ELECTRICITY GENERATION AND TRANSMISSION PLANNING IN DEREGULATED POWER MARKETS

by

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ABSTRACT

This dissertation addresses the long-term planning of power generation and transmission facilities in a deregulated power market. Three models with increasing complexities are developed, primarily for investment decisions in generation and transmission capacity. The models are presented in a two-stage decision context where generation and transmission capacity expansion decisions are made in the first stage, while power generation and transmission service fees are decided in the second stage. Uncertainties that exist in the second stage affect the capacity expansion decisions in the first stage. The first model assumes that the electric power market is not constrained by transmission capacity limit. The second model, which includes transmission constraints, considers the interactions between generation firms and the transmission network operator. The third model assumes that the generation and transmission sectors make capacity investment decisions separately. These models result in Nash-Cournot equilibrium among the unregulated generation firms, while the regulated transmission network operator supports the competition among generation firms. Several issues in the deregulated electric power market can be studied with these models such as market powers of generation firms and transmission network operator, uncertainties of the future market, and interactions between the generation and transmission sectors. Results deduced from the developed models include (a) regulated transmission network operator will not reserve transmission capacity to gain extra profits; instead, it will make capacity expansion decisions to support the competition in the generation sector; (b) generation firms will provide more power supplies when there is more demand; (c) in the presence of future uncertainties,

the generation firms will add more generation capacity if the demand in the future power market is expected to be higher; and (d) the transmission capacity invested by the transmission network operator depends on the characteristic of the power market and the topology of the transmission network. Also, the second model, which considers interactions between generation and transmission sectors, yields higher social welfare in the electric power market, than the third model where generation firms and transmission network operator make investment decisions separately.

1 INTRODUCTION

1.1 Electric Power System and the Electricity Market

A typical electric power system consists of three components, namely generation, transmission and distribution. Electric power is generated by power plants with different technologies. The major technologies in use today include hydro power plants, power plants based on fossil fuels, and nuclear power plants. Electricity is normally generated on a very large scale, and for environmental and safety reasons, most power generations are performed at considerable distances from the customer loads.

The transmission system transports power from generation plants to consumption points. In order to lower power losses during transmission, major transmission takes place through high-voltage lines.

When electricity has been transmitted to a station closer to a set of customer loads, another transmission system with lower voltages relays electricity to end users. This system is the distribution system. Generally, an electricity market can be divided into the wholesale market and the retail market. In the wholesale market, generation firms provide electric power to distribution companies through the transmission network. In the retail market, distribution companies deliver electric power to end-users via the distribution network.

The focus of this dissertation is on power system planning in the wholesale power market. Therefore, only the capacity planning of the generation and transmission sectors are analyzed, and it is assumed that the consumers have unlimited access to the distribution network, which is the case in most power markets.

All three components of the power system are critical to the success of the electric power market. The generation plants should be able to provide sufficient, economic, and reliable electricity to the power market. Electricity transmission and distribution facilities should deliver electric power to consumers, and they are also indispensable in inter-regional power exchanges. A transmission system with sufficient capacity and reliability is very important in the spatial electric power market, where customer loads and generation plants are scattered in a wide region and are connected by a transmission network.

A well-designed power system enhances the performance of the electric power market by providing better market efficiency and system reliability. In the recent trends of electricity market restructuring, a good market design is more important than ever because it determines whether the power industry and consumers achieve desirable overall results.

As the electricity market is always experiencing varying customer loads and changing generation and transmission technologies, it is important to plan the power system periodically to ensure that it is able to serve the power market in the most efficient way. Generally, power system planning is a process that develops timely and efficient generation and transmission facilities expansion plans of building new generation units and modifying transmission line capacities and transmission network topology.

In traditional power markets, electricity is provided to consumers by utility monopolies. A utility monopoly, either private- or public-owned, monopolizes the power market in a region, but is subject to governmental regulations that specify a rate-of-return and inter-utility power exchange policies. Since such a company controls generation, transmission, and distribution facilities in a region, it is also known as a vertically integrated utility (VIU). A key characteristic of this kind of market structure is that there is very limited or no competition among utilities, but their pricing behaviors in the power generation and transmission system are subject to governmental regulations. This characteristic is also reflected in the planning processes, which are guided by governmental regulations.

The main motivation for a VIU to expand electricity generation and transmission capacities is to meet customer demands and ensure the reliability of the power system. Another incentive for capacity expansion in a traditional power market is to allow inter-utility power transactions for cost and seasonal concerns.

Due to the characteristics of the traditional power market, the generation and transmission capacity planning conducted by the VIU is a centralized planning process. The VIU is responsible for new generation and transmission capacity constructions, using specified cost recovery schemas controlled by governmental regulations. It does not need to consider potential competitions from other utilities in its planning process. Inter-utility transmission lines are built based on cooperation between VIUs when both parties can benefit from being connected to each other. The most important concern of the VIU in the planning process is to persuade the government regulating agencies that the proposed capacity expansions will improve market efficiency and the capital investments can be recovered in such a way that the power market's benefits through such expansions will be no less than what has been invested, and thus the overall social benefit is improved.

1.2 Deregulation of the Electricity Market

Some problems in the traditional vertically integrated electricity market have led to the consideration of restructuring of the power industry. The most critical drawback of the traditional power market is the lack of competition and relatively low investment level in new facilities compared to other industries that have been deregulated such as telecommunication and gas industries. The utility monopolies either are private-owned utilities subject to the regulation of rate-of-return and inter-regional power exchanges, or are public utilities controlled at local levels. These utilities earn profits according to the rate-of-return regulation, which is based upon their costs for supplying electric power. The rate-of-return policy has greatly discouraged development of new technologies and new capacity expansion proposals from electricity utilities. For example, a VIU would have little interest in investing in cheaper generation technologies to replace the old expensive incumbents if the expected profit is about the same as before the investments. The rate-of-return policy makes it difficult for those utilities to obtain financial investments as well, if the rate is set at a low level.

In recent years, rapid technology improvements have largely reduced the economies-of-scale requirement in power generation industry and have made information transfer in power markets much faster and easier. New generation technologies such as gas-based generation units have made it easier to enter the industry with less capital investments. This has improved the diversity of power suppliers and enabled the power market to be less dependent on VIUs. As a result, there has been an increasing number of independent generators that are supplying electric power to the market at lower costs. Although they are not allowed to sell power directly to the consumers in a vertically integrated power market, they can trade with the VIUs, and their market share has been increasing significantly in recent years.

The improvement in information technologies has also contributed to make it possible to restructure the vertically integrated power industry to a more decentralized one. It has allowed different utilities to compete in a central auction power market or by bilateral contracts with large consumers. Now unexpected situations can be handled promptly by adjusting power supplies of competing utilities and/or customer loads in different regions.

Based upon the drawbacks of vertically integrated market mechanism and the improvement in technologies, the worldwide electricity industry, including in the United States, is undergoing a restructuring process. The details on how the new market mechanism should be regulated are still under debate, and there have been many different proposals for new market mechanisms. Most paradigms have the common idea that competition should be introduced into the generation sector by increasing the number of generation firms in the power market. This can be done by dividing the traditional VIUs into independent generation firms, encouraging new entries into the industry, and integrating formerly separated power markets, so that the generation firms should compete with each other through maximization of profits. It is expected that the competitive power market will be less regulated and more market-oriented. Furthermore, the competition among the profit-maximizing generation firms will introduce power supplies that are more economical, therefore, the customers in the electric power market will be better-off.

There are also different proposals in the reorganization of the transmission sector. Some proposals allow generation firms to have physical control over transmission facilities and other entities do not have access to these transmission resources without permissions. Other proposals believe that the deregulated power market should adopt the Transmission Open Access (TOA) scheme, which enables all generation firms to have access to the transmission network, and where an Independent System Operator (ISO) determines how the transmission resources are allocated to generators to make efficient use of the limited transmission capacities while ensuring the security of the network.

Advocators of the decentralized transmission sector believe that if the transmission facilities remain in the hands of different parties, the competition among them will enable the transmission network to be planned and operated efficiently with the least amount of regulations. One the other hand, the transmission open access paradigm argues that decentralized control of transmission resources has the drawback that the transmission owners may have the incentives to wield market power in the transmission sector, which is critical to the operation of power market. They propose that the physical control of transmission resources should be given to a regulated ISO, who determines the allocation of transmission resources in an indiscriminate manner. In either case, the power market will be divided into two submarkets, namely the generation market and transmission market. In the generation market, the generation firms will compete in the generation sector to maximize profits by providing electric power. In the transmission market, they will compete for limited transmission capacities to support their competition in the generation sector.

In spite of the debate over the organization of the transmission sector, most restructured power markets have deregulated the generation sector while the transmission sector remains regulated where an ISO operates the transmission network efficiently and reliably by using control tools such as transmission price signals to adjust the power flows in the network. In this dissertation, the transmission open access paradigm is assumed. That is, we assume a deregulated generation sector, and a regulated transmission network, which is open to every generation firm while being operated by an ISO.

The main motivation to transform the vertically integrated power industry to a more competitive one is to encourage investments in more efficient electricity generation and transmission facilities, thus improving the long-term efficiency of the power market. Models that analyze long-term decision-making of the generation firms and the transmission network administrator are needed to obtain insights into long-term operations of the new market mechanism. This dissertation focuses on power system capacity planning in the wholesale power market where the generation sector is deregulated and a regulated ISO operates the transmission grid. Different from the planning process in the traditional power market, where governmental regulations guide the planning process of the VIUs, in a lightly regulated market environment, the generation firms are allowed to make investment decisions on new generation capacities to maximize the long-term profits, and the ISO can modify the transmission network to maximize the benefits of the transmission system according to specified criteria. The main concerns in the power system planning process in a deregulated power market are listed below, some being similar to those in the regulated power market, while others are new issues that arise in a less regulated environment.

1.2.1 Security of the Transmission Network

System security is maintained by establishing standards for system operations. The ISO is responsible for dispatching the power supplies in a way such that the power flows are within established standards. In doing so, the ISO implements some procedures that translate the network congestion due to security standards into price signals to the generation firms. If the price signals are correctly implemented, the generation firms will change their decisions on power supplies so that the power flows in the network can be kept within the transmission line capacity limits. Other control tools may be necessary in addition to implement transmission pricing procedure. In the UK power market, the ISO also uses generation constrained-on and/or -off strategies to control the power flows.

1.2.2 Market Power

A byproduct of the power market deregulation is the potential market power of generation firms and ISO. Because the number of generation firms is relatively small in the power market, generation firms may have the ability and desire to set the electricity prices in the power market instead of being price-takers. Some literature on power system planning in deregulated power market assumes perfect competition, which means that the generation firms are price-takers and they are paid based on their marginal generation cost. The assumption of perfect competitions makes it easier from a modeling perspective, but it ignores possible market power of generation firms, which has existed in some restructured power markets, in UK for example.

Most models that consider market power in competitive power market adopt the Nash equilibrium paradigm, and they can be classified to two categories, namely the supply function models and Cournot models. In supply function models, the generation firms compete through their supply offer curve offer, which describes the amount of power supply they are willing to provide as a function of the market price. In the Cournot model, under the assumption that the demand is elastic, the market price becomes a function of the power supply, which the generation firms use in making decisions on the amount of electricity they will sell. This dissertation adopts the Cournot modeling strategy, because it works well for studying long-term issues in the power market, which is the focus of this dissertation. The Nash-Cournot equilibrium is easier to compute than the supply function equilibrium, although the supply function approach is better for analyzing the short-term and mid-term operations of the competitive power market.

The ISO also has potential market power because it controls the transmission facilities in the power market. The ISO can exploit the power market by setting transmission capacities and prices strategically. This is the reason why the ISO in most deregulated power markets remains regulated. In this dissertation, it is assumed that the ISO is regulated and it allocates the transmission resources fairly to generation firms in order to facilitate the competitions among them, instead of maximizing its profit by charging transmission fees.

1.2.3 Interaction between Generation and Transmission Sectors

In the deregulated environment, the power market is divided into generation and transmission submarkets. Unlike the centralized planning process in the traditional power market, the capacity expansion decisions of different sectors in the restructured power market are made by different entities. The planners and policy-makers must face some new issues such as (a) how the capacity planning decisions in one sector affect the other, (b) the coordination of the planning processes in different sectors, and (c) which sector leads the planning process of the whole power system. Not much has been said about the models and approaches concerning these issues by the researchers in the community of power market restructuring.

1.2.4 Financing Power System Expansions

Cost recovery assurance, if correctly implemented, can provide power market participants incentives to invest. The embedded cost recovery strategy has been used in the regulated power markets, where the investors are guaranteed the recovery of their investments through the rate charged to the consumers. However, in a market-oriented power system, it is not possible to finance the investors with an embedded cost recovery strategy because it conflicts with the operations of a deregulated market, where prices result from competition and not from regulation. In this dissertation, the costs of new generation and transmission capacities are included in the objective functions of generation firms and ISO. That is, the construction costs of new capacities are recovered from the extra benefits of the new capacities.

The cooperative planning approach allows a group of investors to form coalitions to expand the capacities, and they reach the agreement to share the costs and benefits of capacity expansions. This has been used in the traditional power market in the case when two or more VIUs want to share the generation and transmission facilities for economical reasons. It is harder for them to act cooperatively in a competitive power market, where market participants compete to maximize their own profits. In addition, if coalitions are allowed to be formed, it is possible that the coalitions will be too strong, whereby it can get unreasonable benefits at the expenses of other market participants and consumers. It is quite likely that governmental policy-makers will take measures to avoid the formation of such strong coalitions. In this dissertation, the analysis of competition and capacity planning is based on noncooperative game theory; it is assumed that no coalitions among generation firms and ISO are allowed to be formed.

1.2.5 Uncertainties

It takes months or years to complete constructions of generation and transmission facilities after the planning stage. Therefore, when new electricity facilities are available, the situation of the power market may be different from that during the planning stage. In most cases, it is difficult to predict future power market scenario precisely when capacity planning takes place. Uncertain factors must be included in the planning process to consider possible future changes. Future uncertainties in a power market include customer loads, electricity generation costs, power market regulation policies etc. Such uncertainties complicate power system planning. Furthermore, in a lightly regulated power market, where decisions are made in a decentralized manner, different views of uncertainties by the market participants make the problem even more complicated. Some market participants may want to invest in a way to maximize their expected benefits (i.e. they are risk neutral), while others may be risk-averse or risk-prone in their investment decisions. In this dissertation, the capacity planning problems of generation firms and

ISO, under uncertainties, are formulated assuming that they are maximizing their expected benefits, by taking into consideration possible future power market scenarios and their probabilities. To make the models tractable, future demand for electric power is considered to be the only uncertain factor in the power market.

1.3 Contributions of This Research

There have been extensive studies on short-term operations of the deregulated power industry. More insight into the long-term functioning of the deregulated power market is needed to help the policy-makers and power market participants evaluate the long-term effects of power industry deregulation. This thesis addresses this issue.

An important and unavoidable complication in the capacity planning of the deregulated power industry is that the capacity planning of generation and transmission sectors are conducted separately by generation firms and ISO respectively. Most existing works on deregulated power market planning examine capacity expansions of the generation and transmission sectors separately and ignore the fact that they interact with each other. Therefore, an approach that studies the interactions of the planning processes of two power system sectors will provide a better understanding of the long-term efficiency of deregulated power markets.

The contributions of this dissertation can be summarized as follows:

- The long-term competition of generation firms in a spatial power market is formulated as a spatial Nash-Cournot model. We studied how future demand uncertainties of local power markets will affect the long-term decision of generation firms in a spatial power market without transmission constraints. This provides a basis for analyzing the long-term operation of deregulated spatial power market constrained by transmission capacity limits.
- By using the idea of opportunity cost pricing schema for limited transmission capacity proposed by Smeers and Wei (1997), the power system planning

problem that includes both the generation and transmission sectors is represented in a combined power system planning model. The ISO's decision in transmission capacity planning and the long-term competition of the generation firms is integrated in a single formulation by assuming that ISO and generation firms determine new capacity investments by modeling each other's decisions. In doing so, the generation sector is assumed to be deregulated and the spatial Nash-Cournot modeling strategy is adopted. In the transmission sector, in order to avoid the ISO's market power of under-investing transmission resources and marking up transmission prices, it is assumed to be a regulated entity whose goal is to facilitate the competitions among the generation firms while ensuring safe operation of the transmission network.

- How different predictions of future market scenarios affect the capacity expansion decisions of generation firms and ISO is also studied in the combined power system planning model. It is shown that the generation firms tend to invest in more generation capacities if more demand for electric power is expected even if the transmission capacity is limited. But, how the ISO reacts to different future market estimations depends on the physical structure of the transmission network.
- The combined power system planning model is compared with the separate models of the planning processes of generation and transmission sectors. The effects of these two planning strategies on the long-term efficiency of power market are analyzed and compared. The dissertation shows that the combined planning model leads to better social welfare than the separate planning processes.

1.4 Dissertation Outline

The dissertation is organized as follows.

Chapter 2 is a literature review of previous works on power industry deregulation, short-term operations of the deregulated power market, and the long-term planning issues of electric power markets.

Chapter 3 models the long-term competition of generation firms in a spatial power market without transmission capacity constraints, and where the generation firms face uncertain future demand for electric power. The Nash-Cournot paradigm is used in the formulation and solution procedures, which assumes that they compete in quantities in a bilateral wholesale power market. The Nash-Cournot model is compared with perfect competition of generation firms, which assumes that they possess no market power. It is also compared with Pareto optimal solution that maximizes the total profits of the generation firms.

Chapter 4 introduces the basic concepts and notations of electricity flows and transmission line capacities in the transmission network with d.c. (direct current) electric power flow approximation. The results of this chapter are used (in Chapter 5) to analyze the operation of the spatial power market with transmission capacity constraints.

Chapter 5 analyzes transmission network management in a spatial power market with transmission capacity constraints. The inefficiency of the ownership of transmission facilities by profit-maximizing agencies is presented. The generation and transmission planning problem is formulated as a combined model and it is solved for the corresponding Nash equilibrium. Comparisons are made between the separate generation-transmission planning strategy and the combined generation-transmission planning model. A series of results are presented, which indicate that the combined planning strategy results in better social welfare.

Chapter 6 summarizes the results in this dissertation and suggests future research directions.

2 LITERATURE REVIEW

In the last decade, the electric power industry has been significantly changed from a vertically integrated industry to a less regulated one where competition is introduced to improve power market efficiency. In this new framework, both short-term and long-term operations of the market participants depend less on state or federal regulations but more on decentralized decisions of market participants. The new market mechanism has attracted great attention from the industry and the research community. There has been significant research on the short-term operations in the new market environment, but much less so on the theory and models for long-term operations of the competitive power market.

Short-term and long-term operations of the power market are closely related to each other: for determining optimal long-term investment policies, short-term operations must be considered, because the benefits resulting from the long-term planning are reflected in the short-term operations of the power market. In this chapter, previous works on short-term deregulated power market operations are reviewed first. Then, research on electricity facility planning techniques in both the traditional and competitive power markets is reviewed. Reported research on modeling of long-term decision problems of deregulated power market, including both generation and transmission sectors, is scarce, but provides us directions for further research.

2.1 Short-Term Deregulated Power Market

There are many existing works that study the competitive behaviors of generation firms in short-term spot power market. Two most popular modeling approaches are Cournot models and Supply Function models. Cournot models assume a customer demand function and that the generation firms compete in quantities, resulting in the prices in the power market that maximize their profits. In Supply Function models, generation firms compete by offering supply curves that include both quantities and prices. Both kinds of models are based on the concept of Nash equilibrium, which is reached when each party's strategy is optimal in the sense that the party cannot unilaterally change its offer curve and improve its profit. Cournot models are simpler than Supply Function models from computability point of view, but they are different from the actual operations of short-term wholesale power market; whereas Supply Function models are computationally harder, but they better mimic the functioning of the short-term power market.

2.1.1 Cournot Models

Cournot models have been widely employed in the analysis of deregulated electricity market. Borenstein *et al.* (1995) model Californian electricity market using the Cournot modeling strategy to predict possible market power of generation firms after deregulation. Although this method does not precisely model the power market, its simplicity in computation makes it an efficient way for estimating generation firms' market power. Wei and Smeers (1999) use the Variational Inequality (VI) approach to solve for Nash-Cournot equilibrium of deregulated power market by deriving the optimality conditions of the generation firms. Hobbs (2001) uses similar modeling idea and solves the problem as a linear Mixed Complementarity Problem (MCP). The VI and MCP approaches of determining the Nash-Cournot equilibrium make it possible to solve problems of realistic sizes, because there are well-developed algorithms and solvers that are quite efficient in solving such problems. Fabra and Toro (2005) study how changes in demand and cost conditions will lead to generation firms' deviations from a collusive agreement using the Cournot model. Under some continuity and convexity conditions, Cournot models have unique equilibrium solutions where no generation firm can improve its profit by unilaterally changing the quantity offered. The major flaw of the Cournot models is that they can only be applied to power markets that have assumed demand functions; Cournot models cannot be used to solve problems with inelastic customer loads.

2.1.2 Supply Function Models

In Supply Function models, the generation firms provide supply curves that describe the amount of power they are willing to offer corresponding to the different prices they may be paid; the power market equilibrates with respect to the offer curves and demand functions. This approach was first proposed in Klemperer and Meyer (1989). Since then it has attracted much attention in the study of short-term equilibrium of spot electricity markets because of its similarity to the actual functioning of spot power markets whose demands varies during the day. For numerical tractability, research that adopts the Supply Function approach generally assumes linear demand and marginal cost functions, and the equilibrium supply curves can be written in a linear or affine form. Newberry (1998) analyzes the behaviors of the deregulated generation firms in England & Wales Pool using the Supply Function approach. He found that the generation firms bid strategically instead of bidding the marginal cost as in the perfect competition scenario. The results also show that the generation firms who control more generation resources have the incentive to bid higher than the smaller generation firms, and the market power of generation firms decreases as the number of competitors increases. Baldick *et al*. (2000) extend the Linear Supply Function model to a more general case with affine marginal cost functions. Solutions of equilibrium supply functions were obtained in the form of piecewise affine and non-decreasing functions of prices. A complexity in Supply Function models is that there may exist multiple equilibria and convergence to a solution is slow with existing solution algorithms. Furthermore, the existence and uniqueness of an equilibrium solution are hard to prove. The Supply Function model can be applied to power markets with inelastic demand. Rudkevich *et al*. (1998) obtain the equilibrium price of a power market with inelastic demand using the Supply Function approach, which overcomes the difficulty of using Cournot models to solve this type of problems. Gonzalez *et al*. (2005) study the electricity price time series and attempts to discern its relationship with electricity generation firms' strategies. The relationship is represented by a Markov model.

As a conclusion, the Supply Function model is preferable in predicting short-term equilibrium price in a deregulated power market. However, to prove existence and uniqueness of an equilibrium solution, many assumptions need to be made, and its ability to solve large-scale power markets is limited. On the other hand, Cournot models are much easier to solve and fewer assumptions are required to show the existence of a unique equilibrium solution. However, this model is unable to simulate short-term market well. So, to model a deregulated power market, it is important to choose a proper modeling approach based on the objective of the model. Tradeoffs must be made between tractability and representation requirements. Generally speaking, in representing short-term operations of competitive power markets, the supply function approach is a better choice if the problem size is tractable. In long-term planning of competitive power markets, which is generally more complicated, Cournot models are better choices for tractability considerations.

