Deregulated Power Transmission Analysis and Planning in Congested Networks

A thesis submitted for the degree of Doctor of Philosophy

By

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Abstract

In this thesis, methods of charging for the transmission system and optimising the expansion of the transmission network under the competitive power market are described.

The first part of this thesis considers transmission tariff design. In the proposed approach, not only is all the necessary investment in the transmission system recovered, but also an absolute economic signal is offered which is very useful in the competitive power market. A fair power market opportunity is given to every participant by the new nodal-use method.

The second part of this thesis considers transmission system expansion. All the tests are based on the Three Gorges Project in China. In this thesis, to optimally expand the transmission system, the LMP (Locational Marginal Price) selection method and the CBEP (Congestion-Based transmission system Expansion Planning) method are introduced. The LMP selection method is used to select optional plans for transmission system expansion. It is especially suitable for large transmission systems. The outstanding advantages of the LMP selection method are simplicity and computational efficiency. The CBEP method produces the optimal system expansion plan. For the first time, generation congestion and transmission congestion are separated within the system expansion problem. For this reason the CBEP method can be used in a supply-side power market and is suitable for the Chinese power market.

In this thesis, the issue of how to relax the congestion in the transmission system have been solved. The transmission system can obtain enough income to recover the total required cost. For this reason more and more investment will come into the transmission system from investors. The risk for the independent generators is also under control in the CBEP method. Even when the system is congested, the uncertainty of LMP is taken into consideration.

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Finally, I would like to thank my dear mama, my uncle, and my friends for their warming continuous encouragement, support and love.

Declaration

This work described in this thesis has not been previously submitted for a degree in this or any other university, and unless otherwise referenced it is the author's own work.

Statement of Copyright

Contents

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Abbreviations

CAMMESA	Compania Administradora del Mercado Electrico Mayorista SA (Argentina)
CBEP	Congestion-based transmission system expansion planning
CC	Centre China
CDEP	congestion-driven transmission system expansion planning
CNSE	Comision Nacional del Sistema Electrico (Spain)
CPUC	California Public Utility Commission
Disco	distribution company
EC	East China
ENRE	Ente Nacional Regulador de la Electricidad (Argentina)
FERC	Federal Energy Regulatory Commission
Genco	generating company
ISO	Independent system Operator
LMP	Locational Marginal Price
MCP	Market Clearing Price
MLE	Marco Legal Estable (Spain)
NC	North China
NEC	Northeast China
NR	Nodal Revenue
N-U	Nodal-use
NVE	Noregian Water Resource and energy Directorate
NWC	Northwest China
OMEL	Compania Operadora del Mercado Espanol de Electricidad(Spain)
OPF	Optimal Power Flow
PF	Power flow
PJM	Pennsylvania-New Jersey-Maryland, an electricity pool (US)

REE	Red Electrica de Espana SA (Spain)
RTO	Regional Transmission organizing
SC	South China
SERC	the State Electricity Regulatory Commission
TI	Total Income
Transco	transmission company/transmission companies
WC	West China

Chapter1 : Introduction

This chapter introduces the thesis in five sections.

In Section 1.1 the nature of the current power market is described and the topic of the thesis is introduced. The motivation for researching this topic is also discussed. Section 1.2 describes the related background, definition and software information. Section 1.3 and 1.4 briefly introduce the aims and contribution of research of this thesis. Section 1.5 presents the outline of whole thesis.

1.1 New Challenges

Since the power industry has been restructured in China, the new roles of the participants have spurred power investment by diversified investors and encouraged new competition. China's power industry is scaling new heights.

1.1.1 The Energy Demand and Supply Situation in China

In China, the generating capacity has increased very fast (10% per year). Comparing with the largest installed capacity country USA, the capacity difference between these two countries is getting smaller and smaller. In 1995 the installed capacity in USA was about 600GW more than install capacity in China. But after 10 years, the difference in capacity installed between USA and China had declined to 400 GW. (fig1.1)[71] [92].

By 2004 the installed capacity reached 439 GW.

Both the installed capacity and consumption in China has been the second largest in the world since 1996 [77]. However, due to the demand for electricity increasing even faster (10%-15% per year) still 21 out of 29 provinces are enduring power shortages. On the one side it is because of rapid economic growth, on the other side the power industry in China really needs to speed up in its development.

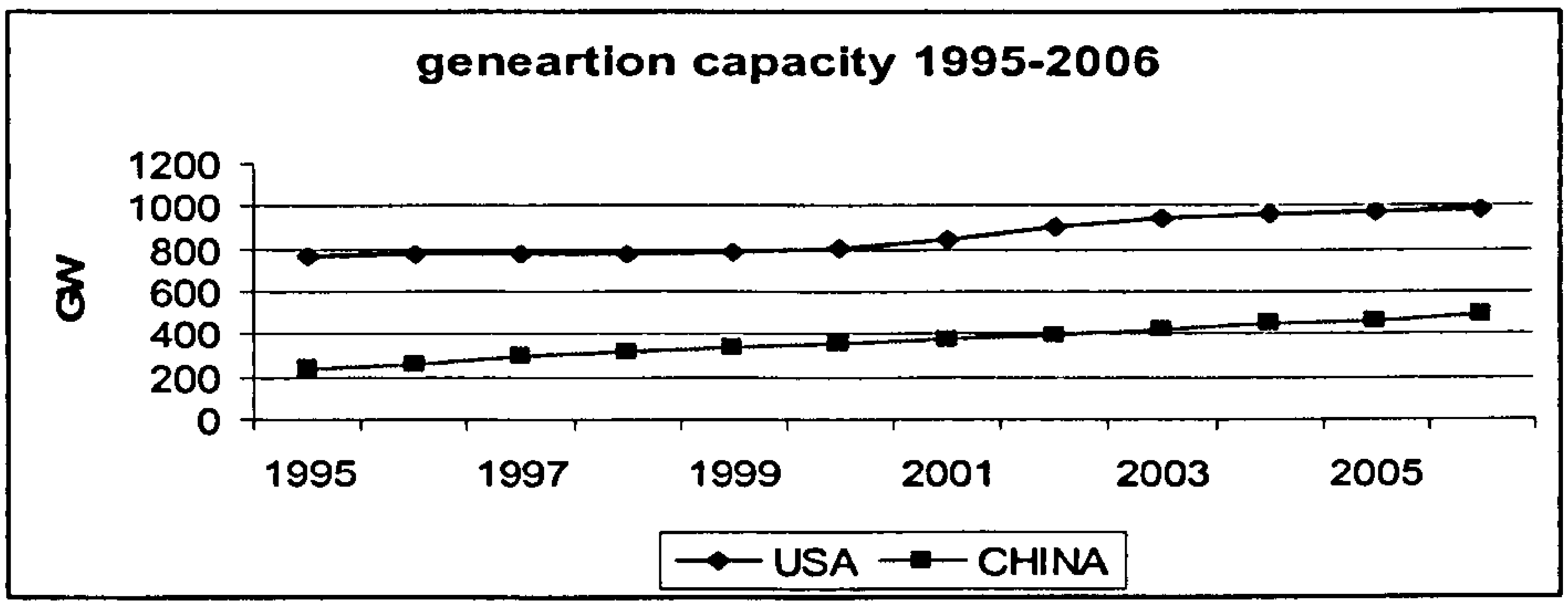


Fig. 1.1 Generation capacity from 1995 to 2006

Transmission price should be 40% of total energy price but currently transmission price is only 24.6% (20%-30%) of the total energy price in China [91]. The capital value of transmission system is just 35% and the capital value of generation is 65% of the total electrical industry capital in 2005. To make sure a competitive power market works properly, the transmission capital should be 60% and the generation capital should be 40%. In the existing case, the Transco cannot get enough benefit for building and maintaining the transmission system. Few companies want to invest in the transmission system under the present conditions.

China is a very large country and the resources (oil, coal, water power, gas, etc.) are quite uneven geographically. Fig 1.2 shows that in EC (East China) and NC (North China) the demand for electricity is much more than NC and NWC (North West China) [73]. But most of the energy resources are in WC (West China) and NC (90% of hydropower resources are concentrated in WC and 80% coal reserves are scattered in the north [75]). This means large quantities of energy need to be transferred over long distances from generators to load centres.

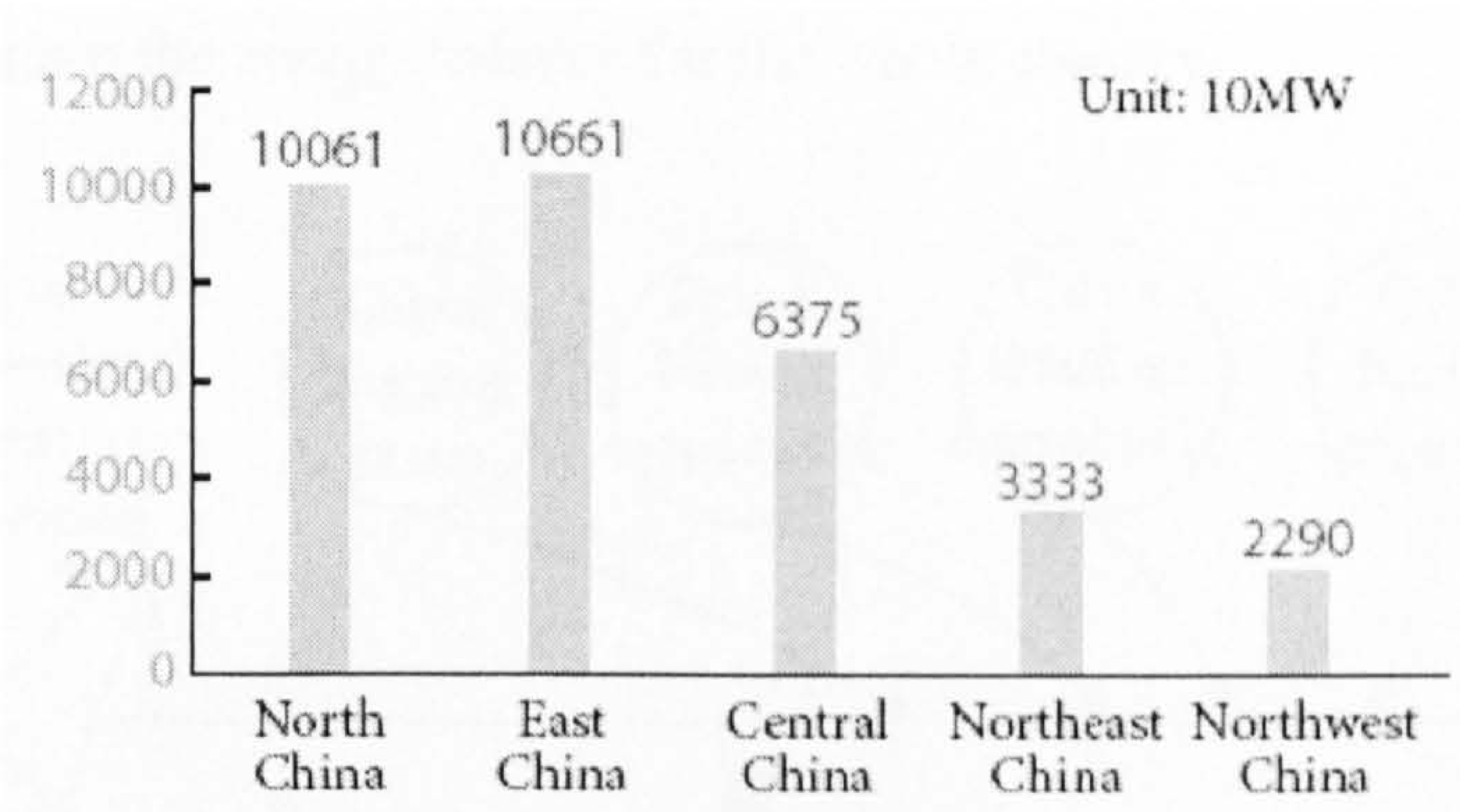


Fig. 1.2 2006 peak power load of major power grids of state grid of China [73]

1.1.2 Current Structure of Chinese Power Market

In the western world the power industry has been reorganized since the 1990s. China's power industry began to deregulate in 2002 [74]. The generating companies (Genco) and transmission companies (Transco) have been restructured into five independent generation companies (China Huaneng group, China Datang corporation, China Huadian corporation, China Guodian corporation, and China Power investment) and two gird owner companies (State grid and South China grid) [76] [77] (fig 1.3). The competition only exists on the generator side; the consumer side is still under a monopoly at present. On the other hand, contracts between big customers and generators are now encouraged.

A mature power market should include Gencos, distribution companies (Discos), retailer, market operator, system operator, Transco, the regulator, small consumers and large consumers etc [83]. In the present Chinese system, in contrast with developed power markets, instead of an independent system operator (ISO), the Transco also works as the system operator. For the Chinese power market, the State Electricity Regulatory Commission (SERC) is working as the regulator to ensure the power market is healthy and efficient (fig 1.3).

In China, there are two transmission companies and six independent transmission networks [73][79]. They are East China (EC), North China (NC), Northeast China (NEC), Northwest China (NWC) Central China (CC) and South China (SC) (fig 1.4) [78]. These six networks are mainly independent grids although some of them are already interconnected. The main task of Transco is interconnecting these six large networks to make the national grid stronger and maintain the energy balance for the whole country.

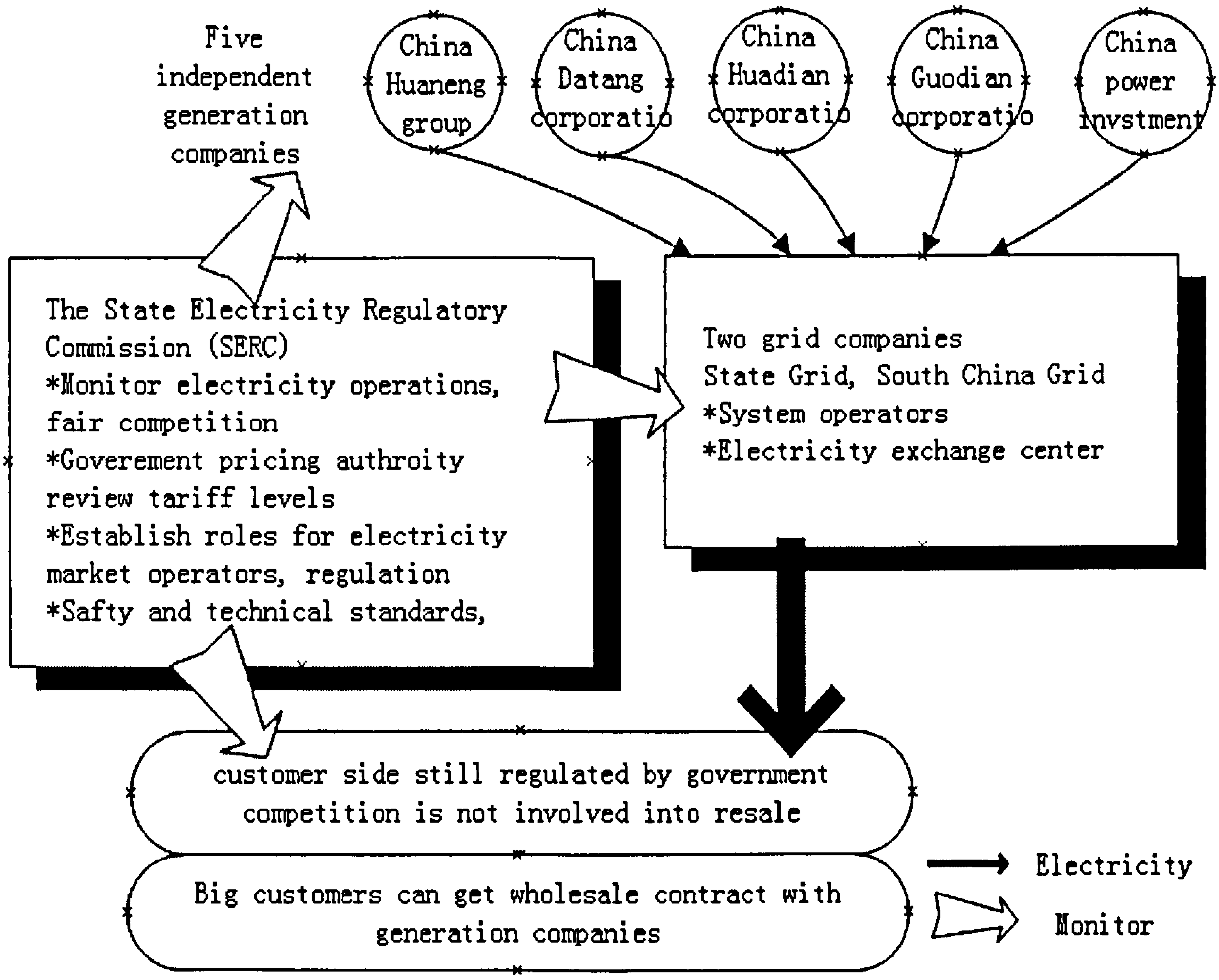


Fig. 1.3 Chinese power market structure

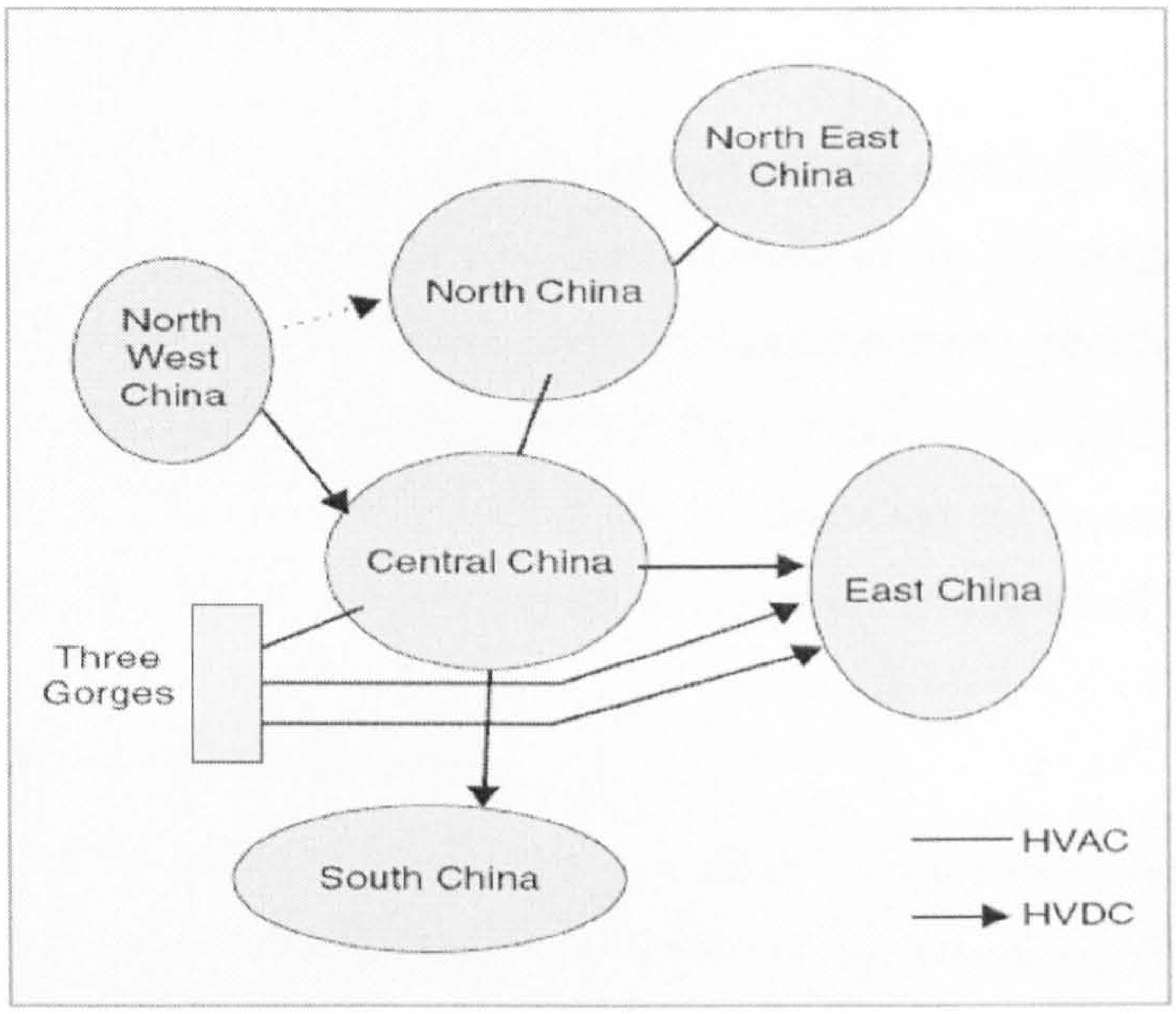


Fig. 1.4 State Grid of China [4]

1.1.3 Motivation for the research topic of this thesis

By 2020, it is expected that the total installed generator capacity in China will be 1,000 GW and the total trans-regional power of the national network will reach 250 GW [77]. At the same time the power market in China will become more mature. Before 2010, transmission systems will have become interconnected and full competition introduced on the generation side [78].

Depending on the actual situation in the Chinese power industry, to relieve the shortage of electricity and to build a mature power market, the transmission bottleneck problem needs to be solved as soon as possible. The independent networks need to be interconnected and the electrical energy needs long-distance transport. The abundant demand needs to be satisfied. The transmission investment should be recovered. Some important questions to be considered are: How to optimally encourage more investment into the transmission side? How to best expand the transmission system with these investments? How to utilize experience of the developed power markets, to benefit the developing power market in China? Research focused on these problems is very valuable and necessary.

Before all these problems are investigated, some relevant background of the research will be presented.

1.2 Background to the research

With the deregulation of the power industry throughout the world, not only the security of the transmission system but also the economic benefit of the transmission system have been analyzed and applied to the transmission system expansion planning. To establish a further effective and efficient transmission system expansion planning method, more aspects should be considered. This section briefly describes the relevant concepts with regard to transmission system expansion planning and transmission tariff design.

1.2.1 Transmission tariff/allocation

Power stations and distribution companies can enter a competitive market if they are connected to the same transmission network. However, the transmission grid is seen as a natural monopoly, and for this reason the transmission tariffs have to be regulated. On the other hand, the transmission tariff can make it possible that the main transmission network can act as an independent broker to buy energy from power stations and sell energy to distribution companies [49]. This implies that transmission tariffs are essential elements for creating competitive electricity markets.

The transmission tariffs are mainly structured according to short term operation fees and long term capital investment. They can be separated into four major components [50]:

1) Return and depreciation of the capital equipment.

2) Operation and maintenance to ensure that the network is robust.

3) Losses incurred in transmitting power.

4) Opportunity costs of system constraints.

A good transmission tariff method should be [51]:

1) Economically efficient;

2) Non-discriminatory;

3) Transparent;

4) Cost recovery based;

5) Congestion avoiding;

6) Tariff stable;

7) Simple and easily intelligible.

There are three basic alternative methods of transmission pricing. They are the postage stamp method, the distance related method and the nodal method (table 1-1).

TABLE 1-1 COMPARING THREE MAIN TRANSMISSION TARIFF METHODS

	Define	***Advantage***	***Disadvantage***	***Related research***
Postage stamp	For transporting a given amount of electrical energy over the grid, a fixed price per energy units charged, independent from the distance or voltage.	Simplicity of rates Tariff stable Cost recovery Transparent	Economically inefficient Discrimination Lack of congestion avoidance	[52] [53] [54] [55] [56] [57] [58]
Distance related	Looks at the distance between generator and customer, the distance and the voltage level are both considered.	Cost recovery Tariff stable Non-discrimination Transparent	Difficulty of rate Economic inefficient Lack of congestion avoidance	[59] [60] [61] [62]
Nodal pricing	Take the actual cost of transmission into account, either based on momentary or on typical load flow	Economic efficient Non-discrimination Congestion avoidance	Tariff stability lack Cost cannot be fully recovered Non-transparent Difficulty of rate	[36][68]

The postage stamp method has many advantages. However, the main problem is this kind of method is not suitable for a restructured power market [56] [58]. Due to the simplicity of postage stamp method it is a kind of transmission cost allocation which has been used in practice until now. Many engineers have focused on how to improve this fixed transmission allocation method to make it more suitable for competitive power markets [52-58].

The distance related allocation method is a name for various methods which depend on distance or electrical distance. Most of them recover a fixed transmission cost based on actual usage of the transmission system, for example the MW-mile method [59] [60]. Compared with the postage stamp method, the distance-related method is fairer to every participant in the unbundled power market. However, people still want to find a method which is very flexible and suitable for the real-time power market.

The Postage-stamp rate method does not require power flow calculation and is independent of the transmission distance and network configuration. It is a form of fixed transmission cost, with only the MW energy delivered being considered. The MW-mile method takes account of MW transmission flows together with transmission line length in miles. A DC power flow calculation is required.

Nodal price can provide useful economic information regarding the transmission system and generator situation. For this reason, the transmission tariff which is based on nodal prices will be more suitable for the competitive power market than the postage stamp method and the distance-related method. The main problems are that the nodal pricing method cannot always recover all of the system cost and the method can become very complex.

Further to these three main types of transmission price allocation methods, people still try to find other ways to make transmission tariff methods simple and fair. For example, game theory [63] [64], equivalent bilateral exchange [65][66] and direct traceable methods [67] were developed into transmission cost allocation methods as well. More detail is given in section 2.1.2 of classic transmission tariff methods

1.2.2 Transmission expansion planning management background

The main aim of transmission expansion in a restructured power market is delivering reliable power from generators to loads, relieving the market power of the transmission system and providing a fair environment to all participants to serve the growing electricity market in an optimal way [7][11].

A workable transmission expansion plan should: [31] [93-96]

1) Be able to meet future transmission capacity requirements;

2) Be able to make an appropriate return on investment;

3) Be able to ensure the level of reliability;

4) Be able to satisfy the expectation of customers.

Transmission system planning has two major differences before deregulation and after the deregulation [11].

Firstly, the objectives of transmission expansion planning are changed. Not only the security of the transmission network but also social welfare and non-discrimination should be considered by the regulated system operator.

Secondly, in restructured electricity markets, there are more uncertainties in the transmission expansion planning. For example, generation planning, in many cases, is separated from transmission expansion planning.

There are many kinds of mathematical methods used for transmission planning, such as branch-and-bound algorithm, sensitivity analysis, Benders decomposition, simulated annealing, genetic algorithms, tabu search algorithms etc[16][17][18] [32]. However these algorithms are not strictly for the new market based situation.

For this reason, currently, more and more people are focusing on market-based methods for transmission system expansion planning [5] [9] [10] [12]. This is the main topic considered in this thesis.

1.2.3 Locational Marginal Price (LMP)

From the 1980s, electrical engineers began to focus on how to deregulate the power system. The most important problem is when generation transmission and distribution are unbundled ensuring the electric grid's security, but at same time allowing economic benefit. F. C. Schweppe's book "Spot Pricing of Electricity" (1988) is regarded as a milestone for electric power markets [26]. Following that work, there is a clearly defined 'Spot Price' or 'Nodal Price'. Based on the definition of spot price the LMP is used in power markets and has become more and more important.

The main function of LMP is to give an economic signal to the system operator for the competitive power market. The basic definition of LMP is "the price of supplying an additional MW of load at each location (bus) in the system" [39].

There are three main factors which will affect LMP:

1) Generation fuel cost and capacity;

2) Transmission and distribution network losses and capacities;

3) Demand and supply patterns.

Actually, both the generators and the transmission network will be involved in the LMP calculations. From the generator side, the fuel price, maintenance and operation costs and revenue reconciliation are related elements. From the transmission side, the related elements are transmission losses and the revenue reconciliation requirement, etc.

After explaining what LMP is, and why we need LMP. The next questions arise immediately: How to calculate LMP? Where can we use LMP in theoretical terms? Which countries use LMP in practice?

The simplest way to calculate LMP depends on the definition of LMP. Many kinds of stimulate software for power system can give LMP as an output, such as Matpower [35], Powerworld [81] and Dash Optimization [82]. There are many research studies on how to calculate LMP, depending on exact market models [40] [41]. Simple equations for calculating LMP will be provided and used in the following chapter.

Theoretically, LMP can be applied everywhere in a power market. For example generation can be paid for energy supply depending on LMP at the point of connection to the transmission system. Customers can be charged for energy consumed depending on LMP at their connection point. Also the Transco can charge a transmission fee depending on the difference in LMP between the 'from bus' of a power flow and the 'to bus'. LMP can be a kind of economic signal for grid security, reducing system congestion [42] [43] [46]. In this thesis LMP will be used for system expansion planning and for calculating system transmission tariffs.

Realistically, several companies use LMP as a very important part of their power market. For example PJM RTO (Regional Transmission Organizing)[46][47], Mid-West ISO (Independent System Operator), ISO New England [44], New York ISO. All these market models are running based on LMP [45]. Even in China, and Thailand, which are younger power markets, are trying to build their market models based on LMP [38] [48].

1.2.4 Cash flow

Transmission expansion is a long-term and large-scale investment, and under competitive conditions, to recover all the investment, cash flow problem is used. For this reason, some basic simple economic concepts are involved in this thesis.

A definition of cash flow is "a term that refers to the amount of cash being received and spent by a business during a defined period of time, sometimes tied to a specific project [80]."

Future value= Prevent value/discount factor

Where: discount factor is related to the project life and discount rate [76].

More detail will be given when we use this principle in the following chapter.

1.2.5 Matpower

In this thesis the simulation package used is Matpower. The test cases were mainly solved by Matpower3.0b3+. It was updated in December 15, 2004 based on Matpower 2.0. Matpower 3.0B3+ is a package that solves Power Flow (PF) and Optimal Power Flow (OPF) problems within the Matlab 7.0 environment. It was programmed by Ray Zimmerman, Deqiang Gan and Robert Thomas at Cornell University. This package is an open resource, it is very easy to use and can be freely downloaded from the internet http://www.pserc.cornell.edu/matpowe/matpower.html

For the Power Flow formulation, there are five solvers in Matpower 3.0b3+. The default Power Flow solver is based on a standard Newton's method. The other four are based on the fast-decoupled method, Gauss-Seidel Method and variants.

For the Optimal Power Flow formulation, there are two kinds of formulations, and four solvers in Matpower 3.0b3+. The first is a traditional OPF formulation which makes the total cost of real/reactive generation the objective function. The solvers for the traditional OPF formulation are the Optimization Toolbox based OPF solver and the Linear Programming (LP) based OPF solver. The second formulation is a generalized formulation which is used by the fimcon and MINOPF solvers. These solvers are not included in the Matpower package, but can still be downloaded on the internet free of charge (http://www.pserc.cornell.edu/minopf/).

1.3 Aims of the research

The main aim of this thesis is to solve the bottleneck problem for the Chinese transmission system. How to encourage more investment for the transmission system and how to expand the transmission system in a competitive power market are also explored in this thesis.

This strategy is performed in the framework of China SERC in order to seek a multi-objective optimal planning for transmission system expansion. In order to ensure that all the investment in the transmission expansion can be recovered and the system operates under a stable condition during the system expansion. An improved transmission tariff method is introduced and research into uncertainty of LMP is undertaken.

1.4 Contribution of the thesis

Two main contributions presented in this thesis are:

To attract more investment into the transmission side and to make sure all the investment is being recovered; this thesis presents a new transmission tariff method. In this new nodal use method, the participation factors are given new definitions. Only the positive power flow is charged by the nodal use method from the network users. For this reason, the total transmission cost is recovered. A same time, the fragmentation of the transmission system for participates are decreased.

To optimally expand the transmission system, the LMP (Locational Marginal Price) selection method and the CBEP (Congestion-Based transmission system Expansion Planning) method are introduced. The LMP selection method is used to select optional plans for transmission system expansion. It is especially suitable for large transmission systems. The outstanding advantages of the LMP selection method are simplicity and computational efficiency. The CBEP method produces the optimal system expansion plan. For the first time, generation congestion and transmission congestion are separated within the system expansion problem. The risks of the generator side are controlled. For this reason the CBEP method can be used in a supply-side power market and is suitable for the Chinese power market.

1.5 Outline of the thesis

The thesis is constituted as follows:

Chapter one introduces the background of the research. The market structure and electricity demand-supply situation in China and the related concepts of transmission system expansion and transmission tariff are explained. The aim of this chapter is to introduce the research work and fundamental concepts, the criteria, the framework, the applications and the scope of the research. In addition, technical terminologies with basic mathematical formulations are briefly pointed out. Finally the aims of the thesis are described.

Chapter two presents a new transmission tariff method for recovering investment in the transmission system and encouraging more investment into the transmission network. The simulation is performed on an IEEE standard 9-bus system.

Chapter three sets out a LMP selection method for selecting an optional plan from hundreds and thousands of expansion possibilities. Deriving from the use of the LMP selection method, the total social cost is minimized. A new 28- bus test system constructed on the basis of the China Three Gorges network, is used to test the proposed method.

Chapter four proposed a new CBEP (Congestion-Based transmission system Expansion Planning) algorithm in order to achieve optimal transmission expansion planning. The IEEE standard 9-bus system and the 28- bus test system based on the China Three Gorges network are analyzed.

Chapter five compares the new CBEP method with another kind of CDEP (Congestion-Driven transmission system Expansion Planning). The CDEP method will be elaborated and contrasting results will be demonstrated.

