demand, -0.20, -0.35 and -0.50 are used as elasticities of demand to calculate the conjectural variation. From them, the extreme bounds of conjectural variation can also be obtained.

Based on the methodology to estimate marginal cost, the parameters about marginal cost could be obtained. Firstly, compute implied marginal cost estimations using bid data submitted by all GENCOs, actual market prices and total market demand. Assume h = AU$ 1.00. The mean marginal costs of all GENCOs from April 2002 to October 2003 are shown in Table 4-5.

Figure 4-4 is a plot of the marginal cost and associated output demand pairs of GENCO BW, $(C_i'(DR_i(p^*)), DR_i(p^*))$, which is the point in the figure, for all values of the half-hourly market clearing price p^*. Using regression analysis method, one can get the linear regression of the implied marginal cost, $C_i'(q)$, on q, the associated implied output of GENCO i: $C_i'(q) = b_i + c_i q$, which can be used in calculating the conjectural variations of GENCOs in Monopoly case. Figure 4-4 also plots the predicted values from the linear regression, which is shown as a straight line in the figure. Although there is a considerable noise in the sample of implied marginal cost and output pairs, the regression results are broadly consistent with the magnitudes of marginal costs.

Table 4-5 Mean Marginal Costs of 11 GENCOs in NEM

No.	GENCO_ID	Marginal cost(AU$)
1	BW	13.21
2	ER	16.76
3	GSTONE	17.65
4	HWPS	17.31
5	LD	16.99
6	LOYY	19.75
7	LY	15.80
8	MP	15.61
9	STAN	18.45
10	TARONG	18.06
11	YWPS	17.74

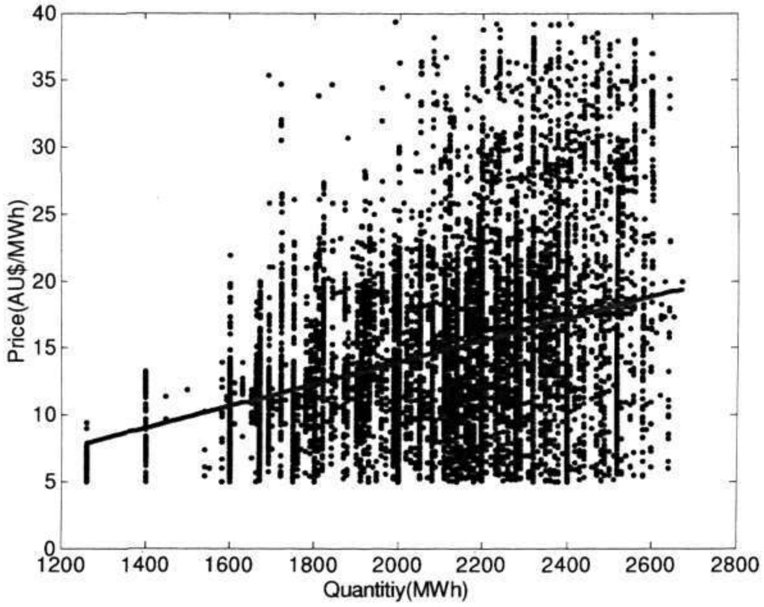

Figure 4-4 Plot of the marginal cost and associated output demand pairs of GENCO BW

The results of implied cost function regression of every GENCO are given in Table 4-6.

Table 4-6 The Parameters of the Implied Cost Function Regression of Every GENCO

No.	GENCO_ID	b	c
1	BW	-2.435453	0.005952
2	ER	12.42053	0.006533
3	GSTONE	4.882643	0.007356
4	HWPS	-48.426416	0.032943
5	LD	-10.883333	0.013645
6	LOYY	-69.044431	0.023335
7	LY	-30.077832	0.019167
8	MP	-4.64969	0.008039
9	STAN	-9.024203	0.019785
10	TARONG	-12.664782	0.02076
11	YWPS	-71.460874	0.033169

4.6.3.4 Estimates of Conjectural Variation

When all the data needed to calculate the conjectural variation, the values of the marginal cost MC_i, the price elasticity α, the market clearing price p and the market share s_i, are estimated, the value of conjectural variation of each GENCO is calculated using (4.35).

Table 4-7 shows the results of conjectural variations of all GENCOs with different price elasticity α = -0.20, -0.35 and -0.50. As it was mentioned above, if the GENCOs can be described by Bertrand, Cournot, and Monopoly model, then the conjectural variations of GENCOs are -1, 0, $c_i \sum_{j=1, j\neq i}^{N} \frac{1}{c_j}$, respectively ($c_i$ can be obtained from Table 4-6). The CVs of all GENCOs in Bertrand, Cournot, and Monopoly model are shown in Table 4-8.

Table 4-7 Conjectural Variations of All GENCOs with Different Price Elasticity

No.	GENCO_ID	CV (α = -0.2)	CV (α = -0.35)	CV (α = -0.50)
1	BW	-0.25	0.31	0.87
2	ER	-0.09	0.59	1.27
3	GSTONE	0.00	0.74	1.49
4	HWPS	-0.14	0.50	1.14
5	LD	-0.17	0.46	1.08
6	LOYY	0.04	0.83	1.61
7	LY	-0.23	0.34	0.92
8	MP	-0.18	0.43	1.04
9	STAN	0.00	0.75	1.50
10	TARONG	-0.09	0.60	1.29
11	YWPS	-0.11	0.56	1.23

Table 4-8 Conjectural Variations of All GENCOs in Different Oligopoly Model

No.	GENCO_ID	Bertrand	Cournot	Monopoly
1	BW	-1	0	4.41
2	ER	-1	0	4.94
3	GSTONE	-1	0	5.69
4	HWPS	-1	0	28.94
5	LD	-1	0	11.4
6	LOYY	-1	0	20.21
7	LY	-1	0	16.42
8	MP	-1	0	6.31
9	STAN	-1	0	16.98
10	TARONG	-1	0	17.87
11	YWPS	-1	0	29.15

4.6.3.5 Discussions and Conclusions

Based on the estimates of conjectural variation above, the behavior of GENCOs in oligopoly market can be analyzed. In Table 4-8, the values of classical oligopoly markets of GENCOs are given as benchmarks. GENCO BW is used as an example to explain. When the estimate of GENCO BW is –1, this GENCO performs Bertrand behavior. If all GENCOs are the same case, a fully competitive electricity market will be observed. There will be no market power existing in the market and the price-cost margins will be caused by factors other than exercising market power by GENCOs. At the opposite extreme, if estimate of GENCO BW is 4.41, it performs monopoly behavior. If all GENCOs perform in the same way, one could observe a monopoly market, i.e. fully collusive market. In this market, all GENCOs tacitly collude with each other and fully exercise their maximal market powers. Within these two extremes, GENCOs exhibit Cournot behavior when estimates of conjectural variation are 0. It means they do exhibit strategic behavior but they perform this noncooperatively and the degree of market power is not extremely high. Comparing the estimate in Table 4-7 with benchmark values in Table 4-8, the competitiveness of GENCOs and the degree of market power in the market could be analyzed. It can be seen that all the calculated conjectural variations in Table 4-7 are all in the reasonable range, i.e. within two extreme bounds (-1, 4.41), which are the estimate of Bertrand case and monopoly case. Note that there is nothing that forces the estimated conjectural variations to be in this range. These values can, from a purely computational point of view, quite easily be large negative or positive numbers. The apparent reasonableness of the calculated conjectural variations shows the effectiveness of the proposed method.

Table 4-7 and Table 4-8 show that when the price elasticity α = -0.20, the estimated conjectural variations are close to Cournot value 0 for all GENCOs. Both the monopoly hypothesis (CV>>1) and the Bertrand hypothesis (CV = -1) will be strongly rejected. However, it can be seen that when the price elasticity α = -0.35 and -0.50, the conjectural variation increases observably. This result is implied by (4.35) that the conjectural variation is increasing with the price elasticity α. If the price elasticity is higher than expected, a given price-cost margin would be "explained" by less competitive, i.e. larger conjectural variation. A natural question to ask is how sensitive these results are to various modifications in the underlying price elasticity and cost parameter estimation.

In order to check on the fragility or robustness of the basic conclusions, a sensitivity analysis over the range of plausible parameters is investigated. The values of price elasticities α are -0.2, -0.35, -0.50, while the values of marginal cost are 95%MC, 100%MC, 105%MC, where MC is the mean marginal cost of any GENCO in Table 4-5. There are therefore nine sets of results, which are shown in Table 4-9 (only results of GENCO BW are reported). It shows that increase in price elasticity causes the estimated conjectural variation to rise substantially. It is clear that an error in price elasticity could undermine the results substantially. As for 5% variation in marginal cost, the estimated conjectural variations are decreasing as marginal cost becomes larger, but this effect is relatively modest. It means that the sensitivity of results to the price elasticity is probably of more concern than sensitivity to marginal cost.

The final observation of this sensitivity analysis is to take note of the "extreme bounds" of the conjectural variation. The highest estimated conjectural variation is 0.99, while the lowest is -0.29. Even these extreme bounds do not approach either the Bertrand or

Monopoly. Thus it shows that strong evidence against the monopoly hypothesis and against the highly competitive Bertrand hypothesis has been found. The Cournot behavior can be plausible for the NEM market, taking into account the various errors and approximations. For the Bertrand model to be supported in the market, prices have to be at or close to marginal costs. The main reason for the poor performance of the Bertrand model here is simply because the mean price is more than the marginal costs. As for the monopoly model, the mean price was simply not large enough in the year 2002 to be consistent with monopoly behavior. Both the Bertrand and monopoly might be regarded by many economists as behavioral extremes which will not be observed very often in the actual data. Thus, a rejection of these models would not be surprising. The relatively strong performance of the Cournot model is perhaps more reasonable in the NEM. This also means that the GENCOs in the NEM perform unilateral market power, but not tacit collusion.

Table 4-9 Sensitivity of Conjectural Variations (GENCO BW)

	$\alpha = -0.2$	$\alpha = -0.35$	$\alpha = -0.5$
95%MC	-0.21	0.39	0.99
100%MC	-0.22	0.36	0.95
105%MC	-0.29	0.23	0.75

4.7 Dynamic Strategic Behavior Analysis Based on Conjectural Variation

The last section empirically analyzes the static behavior of NEM GENCOs in a period by the empirical knowledge of the conjectural variation of GENCOs. In real life, GENCOs play a repeated game. It can be imagined that a GENCO can develop its behaviors by learning the behaviors of its rivals. Dynamic strategic interaction is also an important aspect of strategic bidding study in the oligopolistic electricity market. The dynamic interaction among GENCOs in the actual electricity market will be studied in this section.

4.7.1 Introduction of Dynamic Behavior Analysis

In the previous sections, the conjectural variation CV is treated as "static" value. However, in the actual spot market, each GENCO wants to get maximum profit in the repeated biddings. A GENCO will make rational change in each bidding process according to its learning results on its rivals' behaviors. The learning is based on available information published in the market in order to perceive the responses of its rivals correctly. As a result, tacit collusion may be facilitated by the daily repetition of the bidding game between a set of GENCOs with information about their rivals' behaviors. Thus, the dynamic strategic interaction is very important for the oligopolistic electricity market. The dynamic interaction among GENCOs in the actual electricity market will be investigated using time series historical data in the following part.

