Optimal Procurement and Pricing of Reactive Power Ancillary Services in Competitive Electricity Market

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By

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DEDICATION

This thesis is dedicated to my parents

for their

pure and unconditional love to me

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I would like to express my deepest and sincere gratitude to my supervisor, Professor K. L. Lo, Head of the Power Systems Research Group (PSRG), University of Strathclyde, for his supervision and most valuable guidance throughout the period of my research work. His encouragement and help greatly contributed in my current achievement.

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ABSTRACT

Electricity supply industries in many countries have gone through considerable changes since the deregulation of theirs in the late 1980s. Following deregulation power industry is unbundled into transmission, distribution and generation business. Ancillary services, such as reactive power support, can now be purchased from competitive providers. Reactive power plays an important role in power systems' operation and economic efficiency of electricity markets. This has made it a hot topic for research that attracts considerable attention from both system operators and market participants.

This thesis begins by presenting a general review of deregulated electricity markets as well as the characteristics of reactive power and the different reactive power sources. It continues to review the international reactive power markets in which the market designs and reactive power service compensation schemes are introduced.

Three major issues of reactive ancillary services were investigated in this thesis. An optimal reactive power procurement method is developed which system operator applies to procure reactive ancillary services taking into consideration technical and economical concerns of power system operation. A reactive power placement optimization method is developed to minimize new reactive power sources investment cost with respect to power system efficiency and reliability. A reactive power spot pricing with reactive power generation cost model is proposed and the aim is to use reactive power locational marginal pricing in a pricing mechanism.

Declaration of Author's Right

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Chapter 1

Introduction

1.1 Introduction

Traditionally, electric utilities have been vertically integrated monopolies that have built generation, transmission, and distribution facilities to serve the needs of the customers in their service territories. For the past decade, the electric power industry has gone through a process of transition and restructuring by moving away from these vertically integrated monopolies and towards competitive markets. This has been achieved through a clear separation between generation, transmission and distribution activities, as well as by creating competition in the generation sector. This restructuring process has created certain class of services such as frequency regulation, energy imbalance, voltage and reactive power control, and generation and transmission reserves, which are essential to the power system, in addition to the basic energy and power delivery services. This other class of services is referred to as ancillary services, and they are needed to ensure system security, reliability and efficiency.

Ancillary services are no longer an integral part of the electricity supply, as they used to be in the vertically integrated power industry structure, since they are now unbundled and priced separately. The Independent System Operator (ISO) is the entity entrusted to provide ancillary services through commercial transactions with ancillary services providers. In a competitive environment, the provision of these services must be carefully managed so that the power system requirements and market objectives are adequately met.

The Federal Energy Regulatory Commission (FERC) concluded in its Order No.888 [1], ancillary services consist of reactive supply and voltage control from generation sources; scheduling, system control and dispatch; regulation and frequency response; energy imbalance; operating reserve-spinning reserve and operating reserve-supplemental reserve. Reactive power supply and voltage control from generators is one of the six ancillaries that transmission providers must include in an open access transmission tariff. It also stated that reactive power from capacitors and FACTS controllers, installed as a part of the transmission system, is not a separate ancillary service [1]. However, there are recent recommendations for considering reactive power provision from these sources and to recognize them as ancillary services that are eligible for financial compensation [2]. FERC Order 2003 further states that a reactive power provider should not be financially compensated when operating within a power factor range of 0.95 lagging and 0.95 leading, but an ISO may change this range at its discretion [3].

Adequate provision of reactive power is essential in power systems in order to ensure their secure and reliable operation. Reactive power is tightly related to bus voltages throughout a power network, and hence reactive power services have a significant effect on system security. Insufficient reactive power supply can result in voltage collapse, which has been one of the reasons for some major blackouts worldwide [2]. The US-Canada Power System Outage Task Force states in its report that insufficient reactive power was an issue in the August 2003 blackout, and it recommended strengthening the reactive power and voltage control practices in all North American Electric Reliability Council (NERC) Regions [4].

In the vertically integrated power system structure, provision of reactive power by utilities was embedded within the electricity supply to customers. However, in the deregulated power system structure, reactive power is managed and priced separately as an ancillary service. Competition in generation makes it important to consider the development of a reactive power market that complements the existing energy market. In spite of the fact that the cost of reactive power production is much less than that of real power, reactive power is critical to system reliability since its sufficient provision is necessary to avoid an extremely costly system collapse. Moreover, under stressed system conditions, reactive power requirements from some generators are only met at the expense of reducing their real power output, and hence they significantly increase the cost associated with reactive power production.

Currently, most power system operators procure reactive power services from available providers based on operational experience and expected voltage problems in the system. In real-time, most system operators use power flow programs to dispatch reactive power from the already contracted generators. However, there are several issues and concerns associated with the current procurement practices and pricing policies for reactive power which call for further systematic procedures to arrive at more efficient service management and sufficient reactive power support for a more reliable power system [2]. Some of these issues are technical limitations associated with power system operation, whereas others are policy issues related to the rules under which the electricity market operates in a certain jurisdiction.

Some of the existing issues and potential problems with existing approaches to reactive power pricing and procurement needed more attention. There are several problems and concerns regarding the current procurement practices and pricing policies for reactive power world widely. These include a lack of transparent planning standards, non-competitive procurement, discriminatory compensation policies, rigid interconnection standards that may not meet local needs and poor real-time incentives for production, consumption and dispatch.

On account to the above existing and potential problems with reactive power, a lot of literatures studied and discussed concerned about those problems. A brief review of those literatures is as followed:

Beginning in the early 1980's, researchers were beginning to think about alternate ways of pricing electricity to achieve specific objective, such as maximal social welfare or system reliability. [5] presented a "new concept" in electricity pricing, a method which evolved into what is now known as locational pricing. In this work, it was suggested that a market for electricity can efficiently set location-specific prices based on instantaneous supply and demand that promote consumption patterns that benefit the transmission system. Implementing separate prices for real and reactive power would produce the most efficient pricing outcomes, even though the authors assert that the price of reactive power will often be insignificant compared to real power prices. The calculations for real power from this seminal work were expanded upon by [6] however, this later work does not discuss reactive power. Although some of the early economic publications mention reactive power or various schemes for voltage control, and indicate separate prices might be desirable, none rigorously consider the implications of reactive power prices or mechanisms for setting these prices [7].

In looking to the future of markets and policy, two general areas of research developed. One examines decentralized incentives for reactive power capacity and dispatch, how optimal power flows (OPFs) can be modified to incorporate reactive power costs, and what price signals would best capture the incentives for building capacity and ensuring performance. The other focuses on the role of centralized planning and control of reactive power planning and production in the era of restructured electricity markets.

Two case studies [8] were published in 1995 that represent the two sides of this new research. Both described methods for dispatching reactive power, but one paper described a centralized reactive power management program, which serves to ensure that efficient amounts of reactive power support are supplied by the transmission and distribution system. It also described how to meet unexpected reactive power demand with generators The other paper [9] explained reactive power dispatch based on two complimentary OPF calculations, one minimizing cost to obtain economic benefits, and the other minimizing the amount of "control action" – the number of physical controls that change – in order to maintain physical practicality. Neither paper advocated pure market economics or centralized control, but each placed greater emphasis on one or the other, and this is how most of the debate has been framed since the mid-1990s.

In the following few years, researchers studied the new role of system operators in relation to reactive power and what function centralized planning and control should have. An integrated method for capacity planning was proposed based on OPF iterations, determining the best location and size of capacitor banks on a system [10]. The Reactive Services Working Group at PJM [11] proposed several short- and long-term strategies for combining centralized requirements and planning with decentralized bidding for capacity projects, along with a two-part tariff to encourage capacity and performance. [12] suggested creating Voltage Control Areas (VCA) as a strategy for controlling voltage by blending centralized and decentralized control. Voltage set-points are determined by the VCA system operator, but decisions about dispatch to meet these set-points are based on economic bids and long-term contracts.

Meanwhile, several reports [13-16] were published that examined the implication of using different objective functions in traditional OPF algorithms to optimize reactive power dispatch. These objectives included minimizing network losses, minimizing the movement of transmission devices (like transformer taps), maximizing social welfare and minimizing total costs (including implicit costs like changing transformer taps). These reports also looked at the possibility of pricing reactive reserves, the cost of outages or reactive power curtailments and a responsive demand-side. One report attempted to internalize all aspects of the power system – all traditional OPF constraints as well as load frequency control, harmonic distortions and emission rates – into one set of prices in order to create a truly efficient market with minimal need for centralized planning or control [17].

In recent years, the research interests of reactive power are on the improvement of approaches of reactive power optimization, reactive power market pricing and reactive market structure [18-20].

1.2 Objective and Scope

Under deregulated electricity market, amongst the responsibility of an ISO is to ensure adequate reactive power support through the system. ISO compensates reactive power support providers (in different ways according to each market regulations) and recover this cost from all consumers. Therefore, there are two distinguished areas when concerning reactive power support service under deregulated energy markets. These two areas are:

- Area one: the procurement of reactive power from reactive power sources based on the need of the network in order to satisfy the requirements of system reliability and security standards.

- The allocation of the provided reactive power, and thus its cost, to all system users including reactive power providers (as they might receive reactive power support more than what they produce) according to their utilization of the network [4].

The objective of this thesis was to investigate area one and propose a novel reactive power procurement model and locational spot pricing based on a new proposed reactive generation cost model. The scope of this thesis can be summarized as follows:

- To introduce the physical characteristics of reactive power and various reactive suppliers as ancillary service providers in competitive electricity market

- To review some world experiences on various international reactive power markets.

- To develop a new reactive power procurement model in ancillary services market which can make the ISO to purchase the reactive power supply in an economical and secure consideration.

- To evaluate the impact of renewable generation (wind generation) pattern on the system operation especially reactive power requirement and system voltage profile in the trend of large renewable energy generation penetrating into the power networks.

- To develop a new reactive power placement method to locate and size the new reactive power sources considering both economical investment and secure system operation condition.

- To spot price the reactive power ancillary service locationally with a new reactive power generation cost model

1.3 Original Contributions of the Thesis

Based on the above objectives, this research has achieved the following main original contributions:

1. A new optimal reactive power procurement model has been proposed. It is based on the reactive power procurement approach considering the real power losses, power quality and total reactive power payment at the same time. It is formulated as a multi-objective optimization function and is solved using Differential Evolutionary (DE) algorithm.

2. A new multi-objective optimal reactive power placement method in power system is proposed. It compromises system technical requirement and financial investment concern.

3. A new locational spot pricing of reactive power method is proposed. It uses a proposed opportunity cost function to be the generator's reactive power cost function to calculate the reactive locational marginal price. Using this proposed locational spot pricing method of reactive power makes the generator operate in the economical and secure state which is the strength of the proposed opportunity cost function.

1.4 Organization of the Thesis

This thesis is made up of six chapters. They are organized as follows:

Chapter 1 gives an introduction to the whole thesis, and highlights the contribution of the thesis, outline of the thesis and a list of publications produced as a result of the research work.

Chapter 2 will present a review of deregulated electricity market especially the ancillary services markets. Furthermore, the physical characteristics of reactive power will be introduced. Finally, a literature review of international reactive power markets will be given to compare the difference of various reactive power procurement and charging methods in different countries worldwide.

Chapter 3 will introduce the reactive power costing methods in ancillary services market which includes costs from a generation source and from transmission sources respectively. And reactive power procurement models and their classical mathematical models of optimization in power market are reviewed. Meanwhile, the reactive power optimization algorithms which are categorized into classical algorithms and artificial intelligence algorithms are introduced in this chapter. There into, the principles and calculating flowchart of differential evolution algorithm is discussed in detail. The proposed optimal multi-objective reactive power procurement model is illustrated in IEEE30-bus and IEEE-118-bus systems respectively.

Chapter 4 will evaluate the system-wide reactive power requirement and voltage profile and then a case study of a modified IEEE-30bus system will be used to evaluate the impact of wind penetration on the system-wide reactive power requirement and voltage profile. With high wind penetration into the power system, there will be a bigger risk to system stability which hereby means the shortage of sufficient reactive support. Therefore, a optimal reactive power placement method will be proposed here and it will be illustrated in a IEEE30-bus test system.

Chapter 5 will present locational spot pricing of reactive power. The chapter will review the literatures of real and reactive power pricing methods first, and then introduce the spot pricing theory. The mathematical formula of locational marginal price of reactive power based on AC power flow is presented. The proposed reactive power generation opportunity cost is applied in the above mathematical formula. Finally, the proposed reactive locational marginal pricing will be assessed in a simple 5-bus test system.

Chapter 6 will summarize the thesis and outline the major contributions of the thesis, its limitations and suggest possible future continuation work or advancements from those presented in this thesis.

1.5 Publications

The following have been published or under review as a result of the research work reported in this thesis:

1. K. Yang, A. Garba, C.S. Tan and K.L. Lo, 'The impact of wind generation on reactive power requirement and voltage profile', 2008 IEEE DRPT, The 3rd intertional conference on electric utility deregulation and restructuring and power technologies. 6th-9th April,2008,Nanjing,China
2. A. Garba, C. S. Tan, K. Yang, K.L. Lo, 'the impact of renewable generation on system locational marginal price and total system losses' (under preparation)
3. K. Yang, K.L. Lo, 'optimal reactive power procurement in ancillary services

market using Differential Evolutionary algorithm ' (under preparation)

4. K. Yang, K.L. Lo, 'optimal reactive power placement using Differential Evolutionary algorithm ' (under preparation)

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Chapter 2

Reactive Power as Ancillary Service

2.1 Introduction

From the beginning of the establishment and development of the Electricity Power Industries (EPI) it is a natural monopoly. A vertically integrated electric utility which is traditionally owned by government or state authority and operates its generation plants, electric transmission systems, and its distribution network that delivers electricity to customers. Within a regulated environment it was made responsible for planning, building, operating and maintaining the integrated power systems. Those with exclusive franchise areas were granted the right to provide service in a designated service territory. Within these service areas, public utilities were protected from competition from enterprises offering the same services. The utilities being vertically integrated, it was often difficult to segregate the costs incurred in generation, transmission or distribution. Therefore, the utilities often charged their customers an average tariff rate depending on their aggregated cost over a period. The price setting was done by an external regulatory agency and often involved considerations other than economics.

Apart from operational issues, such vertically integrated utilities also had a centralized system of planning for the long-term. All activities such as long-term generation and transmission expansion planning, medium term planning activities such as maintenance, production and fuel scheduling were coordinated centrally.

In recent years, there have been widespread moves to deregulate, to liberalize and privatize EPI across the world. Under restructuring and deregulation, vertically integrated utilities, in which producers generate, transmit, and distribute electricity, have been legally or functionally unbundled. The EPI has moved from a monopoly structure to a more competitive one. Such structural reforms increase competition among electricity utilities companies. Competition has been introduced in the wholesale generation and retailing of electricity. Wholesale electricity markets are organized with several generation companies that compete to sell their electricity in a centralized pool and /or through bilateral contracts with buyers. Retail competition, in which customers can choose among different sellers or buy directly from the wholesale markets, has also been implemented. With the even deep restructure of the power market now, electricity markets are very complex markets that consist of several interactive markets for different producers (energy market, ancillary services market and transmission services market) and different time periods (long-term, one-day ahead, one-hour ahead, real time). They have been and continue to be developed around the world.

Although every energy market in the world has its own characteristics and rules that make it different from any other market, the underlining general structure is the same which consists of electrical energy market, ancillary services market and spot market.

This chapter presents a background on reactive power as ancillary service in a deregulated environment. It briefs the role of independent system operator in section 2.2 and the underline characteristics and operation of deregulated energy markets in section 2.3. Ancillary services markets and the reactive power as ancillary service are discussed in section 2.4 and 2.5 respectively. In the subsections of section 2.5, physical characteristics of reactive power and the definition of reactive power ancillary service are explored. Finally, section 2.6 presents examples of international reactive power markets which illustrate their practice in reactive power procurement and charging under deregulated environments.

2.2 Role of Independent System Operator (ISO)

The operation of a competitive electricity market would necessitate an independent operational control of the grid, hence an Independent System Operator (ISO) is established to ensure system operation, reliability and security, the ISO functions independent of any market participants, such as transmission network owners, generators, distribution companies, and end-users, and provides a non-discriminatory and fair access to all transmission system users. The roles of ISO are different in different market models. In bilateral market, the ISO is not involved in the energy market and its role is limited to purely ensuring that power transactions can be carried out between generators and loads. In the operational timeframe, the main function of the ISO is to maintain energy balance and system balance. Energy balance is related to the adequacy of the generation to match the load, and system balance is linked to satisfactory levels of reactive power, operating reserve and other Ancillary Services (AS). The ISO also coordinates measures to alleviate transmission congestion and perform contingency analysis for security analysis. In the Pool market, in addition to the above the ISO is also responsible for energy trading. Its roles would include generation and AS scheduling, pricing of transmission facilities, dispatching generation in cases of imbalances, and facilitate the energy and AS markets.

