Allocation of Wheeling Charges and Congestion Management for Cross-Border Trading

A thesis submitted for the degree of

Doctor of Philosophy

At the University of Strathclyde

By

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2012

Declaration of Author's Right

Acknowledgement

I would like to express my sincere appreciation to my supervisor, Prof. K. L. Lo, Head of the Power Systems research Group (PSRG), for his supervision, support, direction and patient guidance throughout my research work. The completion of this thesis would not be possible without his encouragement and constant advice.

I also wish to extend my gratitude to my fellow colleagues at PSRG who helped me in accomplishment of my research work. I would like to acknowledge Dr Zhong Xiaotao, Dr Thamvarit Singhavilai, Dr Shi Peiran, Zhang Mingming, Ibrahim Soliman Naser, Lin Zhemin, Li Rong, Lu Jianfeng, Gu Xinyi, Duan Pengbian, Li Xin for their friendship and encouragement over these last challenging years. With useful information and valuable discussions provided by them, I can offer here only an inadequate acknowledgement of my appreciation.

Last but not least, I would like to express my sincere gratitude to my parents for their financial supports, patience, love and inspiration during my study. A special thanks to my beloved wife for her patience, constant encouragement and unlimited love during my thesis writing.

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$[A_u]$	A (n×n) upstream distribution matrix in power flow tracing method
C	The wheeling charges
F	The long-term wheeling charges
G	The generator
L	The load
P_G	The amount of active power output from a generator
P_T	The total active power flow on a transmission line
P_L	The amount of load (MW) at a bus
$P_{(i.l)}$	The amount of active power on a transmission line from node *i* to node *l*
α	The nodal price
β	The capacity usage in percent
λ	The long-term wheeling charge rate

Glossary of Terms

AP	*Average Participation*	A method to charge transactions wheeling fees by proportional capacity usage on transmission lines
APT	*Average Participation applied to Transit*	A method to charge wheeling fees by combining Average Participation and With and Without Transit
BETTA	*British Electricity Trading Transmission Arrangements*	The name of the system under which electricity is traded in United Kingdom since April 2005
FTR	*Financial Transmission Right*	A financial instrument that entitles the holder to receive compensation for transmission congestion charges
ISO/SO	*Independent System Operator/System operator*	An organisation formed to coordinate, control and monitors operation of the electrical power system
LMP	*Locational Marginal Price*	The cost of serving the next MW of load at a given location
MAP	*Modified Average Participation*	A method that assumes each area is collapsed into a node in Average Participation with either generation or load
MP	*Marginal Participation*	A method to charge wheeling fees with marginal contribution on transmission lines from generators

NETA	*New Electricity Trading Arrangements* The name of the system under which electricity is traded in United Kingdom from March 2001 to April 2005
OPF	*Optimal Power Flow* A load flow that employs techniques to automatically adjust the power system control settings while simultaneously solving the load flows and optimizing operating conditions within specific constraints
PPP	*Pool Purchasing Price* The price paid to generators for each unit of electricity generated and supplied to the pool
PSP	*Pool Selling Price* The price paid by customer for buying electricity from the pool
SAP	*Simplified Average Participation* A method that assumes each area is collapsed into a node in Average Participation with both generation and load
SMP	*System Marginal Price* The price of the most expensive generator needed to meet demand in a settlement period under pool markets
WWT	*With and Without Transit* A method to charge wheeling fees with the concept of transit flow

Abstract

The traditional electricity market provides a vertical monopolistic structure in a certain area which owns and operates generation, transmission and power supply. In the early 90's the deregulation of the power supply market in UK took place. This process has now been repeated in many countries around the world. Although different approaches are adopted during the deregulation process, a similar vein can be found in those markets: all of those vertical monopolistic markets have generally been separated into four parts: generation, transmission, distribution and supply. Nowadays competitive markets have been set up in generation and supply sectors but due to the unique characteristic of transmission network, whose investment needs huge cost and high risk, the transmission sector is to remain in the mode the natural monopoly. Consequently each country or each area only has one transmission company to operate the transmission services.

As the deregulated generation and supply markets are free open access, markets participants not only can trade electrical energy within their local supply areas but they also can trade power between different areas for more benefits. This type of transaction is not restricted to power companies in one country and can well be between a power company in one country with another power company in another country which may not be of immediate neighbour. As a result, these transactions are transported in more than one transmission network. Because this situation rarely exists in traditional markets, transmission owners have not yet come to a common consensus on an acceptable charging tariff to collect transmission fees. Currently several wheeling charging methods for cross-border trading are proposed to resolve this problem but their performances cannot completely fulfil the basic requirement of transparency and fair expectation.

This thesis introduces a method to address the allocation problem of wheeling charges in cross-border trading. This proposed method calculates short-term and long-term wheeling charges respectively and allocates wheeling charges by referring to the location of each transmission line. More importantly, this method is able to provide a transparent and fair allocation result to market participants. The proposed method is illustrated in a 7 bus system and the IEEE 118 bus system. In the case study of the IEEE 118 bus system, three scenarios are set up to test the performance of allocating wheeling charges between two areas and three areas respectively. This thesis has also discussed new challenges of congestion management due to cross-border trading. In addition, an approach of congestion management for the proposed charging method is introduced.

Chapter 1 Introduction

1.1 Introduction

Although electricity is a kind of commodity like other products in the modern world, it is significantly difficult to establish a free market for it due to its special characters. First of all the biggest barrier to introduce a free market is that electricity cannot be stored, which commonly happens to other industrial commodities. Secondly the electricity is the fundamental energy source of modern industries. This characteristic results in any government would not wish to take a high risk to establish a total free electricity market. Even now most of electricity markets are influenced more or less by the governments. Consequently, in most time of the twentieth century, according to the first reason consumers had no choices to choose electricity suppliers except local electrical companies to purchase the needed electric energy. In addition the second reason causes that most of the local electrical companies are vertically integrated, which means they own local generators, local transmission lines and the local distribution networks. This model is convenient for government to regulate electric prices and outputs to satisfy the varieties of demands such as industrial, commercial, residential and others. [1] This traditional market model has been running for years until deregulation.

Since 1980’s the interest of reducing the energy prices and industry costs prompted liberalised markets in despite of monopoly markets. The first deregulation happened in UK in 1990 after the UK government decided to introduce competition into the electric utility. [2] This action was taken to privatise the electric supplier and break the vertically integrated utility. The unbundled utility was separated into generation, transmission and distribution entities, which are independent from each other.

Additionally suppliers sell electricity to customers after buying it from other entities. At the moment free competitive markets exist on generation and supply levels. On the contrary, because of the unique characteristics, some people are on the view that the transmission and distribution networks are better operated if they are being retained as natural monopoly. [3]

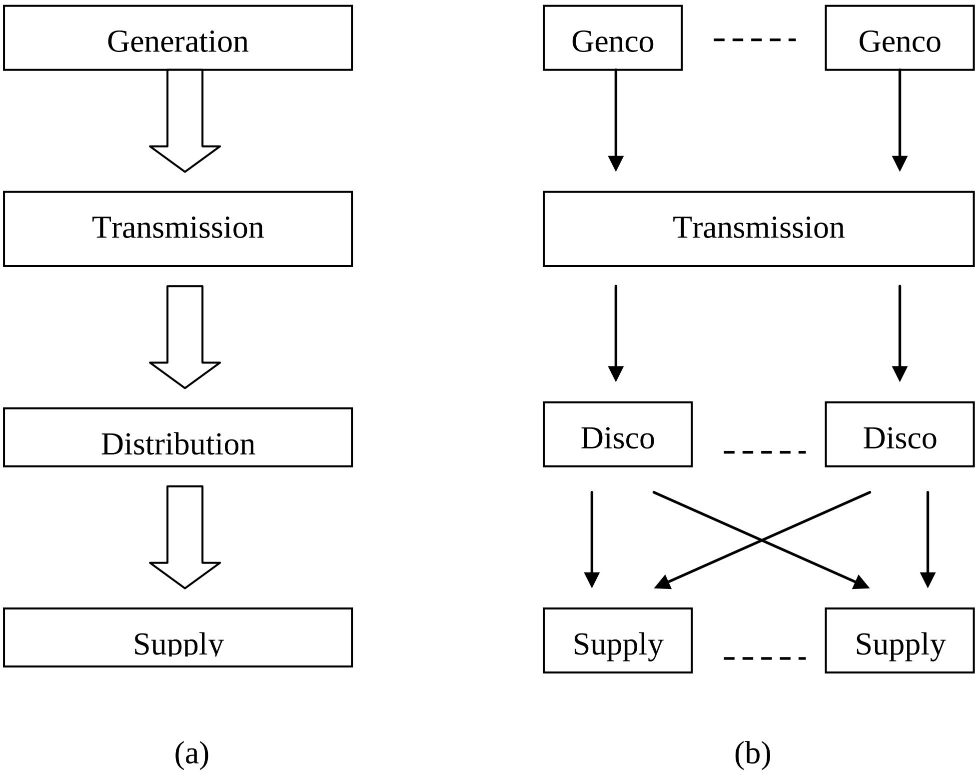

Figure 1.1: (a) vertically integrated utility and (b) deregulated market structures

Figure 1.1 shows the structures of vertically integrated utility and deregulated electricity market. Figure 1.1 (a) provides an intuitive idea to explain how the electricity simply flows throughout the vertically integrated network. It is uncomplicated to operate the system and assign profits as all of those components owned by a single company. As revealed by figure 1.1 (b) the generation, distribution and supplier are broken into different companies in deregulated market meanwhile the transmission network keeps the natural monopoly. In addition, unlike the generation and supply, distribution systems are unbundled with respect to geographic zones. The distribution network in a specific zone is regulated and maintained by a natural monopoly entity. Consequently real competitions only appear in generation and supply markets. The most obvious benefit of deregulation is to decrease energy prices for costumers. However, the disadvantage side with deregulation is because the whole market is operated by several entities instead of one big integrated company, which increases the difficult level of management. A common solution to this issue is to establish an Independent System Operator (ISO) in each operation area, which is not related with either government or electric companies, to regulate the market.

At the same time, new energy pricing mechanisms are created for the deregulation electricity market. In general they are classified as Uniform pricing, Zonal pricing and Nodal pricing. [11] The issues on weighting merits against each other are being debated all the time since the deregulated market operated. But it is commonly agreed that nodal pricing serves the market from the most economic viewing. [11]

To sum up, significant changes have been caused by the deregulation of electricity market. With deepening of deregulation progress, new challenges are increasingly appearing in competitive markets. This thesis will mainly discuss the issue of allocating transmission wheeling charges in cross-border trading in the deregulation market.

1.2 Cross-border trading and current status

Since the electric market in UK became deregulated in early 90’s, the process has been adopted in many other countries, such as USA, Australia and New Zealand.

[4][5][6] As discussed in the previous section, the generation and supply sides are completely open access in the deregulated market. As a result, market participants can not only trade electricity within their local networks but also trade power among different operation areas. For instance, costumers are able to choose cheap suppliers that are located in other operation areas for electricity consume. Those cross-border transactions use more than one transmission network in practice, which never happened in the traditional market. In other words, the transmission tariff for cross-border trading had not been considered until deregulation happens. As a result of this new situation how to charge the cross-border transmission services becomes a new challenge in modern electric market.

There are several cases of electricity markets that involve cross-border trading. In the US, under the supervision of federal Energy Regulatory Commission, several successful independent deregulated markets exist though out the whole country and some of them cover different states. They have familiar market structures and the most famous market is PJM which is a Regional Transmission Operator (RTO). PJM became an independent neutral organisation in 1993 and opened bid-based energy market in 1997. It operates a nodal price based pool market to serve 13 states and the District of Colombia. [7] In PJM, although some transactions are crossing different transmission areas, all of them are dispatched by the same system operator (PJM), which means the safety, reliability and security could be easily achieved.

The Europe also experienced the similar revolution in the last decade. In 2003 Directive 2003/54/EC and Regulation (EC) [8] were adopted to form a single European market in the future. This is the turning point of European electric market. Since then electric markets of different countries try to break the borders of networks and connect to other networks. In other words, electricity could be freely traded by generators and loads throughout Europe whilst each country keeps its former transmission company operating local systems and co-operating with other transmission companies. As a consequence, every country has a local transmission company which could provide transport services for cross-border trading from other participants in Europe.[8][9] Unlike the PJM market, there is not an independent system operator to manage cross-border trading in Europe. All transmission companies have to cooperate with each other to settle the inter-payment for cross-border trading. With the concept of ETSO 2005, European electric market used to use transit flow concept to charge cross-border trading in 2005 and 2006, but it has been found some flaws existing. [10] At the moment, several new methods are under discussion and being examined by the EU energy commit. However, none of them is entirely superior over the other one so the EU energy commit is still gathering views from the electricity industry. [13][14] This thesis will provide detailed information of new methods in EU in addition to list advantages and disadvantages of each method in Chapter 3

1.3 Objective of the thesis

Because not most of generation facilities are near consumers, electricity needs to be transported from sources to end customers. Variety of costs, such as operation costs and security costs, will be added in the duration of transmission. If the system was vertically integrated, those costs could be easily charged as part of the final energy price and fully paid by the consumers. However, the situation would be different for deregulated market in which the transmission network is operated independently. In deregulated market the transmission companies charge everyone who uses their service. In other words, all of the generation and load have to pay transmission services. The payment could be paid by generation or shared by a ratio between generation and demand side, such as 5:5 or 7:3. This ratio is regulated by the ISO in the market.

Nevertheless, as mentioned in the beginning of this chapter, consumers do not only buy electricity from local network but also are able to buy it from other networks. This change makes the allocation of transmission wheeling charges even more complicated because there is not a transmission tariff for allocating transmission fees in cross-border trading. Consequently, an allocation method is needed to overcome this problem.

According to the situation described above, objectives of this thesis are described as the following:

- To review current electricity pricing methods in the deregulated market: Uniform pricing, Zonal pricing and Nodal pricing. In addition, advantages and disadvantages of the three pricing mechanisms are compared with case studies.

- To explore current mechanisms of calculating transmission wheeling charges and discuss disadvantages when they are implemented to allocate transmission charges in cross-border trading.

- To present and analyse advantage and disadvantages of the current allocation methods of transmission wheeling charges in cross-border trading.

- To propose a solution for allocating transmission fees in cross-border trading in deregulated markets, which eliminates disadvantages of current allocation methods in cross-border trading.

- To set up a standard procedure of allocating transmission fees in cross-border trading with the proposed method.

- To simulate and investigate the proposed method under different situations.

- To explain the congestion issue that is accompanied by cross-border trading. An approach of congestion management is suggested for the proposed method after discussing current congestion solutions.

1.4 Original Contributions of the Thesis

Based on the above objectives, the original contributions of this thesis are presented in the following:

- The thesis explains why allocation of transmission wheeling charges in cross-border trading after deregulation is a challenge, which does not previously exist in pre-deregulation era and that current charging methods are not able to fulfil the allocation task. Other charging methods for cross-border trading are discussed but they are discovered to be insufficient to achieve a fair allocation.

- A new method is proposed in the thesis to resolve the problem of allocating transmission wheeling charges in cross-border trading. This proposed method is supposed to perform a fair allocation and meet the need to economic and technical expectations. The effectivities of the proposed method are tested by using two systems: a 7 bus system and the IEEE 118 bus system.

- Three scenarios in the IEEE 118 bus system is used to simulate and analyse the proposed method. The simulation is completed with Matlab and Powerworld software. Simulation results fully support that the proposed method is able to allocate transmission wheeling charges in cross-border trading with non-discrimination and transparency.

- The characteristic of congestion and its influence in deregulated electricity markets are introduced in the thesis. Additionally the reason why congestion needs to be eliminated efficiently is explained. Consequently a measure of congestion management is suggested for the proposed method after comparing current congestion solutions. The aim of this measure is able to give transmission owners incentives to reinforce networks to eliminate congestion.

1.5 Outline of the Thesis

This thesis is organised with seven chapters in the following order:

Chapter 1 presents an overview of deregulated electricity markets and explains the importance of researching allocation of transmission wheeling charges in cross-border trading. Objectives, original contributions and outline of the thesis are also presented in this chapter.

Chapter 2 firstly discusses the traditional electricity market structure which is re-organised into four parts after deregulation from the vertical integrated structure. All of four parts are independently operated so an Independent System Operator (ISO) is needed to operate the market as a supervisor. In addition, three energy pricing mechanisms are discussed in this chapter: Uniform Pricing, Zonal Pricing and Nodal Pricing. Advantages and disadvantages are discussed as well. Finally Chapter 2 introduces the deregulated market experience around the world: UK, PJM (US), California (US), Texas (US) and Nordic markets.

Chapter 3 first describes traditional methodologies for wheeling charges. Although they can help transmission owners collect transmission wheeling charges in conventional markets, drawbacks of those methodologies prevent them from being implemented in cross-border trading. The next section reveals the challenge when cross-border trading is involved during transactions in deregulated markets. By following those contents, the research work in the EU market is reviewed. Two major methods of wheeling methods, Average Participation (AP) and With and Without Transit (WWT), will be compared in this section.

Chapter 4 introduces a new method for resolving allocation of transmission wheeling charges in cross-border trading. This proposed method takes into account both transaction path information and congestion information so that both technical and economic expectations are achieved. The information provided by the proposed method could provide participants a fair market environment and encourage their investment incentives. After the mathematic theory of the proposed method is presented, this proposed method is tested on a 7 bus system and the IEEE 118 system. The results show the proposed method is fully functional.

In Chapter 5 the IEEE 118 bus system is used as an illustration network to set up three different scenarios to analyse the proposed method. Firstly the IEEE 118 bus system is split into two areas to simulate a trade across two areas. Its purpose is to reveal impacts of cross-border trading under the proposed method. After this test, a bilateral contract is added into the first scenario. Additionally, within three areas in the IEEE 118 bus system, a cross-border trade between two areas could require the third area to transport those traded energy through its transmission network. Impacts of the three scenarios are discussed in this chapter.

Chapter 6 explains the congestion issue in power system and how it affects energy prices through the whole market. Current major measures of congestion management in the deregulated electricity market are presented in this chapter. An approach is presented with the proposed method to resolve congestion problem.

Chapter 7 presents the conclusion of this thesis and future research works.

1.6 Publications

- Chunyang Zhao, S. Galloway and K. L. Lo, "A New Method of Charging Transmission Services", 44th International Universities' Power Engineering Conference (UPEC), Glasgow, UK, 1-4 September 2009.

- Chunyang Zhao and K. L. Lo, "A New Method of Charging Transmission Services in Cross-border Trading", 2nd Asia-Pacific Power and Energy Engineering Confference (APPEEC), Chengdu, China, 28-31 March 2010.

- Chunyang Zhao and K. L. Lo, "Allocating Transmission Fees of Cross-border Trading", Under preparation for journal submission.

1.7 Reference

[1]. Daniel Kirschen, Goran Strbac, "Fundamental of Power System Economics", John Wiley & Sons Ltd, England, 2004

[2] Catherine Waddams Price, "The Effect of Liberalizing UK Retail Energy Markets on Consumers", Oxford Review of Economic Policy, Vol. 21, No. 1, pp. 128-144, 2005

[3] Lynne Kiesling "Rethink the Natural Monopoly Justification of Electricity Regulation", available on: http://reason.org/news/show/rethink-the-natural-monopoly-j, accessed on: 31/1/2008.

[4] Nicolai J. Sarad and Dean M. Colucci, "The Competitive Market for Power in the U.S.: The Role of ISOs and PXs", available on: http://library.findlaw.com/2000/Mar/1/127779.html, accessed on: 20/01/2010

[5] "An Introduction to Australia's National Electricity Market", available on: http://www.aemo.com.au/corporate/0000-0262.pdf, accessed on: 09/03/2011

[6] Evans Lewis, Meade Richard, "Alternating Currents or Counter-Revolution? Contemporary Electricity Reform in New Zealand", Victoria University Press, Wellington, pp13-18, 2005

[7] “Company Overview”, Available on: http://www.pjm.com/about-pjm/who-we-are/company-overview.aspx, accessed on: 28/010/2010

[8] Luis Olmos Camacho, Ignacio J. Pe´rez-Arriaga, “Comparison of several inter-TSO compensation methods in the context of the internal electricity market of the European Union”, *Energy Policy 35*, pp. 2379–2389, 2007

[9] Luis Olmos Camacho, Ignacio J. Pe´rez-Arriaga, “An assessment of inter-TSO compensation algorithm in the internal electricity market of the European Union”, *Electrical Power and Energy Systems 29*, pp. 699–712, 2007

[10] “Inter transmission System Operator Compensation Mechanism and Harmonisation of Transmission Tariffs for Electricity”, available on http://ec.europa.eu/energy/gas_electricity/cross-border_committee_en.htm, accessed on: 3/7/2008

[11] Feng Ding, J. David Fuller, “Nodal, Uniform, or Zonal Pricing: Distribution of Economic Surplus”, *IEEE Transactions On Power Systems*, Vol. 20, No. 2, pp. 875-882, May 2005

[12] Kun Yang, “Optimal Procurement and Pricing of Reactive Power Ancillary Services in Competitive Electricity Market”, PhD Thesis, University of Strathclyde, 2010

[13] “Objectives of the consultation”, Available on: http://ec.europa.eu/energy/gas_electricity/consultations/2009_02_28_tso_en.htm, accessed on: 25/2/2011

[14] “Incentive Schemes to Promote Cross-border Trade in Electricity”, available on: http://www.energy-regulators.eu/portal/page/portal/EER_HOME/EER_CONSULT/CLOSED%20PUBLIC%20CONSULTATIONS/ELECTRICITY/Cross%20Border%

20trade%20incentives%20electricity/CD/E08-ENM-07-04_IncentiveSchemes_10-Dec-2009.pdf , accessed on: 25/2/2011

Chapter 2 Structure of Deregulated Electricity Market

2.1 Introduction

The electricity supply industry is one of the fundamental public utilities that support our industry and our daily life. The original industry was vertical, tightly regulated and monopolised by governments. However, economists have long considered that open competitive trading of electricity would benefit both buyers and sellers, there exists strong argument that a competitive electricity market is a better choice to maximise the total social welfare in a modern society. [1] In 1990 the UK became the first western country in which the electric industry was deregulated. Since then the deregulation have happened in many parts of world though the process could be significantly different from one country to another. In the duration of deregulation different market models (uniform pricing, zonal pricing and nodal pricing) have been accepted in different countries. The advantages and disadvantages have been widely discussed in various publications. In practice the chosen model is dependent on the social structure and economic development of the country concerned but nodal pricing is broadly agreed to be the most economical market model at the moment.

However, the most important issue to set up competition is to break the monopoly rather than purely accepting the new market models. For this purpose the vertically integrated structure has been broken into generation, transmission, distribution and supply. Instead of the whole system centrally controlled, there are many companies competing on the generation and supply levels. This means the trading and operation strategy of each company is non-related to others. On the other hand, unlike the daily commodities, the electricity energy must be simultaneously produced by the generators and consumed by the loads. There would be technical faults in the system if an unbalance between generation and load happens. The worst fault is the blackout. To avoid this situation a central-control authority is an acceptable solution. Before deregulation this role was played by the vertically integrated company. In the deregulated market the duty could be fulfilled by an independent authority from both of government and electric companies. In most countries, this kind of authority is called Independent System Operator (ISO).

In addition, another improvement must be accomplished to ensure the competitive market must have open access for generation companies. The open access can be defined as a system in which the electricity producer can enter or quit the market freely and sell electricity to any buyers without discrimination. [2] Only in this way it can be possible for the buyers enjoy the lower electricity prices while the sellers maximise their profits.

Although the deregulation process is not always experiencing total success in every country, one notable example is the huge power shortage in California (USA), yet the trend of deregulation has been extended to larger areas all round the market. In this chapter, the fundamental issues of deregulated market will be introduced. In section 2.2, the main issues of deregulated market are discussed, which includes pricing schemes and the role of ISO (Independent System operator). In addition, comparisons between current pricing schemes are also presented in this section. The section that follows is about the deregulated market experience around the world: UK, PJM (US), California (US), Texas (US) and Nordic markets. This section mainly focuses on the current status in each market, such as: role of ISO, energy trading method and transmission cost recovery.

2.2 Deregulated market

2.2.1 General structure of deregulated electricity market

Unlike the traditional electricity market, which was vertically integrated, the deregulated electricity market has been broken into several parts to co-ordinate the system operation. In practice different parts are involved in different roles. In this section, the general description of the main parts of deregulated market will be presented.

- **Generation**

  In deregulated market the generation companies only own and operate generators to produce electricity. They earn profits by selling electricity energy to the rest of the participants in the system. Furthermore they are not only paid for the active power they produce but also the reactive power production is recovered from the payment. Additionally they also provide other services to keep the system stability, such as frequency regulation and capacity reserves. Because it is technically easy to assign generators to operate separately and independently, the deregulated generation market is completely competitive.

- **Transmission**

  In a specific country the transmission network could be split into several regional transmission companies after the deregulation. However they would not to compete with each other because the natural monopoly in transmission can maximum the benefits for other participants in the system. Therefore only one transmission company exists in a particular transmission area. Otherwise those transmission companies are supervised by a system operator, which is an independent organisation to regulate the whole electrical system. The transmission companies have the duties to ensure secured and reliable operation for generation, distribution and the end customers.

- **Distribution**

  The distribution network is defined as the low voltage level network that transports electricity from the transmission network to the consumers. The distribution network in a specific region is owned by one company but it does not necessarily have to be operated by the same company. Similar to the transmission, natural monopoly provides the most efficient operation for its customers.

- **Supply**

  Unlike the monopolised supply in vertically integrated structure, the supply level is broken into numbers of smaller companies. The duty of those companies focuses on buying electricity form generators and selling it to customers and they are not involved into any technical operation. A competitive market exists in supply level.

- **Independent System Operator (ISO)**

  The ISO did not exist in the traditional market as the vertically integrated structure was central-controlled by the only company. However, after the deregulation, the vertically integrated structure is broken and there is no such a company holding the position of supervision of overall system operation. As a consequence, the system needs an organisation with non-discriminatory to co-ordinate the different companies for safe operation. This is the reason why an ISO is needed in deregulated market. More descriptions of ISO are presented in section 2.2.4.

2.2.2 Pricing schemes

2.2.2.1 Uniform pricing

The main characteristic of this pricing scheme is that energy prices in the market are the same irrespective of the location it is consumed in the network. For most countries the uniform pricing market is also known as the pool market. In the pool market the ISO is the only administrator taking the duty to keep the balance between generation and load in the system. In another words it has the ability of dispatching the outputs of each generator to ensure safe operation. As a result the generation companies have to submit their capacities and bids to ISO on advance for entering into the market. The ISO will create a generation curve stacking from the lowest bids until the amount of generation meets the demand. The price of that generator on the equilibrium point is used to set the system marginal price (SMP). The generators whose bids are below or equal the SMP are chose to output in the market. [3] Figure 2.1 shows what the curve looks like:

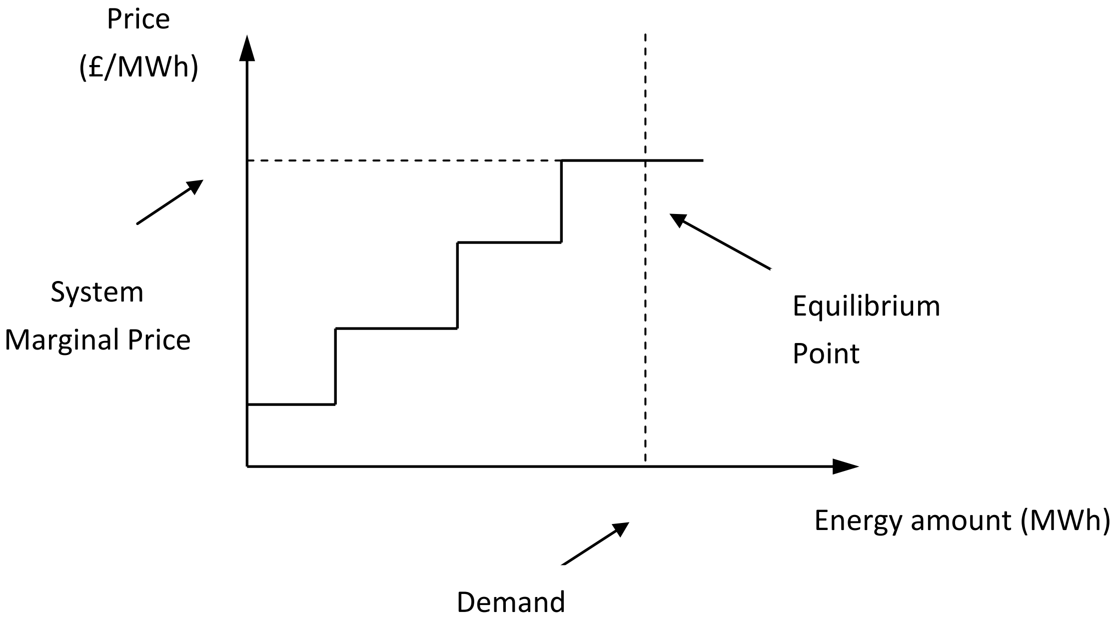

Figure 2.1: Determine of the SMP

The most famous pool market is England and Wales (E&W) began in 1990 and terminated in 1998. The mechanism in E&W precisely explains how the pool market works in practice. [4] As mentioned above, the SMP must be set up before market clearing. After this procedure, the Pool Purchase Price (PPP) is paid to each generator by the ISO for purchasing electrical energy.

$$PPP=SMP+LoLP\times(VoLL-SMP) \tag{2.1}$$

where the VoLL is Value of Lost Load and LoLP means the Loss of Load Probability. The VoLL is the cost that customers are willing to pay for ensuring the electricity supply without disruptions. ISO sets this value of the VoLL and increases it taking into concern the annual rate of inflation (RPI). The LoLP could be described as the likelihood that the output capacity cannot meet the total demand during a given period.

On the other side, the customers buy electricity from ISO at the Pool Selling Price (PSP).

$$PSP=PPP+Uplift \tag{2.2}$$

where Uplift is the component which helps ISO to recover the costs of maintaining the system stability and power balances, such as ancillary services and congestion costs.

The procedures described above are calculated under no congestion and are considered as economically efficient. Even so, when congestion happens in the system, the weakness of uniform pricing appears. If one or some lines are constrained, the ISO has to re-dispatch the generation to meet system demand. In other words, some of outputs of cheaper generators would be curtailed which would need to be replaced by more expensive generators. However, according to the uniform pricing theory, the SMP remains the unchanged. Obviously the ISO pays more to buy electricity energy from generators comparing to the situation that has no congestion. Those additional costs may be added into Uplift. Furthermore the solution to congestion does not provide adequate market signals to market participants. To some points this mechanism does not encourage a completely free competition in the market because the participants cannot freely determine their trading prices.

2.2.2.2 Zonal pricing

Zonal pricing is introduced into the market for the reason that it can be one of solutions to congestion problem in uniform pricing. The most famous zonal pricing market is the Nordic electric market, which is briefly introduced in [5]. In general, two main stages are used in zonal pricing. The first stage is to determine the SMP which is similar to that used in uniform pricing, which is enough to clear the market without congestion.

If congestion is found during generation dispatch, the second stage will be implemented. [6] In the second stage, the ISO will divide the system into different zones on both sides of the transmission lines whose transmission capacities are exceeded. To simplify the explanation, assuming there are only two zones in this case. After splitting the market there likely to have a high-price zone in which the generation cannot meet all the local demands and a low-price zone with generation surplus. By following this step, the ISO may buy electricity from the low-price zone and sell it to the high-price zone through the tie lines which have not yet reached their capacities. The action is considered to draw the price gap between two zones and maximise the social welfare. Figure 2.2 shows the relationship between the prices and power traded by ISO.

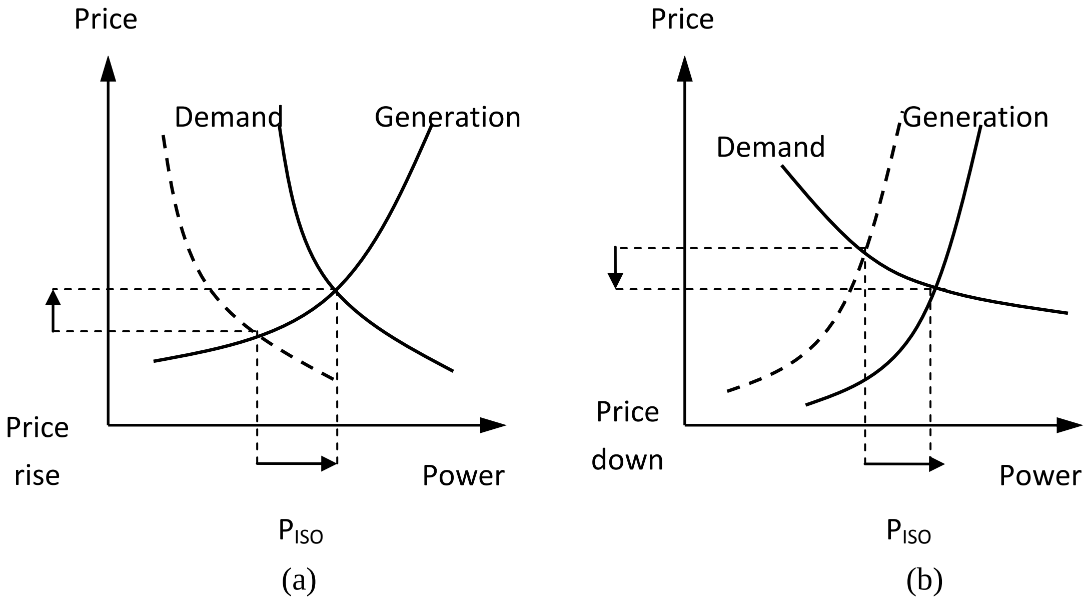

Figure 2.2: (a) low-price zone and (b) high-price zone

The P_{ISO} in Figure 2.2 dedicates the traded power between two zones. Because of the market splitting, the surplus generation in low-price zone can be sold at a higher price whilst the customers in high-price zone enjoy cheaper energy.

Although zonal pricing improves the congestion solution and its handling is more transparent to market participants when it is compared to uniform pricing, yet some people point out the drawbacks when applying this pricing scheme. Those arguments focus on abuses of the market power when intra-congestion happens and inefficient congestion solutions. [7] The advantages and disadvantages of zonal pricing are discussed in section 2.2.3.2.

2.2.2.3 Nodal Pricing

Nodal price is a pricing scheme known for its simplicity and is a considerable combination of physical power flows and economic views. In this scheme every electrical node (busbar) has its own energy price which is determined by the cost of supplying the next MW at this node. As a result nodal pricing is also known as Locational Marginal Pricing (LMP).

To carry out nodal pricing, all participants need to submit their bids and offers to the ISO and it is responsible for determining in the nodal prices at each node by taking into account losses and transfer capacity of the system. [8] Under ideal conditions when a system has zero losses and congestion does not exist, all the nodal prices will be identical. However, in practice, the prices at different nodes are different with respect to the marginal losses and congestion. According to the nodal pricing, the nodal prices are paid to generators and are charged to consumers.

For the purpose of determining nodal prices, the OPF (optimal power flow) algorithm is implemented to calculate marginal costs at each node. The OPF formulation was first developed to solve the objective functions which are subject to certain constraints during traditional power solution. In general, the OPF solution of active power can be written as:

$$Min \sum_{k=1}^{N} (P_{gen,k}) \tag{2.3}$$

And the constraints are:

$$\sum_{Gen} P_{gen,k} = \sum_{Load} P_{Load,k} + \sum_{Injection} P_{Injection} \tag{2.4}$$

$$P_{gen,k}^{min} \leq P_{gen,k} \leq P_{gen,k}^{max} \tag{2.5}$$

$$G_{line,l} \leq G_{line,l}^{max} \tag{2.6}$$

where $P_{gen,k}$ refers to the amount of generation at bus *k*

$P_{gen,k}^{max}$ refers to the maximum active power generation at bus *k*

$P_{gen,k}^{min}$ refers to the minimum active power generation at bus *k*

$P_{Load,k}$ refers to the amount of load at bus *k*

$P_{Injection}$ refers to amount of active power injected into system from bus *k*

$G_{line,l}$ refers to the amount of active power on line *l*

$G_{line,l}^{max}$ refers to the capacity constraint of line *l*

The OPF solution could be used for multi-purposes. For calculating nodal prices, the Lagrange function of the OPF which is subject to the minimum of the operation cost can be written as:

$$L = \sum_{k=1}^{N} C_{gen,k}\, P_{gen,k} + \sum_{k=1}^{N} \lambda_k \left[\sum_{Gen} P_{gen,k} - \sum_{Load} P_{Load,k} - \sum_{Injection} P_{Injection} \right] + \sum_{l=1}^{nl} \mu_l \left[G_{line,l} - G_{line,l}^{max} \right] + \sum_{k=1}^{N} \pi_k^{max} \left[P_{gen,k} - P_{gen,k}^{max} \right] + \sum_{k=1}^{N} \pi_k^{min} \left[P_{gen,k}^{min} - P_{gen,k} \right] \quad (2.7)$$

where $C_{gen,k} P_{gen,k}$ is the energy bid function at bus *k*

λ_k is the lagrange multiplier at bus *k*

μ_l is the marginal cost of transmission constraint on line *l*

π_k^{max} is the lagrange multiplier of maximum limit of active power at bus *k*

π_k^{min} is the lagrange multiplier of minimum limit of active power at bus *k*

By solving the Lagrange function, the nodal marginal cost can be expressed as:

$$\lambda_k = \lambda_k^{energy} + \lambda_k^{cong} + \lambda_k^{loss} \quad (2.8)$$

where λ_k is marginal price of supplying the next MW bus *k*

λ_k^{energy} is the energy cost of supplying the next MW at bus *k*

λ_k^{cong} is the congestion cost of supplying the next MW at bus *k*

λ_k^{loss} is the loss cost of supplying the next MW at bus *k*

The first component is determined by the marginal cost at slack bus. The second and third components can be considered as the costs which are incurred by congestion and losses in the duration of the delivery. Because congestion and losses have different impacts at different buses so that λ^{cong} and λ^{loss} are met the same at those buses. Consequently, each bus likely has a different nodal price for the energy trading. On the other hand, if the congestion and losses are not counted in the calculation, all the nodal prices will be the identical.

To demonstrate nodal pricing, assume two nodes shown in Figure 2.3. The nodal prices are £10/MWh and £15/MWh respectively. As shown in the Figure, the L_1 can buy its 40MW demand from G_1 at £10/MWh. As they are connected to the same bus, there is no transmission surplus:

L_1 pays 40MW×£10/MWh=£400/h

G_1 recieves40MW×£10/MWh=£400/h

The same situation incurs between G_2 and L_2. But this is a 60MW shortage of L_2, so it can buy 60 MW from G_1. According to the nodal price theory,

L_2 pays 60MW×£15/MWh=£900/h

G_1 receives 60MW×£10/MWh=£600/h

The difference, which is £300/h, reflects the transmission costs. It could be paid to the transmission network for the future reinforcement or shared by the market participants. For calculating transmission fees, the information we need to know is only the nodal prices from sending node and receiving node respectively.

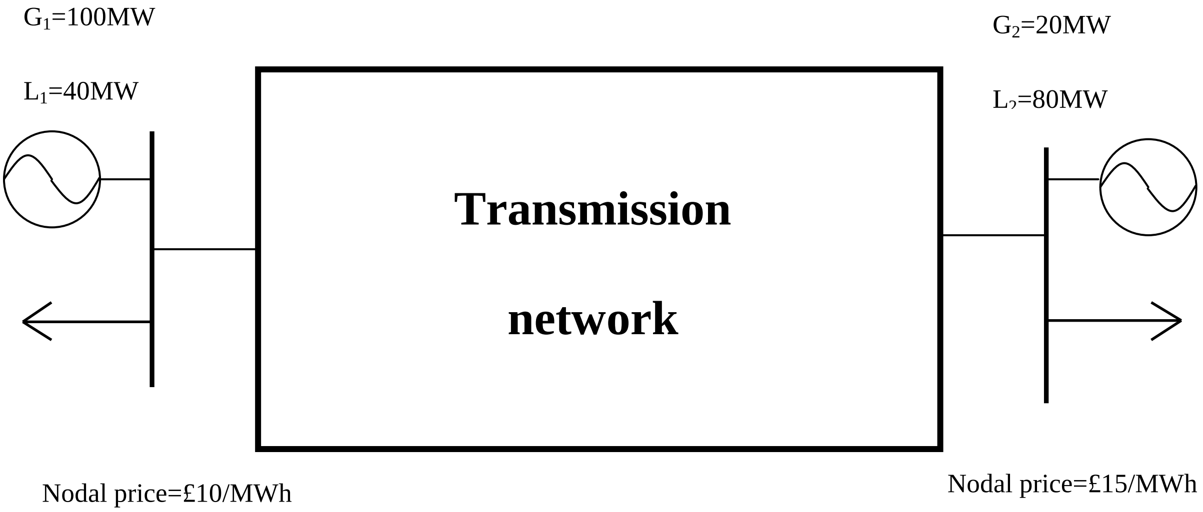

Figure 2.3: Example of nodal pricing

The main criticism on nodal pricing is transmission cost recovery and transmission investment. [9] The methodology claims to be an appropriate pricing scheme to encourage competition amongst market participants. Nodal pricing is widely accepted for a standard market design in the world at the moment, such as New Zealand and US (PJM, New York and New England).

2.2.3 Comparison of pricing mechanisms

The previous section presents the current pricing methodologies for market operation. Different methodology offers different approach to market operation and financial settlement and with its own benefits as well as weaknesses. In this section the advantages and disadvantages of each pricing methodology will be discussed respectively.

2.2.3.1 Advantages and disadvantages of uniform pricing

If the ISO prefers a pricing scheme which is simple to collect revenues, uniform pricing is the most suitable method in the three of charging methodologies described because all the prices in the system are identical. “Simple” seems to be the best advantage of uniform pricing. It provides easy and efficient pricing procedures for the competitive environment because the energy price is the same all over the system. This reduces complexity in the collection of revenue. Furthermore the ISO performs the central-control of generation dispatch in maintaining the balance of generation and demand. The problem of congestion is also handled by the ISO who has the sole responsibility for generation dispatch and thus ensures that any sudden surge in demand or loss of load is met with the most efficient plant.

As mentioned above the ISO plays a significant role in uniform pricing because it is responsible for maintaining system operation and solving the monetary issues at the same time. In other word the ISO is a replacement of the vertically integrated company in deregulated market. This market structure determines that the ISO is able to individually handle the whole system without co-ordination with market participants. This situation results in that ISO does not send out sufficient signals to market participants. All the market participants can do is to follow the operation signals from the ISO. In other words, the participants cannot receive sufficient market signals from ISO for future planning and investment. For instance, assume a transmission line is congested during operation. According to the theory of uniform pricing, the ISO is able to re-dispatch the generators to relieve the congestion, and the additional congestion costs are automatically added into Pool Selling Price (PSP). For market participants, they only know the trading price in the market but have no idea about the ratio of congestion costs in that price. It is obviously that the lack of market information cannot lead to a sustainable development market under a long-term consideration.

2.2.3.2 Advantage and disadvantage of zonal pricing

The most considerable advantage of zonal pricing is to solve the congestion problem in the market. As presented in uniform pricing section, lacking solutions to congestion seems to be an obstruction for performing a full competitive market. Although zonal pricing is using one single price to charge electricity usage similar to uniform pricing under an unconstraint situation, zonal pricing efficiently addresses the congestion issue by splitting market into different operation zones when congestion happens. The process of this solution is explained in section 2.2.1.2. To sum up, splitting market satisfies price concerns on both sides between the congested lines, and this method is much simpler to implement than nodal pricing.