Specifically, like the static behavior analysis in the previous section, the analysis in this section also considers the *N*-GENCO electricity market with a linear inverse demand curve and quadratic cost functions: $C_i(q_i) = a_i + b_i q_i + 0.5 c_i q_i^2$. In a repeated electricity market, GENCOs undertake dynamic interactions in different periods. In the simplest way, GENCO i can act as Bertrand, Cournot, or Monopoly in each period whose CV_i is -1, 0, $c_i \sum_{j=1, j\neq i}^{N} \frac{1}{c_j}$ constantly over time. Alternatively, regime-switching (RS) models can be investigated like the ones in [111]. GENCOs in the market commit a tacit collusion to increase the market clearing price and maximize their profits in some periods. But if prices fall below some trigger level, GENCOs will assume that there is a defection existing in the market. GENCOs will generate the punishment output such as Cournot output for several periods, and then return to perfectly collusive output level. This will give rise to observation that GENCOs switch between regimes. A regime-switching (RS) model, which lets GENCOs in the punishment period to exhibit Cournot behavior, will be considered below. Denote CV_{ic} and CV_{in} as the conjectural variation of GENCO i in collusion and non-collusion periods respectively. In the Cournot based RS model, CV_{in} = 0 and $0 < CV_{ic} < c_i \sum_{j=1, j\neq i}^{N} \frac{1}{c_j}$. By empirically estimating a time series of conjectural variations, one is able to investigate whether repeated Bertrand, Cournot, Monopoly or the Cournot based RS model is supported by the estimated conjectural variations series.

4.7.2 Empirical and Statistical Methodology of Dynamic Behavior Analysis

The theoretical framework of estimating conjectural variation is the same as static behavior analysis mentioned above. In the real oligopolistic electricity markets, there are several dominant GENCOs, which will provide the most part of demand. But there are still some marginal GENCOs existing in the market. Assuming that each of dominant GENCO only takes the behaviors of these dominant GENCOs into account, the marginal supply will simply be taken as an exogenous variable. Then the output of marginal GENCOs can be removed from total demand. The values of market share used for calculating the conjectural variation are proportionally more than the values without considering marginal supply. However, if the output of fringe GENCOs is considered when dominant GENCOs make their strategic choices, then the market share of marginal GENCOs can affect the values of conjectural variations of dominant GENCOs. It means the results of conjectural variation given by (4.35) will include the influence of marginal supply. To analyze this influence, the market share of marginal GENCOs will be considered as an explanatory variable in the regression function, i.e., a linear regression method will be used to understand the presence of marginal supply.

In general, the regression equation is as follows:

$$CV_{it} = CV_{ir} + \beta_i MS_t + \mu_{it} \quad (i = 1, \cdots, N, t = 1 \cdots, T) \tag{4.40}$$

where CV_{it} is the conjectural variation of GENCO i in period t and MS_t is the market share of marginal GENCOs, which are observed values. CV_{ir} is the regime value of conjectural variation of GENCO i, which reflects this GENCO's strategic behavior excluding the influence of marginal supply. For example, it will be CV_{ic} if GENCO i commits collusion and CV_{in} if non-collusion is performed. β_i is the coefficient to be estimated by the observed series data of (CV_{it}, MS_t). μ_{it} is a random independently and identically distributed (iid) error. As the explanatory variable is the market size MS_t, which is relatively non-stochastic and fixed in repeated samples, the use of classical regression model is reasonable. In this model, μ_{it} is assumed to be distributed as normal (Gauss) distribution $N(0, \sigma_{it})$ [112].

Specially, in the RS models, GENCOs will switch between two regimes, i.e, collusion and non-collusion periods which means CV_{ir} changed between CV_{ic} and CV_{in}. Then the observation on the conjectural variation is generated by one of the two regression equations as follows:

$$CV_{it} = \begin{cases} CV_{ic} + \beta_i MS_t + \mu_{it} \\ \\ CV_{in} + \beta_i MS_t + \mu_{it} \end{cases} \tag{4.41}$$

To simplify (4.41), suppose I_t is an indicator variable, which equals 1 in collusion periods and equals 0 in non-collusion periods. Then denote $CV_t=(CV_{1t,}\cdots;CV_{Nt})'$, $CV_n = (CV_{1n,}\cdots,CV_{Nn})'$, $CV_c = (CV_{1c,}\cdots,CV_{Nc})'$, $\beta = (\beta_1,\cdots,\beta_N)'$, $\mu_t = (\mu_{1t},\cdots,\mu_{Nt})'$.

After that, the regression equations in *t*th period can be expressed as follows:

$$CV_t = CV_n + (CV_c - CV_n)I_t + \beta MS_t + \mu_t \quad (t = 1\cdots,T) \tag{4.42}$$

From (4.42), if the sequence $\{I_1,\cdots,I_T\}$ is known, then the estimation of the parameters can be obtained easily by a usual linear regression method. However, in practice, it is impossible to know $\{I_1,\cdots,I_T\}$. So a statistical distribution should be assumed to perform the analysis. In all statistical distributions, Bernoulli distribution is the most suitable to describe all situations with only two outcomes just like the case that is being studied in this paper. In addition, to greatly simplify an otherwise very complicated and possibly infeasible estimation procedure, I_t is assumed to be the Bernoulli distribution as in [113]:

$$I_t = \begin{cases} 1 & \text{with probaility } \lambda \\ 0 & \text{with probaility } 1\text{-}\lambda \end{cases} \tag{4.43}$$

As μ_{it} is distributed as normal distribution, μ_t will be the independently and identically distributed $N(0,C)$, where *0* is a vector of zeros and *C* is the $N \times N$ covariance matrix.

$$C = \begin{pmatrix} \sigma_1^2 & \cdots & \sigma_{1N} \\ \cdots & \cdots & \cdots \\ \sigma_{N1} & \cdots & \sigma_N^2 \end{pmatrix}$$

Then CV_t is a *N*-dimensional random variable vector. Its mean vector in the collusion periods will be $(CV_c + \beta MS_t)$ and in the non-collusion periods will be $(CV_n + \beta MS_t)$. Meanwhile, its covariance matrix is matrix *C*. It means CV_t is distributed as multivariate normal distribution. Thus, denoting the parameters to be estimated as $\Omega = (\lambda, CV_c, \beta, C)$, then the probability density of CV_t is as follows [114]:

$$f(CV_t, MS_t | \Omega) = \lambda f_c(CV_t, MS_t | I_t = 1) + (1-\lambda) f_n(CV_t, MS_t | I_t = 0) \tag{4.44}$$

where

$$\begin{aligned} & f_c(CV_t, MS_t | I_t = 1) = (2\pi)^{-N/2} |C|^{-1/2} \\ & \exp\{-\frac{1}{2}(CV_t - CV_c - \beta MS_t)' C^{-1} (CV_t - CV_c - \beta MS_t)\} \end{aligned} \tag{4.45}$$

$$\begin{aligned} & f_n(CV_t, MS_t | I_t = 0) = (2\pi)^{-N/2} |C|^{-1/2} \\ & \exp\{-\frac{1}{2}(CV_t - CV_n - \beta MS_t)' C^{-1} (CV_t - CV_n - \beta MS_t)\} \end{aligned} \tag{4.46}$$

The likelihood function is as follows:

$$l(\Omega | CV_t, MS_t) = \prod_t f(CV_t, MS_t | \Omega) \tag{4.47}$$

From historical data, the observation of CV_t and MS_t can be obtained. Then, the value of $\Omega = (\lambda, CV_c, \beta, C)$ can be estimated by maximizing $l(\Omega | CV_t, MS_t)$ with respect to Ω. This estimation problem is a problem of mixture distributions concerning shifts in regression regimes at unknown points in the data series, which can be solved like the ones in [115].

4.7.3 The Simulation Study

The proposed method is also used to analyze the Australia National Electricity Market (NEM). The data used in this paper are obtained from the website of NEM [109].

4.7.3.1 Background of Empirical Analysis

The period of analysis is confined from April 2002 to October 2003. Most research background of dynamic behavior analysis is the same as that of static behavior analysis. The difference will be illustrated below.

The theoretical models above have implicitly assumed that GENCOs make one strategic decision per period. In practice, it is hard to say how long a decision period is. Considering GENCOs need certain time to observe the market status and their rivals' market behavior and then make their new decision, this paper assumes GENCOs make one strategic choice per month, which means considering one month as a base decision period.

Without loss of generality, only results of GENCO BW are shown. (BW is the first two letters of GENCO ID.) The results of other dominant GENCOs can be obtained and analyzed in the same way.

4.7.3.2 Estimates of Parameters for Calculating Conjectural Variation

From the historical data, all the parameters are estimated by the methodology in static behavior analysis. The values of monthly mean market clearing price of NEM from April 2002 to October 2003 are shown in Table 4-10. The bidding curve of every GENCO in every half-hourly period can also be obtained. Then the individual market share of each

GENCO's supply can be calculated. The mean market share of each GENCO from April 2002 to October 2003 will also be obtained, which is shown in Table 4-11.

Table 4-10 Monthly Mean Market Clearing Price of NEM ($/MWh)

	Apr '02	May '02	Jun '02	Jul '02	Aug'02
p	24.88	30.13	28.47	33.96	28.12
	Sep '02	Oct '02	Nov '02	Dec '02	Jan '03
p	28.66	26.72	25.53	30.52	24.49
	Feb '03	Mar '03	Apr '03	May '03	Jun '03
p	20.42	17.10	16.12	19.47	22.19
	Jul '03	Aug'03	Sep '03	Oct '03	
p	19.94	19.31	18.81	17.73	

Table 4-11 Monthly Mean Market Shares of GENCO BW

	Apr '02	May '02	Jun '02	Jul '02	Aug'02
MS	8.29%	8.08%	8.80%	8.23%	8.15%
	Sep '02	Oct '02	Nov '02	Dec '02	Jan '03
MS	8.67%	8.75%	8.36%	8.31%	7.89%
	Feb '03	Mar '03	Apr '03	May '03	Jun '03
MS	8.31%	8.24%	8.29%	8.40%	8.51%
	Jul '03	Aug'03	Sep '03	Oct '03	
MS	8.91%	8.39%	7.70%	7.95%	

Estimation of conjectural variation calls for the elasticity of demand, which requires that some elasticity estimation should be obtained. The estimated long run own price elasticity of electricity demand used by this thesis is -0.35.

As for marginal cost of all GENCOs, the values of marginal cost are shown in Table 4-12. The parameters of the implied output of GENCO i: $C_i'(q_i) = b_i + c_i q_i$ can also be estimated. The results of b_i and c_i are shown in Table 4-13. The value of c_i can be used in calculating the conjectural variations of GENCOs in the Monopoly case.

Table 4-12 Monthly Mean Marginal Costs of GENCO BW ($/MWh)

	Apr '02	May '02	Jun '02	Jul '02	Aug'02
MC	11.91	14.63	14.88	17.08	15.66
	Sep '02	Oct '02	Nov '02	Dec '02	Jan '03
MC	17.13	15.14	14.51	16.02	13.32
	Feb '03	Mar '03	Apr '03	May '03	Jun '03
MC	11.10	9.80	9.65	10.78	12.12
	Jul '03	Aug'03	Sep '03	Oct '03	
MC	11.50	12.15	12.08	11.54	

Table 4-13 The Parameters of The Implied Cost Function Regression of GENCO BW

GENCO_ID	b	c
BW	-2.435453	0.005952

4.7.3.3 Estimates of Conjectural Variation

With all the data needed to calculate the conjectural variation, the values of the marginal cost MC_i, the price elasticity α, the market clearing price p and the market share s_i, are estimated. The value of conjectural variation of each GENCO is calculated by the method mentioned above. Table 4-14 shows the results of conjectural variations of GENCO BW considering the output of all GENCOs. The results of considering marginal supply as an exogenous variable are also shown in Table 4-15. As it was mentioned above, if the GENCOs can be described by Bertrand, Cournot, and Monopoly model, then the conjectural variations of GENCOs are -1, 0, $c_i \sum_{j=1, j\neq i}^{N} \frac{1}{c_j}$, respectively. The CVs of GENCO BW in Bertrand, Cournot, and Monopoly model are shown in Table 4-16.