2.3 Deregulated Electrical Energy Markets

The primary motivation for power industry deregulation is to facilitate power systems by utilizing the diverse services available to the market. In another word, establishing deregulated electricity market is a way to enhance the power system security through its economics.

To achieve this goal, several models for the market structure have been considered. Four basic market models are outlined below:

2.3.1 Pool Markets

A pool market is defined as a centralized marketplace that receives generators' bids and suppliers' offer and it dispatches them to balance the system. Although the pool determines the market rules and procedure, it does not sell or buy electricity. The UK pool and Australia NEM are examples of this model [1]. All power supply is controlled and coordinated by the System Operator (SO). The SO would implement the economic dispatch and produce a System Marginal Price (SMP) for electricity, giving market participants an economic signal for consumption and investment decisions. In pool market, the power supply and demand bid curves are established by asking generating companies and consumers to submit offers specifying quantity and price and ranking these offers in increasing or decreasing order of price. The intersection between the generation and demand curves represents the market equilibrium point which determines the total system dispatch generation and the SMP (also called market clearing price), Figure 2.1 illustrates these concepts, it is the cost of one more MWh of electricity. Generators are dispatched to produce electricity at the quantity according to the SMP per MWh and get paid by this price. Similarly, the load consumes the same quantity of power and is charged the same SMP per MWh, irrespective of their actual bids. This process is called uniform auction in which the price is uniform across the network.

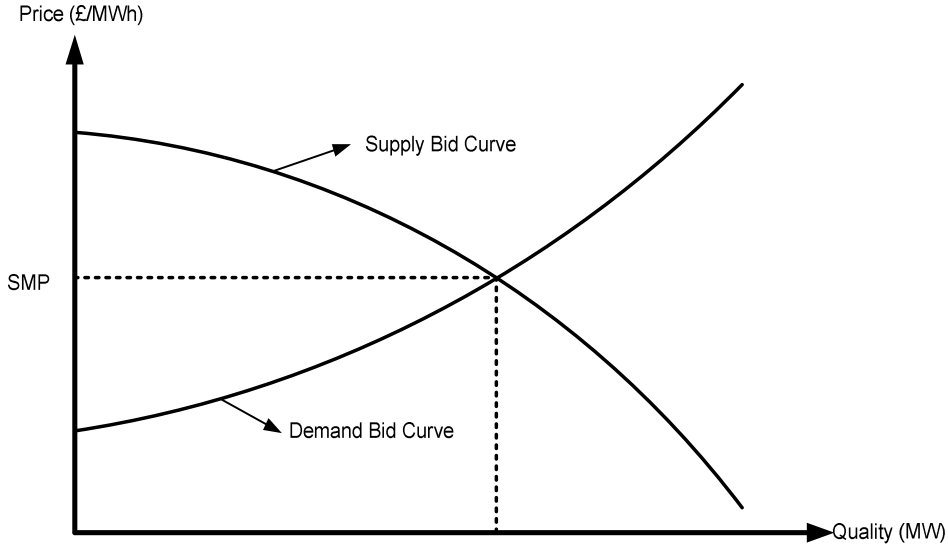

Figure 2.1 Market Equilibrium

The pool model, has a high market price transparency which is an important market driver and is the main benefit of this model, however, in the pool market it is believed that some large generators do exercise market power regularly. The market inefficiency of this model has been documented in [2][3]. In addition, the competition takes place only on the generation side which means there is no demand side participation [4].

2.3.2 Bilateral Markets

In bilateral market contract model, there are only two parties involved in this trading: a buyer and a seller. They negotiate on the agreements on delivery and receipt of power. In bilateral contracts, the terms and conditions of agreements are set independent of the ISO. The role of ISO is narrowed to manage real time balancing and ancillary services. After the participants submit their bilateral contracts which specify the agreements on quantities and the amount of time available of power, the ISO would verify that a sufficient transmission capacity exists to complete the transactions and maintain the system security. The bilateral contract model is quite flexible as the price of each transaction is set independently by the parties involved. There is thus no “official” price. However, the disadvantage of it is its high cost of negotiating and writing contracts, and the risk of the creditworthiness of counterparties. BETTA (British Electricity Trading and Transmission Arrangement) in UK is a practical example of bilateral market model [5][6].

2.3.3 Hybrid Markets

Most electricity markets worldwide are a combination of bilateral and pool market. In this model, market participants have the options of bidding into the pool market and/or make bilateral contracts with each other. This model provides more flexible options for the energy trading due to its wide variety of services and pricing options to best meet individual customer needs. Northeast US (NY, PJM and California ISO) and NordPool markets are examples of this model [7][8][9][10].

2.3.4 Spot Markets

Similar to every commodity, in electricity trading there is almost always imbalances between generation and loads that are contracted in real time dispatches. Loads change continuously over time and generators may experience unexpected problems that force them to go out of services and prevent them from delivering their contracted energy. Other factors such as transmission constraints and outages may contribute to the real time imbalances. Although most of the electricity is traded through energy market, i.e. pool, bilateral and hybrid markets, these markets can not maintain system security and reliability. Thus spot market must be organized in which imbalance between load and generation is maintained as the real time of delivery approaches. ISOs always coordinate the spot market to ensure system security and reliability as well as market efficiency. In order to increase market economic efficiency the spot market participants determine the cost of buying or selling energy to balance the network.

ISOs receive bids and offers from loads and generators which are willing to adjust their production or consumption in real time to balance the network. All buyers and sellers are supposed to be allowed to submit their bids and offers in competitive markets. Loads may offer to increase or decrease their demands and generators may offer to increase or decrease their outputs as well. A load can offer to increase its consumed energy if it values the per unit energy more than the market price whilst it can offer to reduce its consumption if the price is greater than the value of the consumption. On the other hand, a generator may offer to pay to reduce its output if the incremental price of its offer is greater than the marginal cost of its generation. The ISO combines that information with its own forecast of the total load to determine by how much the system is likely to be in imbalance. Figure2.2 [11] illustrates the operation of spot market managed by ISO.

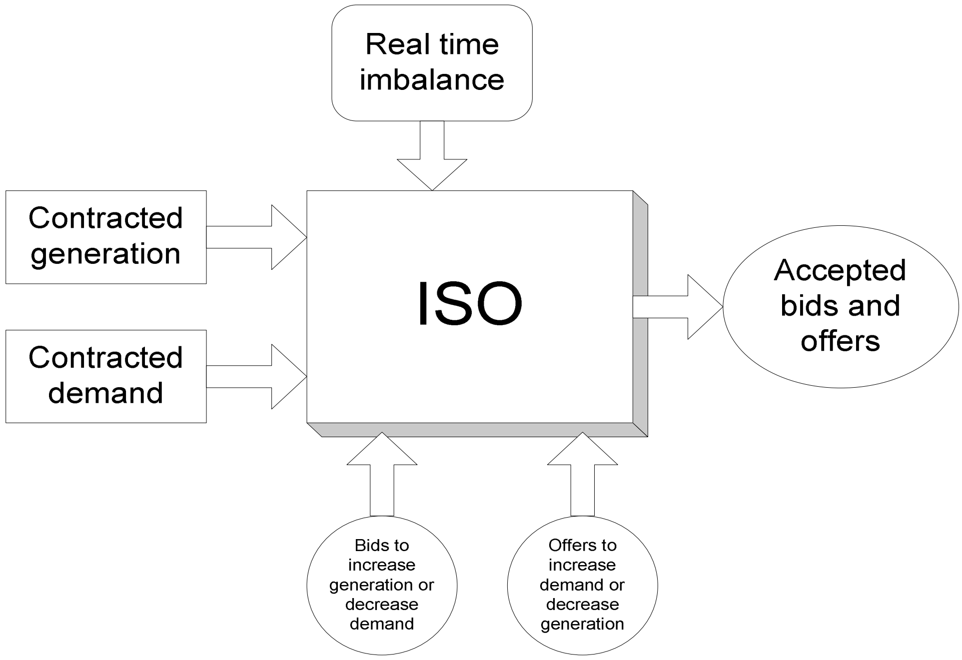

Figure 2.2 The operation of an ISO managed spot market for electricity

Using the BETTA market model in UK as an example, the spot market takes place 24-48 hours before gate closure period. The overview of the interaction of BETTA spot market and other markets is shown in Figure 2.3 [12]. Similarly, the Nordpool spot market is a day-ahead market, where generators and loads submit their bids to market 12-36 hours in advance of energy delivery. Then, for each hour, the price that clears the market which balances supply with demand is determined at the NordPool power exchange. Approximately 45% of total electricity production in the Nordic countries is traded on the spot market. The remaining share is sold through long-term, bilateral contracts, but the spot price has a considerable impact on prices agreed on such contracts. In Demark, the share sold at the spot market is as high as 80 per cent [13].

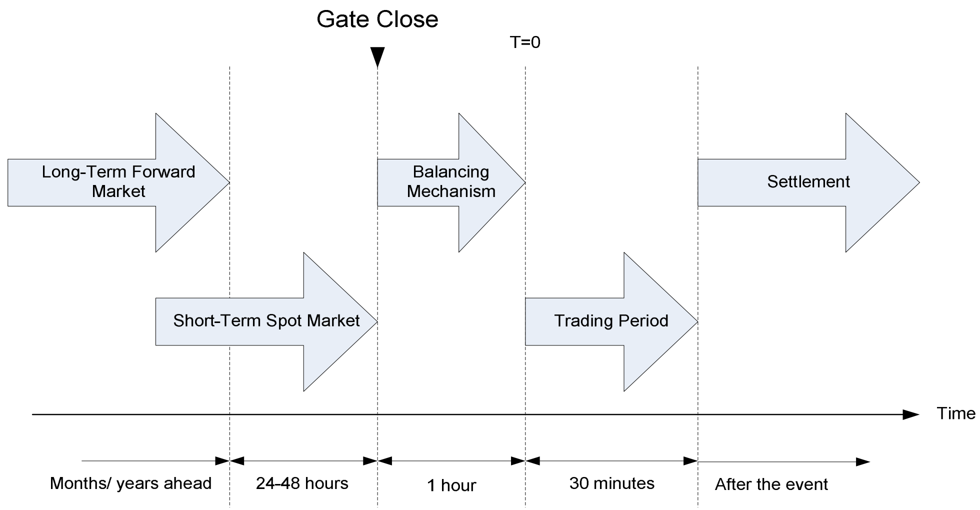

Figure 2.3 BETTA Timeline

2.4 Ancillary Services Markets

Ancillary services (AS) are needed to secure the power grid and to meet system reliability stands. In the regulated power industry, AS are bundled with energy trade. However, after the deregulation of the power market AS are mandated to be unbundled from energy market. They are additional services which are required to produce stable and efficient power supply to meet the real-time power balance. There are many lists of AS which differ mainly in how they are combined in service categories. The following paragraphs present the list of AS defined by FERC in the US.

Ancillary services as defined by the Federal Energy Regulatory Commission (FERC) of the United States are “those services that are necessary to support the transmission of capacity and energy from resources to loads while maintaining reliable operation of Transmission Provider’s Transmission System in accordance with Good Utility Practice" [14][15][16]. They consist of six services which make up the basic components needed for competitive electric power markets [17].

- **Scheduling, system control and dispatch** The ISO offers this service in which generation and transmission utilities are scheduled. It also coordinates transactions with other entities. And it dispatches some generation to keep system reliability at all times of its control area. The response time of this service ranges from seconds to hours. This service could also include post transactions accounting and billing.

- **Reactive supply and voltage control from generation sources** The ISO provides this service to maintain a proper transmission line voltage by controlling reactive power generation throughout the control area. Various reactive power generation sources (e.g. capacitors, reactors, condensers, tap-changing transformers, static var compensators.) are used. This service ensures also that there is enough reactive power reserves to secure the network in all considered contingency conditions. The response time of this service is in seconds.

- **Regulation and frequency response** The generators with Automatic Generation Control (AGC) device quickly track any mismatch in MW per minute between generation and load within the control area and are used in this service to maintain the standard interconnected scheduled frequency levels. The time scale of this service is about one minute.

- **Energy imbalance** This service uses the generators to correct the hourly mismatch between a transmission customer's energy suppliers and the consumers being served in the controlled area due to the mismatch between actual and scheduled energy.

- **Operating reserve - Spinning reserve** This service provides on-line generation synchronized capacity which can respond immediately and fully available within 10 minutes to correct any power mismatch due to unexpected outages. The response time of this generation capacity ranges from seconds to ten minutes.

- **Operating reserve - Supplemental reserve** The provision of generating capacity and interruptible load used to correct for generation/load imbalances caused by generation and transmission outages. This service is fully available within 10 minutes. The difference between this service and the spinning reserve one is that the supplemental reserve does not have to begin responding immediately.

Although a transmission provider must be equipped to offer all six services to customers, FERC clarified that only the first two ancillary services are required to be offered to all customers. For the other four ancillary services, FERC allows the customers obtain the services from transmission provider, third party, or self-provision.

2.5 Reactive Power as an Ancillary Service

2.5.1 Physical Characteristics of Reactive Power

2.5.1.1 System Requirements for Reactive Power

Reactive power plays an important role in power systems. Adequate availability of reactive power is required to maintain the voltage profile across the real power transmission. Both utilities and customer equipments are designed to operate at a certain voltage rating. Prolonged operation of that equipment at voltages under or over this rating, could adversely affect their performance and possibly cause damage.

The demand for reactive power on a transmission system varies significantly with loading conditions and reactive power support provides the main means of regulating the voltage in the system. During light loadings the transmission network generates reactive power which may need to be absorbed to maintain the desired voltage level. On the other hand, during heavy loading conditions the transmission network may absorb a vast amount of reactive power which needs to be supplied to raise the voltage to an appropriate level [18]. Therefore, an efficient management of reactive power is essential for maintaining an acceptable voltage profile.

The consequences and causes of voltage deviations need to be identified before the system reactive requirement can be identified [19]. For instance, under-voltage on the transmission network, which is generally associated with heavy loadings and /or a shortage of reactive support may be an indication that the system is approaching its stability limits. On the other hand, over-voltage is dangerous because of the rise of shortening the useful life of insulation or causing its breakdown. Lightly loaded high voltage transmission lines, particularly cables, can generate considerable amount of reactive power and increase the voltage. Therefore, controllable reactive power sources, either generation or absorption, located at various nodes across the transmission system are used to maintain the voltage within permissible limits.

Clearly, adequate reactive power support is needed to meet the requirements of the transmission system to support the transport of real power in terms of maintaining an acceptable voltage profile. The requirements vary both with location of the system demand and with the daily load cycle [20].

Real power flow profile, in the system determined by real power generation pattern, can influence considerably the reactive requirement in the system. Thus, increasing real power generation in predominantly load (importing) areas can reduce the requirement for reactive support in that area. Hence the reason why DG can reduce power losses and improve the system voltage when connected to the distribution network.

The system requirements for reactive power can be summarized as follows [21]:

i. To satisfy overall system and customer requirements for reactive energy on a continuous basis.

ii. To provide a reserve to cover changed reactive requirements caused by contingencies and by changes in real power trading which is beyond the control of the system operator.

iii. To maintain system voltages within acceptable limits, whilst managing system losses to ensure the efficient operation of transmission system mainly for real power transfer. Good voltage control practice usually coincides with the minimization of reactive power flows in order to manage real power losses and thermal capability of the transmission.

iv. Optimize system losses

2.5.1.2 Reactive Power Sources

Practically, there are various electric devices in AC power system that can produce or absorb reactive power. They are generally divided into two main categories: static and dynamic reactive power sources. Capacitors and inductors (or reactors) supply and consume static reactive power, respectively. These are called static devices since they have no active control of the reactive power output in response to the system voltage. Synchronous generators, synchronous condensers, Flexible AC Transmission Systems (FACTS) including static Var compensators (SVC), static compensators (STATCOM) are considered as dynamic reactive power devices capable of changing their output quickly according to pre-set limits in response to the changing system voltages.