By accompanying the benefits listed above, the defects of zonal pricing are being debated all the time. In [7] it presents defining zone boundaries is a complicated task for the ISO. For the reason that congestion is terminated by trading between zones, well-defined zone boundaries are able to help the ISO process easier administrative works. On the contrary, if the boundaries are badly set up, the ISO would take more complex actions to relief congestion. At the moment two methods are usually used to help the ISO finish the task: Power Transfer Distribution Factor (PTDF) or locational price.

As the pre-defined zones are always defined on the lines where congestion mostly happens during operation, so the zonal boundaries are rarely changed once they are confirmed. This would result in intra-zonal congestion problem. According to zonal theory, the aim of this method is to relief the congestion on tie lines which are most likely congested. However, it does not take into concern the low possibilities of intra-zonal congestion. The intra-zonal congestion problem may result in unfair trades in zonal markets because the intra-congestion could give generators incentives to game in the market for higher profits gain. One example in such as a generator which causes congestion intentionally can keep unnecessary outputs so that loads have to pay the generator for stopping generating excess energy.

Besides the problems discussed above, other disadvantages are also discussed in some articles. In [7] the author mentions zonal pricing also has limited abilities to solve congestion as major companies control most of resources. Additionally complex administrative rules and insufficient price transparency also cause poor incentives for investment. [23]

2.2.3.3 Advantage and disadvantage of nodal pricing

As defined in an efficient and economic method, the advantage of nodal pricing is able to reflect the real marginal cost of supplying each node. This cost is transparent and available to any participants in the market so that it is also treated as the opportunity cost. As a result, this transparent and fair price signal encourages the participants to invest to build more facilities in specific location or area where they could earn profits. It is also believed that those investments can gradually achieve the fair competitive environment under the long-term consideration. As the aim of the deregulation is to introduce the free competition into electrical energy market, nodal pricing is considered as the most suitable pricing schemes amongst deregulated markets.

Regardless of the advantages above, some people argue nodal pricing is not a sound method in practice. The first defect is the fake incentive of investment. Because building new electrical facilities is not only relative to economic concerns but also depends on technical issues. For instance, the first concern of building a wind farm would be the location where the wind resource is rich. Nevertheless the high locational price is not the first factor to build the wind farm. Secondly some researches reveal nodal pricing cannot recover the full operation cost for transmission companies. [9] To solve this problem, a fixed transmission charges can be introduced into the tariff in nodal market. Finally, because the ISO or transmission companies could choose to recover operation costs from the surpluses from solving congestion, it could become an incentive for transmission companies to keep or even create congestion. Obviously this is a hazard of breaking the free competition. To avoid this risk, the ISO can allow transmission companies to charge a fixed connection fee to recover operation costs instead of the surplus from congestion. The congestion surplus can be solved by the financial approach, such as FTR (financial transmission rights). [3]

Although there are defects existing in nodal pricing, researchers are able to find proper solutions of those problems. Furthermore, as the deregulated electricity market needs the support of economic theory, nodal pricing is being widely accepted in many markets.

2.2.4 Roles of ISO

Before the deregulation the electrical system is vertically integrated and central controlled by one company whose structure is efficient for the administrative management and revenue collecting. This structure ensures the maximum possibility on system safety and stability at the expense of free competition. However, this efficient structure has been broken into generation, transmission, distribution and supply after the deregulation. Although those companies could keep close co-operation to maintain the safe operation, this is less inefficient and could lead to unexpected accidents with the comparison to the traditional market structure. For the purpose of efficient management after the deregulation, the role of Independent System Operator (ISO) is introduced into the market by most of countries.

The ISO is an independent and non-profit organisation which is in charge of managing the safety and balance in the system and it regulates the participants in the market. The word of “independent” means ISO cannot be a part of the government and is responsible of guaranteeing a fair and non-discriminatory access to transmission services for market participants. The objectives of ISO are classified in [10] as

- Reliability
- Independence
- Non-discrimination
- Unbundling
- Efficiency

Because the role of the ISO is supposed to be the only organisation which is responsible of the market regulation, the responsibilities of ISO are divided into six parts in the article [11]:

- Planning services
- Power market administration services
- Operations planning service
- Real-time operations
- Metering and settlement services on energy, ancillary and transmission markets
- Open information communication services

In addition, the role of the ISO differs in different transaction models. For the model of bilateral transactions, the ISO is limited to only ensure the safety of transactions between participants and minimise the costs of losses and congestion in the system. However, if the market is using the centralised dispatch model, the ISO has a more important monetary responsibility to be in charge of setting up energy prices, collecting revenues from demands and allocating those revenues with generators. In another word, the ISO operates the monetary market in centralised dispatch model.

Regardless of what the market structure is, the ISO is always operating a spot market which is designed to eliminate the imbalance in real time dispatch. The reason of operating a spot market is that imbalance in real time dispatch is usually caused by unexpected situation, such as sudden load changes or a generator experiences a technical problem. In addition, unlike other daily commodities, the imbalance in power system is required to be resolved as quick as possible. As a result, for the safety reason, the ISO would ask the generators and loads to adjust their outputs and consumption in the spot market when the imbalance happens, and this unscheduled adjustment could be paid by the offers and bids from generators and loads respectively. Consequently the ISO needs to provide a spot market as a trading platform for participants to trade unscheduled energy in the balancing stage. The Figure 2.4 [22] presents the role of ISO in operating the spot market.

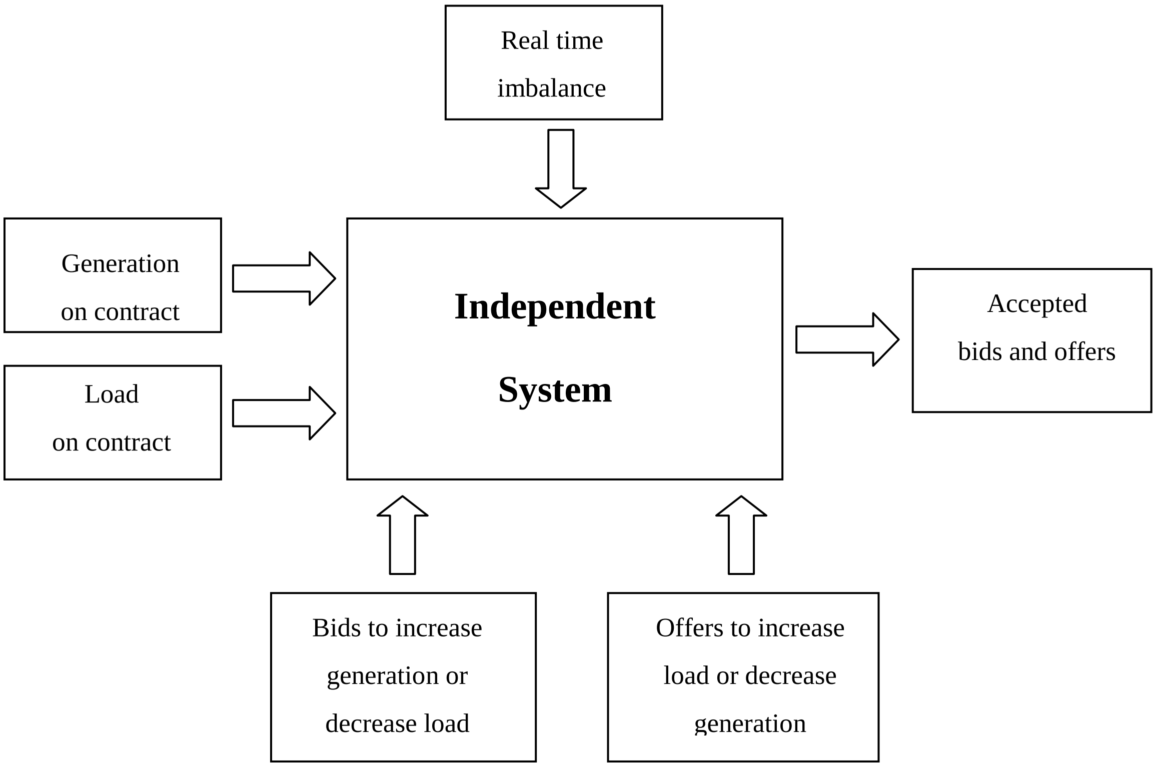

Figure 2.4: The role of ISO in spot market

2.3 World experience

Since UK became the first country in the western world to deregulate, the deregulation progress has happened in many parts of the world. A number of countries design their own deregulated electricity market with respect to their physical and structural characteristics. For instance, the UK implemented electricity pool model (uniform pricing) in England and Wales from 1990 and accepted bilateral transaction when NETA was implemented in 2001. Nodal pricing is largely accepted in regional market of USA whilst the Nordic market prefers zonal pricing. In this section brief descriptions are introduced for famous deregulated markets: UK, USA (PJM, New York and California) and Nordic markets.

2.3.1 UK [12] [13]

The first UK deregulated market existed in the England and Wales from April 1990 to March 2001. Generally it is called as the “English Pool” in which uniform pricing mechanism was in implementation to achieve the financial settlement. In the pool market, the generators needed to submit their offers to ISO and the ISO dispatched those generators from the cheapest offers until the dispatched generation meet the predicted demands at the day-ahead stage. The highest offer among dispatch generators set the System Marginal Price (SMP). The ISO in pool market was supposed to collect the revenue from customers for energy consumed and send the generators payments for their production. Besides the monetary responsibility, the role of ISO is included to maintain system operation safety for all concerned.

Although this model successfully leaded the vertical integrated market to a deregulated market, the flaws of this model were discovered over the years. The most critical disadvantage was the pool could not provide enough market signals to market participants, which would limit the incentives to further investment in the system. According to this issue, in March of 2001, the New Electricity Trading Arrangement (NETA) was implemented in England and Wales. The key design of NETA was to apply the bilateral transaction between generators and demands rather than using the pool platform to trade energy. In other words, the ISO was restricted to system operation and had no right to determine market prices because the market participants would directly negotiate energy prices and amount of trading they accept. So bilateral contracts between participants in NETA can be both physical and financial contracts In practice, the participants needed to inform the ISO the amount of the contract energy before transaction occurred and all the ISO needed to do was to operate a real-time energy trading market to balance the generation and demand. This market model was considered as a more economic market structure when compared to centralised dispatch.

On 1 April 2005, the Scottish network joined into the NETA to form the British Electricity Trading and Transmission Arrangements (BETTA). The new arrangement has minor changes and could be considered as an extension of NETA. In some views, the main change of this arrangement is to complete a competitive electricity market across the Britain.

The charging scheme of transmission services in BETTA is introduced in article [21]. This charging scheme is call Transmission Network Use of System (TNUoS) and set annually by Nation Grid Company. The transmission network is divided into different zones and each zone has a different charging tariff for generation and loads. At the moment the British network is divided into 20 generation zones and 14 demand zones. For the generation, each zone has a wider generation tariff and a local tariff to set up a generation TNUoS tariff of using transmission service. Afterwards setting up tariffs throughout zones, the wheeling charge for a particular generator could be calculated as chargeable generation capacity multiplied by relevant generation tariff.

On the other side, loads in British network are charged by two categories: half-bourly metered (HH) and non-half-hourly metered (NHH). The first category is for those loads whose demand is high at peak time. The peak time can be found in UK during three half hour periods of greatest demand between November and February. A HH metered load is charged by their demand during this period multiplied by its zonal demand tariff. A NHH metered load is simply charged as its demand between 16:00 and 19:00 every day over a year multiplied by its zonal demand tariff. In addition, National Grid Company also charges an annual connection fees from generators and loads.

2.3.2 USA

2.3.2.1 PJM [14]

The PJM (Pennsylvania-New Jersey-Maryland) interconnection is a regional transmission organization which operates the competitive wholesale electricity market in all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and the District of Columbia. The PJM initially began in 1927 and after changes over years it acted as an ISO in 1998. In 2001 the Federal Energy Regulatory Commission (FERC) granted the PJM the status of Regional Transmission Organization (RTO), which was the first RTO in USA. [15]

The role of the PJM is to operate an energy market, a FTR (Financial Transmission Right) auction market and an ancillary service market. In addition the energy can be divided into a day-ahead market and a real-time balancing market. The Pricing scheme in PJM is implementing Locational Marginal Pricing (LMP), which is also known as nodal pricing, to calculate the energy price at each node. The PJM buys energy from generation and sells it to demand. Otherwise the market participants are free to make bilateral transactions as long as they obey the market regulations.

For recovering the transmission service costs, the charges are divided into three services: firm point-to-point transmission service, non-firm point-to-point transmission service and network integration transmission service. [16]

- Firm Point to Point Transmission Service: The transmission customers pay for transmission reserved capacity between specified nodes. The charge for each transaction is

  $$\begin{aligned}&\text{Transmission Service Charge}\\&\qquad = \text{Applicable Firm Point to Point Transaction Charge Rate} \times \text{Contract MW}\end{aligned}$$

  The PJM charges Firm Point to Point Transmission Services monthly by summing the individual transmission service charges for each hour.

- Non-Firm Point-to-Point Transmission Service: The transmission customers pay for transmission reserved capacity between specified nodes. But this service is subject to curtailment or interruption to give Firm Point-to-Point Transmission Service priority. The calculation is

  $$\begin{aligned}&\text{Hourly Non Firm Transmission Service Charge}\\&\qquad = [\text{Hourly Demand Charge Rate} \times (\text{MWs reserved} - \text{MWs curtailed})]\\&\qquad - \text{Hourly Congestion Charge (if congestion charge is} > 0)\end{aligned}$$

  The PJM charges Non Firm Point to Point Transmission Services by summing the individual transmission service charges for each hour.

- Network Integration Transmission Service: The Network customers pay this service for monthly demand charge, direct assignment facilities charge, other supporting facilities charge and ancillary services. This transmission charge is calculated as

$$\text{Sum of}\left(\frac{\text{Zonal Daily Peak Load Contribution} \times \text{Annual Zonal Network Integration Transsmission Serice Rate}}{\text{365 days per year}}\right)$$

2.3.2.2 New York [17]

The New York market was being operated as a central-dispatched market for the purpose of minimising the costs and ensuring safety until 1999. After the restructuring plan was approved by New York Public Service Commission in 1998, the New York pool system became an ISO and started to establish a competitive retail in 1999. Nowadays over 99% capacities of the system is covered by investor owned utilities, New York Power Authority and Long Island Power Authority. Furthermore, the rest capacity is supplied by independent power producers, which sell most of their output under long-term contracts.

There is a wholesale market operated by NY-ISO. The generators may choose to enter this centralised market and sell their output at the market clearing price. At the same time the demands buy electricity energy at the market clearing price from the wholesale market. Otherwise the market participants have the right to trade energy by bilateral contracts with scheduling the transmission service with ISO in advance.

In transmission system market the ISO is responsible for operating a transmission network with an open and non-discriminatory access. All the users are charged by

ISO for the transmission service, which includes a transmission service charge, a transmission use charge and a New York Power Authority transmission access charge. The first component is used to cover the fixed costs in the duration of operation. It is calculated as

$$\text{Transmission service charge} = \frac{\left\{\left({}^{\mathrm{RR}}/_{12}\right) + \left({}^{\mathrm{CCC}}/_{12}\right) - \mathrm{SR} - \mathrm{ECR} - \mathrm{CRR} - \mathrm{WR}\right\}}{{}^{\mathrm{BU}}/_{12}}$$

where RR is annual transmission revenue requirement ($)

CCC is annual scheduling, system control and dispatch costs of the individual transmission owner ($)

SR is sales revenue from sales of transmission congestion contracts ($)

ECR is excess congestion rents ($)

CRR is transmission owner's congestion payment ($)

WR is wheeling revenue ($)

BU is transmission owner's billing units (annual MWh) for the transmission district (MWh)

The second component refers to the congestion and losses costs. The following equation is used to calculate this part of wheeling charges:

$$\begin{aligned}&\text{Transmission Usage Charge}\\&\qquad = \{\text{Locational Marginal Price at sink node (\$/MWh)}\\&\qquad - \text{Locational Marginal Price at source node (\$/MWh)}\}\\&\qquad \times \text{Delivered energy (MWh)}\end{aligned}$$

The final component is supposed to recover any shortfall that is not recovered by the first two components after assessing on all transactions. This charge is calculated as a $/MWh charge.

2.3.2.3 California

The California market began to deregulate in 1996 and a spot market was under operation in 1998. However, due to the design, the energy producer could take generators offline during peak time for the purpose of raising the energy price. As a result, in 2001 the energy price exceeded over ten times than usual price. As a contrary, the wholesale price was capped by regulator, which is much lower than the price offered by generators, so that the wholesale companies would significantly lost benefits if they stayed in business. This situation caused the rolling blackouts in the summer of 2001. Around 1.5 million customers were affected by the blackouts until the government ended the emergency after taking over the market. [18]

After this crisis, the ISO began to migrate from the failed decentralised and zonal based market system to another market design. At the moment there is a centralised electricity market in California with the Locational Marginal Price (LMP) scheme since 2009. This market is regulated by two entities: California Power Exchange (PX) and California Independent System Operator (CAISO). The first entity is in charge of regulating energy trades in the market. On the other side the CAISO provides the technical service to market participants, such as balancing generation and demand, congestion and ancillary service.

The transmission rates in California include Transmission Access Charge (TAC) and Grid Management Charge (GMC). The first part is charged for access service of retail customers. The second part recovers the costs of operation and management in the duration of transmission. [19]

2.3.3 Nordic market [5]

The Nordic market consists of Norway, Sweden, Finland and Denmark to provide 24 million populations electricity supply. The Nordic market is co-ordinated by three key elements: the power exchange, transmission system operators (TSOs) and market participants. The first element, power exchange, is responsible for determining the system price and operating an efficient spot market. In addition it also takes actions on congestion alleviation. Secondly the TSOs, who own the transmission facilities, are in charge of operating the transmission network. Their tasks include managing real-time system, maintaining the main grid, calculating and managing financial settlement of imbalances in real-time. Thirdly the market participants are the large customers who trade energy in the market. They are obligated to inform the TSOs and Power Exchange the transaction amount and time if they are involved in bilateral contracts.

The energy trading in Nordic Market is divided into two types of markets: the wholesale market and the retail market. The wholesale market is a platform for participants to trade electricity at a transparent spot price or a bilateral contract. The retailers usually could buy electricity from the wholesale market for selling to end costumers. The wholesale market has four sub-markets:

- OTC (over-the-counter) market

- Bilateral market
- Nord Pool Group
- Real-time market

In the retail market, the large-scale end-costumers, such as industrial or commercial users, could sign contracts with retailers for electricity supplies. Meanwhile the homeowners, which are called as small-scale end-users, have the right to freely choose the retailers. They may have contracts with retailers or just pay what they use at the spot price.

For recovering the transmission operation costs, the Nordic market uses the point-of-connection tariff to charge the network usage. This point tariff is calculated by considering the location of the node regardless of the transaction path. In addition there are three levels of grid owners: main, regional and local grid owners. The customers pay the transmission charges to the grid which they are connected to. Furthermore the lower-level grid also needs to pay a tariff to the connected higher-level grid. This tariff ensures customers get the free access to the transmission network for trading electricity. For instance, the load customers will not pay surcharges for consuming energy which comes from other national network whilst the generators do not need to pay for transferring their outputs across networks. [20]

2.4 Summary

This chapter presents the top issues of deregulated market. The pricing schemes are firstly introduced because those schemes decide the structure of the market. Three schemes have been presented in this chapter: Uniform Pricing, Zonal Pricing and Nodal Pricing. In addition the comparison is added in the following section to discuss the performance in practice. Furthermore this section lists the roles and responsibilities of the ISO. The following section presents the experiences of deregulation around the world. This section introduces the deregulated markets in the UK, PJM, New York, California and Nordic countries. The statuses of ISO responsibilities, energy trading methods and transmission tariffs are the main topics in this section.

2.5 References

[1] N. Gregory Mankiw, “Principles of Economics”, 5th edition, South-Western College Pub, 2008

[2] “Definitions, Background Information and Abbreviations”, available on: http://www.appro.org/backgroundinformation.html, access on 17/03/2011

[3] Thilo Krause, ‘Congestion Management in Liberalized Electricity Market-theoretical Concepts and International Application’, May 2005, available on: e-collection.ethbib.ethz.ch/eserv/eth:29076/eth-29076-01.pdf 22/03/2010

[4] Frank A. Wolak, Robert H. Patrick, ‘The Impact of Market Rules and Market Structure on the Price Determination Process in the England and Wales Electricity Market’ April 2001, available on: http://www.nber.org/papers/w8248 21/04/2010, accessed on: 22/3/2011

[5] “The Nordic Power Market”, available on: http://www.fer.hr/_download/repository/Nord%20Pool%20-%20The%20Nordic%20Power%20Market.pdf, accessed on: 21/02/2011

[6] Bjorndal M. and K. Jornsten, ‘Zonal Pricing in a Deregulated Electricity Market’, *The Energy Journal*, Vol. 22, No. 1, pp. 51-73, 2001

[7] Tan Ching Sin, “An Analysis of LMP Decomposition for Financial Settlement and Economic Upgrade”, PhD Thesis, University of Strathclyde, 2007.

[8] Drew Phillips, ‘Nodal Pricing Basics’ available on: http://www.ieso.ca/imoweb/pubs/consult/mep/LMP_NodalBasics_2004jan14.pdf, accessed on: 14/10/2008

[9] M. Ghayeni and R. Ghazi “Multiarea Transmission Cost Allocation in Large Power Systems Using the Nodal Pricing Control Approach”, *Iranian Journal of Electrical & Electronic Engineering*, Vol. 6, No. 4, pp. 238-247, December 2010

[10] William W. Hogan, ‘Independent system operator: Pricing and flexibility in a competitive electricity market’, February 1998, available on: http://www.hks.harvard.edu/fs/whogan/iso98.pdf, 16/08/2009

[11] M. Madrigal and M. Flores, “Transmission dispatch and congestion management in the emerging energy market structure”, *IEEE Trans. On Power Systems*, vol.13, no. 4, pp. 1466-1474, November 1998.

[12] Serena Hesmondhalgh, “Is NETA the blueprint for Wholesale Electricity Trading Arrangements of the Future”, *IEEE Trans. On Power Systems*, Vol 18, no. 2 pp. 548-554, May 2003

[13] “UK electricity and gas transmission”, http://www.nationalgrid.com/corporate/Our+Businesses/UKT/ available on 30/03/2011

[14] Jianzhong Tong, “Overview of PJM Energy Market Design, Operation and Experience”, 2004 IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies (DRPT2004), April 2004 Hong Kong.

[15] “PJM history”, Available on:
http://www.pjm.com/about-pjm/who-we-are/PJM-history.asp, access on 15/05/2010

[16] “Open access transmission tariff accounting”, revision: 74, available on: ftp.pjm.com/~/media/documents/manuals/m27.ashx, 18/08/2010

[17] Nicolai J. Sarad, and Dean M. Colucci, “The Competitive Market for Power in the U.S.: The Role of ISOs and PXs”, available on: http://library.findlaw.com/2000/Mar/1/127779.html, accessed on: 11/12/2009

[18] Caril Blumstein, L.S. Firdeman, and R.J.Green, “The history of Electricity Restructuring in California”, Working paper for Center for the Study of Energy Markets, August 2002.

[19] “Transmission Rates”,
http://www.cpuc.ca.gov/PUC/energy/wholesale/01_ratedesign/ , available:
06/04/2011

[20] Tarjei Kristiansen, “Congestion management, transmission pricing and area price hedging in the Nordic region”, *Electrical Power and Energy Systems*, Volume 26, Issue 9, pp685-695, November 2004

[21] “The Statement of the Use of System Charging Methodology”, National Grid, available:
http://www.nationalgrid.com/NR/rdonlyres/590ACE8D-01BE-4ED9-A028-3736D28A7CCE/41181/UoSCMI6R0v10Final.pdf, accessed on: 10/08/2010

[22] Yassir A.A. Alturki, “Real and Reactive Power Allocations in Electricity Market”, PhD Thesis, University of Strathclyde, 2006.

[23] Hogan W. W., “Transmission Congestion: The Nodal-Zonal Debate Revisited”, Harvard University, John F. Kennedy School of Government, Center for Business and Government, available on: http://www.hks.harvard.edu/fs/whogan/nezn0227.pdf, 20/06/2011

Chapter 3 Wheeling Charges in Electricity Market

3.1 Introduction

Since the deregulation was implemented in electrical industry, the vertically integrated structure has been broken into four parts: generation, transmission, distribution and supply. Each part is supposed to establish its own competitive market. However, as discussed in the previous section, the current transmission network is considerably constructed to satisfy energy transport purpose, so introducing competition in the transmission network would cause huge costs and high risks. As a result, a natural monopoly in the transmission market is still maintained to efficiently serve the entire customers at the moment. Consequently only one transmission company exists in a specified area with no competition. All the participants who use transmission services in this area are supposed to pay charges to the specific transmission company for energy transport. This payment is called wheeling charges.

On the other side, the open access to transmission for generation and suppliers is entirely established after the deregulation so that the participants not only are able to trade electricity in local transmission area but also can trade with participants located in other transmission areas. Those cross-border trades introduce a new problem which has never happened in the vertically integrated market: two transmission companies should be paid for wheeling services but how much they should earn from the total payment. In other words, there is a lack of tariffs to guide transmission companies to share the total payment from participants. This has been considered as a challenge in deregulated electricity markets.

The European electricity market can be set as an example to establish a united market with cross-border trading. On 26th June 2003, the European Union commission adopted Directive 2003/54/EC and Regulation (EC) to form a single European market in the future. The purpose of this action aimed to form a single European market by breaking the political borders of different networks. As a result, the transmission network in each country is open access to the neighbour countries and all the participants are able to trade electricity within Europe no matter where they are. For the issue of sharing wheeling charges in the cross-border trading, Europe is using transit flow concept to charge cross-border transmission services, which would result incorrect monetary settlement. At the moment, some people argue new methods to address this problem, such as the Average Participant (AP) or With and Without Transit (WWT).

In this chapter, the traditional methodologies for wheeling charges are described in Section 3.2. The drawbacks of those methodologies in cross-border trading are also presented at the end of this section. The Section 3.3 reveals the challenges when cross-border trading is involved in the duration of transactions. In Section 3.4, the research work for EU market will be reviewed. Two major methods, Average Participation (AP) and With and Without Transit (WWT), will be compared in this section.

3.2 Traditional Mechanisms for Wheeling Charges

The wheeling charges exist in the electricity market no matter what the market structure is. The charging methods are categorised as two different classes:

non-transaction based pricing and transaction-based pricing. [1] The non-transaction based pricing methodology charges participants by depending on the capacity they use on transmission lines regardless of the transaction locations. This methodology is able to provide accurate results but complicated to employ. The other one is also known as the point-point tariff because it only considers the source nodes and end nodes of transactions. The capacity usage on transmission lines is not considered when calculating transmission payments. Despite of the simplicity of the philosophy of the point-point tariff, it is widely implemented in many markets. In this section three methods will be presented: Postage Stamp, Contract Path and Line by Line.

3.2.1 Postage Stamp

The Postage Stamp methodology is classified as a point-point tariff and is described in article [1]. The transmission fees charged by Postage Stamp depend on the total amount of transacted energy in the system because the whole transmission network is considered to carry the transaction. In particular, the transmission fees from a particular transaction *i* can be calculated by the following equation:

$$F_i = TTC \times \frac{P_i}{P_{peak}} \tag{3.1}$$

where the F_i refers to the transmission fees paid by transaction *i*, the *TTC* is the total transmission charges in the whole system and P_i and P_{peak} mean the transacted power for transaction *i* and the peak load amount in the system respectively. What needs to be noticed is that transport distances between sellers and buyers are irrelevant to wheeling charges, which is a significant drawback of this method. The impacts of this drawback will be discussed in following sections.

Because Postage Stamp uses the total transmission charges (TTC in equation 3.1) as an important parameter to calculate the individual wheeling charges, the idea of this method is widely used in different markets. The strongest advantage of Postage Stamp is the simplicity of implementation.

3.2.2 Contract Path

The Contract Path is a methodology that calculates the wheeling charges by assuming the transacted power flowing along a predefined wheeling path so it is not considered as a point-point tariff. The wheeling paths in this method are usually selected by the system operator for specific transactions and only the flows on the predefined path are charged. Those transacted flows which are not within contract path are ignored during the monetary settlement. [2] This method can be found in Florida Reliability Coordinating Council market and Western Electricity Coordinating Council market.

The article [3] presents the calculation process for Contract Path. For calculating wheeling charges by Contract Path, first the system operator needs to determine the lowest the MW capability of the specified path. Secondly the annual wheeling costs on the specified paths will be calculated in £/MW. Finally, when the transactions on the paths start to proceed, the system operator charges the participants as:

$$F_i(£/year) = AWCR(£/MW) \times TP_i \qquad (3.2)$$

where the F_i is the transmission charges for transaction i, AWC refers to the annual wheeling cost rate and the TP_i is the transacted power for transaction i.

3.2.3 Line-by-line [4]

The line-by-line method is also known as MW-mile method, which takes both the transacted MW and distance into account when solving transmission charges. There are two types of MW-mile methods: distance-based MW-mile method and power-flow-based MW-mile method. The first method counts miles based on the airline distance between the source and the sink. As a result, an incorrect market signal could be sending to participants because the airline distance cannot truly reflect the transacted distance. The second method is widely implemented in practice for the reason that the distance only counts the line length of the path used by the wheeling transaction. The superior part of the MW-mile method, when comparing to Postage Stamp and Contract Path, is that this method takes into account the changes in MW flows. [16]

The MW-mile method is currently divided into three classes: net, absolute and positive-only approaches. Usually transmission owners regard the positive-only approach as the best opinion because it provides them sufficient revenues. The algorithm of MW-mile method is presented in equation (3.3):

$$F_t = A_i \sum_i C_i \frac{\sum_i l_i \Delta P_{i,t}}{\sum_i l_i \overline{P}_i} \tag{3.3}$$

where the F_t is the wheeling fees for transaction t, the A_i is the annual fixed charging rate in per-unit or percent on transmission line i, C_i is the annual embedded cost of transmission line i, l is the length of transmission lines, $\Delta P_{i,t}$ is the power flow change in MW on line i due to the transaction t, $\overline{P}_i$ is capacity of the transmission line i in MW.

Note that the ΔP could be either positive or negative. According to the three approaches listed above, different ΔP has been added into calculation

- Net approach: the negative ΔP is deducted from positive ΔP

$$\sum_i \pm \Delta P_i \tag{3.4}$$

- Absolute approach: the absolute value of ΔP is added

$$\sum_i |+\Delta P_i| \tag{3.5}$$

- Only positive approach: only positive ΔP is added

$$\sum_i +\Delta P_i \tag{3.6}$$

3.2.4 Disadvantages of various traditional mechanisms

The traditional wheeling charge methods are widely used in electrical systems, however, each of them suffers the different drawbacks. This section mainly discusses the drawbacks when those methods are implemented in practice.

For the Postage Stamp method, the simplicity is the best selling point meanwhile the most argued disadvantage is still its simplicity algorithm. As Postage Stamp ignores the actual system operation, the market participants are unlikely to receive the correct market signals of the transactions. In addition, it is not a true fair method for every participant in the market. For instance, a short distance transport with high trading amounts could be charged more than the actual usage because the Postage Stamp only takes into account the total trading amount to charge the usage and ignoring the fact of short distance.

The disagreement with Contract Path is always on the loop flow problem. Because of the Kirchoff's laws the electricity energy always flows over the path of the least resistance. [5] As a result, the power flow sometimes moves across unexpected lines or areas. In addition, as described in article [6] the predefined path on the contract is determined by the shortest electrical paths between sellers and buyers so that the paths could not be technically related to the actual transacted flows. As a result, the actual transacted energy could flow over other utilities lines which are not paid by this transaction. This situation is drawn in Figure 3.1.

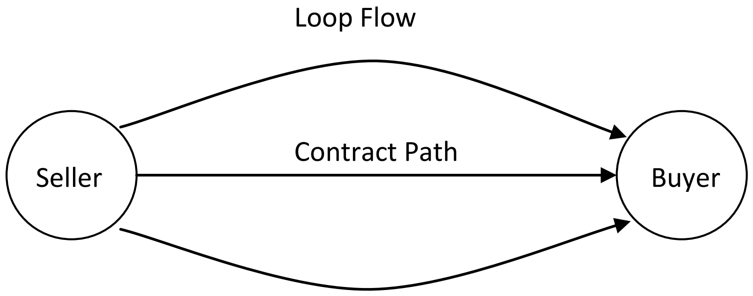

Figure 3.1: Loop flow problem in Contract Path

Compared with the first two methods, the MW-mile method holds the advantage of considering both MW and the distance when charging transmission services. However this method has different variations and each one has its own advantages and disadvantages. The net and absolute approaches are not popular with transmission owners because those approaches cannot recover sufficient revenues if the counter-flows are significantly large. The third approach, the positive-only, is welcomed by transmission owners as they can collect appropriate revenue from it.

But this approach ignores the contribution of counter-flows from market participants which should received for relieving congestion in the system.

In addition, the MW-mile uses ΔP to calculate the wheeling changes but it does not consider the interaction of multi-transactions on a single line. If a single line transports different transactions at the same time, we can only know the total flow change instead of indicating the impacts of each transaction. [6]

3.3 Challenges of traditional mechanisms in cross-border trading

The traditional methodologies of charging wheeling services have been introduced in Section 3.2. Although they are undergoing drawbacks pointed out at the end of Section 3.2, the simplicity of implementation makes them widely implemented at the moment. However, this situation changes when the transactions are involved in cross-border trading. The reason can be pointed as the traditional methods are not able to allocate the wheeling charges in cross-border trading. In other words, there is not an algorithm for transmission owners to determine the share of the collected wheeling charges. The details will be presented in the following part.

For the convenience of explanations, the implementation of traditional wheeling charging methods is illustrated in Figure 3.2. There is a transaction between generator (G) and load (L) and the amount of this transaction is P. In the Figure 3.3, the G, L and P keep the same status and values except the network split into two operation areas, which are owned by different transmission companies. The dash lines in the Figures refer to transaction path.

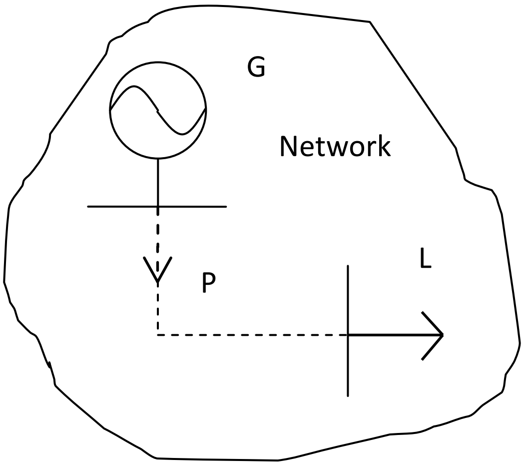

Figure 3.2: Trading in the local network

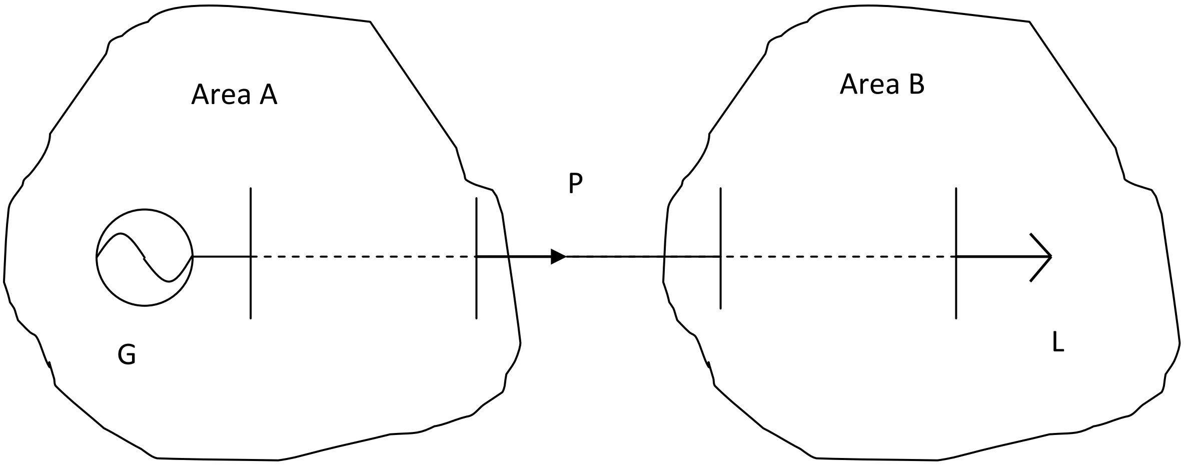

Figure 3.3: Cross-border trading

Although the Postage Stamp and Contract Path methods have drawbacks, they still work efficiently in a single area in Figure 3.2 because the wheeling tariff treats every participant the same. However, if those methods were used in Figure 3.3, the drawbacks of ignoring actual transaction path appear to be of significant problems in cross-border trading. Since the total transmission charge plays a significant role in monetary settlement of wheeling charges, the total transmission charges in both areas should be added into calculations. In this case, from the equation (3.1), the charges for this transaction by Postage Stamp is

$$F_i = (TTC_A + TTC_B) \times \frac{P_i}{P_{peak}} \tag{3.7}$$

$$F_{iA} = TTC_A \times \frac{P_i}{P_{peak}} \tag{3.8}$$

$$F_{iB} = TTC_B \times \frac{P_i}{P_{peak}} \tag{3.8}$$

Where the $F_{iA}$and F_{iB} are the transmission charges for Area A and B from the transaction respectively, *TTC* is Total Transmission Charge and the subtitle refers area names.

At this stage, there is one issue to prevent the Postage Stamp from resolving this cross-border transaction. Assuming that F_i keeps unchanged becasue the G, L and P remain unchanged so that the Area A and B can share the $F_i$by the ratio of $TTC_A/_{TTc_B}$. As the result, the transmission owner with higher TTC (total transmission charges) could gain more payments from this transaction. However, as stated in section 3.2.4, Postage Stamp likely gives incorrect market signals to the market so the disagreements between the two owners are likely to appear when collecting their shares of wheeling charges. For instance, the transmission owner which carries most of transaction energy could be paid less due to lower TTC. This problem also happens when Contract Path is used to settle cross-border trading. In conclusion, the methods which ignore transaction distance may work smoothly within a single area; however, they face serious problems because of the issue mentioned above.

As mentioned in section 3.2.4, the MW-mile has the drawback of mixing multi-transactions. In the vertically integrated market all wheeling charges will be finally paid to the only transmission owner so that no one would argue with the transmission owner about sharing the wheeling charges. However the drawback of mixing multi-transactions becomes a fatal problem in cross-border trading. That is because ΔP in equation (3.3) contains local impacts and cross-border impacts. The cross-border impacts are caused by cross-border trading and it should be paid to all the transmission owners involved into the trade. The local impact refers to the flow changes caused by local transactions and it is supposed to be only charged to the local transmission owner rather than others. However, because of mixing local and cross-border impacts, the transmission owners cannot allocate wheeling charges of a specific cross-border transaction with MW-mile. In conclusion, the MW-mile is not an appropriate method for settling cross-bordering trading either.

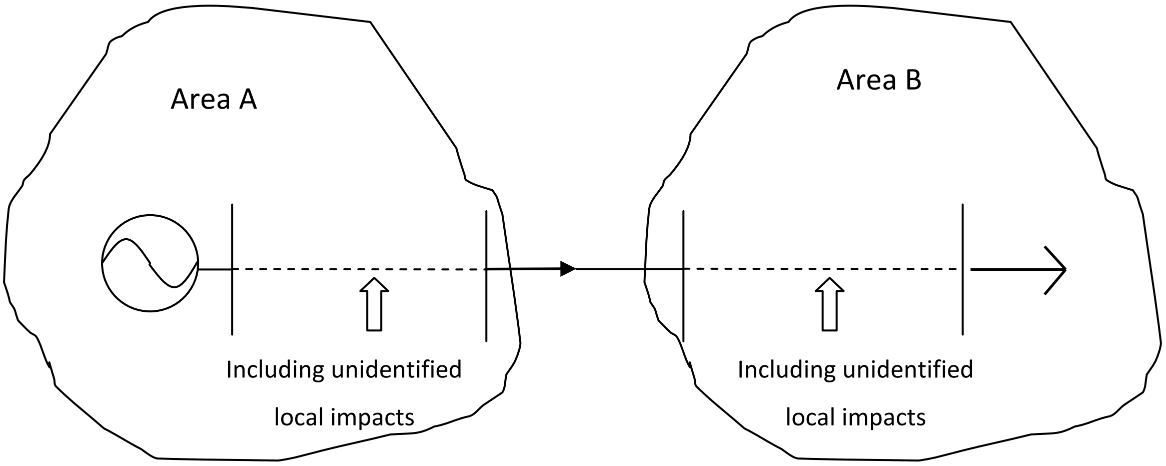

Figure 3.4: Issues of MW-mile in cross-border trading

To sum up, the allocation of wheeling charges becomes a major problem of preventing cross-border trading from implementation as none of those traditional methods are able to address this monetary issue. But the trend of cross-border trading is unstoppable with the development of deregulated markets. The EU has been researching on this area for years and has achieved considerable results. The next section is used to discuss the experience from EU.

3.4 New Methods concerning to cross-border trading in EU

Although various deregulated electricity markets are existing in different countries, they all tend to establish the local competitive markets which rarely interact with other networks. At the moment, the deregulation process in EU is the only practical experience on cross-border trading because the EU commission has decided to break the boundaries of each country to form an united electricity market in the European continent. The EU experience on cross-border trading has been briefly introduced in the previous sections. In this section, the details of EU research will be presented.

The need for establishing an united European electricity market was proposed at the Florence Forum in 1999. In July 2003 the European Commission enacted the Regulation 1229/2003 to set up regulations for cross-border trading amongst different networks. [14] The ETSO 2005 model [15] was proposed to perform the role of addressing challenges in cross-border trading in 2005. However this mechanism was shortly proved to suffer drawbacks in 2006. [7] In January 2007 the European Commission agreed to lead the research on developing new proposals for electricity trades across countries. Therefore the European Commission began to collect public opinions and it has been struggling to build a mechanism to meet the need for cross-border trading in the Europe. [8] However the researchers have created several new mechanisms for settling cross-border trading in the past years.

In article [9] six algorithms are introduced to deal with compensations and charges due to cross-border flows. They are Average participations (AP), Simplified average participations (SAP), Modified average participations (MAP), Marginal participations (MP), With and without transit (WWT) and Average participation applied to transits (APT). In addition the six algorithms are classified into two classes. Class One includes the AP, SAP and MAP as which are using complete actual power flows to calculate the Inter-TSO payment meanwhile the last two methods, which are classified as Class Two, use the concept of transit flows, which will be particularly discussed in section 3.4.5, to decide the Inter-TSO payment. For all methods, the Inter-TSO payment for a particular area can be defined as

$$\textbf{Inter-TSO payment=Compensation - Charges} \qquad (3.9)$$

where “Compensation” is the payment paid from external areas, “Charges” is payment paid to external areas. In the following subsections all of the six algorithms will be discussed respectively.