Table 4-14 Monthly Conjectural Variations of GENCO BW

	Apr ‘02	May ‘02	Jun ‘02	Jul ‘02	Aug‘02
CV	1.08	1.15	0.87	1.03	0.91
	Sep ‘02	Oct ‘02	Nov ‘02	Dec ‘02	Jan ‘03
CV	0.63	0.79	0.80	0.96	0.86
	Feb ‘03	Mar ‘03	Apr ‘03	May ‘03	Jun ‘03
CV	0.89	0.80	0.73	0.88	0.91
	Jul ‘03	Aug‘03	Sep ‘03	Oct ‘03	
CV	0.69	0.55	0.55	0.46	

Table 4-15 Conjectural Variations of GENCO BW when Marginal Supply is Considered as An Exogenous Variable

	Apr ‘02	May ‘02	Jun ‘02	Jul ‘02	Aug‘02
CV	0.38	0.41	0.22	0.32	0.24
	Sep ‘02	Oct ‘02	Nov ‘02	Dec ‘02	Jan ‘03
CV	0.04	0.16	0.16	0.28	0.22
	Feb ‘03	Mar ‘03	Apr ‘03	May ‘03	Jun ‘03
CV	0.23	0.16	0.10	0.22	0.24
	Jul ‘03	Aug‘03	Sep ‘03	Oct ‘03	
CV	0.09	-0.02	-0.02	-0.08	

Table 4-16 Conjectural Variations of GENCO BW in Different Oligopoly Models

GENCO_ID	Bertrand	Cournot	Monopoly
BW	-1	0	4.41

4.7.3.4 Discussions and Conclusions

All the conjectural variations of GENCO BW in Table 4-14 are not shown to be consistent with any value of the Bertrand, Cournot and monopoly case. However, from Table 4-15, the estimated values are somewhat close to the Cournot value 0. There is a possibility to accept the repeated one-shot of Cournot behavior when dominant GENCOs take marginal supply as an exogenous variable. In addition, from Table 4-14, Table 4-15 and Table 4-16, both the monopoly hypothesis ($CV >> 1$) and the Bertrand hypothesis ($CV = -1$) will be rejected strongly.

The maximum likelihood method mentioned above is then used to analyze the Cournot based RS model. The results of this model are shown in Table 4-17. From the results, the regime probability λ is 0.68. It implies GENCOs do switch between collusion and non-collusion regimes throughout the whole sample periods. Figure 4-5 shows the regime series of GENCO BW in the whole process. It could be seen clearly in Figure 4-5 that GENCO BW performs collusion in some periods and non-collusion in other periods. Meanwhile, it also switches back and forth between these two regimes. The estimate of CV_c of GENCO BW is 0.1, which is roughly in the two extremes ($0,\ c_i \sum_{j=1, j\neq i}^{N} \frac{1}{c_j}$). Namely, the price in collusion period is more than that in the Cournot model, but less than that in monopoly. However, the value in the collusive period is very close to the Cournot value of 0. Thus the behavior of the Cournot based RS model is very similar to mere repetition of the Cournot one-shot hypothesis.

Based on the above analysis, one can accept the hypothesis that the continuous Cournot behavior of GENCO BW is monthly consistent from April 2002 to October 2003 in NEM. In addition, the behaviors of others GENCOs in the NEM could be analyzed in the same way. The results of other GENCOs are nearly similar to GENCO BW. The relatively strong performance of the Cournot model is perhaps more reasonable in the NEM, while the monopoly model and the Bertrand model are strongly rejected. This result shows that the GENCO behaviors in the NEM are more consistent with non-cooperative market power, but not tacit collusion, though it is very possible for all GENCOs to reach tacit collusion in the repeated electricity market.

Table 4-17 Estimations of GENCO BW in RS Cournot Model

	CV_n	CV_c	β	λ	log-likelihood
RS_Cournot	0	0.10	2.69	0.68	339.81

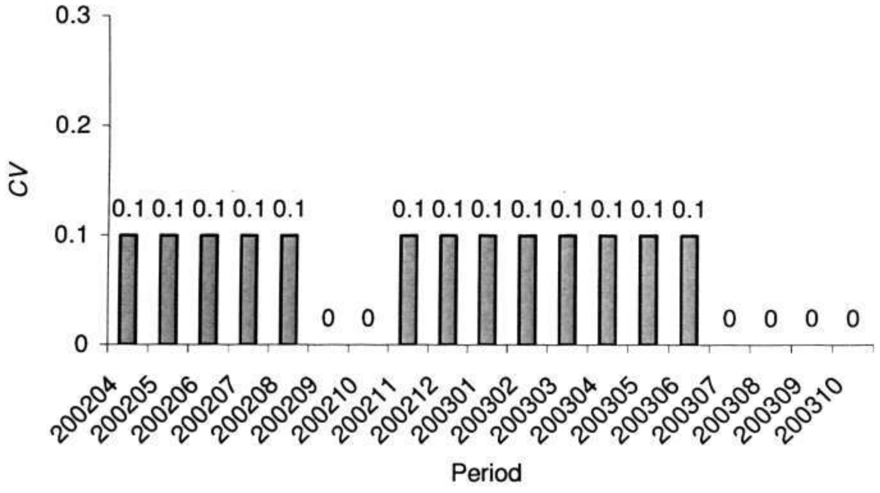

Figure 4-5 Regime series of GENCO BW

4.8 Concluding Remarks

By reviewing strategic bidding and market power in the electricity market, market power has been empirically revealed existing in the electricity markets, but the understanding of the market structure and GENCOs' strategic behaviors underlying the market power is still not clear now. This chapter presents a theory and method for estimating the strategic behavior of GENCO and the underlying market power. The Australia National Electricity Market (NEM) is used as a simulation study case.

The conjectural variations of GENCOs are estimated based on the NEM historical real-time data. Based on these estimates of conjectural variations, the market structure and GENCO's strategic behavior are investigated. At first, the static behavior of GENCOs in the electricity market is analyzed. The result shows that a strong evidence against the monopoly hypothesis and against the highly competitive Bertrand hypothesis has been found. The Cournot behavior can be plausible for the NEM market, taking into account the various errors and approximations.

As GENCOs play a repeated game in the electricity market, an empirical methodology is also proposed to analyze the dynamic oligopoly behaviors underlying market power. From the analysis, the relatively strong performance of the repeated Cournot model is perhaps more reasonable in the NEM, while the repeated monopoly model and the Bertrand model are strongly rejected. This result shows that GENCOs in the NEM do exercise some market power, but shows no evidence of perfect collusion.

Chapter 5 The Mitigation of Market Power by Using Vesting Contract

5.1 Introduction

The objective of setting up an electricity market is to introduce competition and provide benefits to the consumers. However, market power more or less exists in the electricity market as reflected by a higher price than expected market clearing price. Therefore, ways to reduce market power attract attention. One of the best ways is to divide the large GENCOs into small ones. If there are enough competitors having a similar market share, no one could dominate the market and market power would be reduced accordingly. However, not every market could have enough competitors.

Two way Contracts for Differences (CfDs) in the electricity market can also reduce market power. Two-way CfDs require the GENCOs to pay the consumers or retailers the difference between the pool price and the strike price for a given quantity of electricity when the pool price is higher than the strike price. Conversely, they also require the consumers or retailers to pay the difference when the pool price is lower than the strike price [116]. The net effect is that the price for a preset amount of electricity transactions is fixed in the market. CfDs can be signed between any power suppliers and power consumers. CfDs are purely financial arrangements, which are different from physical bilateral contracts.

Powell [117] pointed out that CfDs control the market power even when the generators are assumed to be Cournot players in the spot market. Allaz and Vila [118] analyzed duopoly competition where a future market was set up for the transactions of CfDs. They calculated the equilibrium point and proved that the consumers would benefit from the future market. Green used a supply function to compute the optimum CfD amount for the GENCOs in the future market [52].

However, the ability of CfDs to control market power may not be enough. Therefore, vesting contracts are implemented in some markets to further control market power. In essence, vesting contracts belong to two-way CfDs, but they have their own characteristics. The content of the CfD is negotiated by a GENCO and a retailer while a vesting contract is decided by the regulator. The involved parties, especially the GENCOs, are forced to enter the agreement. The regulators are the ones who calculate the vesting quantity and vesting price, so that neither the GENCO nor the consumer would be biased. Vesting contracts were first introduced in England and Wales Electricity Market [88] in 1990. After that, vesting contracts were arranged between GENCOs and energy retailers in Australian Open Electricity Market [119] in 1997. In the proposed vesting contract, 50% of the market demand is covered in the Australian Open Electricity Market [60, 120]. In January 2004, the Energy Market Authority of Singapore (EMA) imposed vesting contracts on the Singapore Electricity Market. The coverage is 65% and 55% for the peak load and valley load respectively [121].

In the markets where vesting contracts were imposed, the reduction in market clearing price was observed [2, 88, 121]. For example, the Singapore Electricity market observed about a 10% drop in energy price after installing a vesting contract. Lucas [116] was the first one who analyzed the generators' behavior in a duopoly market with a vesting contract.

In Section 5.2, vesting contract is introduced. It also presents how a vesting contract can be used to curb market power. In Section 5.3, an oligopoly electricity market, which is divided into a spot market and a future market, is studied for analyzing the influence of the vesting contracts on market power and the strategic behavior of generators. A way to determinate the optimal vesting contract amount is also presented in this section. The simulation study is investigated in Section 5.4. Section 5.5 presents the conclusions.

5.2 How Vesting Contract Works

5.2.1 Introduction of Vesting Contract

As mentioned above, vesting contracts are a form of Contract of Differences (CfDs) vested on generators by the regulator. Their intention is to limit the potential for misuse of market power by the larger incumbent GENCOs. With an appropriately set strike price, Vesting Contracts also perform the function of stabilizing the retail price [121]. The strike price and contract level, which are decided by the regulator, will be set to keep the incentive to use market power at an acceptable level. Essentially the contract involves agreeing a strike price and the volume of energy for which it covers. The net effect is that both the retailer and the GENCO effectively see a fixed price for the volume of energy covered by this vesting contract. An example of a Vesting Contract below will show how it works between a generator and a retailer and how to hedge the price volatility risk clearly.