Chapter six improves the technique for system expansion planning. The reasons for uncertain total cost when the system is congested are explained, and a simple solution is presented. The simulation is performed on the standard IEEE 30-bus system.

Chapter seven concludes the thesis by summarizing the findings of each chapter in the thesis. Furthermore, future work related to this subject is suggested.

Chapter2 : New Transmission Tariff Method of Transmission Systems: an Analysis for Cost Recovery

Following the analyses of Chapter 1, the first topic to be considered is transmission tariffs. How to recover the transmission cost and how to encourage investment to come into the transmission network are focused on.

This chapter presents an in-depth analysis of complementary charge structures for transmission systems with a new Nodal-Use method (N-U method), and in particular it investigates why the transmission system owner has to invest in the transmission system when the system is congested. The basic theoretical results are presented and how the new N-U method covers the total cost of the transmission system are identified and illustrated with a numerical example. Simple ways of calculating LMP and controlling power flow in the context of a competitive electricity market are analyzed.

2.1 Introduction

Recently, the focus of power markets is on how to enable the electricity sector to continue to meet a nation's needs for reliable and affordable energy [21]. This is due to many reasons (for example: unexpected transmission demands; over large regions; difficulty in recovering the full cost of investment in the transmission system). It has been suggested that people prefer to invest in generators rather than transmission systems [10]. If the capacity gap between generators and transmission systems becomes bigger and bigger, congestion in the transmission system will become an important problem, especially under a competitive market. In the Chinese power market, the market regulator wants to encourage a full competitive generator-side supply market to reduce the total social cost. Until now China represents the second biggest generator capacity, for the full competitive power market the transmission network problems come in front of the regulator very urgently. There are lots of ways to solve this problem. On the one hand, congestion forecasting and a careful transmission plan can relax the congestion. On the other hand, much research focus on increasing the transmission capacity in the transmission system. However if the regulator needs to solve this problem, a good method for calculating the transmission tariff should be a necessity. A good method which can afford enough benefit will give a large incentive to investors.

2.1.1 Background

There are many standards which can measure whether a method of calculating the transmission tariff is good or not. In this chapter we compare the methods based on the following tariff objectives [23] [51]:

Objective 1: Tariff stability. This means the benefit arising from the transmission system is stable and predictable. The risk is low to the investor in the business.

Objective 2: Non-discrimination. This means the method can encourage new investors to put their money into the transmission market and at the same time existing participants would like to retain their investment in the transmission market. There should be no difference between the former and the later, in order to keep the most efficient participants in the market.

Objective 3: Appropriate remuneration for the Transcos. This means the Transcos can achieve enough benefit to recover the investment in the transmission system.

Objective 4: Energy transmission efficiency incentive. This means a good method of transmission tariff definition will give the right signals and information to promote the most economic location of new investments in generation and large industrial loads.

Objective 5: Simplicity of rates. This means that the method should afford an easy and understandable way to calculate the transmission tariff for users.

Objective 6: Rates must be consistent with the other charges faced by the users. This means that the method should consider all relevant aspects for users.

If a method of calculating transmission tariffs satisfies most of the objective it can be regarded as a reasonable method.

2.1.2 Classic transmission tariff methods

a) Postage stamp type methods

The postage stamp method is the simplest and oldest method. In this method, a fixed price per energy unit is charged, independent of the distance or the voltage level [36]. The advantage of this method is the investment for the grid can be recovered precisely and in full. Also it can be used very easily. However the disadvantage of this method is obvious. First, the postage stamp method cannot give a correct incentive to suppliers or users of electrical energy for sitting future investment. Second, the postage stamp method does not improve the transport efficiency of the present system. Third, the method does not encourage future investment to improve or extend the system. For this reasons the postage stamp method does not satisfy the basic requirements of an adequate pricing system.

b) Distance related tariff

Since the postage stamp method exhibits many disadvantages, some new methods consider the distance (geographical distance or electrical distance) between generators and users. In this kind of method the distance and the voltage level are considered. Longer distance and higher voltage will be charged a higher transmission fee. Nevertheless, congestion is not considered and there is no provision of investment. A typical distance related method is the MW-Mile method.

c) Nodal pricing method

In the nodal pricing method, the actual cost of system losses and the opportunity cost of transmission constraints are included in the transmission tariff. The price of electricity is connected with the demand for electricity. The advantage of nodal pricing methods is that this kind of method offers good incentives to investment in the grid. The disadvantage of the nodal pricing method is that sometimes it cannot recover the required total investment for the transmission system. The typical nodal pricing methods are 'long-term marginal cost' methods and 'short-term marginal cost' methods.

As each kind of method is not perfect, power engineers never stop trying to improve them. More and more new methods are being introduced into the power market. For example: the nodal-use method and the nodal distance method, nodal electric distance method, etc.

In this chapter a new Nodal-Use method is built up. It is based on an existing frame which was motioned by Hyde Merrill in 2003.The definitions of 'power participation factor', 'transmission surpluses, 'cash flow' are involved in the new N-U method. All these definitions will be presented one by one in this chapter. Two obvious improvements in the improved N-U method have been proved in this chapter. On the one hand, a stable and predictable profit is offered for Transco by the improved N-U method. On the other hand, investment in the transmission system is encouraged by the improved N-U method.

This chapter is organized as follows: Section 2.2 provides the frame of the N-U method. Based on the original method an improved N-U method is presented. Some important definitions in the improved N-U method (i.e. power participation factor, transmission surplus, and transfer capacity) are made in this section. Section 2.3 points out how to restructure the system when the network is congested, and how to calculate LMPs used in this chapter. Finally, Section 2.4 presents result based on the IEEE 9-bus power system test case that addresses what might happen if the system is congested, and conclusions are drawn in Section 2.5.

2.2 The improved N-U method

The benefit to transmission companies come from the different energy price between 'from bus' and 'to bus'. This benefit is named "Network Revenue". However, because of a number of reasons, there is a gap between network revenue and total cost of the transmission companies. The transmission companies cannot get net benefit from the energy transport. For making the transmission companies recover total cost, in this chapter, N-U method is a kind of "complementary charge" for completing "Network Revenue (NR)" to the total cost.

In this thesis the definition of the total income (TI) to Transco is:

$$TI = \begin{cases} N-U\,method \quad +NR & \text{before transmission system is congested} \\ N-U\,method & \text{after transmission system is congested} \end{cases} \quad (2\text{-}1)$$

Before the improved N-U method is introduced, the NR method and the frame of nodal-use method will be described.

2.2.1 The Network Revenue method

In this method the total cost is recovered by the NR method and the improved N-U method [23].

The NR method is as follows:

$$\text{NR}= \sum_i \rho_i (g_i - d_i) \quad (2\text{-}2)$$

Where:

ρ_i is the LMP of bus '*i*'(\$/MW.hr).

g_i: generation at bus '*i*'(MW).

d_i: demand at bus '*i*' (MW).

Theoretically speaking, if the system had a perfect network, without losses or any kind of limitations, LMP at all nodal points of the system are the same. The NR is equal to zero. In the practical world the losses of system will be charged by the NR method, with the help of the improved N-U method, the Transco can recover the total costs.

In the UK, 40% of the transmission cost is recovered from distribution suppliers, 60% of the transmission cost being recovered from generators. Depending on the transmission system regulator, the rule for splitting transmission costs varies from country to country. In order to change this kind of arbitrary situation into a physically based transmission cost split will be considered in chapter 7.

2.2.2 The frame of the Nodal-Use method

In this nodal use method the use of the system is defined in terms of usage of transmission lines refer to as a 'power participation factor' (equation 2-3). Another nodal-type method also use real physical distance or electrical distance between the load and the generating stations to define the use of system.

Equation (2-2) is the frame of the N-U method [36]:

$$\pi_d(i) = \sum_{k=1}^{m} (I_k / f^k) \times F_{k\_i} \qquad (2\text{-}3)$$

Where

$\pi_d(i)$ the "use" charge at demand node 'i' in $/MW

F_{k_i} the (active) power participation factor (%)

I_k the line 'k' required income ($)

f^k the transfer capacity of line '***k***' (power flow in the line '***k***'). (MW)

m number of lines in the system

k line 'k'

i load 'i'

The new N-U method is based on the frame and defines all the factors for recovery total cost of the transmission companies. For the sake of clarity, we just include the most significant elements into the improved N-U method. This method only considers active power; and only the primary transmission services such as transportation of electric energy in the transmission system is accounted for in the total cost. Other network related services such as load-frequency control, are ignored. This means that the total cost only includes fixed capital charges plus some O&M (operating and maintenance) costs that are practically independent of the actual network operation.

2.2.3 Power participation factor F_{k_i}

The improved N-U method is motivated by the concept of nodal pricing and is based on the "Marginal Participation Factor" method. This method uses the "extent of use" criterion to allocate the "complementary charge" among the system agents. The "usage" is defined as incremental. For example, we can define 'usage' as when demand increases 1MW, the movement of power flows in each line in the whole transmission system.

The original definition of power participation factor is: the contribution to the flow in line 'k' of a 1 MW injection in the reference bus 'r' and 1MW drawn at demand bus 'i' (power participation factor) [24] [36].

However in the improved N-U method, it is not necessary to choose a reference bus. In the real situation it is not very easy to determine which bus should be the reference.

Another improvement in the improved N-U method is that only positive changes are calculated. This means, when a load is increased, the power flow of transmission system would be changed. Some power flows in branches are increased, others are decreased. The improved N-U method defines that the load should pay for the branch when the power flow in this branch is increased. In this case the changed power flow may cause congestion in this branch. Under this situation the transmission income obtained is more stable and rational.

$|P_{ki+}| = |P_k|$ The load '*i*' does not use the branch '*k*'.

$|P_{ki+}| < |P_k|$ The load '*i*' uses the branch '*k*' but the power flow of branch '*k*' is decreased with load '*i*' increased. Load '*i*' need not pay for this branch in the improved N-U method.

$|P_{ki+}| > |P_k|$ The load '*i*' uses the branch '*k*' and the power flow of branch '*k*' is increased with load '*i*' increased. Load '*i*' should pay for branch '*k*'.

Where

P_k the power flow in the branch '*k*' (MW).

P_{ki+} the new power flow in branch '*k*'(MW) when load '*i*' has increased by 1 MW.

Through the power participation factor (F_{k_i}) we can find out, for a given load, how much energy in each branch is used by it.

$$F_{k\_i} = \begin{cases} (|P_{ki+}| - |P_k|)/1MW & |P_{ki+}| > |P_k| \\ 0 & |P_{ki+}| \le |P_k| \end{cases} \qquad (2\text{-}4)$$

2.2.4 Fixed capacity charge I_k

Before the system is congested, only the fixed capital charge and some O&M costs are included. In the improved method discounted cash flow is modelled in the fixed capital charge. This is more reasonable for the Transcos.

Investment in the power system refers to the cost of purchasing and installation of a branch. Projects in the electricity supply industry extend over long periods (25-30 years). The network asset lifetimes are even longer [76]. The Network Revenue (NR) method does not count on cash flow. This is one of reason why the NR method is not able to recover the total cost. The time value of money (discounting) is highly important for capital-intensive long-life projects. For this reason the cash flow element of transmission investment is considered in the method.

The characteristic of investment in a transmission system are:

(1): To buy a new line, the transmission company must investment at a particular time (Capital-intensive).

(2): 25-30 years is the normal useful life for a branch in a power system, so the Transcos needs a long time to recover the investment. Considering the stability of energy prices, the investment should be averaged over the useful life [5].

$$DF = \frac{1}{(1+r)^n} \qquad (2\text{-}5)$$

Where

DF discount factor (%) [76]

r discount rate (%)

n the useful life of a branch (years)

$$PV = DF * FV \qquad (2\text{-}6)$$

Where:

PV present value ($/Km)

FV Future value ($/Km)

2.2.5 Transmission Surplus

Transmission surplus ($/MW.hr) is defined as equal to $|LMP_{frombus} - LMP_{tobus}|$ (see [36] for definition). Before the system is congested the LMP of each bus is same. For this reason there is no transmission surplus in the transmission system. After the system is congested, the LMP of each bus is changed. Not only the fixed capacity charge and O&M fee but also the transmission surplus is included in the total costs. This is why the congested system produces very high costs.

2.2.6 Transfer capacity f^k

Transfer capacity in general is determined by contingencies and is a function of the condition of the network [23]. The reason why the improved N-U method defines the power flow in a branch as the transfer capacity of the line is that there should be reserve capacity in each branch. The reserve capacities should not be used except for security reasons. But the main idea of the N-U method is how much the loads are charged depends on whether the load uses the branch or not. If the method defines the capacity of branch as the transfer capacity, the investment could not be recovered very easily.

2.3 Algorithms

How to implement the improved N-U method will be discuss in this section.

2.3.1 Flowchart

Fig 2.1 shows a flow chart of the proposed algorithm. The program allows a comparison of the cost and income determined by the improved N-U method.

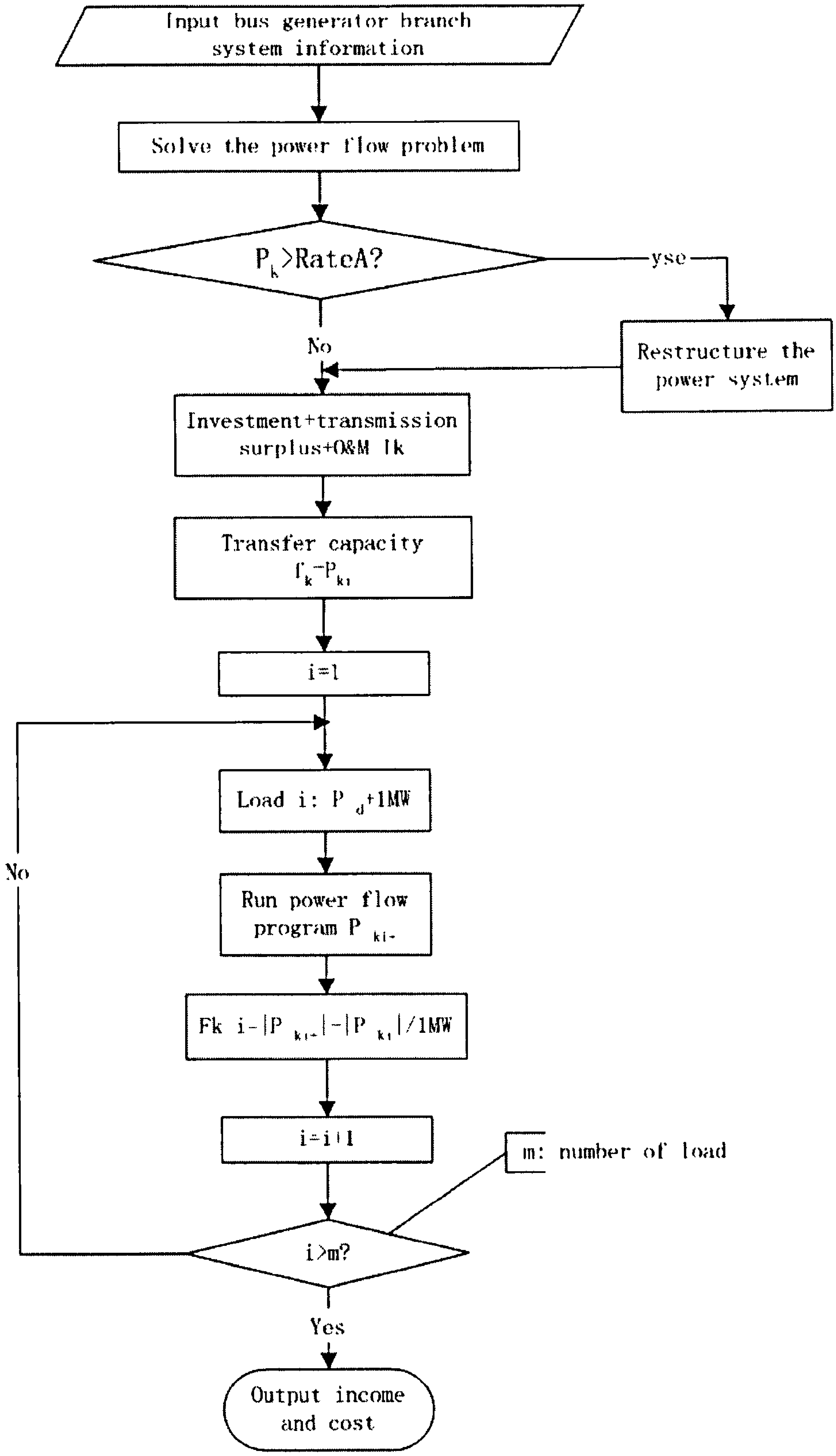


Fig. 2.1 The flowchart of the improved N-U method

There are two main problems which need be solved in this flowchart. One is how to control the power flow when the system becomes congested. The other is how to obtain the LMP of each bus under congestion conditions. We need to know LMP when the transmission surplus is calculated.

2.3.2 Restructuring the transmission system

The first problem is that in Matpower the power flow programming does not consider the question of congestion. The power flow in the line may increase continuously when it is above the capacity of line. For this reason the power flow in the transmission system should be controlled by the program which has been developed for the N-U method. The proposed method of controlling the power flow is as follows (fig 2.2):

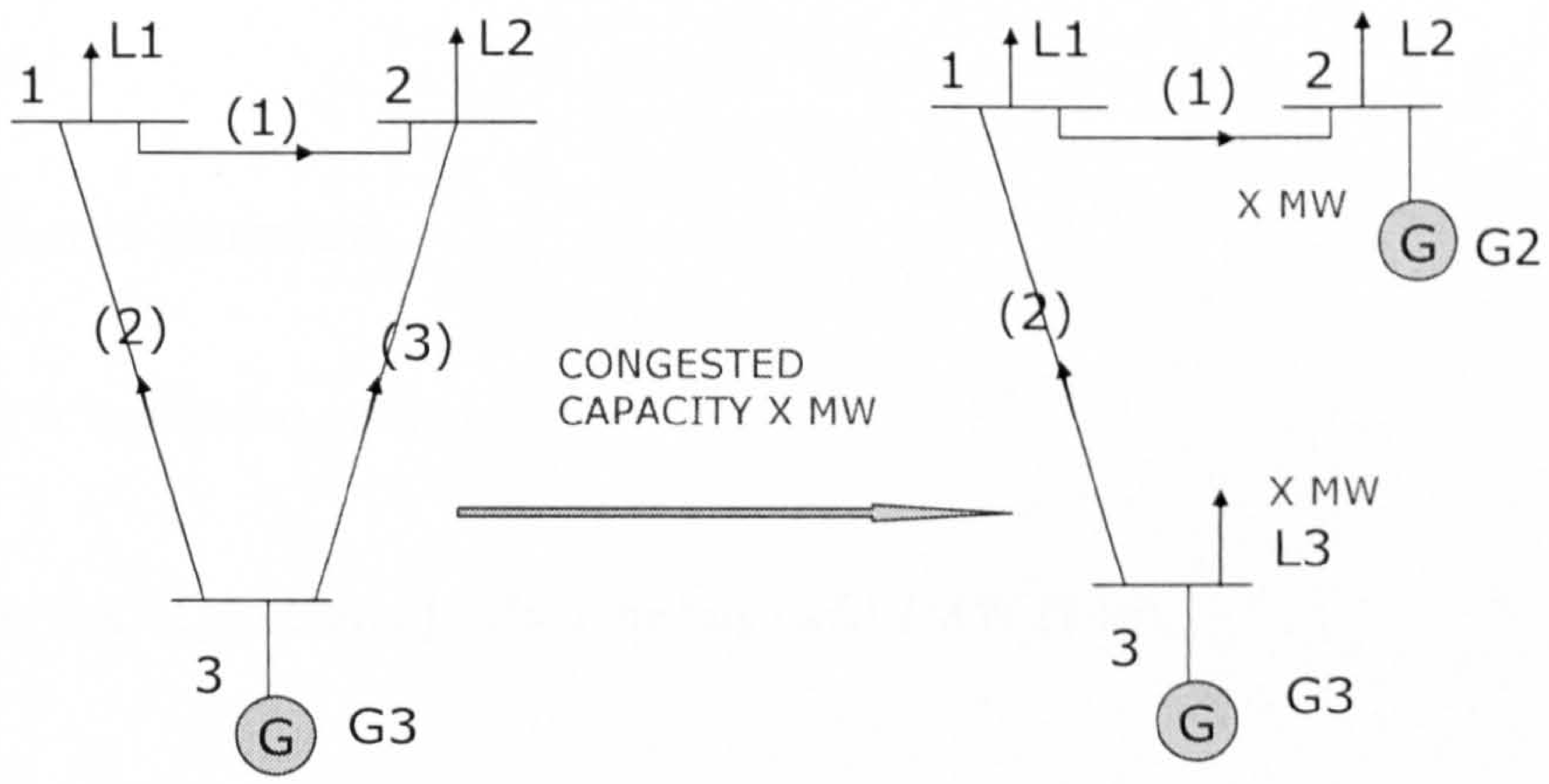


Fig. 2.2 The equivalent of a congested branch in the transmission system

For example, in this 3-bus transmission system, when line 3 is congested the program cuts the line, adding a 'virtual generator' at bus 2 and a 'virtual load' at bus 3. The input of generator 2 is equal to the capacity of line 3. The output of load 3 is equal to the capacity of line 3. The power flow in the congested line is prevented from increasing continuously and is held at the capacity of the line. However in the real system the congested line still exists so the associated cost could be calculated.

2.3.3 The method of calculating the LMP

The second problem is how to calculate the LMP of each bus when the system is congested. In an unconstrained system, generators are dispatched based on their bidding prices. The LMP is the same at any node in the system and is equal to the MCP [25]. However when the system is limited, the value of energy at each node is changed. A simplest approach is used in this chapter. The basic idea in the LMP calculations is to determine for a given set of system conditions, the minimum cost of generation that will be required to supply an incremental load of 1 MW at a given location in the network without the violation of any transmission constraints [25].

$$LMP(i) = (\sum_{j}^{n} G_j^{'} - \sum_{j}^{n} G_j)/1MW \qquad (2\text{-}7)$$

Where

i bus ***i***.

j generator ***j***.

n the number of generators.

G_j the cost of generator j ($/hr)

$G_j^{'}$ the new cost of generator j, when the bus i add 1MW ($/hr).

2.4 Case studies

2.4.1 Data of the test case

The test case is the standard IEEE 9-bus test system. Fig 2.3 illustrates the 9-bus system. Line and load information is presented in fig 2.3 and Tables 2-1 and 2-2. In this system, total energy supply is 445MW and total energy demand is 430MW. (More detailed information is given in appendix A).

The test case is used to find out whether the improved N-U method can recover the investment for the transmission system, and what will happen when there is congestion in the transmission system.

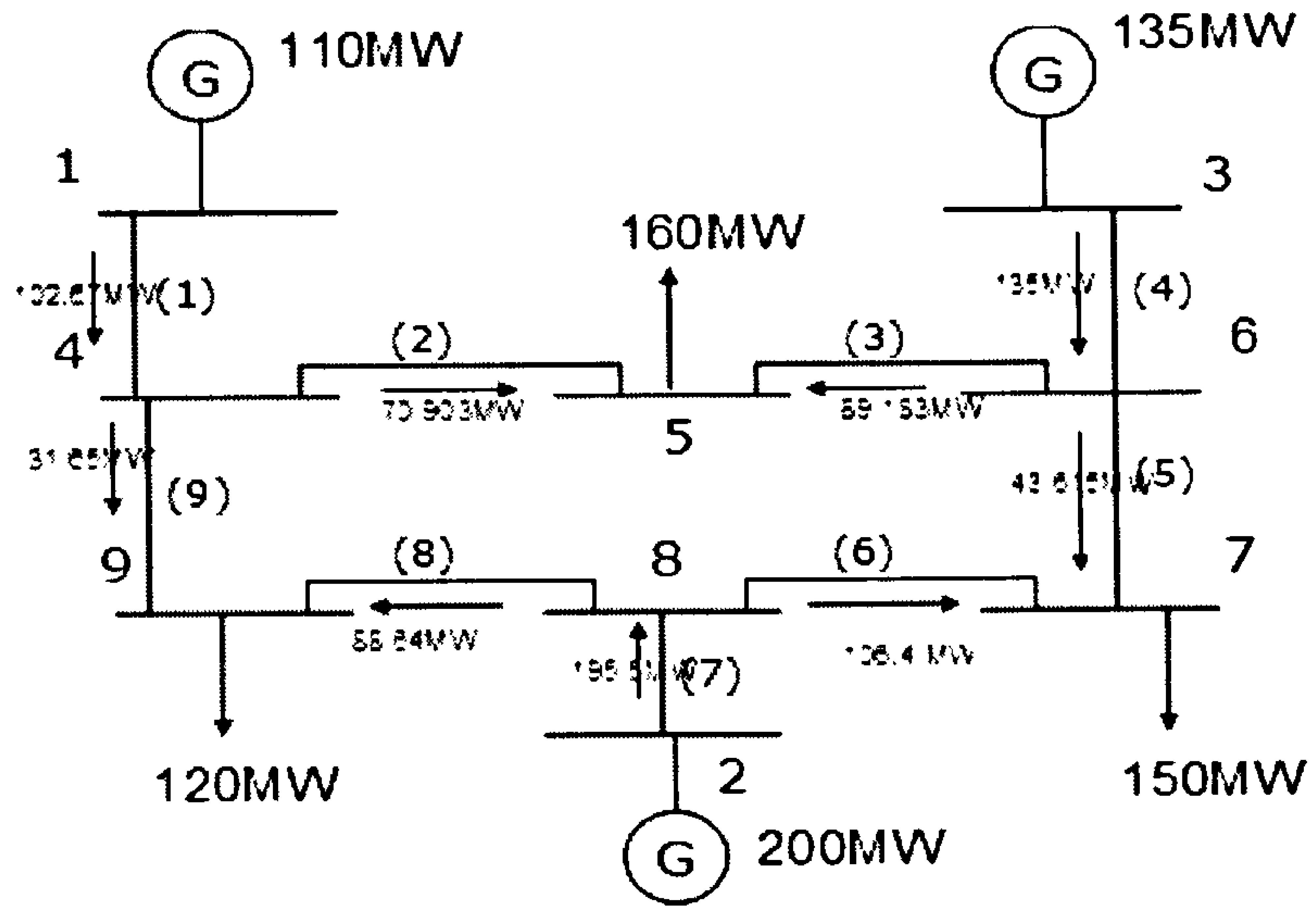


Fig. 2.3 Typical network and its power flow result

TABLE 2-1 TRANSMISSION LINE SPECIFICATIONS

From bus	*To bus*	*R Ω*	*Limit Mw*	*Investment \$/km*	*O&M \$/hr*	*Length km*
1	4	0.0101	250	66000	1.5	64
4	5	0.0716	250	66000	1.5	64
5	6	0.0725	150	66000	1.5	64
3	6	0.0108	600	66000	1.5	64
6	7	0.0805	300	66000	1.5	64
7	8	0.0920	250	66000	1.5	64
8	2	0.0119	250	66000	1.5	64
8	9	0.0234	250	66000	1.5	64
9	4	0.0652	250	66000	1.5	64

TABLE 2-2 COST FUNCTION OF EACH GENERATOR

Generator	Cost function(\$/hr)
G1	$C=0.1225p^2+p+335=2682.15$
G2	$C=0.11p^2+5p+600=3392.14$
G3	$C=0.085p^2+1.2p+150=3171.4$

To test the improved N-U method the consumption of load 5 will be increased from 160 MW to 265MW at the same time the input of generator 3 will increase from 135 MW to 240MW. During this period line 3 should become limited (fig. 2.4).

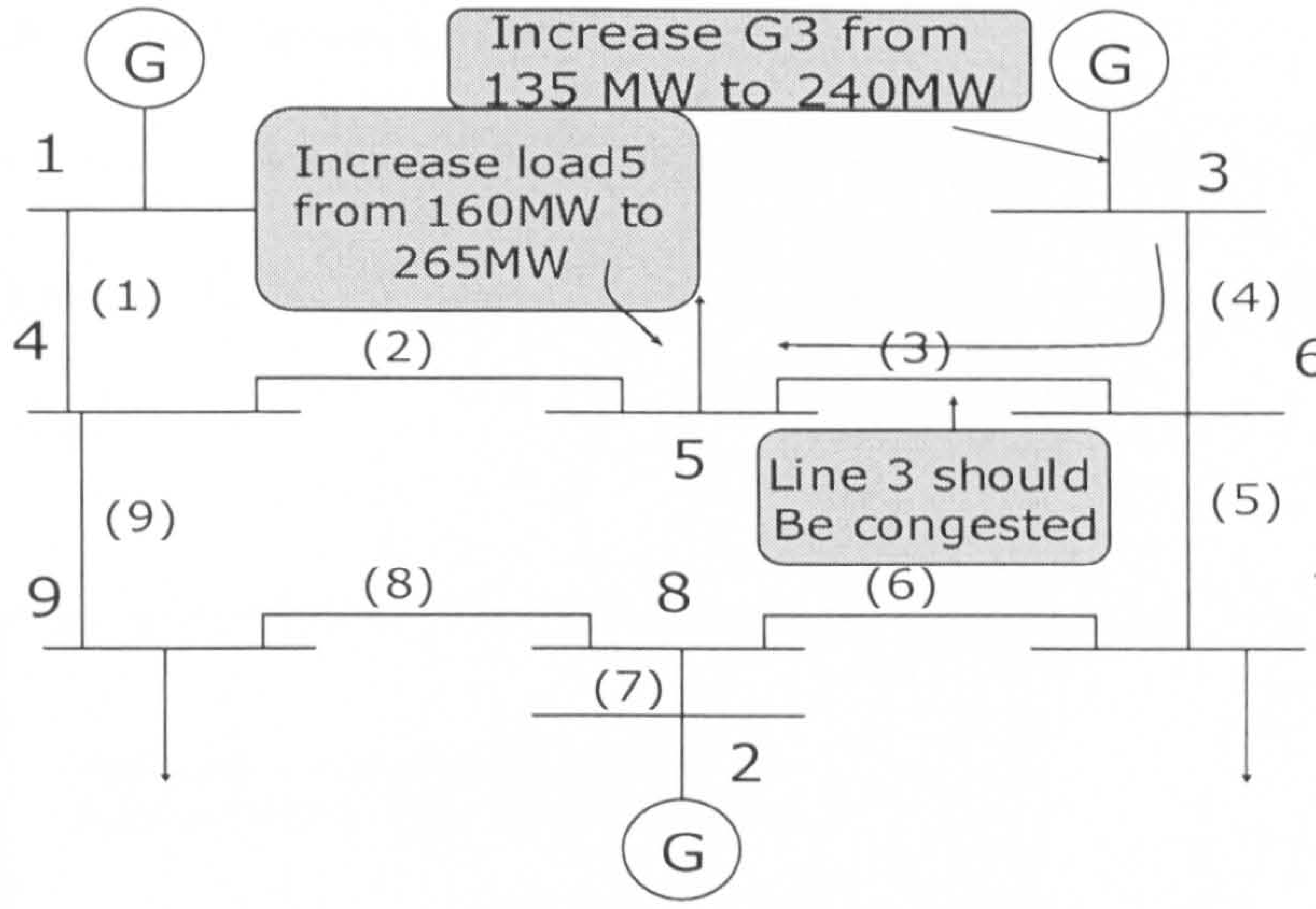


Fig. 2.4 Change G3 and load 5

2.4.2 LMP of each node

Fig. 2.5 shows that before the 9-bus system is congested, the LMP of each bus is low and does not have very big differences. The average LMP of each bus is 35.5$/MW.hr. In this chapter, the average of LMP is regard as MCP. Depending on equation 2.1, the NR is equal to 532.5$/hr. After the 9-bus system is congested, the LMP of each bus is higher than formerly. The LMP of bus 5 is the most expensive. This is due to the fact that line 3 is limited.