3.4.1 Average Participation (AP)

The basic idea of Average Participation is to settle wheeling charges of a specific transaction by calculating the usage rate on each line it occupies. The transaction path is determined by a power tracing algorithm, which assumes that electricity is transported like water flows in the pipes. This algorithm can provide the power flow tracing by upstream or downstream and can decide the usage rate of individual agent on each transmission line. The mathematic theory details can be found on [10].

Because it provides clear results of operation conditions, this algorithm seems to be superior to the rest of algorithms by referring to the conclusion of [9]. In additional it does not take into account political borders during the calculation so any changes of network have fewer inflections in comparison to other algorithms.

However despite of the remarkable advantages mentioned in [9] some disadvantages have been listed by another report [11]. The main disadvantage is the water flow assumption. In article [11] it mentions AP cannot reflect the real network operation condition because of the water flow assumption. In addition, AP is not able to offer participants congestion signals.

3.4.2 Simplified Average Participation (SAP)

Generally this method assumes that the electricity network of a specific area is equalised into a single node, which connects to equalised generation and load. Afterwards this equalisation, the same AP procedure is applied into calculation. As a result, it is noticed that only interconnection lines are included in calculation under this assumption. As widely known, the simplification of electrical system is a significantly complex task to accomplish and likely leads to incorrect operation signals. Meanwhile this method ignores the behaviour of the network flows inside each area. As the result, this method only exists in theory and obviously does not match the needs of real transactions in practice.

3.4.3 Modified Average Participation (MAP)

MAP is a method which is similar to SAP. MAP also assumes that all generators and demands in the specific area are collapsed into a single node. However, this node can only connect to a unit which presents the net MW balance in this area. In other words, this unit could be either a single load or a single generator. Consequently this area would be presented as a node with a single generator or a single load according whether this country exports or imports power flow. This method obviously bears the same disadvantages of SAP as using a single node to represent a country would result in inaccurate results.

3.4.4 Marginal Participation (MP)

This method is well described as “this procedure calculates how much would the flow in line *j* increases if the generation (or load) in node *i* is increased by 1MW”. For instance, the method obtains the per unit measure of marginal participation on line *j* for any participant located at node *i*. This calculation is performed for every participant in the market. Afterwards, the wheeling cost of each line is allocated to the different users according to their participations on this line. [9] Due to Kirchhoff’ laws 1 MW change at any node must be compensated by the slack node. As a result the location of the slack node is playing a significant role in the MP method because a different choice of slack node leads to a different result. At the same time the participants far away from slack node have meaningless participations.

3.4.5 With and Without Transit (WWT)

The WWT method was developed with the concept of transit power flow. This concept can be defined as the minimum value between total export and total import cross-border flows in the specific area

$$T_n = Minimum\ of\ [P_{IMn}, P_{EXn}] \tag{3.10}$$

where T_n is the transit flow in area *n*, the P_{IMn} is the total import power flows in area *n* and the P_{EXn} is the total export flows in area *n*.

After the transit flow for area *n* is determined, the T_n is removed from the network and this area is disconnected from neighbour areas. As a consequence two networks are acquired at the moment: one is the original network of area *n* and the other one is the area *n* without the transit flow. The next step is to compare the wheeling charges in both networks and find the monetary difference before and after the isolation. This difference is used to determine wheeling charges from cross-border trading. The specific processing steps of WWT will be discussed in the 3.6.2.1.

In the comparison with the AP, the advantage of this method is to display the participation of external area in the area *n*. In the 'without transit' network it is easy to determine whether the cross-border flow benefits the area *n* network or not. [11] But the serious drawback of WWT is that this method has totally changed the operation condition of the system so its result is not reasonable in a sense. This drawback will be discussed in section 3.5.3.2.

3.4.6 Average Participation applied to Transits (APT)

This method is the combination of AP and WWT. It uses WWT method to determine the transit flows and implement the tracing theory in AP to trace transit flows. This method sounds good but it has the same drawback as WWT. This drawback will be also discussed in section 3.6.3.2.

3.4.7 Conclusion

In conclusion the core methods of each class are AP and WWT respectively. In the class of charging actual power flow, SAP and MAP methods seem to have impractical assumption which is leading to incorrect results in comparison to AP. MP suffers from the problem of choosing the slack bus. In the other class, APT is similar with WWT in the determining the transit. Consequently the AP and WWT method will be simulated and compared with each other in the next section. In additional the details of comparison are listed in [11].

	Influenced by political border	Change system status	Easy to handle data	Consider transaction path
AP	No	No	No	Yes
SAP	No	Yes	Yes	Yes
MAP	No	Yes	Yes	Yes
MP	No	No	No	No
WWT	Yes	Yes	Yes	No
APT	Yes	Yes	No	No

Table 3.1: Summary of various methodologies for wheeling charges

3.5 Study of AP and WWT

3.5.1 Study of Average Participation (AP)

3.5.1.1 Mathematic theory of AP

The Average Participation uses the assumption that electricity is transported like water flows in pipes. As the result of this assumption AP has included an algorithm that can trace power flows from upstream or downstream and decide the usage rate on each transmission line from specific participants. For instance,

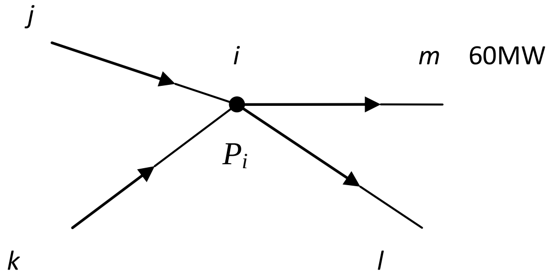

Figure 3.5: Proportional sharing principle

60 MW on line (*i*,*m*) consists of 18 MW from line (*j*,*i*) and 42MW from line (*k*,*i*), and the contributions from other lines are calculated as

$$\text{Contribution from Line } (j,i)\text{:}\ 60 \times \left(\frac{30}{30+70}\right) = 18MW \tag{3.11}$$

$$\text{Contribution from Line } (k,i)\text{:}\ 60 \times \left(\frac{70}{30+70}\right) = 42MW \tag{3.12}$$

In other words AP obeys proportional sharing principle when tracing power flow.

The mathematic theory is shown in the following section. According to article [10], assume the total flow P_i at node *i* in a lossless system when looking from the inflow,

$$P_i = \sum_{j \neq i} \left|P_{(j,i)}\right| + P_{Gi} \qquad for\ i = 1,2,\dots,n \tag{3.13}$$

where the $P_{(j,i)}$ is the power flow from node j to node i, P_{Gi} is the generation at node i.

Let $C_{ji} = {\left|P_{(j,i)}\right|}/{P_j}$, the equation (3.13) can be written into

$$P_i - \sum C_{ji} P_j = P_{Gi} \tag{3.14}$$

Or written into

$$A_u P = P_G \tag{3.15}$$

where

$$[A_u]_{ij} = \begin{cases} 1 & for\ i = j \\ -C_{ji} & for\ node\ j\ supplying\ directly\ node\ i \\ 0 & otherwise \end{cases}$$

Consequently the power flow at node i can be calculated by

$$P_i = \sum_{k=1}^{n} [A_u^{-1}]_{ik} P_{Gk} \qquad for\ i = 1,2,\dots,n \tag{3.16}$$

The equation (3.16) refers that contribution of *k*th generator to node *i* is$[A_u^{-1}]_{ik} P_{Gk}$ in a system which contains the amount of *n* generators, P_{Gk} is the power output from the *k*th generator.

Consequently, the outflow in line (*i*,*l*) from node *i* can be calculated by

$$P_{(i,l)} = \left(\frac{P_{(i,l)}}{P_i}\right) P_i = \frac{P_{(i,l)}}{P_i} \sum_{k=1}^{n} [A_u^{-1}]_{ik} P_{Gk} \tag{3.17}$$

where the $P_{(i,l)}$ means the active power on line (*i,l*), P_i is the outflow from node *i*.

With respect to the proportional theory, the generation contribution to the load at node *i* is

$$P_{Li} = \frac{P_{Li}}{P_i} P_i = \frac{P_{Li}}{P_i} \sum_{k=1}^{n} [A_u^{-1}]_{ik} P_{Gk} \tag{3.18}$$

where P_{Li} is the load at node *i*.

This equation (3.18) is helpful when determining the contributions of different generator for a specific load. Finally according to calculation from above equations, the wheeling charge from generator *k* for line (*i*,*l*) equals to

$$F_{(i,l)} = \frac{P_{(i,l)}}{P_{T(i,l)}} C_{(i,l)} \tag{3.19}$$

where the $F_{(i,l)}$ is the wheeling charge, $P_{T(i,l)}$ is the total capacity of line (*i*,*l*) and $C_{(i,l)}$ is the short-term operation cost on line (*i*,*l*).

To sum up, the AP method calculates the wheeling charges on each transmission line and can allocate those charges to particular generators. In consequence of acknowledging the locational information of each participant, the system operators are able to achieve allocation of wheeling charges for cross-border trading.

3.5.1.2 Case study

For explanations of the way AP works, a 6 bus system, which is split into four areas, is used to demonstrate the process of calculation of AP. This system is shown in Figure 3.6. In this case the main task is to find the wheeling charges due to cross-border trading. To simplify the explanation, the losses are ignored in this system. In addition, all capacity constraints are also neglected and all the voltages are set at the same level.

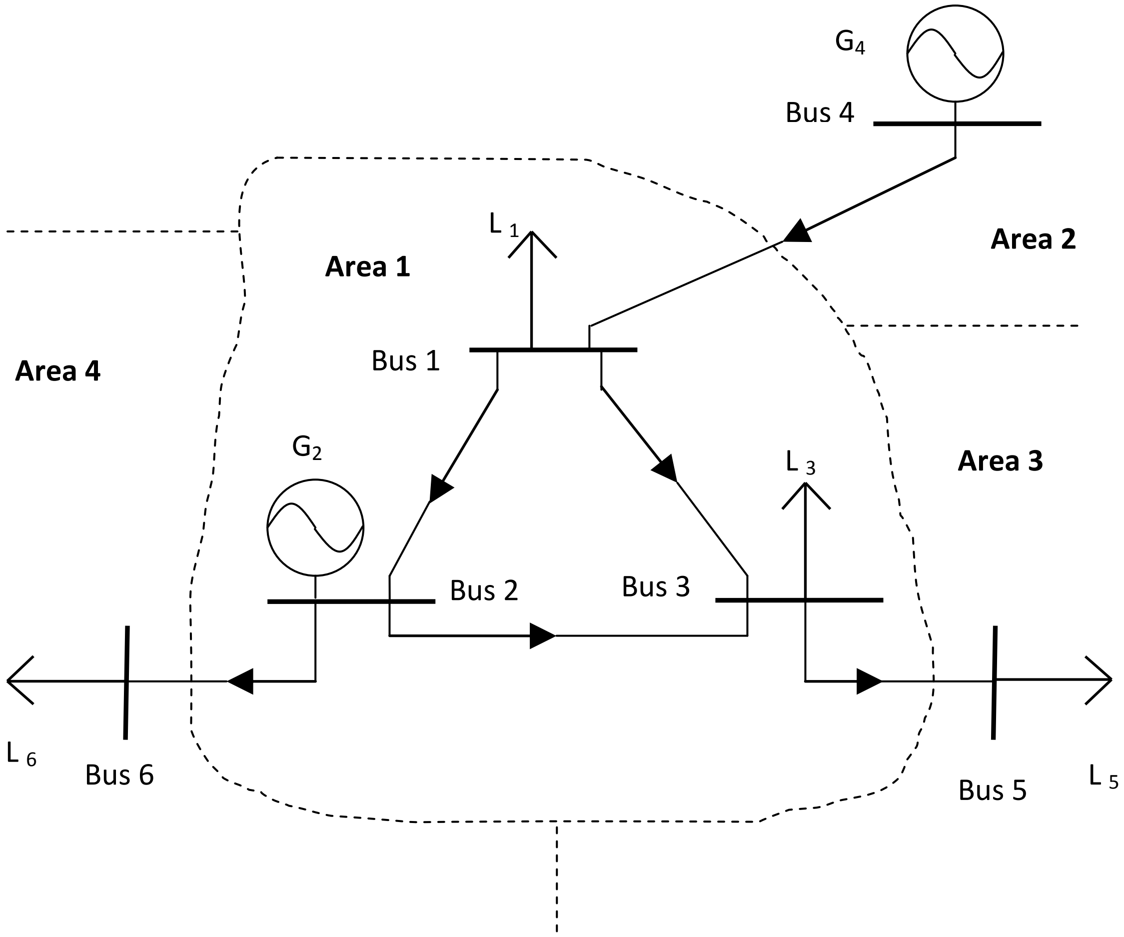

Figure 3.6: 6 bus system

The area information is shown in Table 3.1.

Area	Bus	Generator	Load	Line
1	1,2,3	G_2	L_1, L_3	1-2, 1-3, 2-3
2	4	G_4	-	4-1
3	5	-	L_5	3-5
4	6	-	L_6	2-6

Table 3.2: Area information

The information of bus, generation and load are presented in Table 3.3.

Bus	Area	P_{gen} (MW)	P_{load} (MW)
1	1	0	150
2	1	250	0
3	1	0	300
4	2	500	0
5	3	0	200
6	4	0	100

Table 3.3: Bus, generation and load data

Run Newton-Raphson power flow solution for this system and Table 3.4 lists the power flow on each transmission line.

From bus	To bus	Power flow (MW)
1	2	200
1	3	150
2	3	350
2	6	100
3	5	200
4	1	500

Table 3.4: Power flows on each line

For the purpose of finding the wheeling charges due to cross-border trading, the first step is to calculate the power flow contribution from generators by applying the power flow tracing algorithm, which includes equation (3.13) to (3.18). Because the power tracing method does not consider counter-flow in the calculation, contributions of generators are all positive. The results are shown below in the Table 3.5.

From bus	To bus	Contributing Generator	Contribution (MW)
1	2	G_4	200
1	3	G_4	150
2	3	G_2	194.44
2	3	G_4	155.56
2	6	G_2	55.56
2	6	G_4	44.44
3	5	G_2	77.776
3	5	G_4	122.224
4	1	G_4	500

Table 3.5: Generation contribution to each line

The first two columns of Table 3.3 present the start node and end node of each transmission line respectively. The third column shows which generator contributes power flow on this line and the MW of contribution is listed in the last column.

The second step is to calculate the wheeling charges from different participants. In this case assume that generators are in charge of paying all the wheeling charges and the wheeling rate is set to £1.5/MWh. According to equation (3.19), the payment the Line (2,3) receives from G_4 is,

$$Wheeling\ charge = \frac{generator\ conribution}{actual\ flow} \times operation\ cost$$

$$= \frac{155.56MW}{350MW} \times (£1.5/MWh \times 350MW) = £233.34/h$$

Consequently the payments from all generators for wheeling charges are presented in Table 3.6.

From bus	To bus	Generator Number	Wheeling charges (£/h)
1	2	4	300
1	3	4	225
2	3	2	291.66
2	3	4	233.34
2	6	2	83.34
2	6	4	66.66
3	5	2	116.664
3	5	4	183.336
4	1	4	750

Table 3.6: Wheeling charges from each generator

After determining the wheeling charges on each transmission line from different generators, the cross-border monetary settlement is able to be processed by acknowledging the locations of lines and generators. For instance, G_4 are paying wheeling charges for occupying capacities on Line (1,2), Line (1,3) and Line (2,3). This can be defined as the wheeling charge from Area 2 to Area 1.

$$\begin{aligned} &G_4\ payment\ for\ Area\ 1 \\ &\qquad = G_4\ payment\ for\ Line\ (1,2) + G_4\ payment\ for\ Line\ (1,3) \\ &\qquad + G_4\ payment\ for\ Line\ (2,3) = 300 + 225 + 233.34 \\ &\qquad = 758.34(\pounds/h) \end{aligned}$$

Meanwhile the £291.66/h on Line (2,3) from G_2 is considered as the local payment.

Consequently sum up all wheeling charges in particular area from specific generators. Table 3.7 shows the results.

G locates in Area	Lines in Area	Wheeling charges (£/h)
1	1	291.66
1	2	0
1	3	116.664
1	4	83.34
2	1	758.34
2	2	750
2	3	183.336
2	4	66.66

Table 3.7: Monetary settlement for cross-border trading

Alternatively,

	Payment to Area 1 transmission owner	Payment to Area 2 transmission owner	Payment to Area 3 transmission owner	Payment to Area 4 transmission owner
Payment from G in Area 1	£291.66/h	0	£116.664/h	£83.34/h
Payment from G in Area 2	£758.34/h	£750/h	£183.336/h	£66.66/h
Payment from G in Area 3	0	0	0	0
Payment from G in Area 4	0	0	0	0

Table 3.8: Final wheeling results for cross-border trading

Table 3.8 indicates payments between any two areas. Take Area 1 as an example, £116.664/h and £83.34/h are paid to Area 3 and Area 4 respectively for wheeling charges from Area 1. In addition, there is £291.66/h for local usage.

- **If the loads share the wheeling charges by 30%.**

Notice that the results in Table 3.5 and Table 3.6 are obtained under the assumption that generators pay all the charges. In practice, the load is supposed to share the wheeling charges with relevant generators. For particular lines *L*, the wheeling charge F_{Li} from load *i* can be calculated by

$$F_{Li} = \frac{P_{Gkc}}{P_{Gk}} \times F_{Gi} \times R \qquad (3.20)$$

where P_{Gkc} is the contribution on load *i* from generator *k*, P_{Gk} is the total output of generator *k*, F_{Gi} refers to wheeling charges in Table 3.4 and *R* is the load sharing rate. The *R* could be 50% or 30% depending on the decision of system operator.

According to the power flow tracing algorithm, the contributions of individual generators to different loads are completely accessible. In this case those results are shown in Table 3.9.

Load	Contributing Generator	Generator Contribution (MW)
L_1	G_4	150
L_3	G_2	116.664
L_3	G_4	183.336
L_5	G_2	77.776
L_5	G_4	122.224
L_6	G_2	55.56
L_6	G_4	44.44

Table 3.9: Contributions of individual generators to different loads

Assume the load sharing rate is 30% by loads in this case. For the explanation of calculating load sharing, take L_1 sharing regarding to G_1 on Line (4,1) as an example, by using equation (3.20),

$$F_{L1} = Wheeling\ charge\ on\ Line\ (4{,}1) \times \frac{Generator\ contirbution\ for\ L_1}{Total\ power\ flow\ on\ Line\ (4{,}1)} \times Load\ Sharing\ Rate = £750/h \times \frac{150MW}{500MW} \times 30\% = £67.5/h$$

From Table 3.9, there are three more loads using the energy from G_1. According to above example, all the load sharing charges due to G_4 on Line (4,1) are shown in Table 3.10.

Load Number	From Bus	To Bus	Contributing Generator	Wheeling charges (£/h)	Shared charges (£/h)
1	4	1	G_4	750	67.5
3	4	1	G_4	750	70.002
5	4	1	G_4	750	55.0008
6	4	1	G_4	750	19.998

Table 3.10: Shared charges by loads on Line (4,1)

This calculation procedure will be repeated on all transmission lines afterwards. Table 3.11 indicates all the shared wheeling charges from loads on each line.

Load Number	From Bus	To Bus	Contributing Generator	Shared charges (£/h)
3	1	2	G_4	42.0012
5	1	2	G_4	28.0008
6	1	2	G_4	19.998
3	1	3	G_4	40.5
5	1	3	G_4	27
3	2	3	G_2	52.4988
5	2	3	G_2	34.9992
3	2	3	G_4	42.0012
5	2	3	G_4	28.0008
6	2	6	G_2	25.002
6	2	6	G_4	19.998
5	3	5	G_2	34.9992
5	3	5	G_4	55.0008
1	4	1	G_4	67.5
3	4	1	G_4	70.002
5	4	1	G_4	55.0008
6	4	1	G_4	19.998

Table 3.11: All shared wheeling charges from loads on each line

After accomplishing this step, the cross-border monetary settlement is able to be achieved by considering the ownerships of *G* and *L*. This calculation step is similar to the process in Table 3.7 and 3.8.

G locates in Area	Lines in Area	Wheeling charges (£/h)
1	1	204.162
1	2	0
1	3	81.6648
1	4	58.338
2	1	530.838
2	2	525
2	3	128.3352
2	4	46.662

Table 3.12: Cross-border wheeling charges when G pays 70%

L locates in Area	Lines in Area	Wheeling charges (£/h)
1	1	177.0012
1	2	137.502
1	3	0
1	4	0
2	1	0
2	2	0
2	3	0
2	4	0
3	1	118.0008
3	2	55.0008
3	3	90
3	4	0
4	1	19.998
4	2	19.998
4	3	0
4	4	45

Table 3.13: Cross-border wheeling charges when L pays 30%

Finally the results of cross-border wheeling charges shared by 30% from loads are shown in Table 3.14.

	Payment to Area 1 transmission owner	Payment to Area 2 transmission owner	Payment to Area 3 transmission owner	Payment to Area 4 transmission owner
Payment from G and L in Area 1	£381.1632/h	£137.502/h	£81.6648/h	£58.338/h
Payment from G and L in Area 2	£530.838/h	£525/h	£128.3352/h	£46.662/h
Payment from G and L in Area 3	£118.0008/h	£55.0008/h	£90/h	0
Payment from G and L in Area 4	£19.998	£19.998/h	0	£45/h

Table 3.14: Results when L shares 30% wheeling charges

In comparison to Table 3.8 the noticeable difference in Table 3.14 is that Area 3 and Area 4 are paying charges to other areas. This is the result of taking account into load shares on wheeling charges. It must be aware that the total wheeling charges in this 6 bus system keeps the same whatever the rate of load sharing is.

3.5.2 Study of With and Without Transit (WWT)

3.5.2.1 Fundamental of WWT

In the WWT method, the calculation is mainly based on the simple concept of transit flow, which has been defined by equation (3.10). Obviously only P_{IMn} and P_{EXn} are needed to consider about. As the required data for calculation are less than AP method, this method involves less calculation when compared to AP. As a result

WWT method is a more convenient way to resolve cross-border trading. Figure 3.7 is used to give the explanation of WWT.

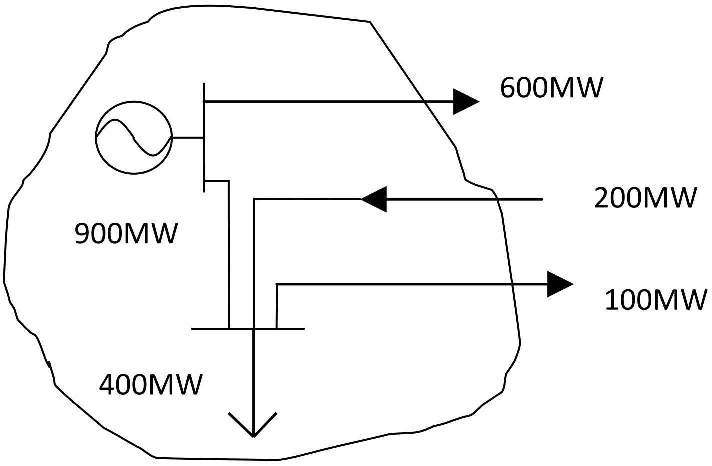

Figure 3.7: Transit flow in Area *n*

There are three main steps to process in this method. [12]

- The first step of WWT is to determine the amount of transit flow. In this case, the import flow of Area *n* is 200MW whilst the export flow is 700MW (600MW+100MW). According to equation (3.10), the transit flow is

$$T_n = Minimum\ of\ [200MW, 700MW] = 200\text{MW}$$

- Secondly the transit flow needs to be eliminated. In particular, all the lines connected to the external areas are modified for future calculations. Those tie lines which carry the same direction as the transit flow are shut down and other tie lines are replaced by generators or loads due to the direction of transit flow. Consequently this system is isolated from external areas. In this case the transit flow is 200MW of the import flow so that only one tie line which carries the import flow is shut down and the other two tie lines with export flows are replaced by loads. This modified network is shown in Figure 3.8.

- The third step is to calculate the wheeling fees for cross-border trading. The equation (3.21) is applied to resolve this issue.

$$F_n = C_n \frac{U - U^w}{U} \tag{3.21}$$

where the F_n is the wheeling charges for Area n, C_n is the total operation cost of Area *N*, the $U$and U^w are the usage in the original system and the isolated system respectively. The U and U^w can be determined by

$$U = \sum L_i P_i \tag{3.22}$$

$$U^w = \sum L_i P_i^w \tag{3.23}$$

where the L is the length of transmission line, P and P^w are the active power flow before and after isolation.

- The final step is to determine the payment contributions from external areas to Area *n*. The proportional net transit flow (import/export or Net(I/E)) from each network can be implemented. For instance, the payment F_a from external Area *a* is

$$F_a = F_n \frac{Net(I/E)_a}{(Net(I/E)_a + Net(I/E)_b + \cdots + Net(I/E)_n)} \tag{3.24}$$

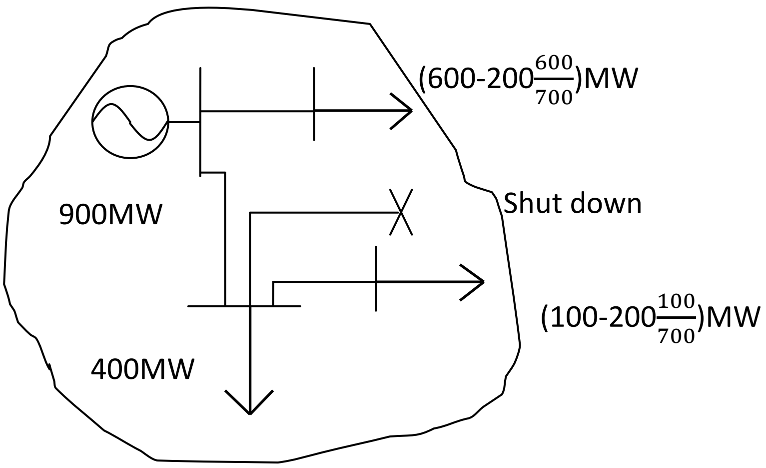

Figure 3.8: Eliminate transit flow in area *n*

3.5.2.2 Case study

The network in Figure 3.6 is used for the demonstration of calculating wheeling charges in Area 1 with WWT in this section. For simplicity, the losses are ignored in this system, all capacity constraints are also neglected and all the voltages are at the same level. In addition, assume all the transmission lines have the same length. As a result, the equation (3.21) can be written as

$$F_n = C_n \frac{U - U^w}{U} = C_n \frac{\sum L_i P_i - \sum L_i P_i^w}{\sum L_i P_i} = C_n \frac{\sum P_i - \sum P_i^w}{\sum P_i} \tag{3.25}$$

According to WWT algorithm, the transit flow needs to be firstly determined by equation (3.10),

$$Transit\ flow\ in\ Area\ 1 = minimum\ of\ [500MW(import), 300MW(export)]$$
$$= 300MW$$

After knowing the 300MW export transit flow in Area 1, the network can be modified by eliminating the outflow from Area 1 and import flow is reduced from 500MW to 200MW. The modified network is displayed in the Figure 3.9.

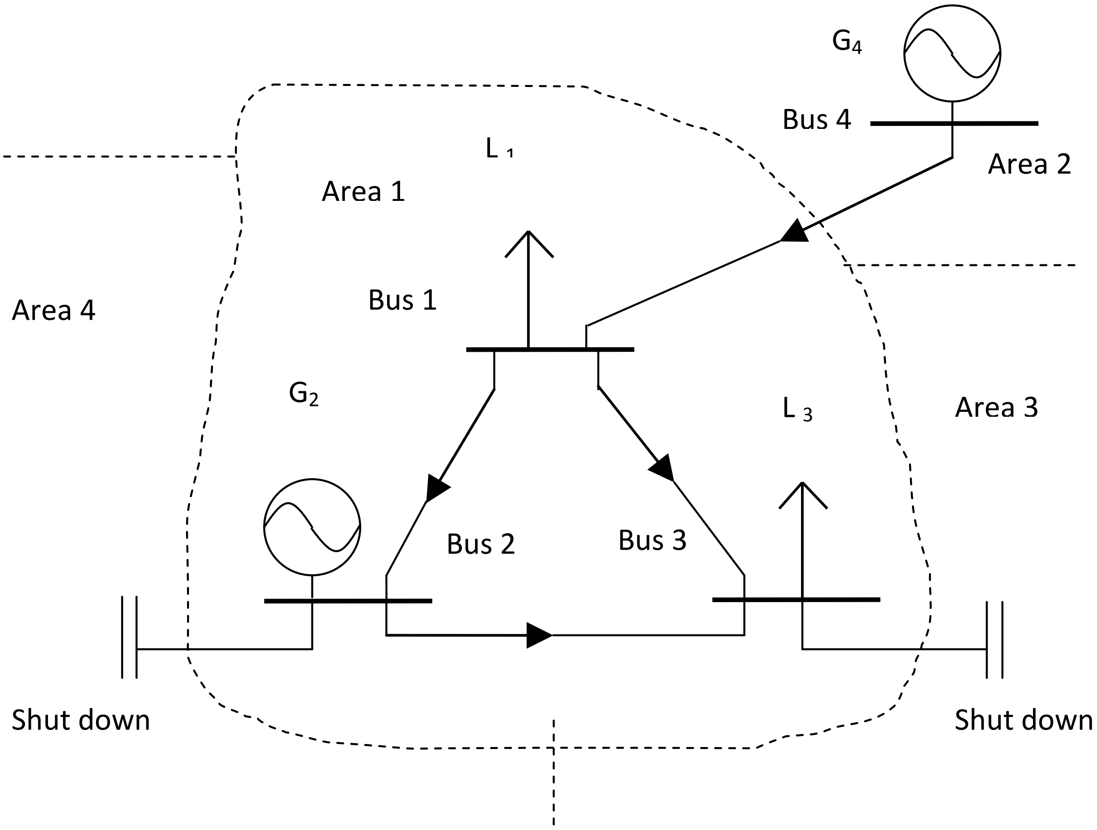

Figure 3.9: The modified network without 300MW transit flow

The data in modified network are in the following Tables.

Bus	Area	P_{gen} (MW)	P_{load} (MW)
1	1	0	150
2	1	250	0
3	1	0	300
4	2	200	0

Table 3.15: Generation and load data in modified network

From bus	To bus	Power flow (MW)
1	2	50
1	3	100
2	3	200
4	1	200

Table 3.16: Power flow in modified network

Assume the wheeling charge rate is £1.5/MWh in Area 1, the local operation cost in original network is

$$\begin{aligned}&Operation\ cost\\ &\quad = Wheeling\ Charge\ Rate\\ &\quad \times \big(Power\ Flow\ on\ Line\ (1,2) + Power\ Flow\ on\ line\ (1,3)\\ &\quad + Power\ Flow\ on\ line\ (2,3)\big)\\ &\quad = £1.5/MWh \times (200MW + 150MW + 350MW) = £1050/h\end{aligned}$$

Consequently the wheeling charge is able to be calculated by equation (3.25) with the data in Table 3.4 and Table 3.16.

$$\begin{aligned}&Wheeling\ charge\ from\ transit\ flow\\ &= Operation\ Cost\\ &\times \frac{(Sum\ of\ power\ flow\ in\ original\ Area\ 1 - sum\ of\ power\ flow\ in\ isolated\ Area\ 1)}{Sum\ of\ power\ flow\ in\ original\ Area\ 1}\\ &= £1050/h \times \frac{700MW - 350MW}{700MW} = £525/h\end{aligned}$$

However, this is the total wheeling charges from all areas, and this result is not good enough to provide cross-border trading signals because the participants need to know the payment ratio from each area for cross-border trading. As a result, a procedure of allocating payments of each area is essential to carry out. According to equation (3.24), the payment from Area 1 for local usages would be

$$\begin{aligned} Payment_{11} &= Wheeling\ charge\ from\ transit\ flow \\ &\times \frac{Transit\ flow\ from\ Area\ 1}{Transit\ flow\ from\ all\ areas} \\ &= £525/h \times \frac{200MW}{(200+500+100+200)MW} = £105/h \end{aligned}$$

Repeat this calculation for payments from other areas to Area 1,

$$\begin{aligned} Payment_{21} &= Wheeling\ charge\ from\ transit\ flow \\ &\times \frac{Transit\ flow\ from\ Area\ 2}{Transit\ flow\ from\ all\ areas} \\ &= £525/h \times \frac{500MW}{(200+500+100+200)MW} = £262.5/h \end{aligned}$$

$$\begin{aligned} Payment_{31} &= Wheeling\ charge\ from\ transit\ flow \\ &\times \frac{Transit\ flow\ from\ Area\ 3}{Transit\ flow\ from\ all\ areas} \\ &= £525/h \times \frac{200MW}{(200+500+100+200)MW} = £52.5/h \end{aligned}$$

$$\begin{aligned} Payment_{41} &= Wheeling\ charge\ from\ transit\ flow \\ &\times \frac{Transit\ flow\ from\ Area\ 4}{Transit\ flow\ from\ all\ areas} \\ &= £525/h \times \frac{100MW}{(200+500+100+200)MW} = £105/h \end{aligned}$$

Consequently the wheeling charges for Area 1 due to cross-border trading are £262.5/h from Area 2, £52.5/h from Area 3 and £105/h from Area 4 respectively.

3.5.3 Comparison between Average Participation and WWT

3.5.3.1 Issues on Average Participation

The core of AP is the power flow tracing algorithm which utilises real operation data and does not depend on the political border. As the result of this the AP is able to be implemented in any system environment and it ignores the system changes to address cross-border trading. In addition it is a fair method to all participants because of the proportional sharing on capacity of transmission lines.

However despite of the significant advantage, the main disadvantage is the assumption of water flow theory. This is the assumption that cannot be proved right or wrong at the moment because no one is able to predict how the energy would flow in an electrical network. Additionally AP is not able to provide enough market information to all participants, for instance the congestion information. The situation is like participants in the pool market. They only know the prices but those prices are not transparent to participants. Consequently AP could be considered to lead to a non-transparent market environment. This is the biggest defect in the theory and would limits adoption of AP in deregulated market.

3.5.3.2 Issues on WWT

The first issue discussed about WWT is the ‘without transit’ assumption. In practice the power system is significantly complicated as even a small change at any nodes or on any transmission line could totally change the whole system operation. As the result of this fact the assumption that isolates each country from each other seems to lead to a significant operation change in the network. This isolated network is unable to compare to the original network from the electrical engineering view as all connection lines between two countries are disconnected.

Another issue is about the transit flow. The concept of transit flow in WWT sounds good but two Figures can prove this concept is not perfect from both engineering and economical views.

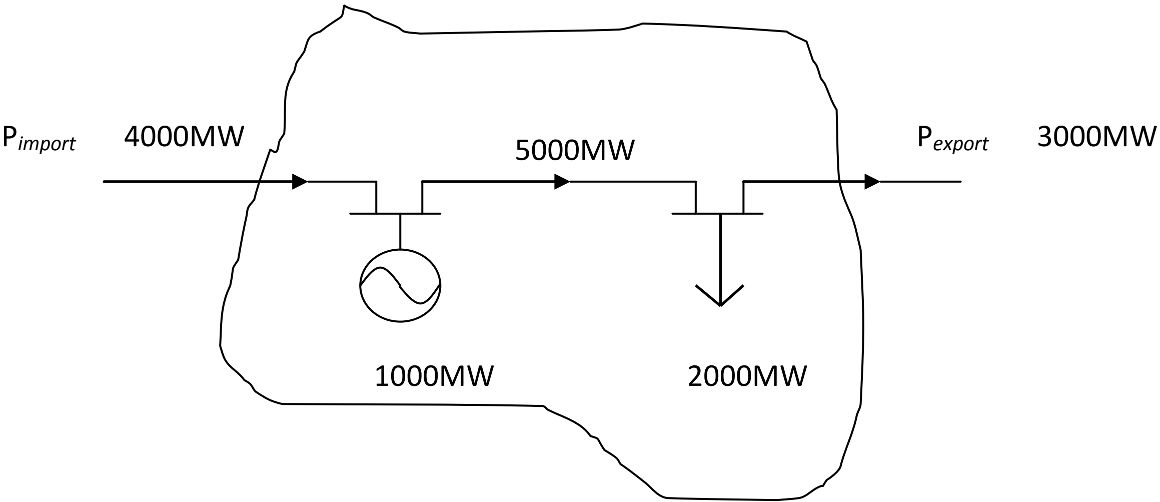

Figure 3.10: Area A

From the Figure 3.10 we can easily point out the transit flow is 3000MW of export by using the equation (3.10).

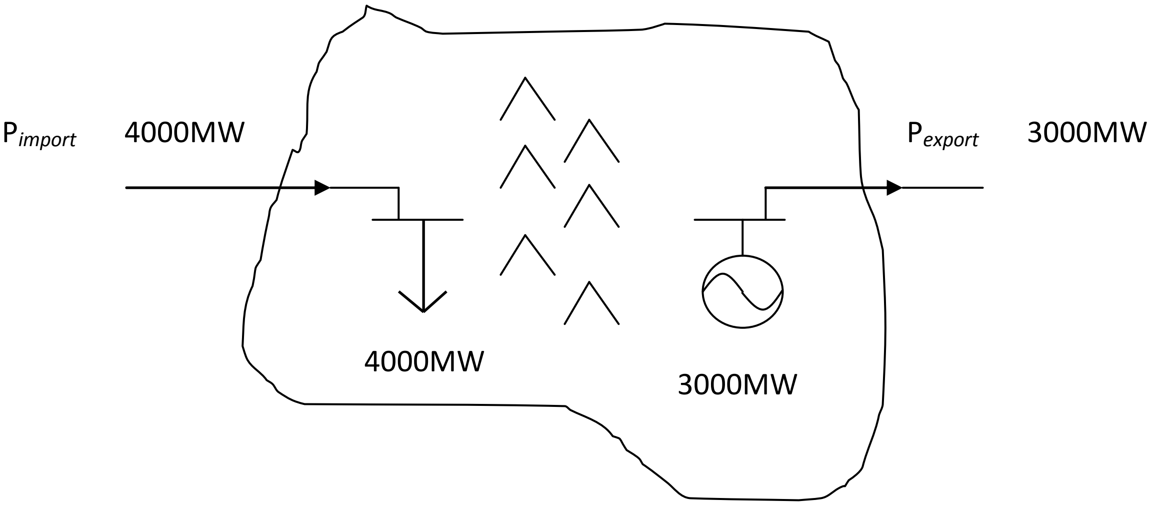

Figure 3.11: Area B

In Figure 3.10 there is no doubt that the Area A is supposed to charge wheeling fees to external areas as they are using the network of Area A for their cross-border trading. On the other hand, from the Figure 3.11 it is apparent that the Area B does not carry any transit flow because the import 4000MW is consumed by the internal load and the export 3000MW is from its own generator. In other words the Area B is not supposed to receive revenues for providing transport service as a third party because there is no transit flows in it at all. But according to WWT theory Area B bear the same transit flow as Area A so it will receive wheeling charges from external areas by being identified to provide transport service for external areas. This is obviously unfair to the external areas. This situation is especially serious in APT (Average participation applied to transit) method. If the situation in Figure 3.11 exists in a particular area, the APT cannot satisfy the need of calculating wheeling charges from cross-border trading as the so-called “transit flow” does not really cross the country. [13]

The final issue is about disconnected lines. When the selected area is isolated, the tie lines must be disconnected, which are supposed to be parts of the payments for wheeling. But they are not involved in the calculation in ‘without transit’ network after they are disconnected because the disconnected lines are replaced by generators or loads. Obviously this situation leads to incorrect payment results and the wheeling area will lose benefits on those disconnected lines.

3.5.3.3 Comparisons between Average Participation and WWT

Both Average Participation and With and Without Transit are sound algorithms to deal with cross-border trading from different views at present. The AP method is able to provide accurate operation details on each transmission line with the proportional assumption. Meanwhile the WWT has the ability of describing whether the transit flow benefits the hosting network or not. However, there could be still a clear conclusion that AP method performs significantly better than WWT. The first reason is that AP does not use modified operation data for calculating wheeling charges of cross-border transactions. Because it is known that the electrical system is complicated and small changes on an element could result in significant system deviations. As a result, isolating the target system in WWT seems not to agree to technical expectations. Consequently this is an important advantage for AP to maintain the system unchanged in the duration of calculations.

Secondly AP is a more transparent method to provide detailed sufficient operation information to market participants. All operation data along the transaction path are accessible to participants. Therefore they have great incentives to invest in the system with detailed wheeling signals. On the other side WWT only provides total payment signals of transit flows and participants cannot acknowledge any locational signals under WWT. The participants may hesitate before the investment because of the high risk of insufficient market signals.

Thirdly AP applies real data from power flow solutions to calculate wheeling charges. If the data were incorrect, AP would return an error feedback. As a consequence, results from AP are reliable. WWT calculates wheeling charges with the concept of the transit flow, which has a critical drawback shown in section 3.5.3.2. The process of determining the transit flow does not take into account the real operation information so a fake transit flow, which does not exist, would be return to participants. This situation results that WWT could provide distorted wheeling information to the market, which put WWT in an unreliable position.

In conclusion, AP is better than WWT from either technical or economic concerns. Although WWT create a sound concept of the transit flow, the disadvantage limits its performance in practice.

3.6 Summary

This chapter presents the traditional mechanisms for wheeling charges in the section 3.2, which are Postage Stamp, Contract Path and MW-mile method. In this part the philosophies and mathematic concerns of three methodologies are explained respectively. The section 3.2 also provides the discussion on advantages and disadvantages of each mechanism. However, those factors are discussed under the environment of the vertically integrated system. As a result the section 3.3 list the challenges of traditional mechanisms when they are involved in cross-border trading. The result is frustrated to show that all the mechanisms fail to address the problems of charging cross-border trading.

Because cross-border trading has been researched in last few years in Europe, their experience is introduced in the section 3.4. This part does not only include a brief history of encouraging cross-border trading in Europe but also presents achievements so far. Six new mechanisms for charging cross-border trading are introduced: Average participations (AP), Simplified average participations (SAP), Modified average participations (MAP), Marginal participations (MP), With and without transit (WWT) and Average participation applied to transits (APT). After comparisons, AP and WWT are considered to be suitable mechanisms from theoretical views at the moment. So they are tested in the section 3.5. Their performances on cross-border trading are successful from different views. But WWT is believed that it may provide inaccurate information about wheeling charges, which causes an unfair monetary settlement in the competitive market. Consequently AP is the best choice for cross-border trading according to the experience in the Europe.