Reactive power is produced or absorbed by all major components of a power system. Four major components categories (i.e. generators, power transfer components, loads and reactive power compensation devices) are presented as follows:

2.5.1.2.1 Generators

- Synchronous Generators

Principlly, synchronous generators are installed to supply real power and reactive power. Reactive power supports the voltage when the generator is over-excited and is absorbed when it is under-excited. The ability of a generator to continuously provide reactive support depends on its real-power production. Figure 2.4 shows the combined limits on real and reactive production for a typical generator which is referred to as reactive power capability curve [22].

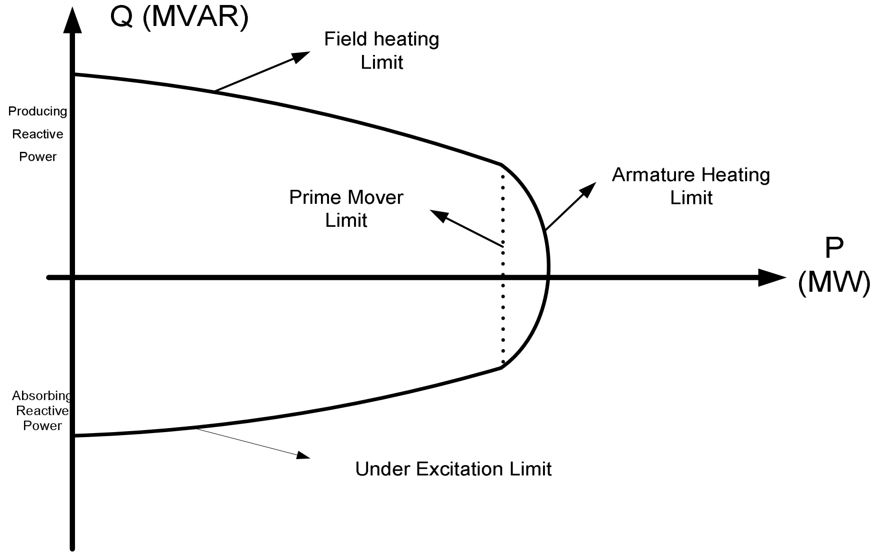

Figure 2.4 Reactive power capability dependent on real power production for a synchronous generator

When a generator increases its reactive power output, its real power output may need to be reduced if the generator is operated at its limits as it can be seen from the figure. A generator can smoothly change its reactive power output within its designed capability limits by using Automatic Voltage Regulators (AVR) to adjust the generators' terminal voltages to a specified set value by system operators.

When a generator can no longer offer more reactive support due to its reactive limits, it looses the ability of voltage control. Generators have a longer time of response if they need to reduce their real power outputs or they are off-line in which their ramp rate and start up times will determine how fast they can adjust their reactive power outputs. The maintenance costs of generators are high due to the moving mechanical parts and cooling systems [23].

- Distributed Generators

Distributed generators are small power sources that are connected to lower voltage electric distribution system. They may be owned by utilities, large industrial plants or customers. Distributed generators have similar characteristics as synchronous generators as they produce dynamic reactive power and the reactive power output can be quickly adjusted within the generator operating limits. However, it will require more time to synchronize a distributed generator to the network if the generator needs to be started or its real power output needs to be adjusted. The major advantage of distributed generator is that they provide reactive power support locally to reduce reactive power losses in transmission lines. As a result, it improves the stability and the efficiency of the power transmission network [24].

2.5.1.2.2 Power Transfer Components

The major power transfer components are transformers, overhead lines and underground cables. HVDC converter stations can also be treated as power transfer components.

- Transformers

Transformers provide the capability to raise or decrease voltage levels. It raises the voltage on generation side and lowers distribution system voltage to make long-distance power transfer practical and efficient. However, they also consume reactive power since they are inductive devices. Normally, transformer-tap changer can be used for voltage control either on its primary or secondary side. It can be seen as pumping reactive power from one side of the transformer to the other to regulate voltage with itself does not consume or supply reactive power. But the control differs from that provided by reactive sources. On the other side, Phase Shifting Transformers with taps to control the phase angle difference across the transformer can control the real power flow. As a result, under the controlling of the real power flow along a line the reactive power consumed or produced by the line is also controlled.

◆ Overhead Lines and Underground Cables

Overhead lines and underground cables generate and consume reactive power according to the line loading conditions. The line capacitance supplies reactive power and the inductance consumes reactive power. In light loading conditions (i.e. at load below natural load, which is known as surge impedance loading), overhead lines produce reactive power while during heavy loading conditions (i.e. at load above natural load) they consume reactive power.

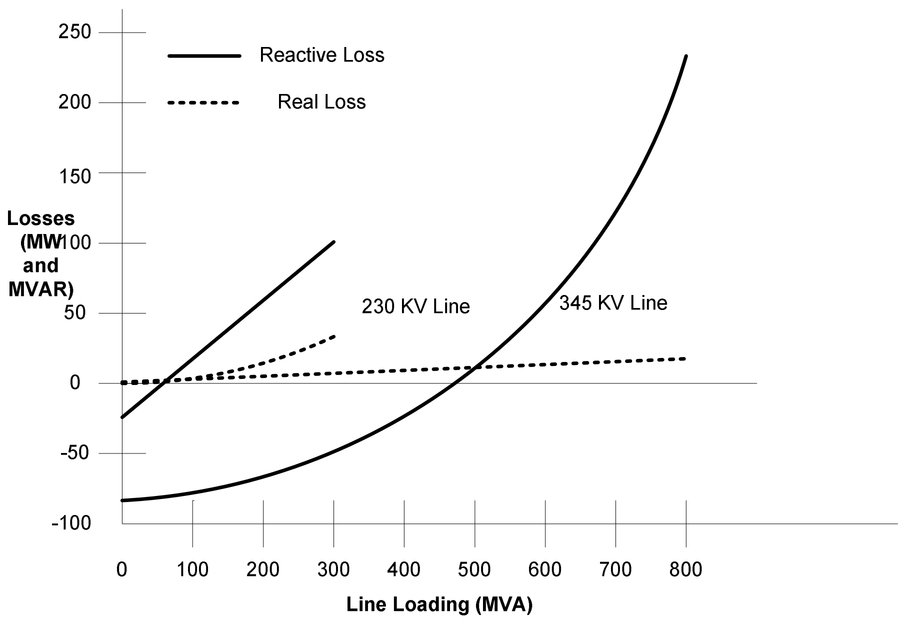

Figure 2.5 Transmission line real and reactive power losses versus line loading

Underground cables have high capacitance resulting in high natural loads. Therefore, they always produce reactive power as they operate below their natural loads in all conditions. The following two equations show the physical expression of this case. When $Q_{generation} = Q_{consumption}$ is called natural load in this case.

$$Q_{Generation} = V^2 B \quad \text{B – shunt susceptance} \tag{2.1}$$

$$Q_{Consumption} = I^2 X \quad \text{X – line / cable impedance} \tag{2.2}$$

As we see from the expressions above, reactive power generation is almost constant due to the voltage of the line is usually constant. However, the line's reactive consumption depends on the current or load connected to the line which is variable.

- HVDC Converters

HVDC converters always consume reactive power when in operation[19,22]. The reactive power requirements of the converter and system have to be met by providing appropriate reactive power in the station. For that reason reactive power compensation devices are used together with reactive power control from the AC side.

2.5.1.2.3 Loads

Load characteristics closely affect system voltage stability. The reactive power consumption of a load has a great impact on voltage profile at the bus. The response of loads to voltage changes occurring over many minutes can affect voltage stability. When industrial loads have poor power factor (low lagging power factor) they are usually charged by the system operator for their reactive power absorption from the network. And this compels them to install power factor correction devices (i.e. shunt capacitor banks) locally.

Some typical reactive power consuming loads examples are given below [23].

- Induction Motors

About 60 % of electricity consumption goes to power motors and induction motors take nearly 90 % of total motor energy depending on industry and other factors.

- Induction Generators (Wind Generators)

Since the wind has the nature of continuous variable and largely uncontrollable, wind generators can be seen as the reactive power loads expansion into the electricity sector. Some old wind plants are equipped with induction generators, which require a significant amount of reactive power. Part of the requirement is usually supplied by local power factor correction capacitors, connected at the terminal of each turbine. The rest is supplied from the network, which can lead to low voltages and increased losses. Thus they need extra reactive power compensation devices. Wind generators are usually self-dispatched which means the network takes whatever is available from them. Therefore, the system operator has to adjust the scheduling pattern to accommodate the variable outputs of wind generators in order to maintain system power balance.

- Discharged Lighting

About one-third of commercial load is lighting – largely fluorescent. Fluorescent and other discharged lighting has a voltage sensitivity PV in the range 1-1.3 and QV in the range 3-4.5. At voltages between 65-80 % of nominal they will extinguish, but restart when voltage recovers [23].

- Constant Energy Loads

Heating loads (i.e. space heating, water heating, industrial process heating and air conditioning) are controlled by thermostats which cause the loads to be constant energy continuously.

2.5.1.2.4 Reactive Power Compensation Devices

- Synchronous Condensers

Synchronous condensers are machines that are designed exclusively to provide reactive power synchronously. They consume real power from the system which is equal to about 3% of the machine's reactive-power rating to compensate their own losses. In North America, some retired fossil or nuclear power plant synchronous generators have been converted as synchronous condensers which are connected to transmission systems [23].

- Static Var Compensators (SVC)

Now the synchronous condensers places have been practically taken over by the Static VAR Compensators (SVC) because they have similar regulating characteristics with much cheaper maintenance cost. An SVC is an electronic device combining conventional capacitors and inductors with fast switching capability. For example, switching can take place in less than 1/50 of a second to provide a continuous range of voltage control by offering from absorbing to generating reactive power.

Considering the advantage of ability of near instantaneous response to system voltage control, SVC is very valuable in heavy load area with little generation. The remaining capacitive capability of an SVC is a good indication of proximity to voltage instability. SVCs provide rapid control of temporary overvoltages. But on the other hand SVCs have limited overload capability, because SVC is a capacitor bank at its boost limit. The critical or collapse voltage becomes the SVC regulated voltage and instability usually occurs once an SVC reaches its boost limit [26]. Compared with shunt capacitor banks, SVCs are expensive. So shunt capacitor banks should first be used to allow unity power factor operation of nearby generators.

- Static Synchronous Compensator (STATCOM)

The STATCOM is a shunt device that generates or absorbs reactive power to provide voltage support. It is one member of a family of devices known as flexible AC transmission system (FACTS) devices. The STATCOM is similar to the SVC in speed of response, control capabilities, and the use of power electronics. Rather than using conventional capacitors and inductors combined with thyristors, the STATCOM uses self-commutated power electronics to synthesize the reactive power output. Consequently, output capability is generally symmetric, providing as much capability for production as absorption [27]. On the other hand, STATCOMs are more compact than SVCs, requiring less space in a substation. Although their maintenance costs are higher than capacitor banks, their costs are still much less than generators.

- Series Capacitor

Series capacitors compensation is usually applied to increase long transmission line loadability and reduce line reactive power losses as well as to improve voltage profile. They are connected in series with the line impedance to reduce the overall line reactance.

- Shunt Capacitors

Transmission systems utilize shunt capacitors which produce real power to compensate for reactive losses and to maintain the voltage level during heavy load period. Switched shunt capacitors are installed in distribution systems to correct power factor and to control feeders' voltages. For voltage stability shunt capacitors are very useful in allowing nearby generators to operate near unity power factor. This maximizes fast acting reactive reserve. Compared to SVCs, shunt capacitors have the advantage of much lower installation and operation costs. However, because reactive power output from shunt capacitors is proportional to the square of the voltage it can be a problem when voltages drop to low value during a contingency or a depressed voltage condition, reactive power output is reduced according to the square of the voltage, causing voltage to fall further.

- Shunt Reactors

Shunt reactors are connected in shunt with line reactance to absorb extra reactive power on the line which is produced by charging capacitance of transmission lines. In the case of light load, they are utilized to compensate the capacitive load of the line.

Besides the above devices, other equipments are also involved in the provision of reactive power and voltage control, such as: Unified Power Flow Controllers (UPFC), other advanced FACTS (flexible ac transmission system) devices, tap staggering of transformers connected in parallel, disconnection of transmission lines, load shedding.

2.5.1.3 Reactive Power Flow in AC Power System

Electric power is usually generated, transferred and consumed in AC networks. There are two kinds of power in AC networks: real power (measured in Volt-Ampere or Watt) and reactive power (measured in Volt-Ampere reactive or Var). The total power is called apparent power (measured in Volt-Ampere or VA). The real power in watts is absorbed by a load at any time and is the product of the instantaneous voltage across the load in volt by the instantaneous current in ampere that passes the load [28]. If the current and voltage are expressed as follows:

$$i_{ab} = I_{\max} \cos(\omega t - \theta) \quad \text{and} \quad v_{ab} = V_{\max} \cos \omega t \tag{2.3}$$

The instantaneous power P is given by:

$$p = i_{ab} v_{ab} = \mathrm{I}_{\max} V_{\max} \cos(\omega t - \theta) \cos \omega t \tag{2.4}$$

Expanding equation (2.4) using the following trigonometric identity

$$\cos\alpha \cos\beta = \frac{1}{2}\cos(\alpha - \beta) + \frac{1}{2}\cos(\alpha + \beta) \tag{2.5}$$

The instantaneous power P is now given as

$$p = \frac{I_{\max} V_{\max}}{2} \cos\theta + \frac{I_{\max} V_{\max}}{2} \cos(2\omega t - \theta) \tag{2.6}$$

Then using the trigonometric identity

$$\cos(\alpha + \beta) = \cos\alpha\cos\beta - \sin\alpha\sin\beta \tag{2.7}$$

Results in the following useful formula

$$p = \frac{I_{\max} V_{\max}}{2} \cos\theta(1 + \cos 2\omega t) + \frac{I_{\max} V_{\max}}{2} \sin\theta\sin(2\omega t - \theta) \tag{2.8}$$

Where $(I_{\max} V_{\max})/2$ for sinusoidal currents and voltages can be replaced with the rms values $(I_{rms} V_{rms})$ as the rms of sinusoidal current and voltage equal $I_{\max}/\sqrt{2}$ and $V_{\max}/\sqrt{2}$ respectively.

Examining equation (2.8) shows that the first term is always positive and its average value is given by

$$P = \frac{I_{\max} V_{\max}}{2} \cos\theta \tag{2.9}$$

or, when using rms values of the currents and voltages,

$$P = I_{rms} V_{rms} \cos\theta \tag{2.10}$$

$\cos\theta$ is the cosine of the phase angle between the voltage and the current and is called the power factor. The lagging power factor indicates that the current lags the voltage (inductive load) whilst leading power factor indicates that the current leads the voltage (capacitive load).

The second term of equation (2.8) is an alternating term leading to an average of zero. This component of the instantaneous power is called the instantaneous reactive power which represents the alternating flow of energy between different elements of AC power networks. The maximum value of this term is called reactive power (Q) and has a very important role in power system operation. The reactive power is

$$Q = \frac{I_{\max} V_{\max}}{2} \sin\theta \tag{2.11}$$

The apparent power or complex power, S, is defined as

$$S = P + jQ \tag{2.12}$$

It is sometimes useful to calculate P and Q in terms of the impedance elements and currents as follows

$$P = I_{rms}^2 R \qquad Q = I_{rms}^2 X \tag{2.13}$$

Where R and X are the resistance and reactance of the impedance respectively.

Real and reactive power flows on transmission lines can be calculated using power equations. Let us assume that we have a simple system as shown in Figure 2.6.