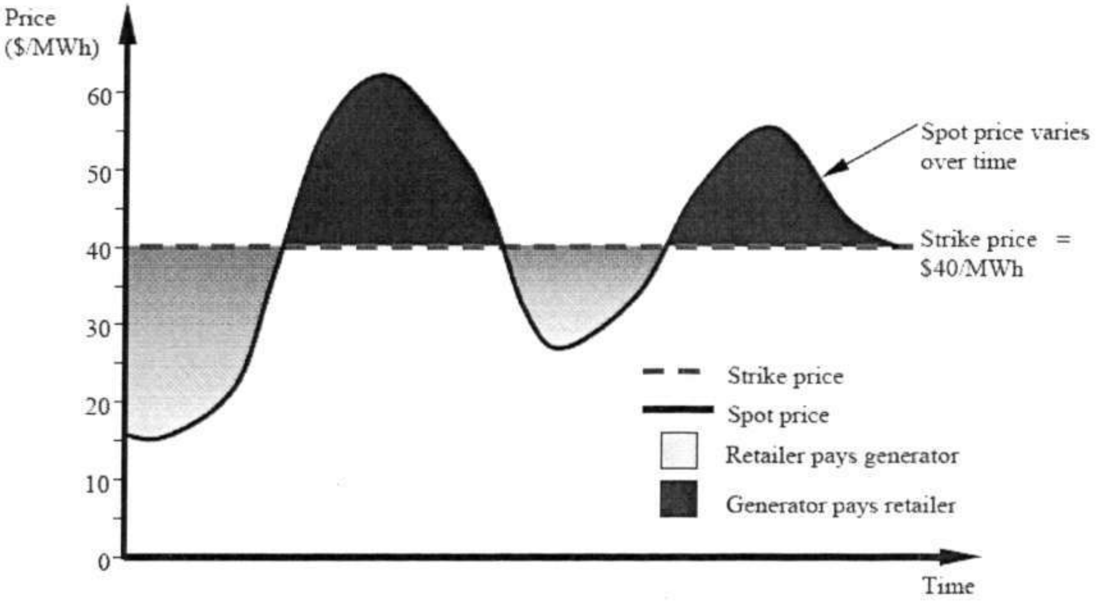

Figure 5-1 Example of vesting contract

Figure 5-1 shows a vesting contract hedge between a retailer and a generator. The hedge strike price has been agreed to be $40/MWh. When the spot price exceeds the strike price, the GENCO pays the retailer the difference between the spot price and the strike price. When the spot price is less than the strike price, the retailer pays the GENCO the difference between the spot price and the strike price. The net effect is that both the retailer and the generator effectively see a price of $40/MWh for the volume of energy covered by this contract (assume 500MW each hour) – thereby limiting the spot price risk for both parties. If the generator only generates 400MW in a given hour and the retailer consumes 600MW in the hour and the spot market price is $80/MWh, the financial settlement is:

- Generator earns in the spot market 400 * $80 = $32,000: spot market settlement.
- Retailer pays in the spot market 600 * $80 = $48,000: spot market settlement.
- Generator compensates retailer for 500 * ($80-$40) = $20,000: side settlement.
- The net effect is that the generator earns $32,000 - $20,000 = $12,000. (This can also be seen as getting $40 * 500 ($20,000) for its contract but having to buy from the market 100 * $80 ($8,000) to meet its shortfall in generation).
- Similarly the net effect is that the retailer pays $48,000 - $20,000 = $28,000. (This can also be seen as it paying $40 * 500 ($20,000) for its contract but having to buy from the market a further 100 at $80 ($8,000) to meet its shortfall in contract cover).

In this example, the retailer has hedged most of its risk and is only exposed to the spot market for 100MWh. The generator is over-hedged and has to buy at a high spot price to meet its hedge quantity. A generator can control its exposure to spot market risk by offering its capacity in the market to cover its contracts. It does this by meeting its contract obligation from its own generation as long as its short-run marginal cost is below the market price.

5.2.2 How Vesting Contract Curbs Market Power

A GENCO has the incentive to exercise market power by withholding some of its capacity to drive up the market price, especially when the revenue loss in the reduced quantity is larger than the revenue gain in the higher market price. One of the most desirable ways to curb the market power is to divide the large GENCOs into smaller GENCOs. However, in some markets such as Singapore Electricity Market, each GENCO owns only one power station that cannot be physically divided. In some other markets, dividing the GENCOs should be a very considerate decision. As a result, the vesting contract is a very good alternative.

A GENCO with several generating units available is used to analyze different scenarios with or without vesting contracts. The GENCO would submit to the market staircase bidding curves for every unit. The bidding quantity is Q_1, Q_2 and etc while the corresponding bidding price is P_1, P_2 and etc. The load demand quantity is D. The load demand is assumed to be fixed, i.e., non-elastic.

1) The Market without Vesting Contracts

Figure 5-2 shows the market situation without market power. The market clearing price for this scenario equals to the marginal bidding price, P_3. The profit that this generator can earn is as follows:

$$PRT_1 = Q_1 \cdot (P_3 - P_1) + (Q_2 - Q_1) \cdot (P_3 - P_2) \tag{5.1}$$

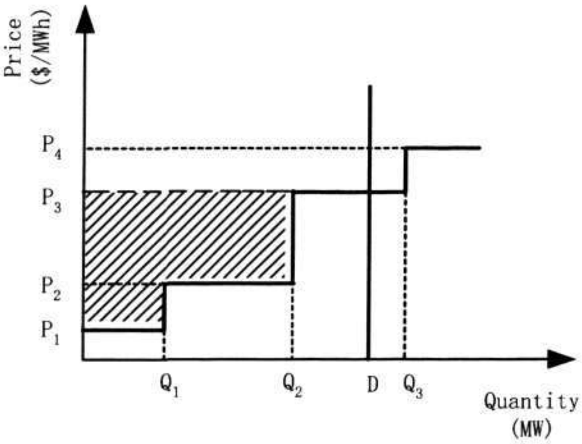

Figure 5-2 Market situation without market power and vesting contracts

If the GENCO holds back part of its capacity, the situation would change. If the quantity of the second segment is reduced from Q_2 to Q_{2A} then, as shown in Figure 5-3, the whole bidding staircase will move inward (Q_2 - Q_{2A}) accordingly. For example, Q_3 will be in the new position $Q_3^{'}$. From Figure 5-3, the market clearing price will go up and equal to P_4. The solid line represents the case that GENCO holds part of its capacity, while the dot line represents the benchmark situation without market power. This GENCO will lose part of its revenue shown as area B due to the quantity reduction of the second segment. However, it gains revenue in area A because the clearing price goes up. The profit it earns in this scenario is as follows:

$$PRT_2 = Q_1 \cdot (P_4 - P_1) + (Q_{2A} - Q_1) \cdot (P_4 - P_2) + (Q_3^{'} - Q_{2A}) \cdot (P_4 - P_3) \qquad (5.2)$$

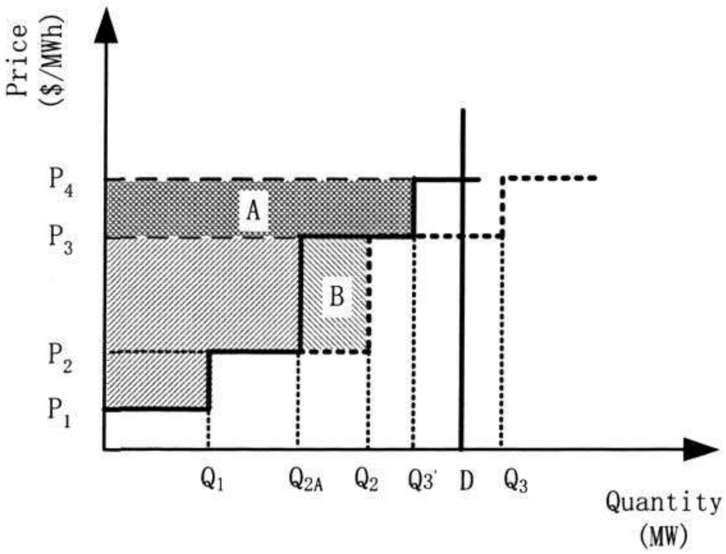

Figure 5-3 Market situation with market power but without vesting contracts

Comparing (5.1) and (5.2), the difference of shadowed area A and B will determine whether the generator would earn money or not through holding back its quantity. This can also be seen in Figure 5-3. It is formulated as follows:

$$PRT_2 - PRT_1 = (P_4 - P_3) \cdot Q_3^{'} - (P_3 - P_2) \cdot (Q_2 - Q_{2A}) \qquad (5.3)$$

2) The Market with Vesting Contracts

When the vesting contract is implemented, part of the energy quantities, Q_V, is fixed to the predefined system long term marginal cost. Figure 5-4 shows the revenue of the GENCO in this scenario.

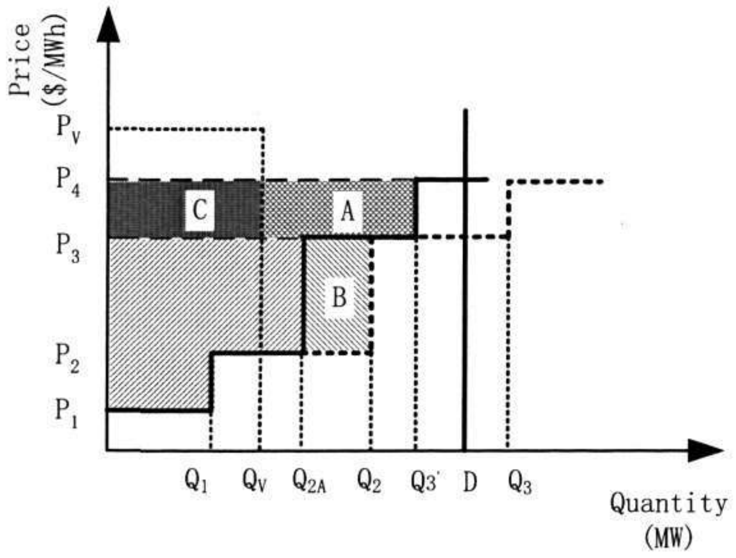

Figure 5-4 Market situation with market power but with vesting contracts

For the GENCO, no matter whether it holds back the capacity or not, it will receive a vesting price P_V for Q_V MW energy according to the rationale of the vesting mechanism. In this case, the profit in area C cannot be earned by the GENCO, even if the market clearing price is increased by withholding capacity. As a result, the area C is then deducted from area A. The profit earning from the rise of the market clearing price A will be squeezed significantly. The revenue that can be earned from holding the capacity under this scenario is as follows:

$$PRT_2' - PRT_1' = (P_4 - P_3)\cdot(Q_3' - Q_V) - (P_3 - P_2)\cdot(Q_2 - Q_{2A}) \tag{5.4}$$

where PRT_1', PRT_2' are the profits that this generator without or with market power can earn in the market with vesting contracts.

From (5.4), the first item is decreased. Therefore, it increases the complexity of holding back the capacity. In other words, the GENCO has to increase the marginal price P_4 if it wants to take advantage of capacity withholding. As a result, the market clearing price will increase. The surveillance panel will identify the abnormal increase of the market clearing price and determine whether the market power has been exercised. The corresponding action will be executed to curb the market power caused by the GENCO. Thus, it will not be profitable for the GENCO to hold back the capacity in the market with vesting contracts.

5.3 Market Equilibria with Vesting Contracts

The transaction of electricity involves three stages, i.e. the determination of the vesting contract, the CfD trade in the future market and the real time trade in the spot market. The vesting contract is decided by the regulator, and the GENCOs are forced to accept it. The future market is transparent in which the trades of CfDs are exposed to all the participants. CfDs are signed between the electricity suppliers and consumers in advance of the real-time operation but after the determination of the vesting contract. The spot market here refers to the gross pool where all the electricity transactions are traded through the pool and no physical bilateral contracts are to be arranged. Every GENCO in the market is assumed to be rational and each one is aiming at maximizing its profit.

A GENCO's behavior in the future market is impacted by the quantity of the imposed vesting contracts. Its behavior in the spot market is influenced by the future market and the vesting contract. In this section, the equilibria in the spot market and the future market, as well as the vesting contract quantity, are solved through backwards induction. The equilibria in the different markets will be analyzed in separate sections and the formulation for the regulator to set desired market clearing price will be given below.

5.3.1 Equilibrium in the Spot Market with CfDs and Vesting Contracts

According to the timetable in the electricity transaction process, the amount of CfD x_i and the amount of vesting contract x_{iv} have already been decided prior to the spot market bidding. Hence, each GENCO would decide their bidding strategy in the spot market considering its respective x_i and x_{iv}.