3.7 References

[1] Dariush Shirmohammadi, Xisto Vieira Filho and Boris Gorenstion, Mario V.P. Pereira, "Some Fundamental Technical Concepts about Cost Based Transmission Pricing", *IEEE Trans. On Power System,* Vol. 11, No. 2, pp. 1002-1008, May 1996

[2] Wei-Jen Lee, C.H. Lin and Larry D. Swift "Wheeling Charge Under a Deregulated Environment", *IEEE Transcation On Industry Applications*, Vol. 37, No. 1, pp. 178-183, January/February 2001

[3] H. H. Happ, "Cost of Wheeling Methodologies", *IEEE Transaction on Power Systems,* Vol. 9, No. 1, pp. 147-156, February 1994

[4] K.L. Lo, M.Y. Hassan and S. Jovanvic, "Assessment of MW-mile method for pricing transmission services: a negative flow-sharing approach", *IET Generation, Transmission & Distribution,* 1, (6), pp. 904-911, 2007

[5] William W. Hogan, "Contract Networks foe Electric Power Transmission: Technical Reference", available on: www.hks.harvard.edu/fs/whogan/acnetref.pdf, 10/05/2011

[6] Assef Zobian, Marija D. Ilić, "Unbundling of Transmission and Ancillary Services Part Two: Cost-Based Pricing Framework", *IEEE Transactions on Power Systems*, Vol. 12, No.2, pp549-558, May 1997

[7] "Commission staff working document-Accompanying document to the Inter Transmission System Operator Compensation Mechanism and Harmonisation of Transmission Tariff for Electricity" 2008, available on: http://ec.europa.eu/governance/impact/ia_carried_out/cia_2008_en.htm#tren, accessed on: 27/04/2010

[8] "Incentive Schemes to promote Cross-Border Trading in electricity", 10/12/2009, available on: http://www.energy-regulators.eu/portal/page/portal/EER_HOME/EER_CONSULT/CLOSED%20PUBLIC%20CONSULTATIONS/ELECTRICITY/Cross%20Border%20trade%20incentives%20electricity/CD, accessed on: 06/07/2010

[9] Ignacio Pérez-Arriaga, Luis Olmos Camacho, Francisco Javier Rubio Odériz, Cost components of cross border exchanges of electricity, Prepared for the Directorate-General for Energy and Transport / European Commission, 2002

[10] J. Bialek, Tracing the flow of electricity, *IET Generation, Transmission & Distribution*, Vol. 143, NO. 4, pp313-320, July 1996

[11] Study on further issues on relating to the inter-TSO payment mechanism, available on: http://ec.europa.eu/energy/gas_electricity/studies/doc/electricity/2006_03_tso_compensation_mechanism.pdf, 03/03/2008

[12] Florence School of Regulation, A study issues on the inter-TSO compensation mechanism, 2005

[13] Luis Olmos Camacho, Ignacio J. Pe´rez-Arriaga, “Comparison of several inter-TSO compensation methods in the context of the internal electricity market of the European Union”, Energy Policy 35 (2007) 2379–2389, April 2007

[14] “Regulation 1228/2003”, Available on: http://www.energy-community.org/portal/page/portal/ENC_HOME/AREAS_OF_WORK/ELECTRICITY/Regional_Market/Regulation_1228, 21/06/2011

[15] ETSO PROPOSAL FOR 2005 CBT MECHANISM, 06/01/2005

[16] J W Marangon Lima, “Allocation of Transmission Fixed Charges: An Overview”, *IEEE Transactions on Power Systems*, Vol. 11, No. 3pp. 1409-1418, August 1996

Chapter 4 A Proposed Method for Allocating Wheeling Charges

4.1 Introduction

As mentioned in chapter 2, the deregulated electricity market has been accepted in many parts of the world. However, no matter what the market structure is, the transmission network is always maintained natural monopoly in a particular area. In other words, unlike other parts of the electrical system, a transmission company faces little competitions in its operation area. As a result, the wheeling tariff in this area mostly takes into account the local usage. For instance, there are postage stamp, contract path and MW-mile method which are introduced in chapter 3 to charge local wheeling usages. On the other side, a free market on the generation level encourages demands purchase cheap electricity across different areas. Those transactions can be defined as cross-border trading. This situation leads the transmission owners to be hard to charge those cross-border wheeling usages because other transmission owners are also involved in those transactions. Although they are not competing with each other, they still have to allocate the payments which they should receive for providing transmission services. However, the three methods mentioned above in Chapter 3 are not able to resolve this issue. Consequently new methodologies are needed to help transmission owners allocate cross-border wheeling charges.

In chapter 3, the EU history and experiences on cross-border trading is also introduced. All charging mechanisms in EU are applicable from different views but none of them is free from drawbacks. As a consequence, a new charging mechanism is proposed in this chapter. This mechanism is a combination of power flow tracing and nodal pricing, which take account into both the transaction path information and congestion information. So that both technical and economic information provided by the proposed method could give participants a fair market environment and encourage their investment incentives. In section 4.2, the mathematic theory of the proposed method is presented. Furthermore this method is tested in a 7 bus system and IEEE 118 system in section 4.3.

4.2 The proposed allocation method

As discussed in chapter 3, although there are methodologies to address the problem of allocating revenues in cross-border trading, none of them has the ability to satisfy the needs from both technical and economic expectations. On the other side, nodal pricing is introduced that price differences between generation and demand reflect the transmission cost. As a result nodal pricing could be theoretically used to collect wheeling charges. However, as shown in the section 2.2.2.3, this charging method ignores the transmission path, which has the same drawback as postage stamp, so that nodal pricing cannot allocate cross-border wheeling charges. Furthermore, nodal pricing is always criticised for insufficient transmission cost recovery. In article [1] and [2], authors list various evidences to prove why nodal pricing is not able to fully recover the transmission cost. Consequently Nodal pricing above is not a considerable method to collect wheeling charges but, in the meantime, it offers excellent congestion information which has been mentioned in the section 2.2.2.3.

The AP method in chapter 3 has been proved as the most acceptable method for cross-border trading at the moment. However it cannot provide congestion signals to market participants, which frustrates investment incentives due to information shortages. For the purpose of building up a fair and transparent market environment, the wheeling method is required to have both technical and economic concerns.

Basing on discussions in the previous chapter, we have understood that the power flow tracing methodology is considerable from technical concerns whilst nodal pricing delivers adequate economic signals.

As a result, this section introduces a proposed method which is used to allocate wheeling charges due to cross-border trading in a deregulated market environment. This proposed method is a combination of both power flow tracing and nodal pricing. It calculates the wheeling charge on every line which is based on two kinds of charges: long-term charges and short-term charges. The long-term charges reflect the fixed cost which is related to administrative expenses and maintaining expenses whilst the short-term charges refer to congestion costs and loss costs during transmission. [3] The long-term charge is also considered as the charges collected by transmission owners for future investment. As the power flow tracing takes part in allocating wheeling charges, the proposed method can provide transparent information to market participants. On the other side the nodal pricing helps participants access to congestion and loss signals. At last the proposed method is able to satisfy both technical and economic concerns when allocating wheeling charges due to cross-border trading.

4.2.1 Methodology and Mathematic Model

In a deregulated electrical system, a simple idea of allocating wheeling charges of cross-border trading is to find the transaction path and impacts along this path. The wheeling charges could be allocated among areas by knowing the locations of transmission lines afterwards. In addition, the wheeling charges are required to reflect long-term charges and short-term charges for the purpose of building up a transparent and competitive market. To illustrate this problem, consider the case below:

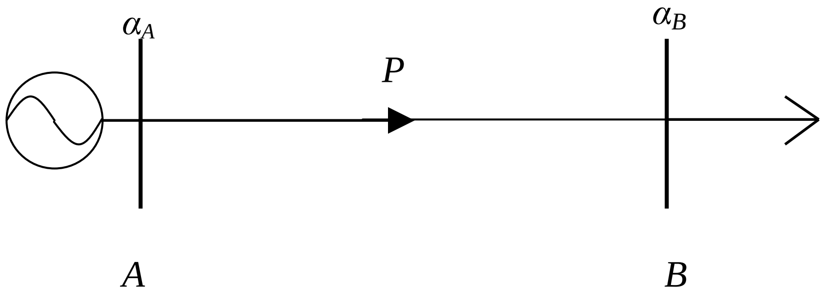

Figure 4.1: Transaction between two nodes

In Figure 4.1, there are two nodes: node A and node B. The nodal prices on both nodes are α_A and α_B respectively. The amount of transported energy is P. According to nodal pricing, the wheeling charges can be calculated as:

$$C = (\alpha_B - \alpha_A)P \tag{4.1}$$

where C is the wheeling charges paid to transmission network owners.

However, as what has been discussed above, C could not guarantee to fully recover the costs spent on maintaining operation and future investment. On the other hand, C in the equation (4.1) only stands for short-term charges from economic views. As a result, a term of long-term charges can be introduced into this equation. C can be written as:

$$C = (\alpha_B - \alpha_A)P + F \tag{4.2}$$

where C is the total transmission charge and F is the long-term charge. As discussed above, the term $(\alpha_B - \alpha_A)P$ is the short-term element reflecting the loss and congestion signals.

Equation (4.2) is an improvement of nodal pricing to help transmission owners fully recover wheeling costs. However this equation is still not sufficient to allocate cross-border trading. The first component can be calculated by nodal pricing theory. However it is not able to allocate cross-border trading by ignoring the path information in the duration of calculation. The second component refers to the long-term wheeling charge. The long-term charge could be set to a fixed annual amount of fees for each participant, which is called the connection fee in some markets. The annual connection fees are charged by regarding to locations of participants, which is similar with postage stamp. [4] [5] As a result the same drawback of ignoring transaction paths in postage stamp prevents it from allocating cross-border wheeling charges. In the proposed method the long-term charge is charged by counting on the real traded energy and its distance during transport.

So far the transaction path plays a key part in allocating wheeling charges for cross-border trading. If the path information is known by ISO, the allocation would be easier for calculation. But it is widely argued that power flow is too complicated to locate precisely. At this step, for a simple explanation of the propose method, assume the ISO had allocated *n* lines used between the source node and the end node,

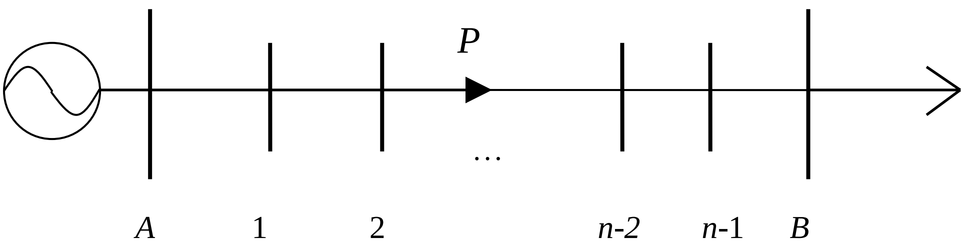

Figure 4.2: n transmission lines between the source and the end

As there are *n* lines in Figure 4.2, (n-1) nodal prices are added into calculation so that there are (n+1) nodal prices in total between source node A and end node B. Modify the equation (4.2) to meet the need of the new system,

$$C = (\alpha_B - \alpha_{n-1})P + (\alpha_{n-1} - \alpha_{n-2})P + \cdots + (\alpha_1 - \alpha_A)P + F \qquad (4.3)$$

From the equation (4.3), the first component of the equation (4.2) has been decomposed for expressing short-term charges on each line. However the long-term charge component is still unknown to participants. Because the proposed method allocates long-term wheeling charges by real-time power flow. Here we can set an coefficient λ, which stands for the long-term charge rate. As a result, the long-term wheeling charge on a particular line is $\lambda \times P$. Additionally λ could be different from each other on different lines due to various factors, such as length of lines and voltage levels. Therefore the equation (4.3) can be written in the form of the following:

$$C = (\alpha_B - \alpha_{n-1})P + (\alpha_{n-1} - \alpha_{n-2})P + \cdots + (\alpha_1 - \alpha_A)P + (\lambda_{(n-1,B)} + \lambda_{(n-2,n-1)} + \cdots \lambda_{(A,1)})P \qquad (4.4)$$

or

$$C = (\alpha_B - \alpha_{n-1})P + \lambda_{(n-1,B)}P + (\alpha_{n-1} - \alpha_{n-2})P + \lambda_{(n-2,n-1)}P \cdots + (\alpha_1 - \alpha_A)P + \lambda_{(A,1)}P \qquad (4.5)$$

The first two components of equation (4.5), the result can be seen:

$$C_{(n-1,B)} = (\alpha_B - \alpha_{n-1})P + \lambda_{(n-1,B)}P \qquad (4.6)$$

This is the wheeling charge for line *(n-1,B)*. In other words, equation (4.5) expresses that the whole wheeling charges between two nodes can be written into the sum of long-term charges and short-term charges on each line which is used by this transaction. Figure 4.3 those charges intuitively.

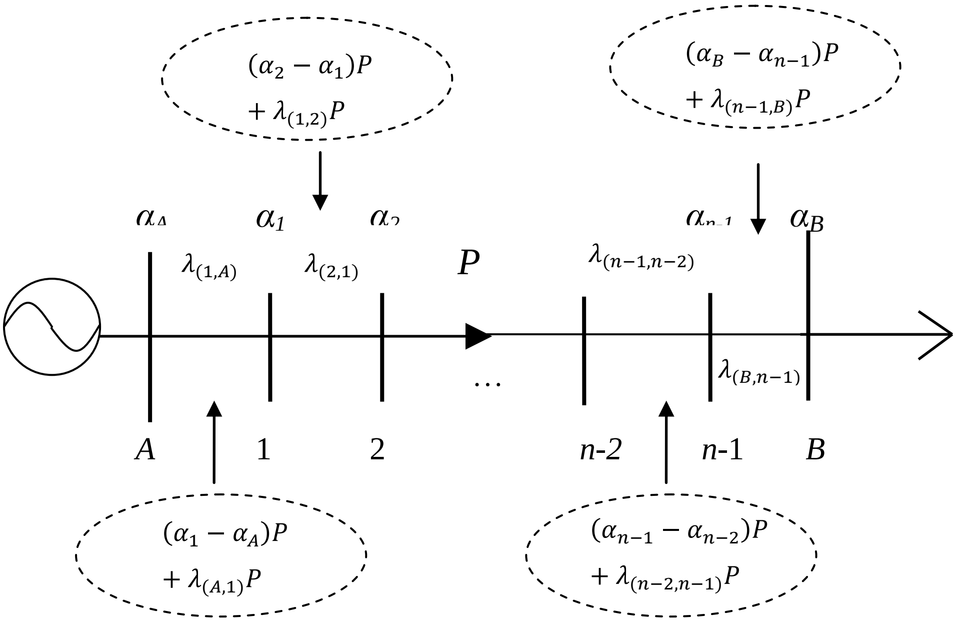

Figure 4.3: Decomposed wheeling charges

For the purpose of allocating cross-border wheeling charges, the next step is simple to achieve as the path information is known. Assume this transaction is across two areas like what are shown in Figure 4.4. The Area 1 includes from node *B* to node *l* and the rest of nodes belong to Area 2, which are from node *m* to node *A*.

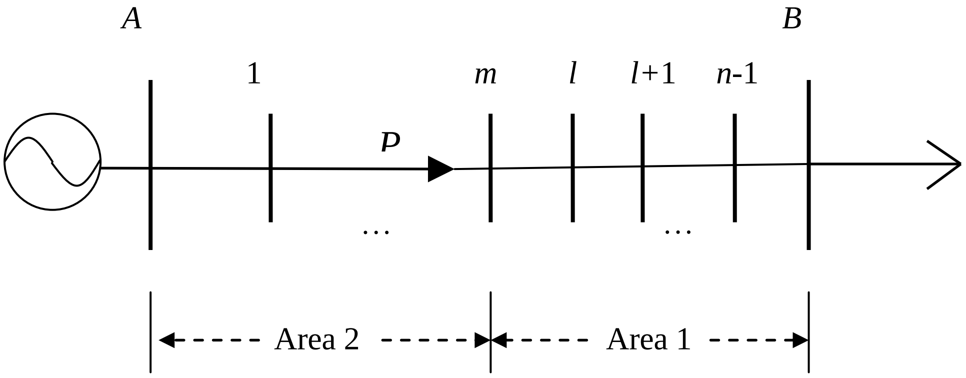

Figure 4.4: Transaction across two areas

For this new situation, the equation (4.5) can be decomposed into:

$$C_1 = (\alpha_B - \alpha_{n-1})P + \cdots + (\alpha_l - \alpha_m)P + (\lambda_{(B,n-1)} + \cdots + \lambda_{l-m})P \tag{4.7}$$

$$C_2 = (\alpha_m - \alpha_{m-1})P + \cdots + (\alpha_1 - \alpha_A)P + (\lambda_{(m,m-1)} + \cdots + \lambda_{1-A})P \tag{4.8}$$

where

$$\mathrm{C} = \mathrm{C}_1 + \mathrm{C}_2 \tag{4.9}$$

The equation (4.7) and (4.8) can be used to allocate the wheeling charges for Area 1 and Area 2 respectively.

However, the above calculation assumes that P is the only power flow impact between A and B. In practice there are likely to have impacts from other transactions along transmission lines if A and B are located in different areas. Furthermore the only power flow information gained from traditional power flow solutions is the total amount of power flow on transmission lines. Because of both factors, P in equation (4.7) and (4.8) cannot be calculated directly from the power flow solution. For this reason, there is a need to introduce another coefficient to address this problem:β, which stands for the capacity usage in percent of P on transmission lines.

$$P = \beta P_T \tag{4.10}$$

where the P_T is the total amount of active power flow on transmission lines from power flow solution and it could be different on each line.

Consequently the equation (4.7) and (4.8) can be written in the following form:

$$\begin{aligned} C_1 = {} & (\alpha_B - \alpha_{n-1})\beta_{(n-1,B)}P_{T(n-1,B)} + \cdots + (\alpha_{l+1} - \alpha_l)\beta_{(l,l+1)}P_{T(l,l+1)} \\ & + (\alpha_l - \alpha_m)\beta_{(m,l)}P_{T(m,l)} + \lambda_{(n-1,B)}\beta_{(n-1,B)}P_{T(n-1,B)} + \cdots \\ & + \lambda_{(l,l+1)}\beta_{(l,l+1)}P_{T(l,l+1)} \\ & + \lambda_{(m,l)}\beta_{(m,l)}P_{T(m,l)} \end{aligned} \tag{4.11}$$

$$\begin{aligned} C_2 = {} & (\alpha_m - \alpha_{m-1})\beta_{(m-1,m)}P_{T(m-1,m)} + \cdots + (\alpha_1 - \alpha_A)\beta_{(A-1)}P_{T(A-1)} \\ & + \lambda_{(m-1,m)}\beta_{(m-1,m)}P_{T(m-1,m)} + \cdots \\ & + \lambda_{(A-1)}\beta_{(A-1)}P_{T(A-1)} \end{aligned} \tag{4.12}$$

To sum up,

$$\mathrm{C} = \mathrm{C}_1 + \mathrm{C}_2$$

$$C_1 = \sum_{i=m}^{B} \{ (\alpha_{i+1} - \alpha_i)\beta_{(i,i+1)}P_{T(i,i+1)} + \lambda_{(i,i+1)}\beta_{(i,i+1)}P_{T(i,i+1)} \} \tag{4.13}$$

$$C_2 = \sum_{i=A}^{m-1} \{ (\alpha_{i+1} - \alpha_i)\beta_{(i,i+1)}P_{T(i,i+1)} + \lambda_{(i,i+1)}\beta_{(i,i+1)}P_{T(i,i+1)} \} \tag{4.14}$$

The equation (4.13) and equation (4.14) can efficiently address the problems of allocating cross-border wheeling charges between two areas as long as the coefficients, which are m and β_i, are known to participants and the ISO. The other coefficient λ_i mostly depends on operation experience and is determined by the ISO.

Although the above discussion has already demonstrated that wheeling charges of cross-border trading can be allocated if the total wheeling charge is decomposed into long-term charges and short-term charges along the transaction path. But finding the flow path is still a challenge for traditional wheeling methods as the same as β on those lines. Fortunately the power flow tracing mechanism introduced in Chapter 3 can fulfil the need of receiving β, m and n in above equations. Even though this mechanism is argued for some assumptions, it is able to provide market participants a fair trading environment. In other words, this mechanism meets the principle of discrimination of the deregulated electricity market.

From equation (3.16) in Chapter 3, the contribution to a particular node from generators can be calculated by this equation:

$$\mathrm{P} = \sum_{\mathrm{k}=1}^{\mathrm{n}} [\mathrm{A_u^{-1}}]_{\mathrm{k}} \mathrm{P_{Gk}}$$

In this case, the contribution to node *i* from generator *A* is calculated as the following equation.

$$\mathrm{P}_{iA} = [\mathrm{A_u^{-1}}]_{iA} \mathrm{P}_{\mathrm{G}A}$$

where P_{iA} is the contribution to node *i* from generator *A* and $\mathrm{P}_{\mathrm{G}A}$ is the output of generator *A*.

If node *i* is the injection node of line (i, *i*+1), β can be determined by dividing P_{iA} with P_{is} which is the total injection amount of energy at node *i*.

$$\beta_{(i,i+1)} = \frac{[\mathrm{A}_{\mathrm{u}}^{-1}]_{iA} P_{GA}}{P_{is}} \tag{4.15}$$

As a result, $P_{A(i,i+1)}$, which is the contribution to line (i, *i*+1) from generator A, is calculated with Equation (4.10) and Equation (4.15). Equation (4.16) presents the result.

$$P_{A(i,i+1)} = \frac{P_{T(i,i+1)}}{P_{iS}} [\mathrm{A}_{\mathrm{u}}^{-1}]_{iA} P_{GA} \tag{4.16}$$

where the P_{Ti} is the total power flow on line *i* which can be calculation in the duration of operation by the ISO.

Replace β in equation (4.11) and (4.12), the allocation for Figure 4.3 is

$$\begin{aligned} C_1 = (\alpha_B - \alpha_{n-1}) \frac{P_{T(n-1,B)}}{P_{(n-1)S}} [A_u^{-1}]_{(n-1)A} P_{GA} + \cdots + (\alpha_l - \alpha_m) \frac{P_{T(m,l)}}{P_{mS}} [A_u^{-1}]_{mA} P_{GA} \\ + \lambda_{(n-1.B)} \frac{P_{T(n-1,B)}}{P_{(n-1)S}} [A_u^{-1}]_{(n-1)A} P_{GA} + \cdots \\ + \lambda_{(m,l)} \frac{P_{T(m,l)}}{P_{mS}} [A_u^{-1}]_{mA} P_{GA} \quad (4.17) \end{aligned}$$

and

$$C_2 = (\alpha_m - \alpha_{m-1})\frac{P_{T(m-1,m)}}{P_{(m-1)S}}[A_u^{-1}]_{(m-1)A}P_{GA} + \cdots + (\alpha_1 - \alpha_A)\frac{P_{T(A,1)}}{P_{AS}}[A_u^{-1}]_{AA}P_{GA}$$

$$+ \lambda_{(m-1,m)}\frac{P_{T(m-1,m)}}{P_{(m-1)S}}[A_u^{-1}]_{(m-1)A}P_{GA} + \cdots$$

$$+ \lambda_{(A,1)}\frac{P_{T(A,1)}}{P_{AS}}[A_u^{-1}]_{AA}P_{GA} \quad (4.18)$$

It is noticed that the above two equations only involve one particular transaction from A to B for generator A. If the calculation is required to process for all transaction between two areas, which is used to find the total inter-payment between A and B, the equation can be written into:

$$\mathrm{C} = \mathrm{C}_1 + \mathrm{C}_2$$

$$C_1 = \sum_{i=m}^{B}\{(\alpha_{i+1} - \alpha_i)\frac{P_{T(i,i+1)}}{P_{iS}}\sum_{k=1}^{n}[A_u^{-1}]_{ik}P_{Gk}$$

$$+ \lambda_{(i,i+1)}\frac{P_{T(i,i+1)}}{P_{iS}}\sum_{k=1}^{n}[A_u^{-1}]_{ik}P_{Gk}\} \qquad (4.19)$$

$$C_2 = \sum_{i=A}^{m-1}\{(\alpha_{i+1} - \alpha_i)\frac{P_{T(i,i+1)}}{P_{iS}}\sum_{k=1}^{n}[A_u^{-1}]_{ik}P_{Gk}$$

$$+ \lambda_{(i,i+1)}\frac{P_{T(i,i+1)}}{P_{iS}}\sum_{k=1}^{n}[A_u^{-1}]_{ik}P_{Gk}\} \qquad (4.20)$$

The allocation of wheeling charges in cross-border trading has been allocated as above. The problem of β has been resolved by equation (4.16). On the other hand, the exact value of m can be found automatically in the duration of applying the power flow tracing mechanism as this mechanism is able to provide the amounts of power flow contribution from a specific generator on transmission lines. As a consequence, those lines can be determined if their capacities are occupied by a specific generator who is involved into cross-border trading. To sum up, those above equations present a process of allocating wheeling charges in cross-border trading and they can address the allocation problem which other methods cannot achieve.

4.2.2 Summary

The mathematic theory of the proposed method has been introduced in this section. The method can be considered as a combination of nodal pricing and power flow tracing. Consequently it satisfies both economic expectations and technical expectations for the deregulated market. In addition, this method collects wheeling charges based on two kinds of fees: short-term charges and long-term charges. The first one is the charge related to congestion and losses during transmission. The latter one is paid for connection and investment. As a result, this method is able to provide sufficient economic signals to market participants for future investments. This method will be tested in the following sections.

4.3 Illustration of the proposed method

4.3.1 Case study of 7 bus system

For explanations of the way the proposed method works, a 7 bus system is used to illustrate the calculation process of the proposed method. This two area system is shown in Figure 4.5. Because this chapter is mainly to explain the fundamental theory and calculation process of the proposed method and test the ability of allocation. As a result no trades have been set up for simplicity of the calculation. The impacts of cross-border trading will be discussed in the next chapter. In addition, there are several assumptions in this case:

- The losses are ignored in this system.
- All the voltages are at the same level.
- The ownerships are split into 5:5 if transmission lines are crossing borders
- The long-term charging rate is set to £1/MWh
- Generators pay 100% of wheeling charges

The information of bus, generation and load are presented in Table 4.1. Further information can be found in Appendix A. From this Table, Bus 1 to Bus 5 are located in Area 1 while Bus 6 and 7 belong to Area 2.

Bus No	Area	Voltage (pu)	P_{gen} (MW)	P_{load} (MW)	Q_{load} (MVar)
1	1	1.05	150	0	0
2	1	1.04	150	40	20
3	1	0.99	0	150	40
4	1	1	50	80	30
5	1	1.017	0	130	40
6	2	1.017	250	200	0
7	2	1.04	200	200	0

Table 4.1: Initial bus, generation and load data of 7 bus system

According to the proposed method, nodal prices in the system are required before allocation. In the case of finding nodal prices, apply the Optimal Power Flow (OPF) to achieve the lowest operation cost in the above system. The mathematic theory of OPF has been introduced in chapter two. The results of power flow and nodal prices are listed in Table 4.2, Table 4.3 and Table 4.4 respectively.

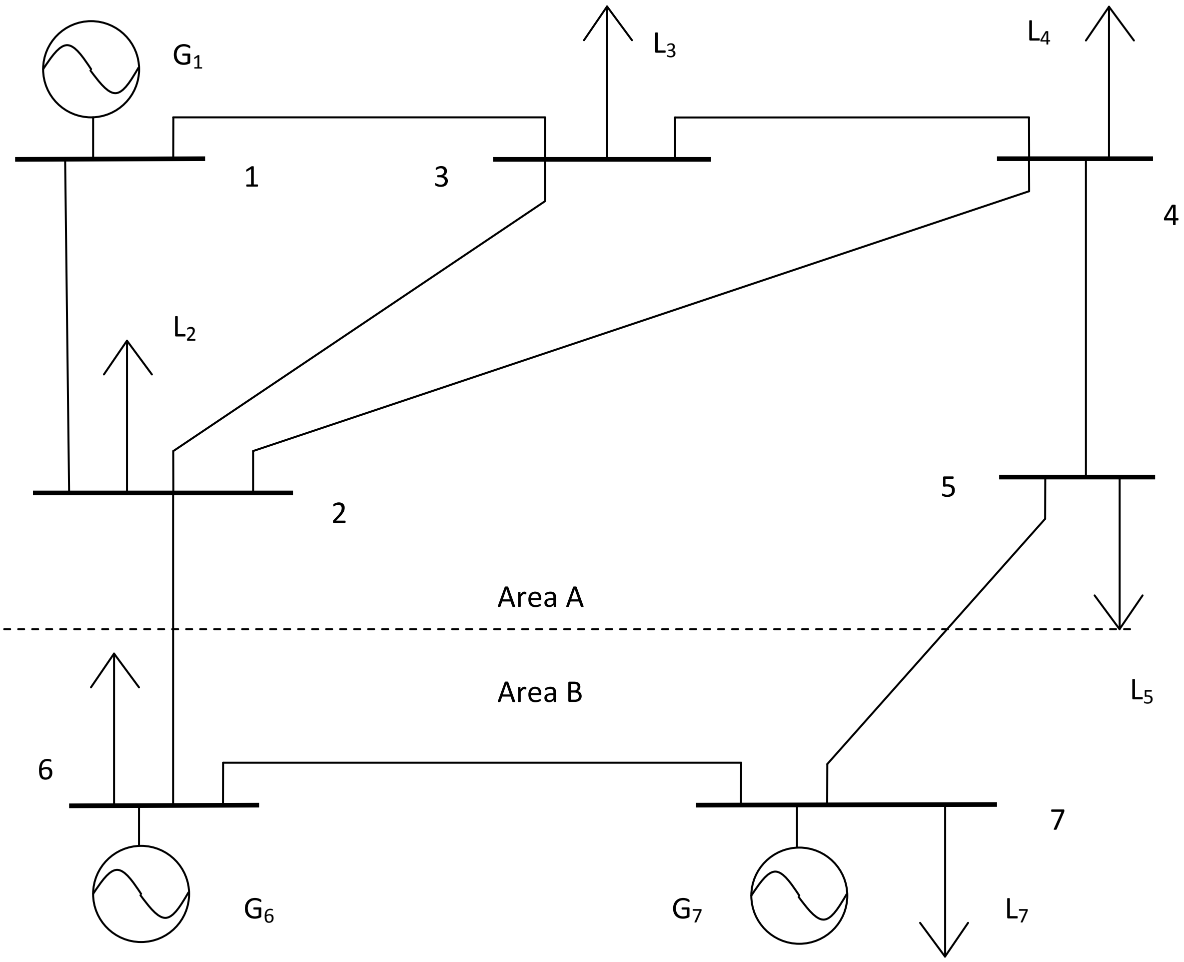

Figure 4.5: The 7 bus system

From Number	To Number	From MW	From Mvar	From MVA	MVA limit	% of MVA Limit	MW Loss	Mvar Loss
1	2	86.4	-4.9	86.6	120	81.7	0	-50.98
1	3	55.1	22.3	59.4	120	49.5	0	2.71
2	3	50	22.8	54.9	100	54.9	0	1.02
2	4	42.2	22.5	47.8	100	47.9	0	-0.19
2	5	117.7	23.6	120	120	100	0	12.88
2	6	-13.3	-2.7	13.6	200	6.8	0	-5.31
3	4	-45	1.4	45	222	20.3	0	-1.39
4	5	25.7	-10.1	27.6	60	46	0	-3.38
7	5	-13.3	32.5	35.2	200	19.2	0	-3.48
6	7	66.7	2.3	66.7	200	33.3	0	4.51

Table 4.2: Power flow on transmission lines

Bus Number	Area Name	Marg. Cost (£/MWh)	Energy (£/MWh)	Congestion (£/MWh)	Losses (£/MWh)
1	A	13	16.77	-3.77	0
2	A	12.85	16.77	-3.92	0
3	A	13.75	16.77	-3.02	0
4	A	14	16.77	-2.77	0
5	A	17.56	16.77	0.79	0
6	B	17.71	20.85	-3.14	0
7	B	20.85	20.85	0	0

Table 4.3: Nodal prices at buses

Generator	Output from OPF (MW)
1	141.51
2	150
4	108.49
6	280
7	120

Table 4.4: Outputs of generators from OPF

The Table 4.2 indicates the power flow results from LP OPF (Linear Programming Optimal Power Flow), which is a function provided by Powerworld® Simulator to use Lagrange multipliers to decide nodal prices. One of those results should be noticed that the capacity of the Line 2-5, which locates in the six row, has been fully occupied so that congestion appears in this system. This is the reason that the fifth column of the Table 4.3, which is the congestion component introduced in section 2.2.2.3, is non-zero. In addition, because this system is designed to be a lossless network, the sixth column is zero for all nodes.

The next step is to apply the power flow tracing mechanism to find contributions of generators to different transmission lines

From bus	To bus	Cross-border	Contributing Generator	Generator Contribution (MW)	Active Flow On line (MW)
1	2	No	1	86.4	86.4
1	3	No	1	55.1	55.1
2	3	No	1	17.302	50
2	3	No	2	30.035	50
2	3	No	6	2.6631	50
2	4	No	1	14.603	42.2
2	4	No	2	25.35	42.2
2	4	No	6	2.2477	42.2
2	5	No	1	40.728	117.7
2	5	No	2	70.703	117.7
2	5	No	6	6.269	117.7
4	3	No	1	4.3583	45
4	3	No	2	7.5659	45
4	3	No	4	32.405	45
4	3	No	6	0.67084	45
4	5	No	1	2.4891	25.7
4	5	No	2	4.321	25.7
4	5	No	4	18.507	25.7
4	5	No	6	0.38313	25.7
5	7	Yes	1	4.008	13.3
5	7	Yes	2	6.9579	13.3
5	7	Yes	4	1.7172	13.3
5	7	Yes	6	0.61693	13.3
6	2	Yes	6	13.3	13.3
6	7	No	6	66.7	66.7

Table 4.5: Generator contribution to each line

The first two columns refer to the start node and the end node of each line respectively. The third column shows whether the related line is across borders or not. The fourth column displays the number of the generator whose outputs contribute to the line in the same row. Furthermore the power flow contributions in MW from those generators are listed in the next column. The last column shows the value of active flow on the related line.

For the purpose of demonstrating how to calculate the wheeling charges on each line, Line (1, 3) is taken for the calculation example. From Table 4.3, it is known that the nodal price at Bus 1, which is a generation node, is £13/MWh and Bus 3, which is a load node, has the price of £13.75/MWh. On the other hand, Table 4.4 shows only G_1 contributes power flow on Line 1-3. According to the equation (4.6), the wheeling charge for Line (1, 3) is

$$\begin{aligned} &Wheeling\ charges\ for\ Line\ (1,3) \\ &\qquad = Contribution\ of\ G_1 \times (price\ at\ node\ 3 - price\ at\ node\ 1) \\ &\qquad - congtribution\ of\ G_1 \times The\ long\ term\ charging\ rate \\ &\qquad = 55.1MW \times (£13.75/MWh - £13/MWh) + 55.1MW \times £1/MWh \\ &\qquad = £96.425/h \end{aligned}$$

The first component of this equation is the short-term wheeling charge while the long-term charge is calculated in the second component.

The above calculation is repeated for all other lines, and results are listed in Table 4.6.

G	From	To	Contribution (MW)	Actual flow (MW)	From price (£/h)	To price (£/h)	short-term charges (£/h)	long-term charges (£/h)	Total charges (£/h)
1	1	2	86.4	86.4	13	12.85	-12.96	86.4	73.44
1	1	3	55.1	55.1	13	13.75	41.325	55.1	96.425
1	2	3	17.302	50	12.85	13.75	15.5718	17.302	32.8738
2	2	3	30.035	50	12.85	13.75	27.0315	30.035	57.0665
6	2	3	2.6631	50	12.85	13.75	2.39679	2.6631	5.05989
1	2	4	14.603	42.2	12.85	14	16.79345	14.603	31.3965
2	2	4	25.35	42.2	12.85	14	29.1525	25.35	54.5025
6	2	4	2.2477	42.2	12.85	14	2.584855	2.2477	4.83256
1	2	5	40.728	117.7	12.85	17.56	191.82888	40.728	232.557
2	2	5	70.703	117.7	12.85	17.56	333.01113	70.703	403.714
6	2	5	6.269	117.7	12.85	17.56	29.52699	6.269	35.796
1	4	3	4.3583	45	14	13.75	-1.089575	4.3583	3.26873
2	4	3	7.5659	45	14	13.75	-1.891475	7.5659	5.67443
4	4	3	32.405	45	14	13.75	-8.10125	32.405	24.3038
6	4	3	0.67084	45	14	13.75	-0.16771	0.67084	0.50313
1	4	5	2.4891	25.7	14	17.56	8.861196	2.4891	11.3503
2	4	5	4.321	25.7	14	17.56	15.38276	4.321	19.7038
4	4	5	18.507	25.7	14	17.56	65.88492	18.507	84.3919
6	4	5	0.38313	25.7	14	17.56	1.3639428	0.38313	1.74707
1	5	7	4.008	13.3	17.56	20.85	13.18632	4.008	17.1943
2	5	7	6.9579	13.3	17.56	20.85	22.891491	6.9579	29.8494
4	5	7	1.7172	13.3	17.56	20.85	5.649588	1.7172	7.36679
6	5	7	0.61693	13.3	17.56	20.85	2.0296997	0.61693	2.64663
6	6	2	13.3	13.3	17.71	12.85	-64.638	13.3	-51.338
6	6	7	66.7	66.7	17.71	20.85	209.438	66.7	276.138

Table 4.6: Wheeling charges on each line

The formats of the first fifth columns are similar with the Table 4.5. The data of "From price" column refer to the nodal prices at the start bus of this transmission line. Similarly the prices at "End bus" are in the "To price" column. The next columns are presenting short-term charges and long-term charges on those lines respectively. The last column includes the total wheeling charge on each line, which is the sum of the previous two columns. It should be noticed that the wheeling charge on line (6, 2) is negative. This is because the short-term charges, which is known congestion cost in this case, is negative and its absolute value is greater than the absolute value of long-term charge. From the expectation of calculation, the transmission owner is supposed to pay G_6 instead of charging wheeling fess from G_6.

After determining wheeling charges on each transmission line from different generators, the cross-border monetary settlement is able to be processed by acknowledging the locations of lines and generators. As mentioned in the beginning, generators pay 100% of wheeling charges. For instance, the Line 2-3 has £5.05989/h payment from G_6 in the fifth row of Table 4.6. As Bus 6 and Line 2-3 locate in different networks, this payment can be defined as the cross-border wheeling charge from Area B to Area A. Furthermore, for tie lines between two areas, the payment is equally shared by contribution. For example, the total wheeling charge on Line 5-7 is £57.057/h with contribution from G_1, G_2, G_4 and G_6 respectively. As mentioned above the Line 5-7 is split equally between two areas, as a consequence half of the payment on Line 5-7 belongs to Area A while the rest is paid to Area B. Half of the payment on Line 5-7 is calculated by following this equation:

$$\begin{aligned} &Cross - border\ paymenet \\ &\qquad = \frac{G_1\ payment + G_2\ payment + G_4\ payment + G_6\ payment}{2} \\ &\qquad = \frac{17.1943 + 29.8494 + 7.36679 + 2.64663}{2} = 28.5285(£/h) \end{aligned}$$

Consequently transmission owners of Area A and Area B receive £28.5285/h for their wheeling services respectively. In addition, the result of allocation is that G_1, G_2 and G_4 in Area A are paying £8.59715/h ($\frac{£17.1943/h}{2}$), £14.9247/h ($\frac{£29.8494/h}{2}$) and £3.683395/h ($\frac{£7.36679/h}{2}$) to Area A as local wheeling charges and the same amount to Area B as cross-border wheeling charges. Similarly G_6 pays £1.323315/h ($\frac{£2.64663/h}{2}$) to each transmission owner.

According to the above discussion to allocate wheeling charges, repeat the allocation on each line and sum up with respect to the same kind. The result is presented in Table 4.7.

G locate in Area	Lines start in Area	Lines end in Area	Wheeling charges (£/h)
A	A	A	1130.6681
A	A	B	54.4105
A	B	A	0
A	B	B	0
B	A	A	47.9386
B	A	B	2.6466
B	B	A	-51.338
B	B	B	276.138

Table 4.7: Local and cross-border monetary settlement between two areas

From Table 4.7, the payment from participants in Area A paid to the transmission owner of Area A is

$$\begin{aligned}&Payment\ from\ generators\ in\ Area\ A\ to\ the\ transmission\ owner\ of\ Area\ A\\&= local\ wheeling\ charges\\&+ shared\ cross\ border\ wheeling\ charges\\&= £1130.6681/h + \left(\frac{£54.4105/h}{2} + 0\right) = £1157.87335/h\end{aligned}$$

The payment from Area A to Area B is

$$\begin{aligned}&Payment\ from\ generators\ in\ Area\ A\ to\ the\ transmission\ owner\ of\ Area\ B\\ &= cross\ border\ wheeling\ charges\\ &+ shared\ cross\ border\ wheeling\ charges\\ &= 0 + (\frac{£54.4105/h}{2} + 0) = £27.20525/h\end{aligned}$$

Similarly payments from generators in Area B are calculated as

$$\begin{aligned}&Payment\ from\ generators\ in\ Area\ B\ to\ the\ transmission\ owner\ of\ Area\ B\\ &= local\ wheeling\ charges\\ &+ shared\ cross\ border\ wheeling\ charges\\ &= £276.138/h + \left(\frac{-£51.338/h}{2} + \frac{£2.6466/h}{2}\right) = £251.7923/h\end{aligned}$$

$$\begin{aligned}&Payment\ from\ generators\ in\ Area\ B\ to\ the\ transmission\ owner\ of\ Area\ A\\ &= cross\ border\ wheeling\ charges\\ &+ shared\ cross\ border\ wheeling\ charges\\ &= £47.9386/h + (\frac{-£51.338/h}{2} + \frac{£2.6466/h}{2}) = £23.5929/h\end{aligned}$$

Finally, the allocation of payment for wheeling charges between two areas is summarised in Table 4.8.

	Payment to Area A transmission owner	Payment to Area B transmission owner
Payment from G in Area A	£1157.87335/h	£27.20525/h
Payment From G in Area B	£23.5929/h	£251.7923/h

Table 4.8: Final allocation between Area A and Area B

Table 4.8 presents the final allocation for cross-border wheeling charges. According to the result, Area A needs to pay £27.205/h to Area B for cross-border wheeling charges whilst Area B pays £23.592/h to Area A for this service. To sum up, the proposed method has efficiently addressed the problem of allocating cross-border wheeling charges.

4.3.2 Impacts of loads in allocation

The previous section has demonstrated the calculation process of the proposed method. In that section, generators are asked to pay all the wheeling charges in the system. However, in practice, loads are supposed to share parts of the wheeling charges because they participate in energy transactions. The rate of how much loads need to pay depends on the ISO decisions. Generally this rate is set to 50% or 30% depending on the market model. This section discusses the impacts when wheeling charges from loads are taken into calculation. The analysis is based on the case in the previous section and the sharing rate of loads is set to 30%. In other words, generators are supposed to pay 70% of total charges in the last column in Table 4.6. As a result, wheeling charges for generators in this case are calculated in the fifth column in Table 4.9.

G	From	To	Total charge (£/h)	Charge for G (£/h)
1	1	2	73.44	51.408
1	1	3	96.425	67.4975
1	2	3	32.8738	23.01166
1	2	4	31.39645	21.977515
1	2	5	232.55688	162.78982
1	4	3	3.268725	2.2881075
1	4	5	11.350296	7.9452072
1	5	7	17.19432	12.036024
2	2	3	57.0665	39.94655
2	2	4	54.5025	38.15175
2	2	5	403.71413	282.59989
2	4	3	5.674425	3.9720975
2	4	5	19.70376	13.792632
2	5	7	29.849391	20.894574
4	4	3	24.30375	17.012625
4	4	5	84.39192	59.074344
4	5	7	7.366788	5.1567516
6	2	3	5.05989	3.541923
6	2	4	4.832555	3.3827885
6	2	5	35.79599	25.057193
6	4	3	0.50313	0.352191
6	4	5	1.7470728	1.222951
6	5	7	2.6466297	1.8526408
6	6	2	-51.338	-35.9366
6	6	7	276.138	193.2966

Table 4.9: wheeling charges for generators when they are paying 70% of total charges

To determine payments from loads, contributions of generators to each load need to be determined at first. The information of contributions can be delivered during the tracing power flow method according to Equation (3.18):

$$P_{Li} = \frac{P_{Li}}{P_i} P_i = \frac{P_{Li}}{P_i} \sum_{k=1}^{n} [A_u^{-1}]_{ik} P_{Gk}$$

where P_{Li} is the load at node *i*, P_{Gk} is the power output from the generator *k*, P_i is the power flow at node *i*.