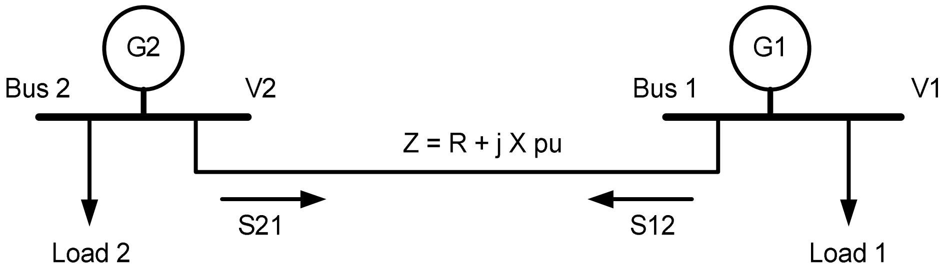

Figure 2.6 Power flows on a two bus system

We know that the complex power equals the voltage vector multiplied by the conjugate current vector, i.e. [49]

$$S_{12} = V_1 I_1^* = V_1 \left(\frac{V_1 - V_2}{Z} \right)^*$$

$$= \frac{V_1^2}{Z^*} - \frac{V_1 V_2^*}{Z^*} = \frac{V_1^2}{Z} e^{j\angle z} - \frac{V_1 V_2}{Z} e^{j\angle z} e^{j\theta_{12}} \tag{2.14}$$

Where $\theta_{12} = \theta_1 - \theta_2$, $\mathrm{V}_1 = V_1 \angle \theta_1$ and $\mathrm{V}_2 = V_2 \angle \theta_2$. Assume that the line resistance is neglected $(R = 0)$

$$Z = jX \text{ pu} \qquad \text{and} \qquad P_{loss}^{ij} = I^2 R_{ij} = R_{ij} \frac{P_j^2 + Q_j^2}{V_j^2} \tag{2.15}$$

Then

$$\mathrm{S}_{12} = j\frac{V_1^2}{X} - j\frac{V_1 V_2}{X} \cos\theta_{12} - j\left(j\frac{V_1 V_2}{X} \sin\theta_{12} \right) \tag{2.16}$$

So,

$$P_{12} = \frac{V_1 V_2}{X} \sin\theta_{12}$$

$$Q_{12} = \frac{V_1^2}{X} - \frac{V_1 V_2}{X} \cos\theta_{12} \tag{2.17}$$

Similarly, P_{21} and Q_{21} can be derived to get

$$P_{21} = -P_{12}$$

$$Q_{21} = \frac{V_2^2}{X} - \frac{V_1 V_2}{X}\cos\theta_{12} \tag{2.18}$$

In a typical multibus system, the following observations should stand [49]:

- $V_i \approx V_j \approx$ contant
- $\angle Z_{ij} \approx 90^o$
- $\theta_{ij} < 10^o$ for stability resaon

So, P and Q control are reasonably decoupled, i.e. it is possible to control one without significantly affecting the other. We notice from equations (2.17) that P_{12} has large $\sin\theta_{12}$ variation $(\approx 20\%)$ for small angles $(< 10^o)$ whilst $\cos\theta_{12}$ varies by only $\approx 1\%$ in Q_{12}. As a result, real power transfer is primarily controlled by voltage angle and it flows from a leading to a lagging angle. On the other hand, reactive power is more directly influenced by voltage magnitudes and it flows from a high voltage magnitude to a lower voltage magnitude.

More generally (i.e. $R \neq 0$), power received at bus j coming from bus i can be derived as follows

$$P_{ij} + jQ_{ij} = \mathrm{V}_j \mathrm{I}_{ij}^* \tag{2.19}$$

but

$$\mathrm{I}_{ij} = \frac{V_i\angle\theta_i - V_j\angle\theta_j}{\mathrm{Z}_{ij}} \tag{2.20}$$

$$\Rightarrow \quad \mathrm{I}_{ij}^* = \frac{V_i\angle-\theta_i - V_j\angle-\theta_j}{\mathrm{Z}_{ij}^*} \tag{2.21}$$

$\theta_j = 0$ if it is taken as the reference, then $\delta = \theta_i - \theta_j = \theta_i$, equation (3.17) becomes

$$P_{ij} + jQ_{ij} = \frac{V_i V_j \angle -\delta - V_j^2}{Z_{ij}^*} = \left(V_i V_j \angle -\delta - V_2^2\right) Y_{ij}^* \tag{2.22}$$

where $Y_{ij}^* = g_{ij} + jb_{ij}$. After some manipulations, we get

$$\begin{aligned} P_{ij} &= V_j \left[g_{ij}\left(V_i \cos\delta - V_j\right) + b_{ij} V_i \sin\delta \right] \\ Q_{ij} &= V_j \left[b_{ij}\left(V_i \cos\delta - V_j\right) - g_{ij} V_i \sin\delta \right] \end{aligned} \tag{2.23}$$

2.5.1.4 Reactive Power Losses

Power systems are not lossless networks but rather transmission lines have some impedances. This creates some losses in the network that vary according to operating conditions and system topology. System losses are the difference between total system generation and total system demands which can be solved in different ways. Load flow analysis provide the solution on AC networks in which all currents, voltages, and generation dispatches are determined. From a solved load flow, one can calculate total system losses as well as losses on individual components such as transmission lines and transformers.

Mathematically, total system losses (S_{loss}) is equal to the complex sum of injected complex power at all buses on the network [49].

$$\mathrm{S}_{loss} = P_{loss} + jQ_{loss} = \sum_{i=1}^{N}\left(P_i + jQ_i\right) \tag{2.24}$$

Where N is the total number of buses on the network and

$$P_i = \sum_{j=1}^{N} Y_{ij} V_j V_i \cos(\theta_{ij} + \delta_j - \delta_i) \tag{2.25}$$

$$Q_i = -\sum_{j=1}^{N} Y_{ij} V_j V_i \sin(\theta_{ij} + \delta_j - \delta_i) \tag{2.26}$$

Where,

P_i : Real power entering the system at bus i

Q_i : Reactive power entering the system at bus i

$V_{i,}V_j$: rms voltages at buses i and j respectively

Y_{ij} : elements of bus admittance matrix between buses i and j

θ_{ij} : angle associated with Y_{ij} in radians

δ_i, δ_j : angle of voltages V_i and V_j respectively

Total system losses can also be determined by the following formula [28][29]

$$P_{loss} = \frac{1}{2} \sum_{k=1}^{N} \sum_{m=1}^{N} G_{km} \left[V_k^2 + V_m^2 - 2V_k V_m \cos\left(\theta_k - \theta_m\right) \right] \tag{2.27}$$

and

$$Q_{loss} = \frac{1}{2} \sum_{k=1}^{N} \sum_{m=1}^{N} B_{km} \left[V_k^2 + V_m^2 - 2V_k V_m \cos\left(\theta_k - \theta_m\right) \right] \tag{2.28}$$

Where,

V_k, V_m : rms voltages at buses k and m respectively

G_{km} : conductance of the line between buses k and m

B_{km} : susceptance of the line between buses k and m

Y_{km} : element of bus admittance matrix between buses k and m

$Y_{km} = G_{km} + jB_{km}$

$\theta_{k,}\theta_m$: angles of voltages V_k and V_m respectively

One can also use the currents flows on branches to calculate real and reactive losses as follows [22]

$$P_{loss}^{ij} = I^2 R_{ij} = R_{ij} \frac{P_j^2 + Q_j^2}{V_j^2} \tag{2.29}$$

$$Q_{loss}^{ij} = I^2 X_{ij} = X_{ij} \frac{P_j^2 + Q_j^2}{V_j^2} \tag{2.30}$$

Where

$P_{loss}^{ij}, Q_{loss}^{ij}$: real and reactive power losses in branch ij respectively

P_j, Q_j : real and reactive power received at bus j

V_j : voltage magnitude at bus j

Equations (2.29) and (2.30) show that an increase of transferred reactive power causes an increase on both real and reactive power. This characteristic needs to be realized in voltage regulation in order to achieve acceptable level of system reliability.

2.5.2 The Definition of Reactive Power Ancillary Service

Although there is no standard definition of unbundled “reactive power service,” there does seem to be a common understanding of what it means shown in Table 2.1 [30].

Table 2.1 The Definition of Reactive Power Ancillary Service in different countries

Regions	Definition
New Zealand	The service is defined as “the dispatch of reactive power and other support resources with the objective of managing voltage within the normal limits set out in the Co-ordination Policy”. Although New Zealand recognizes that voltage control can be provided by a wide

	variety of resources, the only resources that receive payment for voltage support ancillary services are certain capacitors owned by the transmission firm, static VAr compensators, generators in synchronous comp mode, and generators that are constrained-on to provide voltage support.
California ISO	The California ISO defines reactive power control as action taken to maintain acceptable voltage levels throughout the transmission system and to meet reactive capacity requirements at points of interconnection.
New York ISO	The New York ISO defines Voltage Support Service as including the ability to produce or absorb reactive power, and the ability to maintain a specific voltage level under both steady-state and post-contingency operating conditions, subject to the resource's capability limitations
PJM	PJM divides generator reactive power products into two distinct types: "reactive power capability at rated generator output and reactive power provided at reduced generator output".

2.6 International Reactive Power Markets

2.6.1 UK

Operation code requires that all the scale of operation in more than 50 MW generating units are required to provide reactive power within a certain range of power factor. This part of reactive power is called Obligatory Reactive Power Service (ORPS). Of course, the generator can also provide reactive power outside this range. This part of reactive power is called Enhanced Reactive Power Service (ERPS) [31].

Unlike some power markets, in UK power market ORPS also receives financial compensation. There are two ways to receive financial compensation: Default Payment Mechanism (DPM) and Tender Market. If ORPS Services provided by generators do not take part in or they are not successful bidder in tender market, then it can obtain economic compensation through DPM. DPM consists of two parts: the capacity remuneration and the electricity remuneration. The capacity of remuneration depends primarily on the capacity of the quantity of generator, the associated installed capacity and reactive power requirement in one region. Whist the remuneration of electricity has to be adjusted in accordance with the UK consumer price index. Before April 1st, 2000, the ratio of the capacity of compensation and remuneration of electricity in DPM is around 80:20. After that, the ratio of the two was adjusted to 0:100 which means DPM compensated for electricity only. The generators who accept the remuneration of electricity must be able to correctly respond to system operator's instructions, or else their remuneration of electricity will be reduced to the original 20% [32].

National Grid Company (NGC) holds reactive services tender twice a year in which the reactive power service providers can bid on the capacity of reactive power and reactive power separately. They can bid for leading reactive power service, lagging reactive power service or both cases. Leading and lagging reactive power services separately are permitted to bid for a maximum of three times. Finally, NGC will decide which bid is been taken according to the system reactive power demand, the existing reactive service contracts as well as the current bid prices of the reactive power service providers. ERPS generally determined through the tender, the process is similar to ORPS [33].

2.6.2 Sweden

In Sweden, the procurement of reactive services is obligatory. Namely, there are no financial compensations for the reactive power service providers. Svenska Kraftnat owns the Sweden transmission networks (400 kV and 220 kV). It is also responsible for the system operation and controlling the reactive power exchange on high-voltage transmission line. Under normal circumstances, there is no reactive power exchange on high-voltage transmission networks, namely, the reactive power are compensated locally [34].

Regional power grids consist of the low-voltage transmission network and distribution network. Under normal circumstances, the regional power grid operators use static reactive power compensation equipments to obtain the necessary reactive power. Large generators are rarely used for secondary voltage control, which is mainly used to provide reactive power reserve. When a regional power grid lacks reactive power it may purchase reactive power from other regional grids, but the prices generally are very expensive.

Svenska Kraftnat through the grid code makes clear the responsibilities of reactive power supply when regional power grids and generators are connected to high-voltage transmission networks, as follows [35]:

1. For a hydro generation unit which is connected to high-voltage transmission networks directly, and the reactive power absorption capacity should be able to reach 1/6 of its maximum real power output.

2. For a thermal generation unit which is connected to high-voltage transmission networks directly, its reactive power injected capability should be to achieve 1/3 of its maximum real power output, but there is no requirement for reactive power absorption capacity.

3. For a regional power grid which is connected to high-voltage transmission networks directly, if it injects real power to high-voltage transmission network, then its reactive power injected capability should be to achieve 1/3 of its maximum real power output; but if it absorbs real power from the high-voltage transmission networks, there are no requirements for its reactive power injection and absorption abilities.

2.6.3 Republic of Finland

State Grid Company of Finland (Fingrid) strictly controls reactive power flows on its main transmission networks. Under general circumstances, it does not allow too much reactive power exchange on transmission network. The permitted reactive power exchange quantity is related to real power exchange quantity and it is free of charge inside the range of reactive power exchange of the Fingrid. In the case of exceeding the range of reactive power exchange, Fingrid collects the fees according to a fixed rate [34].

Because reactive power flows are strictly controlled on transmission network, Fingrid mainly uses capacitors and reactors for reactive power supply to maintain system voltage at a reasonable level. Generator's reactive power capacity is mainly used for reactive power reserve. The procurement of this service previously is obligatory, but after year 2002 it is compensated.

According to system operation regulation, generators with rated capacity of more than 10 MVA are required to maintain a certain amount of reactive power reserve under system normal operating condition [35]:

I. For generator connected to 400 kV power grid, apart from required reactive power capacity of its own running, its remaining reactive capacity should be as system Momentary Reserve.

II. For generator connected to 220 kV or 110 kV power grid, more than half of its reactive power capacity is used for momentary reserve and the remaining are used for commercial purpose.

III. For generator connected to lower than 110kV grid, more than half of its reactive power capacity is used for momentary disturbance reserve.

2.6.4 Netherlands

In Netherlands, voltage regulation and reactive power procurement are managed by network administrator instead of system operator. Except generators, reactive power Compensation equipments (i.e. capacitors and FACTS, etc.) and rechargeable power transmission lines, reactive power exchange with neighbor networks is also a source of reactive services. Among them, reactive services obtained from rechargeable power transmission lines and reactive power compensation equipments account for a considerable proportion. In addition, the network administrator can purchase reactive service through bilateral contracts according to the system reactive generation supply and load demand. Reactive service payment is only for reactive power capacity, not reactive power quantity [35].

2.6.5 Spain

In Spain power market, some reactive services are free but some are paid. Reactive power service providers can be generation companies, the transmission service suppliers, customers who buy the electricity from the market and distribution service providers.

All generators direct access to transmission networks with more than 30 MW installed capacity are required to provide reactive power output within power factor range from 0.989 leading to 0.989 lagging. This part of reactive power is free of charge. The generation companies may apply for offering reactive power service beyond this power factor range if they are willing to and system operator will determine whether or not to accept this application according to their contribution to system operation safety. If accepted, generation companies will get financial compensation based on fixed rate and their performance for response for their offering reactive quantity and reserve [35].

The cost of purchasing reactive power is average allocated in all the system users, regardless of its position in the system.

2.6.6 Australia

Reactive power service only provided by generators and synchronous condensers are treated as ancillary services in Australia and they receive financial compensation. All reactive power service providers will receive Availability Payment Component. If a synchronous condenser is dispatched by system operator, then it will also receive operation payment (Enabling Payment Component). If a generator is dispatched by system operator to provide reactive power service then it will get the payment of opportunity cost (Compensation Payment Component) [36].

Reactive power output from generators can be divided into two parts. The first part is within the range from 0.9 lagging to 0.93 leading power factor and generators are obligatory to produce reactive power. Namely, no matter whether generators have signed contracts to offer the reactive power service with the system they must provide it when necessary. The second part is to be regarded as ancillary services and given reactive power service compensation [37].

The process of how the system operator (SO) obtains reactive power services is as follows:

I. The SO calculates the reactive power requirement in systems.
II. In accordance with reactive power requirement switching capacitors, reactors and SVCs, etc.
III. Dispatch generators' reactive power output without reducing real power output. These generators consist of all generators which have signed bilateral contracts for reactive power service and the ones without contracts which are dispatched for obligatory reactive power output.
IV. In some specific regions in the system, dispatching synchronous condensers according to the high and low order of enabling price.
V. If extra reactive power services are needed then consider dispatching those generators who can only provide reactive power support when reducing real power output.
VI. If all the reactive power sources which have been used are still unable to meet the system reactive power requirement then consider cutting system trade.

2.6.7 Canada

In Ontario, all generators of more than 10 MW installed capacity are required by Independent Electricity System Operator (IESO) to be capable of supplying reactive power within a standard power factor range (i.e. 0.9 lagging – 0.95 leading). And generators are specially paid the compensation due to its capability to produce or consume reactive power only when an investment incremental to that required to produce real power within the standard power factor range and when such an investment requirement is not applied to other generators. Hence, there is no payment for reactive power capability within the standard power factor range. On the other hand, generator is compensated for its ability of operation beyond the standard power factor range. Besides, IESO compensates all generators which incur the real power losses due to operating with a non-utility power factor, whether within or outside of the standard power factor range. If it is applicable generators are also paid for lost opportunity costs [23] [38].

In Alberta, the Alberta Electric System Operator (AESO) requires all generators must operate continuously within power factor range (0.9 lagging – 0.9 leading) at normal power output. If generators are not capable of producing or absorbing reactive power within this range they may be penalized. Furthermore, generators do not get the compensations for operating within the specified range [39] [40].

2.6.8 USA

2.6.8.1 New York

In New York power market, ISO obtains the reactive power service mainly through a cost-based pricing mechanism. This pricing mechanism includes Capacity Payments, Lost Opportunity Cost (LOC) and performance requirement [41].