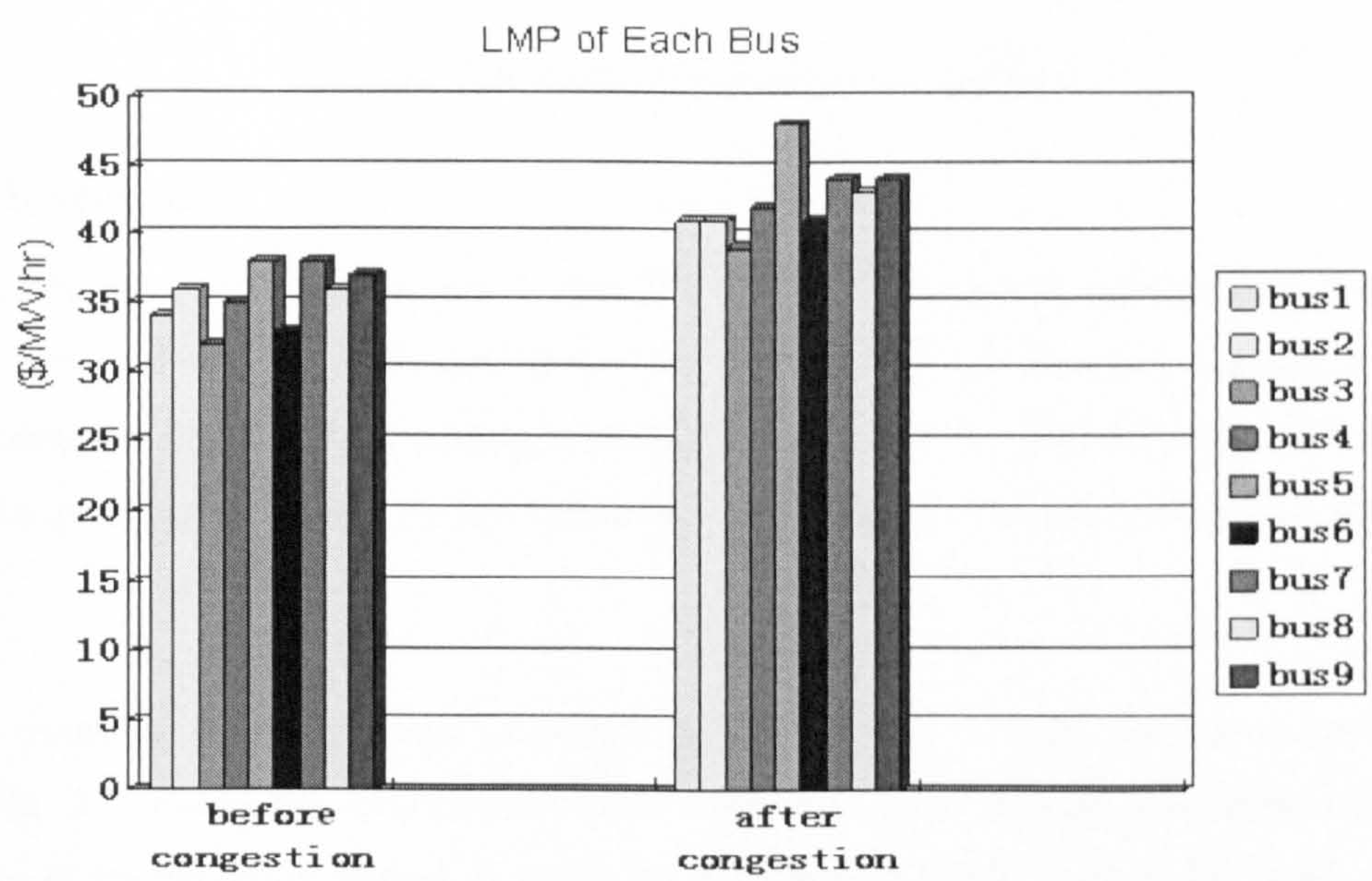


Fig.2.5 LMP of each bus

2.4.3 Result of the improved nodal-use method

From the flow chart we know I_k (the line 'k' required income) is the cost. The income is $\sum_{i}^{n} \pi_d(i)$ (where 'n' is the number of loads). In this way, we can obtain the result as follows (fig. 2.6):

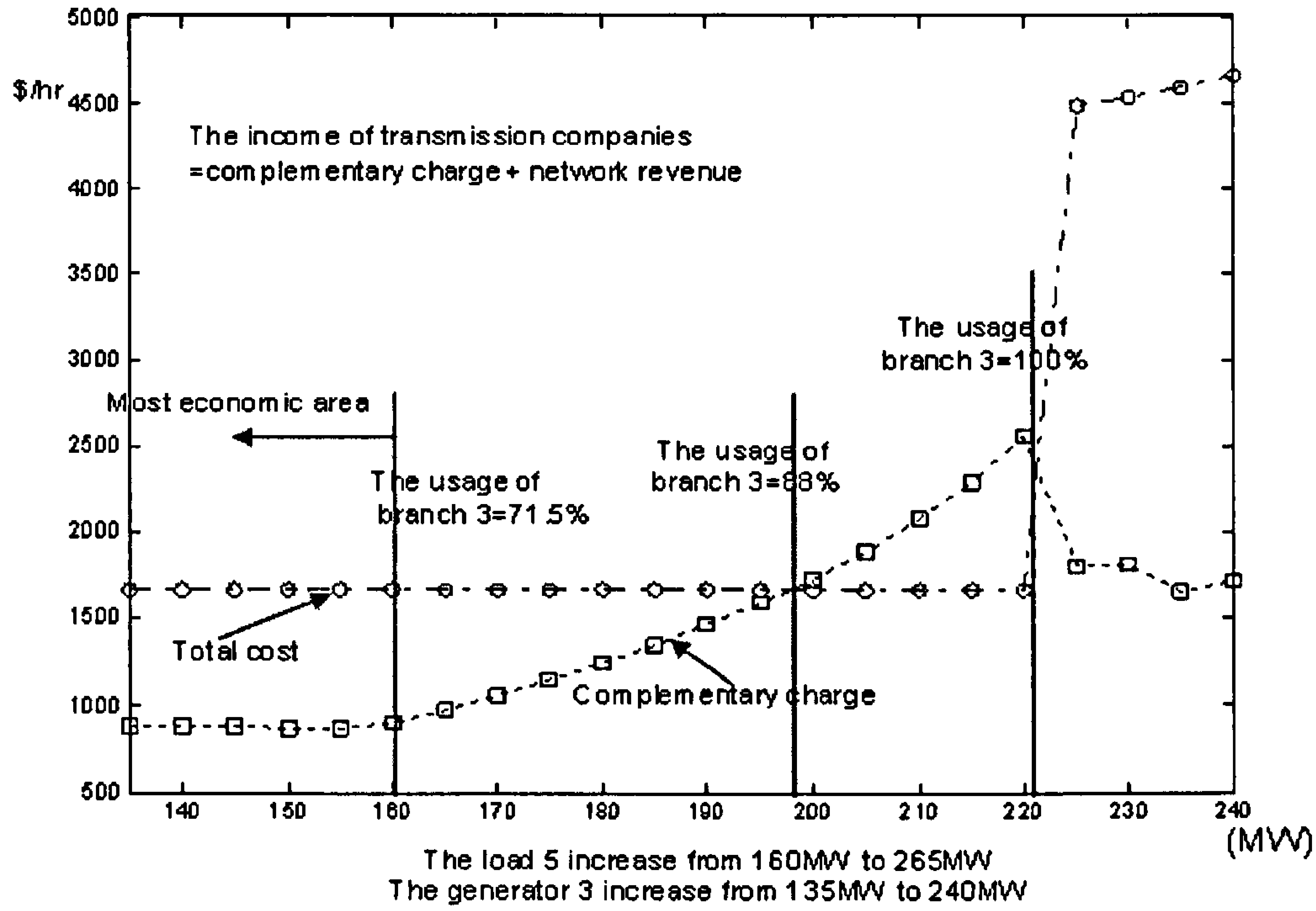


Fig. 2.6 The result of improved N-U method

2.4.4 Discussion

In general, a transmission system is operated under conditions in which the load of each line is less than or equal to the half of the line capacity (<50%). This is a reasonably secure and economic situation for a transmission system. Whether the proposed method can offer a stable, predictable benefit for the Transcos in this kind of situation is the most important issue.

In the example, when the usage of branch 3 is less than the 71.5%, the curves are nearly flat. Fig. 2.6 shows the total cost and the "complementary charge" are stable when the loading of transmission system is light. In the improved N-U method the small change (1MW) at the demand bus cannot affect the power flow in the transmission system very much. Equation (2-2) shows that when the transmission system is unconstrained and the supply and demand in the system are changed at the same time, the result of the NR method is unchanged. Under general conditions, the total income of Transcos which is obtained from the N-U method is 1410.521$/hr. For this reason it is very easy to show that the improved N-U method can offer a stable predictable profit for the Transco.

With the increase of generator 3 and load 5, the loading of line 3 becomes heavier and heavier. At this point, a 1MW change in the demand bus will have a greater influence on the power flow in the transmission system. Through the improved N-U method the "complementary charge" from each user is increased. This means the benefit to Transco is increased. However, the loading of the transmission system is heavy. In the test system when the complementary charge becomes larger than the total cost the utilization of branch 3 is 88%. In another respect, it is a signal that the system will be congested. After the usage of transmission line over 100%, the total cost and transmission complementary charge get very dramatic change. The reasons are as follows:

When the transmission system is limited the congestion fee will be accounted for in the total cost by the transmission surplus, which is an element in the improved N-U method. The result of the NR method is replaced by the transmission surplus. For this reason, the total cost suddenly increase because of congestion cost. With the increase of the total cost the "complementary charge" is decreased. When the load becomes heavier the "complementary charge" obtained from the improved N-U method will decrease continuously. There is then no benefit to a transmission company. This provides the main incentive to the transmission company to put more investment into the transmission system.

2.5 Conclusions

This chapter presents an improved, simple, efficient and practical N-U method for determining the transmission tariff, which extends the NR method to recover the investment for the transmission system. The method depends on the nodal pricing method and "marginal participation factor".

In terms of the tariff objectives, when the transmission system operates under normal conditions the improved N-U method can offer a stable and predictable income to Transco.

At the same time the value of electrical energy is not too expensive, and society can obtain efficient welfare. For the Transco, if the transmission system is congested, the benefit is reduced and the cost increased because the transmission surplus is put into the cost. For this reason, investing in the transmission system is given a significant incentive by the improved N-U method.

Chapter3 : LMP Selection Method

The topic of the previous chapter was the transmission tariff. This mainly discussed how to encourage more investment in transmission systems; how to recover the total cost of the transmission system and relieve congestion by the introduction of a new transmission tariff method. However to avoid the transmission bottleneck issue, merely encouraging investment into the transmission system is not enough. In the remainder of this thesis, the main topic is how to encourage adequate transmission system expansion planning.

Chapter 3 introduces a new method for discovering optional plans for transmission system expansion.

3.1 Introduction

The goal of transmission system planning is to establish where to install the new equipment required for an economic and reliable supply of the predicted load. There are many kinds of mathematical methods used for transmission planning, such as branch-and-bound algorithm[16], sensitivity analysis, Benders decomposition, simulated annealing, genetic algorithms, tabu search algorithms etc[17] [18] [32] [97] [98]. However these are not strictly designed for the competitive power market. Hence in this chapter a new LMP selection method will be proposed.

The proposed method which solves the expansion problem has the following features:

1. The LMP selection method alone is not suitable for selecting optimal transmission expansion plans. It is suitable, however, for finding out which locations are appropriate to add new circuits to relieve the energy shortages. For selecting optimal transmission plans, an optimal transmission expansion planning method should be used together. Such as Congested-Based System Expansion Planning (CBEP) method which will be introduced in the next chapter.

2. The LMP which is derived from MATPOWER is a very important signal in the LMP selection method. Except for the OPF formulation, the remaining part of method is linear.

3. The main idea of the LMP selection method is that new circuits which satisfy new energy requirements should not adversely affect existing loads, i.e. the LMP of the original load should not be increased. The total operation cost should reduce due to the relaxation of congestion by the new circuits.

4. Due to the simplicity of the LMP selection method, it is suitable for large-scale transmission systems. It is especially designed for a restructured power market because it focuses on minimizing discrimination and maximizing total social welfare. This LMP selection method is suitable for use by a non-profit transmission administrator.

5. Load increases at existing bus are not included in LMP selection method. However, it will be considered in CBEP method (chapter 4).

A new 28- bus test system constructed on the basis of the China Three Gorges network is used to test the proposed method.

3.2 Proposed concepts and algorithm

In a small transmission system, every possibility of expansion can be calculated individually. However in a large system, a way to select the optional expansion plans has to be found. The number of optional expansion plans should be an acceptable number. The method to select optional expansion plans in this chapter is introduced as follows:

In the LMP selection method, LMP can be regarded as a very important signal for system expansion. The main idea is that: a good expansion method must minimize disruption for every user and maximize social welfare. If new lines are built which make the LMP of certain buses increase more than others, it could be regarded as unfair for users in those locations. On the other hand, a good system expansion plan option should minimize total social cost. For this reason the average LMP in the whole system is considered as well. Some transmission expansion plans are equitable but the average LMP in the system is quite high. This kind of expansion plan will not be selected as an option.

More details about the proposed way to select system expansion options are as follows (fig 3.1):

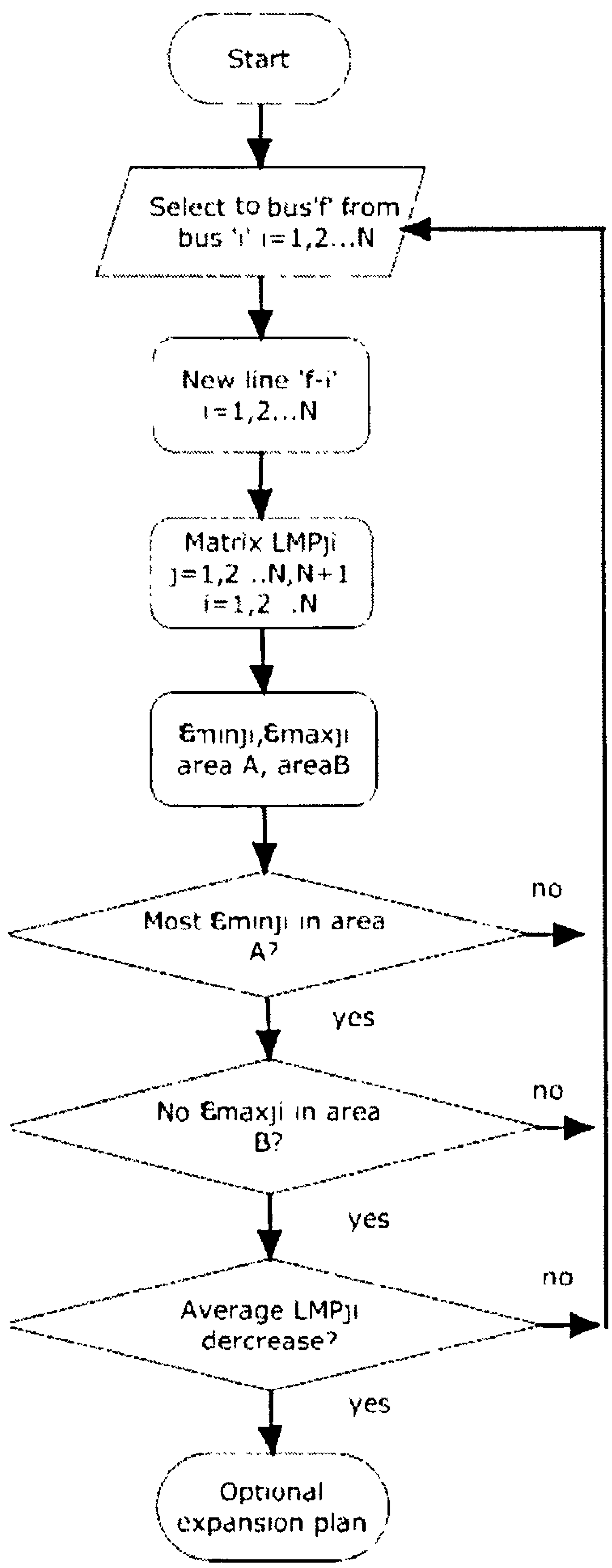


Fig. 3.1 Flowchart of selection of transmission planning options

Step1: A 'to bus' will be selected. 'To bus' means a transmission line is going to be connected on this bus and the electric power will usually be injected form the line into this bus. At beginning, the 'to bus' is a new load.

Step2: If the number of buses in this system is N and each time only one new line which may connect to any existing bus is put into the system, there are N expansion plans. They are line '$f-i$' where '*f*' is the 'to bus' and '*i*' is the 'from bus'. In this step all the possibilities are there for included.

Step3: Each time a new line connects the new load into the existing system, the LMP of each bus will change. At this moment the number of buses in the system should be N+1. We suppose 'j' is bus number and j=1, 2....N, N+1. We can obtain a matrix LMP_{ji} (N+1×N) which is named the LMP matrix in this thesis (fig 3.2).

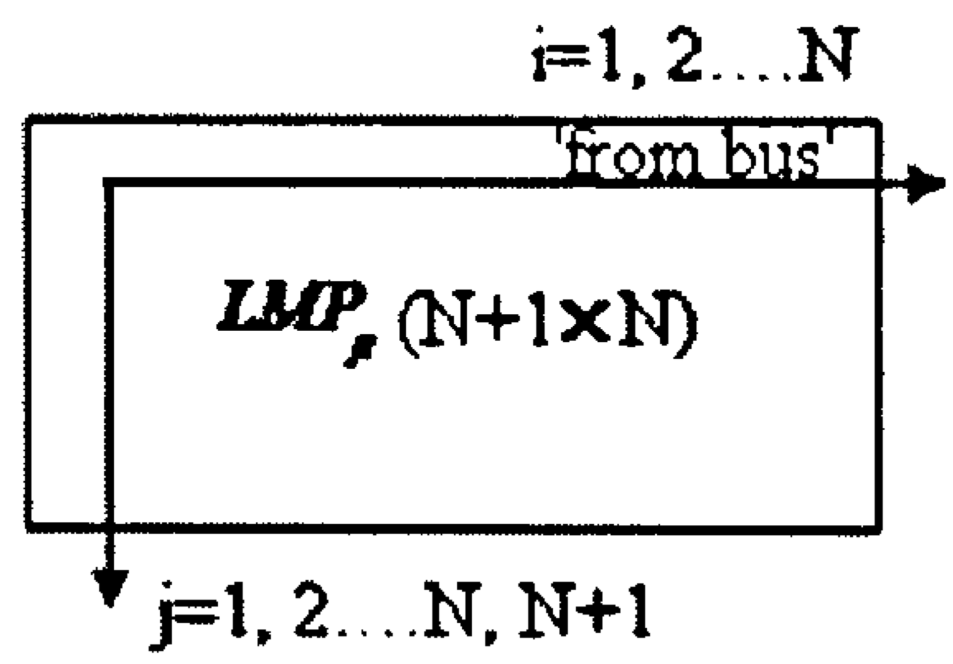


Fig. 3.2 LMP matrix for LMP selection method

Step4: Depending on this matrix (fig 3.2), $\varepsilon_{\min ji}$, $\varepsilon_{\max ji}$, area A and area B are defined. This will make sure that after a new line is put into the system, the LMP at every bus does not change too much.

i is the bus number not including the new load. This means there are ***i*** optional expansion plans. In equation 3-1 $\varepsilon_{\min ji}$ measures in these ***i*** expansion plans which plan gives the minimum impact to the LMP of each bus in the new transmission network. In equation 3-2 $\varepsilon_{\max ji}$ measures in these ***i*** expansion plans which plan will affect the LMP of each bus in the new system significantly.

$$\varepsilon_{\min\ ji} = \frac{LMP_{ji}}{LMP_{\min\ j}} \qquad (3-1)$$

$$\varepsilon_{\max\ ji} = \frac{LMP_{ji}}{LMP_{\max\ j}} \qquad (3-2)$$

Area A $\quad 1 \le \varepsilon_{\min ji} \le \overline{\varepsilon_{\min}}$ j=1, 2....N, N+1 (3-3)

Area B $\quad \underline{\varepsilon_{\max}} \le \varepsilon_{\max ji} \le 1$ j=1, 2....N, N+1 (3-4)

Where

$LMP_{\max j}$ the Maximum LMP of bus j when 'from bus i' is changed.

$LMP_{\min j}$ the minimum LMP of bus j when 'from bus i' is changed.

$\overline{\varepsilon_{\min}}$ is upper limit of area A.

$\underline{\varepsilon_{\max}}$ is lower limit of area B.

$\overline{\varepsilon_{\min}}$ and $\underline{\varepsilon_{\max}}$ can be defined depending on the conditions of the network and depending on how many optional expansion plans are desired to be selected.

Step5: If the expansion plan satisfies all three constraints at the same time, it will be selected as an expansion option.

Constraint one: most of the $\varepsilon_{\min ji}$ in area A (for example 80%)

The more of $\varepsilon_{\min ji}$ of the system in area A, the less a new expansion plan will affect the system, which is fair to every load.

Constraint two: no $\varepsilon_{\max ji}$ in area B

The more $\varepsilon_{\max ji}$ of the system in area B, the more a new expansion plan will affect the system, which means the new transmission would be unfair to some loads at which the LMP is increased.

Constraint three: compared with the existing transmission system, the average LMP is not increased.

There are three possibilities:

Possibility ONE: good options. When a new line $f-i$ is put into the system, in the entire system most of the $\varepsilon_{\min ji}$ cases are in area A and there are no $\varepsilon_{\max ji}$ cases in area B; and the LMP does not increase compared with the LMP of the former system. Then this new line will be selected as an optional transmission plan.

Possibility TWO: bad options. When a new line $f-i$ is put into the system, in the entire system most of the $\varepsilon_{\max ji}$ cases are in area B. This new line will not be considered as an optional transmission plan.

Possibility THREE: improvable options. When a new line $f-i$ is put into the system, most of the $\varepsilon_{\min ji}$ cases are in area A. But there are one or two $\varepsilon_{\max ji}$ cases in area B, these lines are not perfect transmission expansion plans, however they can be options which can be improved.

If the third situation happens, the 'from bus' 'i' will be selected as a new start point. Another new line will be considered to link into this system.

3.3 Case Studies

3.3.1Simple case for LMP matrix

To make clearer the LMP selection method, a three-bus system is introduced here to illustrate how the LMP matrix is constructed.

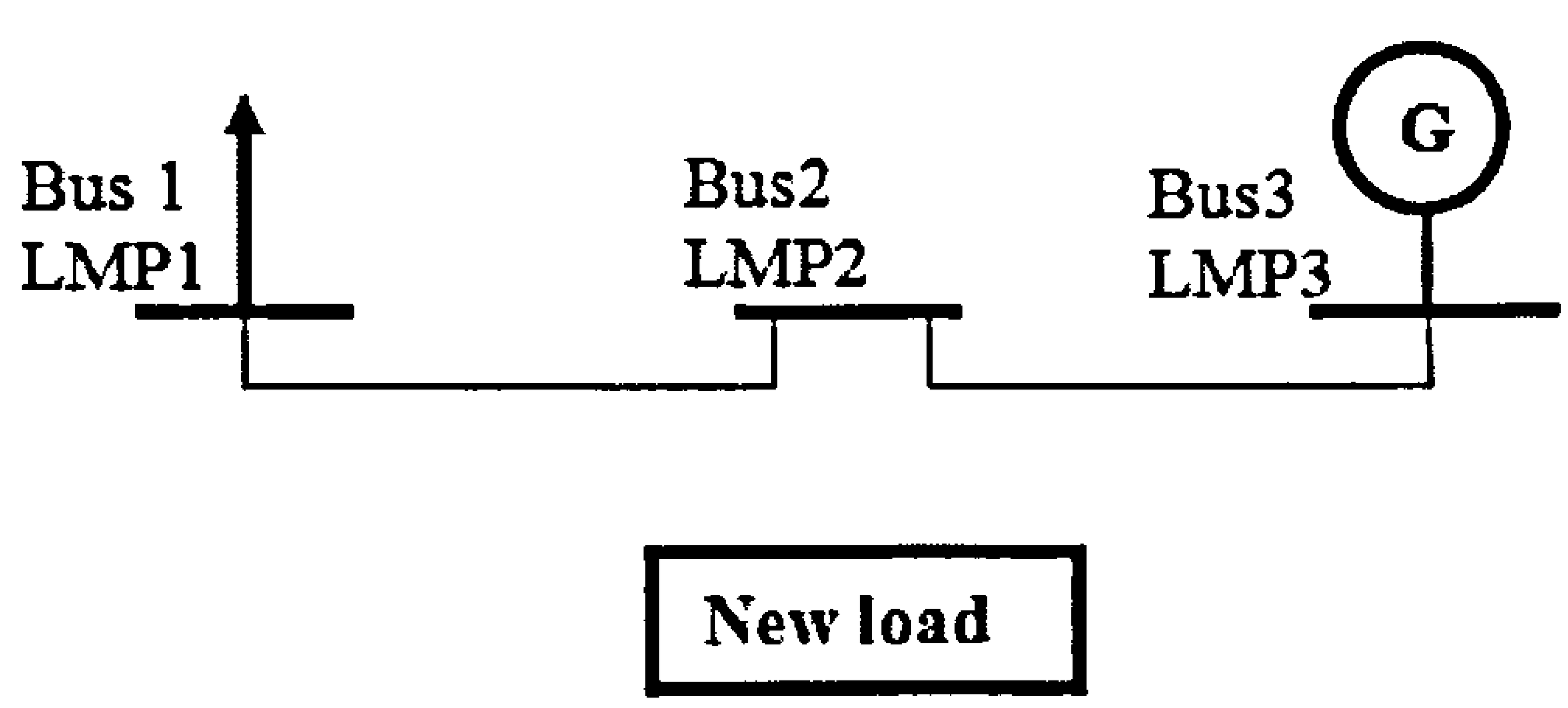


Fig. 3.3a Original LMP at three-bus transmission system

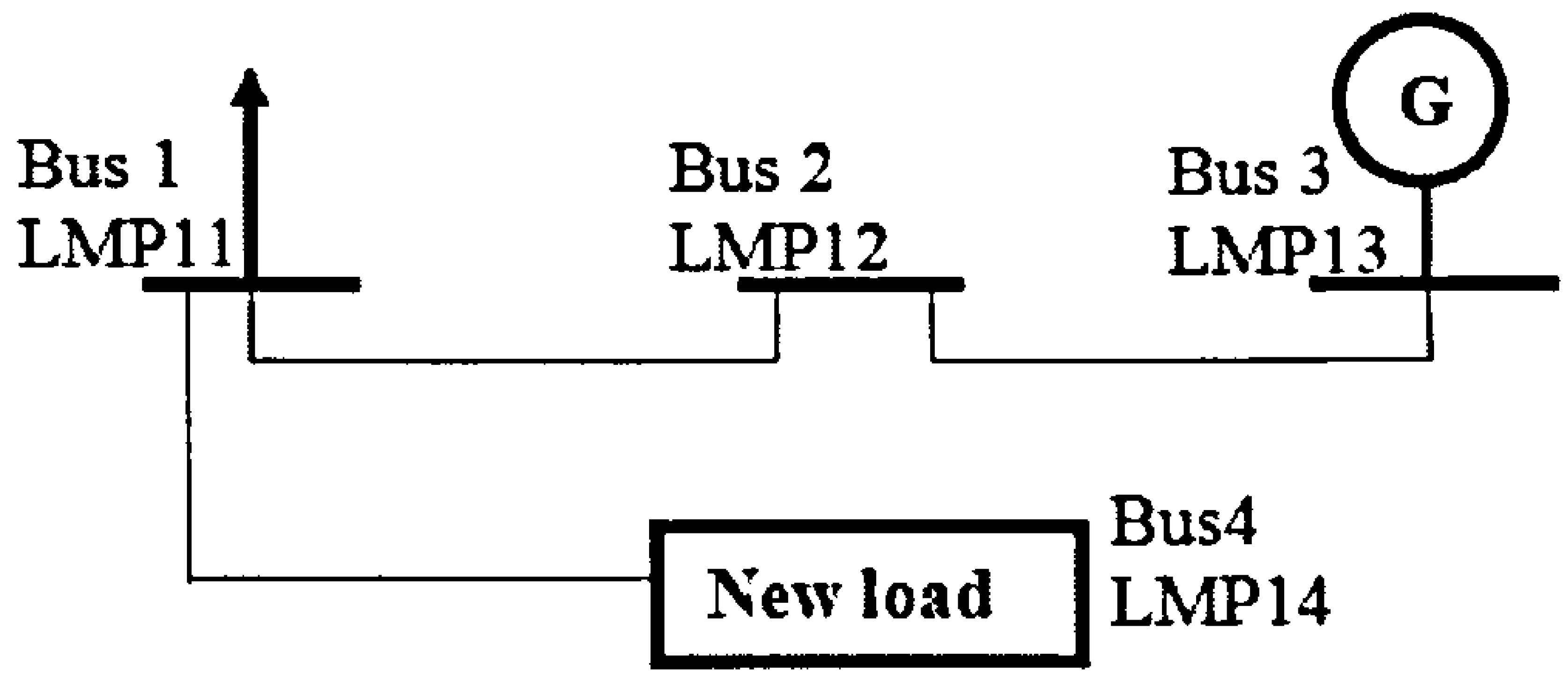


Fig. 3.4b New LMP when bus 4 connects with bus 1

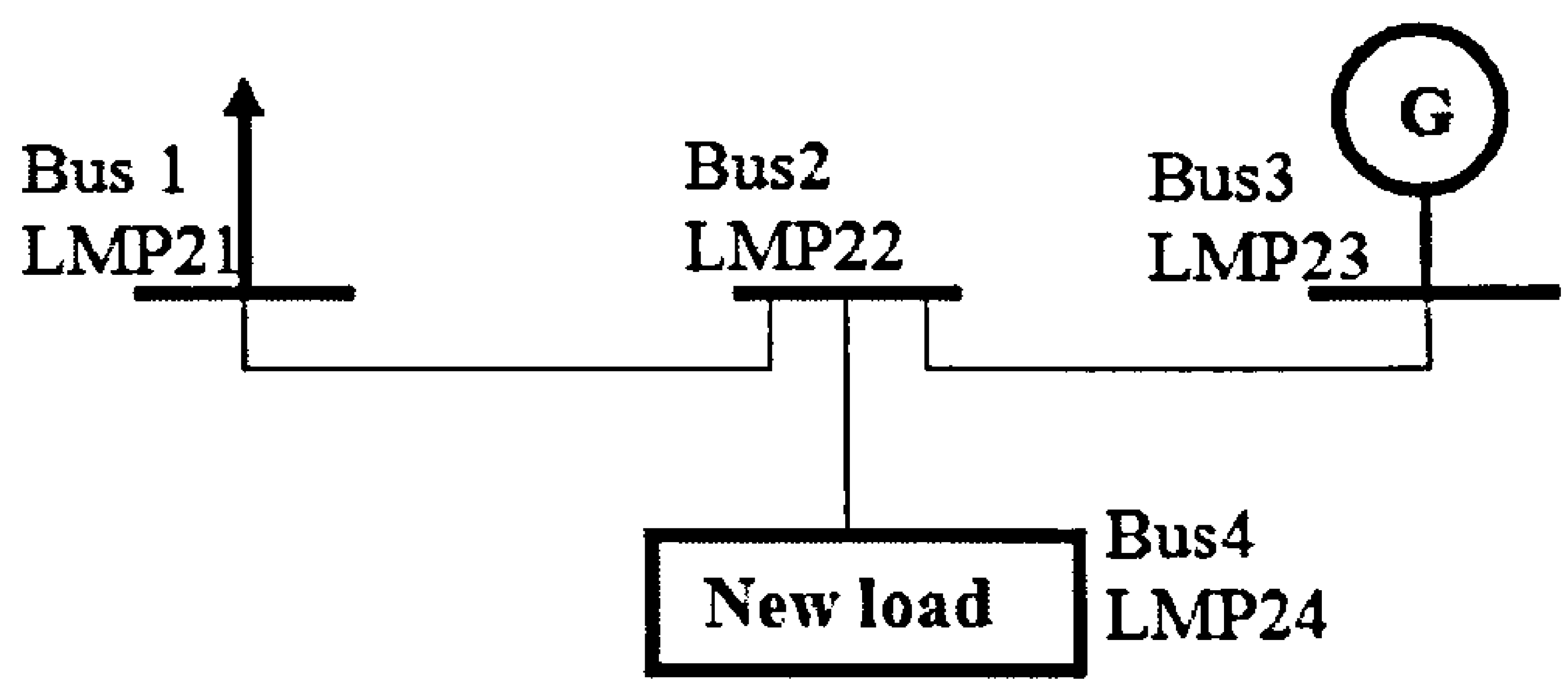


Fig. 3.5c New LMP when bus 4 connects with bus 2

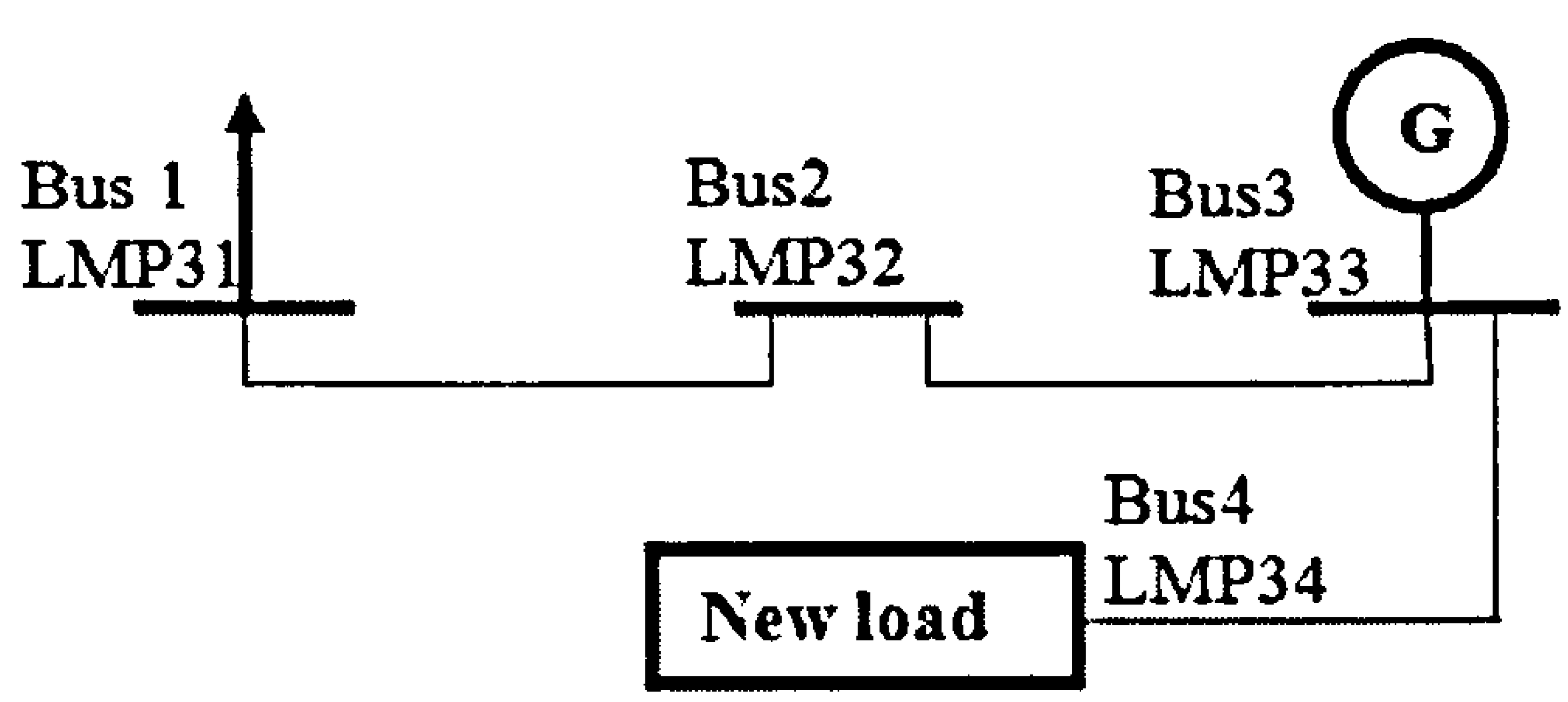


Fig. 3.6d New LMP when bus 4 connects with bus 3

In this three-bus test transmission system, we can abtain (fig 3.3b, fig 3.3c, fig 3.3d):

$LMP_{ij}=LMP_{34}=$

$$\begin{vmatrix} LMP11 & LMP12 & LMP13 & LMP14 \\ LMP21 & LMP22 & LMP23 & LMP24 \\ LMP31 & LMP32 & LMP33 & LMP34 \end{vmatrix}$$

For ease of calculation in Matlab, the LMP matrix is defined according to $LMP_{ij}'=LMP_{ji}$ (fig 3.2).