2.1.3 Transmission Constraints

Transmission congestion management is an important issue for deregulated spatial power markets. Oren (1997) includes transmission constraints in modeling the Cournot competition of deregulated generation firms. Berry *et al* (1999) include the representation of the transmission network in a Supply Function model. To make the problem tractable, the supply curves of generation firms are assumed to be affine. In the above models, no existence or uniqueness conditions of equilibrium solutions are provided. Smeers and Wei (1997) propose the opportunity cost pricing scheme for transmission services in the deregulated power market constrained by limited transmission capacities based on Cournot competition; existence of a unique equilibrium solution is proved. Wei and Smeers (1999) model the competition of Cournot generation firms using transmission constraints in their optimization problems. The existence of a Nash-Cournot equilibrium is proved, but multiple equilibria may exist. Hobbs (2001) models the competition of deregulated generation firms in a spatial power market with both Kirchhoff's laws included. A linearized d.c. transmission network is assumed for computational tractability, and a unique equilibrium solution is shown to exist. Neuhoff *et al*. (2005) apply the same data set to different models that deal with generation firms' competition where transmission constraints exist. The results show that different assumptions about the electric power market and generation firms' behavior affect Cournot equilibria considerably.

2.2 Traditional Long-Term Power System Planning Approaches

In the vertically integrated power industry, VIUs invest in electricity facilities to accommodate the projected customer loads if the current generation and transmission capacities are not capable of providing the predicted required services. The expansions are carried out by VIUs under governmental regulations, whose planning objective is to minimize the expansion costs given the current power system capacities and the forecasted market demand in the planning horizon.

Power system planning models for the wholesale power market can be classified into generation capacity planning, transmission capacity planning, and combined generation and transmission capacities planning. By making certain simplifying assumptions, the power system planning problem can be modeled and solved as mathematical optimization programs. For complicated optimization problems that are not tractable, heuristic approaches are used.

2.2.1 Generation Planning

There has been extensive research on modeling and solution approaches of generation capacity expansion problems in traditional power industry. Bloom (1982) presents the application of mathematical programming decomposition techniques for finding least-cost investments in generation capacities subject to reliability constraints. The capacity expansion problem is decomposed into a set of subproblems, each representing the operation of a set of generation units of fixed capacity in one year. A master problem represents the optimal generation capacity investments over the entire planning horizon. The subproblems are solved using the probabilistic simulation procedure. The master problem is a linear program that uses Lagrange multipliers from the subproblems and the solution is obtained by iteratively solving the master problem and the subproblems.

Linares and Romero (2000) formulate the generation capacity expansion problem using a multi-criteria decision-making approach that considers the social concerns on the impacts of new generation facilities on environmental issues. The criteria to judge whether an expansion strategy is appropriate include the economic benefits of new generation capacities and associated environmental costs. In their paper, several multi-criteria methods that address the generation capacity planning problem are used to obtain the satisfactory compromise between conflicting objectives.

2.2.2 Transmission Planning

Kaltenbach *et al*. (1970) were among the first to model and solve the transmission planning problem with projected customer loads as a mathematical programming problem. Their work uses a linear d.c. transmission network as an approximation of the actual nonlinear a.c. (alternate current) transmission network. They show that this approximation works well in high-voltage transmission systems. With linearized representation of the transmission network, the transmission planning problem that minimizes the expansion cost is modeled and solved as a linear program. Youssef and Hackam (1989) include a nonlinear property of the transmission network and formulate the transmission expansion problem as a nonlinear program. Such a formulation yields better results for low-voltage transmission systems, but requires a large amount of computational efforts, which often prevents its use to solve the planning problems for large-scale transmission networks.

A feature of the transmission planning problem is that the decision space is discrete instead of being continuous, since the transmission link capacity can only be changed in discrete increments due to the technological considerations. While the works of Kaltenbach *et al*. and Youssef and Hackam assume that transmission capacities can be modified in a continuous fashion, some researchers have considered discrete decision variables in modeling the transmission planning problem. Lee and Hnyilicza (1974) model the transmission planning problem as an 0-1 integer program that works directly with discrete transmission line additions; it was solved using a branch-and-bound algorithm. Bahiense *et al*. (2001) formulate the transmission planning as a mixed integer disjunctive model, which includes both of the Kirchhoff's laws. Choi *et al.* (2005) include uncertain and "ambiguous" factors such as investment budget and reliability for constructing new transmission lines. The problem is modeled as a fuzzy integer program and it is solved using a fuzzy set theory-based branch-and-bound method.

The complexity of electricity transmission networks is a real obstacle to obtain the optimal solution of the transmission planning problem. The resultant mathematical formulations are often nonlinear and/or nonconvex, and hard to solve. To cope with computational difficulties in transmission planning problems, various heuristic methods have been proposed. Garver (1970) solves the transmission planning problem using a mathematical programming based heuristic that uses fictitious transmission line additions. A linear program is used to estimate the power flows in the transmission network and locate the links where overloads exist. Then, an uncapacitated transmission circuit is added to the part of the transmission network that is the most overloaded. To assure that the flows use existing transmission capacities first, flows through the fictitious lines are penalized. This procedure is repeated until there is no overload in the transmission network.

Another category of heuristic methods uses sensitivity analysis in the planning process. In Monticelli *et al*. (1982), an interactive transmission planning tool based on sensitivity analysis of line additions is designed. An approach that evaluates the impacts of additional transmission lines on transmission network congestion is presented. The least effort criterion is used to help transmission planners to select the most appropriate transmission expansion strategy.

2.2.3 Composite Generation-Transmission Planning

There have been a few works on combined power system planning approaches that handle capacity planning of the generation and transmission simultaneously. Pereira *et al*. (1987) develop a composite generation-transmission planning approach by incorporating the costs of generation and transmission facilities in a single formulation. The transmission network is represented by a transportation model and the solution approach is based on Benders decomposition, maximum flow algorithms and linear programming. Li and Billinton (1993) propose a similar composite planning model that assumes a linear power flow network. In their model, the maximum flow problem is combined with the generation capacity planning formulation, and the total power system investments are minimized.

2.3 Long-Term Power System Planning in Competitive Power Markets

Along with the restructuring of the worldwide power industry, some research works have appeared on power system planning in the new competitive environment. However, the theory and models developed so far are not yet able to meet the needs of planners and policy-makers. This is due to both the complexity of the problem itself, and certain ambiguities in the policies regarding long-term operations of deregulated power markets. However, some pioneer research has provided insight into the nature of the problem and indicated promising research directions.

2.3.1 Generation Planning

Newberry (1998) discusses generation capacity expansion in competitive power markets implicitly. The market power of generation firms in generation capacity planning is implied in that paper. He found that larger generation firms have the incentive to be able to provide more electric power in order to prevent new entries into the industry. Wei and Smeers (1999) include generation capacity expansion in the Nash-Cournot formulation of a spatial power market. Transmission network capacity constraints are included in the planning process of the generation firms. However, transmission capacity expansion is not considered in that paper, and the generation firms determine new generation capacity additions assuming that the transmission network capacity will not change.

More recently, Ventosa *et al*. (2002) proposes two modeling approaches of generation planning in deregulated power market. The first approach assumes that generation firms make capacity expansion decisions simultaneously. The second approach assumes that there exists a leader generation firm that anticipates the reaction of the follower firms. The first modeling approach is equivalent to the Nash-Cournot model, and the second modeling approach results in Stackelberg game. It is shown that these two approaches yield similar results, and the Nash-Cournot model is more computationally tractable than the Stackelberg model. Furthermore, the existence and uniqueness of equilibrium solution in the Stackelberg model is not proved. Olsina *et al*. (2006) use a simulation method to study the long-term behavior of the restructured electric power market. Generation firms' decisions on new generation capacities are considered. Their results show that the long-term electricity market may exhibit a very volatile behavior that depends on exogenous inputs.

Cavaliero and Silva (2005) study how government can use regulatory incentives to encourage the construction of power generation facilities of renewable energy resources, which are usually expensive to generate. Agnolucci (2006) surveys the economic instruments for renewable electricity generation used in Germany. It is found that the effects of such instruments diminish if the future of the system is uncertain.

Genc (2003) studies several stochastic programming models of generation firms' decision-making in a single power market with future demand uncertainties. It is pointed out that even in a volatile power market, the generation firms may still have an incentive to participate in the market. Botterud and Wangensteen (2005) use a stochastic dynamic programming algorithm to determine the optimal amount and timing of the investments under demand uncertainty. In their model, the uncertainty in demand is represented as a discrete Markov chain.

2.3.2 Transmission Planning

The proposed transmission planning approaches in deregulated power market can be classified into centralized and decentralized models. The transmission planning approach of the National Grid Company (NGC) in the UK power market uses a centralized transmission planning method. An independent planning agency is responsible for upgrading the transmission network to meet future demands for transmission services. In the NGC's planning approach, the behaviors of generation firms in the planning horizon are quantified by additional generation capacities of new entries and withdrawals of current capacities. With the projected future customer loads, the amounts and locations of new transmission capacities are determined by the planning model. Borenstein *et al*. (2000) discusses transmission capacities' effects on competition in generation sector. Now, the market administrator determines the capacity of the transmission line that connects two separate power markets with a generation firm residing in each of them. The administrator's objective is to build enough transmission capacity so that the market power of the generation firms is minimized and competition is introduced into the power market. They found that a limited amount of new transmission capacity is enough to integrate two power markets effectively and decrease market power of the generation firms on the residual demands in their local markets. Their paper provides some insight into the role of transmission network in supporting power market competition. However, it is very hard to apply this method in a meshed spatial power market where there are several generation firms that are connected by many links of the electricity transmission network.

In addition to the centralized transmission planning approach, there have been some works on decentralized transmission planning in the deregulated power market, where different owners of the transmission resources determine investments in new transmission capacities. Baldick and Kahn (1993) introduce the concept of externalities in transmission network planning. Externalities occur when a modification of the transmission network has either beneficial or detrimental impacts on other participants of the power market. It is shown that if transmission planning is conducted in a decentralized manner, conflicts are likely to arise. Because an investment decision affects the entire transmission network, and all the generation firms that rely on it.

Wu *et al*. (2006) attempt to bridge the gap between economic and engineering considerations in transmission planning in restructured electricity market. Their work attempts to clarify some currently ambiguous interactions among various economic and engineering issues.

Hogan (1992) studies possible incentive-generating mechanisms for transmission capacity investments by transmission owners. He found that in some situations, transmission owners will expand the transmission network in a way so that the social welfare is improved, which is the ideal case for a decentralized transmission planning strategy. However, under other situations, they will modify the transmission network in a way that worsens market efficiency. Bushnell and Stoft (1998) summarize previous works on private incentives of transmission network investment. They pointed out that the embedded cost recovery and cooperative planning procedures used in the traditional power markets are problematic in the competitive environment, and the most promising solution for decentralized transmission planning problem is through private investment incentives stimulated by market-oriented tools such as financial transmission rights that allow transmission investors to collect congestion fees on the lines invested by them. However, they did not provide a general rule for allocating financial transmission rights to avoid detrimental transmission investments.

Contreras and Gross (2004) propose an analytical framework for transmission investments in a deregulated power market. Private transmission investors are included in their model. They argue that in a capacity-constrained transmission network, only under certain conditions will the potential investors have the desire to invest in new transmission capacities. Also, they may under-invest in new capacities to possess market power in the transmission market. Kristiansen and Rosellon (2006) propose a trading mechanism to allocate the long-term financial transmission rights. They assume that the system operator uses a protocol so that the financial transmission rights being allocated will not harm existing financial transmission rights. They propose a bilevel model to solve this problem.

3 LONG-TERM COMPETITION OF DEREGULATED GENERATION FIRMS

3.1 Cournot Modeling of Generation Firms

3.1.1 Representation of Spatial Power Market

Generally, the deregulation of power industry is conducted in two ways, one way divides the VIU in a geographical region into several independent generation firms and lowers the new entry requirements so that several generation firms can compete in the power market. The second way introduces competition by integrating formerly isolated power markets controlled by different VIUs so that VIUs are allowed to export electricity to the regions that were not open to them in regulated environment. The two deregulation methods are often used together to intensify competition, and it leads to the case where a number of generation firms compete in several local markets that are geographically apart and connected by transmission lines. Figure 3.1 shows a typical spatial power market. In the figure, the nodes of G_1, G_2, and G_3 represent generation firms located at different places; M_1, M_2, and M_3 represent local power markets in which the generation firms compete with each other. The generation firms and customer loads are located in different locations for safety and environmental reasons, and they are connected by a transmission network. Generation firms and customer loads get access to the transmission network through the bus nodes. In Figure 3.1, there are six bus nodes denoted by b_1, b_2, b_3, b_4, b_5 and b_6. Each generation firm and each local market get access to the network through one of these buses. At each bus, there exist electric equipments such as transformers that adapt the power flows to meet the technological constraints and standards of the transmission network.

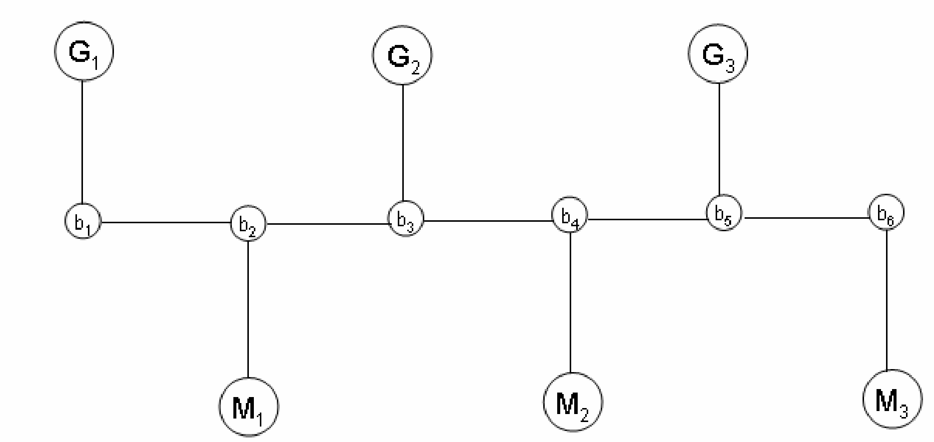

Figure 3.1: A typical spatial power market

3.1.2 Notation

Suppose that the power market is deregulated, and the generation firms are allowed to supply electricity to any local power market and add new generation capacities to maximize their profits in the long run. We also assume that the generation firms are Cournot firms, who compete in quantities of electric power supplied. In doing this, the electricity price of each local power market is assumed to be a function of the total amount of power supplied. We let $i \in I$ denotes the set of generation firms in the spatial power market, $j \in J$ denote the set of local power markets, and $k \in K$ denote the set of the generation technologies available to the generation firms. The decision variables of generation firm i are represented by the vector of $y_i = (q_{ij}, g_{ik}, x_{ik})$, where q_{ij} is the amount of power sold by generation firm i to local market j, g_{ik} is the amount of power generated by generation firm i using technology k, and x_{ik} is the generation capacity of technology k added to generation firm i's power plants. Let p_j denote the electricity price of local power market j, under the assumption that the demand of each local power market is elastic with respect to electricity price, p_j can be represented by a function of the power supply of market j:

$$p_j = P_j(\sum_{i \in I} q_{ij}), \ \forall j. \tag{3.1}$$

The initial generation capacity of generation firm i is denoted by GC_{ik}, which means that generation firm i cannot generate more than GC_{ik} units of electricity using technology k. Different generation technologies have different generation costs, and they also cost differently for new capacity investment. The generation cost function of technology k is denoted by $c_k(g_k)$, and the capacity expansion cost function of technology k is denoted by $f_k(x_k)$.

3.1.3 Nash-Cournot Formulation

Perfect competition in a deregulated power market is difficult to obtain because there is a small number of generation firms that compete in the power market, and generally, this small number of competitors do not satisfy the assumption of numerous competitors required in a perfect competition. We also assume that the generation firms will not form any coalitions, and each generation firm makes decisions on power supply and capacity expansion to maximize its own profit. The long-term profit of a generation firm is the sum of its revenue from selling electricity to the local power markets minus the costs of electricity generation and capacity expansion. Thus that the objective function of a generation firm f can be written as

maximize

$$\sum_{j \in J} P_j(\sum_{i \in I} q_{ij}) q_{fj} - \sum_{k \in K} c_k(g_{fk}) - \sum_{k \in K} f_k(x_{fk}). \tag{3.2}$$

The decision space of generation firm *f* is the set represented by the following constraints.

$$g_{fk} \le GC_{fk} + x_{fk}, \forall k \quad (3.3)$$

$$\sum_{j \in J} q_{fj} = \sum_{k \in K} g_{fk} \quad (3.4)$$

where q_{fj}, g_{fk}, and x_{fk} are nonnegative variables.

Constraint (3.3) is the generation capacity limit for the generation firm *f*, and constraint (3.4) states that the amount of power sold by the generation firm must be equal to the amount of power generated by it. This is also known as the power balance condition, which states that the total amount of electricity generated should be equal to the total amount of electricity consumption in the power market, because it is difficult and expensive to store electric power for future use in the power industry.

The term of $\sum_{j \in J} P(\sum_{i \in I} q_{ij}) q_{fj}$ in the objective function of a generation firm indicates that its revenue is related to the decisions of its competitors. So that, the long-term planning problem of the generation firms in a competitive power market is a multi-firm game instead of being a single-firm optimization problem, which requires that each generation firm should consider the decisions of the others in its decision-making process. In this dissertation, the concept of Nash equilibrium is adopted to determine if the long-term competition of the generation firms can reach a stable state where none of the generation firms will be better off by deviating from its current decision while other firms' decisions stay unchanged.

3.2 Theories of Nash Equilibrium

Suppose that there are i = 1, …, n players who behave noncooperatively to maximize their own benefits, where each player's decision is denoted by a vector y_i in the Euclidean space E^{m_i}, i = 1, …, n. The decision of player i is limited by the requirement that y_i is in the set $R_i \subseteq E^{m_i}$. If the decision spaces of the players are independent on each other, the joint decision space of the players is represented by $R = R_1$ x R_2 x …x R_i x…x R_n. The payoff of a player in the game is a function of its own decision and the decisions of other players; the payoff function of player i is given by $\pi_i(y_1,...,y_i,...,y_n)$. The equilibrium point of this n-person game is a point $y^* \in R$ so that

$$\pi_i(y^*) = \max_{y_i}\{\pi_i(y_1^*,...,y_i,...,y_n^*) \,|\, (y_1^*,...,y_i,...,y_n^*) \in R\},\ \forall i. \tag{3.5}$$

At such a point, no player can improve its payoff by changing its decision unilaterally, and the system is in a stable state. This is the concept of Nash equilibrium of n-person noncooperative game. Rosen (1965) proved the existence and uniqueness of the Nash equilibrium for a special category of n-person noncooperative games. The following Theorem 3.1 and Theorem 3.2 are by Rosen (1965).

Theorem 3.1: An equilibrium point exists for a continuous and concave n-person noncooperative game with convex and compact decision spaces.

Proof: An n-person game is said to be continuous and concave if $\pi_i(y)$ is continuous in y and is concave in y_i for each fixed value of $(y_1,...,y_{i-1},y_{i+1},...,y_n)$ for $y \in R$. Now construct the function $\omega(y,z)$ defined for $(y,z) \in R\ X\ R$, which is

$$\omega(y,z)=\sum_{i=1}^{n}\pi_i(y_1,\ldots,z_i,\ldots,y_n),\ (y,z)\in R\ X\ R. \qquad (3.6)$$

It can be seen that $\omega(y,z)$ is continuous in y and z and is concave for every fixed y, for $(y,z)\in R\ X\ R$. Consider the point-to-set mapping $y\in R\rightarrow\Gamma y\subset R$ given by

$$\Gamma y=\{z\,|\,\omega(y,z)=\max_{u\in R}\omega(y,u)\}. \qquad (3.7)$$

Since $\omega(y,u)$ is continuous and concave in u for fixed y, Γ is an upper semicontinuous mapping that maps each point of the convex and compact set R into a closed convex subset of R, then by Kakutani fixed point theorem, there exists a point $y^*\in R$ such that $y^*\in\Gamma y^*$. Then this fixed point y^* is an equilibrium point, because if it is supposed that y^* is not an equilibrium point, there exists a point $y=(y_1^*,\ldots,y_i^0,\ldots,y_n^*)\in R$ such that $\pi_i(y)>\pi_i(y^*)$, which results in $\omega(y^*,y)>\omega(y^*,y^*)$, and this contradicts the fact that $y^*\in\Gamma y^*$. □

For an n-person noncooperative game, it is possible that there exist multiple equilibrium points, which sometimes makes it difficult to predict players' behaviors in a game. Researchers sometimes construct games that have a unique equilibrium point by making some reasonable assumptions on the structure of the games. Rosen (1965) proved the uniqueness of equilibrium for a category of n-person games. In such games, the decision space of player i is given by

$$R_i=\{y_i\,|\,h_i(y_i)\geq 0\},\ i=1,\ldots,n. \qquad (3.8)$$

Each component of $h_i(y_i)$ is denoted by $h_{ij}(y_i),\ j=1,\ldots,k_i$, and it is assumed to be a concave function of y_i, so that R_i is a convex set in E^{m_i}. As in Theorem 3.1, it is also assumed that the payoff function $\pi_i(y),\ i=1,...,n$ is concave in y_i for each fixed value of $(y_1,...,y_{i-1},y_{i+1},...,y_n)$ for $y\in R$. If we also assume that $h_i(y_i)$ is continuously first-order derivable for $y_i\in R_i$ and that the payoff function $\pi_i(y)$ possesses continuous first-order derivatives with respect to $y_i\in R_i$, then the necessary and sufficient optimality conditions of player *i*'s decision problem are given by the Karush-Kuhn-Tucker (KKT) conditions (3.9) ~ (3.11):

$$h_i(y_i)\ge 0, \tag{3.9}$$

there exist $u_i\ge 0,\ u_i\in E^{ki}$, which satisfies

$$u_i h_i(y_i)=0, \tag{3.10}$$

and

$$\nabla_i\pi_i(y)+\sum_{j=1}^{k_i}u_{ij}\nabla h_{ij}(y_i)=0. \tag{3.11}$$

From the concavity assumption of $h_i(y_i)$, it can be seen that for every $y_i^0,\ y_i^1$ in R_i, we have

$$h_{ij}(y_i^1)-h_{ij}(y_i^0)\le(y_i^1-y_i^0)\nabla h_{ij}(y_i^0). \tag{3.12}$$

A weighted nonnegative sum of the payoff functions $\pi_i(y)$ is given by

$$\sigma(y,r)=\sum_{i=1}^{n}r_i\pi_i(y),\ r_i\ge 0. \tag{3.13}$$

The pseudogradient of $\sigma(y,r)$ is given by

$$g(y,r)=\begin{bmatrix} r_1\nabla_1\pi_1(y) \\ r_2\nabla_2\pi_2(y) \\ . \\ . \\ . \\ r_n\nabla_n\pi_n(y) \end{bmatrix}. \tag{3.14}$$

Definition 3.1: $\sigma(y,r)$ is diagonally strictly concave for $y \in R$ and fixed $r \geq 0$ if for every $y^0, y^1 \in R,$ we have

$$(y^1-y^0)g(y^0,r)+(y^0-y^1)g(y^1,r)>0. \tag{3.15}$$

Theorem 3.2: An n-person noncooperative game with payoff functions $\pi_i(y), i=1,...,n$ and constraints $h_i(y_i)\geq 0,\ i=1,...,n$ has a unique equilibrium point if $\sigma(y,r)$ associated with $\pi_i(y)$ is diagonally strictly concave for some $r=\overline{r}>0,$ and $h_i(y_i),\ i=1,...,n$ are concave functions.