1) Capacity Payments

Capacity payments generally use \$/MVar per year as a unit, therefore, it is also called the annual capacity payments which includes the related expenditure of annual fixed costs of power generation equipments, liquidity costs of the provision of reactive power service equipment and equipments' operation and maintenance costs. Capacity payments are paid monthly. Generators that have signed contracts for an installed capacity are monthly 1/12 of annual capacity payments; synchronous condensers and the generators without signing the contracts for an installed capacity are monthly paid by the 1/12 of annual capacity payments of multiplied by a certain ratio. This ratio is determined by the number of equipments' actual current month operation hours.

2) Lost Opportunity Costs (LOC)

The aim of designing the opportunity cost payments for generators with providing reactive power Services is to make up for their financial losses in real power market. The lost opportunity cost can be calculated by equation (2.31):

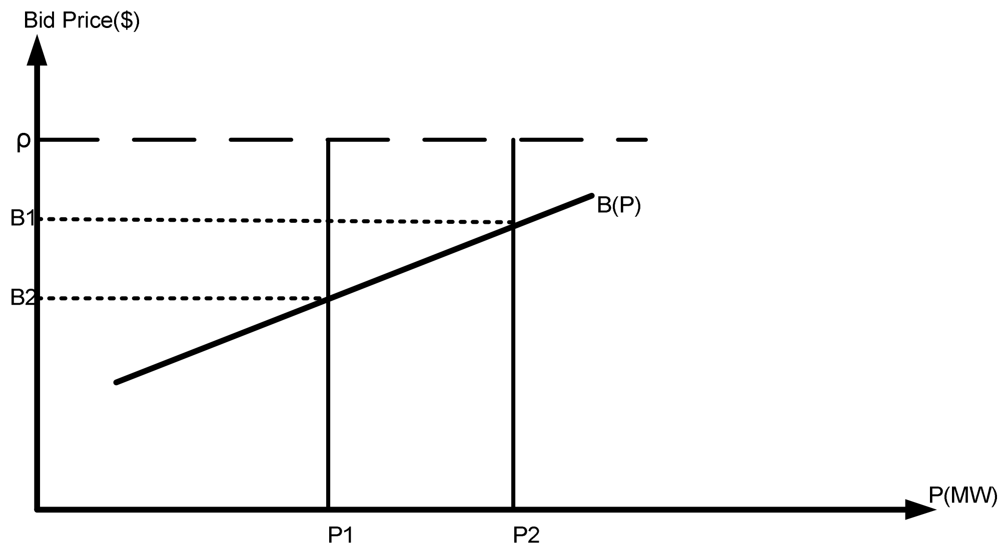

Figure 2.7 Lost opportunity cost

$$C_{op} = \rho_{mc} \cdot (P_1 - P_2) - \int_{P_2}^{P_1} B(p) \cdot dp \qquad (2.31)$$

C_{op} : the opportunity cost for generators providing reactive power services;

ρ_{mc} : real power price or market clearing price;

P1 : the real power output from generator on its initial operation position (namely, without providing reactive power service);

P2 : real power output from generator after offering reactive power service

$B(P)$: the bid price of generator's real power output

3) Performance Requirements

Generators which provide the reactive power services must be equipped with Automatic Voltage Regulator (AVR) and need to pass the test of reactive power response ability. In the practical system operation process, reactive power equipments are penalized for not responding to the ISO dispatch order according to the number of response failure times in one month. Reactive power equipments which do not meet the response requirement in the first time will be taken off on monthly capacity payments. At the same time, they need to pay to the ISO for corresponding reactive power alternative cost. Reactive power equipments which did not meet the response requirement three times in 30 days will loose their acceptance of receiving reactive power payments until they pass ISO stringent test of reactive response capability.

2.6.8.2 PJM

Generator reactive power services are divided into two parts. The first part reactive power is produced when generator providing real power services and second part reactive power is produced when generator reducing the real power output to produce more reactive power. The first part reactive power financial compensation has been included in the PJM integrated price whilst the second part is compensated by lost opportunity cost payment [42].

ISO needs to pay fees monthly of the reactive power service offered from generators’ "for convenience" provision of reactive power services and these fees are determined by the government’s monthly income of generators’ reactive power services. The income of generators’ reactive power services mainly determined by generator’s fixed cost which are allocated to offer the reactive power services and the losses produced by generators and voltage raising transformers when offering the reactive power services [43].

2.6.8.3 California

California ISO obtains reactive services through two methods: short-term reactive service payments and long-term contracts. Short-term reactive service payment is based on lost opportunity cost and calculated in every 10 minutes [44] [45] [46]. The calculating formula as follows[46]:

$$C_{op} = \max\{0, \rho_t - B_t\} \cdot P_{dec,t} \tag{2.32}$$

ρ_t : the energy price in trading hour t.

B_t : the bid energy price of generation unit;

$P_{dec,t}$: the reduction of real power dispatch when offering the reactive power in trading hour t. This payment is used to pay for the reactive power services offered when generators are obligatory to produce reactive power beyond the power factor range (from 0.9 lagging to 0.95 leading).

Long-term contracts are signed by ISO and Reliability Must-run Units signed. When ISO dispatches the reactive power output from these units beyond their obligatory reactive output the ISO needs to pay extra fees to these units.

2.6.8.4 New England

ISO New England (ISO-NE) compensates all generators providing reactive power support based on four ways: (1) capacity cost; (2) lost opportunity cost; (3) cost of energy consumed; and (4) cost of energy produced [23] [47]. There are no penalties for generators when they fail to provide reactive power in this market.

2.6.9 Japan

Tokyo Electric Power Company (TEPCO) makes retail customers to improve their power factor through financial incentive. The electricity rate is a two part combination: Base Rate and Electricity Rate, where [23]:

$$\text{Base Rate} = [\text{Unit Price (Yen/kW)}] * [\text{Contract (kW)}] * [1.85 - \text{Power Factor}]$$
$$\text{Electricity Rate} = [\text{Unit Price (Yen/kWh)}] * \text{Total Usage (kWh)} \tag{2.33}$$

The financial incentive appears in the form of a discount in the Base Rate which is based on the customer's power factor. If the customer's power factor is more close to the unity power factor then the customers can get more discounts. The unit price for Base Rate is about US10$/kW and the unit price for Electricity is US10¢/kWh. Under this tariff the average customer power factor is maintained at 0.99 because this charging scheme creates incentives to loads to install power factor correction equipments to reduce base rates.

2.6.10 China

In China, before electricity industry deregulation the power industry is integrated. Under this kind of industry management model, the reactive power management complies with technical guidelines of power system reactive power support and voltage control and other related industry standards and regulations. As a result of power system safety is put in the first place, the management of reactive power is essentially mandatory in the generation and transmission utility. On the load side, in accordance with the power factor management practices, through the power factor incentive pricing to encourage large users to build reactive power compensation equipment, improve the user side of the load power factor, and to participate in the normal voltage regulation process. The process of voltage control and reactive power management by the dispatch centre are different ways in accordance with the adaptability and voltage adjust demand to the regional power grid voltage monitoring points released through operating voltage curve.

With the reform of the electricity market, the regional power grids companies segment preview of operation and management in accordance with the different voltage levels and geographical and political areas. At present, 500 kV grid has become most of the provincial power grid backbone frame, characterized by the development of provincial electrical power grid links the gradual enhancement of regional power grids through the highest voltage interconnect implementation. Such features make the 500 kV regional grid voltage control operation of a gradual transition to a regional power network dispatch centre. Provincial power grid only controls 220 kV and below voltage network. The management changes are adapted to the development of regional power grids. At the same time it also develops a foundation for the regional electricity market. At the current stage of development of China's electric power market, after the separation of generation and transmission utility the power generation becomes market competitive, but the management of transmission and distribution remains integrated. At this stage of development of the electricity market, reactive power management mechanism also will be greatly affected [48].

2.7 Summary

This chapter has presented the biography of the transition from vertically integrated utilities environments towards deregulated electricity markets. Then the function of the independent system operator in the deregulated environment and the three types of energy markets were explained. Besides energy markets, this chapter has briefly highlighted the importance and mechanism of spot market. Then, the need for ancillary services markets and the categories of ancillary services defined by FERC were briefly presented. It has also introduced the physical characteristics of reactive power in power systems what are the system requirements for reactive power, reactive power production and consumption sources, reactive power flow in AC power system and the reactive power losses. This chapter points out the needs of reactive power ancillary services and difficulties of economical reactive power procurement and compensation in new deregulated market environment.

In addition, this chapter has briefly presented practical examples of some international reactive power markets. This includes the reactive power markets in UK, Sweden, Republic of Finland, Netherlands, Spain, Australia, Canada, USA (New York, PJM, California and New England), Japan and China. Based on these practical experiences as well as the previous sections of this chapter, this thesis emphasizes the fact that reactive power procurement and valuation especially under deregulated energy markets are not simple and present a very challenging task. As a result, the compensation and pricing scheme for reactive power supports vary significantly around the world. It also results in a common practice of obligatory range of operation of all connecting generators.

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Chapter 3
Optimal Reactive Power Procurement in Ancillary Services Market

3.1 Introduction

In the context of vertically integrated utilities, the cost of reactive power support was bundled within the single electricity tariff, and service providers were not paid separately for this service. Accordingly, the "traditional" procurement approaches did not consider the cost incurred by the system operator to provide the required reactive power support.

However, reactive power as an ancillary service is now unbundled and priced separately, and it is no longer part of the electricity supply. The ISO is responsible for providing ancillary services such as reactive power, often through commercial transactions with service providers. In a competitive environment, the provision of these services must be deployed and managed carefully in order to meet system and market requirements.

Under such circumstances, how to find an appropriate method to obtain reactive power service considering both technical and economical requirements which are to procure sufficient reactive power capacity and also to ensure that higher short-term operating efficiency is particularly important.

Different from the classical reactive power procurement model, a novel optimal multi-objective reactive power procurement model in ancillary services market is proposed in this chapter. In the proposed optimal reactive power procurement model, except for the minimization of the real power losses and power quality, the reactive power payment from the ISO to the reactive power services suppliers has been considered as well. The reactive power procurement under the novel model creates incentives for reactive power service participants to optimize their reactive power service behaviour and get sufficient compensation for their provision of reactive power

This chapter is divided as follows: section 3.2 provides the reactive power costing in ancillary services; section 3.3 reviews the two reactive power procurement models in power market in sub-section 3.3.1 and 3.3.2 separately. The classical mathematical models of optimal reactive power procurement are introduced in section 3.4. Section 3.5 provides detailed of the proposed model in which the methodology is explained. Section 3.6 gives a review of algorithms which are used on reactive power procurement optimization and the classical algorithms and artificial intelligence algorithms are introduced separately in sub-section 3.6.1 and 3.6.2. The differential evolution algorithm which is used for the proposed reactive power procurement model is explained in detailed in section 3.7. Finally, the proposed reactive power procurement model is studied using IEEE30-bus system and IEEE118-bus system in section 3.8.1 and section 3.8.2 separately.

3.2 Reactive power costing in ancillary services market

Analyzing reactive power utilization is a fundamental determination of reactive power price and procurement in ancillary services market. The economic costs of reactive power services include cost from a generation source and costs from transmission sources [1-3]. At the same time, the cost of reactive power services also can be divided into explicit costs and implicit costs [2, 3]. The explicit costs include the fixed costs represented by the costs of capital and administration and the variable costs associated with scheduled maintenance and operating costs. The implicit costs can be classified as variable and correspond any loss of profit which arises as result of producing reactive power.

In the following section 3.2.1, for each component with the capacity to provide reactive power service to the system, the respective costs from generation source are identified. Costs from transmission sources are considered in section 3.2.2.

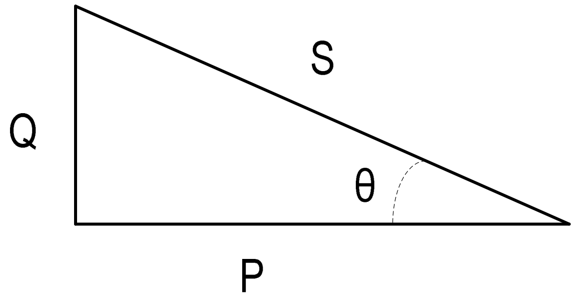
3.2.1 Cost from a generation source

Generators that provide reactive power service in general will lead to increased investment in equipment, energy loss increases, equipment wear and tear as well as maintenance and repair costs increases [4]. Meanwhile, generators to provide reactive power service may lead to a reduction in real power service and in turn of opportunity cost. All these should be included in the reactive power cost of generator.

3.2.1.1 Fixed cost of reactive power generation

Unlike the fuel costs that represent the operating costs of real power production, there are only small operating costs, such as maintenance costs, for reactive power production. The capital cost that represents the capacity used to produce reactive power Q constitutes a large part of the explicit cost.

Traditionally, the capital cost of a generator is specified only in terms of the real power P in £/MVA. However, the capacity of a generator is used to produce not only the real power P, but also the reactive power Q. The capital cost in terms of the capacity S, £/MVA, turns out to be a more proper term in defining the capital cost of a generator. Basic circuit theory shows the triangular relationship between P, Q and S.



$$S^2 = P^2 + Q^2$$

S= Apparent Power

Figure 3.1 Triangular relationship between P, Q and S

Although data is usually given in terms of £/MVA/MW, nominal operation of a generator is always preferred, the capital cost in term of capacity £/MVA can be derived from the following equation:

$$\text{£MVA} = \frac{\text{£MW}}{P_f} \tag{3.1}$$

Where P_f is the nominal power factor of the generator.

Therefore, the capital cost in terms of reactive power can also be specified [1]:

$$C_q = C_s \cdot \sin(\cos^{-1} P_f) = \frac{C_p}{P_f} \cdot \sin(\cos^{-1} P_f) \tag{3.2}$$

Where,

C_q : the generator reactive power capital cost, unit £/MVar;

C_s : total generation capital cost, unit £/MVA;

C_P : the generator real power capital cost , unit £/MW;

P_f : the generator rated power factor.

This capital cost C_q is the fixed cost which represents the total explicit cost of reactive power when other forms of explicit costs are usually small enough to be ignored.

There are several methods used to determine fixed reactive generation capacity cost. Here we will discuss the following three methods [5].

(1) The first method applied engineering judgment to determine the devices and their share of the costs for producing reactive power. For example, the triangular relation between the active, reactive and apparent power, or the designed power factor of generating units can be used, namely:

$$C_q^{gen} = C_s^{gen} \cdot \frac{R_q^{gen}}{R_s^{gen}} \tag{3.3}$$

Where,

C_q^{gen} : generator's reactive capital cost;

C_s^{gen} : total generation capital cost;

R_q^{gen} : generator's reactive capacity;

R_s^{gen} : generator's apparent capacity.

(2) The second method used the costs of synchronous compensators as the valuation proxy. Reactive power supplied from a generation plant can, in principle, be substituted by reactive power produced by synchronous compensators. Technically, synchronous compensators can perform exactly the same functions as electric generators in terms of the reactive power capability and voltage control. Therefore, the reactive generation capital cost can be calculated as follows:

$$C_q^{gen} = C_q^{syn} \cdot \frac{R_q^{gen}}{R_q^{syn}} \tag{3.4}$$

Where,

C_q^{syn} : investment cost of synchronous compensators;

R_q^{syn} : reactive capacity of synchronous compensators.

(3) The third method applied cooperative game theory principles for resolving the joint cost allocation problem. Methods based on the cooperative game theory enable the allocation of fixed capital and operation and maintenance (O&M) costs to several products by recognizing the savings for producing these products using a single plant. In applying this theory to the case of reactive power cost allocation, the products under consideration are active power production (energy), load following and reserve services (capacity), and reactive power service. The method allocates to each product at least the separable portion of the total cost for producing each product and at most the alternative costs for producing the individual product alone. The fixed reactive generation cost using this method is fitting the following equation:

$$C_s^{gen} - C_p^{gen} \le C_q^{gen} \le C_q^{syn} \cdot \frac{R_q^{gen}}{R_q^{syn}} \tag{3.5}$$

Where C_p^{gen} is the real power generation investment cost.

In the above three methods, method (1) is relatively simple and obvious, but it lacks rigorous theoretical foundation; method (2) which is based on the investment costs of synchronous compensators, however, the cost structure of generators and synchronous compensators is not exactly the same, so fixed reactive power generation costs obtained by using this method is generally higher than its' true costs. But it still can be used as reference for setting the upper limit of reactive generation price, given in equation (3.5). As regards the method (3), it can use the well-known Aumann-Shapley value for analysis [5].

3.2.1.2 Variable cost of reactive power generation

The implicit costs can be classified as variable and correspond to any loss of profit which arises as a result of producing reactive power.