The demand is represented by the linear demand function. Assume that the linear demand function can be estimated by all participants by investigating the historical data in the electricity market. This means that each participant is assumed to know the same system demand function as follows:

$$Q = A - fp \tag{5.5}$$

where $Q = \sum_{i=1}^{N} q_i$

The cost of generation is given by a convex quadratic function $C_i(q_i)$ as follows:

$$\mathrm{C}_i(q_i) = \frac{1}{2} c_i q_i^2 + b_i q_i + a_i \tag{5.6}$$

Given the GENCO i's MW amount in the future market x_i and the MW amount in the vesting contract x_{iv}, the payoff function of GENCO i can be represented as follows:

$$\pi_i = pq_i(p) + (p_c - p)x_i + (p_v - p)x_{iv} - C_i(q_i(p)) \tag{5.7}$$

The payoff function has four terms. The first term is the revenue the GENCO would get from the spot market. The second and the third term is the impact of the CfD and vesting contract respectively. The last term is the cost of the generation for the GENCO to produce energy.

From (5.7), replacing output of GENCO i by the residual demand in (5.5), i.e.

$$q_i(p) = A - fp - q_{-i}(p) \tag{5.8}$$

the GENCO's profit π_i can be differentiated with respect to price,

$$\begin{aligned}\frac{d\pi_i}{dp} = A - fp - q_{-i}(p) - x_i - x_{iv} + p\left[-f - \frac{dq_{-i}(p)}{dp}\right] - \\ \left\{c_i\left[A - fp - q_{-i}(p)\right] + b_i\right\}\cdot\left[-f - \frac{dq_{-i}(p)}{dp}\right]\end{aligned} \tag{5.9}$$

Meanwhile, as a countercheck, the GENCO's profit π_i will also be differentiated with respect to quantity,

$$\begin{aligned}\frac{d\pi_i}{dq_i} &= \frac{dp}{dq_i}q_i + p - \frac{dp}{dq_i}x_i - \frac{dp}{dq_i}x_{iv} - (c_iq_i + b_i) \\ &= \frac{dp}{dq_i}(q_i - x_i - x_{iv}) + (p - c_iq_i - b_i)\end{aligned} \tag{5.10}$$

On one hand, setting the derivative in (5.9) to zero to obtain the profit-maximizing equilibrium,

$$q_i(p) = x_i + x_{iv} + p\left[f + \frac{dq_{-i}(p)}{dp}\right] - c_iq_i(p)\left[f + \frac{dq_{-i}(p)}{dp}\right] - b_i\left[f + \frac{dq_{-i}(p)}{dp}\right] \tag{5.11}$$

On the other hand, the profit-maximizing equilibrium could also obtained by setting the derivative in (5.10) to zero. As a result, (5.12) can be derived as follows:

$$(q_i - x_i - x_{iv}) = -(p - c_iq_i - b_i)\frac{dq_i}{dp} \tag{5.12}$$

Differentiating both sides in (5.5) with respect to p gives,

$$-f = \frac{dq_{-i}(p)}{dp} + \frac{dq_i(p)}{dp} \tag{5.13}$$

Derived from (5.12) and (5.13) , the price-quantity equilibrium pair for GENCO *i* is,

$$q_i(p) - (x_i + x_{iv}) = \left(p - c_i q_i(p) - b_i\right)\left(f + \frac{dq_{-i}(p)}{dp}\right) \tag{5.14}$$

Comparing (5.14) with (5.11), the both equations are exactly the same. By this way, the price-quantity equilibrium obtained is counterchecked.

In (5.14), since $dq_{-i}(p)/dp$ has a positive value due to the characteristics of the bidding supply function, $[f + dq_{-i}(p)/dp]$ would be positive. When the quantity is larger than the sum of the MW amount in the CfD and vesting contract, the spot market price should be higher than the GENCO's marginal cost.

In the spot market, each GENCO has to submit a piecewise linear, non-decreasing supply function. The supply function matches the quadratic cost function. It can be represented as follows:

$$q_i = \alpha_i + \beta_i p \tag{5.15}$$

The basis for the GENCO in choosing the right supply function is to make its profit maximum. Hence, the proper way for the GENCO to bid in the spot market is to make its supply function equal to the amount in (5.13). It is shown as follows:

$$\begin{aligned} \alpha_i + \beta_i p &= x_i + x_{iv} + p\left(f + \beta_{-i}\right) - c_i\left(\alpha_i + \beta_i p\right)\left(f + \beta_{-i}\right) - b_i\left(f + \beta_{-i}\right) \\ &= x_i + x_{iv} - c_i\alpha_i\left(f + \beta_{-i}\right) - b_i\left(f + \beta_{-i}\right) + p\left[\left(f + \beta_{-i}\right) - c_i\beta_i\left(f + \beta_{-i}\right)\right] \end{aligned} \tag{5.16}$$

Equation (5.16) can hold at any market clearing price, if the coefficient of *p* and the constant at both sides of (5.16) are equal. They are formulated in (5.17) and (5.18),

$$\alpha_i = \frac{x_i + x_{iv} - b_i\left(f + \beta_{-i}\right)}{1 + c_i(f + \beta_{-i})} \tag{5.17}$$

$$\beta_i = \frac{f + \beta_{-i}}{1 + c_i(f + \beta_{-i})} \tag{5.18}$$

There are N GENCOs in the market, and each of them would choose the coefficients of its supply function as shown in (5.17) and (5.18). The spot market clearing price is decided by the system demand function and the supply functions the GENCOs bid,

$$A - fp = Q = \alpha_i + \beta_i p + \alpha_{-i} + \beta_{-i} p \tag{5.19}$$

Solving (5.19), the spot market clearing price is as follows:

$$p = \frac{A - \alpha_i - \alpha_{-i}}{f + \beta_i + \beta_{-i}} \tag{5.20}$$

From (5.17) and (5.18), the relation of α_i and β_i in the supply function is determined in (5.21).

$$\frac{\alpha_i}{\beta_i} = \frac{x_i + x_{iv} - b_i(f + \beta_{-i})}{f + \beta_{-i}} \tag{5.21}$$

Incorporating (5.21) into (5.20), the spot market clearing price can be transformed to

$$p = \frac{1}{f + \beta_i + \beta_{-i}} \begin{pmatrix} A - \left[x_i + x_{iv} - b_i(f + \beta_{-i})\right] \dfrac{\beta_i}{f + \beta_{-i}} - \\ \sum\limits_{j=1, j \neq i}^{N} \left[x_j + x_{jv} - b_j(f + \beta_{-j})\right] \dfrac{\beta_j}{f + \beta_{-j}} \end{pmatrix} \tag{5.22}$$

After the price is calculated in (5.22), the output of GENCO i can be deduced from its supply function,

$$
\begin{aligned}
q_i &= \alpha_i + \beta_i p \\
&= \frac{\beta_i}{f+\beta_{-i}}\left[x_i + x_{iv} - b_i\left(f+\beta_{-i}\right)\right] + \frac{\beta_i}{f+\beta_i+\beta_{-i}} \\
&\quad \left\{\begin{aligned} & A - \left[x_i + x_{iv} - b_i\left(f+\beta_{-i}\right)\right]\frac{\beta_i}{f+\beta_{-i}} - \\ & \sum_{j=1, j\neq i}^{N}\left[x_j + x_{jv} - b_j\left(f+\beta_{-j}\right)\right]\frac{\beta_j}{f+\beta_{-j}} \end{aligned}\right\} \\
&= \frac{\beta_i}{f+\beta_i+\beta_{-i}} \cdot \\
&\quad \left\{\begin{aligned} & A - \left[x_i + x_{iv} - b_i\left(f+\beta_{-i}\right)\right]\frac{\beta_i}{f+\beta_{-i}} - \\ & \sum_{j=1, j\neq i}^{N}\left[x_j + x_{jv} - b_j\left(f+\beta_{-j}\right)\right]\frac{\beta_j}{f+\beta_{-j}} + \\ & \frac{f+\beta_i+\beta_{-i}}{f+\beta_{-i}}\left[x_i + x_{iv} - b_i\left(f+\beta_{-i}\right)\right] \end{aligned}\right\} \\
&= \frac{\beta_i}{f+\beta_i+\beta_{-i}} \cdot \\
&\quad \left\{ A + \left[\begin{aligned} & x_i + x_{iv} - b_i\left(f+\beta_{-i}\right) - \\ & \sum_{j=1, j\neq i}^{N}\left[x_j + x_{jv} - b_j\left(f+\beta_{-j}\right)\right]\frac{\beta_j}{f+\beta_{-j}} \end{aligned}\right]\right\}
\end{aligned} \tag{5.23}
$$

Equations (5.22) and (5.23) give a picture of the spot market equilibrium. As can be seen, the quantity and price are determined not only by the supply functions the GENCOs submit, but also by the fixed amount in the CfD and vesting contract. As in (5.22), when the total contract amount ($x_i + x_{iv}$) increases, the price in the spot market p decreases. As shown in (5.23), when ($x_i + x_{iv}$) increases, the spot market cleared quantity q_i increases as well.

5.3.2 Equilibrium in the Future Market with Vesting Contract

Given the equilibrium in the spot market, GENCO i needs to get its best position in the future market. In other words, GENCO i has to choose the best CfD amount, x_i, for itself given the vesting amount x_{iv}. For simplicity, the GENCOs are assumed to have the same marginal cost, i.e. the same c_i and b_i. From (5.18), β_i in the supply function should be the same for all the GENCOs in the market. Hence, the subscript is omitted such that c and b represent the uniform cost parameter while β is the uniform supply function parameter in the market.

Since the strike price p_v for the vesting contract is determined by the regulator, it might not be equal to the spot market clearing price. Meanwhile, because the future market is transparent and the trades of CfDs are exposed to all the participants, the price for the CfD would be the same. At the same time, all the participants know the spot market equilibrium. These two factors would lead the CfD strike price p_c in the future market equal to the expected spot market clearing price p.

$$p_c = p = \frac{1}{f+N\beta}\left\{A - \frac{\beta}{f+(N-1)\beta}\left[\begin{array}{l} x_i + x_{iv} + \sum\limits_{j=1, j\neq i}^{N}\left(x_j + x_{jv}\right) \\ -Nb\left(f+(N-1)\beta\right) \end{array}\right]\right\} \tag{5.24}$$

Therefore, with $(p_c - p)x_i = 0$, equation (5.7), as the profit of the GENCO i, can be rewritten as,

$$\pi_i = p(x_i, x_{-i})q_i(x_i, x_{-i}) - \frac{1}{2}cq_i(x_i, x_{-i})^2 - bq_i(x_i, x_{-i}) - a + (p_v - p)x_{iv} \tag{5.25}$$

Differentiate it with respect to the firm's contract sales x_i, we obtain

$$\begin{aligned} \frac{d\pi_i}{dx_i} &= \frac{dp}{dx_i}q_i + (p - cq_i - b)\frac{dq_i}{dx_i} - \frac{dp}{dx_i}x_{iv} \\ &= \frac{dp}{dx_i}(q_i - x_{iv}) + (p - cq_i - b)\frac{dq_i}{dx_i} \end{aligned} \tag{5.26}$$

Substituting p, q_i and $(p - cq_i - b)$ from (5.22), (5.23) and (5.14) respectively to (5.26), the expression is transformed to:

$$\begin{aligned}\frac{d\pi_i}{dx_i} &= \frac{1}{f+N\beta}\frac{\beta}{f+(N-1)\beta}\left(-1-\frac{dx_{-i}}{dx_i}\right)(q_i-x_{iv})+ \\ &\quad \frac{\beta}{f+N\beta}\left(1-\frac{dx_{-i}}{dx_i}\frac{\beta}{f+(N-1)\beta}\right)\left(\frac{q_i-x_i-x_{iv}}{f+(N-1)\beta}\right) \\ &= \frac{1}{f+N\beta}\frac{\beta}{f+(N-1)\beta}\left\{-x_i-\frac{dx_{-i}}{dx_i}\left[\begin{matrix}q_i-x_{iv}+ \\ \dfrac{\beta}{f+(N-1)\beta}(q_i-x_i-x_{iv})\end{matrix}\right]\right\}\end{aligned} \tag{5.27}$$