Proof: Assume that there are two distinct equilibrium points $y^0, y^1 \in R$, then the KKT conditions of the n-person game are

$$h_i(y_i^{\,l})\geq 0 \tag{3.16}$$

$$\exists u_i^{\,l}\geq 0,\ \text{such that } u_i^{\,l}h_i(y_i^{\,l})=0 \tag{3.17}$$

$$\nabla_i\pi_i(y^l)+\sum_{j=1}^{k_i}u_{ij}^{\,l}\nabla h_{ij}(y_i^{\,l})=0 \tag{3.18}$$

where l = 0,1 in (3.16) ~ (3.18).

Multiply (3.18) by $\overline{r}_i(y_i^1-y_i^0)$ for l = 0 and by $\overline{r}_i(y_i^0-y_i^1)$ for l = 1, and sum over all i. Then we get

$$\beta + \gamma = 0 \tag{3.19}$$

where

$$\beta = (y^1 - y^0)g(y^0, \overline{r}) + (y^0 - y^1)g(y^1, \overline{r}) > 0 \tag{3.20}$$

$$\gamma = \sum_{i=1}^{n} \sum_{j=1}^{ki} \overline{r}_i \{u_{ij}{}^0 (y_i{}^1 - y_i{}^0) \nabla_i h_{ij} (y_i{}^0) + u_{ij}{}^1 (y_i{}^0 - y_i{}^1) \nabla_i h_{ij} (y_i{}^1)\}. \tag{3.21}$$

From (3.12) and (3.17), it can be shown that equation (3.21) is nonnegative, which contradicts (3.19), and therefore there cannot exist more than one equilibrium point.□

3.3 Solution of Nash-Cournot Competition of Generation Firms

3.3.1 Assumptions on Deregulated Power Market

From Section 3.1 and Section 3.2, it can be seen that the concept of Nash equilibrium is a promising solution strategy for the long-term competition of the generation firms in deregulated power markets. To fit generation firms' long-term planning problem into the theoretic framework of an *n*-person game that possesses a unique Nash equilibrium point, some assumptions on the power market and generation firms need to be made.

As mentioned in Section 3.1, the generation firms are assumed to be Cournot firms that compete in quantities of power supplies, and q_{ij}, g_{ik} and x_{ik} are all the decision variables considered by the generation firms. The electricity demands of the local power markets are assumed to be elastic to electricity prices in a way that the power demanded by a local power market decreases as electricity price increases. Now we assume that the price functions of the local power markets, which are also known as the inverse demand functions, are linear and given by

$$p_j = a_j - b_j d_j, \forall j \in J, \qquad (3.22)$$

where

p_j is the electricity price in market j;

a_j and b_j are positive parameters that determine the inverse demand function of market j; and

d_j is the amount of electricity consumed in market j, $d_j = \sum_{i \in I} q_{ij}$.

With the linear inverse demand functions of the local power markets, the formulation of the long-term planning problem of a generation firm f is

maximize

$$\sum_{j \in J}(a_j - b_j \sum_{i \in I} q_{ij})q_{fj} - \sum_{k \in K} c_k(g_{fk}) - \sum_{k \in K} f_k(x_{fk}) \tag{3.23}$$

subject to

$$g_{fk} \leq GC_{fk} + x_{fk}, \forall k \tag{3.24}$$

$$\sum_{j \in J} q_{fj} = \sum_{k \in K} g_{fk} \tag{3.25}$$

where q_{fj}, g_{fk}, and x_{fk} are nonnegative variables.

In the above formulation, it is assumed that the decision variables of the generation firms are continuous variables. However, in the actual power industry, the power supply of a generation firm changes in a discrete form due to the discreteness of the number of generation units owned by it. To make the problem tractable and because this dissertation deals with long-term operations of the power market, we assume that the power supplies and new generation capacities take continuous values. Previous works show that the assumption of continuity approximates the actual power market well if the number of generating units owned by the generation firms is large enough. In most power industries, the number of generating units is generally large enough, so that the continuity assumption does not result in significant errors in approximating the long-term supply and capacity expansion strategies of the generation firms.

In this chapter, it is assumed that the transmission network has unlimited capacities; spatial power market with transmission capacity constraints will be modeled in the succeeding chapters.

3.3.2 Equilibrium Conditions

Under the assumption that a generation firm believes that the other generation firms stick to their decisions at equilibrium, the necessary optimality conditions of generation firm *f* can be obtained by deriving the Karush-Kuhn-Tucker (KKT) conditions of its long-term planning problem by taking other generation firms' decision variables as constants. The KKT conditions are

$$\begin{aligned} & g_{fk} \geq 0, \forall k \\ & c'_k(g_{fk}) + u_{fk} - u_f \geq 0, \forall k \\ & g_{fk}[c'_k(g_{fk}) + u_{fk} - u_f] = 0, \end{aligned} \tag{3.26}$$

$$\begin{aligned} & q_{fj} \geq 0, \forall j \\ & -[a_j - b_j(2q_{fj} + \sum_{i \neq f} q_{ij})] + u_f \geq 0, \forall j \\ & q_{fj}\{-[a_j - b_j(2q_{fj} + \sum_{i \neq f} q_{ij})] + u_f\} = 0, \end{aligned} \tag{3.27}$$

$$\begin{aligned} & x_{fk} \geq 0, \forall k \\ & f'_k(x_{fk}) - u_{fk} \geq 0 \\ & x_{fk}[f'_k(x_{fk}) - u_{fk}] = 0, \end{aligned} \tag{3.28}$$

$$\begin{aligned} & u_{fk} \geq 0, \forall k \\ & g_{fk} \leq GC_{fk} + x_{fk}, \forall k \\ & u_{fk}[g_{fk} - GC_{fk} - x_{fk}] = 0, \end{aligned} \tag{3.29}$$

$$\begin{aligned} & u_f, \textit{ free} \\ & \sum_{j \in J} q_{fj} = \sum_{k \in K} g_{fk}. \end{aligned} \tag{3.30}$$

In the KKT conditions described in (3.26) ~ (3.30), u_{fk} is the dual variable associated with constraint (3.24), and u_f is the dual variable for constraint (3.25).

3.3.3 Existence and Uniqueness of Equilibrium Solution

The major questions now are “Will the game of the generation firms have an equilibrium point?” and “If so, is the equilibrium point unique?” Using Theorems 3.1 and 3.2, the existence and uniqueness of the equilibrium point can be proven for the long-term planning problem of the generation firms in a competitive spatial power market.

Theorem 3.3: The *n*-person game of generation firms defined by (3.23) ~ (3.25) has a unique market equilibrium point if the generation cost functions $c_k(g_{fk}),\ k \in K,\ f \in I$ and the generation capacity construction cost functions $f_k(x_{fk}),\ k \in K,\ f \in I$ are continuous convex functions that are monotonically increasing and have continuous first-order derivatives.

Proof: Since we assume the inverse demand functions of the local power markets to be of the form $p_j = a_j - b_j d_j,\ j \in J$, then $\sum_{j \in J}(a_j - b_j \sum_{i \in I} q_{ij}) q_{fj}$ is a concave function of q_{fj}. Also, by assuming $c_k(g_{fk}),\ k \in K,\ f \in I$ and $f_k(x_{fk}),\ k \in K,\ f \in I$ to be convex and continuously first-order derivable, the n-person game of generation firms is continuous and concave. The decision spaces of generation firms are convex and compact because all constraints are linear and we assume that the cost functions are monotonically increasing. Then by Theorem 3.1, we can see that the game has at least one equilibrium point.

The weighted nonnegative sum of the payoff functions of the generation firms is

$$\sigma(y,r) = \sum_{f \in I} r_f [\sum_{j \in J}(a_j - b_j \sum_{i \in I} q_{ij}) q_{fj} - \sum_{k \in K} c_k(g_{fk}) - \sum_{k \in K} f_k(x_{fk})],\ r_f \geq 0 \tag{3.31}$$

where $y = (q_{ij}, g_{ik}, x_{ik})$.

By setting the value of r_f to 1, the pseudogradient of $\sigma(y,r)$ is given by

$$g(y,r)=\begin{bmatrix}\nabla_1\pi_1(y)\\ .\\ .\\ \nabla_f\pi_f(y)\\ .\\ .\\ \nabla_n\pi_n(y)\end{bmatrix}. \qquad (3.32)$$

Suppose that there are two distinct equilibrium points y^0 and y^1, then for generation firm f, power market j and technology k, we have

$$\begin{aligned}&(y_{fjk}{}^1-y_{fjk}{}^0)g(y_{fjk}{}^0,r)+(y_{fjk}{}^0-y_{fjk}{}^1)g(y_{fjk}{}^1,r)\\ &=(g_{fk}{}^1-g_{fk}{}^0,q_{fj}{}^1-q_{fj}{}^0,x_{fk}{}^1-x_{fk}{}^0)\begin{bmatrix}-c_k{}'(g_{fk}{}^0)\\ a_j-b_j(q_{fj}{}^0+\sum_{i\in I}q_{ij}{}^0)\\ -f_k{}'(x_{fk}{}^0)\end{bmatrix}\\ &+(g_{fk}{}^0-g_{fk}{}^1,q_{fj}{}^0-q_{fj}{}^1,x_{fk}{}^0-x_{fk}{}^1)\begin{bmatrix}-c_k{}'(g_{fk}{}^1)\\ a_j-b_j(q_{fj}{}^1+\sum_{i\in I}q_{ij}{}^1)\\ -f_k{}'(x_{fk}{}^1)\end{bmatrix}.\end{aligned} \qquad (3.33)$$

Equation (3.33) can be rewritten as

$$(y_{fjk}{}^1-y_{fjk}{}^0)g(y_{fjk}{}^0,r)+(y_{fjk}{}^0-y_{fjk}{}^1)g(y_{fjk}{}^1,r)\ =A+B+C \qquad (3.34)$$

where

$$A=(g_{fk}{}^1-g_{fk}{}^0)[c_k{}'(g_{fk}{}^1)-c_k{}'(g_{fk}{}^0)] \qquad (3.35)$$

$$B=(x_{fk}{}^1-x_{fk}{}^0)[f_k{}'(x_{fk}{}^1)-f_k{}'(x_{fk}{}^0)] \qquad (3.36)$$

$$C=b_j(q_{fj}{}^1-q_{fj}{}^0)(q_{fj}{}^1-q_{fj}{}^0+\sum_{i\in I}q_{ij}{}^1-\sum_{i\in I}q_{ij}{}^0). \qquad (3.37)$$

A and B are nonnegative based upon the assumptions that the generation cost functions $c_k(g_{fk}),\ k \in K,\ f \in I$ and the generation capacity construction cost functions $f_k(x_{fk}),\ k \in K,\ f \in I$ are continuous convex functions, which are monotonically increasing.

If we sum C over $f \in I,$ we get

$$\sum_{f \in I} b_j (q_{fj}{}^1 - q_{fj}{}^0)(q_{fj}{}^1 - q_{fj}{}^0 + \sum_{i \in I} q_{ij}{}^1 - \sum_{i \in I} q_{ij}{}^0) = b_j \sum_{f \in I} (q_{fj}{}^1 - q_{fj}{}^0)^2 + b_j [\sum_{f \in I} (q_{fj}{}^1 - q_{fj}{}^0)]^2. \qquad (3.38)$$

If we assume that at least one pair of $q_{fj}{}^0$ and $q_{fj}{}^1$ are distinct, equation (3.38) is positive because $b_j > 0$. And since A and B are always nonnegative, we have $A + B + C > 0$. According to Definition 3.1, the weighted nonnegative sum of the payoff functions of generation firms is diagonally strictly concave for $y \in R$ and fixed $r = 1$. According to Theorem 3.2, the n-person game of generation firms has the unique market equilibrium in terms of power supply q_{fj}. However, it is possible that there exist multiple equilibrium points in terms of power generation because for example, if a generation firm has two generation technologies with the same constant marginal cost, there may be alternative generation plans that have the same cost and output level. □

3.3.4 Solution Strategy and Numerical Example

If the long-term planning problem of the generation firms defined in (3.23) ~ (3.25) satisfies the conditions stated in Theorem 3.3, the KKT conditions of all the generation firms are sufficient and necessary for a unique market equilibrium point. Furthermore, if the generation cost functions and construction cost functions are assumed to have constant or linear marginal functions, the KKT conditions of the generators given by

(3.26) ~ (3.30) form a linear Mixed Complementarity Problem (MCP), which involves both linear equality and complementarity conditions, and the number of variables is the same as the number of linear complementarity and equality conditions. The linear MCP problem can be solved efficiently using Lemke's algorithm, and there are commercial solvers such as PATH and MILES that have been developed specially for this kind of problems.

The following numerical example describes generation firms' long-term competition in a spatial power market without transmission constraints.

Numerical Example 3.1

Consider the spatial power market with three generation firms and three local power markets depicted in Figure 3.1, the parameters of the generation firms and local power markets are given in Table 3.1 and Table 3.2 respectively.

Table 3.1: Generation firms' generation and expansion parameters

	c'	f'	GC_1	GC_2	GC_3
LOW	$0.2g$	5	4	0	0
MEDIUM	$0.5g$	4	0	6	0
HIGH	$0.8g$	3	0	0	10

Table 3.2: Market parameters

Market j	a_j	b_j
1	40	1.8
2	36	1.5
3	32	2

In this example, it is assumed that there are three types of generation technologies denoted as LOW, MEDIUM and HIGH, all of which have quadratic generation cost functions. *c'* and *f'* denote the marginal generation and expansion costs respectively. Technology LOW has the lowest marginal generation cost and technology HIGH has the highest marginal generation cost. They also have different constant marginal construction costs, and it is assumed that it costs more to build generation units of a cheaper technology. The local power markets described in this example have different maximum possible prices, and they also differ in the elasticity of demands with regard to electricity prices. There exist unique market equilibrium in this example. The problem was solved by the PATH solver, which is efficient in solving linear MCPs. The decisions of the generation firms are summarized in Table 3.3 and Table 3.4.

Table 3.3: Generation capacity expansions

	LOW	MEDIUM	HIGH
Firm 1	0.972	3.989	3.743
Firm 2	3.711	0	3.428
Firm 3	3.092	3.237	0

Table 3.4: Power supplied to markets and produced with different technologies

	Market 1	Market 2	Market 3	LOW	MEDIUM	HIGH
Firm 1	4.636	4.896	3.172	4.972	3.989	3.743
Firm 2	4.776	5.064	3.298	3.711	6	3.428
Firm 3	4.845	5.147	3.36	3.092	3.237	7.023

3.4 Comparisons of Nash-Cournot Competition with Perfect Competition and Pareto Optimality among Generation Firms

3.4.1 Perfect Competition among Generation Firms

The perfect competition of generation firms in a spatial power market assumes that the generation firms are price-takers, and the competition among them maximize the social welfare of the power market. The social welfare is the sum of consumer surplus and supplier surplus minus the costs of supplying electricity to the power market.

Suppose there is a perfect competition power market, let $j = 1, 2, ..., N$ denote the local power markets, each local market j has the inverse demand function $p_j = P_j(D_j)$ that is convex and monotonically decreasing as shown in Figure 3.2.

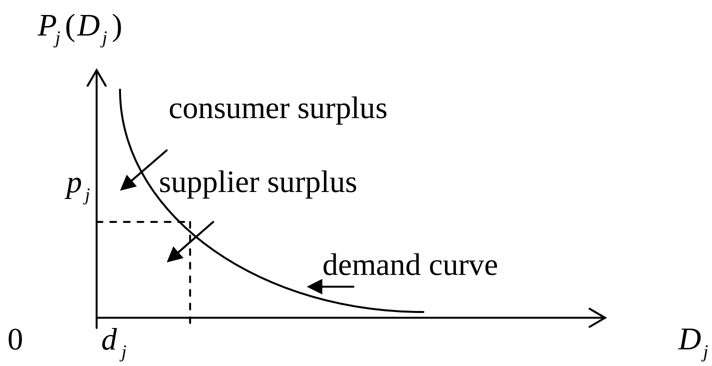

Figure 3.2: Social welfare in a power market

As can be seen in Figure 3.2, the consumer surplus of a local power market increases when there is more power supply and the price drops. The supplier surplus is what the consumers pay for electricity in that market. The sum of consumer surplus and supplier surplus in market j when total demand for electricity is d_j is the area below the demand curve and can be expressed by

$$\int_0^{d_j} P_j(D_j)dD_j. \tag{3.39}$$

To calculate the social welfare of the power market, generation and capacity expansion costs have to be deducted from the sum of total consumer and supplier surplus, let $c_k(g_k)$ denote the cost function of generation technology *k*, and let $f_k(x_k)$ denote the construction cost of generation capacity using technology *k*. In perfect competition, generation firms maximize the social welfare, which may be written as

maximize

$$\sum_{j\in J}\int_0^{d_j} P_j(D_j)dD_j - \sum_{i\in I}\sum_{k\in K} c_k(g_{ik}) - \sum_{i\in I}\sum_{k\in K} f_k(x_{ik}). \tag{3.40}$$

If we ignore the transmission network transmission capacity limits, the constraints faced by the generation firms are the generation capacities for power supply and the balance of power supplies and demands, which are

$$g_{ik} \le GC_{ik} + x_{ik}, \forall_i, \forall k \tag{3.41}$$

$$d_j = \sum_{i\in I} q_{ij}, \forall j \qquad (3.42)$$

$$\sum_{j\in J} q_{ij} = \sum_{k\in K} g_{ik}, \forall i \tag{3.43}$$

where q_{ij}, g_{ik}, and x_{ik} are nonnegative variables.

If we assume linear inverse demand functions of the local power markets as we did in Section 3.3, the problem of maximizing the social welfare can be written as

maximize

$$\sum_{j\in J}[a_j \sum_{i\in I} q_{ij} - 0.5b_j(\sum_{i\in I} q_{ij})^2] - \sum_{i\in I}\sum_{k\in K} c_k(g_{ik}) - \sum_{i\in I}\sum_{k\in K} f_k(x_{ik}) \tag{3.44}$$

subject to

$$g_{ik} \leq GC_{ik} + x_{ik}, \forall_i, \forall k \quad (3.45)$$

$$\sum_{j \in J} q_{ij} = \sum_{k \in K} g_{ik}, \forall i \quad (3.46)$$

where q_{ij}, g_{ik}, and x_{ik} are nonnegative variables.

3.4.2 Quadratic Formulation of Nash-Cournot Competition

Hashimoto (1985) shows that the Nash-Cournot equilibrium on a transportation network can be calculated by transforming it to a single quadratic programming problem under the assumptions that the inverse demand functions are linear and the cost functions are linear or quadratic. Similarly, the Nash-Cournot competition of the generation firms in a spatial power market can be also transformed to an equivalent quadratic program under the assumptions of linear inverse demand functions of local power markets and linear or quadratic cost functions of power generation and new capacity construction. The equivalent quadratic program is as follows.

maximize

$$\sum_{j \in J}[a_j \sum_{i \in I} q_{ij} - 0.5 b_j (\sum_{i \in I} q_{ij})^2 - 0.5 b_j \sum_{i \in I} q_{ij}{}^2] - \sum_{i \in I}\sum_{k \in K} c_k(g_{ik}) - \sum_{i \in I}\sum_{k \in K} f_k(x_{ik}) \quad (3.47)$$

subject to

$$g_{ik} \leq GC_{ik} + x_{ik}, \forall i, \forall k \quad (3.48)$$

$$\sum_{j \in J} q_{ij} = \sum_{k \in K} g_{ik}, \ \forall i \quad (3.49)$$

where q_{ij}, g_{ik}, and x_{ik} are nonnegative variables.

It can be seen that the KKT conditions of the quadratic program defined in (3.47) ~ (3.49) are the same as the complementarity slackness conditions of (3.26) ~ (3.30). Therefore, the Nash-Cournot equilibrium of the generation firms is equivalent to the solution of this quadratic program. The only difference between the perfect competition model and the quadratic program of the Nash-Cournot competition resides in their objective functions. The additional term of $0.5b_j \sum_{i \in I} q_{ij}^2$ in the objective function of the quadratic program of the Nash-Cournot competition explains the desire of generation firms to lower the amount of power supplied to the market in order to keep the electricity prices at a higher level than in the perfect competition market. Another insight into the Nash-Cournot competition is that the generation firms would compete more intensely in a local power market with less elastic demand by providing more power supplies; and in a local power market that is more elastic, the Nash-Cournot competition is less intense. Also, the electricity price is higher in Nash-Cournot competition than in the perfect competition case.

3.4.3 Pareto Optimality among Generation Firms

Another model for the power market is when the generation firms form coalitions when making decisions on generation capacity and power supply to maximize their total profits. This kind of model leads to Pareto optimality among generation firms. It can be formulated as

maximize

$$\sum_{j \in J}[a_j \sum_{i \in I} q_{ij} - b_j (\sum_{i \in I} q_{ij})^2] - \sum_{i \in I}\sum_{k \in K} c_k(g_{ik}) - \sum_{i \in I}\sum_{k \in K} f_k(x_{ik}) \tag{3.50}$$

subject to

$$g_{ik} \le GC_{ik} + x_{ik}, \forall i, \forall k \tag{3.51}$$

$$\sum_{j \in J} q_{ij} = \sum_{k \in K} g_{ik}, \ \forall i \tag{3.52}$$

where q_{ij}, g_{ik}, and x_{ik} are nonnegative variables.

The objective function represents the total profit, which is the total revenue minus the generation and capacity expansion costs; the first term is the total revenue, and the second term and third term are the generation and capacity costs. The difference between the Pareto optimality formulation and the perfect competition model is in that consumer surplus is not considered in the Pareto optimality formulation. It is expected that in the Pareto optimality model, less power will be supplied to the power market and the electricity prices will be set at a higher level than in the perfect competition and Nash-Cournot competition models.

Next a numerical example is presented to compare the decisions of generation firms in three different models.

Numerical Example 3.2

Consider a spatial power market consisting of two generation firms and two local power markets, with two types of generation technologies HIGH and LOW available. The parameters of the generation firms and the markets are given in Tables 3.5 and 3.6.

Table 3.5: Generation firms' generation and expansion parameters

	c'	*f'*	GC_1	GC_2
LOW	0.2g	5	4	0
HIGH	0.5g	4	0	6

Table 3.6: Market parameters

Market *j*	a_j	b_j
1	40	1.8
2	36	1.5

Generation firms' decisions on power supplies and new capacity investments that result from the different models are given in Tables 3.7 ~ 3.10.