With respect to this equation, contributions of generators to each load are obtained during the power flow tracing mechanism. Those results are shown in Table 4.10.

Load	Load Area	Generator	Generator Area	Contribution (MW)
2	A	1	A	13.841
2	A	2	A	24.028
2	A	6	B	2.1305
3	A	1	A	76.722
3	A	2	A	37.563
3	A	4	A	32.385
3	A	6	B	3.3306
4	A	1	A	7.748
4	A	2	A	13.45
4	A	4	A	57.609
4	A	6	B	1.1926
5	A	1	A	39.176
5	A	2	A	68.009
5	A	4	A	16.784
5	A	6	B	6.0302
6	B	6	B	200
7	B	1	A	4.0081
7	B	2	A	6.9579
7	B	4	A	1.7172
7	B	6	B	67.317
7	B	7	B	120

Table 4.10: Contributions of generators to each load

The first two columns indicate the load number and its location. The third column is used for presenting the generator which is supplying the load in the first column. The fourth column refers to the location of generator in the previous column. The final column is the energy contribution from the related generator.

To calculate wheeling charges from a particular load, it is a considerable idea to also calculate load payment based by the proportional sharing. For this purpose, the following equation is applied:

$$C_L = \sum \frac{P_{Gcon}}{P_{Gout}} \times C_G \times 30\% \qquad (4.21)$$

where C_L is the wheeling charge of the load, P_{Gcon} is the contribution in MW of related generators and P_{Gout} is the outputs of related generators, C_G is total wheeling charges caused by related generators, and 30% refers to the sharing rate set above. Additionally, the value of $\frac{P_{Gcon}}{P_{Gout}}$ is the proportional sharing rate for loads and C_G for a specific generator can be calculated by summarising the charges on transmission lines which are used by this generator and shown in the fourth column of Table 4.9. Those results are in Table 4.11.

G	Charges caused by G (£/h)
1	498.505
2	570.51
4	116.062
6	275.385
7	0

Table 4.11: Wheeling charges caused by each generator

It is noticed that the wheeling charge for G_7 is zero but this does not mean G_7 produces 0MW. In fact all output of G_7 is consumed by L_7, which is at the same busbar. Therefore G_7 injects 0MW to the system and no wheeling charges are caused by G_7. Other generators also supply loads at the same bus. For instance, G_4 provides 57.609MW to L_4. Obviously this part of outputs of G_4 is immediately consumed by L_4 instead of transporting along transmission lines to serve other demands. As a result those local usages are excluded in outputs of generators during calculation. For instance, G_2 are injecting 150MW into system and L_2 consumes 24.028MW from G_2

according to results in Table 4.10. Consequently the output of G_2 is 125.975MW when it is looked from the system. Other outputs are shown in Table 4.12.

By using equation (4.21) to calculate the wheeling charge of L_2 due to G_1, it is

$$C_{L2} = \frac{P_{G2con}}{P_{G2out}} \times C_{G2} \times 30\%$$

$$= \frac{13.841MW}{141.51MW} \times £498.505/h \times 30\% = £14.62753382/h$$

This calculation process is repeated for every load and those results are presented in Table 4.12.

Load	L Area	Generator	G Area	Contribution (MW)	G output (MW)	Proportion of Contribution	Load payment (£/h)
2	A	1	A	13.841	141.51	0.097809	14.62753382
2	A	6	B	2.1305	80	0.026631	2.200154034
3	A	1	A	76.722	141.51	0.542167	81.08183297
3	A	2	A	37.563	125.975	0.298178	51.03409517
3	A	4	A	32.385	50.881	0.636485	22.16152122
3	A	6	B	3.3306	80	0.041633	3.439489804
4	A	1	A	7.748	141.51	0.054752	8.188290736
4	A	2	A	13.45	125.975	0.106767	18.27352927
4	A	6	B	1.1926	80	0.014908	1.231590566
5	A	1	A	39.176	141.51	0.276843	41.40222998
5	A	2	A	68.009	125.975	0.539861	92.39884403
5	A	4	A	16.784	50.881	0.329868	11.48553256
5	A	6	B	6.0302	80	0.075378	6.227349851
7	B	1	A	4.0081	141.51	0.028324	4.235865784
7	B	2	A	6.9579	125.975	0.055232	9.453188797
7	B	4	A	1.7172	50.881	0.033749	1.175104654
7	B	6	B	67.317	80	0.841463	69.51784517

Table 4.12: Wheeling charges for loads

Table 4.12 indicates payments for wheeling services for each load. However, the final goal in this study is to find out the allocation information of cross-border wheeling charges. The next step of work is to allocate the charges for each area. According to the allocation process for generators in the last section, this monetary issue can be allocated by knowing the wheeling charge in each transmission line with the help of the proposed method. In the previous section, this allocation was completed under the assumption of generators paying all wheeling charges. In this section, loads are supposed to pay part of the wheeling charges, which is 30%. And the allocation for loads also depends on transaction paths which are traced for outputs of generators in the previous section.

Additionally, the amount of a specific load paying to a transmission line is based on the proportion of the related generator paying to this line by comparing to the total payment of this generator. For instance, L_2 is supplied by G_1 and G_6 according to Table 4.6. For the aim of finding out wheeling charges for L_2 on related lines, charges for generators need to be acknowledged first. According to 30% wheeling charge sharing of loads, total wheeling charges for each generator are 70% as shown in Table 4.13. The last column shows the actual charges for generators using transmission services.

G	Wheeling charge caused by G (£/h)	Wheeling charge paid 70% by G (£/h)
1	498.505	348.9535
2	570.51	399.357
4	116.062	81.2434
6	275.385	192.7695
7	0	0

Table 4.13: Wheeling charges for each generator

Furthermore, pick up wheeling charges which are from G_1 and G_6 in Table 4.9. They are shown in Table 4.14:

G	From Bus	To Bus	Charge for G (£/h)	Total wheeling charge of G (£/h)	Proportion
1	1	2	51.408	348.9535	0.14732
1	1	3	67.4975	348.9535	0.193428
1	2	3	23.01166	348.9535	0.065945
1	2	4	21.97752	348.9535	0.062981
1	2	5	162.7898	348.9535	0.466509
1	4	3	2.288108	348.9535	0.006557
1	4	5	7.945207	348.9535	0.022769
1	5	7	12.03602	348.9535	0.034492
6	2	3	3.541923	192.7695	0.018374
6	2	4	3.382789	192.7695	0.017548
6	2	5	25.05719	192.7695	0.129985
6	4	3	0.352191	192.7695	0.001827
6	4	5	1.222951	192.7695	0.006344
6	5	7	1.852641	192.7695	0.009611
6	6	2	-35.9366	192.7695	-0.18642
6	6	7	193.2966	192.7695	1.002734

Table 4.14: Proportions for L_2 on related lines

It should be noticed that the last column refers to the proportion of the total wheeling charge paid from a generator on a transmission line, which is $\frac{Charge\ for\ G}{Total\ charge\ for\ G}$. Consequently, the wheeling charges for a load using this related line is

$$Wheeling\ charge\ for\ load = \frac{Charge\ for\ G}{Total\ charge\ for\ G} \times Total\ charge\ for\ load$$

In this case, wheeling charges for L_2 are explained. The wheeling charges for L_2 on related lines are

L	Contributing Generator	From Bus	To Bus	Wheeling charge for load participants (£/h)	Proportion for L	Wheeling charge for L (£/h)
2	1	1	2	14.6275338	0.14732	2.154935
2	1	1	3	14.6275338	0.193428	2.82938
2	1	2	3	14.6275338	0.065945	0.964609
2	1	2	4	14.6275338	0.062981	0.92126
2	1	2	5	14.6275338	0.466509	6.823871
2	1	4	3	14.6275338	0.006557	0.095914
2	1	4	5	14.6275338	0.022769	0.333049
2	1	5	7	14.6275338	0.034492	0.50453
2	6	2	3	2.20015403	0.018374	0.040425
2	6	2	4	2.20015403	0.017548	0.038609
2	6	2	5	2.20015403	0.129985	0.285988
2	6	4	3	2.20015403	0.001827	0.00402
2	6	4	5	2.20015403	0.006344	0.013958
2	6	5	7	2.20015403	0.009611	0.021145
2	6	6	2	2.20015403	-0.18642	-0.41016
2	6	6	7	2.20015403	1.002734	2.20617

Table 4.15: Allocation of wheeling charges for L_2

The fifth column is the wheeling charge for L_2 with respect to G_1 and G_6, which has been shown in Table 4.12. The sixth column is the proportion listed in Table 4.14. The final column is the wheeling charge on each transmission line.

The above process shows how to allocate wheeling charges for a specific load on transmission lines. To complete the monetary allocation for cross-border wheeling service, this calculation process could be repeated for all loads by following the steps of the example of L_2. Consequently the allocation can be achieved by replicating actions on Table 4.7 after all wheeling charges for loads are calculated. Those results are presented in the following Tables:

G locate in Area	Lines start in Area	Lines end in Area	Wheeling charges for G (£/h)
A	A	A	791.4676
A	A	B	38.087
A	B	A	0
A	B	B	0
B	A	A	33.5566
B	A	B	1.8522
B	B	A	-35.9366
B	B	B	193.2966

Table 4.16: Wheeling charges for generators

L locate in Area	Lines start in Area	Lines end in Area	Wheeling charges for L (£/h)
A	A	A	327.3261
A	A	B	15.7337
A	B	A	-2.4418
A	B	B	13.1344
B	A	A	26.2504
B	A	B	1.3833
B	B	A	-12.9597
B	B	B	69.7079

Table 4.17: Wheeling charges for loads

Table 4.16 and Table 4.17 indicate the wheeling charges for generators and loads respectively. Consequently, by summarising data in Table 4.16 and Table 4.17, the final allocation between Area A and Area B is

	Payment to Area A transmission owner	Payment to Area B transmission owner
Payment from G and L in Area A	£1144.483395/h	£38.824025/h
Payment from G and L in Area B	£36.97723/h	£240.17431/h

Table 4.18: Allocation for two areas

Figure 4.6 and 4.7 compare the allocation between different sharing rates of loads. From Figure 4.6, the transmission owner of Area A receives less wheeling charges from generators and loads in Area A when loads also pay wheeling charges at the sharing of 30%. Meanwhile the transmission owner of Area B gain more benefits from those generators and loads by comparing to the case where generators pay 100% wheeling charges. Because the total wheeling charge for all areas keeps unchanged, the wheeling payment for the transmission owner of Area A from generators and loads in Area B is increased and it is reduced for the transmission owner of Area B simultaneously. This is shown in Figure 4.7.

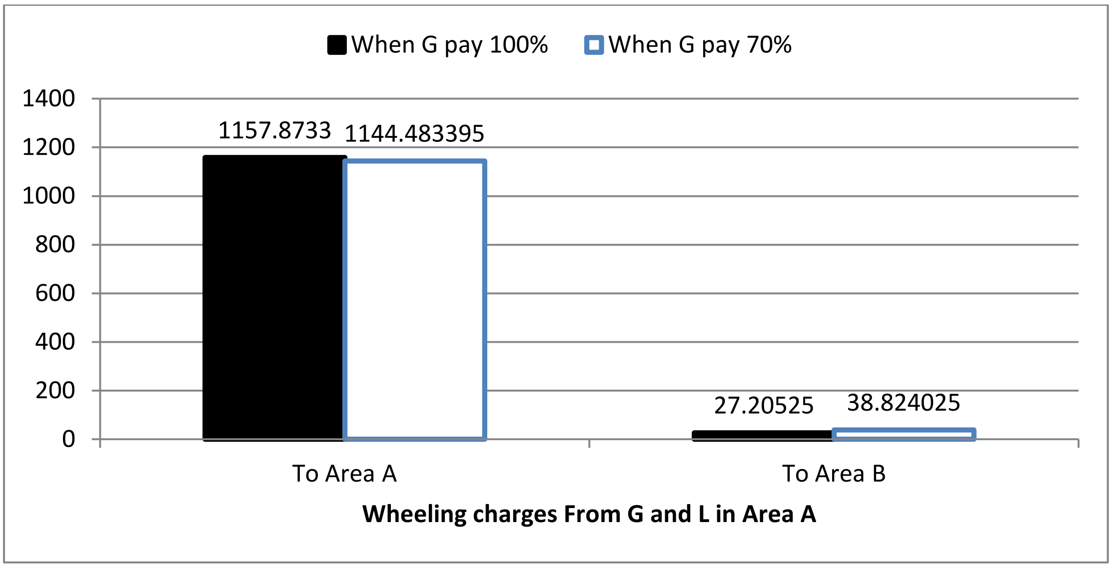

Figure 4.6: Total wheeling charges from G and L in Area A

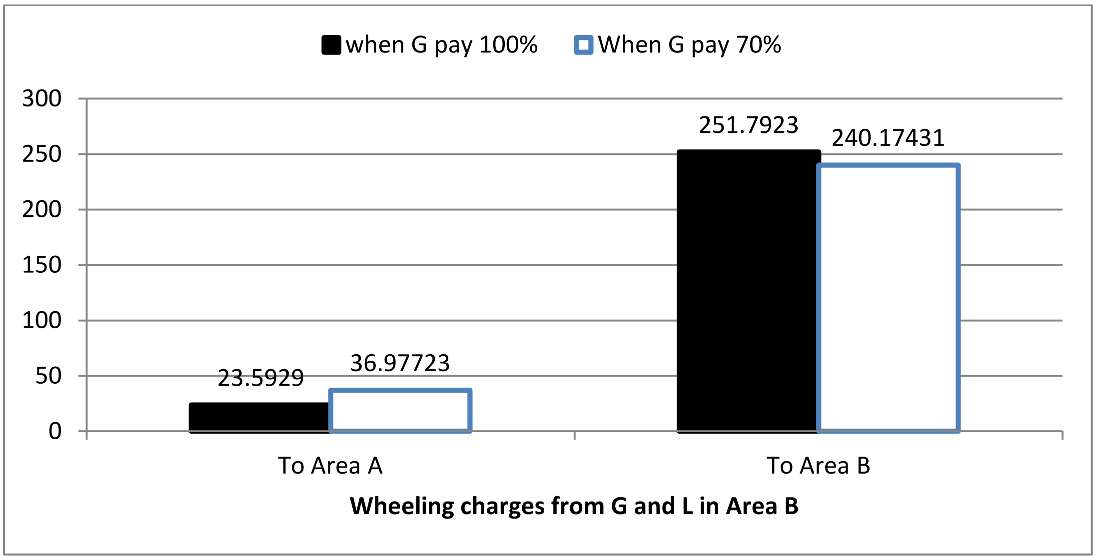

Figure 4.7: Total wheeling charges from G and L in Area B

In summary, collecting part of wheeling charges from loads reduces in burdens on generators. This change does not affect the total payments collected by transmission owners but the influence of this method is the allocation of wheeling charges among areas. Additionally what reflects by wheeling contributions from loads could be considered as a market signal for future investments.

4.3.3 Case study of IEEE 118 bus system

The electrical network contains hundreds of nodes in practice so that it is valuable to simulate the propose method in a bigger network. For this purpose, the IEEE 118 bus system has been chosen to fulfil this goal. The data of the IEEE 118 bus can be found in [6]. This network is split into two areas. Area 1 consists of 40 buses, which includes bus 1 to Bus 36 and Bus 113, Bus 114, Bus 115 and Bus 117, and the remaining buses belong to Area 2. Assumptions used for the analysis in this network are similar to those used for the 7 bus system which are described in Section 4.3.1.

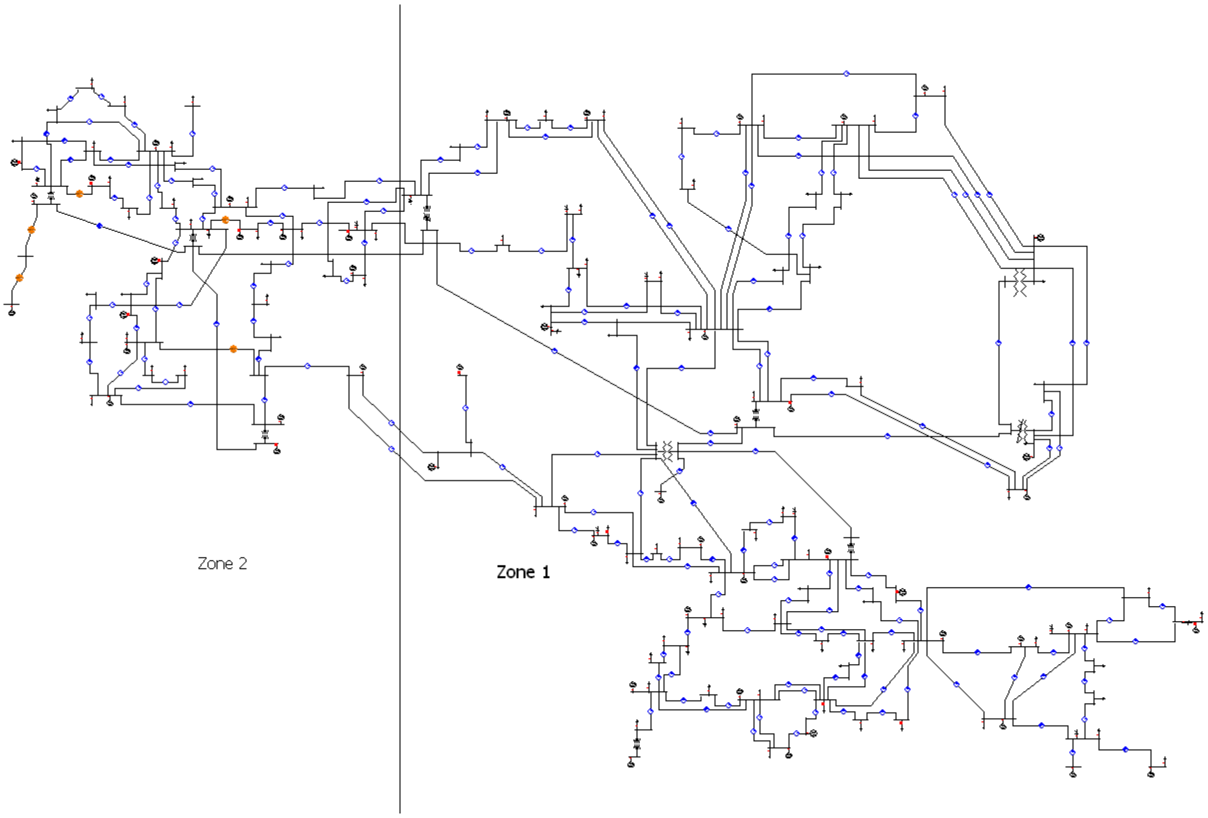

Figure 4.8: IEEE 118 system split into two areas

G locate in Area	Lines start in Area	Lines end in Area	Wheeling charges for G (£/h)
1	1	1	3829.251
1	1	2	-0.122
1	2	1	0.464
1	2	2	0
2	1	1	279.487
2	1	2	0.469
2	2	1	417.731
2	2	2	3188.537

Table 4.19: Charge allocation for G

Generator	Area	Short-term charges (£/h)	Long-term charges (£/h)	Total transmission charges (£/h)
1	2	0.070126	3.5063	3.576426
6	2	1.16291792	44.741973	45.90489092
10	2	277.7717425	2830.543507	3108.315249
12	2	1.181328	24.2684	25.449728
15	2	7.728252	9.2003	16.928552
18	2	2.995265537	17.76421708	20.75948262
19	2	3.989326194	31.2706472	35.25997339
25	2	8.5618452	109.95828	118.5201252
26	2	21.81809162	178.0712155	199.8893071
31	2	0.28157627	29.559843	29.84141927
32	2	-0.3878204	38.10364	37.7158196
34	2	1.9439589	113.709545	115.6535039
36	2	0.91340696	127.496198	128.409605
46	1	0.66914582	106.438289	107.1074348
49	1	2.140893	85.28787	87.428763
54	1	0.07723484	47.594819	47.67205384
55	1	0.080172103	51.43821735	51.51838945
56	1	0.0710485	49.09345	49.1644985
61	1	-0.001735608	242.646732	242.6449964
62	1	-0.01577787	37.185823	37.17004513
65	1	-5.0695495	260.743951	255.6744015
66	1	0.5526736	113.64901	114.2016836
69	1	9.96769858	215.424977	225.3926756
70	1	-10.18317312	56.1458653	45.96269218
74	1	1.325202531	35.49795439	36.82315692
76	1	-0.466616587	35.1822641	34.71564751
77	1	-0.274281	69.1804	68.906119
80	1	1.41843073	96.688751	98.10718173
85	1	-0.540461934	178.4357852	177.8953233
87	1	-0.42696125	319.9630859	319.5361247
89	1	0.00116188	149.0029883	149.0041502
92	1	0.015144625	99.0827132	99.09785783
100	1	0.28104066	191.101056	191.3820967
103	1	0.351556669	364.1443073	364.495864
104	1	0.168779947	184.1431069	184.3118868
105	1	0.057540044	148.1134907	148.1710307
110	1	0.081423411	236.0245727	236.1059961
111	1	0.11073949	456.992987	457.1037265

Table 4.20: Transmission charges in IEEE 118 system

	Payment to Area 1 transmission owner	Payment to Area 2 transmission owner
Payment from G in Area 1	£3829.423/h	£0.232/h
Payment from G in Area 2	£488.758/h	£318.537/h

Table 4.21: Final allocation

This study of the 118 bus system follows a similar path to the 7 bus system. The results here are those that generators pay 100% of wheeling charges. As shown in Section 4.3.2, the allocation procedure that takes account into both generators and loads is similar to the procedure that only charges generators except little additional calculation so that load impacts are not considered in this case. Table 4.20 gives a survey of short-term transmission charges, long-term transmission charges and total transmission charges. The allocations of charges to generators are listed in Table 4.19. Table 4.21 gives the total payments to transmission owners in individual areas.

4.4 Summary

This chapter has introduced a proposed method to resolve the allocation problem of wheeling charges in cross-border trading. This proposed method is a combination mechanism of nodal pricing and power flow tracing, which can meet the need to economic and technical expectations. In particular, this method addresses the cross-border problem by calculation long-term and short-term wheeling charges on each line and allocates them by referring to locations of transmission lines.

The effectivities of the proposed method are illustrated by using two systems: 7 bus system and the IEEE 118 bus system. In the former system calculations of allocating transmission charges are illustrated in two case studies. The first one is a 100% charge to generators with no contributions on loads. In the second case 70% of charges is allocated to generators and 30% is allocated to loads respectively. The 118 bus system illustrates that the proposed method can be used for a large system.

4.5 Reference

[1] I.J. Pérez-Arriaga, F.J. Rubio, J.F. Puerta, J. Arceluz, J. Marín, "Marginal Pricing of Transmission Services: An Analysis of Cost Recovery", *IEEE Transmission on Power Systems, Vol. 10, No. 1*, pp 546-553, February 1995.

[2] Shmuel S. Oren, Pablo T. Spiller, Pravin Varaiya, Felix Wu, "Nodal prices and transmission rights: A critical appraisal", The Electricity journal, Vol. 8, Issue. 3, pp 24-35, April 1995.

[3] Hyde M, Merrill, Bruce W. Erickson, "Wheeling Rates Based on Marginal-Cost Theory", IEEE Transmission on Power Systems, Vol. 4, No. 4, pp 1445-1451, October 1989.

[4] "The Statement of Use of System Charges", available on: http://www.nationalgrid.com/NR/rdonlyres/590ACE8D-01BE-4ED9-A028-3736D28A7CCE/41181/UoSCMI6R0v10Final.pdf, accessed on: 10/12/2010

[5] "The Statement of the Use of Connecting Charging Methodology", available on: http://www.nationalgrid.com/NR/rdonlyres/590ACE8D-01BE-4ED9-A028-3736D28A7CCE/41181/UoSCMI6R0v10Final.pdf, accessed on: 08/04/2011

[6] Data of IEEE 118 system, available on: http://www.ee.washington.edu/research/pstca/, 15/11/2007

Chapter 5 Allocation of Wheeling Charges for Cross-Border Trading

5.1 Introduction

A proposed method, which is designed to resolve the allocation problem in cross-border trading, has been introduced in Chapter 4. It is a method that combines both nodal pricing and power flow tracing and charges short-term charges and long-term charges from participants. It is believed that both economic and technical views are satisfied simultaneously by implementing this method. Additionally the ability of allocation is tested in the last chapter and results turn out that the proposed method can be fully functional. The next work is to analyse performances of the proposed method within cross-border trading.

In this chapter, the IEEE 118 bus system is still used as the illustration network and there are three different scenarios to test. Firstly this network is split into two areas to simulate bilateral contract which is traded across different areas. Its purpose is to reveal impacts of cross-border trading under the proposed method. In addition, within three areas in the IEEE 118 bus system, a cross-border trade between two areas could require the third area to transport those traded energy thought its transmission network. The analysis of impacts in the third area is also discussed in this chapter.

The arrangement of this chapter is following this order: a two-area network is presented in Section 5.2. To clearly test impacts of cross-border trading, two areas are isolated to obtain initial operation data respectively. After this step, a transaction between two areas is added into the network to test their impacts on wheeling services. In Section 5.3 the IEEE 118 bus system is split into three areas to test impacts to an area which carries energy of cross-border trading for other areas.

5.2 Allocation of wheeling charges between two areas

5.2.1 Network description

Because a large system would show clearer impacts of cross-border trading, the IEEE 118 system is chosen to be the testing network and the default data are used in testing. The default data of IEEE 118 system can be found in Appendix B. In this case, this network is implemented to simulate cross-border trading between two areas. The status of both areas is as the same as the study in Section 4.3.3. Additionally, for a clear observation of impacts of cross-border trading, two areas are isolated from each other for gain independent operation data, which is shown in Figure 5.1.

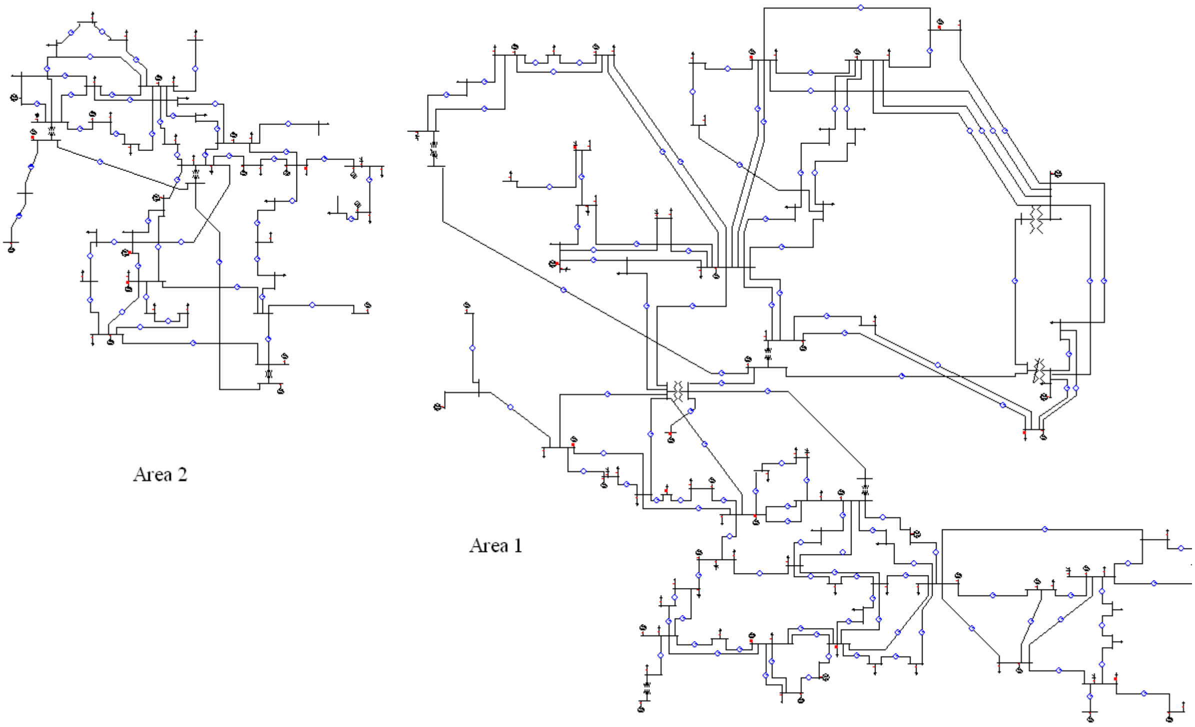

Figure 5.1: Two isolated areas in the IEEE 118 bus system

To focus cross-border issues, there are also assumptions for simplifying simulation process:

- Transmission capacity constraints are neglected except the tie lines.
- The losses are ignored in this system.
- All the voltages are at the same level.
- The ownerships are split into 5:5 if transmission lines are crossing borders.
- Negative outputs of generators in default database are considered as loads.
- If there are more than one line between two nodes, they will be replaced by equivalent single circuit to simplify the calculation.
- The long-term charging rate is set to £2/MWh in Area 1 and £1/MWh in Area 2. This can be considered as Area 1 is a richer region than Area 2.
- Generators pay 100% of wheeling charges.

Because values of loads are kept constant after splitting, it is not necessary to list them. However, splitting system changes outputs of generators. Therefore outputs of generators in this system are shown in the figure below.

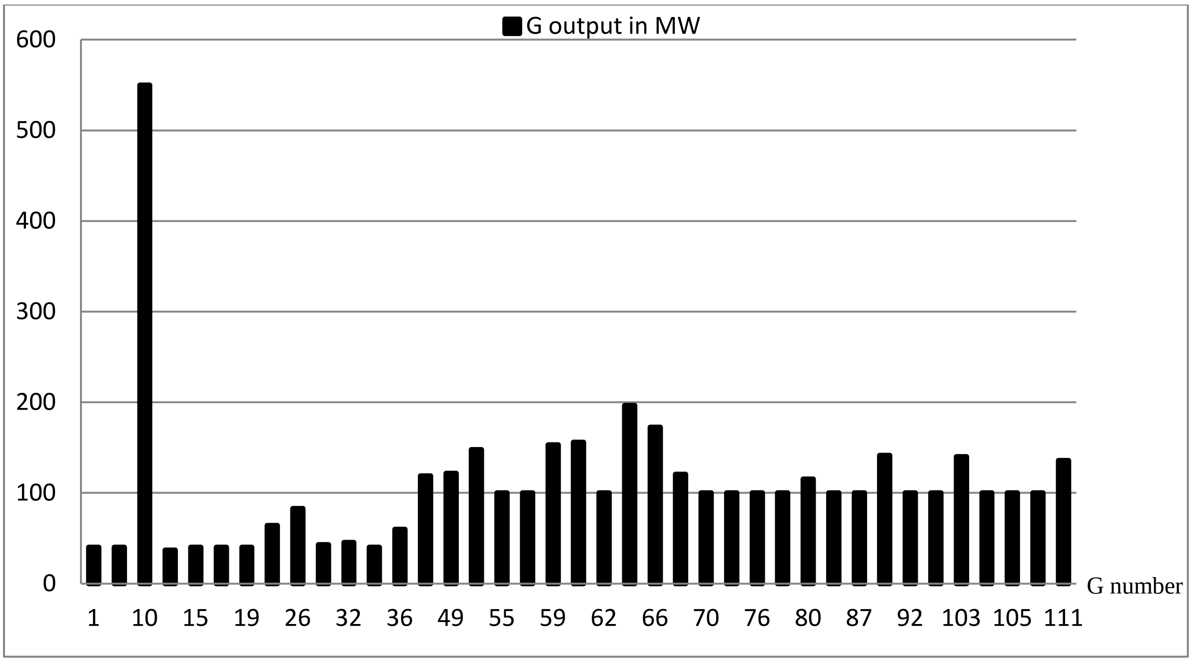

Figure 5.2: Generation outputs in two-isolated-area system

The main aim in this research is to allocate wheeling charges on transmission lines and it is valuable to analyse power flow changes which are brought by cross-border trading. According to this consideration, initial power flows in this system are presented in Table 5.1. The first two columns are nodes where a transmission line starts and ends. The last three columns are MW, Mvar and MVA on this line respectively.

From Bus	To Bus	MW on line	Mvar on line	MVA on line
1	2	-9.7	-10.1	14
1	3	-41.3	-16.9	44.6
2	12	-29.7	-16.9	34.2
3	5	-73.8	-17.3	75.8

3	12	-6.4	-9.4	11.4
4	5	-72.7	-7.9	73.2
4	11	79.7	16.3	81.4
5	6	96.6	17.8	98.2
8	5	332	137.1	359.2
5	11	88.9	17.9	90.7
6	7	44.6	1	44.6
7	12	25.6	-0.9	25.6
8	9	-450	-122.6	466.4
8	30	90	26.8	93.9
9	10	-450	-60.7	454.1
11	12	47.7	-11.7	49.2
11	13	50.9	16.1	53.4
12	14	36.6	6.1	37.1
12	16	18.5	4	18.9
12	117	20	4.6	20.5
13	15	16.9	-0.3	16.9
14	15	22.6	5.9	23.4
15	17	-151.2	-40.4	156.5
15	19	77.8	20.5	80.4
15	33	23	6.8	24
16	17	-6.5	-4.3	7.8
17	18	126.8	36.1	131.8
30	17	304.4	127	329.8
17	31	5.7	12.4	13.7
17	113	3.1	-11.5	11.9
18	19	66.8	22.3	70.4
19	20	-23.5	-0.3	23.5
19	34	123	30.2	126.6
20	21	-41.5	-1.2	41.5
21	22	-55.5	-8.8	56.1
22	23	-65.5	-14.8	67.1
23	24	13	10.2	16.5
23	25	-176.7	-56.9	185.6
23	32	91.2	25.3	94.6
26	25	99.6	21.9	102
25	27	142.9	59.7	154.9
26	30	214.4	3.1	214.4
27	28	33.4	3.7	33.6
27	32	16.1	-0.8	16.1
27	115	22.5	3.2	22.7
28	29	16.4	-2.3	16.5
29	31	-7.6	-4.4	8.8
31	32	-29.9	-1.7	29.9
113	31	8	25.9	27.1
32	113	10.9	-14.2	17.9
32	114	7.5	3.6	8.3
34	36	64	2.7	64.1
35	36	-33	-9	34.2

38	37	106.5	80	133.2
37	39	58.4	26.7	64.2
37	40	48.1	21.7	52.8
38	65	-106.5	-80	133.2
39	40	31.4	14	34.3
40	41	20.3	-2.4	20.4
40	42	-6.8	-10.1	12.2
41	42	-16.7	-11.5	20.3
42	49	-39.8	-13.8	42.2
42	49	-39.8	-13.8	42.2
42	49	-39.8	-13.8	42.2
43	44	-18	-7	19.3
44	45	-34	0.4	34
45	46	-34.8	-0.2	34.8
45	49	-52.2	-10.1	53.1
46	47	-27.5	-14.5	31.1
46	48	-16.3	-12	20.3
47	49	-22.7	-5.8	23.4
47	69	-38.8	-6.6	39.4
48	49	-36.3	-3.1	36.5
49	50	48.7	24.9	54.7
49	51	60.2	34.9	69.5
49	54	32.4	22.5	39.5
49	54	32.2	22.4	39.2
49	54	32.4	22.5	39.5
49	66	-96.9	-25.2	100.1
49	66	-96.9	-25.2	100.1
49	66	-96.9	-25.2	100.1
49	69	-29	-6.2	29.7
50	57	31.7	20.7	37.8
51	52	27	11.6	29.3
51	58	16.2	12.3	20.3
52	53	9	7.4	11.6
53	54	-14	-0.1	14
54	55	9.9	-1.7	10
54	56	28.4	-30.2	41.5
54	59	-20.3	-14.7	25
55	56	-28.3	-15.1	32.1
55	59	-24.9	-14.9	29
56	57	-19.7	-20.5	28.4
56	58	-4.2	-12.7	13.4
56	59	-19.7	-12.4	23.3
56	59	-20.7	-12.7	24.3
56	59	-19.7	-12.4	23.3
59	60	-39.8	-7.3	40.5
59	61	-48.5	-6.6	48.9
63	59	138.8	74.6	157.6
60	61	-111.9	-1.9	111.9
60	62	-5.9	-7	9.2

61	62	31.4	-9	32.7
64	61	31.8	19.6	37.4
62	66	-32.2	-25.5	41
62	67	-19.4	-22.6	29.7
63	64	-138.8	-74.6	157.6
64	65	-170.6	-78.5	187.8
65	66	17.1	72.3	74.3
65	68	96.8	-18.4	98.6
66	67	47.4	27.3	54.7
68	69	-47	109.5	119.1
68	81	-40.2	-6.8	40.8
68	116	184	-58.4	193
69	70	94.7	34.3	100.8
69	75	95.1	35.9	101.7
69	77	30.4	10.3	32.1
70	71	18	2.2	18.1
70	74	13.6	3.5	14.1
70	75	-2.9	-1.4	3.2
71	72	12	3.9	12.6
71	73	6	-1	6.1
74	75	-54.4	-14.9	56.4
75	77	-42.6	-14.9	45.1
75	118	33.4	27	43
76	77	-67.6	-30.5	74.1
76	118	-0.4	-13.5	13.5
77	78	53.7	9.9	54.6
77	80	-76.5	-43.3	87.8
77	80	-35.3	-20	40.6
77	80	-76.5	-43.3	87.8
77	82	-6.2	19.6	20.6
78	79	-17.3	-15.2	23
79	80	-56.3	-25.7	61.9
81	80	-40.2	73.4	83.7
80	96	12	17.9	21.6
80	97	19.4	22.6	29.8
80	98	20.1	9.7	22.3
80	99	10.8	12.3	16.4
82	83	-43.5	7	44
82	96	-16.8	-10.4	19.8
83	84	-25.2	5.2	25.7
83	85	-38.3	4.8	38.6
84	85	-36.2	-0.1	36.2
85	86	17	-4.9	17.7
85	88	-47.8	-4.4	48
85	89	-67.7	-7.5	68.1
86	87	-4	-12.5	13.2
88	89	-95.8	-14.1	96.8
89	90	41.4	9.7	42.5
89	90	78.1	17.9	80.1

89	90	41.4	9.7	42.5
89	92	121.8	11.8	122.4
89	92	38.9	2.6	39
89	92	121.8	11.8	122.4
91	90	2.1	-6.9	7.2
91	92	-12.1	-16.5	20.5
92	93	65.5	3.7	65.6
92	94	60.1	0.1	60.1
92	100	33.4	-8.2	34.3
92	102	46.5	1.5	46.6
93	94	53.5	-4.8	53.8
94	95	50.1	13.4	51.8
94	96	30.3	-4.8	30.7
94	100	3.2	-31.2	31.4
95	96	8.1	-17.6	19.4
96	97	-4.4	-17.7	18.2
98	100	-13.9	4.3	14.5
99	100	-31.2	-9.4	32.6
100	101	-19.5	12.6	23.3
100	103	114.3	14.2	115.2
100	104	54.1	9.8	55
100	106	57.6	15.9	59.8
101	102	-41.5	0.3	41.5
103	104	32.1	6.5	32.8
103	105	42.5	10.8	43.8
103	110	56.7	19.6	60
104	105	48.2	16.1	50.8
105	106	9	15.6	18
105	107	26.4	19.8	33
105	108	24.3	9.1	25.9
106	107	23.6	14.7	27.8
108	109	22.3	9.4	24.2
109	110	14.3	6.9	15.9
110	111	-36	-5.9	36.5
110	112	68	-0.2	68
114	115	-0.5	2.1	2.2

Table 5.1: Power flows in two-isolated-area system

In addition, total amount of generation and load of each area is shown in Table 5.2.

Area	Total Generation (MW)	Total Load (MW)
1	2611	2611
2	1057	1057

Table 5.2: Generation and demand in both areas

Because of the first two assumptions for simplifying simulation process, no congestion and losses exist in both isolated areas. As a result, the energy price across an individual area is the same and they are shown in Table 5.3 which are obtained by implementing the OPF solution. At this stage, all data that are required for allocation are prepared. Because the allocation is similar to the case in Section 4.3.3, the calculation process is not repeated here. By applying the proposed method, wheeling charges in each area are calculated and presented in Table 5.4.

Area	Energy Price
1	£12.95/h
2	£11/h

Table 5.3: Energy prices in both areas

	Payment to transmission owner in Area 1	Payment to transmission owner in Area 2
Payment from generators in Area 1	£8680.8/h	0
Payment from generators in Area 2	0	£3327.5/h

Table 5.4: Wheeling charges for two-isolated-area system

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5.2.2 400MW trade between two areas

As shown in Table.5.3, Area 1 has the higher price, which is £12.95/h, for local electricity consumption. On the contrary, local electricity price in Area 2 is only £11/h. As a result, it is sensible that loads in Area 1 want to trade electrical energy from Area 2 so do generators in Area 2. Because loads in Area 1 can benefit from cheaper energy and generators in Area 2 can earn profits from trading. More importantly, trading between them can lead to optimal social welfares. In practice ISOs are most likely to pursue lowest generation operation costs because lower generation costs mean lower energy selling prices. According to this aim, the purpose of cross-border trading in this case is to achieve lowest generation operation costs. Two areas are connected for transporting energy and the network structure is presented in Figure 5.4. Additionally, tie lines are the places where congestion is most likely to happen so that those tie lines are set up capacity constraints according to real situations. By applying OPF solution in the Powerworld simulator, the amount of cross-border trading in this network is increased at the step of 100MW from 100MW and the amount of 400MW is found to mostly satisfy the goal of the lowest operation cost after several simulations. Exceeding 400MW will lead to a rising operation cost. Impacts on operation costs of different trade amounts can be found in Figure 5.3.