3.3.2 Test case based on Three-Gorge Project in China

The Three Gorges Hydrodynamic station has two stations with four independent bus bars (see fig 3.3 left1- right4), 18.2 GW capacity in 2010[4][15][31]. Three-Gorge supplies energy to Central China (buses: nanyang, xingyang, xiangfan, xiaogang, jingmen, hankou, jinsha, huangzhou, qianjang hanyang, xianning, xialu, fenghangshan) East of China (buses: xinyu, changxi, changdong, xinchang, loudi, yiyang, gangshi) and Sichuan-ChongQing (buses: wanzhou, changshou, jianbei, chenjiaqiao). More data about the test case is given in appendix B

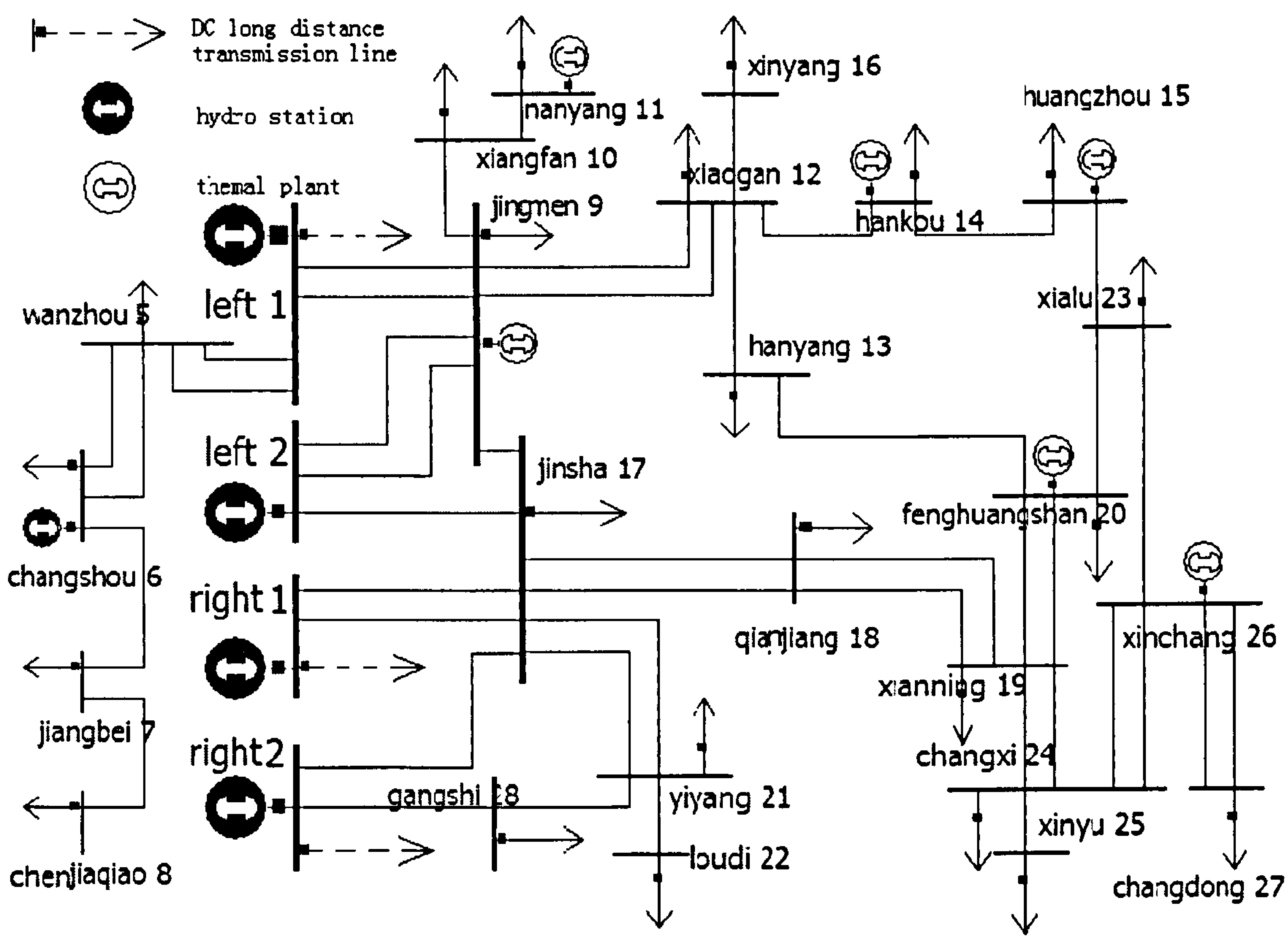


Fig. 3.7 Three-Gorge AC transmission system

TABLE 3-1 BUS INFORMATION

Bus number	***Name***	***Population (10,000)***	***Chinese name***	***Bus type***	***Pd (MW)***	***Qd (MVar)***
1	left 1	null	左岸 1	3	5000	2150
2	left 2	null	左岸 2	2	0	0
3	right 1	null	右岸 1	1	5000	2150
4	right 2	null	右岸 2	1	5000	2150
5	Wanzhou	167.95	万州	2	251.93	108.33
6	Changshou	88	长寿	1	132	56.76
7	Jiangbei	49	江北	2	73.5	31.605
8	Chenjiaqiao	30	陈家桥	2	45	19.35
9	Jingmen	299	荆门	1	448.5	192.85
10	Xiangfan	571	襄樊	2	856.5	368.3
11	Nanyang	1090	南阳	1	1635	703.05
12	Xiaogan	470	孝感	2	705	303.15
13	Hanyang	50.7	汉阳	2	76.05	32.701
14	Hankou	230	汉口	1	345	148.35
15	Huangzhou	34	黄州	1	51	21.93
16	Xinyang	787.55	信阳	2	1181.3	507.97
17	Jinsha	54	金沙	2	81	34.83
18	Qianjiang	94	潜江	2	141	60.63
19	Xianning	279	咸宁	2	418.5	179.95
20	fenghuangshan	30	凤凰山	1	45	19.35
21	Yiyang	453	益阳	2	679.5	292.19
22	Loudi	378	娄底	2	567	243.81
23	Xialu	14.6	下陆	2	21.9	9.417
24	Changxi	15	厂西	2	22.5	9.675
25	Xinyu	113	新余	2	169.5	72.885
26	Xinchang	20	新厂	2	30	12.9
27	Changdong	15	厂东	2	22.5	9.675
28	Gangshi	25	冈市	2	37.5	16.125

*Buses 1- 4 (left1 left2 right1 right2) are the location of the generators of Three Gorges. Real load 1-4 is the electrical power that is transmitted to East China or Central China.

** Buses 5-28 are cities. Some of them include generators others are loads only.

In China an average 150-watt load is needed per person. The demand varies between different cities. For simplicity, 150-watt is defined as an average demand per person, and investment for each line is taken to be 10000$/km.

Real load= population $\times$demand/person (MW)

Reactive load= real load $\times$ 43% (MVar) [35]

In this test case a new load will be put into the 28-bus system. The new load is at bus 29 with active power 117.9MW and reactive power 50.69Mvar.

Assume the new transmission line 'to bus' is bus 29 'from bus' is bus 'i' (i=1, 2…28). Capacity of line29-i is 1300MVA. When 'i' ranges from 1 to 28 we can get a matrix of LMP (29$\times$28). (See appendix C)

In is chapter, $\overline{\varepsilon_{\min}}$ is equal to1.03. $\underline{\varepsilon_{\max}}$ is equal to 0.99.

As the Three Gorges Project is used as the test case, the need to calculate power price for hydro electricity cannot be avoided in this chapter. There are many papers which discuss how to define the energy price for hydro generation. However, the price model which is currently used in the Three Gorges Project in China will be used.

In China currently the power price of Three Gorges is stable instead of flexible. Because on the one hand, electricity is a kind of energy in which demand is more than supply, bidding would make electricity prices higher and higher. On the other hand, the investment in the Three Gorges Project is a government regulated investment (in total 9,100,000,000$). The huge investment must be recovered. The Chinese power market is not a mature power market, and at present 'monopoly' and 'competition' is mixed together. More and more generators and transmission circuits are being built in China to make sure competition will become possible [28] [29] [37]. Presently, the electricity price of Three Gorges is the average LMP in China which is decided by the SERC. For this reason, the energy price of Three Gorges used in this chapter is the average LMP in the grid [33].

Following the flowchart (fig 3.1) the 'to bus' is the new load centre (bus no.29). Table 3-2 shows how many buses in the existing grid are suitable for a new transmission line. In the third column which is named 'improvable options' shows the 'from bus' of line will become the new start bus. For example, in the new line '29-5-?' bus 5 is new 'to bus' which will be connected to every existing bus except bus 29. After that, new 'good options', 'bad options' and 'improvable options' which depend on the new LMP map, will emerge. In this test case, the maximum number of transmission lines is three. Depending on circumstances, the number is flexible.

TABLE 3-2 BUS 29 AS 'TO BUS'

Good options	***Bad options***	***Improvable options***
29--1	29--3	29-5-?
29--2	29--4	29-8-?
29--6	29--14	29-12-?
29--7	29--17	29-13-?
29--9	29--18	29-16-?
	29--28	

More detail about the transmission network of the test case:

Depending on functions (3-1) (3-2) (3-3) (3-4), the optional plans for this test case are as follows (table3-3):

TABLE 3-3 OPTIONAL EXPANSION PLANS AND LENGTH FOR EVERY NEW PLANS

Optional plans	*Line no.1*		*Line no.2*		*Line no.3*		*Total Length (km)*
	Bus NO.	*Length (km)*	*Bus NO.*	*Length (km)*	*Bus NO.*	*Length (km)*	
1	29--1	509.4					509.4
2	29--2	509.4					509.4
3	29--6	969.5					969.5
4	29--7	924.1					924.1
5	29--9	431.4					431.4
6	29--5	875.8	5--28	618.4			1494.2
7	29--13	245.9	13--23	93.3			339.2
8	29--13	245.9	13--15	53.8	153	374.7	674.4
9	29--13	245.9	13--15	53.8	1517	118.1	417.8
10	29--8	1024.9	8--23	890.8	233	385.1	2300.8
11	29--8	1024.9	8--23	890.8	2317	97.3	2013

*Setting the distance of two cities as the length of transmission line [33].

3.4 Conclusions

The LMP selection method is a good way for finding optional transmission plans. The first advantage is that this method is suitable for a competitive power market. It is quite fair to every generator and load. The total social welfare is also considered. A second advantage in this kind of method is that it is simple and fast. There is no complex mathematics method required. There is not too much data which needs to be dealt with either. The method is suitable for a real transmission system. Even in a 28-bus transmission system the possibilities of expansion plans are huge (the number equal to $C_{28}^{28}+C_{28}^{27}+...+C_{28}^{2}+C_{28}^{1}$); the most important advantage of this method is that it can select reasonable optional expansion plans very quickly. The third advantage is that this method is flexible enough. Area A and area B can be defined depending on the situation of the system and depending on how many options the user wishes to consider.

The next chapter will be based on the results which are determined by the LMP selection method, and will define an optimal system expansion plan.

Chapter4 : Congestion-Based Transmission System Expansion Planning Method

Chapter 3 presented a new LMP selection method for optional transmission system expansion planning. In Chapter 4 we will focus on how to find the optimal transmission system expansion planning based on the available optional plans.

A new objective function which is based on minimizing total social cost is introduced in this chapter. Results obtained from the 9-bus test system and 28-bus test system will be discussed in this chapter.

4.1 Introduction

Transmission system expansion planning in a market-based transmission system has become a very important issue, and extensive research on all aspects has been presented [1-3], [5], [6], [8-11]. Before the power market is restructured, the main task of system expansion is to maintain the reliability of the transmission system. After privatization, under a competitive power market, the Transco responsible for transmission planning considers not only the system stability but also many other issues. For example, after the transmission system has been expanded, can the new transmission lines encourage competition and decrease discrimination for every participant in the power market? Who will provide the funds to finance the new transmission lines? How should the investment recovery and return be implemented? To minimize the expansion investment or maximize the total social warfare, the system operator has to consider more uncertainty factors and risks. For example, the Transco needs to consider the generation plan and transmission system expansion at the same time, and long-term expansion planning should be coordinated with short-term transmission plans.

Briefly, there are two main differences between regulated and deregulated transmission system expansion planning [11]. Most of the previous research is cantered on these two topics depending on different mathematical or economic methods.

1. The objectives of transmission expansion planning are changing.

Before the market restructuring, all the generators, transmission system and distribution belong to one owner, the objective function of system expansion is to minimize the total expansion cost. After market restructuring, the objective function needs to consider fair competition, minimize total social cost, control risk etc.

2. In deregulated electricity markets, there are more uncertainties and risks in the transmission expansion planning problem.

In this chapter, which focuses on the power market in China, the main problems that will be addressed are:

1. How can we define a CBEP (Congestion-based transmission system expansion planning) method?

2. How can the optional expansion plans be provided for a large-scale system?

3. How can the new methods encourage competition in the power market, and at same time, decrease discrimination for each participant?

4. How suitable is the CBEP method for China?

Section 4.2 provides the model of transmission expansion planning and gives some improvements under the competitive power market. Section 4.3 present two test cases. A simple 9-bus test case under a normal situation and a 28-bus transmission system based on the Chinese Three Gorges power grid are presented. We will also discuss why the new method is suitable for China, and draw conclusions in the Section 4.4.

4.2 Proposed concepts and algorithm

4.2.1Traditional Transmission System Expansion Planning Method

Objective function: [12]

$$Min \quad v = \sum_i C_i m_i + \sum_l \alpha_l r_l \quad (4-1)$$

Subject to:

$Sf + g + r = d$ Supply demand balance

$f_l - (\gamma_l^o + x_l)\Delta\theta = 0$ "DC" load flow equations

$|f_l| \le \overline{f}_l$ Power flow constraint

$0 \le g \le \overline{g}$ Generator constraint

Where:

v total cost of system expansion plan ($)

i new branch number

l line number in intact transmission system

m_i number of circuits added to branch i

C_i investment to new branch i ($)

α penalty parameter associated with loss of load caused by lack of transmission capacity. ($/MW)

x_l total new circuit susceptance added to branch l

γ_l^o before new branches are added, initial susceptance in branch l

r vector of artificial generation, representing load curtailment (MW)

f power flow (VA)

g generation vector (MW)

$\overline{g}$ maximum generation capacity (MW)

d demand vector (MW)

6 nodal voltage angles vector

S branch-node incidence matrix

4.2.2 Congestion-based transmission system expansion planning method (CBEP)

It is assumed that generation is a competitive market. Generator companies will maximize their benefit when they sell their electrical energy. For this reason minimizing the cost of generators is not considered in the present function.

Objective function of CBEP method:

$$Min \quad v = \sum_{n}(\sum_{i} C_{(n,i)}\, m_i + \sum_{j} \frac{\partial tc_n}{\partial L_{(n,j)}} L_{(n,,j)} + \sum_{l} \alpha_{(n,l)} r_{(n,l)}) \qquad (4-2)$$

Subject to

$Sf + g + r = d$ Supply-demand balance

$f_l - (\gamma_l^o + x_l)\Delta\theta = 0$ 'DC' load flow equations

$|f_l| \leq \overline{f}_l$ Power flow constraint

$0 \leq g \leq \overline{g}$ Generator constraint

Where:

$\boldsymbol{v}$ total cost of system expansion plan ($)

n n^{th} year in the life of a new branch

i new branch number

j bus number in intact transmission system

l line number in intact transmission system

$C_{(n,i)}$ present value of line i at year n (\$)

m_i number of circuits added to branch i

tc total cost of transmission, representing transmission cost and maintenance operation costs. (\$)

$L_{(n,j)}$ load at bus j at year n. (MW)

d demand (MW)

α penalty parameter associated with loss of load caused by lack of transmission capacity. (\$/MW)

x_l total new circuit susceptance added to branch l

γ_l^o before new branches are added, initial susceptance in branch l

r vector of artificial generation, representing load curtailment (MW)

f power flow (VA)

g generation vector (MW)

$\overline{g}$ maximum generation capacity (MW)

θ nodal voltage angles vector

S branch-node incidence matrix

For the CBEP function, a period of 'n' years is introduced into the new function, not only to allow for investment cash flow, but also because load increases year by year. The congestion in the near future should be considered when the expansion is planned.

Furthermore, there are three parts in this CBEP function.

The first part is $\sum_{n}\sum_{i} C_{(n,i)} m_i$. This is for the investment in new transmission lines. The lifetime, capacity and distance of transmission lines are included in this function.

The second part is $\sum_{n}\sum_{j} \frac{\partial tc_n}{\partial L_{(n,j)}} L_{(n,j)}$. In the competitive power market the generator expansion planning and the transmission system expansion planning are separated. The capacity of generators is controlled by market demand, rather than by the system operator. This part will make sure that when the network is expanded the energy will come from the cheapest power stations and energy demand will be satisfied. For this reason, if the generators want to sell energy in the new transmission plan, they will do their best to decrease energy prices. Hence the risks and uncertainties on the generator side are partly controlled. This advantage is especially suitable for a supply-side-management power market (such as the power market in China).

The third part is $\sum_{n}\sum_{l} \alpha_{(n,l)} r_{(n,l)}$. This evaluates the loss of load caused by lack of transmission capacity. The simplest way to define this part is the difference between total limited-transmission-capacity system cost and total unlimited-transmission-capacity system cost.

The second part and third part of the function are included to decrease the congestion in transmission expansion planning. This is the reason why the method is termed 'congestion-based'.

4.3 Case studies

4.3.1 Test case one

The first example to test the search algorithm is shown in fig 4.1. The test case is a standard IEEE 9-bus test system (appendix A).

In this test case load 10 is the new load centre, G2 is the cheapest generator. Due to G1 and G3 being far away from load 10, the energy of G1, G3 is much more expensive than G2. In the whole transmission network bus 7 is the nearest bus to bus 10 (table 4-1, table 4-2).

Plan 1: new transmission line: line 2-10

Plan 2: new transmission lines: line 2-7 and line 7-10

Plan 3: transmission line: line 7-10 (this is the shortest transmission line)

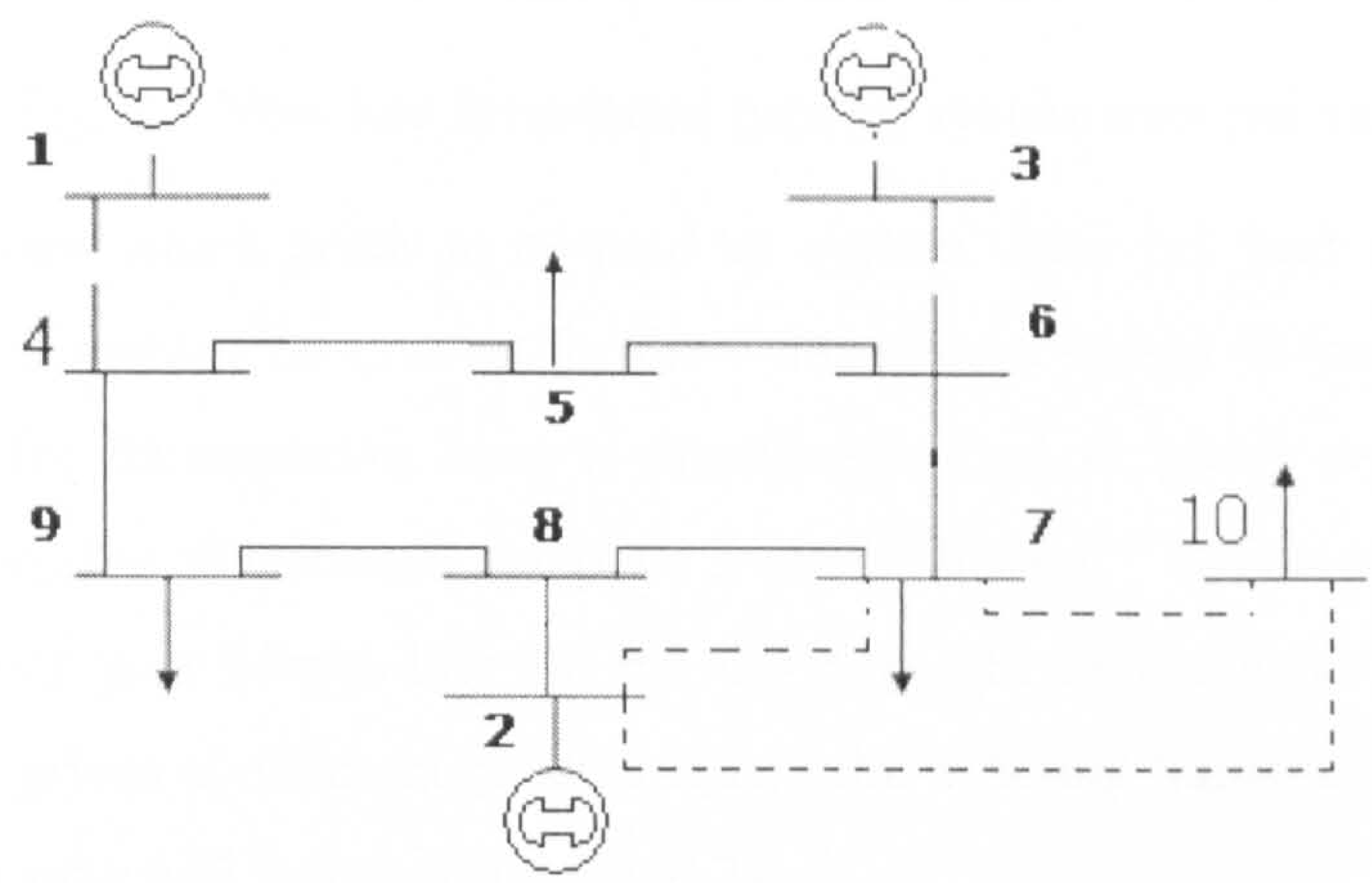


Fig. 4.1. Nine-bus system

TABLE 4-1 GENERATOR INFORMATION

Gen NO.	*Model*	*Start up $*	*Shut down $*	*c0*	*c1*	*c2*
1	polynomial	3000	0	11	10	1500
2	polynomial	2000	0	0.085	1.2	600
3	polynomial	3000	0	12.25	10	1500

TABLE 4-2 SOME INFORMATION OF TRANSMISSION LINES

From bus	*To bus*	*R Ω/m*	*Limit MVA*	*Inv $/km*	*L km*
2	7	0.07	500	15000	140
7	10	0.05	200	10000	20
2	10	0.05	200	10000	150

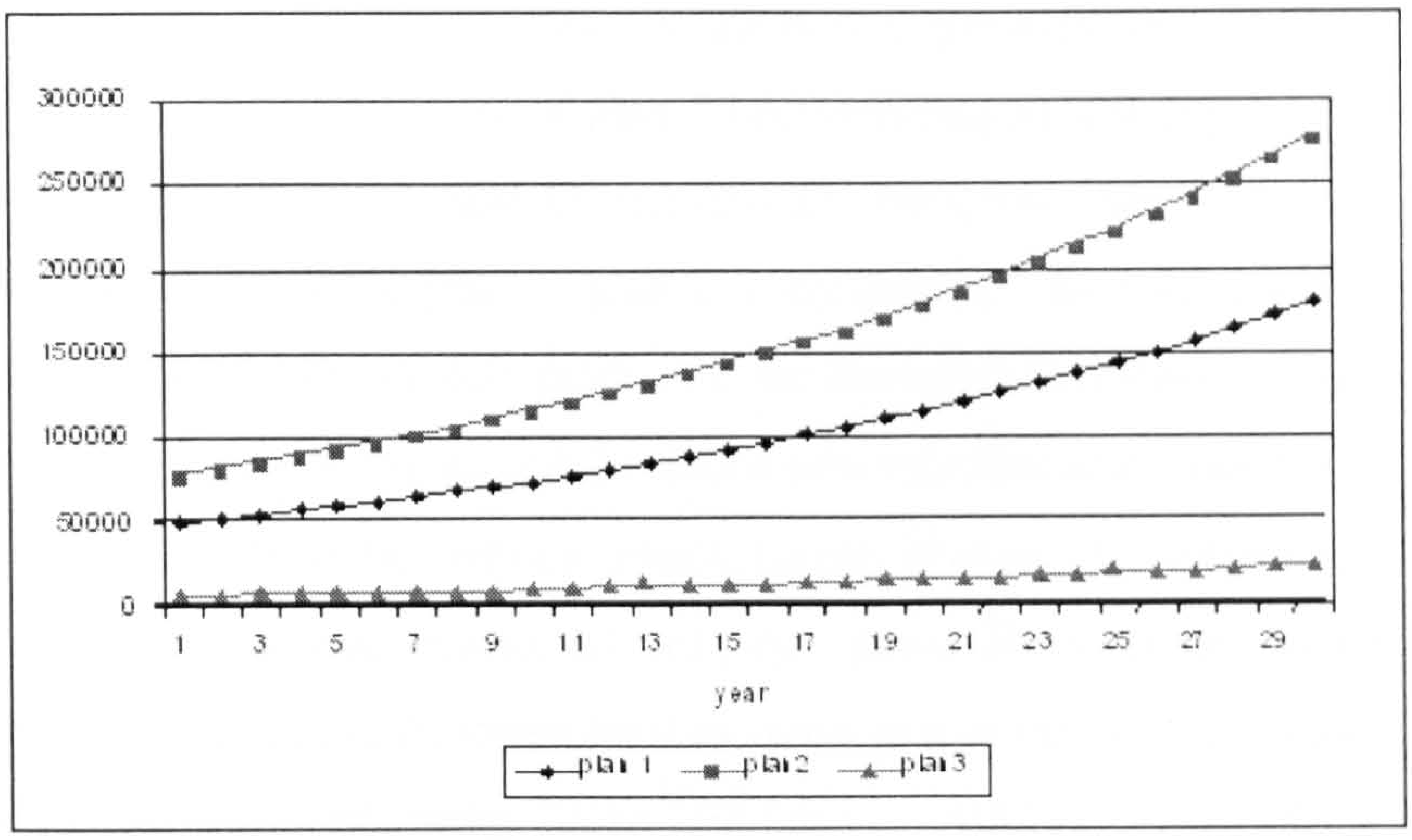


Fig. 4.2 New line investment paid by system user per year

Fig. 4.2 shows how much needs to be paid by system users per year if the transmission company wants to recover investment for the 9-bus system within 30 years. In fig 4.2, only the investment for transmission lines is considered. Due to plan3 needing the shortest transmission line, the investment for plan 3 is the lowest. However, if the load will increase 1.5% per year (depending on the develop rate of the local area), considering different energy prices at different generators and the different transmission losses, another better expansion plan will be produced (fig 4.3).

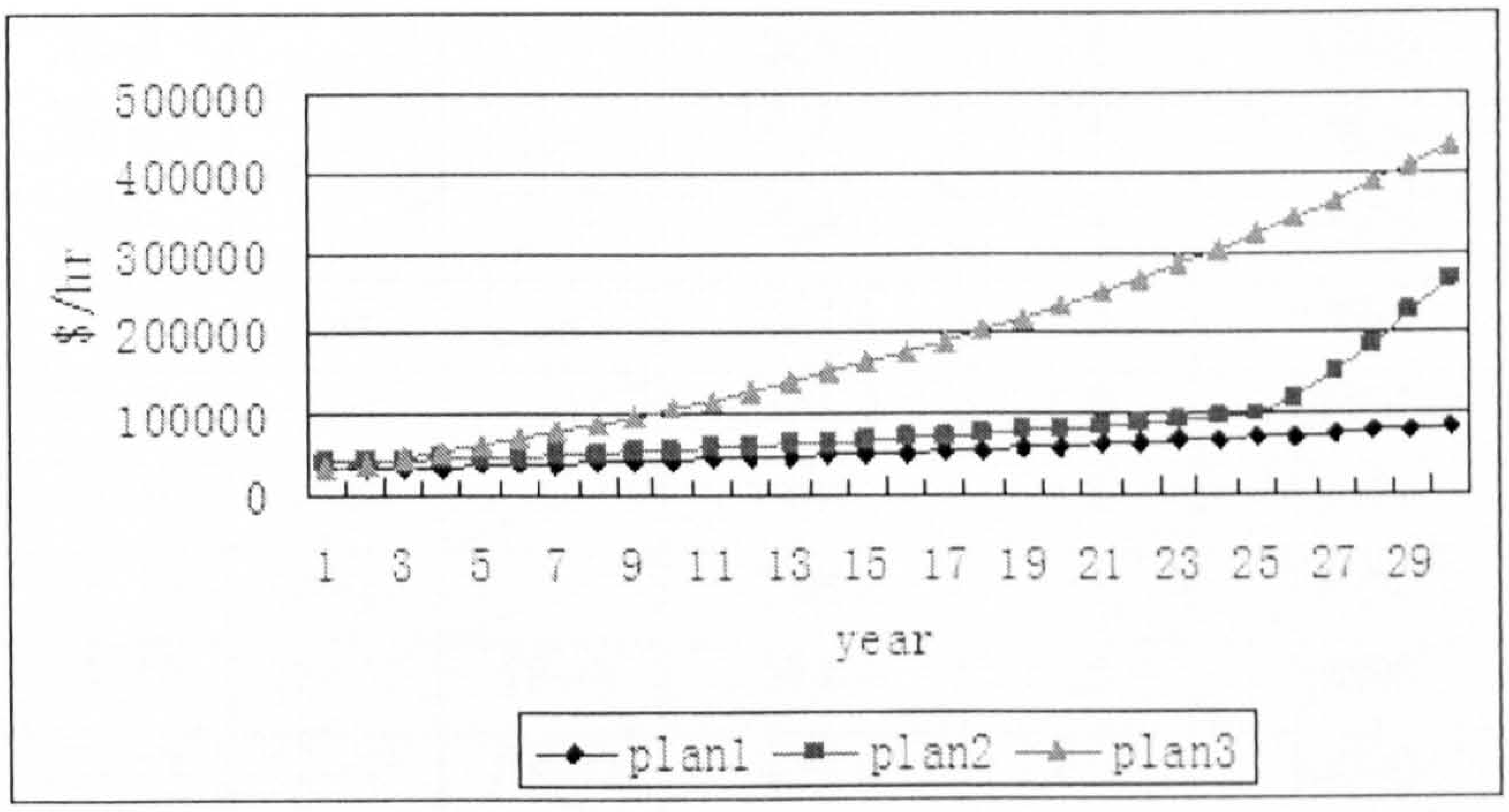


Fig. 4.3 Result comes from CBEP method

Fig. 4.3 shows the total social cost per year in the 9-bus system over 30 years depending on the CBEP method. The final expansion plan should be plan 1, i.e. a new line is to be built from bus 2 to bus 10.

At the beginning (first two years), plan 3 is the best expansion plan. However, during the following year, the total social cost of plan 3 becomes higher and higher. The total social cost of plan 1 and plan 2 are similar for the first 25 years, but after that, even though there are two new lines are built in plan 2, plan 2 is congested. The total social cost increases very fast. From the results we can point out: the cheapest investment does not mean the best transmission expansion plan, and the more new transmission lines (more investment) do not mean a much more secure transmission system. In addition, a reasonable transmission expansion plan needs to consider generator capacity, transmission line capacity, operation schedule, different load increase rate at different locations, and the life of transmission expansion planning. More detail about CBEP method will be introduced in test case two.