Table 3.7: Generation capacity expansions in different models

	Perfect competition		Nash-Cournot		Pareto optimality	
	LOW	HIGH	LOW	HIGH	LOW	HIGH
Firm 1	7.861	6.745	3.633	5.053	0.78	3.912
Firm 2	11.861	0.745	6.872	0	4.78	0

Table 3.8: Power supplied to markets and produced with different technologies in perfect competition

	Market 1	Market 2	LOW	HIGH
Firm 1	9.61	8.996	11.861	6.745
Firm 2	8.517	10.089	11.861	6.745

Table 3.9: Power supplied to markets and produced with different technologies in Nash-Cournot competition

	Market 1	Market 2	LOW	HIGH
Firm 1	6.171	6.516	7.633	5.053
Firm 2	6.255	6.617	6.872	6

Table 3.10: Power supplied to markets and produced with different technologies in Pareto optimality

	Market 1	Market 2	LOW	HIGH
Firm 1	4.312	4.38	4.78	3.912
Firm 2	5.145	5.635	4.78	6

From the results shown in Table 3.7, it can be seen that more generation capacities are added in perfect competition than in Nash-Cournot competition and at Pareto optimality of generation firms. This implies that the generation firms generate more electric power in perfect competition because they will not invest in redundant generation capacities that are not used at all. Tables 3.8, 3.9 and 3.10 also show that perfect competition yields the greatest amount of power supplied, while Nash-Cournot competition provides more power supply than at Pareto optimality among generation firms. As discussed before, consumer surplus increases if there is more power supply. Figure 3.3 shows the consumer surplus in each local market in each of the three models.

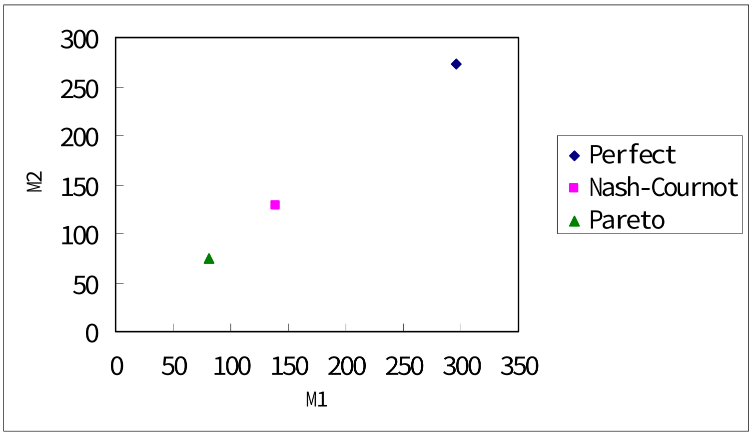

Figure 3.3: Consumer surplus in each model

Figure 3.3 shows that consumers benefit the most in perfect competition of generation firms; this is because consumer surplus is explicitly included in the objective function of perfect competition. In Nash-Cournot competition, the generation firms have the incentive to reserve part of their generation capacities to set the prices at a higher level and make more profits. In Pareto optimal behavior of generation firms, no consumer surplus is considered and the generation firms form a coalition to maximize the supplier surplus; this explains why consumer surplus is the least at Pareto optimality among the generation firms.

Figure 3.4 displays electricity prices in two local markets in the these different models. It can be seen that in perfect competition, the local market prices are at the lowest level, and there is no price difference. In Nash-Cournot competition, the market prices are higher and there exists price difference. In Pareto optimality among generation firms, the market prices are the highest and price difference between two local power markets is the largest.

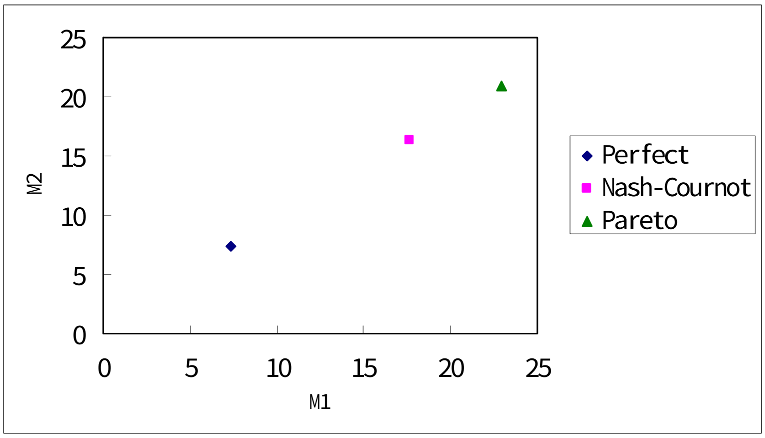

Figure 3.4: Electricity prices in each model

The difference in the local market prices in a spatial power market without transmission capacity constraints is due to different inverse demand functions of the local power markets. In Nash-Cournot competition and Pareto optimal solution, the generators choose to supply more power to the markets whose prices decrease at slower rates as the power supply increases. In this numerical example, electricity price in Market 1 is more sensitive to power supply, and therefore the generation firms in Nash-Cournot competition and Pareto optimal solution supply less power to Market 1 and the price in Market 1 is higher than in Market 2.

Figure 3.5 compares generation firms' profits in the three different models of the power market. It can be seen that generation firms make more profit in the Pareto optimal solution and the profit is the least in perfect competition. This is because in the Pareto optimality formulation, generation firms maximize their total profits at the cost of reduced consumer surplus in the power market.

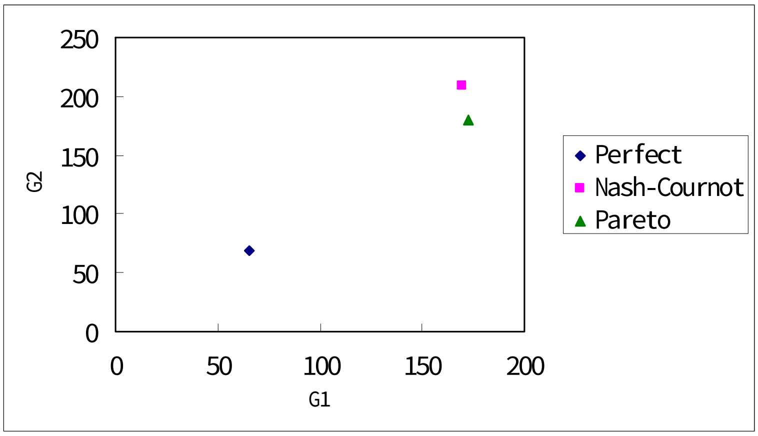

Figure 3.5: Generation firms' profits in each model

In practice, perfect competition is very hard to achieve in the power industry, because perfect competition requires a large number of competitors, but the economy-of-scale in the power industry leads to a limited number of generation firms in the power market. Therefore, it is unrealistic to assume that the generation firms are price-takes.

Pareto optimality among generation firms is obtained by assuming that they act monopolistically and together they try to maximize the total profit of the generation firms. This kind of power market hurts the interests of the electricity consumers and it conflicts with the objective of power market deregulators.

This dissertation assumes that the generation firms behave in a noncooperative manner and they compete against each other to maximize individual profits. As shown in Numerical Example 3.2, results from the Nash-Cournot competition of generation firms lie somewhere between perfect competition and Pareto optimality among generation firms. It can be shown that as the number of generation firms in a deregulated power market increases, the competition results are closer to those of perfect competition. After all, this is the reason why policy-makers hope to lower electricity prices by introducing more competition into the power market through deregulation.

3.5 Modeling Generation Firms' Long-Term Competition in Spatial Power Market under Future Uncertainties

Future uncertainties exist in the long-term planning and building of electricity generation facilities, because it takes several years to install new generation facilities. Since generation capacity investment decisions precede their operations by a long period of time, some factors in the power market may change considerably from their original values when new generation capacities are being planned. It is hard to predict the future values of these factors of the power market. An approach to represent future uncertainties is to estimate probability distributions of the uncertain factors.

3.5.1 Assumptions and Formulation

This section analyzes long-term decisions of generation firms in an uncertain environment. In doing so, we need to make some assumptions on future uncertainties and the decision-making processes of the generation firms. One assumption is that the generation firms make capacity expansion decisions to maximize the expected profit based on probabilistic future scenarios of the power market. In such a decision-making process, the generation firms explicitly consider the profit they can make in each possible future scenario by adding new generation capacities before future uncertainties unfold.

Another modeling approach assumes that the generation firms make capacity investment decisions based on the expected values of the uncertain factors, and the capacity planning problem is solved as if it is in a deterministic situation. Then, after the investment decisions are made and one of the possible scenarios unfolds, the generation firms make electricity supply decisions accordingly. Genc (2003) points out that although the assumption that the generation firms take decisions based upon the expected values of future uncertainties makes the problem easier to solve, the solution may not be optimal, because it is more profitable for a generation firm to explicitly consider each possible future scenario if other generation firms use expected values of future uncertainties in their planning processes.

To make the planning problems under future uncertainties tractable, we assume that future uncertainties of the power market can be represented by a finite set of scenarios where each scenario is assigned a probability of occurrence. Furthermore, it is assumed that the only uncertain factor in the power market is consumer demand for electricity, which is represented by $a_j,\ j \in J$.

Under the uncertain environment of future power market, the inverse demand function of each local market is:

$$p_j^s = a_j^s - b_j d_j^s,\ s \in S,\ j \in J \tag{3.53}$$

where

S is the set of future scenarios;

a_j^s is the demand parameter in scenario s; and

$d_j^s = \sum_{i \in I} q_{ij}^s$ is the total amount of power supply to market j in scenario s.

Let $y_i^s = (g_{ik}^s, q_{ij}^s, x_{ik})$ denote the vector of decision variables of firm i, and let $w^s,\ s \in S$ denote the probability of occurrence for each future scenario. Then, the generation firms' long-term planning problem under future uncertainties is formulated as

maximize

$$\sum_{s\in S} w^s [\sum_{j\in J} (a_j^s - b_j \sum_{i\in I} q_{ij}^s) q_{fj}^s - \sum_{k\in K} c_k (g_{fk}^s)] - \sum_{k\in K} f_k (x_k) \tag{3.54}$$

subject to

$$g_{fk}^s \leq GC_{fk} + x_{fk},\ \forall k,\ \forall s \tag{3.55}$$

$$\sum_{j\in J} q_{fj}^s = \sum_{k\in K} g_{fk}^s,\ \forall s \tag{3.56}$$

where $g_{fk}^s, q_{fj}^s, x_{fk}$ are nonnegative variables.

In the above formulation, objective function (3.54) states that the expected long-term profit of a generation firm is its expected revenue in the future power market minus the cost of building new generation capacities, which is made before future uncertainties unfold. Equations (3.55) and (3.56) state that the generation firms must ensure that no matter which scenario unfolds in the future, the amount of power generated cannot exceed the generation capacities available, and the power generation and consumption balance must be maintained in any future scenario.

3.5.2 A Numerical Example

If we assume that the cost functions $c_k(g_{fk}^s)$ and $f_k(x_k)$ are strictly increasing and convex, the above long-term planning model has unique market equilibrium, because the decision space for each generation firm is compact and convex. In this section, we present a numerical example, which considers future uncertainties in the power market. The numerical example can be formulated as a linear MCP and the market equilibrium can be obtained by using the PATH solver.

Numerical Example 3.3

Consider the spatial power market that has three local markets, where three generation firms compete with each other to maximize their long-term profits. Now suppose that the generation firms want to decide on investments on new generation capacities, but the demand for electricity when new generation capacities become available is not known exactly. It is assumed that future demand for electricity has two scenarios, which are denoted by the set S = {UP, DOWN}. If UP scenario occurs, there will be more demand, and in DOWN scenario there will be less demand. It is also assumed that each scenario's probability of occurrence is 0.5. Generation firms' parameters and market parameters in the two scenarios are given in Tables 3.11 and 3.12.

Table 3.11: Generation firms' generation and expansion parameters

	c'	*f'*	GC_1	GC_2	GC_3
LOW	0.2*g*	5	4	0	0
MEDIUM	0.5*g*	4	0	6	0
HIGH	0.8*g*	3	0	0	10

Table 3.12: Market Parameters

Market *j*	a_j^{UP}	a_j^{DOWN}	b_j
1	50	30	1.8
2	45	25	1.5
3	40	20	2

The generation firms' long-term planning problem with uncertain future demands can be solved by transforming it to a linear MCP problem, because the generation cost functions are assumed to be quadratic and the capacity construction cost functions are assumed to be linear. The generation firms' decisions in new generation capacity investments and power generation and supply in UP and DOWN scenarios are shown in Tables 3.13 ~ 3.15.

Table 3.13: Generation capacity expansions

	LOW	MEDIUM	HIGH
Firm 1	0.781	4.37	5.231
Firm 2	4.196	0	4.792
Firm 3	3.203	3.281	0

Table 3.14: Power supplied to markets and produced with different technologies in UP scenario

	Market 1	Market 2	Market 3	LOW	MEDIUM	HIGH
Firm 1	5.312	5.541	3.53	4.781	4.37	5.231
Firm 2	5.507	5.775	3.706	4.196	6	4.792
Firm 3	5.989	6.354	4.141	3.203	3.281	10

Table 3.15: Power supplied to markets and produced with different technologies in DOWN scenario

	Market 1	Market 2	Market 3	LOW	MEDIUM	HIGH
Firm 1	4.025	3.997	2,372	4.781	3.454	2.159
Firm 2	3.96	3.918	2.314	4.196	3.69	2.306
Firm 3	3.698	3.604	2.078	3.203	3.281	2.895

3.5.3 Effects of Uncertainties on Generation Firms' Decisions

In the results of Numerical Example 3.3, there are two points that should be noted. The first point is that, in the UP scenario, which indicates more electricity demand in each local power market, the generation firms use all the new generation capacities added. The second point is that the generation firms produce more power in the UP scenario than in the DOWN scenario. Genc (2003) studies the how uncertain future market demand affects the behavior of generation firms in a deregulated power market. It shows that the generation firms have the incentive to participate in the market with future uncertainties. In this section, we study how future demand uncertainties affect the behavior of generation firms in a deregulated spatial power market.

Proposition 3.1: For two distinct future market scenarios represented by UP and DOWN, if it is assumed that each local market has more demand in the UP scenario than in the DOWN scenario, then each generation firm in the power market will supply no less electricity in the UP scenario than in the DOWN scenario.

Proof: The claim is that $\sum_{k\in K} g_{ik}^D \le \sum_{k\in K} g_{ik}^U,\ \forall i \in I$, where D and $U \in S$ represent UP and DOWN scenarios respectively, and it is assumed that $a_j^U > a_j^D,\ \forall j \in J$. If we suppose that there exists a set $I^M \subseteq I$ and that $\sum_{k\in K} g_{ik}^D > \sum_{k\in K} g_{ik}^U,\ \forall i \in I^M$, then for an $i \in I^M$, there exists a $k \in K$ such that $g_{ik}^D > g_{ik}^U$. From the KKT conditions associated with generation firms' long-term planning problem defined in (3.54) ~ (3.56), we have

$$c_k^{'}(g_{ik}^s) + u_{ik}^s - u_i^s \ge 0,\ \forall s \in S,\ i \in I, \tag{3.57}$$

and

$$g_{ik}^s[c'_k(g_{ik}^s) + u_{ik}^s - u_i^s] = 0,\ \forall s \in S,\ i \in I. \tag{3.58}$$

Then, from (3.57) and (3.58), it must be true that $u_i^D \ge u_i^U$ for $i \in I^M$.

Also, for $i \in I^M$, there exists a $j \in J^L \subseteq J$ thus that $q_{ij}^D > q_{ij}^U$. Again, from the KKT conditions associated with generation firms' long-term planning problem defined in (3.54) ~ (3.56), we have

$$-a_l^s + b_j (q_{ij}^s + \sum_{i \in I} q_{ij}^s) + u_i^s \geq 0, \ \forall s \in S, i \in I, j \in J, \tag{3.59}$$

and

$$q_{ij}^s \{-[a_j^s - b_j^s (q_{ij}^s + \sum_{i \in I} q_{ij}^s)] + u_i^s\} = 0, \ \forall s \in S, i \in I, j \in J. \tag{3.60}$$

Since $u_i^D \geq u_i^U$ for $i \in I^M$, it must be true that $-a_j^U + b_j \sum_{i \in I} q_{ij}^U > -a_j^D + b_j \sum_{i \in I} q_{ij}^D$ and $\sum_{i \in I} q_{ij}^D < \sum_{i \in I} q_{ij}^U$, for $j \in J^L$.

For a $j \in J^L$, there must exist $i \in I$ such that $q_{ij}^D < q_{ij}^U$. From (3.59) and (3.60), it can be deduced that $u_i^D \geq u_i^U$, which, by using (3.57) and (3.58), it can be seen that for such an $i \in I$, we have $\sum_{k \in K} g_{ik}^D \geq \sum_{k \in K} g_{ik}^U$.

From the above analysis, for each $i \in I^M$ with $\sum_{k \in K} g_{ik}^D > \sum_{k \in K} g_{ik}^U$, if there exists $q_{ij}^D > q_{ij}^U$, there must also exists $q_{ij}^D < q_{ij}^U$, and the difference between q_{ij}^D and q_{ij}^U in $q_{ij}^D < q_{ij}^U$ is more than that in $q_{ij}^D > q_{ij}^U$. Therefore, the total amount of power supply of $i \in I^M$ in UP scenario is more than that in DOWN scenario, which contradicts the supposition that $\sum_{k \in K} g_{ik}^D > \sum_{k \in K} g_{ik}^U, \ \forall I \in I^M$. Therefore, we must have $\sum_{k \in K} g_{ik}^D \leq \sum_{k \in K} g_{ik}^U, \ \forall i \in I$. □

Lemma 3.1: The generation firms generate no less electricity in the UP scenario than in the DOWN scenario for each type of the generation technology available if the marginal generation cost functions are monotonically increasing.

Proof: we are going to prove that $g_{ik}^{D} \le g_{ik}^{U},\ \forall i \in I,\ \forall k \in K.$ Suppose that there exists an $i \in I$ and $k \in K$ such that $g_{ik}^{D} > g_{ik}^{U},$ then from (3.57) and (3.58), it can be deduced that if there exists a $k \in K$ that $g_{ik}^{D} > g_{ik}^{U}$ for an $i \in I,$ then we have $u_{i}^{U} < u_{i}^{D}.$ And by using the result of Proposition 3.1, which states that $\sum_{k \in K} g_{ik}^{D} \le \sum_{k \in K} g_{ik}^{U},\ \forall i \in I$, there must exist a $k \in K$ such that $g_{ik}^{D} < g_{ik}^{U}$ for an i. If there is a k that $g_{ik}^{D} < g_{ik}^{U},$ it implies that $u_{i}^{U} > u_{i}^{D},$ which contradicts $u_{i}^{U} < u_{i}^{D}$ in case that $g_{ik}^{D} > g_{ik}^{U}.$ Therefore, it is impossible to have $g_{ik}^{D} > g_{ik}^{U},$ and it is true that $g_{ik}^{D} \le g_{ik}^{U},\ \forall i \in I,\ \forall k \in K.$ □

Next, Theorem 3.4, which describes the behavior of generation firms in capacity investment in an uncertain market environment is presented and proven.

Theorem 3.4: If the future power market demand is uncertain, having a set of possible scenarios, the amount of new generation capacities added by a generation firm is no more than the amount of new generation capacities needed in the scenario with the most demand for electricity.

Proof: Suppose that the generation firms know with certainty that the scenario with the least demand for electricity will occur in the future, and $\sum_{k \in K} x_{ik}^{D},\ i \in I$ denotes new generation capacities the generation firms will invest. $\sum_{k \in K} x_{ik}^{U},\ i \in I$ denotes the new capacities invested if the generation firms are certain that the scenario of most demand will happen in the future. According to Proposition 3.1, $\sum_{k\in K} g_{ik}^{D} \le \sum_{k\in K} g_{ik}^{U}$. Therefore, under the uncertain environment, the maximum amount of new generation capacities a generation firm will invest is the amount of new capacities added when the generation firm *i* expects the scenario with the most demand will happen. □

Theorem 3.4 explains the observation in Numerical Example 3.3 that the generation firms use all the capacities added in the UP scenario, because the UP scenario is the one with the most demand in the set of possible future scenarios. In generation firms' long-term planning problem faced in an uncertain future market demand, the estimation of demand in future scenarios is closely associated with the firms' decisions on capacity expansion. The estimation of future market includes estimating the demand for power in each local market in each scenario, and estimating the probability of occurrence of each future scenario. Theorem 3.4 indicates that if the future market demand is expected to be higher, the generation firms will have the incentive to add more generation capacities.

Figure 3.6 plots the generation capacities each generation firm add corresponding to different projected future scenarios based upon the data of Numerical Example 3.3 where it is assumed that the only parameter that changes is a_j^{UP}, $j = 2$.

The figure demonstrates that each generation firm will add more generation capacity if a_j^{UP} is expected to be higher. In addition to the estimation of demand in future scenarios, the probability of occurrence associated with each future scenario also affects generation firms' decisions in capacity expansions.

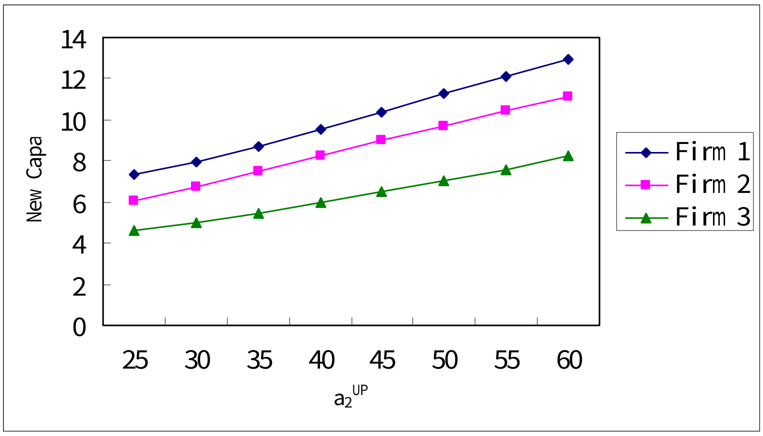

Figure 3.6: Generation firms' capacity expansion vs. different estimation of future demands

Theorem 3.5: Suppose that the future uncertainties of the power market can be represented by two possible scenarios: UP and DOWN. In the UP scenario each local power market has more demand than in the DOWN scenario as reflected in larger values of a_j^{UP} than a_j^{DOWN}, $j \in J$. Let w^{UP} and w^{DOWN} denote the probability of UP and DOWN scenarios respectively. Then the generation firms will invest in the same or more amount of generation capacity if w^{UP} increases and w^{DOWN} decreases correspondingly.

Proof: Suppose that there are two distinct estimations of the probability of future scenarios in the power market: w_1^s and w_2^s. Assume that $w_1^{up} < w_2^{up}$ and $w_1^{DOWN} > w_2^{DOWN}$. Let x_i^1 and x_i^2 denote generation capacities added by generation firms corresponding to w_1^s and w_2^s respectively. Suppose that there exists $i \in I$ such that $x_i^1 > x_i^2$. According to Theorem 3.4, the extra capacity x_i^1 added will be used in the UP scenario. Since $w_1^{up} < w_2^{up}$, according to the objective function of generation firms, in the case of w_2^s, the generation firm will make more profit if x_i^2 is at least the same as x_i^1. Therefore, it is impossible to have $x_i^1 > x_i^2$. □

Based on the parameters of Numerical Example 3.3, Figure 3.7 illustrates how the generation firms react to changes in probabilities of future scenarios.