When (5.27) is set to 0, GENCO *i* can find its optimized amount x_i in the future market. The formulation is,

$$\begin{aligned}x_i &= -(q_i-x_{iv})\frac{\left(1+\dfrac{\beta}{f+(N-1)\beta}\right)\dfrac{dx_{-i}}{dx_i}}{1-\dfrac{dx_{-i}}{dx_i}\dfrac{\beta}{f+(N-1)\beta}} \\ &= -(q_i-x_{iv})\left[\frac{(f+N\beta)\dfrac{dx_{-i}}{dx_i}}{f+(N-1)\beta-\beta\dfrac{dx_{-i}}{dx_i}}\right]\end{aligned} \tag{5.28}$$

The conjectural variation dx_{-i}/dx_i refers to the belief or expectation of GENCO *i* on its rivals' reaction to its contract amount change in the future market and its range is [-1, 0]. When dx_{-i}/dx_i is equal to -1, it is also called "Bertrand conjecture". This means that GENCO *i* believes that other GENCOs would take in every MW it drops in the future market. When dx_{-i}/dx_i is equal to 0, it is also called "Cournot conjecture". Under this situation, other GENCOs would not take in any MW no matter what the amount GENCO *i* drops in the future market. As can be seen in (5.28), if GENCO *i* holds a "Bertrand conjecture", it would cover the remaining output that is not under the protection of the vesting contract in the future market, i.e. $x_i = q_i - x_{iv}$. If GENCO *i* holds a "Cournot conjecture", it would not cover any output in the future market, i.e. $x_i = 0$.

For general cases, the conjectural variation index *m* is used to represent the square bracket term in (5.28). The formulation for x_i can be rewritten as,

$$x_i = -(q_i - x_{iv})m \tag{5.29}$$

where

$$m = \frac{(f + N\beta)\dfrac{dx_{-i}}{dx_i}}{f + (N-1)\beta - \beta\dfrac{dx_{-i}}{dx_i}} \tag{5.30}$$

The conjectural variation index *m* is a monotonous increasing function with respect to dx_{-i}/dx_i. Its value is within [-1, 0] since dx_{-i}/dx_i holds the value in the range of [-1, 0].

Meanwhile, the second order condition of GENCOs to maximize their profit is derived as follows. The derivation steps are presented fully in APPENDIX B.

$$\frac{d^2\pi_i}{dx_i^2} = \frac{1}{f + N\beta}\frac{-\beta}{f + (N-1)\beta}\left[1 - \left(\frac{dx_{-i}}{dx_i}\frac{\beta}{f + (N-1)\beta}\right)^2\right] \tag{5.31}$$

Since dx_{-i}/dx_i is between –1 and 0, it can be seen easily that this second derivative is negative. Then the result of the first order condition will be the maximum point of the profit. It means the market result obtained would be a Nash equilibrium.

If every GENCO has the same conjectural variation and the same amount in the vesting contract, at the equilibrium point in the spot market, GENCO *i* would get from (5.23),

$$\begin{aligned} q_i &= \frac{\beta}{f + N\beta}\left\{\begin{matrix} A + \left[-(q_i - x_{iv})m + x_{iv} - b(f + (N-1)\beta)\right] - \\ (N-1)\begin{bmatrix} -(q_i - x_{iv})m + x_{iv} - \\ b\left(f + (N-1)\beta\right) \end{bmatrix}\dfrac{\beta}{f + (N-1)\beta} \end{matrix}\right\} \\ &= \frac{\beta}{f + N\beta}\left\{A + \frac{f}{f + (N-1)\beta}\begin{bmatrix} -q_i m + m x_{iv} + x_{iv} \\ -b\left(f + (N-1)\beta\right) \end{bmatrix}\right\} \end{aligned} \tag{5.32}$$

Equation (5.32) can be re-arranged, and q_i can be solved as follows:

$$\begin{aligned} q_i &= \frac{\dfrac{\beta A}{f+N\beta}+\dfrac{\beta f(1+m)x_{iv}-\beta fb(f+(N-1)\beta)}{(f+N\beta)[f+(N-1)\beta]}}{1+\dfrac{\beta fm}{(f+N\beta)[f+(N-1)\beta]}} \\ &= \frac{\beta A[f+(N-1)\beta]+\beta f(1+m)x_{iv}-\beta fb[f+(N-1)\beta]}{(f+N\beta)[f+(N-1)]+\beta fm} \end{aligned} \tag{5.33}$$

Because the term $\beta f(1+m)x_{iv}$ is a positive one, comparing to "no vesting contract" in the spot market where x_{iv} is 0, at the equilibrium point, q_i with the vesting contact increases in the spot market. Then the price in the spot market will decrease and the consumers would benefit from the reduced price.

5.3.3 Determination of the Optimal Vesting Amount

Based on the profit maximization rule, each GENCO would choose the proper CfD amount as in (5.30) and finally get the cleared amount in (5.33). The objective in the vesting contract is for the regulator to partially adjust the market competitiveness. Through the adjustment of the vesting amount, the regulator can curb the market power by maintaining the market clearing price and the total cleared amount at a reasonable level.

The key is how much is a reasonable level of price. Under the perfectly competitive market, each GENCO would bid its short term running cost. The consumers would benefit most in this situation. However, as mentioned before, the power industry needs to get enough revenue to cover the fixed costs of the plant and to sustain its development. Therefore, a perfect competition is not necessarily the appropriate standard to be aiming at and a market clearing price higher than that in the perfect market is needed. An expected price ratio φ is used to represent the ratio of the equilibrium market clearing price to the fully competitive market price. The relation between the expected clearing price p and the fully competitive price p_B is,

$$p = \varphi p_B \tag{5.34}$$

From (5.34), the projected quantity index k, i.e. the ratio of the expected market clearing quantity over the fully competitive quantity is as follows:

$$k = \frac{Nq_i}{Nq_B} = \frac{A - f\varphi p_B}{A - fp_B} \tag{5.35}$$

Under the fully competitive market, the GENCOs bid a price at marginal cost ($cq_B + b$). Together with the system demand function in (5.5), the quantity cleared for each GENCO can be solved and shown to be:

$$q_B = \frac{A - fb}{fc + N} \tag{5.36}$$

Incorporating q_i and q_B in (5.33) and (5.36), (5.35) can be transformed into,

$$\frac{\dfrac{\beta A}{f + N\beta} + \dfrac{\beta f(1+m)x_{iv} - \beta fb\left[f + (N-1)\beta\right]}{(f + N\beta)\left[f + (N-1)\beta\right]}}{1 + \dfrac{\beta fm}{(f + N\beta)\left[f + (N-1)\beta\right]}} = k\frac{A - fb}{fc + N} \tag{5.37}$$

The vesting contract MW amount with respect to the parameter k can be calculated as follows:

$$\begin{aligned} x_{iv} = {} & \frac{k(A - fb)\left\{(f + N\beta)\left[f + (N-1)\beta\right] + \beta fm\right\}}{(fc + N)(1+m)\beta f} \\ & + \frac{-\beta A\left[f + (N-1)\beta\right] + \beta fb\left[f + (N-1)\beta\right]}{(1+m)\beta f} \end{aligned} \tag{5.38}$$

The amount in the vesting contract x_{iv} has its range. The minimum amount is 0, which means that the regulator would not impose a vesting contract in the market. The maximum amount of x_{iv} is q_i, which means that the GENCO i's MW output is covered by the vesting contract. In other words, if k is too large or too small, then x_{iv} may exceed its range and that makes no sense. The typical value of k is less than but close to 1.

5.4 The Simulation Study

5.4.1 Introduction of the Simulation Case

The example system in [122] and [57] is modified to do the case studies. Each GENCO carries the same cost function. The operation cost represented by $/h is defined by, $C_i(q_i)=\frac{1}{2}0.02q_i^2+10q_i$ ($i=1,2,...,\mathrm{N}$). In the meantime, the demand utility function is $C(Q)=-0.04Q^2+30Q$. The marginal utility of the demand can be obtained by differentiating the demand utility function. When the marginal utility function is transformed, the corresponding demand function can be obtained as $Q=375-12.5p$. In the study case of these two reference papers, the demand function $Q=375-12.5p$ will face two identical Gencos, i.e. each Genco will face a demand $Q={}^1\!/_2(375-12.5p)$. When we considered N-Gencos case, to make a fair comparison, the demand function is assumed to proportionally change according to the number of the players. That means that the demand curve for N Gencos will be $Q=N/2*(375-12.5p)$.

5.4.2 Influence of the Vesting Contract on the Market and GENCOs' Strategic Behavior

Without loss of the generality, the market with 3 identical GENCOs is analyzed below. If not mentioned explicitly, N is assumed to be 3 in the analysis. To begin with, the equilibrium under perfectly competitive market and supply function competition without a future market and a vesting contract will be calculated as the benchmarks. When the GENCOs bid marginal cost as the price, the quantity and price in the perfectly competitive market can be calculated. The market clearing price and quantity under the supply function could also be obtained by setting x_i and x_{iv} to 0 in (5.22) and (5.23). The equilibria are shown in Table 5-1.

Table 5-1 Market Situation without Vesting Contract and Future Market

Market condition	Perfectly competitive	Supply Function
q_i (MW)	111.11	103.93
p (\$/MWh)	12.22	13.37

With the presence of the future market and vesting contracts, the market equilibria would shift. The market performance under different vesting contract levels and conjectural variation index m are shown in Table 5-2.

As can be seen in the first part of Table 5-2 where x_{iv} is 0 MW, the maximum price is 13.26 \$/MWh. This price is still less than that of the supply function equilibrium i.e. 13.37 \$/MWh in Table 5-1. This means that the market clearing price with the future market is less than that without even though the vesting contract is not imposed. It proves that the utilization of CfDs can curb the market power to some extent. This observation agrees with the conclusion in [52].

Besides the observation above, it can also be seen that when the quantity fixed in the vesting contract increases, the GENCOs would reduce the contract amount in the future market. However, the total amount of the vesting contract and CfD increases instead. For example, under the situation where m is fixed at -0.5, the GENCO would reduce the CfD amount x_i from 53.70 MW to 19.87 MW if the vesting contract quantity x_{iv} increases from 0 MW to 70 MW. Meanwhile, the total amount of CfD and vesting contract ($x_i + x_{iv}$) will increase from 53.70 MW to 89.87 MW. As a result, the cleared quantity of each GENCO q_i increases from 107.40 MW to 109.74 MW and the market clearing price p decreases from 12.82 \$/MWh to 12.44 \$/MWh. This result numerically illustrates the conclusion, which has been pointed out above, i.e. a larger amount of ($x_i + x_{iv}$) would lead to a larger cleared amount for each GENCO and would subsequently result in a lower market clearing price. This shows that the implementation of vesting contract is able to reduce the clearing price and hence it is a good tool for the regulator to curb market power. The consumers would benefit from the market efficiency brought by the vesting contract.