4.3.2 Test case two (Three Gorges transmission system in China)

Test case two is based on the results obtained from Chapter 3 for the 28-bus network. There are 11 optional plans for transmission system expansion planning. Table 4.3 provides more details of the 11 optional plans.

TABLE 4-3 OPTIONAL EXPANSION PLANS AND LENGTH FOR EVERY NEW PLANS

Optional plans	*Line No.1*	*Line No.2*	*Line No.3*	*Total length(km)*	*O&M ($/hr)*	*Investment ($/km)*	*Capacity (MVA)*
1	29--1			509.4	1.5	10000	1300
2	29--2			509.4	1.5	10000	1300
3	29--6			969.5	1.5	10000	1300
4	29--7			924.1	1.5	10000	1300
5	29--9			431.4	1.5	10000	1300
6	29--5	5--28		1494.2	1.5	10000	1300
7	29--13	13--23		339.2	1.5	10000	1300
8	29--13	13--15	15--3	674.4	1.5	10000	1300
9	29--13	13--15	15--17	417.8	1.5	10000	1300
10	29--8	8--23	23--3	2300.8	1.5	10000	1300
11	29--8	8--23	23--17	2013	1.5	10000	1300

*O&M operation and maintain fee

1. Due to the energy demand in China increasing very fast, the system expansion planning is for 15 years.

2. Discount rate of cash flow for investment in this test case is 1.5% per year.

3. Active and reactive load at each bus increases 15% per year.

4. A new load bus 29, named 'Leping', is introduced with active load 117.9MW, and reactive load 50.69MvAr

The results are as follows:

It can be noted that the investment in transmission lines is just a small part of the total social cost. Table 4-4 shows how much investment is needed by each plan in fifteen years. Plan 7 is the cheapest investment (536.53$/hr) and plan 10 is the highest investment (3639.3$/hr).

TABLE 4-4 TOTAL INVESTMENT FOR BUILDING A NEW LINE

	Year1	*Year3*	*Year5*	*Year7*	*Year9*	*Year11*	*Year13*	*Year15*	*TC $/hr*
Plan1	38.767	42.335	46.231	50.485	55.131	60.204	65.744	71.795	805.74
Plan2	38.767	42.335	46.231	50.485	55.131	60.204	65.744	71.795	805.74
Plan3	73.782	80.572	87.987	96.084	104.93	114.58	125.13	136.64	1533.5
Plan4	70.327	76.799	83.867	91.584	100.01	109.22	119.27	130.24	1461.7
Plan5	32.831	35.852	39.152	42.755	46.689	50.986	55.678	60.801	682.36
Plan6	113.71	124.18	135.61	148.09	161.71	176.59	192.85	210.59	2363.4
Plan7	25.814	28.19	30.784	33.617	36.711	40.089	43.778	47.807	536.53
Plan8	51.324	56.047	61.205	66.837	72.988	79.705	87.04	95.05	1066.7
Plan9	31.796	34.722	37.917	41.407	45.217	49.378	53.922	58.885	660.85
Plan10	175.1	191.21	208.81	228.02	249.01	271.92	296.95	324.27	3639.3
Plan11	153.2	167.29	182.69	199.5	217.86	237.91	259.8	283.71	3184

* TC $/hr means Total Cost in fifteen years, the cash flow is considered into the cost.

Table 4-6 shows that plan 6 (new line 29-5, line 5-28) involves the most extra cost for the energy (31,315,100$/hr). This means the energy supply is not enough for this expansion plan. Plan 9 (line 29-13, line 13-15, line15-17) involves the least payment for lack of generator capacity (21,391,230$/hr). This kind of expansion plan could relax the transmission system constraints.

Table 4-7 shows how much loss of benefit is caused by lack of transmission capacity. If the system becomes congested the cost will become higher and higher. With increasing load, the loss of benefit will be higher and higher. From table 4-7 we can note plan 7 which has the cheapest investment but has a high un-serviced demand (10,331,370$/hr). And the plan with least demand un-serviced demand plan is plan 9 (5,261,760 $/hr) the highest un-serviced demand is in plan 6 (14,998,370 $/hr). The plans 1,3,4,5 get very similar unserviceable waste ranging from 17,786,320$/hr to 17,787,910$/hr. Because the load is increasing very rapidly in China, the lifetime for system expansion planning should be shorter than for other more developed power markets.

TABLE 4-5 TOTAL COST FOR TRANSMISSION SYSTEM PLANNING IN DIFFERENT PLANNING SCHEDULE

	5 years planning $/h	*10 years planning $/h*	*15 years planning $/h*
Plan1	8096600	20992000	41897700
Plan2	7955800	20500700	40955900
Plan3	8096100	20990700	41894600
Plan4	8096100	20990700	41894600
Plan5	8096500	20991800	41897600
Plan6	8452000	22881600	46316000
Plan7	8227000	19535400	36874000
Plan8	5807500	13594000	27034900
Plan9	5850700	13693500	26653600
Plan10	6149700	15282300	31815700
Plan11	6166400	15304400	31171500

Table 4-5 shows the final result obtained from the CBEP method. At same time the table shows the planning schedule is a very important factor for the transmission planning. If the planning is only for 5 years or 10 years the best plan is plan 8 (plan 9 13,693,500, plan 8 13,594,000) but if the planning for 15 years the best plan changes to plan 9 (plan 9 26,653,600$/hr, plan8 27,034,900$/hr).

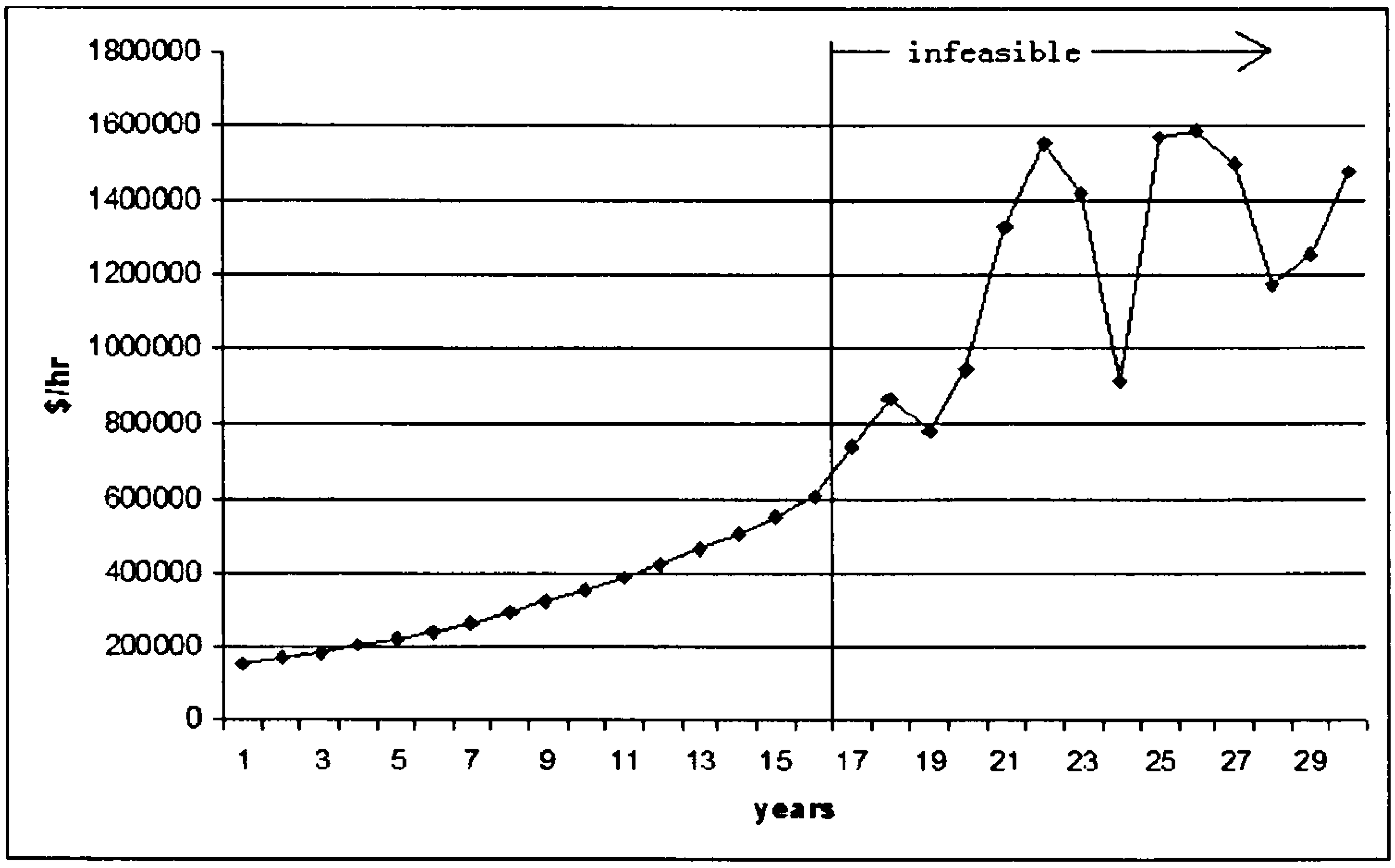


Fig. 4.4 Thirty years expansion planning

In this CBEP method, the lifetime of the planning is only fifteen years. Fig 4.4 shows that during the first fifteen years, the objective function value of plan 1 is stable. However after fifteen years, the results become uncertain. In this 28-bus test case, at the 30th year, the total generator capacity is: active power 41250.0 MW, reactive power -13840.0MvAr~24220.0MvAr. Total load and losses in this system are: active power 29335.38MW, reactive power 12976.84MvAr. But in this case the OPF program in Matlab cannot obtain the optimal solution. G.Gross and his colleague Ettore Bompard in their paper "Optimal Power Flow Application Issues in the Pool Paradigm" also mentioned this phenomenon [86]. In the next chapter, we will analyze the uncertainty of LMP, and will address question such as: How does the un-certainty happen? How will the participants be affected in an unbundled power market? How can the uncertainty of LMP be avoided? All these problems will be considered in Chapter 6.

4.4 Conclusions

A good system expansion planning approach is required urgently by the growing Chinese power market. In this chapter a new CBEP method has been introduced. In this method, not only the investment of transmission lines for system expansion but also the cheapest energy source and lowest transmission cost are considered. There are two test cases in this chapter. The first test case is the IEEE 9-bus test system. This test case briefly introduces the kind of elements that will be involved in transmission system expansion planning. The second test case is a 28-bus network based on the Three Gorges Project in China. In this test case three parts of the CBEP method are analysis one by one. The optimal system expansion plan is selected from 11 optional plans which come from the LMP selection method. The new CBEP method can minimize total social cost and control the risk involved in system expansion. At the same time the economic signal for system congestion is given. The factor of '15 years' is especially suitable for a country in which demand is rising very fast.

The following chapters will analysis the uncertainty in the transmission system expansion planning.

TABLE 4-6 ENERGY COST ($/H)

	Year1	Year3	Year5	Year7	Year9	Year11	Year13	Year15	TC $/hr
Plan1	1026800	1183600	1354300	1638800	1997000	2384700	2801700	3266700	29108900
Plan2	1013800	1169600	1338900	1604700	1960100	2344700	2759700	3207800	28638100
Plan3	1026700	1183500	1354300	1638600	1996800	2385000	2801500	3266000	29106900
Plan4	1026700	1183500	1354300	1638600	1996800	2385000	2801500	3266000	29106900
Plan5	1026800	1183600	1354300	1638800	1997000	2384600	2801600	3266900	29109000
Plan6	1049700	1210200	1427800	1779200	2163400	2583800	3039400	3594900	31315100
Plan7	1037600	1194900	1365800	1551400	1753300	2062800	2439000	2861100	26542500
Plan8	834230	952840	1081400	1220700	1374800	1638500	2039900	2500800	21570200
Plan9	838100	957460	1086900	1227300	1379400	1633800	1989100	2415500	21391230
Plan10	860150	985160	1123600	1290500	1555300	1927400	2348500	2817400	23928950
Plan11	861280	987100	1126700	1298200	1554300	1898100	2284700	2712600	23618880

TABLE 4-7 UN-SEVERED DEMAND OF
EACH PLAN IN 15 YEARS ($/H)

	Year1	Year3	Year5	Year7	Year9	Year11	Year13	Year15	TC $/hr
Plan1	380810	431110	485910	644380	865600	1104600	1360100	1649700	12787660
Plan2	367880	417170	470550	610300	828700	1064500	1318000	1590700	12316690
Plan3	380720	431030	485940	644220	865500	1104900	1359900	1649100	12786320
Plan4	380720	431030	485940	644220	865500	1104900	1359900	1649100	12786320
Plan5	380810	431110	485920	644400	865600	1104500	1360000	1650000	12787910
Plan6	403740	457780	559530	784980	1032300	1304100	1598300	1978700	14998370
Plan7	394290	445990	502080	562960	629400	792000	1008900	1258200	10331370
Plan8	191870	205830	220870	237120	257900	377400	622600	914100	5463520
Plan9	195320	209840	225510	242560	261000	370700	569300	825500	5261760
Plan10	219180	240090	265690	310360	442900	671900	938200	1235400	7883190
Plan11	219850	241380	267890	316860	440300	640500	871800	1127200	7549460

Chapter5 : Comparative Study of Congestion-Based Transmission System Expansion Planning (CBEP) Method

The CBEP (Congestion-based transmission system expansion planning) has been introduced in Chapter 3 and Chapter 4. In this chapter, an existing similar transmission system expansion planning method which is named CDEP (Congestion-driven transmission system expansion planning) method will be presented.

There are two parts in this chapter. The first part mainly introduces the objective function of the CDEP method. Differences and similarities of these two methods are then analyzed.

The second part of the chapter is a comparison. Both of these methods will be applied to the same test case. The advantages of the CBEP method found in the test case will be analysis.

5.1 Introduction

In this chapter, an existing CDEP method is introduced. Compared with the CBEP method which is presented in this thesis, both methods focus on system congestion in a competitive power market but in a totally different way. The main structure and functions of the CDEP method will be introduced in Section 5.2. In Section 5.3, these two methods will be applied to the same test case and the results will be compared. Conclusions are drawn in Section 5.4.

5.2 Congestion-driven transmission system expansion planning method

This method is defined by G. B. Shrestha and P. A. J. Fonseka of the power market research group of Nanyang Technological University, Singapore. Their paper "Congestion-Driven Transmission Expansion in Competitive Power Markets" was published in IEEE Transaction on Power system, Volume 19 in August 2004[5].

5.2.1 Production cost and consumer benefit

The main idea of CDEP method is to minimize the total social cost. In this objective function the cost of production will be minimized and the benefit of production will be maximized.

A) Cost of production (supply side)

Price and quantity curve for supplier ***i*** (fig 5.1a)

$p_i = b_i + m_g g_i$ for i= 1,2,3,.....I (5-1)

Apparent production cost:

$$C_i(g_i) = \frac{1}{2} m_g g_i^2 + b_i g_i \qquad (5\text{-}2)$$

Where:

i supplier index (total number of generator, I)

p_i price at which i is willing to supply in \$/MWh

b_i intercept (b_i>0) in \$/MWh

m_g slope(m_g>0)in \$/MW^{2}h

g_i supply in MW

B) Benefit of production (demand side)

Demand curve for a consumer j is (fig 5.1 b)

$p_j = b_j + m_d d_j$ for j=1,2,3,....J (5-3)

Consumer benefit cost:

$$B_j(d_j) = \frac{1}{2} m_d d_j^2 + b_j d_j \qquad (5\text{-}4)$$

Where

j consumer index (total number of load, J)

p_j price at which i is willing to pay for energy in \$/MWhr

b_j intercept (b_j>0) in \$/MWhr

m_d slope(m_g<0)in \$/MW^{2}h

d_j demand in MW

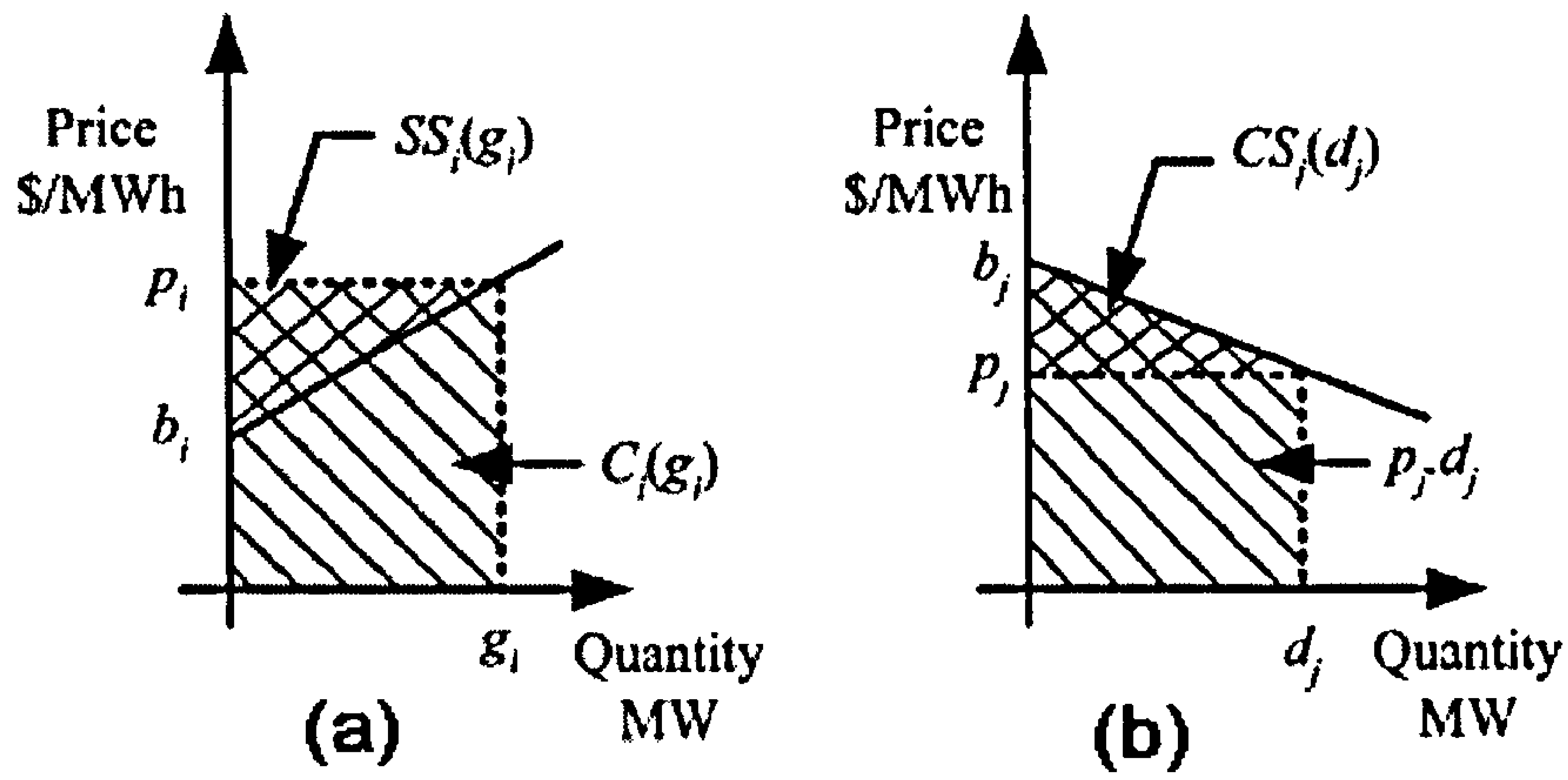


Fig. 5.1 (a) Supplier's surplus and supply curve (b) Consumer's surplus and demand curve

C) The objective function is:

$$\underset{g_i(y_h),d_j(y_h)}{Min} \sum_i C_i(g_i(y_h)) - \sum_j B_j(d_j(y_h)) \qquad (5\text{-}5)$$

Subject to

$\sum_j d_j(y_h) - \sum_i g_i(y_h) = 0$ Power balance without losses

$\underline{g}_i \le g_i(y_h) \le \overline{g}_i$ Supply limit

$\underline{d}_j \le d_j(y_h) \le \overline{d}_j$ Demand limit

$\underline{z}_m \le z_{mi}(y_h) \le \overline{z}_m$ Line flow limit

Where

i supplier index (total number of generator, I)

j consumer index (total number of load, J)

m branch index (total number of branches, M)

n bus index (total number of bus node, N)

y_h time period index (in 1- hour steps)

g_i supply in MW

d_j demand in MW

$C_i(g_i)$ apparent production cost

$B_j(d_j)$ consumer benefit cost

5.2.2 Objective function for CDEP method

$$\underset{n_{m,t_y},g_i(t_h),d_j(t_h)}{Min} \sum_{t_y \in T}\sum_{n_{m,y_Y}} \frac{ent_{m,y_Y} n_{m,y_Y}}{(1+\tau)^{y_Y-y_0}} + \sum_{t_h \in T}\sum_{i \in I} \frac{C_i(g_i(y_h))}{(1+\tau)^{y_Y-y_0}} - \sum_{t_h \in T}\sum_{j \in J} \frac{B_j(d_j(y_h))}{(1+\tau)^{y_Y-y_0}} \quad (5\text{-}6)$$

Objective function:

$\underline{g}_i \le g_i(y_h) \le \overline{g}_i$ Supply limit

$\underline{d}_j \le d_j(y_h) \le \overline{d}_j$ Demand limit

$\underline{z}_m \le z_{mi}(y_h) \le \overline{z}_m$ Line flow limit

$\underline{n}_{m,y_Y} \le n_{m,y_Y} \le \overline{n}_{m,y_Y}$ Expansion limit

Where:

y_h hourly time domain

y_Y time period index (in 1- year steps) yearly time domain

y_0 time period index (in first year)

τ cash flow discount rate (%)

ent investment to system expansion ($/circuit) of branch m

n_{m,y_Y} number of circuits added for branch m in year y_Y.

The congestion cost (saving) and the investment cost (spending) are balanced in this objective function. Also there is a balance between congestion cost, consumer surplus and suppliers' surplus.

This objective function includes three parts. The first part is $\sum_{y_Y \in Tn_{m,Y_Y}} \sum \frac{ent_{m,y_y} n_{m,y_Y}}{(1+\tau)^{y_Y - y_0}}$, evaluating investment in system expansion. This term is exactly the same as in part one of the CBEP's objective function (equation 4-2). Both of them include expansion limits and cash flow.

The second part is $\sum_{y_h \in T} \sum_{i \in I} \frac{C_i(g_i(y_h))}{(1+\tau)^{y_y - y_0}}$. This part is the production cost (equation 5-2). Because the objective function of CDEP does not consider the load increasing year by year, the cash flow is also included in this part.

The third part is $\sum_{y_h \in T} \sum_{j \in J} \frac{B_j(d_j(y_h))}{(1+\tau)^{y_y - y_0}}$. This part is the customer benefit (equation 5-4). Cost is positive and benefit is negative in this objective function.

5.2.3 Comparison

The two methods will be compared on many aspects which include what are their objective functions, what similar parameters are in the objective function and how to realize the objective function (seeTable5-1). And in the next section, from the calculated result, the two system expansion methods will be compared based on the same test case.

TABLE 5-1 COMPARING THREE MAIN TRANSMISSION TARIFF METHODS

		Congestion driven method	*Congestion based method*
Common	*Objective function*	Minimize total social cost	Minimize total social cost
	Parameters	Year 'y' involved in the objective function ,Cash flow	Year 'y' involved in the objective function, Cash flow
Difference	*Realize objective function*	Balance supplier's surplus and customer's surplus by supply and demand curve	Depending on the transmission capacity and generator capacity, minimize the congestion cost
	Economic signal	Shadow price	LMP
	The way to select expansion plans	Increase capacity of transmission lines with decrease congestion cost (no more details provided)	LMP selection method

5.3 Test case

In this chapter, the test case is the same as in Chapter 4 which is the 28-bus transmission system. The optional plans are also based on the LMP selection method. Eleven optional plans will be considered in this test case.

5.3.1 Result

The data for the test case is presented in table 5-2. In table 5-2, m_g, g_i, b_i come from the generator side. The parameters m_d, d_j, b_j come from the distribution side. Because published information on the distribution side is not available, the data has been generated based on experience or historical information.

TABLE 5-2 TEST CASE DATA

Bus No.	Supply function			Demand function		
	m_g	g_i	b_i	m_d	d_j	b_j
1	0.09	5600	30	0.054	5000	40
2	0.09	2824.9	30	0.013	5000	40
3	0.09	4200	30	0.031	0	40
4	0.09	4200	30	0.052	5000	40
5	—	—	—	0.034	251.93	80
6	0.031	347.69	35	0.037	132	120
7	—	—	—	0.041	73.5	40
8	—	—	—	0.026	45	50
9	0.046	348.06	30	0.073	448.5	100
10	—	—	—	0.055	856.5	75
11	0.043	609.93	37	0.059	1635	100
12	—	—	—	0.04	705	90
13	—	—	—	0.054	76.05	80
14	—	—	—	0.013	345	40
15	0.057	891.57	35	0.031	51	75
16	—	—	—	0.052	1181.3	85
17	—	—	—	0.034	81	60
18	—	—	—	0.037	141	50
19	—	—	—	0.041	418.5	50
20	0.071	336.31	40	0.026	45	40
21	—	—	—	0.073	679.5	70
22	—	—	—	0.055	567	80
23	0.074	1914.9	40	0.059	21.9	120
24	—	—	—	0.015	22.5	80
25	—	—	—	0.061	169.5	70
26	0.044	775.25	45	0.057	30	50
27	—	—	—	0.071	22.5	100
28	0.044	1220.9	50	0.025	37.5	80
29	—	—	—	0.04	117.9	70

*Units: m_g, m_d: \$/MW^{2}hr g_i, d_j: MW b_i, d_j \$/MWhr

*—: No generator at this bus

Fig 5.2 shows the cost of CDEP method over 15 years. Fig 5.3 shows the cost of CBEP method over 15 years. Table 5-3 shows the total cost for every plan. The dramatic result is that according to the congestion-driven method, plan 6 is the best one. But plan 6 is the worst in the CBEP method. Contrarily, plan 8 and plan 9 are the best two options in the CBEP method. Based on the CDEP method, plan 8 and plan 9 are the worst two options.

However, according to fig 5.2 we can see that, even between the best option (plan6) and the worst option (plan 8) the values of objective function do not exhibit too much difference. All the curves of optional plans are close together.

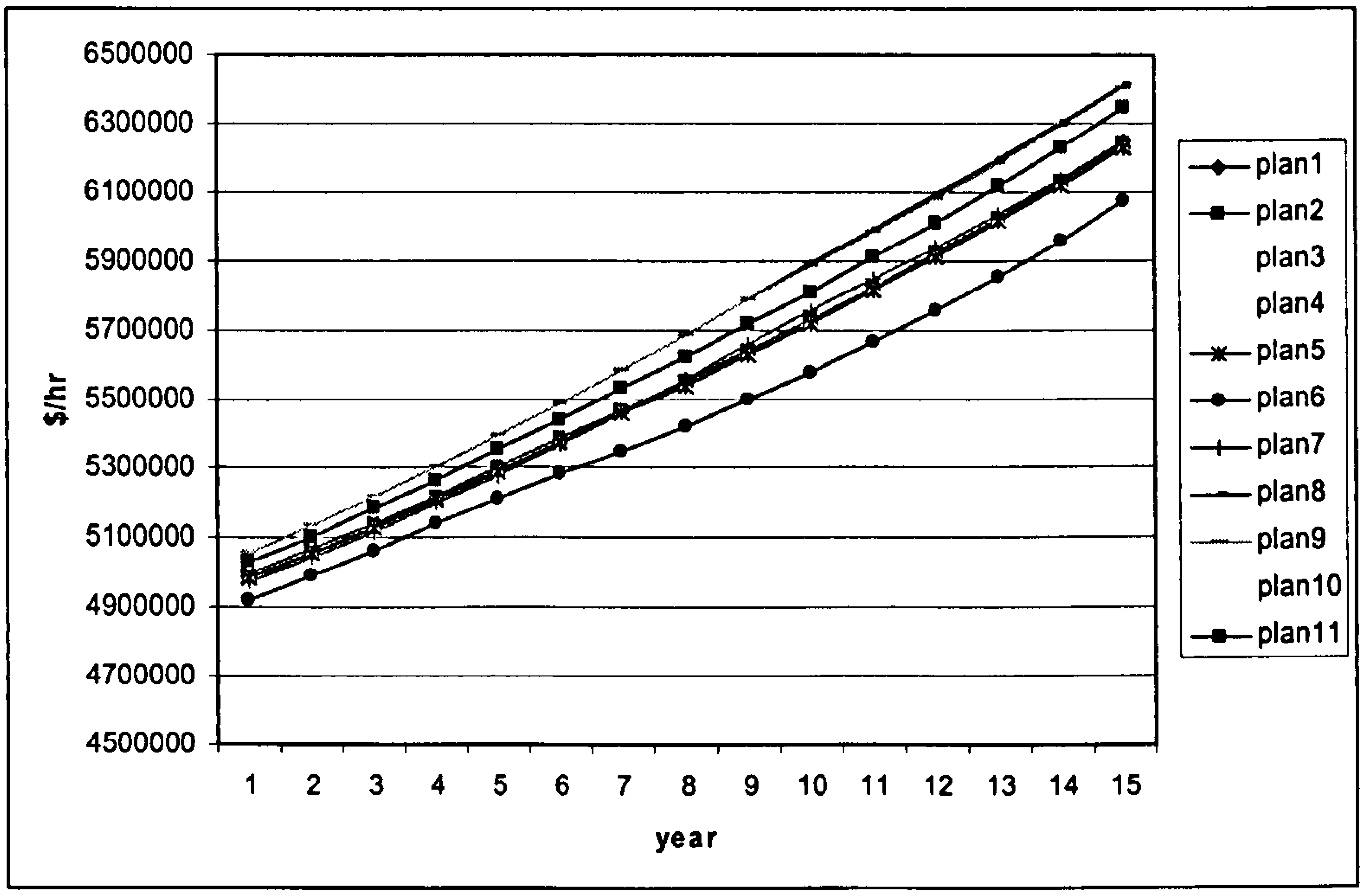


Fig. 5.2 Cost of CDEP method

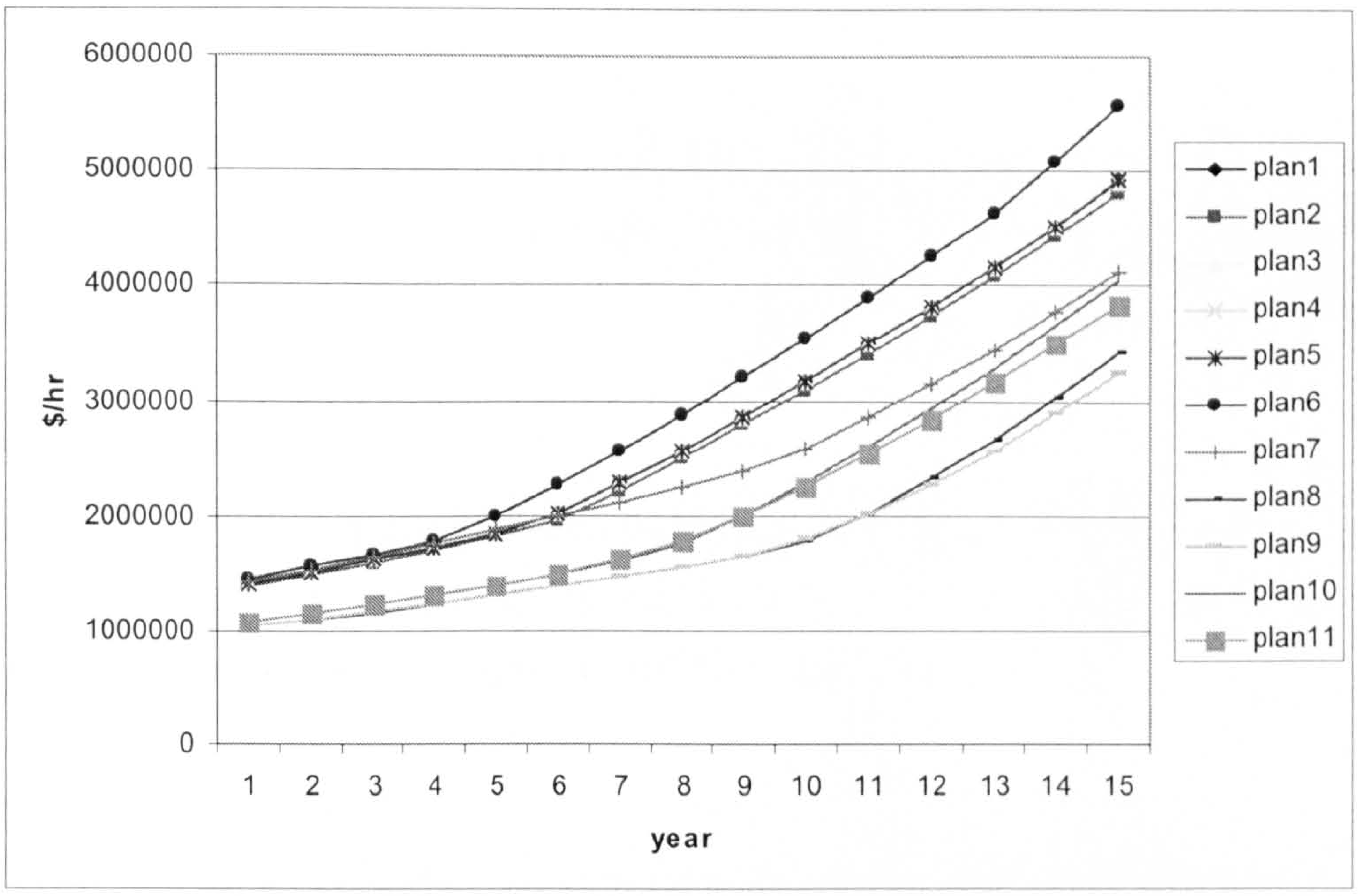


Fig. 5.3 Cost of CBEP method

TABLE 5-3 CDEP AND CBEP RESULTS COMPARING

CDEP method		***CBEP method***	
Options	***Objective function value ($/hr)***	***Options***	***Objective function value ($/hr)***
plan6	81,754,800	plan 9	26,653,600
plan3	83,461,400	plan8	27,034,900
plan4	83,461,400	plan11	31,171,500
plan1	83,461,800	plan10	31,815,700
plan5	83,462,400	plan7	36,874,000
plan7	83,603,500	plan2	40,955,900
plan2	83,639,200	plan3	41,894,600
plan11	84,661,500	plan4	41,894,600
plan10	84,667,000	plan5	41,897,600
plan9	85,459,400	plan1	41,897,700
plan8	85,527,900	plan6	46,316,000

In table 5-3, we can tell that the optimal system expansion plan is different between CBEP and CDEP method. The reasons are as follow:

The CDEP method is based on the suppliers' surplus and consumers' surplus. However, depending on the economic principle, during same period in the whole society, the social productive force is the same (If any industry could make extra benefit, all the investment will come to this field. The demand and supply in market will balance the benefit again.). Hence, every supplier and each customer obtains almost the same surplus. Because every optional plan has a similar objective function value, the CDEP method cannot give the optimal expansion plan.