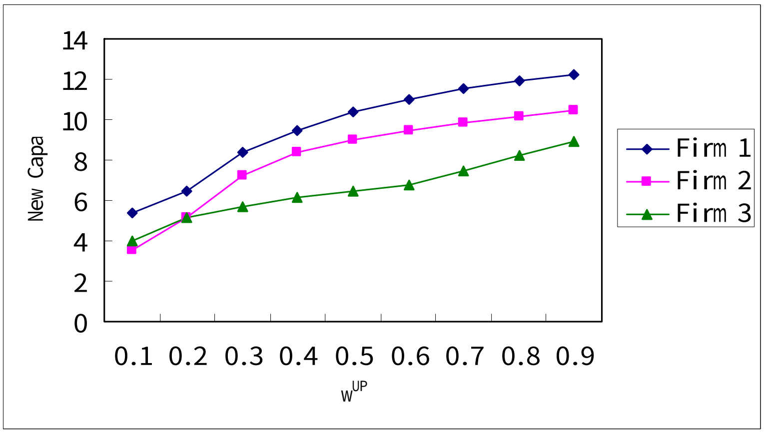

Figure 3.7: Generation firms' capacity expansion vs. different scenario probabilities

In this chapter, various models on long-term competition among generation firms in a spatial electric power market are formulated and analyzed. All of the models assume that the electricity transmission network that connects generation firms and local markets has unlimited capacity and will not get congested. In general, this is not true for spatial power markets, which are normally constrained by limited transmission capacities. In the next chapter, we present a method of calculating electric power flows within a limited-capacity transmission network. In the succeeding Chapter 5, more models on transmission congestion management and transmission capacity planning will be presented and studied.

4 TRANSMISSION LINE CAPACITY AND ELECTRIC POWER FLOW COMPUTATION

In Chapter 3, the long-term competition of generation firms in a spatial power market with unlimited transmission capacities was modeled. However, in real-world operations of the power market, the transmission system often gets congested, especially when one considers long-term operations of the power market, where the increases in customer loads and power supplies often require more transmission capacities. Therefore, it is important to estimate if there is enough transmission capacity to support the power market in the long run. If it is found that the power market is short of transmission capacity, measures have to be taken to keep the power flows within the transmission capacity limits and guarantee the reliability of the power market.

In this chapter we present approaches to calculate electric flows in a transmission network when line capacities are given. Under the assumption that the electricity transmission network is operated in high voltage, the electric flows can be approximated by appealing to the direct current power flow theory. If the electric transmission network is radial, the computation can be further simplified.

4.1 Approximation of Electric Power Flows in a Transmission Network

A key characteristic of the electricity transmission network is that, unlike other industries that rely on networks, such as natural gas and telecommunication networks, the power flows in a electricity transmission network cannot be directed. Once the power is injected into the transmission network, the electric currents choose their own paths in the network, based upon the network structure and transmission line capacities. When a link in the transmission network gets overloaded, the power flow on it will not choose other routes unless the overloaded link fails; then the power seeks alternative flow routes. This link failure may cause a chain reaction of transmission link failures, often the cause of large blackouts. This characteristic of the electric power transmission network makes it extremely important to estimate the power flows in the transmission network so that precautions can be taken to avoid disastrous blackouts from link failures. This section presents an approach for estimating power flows in high-voltage electricity transmission networks.

The exchange of electricity in a power system takes place within a certain geographical area, which contains customer loads and power generation sites, each of them is represented by a node, and all the nodes are connected by transmission lines. For each node i, g_i represents the power generated at that node, q_{ij} represents the power supplied by the generators at node i to the customer loads located at node j. The flow on link (i, j) is denoted by f_{ij}, and the flows in the transmission network are represented by the vector of $f \cong \{f_{ij}\}$ of flows. Figure 4.1 illustrates our notation for a simple power system connected by transmission lines.

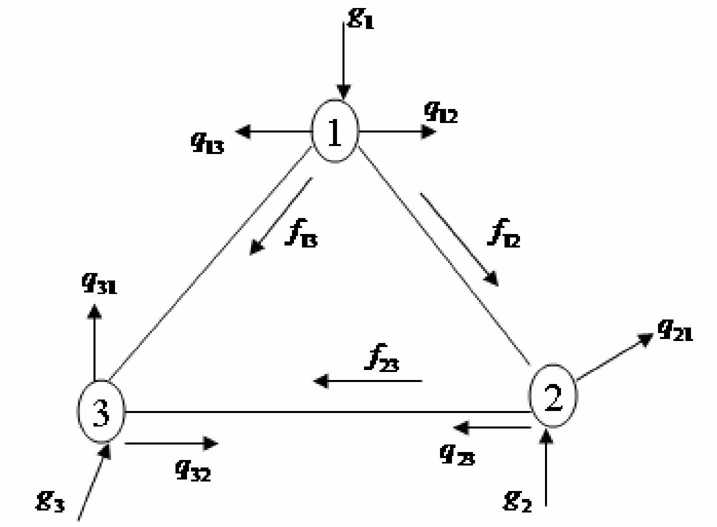

Figure 4.1: A simple electricity transmission system

With given network structure, transmission line parameters, and nodal power injections, the power flows in the transmission network can be determined by using the following equations:

$$f_{ij} = V_i V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) - t_{ij} G_{ij} V_i^2, \ (i, j) \in A \tag{4.1}$$

$$y_i = \sum_{j:(i,j)\in A} f_{ij}, i \in N \tag{4.2}$$

$$G_{ij} = \frac{-r_{ij}}{r_{ij}^{\ 2} + \frac{1}{x_{ij}^{\ 2}}}, \ (i, j) \in A \tag{4.3}$$

$$B_{ij} = \frac{\frac{1}{x_{ij}}}{r_{ij}^{\ 2} + \frac{1}{x_{ij}^{\ 2}}}, \ (i, j) \in A \tag{4.4}$$

where

N is the set of nodes;

A is the set of transmission links in the network;

f_{ij} is the power flow on link *(i, j)*;

y_i is the net injection of power at node *i*, which is the amount of power generated at node *i* minus the amount of power consumed at node *i*;

r_{ij} is the resistance of link *(i, j)*;

x_{ij} is the susceptence of link *(i, j)*;

t_{ij} is the circuit transformer ratio per unit of link *(i, j)*;

V_i is the voltage level at node *i*;

θ_i is the voltage phase at node *i*;

θ_{ij} is the voltage phase difference between nodes *i* and *j* on link *(i, j)*, and it is equal to $\theta_i - \theta_j$;

G_{ij} is the element of the real part of admittance on link *(i, j)*;

B_{ij} is the element of the imaginary part of admittance on link *(i, j)*.

Equations (4.1) and (4.2) are known as Kirchoff's laws; equation (4.1) is the electric voltage law, which states that the power flow on a transmission line are determined by voltage magnitudes and voltage differences of the adjacent nodes; equation (4.2) is the electric current law, which states that the net power injected at a node is the sum of power flows on the links adjacent to that node. Given the net injection of each node in the transmission network, the power flows can be determined by equations (4.1) ~ (4.4).

In a high-voltage transmission network, the following simplifying assumptions can be made to approximate the power flows without large errors being introduced according to Wang and McDonald (1994):

1. The resistance of a high-voltage line is very small compared to the line reactance, so we can set r_{ij} to be zero.
2. Node voltage magnitude V_i may be assumed to be equal to 1.0.
3. Circuit transformer ratio per unit t_{ij} may be assumed to be 1.0.
4. Since the voltage phase difference of a high-voltage line is very small, one may assume that $\cos\theta_{ij} \approx 1$ and $\sin\theta_{ij} \approx \theta_{ij}$.

With those assumptions, the nonlinear alternating current (a.c.) power flow can be represented approximately by linear direct current (d.c.) power flow, and Kirchoff's voltage law becomes

$$f_{ij} = x_{ij}(\theta_i - \theta_j). \tag{4.5}$$

By setting an arbitrary node *i* in the transmission network to be the ground node so that θ_i is zero, using N-1 equations of (4.2) and equation (4.5), we can deduce a Power Transmission Distribution Factors (*PTDF*) matrix so that the power flows in the transmission network can be expressed in the form of

$$f_l = \sum_{i \in N} PTDF_{li} * y_i \tag{4.6}$$

where f_l is the power flow on link *l*, $l \in A$, and $PTDF_{li}$ is the power transmission distribution factor on line *l*, which is the fraction of flow on line *l* contributed by the net power injection at node *i*.

In equation (4.6), the network association of f_l are ordered pairs of adjacent nodes in the transmission network. If the value of f_l is negative, it means that the direction of actual power flow on line l is opposite to the direction of the ordered pair defined in equation (4.6).

The numerical example below illustrates the calculation of the $PTDF$ matrix and its application in obtaining power flows with given nodal power injections.

Numerical Example 4.1

Consider the transmission network in Figure 4.1, let y_i, $i = 1, 2, 3$ be the net nodal power injection at the nodes, with node *3* being the ground node, (therefore $\theta_3 = 0$). The transmission lines are represented by the ordered pairs of nodes: $(1, 2), (1, 3), (2, 3)$. Suppose that the transmission lines have equal susceptence of 1.

By using equations (4.2) and (4.5), we obtain the following system of equations

$$\begin{cases} y_1 = x_{12}(\theta_1 - \theta_2) + x_{13}(\theta_1 - \theta_3) \\ y_2 = x_{12}(\theta_2 - \theta_1) + x_{23}(\theta_2 - \theta_3). \end{cases} \tag{4.7}$$

Since $\theta_3 = 0$, (4.7) can be reduced to

$$\begin{cases} \theta_1 = \dfrac{2}{3} y_1 + \dfrac{1}{3} y_2 \\ \theta_2 = \dfrac{1}{3} y_1 + \dfrac{2}{3} y_2. \end{cases} \tag{4.8}$$

By substituting (4.8) back into equation (4.5), we get

$$\begin{cases} f_{12} = \dfrac{1}{3} y_1 - \dfrac{1}{3} y_2 \\ f_{13} = \dfrac{2}{3} y_1 + \dfrac{1}{3} y_2 \\ f_{23} = \dfrac{1}{3} y_1 + \dfrac{2}{3} y_2. \end{cases} \tag{4.9}$$

Therefore, from (4.9), it can be seen that the *PTDF* matrix associated with the transmission network of Figure 4.1 is

$$PTDF = \begin{pmatrix} \frac{1}{3} & -\frac{1}{3} \\ \frac{2}{3} & \frac{1}{3} \\ \frac{1}{3} & \frac{2}{3} \end{pmatrix}. \tag{4.10}$$

Suppose that node 1 and node 2 are supply nodes that generate 10MW of power each, node 3 is the demand node where 20MW customer loads are located, then by equation (4.6), the power flows are: f_{12} = 0MW, f_{13} = 10MW, f_{23} = 10MW.

The maximum amount of power that is allowed to flow through a transmission line is affected by many factors. For example, the surrounding air temperature and humidity determines when the transmission line will be overheated and start to melt. Despite the environmental factors, the crucial factor that determines the transmission line capacity is the physical characteristic of the transmission line, which is reflected in the value of the line susceptence *x*; the larger the *x* is, the more power flow is allowed in the transmission line before it starts to melt. Thus, a congested transmission line can be strengthened by increasing its susceptence. In reality, a transmission link is sometimes composed by a number of transmission lines. Therefore, instead of replacing a single line with a stronger one, a transmission link can be strengthened by adding extra lines to increase the overall susceptence of the transmission link. Because of the limits in manufacturing standards, only several types of transmission lines are available, so that the susceptence of a transmission link can be only increased in discrete values. Similar to generation capacity expansions of generation firms, it may be assumed that the capacities of the transmission network can be treated as continuous variables when the transmission network carries high volumes of electric flows, a good approximation for an interregional transmission network that connects many power generators and several consumptions markets.

4.2 Computation of Power Flows in a Radial Transmission Network

A common transmission network structure in the power industry is the radial transmission network as shown in Figure 4.2.

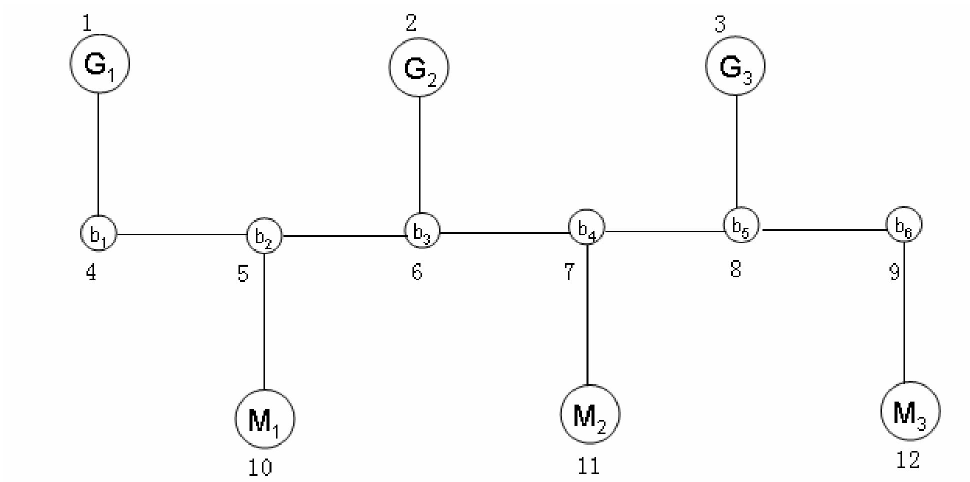

Figure 4.2: A radial transmission network

In Figure 4.2, the generation firms are represented by G_i, and the local power markets are represented by M_j. Each generation firm and local market is connected to a bus, which provides access to a backbone transmission system that transports electricity to different parts of the power market. The nodes in the transmission network include generation firms, local markets, and buses. In Figure 4.2, there are 12 nodes. Such a transmission network is connected and acyclic and can be considered as a tree network with N nodes and $N - 1$ arcs. With one node being the ground node, the numbers of nodes with unknown voltages and arcs in the transmission network are both equal to $N - 1$. Therefore, given the values of nodal power injections, the power flows in the transmission network can be determined by equation (4.2), which is equivalent to

$$y = Mf \tag{4.11}$$

where

y is the vector of power injections of N - 1 nodes;

M is the node-arc adjacency matrix;

f is the vector of power flows in the transmission network.

Then, the power flows can be calculated by

$$f = M^{-1} y. \tag{4.12}$$

Numerical Example 4.2

Consider the spatial power market with the transmission network described in Figure 4.2. By using the data and results of Numerical Example 3.1, the nodal power injections are y_1 = 12.704, y_2 = 13.139, y_3 = 13.352, y_{10} = -14.256, y_{11} = -15.108, y_{12} = -9.831. There are no power generations or consumptions at bus nodes, so that the net power injections at bus nodes are zero.

If we assume that the transmission lines that connect supply and demand nodes to the backbone transmission network have unlimited capacities, the bus node can be deleted from the node-arc adjacency matrix, and by taking M_3 as the ground node, the node-arc adjacency matrix can be simplified to

$$M = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 & 1 \\ -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 \end{bmatrix}. \tag{4.13}$$

Then, using equation (4.12), the power flows in the transmission network can be calculated; the results are shown in Figure 4.3.

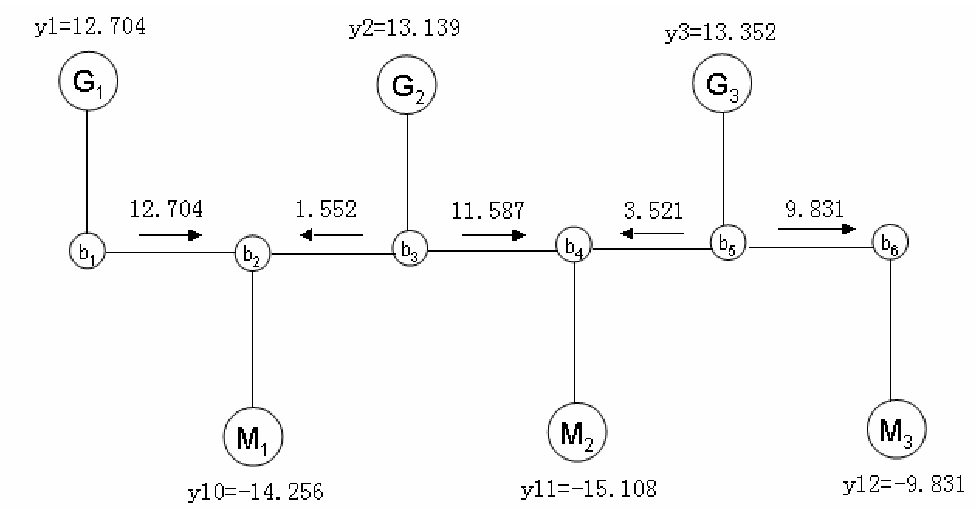

Figure 4.3: Power flows in a transmission network

5 TRANSMISSION NETWORK MANAGEMENT AND A COMBINED MODEL FOR LONG-TERM GENERATION TRANSMISSION PLANNING

5.1 Line Capacities and Congestion Management

In Chapter 3, the competition of deregulated generation firms in a spatial electricity market is modeled and analyzed without considering transmission network congestion in the long-term generation planning. Now consider the case where each link of the transmission network is associated with a capacity value indicating the maximum amount of power flow allowed on it. Figure 5.1 shows a spatial power market with two generation firms and two local power markets. Assume that the transmission links connecting bus 1 and bus 2, bus 2 and bus 3, and bus 3 and bus4 have the capacities of 10, 10, and 15, respectively.

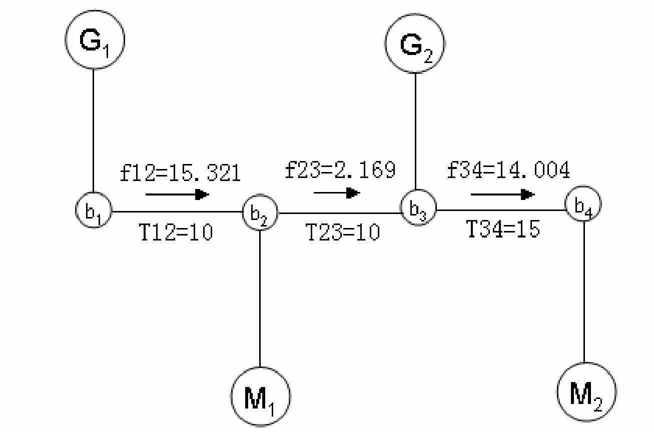

Figure 5.1: A spatial power market with transmission constraints

Suppose generation firms' generation costs and market parameters are given in Table 5.1 and 5.2 respectively, and for simplicity, assume that the generation firms have unlimited available generation capacities.

Table 5.1: Generation firms' generation parameters

	c'	GC_1	GC_2
LOW	0.2g	∞	0
MEDIUM	0.5g	0	∞

Table 5.2: Market parameters

Market j	a_j	b_j
1	40	1.8
2	36	1.5

If transmission capacity limits are not considered, the resulted power flow in the transmission network is 15.321 from b_1 to b_2, 2.169 from b_2 to b_3 and 14.004 from b_3 to b_4. Observe that the power flow in line$\{b_1b_2\}$ exceeds the capacity limit of 10. Therefore, measures must be taken to keep the power flows in the transmission network within capacity limits.

There have been some models for competitive power markets with transmission capacity constraints. They can be classified into two categories. The first approach is that the generation firms are aware of the transmission line capacities in the grid, and capacity constraints of the transmission facilities are explicitly considered in each generation firm's decision-making process. This kind of formulation is known as *equilibrium model with coupled constraints*. Wei and Smeers (1999) modeled generation firms' competition in a spatial power market by including the transmission constraints in each generation firm's optimization problem and solved it using the variational inequality approach. Although they proved that a variational inequality solution exists and is unique, there actually exist multiple Nash-Cournot equilibria, so that it is hard to determine which equilibrium the generation firms will reach.

Another modeling approach assumes that there is an Independent System Operator (ISO) that is responsible for keeping the power flows within transmission capacity limits. If it is found that the generation firms will supply electricity to the power market in a way that the transmission constraints are violated, the ISO will increase transmission fees to the generation firms in order to curtail the power flows in the overloaded transmission links. This kind of formulation is equivalent to a *mathematical program with equilibrium constraints* because generation firms' decisions on power supply depend on the transmission prices the ISO sets. In doing this, the KKT conditions of each generation firm's optimization problem are embedded in the ISO's decision making problem. Mathematical programs with equilibrium constraints are known to be highly nonconvex and multiple equilibria may exist.

In addition to computational difficulties, possible market power in scarce transmission resources is another concern in the spatial power market constrained by transmission capacities. First, suppose that the generation firms explicitly consider transmission capacities, and the ownerships of transmission resources are in the hands of generation firms. It is likely that a generation firm that owns the transmission facilities will under-invest in new transmission capacities or even reduce the transmission capacities in order to limit the competition from other generation firms. An example is presented below to illustrate a generation firm's incentive to reserve transmission capacities.

Numerical Example 5.1

Consider the spatial power market described in Figure 5.1, Table 5.1 and Table 5.2. Suppose that Generation Firm 2 owns the transmission facilities of the power system. Since the transmission link connecting Bus 1 and Bus 2 has capacity of 10, Generation Firm 1 cannot generate more than 10 units of power. By embedding this new constraint to the optimization problem of Firm 1, the Nash-Cournot equilibrium can be solved using the method described in Chapter 3. It can be seen that when $T_{12} = 10$, Generation Firm 2 supplies 6.71 and 7.163 units of power to Market 1 and Market 2, and its profit is 206.102. If we assume that Generation Firm 2 adds 1 unit transmission capacity to line$\{b_1 b_2\}$, then it supplies 5.404 units of power to Market 1 and 5.596 units of power to Market 2, and its profit decreases to 184.034. The profit of Generation Firm 2 corresponding to different transmission capacity values for line$\{b_1 b_2\}$ is plotted in Figure 5.2, which indicates that the more transmission capacity added to line$\{b_1 b_2\}$, the less profit Generation Firm 2 makes. Therefore, Firm 2 will not have any incentive to expand the transmission capacity of that line, and it can even reduce its transmission capacity by putting it on more maintenance than required.

If we allow the transmission owner to charge service fees for power flows that use its transmission facilities to encourage investments in transmission capacities, it may be still difficult to avoid the transmission owner’s desire to under-invest.

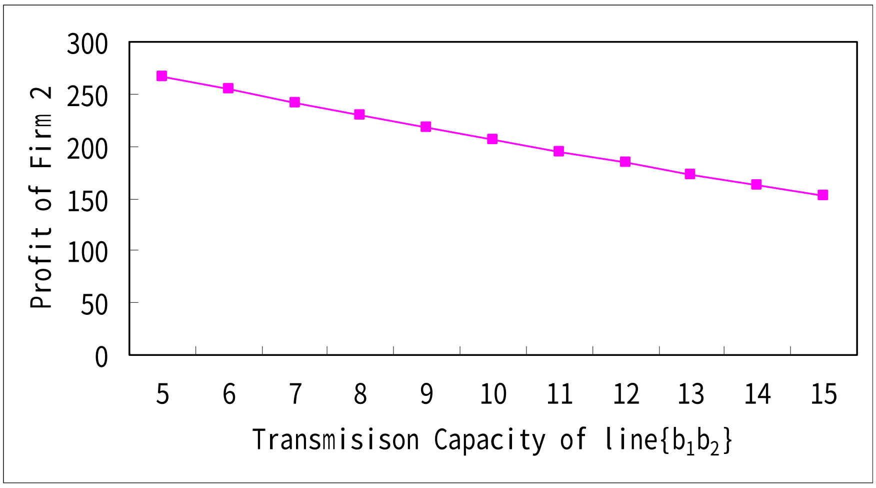

Figure 5.2: Generation Firm 2's profit with different transmission capacity of line{b_1b_2}

Numerical Example 5.2

Consider the spatial power market described in Numerical Example 5.1. Suppose that the owner of the transmission line that connects Bus 1 and Bus 2 has the right to charge fees for providing transmission service. Table 5.3 shows the power flow in line{b_1b_2} and the revenue of the transmission line owner corresponding to different transmission fees.