The provision of reactive power service from generator increases the excitation current thus gives rise to power loss. In the electricity market environment, this part of power loss of reactive power services should be included in the variable cost, the cost of the corresponding node in accordance with the generator where the marginal prices of real power. However, due to reactive power caused by a slight increase of the generator real power loss is highly non-linear, making it difficult to calculate accurately [6]. In fact, compared with real power operation costs, this part of cost is very small, and therefore is often neglected.

Generator real and reactive power outputs are constricted by its capacity curve. When the generator is to provide reactive power service, its' real output is sometimes limited, resulting in revenue loss in energy market. This is opportunity cost of supplying the reactive power service. And it is also the main part of the reactive power variable costs.

The reactive power variable costs which are widely used are discussed in detail as follows:

Ideally, a generator should produce real power at its rated power factor so that its productive capacity is completely used, thus maximizing its profit [6]. However, due to system requirements, it is possible that the generator would have to reduce its real power in order to produce reactive power. This fact is illustrated in Figure 3.2 [7], in which a typical synchronous generator capability curve is shown.

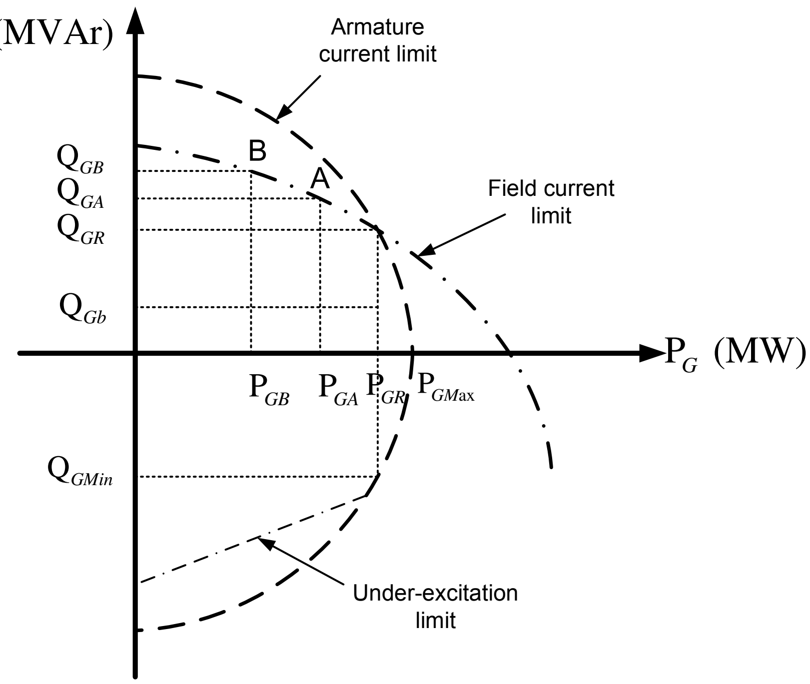


Figure 3.2 Synchronous generator capability curve

In Figure 3.2, Q_{Gb} is the reactive power required by the generator for its auxiliary equipment. If the operating point lies inside the limiting curves, say at (P_{GA}, Q_{Gb}), then the unit can increase its reactive generation from Q_{Gb} up to Q_{GA} without requiring re-adjustment of P_{GA}. This will however, result in increased losses in the windings and hence increase the cost of loss.

If the generator is operating on the limiting curve, any increase in Q will require a decrease in P so as to adhere to the winding heating limits. Consider the operating point 'A' on the curve defined by (P_{GA}, Q_{GA}). If more reactive power is required from the unit, say Q_{GB}, the operating point requires shifting back along the curve to point B (P_{GB}, Q_{GB}), where $P_{GB} < P_{GA}$. This signifies that the unit has to reduce its real power output to adhere to field heating limits when higher reactive power is demanded.

For reactive power production higher than Q_{GA}, the generator has to reduce its real power generation in order to meet the constraints imposed by field or armature heating limits. It will hence incur revenue loss that can also be called the opportunity cost C_{op}, which needs to be compensated net of its cost savings from reduced generation, expressed as follows:

$$C_{op} = \mu\left(P_A - P_B\right) - \left[C\left(P_A\right) - C\left(P_B\right)\right] \tag{3.6}$$

Where,

μ : the real power price;

$C(P_A), C(P_B)$: the generation cost as a function of real power production;

C_{op} : the opportunity cost component of reactive power generation for the generator.

Figure 3.2 also includes a lower limit on Q, which restricts the units operation in under-excited mode due to localized heating in the end region of the armature.

It is seen from Figure 3.2 that field and armature limits restrict reactive power provision and the fulfillment of contracted transactions. In all the reactive power procurement models, to be discussed in this thesis, we consider synchronous generator capability curve as an important factor.

The cost of loss and the opportunity cost are explained in Figure 3.3[8]. However, it is to be noted that the nature of the plot shown is only figurative to illustrate these two components i.e. the cost of loss plot need not necessarily be a parabolic curve nor the opportunity cost is necessarily parabolic.

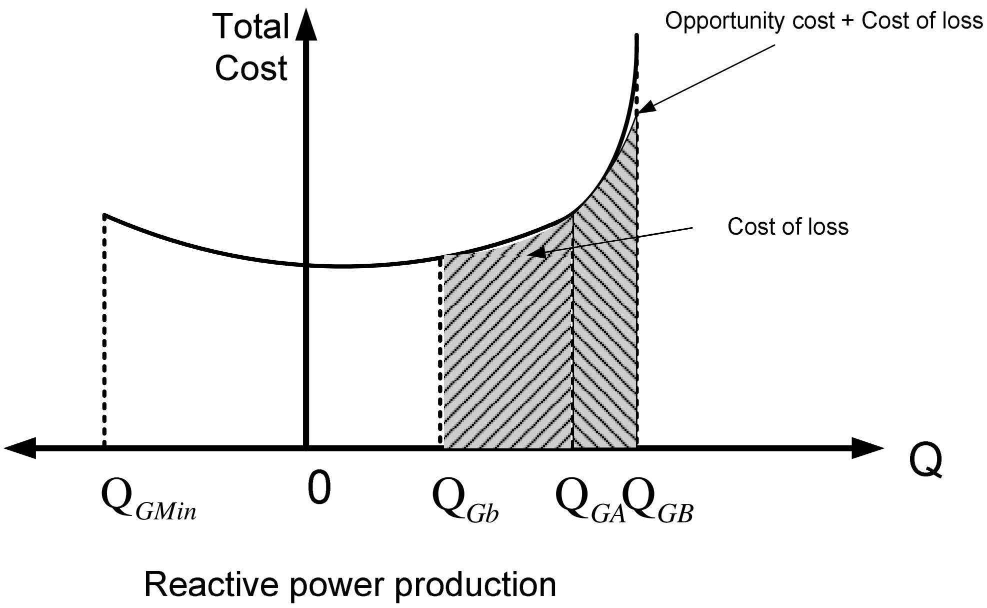


Figure 3.3 Reactive power production versus increased costs incurred by a synchronous generator

Understandably, the ISO will not be in a position to determine the opportunity cost component and the cost of loss component for a generator since information on real power prices may not be known to the ISO if these are fixed through a bilateral contract, nor will the generator's cost of loss function be known.

An appropriate option in such a case is to call for reactive power offers from all generators. A possible structure of such reactive power offers, which the ISO should call for, from independent generators, is discussed in the section 3.3.2.

3.2.2 Costs from transmission sources

The transmission system provides reactive support by changing the operation of certain facilities such as reactive compensators and tap changing transformers. The cost of these facilities plus the cost of transmission losses constitutes the reactive support costs. These costs will be discussed in the following sections.

3.2.2.1 Explicit Costs

Similar to the generating units, the operating costs for transmission facilities that provide reactive support are often small enough to be ignored. The explicit costs from transmission sources mainly refer to the capital costs of reactive facilities and the cost of losses.

Some reactive compensators such as capacitor banks are switchable facilities. Because of the mechanical depreciation of switching, there is a limited number of switching operations that could be performed during their lifetime. So, each switching operation corresponds to a depreciated capital cost, which is expressed in terms of £/switching operation.

A transformer can also be looked as a “switchable” facility, as only limited number of step changes can be achieved during its lifetime. Its depreciated capital cost is expressed as £/step change. For each step change that is required for reactive support, this cost should be considered.

The reactive support will change the voltage profile, which will in turn change the transmission losses. The fuel cost of generators constitutes the primary cost of losses, which is expressed in terms of £/MW. This cost is also one part of the explicit costs of reactive support from transmission sources.

For the reactive power services provide by capacitor banks, the reactive power service cost either can be covered into £/MVArh which is the equipment operation cost [3] [9, 10], the operation cost of capacitor banks can be expressed as follows and is used in this thesis:

$$C_{Ci}\left(Q_{Ci}\right)=\frac{C_f}{Y\times 365\times 24\times h}\cdot Q_{Ci} \tag{3.7}$$

Where,

$C_{Ci}\left(Q_{Ci}\right)$: operation cost of capacitor bank;

Q_{Ci} : reactive power output of capacitor bank;

C_f : fixed cost of capacitor bank unit capacity;

Y : usage life of capacitor bank;

h : average usage ratio.

Or reactive power service cost can be coverted into annual fixed cost of the equipment [2].

3.2.2.2 Implicit Costs

For the installed transmission facilities, there is no alternative usage. They will be either in operation, or not. The opportunity cost under this situation is zero.

The characteristics of voltage control equipment are provided in the Table 3.1 [11]:

Table 3.1 Characteristics of voltage control equipments

Equipment Type	Speed of Response	Ability to Support Voltage	Costs (£)		
			Capital (Per KVAr)	Operating	Opportunity
Capacitor	Slow, stepped	Poor, drops with V^2	£4-5	Very low	No
STATCOM	Fast	Fair, drops with V	£25-27.5	Moderate	No
SVC	Fast	Poor, above its rated value it drops with V^2	£22.5-25	Moderate	No
Synchronous condenser	Fast	Excellent, additional short-term capacity	£15-17.5	High	No
Distributed generation	Fast	Fair, drops with V	Difficult to separate	High	Yes
Generator	Fast	Excellent, additional short-term capacity	Difficult to separate	High	Yes

3.3 Review of reactive power procurement methods in power market

After the deregulation of the electricity industry, the traditional command dispatching way for system operator to procure the reactive power is no longer applicable. At the same time, accompanied by the increasing load, the demand of the system reactive power is also rising. Under such circumstances, how to find an appropriate method to obtain reactive power service considering both technical and economical requirements which are to procure sufficient reactive power capacity and also to ensure that higher short-term operating efficiency is particularly important.

So far, seven reactive power service procurement methods have been in use and have been put in practice in international electricity markets. They are as follows:

1) A mandatory order approach. The system operator procures the reactive power services by giving the mandatory order in the form of grid access agreements or power market operation regulations to all reactive sources (practically to all generators). Specifically, the system operator requires the generators to provide the reactive power within a specified power factor range. The power factor range of mandatory reactive power output is usually small and it does not result in lots of revenue losses for generators. However, this approach benefits to maintain the secure operation of the system in which not only the system operator have the sufficient reactive capacity to dispatch but also inhibit the behaviour that the reactive power suppliers strategically raise the reactive power bid prices. This approach is used widely in the international electricity market.

2) Approach according to the rate of settlement. The cost of reactive power service is recovered from the electricity price through a specific rate. This mechanism enables the reactive power service providers obtain some economic compensation. However, the method of determining the rate is simple but not transparent, so it is generally applicable to the primary stage of the electricity market.

3) Approach based on cost compensation. This approach has been widely used in the deregulated electric power industry. Its basic idea is: firstly, analysis and assess the reactive power service costs, and then compensate the reactive power suppliers according to the cost analysis information.

4) Approach through bilateral contracts. The system operator signs the reactive power service supplying contracts with the generator companies. If the contract price is negotiated by the two parties the third-party cannot know the reactive power prices and other information thus the system cannot obtain the services with low-cost but high quality; If using the uniform pricing rules, it is necessary to make a reasonable reactive power procurement algorithm [12].

5) Approach through market tender. Reactive power service providers bid in accordance with certain technical requirements, system operator choose among all suppliers in accordance with service standards and bidding prices. The two parties sign a long-term or a mid-long term contract and the prices are fixed within the life of the contract [12]. This method is particularly applicable to reactive power service which is a short-term regional monopoly service [13].

6) Approach through spot pricing. The disadvantage of such a mechanism is, it is complicated to operate, the operation cost is large and the locational marginal price fluctuates largely while the system operation circumstance changes. Therefore, it is difficult for customers to adapt. For the reactive power suppliers, the reactive power services cost cannot be fully recovered [12].

7) Procurement based on value assessment. This method first estimates the value which the reactive power buyers create after obtaining the reactive power services, which is used as a base case, then priced and procured using this base case. In most cases the valuation may be significantly more than the cost, so it is easy to make the system have stable and adequate services, but it increases the cost to end-users [13].

Comparing the above seven approaches of reactive power procurement, the approach 3) which is based on cost compensation and approach 5) which is through market tender have obvious advantages if they are adopted in the competitive ancillary services market. However, comparing between these two approaches, tender market approach is more favorable than the cost compensation approach method, because it gives full incentives to reactive power suppliers in the way of bidding.

So, in this chapter we discuss methods 3) and 5) in details in section 3.3.1 and section 3.3.2 respectively.

3.3.1 Reactive power procurement based on cost compensation

The cost compensation of the reactive power can consists of fixed cost compensation and variable cost compensation. For this reason, [14] proposed the mechanism of reactive power capacity payment and reactive power energy payment.

Reactive power capacity payment is mainly used to compensate for reactive power sources' investment costs. In the long run, the provision of reactive power capacity payment is in favor of incentive the reactive power source capacity investment to meet the increasing system reactive power demand. The reactive power capacity payment can be optimized through long-term planning. [2] denotes a method to determine the annual equivalent reactive power capacity cost. However, due to the regional characteristics of reactive power the created values of the same reactive power quality at different locations are different. Therefore, when considering the reactive power source capacity payment the created value of reactive power sources should be taken into account. In [15] the procurement of reactive power takes into account the created value from various reactive power sources by using Equivalent Reactive Compensation (ERC) assessment method. The assessment of the value of reactive power can be carried out from different perspectives (i.e. the impact on system security, the impact on system losses, etc.) the assessment results may be slightly different so how to assess the created value should be determined by the practical system operation condition. [10] determines the reactive power capacity payment considering the power losses' sensitivity analysis to reactive power resources. [16] determines the reactive power capacity payment combined with the requirement factor of reactive power capacity. [14] Determines the reactive power capacity payment by the effect of reactive power capacity investment to relieve the system security constraints.

Reactive power energy payment is mainly to compensate various variable costs of providing reactive power services. It consists of energy losses causes by reactive power output and lost opportunity cost by providing reactive power. There are two methods to calculate the reactive power energy payment. The first one is to access the unit production cost of reactive power sources and then make the energy payment based on the unit production cost and practical reactive output. The second one is to make the reactive power energy payment by calculating the reactive power real time price and reactive power output on all reactive power sources' buses. The major difference between these two methods are: the first one is based on the variable cost and gives the reactive output cost information; however, the second method is based on marginal cost which reflects the reactive power dispatching cost on system operation side. Comparing these two methods, the second method provides a better economical signal and it is a better guide for reactive power dispatch and investment.

At present, cost-based reactive power compensation method is widely used in international reactive power markets in practice, but the specific methods vary. For example, in New York power market the reactive power procurement is by considering both reactive power capacity payment and reactive power energy payment, the Spanish power market is mainly carried out on the reactive power energy compensation and in Dutch power market only the reactive power capacity is compensated.

3.3.2 Reactive power procurement based on reactive power source bidding

As we have discussed in Section 3.2.1.2, the ISO would call for reactive power offers from generators and other participants in the reactive power market - depending on the market design. In this section we consider the possible reactive power offer structure of synchronous generators. We define three operating regions of a synchronous generator on the reactive power co-ordinate to formulate the generator's Reactive Payment Function (QPF). An analysis and understanding of the QPF is desirable on the part of the ISO also, so as to retain control over the market and prevent unwarranted payments made due to an irrational bidding structure. The operating regions on the reactive co-ordinate can be defined as given in Figure 3.2 as follows:

Region-I: 0 to Q_{Gb} : Production in this region caters for the reactive power needed by the generator to maintain its own equipment. This includes reactive consumption by unit’s auxiliaries (such as boiler feed pump motors, circulating water system pump motors, induced draft fan motors, forced draft fan motors, step-up transformers, etc.). Therefore any reactive power generated in this region does not qualify as an ancillary service.