5.3.2 Discussion

Even though these two system expansion planning methods give different result, we can still compare these two methods according to four aspects: data collection, data organization, and result analysis and power market application.

Data collection

In the CDEP method, the supplier's supply curve (generator side) and consumer's demand curve are necessary. From generator side the supplier's data are stable compared with the distribution side. Because the lifetime of transmission expansion planning is quite long and productivity rises very fast with improvements in technology. The consumer's surplus will become very difficult to forecast. On the other hand, since only current information is collected, it is almost impossible to obtain an exact demand curve for every load. In these cases the CDEP method cannot offer a proper system expansion planning over a long period.

The CBEP method, depending on the increasing load, evaluates the LMP in the future. The increase in load is much more regular than consumer's surplus. In this way the CBEP method can find reliable transmission expansion plans.

Data organization

In the CDEP method, the data depends on the bidding information coming from the generator side and the distribution side every hour. But for a 15 year or much longer expansion planning problem, too much data will be involved in the calculation. It would make the calculate become very complex and may not be necessary. In addition, depending on equations (5-1) (5-2) (5-3) (5-4), from the generator side and distribution side, no reactive power price is included in the CDEP method.

In the CBEP method, every step is one year instead of one hour. For this reason the method is much simpler compared with the CDEP method. Both the active power and reactive power are considered in the CBEP method. These advantages will make the congestion-based method more transparent and easy to be accepted.

Result analysis

From the results of the CDEP method (fig 5.2), we can easily find out that all the optional plans have similar values of objective function. The reason is that during the same period, the consumer's surplus and the production cost in the whole transmission system cannot involve too many differences.

The results which come from the CBEP method (fig 5.3) are based on LMP in the whole system. When the system is congested, it will be shown by the LMP directly. With increasing load, the CBEP method can point out the option which can relax the system congestion most clearly.

Power market

First, the CDEP method is suitable for a power-pool model market, which includes bidding from the generator side and the distribution side at one hour before market closure. However it is not suitable for a power market which does not include such full competition, such as the Chinese power market.

Second, bidding details for future years are quite closely involved in the CDEP method. This is very sensitive and difficult to forecast. This will make the results obtained from the CDEP method unreliable. For this reason, the transparency of this method is not good enough. However this feature is very important for a good system expansion method.

Third, the results that come from the CDEP method are 'flat'. The economic signal is not distinct enough. It is not clear whether congestion in the transmission system is serious or not. When does the new system expansion planning need to be organized? These questions cannot be answered by results based on the CDEP method.

All the problems above can be solved by the CBEP method, which is presented in this thesis. However measuring transmission system expansion planning by production cost and consumer's surplus is a valid idea as well. With deeper research, the CDEP method could be greatly improved.

5.4 Conclusion

In this chapter the CBEP method is compared with an existing transmission system expansion method named CDEP method. Two results which come from CBEP method and CDEP method are compared. Depending on the result coming from the CBEP method, we could safely point out that CBEP method has more advantages when it is applied in the restructured power market.

Chapter6 : Uncertainty of Locational Marginal Prices in Optimal Power Flow Formulations

This chapter focuses on the impact of LMP uncertainty in a competitive power market. Moreover, this chapter pays attention to how the uncertainty can be reduced. Since the LMP is a very significant economic signal, for example from the UK pool paradigm to Pennsylvania-New Jersey-Maryland Interconnection (PLM), the LMP is used widely. There are some challenges associated with the effective LMP application in the competitive environment due to the uncertainty of LMP when calculated by an OPF formulation. In this chapter, we analysis how the parameters of the transmission system affect the uncertainty of the LMP; how the uncertainties in LMP affect the power market participants, such as independent generators and system operator. The effect on social welfare will also be discussed. Finally, a method to overcome the uncertainty in LMP is suggested. The uncertainty of the OPF formulation can also be solved. This chapter provides extensive numerical results on a test system based on the IEEE 30-bus network.

6.1 Introduction

Several decades ago, the traditional organizational structures of electrical energy supply have been reformulated as markets. The system has changed from a formerly vertically integrated and highly regulated structure, separated into participants which include the generation entities, transmission owners, distribution wires business, system operators, market trading customer services, etc. In the generation, transmission and distribution of electric power, the attraction of market-inspired efficiency has spawned a variety of studies on market design. In the traditional bundled structure, the optimal power flow can perform the dual function of minimizing production costs and avoiding congestion in a least cost manner [85]. However, under the competitive environment, more attention is paid on how to maximize the social warfare and how to build a fair competitive environment for each participant in the power market. Hence, there are some changes associated with the effective OPF application in the unbundled competitive power market, such as the flatness of the optimum surface and the consequent continuum associated with the optimum.

Gross and Bompard [86] have identified some characteristics of OPF formulation such as lack of sensitivity of OPF solution, uncertainty in system parameter values and non-economic power flow, etc. In this chapter, we focus on the uncertainty in the system parameter values. What kind of parameters of the transmission system will impact the uncertainty LMP when calculated by the OPF formulation? Why does the uncertainty in LMP occur? How will the participants of the power market be affected by the uncertainty of LMP? How will we overcome the uncertainty of LMP? All these questions will be considered in this chapter.

In [85-88] the authors discuss the effect of OPF formulation on the competitive power market and how the sensitivity of LMP depends on the OPF formulation. In particular, reference [87] provides expressions to compute the sensitivities of LMP with respect to power demands.

In this chapter, Sections 6.2 and 6.3 describe the OPF model, defining the LMP and LMP uncertainty, and introducing the parameters which will affect the uncertainty of OPF. Three test cases will be presented. In Section 6.4, how and why the LMP uncertainty will affect all kinds of power market participators will be explained. Section 6.5 introduces a procedure on how to overcome the uncertainty of LMP and a test case will be presented. Finally, Section 6.6 will draw conclusions.

6.2 Problem formulation

6.2.1 Optimal Power Flow (OPF)

Optimal power flow (OPF) is a central decision-making tool. From 1962, OPF has had a long history of development. Now OPF has become a successful algorithm that could be applied on an everyday basis, in different kinds of power markets. The OPF is used for a wide range of tasks from calculating minimum cost generation dispatch to setting generation voltage, and transformer taps [89]. Obviously, we can also calculate LMP based on the results of OPF.

Using the traditional OPF formulation, in this chapter the objective function of OPF is to minimize the total generator cost for the transmission system. In addition, the cost for each generator is defined by polynomials in the generator output.

Objective function:

$$\min \sum F_{1i}(P_{gi}) + F_{2i}(Q_{gi}) \qquad (6\text{-}1)$$

Equality constraint

$$\begin{aligned} &\sum P_{gi} - \sum P_{li} - P_{loss} = 0 \\ &\sum Q_{gi} - \sum Q_{li} - Q_{loss} = 0 \end{aligned} \qquad (6\text{-}2)$$

Active and reactive power balance equations

Inequality constraint

$$\begin{aligned} &| S_{ij}^{f} | \leq S_{ij}^{\max} \\ &| S_{ij}^{t} | \leq S_{ij}^{\max} \end{aligned} \qquad (6\text{-}3)$$

Apparent power flow limit

$$V_i^{\min} \le V_i \le V_i^{\max}$$
$$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max}$$
$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max} \qquad (6\text{-}4)$$

Where

F_{1i} is clearly based on thermal efficiency and fuel cost but F_{2i} is less physical based and could be used to model reactive power penalty costs. For example, from different reactive sources, the reactive power price may vary and most of the time reactive power is regarded as a form of ancillary service.

g generator

l load

i, j bus number

f, t "from" bus, "to" bus

Obviously, there is more than one kind of objective function that could be chosen. For example, it would be possible to maximize the social welfare S^s [86].

6.2.1 Locational marginal price

LMP is a very important economic signal [90]. In a competitive electricity market, especially where some congestion exists in the transmission system, the independent generators are paid for the energy that they supply to the market, according to the LMP at their point of connection to transmission system. The independent generators will self-schedule their economic dispatch, bidding their supply to maximize the profit of generation according to the LMP. The loads pay for the energy that they demand based on the LMP at their connection point in the transmission system. The energy suppliers are paid based on the difference in the LMP between the delivery points to the receiving points in the transmission system. At same time, energy consumers pay the Transco for the transmission service based on the difference in the LMP between the delivery points to receiving points in the transmission system. Almost all the trade activity in the competitive electricity market has some relationship with the LMP.

In this chapter, we define the LMP as:

$$\frac{dF}{dP_{li}} = \lambda \qquad (6\text{-}5)$$

The effect of incremental demand will express the incremental cost of generators in the transmission system.

Where

F cost function of generators in the transmission system. The active and reactive power generator costs are included in ($)

P_{li} the real power load at bus i line l (MW)

λ LMP ($/MW)

It is well known that before the system becomes congested, the electricity market should have a MCP but if the system is congested, different locations will have different LMPs. In this chapter, the LMP of certain locations will be discussed. As usual, the congested LMP will be higher than for the system without congestion, and the LMP should be stable when the parameters of transmission lines are only changed by a small amount. If a small change of transmission parameters will make the LMP change radically, we say the LMP has uncertainty. The next sections will analysis how the parameters in the transmission line affect the LMP in the transmission system and how the electricity market participants will be affected.

6.3 Uncertainty of LMP

In this section, some parameters of transmission lines will be analyzed to explain how the transmission parameters affect the LMP in the transmission system.

6.3.1 Case study 1: Apparent power limit of line

In this test case, the apparent power limit of a transmission line will be varied over the range [10%,-10%], the transmission system will be congested as a result of the changes. In the IEEE 30-bus test system, the apparent power limit of line 6-8 ranges from 90% to 110%, with a step of 1%. (See appendix D)

Corresponding to the parameter changes the LMP of bus 8 will be affected. However, the LMP curve should be a smooth curve. Fig 6.1 is the LMP of bus 8 when the real power cost and reactive power cost are both considered. The minimum generator cost is 623.01$/hr when the apparent power limit of line 6-8 is 100% (32MVA).

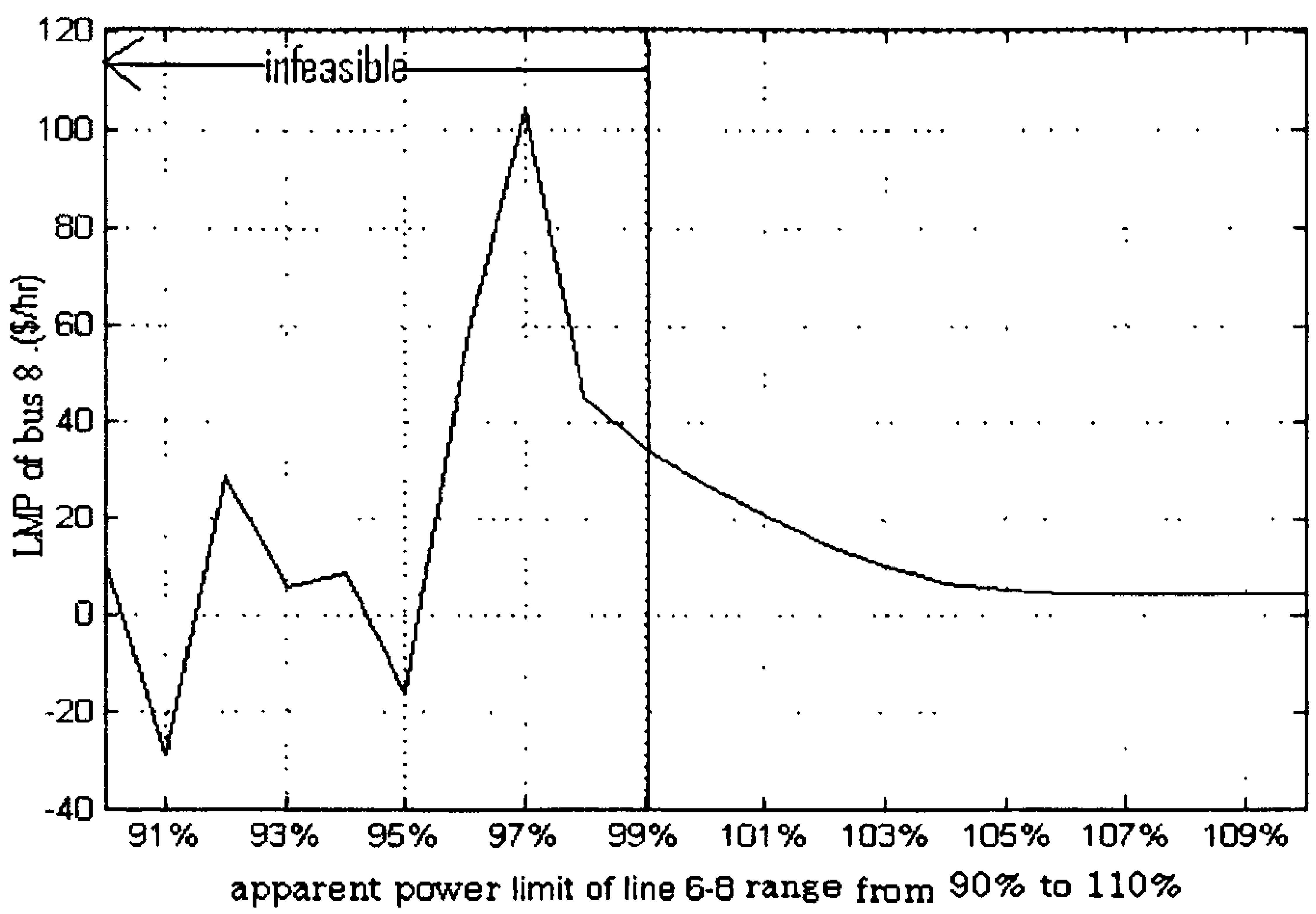


Fig. 6.1 Apparent power limit of line 6-8 range from 90% to 110%

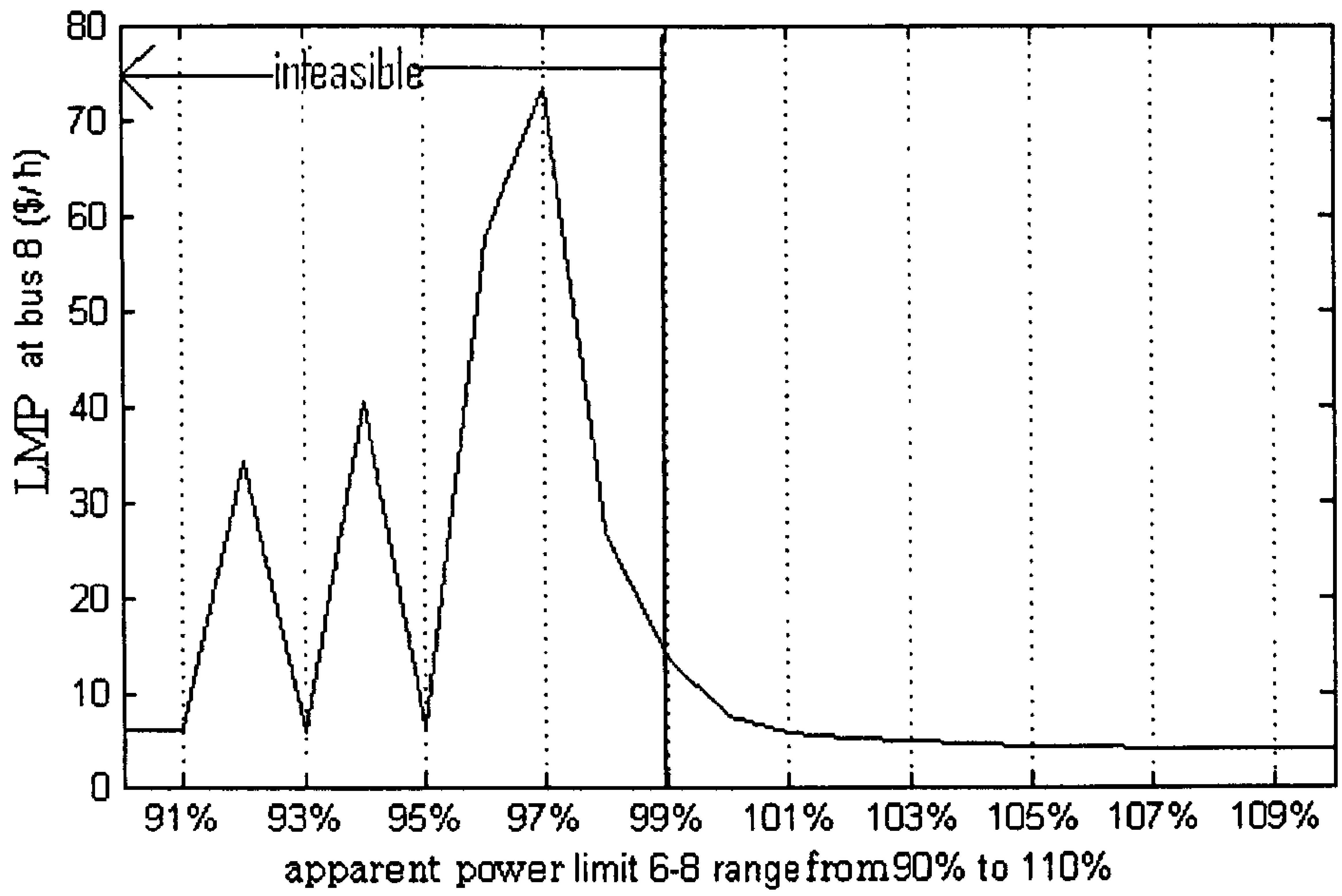


Fig. 6.2 Real power cost when apparent power limits of line 6-8 range from 90% to 110%

Fig 6.2 is the LMP of bus 8 when only the real power cost is considered. The minimum generator cost is 574.52 $/hr when the apparent power limit of line 6-8 is 100% (32MVA). Fig 6.1 and fig 6.2 show that when the apparent power limit is less than 97% the LMP of bus 8 will change with great uncertainty. A small change of apparent power limit will change the LMP at bus 8 dramatically.

Defining the LMP as the price of supplying an additional 1 MW of load at each bus in the system, fig 6.3 shows the power flow information of line 6-8 when the real power and reactive power are considered.

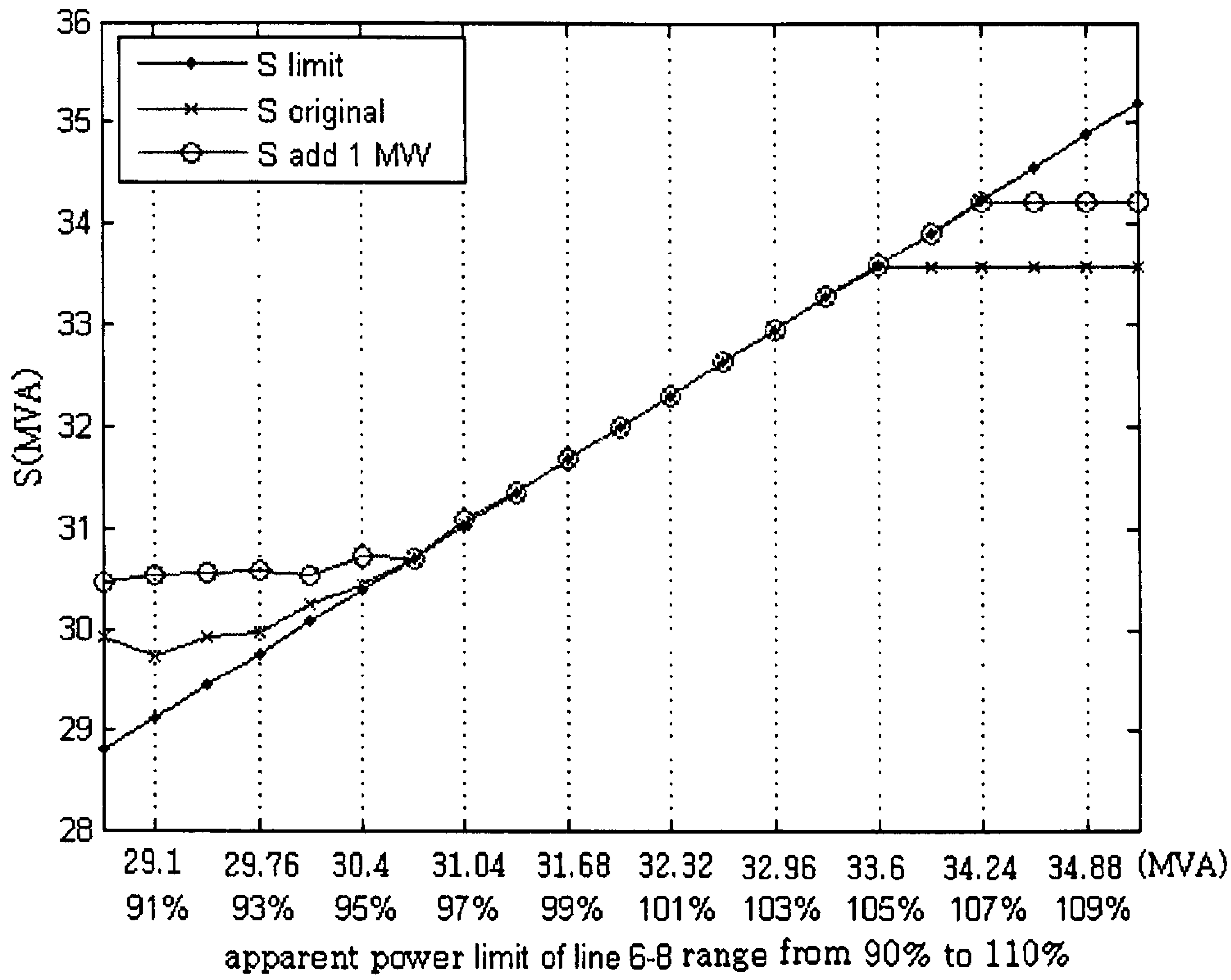


Fig. 6.3 Power flow of line 6-8 when apparent power limit range from 90% to 110%

In fig 6.3 curve "S limit" shows the apparent power limit of line 6-8 range from 90% to the 110%. Curve "S original" shows the power flow information in line 6-8 (MVA), when the load at bus 8 is the original output. Curve "S add 1MW" shows the power flow information in line 6-8 (MVA), when the load at bus 8 increases by 1MW.

6.3.2 Case study 2: Reactance

There are a number of parameters to describe a transmission line such as resistance, reactance, susceptance, etc. Case study 2 compares the uncertainty of LMP under varying reactance of a transmission line. In test case 2, the reactance of the transmission line will be changed by a small amount to test how the parameters of the transmission line affect the LMP uncertainty. The original transmission line data in the OPF program is x=0.04 (reactance p.u.). When the apparent power limit of transmission line is decreased, the result of LMP at bus 8 becomes uncertain. At the same time, if we increase x from 0.04 to 0.08 the result is as follows (fig 6.4):

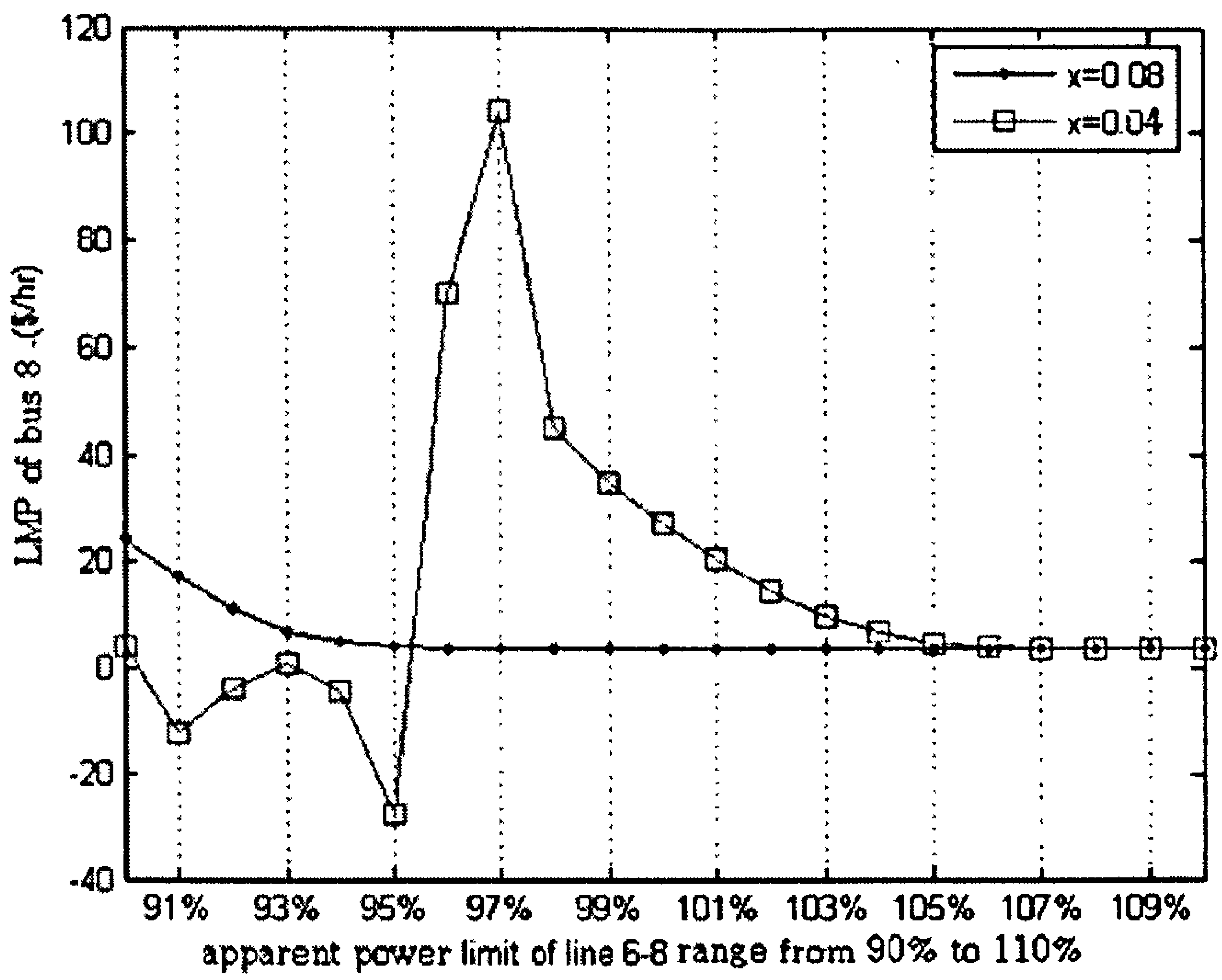


Fig. 6.4 Reactance of line 6-8

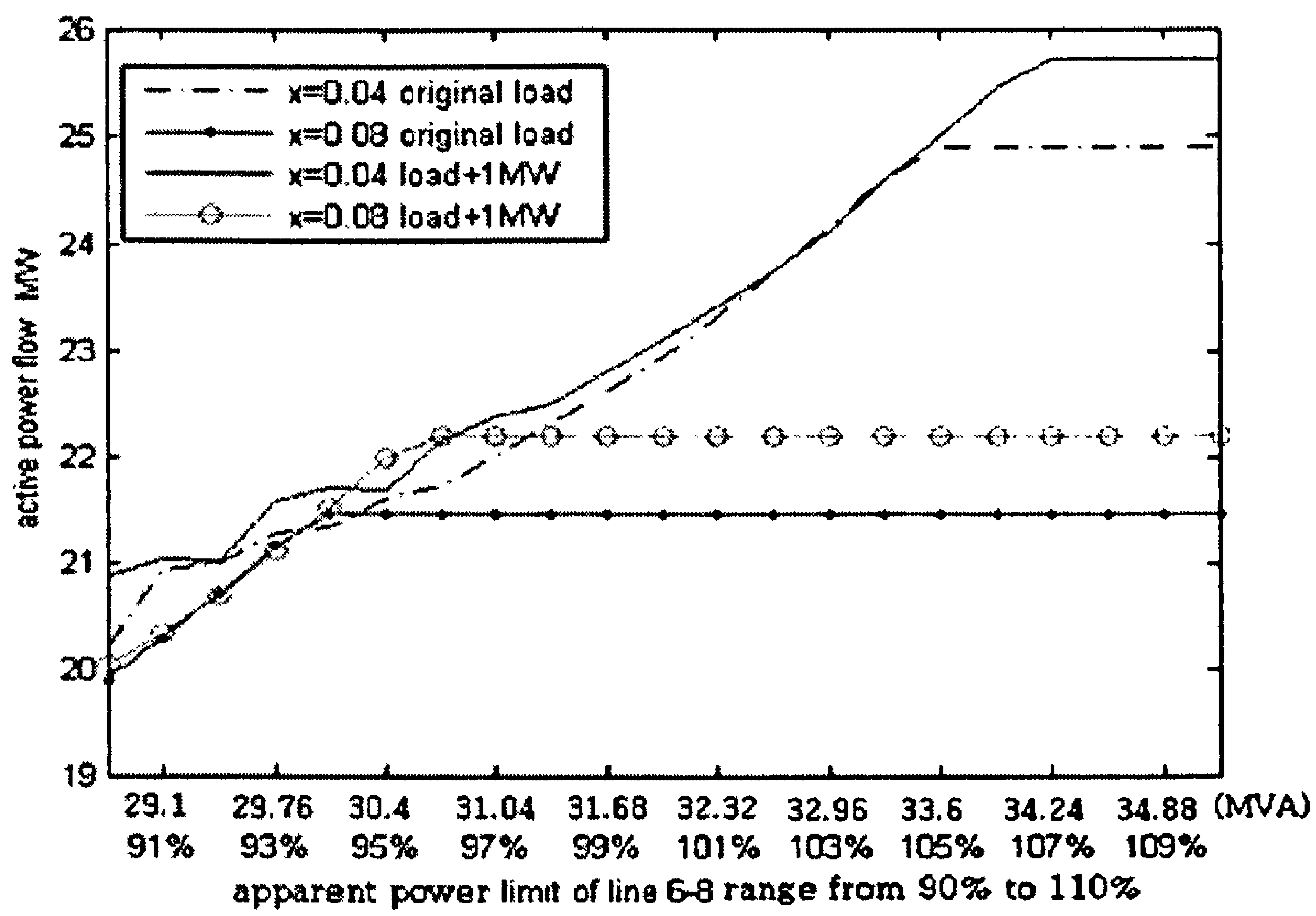


Fig. 6.5 The active power flow information of line 6-8

Fig 6.5 shows the active power flow information.

The curve "x=0.04 (0.08) original load" shows the real power flow information, when the reactance of line 6-8 equals 0.04 (0.08) and load 8 is the original load.

The curve "x=0.04 (0.08) load +1MW" shows the real power flow information, when the reactance of line 6-8 equals 0.04(0.08) and the load 8 increase by 1MW.

As the apparent power capacity ranges from 80%-105%, the uncertainty of LMP still exists (fig 6.6). However, the tolerance to the congestion will increase; the uncertainty situation will be delayed. If the line charging susceptance is changed, the result is similar. As the reactance of a transmission line is affected easily by temperature, for example, the uncertainty of LMP will be common in practice.