From Table 5.3, note that the owner of line{b_1b_2} makes the most revenue if the power flow in that line is between 6.129 and 8.775 units, so that the transmission line owner will not expand the transmission capacity beyond 8.775 units. If the transmission capacity of line{b_1b_2} is already 10 units, the owner of Line{b_1b_2} will not invest in new transmission capacities.

Table 5.3: Transmission line owner's profit vs. power flow in a congested line

Transmission fee on Line{b_1b_2}	Power flow	Transmission line owner's profit
4	12.695	50.78
6	11.382	68.292
8	10.069	80.552
10	8.755	87.55
12	7.442	89.304
14	6.129	85.806
16	4.816	77.056
18	3.503	63.054
20	2.189	43.78

To summarize, the main issues in modeling the competitive power market with transmission capacity constraints are (1) multiple equilibria and (2) market power of transmission resources. If there are multiple equilibria, it is hard to predict the decisions of the market participants. Furthermore, since scarce transmission resources are crucial in the operations of the power market, it is dangerous to grant the control of transmission facilities to any one party that may exercise market power to gain extra profits. Thus, it seems that the transmission sector should be regulated in a power market where generation is unregulated.

5.1.1 Transmission Regulation and a Combined Power System Planning Model

In this dissertation, the modeling of long-term power market operations with transmission constraints needs the consideration of two submarkets, namely, the electricity transmission market and the power generation market. In the electricity transmission market, a transmission operator or an ISO is responsible for levying transmission access fees to the generation firms to adjust their power supplies into order to keep the power flows in the transmission network within capacity limits. The transmission operator or ISO can also expand the transmission network if necessary. If it is assumed that the ISO's objective is to maximize the revenue from collecting the transmission fees, the ISO's decision problem is formulated as

maximize

$$\sum_{i\in I}\sum_{j\in J} h_{ij} q_{ij} - \sum_{l\in L} n_l(m_l) \tag{5.1}$$

subject to

$$T_l + m_l \geq \sum_{i\in I} PTDF_{li}(\sum_{j\in J} q_{ij}) - \sum_{j\in J} PTDF_{li}(\sum_{i\in I} q_{ij}),\ \forall l \in L \tag{5.2}$$

$$-T_l - m_l \leq \sum_{i\in I} PTDF_{li}(\sum_{j\in J} q_{ij}) - \sum_{j\in J} PTDF_{li}(\sum_{i\in I} q_{ij}),\ \forall l \in L \tag{5.3}$$

$m_l \geq 0,\ \forall l \in L,\ h_{ij}$ free, $\forall i,\ \forall j$

where

h_{ij} is the transmission price for Generation Firm *i*'s sale to Market *j*;

m_l is the variable that represents the amount of new transmission capacity the ISO adds to line *l*, $l \in L$;

T_j is the original transmission capacity of line *l*;

$n_c(.)$ is the cost function of transmission capacity expansion for line *l*.

In the above formulation, (5.2) and (5.3) are transmission line capacity constraints. The constraints state that for a given transmission line $l \in L$, with the new capacity added, the power flow on the line cannot exceed its capacity in either direction.

The long-term competition of generation firms is formulated by embedding the transmission prices in the Nash-Cournot model described in Chapter 3. Then, the formulation of a generation firm f can be written as

maximize

$$\sum_{j \in J} [(a_j - b_j \sum_{i \in I} q_{ij}) - h_{fj}] q_{fj} - \sum_{k \in K} c_k(g_{fk}) - \sum_{k \in K} f_k(x_{fk}) \tag{5.4}$$

subject to

$$g_{fk} \leq GC_{fk} + x_{fk}, \ \forall k \tag{5.5}$$

$$\sum_{j \in J} q_{fj} = \sum_{k \in K} g_{fk} \tag{5.6}$$

$$g_{fk},\ q_{fj},\ x_{fk} \geq 0.$$

In the generation firms' long-term planning problem, if we assume that the generation cost functions and generation capacity expansion cost functions are convex, monotonically increasing, and possess continuous first-order derivatives, then by using Theorems 3.1 and 3.2, it is easy to show that there exists a unique equilibrium when transmission fees are imposed. Then, for any decision made by the ISO, the decisions of the generation firms in power supply are predictable.

It is also true that if the ISO imposes a positive transmission fee on a generation firm for selling power to a local power market, the generation firm will reduce power supply to that market accordingly. Therefore, if some transmission links in the network are predicted to get congested, the overloads can be eliminated through transmission fees. In Numerical Example 5.1, the transmission link between Bus 1 and Bus 2 will be overloaded to 15.321 units of power flow if the generation firms pay no transmission fees. From Numerical Example 5.2, it can be seen that if Generation Firm 1 is charged an appropriate transmission fee for supplying electricity to both Market 1 and Market 2, the power flow in line$\{b_1b_2\}$ can be kept within the capacity limit of 10 units.

Now, the remaining issue is how to eliminate the market power of the ISO and generation firms in the transmission sector of the power market. Under the assumption that an ISO has the right to set transmission prices and determine transmission capacity expansions, then according to Numerical Example 5.2, it has the incentive to mark up transmission prices and under-invest in new transmission capacities. The generation firms also possess potential market power in this situation, because they can make decisions on power generation and supply strategically to affect the decisions of the ISO and other generation firms.

In the model of a short-term spatial power market by Smeers and Wei (1997), the idea of opportunity cost pricing for limited transmission resources was proposed. The model assumes that the ISO will not exercise market power in determining transmission fees; the transmission fees are charged based upon the willingness of the generation firms to pay in order to reserve the transmission service they need. This dissertation expands the opportunity cost pricing model to long-term planning of a competitive power market with transmission capacity constraints. Here we have made two assumptions. Firstly, the ISO is regulated and it will not exercise market power to maximize its profit in the transmission market. Therefore, the ISO may charge transmission fees and add new transmission capacities in order to support the competition in the generation sector of the power market while keeping the power flows in the transmission network within capacity limits. The second assumption is that the generation firms are price-takers of transmission fees; they treat transmission fees as constants in their decision-making processes, and therefore they will not behave strategically to force the ISO to change its decisions in transmission pricing and capacity expansions.

Accordingly, the long-term planning problem of ISO can be reformulated as

maximize

$$\sum_{i \in I} \sum_{j \in J} h_{ij} y_{ij} - \sum_{l \in L} n_l(m_l) \tag{5.7}$$

subject to

$$T_l + m_l \geq \sum_{i \in I} PTDF_{li} (\sum_{j \in J} y_{ij}) - \sum_{j \in J} PTDF_{lj} (\sum_{i \in I} y_{ij}), \ \forall l \in L \tag{5.8}$$

$$-T_l - m_l \leq \sum_{i \in I} PTDF_{li} (\sum_{j \in J} y_{ij}) - \sum_{j \in J} PTDF_{lj} (\sum_{i \in I} y_{ij}), \ \forall l \in L \tag{5.9}$$

$$m_l \geq 0, \ \forall l \in L, \ y_{ij} \text{ free}, \ \forall i, \ \forall j.$$

In the modified formulation, the transmission prices h_{ij} are treated as constants instead of variables, this eliminates the market power of the ISO to set the transmission prices arbitrarily. In the model for generation firms, the transmission prices are also treated as constants, based on which the generation firms determine the amount of new generation capacities to maximize their profits. The generation firms will not act strategically to affect transmission prices.

The problem with this formulation is that transmission prices are still unknown, while in the long-term planning model of both the ISO and generation firms, transmission prices are assumed known constants. Therefore, we need a transmission market clearing condition to integrate the long-term planning problems of the ISO and generation firms. The market clearing condition may be written as

$$y_{ij} = q_{ij},\ \forall i,\ \forall j. \tag{5.10}$$

Equation (5.10) states that the amount of transmission service the ISO provides is equal to the generation firms' demand for transmission service, which guarantees that the electricity transmission market is cleared. Since the ISO cannot set the transmission service prices arbitrarily, it allocates the transmission resources to the generation firms based on their willingness to pay for transmission services. With (5.10), the combined generation-transmission planning model presented above satisfies the assumption that the ISO determines transmission prices and new transmission capacity investments to support competition in the generation sector of the power market.

5.1.2 Solution Strategy and Numerical Example

The combined power system planning model can be solved by deriving the KKT conditions of the ISO's long-term planning problem and the generation firms' long-term planning problems. The KKT conditions of the a generation firm *f* are given as

$$\begin{aligned} & g_{fk} \geq 0, \forall k \\ & c_k^{'}(g_{fk}) + u_{fk} - uf \geq 0, \forall k \\ & g_{fk}[c_k^{'}(g_{fk}) + u_{fk} - uf] = 0 \end{aligned} \tag{5.11}$$

$$q_{fj} \geq 0, \forall j$$

$$-a_j - b_j(q_{fj} + \sum_{i \in I} q_{ij}) + h_{fj} + u_f \geq 0 \tag{5.12}$$

$$q_{fj}[-a_j + b_j(q_{fj} + \sum_{i \in I} q_{ij}) + h_{fj} + u_f] = 0$$

$$x_{fk} \geq 0, \forall k$$

$$f_k^{'}(x_{fk}) - u_{fk} \geq 0, \ \forall k \tag{5.13}$$

$$x_{fk}[f_k^{'}(x_{fk}) - u_{fk}] = 0$$

$$u_{fk} \geq 0, \ \forall k$$

$$g_{fk} \leq Gc_{fk} + x_{fk}, \ \forall k \tag{5.14}$$

$$u_{fk}(g_{fk} - Gc_{fk} - x_{fk}) = 0$$

$$u_f \text{ free}$$

$$\sum_{j \in J} q_{fj} = \sum_{k \in K} g_{fk}. \tag{5.15}$$

The KKT conditions of the ISO are

$$y_{ij} \text{ free}, \forall i, \forall j \tag{5.16}$$

$$-hij + \sum_{l \in L} V\_Positive_l(PTDFli - PTDFlj) - \sum_{l \in L} V\_Negative_l(PTDFli - PTDFlj) = 0$$

$$m_l \geq 0, \ \forall \text{l}$$

$$n_l^{'}(m_l) - V\_Positive_l - V\_Negative_l \geq 0 \tag{5.17}$$

$$m_l[n_l^{'}(m_l) - V\_Positive_l - V\_Negative_l] = 0$$

$$V\_Positive_l \geq 0, \forall l$$

$$T_l + m_l \geq \sum_{i \in I} PTDF_{li} (\sum_{j \in J} y_{ij}) - \sum_{j \in J} PTDF_{lj} (\sum_{i \in I} y_{ij}) \quad (5.18)$$

$$V\_Positive_l [T_l + m_l - \sum_{i \in I} PTDF_{li} (\sum_{j \in J} y_{ij}) + \sum_{j \in J} PTDF_{lj} (\sum_{i \in I} y_{ij})] = 0$$

$$V\_Negative_l \geq 0, \forall l$$

$$\sum_{i \in I} PTDF_{li} (\sum_{j \in J} y_{ij}) - \sum_{j \in J} PTDF_{lj} (\sum_{i \in I} y_{ij}) \geq -T_l - m_l \quad (5.19)$$

$$V\_Negative_l [\sum_{i \in I} PTDF_{li} (\sum_{j \in J} y_{ij}) - \sum_{j \in J} PTDF_{lj} (\sum_{i \in I} y_{ij}) + T_l + m_l] = 0.$$

In the KKT conditions of the ISO, *V_Positive* and *V_Negative* are the dual variables associated with constraints (5.8) and (5.9) respectively. It can be seen that if equilibrium exists in the combined power system planning model, it must satisfy the KKT conditions in (5.11) ~ (5.19) simultaneously. If we assume that the marginal cost functions of generation firms and ISO are linear, the system of equations defined in (5.11) ~ (5.19) is a linear mixed complementarity problem (MCP), but there are more variables than equations because the transmission prices h_{ij} are unknown although the generation firms and ISO treat them as constants. If we include equation (5.10) in the linear MCP, there will be equal number of variables and equations, and it ensures that the amount of transmission service the ISO provides is equal to the demand of generation firms for transmission service. The PATH solver can be used to solve the linear complementarily problem defined in (5.10) ~ (5.19).

Numerical Example 5.3

Recall the spatial power market defined in Numerical Example 3.1, if no transmission fees are charged, each generation firm's power supply and the resulted power flows in the transmission network are shown in Figure 5.3, and generation firms' capacity expansions are shown in Table 5.4.

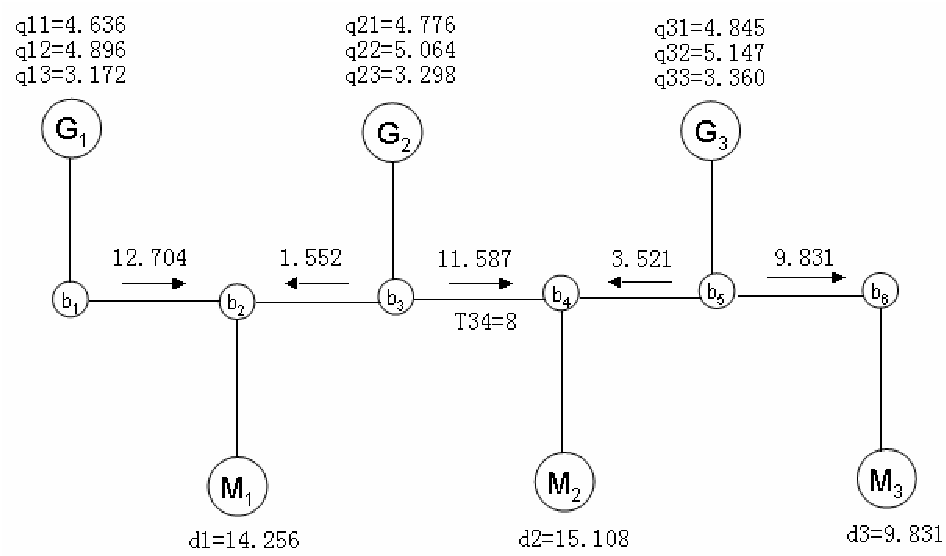

Figure 5.3: Power flows with no transmission constraints

Table 5.4: Generation capacity expansions with no transmission constraints

	LOW	MEDIUM	HIGH
Firm 1	0.972	3.989	3.743
Firm 2	3.711	0	3.428
Firm 3	3.092	3.237	0

Now suppose that the transmission line between b_3 and b_4 has the capacity of 8. Then, according to the assumptions in this dissertation, an ISO will keep the power flow in this transmission line within the capacity limit by charging transmission fees and add new transmission capacities. If we formulate the problem under the assumption that the generation firms and ISO will not wield market power in the transmission sector, and the marginal construction cost of the congested line is constant at 1.5, the combined power system planning problem can be solved as a linear MCP. Its solution determines that the ISO adds 1.541 units of capacity to the congested line. The other results of the long-term power market are given in Tables 5.5 ~ 5.7 and Figure 5.4.

Table 5.5: Transmission service prices per unit of power

	Market 1	Market 2	Market 3
Firm 1	0	1.5	1.5
Firm 2	0	1.5	1.5
Firm 3	-1.5	0	0

Table 5.6: Generation capacity expansions with transmission constraints

	LOW	MEDIUM	HIGH
Firm 1	0.405	3.762	3.601
Firm 2	3.002	0	3.25
Firm 3	3.82	3.528	0

Table 5.7: Power supplied to markets and produced with different technologies with new generation and transmission capacities

	Market 1	Market 2	Market 3	LOW	MEDIUM	HIGH
Firm 1	4.475	4.454	2.84	4.405	3.762	3.601
Firm 2	4.631	4.641	2.981	3.002	6	3.25
Firm 3	5.373	5.532	3.649	3.82	3.528	7.205

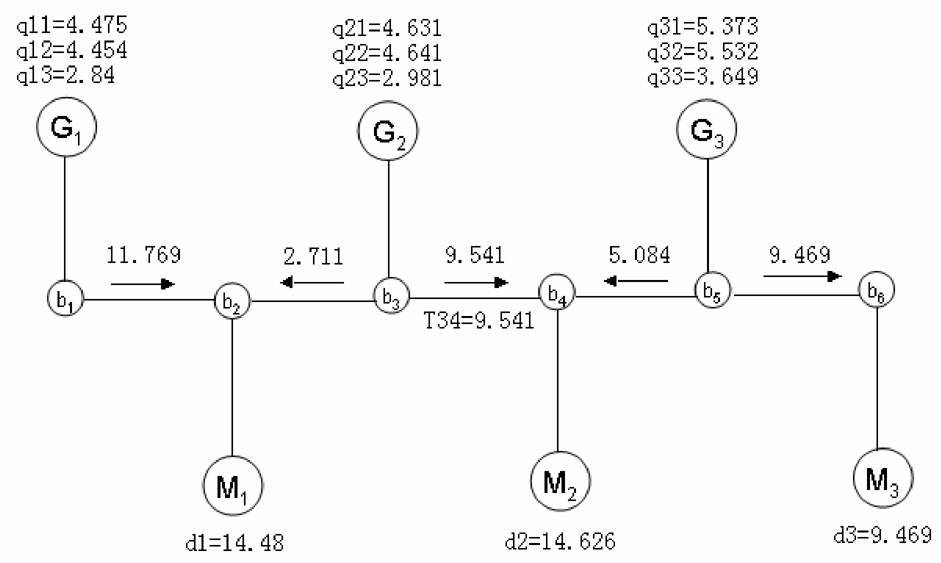

Figure 5.4: Power flows resulted in the combined power system planning model

With the extra capacity of 1.541 units, the capacity of line$\{b_3b_4\}$becomes 9.541 units. From Figure 5.3, it can be seen that the power flow on line$\{b_3b_4\}$ is 11.587 units if no transmission fee is imposed. Since the direction of power flow in that line is from b_3 to b_4, Generation Firm 1 and Generation Firm 2 are charged positive transmission fees for the power supplied to Market 2 and Market 3, while Generation Firm 3 is charged a negative transmission fee to sell power to Market 1. This is because if Generation Firm 3 supplies more power to Market 1, the extra power flow from b_4 to b_3 helps alleviate the congestion on line$\{b_3b_4\}$. It can be also seen from Numerical Example 5.3 that due to the congestion in line$\{b_3b_4\}$ and the associated transmission fees, Generation Firm 1 and Generation Firm 2 add less generation capacities than in the case that the transmission network has no capacity limits, while Generation Firm 3 adds more generation capacity because its market share increases since now Generation Firm 1 and Generation Firm 2 have to supply less electricity to the power market.

5.1.3 Alternative Formulation for Combined Power System Planning

The combined long-term power system planning model described above eliminates the possibility that the ISO or generation firms can exercise market power in the transmission sector. Thus, it is a useful tool for market regulators to judge whether there exists any market power in the transmission sector. Recall that in Chapter 3, an equivalent quadratic program can be used to formulate the competition of generation firms in a spatial power market without transmission constraints. Now, with the transmission fees included, the quadratic formulation of generation firms' competition is given as

maximize

$$\sum_{j\in J}[a_j\sum_{i\in I}q_{ij}-0.5b_j(\sum_{i\in I}q_{ij})^2-0.5b_j\sum_{i\in I}q_{ij}^2]-\sum_{i\in I}\sum_{j\in J}h_{ij}q_{ij}-\sum_{i\in I}\sum_{k\in K}c_k(g_{ik})-\sum_{i\in I}\sum_{k\in K}f_k(x_{ik}) \quad (5.20)$$

subject to

$$g_{ik}\le GC_{ik}+x_{ik},\ \forall i,\ \forall k \quad (5.21)$$

$$\sum_{j\in J}q_{ij}=\sum_{k\in K}g_{ik},\ \forall i \quad (5.22)$$

g_{ik}, q_{ij} nonnegative.

According to the transmission market clearing condition of (5.10), the transmission capacity constraints of (5.8) and (5.9) can be included in the above quadratic formulation as

$$T_l\ge\sum_{i\in I}PTDF_{li}(\sum_{j\in J}q_{ij})-\sum_{j\in J}PTDF_{lj}(\sum_{i\in I}q_{ij}),\ \forall l\in L \quad (5.23)$$

$$-T_l \le \sum_{i\in I} PTDF_{li}(\sum_{j\in J} q_{ij}) - \sum_{j\in J} PTDF_{lj}(\sum_{i\in I} q_{ij}),\ \forall l \in L. \tag{5.24}$$

Since the transmission prices h_{ij} are unknown to the generation firms and ISO, and it is assumed that no party sets h_{ij} to gain market power, the term $\sum_{i\in I}\sum_{j\in J} h_{ij}q_{ij}$ can be removed from the objective function of (5.20), and the transmission pricing model without transmission capacity expansion is equivalent to the quadratic program with modified objective function (5.20) (without the term $\sum_{i\in I}\sum_{j\in J} h_{ij}q_{ij}$) and the constraints of (5.21) to (5.24). The implication of this quadratic program is that the ISO sets transmission fees only to keep the power flows within transmission network capacities; if the transmission network is not congested, then there will be no transmission fees charged.

Then, the combined power system planning model formulated in (5.1) ~ (5.3), (5.4) ~ (5.6), and (5.10) is equivalent to the following quadratic program,

maximize

$$\sum_{j\in J}[a_j \sum_{j\in J} q_{ij} - 0.5b_j(\sum_{i\in I} q_{ij})^2 - 0.5b_j \sum_{i\in I} q_{ij}^2] - \sum_{i\in I}\sum_{k\in K} c_k g_{ik} - \sum_{i\in I}\sum_{k\in K} f_k(x_{ik}) - \sum_{l\in L} n_l(m_l) \tag{5.25}$$

subject to

$$g_{ik} \le Gc_{ik} + x_{ik},\ \forall i,\ \forall k \tag{5.26}$$

$$\sum_{i\in I} q_{ij} = \sum_{k\in K} g_{ik},\ \forall i \tag{5.27}$$

$$T_l + m_l \ge \sum_{i\in I} PTDF_{li}(\sum_{j\in J} y_{ij}) - \sum_{j\in J} PTDF_{lj}(\sum_{i\in I} y_{ij}),\ \forall l \tag{5.28}$$

$$\sum_{i\in I} PTDF_{li}(\sum_{j\in J} y_{ij}) - \sum_{j\in J} PTDF_{lj}(\sum_{i\in I} y_{ij}) \geq -T_l - m_l,\ \forall l \quad (5.29)$$

$$q_{ij} = y_{ij},\ \forall i,\ \forall j \quad (5.30)$$

q_{ij}, g_{ik}, x_{ik}, m_l nonnegative.