Mandatory reactive power service from generator G without any payment in region-I:

$$QPF = 0$$

However, it may be very difficult for the ISO to determine Q_{Gb} , unless the generator reports this parameter correctly, which may be unlikely, given the competitive market environment. One way to go about this is to pre-calculate the technical requirements based on machine and equipment ratings and decide on certain standard Q_{Gb} , which does not qualify for payment. For example, setting a qualifying limit of 0.95 lagging power factor may be one of the ways.

Region-II: (Q_{Gb} to Q_{GA}) and (0 to Q_{GMin}): This region shows the amount of reactive power, which the generator can provide or absorb, without having to reschedule its real power generation. However, as mentioned earlier, this will increase the generator's real power losses in the windings. These losses increase with the amount of reactive power generated or absorbed. Therefore, the generator will expect to be paid for the cost of losses (probably at the prevailing spot-market rates) and also for making available its service. This payment structure is very difficult to formulate because of the complexity involved in determining the availability payment. Probably this can be found by the ISO by determining the cost to the system due to its unavailability - the opportunity cost of not having the service of the generator. Also, determining the cost of loss can be difficult due to the variation of system prices and machine parameters.

Generator G is entitled to receive two components of payments in Region-II:

$$QPF = Availability\ Component + Cost\ of\ \ Loss\ Component$$

Region-III: Q_{GA} to Q_{GB}: This region denotes that amount of reactive power which a generator is willing to produce, at the cost of having to reduce its own real power generation. The generator stands to lose revenue from the unfulfilled real power selling contracts. The financial compensation that the generator expects from its reactive power service is the revenue lost due to its scheduled real power sell, given by (3.9).

The generator G is entitled to reactive payment commensurate with its opportunity cost of reduced real power production in region-III:

$$QPF = Availability\ Cost + Cost\ of\ \ Loss + Opportunity\ Cost$$

However, the ISO will not be in a position to estimate the QPF for a generator in deregulated markets. An appropriate option for the ISO is to call for reactive power offers from all generators based on the QPF structure. A possible structure of such reactive offers is discussed as follows: based on the classification of reactive power production costs, a generalized QPF and hence an offer structure can be formulated mathematically [8].

$$QPF = \begin{cases} 0, 0 \le Q_G \le Q_{Gb} \\ c_G + b_{1G}\left|Q_G\right|, Q_{GMin} \le Q_G < 0 \\ c_G + b_{2G}Q_G, Q_{Gb} < Q_G \le Q_{GA} \\ c_G + b_{2G}Q_G + a_G Q_G^2, Q_{GA} < Q_G \le Q_{GB} \end{cases} \tag{3.8}$$

Where,

c_G : Availability price offer of reactive power for generator G, in £/h;

b_{1G} : Cost of loss price offer for operating in under-excited mode (absorb reactive power), $Q_{Min} \le Q_G \le 0$, in £/MVArh

b_{2G} : Cost of loss price offer for operating in the region $Q_{Gb} \le Q_G \le Q_{GA}$, in £/MVArh

a_G : Lost opportunity price offer for operating in the region $Q_{GA} \le Q_G \le Q_{GB}$, (£/MVArh)/MVArh. Note that the lost opportunity price offer is a function of reactive power output and hence the corresponding QPF component will be a quadratic function of Q_G .

The generalized QPF offer parameters, discussed above, are shown in Figure 3.4, which also holds for synchronous compensators, except the opportunity cost component. Synchronous compensators will be assumed to offer all components, except the opportunity price.

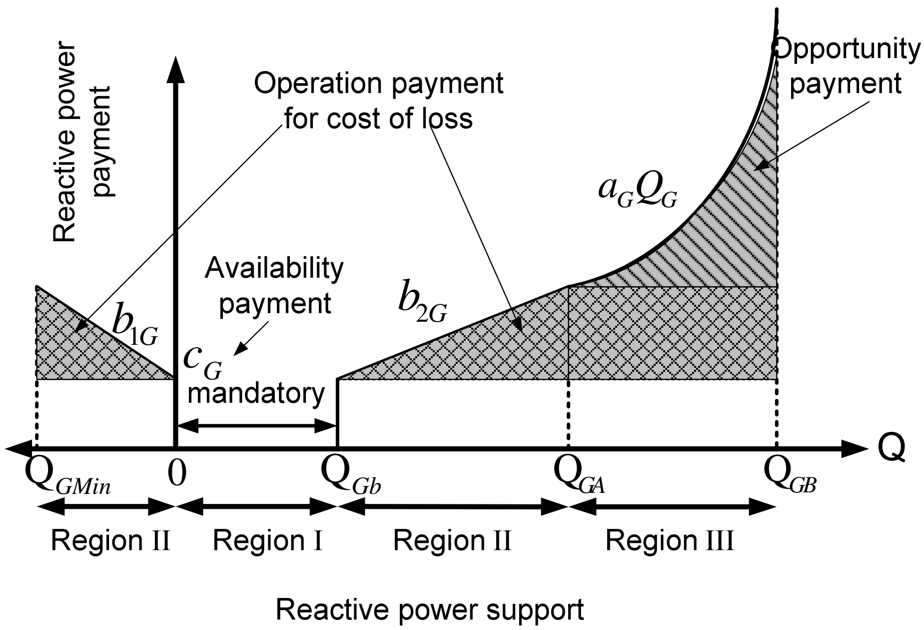


Figure 3.4 Structure of reactive power offers from providers

We should note here that the 'availability' offer typically represents a part of the generator's capital cost that goes towards providing reactive power. This is annualized and further reduced on a day's scale. Understandably, this is very difficult to separate from the total capital cost, but in any case, is a small fraction only. The ‘cost of loss offer’ represents the generator's operational costs in providing the service. These two components are therefore not very different in magnitude, both being of similar orders in the model.

3.4 Classical mathematical models of optimal reactive power procurement

Traditionally, reactive power procurement in the power system has been viewed by researchers as an optimization problem, in which reactive power is provided from different sources, including capacitor banks, synchronous generators, subject to various system constraints such as nodal real and reactive power balance, bus voltage limits, and power generation limits. Thus, reactive power is dispatched by solving the following different optimization problems:

3.4.1 Minimize real power losses

To reduce the power system losses is an important objective whether in the traditional power industry or in the power market environment. Rational allocation of reactive power support and an appropriate voltage level can reduce the network real power loss, thereby enhancing the operational efficiency of the whole system. Thus, to minimize the real power losses is often used as the objective function of reactive power procurement.

$$Min\ \mathrm{P}_{Loss} = 0.5\sum_{i,j}\left(G_{ij}\left(V_i^2 + V_j^2 - 2V_iV_j\cos\left(\delta_j - \delta_i\right)\right)\right) \tag{3.9}$$

$$s.t.\quad P_{Gi} - P_{Di} = \sum_j V_iV_jY_{ij}\cos\left(\theta_{ij} + \delta_j - \delta_i\right) \tag{3.10}$$

$$Q_{Gi} - Q_{Di} + Q_{Ci} = -\sum_j V_iV_jY_{ij}\sin\left(\theta_{ij} + \delta_j - \delta_i\right) \tag{3.11}$$

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \tag{3.12}$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \tag{3.13}$$

$$V_i^{\min} \le V_i \le V_i^{\max} \tag{3.14}$$

$$\left|P_{ij}(V,\delta)\right| \le P_{ij}^{\max} \tag{3.15}$$

Where,

V_i : voltage magnitude at bus i ;

δ_i : voltage angle at bus i ;

G_{ij} : conductance of the line connecting buses i and j ;

Y_{ij} : magnitude of the ij entry of the admittance (Y) matrix;

θ_{ij} : angle of the ij entry of the admittance (Y) matrix;

P_{Di} : active power demand at bus i ;

Q_{Di} : reactive power demand at bus i ;

$P_{Gi}^{\min}$: minimum real power limit of a generator at bus i ;

$P_{Gi}^{\max}$: maximum real power limit of a generator at bus i ;

$Q_{Gi}^{\min}$: minimum reactive power limit of a generator at bus i ;

$Q_{Gi}^{\max}$: minimum reactive power limit of a generator at bus i ;

$V_i^{\min}$: minimum allowable voltage at bus i ;

$V_i^{\max}$: maximum allowable voltage at bus i ;

P_{ij} : power flow from bus i to bus j ;

$P_{ij}^{\max}$: maximum allowable power flow from bus i to bus j .

3.4.2 Optimize the power quality

After the deregulation of power industry, power quality concerns are more and more because good power quality will help to extend the operational life of electrical equipment and improve the efficiency of energy supply. Nodal voltage fluctuation is an important factor of affecting the power quality. Therefore, reactive power procurement can be obtained through the objective function of minimizing the voltage fluctuations to ensure the power quality on the load buses especially on some important load buses. In this case, the procurement of reactive power can be described mathematically as follows:

$$Min \ \mathrm{F} = \sum_{i \in PQ} \left(V_i - V_i^{ref} \right)^2 \tag{3.16}$$

$$s.t. \ (3.10) - (3.15)$$

Where,

PQ : load buses congregation;

V_i^{ref} : reference voltage value at bus i .

In some cases, the nodal weighting factors α_i can be added to equation (3.16) to reflect the voltage profile requirements on different load buses.

$$Min\ \mathrm{F} = \sum_{i \in PQ} \alpha_i \left(V_i - V_i^{ref} \right)^2 \tag{3.17}$$

3.4.3 Optimize the system security

One of the important roles of reactive power support is to guarantee voltage stability to maintain the power system operation. Although power system economic operation draws more attention in electricity market environment the security operation is still a very important factor that cannot be ignored. In some cases, the system operator must procure the reactive power service based on system security requirement. [17] proposed a reactive power procurement model based on the system security index – security margin.

$$Min\ \mathrm{F} = \lambda_0 - \lambda^* \tag{3.18}$$

System constraints:

(1) Equality constraints:

$$P_{Gi} - \lambda_0 P_{Di} = \sum_j V_i V_j Y_{ij} \cos\left(\theta_{ij} + \delta_j - \delta_i\right) \tag{3.19}$$

$$Q_{Gi} - \lambda_0 Q_{Di} = -\sum_j V_i V_j Y_{ij} \sin\left(\theta_{ij} + \delta_j - \delta_i\right) \tag{3.20}$$

$$P_{Gi}^* - \lambda^* P_{Di} = \sum_j V_i^* V_j^* Y_{ij} \cos\left(\theta_{ij}^* + \delta_j^* - \delta_i^*\right) \tag{3.21}$$

$$Q_{Gi}^* - \lambda^* Q_{Di} = -\sum_j V_i^* V_j^* Y_{ij} \sin\left(\theta_{ij}^* + \delta_j^* - \delta_i^*\right) \tag{3.22}$$

(2) Inequality constraints: except for equations (3.12), (3.13) and (3.15), there are

$$Q_{Gi}^{Min} \le Q_{Gi}^* \le Q_{Gi}^{Max} \tag{3.23}$$

$$V_{iMin} \le V_i^* \le V_{iMax} \tag{3.24}$$

$$\left| P_{ij}^*(V, \delta) \right| \le P_{ij}^{\max} \tag{3.25}$$

In the above equations ‘ * ’ stands for the system critical state. λ_0 is the load profile under the initial system operation condition and λ^* is the load profile under the critical system operation condition. Therefore, the objective of reactive power procurement becomes to maximize system security margin which is the distance from the system initial operation condition to the system critical operation condition. However, the meaning of critical condition here is the system condition in which the voltage profile is over limit nor the system collapses. In the optimization process each load profile on PQ bus increases by a certain ratio. The increase of real power loads are balanced by the slack generator but the real power outputs of other generators remain unchanged.

The above three classical OPF-based models are non-linear optimization problems, with a loss minimization objective function (3.9), a power quality optimization function (3.16) and a system security optimization function (3.18) separately.

3.5 Proposed multi-objective reactive power procurement optimization model in ancillary services market

In the context of vertically integrated utilities, the cost of reactive power support was bundled within the single electricity tariff, and service providers were not paid separately for this service. Accordingly, the “traditional” procurement approaches did not consider the cost incurred by the system operator to provide the required reactive power support.

With a reactive power offer structure established in Section 3.3.2, the ISO requires a proper criterion to determine the best offers and thus formulate its reactive power procurement plan. Unlike real power markets where bids are selected in ascending order of prices, reactive power markets need to consider the location aspects also because of the transmission loss considerations.

For example, a low priced reactive power offer at a bus remotely located is not necessarily an attractive option for the ISO. On the other hand, even a somewhat expensive reactive power offer at a heavily loaded demand center could well be considered for procurement.

The reactive power providers can enter into either long or short-term contracts with the ISO for reactive power provision. Contracted provisions involve payments to be made by the ISO, and it remains an objective of the ISO to procure the service so as to minimize the total payment while meeting the system constraints. Although this is seemingly a fair enough objective, such an optimal selection can result in increased losses in the system or may require curtailment of real power transaction contracts, both of which are undesirable. Increased energy loss requires the ISO to increase its procurement of loss compensation services from balance providers (generators or loads) involving additional payments. Thus, a minimum payment objective may not necessarily satisfy all the concerns of the ISO.

We consider the ISO's problem of obtaining optimal reactive power contracts, assuming that the reactive power providers offer their prices to the ISO rationally.

Therefore, a novel method is proposed in this chapter to address the problem of optimal reactive power procurement considering both technical and financial efficiency of the ISO.

It is seen that the reactive power market can be based on different objective functions for the ISO. For example, besides the objectives we discussed in the previous sub-sections from the power system technical point of view, the new objective of reactive power optimization from the economical aspect need to be considered in the new power market environment which is the minimization of the reactive power payment for ISO.

In another word, all the objectives ISO would consider are as follow:

1) Minimize real power losses
2) Minimize the reactive power payment

3) Optimize the power quality

4) Optimize the system security

While each model independently seeks important targets, an ISO would often desire to achieve all these targets simultaneously. Therefore, it is a big consideration for ISO to decide to choose which procurement objectives and how to coordinate different procurement objectives.

3.5.1 Compromise of procurement objectives model

To achieve that, [8] proposes a 'compromise programming' model that attains the 'best compromise' among the conflicting objectives. By using this model, more than one objectives can be combined into a 'compromise function' (3.26), which when minimized, will ideally represent the ISO's requirement of meeting contradictory objectives simultaneously.

In this chapter, we assume the ISO procure the reactive power without the power system security problem; in other word, the reactive power transactions are made based on the condition of a secured system. Then the objective function is as follows:

$$F_{compromise} = \sqrt{\left(\frac{F_Q}{F_Q^*}\right)^2 + \left(\frac{F_{Loss}}{F_{Loss}^*}\right)^2 + \left(\frac{F_V}{F_V^*}\right)^2} \tag{3.26}$$

Where,

F_Q : Objective function which to minimize the reactive power payment to procure reactive power;

F_{Loss} : Objective function which to minimize the real power losses to procure reactive power;

F_V : Objective function which to optimize the power quality to procure reactive power;

F_Q^*, F_{Loss}^* and F_V^* are the respective minimum values when F_Q, F_{Loss} and F_V are optimized independently. Note that while we have used an equal weight for each conflicting component in (3.26), this need not necessarily be the case in actual markets. The ISO may choose to have priority on the objectives, depending on the market condition. For example, if the participants are willing to pay for increased reactive power payment in order to have better power quality, the weight on F_Q could be very small. Thus, the choice of weights to be associated with the three components of (3.29) should be made by the ISO, as per its decision-making criteria.

The working scheme of the reactive power market based on the compromise of procurement objectives is shown in Figure 3.5.

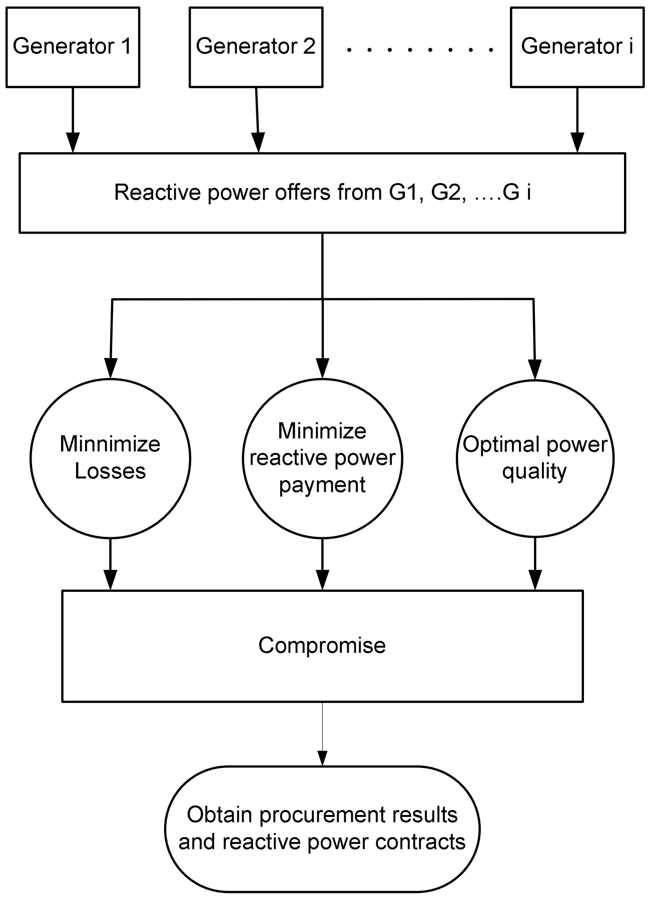


Figure 3.5 The working scheme of the reactive power market based on the compromise of procurement objectives

The objective that the power system security is considered will not be addressed in thesis.