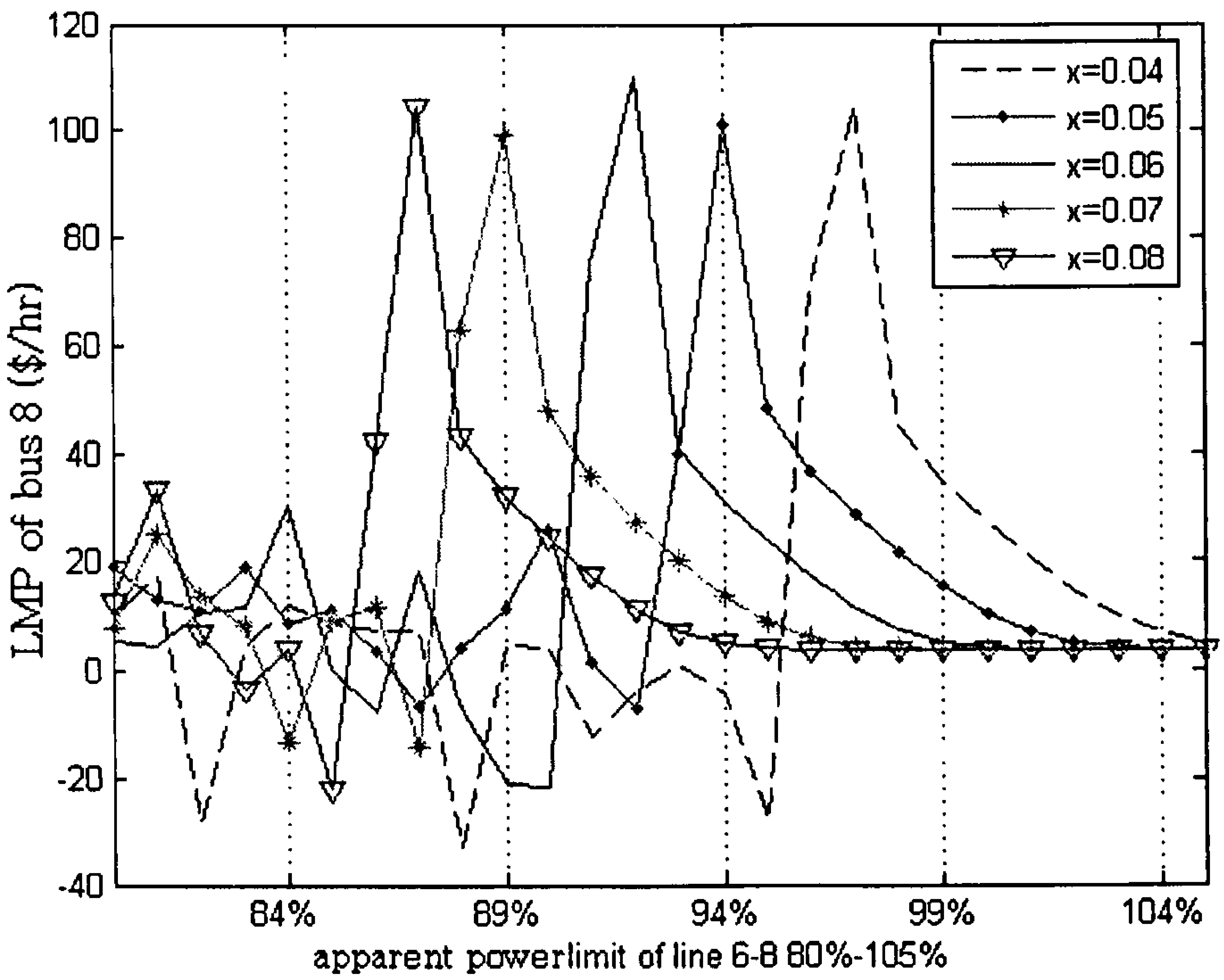


Fig.6.6 apparent power limit of line 6-8 ranges from 80% to 105%

6.3.3 Case study 3: OPF formulation

In test case 3, the LMP of bus 8 will be calculated by different formulations of OPF to compare the uncertainty of LMP.

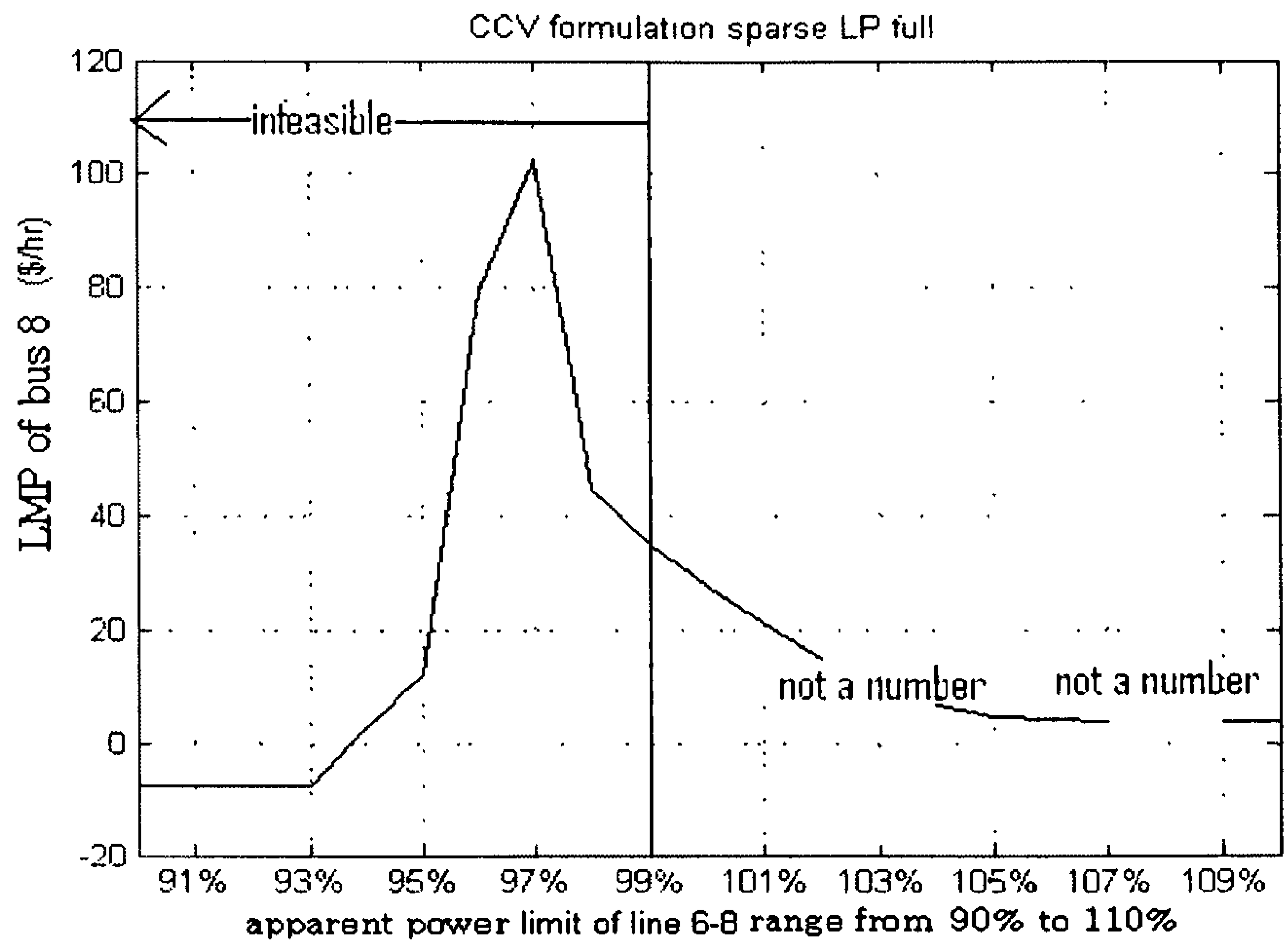


Fig. 6.7 CCV formulation

The formulation of OPF is the Constrained Cost Variable (CCV) formulation and based on linear programming (fig 6.7). The pauses in the curve indicate numerical failure of the OPF software [5].

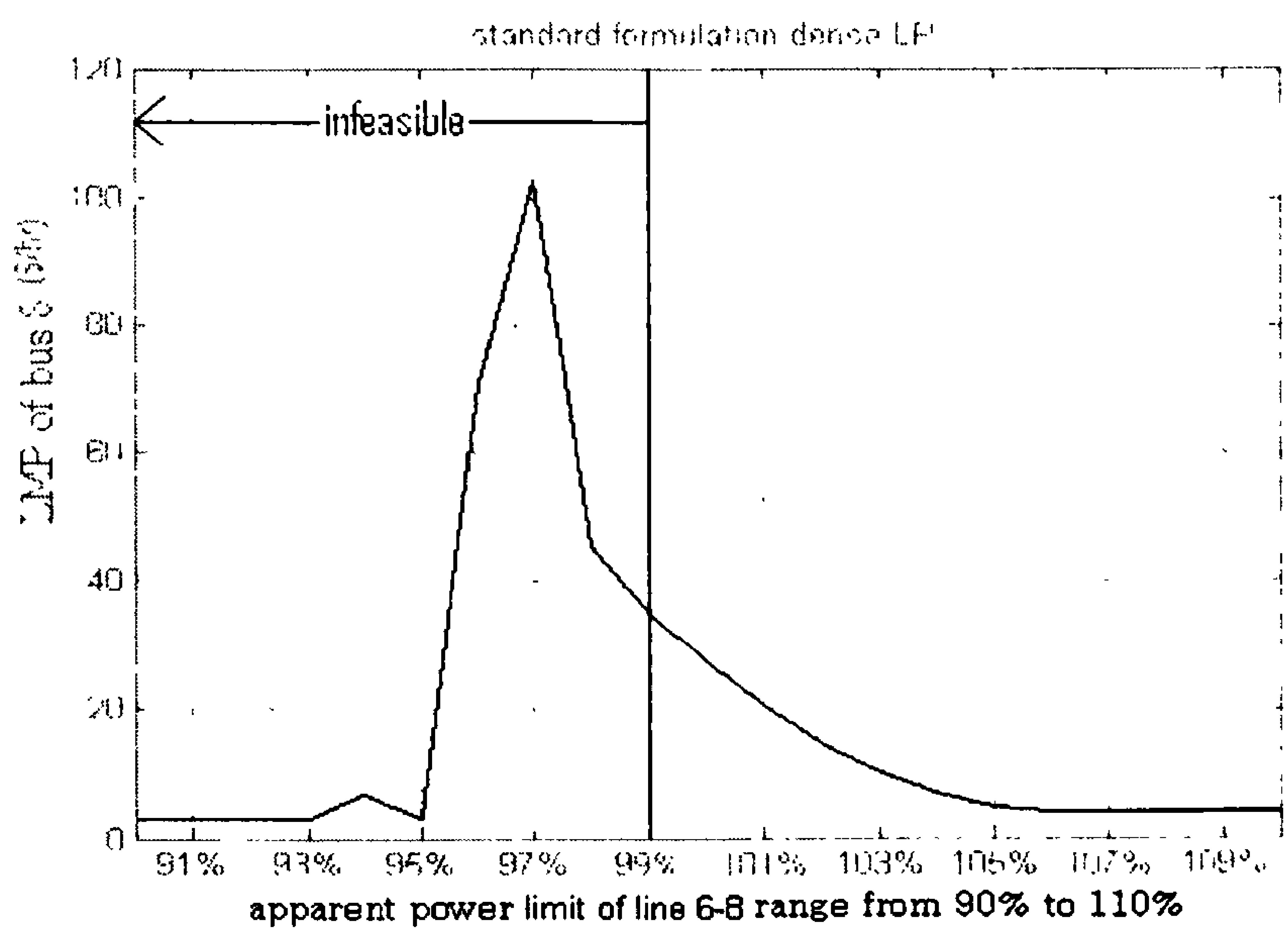


Fig. 6.8 Standard formulation

Fig 6.8 shows the LMP of bus 8 calculated by an OPF which is based on a standard linear programming formulation.

In addition, an OPF based on a standard sparse linear programming formulation and an OPF based on the generalized MINOS formulation can be used to calculate the LMP of bus 8. The results are similar and the uncertainty still exists. When the apparent power limit of line 6-8 is equal to 97% there is a high ridge in the LMP.

6.4 Impact on participants in the power market

6.4.1 From the viewpoint of an independent generator

Independent generators, unlike regulated utilities, do not have a guaranteed retail customer base for their electrical output. The only objective of independent generators is maximizing their profit. The independent generators in the competitive power market will focus on the forecasting of locational marginal cost due to the congestion, bidding and generator dispatch.

The profit of an independent generator is given by:

$$F(i,t) = \rho_g(i,t)[P(i,t) + B(i,t) - P_0(i,t)] - S(i,t) - C_t(i,t) \quad (6\text{-}6)$$

Where:

$F(i,t)$: Profit of unit i at time t ($)

$\rho_g(i,t)$: Forecasting location marginal price for energy at bus i at time t ($/MVA)

$P(i,t)$: Generation of unit i at time i (MVA)

$P_0(i,t)$: Bilateral contract (sell) of unit i at time t (MVA)

$B(i,t)$: Power purchase of unit i at time t (MVA)

$C_t(i,t)$: Cost function of unit i ($)

$S(i,t)$: Star up cost ($)

The ISO and Gencos are two main market participants, but they have different goals for price forecasting. Independent generators estimate energy price to build their bidding strategy and bilateral contract before submitting bids for benefit maximizing. In equation (6-6) $\rho_s(i,t)$, the price forecasting means short-term price forecasting by Gencos.

The factors impacting electricity price forecasting are: historical electrical price, historical and forecasted load, fuel price etc.

Objective function of the independent generator is $Max\sum_i\sum_t F(i,t)$. The marginal cost uncertainty at certain locations due to small change in parameters will make the LMP change radically. If an independent generator owns a unit at such a location, it becomes very difficult to try to forecast the LMP. In the pool market, this kind of uncertainty makes the independent generator very difficult to find correct information for self-schedule optimization, bidding etc.

Furthermore, if the congestion fee is being defined by the different LMP at different locations, the uncertainty of LMP will also make the congestion charge uncertain.

6.4.2 From the viewpoint of the system operator

The system operator needs to consider the economy and security of the transmission system at the same time. For security analysis, the system operators need factors which show the approximate change in line flow for changes in generation in the given network configuration. The generation shift factor is one such factor.

Generally, the generation shift factor is defined as:

$$a_{li} = \frac{\Delta f_l}{\Delta P_i} \qquad (6\text{-}7)$$

Where

l the line number

i the bus number

Δf_i change in Megawatt power flow on line (MW)

ΔP_i change in generation at bus i (MW)

For simplicity, the test case is based on the apparent power limit of line 6-8 varying over a range from 90% to 110%, considering the real power flow in line 6-8 divided by the real power output of generator 1.

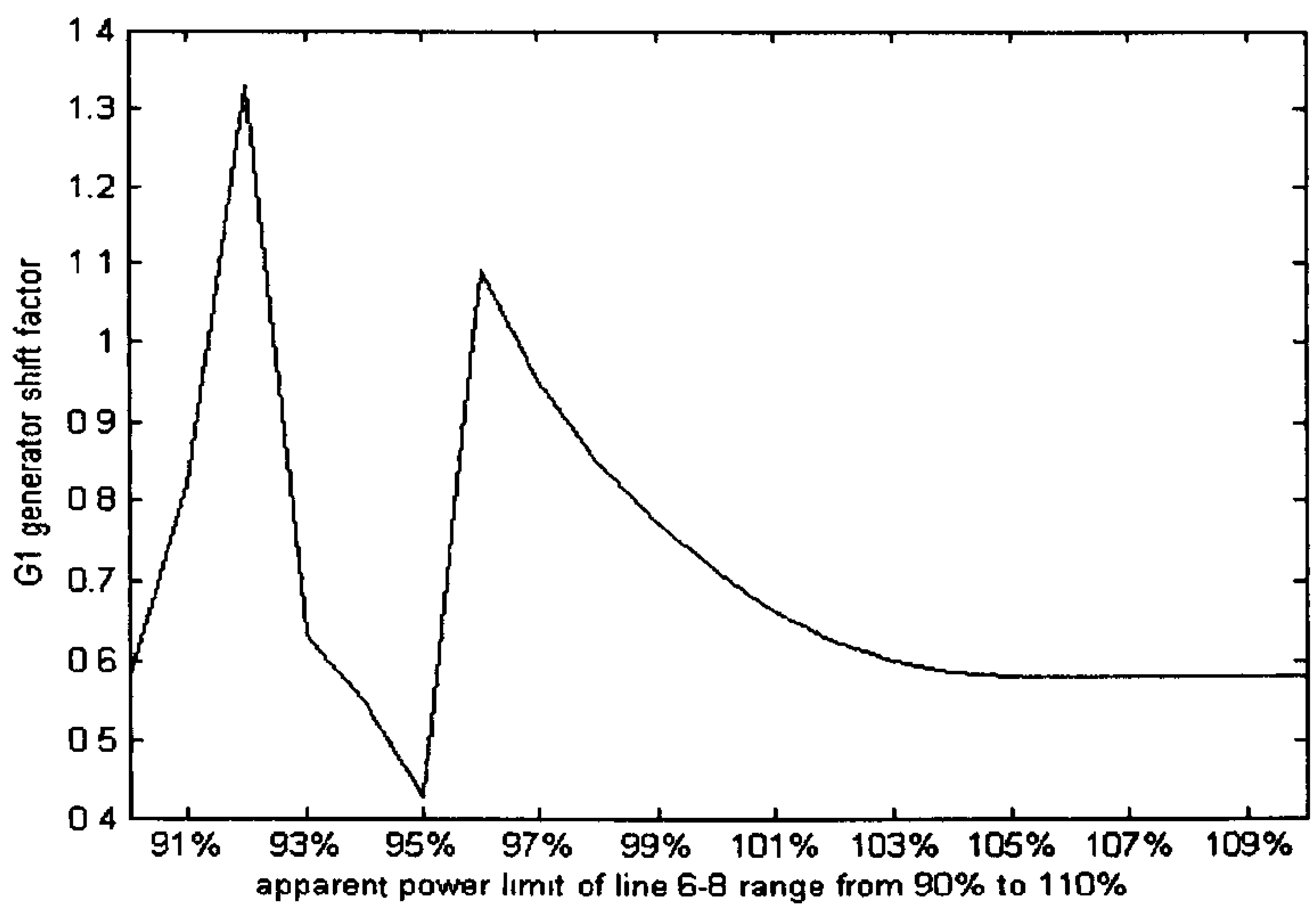


Fig. 6.9 Generator shift factor

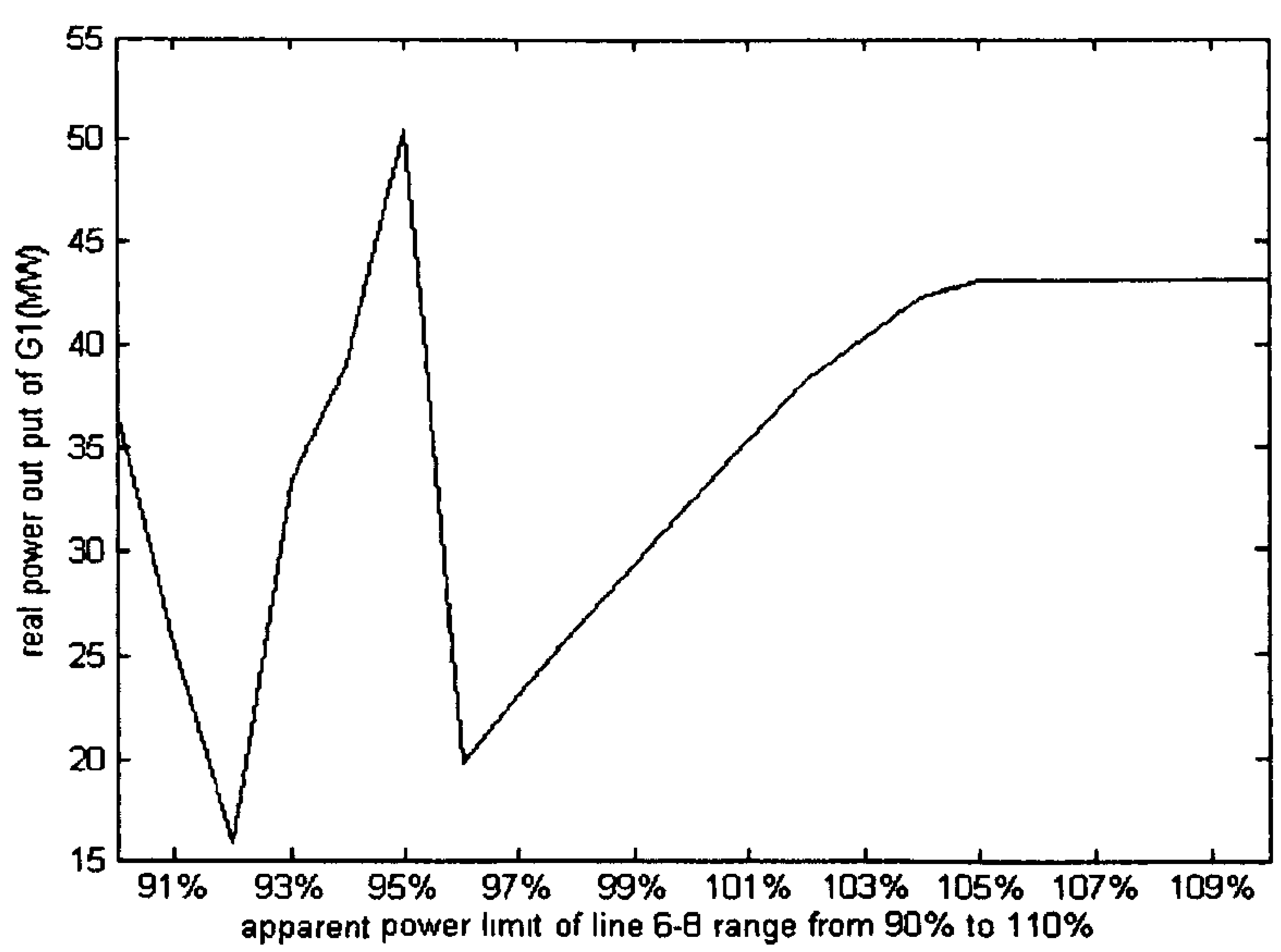


Fig.6.10 Real power information

Fig 6.9 and fig 6.10 show that when the capacity (apparent power) of line 6-8 is changed a little, the G1 real generator output and the G1generation shift factor will be severely altered.

There are six generators in the 30-bus test transmission system. Some of the generation factors are obviously affected by the parameters of line 6-8, such as the generation shift factors of G1, G2, G22, which exhibit great uncertainty.

This kind of uncertainty will prevent the system operator from analyzing the transmission system easily and quickly. A small change of some parameters will strongly affect the security analysis of the transmission system. The network will be very difficult to operate securely and efficiently.

6.5 Solution: Artificial generators

Due to constraints in the transmission network, the OPF code may not be able to find the optimal solution for power flow. In this case, a small change of system parameter will affect the important economic signals. To solve this problem of uncertainty of LMP, we introduce artificial generators at each bus in the transmission system. These artificial generators only afford active power at an artificial very high price for energy. The very high energy prices of artificial generators ensure that the artificial generator will not be used when the transmission system can operate without congestion. When the system is congested, to find the optimal solution, the artificial generator will have to be used and the energy will be very expensive. However, the LMP uncertainty will disappear (fig 6.11).

From fig 6.11 we can see that when the system is without artificial generators and the power limit of line 6-8 is less than 97% of apparent power limit, the LMP at bus 8 is not stable. However, when the artificial generators are put into the system, the situation is totally changed. When the transmission line 6-8 is congested, the LMP at bus 8 increases but the uncertainty of LMP has disappeared. The expensive energy price at bus 8 will decrease the electrical demand in that area. In this way, the demand and supply of energy will be balanced.

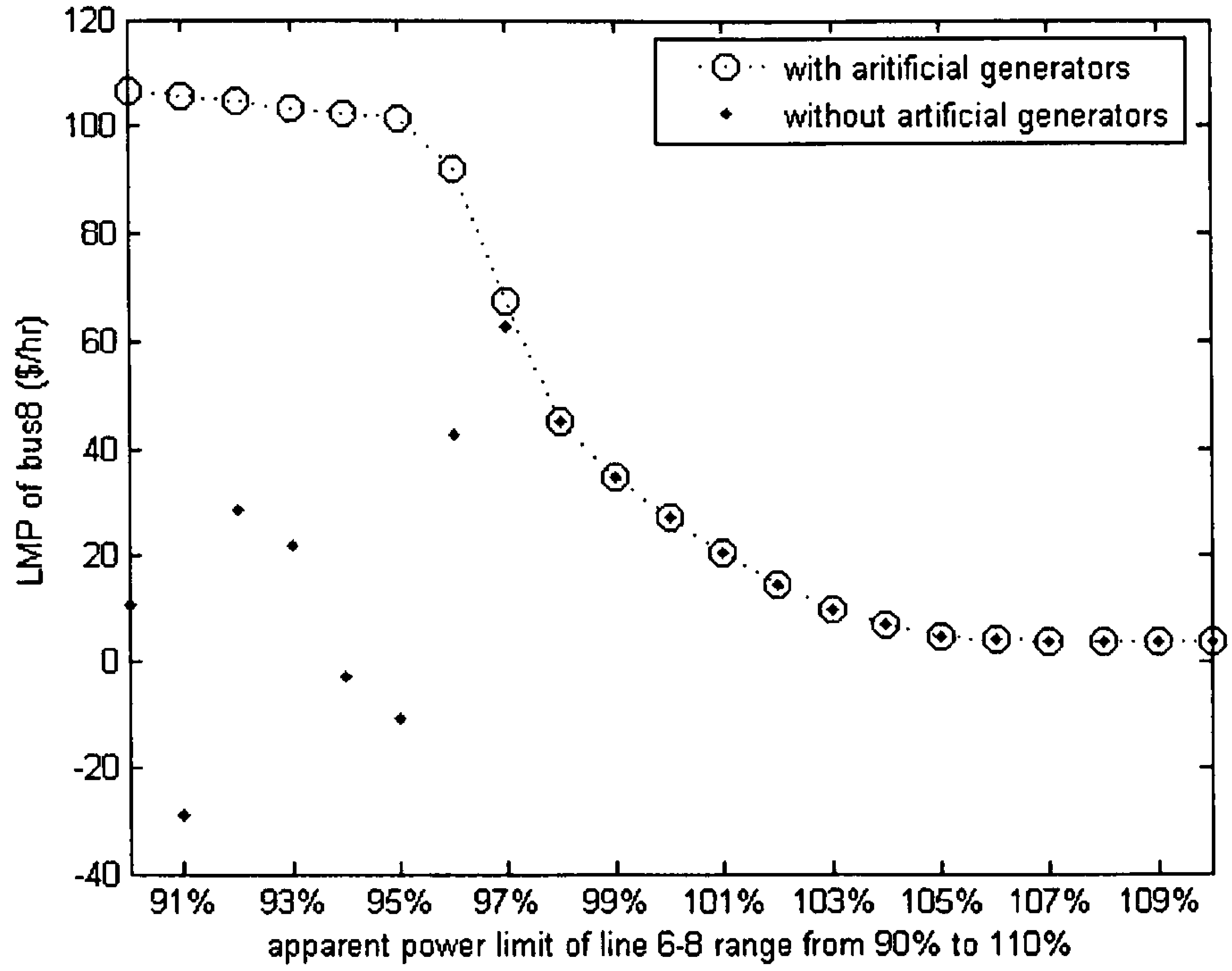


Fig. 6.11 Results when the system includes artificial generators

The test case considers bus 8 and line 6-8, as before. From fig 6.11, we can see that after reaching the 97% apparent power limit of line 6-8, the result of the two kinds of solution is the same. There are two further questions which need to be considered. The first question is when so many artificial generators are put into the OPF code, how will the computer time be affected? Before the transmission network becomes congested, we don't need to put artificial generators into the transmission system. After the network is congested, if the artificial generators are not present, the OPF code will exceed the maximum iteration limit (average run time 29.79 seconds). This will cost more computer time than with artificial generators (average run time 19.82 seconds).

The second question is when the system is congested, the artificial generator will inject artificial power into the transmission network, is there any risk to the security of transmission system? As the artificial power is very expensive, from fig 6.11 we can see that when the artificial power is used, the LMP of bus 8 is more than 100$/hr. The supply and demand will keep in balance. However, very high but consistent LMP is better than uncertain and erratic LMP.

6.6 Conclusion

In a competitive electric market, the non-discriminatory requirement is very important to every participant. The uncertainty in LMP will affect the equitability of participants in the power market. In this chapter, we have analyzed the uncertainty of LMP, and the impact of LMP uncertainty on the participants in the power market. The chapter has also proposed a feasible and simple solution for overcoming the LMP uncertainty. We have found that we need to pay more attention to the uncertainty of LPM when the transmission system becomes congested.

Chapter7 : Conclusion and Future Work

7.1 Summary of the aims

With the deregulation and restructuring of the power industry, the power market is developing towards a more competitive market. Some countries began the power market revolution very early (table 7-1) [83].

TABLE7-1 ELECTRICITY RESTRUCTURING REFORMS IN CALIFORNIA, NORWAY, SPAIN, AND ARGENTINA

	California	*Norway*
Regulatory	*FERC and CPUC (federal and state regulators) *ISO (system Operator)	*NVE (regulator) *Statnett (grid owner and system operator) *Nord Pool (market operator)
Wholesale market	*Centralized and physical bilateral trades *Several transmission owners	*Centralized and physical bilateral trades *Trading in the Nordic Pool
Retail	*All customers (1998) *Metering and billing competition	*All customers (1991)

(Continues)

TABLE7-2 ELECTRICITY RESTRUCTURING REFORMS IN CALIFORNIA, NORWAY, SPAIN, AND ARGENTINA *(CONTINUED)*

	Spain	*Argentina*
Regulatory	*MIE and CNSE (regulators) *REE (system operator and transmission grid operator) *OMEL (market operator)	*Secretary of energy and ENRE (regulators) *CAMMESA (system and market operator)
Wholesale market	*Centralized and physical bilateral trades	*Mandatory pool with financial bilateral contracts
Retail	*Gradual implementation in a 5-year period *All customers in 2003	*Large users (1992), and small customers in the future

Because electricity is a primary input for many industries, a deep transformation in the electricity industry has taken place in more and more countries, aimed at helping them win in the global economic competition by reducing primary energy costs.

China is one of these countries. From 1997, the Chinese government prepared a restructuring law for restructure the Chinese power market. In 2002 SERC began to work as market regulator. Until now the Chinese power market has only 5 years experience. The Chinese power market can build on much valuable experience from all the developed power markets. However due to many differences from country to country, there are a great deal of problems still to be solved.

Presently the most urgent problem in the Chinese power market is the transition from electricity shortages to transmission capacity shortages. Not only in the Chinese power market but also in the whole world, the question of how to build and run a healthy transmission network is waiting for a good answer.

In this thesis, we focused on how to solve the transmission bottleneck problem as exemplified in the Chinese power market. Chapter 2 mainly discussed how to make sure the total cost of transmission system will be recovered to encourage more investment come into the transmission network. Chapter 3 and Chapter 4 presented the congestion- based transmission system expansion planning method. Chapter 5 compared the CBEP method with another transmission system expansion planning method. Chapter 6 discussed how the uncertainty of LMP will affect the transmission system expansion planning. Some analysis about the OPF formulation was also presented.

7.2 Contributions

Recently, more and more countries have been restructuring power systems to increase the social efficiency. The Chinese power system introduced privatisation and deregulation from 2002 onwards. However, the biggest problem is that the development of the transmission system lags far behind the electrical demand. How to build a strong and economic transmission system in China is an urgent issue.

In this thesis, methods of charging for the transmission system and optimising the expansion of the transmission network under the competitive power market are described.

The first contribution of this thesis is transmission tariff design. In the proposed approach, not only is all the necessary investment in the transmission system recovered, but also an absolute economic signal is offered which is very useful in the competitive power market. A fair power market opportunity is given to every participant by the new nodal-use method.

The second contribution of this thesis is the introduction of a congestion-based transmission system expansion method. This has been validated on the Three Gorges Project in China. In this thesis, to optimally expand the transmission system, the LMP (Locational Marginal Price) selection method and the CBEP (Congestion-Based transmission system Expansion Planning) method are introduced. The LMP selection method is used to select optional plans for transmission system expansion. It is especially suitable for large transmission systems. The outstanding advantages of the LMP selection method are simplicity and computational efficiency. The CBEP method produces the optimal system expansion plan. For the first time, generation congestion and transmission congestion are separated within the system expansion problem. For this reason the CBEP method can be used in a supply-side power market and is suitable for the Chinese power market.

In this thesis, the issue of how to relax the congestion in the transmission system has been solved. The transmission system can obtain enough income to recover the total required cost. For this reason more and more investment will come into the transmission system from investors. The risk for the independent generators is also under control in the CBEP method. Even when the system is congested, the uncertainty of LMP is taken into consideration.