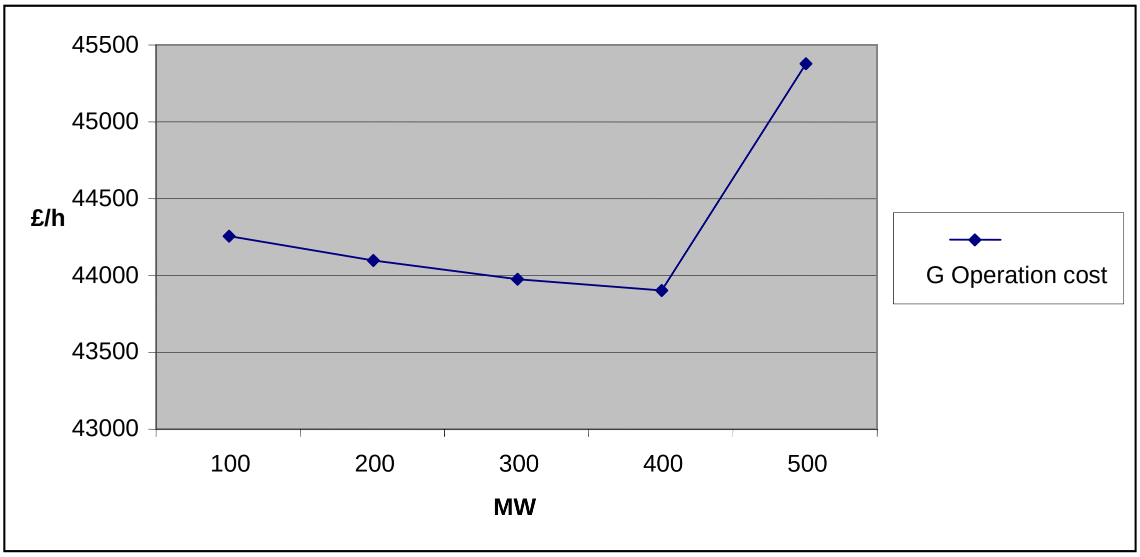

Figure 5.3: Trend of operation costs of different trades

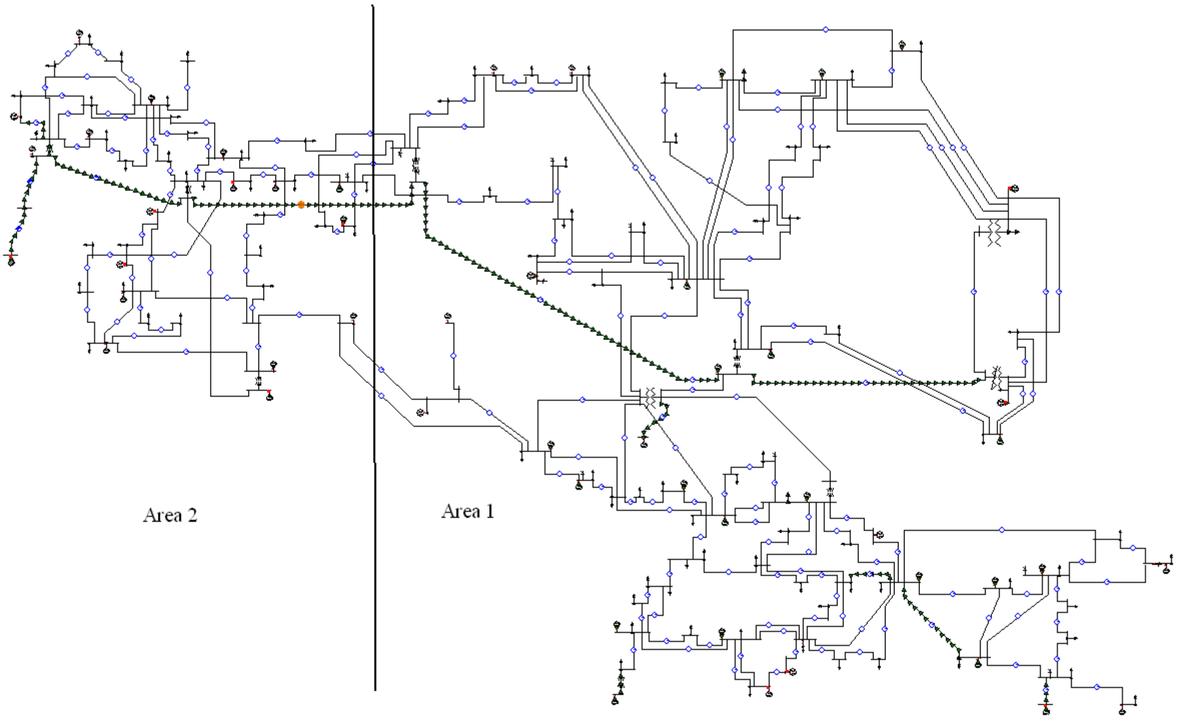

Figure 5.4: 400MW trading between two areas

Consequently, 400MW trading is set between two areas and operation costs of both area are £25492/h in Area 1 and £18405/h in Area 2 respectively after trading. Nodal prices after cross-border trading are shown in the table below by applying first steps of the proposed method. The loss component is ignored in this table because this network is a lossless system.

Bus	Area	Nodal price (£/MWh)	Energy cost component (£/MWh)	Congestion cost component (£/MWh)
1	2	11.47	11.78	-0.31
2	2	11.47	11.78	-0.31
3	2	11.47	11.78	-0.31
4	2	11.46	11.78	-0.32
5	2	11.46	11.78	-0.32
6	2	11.47	11.78	-0.31
7	2	11.47	11.78	-0.31
8	2	11.45	11.78	-0.33
9	2	11.45	11.78	-0.33

10	2	11.45	11.78	-0.33
11	2	11.47	11.78	-0.31
12	2	11.47	11.78	-0.31
13	2	11.49	11.78	-0.3
14	2	11.49	11.78	-0.29
15	2	11.53	11.78	-0.25
16	2	11.48	11.78	-0.3
17	2	11.49	11.78	-0.3
18	2	11.52	11.78	-0.27
19	2	11.55	11.78	-0.24
20	2	11.55	11.78	-0.24
21	2	11.54	11.78	-0.24
22	2	11.54	11.78	-0.24
23	2	11.54	11.78	-0.25
24	2	11.57	11.78	-0.21
25	2	11.5	11.78	-0.29
26	2	11.48	11.78	-0.31
27	2	11.5	11.78	-0.28
28	2	11.5	11.78	-0.28
29	2	11.5	11.78	-0.28
30	2	11.43	11.78	-0.36
31	2	11.5	11.78	-0.29
32	2	11.51	11.78	-0.28
33	2	11.66	11.78	-0.12
34	2	11.8	11.78	0.02
35	2	11.8	11.78	0.02
36	2	11.8	11.78	0.02
37	1	12.08	12.05	0.02
38	1	12.15	12.05	0.1
39	1	12.08	12.05	0.03
40	1	12.08	12.05	0.02
41	1	12.07	12.05	0.02
42	1	12.07	12.05	0.02
43	1	12.07	12.05	0.02
44	1	12.07	12.05	0.02
45	1	12.07	12.05	0.02
46	1	12.07	12.05	0.02
47	1	12.07	12.05	0.02
48	1	12.07	12.05	0.02
49	1	12.07	12.05	0.02
50	1	12.07	12.05	0.02
51	1	12.07	12.05	0.02
52	1	12.07	12.05	0.02
53	1	12.07	12.05	0.02
54	1	12.07	12.05	0.02
55	1	12.07	12.05	0.02
56	1	12.07	12.05	0.02
57	1	12.07	12.05	0.02
58	1	12.07	12.05	0.02

59	1	12.07	12.05	0.02
60	1	12.07	12.05	0.02
61	1	12.07	12.05	0.02
62	1	12.07	12.05	0.02
63	1	12.07	12.05	0.02
64	1	12.07	12.05	0.02
65	1	12.08	12.05	0.02
66	1	12.07	12.05	0.02
67	1	12.07	12.05	0.02
68	1	12.07	12.05	0.01
69	1	12.05	12.05	0
70	1	12	12.05	-0.05
71	1	11.99	12.05	-0.06
72	1	11.92	12.05	-0.13
73	1	11.99	12.05	-0.06
74	1	12.02	12.05	-0.03
75	1	12.03	12.05	-0.02
76	1	12.04	12.05	-0.01
77	1	12.05	12.05	0
78	1	12.05	12.05	0
79	1	12.05	12.05	0
80	1	12.05	12.05	0
81	1	12.06	12.05	0.01
82	1	12.05	12.05	0
83	1	12.05	12.05	0
84	1	12.05	12.05	0
85	1	12.05	12.05	0
86	1	12.05	12.05	0
87	1	12.05	12.05	0
88	1	12.05	12.05	0
89	1	12.05	12.05	0
90	1	12.05	12.05	0
91	1	12.05	12.05	0
92	1	12.05	12.05	0
93	1	12.05	12.05	0
94	1	12.05	12.05	0
95	1	12.05	12.05	0
96	1	12.05	12.05	0
97	1	12.05	12.05	0
98	1	12.05	12.05	0
99	1	12.05	12.05	0
100	1	12.05	12.05	0
101	1	12.05	12.05	0
102	1	12.05	12.05	0
103	1	12.05	12.05	0
104	1	12.05	12.05	0
105	1	12.05	12.05	0
106	1	12.05	12.05	0
107	1	12.05	12.05	0

108	1	12.05	12.05	0
109	1	12.05	12.05	0
110	1	12.05	12.05	0
111	1	12.05	12.05	0
112	1	12.05	12.05	0
113	2	11.49	11.78	-0.29
114	2	11.51	11.78	-0.28
115	2	11.51	11.78	-0.28
116	1	12.07	12.05	0.01
117	2	11.47	11.78	-0.31
118	1	12.03	12.05	-0.02

Table 5.5: Nodal prices after 400MW trading

	Area 1	Area 2
Average Price	£12.06/MWh	£11.52/MWh

Table 5.6: Averages nodal prices after 400MW trading

By comparing Table 5.3 with Table 5.6, nodal prices in Area 1 generally decrease from £12.95/h to £12.06/h and nodal prices are raised by £0.52/h from £11/h in Area 2.

Calculate wheeling charges by following the calculation steps in the last chapter. Inter-payments between two areas are presented in Table 5.7.

	Payment to transmission owner in Area 1	Payment to transmission owner in Area 2
Payment from generators in Area 1	£6594.476/h	0
Payment form generators in Area 2	£2341.299/h	£3633.525/h

Table 5.7: Wheeling charges after 400MW trading

Consequently, by comparing Table 5.7 with Table 5.4, changes of wheeling charges for both areas owing to 400MW trading are shown in Table 5.8.

	Difference of payment to transmission owner in Area 1	Difference of payment to transmission owner in Area 2
Payment from generators in Area 1	-£2086.324/h	0
Payment from generators in Area 2	£2341.299/h	£306.025/h

Table 5.8: Differences of wheeling charges after 400MW trading

From Table 5.8, generators in Area 2 are paying £2341.299/h to the transmission owner of Area 1. On the other side, the transmission owner of Area 1 loses £2086.324/h profit from local generators and the transmission owner of Area 2 gains additional £306.025/h profit after 400MW trading. Those changes are due to Area 2 exporting energy to Area 1. As generators are supposed to pay all wheeling charges during trading, those generators in Area 2 which export additional energy to Area 1 are required to pay their usage in both areas. This is the reason why generators of Area 2 are paying more wheeling charges after trading. On the contrary, generators in Area 1 decrease their outputs due to imported 400MW so that their payments for wheeling services are reduced. Although generators of Area 2 pay more wheeling charges than what they used to pay, they still gain benefits from higher nodal prices.

Additionally, payments of loads for energy supplies are also changed after 400MW trading. This is also a consequence of 400MW trading which is worth analysing. Table 5.9(a) shows changes of load payments in Area 1 meanwhile similar changes in Area 2 are presented in Table 5.9(b).

Trading amount	Demand×Price	Load payment for energy
0MW	2611MW×£12.95/h	£33812.45/h
400MW	2611MW×£12.06/h	£31488.66/h
Load payment changes		£-2323.79/h

Table 5. 9(a): Comparison of load payment in Area 1

Trading amount	Demand×Price	Load payment
0MW	1057MW×£11/h	£11627/h
400MW	1057MW×£11.52/h	£12176.64/h
Load payment changes		£549.64/h

Table.5.9(b). Comparison of load payment in Area 2

Obviously loads in Area 1 save £2323.79/h from trading and loads in Area 2 pay £549.64/h more after trading. For the purpose of discovering how this 400MW trading influences each area, both changes on wheeling charges and load payments are supposed to be taken into account.

$$Payments\ change = Wheeling\ charges\ change + Load\ payments\ change$$

To sum up,

$$\begin{aligned} &Payments\ change\ in\ Area\ 1 \\ &\qquad = Wheeling\ charges\ change\ in\ Area\ 1 \\ &\qquad + load\ payments\ change\ in\ Area\ 1 \\ &\qquad = £-2086.423/h + £-2323.78/h = £-4410.114/h \end{aligned}$$

In the meantime,

$$\begin{aligned} &Payments\ change\ in\ Area\ 2\\ &\qquad = Wheeling\ charges\ change\ in\ Area\ 2\\ &\qquad + load\ payments\ change\ in\ Area\ 2\\ &\qquad = (£2341.299/h + £306.025/h) + £549.64/h\\ &\qquad = £2647.324/h + £549.63/h = £3176.964/h \end{aligned}$$

Two equations above indicate that participants in Area 1 pay £4410.114/h less after trading. In other words, they save £4410.114/h in total due to import 400MW from Area 2. At the same time, payments from participants in Area 2 increase £3176.964/h after trading.

Obviously, if participants in Area 2 lose benefits from 400MW trading, they could not have incentives to complete this transaction. Furthermore, this is a general issue when trading electricity energy from a low price area to a high price area. To solve this issue, in this case, participants in Area 1 could use its monetary saving to compensate losses of participants in Area 2 and remaining savings could be considered as social benefits of Area 1 from 400MW trading. In this case, participants in Area 1 need to compensate £3176.946/h to Area 2, which includes £2647.324/h for compensating wheeling losses and £549.64/h for compensating load payment losses respectively. As a result, load consumers in Area 2 still pay for electricity supply at £11/MWh after compensation from participants in Area 1 but generators in Area 2 sell their product at £11.52/MWh when wheeling charges they need to pay keep the same as what they used to pay. The difference between savings of Area 1 and its compensation, which is £1233.15/h, is the social benefits in Area 1. This process could be called the compensation stage after allocation of wheeling charges and could be operated by the ISO in Area 1.

In conclusion, trading 400MW from Area 2 to Area 1 can offer optimal social welfares. It provides monetary savings on wheeling charges and load payments in Area 1. However, it also leads to negative issues in Area 2. Generators in Area 2 pay more wheeling charges as they inject more energy into the system. At the same time nodal prices become higher with respect to more electricity production in this area, which causes loads pay more for their ordinary demands. Those issues can be resolved by using the saving of Area 1 to compensate losses in Area 2. At the end, Area 1 earns £1233.15/h social benefits, loads in Area 2 are not affected and generators in Area 2 gain more profits for selling energy to Area 1.

5.2.3 Impact of bilateral contract

The above case has indicated allocation of cross-border trading between two areas besides arising issues due to this trading and proper solutions have been given after analysing those issues. However this case mainly discusses cross-border trading on the ISO level, which seeks optimal social benefits. It is allowed to perform bilateral contracts in deregulated electricity markets. As a result this type of trading will be discussed in this section. The analysis includes impacts of bilateral contracts and issues introduced by them.

In this case, a bilateral contract across two areas will be added onto cross-border trading based on the 400MW trading in the last section. Consider that L_{73} in Area 1 needs an additional 20MW after 400MW trading between two areas and it wishes to choose a supplier from Area 1 because of the lower price. Finally G_{25} is chosen as the supplier due to the shortest distance from the load. Consequently the generation operation cost in Area 1 is unchanged and generation cost in Area 2 increases to £18635/h from £18405/h which is presented in last section. According to the last case, nodal prices are calculated first.

Bus	Area	Nodal prices (£/MWh)	Energy cost component (£/MWh)	Congestion cost component (£/MWh)
1	2	11.47	11.78	-0.31

2	2	11.47	11.78	-0.31
3	2	11.47	11.78	-0.31
4	2	11.46	11.78	-0.32
5	2	11.46	11.78	-0.32
6	2	11.47	11.78	-0.31
7	2	11.47	11.78	-0.31
8	2	11.45	11.78	-0.33
9	2	11.45	11.78	-0.33
10	2	11.45	11.78	-0.33
11	2	11.47	11.78	-0.31
12	2	11.47	11.78	-0.31
13	2	11.49	11.78	-0.3
14	2	11.49	11.78	-0.29
15	2	11.53	11.78	-0.25
16	2	11.48	11.78	-0.3
17	2	11.49	11.78	-0.3
18	2	11.52	11.78	-0.27
19	2	11.55	11.78	-0.24
20	2	11.55	11.78	-0.24
21	2	11.54	11.78	-0.24
22	2	11.54	11.78	-0.24
23	2	11.54	11.78	-0.25
24	2	11.57	11.78	-0.21
25	2	11.5	11.78	-0.29
26	2	11.48	11.78	-0.31
27	2	11.5	11.78	-0.28
28	2	11.5	11.78	-0.28
29	2	11.5	11.78	-0.28
30	2	11.43	11.78	-0.36
31	2	11.5	11.78	-0.29
32	2	11.51	11.78	-0.28
33	2	11.66	11.78	-0.12
34	2	11.8	11.78	0.02
35	2	11.8	11.78	0.02
36	2	11.8	11.78	0.02
37	1	12.08	12.05	0.02
38	1	12.15	12.05	0.1
39	1	12.08	12.05	0.03
40	1	12.08	12.05	0.02
41	1	12.07	12.05	0.02
42	1	12.07	12.05	0.02
43	1	12.07	12.05	0.02
44	1	12.07	12.05	0.02
45	1	12.07	12.05	0.02
46	1	12.07	12.05	0.02
47	1	12.07	12.05	0.02
48	1	12.07	12.05	0.02
49	1	12.07	12.05	0.02
50	1	12.07	12.05	0.02

51	1	12.07	12.05	0.02
52	1	12.07	12.05	0.02
53	1	12.07	12.05	0.02
54	1	12.07	12.05	0.02
55	1	12.07	12.05	0.02
56	1	12.07	12.05	0.02
57	1	12.07	12.05	0.02
58	1	12.07	12.05	0.02
59	1	12.07	12.05	0.02
60	1	12.07	12.05	0.02
61	1	12.07	12.05	0.02
62	1	12.07	12.05	0.02
63	1	12.07	12.05	0.02
64	1	12.07	12.05	0.02
65	1	12.08	12.05	0.02
66	1	12.07	12.05	0.02
67	1	12.07	12.05	0.02
68	1	12.07	12.05	0.01
69	1	12.05	12.05	0
70	1	12	12.05	-0.05
71	1	11.99	12.05	-0.06
72	1	11.92	12.05	-0.13
73	1	11.99	12.05	-0.06
74	1	12.02	12.05	-0.03
75	1	12.03	12.05	-0.02
76	1	12.04	12.05	-0.01
77	1	12.05	12.05	0
78	1	12.05	12.05	0
79	1	12.05	12.05	0
80	1	12.05	12.05	0
81	1	12.06	12.05	0.01
82	1	12.05	12.05	0
83	1	12.05	12.05	0
84	1	12.05	12.05	0
85	1	12.05	12.05	0
86	1	12.05	12.05	0
87	1	12.05	12.05	0
88	1	12.05	12.05	0
89	1	12.05	12.05	0
90	1	12.05	12.05	0
91	1	12.05	12.05	0
92	1	12.05	12.05	0
93	1	12.05	12.05	0
94	1	12.05	12.05	0
95	1	12.05	12.05	0
96	1	12.05	12.05	0
97	1	12.05	12.05	0
98	1	12.05	12.05	0
99	1	12.05	12.05	0

100	1	12.05	12.05	0
101	1	12.05	12.05	0
102	1	12.05	12.05	0
103	1	12.05	12.05	0
104	1	12.05	12.05	0
105	1	12.05	12.05	0
106	1	12.05	12.05	0
107	1	12.05	12.05	0
108	1	12.05	12.05	0
109	1	12.05	12.05	0
110	1	12.05	12.05	0
111	1	12.05	12.05	0
112	1	12.05	12.05	0
113	2	11.49	11.78	-0.29
114	2	11.51	11.78	-0.28
115	2	11.51	11.78	-0.28
116	1	12.07	12.05	0.01
117	2	11.47	11.78	-0.31
118	1	12.03	12.05	-0.02

Table 5.10: Nodal prices after adding a 20MW bilateral contract

	Area 1	Area 2
Average Price	£11.65/h	£11.52/h

Table 5.11: Average nodal prices after adding a 20MW bilateral contract

By applying the proposed method, inter-payments between two areas are known by participants and ISOs. The compensation stage can be repeated by following the instructions in section 5.2.2. As a result, those results will be not presented here owing to similar calculation processes. In this section, the main aim is to discuss impacts of the bilateral contract. Because the bilateral contract is injected into the system from G_{25} and generators are supposed to pay for transmission services, total wheeling charges related to G_{25} are shown in the table below.

G	From bus	From Area	To bus	To Area	Power flow on line (MW)	Wheeling charge (£/h)
25	22	2	21	2	1.5449	1.5449
25	23	2	22	2	7.2667	7.2667
25	23	2	24	2	41.998	43.25794
25	24	2	70	1	14.934	29.71866
25	24	2	72	1	19.626	39.05574
25	25	2	23	2	53.27	55.4008
25	25	2	27	2	30.73	30.73
25	27	2	115	2	1.3649	1.378549
25	47	1	49	1	0.059799	0.119598
25	49	1	42	1	0.088361	0.176722
25	49	1	45	1	0.014094	0.028188
25	49	1	48	1	0.006867	0.013733
25	49	1	50	1	0.045897	0.091794
25	49	1	51	1	0.058727	0.117454
25	49	1	54	1	0.04915	0.0983
25	50	1	57	1	0.015179	0.030358
25	51	1	52	1	0.030683	0.061366
25	52	1	53	1	0.00099	0.00198
25	54	1	53	1	0.007825	0.01565
25	54	1	59	1	0.001851	0.003703
25	68	1	116	1	1.6074	3.2148
25	69	1	47	1	0.3931	0.7862
25	69	1	49	1	0.3605	0.721
25	69	1	68	1	1.6069	3.2138
25	69	1	75	1	0.051774	0.103548
25	69	1	77	1	0.34708	0.69416
25	70	1	69	1	2.7594	5.5188
25	70	1	71	1	0.43819	0.87638
25	70	1	74	1	1.2672	2.5344
25	70	1	75	1	2.6528	5.3056
25	71	1	73	1	13.198	26.396
25	72	1	71	1	12.76	25.52
25	74	1	75	1	0.48879	0.97758
25	75	1	77	1	0.33962	0.67924
25	75	1	118	1	0.63679	1.27358
25	77	1	78	1	0.40343	0.80686
25	77	1	80	1	0.004569	0.009138
25	78	1	79	1	0.079041	0.158082
25	80	1	79	1	0.000577	0.001154
25	80	1	81	1	0.000518	0.001037
25	80	1	97	1	1.86E-05	3.72E-05
25	81	1	68	1	0.000518	0.001037

Table 5.12: Power flow and wheeling charges related to G_{25}

An issue has been found that not all of additional 20MW from G_{25} flows to L_{73} because of loop flow. This conclusion can be also proved by results of tracing power flows from loads to generation. Figure 5.5 indicates differences of MW contributions of G_{25} on different loads before and after adding 20MW bilateral contract. It is clearly observed that parts of additional 20MW of G_{25} flows to other loads rather than $L_{73.}$ This phenomenon of loop flow has been discussed in the duration of introducing Contract Path method in Chapter 3 and the solution is to set up predefined paths to charge wheeling services. In this case, predefined paths obviously violate proportional theory of the tracing method. As a consequence, a new approach has to be implemented to address the loop flow problem with respect to bilateral contracts in the proposed method.

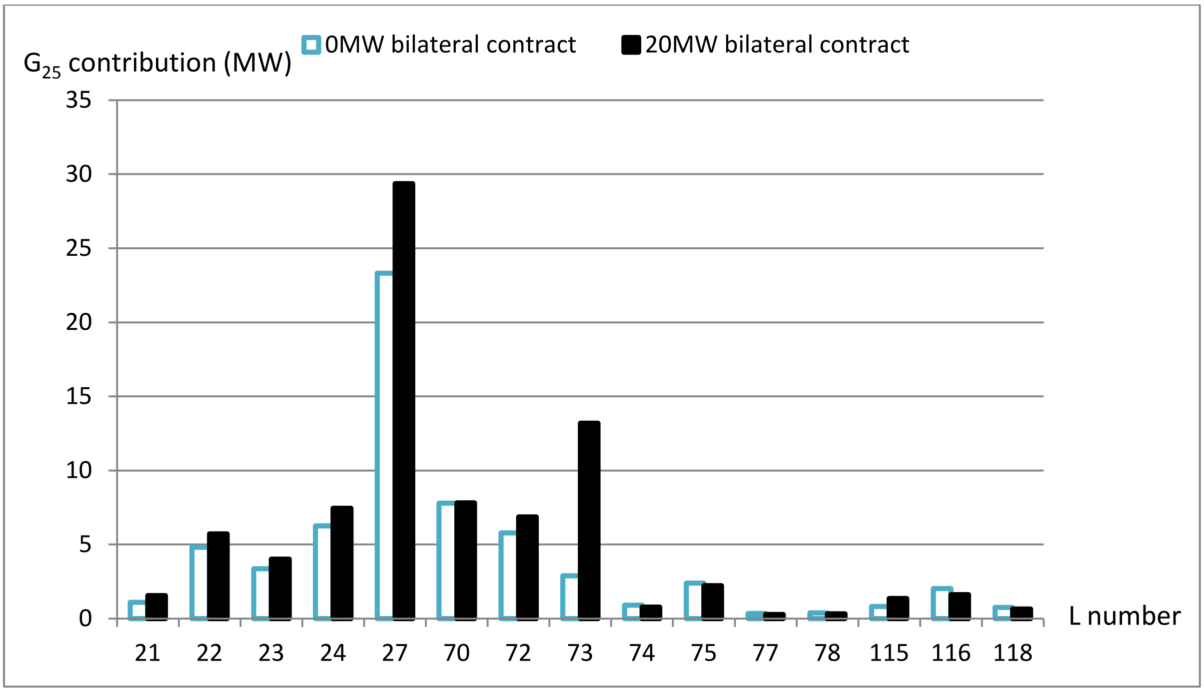

Figure 5.5: Differences of MW contributions from G_{25} before and after adding 20MW bilateral contract

Because of loop flow theory, a bilateral contract in a complicated system is most unlikely to fulfil its duty completely. For this reason, contractual electrical energy is always assumed to be 100% transported between sources and sinks in practice. In this case this assumption continues to be used and all additional wheeling charges due to G_{25} on any lines are counted for wheeling charges paid for the bilateral contract between G_{25} and L_{73}. Table 5.14 presents results of differences of wheeling charges due to G_{25} on transmission lines before and after 20MW bilateral trading.

From Bus	From Area	To Bus	To Area	Charges before 20MW trading (£/h)	Charges after 20MW trading (£/h)	Difference (£/h)
22	2	21	2	1.1074	1.5449	0.4375
23	2	22	2	5.9222	7.2667	1.3445
23	2	24	2	31.49122	43.25794	11.76672
24	2	70	1	20.44449	29.71866	9.27417
24	2	72	1	25.3857	39.05574	13.67004
25	2	23	2	41.46064	55.4008	13.94016
25	2	27	2	24.134	30.73	6.596
27	2	115	2	0.829079	1.378549	0.54947
47	1	49	1	0.16375	0.119598	-0.04415
49	1	42	1	0.23108	0.176722	-0.05436
49	1	45	1	0.03806	0.028188	-0.00987
49	1	48	1	0.01767	0.013733	-0.00394
49	1	50	1	0.11463	0.091794	-0.02284
49	1	51	1	0.1468	0.117454	-0.02935
49	1	54	1	0.122334	0.0983	-0.02403
50	1	57	1	0.037606	0.030358	-0.00725
51	1	52	1	0.076698	0.061366	-0.01533
52	1	53	1	0.002474	0.00198	-0.00049
54	1	53	1	0.01949	0.01565	-0.00384
54	1	59	1	-0.2932	0.003703	0.296898
68	1	116	1	4.0336	3.2148	-0.8188
69	1	47	1	0.991256	0.7862	-0.20506
69	1	49	1	0.901	0.721	-0.18
69	1	68	1	4.0296	3.2138	-0.8158
69	1	75	1	0.018111	0.103548	0.085437
69	1	77	1	0.82404	0.69416	-0.12988
70	1	69	1	6.7552	5.5188	-1.2364
70	1	71	1	3.0234	0.87638	-2.14702
70	1	74	1	5.92883	2.5344	-3.39443
70	1	75	1	10.12379	5.3056	-4.81819
71	1	73	1	5.7778	26.396	20.6182
72	1	71	1	15.8888	25.52	9.6312
74	1	75	1	1.20076	0.97758	-0.22318
75	1	77	1	0.8756	0.67924	-0.19636
75	1	118	1	1.4865	1.27358	-0.21292

77	1	78	1	0.98792	0.80686	-0.18106
77	1	80	1	0.0323	0.009138	-0.02316
78	1	79	1	0.19714	0.158082	-0.03906
80	1	79	1	0.003956	0.001154	-0.0028
80	1	81	1	0.004086	0.001037	-0.00305
80	1	97	1	0.000111	3.72E-05	-7.4E-05
81	1	68	1	0.004086	0.001037	-0.00305

Table 5.13: Differences of wheeling charges of G_{25} before and after bilateral trading

According to the assumption in last paragraph, the total wheeling charge for 20MW bilateral trading is the algebraic sum of values in the last column of Table 5.13, which is £73.364/h. Furthermore, the allocation of wheeling charges for two areas can follow processes of allocation which creates Table 4.7 in Section 4.3.1. Consequently, wheeling charges of the 20MW bilateral contract for each transmission owner, which is paid by G_{25}, can be allocated and shown in Table 5.14.

Payment from G	Payment to transmission owner in Area 1	Payment to transmission owner in Area 2
25	£27.258/h	£46.106/h

Table 5.14: Wheeling charges for each area from 20MW bilateral contract

To sum up, the proposed method cannot avoid effects of loop flows when allocating wheeling charges of bilateral contracts. However, unlike Contract Path method to set up a predefined path (usually the shortest path between seller and buyer), the proposed method uses the real impacts of traded energy to charge wheeling services. In other words, it is considered as a more transparent and more precise method for allocating wheeling charges for bilateral contracts.

5.3 Cross-border trading among three areas

The last section discussed issues of cross-border trading between two areas. In practice, there likely would be another type of cross-border trading which an area carries external cross-border trading for others. In other words, energy traded between two sides is across the transmission network of a third-area to fulfil the contract. This section will discuss cross-border trading among multi-areas. The IEEE 118 system is used to illustrate this issue and is split into three areas. There are also assumptions for the three area system.

- Transmission capacity constraints are also neglected.
- The losses are ignored in this system.
- All the voltages are at the same level.
- The ownerships are split into 5:5 if transmission lines are crossing borders.
- Negative outputs of generators in default database are considered as loads.
- If there are more than one line between two nodes, they will be replaced by one line which carries all flows between two nodes.
- The long-term charging rate is set to £1/MWh for all areas.
- Generators pay 100% of wheeling charges.

By comparing to assumptions made in Section 5.2, transmission capacity limits are ignored in this case and the fixed transmission rate is set to £1/MWh for all transmission lines for simplifying analysis steps. The Figure 5.3 presents the modified IEEE 118 bus system.

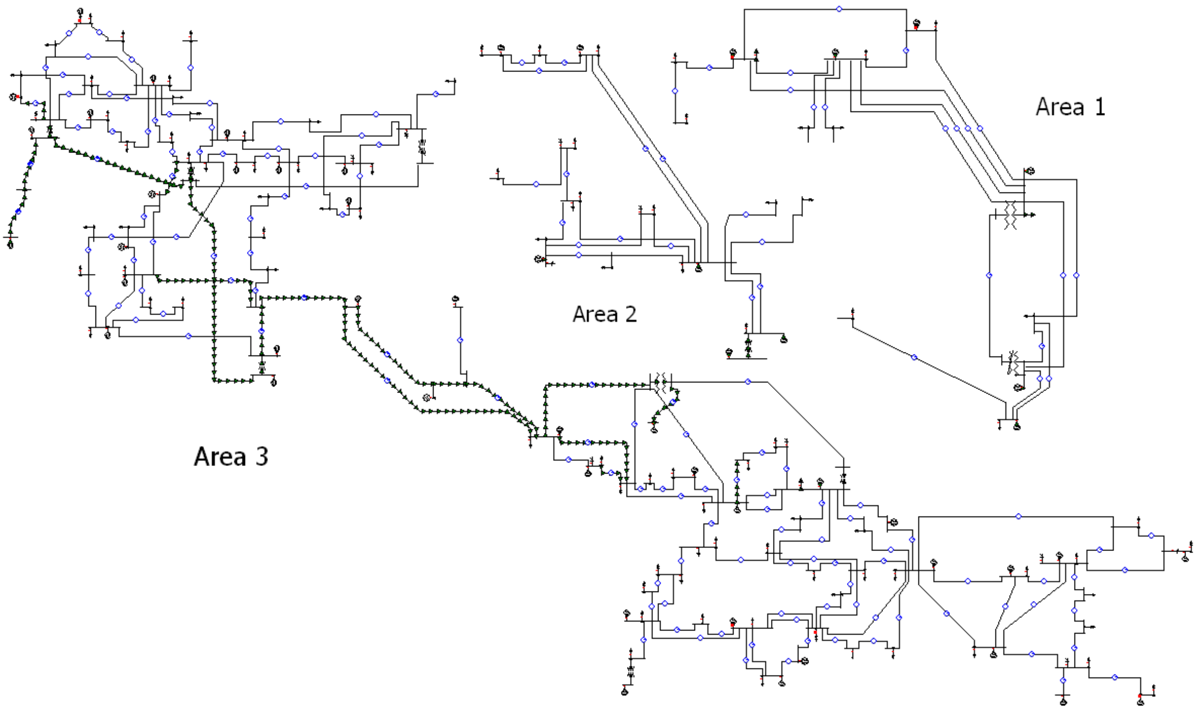

Figure 5.6: IEEE 118 system split into three areas

Buses included by each area are shown in the following:

- Area 1: Bus 52 to Bus 64, Bus 67
- Area 2: Bus 40 to Bus 51, Bus 65, Bus 66
- Area 3: Bus 1 to Bus 39, Bus 68 to Bus118

Furthermore, because of ignoring transmission capacity limits, all nodal prices in an area are the same. Other data in this system are presented in the following.

	Area 1	Area 2	Area 3
Nodal price	£13.57/MWh	£12.95/MWh	£11.8/MWh

Table 5.15: Nodal prices in three-area system

	Total Generation	Total Load
Area 1	785MW	785MW
Area 2	423MW	423MW
Aera 3	2460MW	2460MW

Table 5.16: Total generation and total load in three-area system respectively

	Payment to transmission owner in Area 1	Payment to transmission owner in Area 2	Payment to transmission owner in Area 3
Payment from generators in Area 1	£612.5/h	0	0
Payment from generators in Area 2	0	£796.5/h	0
Payment from generators in Area 3	0	0	£7971.7/h

Table 5.17: Wheeling charges in three-area system before trading

It is clearly observed that Area 3 has the lowest price for energy consuming and loads in Area 1 are paying the highest price to use electricity. For the aim of testing impacts of cross-border trading across an neighbouring transmission network, it is considerable to establish a cross-border trading from Area 3 to Area 1 for the optimal operation like the last case. A 200MW trading is considered as the optimal option to trade after studying the changing trend of generation operation costs in all three areas. Figure 5.7 shows the power flow after trading.

Connect three areas and trade 200MW like the last section. Once this trading is completed, results of nodal prices and wheeling charges can be calculated by the proposed method. Prices after trading are shown in Table 5.18. Furthermore, according to the proposed method and the calculation process in Chapter 4, inter-payments for wheeling charges among three areas are shown in Table 5.19. Because the compensation stage for participants in Area 3 can be repeated by following the same calculation steps in Section 5.2.2, benefits of each area after compensation will not be presented here.

	Area 1	Area 2	Area 3
Nodal prices	£11.8/MWh	£12.95/MWh	£11.8/MWh

Table 5.18: Nodal prices after 200MW trading

	Payment to transmission owner in Area 1	Payment to transmission owner in Area 2	Payment to transmission owner in Area 3
Payment from generators in Area 1	£246.411/h	£1.656/h	0
Payment from generators in Area 2	£118.762/h	£280.727/h	£122.196/h
Payment from generators in Area 3	£90.159/h	£598.42/h	£6285.619/h

Table 5.19: Wheeling charges after 200MW trading

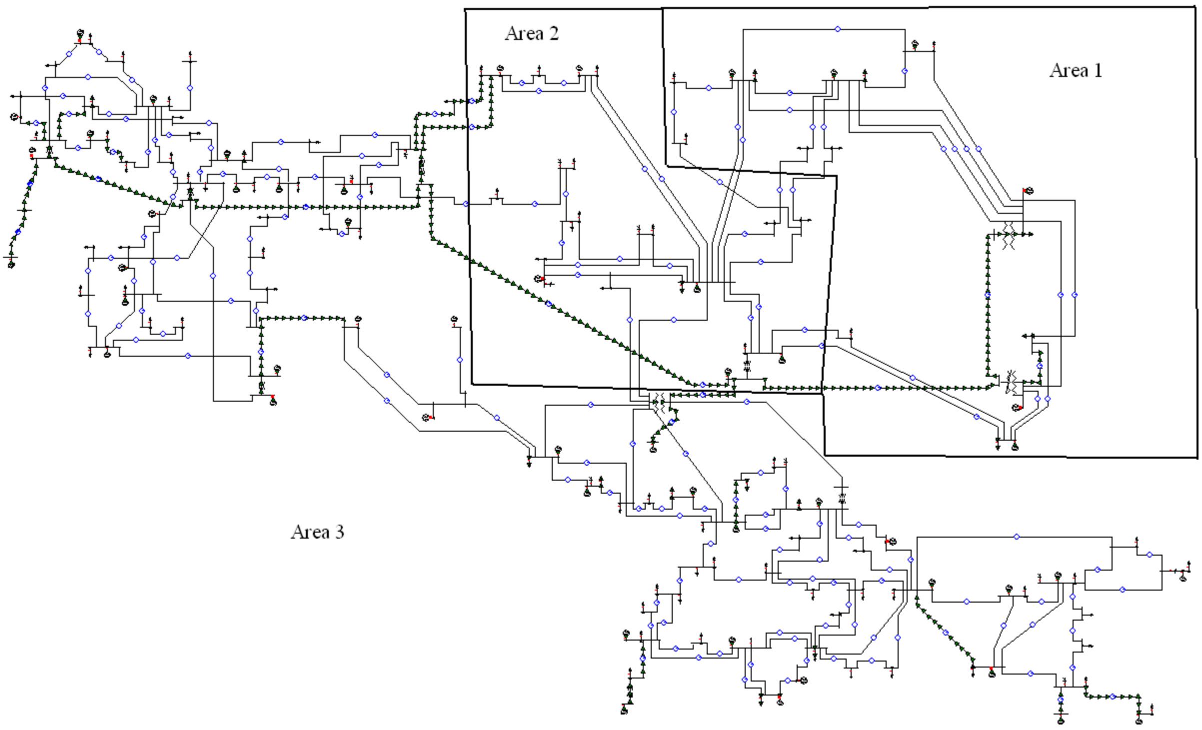

Figure 5. 7: Cross-border trading from Area 3 to Area 1

It is noticed that generators in Area 2 pay wheeling charges to Area 1 and Area 3 respectively. However, there is supposed to be no energy exports from Area 2 because cross-border trading only exists between Area 1 and Area 3. The reason for this phenomenon is due to the loop flow generated during the transaction which causes inter-change flows between two areas. Table 5.20 indicates the loop flow between Area 2 and other areas.

	To Area 1	To Area 2	To Area 3
From Area 1	0	1.6MW	0
From Area 2	201.6MW	0	173.203MW
From Area 3	0	373.203MW	0

Table 5.20: Inter-changes between Area 2 and other areas

It can be seen from Table 5.20 that the inter-change flow between any two areas is not 200MW due to loop flow. For instance, Table 5.21 and Table 5.22 point out all results of traced power flows which are across between Area 2 and Area 1. 201.6MW flows from Area 2 to Area 1 whilst Area 1 exports 1.6MW to Area 2. However, the net inter-change of them is 200MW, which is the traded amount. From the similar calculation, the inter-change between Area 3 and Area 2 is also 200MW. As a result, loop flow causes that the inter-change between Area 2 and other areas is not exactly 200MW but it does not influence the traded amount of energy between Area 1 and Area 3. Consequently, by looking at total inter-changes among three areas, 200MW has been transported from Area 3 to Area 1 and this is the exact traded amount. This does not correspond to the proposed trading between Area 1 and Area 3, but the aim of cross-border trading is fulfilled.

G	G Area	From Bus	From Area	To Bus	To Area	Power Flow on line (MW)
1	3	49	2	54	1	4.01E-06
6	3	49	2	54	1	7.14E-05
10	3	49	2	54	1	1.8156
12	3	49	2	54	1	0.0001652
25	3	49	2	54	1	0.064389
26	3	49	2	54	1	0.17553
31	3	49	2	54	1	0.0020682
32	3	49	2	54	1	0.015782
46	2	49	2	54	1	1.4814
49	2	49	2	54	1	17.735
65	2	49	2	54	1	2.4873
66	2	49	2	54	1	7.6942
69	3	49	2	54	1	1.728
70	3	49	2	54	1	0.30029
1	3	50	2	57	1	1.23E-06
6	3	50	2	57	1	2.20E-05
10	3	50	2	57	1	0.55822
12	3	50	2	57	1	5.08E-05
25	3	50	2	57	1	0.019797
26	3	50	2	57	1	0.053968
31	3	50	2	57	1	0.0006359
32	3	50	2	57	1	0.0048525

46	2	50	2	57	1	0.45549
49	2	50	2	57	1	5.4529
65	2	50	2	57	1	0.76477
66	2	50	2	57	1	2.3657
69	3	50	2	57	1	0.53129
70	3	50	2	57	1	0.092329
1	3	51	2	52	1	2.22E-06
6	3	51	2	52	1	3.95E-05
10	3	51	2	52	1	1.0052
12	3	51	2	52	1	9.15E-05
25	3	51	2	52	1	0.035649
26	3	51	2	52	1	0.097179
31	3	51	2	52	1	0.0011451
32	3	51	2	52	1	0.0087378
46	2	51	2	52	1	0.8202
49	2	51	2	52	1	9.819
55	1	51	2	52	1	0.16283
56	1	51	2	52	1	0.68995
65	2	51	2	52	1	1.38E+00
66	2	51	2	52	1	4.2599
69	3	51	2	52	1	0.9567
70	3	51	2	52	1	0.16626
10	3	65	2	64	1	43.43
26	3	65	2	64	1	2.6105
65	2	65	2	64	1	59.56
10	3	66	2	62	1	1.3186
26	3	66	2	62	1	0.079258
65	2	66	2	62	1	1.81E+00
66	2	66	2	62	1	5.5938
10	3	66	2	67	1	3.6112
26	3	66	2	67	1	0.21706
65	2	66	2	67	1	4.9524
66	2	66	2	67	1	15.319
Inter-change flow						201.6

Table 5. 21: Power flow results from Area 2 to Area 1

G	G Area	From Bus	From Area	To Bus	To Area	Power Flow on line (MW)
55	1	58	1	51	2	0.3055
56	1	58	1	51	2	1.2945
Inter-change flow						1.6

Table 5.22: Power flow from Area 1 to Area 2

Although loop flows do not affect the aim of cross-border trading, it causes participants in Area 2, who are irrelevant to cross-border trading between Area 1 and Area 3, to change the way they use wheeling services. Most particularly, they have to pay charges to external transmission owners for wheeling services. Table 5.23 shows generators in Area 2 which use external transmission paths. In addition, by calculating from Table 5.19, generators in Table 5.23 pay £118.762/h to Area 1 and £122.196/h to Area 3 respectively.