The above formulation has the same KKT conditions as the combined power system planning model. It should be noted that the dual variables associated with equation (5.30) are transmission prices h_{ij}, which can be interpreted as the price a generation firm has to pay that reflects the value of limited transmission resource that is available for Generation Firm *i* to sell power to Market *j*. Another implication of the quadratic formulation is that the ISO will invest an amount for new transmission capacities to maximize an objective function that reflects the system benefit of the power market where generation firms compete in the generation sector. In Numerical Example 5.3, if the transmission line expansion cost is assumed to be zero, the ISO will add 3.587 units of transmission capacity to the congested line, and no congestions will occur in the transmission network. The new capacity added to line{b_3b_4} corresponding to different marginal cost is plotted in Figure 5.5.

The ISO's profit corresponding to different capacities added to line{b_3b_4} is plotted in Figure 5.6. From Figure 5.6, it can be seen that the ISO will not under-invest in the congested line for profit because its profit is zero when the cost is zero for the new transmission capacity.

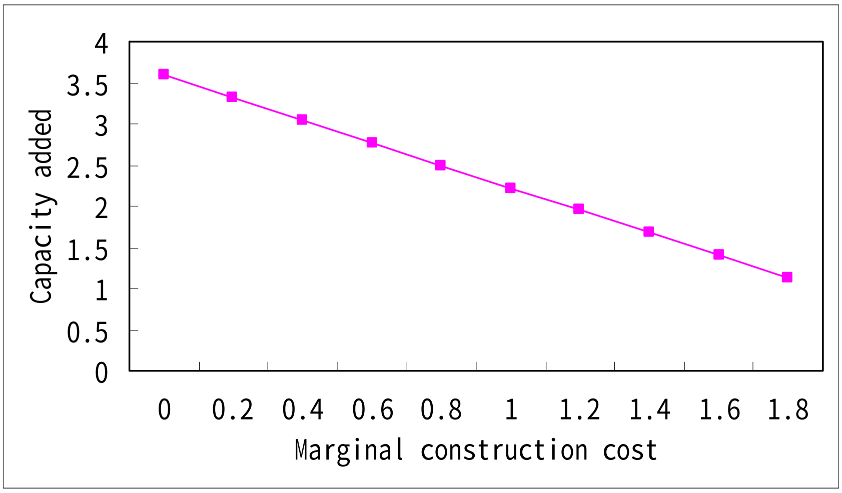

Figure 5.5: Transmission capacity added to line{b_3b_4} corresponding to different marginal cost of transmission expansion

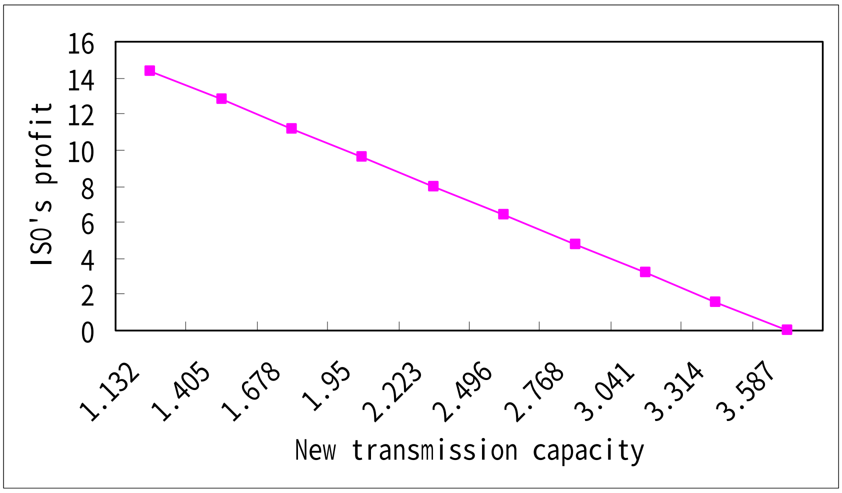

Figure 5.6: ISO's profit corresponding to different capacities added to line{b_3b_4}

5.2 Combined Generation Transmission Planning Model with Future Uncertainties

5.2.1 Formulation and Numerical Solution

Like in Chapter 3, future uncertainties also exist in the combined planning process of the generation and transmission sectors. As before, it is assumed that the only uncertain factor in future power market is the demand for electricity and there is a finite set of future scenarios.

Let $(g_{ik}^s, q_{ij}^s, x_{ik})$ and (y_{ij}^s, m_l) denote the decision variables of generation firms and ISO respectively, and let h_{ij}^s be the transmission prices in scenario *s*, the combined model of the long-term generation-transmission planning under future uncertainties is formulated as

maximize

$$\sum_{s\in S} w^s \{\sum_{j\in J}[(a_j^s - b_j^s \sum_{i\in I} q_{ij}^s) - h_{fj}^s] q_{fj}^s - \sum_{k\in K} c_k(g_{fk}^s)\} - \sum_{k\in K} f_k(x_{fk}) \tag{5.31}$$

subject to

$$g_{fk}^s \le Gc_{fk} + x_{fk},\ \forall k,\ \forall s \tag{5.32}$$

$$\sum_{j\in J} q_{fj}^s = \sum_{k\in K} g_{fk}^s,\ \forall s \tag{5.33}$$

$g_{fk}^s,\ q_{fj}^s,\ x_{fk}$ *nonnegative*;

maximize

$$\sum_{s\in S} w^s [\sum_{i\in I}\sum_{j\in J} h_{ij}^s y_{ij}^s] - \sum_{l\in L} n_l(m_l) \tag{5.34}$$

subject to

$$T_l + m_l \geq \sum_{i \in I} PTDF_{li}(\sum_{j \in J} y_{ij}^s) - \sum_{j \in J} PTDF_{lj}(\sum_{i \in I} y_{ij}^s),\ \forall l,\ \forall s \tag{5.35}$$

$$\sum_{i \in I} PTDF_{li}(\sum_{j \in J} y_{ij}^s) - \sum_{j \in J} PTDF_{lj}(\sum_{i \in I} y_{ij}^s) \geq -T_l - m_l,\ \forall l,\ \forall s \tag{5.36}$$

$$m_l \geq 0.$$

The transmission market clearing condition is

$$y_{ij}^s = q_{ij}^s. \tag{5.37}$$

The problem can be solved by reformulating it as a linear MCP if the cost functions $c_k(g_{fk}^s),\ f_k(x_k)$ and $n_l(m_l)$ have linear marginal cost functions.

Numerical Example 5.4

Use the parameters in Numerical Example 5.3, and suppose that the future market is uncertain with two possible scenarios, UP and DOWN, each with probability of 0.5, and the market parameters as shown in Table 5.8.

Table 5.8: Market parameters

Market j	a_j^{UP}	a_j^{DOWN}	b_j
1	50	30	1.8
2	45	25	1.5
3	40	20	2

Similar to Numerical Example 5.3, assume that the transmission line between b_3 and b_4 has the capacity of 8 and its marginal expansion cost is constant at 1.5. Then, the combined power system planning problem can be solved as a linear MCP. The ISO adds

1.269 units of transmission capacity to line{b_3b_4}. Table 5.9 and Table 5.10 list the transmission prices in the two future scenarios.

Table 5.9: Transmission service prices per unit of power in UP scenario

	Market 1	Market 2	Market 3
Firm 1	0	3	3
Firm 2	0	3	3
Firm 3	-3	0	0

Table 5.10: Transmission service prices per unit of power in DOWN scenario

	Market 1	Market 2	Market 3
Firm 1	0	0	0
Firm 2	0	0	0
Firm 3	0	0	0

The generation firms' decisions in capacity expansion and power supply in two future market scenarios are given in Table 5.11 to Table 5.13.

Table 5.11: Generation capacity expansions

	LOW	MEDIUM	HIGH
Firm 1	0.224	3.75	4.844
Firm 2	3.417	0	4.237
Firm 3	4.227	3.754	0

Table 5.12: Power supplied to markets and produced with different technologies in UP scenario

	Market 1	Market 2	Market 3	LOW	MEDIUM	HIGH
Firm 1	5.089	4.774	2.955	4.224	3.75	4.844
Firm 2	5.359	5.097	3.198	3.417	6	4.237
Firm 3	6.755	6.772	4.454	4.227	3.754	10

Table 5.13: Power supplied to markets and produced with different technologies in DOWN scenario

	Market 1	Market 2	Market 3	LOW	MEDIUM	HIGH
Firm 1	3.937	3.891	2.293	4.224	3.629	2.268
Firm 2	3.847	3.783	2.212	3.417	3.954	2.471
Firm 3	3.937	3.892	2.294	4.227	3.628	2.267

5.2.2 Effects of Uncertainties on Decisions of Generation Firms and ISO

We have shown in Chapter 3 that the generation firms supply more power if the market demand increases under the assumption that the transmission network never gets congested. In this chapter, possible congestion in the transmission network is included in the formulation of generation firms' long-term competition in the power market. It can be proven that even if the transmission network is constrained with capacity limits, the generation firms' desire to generate more power in the case that there is more demand for electricity will not be dampened by limited transmission resources.

Proposition 5.1: For two distinct market scenarios represented by UP and DOWN, if it is assumed that each local market has more demand in the UP scenario than in the DOWN scenario, each generation firm in the power market will supply no less electricity in the UP scenario than in the DOWN scenario even if the transmission network is constrained by capacity limits.

Proof: The claim is that $\sum_{k\in K} g_{ik}^{D} \le \sum_{k\in K} g_{ik}^{U},\ \forall i \in I$, where D and U represent UP and DOWN scenarios respectively and it is assumed that $a_j^U > a_j^D,\ \forall j \in J$. If we suppose that there exists a set $I^M \subseteq I$ such that $\sum_{k\in K} g_{ik}^{D} > \sum_{k\in K} g_{ik}^{U},\ \forall i \in I^M$, then for $i \in I^M$, there exists $k \in K$ thus that $g_{ik}^D > g_{ik}^U$. From the KKT conditions associated with the combined generation-transmission planning model, we have

$$c_k^{'}(g_{ik}^s) + u_{ik}^s - u_i^s \ge 0,\ \forall s \in S,\ i \in I \tag{5.38}$$

and

$$-a_j^s + b_j(q_{ij}^s + \sum_{i\in I} q_{ij}^s) + u_i^s + h_{ij}^s \ge 0,\ \forall s \in S,\ i \in I,\ j \in J \tag{5.39}$$

where u_{ik}^s *and* u_i^s are dual variables associated with constraints (5.32) and (5.33) respectively. From (5.38), it can be seen that if there exists $k \in K$ such that $g_{ik}^D > g_{ik}^U$, then $u_i^D > u_i^U$. If we apply this to (5.39), it can be shown that if $q_{ij}^D > q_{ij}^U$ and $u_i^D > u_i^U$, it must be true that

$$-a_j^U + b_j \sum_{i\in I} q_{ij}^U + h_{ij}^U > -a_j^D + b_j \sum_{i\in I} q_{ij}^D + h_{ij}^D. \tag{5.40}$$

It can be deduced from the proof of Proposition 3.1 that if $\sum_{i\in I} q_{ij}^D < \sum_{i\in I} q_{ij}^U$ and (5.40) is true, then it is impossible to have any $i \in I$ such that $\sum_{k\in K} g_{ik}^{D} > \sum_{k\in K} g_{ik}^{U}$. Therefore in (5.39), we need to assume that $\sum_{i\in I} q_{ij}^D \ge \sum_{i\in I} q_{ij}^U$.

Then, because $a_j^D < a_j^U$ and $q_{ij}^D > q_{ij}^U$, we have

$$h_{ij}^U - h_{ij}^D > (a_j^U - b_j \sum_{i\in I} q_{ij}^U - b_j q_{ij}^U) - (a_j^D - b_j \sum_{i\in I} q_{ij}^D - b_j q_{ij}^D), \tag{5.41}$$

where $a_j^s - b_j \sum_{i\in I} q_{ij}^s - b_j q_{ij}^s,\ s = \{U, D\}$ is the marginal revenue of generation firm *i* selling power to market *j*.

We argue that at the optimality of the UP and DOWN scenarios, the difference of transmission price of generation firm *i* supplying power to market *j* in these two scenarios cannot exceed the difference of the corresponding marginal revenue, because this contradicts with the assumption that the transmission fees are charged based on generation firms' willingness to pay. Therefore, the supposition that $\sum_{i\in I} q_{ij}^D \geq \sum_{i\in I} q_{ij}^U$ is incorrect.

The above results contradict the supposition that there exist $i \in I_M \subseteq I$ with $\sum_k g_{ik}^D > \sum_k g_{ik}^U$. Therefore, $\sum_k g_{ik}^D \leq \sum_k g_{ik}^U,\ \forall i \in I$. □

Proposition 5.1 is important to understand the behaviors of competitive generation firms in a spatial power market with transmission capacity constraints. It states that if there is more demand for electricity in the power market, a generation firm will increase its power supply or maintain its current amount of power supply even if the transmission network is congested. The above discussion provides an explanation why generation firms will continue competing in a power market constrained by transmission capacity limits. As an example, suppose that in the power market defined in Numerical Example

5.3, the market parameters a_j increase to $a_1 = 50,\ a_2 = 46,\ a_3 = 42,$ the generation firms' decisions in capacity expansion and power supply are given in Tables 5.14 and 5.15.

Table 5.14: Generation capacity expansions with increased market demands

	LOW	MEDIUM	HIGH
Firm 1	2.917	4.767	4.229
Firm 2	6.143	0	4.036
Firm 3	6.332	4.533	0

Table 5.15: Power supplied to markets and produced with different technologies with increased market demands

	Market 1	Market 2	Market 3	LOW	MEDIUM	HIGH
Firm 1	5.812	6.057	4.043	6.917	4.767	4.229
Firm 2	5.898	6.161	4.120	6.143	6.000	4.036
Firm 3	6.710	7.135	4.852	6.332	4.533	7.833

Compared to the results of Numerical Example 5.3, the generation firms in this example supply more power to the power market although line{b_3b_4} is congested.

Following the same procedures as in Section 3.5, we can deduce how generation firms respond to different estimations of future scenarios in an uncertain planning environment.

Theorem 5.1: Suppose that the future uncertainties of the power market with transmission capacity limits can be represented by two possible scenarios: UP and DOWN, and it is assumed that in the UP scenario, each local power market has more demands than in the DOWN scenario as reflected in $a_j^{UP} > a_j^{DOWN}$, $\forall j \in J$. Let

w^{UP} *and* w^{DOWN} denote the probability of UP and DOWN scenarios respectively. Then the generation firms will invest in the same or more amount of generation capacities if w^{UP} increases.

Based on the parameters of Numerical Example 5.4, Figure 5.7 shows the amounts of new generation capacities added by the generation firms corresponding to different probabilities of future scenarios.

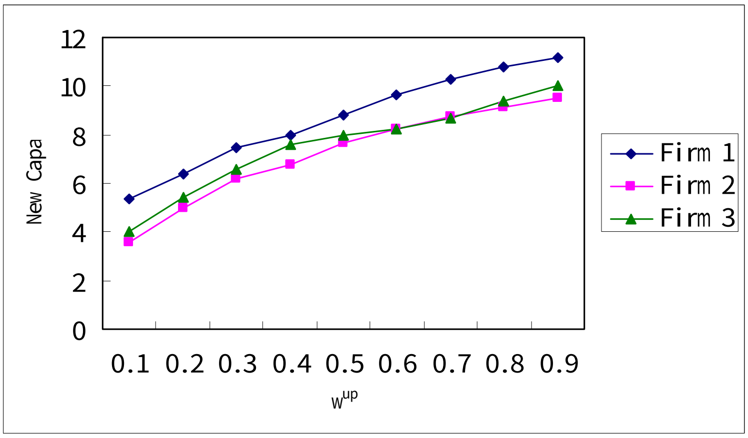

Figure 5.7: Generation firms' capacity expansion vs. different scenario probabilities

Above we discussed how future uncertainties in a spatial power market with transmission capacity constraints affect the generation sector of the power system. How the transmission sector will be affected by future uncertainties depends on the topology of the transmission network and how the demand of each local power market changes.

Numerical Example 5.5

In Numerical Example 5.4, the transmission network is congested in the line that connects Bus 3 and Bus 4. The ISO adds 1.269 units of transmission capacity to that line given the parameters of future market scenarios. Now suppose that the probability of the occurrence of the UP scenario increases to 0.6, and the probability of the occurrence of the DOWN scenario decreases to 0.4. Then the ISO invests 2.283 units of transmission capacity to line{b_3b_4}. The amount of transmission capacity the ISO adds to line{b_3b_4} corresponding to different estimations of future scenario probabilities is plotted in Figure 5.8.

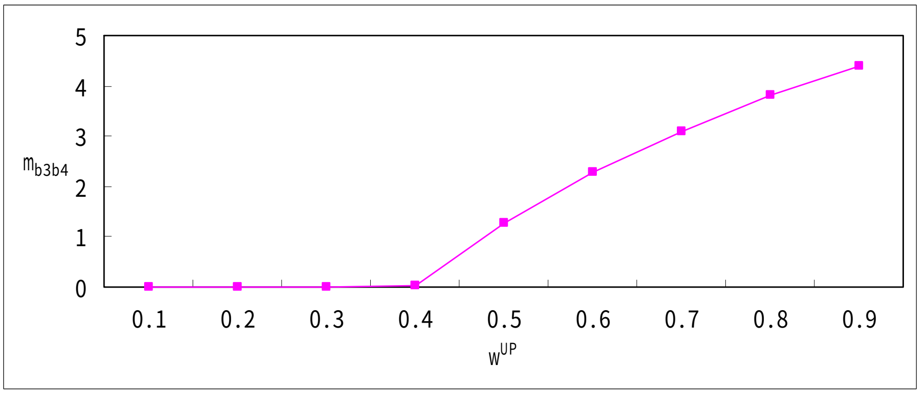

Figure 5.8: Transmission capacity added to Line{b_3b_4} corresponding to different UP scenario probabilities

From Figure 5.8, it can be seen that the ISO adds more transmission capacity to line{b_3b_4} if the probability of the UP scenario is higher.

Now suppose that in the spatial power market defined in Numerical Example 5.4, the only transmission line that has capacity limit is the one that connects Bus 4 and Bus 5, which has the capacity of 2 units, and the marginal cost of capacity expansion for line{b_4b_5} is constant at 1.5. The market parameters in both scenarios are redefined in Table 5.16.

Table 5.16: Market parameters

Market j	a_j^{UP}	a_j^{DOWN}	b_j
1	25	20	1.8
2	30	25	1.5
3	55	50	2

The transmission capacity added to line{b_4b_5} corresponding to different probabilities of future scenarios is plotted in Figure 5.9.

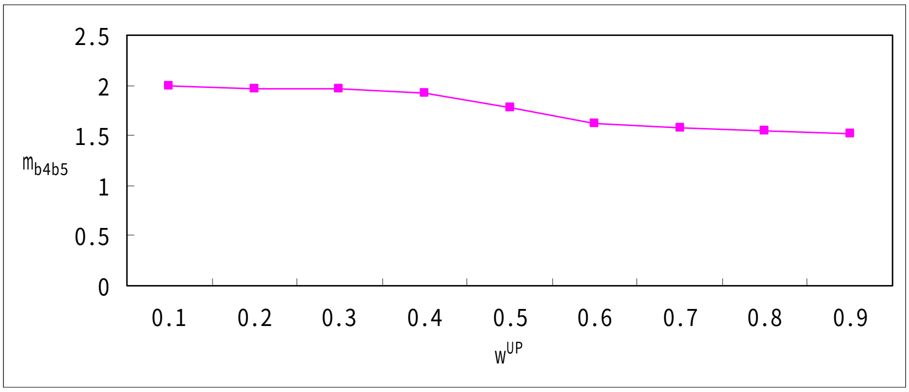

Figure 5.9: Transmission capacity added to Line{b_4b_5} corresponding to different UP scenario probabilities

It can be seen from Figure 5.9 that as the probability of the UP scenario increases, the ISO adds less transmission capacity to line{b_4b_5}. This is because if the UP scenario unfolds, relatively less power will be supplied to Market 3, and therefore there is less amount of power flow in line{b_4b_5}, and the ISO will add less transmission capacity to that line if the UP scenario has a larger probability of occurrence.

5.3 Comparison of the Combined Generation Transmission Planning Model and Separate Planning of Generation and Transmission Sectors

Most of the existing works on long-term power system planning in competitive power markets treat the generation sector and transmission sector separately. For example, take generation capacity planning, the existing models usually make the assumption that the capacity of the transmission network is fixed and will not change, based on which, the capacity planning of the generation firms is modeled. The separate capacity planning models avoid the complexity of the interactions between different sectors of the power system, and are easier to solve. This section compares the results and efficiencies of the separate planning approach to that of the combined power system planning model proposed in this dissertation.

5.3.1 Separate Generation Transmission Planning

In the combined generation transmission planning model formulated in section 5.1, it is assumed that the spatial power market is divided into two sectors, namely, the generation sector and the transmission sector. It is further assumed that neither the generation firms nor the ISO will exercise market power in the transmission sector. If we treat the long-term generation and transmission planning separately by following the above assumptions, the long-term planning problem of the competitive power market can be presented in two formulations.

Formulation 1: Generation firms' long-term planning model

Generation Firms' Capacity Decision:

Maximize

$$\sum_{j\in J}[(a_j - b_j\sum_{i\in I}q_{ij}) - h_{fj}]q_{fj} - \sum_{k\in K}c_k(g_{fk}) - \sum_{k\in K}f_k(x_{fk})$$

subject to

$$g_{fk} \le GC_{fk} + x_{fk},\ \forall k$$
$$\sum_{j\in J}q_{fj} = \sum_{k\in K}g_{fk}$$
$$g_{fk},\ q_{fj},\ x_{fk} \ge 0.$$

Generation Firms' Assumption on Transmission:

Maximize

$$\sum_{i\in I}\sum_{j\in J}h_{ij}y_{ij}$$

subject to

$$T_l \ge \sum_{i\in I}PTDF_{li}(\sum_{j\in J}y_{ij}) - \sum_{j\in J}PTDF_{lj}(\sum_{i\in I}y_{ij}),\ \forall l\in L$$
$$-T_l \le \sum_{i\in I}PTDF_{li}(\sum_{j\in J}y_{ij}) - \sum_{j\in J}PTDF_{lj}(\sum_{i\in I}y_{ij}),\ \forall l\in L$$
$$y_{ij}\ free,\ \forall i\in I,\ \forall l\in L.$$

Market Clearing Condition: $y_{ij} = q_{ij},\ \forall i,\ \forall j.$

In Formulation 1, it is assumed that the generation firms determine generation capacity investments based upon the current transmission network capacity. Therefore, they anticipate that the ISO will charge transmission access fees in the future based on the current transmission capacity available. As in Section 5.1, the problem is formulated in a way that the ISO and generation firms have no market power on the transmission sector. Therefore, the generation firms' long-term planning problem can be solved using the same method presented in Section 5.1. We use $x_{ik}^*,\ i\in I,\ k\in K$ denote the capacity expansion decisions made by the generation firms.

Similarly, the ISO's long-term transmission planning problem is given below.