The main publications arising from this thesis are:

Fei Song, M. R. Irving; "New Transmission Tariff Method of Transmission System: An Analysis of cost recovery"; 2005 IEEE/PES Transmission and Distribution Conference &Exhibition: Asia and Pacific, Dalian, China

Fei Song, M. R. Irving; "Congestion-Based Transmission System Expansion Planning in Developing Chinese Power Market"; UPEC 2007 - 42nd International University's Power Engineering Conference, Brighton, UK

Fei Song, M. R. Irving; "Uncertainty of Locational Marginal Prices in Optimal Power Flow Formulation"; Submitted for review to Int. Jnl. of Electric Power System Research

7.3 Future Work

Further improvements should answer these questions

1. Who will be responsible for transmission expansion planning?

Is it a non-profit transmission administrator or a for-profit Transmission Company (Transco) or the transmission market?

A transmission company prefers to decrease transmission system expansion investment. Transmission system users prefer to decrease congestion cost. The non-profit transmission administrator should find an acceptable level to balance 'congestion cost' and 'investment'.

2. Who should pay the transmission expansion?

In different countries, or different power systems, we may have different answers. This is a topic about 'cost recovery'. However, very obviously, due to the large investment and long recovery period, increasing uncertainties in generation planning result in fewer investors wanting to invest in system expansion after deregulation.

3. What are the challenges of transmission expansion planning under the competitive environment?

a. Relationship and coordination of transmission and generation planning

b. More uncertain factors and risks

c. Reconciling the interests of 'public' and 'private' organizations and individuals

d. Changes in power patterns (bid-based dispatch)

To answer all these questions, actual power market working should be analysed in depth. Further research should be based on the transmission tariff method that was introduced in Chapter 2 of this thesis. For example a transmission tariff method should include not only the congestion cost of transmission system but also the transmission system extension fee.

In Chapter 4, the congestion-based transmission system expansion planning method has three parts. ***The first part*** is investment for the transmission system expansion. ***The second part*** accounts for the cost of transmission system which caused by high energy prices. Depending on part two, when the load changes one unit, the total cost of transmission system will be changed as well. The change of total cost relates with the energy price. Expensive generation impacts the system user. ***The third part*** accounts for the cost of the transmission system from congestion which caused by heavy load. Since in CDEP method the transmission costs are speared into two parts (from the generator side and from the user side) the transmission system regulator could charge them based on physical instead of arbitrary basis.

The aim of future research is: based on nodal-use method build a transmission tariff method which consider not only total transmission cost recovery but also transmission charge split. The next step of future research would be to combine the Nodal-use method and the CBEP method in an extended method, and evaluate the use of the model on large networks.

Appendix:

A. The data of 9-bus transmission system

APPENDIX TABLE I 9-BUS SYSTEM BUS DATA

bus	*bt*	P_d	Q_d	G_s	B_s	*area*	V_m	V_a	*baseKV*	*z*	$maxV_m$	$minV_m$
1	3	0	0	0	0	1	1	0	345	1	1.1	0.9
2	2	0	0	0	0	1	1	0	345	1	1.1	0.9
3	2	0	0	0	0	1	1	0	345	1	1.1	0.9
4	1	0	0	0	0	1	1	0	345	1	1.1	0.9
5	1	160	30	0	0	1	1	0	345	1	1.1	0.9
6	1	0	0	0	0	1	1	0	345	1	1.1	0.9
7	1	150	35	0	0	1	1	0	345	1	1.1	0.9
8	1	0	0	0	0	1	1	0	345	1	1.1	0.9
9	1	120	50	0	0	1	1	0	345	1	1.1	0.9

bus, bus number

bt, bus type

PQ bus = 1

PV bus = 2

Reference bus = 3

Isolated bus = 4

P_d, real power demand (MW)

Q_d, reactive power demand (MVAR)

G_s, shunt conductance

B_s, shunt susceptance

area, area number, 1-100

V_m, voltage magnitude (p.u.)

V_a, voltage angle (degrees)

baseKV, base voltage (kV)

z, loss zone (1-999)

maxV_m, maximum voltage magnitude (p.u.)

minV_m, minimum voltage magnitude (p.u.)

APPENDIX TABLE II GENERATION DATA

bus	P_g	Q_g	Q_{max}	Q_{min}	V_g	*mBase*	*status*	P_{max}	P_{min}
1	110	0	300	-300	1	100	1	250	10.0
2	200	0	300	-300	1	100	1	300	10.0
3	135	0	300	-300	1	100	1	270	10.0

bus, bus number

P_g, real power output (MW)

Q_g, reactive power output (MVAR)

Q_{max}, maximum reactive power output (MVAR)

Q_{min}, minimum reactive power output (MVAR)

V_g, voltage magnitude setpoint (p.u.)

mBase, total MVA base of this machine, defaults to baseMVA

status, 1 - machine in service, 0 - machine out of service

P_{max}, maximum real power output (MW)

P_{min}, minimum real power output (MW)

APPENDIX TABLE III BRANCH DATE

f	*t*	*r*	*x*	*b*	*rateA*	*rateB*	*rateC*	*ratio*	*angle*	*status*
1	4	0.0001	0.0576	0	250	250	250	0	0	1
4	5	0.0016	0.092	0.158	250	250	250	0	0	1
5	6	0.0025	0.17	0.358	150	150	150	0	0	1
3	6	0.0108	0.0586	0	600	300	300	0	0	1
6	7	0.0005	0.1008	0.209	150	150	150	0	0	1
7	8	0.0009	0.072	0.149	250	250	250	0	0	1
8	2	0.0119	0.0625	0	250	250	250	0	0	1
8	9	0.0034	0.161	0.306	250	250	250	0	0	1
9	4	0.0052	0.085	0.176	250	250	250	0	0	1

f, from bus number

t, to bus number

r, resistance (p.u.)

x, reactance (p.u.)

b, total line charging susceptance (p.u.)

rateA, MVA rating A (long term rating)

rateB, MVA rating B (short term rating)

rateC, MVA rating C (emergency rating)

ratio, transformer off nominal turns ratio (= 0 for lines)

angle, transformer phase shift angle (degrees)

status, 1 initial branch status, 1 - in service, 0 - out of service

B. The data of 29-bus transmission system (Three Gorges Project)

APPENDIX TABLE IV 29-BUS TRANSMISSION SYSTEM BUS DATA

bus	*bt*	P_d	Q_d	G_s	B_s	*area*	V_m	V_a	*baseKV*	*z*	*max*V_m	*min*V_m
1	3	5000	2150	0	0	1	1	0	100	1	1.05	0.95
2	2	0	0	0	0	1	1	0	100	1	1.1	0.95
3	1	5000	2150	0	0	1	1	0	100	1	1.05	0.95
4	1	5000	2150	0	0	1	1	0	100	1	1.05	0.95
5	2	251.93	108.33	0	0	1	1	0	100	1	1.05	0.95
6	1	132	56.76	0	0	1	1	0	100	1	1.05	0.95
7	2	73.5	31.605	0	0	1	1	0	100	1	1.05	0.95
8	2	45	19.35	0	0	1	1	0	100	1	1.05	0.95
9	1	448.5	192.85	0	0	1	1	0	100	1	1.05	0.95
10	2	856.5	368.3	0	0	1	1	0	100	1	1.05	0.95
11	1	1635	703.05	0	0	1	1	0	100	1	1.05	0.95
12	2	705	303.15	0	0	1	1	0	100	1	1.05	0.95
13	2	76.05	32.701	0	0	1	1	0	100	1	1.1	0.95
14	1	345	148.35	0	0	1	1	0	100	1	1.05	0.95
15	1	51	21.93	0	0	1	1	0	100	1	1.05	0.95
16	2	1181.3	507.97	0	0	1	1	0	100	1	1.05	0.95
17	2	81	34.83	0	0	1	1	0	100	1	1.05	0.95
18	2	141	60.63	0	0	1	1	0	100	1	1.05	0.95
19	2	418.5	179.95	0	0	1	1	0	100	1	1.05	0.95
20	1	45	19.35	0	0	1	1	0	100	1	1.05	0.95
21	2	679.5	292.19	0	0	1	1	0	100	1	1.05	0.95
22	2	567	243.81	0	0	1	1	0	100	1	1.1	0.95
23	2	21.9	9.417	0	0	1	1	0	100	1	1.1	0.95
24	2	22.5	9.675	0	0	1	1	0	100	1	1.05	0.95
25	2	169.5	72.885	0	0	1	1	0	100	1	1.05	0.95
26	2	30	12.9	0	0	1	1	0	100	1	1.05	0.95
27	2	22.5	9.675	0	0	1	1	0	100	1	1.1	0.95
28	2	37.5	16.125	0	0	1	1	0	100	1	1.05	0.95
29	1	117.9	50.69	0	0	1	1	0	100	1	1.05	0.95

APPENDIX TABLE V 29-BUS TRANSMISSION SYSTEM BRANCH DATA

f	*t*	*r*	*x*	*b*	*rateA*	*rateB*	*rateC*	*ratio*	*angle*	*status*
5	1	0.0002	0.0006	0.0003	1300	1300	1300	0	0	1
5	1	0.0005	0.0019	0.0002	1300	1300	1300	0	0	1
1	9	0.0006	0.0017	0.0002	1300	1300	1300	0	0	1
1	9	0.0001	0.0004	0	2600	2600	2600	0	0	1
2	9	0.0005	0.002	0.0002	1300	1300	1300	0	0	1
2	9	0.0006	0.0018	0.0002	1300	1300	1300	0	0	1
2	17	0.0001	0.0004	0	1300	1300	1300	0	0	1
3	17	0.0005	0.0012	0.0001	1300	1300	1300	0	0	1
3	17	0.0003	0.0008	0.0001	1300	1300	1300	0	0	1
4	17	0.0001	0.0004	0.0003	1300	1300	1300	0	0	1
4	28	0	0.0021	0.0002	1300	1300	1300	0	0	1
6	5	0	0.0056	0.0002	1300	1300	1300	0	0	1
6	5	0	0.0021	0	1300	1300	1300	0	0	1
7	6	0	0.0011	0.0002	1300	1300	1300	0	0	1
8	7	0	0.0026	0.0002	1300	1300	1300	0	0	1
9	10	0	0.0014	0	1300	1300	1300	0	0	1
9	10	0.0012	0.0026	0.0001	1300	1300	1300	0	0	1
9	12	0.0007	0.0013	0.0001	2600	2600	2600	0	0	1
9	12	0.0009	0.002	0.0003	1300	1300	1300	0	0	1
9	17	0.0022	0.002	0.0002	1300	1300	1300	0	0	1
10	11	0.0008	0.0019	0.0002	1300	1300	1300	0	0	1
12	13	0.0011	0.0022	0	2600	2600	2600	0	0	1
12	14	0.0006	0.0013	0.0002	2600	2600	2600	0	0	1
12	16	0.0003	0.0007	0.0002	2600	2600	2600	0	0	1
13	20	0.0009	0.0021	0	2600	2600	2600	0	0	1
14	15	0.0003	0.0008	0.0001	2600	2600	2600	0	0	1
15	23	0.0003	0.0007	0.0001	2600	2600	2600	0	0	1
17	18	0.0007	0.0015	0.0003	1300	1300	1300	0	0	1
17	18	0.0001	0.0002	0.0002	2600	2600	2600	0	0	1
17	21	0.001	0.002	0.0002	1300	1300	1300	0	0	1
17	21	0.0012	0.0018	0	1300	1300	1300	0	0	1
18	19	0.0013	0.0027	0.0002	2600	2600	2600	0	0	1
18	19	0.0019	0.0033	0.0002	1300	1300	1300	0	0	1

19	20	0.0025	0.0038	0	1300	1300	1300	0	0	1
20	19	0.0011	0.0021	0.0001	1300	1300	1300	0	0	1
19	24	0	0.004	0.0001	1300	1300	1300	0	0	1
19	24	0.0022	0.0042	0.0001	1300	1300	1300	0	0	1
20	23	0.0032	0.006	0.0001	1300	1300	1300	0	0	1
21	22	0.0024	0.0045	0.0003	1300	1300	1300	0	0	1
28	21	0.0006	0.002	0.0002	1300	1300	1300	0	0	1
28	22	0.0002	0.0006	0.0002	1300	1300	1300	0	0	1
23	26	0.0012	0.0026	0	1300	1300	1300	0	0	1
24	25	0.0007	0.0013	0.0002	1300	1300	1300	0	0	1
24	26	0.0009	0.002	0.0002	2600	2600	2600	0	0	1
24	26	0.0022	0.002	0	1300	1300	1300	0	0	1
26	27	0.0008	0.0019	0.0001	1300	1300	1300	0	0	1
26	27	0.0011	0.0022	0.0001	1300	1300	1300	0	0	1

APPENDIX TABLE VI 29-BUS TRANSMISSION SYSTEM GENERATOR DATA

bus	P_g	Q_g	Q_{max}	Q_{min}	V_g	*mBase*	*status*	P_{max}	P_{min}
1	5000	0	3500	-2000	1	100	1	5600	0
2	3500	0	2450	-1400	1	100	1	4200	0
3	3500	0	2450	-1400	1	100	1	4200	0
4	3500	0	2450	-1400	1	100	1	4200	0
6	2000	0	1400	-800	1	100	1	2750	0
9	1800	0	1260	-720	1	100	1	2200	0
11	2500	0	1750	-1000	1	100	1	3100	0
15	1800	0	1260	-720	1	100	1	2200	0
20	2500	0	1750	-1000	1	100	1	3000	0
23	2500	0	1750	-1000	1	100	1	3000	0
26	3000	0	2100	-1200	1	100	1	3400	0
28	3000	0	2100	-1200	1	100	1	3400	0

C. 29-bus transmission system LMP matrix for LMP selection method

APPENDIX TABLE VII LMP MATRIX

j \ i	*L29–1*	*L29–2*	*L29–3*	*L29–4*	*L29–5*	*L29–6*	*L29–7*
1	44.883	43.998	46.011	45.992	44.878	44.87	44.87
2	1	1	1	0.99998	1	1	1
3	133.92	131.59	137.81	137.67	133.9	133.9	133.9
4	133.28	130.98	137.06	137.04	133.27	133.27	133.27
5	44.831	43.949	45.955	45.936	44.848	44.84	44.841
6	44.808	43.926	45.941	45.922	44.825	44.826	44.826
7	44.813	43.931	45.943	45.925	44.83	44.83	44.836
8	44.817	43.936	45.946	45.927	44.835	44.835	44.84
9	44.909	44.037	46.054	46.034	44.904	44.896	44.896
10	65.716	65.708	65.555	65.555	65.714	65.706	65.708
11	66.417	66.411	66.26	66.26	66.415	66.406	66.407
12	60.868	59.608	62.567	62.539	60.861	60.852	60.853
13	71.714	70.486	73.55	73.521	71.708	71.703	71.703
14	78.411	76.537	80.934	80.893	78.404	78.4	78.4
15	34.099	34.561	33.844	33.851	34.1	34.099	34.099
16	61.508	60.238	63.21	63.182	61.5	61.489	61.49
17	133.27	130.95	137.06	137	133.26	133.25	133.25
18	129.49	127.26	133.14	133.09	129.48	129.47	129.47
19	97.453	95.963	99.917	99.881	97.447	97.445	97.445
20	81.476	80.28	83.418	83.389	81.471	81.469	81.469
21	133.6	131.3	137.36	137.32	133.58	133.58	133.58
22	133.12	130.84	136.85	136.83	133.11	133.11	133.11
23	43.932	44.048	44.134	44.133	43.932	43.932	43.932
24	78.748	77.817	80.425	80.401	78.744	78.743	78.743
25	78.985	78.053	80.668	80.645	78.981	78.98	78.98
26	67.2	66.602	68.392	68.376	67.198	67.199	67.199
27	67.218	66.62	68.411	68.394	67.216	67.218	67.217
28	132.7	130.43	136.41	136.4	132.69	132.69	132.68

29	45.054	0.90993	138.31	137.54	45.015	44.984	44.995

(Continues)

APPENDIX TABLE VIII LMP MATRIX ***(CONTINUED)***

j \ *i*	*L29–8*	*L29–9*	*L29–10*	*L29–11*	*L29–12*	*L29–13*	*L29–14*
1	44.872	44.874	44.043	44.035	45.185	45.11	45.702
2	0.99998	1	1	1	1	1	1
3	133.9	133.93	131.96	131.96	134.8	134.87	136.12
4	133.27	133.29	131.34	131.34	134.16	134.23	135.46
5	44.842	44.821	43.994	43.986	45.132	45.058	45.647
6	44.827	44.798	43.977	43.97	45.109	45.038	45.625
7	44.837	44.803	43.981	43.973	45.114	45.042	45.629
8	44.853	44.808	43.984	43.976	45.118	45.046	45.633
9	44.897	44.914	44.081	44.073	45.227	45.151	45.743
10	65.71	65.718	72.211	72.063	65.714	65.641	65.72
11	66.41	66.42	72.8	72.839	66.416	66.345	66.422
12	60.854	60.874	59.713	59.705	61.42	61.282	62.208
13	71.703	71.719	70.638	70.633	72.215	72.362	72.894
14	78.401	78.418	76.742	76.733	79.246	78.998	80.67
15	34.099	34.098	34.522	34.524	33.782	34.21	33.024
16	61.492	61.515	60.335	60.326	62.068	61.923	62.863
17	133.25	133.28	131.32	131.32	134.15	134.22	135.46
18	129.47	129.5	127.61	127.61	130.33	130.41	131.59
19	97.444	97.459	96.212	96.212	98.012	98.175	98.778
20	81.469	81.481	80.465	80.463	81.929	82.114	82.512
21	133.58	133.6	131.66	131.66	134.46	134.53	135.77
22	133.11	133.13	131.2	131.2	133.99	134.05	135.28
23	43.932	43.931	44.06	44.061	43.776	44.139	43.308
24	78.742	78.75	77.994	77.995	79.06	79.29	79.401
25	78.979	78.989	78.23	78.231	79.299	79.53	79.642
26	67.199	67.201	66.727	66.728	67.365	67.626	67.46
27	67.217	67.219	66.745	66.746	67.384	67.644	67.479
28	132.68	132.71	130.79	130.79	133.56	133.63	134.85
29	45.013	45.089	72.471	73.093	61.651	72.618	80.962

(Continues)

APPENDIX TABLE IX LMP MATRIX *(CONTINUED)*

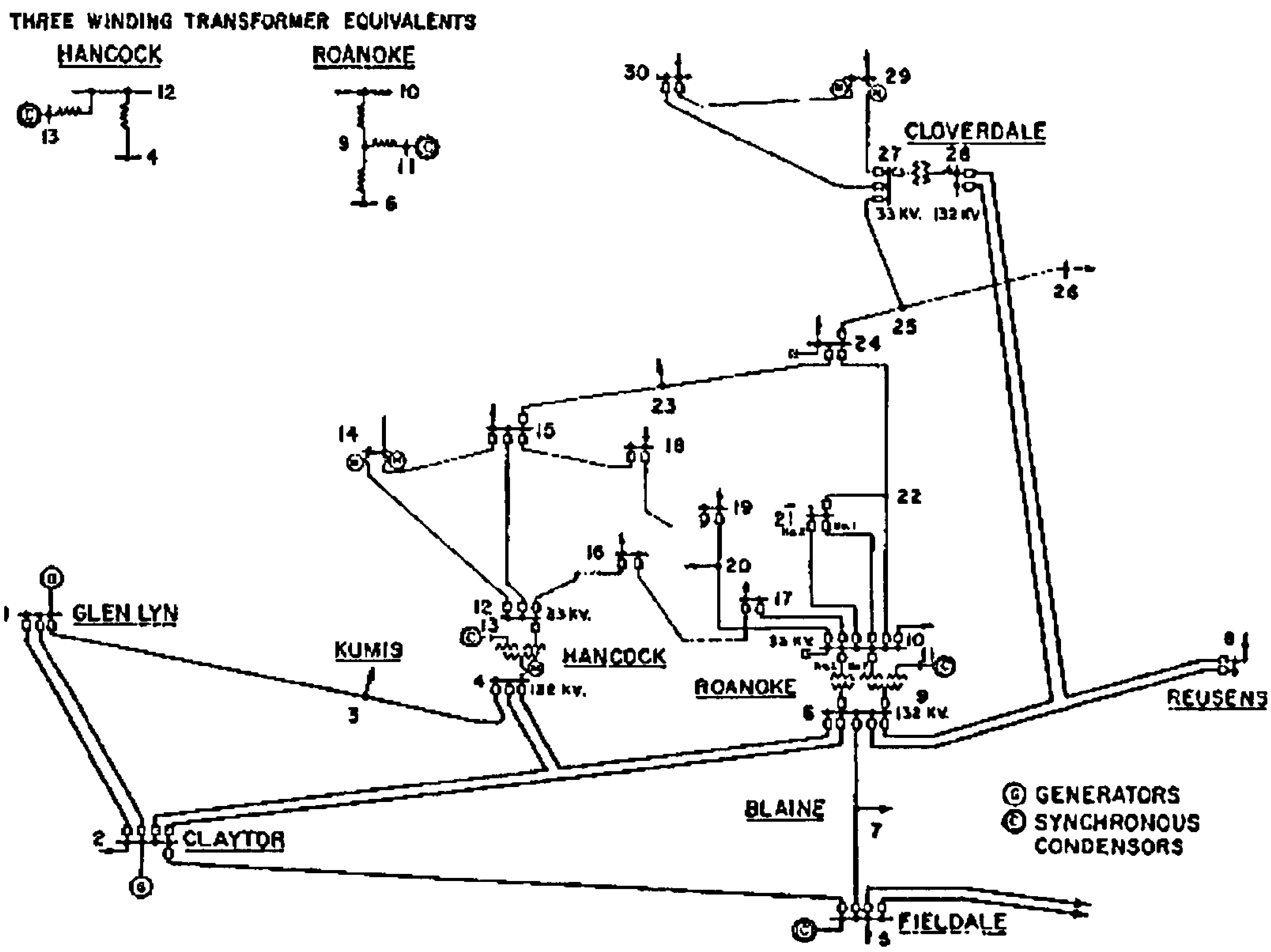
j \ i	*L29–15*	*L29–16*	*L29–17*	*L29–18*	*L29–19*	*L29–20*	*L29–21*
1	43.565	45.203	45.999	45.923	45.289	45.044	45.988
2	0.99994	1	1	0.99999	1	1	1
3	131.25	134.83	137.69	137.48	135.69	134.92	137.66
4	130.64	134.19	137.02	136.82	135.04	134.28	137.01
5	43.518	45.149	45.943	45.868	45.236	44.992	45.932
6	43.504	45.126	45.929	45.854	45.222	44.976	45.918
7	43.507	45.131	45.932	45.856	45.224	44.979	45.921
8	43.509	45.135	45.934	45.859	45.227	44.982	45.923
9	43.602	45.244	46.041	45.965	45.33	45.084	46.031
10	65.544	65.723	65.555	65.555	65.562	65.587	65.555
11	66.249	66.425	66.259	66.26	66.267	66.291	66.26
12	58.907	61.446	62.55	62.441	61.515	61.159	62.535
13	70.297	72.237	73.533	73.434	72.596	72.273	73.517
14	75.176	79.281	80.91	80.741	79.314	78.769	80.887
15	36.782	33.772	33.848	33.916	34.493	34.613	33.851
16	59.516	62.161	63.193	63.083	62.15	61.793	63.178
17	130.61	134.18	137.03	136.82	135.04	134.27	137
18	126.98	130.36	133.11	132.94	131.22	130.48	133.08
19	96.176	98.033	99.895	99.785	98.855	98.315	99.876
20	80.54	81.947	83.401	83.312	82.56	82.276	83.385
21	130.96	134.5	137.33	137.12	135.35	134.59	137.47
22	130.51	134.02	136.82	136.61	134.86	134.11	136.88
23	45.851	43.772	44.134	44.169	44.464	44.48	44.133
24	78.591	79.072	80.411	80.351	79.84	79.498	80.398
25	78.829	79.311	80.654	80.594	80.083	79.739	80.642
26	67.67	67.373	68.383	68.352	68.089	67.866	68.374
27	67.688	67.391	68.401	68.37	68.108	67.884	68.392
28	130.09	133.59	136.38	136.18	134.43	133.68	136.43
29	36.906	62.403	137.52	133.42	99.208	82.557	137.97

(Continues)

APPENDIX TABLE X LMP MATRIX *(CONTINUED)*

i \ *j*	*L29–22*	*L29–23*	*L29–24*	*L29–25*	*L29–26*	*L29–27*	*L29–28*
1	45.97	43.873	44.757	44.76	44.489	44.49	45.962
2	0.99999	1	1	1	1	1	1
3	137.61	132.02	134.33	134.34	133.61	133.62	137.58
4	136.98	131.41	133.69	133.7	132.98	132.99	136.95
5	45.914	43.825	44.706	44.709	44.44	44.44	45.907
6	45.901	43.811	44.691	44.694	44.426	44.426	45.893
7	45.903	43.814	44.694	44.697	44.429	44.429	45.896
8	45.905	43.816	44.697	44.7	44.431	44.432	45.898
9	46.012	43.91	44.796	44.799	44.528	44.528	46.005
10	65.555	65.548	65.553	65.552	65.549	65.548	65.555
11	66.26	66.252	66.257	66.257	66.253	66.253	66.26
12	62.508	59.377	60.712	60.717	60.314	60.314	62.497
13	73.49	70.698	71.888	71.894	71.521	71.522	73.478
14	80.847	75.933	78.042	78.049	77.426	77.427	80.83
15	33.858	36.302	35.164	35.168	35.472	35.473	33.861
16	63.15	59.991	61.339	61.344	60.936	60.937	63.139
17	136.94	131.39	133.68	133.69	132.97	132.97	136.92
18	133.03	127.72	129.92	129.93	129.23	129.24	133
19	99.841	96.623	98.03	98.039	97.577	97.579	99.826
20	83.357	80.881	81.937	81.945	81.599	81.601	83.345
21	137.33	131.72	134	134.01	133.3	133.3	137.3
22	136.95	131.27	133.53	133.54	132.83	132.83	136.84
23	44.133	45.575	44.871	44.875	45.056	45.057	44.132
24	80.375	78.786	79.548	79.557	79.281	79.282	80.365
25	80.618	79.025	79.79	79.97	79.521	79.523	80.609
26	68.358	67.721	67.999	68.006	67.981	67.982	68.351
27	68.376	67.74	68.018	68.025	67.999	68.099	68.37
28	136.43	130.85	133.1	133.11	132.4	132.41	136.4
29	137.45	45.729	79.812	80.239	68.212	68.332	136.89

D. IEEE 30-bus test transmission system



The IEEE 30-bus test transmission system data, include buses, branches, and generators, were not be changed in this test case. All of the data can be also found in the Matpower package.

APPENDIX TABLE XI 30-BUS TRANSMISSION SYSTEM BUS DATA

f	*t*	*r*	*x*	*b*	*rateA*	*rateB*	*rateC*	*ratio*	*angle*	*status*
1	2	0.02	0.06	0.03	130	130	130	0	0	1
1	3	0.05	0.19	0.02	130	130	130	0	0	1
2	4	0.06	0.17	0.02	65	65	65	0	0	1
3	4	0.01	0.04	0	130	130	130	0	0	1
2	5	0.05	0.2	0.02	130	130	130	0	0	1
2	6	0.06	0.18	0.02	65	65	65	0	0	1
4	6	0.01	0.04	0	90	90	90	0	0	1
5	7	0.05	0.12	0.01	70	70	70	0	0	1
6	7	0.03	0.08	0.01	130	130	130	0	0	1
6	8	0.01	0.04	0	32	32	32	0	0	1

6	9	0	0.21	0	65	65	65	0	0	1
6	10	0	0.56	0	32	32	32	0	0	1
9	11	0	0.21	0	65	65	65	0	0	1
9	10	0	0.11	0	65	65	65	0	0	1
4	12	0	0.26	0	65	65	65	0	0	1
12	13	0	0.14	0	65	65	65	0	0	1
12	14	0.12	0.26	0	32	32	32	0	0	1
12	15	0.07	0.13	0	32	32	32	0	0	1
12	16	0.09	0.2	0	32	32	32	0	0	1
14	15	0.22	0.2	0	16	16	16	0	0	1
16	17	0.08	0.19	0	16	16	16	0	0	1
15	18	0.11	0.22	0	16	16	16	0	0	1
18	19	0.06	0.13	0	16	16	16	0	0	1
19	20	0.03	0.07	0	32	32	32	0	0	1
10	20	0.09	0.21	0	32	32	32	0	0	1
10	17	0.03	0.08	0	32	32	32	0	0	1
10	21	0.03	0.07	0	32	32	32	0	0	1
10	22	0.07	0.15	0	32	32	32	0	0	1
21	22	0.01	0.02	0	32	32	32	0	0	1
15	23	0.1	0.2	0	16	16	16	0	0	1
22	24	0.12	0.18	0	16	16	16	0	0	1
23	24	0.13	0.27	0	16	16	16	0	0	1
24	25	0.19	0.33	0	16	16	16	0	0	1
25	26	0.25	0.38	0	16	16	16	0	0	1
25	27	0.11	0.21	0	16	16	16	0	0	1
28	27	0	0.4	0	65	65	65	0	0	1
27	29	0.22	0.42	0	16	16	16	0	0	1
27	30	0.32	0.6	0	16	16	16	0	0	1
29	30	0.24	0.45	0	16	16	16	0	0	1
8	28	0.06	0.2	0.02	32	32	32	0	0	1
6	28	0.02	0.06	0.01	32	32	32	0	0	1

APPENDIX TABLE XII 30- BUS TRANSMISSION SYSTEM BRANCH DATA

f	*t*	*r*	*x*	*b*	*rateA*	*rateB*	*rateC*	*ratio*	*angle*	*status*
1	2	0.02	0.06	0.03	130	130	130	0	0	1
1	3	0.05	0.19	0.02	130	130	130	0	0	1
2	4	0.06	0.17	0.02	65	65	65	0	0	1
3	4	0.01	0.04	0	130	130	130	0	0	1
2	5	0.05	0.2	0.02	130	130	130	0	0	1
2	6	0.06	0.18	0.02	65	65	65	0	0	1
4	6	0.01	0.04	0	90	90	90	0	0	1
5	7	0.05	0.12	0.01	70	70	70	0	0	1
6	7	0.03	0.08	0.01	130	130	130	0	0	1
6	8	0.01	0.04	0	32	32	32	0	0	1
6	9	0	0.21	0	65	65	65	0	0	1
6	10	0	0.56	0	32	32	32	0	0	1
9	11	0	0.21	0	65	65	65	0	0	1
9	10	0	0.11	0	65	65	65	0	0	1
4	12	0	0.26	0	65	65	65	0	0	1
12	13	0	0.14	0	65	65	65	0	0	1
12	14	0.12	0.26	0	32	32	32	0	0	1
12	15	0.07	0.13	0	32	32	32	0	0	1
12	16	0.09	0.2	0	32	32	32	0	0	1
14	15	0.22	0.2	0	16	16	16	0	0	1
16	17	0.08	0.19	0	16	16	16	0	0	1
15	18	0.11	0.22	0	16	16	16	0	0	1
18	19	0.06	0.13	0	16	16	16	0	0	1
19	20	0.03	0.07	0	32	32	32	0	0	1
10	20	0.09	0.21	0	32	32	32	0	0	1
10	17	0.03	0.08	0	32	32	32	0	0	1
10	21	0.03	0.07	0	32	32	32	0	0	1
10	22	0.07	0.15	0	32	32	32	0	0	1
21	22	0.01	0.02	0	32	32	32	0	0	1
15	23	0.1	0.2	0	16	16	16	0	0	1
22	24	0.12	0.18	0	16	16	16	0	0	1
23	24	0.13	0.27	0	16	16	16	0	0	1
24	25	0.19	0.33	0	16	16	16	0	0	1

25	26	0.25	0.38	0	16	16	16	0	0	1
25	27	0.11	0.21	0	16	16	16	0	0	1
28	27	0	0.4	0	65	65	65	0	0	[illegible]
27	29	0.22	0.42	0	16	16	16	0	0	[illegible]
27	30	0.32	0.6	0	16	16	16	0	0	[illegible]
29	30	0.24	0.45	0	16	16	16	0	0	1
8	28	0.06	0.2	0.02	32	32	32	0	0	1
6	28	0.02	0.06	0.01	32	32	32	0	0	1

APPENDIX TABLE XIII 30-BUS TRANSMISSION SYSTEM GENERATOR DATA

bus	P_g	Q_g	Q_{max}	Q_{min}	V_g	*mBase*	*status*	P_{max}	P_{min}
1	23.54	0	150	-20	1	100	1	80	0
2	60.97	0	60	-20	1	100	1	80	0
22	21.59	0	62.5	-15	1	100	1	50	0
27	26.91	0	48.7	-15	1	100	1	55	0
23	19.2	0	40	-10	1	100	1	30	0
13	37	0	44.7	-15	1	100	1	40	0

List of Publication

The following publications have been derived from this thesis.

Fei Song, M. R. Irving; "New Transmission Tariff Method of Transmission System: An Analysis of cost recovery"; 2005 IEEE/PES Transmission and Distribution Conference &Exhibition: Asia and Pacific, Dalian, China

Fei Song, M. R. Irving; "Congestion-Based Transmission System Expansion Planning in Developing Chinese Power Market"; UPEC 2007 - 42nd International University's Power Engineering Conference, Brighton, UK

Fei Song, M. R. Irving; "Uncertainty of Locational Marginal Prices in Optimal Power Flow Formulation"; Submitted for review to Int. Jnl. of Electric Power System Research

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