G	G Area	From	From Area	To	To Area	Flow (MW)
46	2	49	2	54	1	1.4814
49	2	49	2	54	1	17.735
65	2	49	2	54	1	2.4873
66	2	49	2	54	1	7.6942
46	2	50	2	57	1	0.45549
49	2	50	2	57	1	5.4529
65	2	50	2	57	1	0.76477
66	2	50	2	57	1	2.3657
46	2	51	2	52	1	0.8202
49	2	51	2	52	1	9.819
65	2	51	2	52	1	1.38E+00
66	2	51	2	52	1	4.2599
46	2	52	1	53	1	0.05919
49	2	52	1	53	1	0.70859
65	2	52	1	53	1	0.099379
66	2	52	1	53	1	0.30742
46	2	54	1	53	1	0.2302
49	2	54	1	53	1	2.7559
65	2	54	1	53	1	3.87E-01
66	2	54	1	53	1	1.20E+00
46	2	54	1	59	1	4.80E-02
49	2	54	1	59	1	5.74E-01
65	2	54	1	59	1	0.080523
66	2	54	1	59	1	0.24909
65	2	60	1	59	1	1.5833
66	2	60	1	59	1	0.27186
65	2	61	1	59	1	2.2976
65	2	61	1	60	1	5.94E+00
65	2	61	1	62	1	0.09837
65	2	62	1	60	1	0.36993
66	2	62	1	60	1	1.0852
65	2	62	1	67	1	7.40E-02

66	2	62	1	67	1	0.21703
65	2	63	1	59	1	51.212
65	2	64	1	61	1	8.3474
65	2	64	1	63	1	51.212
65	2	65	2	64	1	59.56
65	2	65	2	68	3	9.76E+01
65	2	66	2	62	1	1.81E+00
66	2	66	2	62	1	5.5938
65	2	66	2	67	1	4.9524
66	2	66	2	67	1	15.319
65	2	68	3	81	3	2.33E+01
65	2	68	3	116	3	74.356
65	2	80	3	79	3	2.1379
65	2	80	3	96	3	1.4571
65	2	80	3	97	3	2.3409
65	2	80	3	98	3	1.4571
65	2	80	3	99	3	0.3583
65	2	81	3	80	3	23.277
65	2	96	3	95	3	0.30764
65	2	97	3	96	3	0.5494

Table 5.23: Generators in Area 2 using other networks

On the contrary, the transmission owner of Area 2 receives payments from generators located in Area 1 and Area 3 due to cross-border trading. Those payments, which are shown in Table 5.19, are £1.656/h from Area 1 and £598.42/h from Area 3 respectively. In addition, the last component of payment received by transmission owner of Area 2 is £280.727/h from local usages. By comparing to £796.5/h of wheeling charges before cross-border trading, all of which are charged for local usage, the transmission owner of Area 2 receives £600.076/h from transporting cross-border trading and £280.727/h from local usage. The total benefit is increased by £84.303/h after carrying power flows from cross-border trading.

$$\begin{aligned}
&Increased\ benefit\ in\ Area\ 2 \\
&\qquad = Wheeling\ charge\ after\ cross\ border\ trading \\
&\qquad - Wheeling\ charge\ before\ cross\ border\ trading \\
&\qquad = (£600.076/h + £280.727/h) - £796.5/h\ = £84.303/h
\end{aligned}$$

In conclusion, the transmission owner of Area 2 can earn profits for transporting cross-border trading between Area 1 and Area 3. Although loop flows cause inter-changes between two areas are different from supposed amount, the final result meets interests of each area.

5.4 Summary

This chapter has discussed three scenarios of cross-border trading. The first scenario is to set up cross-border trading between two areas to test the ability of resolving allocation problems in cross-border trading by the proposed method. In addition a compensation stage is introduced in this section to create a fairer trading mechanism. The second scenario is based on the first scenario by adding a bilateral contract across two areas. Although the allocating process suffers effects of loop flows as the same as Contract Path method, real impacts of bilateral contracts can be detected by the proposed method. As a result, wheeling charges for bilateral contracts are calculated by their impacts on transmission lines. The last scenario is to examine cross-border trading among multi-areas. Especially an irrelevant area carries cross-border trading for other areas. Finally, after the simulation, the transmission owner in the carrier-area can earn profits from providing transporting services for cross-border trading while the contract is completely fulfilled.

Chapter 6 Congestion Management in Cross-Border Trading

6.1 Introduction

Chapter two has introduced the general structure of the current deregulated markets. This modern electrical structure could be usually split into generation, transmission, distribution and supply during deregulation. Then ISOs dispatch generation under market rules. However, no matter what the market structure is, one ISO is always in charge of managing the transmission network in a certain area. In this way, a natural monopolised transmission network supervised by one independent organisation can maximise social benefits. On the other hands, congestion is an unavoidable problem in transmission networks. As a result, ISOs have to manage congestion which is considered a significantly important issue in deregulated markets.

The issue of congestion can be found back in Section 2.2.2 where pricing mechanisms are introduced. In Section 2.2.2, congestion has been proved as a significant factor to raise energy prices regardless of pricing mechanisms. In other words, if congestion does not exist in an electrical system, energy prices could be lower than what they are. Obviously optimal prices in an electricity market can be achieved by eliminating congestion. But this objective is most unlikely to be fulfilled in practice because congestion is usually caused by insufficient capacity on some transmission lines. If the ISO determines to address the issue on insufficient capacity, the transmission owner has to invest significant capitals into this reinforcement. When transmission owners do not have initiatives to reinforce their networks then congestion becomes a common and trouble issue for all market participants. Several solutions for congestion management have been studied. [1] [2] [3] This chapter will provide brief descriptions of the current measures of congestion managements and propose a congestion solution in the environment of cross-border trading which encourages transmission owners to reinforce networks.

In this chapter Section 6.2 presents the cause of congestion and illustrates how it affects energy prices. Section 6.3 explains current major measures of congestion management in the deregulated electricity market. A proposed congestion management is described in Section 6.4. Finally the conclusion is included in Section 6.5.

6.2 Fundamental of congestion

6.2.1 Introduction of congestion

The beginning of this chapter has discussed the importance of congestion in deregulated electricity markets. In this section, congestion will be explained in a diagram accompanied by the calculation process. Figure 6.1 shows a lossless four bus system with two generators and one load. Additionally all lines have equal impedance. The load at Bus 4 demands 100MW. If capacity constraints of transmission lines are ignored in this system, load L_4 will be supplied by generator G_1 with the price of £30/MWh. The allocation of power flows is illustrated in Figure 6.2.

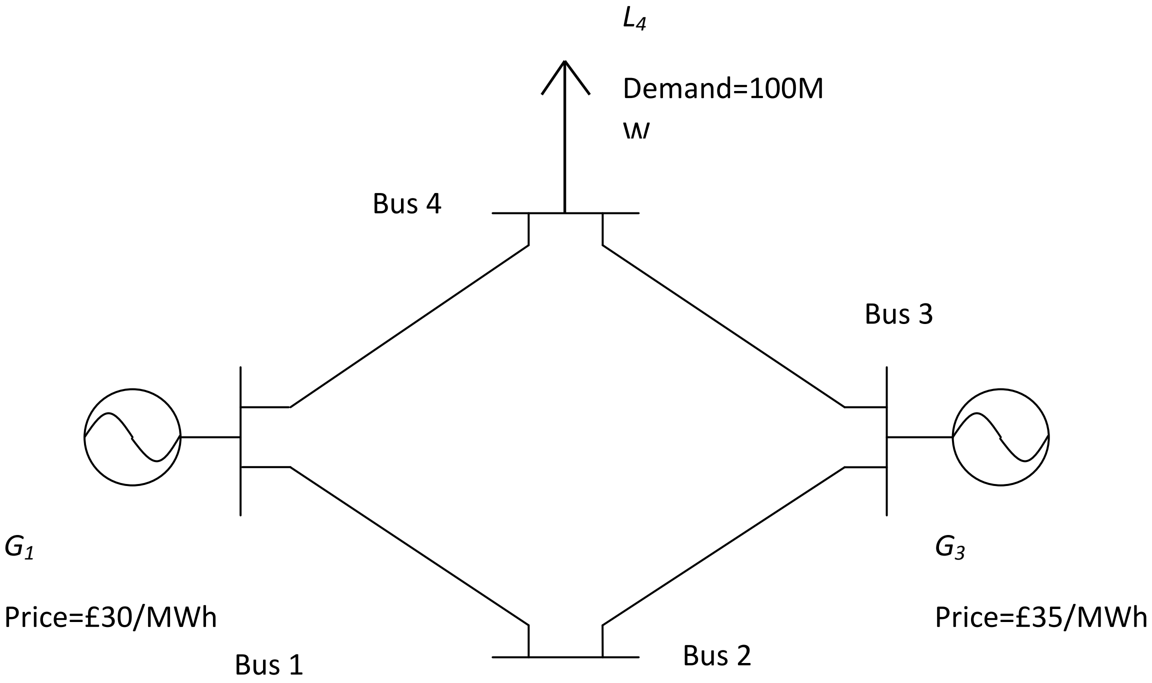

Figure 6.1: Four bus system

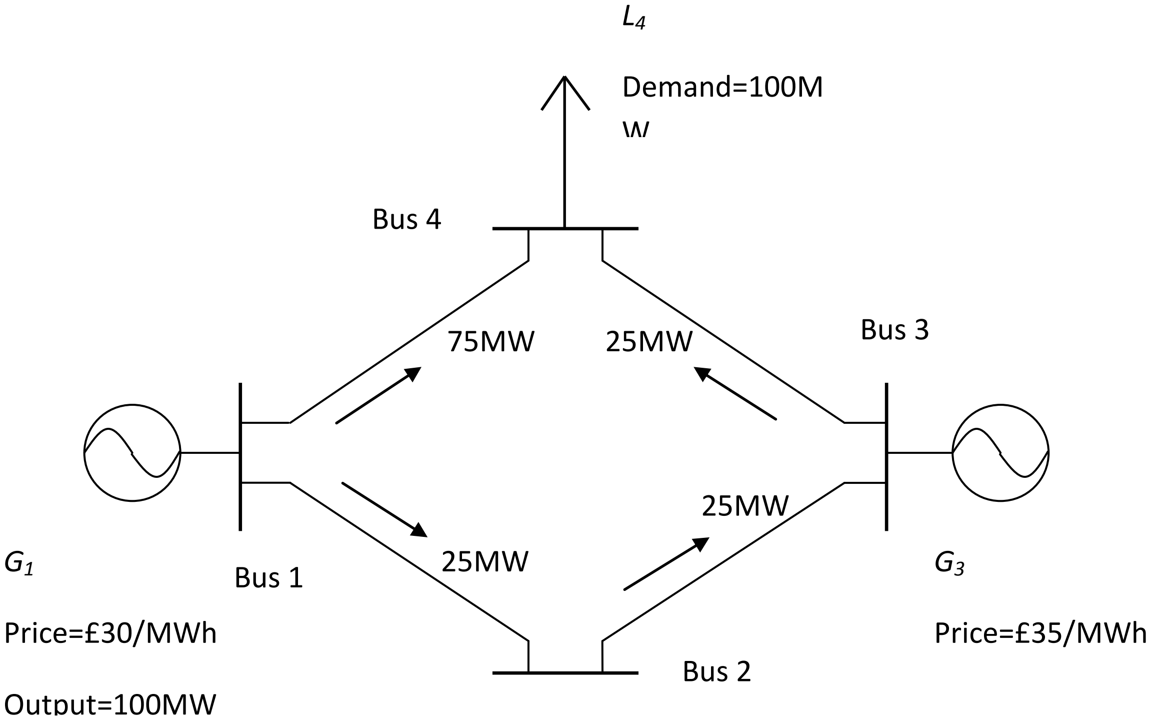

Figure 6.2: Four bus system without congestion

This case is primarily supposed to illustrate congestion management so the concern of (n-1) security is not considered here. Due to this assumption, when capacity constraints are set to 75.2MW on all transmission lines, congestion will appear if L_4 requires additional 1MW of demand. When 1MW is increased on L_4, G_1 cannot provide this additional demand through Line (1,4) due to the capacity constraint. At this stage, G_1 and G_2 must be re-dispatched for security reason. The result is G_1 decreases its output by 0.1MW whilst G_2 is selected to generate 1.1MW to balance the system. Consequently the new operation situation is illustrated in Figure 6.3.

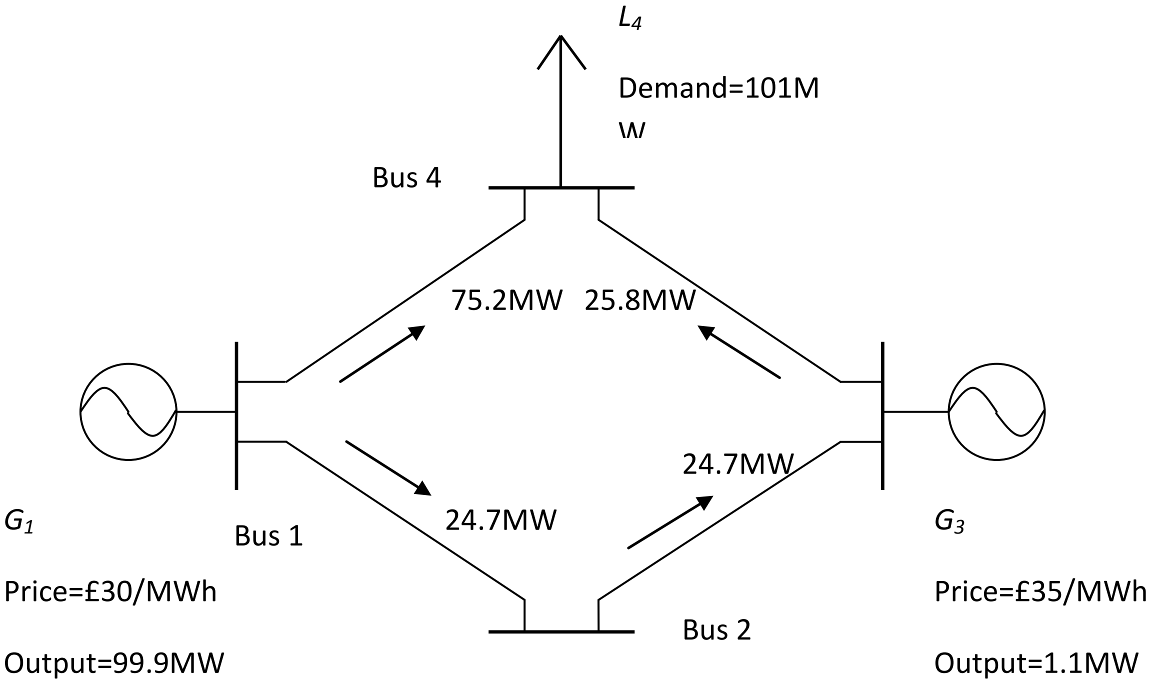

Figure 6.3: Four bus system when load requires additional 1MW

The following discussions indicate how congestion influences energy prices under different pricing mechanisms:

- **Congestion in Uniform pricing**

  Uniform pricing uses system marginal price (SMP) to charge energy consumes. In Section 2.2.2.1, SMP is defined as the highest bid from the generator serving the last MW without constraint limits. In this case G_1 is the marginal generator and its bid price is £30/MWh. However the ISO has to buy 1.1MW from G_3 by £35/MWh due to the capacity limit on line 1-4 whilst reduces output of G_1 by 0.1MW. As a consequence, the final payment which ISO buys 101MW from generators is higher than the payment with no constraint existing in the system. The calculation will be presented in the following section.

- **Congestion in Nodal pricing**

  In the theory of Nodal pricing, the price at a node is determined by the cost of supplying the next MW at this node. When no congestion exists in this system, all demands at node 4 are supplied by G_1. According to Nodal pricing, the price for L_4 equals to the bid of G_1 which is £30/MWh. If L_4 needs additional 1MW from 101MW, G_3 needs to produce 1.5MW whilst G_1 reduces its production by 0.5MW due to the line constraint. Consequently the nodal price of L_4 after congestion is calculated by the following equation.

$$\begin{aligned} &Nodal\ Price\ for\ L_4 \\ &\qquad = increased\ output\ of\ G_3 \times G_3\ bid\ price \\ &\qquad - decreased\ output\ of\ G_1 \times G_1\ bid\ price \\ &\qquad = 1.5MW \times £35/MWh - 0.5MW \times £30/MWh \\ &\qquad = £37.5/MWh \end{aligned}$$

  As a result, £37.5/MWh is the nodal price for L_4 when it consumes 101MW.

It is observed from above example that congestion raises the cost of consuming electricity no matter what pricing mechanisms are implemented in the system. Therefore preventing congestion is a considerable approach to bring more benefits to participants. However, as mentioned above, congestion cannot be easily resolved by enhancing capacity limits so that efficient measures of congestion management are solutions to address congestion issues.

6.2.2 Current congestion management

For relieving congestion in practice, ISOs have introduced different approaches to resolve congestion problems. This section discusses practical measures of congestion management by non cross-border trading and cross-border trading.

6.2.2.1 Redispatch first, compensate later

This method is usually used in pool market like old the England & Wales pool system. In this method, two stages are introduced into the operation. The first stage is to carry out an unconstraint dispatch to discover operation costs without the consideration of capacity limits of transmission lines. In this stage, generators are dispatched to inject energy into system by an ascending order from the lowest bid. The price of the last dispatched generator that meets the marginal MW is set to be the system marginal price (SMP). The second stage completes the constraint dispatch which means all generators are dispatched by considering capacity limits. If no constraint violation exists at this stage, the dispatch order would be the same as the first stage. If constraint violation appears in the system, ISOs have to reduce some output from lower bid generators and dispatch higher bid generators to ensure system safety. Obviously ISOs most likely buy the same amount of energy with higher price and additional costs are added into pool selling price (PSP). Without considering other issues like losses and loss of load probability, the PSP is calculated as

$$PSP = SMP + uplift$$

In this case the component of uplift refers to additional costs due to congestion.

For instance, the SMP in the system of Figure 6.1 is £30/MWh. If the generators are dispatched without constraint limits, the price for energy consume is

$$Payment\ under\ unconstraint = SMP \times output\ of\ G_1 = £30/MWh \times 101MW$$
$$= £3030/h$$

When considering constraints of transmission lines, the payment will be charged as

$$\begin{aligned} &Payment\ under\ constraint \\ &\quad = output\ of\ G_1 \times G_1\ bid\ price + output\ of\ G_3 \times G_3\ bid\ price \\ &\quad = 99.9MW \times £30/MWh + 1.1MW \times £35/MWh = £3035.5/h \end{aligned}$$

The difference of payment between unconstraint and constraint is the uplift cost due to congestion. Because ISOs buy electricity from generators by SMP, G_3 needs to be compensated for the difference between its bid price and SMP. [4] Consequently, the compensation is calculated as the following

$$Compensation\ for\ G_3 = (G_3\ bid\ price - SMP) \times increased\ output\ of\ G_3$$
$$= (£35/MWh - £30/MWh) \times 1.1MW = £5.5/h$$

This method of relieving congestion problem is supposed to be an efficient solution because generators are centrally dispatched by ISOs. However, in practice, this proposed advantage turns out to be a disadvantage because it does not follow the principle of competitive markets to provide clear market information. [5]

6.2.2.2 Congestion management of Nodal Pricing

With the spread of Nodal Pricing in deregulated electricity markets, it is claimed that this method can be also implemented as an efficient approach of congestion management. [6] As introduced in Section 2.2.2.3, there are three components in a nodal price: energy cost, congestion cost and loss cost. In a lossless system, if constraint limits are not considered, all the prices through over the system are the same. When congestion is included in calculation, nodal prices are likely to be different at different locations. Additionally, ISOs pay generators for their output and charge loads for their usages by locational nodal prices respectively. For example, the system in Figure 6.3 indicates that the nodal price for L_4 is £37.5/MWh under congestion. As a consequence, L_4 pays

$$\begin{aligned} L_4\ payment &= total\ demand\ of\ L_4 \times nodal\ price\ at\ node \\ &= 101MW \times £37.5/MWh = £3787.5/h \end{aligned}$$

In the mean time, generators receive

$$\begin{aligned} &Total\ generation\ revenue \\ &\qquad = G_1\ output \times Nodal\ price\ at\ G_1 + G_3\ output \\ &\qquad \times Nodal\ price\ at\ G_3 \\ &\qquad = 99.9MW \times £30/MWh + 1.1MW \times £35/MWh = £3035.5/h \end{aligned}$$

As a result, the total congestion cost for 101MW usage is calculated as the following:

$$\begin{aligned} L_4\ payment\ for\ congestion &= L_4\ payment - Total\ generation\ revenue \\ &= £3787.5/h - £3035.5/h = £752/h \end{aligned}$$

This result is called as the merchandising surplus. In different market environments, this surplus is used in different ways. Generally there are two kinds of solutions. The first solution is considered that the merchandising surplus can be kept by transmission owners as parts of wheeling charges and is used for future network reinforcement. On the contrary ISOs can return the merchandising surplus to participants in the market.

Some people argue that the first solution could give transmission owners incentives to remain line constraints for gaining more profits from congestion. For the purpose of avoiding this situation, some markets accept the second option and introduce financial solutions to address this issue. Financial Transmission Right (FTR) is the most discussed solution in deregulated electricity markets. [7] [8] FTR ensures that differences in congestion charges are received by transmission right holders between two locations defined by the transmission right. For the three bus system under constraints, L_4 pays additional £752/h after congestion. If L_4 holds 99.9MW transmission right with node 1 and another 1.1MW with node 3, it will receive

$$\begin{aligned} FTR\ payment\ for\ L_4 &= Transmission\ right\ with\ node\ 1 \\ &\times congestion\ charge\ from\ node\ 1 \\ &+ Transmission\ right\ with\ node\ 3 \\ &\times congestion\ charge\ from\ node\ 3 \\ &= 99.9MW \times £7.5/MWh + 1.1MW \times £2.5/MWh = £752/h \end{aligned}$$

According to previous calculation, L_4 spends £3787.5/h to purchase electricity supply. As a consequence, the net payment of L_4 is £3035.5/h. It is concluded from above calculations that loads pay additional charges under capacity constraint conditions but they are compensated with the amount of what they have paid by FTR.

6.2.3 Congestion management between areas

The previous section discusses measures of congestion management inside an area. As mentioned before, cross-border trading is carried out frequently between two areas in deregulated markets. In additional tie lines between areas are most likely to be weak because they are not designed to transport large amount of energy. In other words, tie lines are the places where congestion most likely to appear. Consequently it is also important to review intra-area congestion management. [9] [10] indicate several solutions for relieving intra-area congestion which are presented in the following:

Explicit auctioning

In this management method, ISOs between two areas where the congestion exists sell the interconnector capacity to the highest bidder. This method considers the transmission capacity as a product that can be traded in the market. This is the advantage in the deregulated environment. On the other hand, bidding available capacity makes the cross-border trading more complicated than usual.

Implicit auctioning

In contrast with explicit auctioning, the implicit auctioning adds a surcharge to every bid which uses the interconnector to get into a power pool market. This method does not trade interconnector separately so it is simpler to calculate. But the disadvantage is that a power pool market is required in the downstream side where the ISO can choose best offers for market participants.

Market splitting

At first all areas in the system must be cleared as pool market respectively. Afterward ISOs need to buy cheap electricity from the pool with lower price and sell it to the local area with higher price. This method has the ability of increasing the price in the lower–priced area whilst decreasing the price in the higher-priced area at the same time. This method is widely known to implement in Nordic market. [11]

Redispatching

This method allows the participants to trade freely and do not consider the transmission capacity. When congestion happens the ISO is responsible to re-dispatch generation to avoid safety limit violation. This method needs a strong cooperation between ISOs and generators. However the participants can receive market signals from this method.

Counter trading

The basic idea of counter trading is as the same as re-dispatching. The difference is that ISOs have to enter the market and trade generation to create counter-flow to relieve congestion. The benefit of this method is to free participant transactions from the technical issues so that the market could become more competitive.

6.3 Congestion management for the proposed method

It is indicated from above discussion that congestion may benefit transmission in particular solutions. This situation obviously does not give transmission owners incentives to upgrade their networks to eliminate congestion. In other words, system participants are likely to lose profits due to congestion. However, an ideal electricity market is supposed to offer the maximum possible protection to participants of generators and loads. On the other hand, it is believed electrical systems would offer better performance without congestion so that an efficient congestion management ends the incentive of transmission owners to retain congestion in the system. In this section, an approach of intra-area congestion management, which is suitable for the proposed method, is presented and proved with a case study.

In this study, intra-area congestion will be dealt with and this type of congestion is different from internal congestion that is introduced in Section 6.2.2. Internal congestion is described to uplift energy costs for loads in a particular area. But intra-area congestion causes different consequences. In the proposed method, by considering loads form previous simulation, loads in the import area have price drops because low-price energy is sold from external area. As a result loads always gain benefits from cross-border trading so that they do not need to be compensated. On the other side, although loads in the export area have to pay higher prices to buy electricity, but their benefit losses are made up by a compensation stage in the proposed method. As a result, loads in both areas do not need to be compensated either. Consequently all of loads are not obliged to be parts of congestion management in the proposed method because none of them are losing benefits.

In the proposed method generators receive revenues for their production and pay all of wheeling charges for transport. The next two tables are taken from the case in Section 5.2.2 and present generation incoming revenue from selling energy and their wheeling payments.

Table 6.1 and 6.2 indicate that G_{31} and G_{34} have output changes after security re-dispatch with respect to congestion. In addition, nodal prices are slightly changed at every node. Therefore incoming revenues of generators are affected after re-dispatch and some generators are likely to lose revenues. Without doubt they are not willing to lose profits because of congestion. Furthermore, wheeling charges paid by each generator differs from payments without capacity constraints. Consequently there are two parts needed to be compensated: generation output revenues and wheeling charges. The following sections are assigned to solve this congestion problem with same background data which is introduced in the case in Section 5.2.2

G number	G output (MW)	Price (£/MWh)	energy revenue (£/h)	Wheeling charge (£/h)
1	80	11.75	940	33.22929
6	80	11.75	940	119.9188
10	550	11.75	6462.5	4037.522
12	74	11.75	869.5	98.55588
15	80	11.75	940	126.077
18	80	11.75	940	66.59418
19	80	11.75	940	134.0341
25	64	11.75	752	214.5864
26	82.8	11.75	972.9	420.578
31	85.6	11.75	1005.8	67.53062
32	80	11.75	940	60.10951
34	85.6	11.75	1005.8	275.6666
36	100	11.75	1175	203.7977
46	95.2	12.05	1147.16	145.6999
49	121.6	12.05	1465.28	185.4759
54	102.4	12.05	1233.92	40.3162
55	100	12.05	1205	93.80107
56	100	12.05	1205	73.91379
59	102	12.05	1229.1	0
61	104	12.05	1253.2	245.43
62	100	12.05	1205	69.6381
65	98.2	12.05	1183.31	488.8806
66	98.4	12.05	1185.72	234.7943
69	120.6	12.05	1453.23	441.9984
70	100	12.05	1205	209.3642
74	100	12.05	1205	113.9417
76	100	12.05	1205	84.07912
77	100	12.05	1205	145.5015
80	115.4	12.05	1390.57	117.9845
85	100	12.05	1205	329.417
87	100	12.05	1205	618.234
89	141.4	12.05	1703.87	306.1023
92	100	12.05	1205	182.668
100	100	12.05	1205	317.6416
103	112	12.05	1349.6	504.251
104	100	12.05	1205	327.2445
105	100	12.05	1205	263.2928
110	100	12.05	1205	404.6484
111	108.8	12.05	1311.04	657.801

Table 6.1: **Revenues and charges of generators under unconstraints**

G number	G output (MW)	Price (£/h)	energy revenue (£/h)	Wheeling charges (£/h)
1	80	11.47	917.6	33.28234
6	80	11.47	917.6	121.6712
10	550	11.45	6297.5	4117.369
12	74	11.47	848.78	102.2733
15	80	11.53	922.4	124.5846
18	80	11.52	921.6	66.58826
19	80	11.55	924	140.8647
25	64	11.5	736	214.54
26	82.8	11.48	950.544	419.6287
31	72	11.5	828	64.2672
32	80	11.51	920.8	67.44716
34	99.2	11.8	1170.678	292.0165
36	100	11.8	1180	210.2911
46	95.2	12.07	1149.064	145.6769
49	121.6	12.07	1467.712	185.3217
54	102.4	12.07	1235.8473	40.1976
55	100	12.07	1207	93.80073
56	100	12.07	1207	73.90892
59	102	12.07	1231.14	0
61	104	12.07	1255.28	245.4181
62	100	12.07	1207	69.51619
65	98.2	12.08	1186.256	488.4739
66	98.4	12.07	1187.688	234.2868
69	120.6	12.05	1453.23	441.5224
70	100	12	1200	206.1894
74	100	12.02	1202	112.7477
76	100	12.04	1204	83.74348
77	100	12.05	1205	145.7281
80	115.4	12.05	1390.57	117.2495
85	100	12.05	1205	329.3962
87	100	12.05	1205	618.2231
89	141.4	12.05	1703.87	306.1012
92	100	12.05	1205	182.6588
100	100	12.05	1205	317.4443
103	112	12.05	1349.6	504.0587
104	100	12.05	1205	327.1442
105	100	12.05	1205	263.2663
110	100	12.05	1205	404.6005
111	108.8	12.05	1311.04	657.8532

Table 6.2: Revenues and charges of generators with constraints

6.3.1 Generation revenue

From Table 5.5, it is noticed that the congestion cost component could be negative for some nodes. As the result of this situation, nodal prices could be decreased if congestion exists in the network. For the expectation of generation participants, they have the possibility to lose their revenues due to congestion. In addition, it is believed that an absence of compensation mechanism would result in fewer incentives for generators to maintain adequate energy. By comparing Table 6.1 to Table 6.2, it is found that some generators lose incoming revenues due to congestion whilst other gain more benefits from it. Figure 6.1 shows differences of incoming revenues of generators when congestion exists.

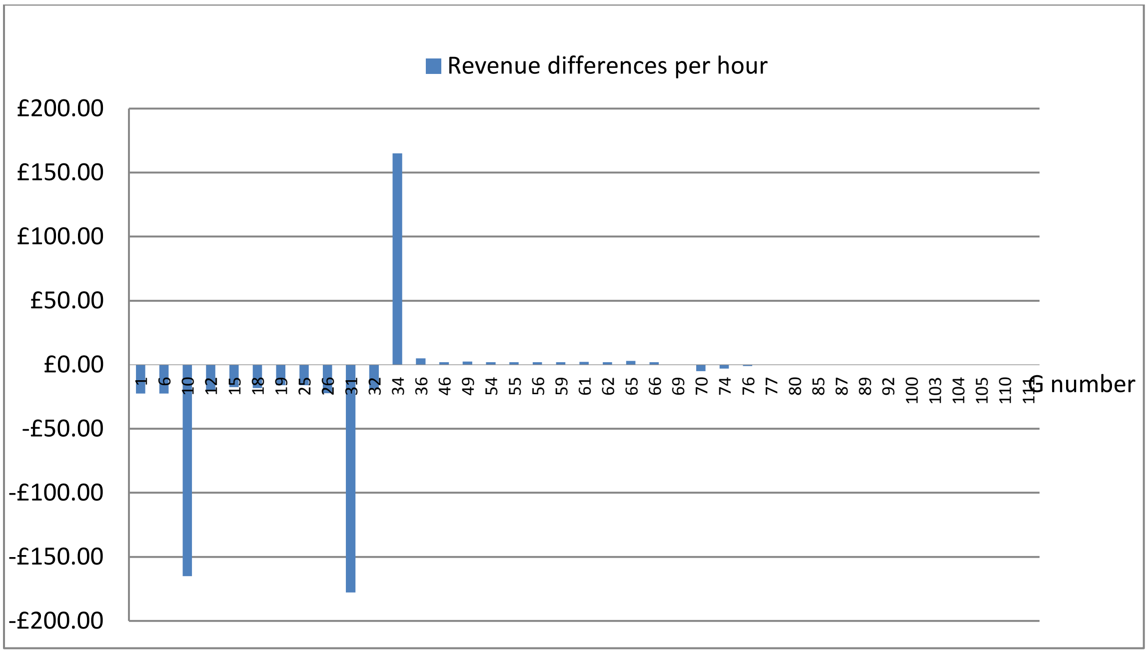

Figure 6.4: Differences of generation incoming revenues due to congestion

It is noticed that congestion greatly reduces generation revenues in Area 2 where most of generators lose benefits owing to congestion. For instance, G_{10} receives £6462.5/h ($550MW \times £11.75/MWh$) without constraints. However, it only receives £6297.5/h ($550MW \times £11.45/MWh$) under constraint operation. As a result G_{10} loses £165/h due to congestion. As discussed above the transmission owner is responsible of compensating this loss, which is £165/h. In addition allocation of this compensation needs to be resolved by implementing proportional impacts of transmission networks. In this case only Line (30,38) is congested and both transmission owners have half possession of it. Consequently the compensation is split into two parts for transmission owners and each of them pays £82.5/h to G_{10}.

On the other hand, some generators are likely to earn more benefits under constraints. For example, G_{34} is supposed to provide 85.6MW for energy consuming with unconstraint operation. When the system is operated under constraints, G_{34} is dispatched to output 99.2MW instead. Consequently the incoming revenue of G_{34} rises from £1005.8/h ($85.6MW \times £11.75/h$) to £1170.678/h ($99.2MW \times £11.8/h$). In this study, this additional revenue is suggested to be kept by generators for relieving congestion. This solution can be considered as an approach to prevent transmission owners from earning benefits from congestion.

To sum up, allocations of compensation from each area are presented in Table 6.3. Values in the second and third columns indicate compensations for related generators from transmission owners in Area 1 and Area 2 respectively.

G number	Compensation from transmission owner in Area 1 (£/h)	Compensation from transmission owner in Area 2 (£/h)
1	11.2	11.2
6	11.2	11.2
10	82.5	82.5
12	10.36	10.36
15	8.8	8.8
18	9.2	9.2
19	8	8
25	8	8
26	11.178	11.178
31	88.9	88.9
32	9.6	9.6
34	0	0
36	0	0
46	0	0
49	0	0
54	0	0
55	0	0
56	0	0
59	0	0
61	0	0
62	0	0
65	0	0
66	0	0
69	0	0
70	2.5	2.5
74	1.5	1.5
76	0.5	0.5
77	0	0
80	0	0
85	0	0
87	0	0
89	0	0
92	0	0
100	0	0
103	0	0
104	0	0
105	0	0
110	0	0
111	0	0

Table 6.3: Compensations for generators from both transmission owners

6.3.2 Wheeling charges

It is introduced that transmission owners would receive extra wheeling charges due to congestion. This additional earning of wheeling charges is called as the congestion charges and one way is to return it to system participants for a fairer consideration. In Section 6.2.2.2, FTR is introduced to eliminate the congestion charges but it needs to pre-define the transport energy amount between two nodes. If the actual transport energy is varied from the expected energy, FTR owners are possible to lose benefits according to their FTR contracts. In addition, FTR is based on traditional Nodal pricing which means it suffers the disadvantage of solving cross-border trading of Nodal pricing. Consequently, FTR is not a considerable solution for intra-area congestion.

In the proposed method, congestion costs are allocated to their payers in order that ISOs are able to return the merchandising surplus by real-time power flow instead of pre-defining transported energy. In Chapter 5, Table 5.14 presents that contributions of G_{25} on transmission lines are received in the calculation. Similarly, such information can be calculated for all generators in the system. Then, according to ownerships of transmission lines, payments for wheeling services to each transmission owners from particular generators is able to be calculated. As the result data are too massive to present here, only calculation of final results are shown in this section. For instance, in this case, G_1 payments to each transmission owner in the unconstraint condition are calculated by the following equations.

$$
\begin{aligned}
&G_1\ payment\ to\ transmission\ owner\ of\ Area\ 1 \\
&\qquad = G_1\ payment\ to\ lines\ in\ Aera\ 1 + \frac{G_1\ payment\ to\ tie\ lines}{2} \\
&\qquad = £0.2648/h + \frac{£0.1253/h}{2} = £0.32745/h
\end{aligned}
$$

$$G_1\ payment\ to\ transmission\ owner\ of\ Area\ 2$$
$$= G_1\ payment\ to\ lines\ in\ Aera\ 2 + \frac{G_1\ payment\ to\ tie\ lines}{2}$$
$$= £32.8391/h + \frac{£0.1253/h}{2} = £32.90175/h$$

where the payment to tie lines are divided by 2 because of the assumption in Section 5.2.1 that the ownerships are split into 5:5 if transmission lines are crossing borders.

Consequently this calculation is repeated for all generators and wheeling payments to each transmission owner without constraints can be presented in Table 6.4. The second and third columns are indicating wheeling charges paid to each transmission owner from particular generators respectively.

Similarly, payments for wheeling services from generators with constraints are presented in Table 6.5. Additionally differences of wheeling charges between unconstraints and constraints are calculated by the calculation below which takes G_1 as an example and results are presented in Table 6.6.

$$G_1\ Wheeling\ charge\ difference\ in\ Area\ 1$$
$$= Payment\ with\ constraint - Payment\ without\ constraint$$
$$= £0.29985/h - £0.32745/h = £-0.0276/h$$

$$G_1\ Wheeling\ charge\ difference\ in\ Area\ 2$$
$$= Payment\ with\ constraint - Payment\ without\ constraint$$
$$= £32.98245/h - £32.90175/h = £0.0807/h$$

G Number	Payment to transmission owner in Area 1 (£/h)	Payment to transmission owner in Area 2(£/h)
1	0.32745	32.90175
6	5.80545	114.1136
10	1563.3	2474.223
12	13.3627	85.1928
15	77.09545	48.98265
18	19.4435	48.98265
19	62.4918	71.5423
25	89.1464	125.4401
26	185.2516	235.3264
31	0.72595	66.80475
32	4.5662	55.5434
34	221.6153	54.0513
36	110.9222	92.87555
46	145.7	0
49	185.476	0
54	40.3162	0
55	93.80107	0
56	73.91379	0
59	0	0
61	245.43	0
62	69.6381	0
65	488.8806	0
66	234.7943	0
69	441.9984	0
70	209.3642	0
74	113.9417	0
76	84.07912	0
77	145.5015	0
80	117.9845	0
85	329.417	0
87	618.234	0
89	306.1023	0
92	182.668	0
100	317.6416	0
103	504.251	0
104	327.2445	0
105	263.2928	0
110	404.6484	0
111	657.801	0

Table 6.4: Wheeling charges paid to different transmission owners from each generator without constraints

G Number	Payment to transmission owner in Area 1(£/h)	Payment to transmission owner in Area 2(£/h)
1	0.29985	32.98245
6	5.36065	116.3106
10	1551.758	2565.611
12	12.2956	89.9776
15	70.13135	48.45315
18	18.8799	47.7083
19	63.30305	77.56165
25	86.6804	127.8596
26	175.3575	244.2712
31	-0.14475	64.41195
32	0.9428	66.5044
34	236.5682	55.44845
36	116.8663	93.4248
46	145.6769	0
49	185.3217	0
54	40.1976	0
55	93.80073	0
56	73.90892	0
59	0	0
61	245.4181	0
62	69.51619	0
65	488.4739	0
66	234.2868	0
69	441.5224	0
70	206.1894	0
74	112.7477	0
76	83.74348	0
77	145.7281	0
80	117.2495	0
85	329.3962	0
87	618.2231	0
89	306.1012	0
92	182.6588	0
100	317.4443	0
103	504.0587	0
104	327.1442	0
105	263.2663	0
110	404.6005	0
111	657.8532	0

Table 6.5: Wheeling charges paid to different transmissions from each generator with constraints

G Number	Difference of payment to transmission owner in Area 1(£/h)	Difference of payment to transmission owner in Area 2 (£/h)
1	-0.0276	0.0807
6	-0.4448	2.197
10	-11.5415	91.38815
12	-1.0672	4.7848
15	-6.9641	-0.5295
18	-0.5636	0.5576
19	0.81125	6.01935
25	-2.466	2.4195
26	-9.8941	8.9448
31	-0.8707	-2.3928
32	-3.6234	10.961
34	14.95285	1.39715
36	5.94415	0.54925
46	-0.02309	0
49	-0.15426	0
54	-0.1186	0
55	-0.00034	0
56	-0.00487	0
59	0	0
61	-0.01192	0
62	-0.12191	0
65	-0.4067	0
66	-0.50749	0
69	-0.47597	0
70	-3.17479	0
74	-1.19396	0
76	-0.33564	0
77	0.226593	0
80	-0.73499	0
85	-0.02079	0
87	-0.01088	0
89	-0.00116	0
92	-0.00917	0
100	-0.19725	0
103	-0.19227	0
104	-0.10032	0
105	-0.02652	0
110	-0.04796	0
111	0.052138	0

Table 6.6: Differences of wheeling charges between unconstraints and constraints

As discussed above, the compensation to system participants is determined by differences of payments between unconstraints and constraint. As found in Table 6.6

differences could be positive or negative. The positive value means that generators pay more wheeling charges under constraint operation. This is a disadvantage for generators paying more charges due to congestion, so transmission owners are obliged to compensate those generators with exact values in Table 6.6. For instance, G_{34} receives £14.95289/h from Area 1 and £1.39715/h from Area 2 respectively. On the contrary negative values refer to less wheeling charges for a particular generator under constraint operation. There are two options for negative values: firstly, generators return their saving to transmission owners; secondly, generators keep their saving as they are considered as contributing to relieve congestion. Participant and transmission owners could discuss to choose an optimum solution to implement into operation.

6.4 Summary

This chapter has discussed the congestion issue in deregulated electricity markets and a measure of congestion management for the proposed method is introduced in this chapter. Firstly, the characteristic of congestion is presented in the beginning of this chapter and this section explains why congestion is supposed to be eliminated efficiently. Additionally, Section 6.2 presents current solutions for both inter-congestion and intra-congestion respectively. In Section 6.3, the congestion issue brought by the proposed method is analysed and a measure of congestion management is proposed to compensate benefit losses of energy revenues and additional wheeling charges for generators due to congestion. For compensating energy revenues of generators, transmission owners need to pay benefit losses but those generators that earn more benefits can keep their revenues as they are considered to relief congestion. Similarly, generators could pay extra wheeling charges under constraint operation, which is considered as benefits losses due to congestion. Those losses of generators also needs to be compensated by transmission owners. Consequently, this measure is believed to be able to give transmission owners incentives to reinforce networks to eliminate congestion.

6.5 Reference

[1]. “Balancing Services”, Available: http://www.nationalgrid.com/uk/Electricity/Balancing/, accessed on: 15/06/2011.

[2]. “Congestion Management in the Nordic Market - evaluation of different market models”, Available: http://www.respoint.se/itp/event/elmarknad/content/File/Nordic_CM_study_FD_may_2008.pdf, access on 10/04/2008.