Table 5-2 Market Performance with Vesting Contracts

x_{iv} = 0 MW				
m	x_i (MW)	$x_{iv} + x_i$ (MW)	q_i (MW)	p ($/MWh)
-0.1	10.46	10.46	104.61	13.26
-0.3	31.80	31.80	105.99	13.04
-0.5	53.70	53.70	107.40	12.82
-0.7	76.20	76.20	108.85	12.58
-0.9	99.31	99.31	110.35	12.34
x_{iv} = 30 MW				
m	x_i (MW)	$x_{iv} + x_i$ (MW)	q_i (MW)	p ($/MWh)
-0.1	7.64	37.64	106.36	12.98
-0.3	23.21	53.21	107.37	12.82
-0.5	39.20	69.20	108.40	12.66
-0.7	55.62	85.62	109.46	12.49
-0.9	72.50	102.5	110.55	12.31
x_{iv} =50 MW				
m	x_i (MW)	$x_{iv} + x_i$ (MW)	q_i (MW)	p ($/MWh)
-0.1	5.75	55.75	107.53	12.79
-0.3	17.49	67.49	108.29	12.67
-0.5	29.54	79.54	109.07	12.55
-0.7	45.91	95.91	109.87	12.42
-0.9	54.62	104.62	110.69	12.29
x_{iv} = 70 MW				
m	x_i (MW)	$x_{iv} + x_i$ (MW)	q_i (MW)	p ($/MWh)
-0.1	3.87	73.87	108.70	12.61
-0.3	11.76	81.76	109.21	12.53
-0.5	19.87	89.87	109.74	12.44
-0.7	28.19	98.19	110.28	12.36
-0.9	36.75	106.75	110.83	12.27

In addition, the impact of m is analyzed. From Table 5-2, with the increase of m from -1 to 0, the influence of the vesting contract on the spot price is getting stronger. For instance, when m is -0.9, the clearing price only changes (12.34 - 12.27) = 0.07 \$/MWh as x_{iv} changes from 0 MW to 70 MW. In fact, the prices at $m = 0.9$ and $x_{iv} = 70$ MW are also very close to that in the perfectly competitive situation. This means that the implementation of the vesting contract does not function effectively. On the other hand, when m is close to 0, say -0.1, the picture is quite different. The market clearing price reduces (13.26 - 12.61) = 0.65 \$/MWh as x_{iv} changes from 0 MW to 70 MW. The comparison reveals that the vesting contract is more effective in the future market with a Cournot conjecture than with a Bertarnd conjecture. As has been shown in [52], when conjectural variation of GENCOs on CfD is near Bertrand conjecture, the CfD of GENCO covers nearly the whole generation, which makes the price in the spot market close to that in the perfectly competitive market. Since the CfD would have already curbed market power so well, it is not necessary to utilize the vesting contract. However, when conjectural variation of GENCOs on CfD is approaching Cournot conjecture, GENCOs would hardly sell any CfD. As a result, the MW amount of GENCO in the spot market decreases and market power emerges. In this case, vesting contracts are very useful to increase the total contract amount and hence to decrease the market clearing price, i.e. control market power effectively.

The ability to foresee the market equilibrium is critical to the GENCOs. According to the definition of the Nash equilibrium, if any GENCO deviates from the equilibrium unilaterally, its profit will be worse off. As a result, being a rational participant, each GENCO should accordingly set its strategy to the new equilibrium point to maximize its benefit. The analysis above is useful for directing GENCOs how to appropriately adjust the strategy in the future and spot market.

5.4.3 Determination of the Vesting Contract Amount

The proper vesting contract amount the regulator would set depends on two factors. The first factor is the target market competitiveness represented by the expected price ratio φ, i.e. the expected market clearing price over the fully competitive market clearing price.

The smaller the regulator sets the value of φ, the closer the market would move towards the fully competitive price. The second factor is the current market performance. It comprises the degree of future market competition represented by dx_{-i}/dx_i, its corresponding m, the demand function and the number of market participants.

The influence of the expected price ratio φ and the conjectural variation index m for the regulator to decide x_{iv} as well as x_{iv}/q_i is shown in Table 5-3. Here, x_{iv}/q_i refers to the percentage of the vesting contract amount over the spot market cleared quantity.

Table 5-3 Contract Amount under Different φ and m

φ	1.01	1.02	1.03	1.04
k	0.9931	0.9862	0.9794	0.9725
q_i (MW)	110.35	109.58	108.82	108.06
m = -0.1 or dx_{-i}/dx_i = -0.07				
x_{iv} (MW)	101.77	85.01	71.97	58.92
x_{iv}/q_i (%)	88.87	77.58	66.13	54.52
m = -0.3 or dx_{-i}/dx_i =-0.23				
x_{iv} (MW)	94.55	77.99	61.44	44.88
x_{iv}/q_i (%)	85.69	71.17	56.46	41.53
m = -0.5 or dx_{-i}/dx_i =-0.42				
x_{iv} (MW)	88.23	65.36	42.48	19.61
x_{iv}/q_i (%)	79.96	59.64	39.04	18.14

As can be seen in Table 5-3, when the regulator sets a higher φ, the quantity cleared in the market decreases. This is because the market clearing price and the cleared quantity in the system demand function in (5.5) has an inverse proportion relationship. Meanwhile, the increase of φ also leads to the decrease of the vesting contract amount x_{iv} under the same m. Although both the cleared market quantity and vesting contract amount decrease when φ increases, it can be observed that the percentage x_{iv}/q_i decreases. For example, when the value of m is equal to -0.1, the percentage would decrease from 88.87% to 54.52% when

φ moves from 1.01 to 1.04. This means that more vesting contract amount is required if the expected market competitive situation is set at a higher level.

From Table 5-3, it can also be seen that the conjectural variable dx_{-i}/dx_i in the future market and its corresponding m also play important roles in the determination of the vesting contract amount. If φ is fixed, the larger the $|m|$, the less x_{iv}/q_i needs to be imposed. This is because $|m|$ with a larger value indicates a more fierceful competition in the future market, which results in a bigger CfD amount. Hence less vesting contract amount is needed to control the price in the spot market down to the expected low level.

The system demand function in the market can also influence the vesting contract amount. In the base case, A and f is set at 562.5 and 18.5 respectively. m is fixed at -0.5 and the objective is to maintain the value of φ at 1.04.

First, the influence f is examined. The constant A remains unchanged at 562.5. Figure 5-5 shows the vesting contract amount x_{iv} and the percentage x_{iv}/q_i under different f.

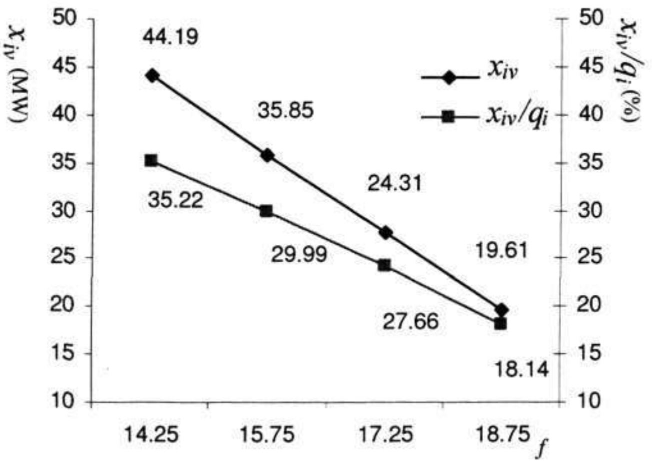

Figure 5-5 Vesting contract under different f

The decease of f will make the demand curve flatter and more energy is needed. From Figure 5-5, the vesting contract imposed decreases along with the increase of the value of *f*. Meanwhile, the speed x_{iv} increases is faster than that of q_i, which results in the rise of the percentage x_{iv}/q_i. This shows the smaller *f* is, the more the vesting contract amount is required for the regulator to adjust the market situation to the expected point.

Second, the influence of *A* is examined. The first order parameter *f* remains unchanged at 18.5. Figure 5-6 shows how much vesting contract amount is needed under different *A* in order to maintain the same φ.

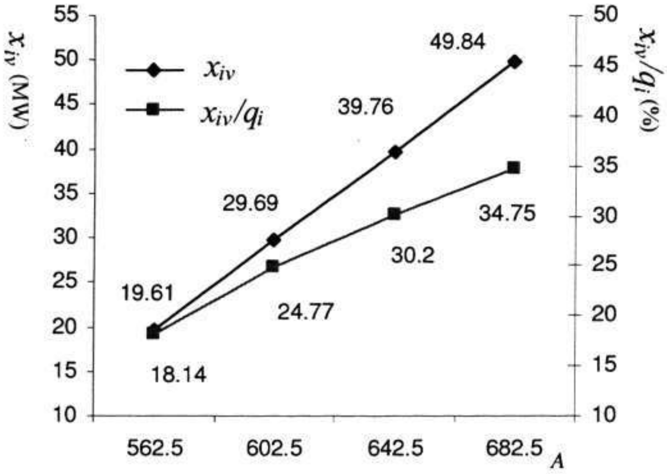

Figure 5-6 Vesting contract under different A

The increase of *A* means there is more energy needed. From Figure 5-6, the increase of *A* will lead to the increase of vesting contract amount x_{iv} and the percentage x_{iv}/q_i.

Examining the influence of *A* and *f* gives us useful suggestions that the vesting contract amount should be discriminated during the peak load and the valley load periods. Besides, vesting contract should be updated regularly. Singapore market also has similar consideration.

In the competitive electricity market, the market mechanism is well designed to trigger new investment. As a result, new entrants are always expected and the market equilibria will also shift accordingly along with the increasing number of the GENCOs. In the following analysis, N is varied to see the impact of the number of GENCOs. To exclude other factors, m and φ are fixed at -0.3 and 1.03 respectively. The demand function will also be increased proportionally with the number of GENCOs, i.e. $Q = N/2*(375*-12.5p)$

As a result, the spot market price under the perfect competition p_B remains the same at 12.22 $/MWh. The quantity that each GENCO carries under the perfect competitive competition would not change either. The amount is 111.11 MW. According to (5.35), k is decided by φ and consequently q_i can be calculated. The value for φ, k and q_i are 1.03, 0.9794 and 108.82 MW respectively.

Table 5-4shows the vesting contract amount and percentage x_{iv}/q_i as the number of market players is varied. As can be seen, the number of the players has a significant impact on the vesting contract. To maintain a spot market price that is 1.03 times the perfect competitive clearing price, the regulator needs to impose 82.66% vesting contract coverage under a 2-player market while only 27.27% is required under a 4-player market.

Table 5-4 Influence of Player Number

N	2	3	4
x_{iv} (MW)	89.95	61.44	29.67
x_{iv}/q_i (%)	82.66	56.46	27.27

From the analysis in this section, it is clear that the target market competitiveness (represented by φ) and the market performance (represented by m, A, f and N) have critical impacts on the decision of the vesting contract amount. As a result, the regulator must adjust the vesting contract amount along with the change of these factors. Through the adjustment, the possible market power can be controlled and the expected market price will be obtained.

5.5 Concluding Remarks

In this chapter, vesting contracts are introduced as a good way to curb strategic bidding and market power. To analyze the impact of the vesting contracts on market power and the strategic behavior of generators, the oligopoly electricity transaction process comprises the determination of vesting contract content, trade in a transparent future market and a bid-based electricity spot market. The spot market and the future market equilibria under vesting contract are theoretically analyzed through the supply function and conjectural variation respectively. Note that both the market equilibria could be analyzed under conjectural variation. However, if we do so, it would have been very cumbersome to solve the model [123]. To explain the methodology clearer, we chose to restrict the generality of the analysis by imposing supply function on the spot market. It proves that the total mount of vesting contract and CfD would lead to the increase of the cleared quantity in the spot market and would result in the reduction of the market clearing price, which means the decrease of market power. Based on the formulation derived for the spot market and future market equilibrium, the GENCOs can move to the new equilibrium points where their profits are maximized. In addition, formulations for the regulators are also derived to compute the proper vesting contract amount so that the existing market power can be reduced and the expected market competitiveness can be obtained.