Formulation 2: ISO's long-term planning model

ISO's Capacity Decision:

Maximize

$$\sum_{i\in I}\sum_{j\in J} h_{ij} y_{ij} - \sum_{l\in L} n_l (m_l)$$

subject to

$$T_l + m_l \geq \sum_{i\in I} PTDF_{li} (\sum_{j\in J} y_{ij}) - \sum_{j\in J} PTDF_{lj} (\sum_{i\in I} y_{ij}),\ \forall l \in L$$
$$-T_l - m_l \leq \sum_{i\in I} PTDF_{li} (\sum_{j\in J} y_{ij}) - \sum_{j\in J} PTDF_{lj} (\sum_{i\in I} y_{ij}),\ \forall l \in L$$
$$m_l \geq 0,\ \forall l \in L,\ y_{ij}\ free,\ \forall i \in I,\ \forall j \in J.$$

ISO's Assumption on Generation:

Maximize

$$\sum_{j\in J} [(a_j - b_j \sum_{i\in I} q_{ij}) - h_{fj}] q_{fj} - \sum_{k\in K} c_k (g_{fk})$$

subject to

$$g_{fk} \leq GC_{fk} + x_{fk},\ \forall k$$
$$\sum_{j\in J} q_{fj} = \sum_{k\in K} g_{fk}$$
$$g_{fk},\ q_{fj} \geq 0.$$

Market Clearing Condition: $y_{ij} = q_{ij},\ \forall i,\ \forall j.$

Formulation 2 assumes that the ISO determines the amount of new transmission capacities based on the current generation capacities, and the decision made by the ISO is denoted by $m_l^*,\ l \in L.$

When the generation firms and ISO have made their decisions on generation expansions, x_{ik}^{*}, and transmission capacity expansions, m_l^{*}, respectively, the operation in the power market can be obtained by solving the following problems.

Actual Electricity Generation:

Maximize

$$\sum_{j\in J}[(a_j - b_j\sum_{i\in I} q_{ij}) - h_{fj}]q_{fj} - \sum_{k\in K} c_k(g_{fk})$$

subject to

$$g_{fk} \le GC_{fk} + x_{fk}^{*},\ \forall k$$
$$\sum_{j\in J} q_{fj} = \sum_{k\in K} g_{fk}$$
$$g_{fk},\ q_{fj}, x_{fk} \ge 0.$$

Actual Transmission Service:

Maximize

$$\sum_{i\in I}\sum_{j\in J} h_{ij} y_{ij}$$

subject to

$$T_l + m_l^{*} \ge \sum_{i\in I} PTDF_{li}(\sum_{j\in J} y_{ij}) - \sum_{j\in J} PTDF_{lj}(\sum_{i\in I} y_{ij}),\ \forall l \in L$$
$$-T_l - m_l^{*} \le \sum_{i\in I} PTDF_{li}(\sum_{j\in J} y_{ij}) - \sum_{j\in J} PTDF_{lj}(\sum_{i\in I} y_{ij}),\ \forall l \in L$$
$$y_{ij}\ free,\ \forall i \in I,\ \forall j \in J.$$

Market Clearing Condition: $y_{ij} = q_{ij},\ \forall i,\ \forall j.$

From the above model, it can be seen that once the generation firms and ISO have come up with their capacity investment decisions and built new facilities, the daily market operation is based on the available generation and transmission capacities.

5.3.2 Market Efficiencies of Two Planning Approaches

The combined and separate power system planning models can be compared in many ways. Recall that in Section 5.1, the combined generation-transmission planning model can be formulated as an equivalent quadratic program with the objective function of

$$\sum_{j\in J}[a_j\sum_{i\in I}q_{ij}-0.5b_j(\sum_{i\in I}q_{ij})^2-0.5b_j\sum_{i\in I}q_{ij}^2]-\sum_{i\in I}\sum_{k\in K}c_k(g_{ik})-\sum_{i\in I}\sum_{k\in K}f_k(x_{ik})-\sum_{l\in L}n_l(m_l). \tag{5.42}$$

Expression (5.42) is the long-term system benefit of the competitive power market with oligopoly of generation firms and a regulated ISO. In the separate planning procedure, the resulted long-term system benefit is,

$$\sum_{j\in J}[a_j\sum_{i\in I}q_{ij}-0.5b_j(\sum_{i\in I}q_{ij})^2-0.5b_j\sum_{i\in I}q_{ij}^2]-\sum_{i\in I}\sum_{k\in K}c_k(g_{ik})-\sum_{i\in I}\sum_{k\in K}f_k(x_{ik}^*)-\sum_{l\in L}n_l(m_l^*) \tag{5.43}$$

where x_{ik}^* *and* m_l^* are the capacity expansion decisions made in Formulation 1 and Formulation 2 respectively.

Theorem 5.2: The long-term system benefit of the combined generation transmission planning model is no less than that of the separate power system planning model in a competitive spatial power market with a regulated ISO.

Proof: Let $x_{ik}^0,\ i\in I,\ k\in K$ *and* $m_l^0,\ l\in L$ denote the capacity expansion decisions made by the generation firms and ISO in the combined power system planning model. Let $x_{ik}^*,\ i\in I,\ k\in K$ *and* $m_l^*,\ l\in L$ denote the capacity expansion decisions made by the generation firms and ISO in the separate power system planning model. If it is assumed that x_{ik}^{*} and m_{l}^{*} yield better system benefit than that in the combined planning model, then x_{ik}^{0} *and* m_{l}^{0} must not be the optimal capacity expansion decisions associated with the combined planning model, which contradicts the supposition that x_{ik}^{0} *and* m_{l}^{0} are optimal. □

The inefficiency of the separate planning model compared to the combined planning model in system benefit is due to the fact that the participants in one market sector ignore the information from the other market sector, and such information is helpful for the decision-makers to come up with better capacity expansion strategies.

Numerical Example 5.6

Recall the spatial power market in Numerical Example 5.3. In this example, it is assumed that all the parameters are the same as those defined in Numerical Example 5.3, and the transmission line connecting Bus 3 and Bus 4 has the capacity of 8. If we apply the separate planning models instead of the combined planning model to this power market, we can calculate the capacity expansion decisions of the generation firms and ISO respectively. As the result of the separate planning model, the ISO adds no transmission capacity to line{b_3b_4}, and Table 5.17 gives the resulting generation capacity expansions.

Table 5.17: Generation capacity expansions in the separate planning models

	LOW	MEDIUM	HIGH
Firm 1	0	3.581	3.488
Firm 2	2.465	0	3.116
Firm 3	4.37	3.748	0

Compared to the results of Numerical Example 5.3, the ISO invests less in new transmission capacity by assuming that the generation capacities remain the same. This is because with the existing generation capacities and generation costs, line{b_3b_4} will not get congested, Therefore the ISO has no desire to add any transmission capacity to line{b_3b_4}. And in the generation sector, it is found that both Generation Firm 1 and Generation Firm 2 invest less in new generation capacities. The reason for this is that their power supplies to Market 2 and Market 3 are constrained by the limited capacity of line{b_3b_4}. On the other hand, Generation Firm 3 adds more generation capacity because if the ISO is assumed to invest nothing in line{b_3b_4}, more power is supplied from Generation Firm 3 to balance the power flow in the congested transmission line.

The power generation and supplied as the result of the separate planning model are given below.

Table 5.18: Power supplied to markets and produced with different technologies resulted from separate planning models

	Market 1	Market 2	Market 3	LOW	MEDIUM	HIGH
Firm 1	4.356	4.122	2.591	4	3.581	3.488
Firm 2	4.521	4.32	2.74	2.465	6	3.116
Firm 3	5.772	5.821	3.866	4.37	3.748	7.342

From Table 5.18, it can be seen that as the result of less investment in transmission capacities, Generation Firm 3, which is the most expensive one in the generation sector, is better-off compared to the results of the combined power system planning model. Generation Firm 3 can supply more power to Market 1. Also, because the most significant advantage of Generation Firm 3 lies in its enhanced market power in Market 2 and Market 3, it is able to exploit the residual demands of these local power markets since the other generation firms cannot compete effectively due to limited transmission capacity of line{b_3b_4}. In the combined planning model, the prices of Market 2 and Market 3 are 14.061 and 13.061 respectively, while in the separate planning models, due to the enhanced market power of Generation Firm 3, the prices of Market 2 and Market 3 are higher at 14.606 and 13.606 respectively.

Theorem 5.2 states the inefficiency of the separate power system planning models with regard to the system benefit defined in expression (5.42), it should be noted that the system benefit defined in expression (5.42) includes the market power of the generation firms in the generation sector of the power market.

As shown in Section 3.4, the long-term social welfare of the power market is the sum of the consumer surplus and supplier surplus minus power generation costs and generation capacity expansion costs. In this chapter, the social welfare also includes the cost of adding new transmission facilities. Therefore, the long-term social welfare of a spatial power market with transmission capacity constraints is

$$\sum_{j\in J}[a_j\sum_{i\in I}q_{ij}-0.5b_j(\sum_{i\in I}q_{ij})^2]-\sum_{i\in I}\sum_{k\in K}c_k(g_{ik})-\sum_{i\in I}\sum_{k\in K}f_k(x_{ik})-\sum_{l\in L}n_l(m_l). \tag{5.44}$$

The difference between the system objective function (5.42) and social welfare function (5.44) is that in the competitive power market discussed in this dissertation, the market power of the generation firms is considered to exist in the generation sector, so that system objective function (5.42) is obtained instead of social welfare function (5.44). The extra term of $-\sum_{j\in J}[0.5b_j\sum_{i\in I}q_{ij}^2]$ in the system objective function due to non-perfect competition illustrates the desire of generation firms to mark up electricity prices in order to gain more profits than in the perfect competition case. Therefore, it is reasonable to compare the efficiency of different power market planning procedures by using the social welfare. In the above example, the social welfare that resulted from the combined planning model was 831.638, while the social welfare that resulted from the separate planning models was 830.22, which is lower.

Theorem 5.3: The long-term social welfare of the electric power market resulting from the combined generation transmission planning model is no less than that resulting from the separate planning models for generation and transmission sectors.

Proof: Let $f_c(\tau)$ and $f_s(\tau)$ denote the social welfare of the combined and separate power system planning models respectively, τ stands for the vector of the decision variables of the generation firms and ISO. We use $F_c(\tau)$ and $F_s(\tau)$ to denote the system objective functions of two different models. Therefore, we have $F_c(\tau) = f_c(\tau) - w_c(q)$ and $F_s(\tau) = f_s(\tau) - w_s(q)$, where $w(q)$ stands for the term of $\sum_{j\in J} 0.5 \sum_{i\in I} q_{ij}^2$ in the system objective function. According to Theorem 5.2, $F_c(\tau^o) \geq F_s(\tau^*)$, where τ^o and τ^* are the optimal solutions of the combined planning model and separate planning model respectively. If it is assumed that $f_c(\tau^o) < f_s(\tau^*)$, it must be true that $w_c(q^o) < w_s(q^*)$.

The feasible set Γ of the power system planning problem is compact and convex, $f(\tau)$ is strictly concave and $w(q)$ is strictly convex. Therefore, if the assumption that

$f_c(\tau^o) < f_s(\tau^*)$ is true, in the separate planning model, the feasible region of q_{ij} and g_{ik} must contain the point that no direction exists such that $f_s(\tau)$ increases faster than $w_s(q)$ increases. In this way, due to the convexity of the feasible set of q_{ij} and g_{ik}, the optimal value of the system objective function of the separate planning model can be improved by moving along the direction that $f_s(\tau)$ decreases slower than $w_s(q)$ decreases. This contradicts with the supposition that $F(\tau^*)$ is the optimal system solution for the separate planning model. Therefore, the assumption of $f_c(\tau^o) < f_s(\tau^*)$ is wrong, which indicates that the social welfare of the combined planning model cannot be smaller than that of the separate planning model. □

Theorem 5.2 and Theorem 5.3 show that the separate power system planning models are inefficient compared to the combined power system planning model in both the system benefit that considers generation firms' market power and the social welfare that measures the efficiency of the power market. The reasons for the inefficiency of the separate planning models are the under-investments and over-investments in new generation and transmission facilities, which are due to the fact that valuable information from the other sector of the electric power market is not used in the decision-making.

In Numerical Example 5.6, both the ISO and generation firms invest less in new facility constructions in the separate planning models. The ISO adds no transmission capacity to the transmission network because it ignores the fact the Generation Firm 1 and Generation Firm 2 would like to increase their generation capacities in order to increase their supplies to Market 2 and Market 3, which will result in more power flow on line{b_3b_4}. In generation sector, because of the possible congestion on line{b_3b_4} when the ISO adds no extra capacity to it, Generation Firm 1 and Generator Firm 2 add less generation capacities than in the combined planning model, while Generation Firm 3, which is not constrained by capacity limit of line{b_3b_4}, adds more generation capacities because the under-investments of other generation firms leave more market share to it. In Numerical Example 5.6, the transmission investment is zero compared to the 2.3115 units in the combined planning model. The generation firms' total investment in generation capacities in the separate models is 83.303 compared to 85.855 in the combined planning model.

The under-investments in new capacities cause the following inefficiencies of the power market. Firstly, there is less transmission capacity available and the ISO is able to impose more transmission fees on Generation Firm 1 and Generation Firm 2 who rely on line{b_3b_4} to sell power to Market 2 and Market 3. As a result, the income of the ISO in the separate planning models is more than that in the combined planning model. Secondly, the under-investments in generation capacities and transmission capacities cause more discrepancy in electricity prices of different local power markets. In the combined planning model, the price of electricity is 13.936 for Market 1, 14.061 for Market 2, and 13.061 for Market 3, and in the separate planning models, the electricity prices are 11.687 for Market 1, 14.755 for Market 2, and 13.755 for Market 3. It can be seen that in the separate planning models, the electricity prices of Market 2 and Market 3 are more than those in the combined planning model, while Market 1's price becomes lower in the separate planning models. The larger price differences indicate insufficiency of transmission resources and inefficient generation capacities in the power market. The electricity consumers in Market 2 and Market 3 suffer from the separate power system planning approach.

The separate planning models may also cause over-investments in generation and transmission facilities compared to the combined planning model. Some generation and transmission capacities invested may not be used in real operation of the power market.

Numerical Example 5.7

Consider the spatial power market in Numerical Example 5.6. Suppose that line$\{b_4b_5\}$ has the transmission capacity limit of 2, and the marginal construction cost of line$\{b_4b_5\}$is 1.5. The generation capacities of each generation firm and the marginal costs of generation capacity expansions are given in Table 5.19. The market parameters are given in Table 5.20.

Table 5.19: Generation firms' generation and expansion parameters

	c'	*f'*	GC_1	GC_2	GC_3
LOW	0.2g	5	10	10	0
MEDIUM	0.5g	4	4	4	0
HIGH	0.8g	3	0	0	10

Table 5.20: Market parameters

Market *j*	a_j	b_j
1	40	1.8
2	36	1.5
3	60	1.5

In the separate planning models, the ISO adds 8.103 units of transmission capacities to line{b_4 b_5}, and generation firms' capacity expansions are listed in Table 5.21.

Table 5.21: Generation capacity expansions in separate planning models

	LOW	MEDIUM	HIGH
Firm 1	0	0	2.568
Firm 2	0	0	2.568
Firm 3	9.17	5.668	0

The ISO in the combined planning model adds 4.373 units of transmission capacities to line{b_4b_5}. Table 5.22 shows the generation firms' decisions in generation capacity expansions.

Table 5.22: Generation capacity expansions in combined planning model

	LOW	MEDIUM	HIGH
Firm 1	0	0.103	3.814
Firm 2	0	0.103	3.814
Firm 3	7.144	4.858	0

The cost of new generation capacity investments resulting from the separate planning models is 83.92, and the transmission capacity expansion cost is 12.06. In the combined planning model, the generation capacity expansion cost is 78.86, and the transmission capacity expansion cost is 6.56. Power generations and supplies resulting from the two planning models are given in Table 5.23 and 5.24.

Table 5.23: Power supplied to markets and produced with different technologies resulting from separate planning models

	Market 1	Market 2	Market 3	LOW	MEDIUM	HIGH
Firm 1	4.089	4.24	8.24	10	4	2.568
Firm 2	4.089	4.24	8.24	10	4	2.568
Firm 3	5.541	5.982	9.982	9.17	5.668	6.667

Table 5.24: Power supplied to markets and produced with different technologies resulting from combined planning model

	Market 1	Market 2	Market 3	LOW	MEDIUM	HIGH
Firm 1	4.559	4.804	8.554	10	4.103	3.814
Firm 2	4.559	4.804	8.554	10	4.103	3.814
Firm 3	5.183	5.553	9.303	7.144	4.858	8.036

From Tables 5.21 ~ 5.24, it can be seen that although there are more investments in generation capacities in the separate planning models, the power supplied to the power market is not changed much compared to the combined planning model. This is because, by assuming that the transmission capacity of line$\{b_4b_5\}$ will not be changed, Generation Firm 3 expects that it will have more market share in Market 3 and it will also be able to supply more power to Market 1 and Market 2 to alleviate the congestion in line$\{b_4b_5\}$. But, in fact, the ISO adds 8.103 units of transmission capacity to line$\{b_4b_5\}$, so that in the real operation of the power market, Generation Firm 1 and Generation Firm 2 are able to supply more electricity to Market 3, and less power is needed from Generation Firm 3 to supply Market 1 and Market 2 to alleviate the congestion in line$\{b_4b_5\}$. As a result, the generation capacity investment of Generation Firm 3 is more than the amount required, and therefore a large proportion of its generation capacities is not used in real operation.

In the transmission sector, it is interesting to note that in the separate planning models, the ISO adds more transmission capacity to line$\{b_4b_5\}$ than in the combined planning model, but the actual power flow in line$\{b_4b_5\}$ is less that in the combined planning model. This means that the transmission network investment is not efficient in the separate planning models. The over-investment in line$\{b_4b_5\}$ in the separate planning model is due to the fact that the ISO adds more transmission capacities to the congested line in order to allow Generation Firm 1 and Generation Firm 2 to supply more power to Market 3 without considering the possibility that Generation Firm 3 would increase its power supplied to Market 1 and Market 2, which will help reduce the congestion in Line$\{b_4b_5\}$. Therefore, since it turns out that Generation Firm 3 supplies more electricity to Market 1 and Market 2, part of the transmission capacities of line$\{b_4b_5\}$ is not used in real market operation.

6 CONCLUSIONS

This dissertation presented capacity expansion models in the context of a deregulated electric power market. Capacity investments in both electricity generation and electricity transmission were included to study long-term behaviors of generation firms and the ISO in a deregulated environment. In these models, it was assumed that the generation firms are Cournot firms who compete in quantities to maximize their profits, which assumes that the generation firms possess market power in the deregulated electric power market. The idea of Nash equilibrium theory was adopted thus that equilibrium is reached when no generation firm can improve profit by changing its decision unilaterally. The ISO in these models was assumed a regulated entity that operates the electricity transmission sector and makes investment decisions to support competition among generation firms.

We analyzed the decisions of generation firms and the ISO within the framework described above. The models developed in this dissertation allow us to analyze the market power in a spatial electricity power market and compare it to the case when the generation firms operate under perfect competition and to the case when the generation firms form a coalition and maximize the overall profit. With capacity investments included, the models provide an analysis tool for studying the long-term decisions in the deregulated power market. The models consider both generation and transmission capacity expansions by assuming that the generation firms and the ISO make capacity expansion strategies by considering each other's decision, that is, the investment decisions in each sector are not isolated from each other.

To make the models computationally tractable and to obtain some insights into the long-term operation of the deregulated electricity market, the models in this dissertation have been developed using some simplifying assumptions: the inverse demand function in each local market is assumed to be linear, and the cost functions are assumed to be quadratic. These assumptions ensure that the models can be applied to electricity capacity expansion problems of realistic size, and that a unique market equilibrium exists.

Another simplifying assumption is that capacity expansion decisions are continuous variables, this makes the models relatively easy to solve and calculate the unique equilibrium, when it exists.

6.1 Dissertation Contributions

The electric power industry is experiencing changes with the restructuring and deregulation process. Traditional methods need to be modified and updated to study the power market in the new environment. In the literature on deregulated electric power market, the effects of deregulation on short-term operation are actively researched. However, less literature is available on issues and effects on capacity expansions. Models that deal with electric power markets with capacity investments are needed to understand the long-term efficiency of the restructured power industry.

This dissertation formulates the long-term operation of the spatial electric power market in a two-stage decision context, where generation and transmission capacity expansion decisions are made in the first stage, while power generation and transmission service fees are decided in the second stage. Uncertainties that exist in the second stage affect the capacity expansion decisions. Several models have been built to study different aspects of the capacity expansion problem.

The first model (power system planning without transmission constraints) is developed to study generation firms' capacity expansion decisions in a spatial power market without transmission capacity limits. Then, the ISO's capacity expansion decisions are not included.

The second model (combined power system planning) formulates the power system planning in a spatial market that is constrained by limited transmission capacity. The models include the interactions between the generation sector and transmission sector in generation and transmission capacity decisions; this has not been done in the reported literature to our knowledge.

The third model (separate power system planning) in this dissertation considers the situation where the capacity expansion decisions in the generation sector and transmission are isolated from each other; this is similar to models in existing literature. The model was developed to compare with the realistic case where there are information exchanges between the generation transmission sectors.

The developed models can be used by the stakeholders of the power industry to understand the long-term issues in the restructured electric power market. Some results from these models are summarized as follows.

1. The Nash-Cournot assumption on generation firms provide a compromise between perfect competition and coalition of generation firms, which is a realistic representation of the restructured electric power market.

2. Under the assumption that the regulated ISO will not wield market power in the transmission sector of the power market, the ISO will not reserve transmission capacity to gain extra profits; that is the ISO will make capacity expansion decisions to support the competition in the generation sector, and hence the consumers of electricity.

3. The generation firms will provide more power supplies to the market when there is more demand. In the presence of future uncertainties, the generation firms will add more generation capacity if the demand in the future power market is expected to be higher.

4. The transmission capacity invested by the ISO depends on the characteristic of the power market and the topology of the transmission network.

5. The combined power system planning model yields higher social welfare than the separate power system planning model. The inefficiency related to the separate power planning model is due to the fact that the generation sector and transmission sector come up with capacity expansion decisions, ignoring information available from each other. The inefficiency is reflected in under- or over-investment of new generation and/or transmission capacities

6.2 Future Research

This dissertation developed several models that can be used to analyze the long-term operation of the deregulated power market. Some assumptions have been made in this research to provide a compromise between the accuracy and tractability of the models developed. Future research will be endeavored at relaxing some of the assumptions in order to add more flexibility for studying the long-term issues of the electric power market.

We have assumed that new generation and transmission capacity decisions can be represented as continuous variables. The continuity assumption will not introduce significant error in predicting new capacities that will be built in the future because they are generally in large amounts. However, treating capacity expansion decisions as discrete variables, which is the case in the electric power industry, will provide more accurate estimations of capacity investments. To our knowledge, there exists no documented work on multi-player decision models that include discrete decision variables. Some search or heuristic methods may have to be developed to find satisfactory solutions to such problems.

Another assumption we have made is that, in the presence of future uncertainties, the generation firms and the ISO have the same prediction of future scenarios. A possible research direction is to allow the generation firms and the ISO to have different views of future uncertainties, such as different likelihoods of the set of future scenarios and the probabilities of future scenarios. This enables us to evaluate how different views of future uncertainties by the players will affect their capacity investment decisions.

In this dissertation, we assume that the generation firms and the ISO are risk-neutral. That is, in the presence of future uncertainties, they maximize the expected gains. We may allow the electric market participants to deal with risks differently; associated decision-makers may be risk-neutral, risk-prone, or risk-averse. In this way, the behaviors of the market participants can be represented more appropriately.

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