[3]. Andrew L. Ott, “Experience with PJM Market Operation, System Design, and Implementation”, *IEEE Transaction on Power Systems*, Vol. 18, No. 2, pp528-534, May 2003

[4]. M.P. Abdullah, M. Y. Hassan and F. Hussin, “Congestion Cost Allocation in a Pool-Based Electricity Market”, *2nd IEEE International Conference on Power and Energy (PECon 08),* Johor Baharu, Malaysia, pp1033-1037, December 1-3, 2008

[5]. X. Ma, D. Sun and K. Cheung, “Evolution toward Standardized Market Design”, *Power System, IEEE Transactions on*, vol. 18, no. 2, pp460-469, 2003

[6]. S.N. Pandey, S. Tapaswi and L. Srivastava, “Nodal Congestion Price Estimation in Spot Power Market Using Artificial Neural Network”, *IET Generation Transmission Distribution*, 2, (2), pp280-290, 2008

[7]. G. Bautista and V. Quintana, “Congestion rents allocation based on transmission usage,” *in Proc. IEEE Power Eng. Soc. General Meeting*, Toronto, ON, Canada, vol. 2, pp. 843–848, Jul. 2003

[8]. X. Ma, I. U. Sun and A. Ott, “Implementation of the PJM financial transmission rights auction market system” in *Power Engineering Society Summer Meeting*, pp. 1360-1365, July 2002

[9]. François Boisseleau, Laurens de Vries, “Congestion management and power exchanges: their significance for a liberalized electricity market and their mutual dependence”, available on: http://www.dauphine.fr/cgemp/Publications/Articles/Boisseleau-%20De%20vries%20%282001%29%20Congestion%20management%20Power%20exchange.pdf, accessed on: 30/10/2009

[10]. “Sixth meeting of the European electricity Regulatory Forum”, Florence, 9-10 November 2000 available on: http://ec.europa.eu/energy/gas_electricity/forum_electricity_florence_en.htm, accessed on: 13/10/2011

[11]. “Congestion Management in the Nordic Market - evaluation of different market models”, available on: http://www.ea-energianalyse.dk/projects-english/730_congestion_management_in_the_nordic_electricity_market.html, accessed on: 07/02/2010

Chapter 7 Conclusions and Future Work

7.1 Conclusions

This thesis introduces an allocation method of charging transmission fees for cross-border trading in deregulated electricity markets. This method is proposed based on the need of technical and economic expectations in competitive markets. In particular, both long-term wheeling charges and short-term wheeling charges are considered in the calculation and are allocated according to locations of transmission lines.

An overview of the regulated electricity market is presented in the first two chapters of the thesis. Firstly, changes of the industry structure are discussed. The most obvious change of deregulation is that the traditional vertical integrated structure is re-organised into four parts: generation, transmission, distribution and supply. An Independent System Operator (ISO) is supposed to operate the system for ensuring a fair and transparent market. Secondly, new pricing mechanisms are adapted to charge energy consumption after deregulation, which are Uniform Pricing, Zonal Pricing and Nodal Pricing. They are illustrated and compared in Chapter 2. Finally, experience of different deregulated markets is introduced to explain the current status of ISO responsibilities, energy trading methods and transmission tariffs.

Traditional methodologies for wheeling charges are also reviewed in conjoined with the philosophies and mathematics. A conclusion is proposed after discussion and illustrations that none of them is able to address the allocation problem of wheeling charges in cross-border trading because they cannot provide solutions for transmission owners to determine the share of the collected wheeling charges. A review of the EU experience in cross-border trading is also presented. Several mechanisms for charging transmission fees in cross-border trading are discussed and illustrated. After comparisons, Average participations (AP) and With and without transit (WWT) are considered as suitable charging mechanisms from a theoretical point of view. But they suffer different disadvantages as AP is not able to offer sufficient congestion information to market participants for future investments whilst WWT sometimes leads to fictive cross-border flows to charge irrational wheeling fees from market participants.

A proposed method is introduced to resolve the allocation problem described above after the discussion of current challenges. This method is a combination of both power flow tracing and nodal pricing to calculate the wheeling charge on every line which is divided into the long-term charge and the short-term charge. The long-term charges reflect the fixed costs which are used for maintaining expenses and future investment whilst the short-term charges refer to congestion costs and loss costs during transmission. The allocation of wheeling charges for cross-border trading can be achieved by referring to locations of transmission lines after those charges are completely calculated.

The proposed method is simulated in the IEEE 118 bus system. Three scenarios are used to test the function of the proposed method. The first scenario is to split the IEEE 118 bus system into two areas and two areas trade electrical energy for optimal social benefits. This simulation indicates generators and loads in the export area could be generally at a disadvantage so that a compensation stage is implemented after allocation of transmission charges. This solution asks the import area to use its monetary saving to compensate losses of participants in the export area during cross-border trading. The result shows this compensation process can benefit generators involved in cross-border trading and loads in the import area whilst loads in the export area are not influenced by cross-border trading. The second scenario is simulated based on the first case with an additional bilateral transaction across the border. The effect of loop flow affects the performance of the proposed method. As effects of loop flow cannot be avoided when allocating wheeling charges of bilateral contracts, all power flow impacts from bilateral contracts are used to charge wheeling services. The last scenario is to examine cross-border trading among multi-areas. In this case study, the IEEE 118 bus system is split into three areas instead of two areas and a transaction is carried between two non-adjacent areas. Then the third area provides transmission service for this transaction. Finally, after the simulation, the transmission owner in the carrier-area can earn more benefits for providing transporting services for cross-border trading.

In the thesis impacts of congestion in cross-border trading is discussed and current measures of congestion management are explained in Chapter 6. A modified congestion solution is suggested to resolve congestion problem in the proposed wheeling charging method. In the proposed congestion solution, the transmission owner has to compensate generators and loads which lose benefits due to congestion. This solution is tested in the first scenario system and believed to be able to give transmission owners incentives to reinforce networks to eliminate congestion.

7.2 Future Work

According to the time constraint, some issues in allocating wheeling charges for cross-border trading are not yet investigated in the thesis. In the following section, several suggestions and improvements are listed for future research:

- The proposed method is introduced to resolve the allocation problem of active power wheeling charges in this thesis. In practice, reactive power is also charged and allocated for transport. However, charging reactive power is different from charging active power so that the proposed method can be used for charging reactive power. Nevertheless a method for reactive power can be proposed based on the experience in this thesis.

- In the simulation, transmission losses are not included in the calculation due to assumption. Following works should include transmission losses in the calculation.

- In the three testing scenarios, all wheeling charges are assumed to be paid by generators for simplifying the discussion. As a result, the compensation stage in the proposed method only takes into account benefits losses of generators. In practice, wheeling charges are paid by both generators and loads with an agreed ratio. Usefully information for the compensation stage could be received if wheeling charges of loads were included in the future simulation.

- The proposed congestion management is simulated in the first scenario where cross-border trading happens across two areas. More valuable results could be obtained if this congestion management is tested in multi-area cross-border trading.

- The proposed congestion management in the thesis indicates that compensating market participant benefits losses due to congestion gives transmission owners incentives to invest more transmission capacity. The investment return period could be included in future work.

Reference

"Sixth meeting of the European electricity Regulatory Forum", Florence, 9-10 November 2000 available on: http://ec.europa.eu/energy/gas_electricity/forum_electricity_florence_en.htm, accessed on: 13/10/2011

"Regulation 1228/2003", Available on: http://www.energy-community.org/portal/page/portal/ENC_HOME/AREAS_OF_WORK/ELECTRICITY/Regional_Market/Regulation_1228, access on: 21/06/2011

Hogan W. W., "Transmission Congestion: The Nodal-Zonal Debate Revisited", Harvard University, John F. Kennedy School of Government, Center for Business and Government, available on: http://www.hks.harvard.edu/fs/whogan/nezn0227.pdf, 20/06/2011

"Balancing Services", Available: http://www.nationalgrid.com/uk/Electricity/Balancing/, accessed on: 15/06/2011

William W. Hogan, "Contract Networks foe Electric Power Transmission: Technical Reference", available on: www.hks.harvard.edu/fs/whogan/acnetref.pdf, 10/05/2011

"The Statement of the Use of Connecting Charging Methodology", available on: http://www.nationalgrid.com/NR/rdonlyres/590ACE8D-01BE-4ED9-A028-3736D28A7CCE/41181/UoSCMI6R0v10Final.pdf, accessed on: 08/04/2011

"Transmission Rates",
http://www.cpuc.ca.gov/PUC/energy/wholesale/01_ratedesign/, available: 06/04/2011

UK electricity and gas transmission",
http://www.nationalgrid.com/corporate/Our+Businesses/UKT/ available on 30/03/2011

"Definitions, Background Information and Abbreviations", available on: http://www.appro.org/backgroundinformation.html, access on 17/03/2011

"An Introduction to Australia's National Electricity Market", available on: http://www.aemo.com.au/corporate/0000-0262.pdf, accessed on: 09/03/2011

"Incentive Schemes to Promote Cross-border Trade in Electricity", available on: http://www.energy-regulators.eu/portal/page/portal/EER_HOME/EER_CONSULT/CLOSED%20PUBLIC%20CONSULTATIONS/ELECTRICITY/Cross%20Border%20trade%20incentives%20electricity/CD/E08-ENM-07-04_IncentiveSchemes_10-Dec-2009.pdf , accessed on: 25/2/2011

"Objectives of the consultation", Available on:
http://ec.europa.eu/energy/gas_electricity/consultations/2009_02_28_tso_en.htm, accessed on: 25/2/2011

"The Nordic Power Market", available on: http://www.fer.hr/_download/repository/Nord%20Pool%20-%20The%20Nordic%20Power%20Market.pdf, accessed on: 21/02/2011

Frank A. Wolak, Robert H. Patrick, 'The Impact of Market Rules and Market Structure on the Price Determination Process in the England and Wales Electricity Market' April 2001, available on: http://www.nber.org/papers/w8248 21/04/2010, accessed on: 22/3/2011

"The Statement of Use of System Charges", available on: http://www.nationalgrid.com/NR/rdonlyres/590ACE8D-01BE-4ED9-A028-3736D28A7CCE/41181/UoSCMI6R0v10Final.pdf, accessed on: 10/12/2010

"Company Overview", Available on: http://www.pjm.com/about-pjm/who-we-are/company-overview.aspx, accessed on: 28/10/2010

M. Ghayeni and R. Ghazi "Multiarea Transmission Cost Allocation in Large Power Systems Using the Nodal Pricing Control Approach", *Iranian Journal of Electrical & Electronic Engineering*, Vol. 6, No. 4, pp. 238-247, December 2010

"Congestion Management in the Nordic Market - evaluation of different market models", available on: http://www.ea-energianalyse.dk/projects-english/730_congestion_management_in_the_nordic_electricity_market.html, accessed on: 07/02/2010

"Open access transmission tariff accounting", revision: 74, available on: ftp.pjm.com/~/media/documents/manuals/m27.ashx, 18/08/2010

"The Statement of the Use of System Charging Methodology", National Grid, available: http://www.nationalgrid.com/NR/rdonlyres/590ACE8D-01BE-4ED9-A028-3736D28A7CCE/41181/UoSCMI6R0v10Final.pdf, accessed on: 10/08/2010

"Incentive Schemes to promote Cross-Border Trading in electricity", 10/12/2009, available on: http://www.energy-regulators.eu/portal/page/portal/EER_HOME/EER_CONSULT/CLOSED%20PUBLIC%20CONSULTATIONS/ELECTRICITY/Cross%20Border%20trade%20incentives%20electricity/CD, accessed on: 06/07/2010

"PJM history", Available on: http://www.pjm.com/about-pjm/who-we-are/PJM-history.asp, access on 15/05/2010

"Commission staff working document-Accompanying document to the Inter Transmission System Operator Compensation Mechanism and Harmonisation of Transmission Tariff for Electricity" 2008, available on: http://ec.europa.eu/governance/impact/ia_carried_out/cia_2008_en.htm#tren, accessed on: 27/04/2010

Nicolai J. Sarad and Dean M. Colucci, "The Competitive Market for Power in the U.S.: The Role of ISOs and PXs", available on: http://library.findlaw.com/2000/Mar/1/127779.html, accessed on: 20/01/2010

Kun Yang, "Optimal Procurement and Pricing of Reactive Power Ancillary Services in Competitive Electricity Market", PhD Thesis, University of Strathclyde, 2010

Thilo Krause, 'Congestion Management in Liberalized Electricity Market-theoretical Concepts and International Application', May 2005, available on: e-collection.ethbib.ethz.ch/eserv/eth:29076/eth-29076-01.pdf 22/03/2010

Nicolai J. Sarad, and Dean M. Colucci, "The Competitive Market for Power in the U.S.: The Role of ISOs and PXs", available on: http://library.findlaw.com/2000/Mar/1/127779.html, accessed on: 11/12/2009

François Boisseleau, Laurens de Vries, "Congestion management and power exchanges: their significance for a liberalized electricity market and their mutual dependence", available on: http://www.dauphine.fr/cgemp/Publications/Articles/Boisseleau-%20De%20vries%20%282001%29%20Congestion%20management%20Power%20exchange.pdf, accessed on: 30/10/2009

William W. Hogan, 'Independent system operator: Pricing and flexibility in a competitive electricity market', February 1998, available on: http://www.hks.harvard.edu/fs/whogan/iso98.pdf, 16/08/2009

M.P. Abdullah, M. Y. Hassan and F. Hussin, "Congestion Cost Allocation in a Pool-Based Electricity Market", *2nd IEEE International Conference on Power and Energy (PECon 08),* Johor Baharu, Malaysia, pp1033-1037, December 1-3, 2008

Drew Phillips, ‘Nodal Pricing Basics’ available on: http://www.ieso.ca/imoweb/pubs/consult/mep/LMP_NodalBasics_2004jan14.pdf, accessed on: 14/10/2008

“Inter transmission System Operator Compensation Mechanism and Harmonisation of Transmission Tariffs for Electricity”, available on http://ec.europa.eu/energy/gas_electricity/cross-border_committee_en.htm, accessed on: 3/7/2008

]. “Congestion Management in the Nordic Market - evaluation of different market models”, Available: http://www.respoint.se/itp/event/elmarknad/content/File/Nordic_CM_study_FD_may_2008.pdf, access on 10/04/2008

Study on further issues on relating to the inter-TSO payment mechanism, available on: http://ec.europa.eu/energy/gas_electricity/studies/doc/electricity/2006_03_tso_compensation_mechanism.pdf, 03/03/2008

Lynne Kiesling "Rethink the Natural Monopoly Justification of Electricity Regulation", available on: http://reason.org/news/show/rethink-the-natural-monopoly-j, accessed on: 31/1/2008

N. Gregory Mankiw, “Principles of Economics”, 5th edition, South-Western College Pub, 2008

S.N. Pandey, S. Tapaswi and L. Srivastava, “Nodal Congestion Price Estimation in Spot Power Market Using Artificial Neural Network”, *IET Generation Transmission Distribution*, 2, (2), pp280-290, 2008

Data of IEEE 118 system, available on: http://www.ee.washington.edu/research/pstca/, 15/11/2007

Luis Olmos Camacho, Ignacio J. Pe´rez-Arriaga, “Comparison of several inter-TSO compensation methods in the context of the internal electricity market of the European Union”, Energy Policy 35 (2007) 2379–2389, April 2007

K.L. Lo, M.Y. Hassan and S. Jovanvic, “Assessment of MW-mile method for pricing transmission services: a negative flow-sharing approach”, *IET Generation, Transmission & Distribution*, 1, (6), pp. 904-911, 2007

Luis Olmos Camacho, Ignacio J. Pe´rez-Arriaga, “Comparison of several inter-TSO compensation methods in the context of the internal electricity market of the European Union”, *Energy Policy 35*, pp. 2379–2389, 2007

Luis Olmos Camacho, Ignacio J. Pe´rez-Arriaga, “An assessment of inter-TSO compensation algorithm in the internal electricity market of the European Union”, *Electrical Power and Energy Systems 29*, pp. 699–712, 2007

Tan Ching Sin, “An Analysis of LMP Decomposition for Financial Settlement and Economic Upgrade”, PhD Thesis, University of Strathclyde, 2007

Yassir A.A. Alturki, “Real and Reactive Power Allocations in Electricity Market”, PhD Thesis, University of Strathclyde, 2006

Feng Ding, J. David Fuller, “Nodal, Uniform, or Zonal Pricing: Distribution of Economic Surplus”, *IEEE Transactions On Power Systems*, Vol. 20, No. 2, pp. 875-882, May 2005

Catherine Waddams Price, “The Effect of Liberalizing UK Retail Energy Markets on Consumers”, Oxford Review of Economic Policy, Vol. 21, No. 1, pp. 128-144, 2005

Evans Lewis, Meade Richard, “Alternating Currents or Counter-Revolution? Contemporary Electricity Reform in New Zealand”, Victoria University Press, Wellington, pp13-18, 2005

Florence School of Regulation, A study issues on the inter-TSO compensation mechanism, 2005

Tarjei Kristiansen, “Congestion management, transmission pricing and area price hedging in the Nordic region”, *Electrical Power and Energy Systems*, Volume 26, Issue 9, pp685-695, November 2004

Daniel Kirschen, Goran Strbac, "Fundamental of Power System Economics", John Wiley & Sons Ltd, England, 2004

Jianzhong Tong, "Overview of PJM Energy Market Design, Operation and Experience", 2004 IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies (DRPT2004), April 2004 Hong Kong

G. Bautista and V. Quintana, "Congestion rents allocation based on transmission usage," *in Proc. IEEE Power Eng. Soc. General Meeting*, Toronto, ON, Canada, vol. 2, pp. 843–848, Jul. 2003

Serena Hesmondhalgh, "Is NETA the blueprint for Wholesale Electricity Trading Arrangements of the Future", *IEEE Trans. On Power Systems,* Vol 18, no. 2 pp. 548-554, May 2003

Andrew L. Ott, "Experience with PJM Market Operation, System Design, and Implementation", *IEEE Transaction on Power Systems,* Vol. 18, No. 2, pp528-534, May 2003

X. Ma, D. Sun and K. Cheung, "Evolution toward Standardized Market Design", *Power System, IEEE Transactions on*, vol. 18, no. 2, pp460-469, 2003

Caril Blumstein, L.S. Firdeman, and R.J.Green, "The history of Electricity Restructuring in California", Working paper for Center for the Study of Energy Markets, August 2002

X. Ma, I. U. Sun and A. Ott, “Implementation of the PJM financial transmission rights auction market system” in *Power Engineering Society Summer Meeting*, pp. 1360-1365, July 2002

Ignacio Pérez-Arriaga, Luis Olmos Camacho, Francisco Javier Rubio Odériz, Cost components of cross border exchanges of electricity, Prepared for the Directorate-General for Energy and Transport / European Commission, 2002

Wei-Jen Lee, C.H. Lin and Larry D. Swift “Wheeling Charge Under a Deregulated Environment”, *IEEE Transcation On Industry Applications*, Vol. 37, No. 1, pp. 178-183, January/February 2001

Bjorndal M. and K. Jornsten, ‘Zonal Pricing in a Deregulated Electricity Market’, *The Energy Journal*, Vol. 22, No. 1, pp. 51-73, 2001

M. Madrigal and m. Flores, “Transmission dispatch and congestion management in the emerging energy market structure”, *IEEE Trans. On Power Systems*, vol.13, no. 4, pp. 1466-1474, November 1998

Assef Zobian, Marija D. Ilić, “Unbundling of Transmission and Ancillary Services Part Two: Cost-Based Pricing Framework”, *IEEE Transactions on Power Systems,* Vol. 12, No.2, pp549-558, May 1997

J W Marangon Lima, “Allocation of Transmission Fixed Charges: An Overview”, *IEEE Transactions on Power Systems*, Vol. 11, No. 3pp. 1409-1418, August 1996

J. Bialek, Tracing the flow of electricity, *IET Generation, Transmission & Distribution*, Vol. 143, NO. 4, pp313-320, July 1996

Dariush Shirmohammadi, Xisto Vieira Filho and Boris Gorenstion, Mario V.P. Pereira, “Some Fundamental Technical Concepts about Cost Based Transmission Pricing”, *IEEE Trans. On Power System*, Vol. 11, No. 2, pp. 1002-1008, May 1996

S. S. Oren, P. T. Spiller, P. Varaiya and F. Wu, “Nodal Prices and Transmission Rights: A Critical Appraisal”, *The Electricity Jounal*, pp. 24-35, April 1995

I.J. Pérez-Arriaga, F.J. Rubio, J.F. Puerta, J. Arceluz, J. Marín, “Marginal Pricing of Transmission Services: An Analysis of Cost Recovery”, *IEEE Transmission on Power Systems, Vol. 10, No. 1*, pp 546-553, February 1995

H. H. Happ, “Cost of Wheeling Methodologies”, *IEEE Transaction on Power Systems*, Vol. 9, No. 1, pp. 147-156, February 1994

Hyde M, Merrill, Bruce W. Erickson, “Wheeling Rates Based on Marginal-Cost Theory”, IEEE Transmission on Power Systems, Vol. 4, No. 4, pp 1445-1451, October 1989

Appendix A: the 7 bus system

Bus No	Area	Voltage (pu)	P_{gen} MW (pu)	P_{load} MW (pu)	Q_{load} MWvar (pu)
1	1	1.05	153.08	0	0
2	1	1.04	150	40	20
3	1	0.99	0	150	40
4	1	1	50	80	30
5	1	1.017	0	130	40
6	2	1.017	250	200	0
7	3	1.04	200.27	200	0

Table A.1: Line data of the 7 bus system

G No	Fixed cost (MBtu/h)	Generator cost co-efficient b (MBtu/MWh)	Generator cost co-efficient c (MBtu/(MWh)^2)	Fuel Cost (£/MBtu)	P_{min} (MW)	P_{max} (MW)
1	373.5	8	0	1	0	400
2	403.6	0	0.025	1	150	500
4	253.2	7.84	0.0013	2.09	50	300
6	388.9	7.57	0.0013	2.14	150	500
7	194.28	7.771	0.0019	2.574	0	600

Table A.2: Generation and load data of the 7 bus system

Branch	From bus	To bus	R (pu)	X (pu)	B (pu)	Limit (MVA)
1	1	3	0.02	0.24	0.05	120
2	1	2	0.05	0.05	0.5	120
3	2	6	0.005	0.06	0.05	200
4	2	4	0.015	0.18	0.04	100
5	2	5	0.01	0.12	0.03	120
6	2	3	0.015	0.18	0.04	100
7	3	4	0.0025	0.03	0.02	222
8	4	5	0.02	0.24	0.05	60
9	6	7	0.02	0.24	0.05	200
10	6	7	0.02	0.24	0.05	200
11	7	5	0.005	0.06	0.04	200

Table A.3: Cost models of generators in the 7 bus system

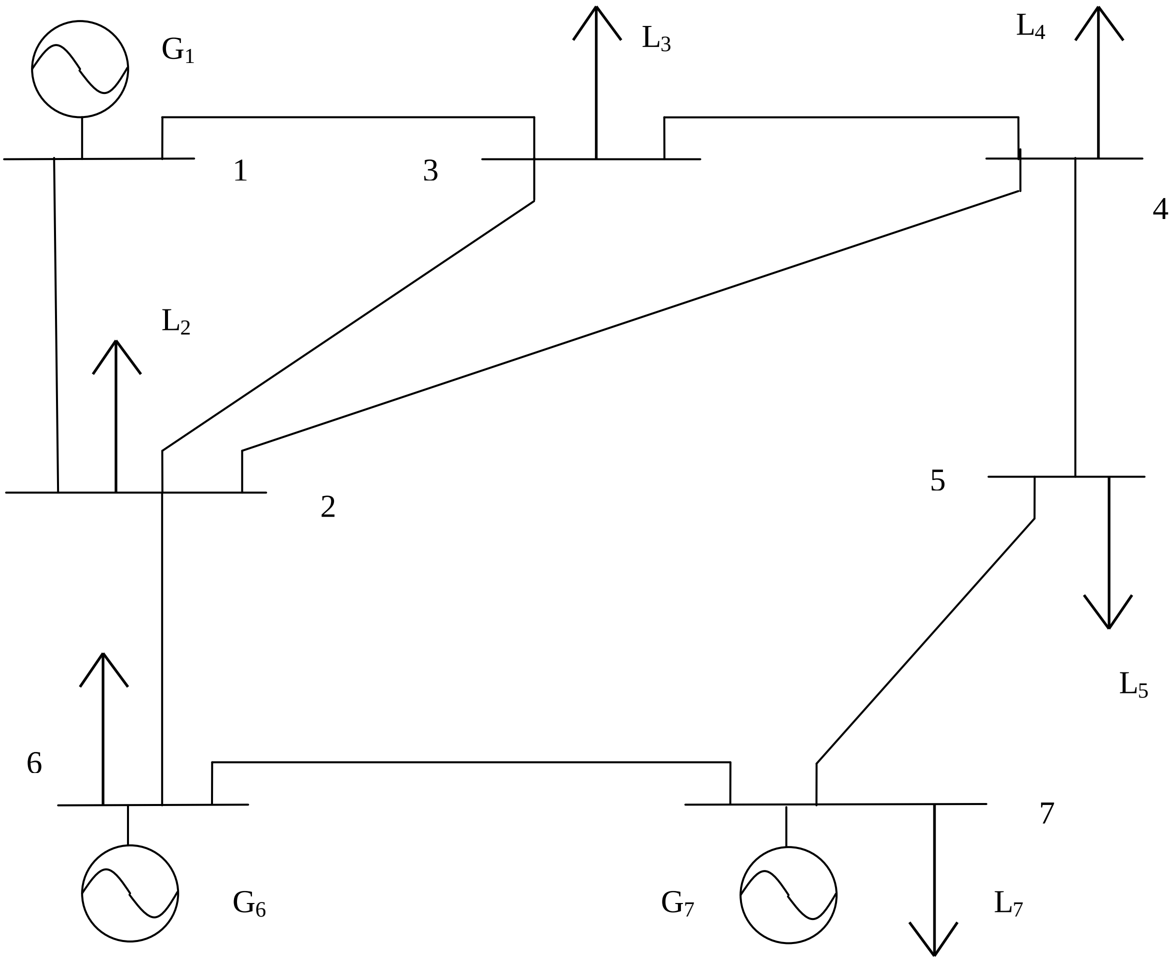

Figure A.1: The 7 bus system

Appendix B: the IEEE 118 bus system

From bus	To bus	R (pu)	X (pu)	B (pu)
1	2	0.0303	0.0999	0.025
1	3	0.0129	0.0424	0.0108
2	12	0.0187	0.0616	0.0158
3	5	0.0241	0.108	0.0284
3	12	0.0484	0.16	0.0406
4	5	0.0018	0.008	0.0021
4	11	0.0209	0.0688	0.0174
5	6	0.0119	0.054	0.0142
8	5	0	0.0267	0
5	11	0.0203	0.0682	0.0174
6	7	0.0046	0.0208	0.0054
7	12	0.0086	0.034	0.0088
8	9	0.0024	0.0305	1.162
8	30	0.0043	0.0504	0.514
9	10	0.0026	0.0322	1.23
11	12	0.0059	0.0196	0.005
11	13	0.0225	0.0731	0.0188
12	14	0.0215	0.0707	0.0182
12	16	0.0212	0.0834	0.0214
12	117	0.0329	0.014	0.0358
13	15	0.0744	0.2444	0.0626
14	15	0.0595	0.195	0.0502
15	17	0.0132	0.0437	0.0444
15	19	0.012	0.0394	0.01
15	33	0.038	0.1244	0.032
16	17	0.0454	0.1801	0.0466
17	18	0.0123	0.0505	0.013
30	17	0	0.0388	0
17	31	0.0474	0.1563	0.0398
17	113	0.0091	0.0301	0.0077
18	19	0.0112	0.0493	0.0114
19	20	0.0252	0.117	0.0298
19	34	0.0752	0.247	0.0632
20	21	0.0183	0.0849	0.0216
21	22	0.0209	0.097	0.0246
22	23	0.0342	0.159	0.0404
23	24	0.0135	0.0492	0.0498
23	25	0.0156	0.08	0.0864
23	32	0.0317	0.1153	0.1174
24	70	0.1022	0.4115	0.102
24	72	0.0488	0.196	0.0488
26	25	0	0.0382	0
25	27	0.0318	0.163	0.1764
26	30	0.008	0.086	0.908
27	28	0.0191	0.0855	0.0216
27	32	0.0229	0.0755	0.0192
27	115	0.0164	0.0741	0.0197
28	29	0.0237	0.0943	0.0238
29	31	0.0108	0.0331	0.0084
30	38	0.0046	0.054	0.422
31	32	0.0298	0.0985	0.0252

113	31	0	0.1	0
32	113	0.0615	0.203	0.0518
32	114	0.0135	0.0612	0.0163
33	37	0.0415	0.142	0.0366
34	36	0.0087	0.0268	0.0056
34	37	0.0026	0.0094	0.0098
34	43	0.0413	0.1681	0.0422
35	36	0.0022	0.0102	0.0026
35	37	0.011	0.0497	0.0132
38	37	0	0.0375	0
37	39	0.0321	0.106	0.027
37	40	0.0593	0.168	0.042
38	65	0.009	0.0986	1.046
39	40	0.0184	0.0605	0.0156
40	41	0.0145	0.0487	0.0122
40	42	0.0555	0.183	0.0466
41	42	0.041	0.135	0.0342
42	49	0.0715	0.323	0.086
42	49	0.0715	0.323	0.086
42	49	0.0715	0.323	0.086
43	44	0.0608	0.2454	0.0606
44	45	0.0224	0.0901	0.0224
45	46	0.04	0.1356	0.0332
45	49	0.0684	0.186	0.0444
46	47	0.038	0.127	0.0316
46	48	0.0601	0.189	0.0472
47	49	0.0191	0.0625	0.016
47	69	0.0844	0.2778	0.071
48	49	0.0179	0.0505	0.0126
49	50	0.0267	0.0752	0.0188
49	51	0.0486	0.137	0.0342
49	54	0.0869	0.291	0.073
49	54	0.073	0.289	0.0738
49	54	0.073	0.289	0.0738
49	66	0.018	0.0919	0.0248
49	66	0.018	0.0919	0.0248
49	66	0.018	0.0919	0.0248
49	69	0.0985	0.324	0.0828
50	57	0.0474	0.134	0.0332
51	52	0.0203	0.0588	0.014
51	58	0.0255	0.0719	0.0178
52	53	0.0405	0.1635	0.0406
53	54	0.0263	0.122	0.031
54	55	0.0169	0.0707	0.0202
54	56	0.0027	0.0096	0.0074
54	59	0.0503	0.2293	0.0598
55	56	0.0049	0.0151	0.0038
55	59	0.0474	0.2158	0.0564
56	57	0.0343	0.0966	0.0242
56	58	0.0343	0.0966	0.0242
56	59	0.0803	0.239	0.0536
56	59	0.0825	0.251	0.0568
56	59	0.0825	0.251	0.0568
59	60	0.0317	0.145	0.0376
59	61	0.0328	0.15	0.0388
63	59	0	0.0386	0
60	61	0.0026	0.0135	0.0146
60	62	0.0123	0.0561	0.0146
61	62	0.0082	0.0376	0.0098

64	61	0	0.0268	0
62	66	0.0482	0.218	0.0578
62	67	0.0258	0.117	0.031
63	64	0.0017	0.02	0.216
64	65	0.0027	0.0302	0.38
65	66	0	0.037	0
65	68	0.0014	0.016	0.638
66	67	0.0224	0.1015	0.0268
68	69	0	0.037	0
68	81	0.0018	0.0202	0.808
68	116	0.0003	0.0041	0.164
69	70	0.03	0.127	0.122
69	75	0.0405	0.122	0.124
69	77	0.0309	0.101	0.1038
70	71	0.0088	0.0355	0.0088
70	74	0.0401	0.1323	0.0337
70	75	0.0428	0.141	0.036
71	72	0.0446	0.18	0.0444
71	73	0.0087	0.0454	0.0118
74	75	0.0123	0.0406	0.0103
75	77	0.0601	0.1999	0.0498
75	118	0.0145	0.0481	0.012
76	77	0.0444	0.148	0.0368
76	118	0.0164	0.0544	0.0136
77	78	0.0038	0.0124	0.0126
77	80	0.0294	0.105	0.0228
77	80	0.017	0.0485	0.0472
77	80	0.017	0.0485	0.0472
77	82	0.0298	0.0853	0.0817
78	79	0.0055	0.0244	0.0065
79	80	0.0156	0.0704	0.0187
81	80	0	0.037	0
80	96	0.0356	0.182	0.0494
80	97	0.0183	0.0934	0.0254
80	98	0.0238	0.108	0.0286
80	99	0.0454	0.206	0.0546
82	83	0.0112	0.0366	0.038
82	96	0.0162	0.053	0.0544
83	84	0.0625	0.132	0.0258
83	85	0.043	0.148	0.0348
84	85	0.0302	0.0641	0.0123
85	86	0.035	0.123	0.0276
85	88	0.02	0.102	0.0276
85	89	0.0239	0.173	0.047
86	87	0.02828	0.2074	0.045
88	89	0.0139	0.0712	0.0193
89	90	0.0238	0.0997	0.106
89	90	0.0518	0.188	0.0528
89	90	0.0518	0.188	0.0528
89	92	0.0393	0.1581	0.0414
89	92	0.0099	0.0505	0.0548
89	92	0.0099	0.0505	0.0548
91	90	0.0254	0.0836	0.0214
91	92	0.0387	0.1272	0.0327
92	93	0.0258	0.0848	0.0218
92	94	0.0481	0.158	0.0406
92	100	0.0648	0.295	0.0772
92	102	0.0123	0.0559	0.0146
93	94	0.0223	0.0732	0.0188

94	95	0.0132	0.0434	0.0111
94	96	0.0269	0.0869	0.023
94	100	0.0178	0.058	0.0604
95	96	0.0171	0.0547	0.0147
96	97	0.0173	0.0885	0.024
98	100	0.0397	0.179	0.0476
99	100	0.018	0.0813	0.0216
100	101	0.0277	0.1262	0.0328
100	103	0.016	0.0525	0.0536
100	104	0.0451	0.204	0.0541
100	106	0.0605	0.229	0.062
101	102	0.0246	0.112	0.0294
103	104	0.0466	0.1584	0.0407
103	105	0.0535	0.1625	0.0408
103	110	0.0391	0.1813	0.0461
104	105	0.0099	0.0378	0.0099
105	106	0.014	0.0547	0.0143
105	107	0.053	0.183	0.0472
105	108	0.0261	0.0703	0.0184
106	107	0.053	0.183	0.0472
108	109	0.0105	0.0288	0.0076
109	110	0.0278	0.0762	0.0202
110	111	0.022	0.0755	0.02
110	112	0.0247	0.064	0.062
114	115	0.0023	0.0104	0.0028

Table B.1: Line data of the IEEE 118 bus system

Bus number	Voltage (pu)	P_{gen} (MW)	P_{Load} (MW)	Q_{Load} (Mvar)
1	0.95717	0	51	27
2	0.97222	0	20	9
3	0.96902	0	39	10
4	0.998	-9	30	12
5	1.00207	0	0	0
6	0.99	0	52	22
7	0.98932	0	19	2
8	1.015	-28	0	0
9	1.04278	0	0	0
10	1.05	450	0	0
11	0.9851	0	70	23
12	0.99	85	47	10
13	0.96824	0	34	16
14	0.98359	0	14	1
15	0.97	0	90	30
16	0.98395	0	25	10
17	0.99524	0	11	3
18	0.973	0	60	34
19	0.96332	0	45	25
20	0.9575	0	18	3
21	0.95772	0	14	8
22	0.96833	0	10	5
23	0.99761	0	7	3
24	0.992	-13	0	0
25	1.05	220	0	0
26	1.015	314	0	0

27	0.968	-9	62	13
28	0.96158	0	17	7
29	0.9632	0	24	4
30	0.98585	0	0	0
31	0.967	7	43	27
32	0.96324	0	59	23
33	0.97162	0	23	9
34	0.98592	0	59	26
35	0.9807	0	33	9
36	0.98	0	31	17
37	0.9921	0	0	0
38	0.96328	0	0	0
39	0.97082	0	27	11
40	0.97	-46	20	23
41	0.96667	0	37	10
42	0.985	-59	37	23
43	0.97868	0	18	7
44	0.98529	0	16	8
45	0.98688	0	53	22
46	1.005	19	28	10
47	1.01729	0	34	0
48	1.02063	0	20	11
49	1.025	204	87	30
50	1.00148	0	17	4
51	0.96759	0	17	8
52	0.95755	0	18	5
53	0.94634	0	23	11
54	0.955	48	113	32
55	0.952	0	63	22
56	0.95459	0	84	18
57	0.97124	0	12	3
58	0.95973	0	12	3
59	0.985	155	277	113
60	0.99322	0	78	3
61	0.995	160	0	0
62	0.998	0	77	14
63	0.96905	0	0	0
64	0.98389	0	0	0
65	1.005	391	0	0
66	1.05	392	39	18
67	1.01985	0	28	7
68	1.00319	0	0	0
69	1.035	503.33	0	0
70	0.984	0	66	20
71	0.98686	0	0	0
72	0.98	-12	0	0
73	0.991	-6	0	0
74	0.95858	0	68	27
75	0.96823	0	47	11
76	0.943	0	68	36
77	1.01173	0	61	28
78	1.00844	0	71	26
79	1.01307	0	39	32
80	1.04	477	130	26
81	0.99674	0	0	0

82	1	0	54	27
83	0.9939	0	20	10
84	0.98522	0	11	7
85	0.98832	0	24	15
86	0.98883	0	21	10
87	1.015	4	0	0
88	0.98914	0	48	10
89	1.005	607	0	0
90	0.985	-85	78	42
91	0.98	-10	0	0
92	0.99781	0	65	10
93	0.99121	0	12	7
94	0.99408	0	30	16
95	0.98534	0	42	31
96	0.99816	0	38	15
97	1.01423	0	15	9
98	1.02353	0	34	8
99	1.01	-42	0	0
100	1.017	252	37	18
101	0.99468	0	22	15
102	0.99538	0	5	3
103	1.00632	40	23	16
104	0.9882	0	38	25
105	0.98238	0	31	26
106	0.97259	0	43	16
107	0.952	-22	28	12
108	0.97665	0	2	1
109	0.97459	0	8	3
110	0.97285	0	39	30
111	0.98	36	0	0
112	0.975	-43	25	13
113	0.993	-6	0	0
114	0.96024	0	8	3
115	0.96015	0	22	7
116	1.005	-184	0	0
117	0.98241	0	20	8
118	0.94992	0	33	15

Table B.2: Generation and load data of the IEEE 118 bus system

G No	Fixed Cost (MBtu/h)	Generator costco-efficient b (MBtu/MWh)	Generator cost co-efficient c (MBtu/(MWh)^2)	Fuel Cost (£/MBtu)
4	0	10	0.01	1
6	0	10	0.01	1
8	0	10	0.01	1
10	0	10	0.01	1
12	0	10	0.01	1
15	0	10	0.01	1
18	0	10	0.01	1
19	0	10	0.01	1
24	0	10	0.01	1
25	0	10	0.01	1
26	0	10	0.01	1
27	0	10	0.01	1

31	0	10	0.01	1
32	0	10	0.01	1
34	0	10	0.01	1
36	0	10	0.01	1
40	0	10	0.01	1
42	0	10	0.01	1
46	0	10	0.01	1
49	0	10	0.01	1
54	0	10	0.01	1
55	0	10	0.01	1
56	0	10	0.01	1
59	0	10	0.01	1
61	0	10	0.01	1
62	0	10	0.01	1
65	0	10	0.01	1
66	0	10	0.01	1
69	0	10	0.01	1
70	0	10	0.01	1
72	0	10	0.01	1
73	0	10	0.01	1
74	0	10	0.01	1
76	0	10	0.01	1
77	0	10	0.01	1
80	0	10	0.01	1
82	100	10	0.01	1
85	0	10	0.01	1
87	0	10	0.01	1
89	0	10	0.01	1
90	0	10	0.01	1
91	0	10	0.01	1
92	0	10	0.01	1
99	0	10	0.01	1
100	0	10	0.01	1
103	0	10	0.01	1
104	0	10	0.01	1
105	0	10	0.01	1
107	0	10	0.01	1
110	0	10	0.01	1
111	0	10	0.01	1
112	0	10	0.01	1
113	0	10	0.01	1
116	0	10	0.01	1

Table B.3: Cost models of generators in the IEEE 118 bus system

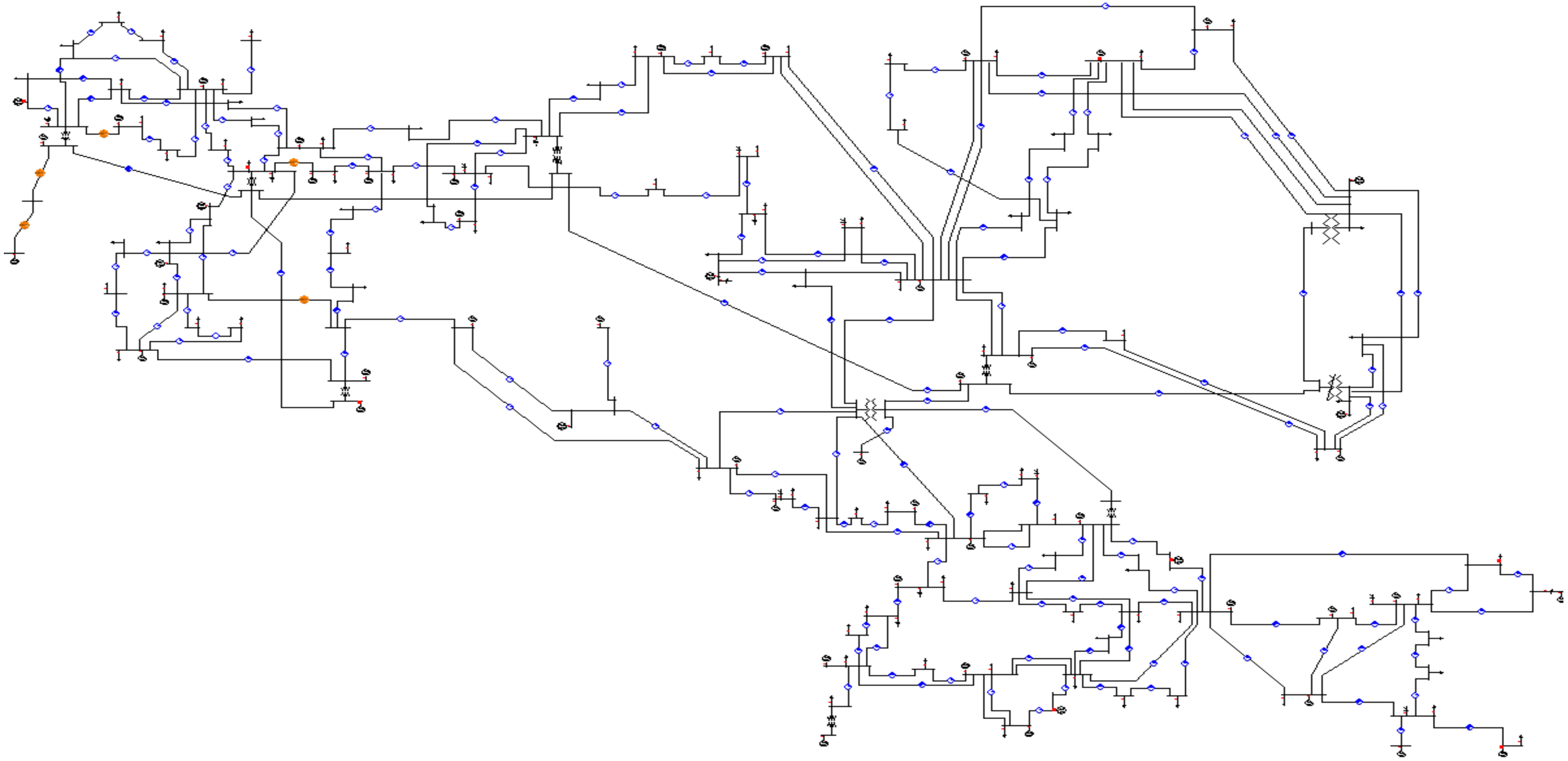

Figure B.1: The IEEE 118 bus system