Chapter 6 Conclusions and Recommendations

6.1 Conclusions

The way to empirically detect strategic bidding behavior and market power is presented in this thesis. Meanwhile, the technique to limit strategic bidding behavior and market power is studied as well.

In the first part of the thesis, a theory and method for the statistical estimation of the conjectural variation are proposed. This proposed method is applied to the Australia National Electricity Market (NEM). After that, the static behaviors of GENCOs over a long period are investigated. All the parameters needed to calculate the conjectural variation, the values of the marginal cost c_i, the price elasticity α, the market clearing price p and the market share s_i, are first estimated based on the actual data of the NEM. The mean value of conjectural variation of GENCOs during a given period in the NEM is calculated through these estimated parameters. The mean values of conjectural variation on Cournot, Bertrand and Monopoly are also estimated as benchmarks. By comparing the value of conjectural variation of GENCOs with these benchmark values, it could be found that the Cournot behavior can be accepted more reasonably, while the Bertrand and monopoly behavior are strongly rejected.

In the repeated electricity, GENCOs will learn from its rival's behaviors over time. Dynamic behavior of GENCOs is closer to the reality situation. Monthly mean values of all parameters are estimated first. Then the monthly mean conjectural variation series could be calculated to perform dynamic empirical analysis. Based on the methodology of dynamic behavior analysis, the Cournot behavior hypothesis is more reasonable, while the hypothesis of repeated monopoly and Bertrand behavior is rejected. This result shows the GENCO behaviors in the NEM are more consistent with non-cooperative market power, but not tacit collusion, though there is a great possibility for all GENCOs to reach tacit collusion in the repeated electricity market.

In the second part of the thesis, vesting contracts are used as an effective method to curb strategic bidding and market power. The impact of vesting contracts on market power and the strategic behavior of GENCOs is analyzed through an electricity market with a spot market and future market. Vesting contract is a mandatory type of CfD. It is observed in several markets that the implementation of vesting contract brought market clearing price reduction. In this research, the oligopoly electricity transaction process comprises the determination of vesting contract content, trade in a transparent future market and a bid-based electricity spot market. The future market and spot market equilibrium under vesting contract is theoretically analyzed through the supply function and conjecture variation respectively. The equilibria results show that the implementation of the vesting contract can change the market equilibrium. The increase of the total mount of vesting contract and CfD would result in an increase of the cleared quantity in the spot market. The market clearing price will reduce accordingly, which means a decrease of the market power level. It proves the implementation of vesting contract could reduce the incentive of GENCO to bid strategically and limit the ability of GENCO to exercise market power. A proper vesting quantity is also obtained aiming at driving the anticipated market clearing price to a predetermined level. Thus, formulations for the regulators are also derived to compute the proper vesting contract amount so that the existing market power can be reduced and the expected market competitive situations can be obtained. As the equilibrium will move, GENCOs also need to be clear where these points are and modify their strategies to maximize their profit under the new environment. The case study also gives examples showing the impact of the factors, such as number of GENCOs, system demand function and conjecture variation attitude in the market, on the vesting contract amount and the market equlibria.

6.2 Recommendations

In this thesis, the techniques on detecting and mitigating strategic bidding and market power are studied. There is ample scope for extension of the research work and a few specific topics are suggested below.

- In the first major part of this research work, only the strategic behavior of GENCOs in pool model is investigated. However, hybrid model is widely used in many electricity markets worldwide. In the hybrid model, power suppliers have the choice to sell bilateral contracts to consumers directly without entering into pooling arrangement. The bilateral contracts sold will indirectly affect the market clearing because the quantity of bilateral contracts sold by a generator will directly affect the bidding strategy of the generator in the pool market. Thus the measurement of marginal cost and conjectural variation can be further researched to incorporate the effect of bilateral contracts.

- This research analyzes the static and dynamic behavior of GENCOs in the NEM by the empirical knowledge of the conjectural variation of GENCOs. However, the constraints of transmission line are ignored. In actual electricity, these constraints will have great impact on the market clearing results, the ability of exercising market power by GENCOs, and the bidding strategy of GENCOs. In the future research, the constraints of transmission line could be taken into account.

- Some assumptions have been made throughout the study in the second part of the thesis: linear demand function and competing GENCOs are identical. The latter assumes that the GENCOs are of the same size and have the same cost structure without uncertainty or asymmetric information about the spot and future/CfD markets. Further studies may consider relaxing one or more of the above assumptions to bring the analysis closer to reality.

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APPENDIX A: Proof of Nash Equilibrium via CVBS

Proof: According to Equation (4.14) and knowing that

$$CV_i = \sum_{j=1, j\neq i}^{N} \frac{\partial q_j}{\partial q_i} = \frac{\partial Q}{\partial q_i} - \frac{\partial q_i}{\partial q_i} = \frac{\partial Q}{\partial q_i} - 1$$

and $q_{-i} = Q - q_i$, (4.14) can be rewritten as follows:

$$q_i[f(2+CV_i)+c_i]-(e-fq_{-i}-b_i)=0$$

Then

$$fq_i\frac{\partial Q}{\partial q_i}-(e-fQ)+(b_i+c_iq_i)=0 \quad (i=1,\cdots,N)$$

Therefore the optimal solution for (4.8)should satisfy:

$$\begin{cases} fq_1\dfrac{\partial Q}{\partial q_1}-(e-fQ)+(b_1+c_1q_1)=0 \\ \qquad\qquad\vdots \\ fq_i\dfrac{\partial Q}{\partial q_i}-(e-fQ)+(b_i+c_iq_i)=0 \\ \qquad\qquad\vdots \\ fq_N\dfrac{\partial Q}{\partial q_N}-(e-fQ)+(b_N+c_Nq_N)=0 \end{cases} \quad (1)$$

In terms of the assumptions, each firm holds a constant conjecture CV_i^* when time goes to infinite. Then $\frac{\partial Q}{\partial q_i}$ in (1) is also a constant and fixed as $(1+CV_i^*)$, which makes (1) become a set of linear algebraic equations. Replacing Q by $\sum_{i=1}^{N} q_i$ and $\frac{\partial Q}{\partial q_i}$ by $(1+CV_i^*)$ and rearranging (1), it can easily be found that the optimal decisions of Firm i ($i = 1,2,\ldots, N$) should satisfy

$$\begin{bmatrix} f(2+CV_1^*)+c_1 & f & \cdots & f \\ f & f(2+CV_2^*)+c_2 & \cdots & f \\ & & \cdots & \\ f & f & \cdots & f(2+CV_N^*)+c_N \end{bmatrix} \begin{bmatrix} q_1^* \\ q_2^* \\ \vdots \\ q_N^* \end{bmatrix} = \begin{bmatrix} e-b_1 \\ e-b_2 \\ \vdots \\ e-b_N \end{bmatrix} \qquad (2)$$

In addition, it can be derived from (4.14) that

$$CV_i = \frac{(e - fq_{-i} - b_i) - (2f + c_i)q_i}{fq_i} = \frac{p - (b_i + c_i q_i)}{fq_i} - 1 = \frac{p - MC_i}{fq_i} - 1 \quad (3)$$

Physically $p\text{-}MC_i \geqslant 0$, since the decision of Firm i on q_i will always make $MC_i = \frac{\partial C_i(q_i)}{\partial q_i} \leq p$ in order to make profits. Therefore CV_i will satisfy the following condition:

$$CV_i = \frac{p - MC_i}{fq_i} - 1 \geq -1 \qquad (4)$$

In the meantime, it can be seen that the second order derivative of the objective function of (4.8) w. r. t. q_i at CV_i^* can be expressed as follows:

$$\frac{\partial^2 \pi_i}{\partial q_i^2} = -2f(CV_i^* + 1) - c_i$$

From (4), it can be shown that:

$$\frac{\partial^2 \pi_i}{\partial q_i^2} \leq 0 \qquad (5)$$

which means π_i reaches global maximum for Firm *i* at the solution point. From (5) it can be concluded that if time goes to infinite, each firm tends to hold constant CV_i^*, and if other firms do not change their outputs q_j^*, Firm *i* will not change its output q_i^* (*i* = *1, 2, …, N*), which satisfies (2). This means that the bidding strategy set $\{q_1^*, q_2^*, \cdots, q_N^*)$ is a Nash equilibrium and the equilibrium is stable. (End of proof)

APPENDIX B: Derivation of Equation (5.31)

Derivation: Noted that, for $\frac{dx_{-i}}{dx_i}$, x_{iv} and x_{-iv}, none of them is the function of x_i and thus the differentiation with respect to x_i is 0. According to the first order condition (5.26), the second order condition of GENCO *i* to maximize its profit is derived as follows:

$$\begin{aligned} \frac{d^2\pi_i}{dx_i^2} &= \frac{1}{f+N\beta}\frac{-\beta}{f+(N-1)\beta}\left\{1+\frac{dx_{-i}}{dx_i}\left[\frac{dq_i}{dx_i}+\frac{\beta}{f+(N-1)\beta}(\frac{dq_i}{dx_i}-1)\right]\right\} \\ &= \frac{1}{f+N\beta}\frac{-\beta}{f+(N-1)\beta}\left\{1+\frac{dx_{-i}}{dx_i}\left[\frac{(f+N\beta)\frac{dq_i}{dx_i}-\beta}{f+(N-1)\beta}\right]\right\} \end{aligned} \qquad (1)$$

From (5.23), based the assumption that the GENCOs have the same marginal cost in Section 5.3.2, the optimal output of GENCO *i* is transformed to:

$$q_i = \frac{\beta}{f+N\beta}\left\{A+\left[\begin{array}{l} x_i + x_{iv} - b\big(f+(N-1)\beta\big) - \\ \big[x_{-i}+x_{-iv}-b\big(f+(N-1)\beta\big)\big]\frac{\beta}{f+(N-1)\beta}\end{array}\right]\right\} \qquad (2)$$

Then differentiate it with respect to the GENCO's contract sales x_i, it could be obtained that:

$$\frac{dq_i}{dx_i} = \frac{\beta}{f+N\beta}\left[1-\frac{dx_{-i}}{dx_i}\frac{\beta}{f+(N-1)\beta}\right] \qquad (3)$$

Submitting (3) into (1), the expression of the second order condition of GENCO *i* is transformed to:

$$\frac{d^2\pi_i}{dx_i^2} = \frac{1}{f+N\beta}\frac{-\beta}{f+(N-1)\beta}\left[1-(\frac{dx_{-i}}{dx_i}\frac{\beta}{f+(N-1)\beta})^2\right] \qquad (4)$$

Therefore, (4), which is also (5.31), is derived through the above derivation steps.

VITA

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J. D. Liu, T. T. Lie, and K. L. Lo, "An Empirical Method of Dynamic Oligopoly Behavior Analysis in Electricity Markets", Accepted for publications in IEEE Transactions on Power Systems.

L. M. Xia, J. D. Liu, H. B. Gooi and T. T. Lie, "Vesting Contracts in Electricity Markets", Submitted for publication to IEEE Transactions on Power Systems.

J. D. Liu and T. T. Lie, "Measurement of Conjectural Variations in Oligopoly Electricity Markets" *Proceedings of AUPEC'03*, New Zealand, 2003.

J. D. Liu and T. T. Lie, "Empirical Dynamic Oligopoly Behavior Analysis in Electricity Markets", *Proceedings of POWERCON'04*, Singapore, 2004