3.5.2 The mathematical model of proposed multi-objective reactive power procurement optimization

We adopt the market sequence clearing model for reactive power procurement in the proposed reactive power procurement optimization, in which the reactive power is procured after the real power transactions have been determined. In such a market clearance model, the reactive power procurement is relatively simple and does not need to take into account the impact of real power. Another market clearance model is uniform clearing which is clearing the real and reactive power at the same time. In theory, the uniform market clearing model leads to lower overall procurement costs than the sequence market clearing model; however, due to the real and reactive power mutual coupling, thus the volume of calculation is larger and implementation cost is higher. Under the uniform market clearing model the two markets easily affect each other, resulting in increasing the strategic bidding opportunities for market participants.

Compare to the simple compromise optimization method discussed in section 3.5.1, the proposed multi-objective reactive power procurement optimization model directly integrates those different objectives into one objective function in the way of weighting and its mathematical expression is as follow:

$$F_m = \lambda_1 F_1 + \cdots + \lambda_n F_n \tag{3.27}$$

Where, F_m is the overall procurement objective and $\lambda_1 \cdots \lambda_n$ are the weighting factor of each individual single procurement objective.

This model does not require the individual calculation of each procurement objectives. It calculates the optimal solution which matches every individual optimization aspect and search the solution in the whole solution area. Therefore, it is not the sum of individual objectives mathematically and it is much more accurate and reasonable in obtaining the optimization solution.

However, because of the different dimension of various objectives how to determine the appropriate value of weighting factor becomes an important and difficult problem. In addition, the approach also needs to consider the consequence of the importance of each objective in the overall procurement objective which is generally expressed in the weighting factor. The value of the weighting factor of each single procurement objective is usually determined either by system operator's operation experiences or by determining matrix set. In this chapter, we consider equal weights of unity for the all components.

Different from the other reactive power procurement methods for ISO, we consider reactive power provision from both synchronous generators and capacitor banks.

The objective of the proposed reactive power procurement optimization for ISO is to minimize the reactive power payment, real power losses and the power quality in one minimization function to get the optimal solution.

To achieve the optimization targets we establish the following mathematical formula of proposed objective function:

$$Min.\ F_m(Y,Z) = F_{Loss} + F_Q + F_V \tag{3.28}$$

Where,

$$Y^T = \left[V_G, K_T, Q_C\right]$$

$$Z^T = \left[V_L, Q_G\right]$$

Y is the vector of control variables comprising generator voltages V_G, shunt VAR compensation Q_C and transformer tap settings K_T. Z is the vector of dependent variables consisting of load bus voltages V_L and generator reactive outputs Q_G.

$$F_{Loss} = \lambda_L P_{Loss} \tag{3.29}$$

$$\mathrm{P}_{Loss} = 0.5\sum_{i,j}\left(G_{ij}\left(V_i^2 + V_j^2 - 2V_iV_j\cos\left(\delta_j - \delta_i\right)\right)\right) \tag{3.9}$$

$$F_V = \lambda_V \sum_{i\in PQ} N_i \tag{3.30}$$

$$N_i = \begin{cases} 1, & \text{if } \left|V - V^{ref}\right| > 0.05; \\ 0, & \text{otherwise} \end{cases} \tag{3.31}$$

$$F_Q = F_{GQ} + F_{CQ} \tag{3.32}$$

$$F_{GQ} = \sum_{i\in G} f_{GQi}\left(Q_{Gi}\right) = \sum_{i\in G} QPF_i \tag{3.33}$$

Here, we express the QPF_i in equation (3.8) in another way as follow:

$$QPF_i = W_{1Gi}\left(c_{Gi} + b_{1Gi}\left|Q_{Gi}\right|\right) + W_{2Gi}\left(c_{Gi} + b_{2Gi}Q_{Gi}\right) + W_{3Gi}\left(c_{Gi} + b_{2Gi}Q_{Gi} + a_{Gi}Q_{Gi}^2\right) \tag{3.34}$$

$$W_{1Gi} = \begin{cases} 1, & \text{if } Q_{GiMin} \le Q_{Gi} < 0; \\ 0, & \text{otherwise} \end{cases}$$

$$W_{2Gi} = \begin{cases} 1, & \text{if } Q_{Gbi} < Q_{Gi} \le Q_{GAi}; \\ 0, & \text{otherwise} \end{cases}$$

$$W_{3Gi} = \begin{cases} 1, & \text{if } Q_{GAi} < Q_{Gi} \le Q_{GBi}; \\ 0, & \text{otherwise} \end{cases} \tag{3.35}$$

$$F_{CQ} = \sum_{i\in C} C_{Ci}\left(Q_{Ci}\right) \tag{3.36}$$

$$C_{Ci}\left(Q_{Ci}\right) = \frac{C_{fi}}{Y_i \times 365 \times 24 \times h_i} \cdot Q_{Ci} \tag{3.7A}$$

So the objective function (3.28) can be expressed in details as:

$$Min.\ F_m(Y,Z) = \lambda_L P_{Loss} + \lambda_V \sum_{i\in PQ} N_i + \sum_{i\in C} \frac{C_{fi}}{Y_i \times 365 \times 24 \times h_i} \cdot Q_{Ci}$$

$$+\sum_{i\in G}\left[W_{1Gi}\left(c_{Gi}+b_{1Gi}\left|Q_{Gi}\right|\right)+W_{2Gi}\left(c_{Gi}+b_{2Gi}Q_{Gi}\right)+W_{3Gi}\left(c_{Gi}+b_{2Gi}Q_{Gi}+a_{Gi}Q_{Gi}^2\right)\right]$$

(3.37)

The minimization of the above function is also subject to a number of constraints:

$$s.t. \quad P_{Gi} - P_{Di} = \sum_j V_i V_j Y_{ij} \cos\left(\theta_{ij} + \delta_j - \delta_i\right) \tag{3.10}$$

$$Q_{Gi} - Q_{Di} + Q_{Ci} = -\sum_j V_i V_j Y_{ij} \sin\left(\theta_{ij} + \delta_j - \delta_i\right) \tag{3.38}$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \tag{3.13}$$

$$Q_{Ci}^{\min} \le Q_{Ci} \le Q_{Ci}^{\max} \tag{3.39}$$

$$V_{Gi}^{\min} \le V_{Gi} \le V_{Gi}^{\max} \tag{3.40}$$

$$V_{Li}^{\min} \le V_{Li} \le V_{Li}^{\max} \tag{3.41}$$

$$K_{Ti}^{\min} \le K_{Ti} \le K_{Ti}^{\max} \tag{3.42}$$

$$\left|P_{ij}(V,\delta)\right| \le P_{ij}^{\max} \tag{3.15}$$

Where,

V_i : voltage magnitude at bus i;

δ_i : voltage angle at bus i;

G_{ij} : conductance of the line connecting buses i and j;

Y_{ij} : magnitude of the ij entry of the admittance (Y) matrix;

θ_{ij} : angle of the ij entry of the admittance (Y) matrix;

P_{Di} : active power demand at bus i;

Q_{Di} : reactive power demand at bus i;

$P_{Gi}^{\min}$: minimum real power limit of a generator at bus i;

$P_{Gi}^{\max}$: maximum real power limit of a generator at bus i ;

$Q_{Gi}^{\min}$: minimum reactive power limit of a generator at bus i ;

$Q_{Gi}^{\max}$: minimum reactive power limit of a generator at bus i ;

$V_{Gi}^{\min}$: minimum allowable voltage at PV bus i ;

$V_{Gi}^{\max}$: maximum allowable voltage at PV bus i ;

$V_{Li}^{\min}$: minimum allowable voltage at PQ bus i ;

$V_{Li}^{\max}$: maximum allowable voltage at PQ bus i ;

K_{Ti} : transformer tap setting ;

P_{ij} : power flow from bus i to bus j ;

$P_{ij}^{\max}$: maximum allowable power flow from bus i to bus j ;

λ_L : real power price;

λ_V : penalty factor of voltage violation;

N_i : the number of voltage violated PQ buses;

F_V : penalty function of voltage violation on PQ buses;

F_L : real power losses cost;

F_Q : overall reactive power payment;

P_{Loss} : real power losses;

F_{GQ} : reactive power payment for all generators;

F_{CQ} : reactive power payment for all capacitor banks;

W_{1Gi}, W_{2Gi} : binary variable associated with Region II of reactive power operation for generator i , respectively;

W_{3Gi} : binary variable associated with Region III of reactive power operation for generator i .

The cost of real power losses is defined in equation (3.29) as the product of power losses quantity and real power price λ_L .

In the equation (3.30), the power quality has been expressed as a penalty function of voltage violation which using high weighting factor λ_V as a means of penalty to prevent the result of voltage violation in the system

In the equation (3.34), the binary variables are needed to reflect the fact that the generator operators in only one of the three reactive power operating regions defined in Figure 3.4. Observe that QPF_i does not include the mandatory component of reactive power generation in region I $\left(0 \le Q_{Gi} \le Q_{Gbi}\right)$, since generators are not financially compensated for such obligatory amount of reactive power.

3.6 Review of reactive power optimization algorithm

The reactive power procurement models which are either the single objective optimization models in subsection 3.4 or multi-objective optimization model in subsection 3.5 are mixed-integer non-linear programming problems with presence of non-convexities. In practical computation, there are various computational algorithms about reactive power optimization. But generally speaking, there are two main categories: one is a conventional algorithm which starts searching the optimal value from an initial value, then improves the current solution according to the determinate trajectory of, and ultimately converges to the optimal solution. These types of algorithms are linear programming, nonlinear programming, mixed integer programming, dynamic programming, are more commonly known as mathematical programming technique; the other is intelligent programming technique which starts from a population of the initial solutions and then according to the principle of probability transfer searches the optimal solution by using fitness function. The most popular methods that go beyond simple local search are Genetic Algorithms GAs, Simulated Annealing (SA), Tabu Search (TS), Particle Swarm Optimization (PSO) and other evolutionary techniques, such as Differential Evolutionary programming (DE) that has shown great potential lately. However, more experience is still necessary to indicate its efficiency and robustness.

3.6.1 Classical optimization algorithms

Linear programming method has been developed in the most mature manner. Although reactive power optimization is a nonlinear problem, it can be solved using the method of local linearization. However, as a result of its non-linear character there are many non-linear programming methods which are applied to reactive power optimization in power system, such as simplified gradient method, Newton's method and quadratic programming. The characteristics of those classical optimization algorithms are described in table 3.2 [18-24] as follows:

Table 3.2 Classical optimization algorithms characteristics comparison

Classical algorithms	**Characteristics of algorithm**		
	Algorithm theory	**Advantages**	**Disadvantages**
Linear programming	It is to use Newton-Raphson power flow calculation of the Jacobian matrix to get the sensitivity relationship between system state variables and system control variables. In reactive power optimization, the use of the sensitivity matrix can easily be bound to introduce a variety of system constraints [18-20].	The mathematical model of Linear programming is simple; the physical concept of the model is clear; and the calculation speed is fast. Moreover, as a result of perfection of linear programming method itself the calculation size has fewer restrictions.	However, due to its optimization model of the real system were made by the linearization approximation and the discrete variables are made to be continuous so that the actual results are often very different from the actual situation in power systems.
Quadratic Programming	A quadratic programming optimization model consists of two factors: one is to make the objective function using second-order Taylor expansion, the other is exchange non-linear constraints into a series of linear constraints, finally	Since the quadratic objective function can be better adapted to reactive power optimization objective function of the non-linear characteristics and the speed of convergence is faster	The computing time rapidly increases with the increases of the number of variables and constraints. It may lead to the non-convergence when critical issues happen.

	using a series of quadratic programming approximation to close in to the final optimal solution [21].	so it has been applied in reactive power optimization.	
Newton's method	Newton method compared with the simplified gradient method is a second-order convergence speed algorithm [22]. The solution is gotten by using non-linear programming method based on Lagrange multiplier method and two matrixes: Hansen matrix that is the second derivative of objective function; Jacobian matrix that is composed of the first derivation of the network power flow equations.	The volume of the calculation decreases because of the highly sparse character of Hansen matrix and Jacobian matrix.	It has not effectively deal with reactive power optimization of a large number of inequality constraints.
Simplified gradient method	Simplified gradient method based on the polar coordinate form of Newton-Raphson power flow calculation deals with equality constraints using Lagrange multiplier method and deals with the inequality constraints with Kuhn-Tucker penalty function. It develops optimization along with the negative gradient direction of control variables [23, 24].	It is the first algorithm for successfully solving large-scale optimal power flow. Its algorithm is relatively simple; storage requirement is small; and the program design is simple.	However, there are also many disadvantages: the jagged phenomenon during the calculation process; poor convergence especially when close to the optimal solution; the volume of calculation is large due to re-calculating power flow on each iteration and time consumes more.

The mathematical model of non-linear programming method is more precise and reflects the actual power system. Although this method has high accuracy it requires a large amount of derivation and inverse operation which takes up more computer memory. As a result, it makes the scale of problem restricted and is difficult to deal with the inequality constraints. In more detail, it cannot handle the discrete variables such as the capacity of capacitors and transformer ratio. So these variables are usually treated as continuous variables and at the end of the optimization are set to the nearest discrete point. Thus this method can only obtain an approximate optimal solution. Therefore it limits its application in real power system.

3.6.2 Artificial intelligence algorithms

Optimization is the basic concept behind the application of GAs, or any other evolutionary algorithm to any field of interest. Over and above the problems in which optimization itself is the final goal, it is also a way for achieving (or the main idea behind) modelling, forecasting, control, simulation, and so on.

Reactive power optimization has the typical features of a large-scale combinatorial optimization problem. In problems of this kind, the number of possible solutions grows exponentially with the problem size. Therefore, the application of optimization methods to find the optimal solution is computationally impracticable. Various artificial intelligence algorithms are frequently employed in this case for achieving high-quality solutions within reasonable run time.

A general review of Genetic Algorithms GAs, Simulated Annealing (SA), Tabu Search (TS), Particle Swarm Optimization (PSO) and other evolutionary techniques, such as Differential Evolutionary programming (DE) is as follows [25]:

1. Genetic Algorithms (GA) [25]

Traditional optimization techniques begin with a single candidate and search iteratively for the optimal solution by applying static heuristics. On the other hand, the GA approach uses a population of candidates to search several areas of a solution space, simultaneously and adaptively. Genetic algorithms have a lot advantages like strong robustness, parallel computation characteristic and fitness searching capability and they have made a lot of research results on reactive power optimization problem. However, in the practical utilization of the GAs there are still some problems. Such as, GAs are the optimization based on the population so in the large and complex power system model GAs need to spend a lot of time to test and combination on the individuals to calculate the fitness function. Therefore, it will inevitably affect the operation in real-time.

2. Simulated Annealing (SA) [25]

Simulated Annealing (SA) algorithm is a heuristic random search algorithm based on the thermodynamic principle of the establishment of the annealing. And SA is one of the most flexible techniques available for solving hard combinatorial problems. The main advantage of SA is that it can be applied to large problems regardless of the conditions of differentiability, continuity, and convexity that are normally required in conventional optimization methods. However, in practical application the algorithm convergence and the convergence rate depends on the annealing program parameters which are difficult to determine.

3. Tabu Search (TS) [25]

Tabu search (TS) consists of a meta-heuristic procedure used to manage heuristic algorithms that perform local search. Meta-heuristics consists of advanced strategies that allow the exploitation of the search space by providing means of avoiding being entrapped into local optimal solutions. The name tabu is related to the fact that in order to avoid revisiting certain areas of the search space that have already been explored, the algorithm turns these areas tabu (or forbidden). It means that for a certain period of time (the tabu tenure), the search will not consider the examination of alternatives containing features that characterize the solution points belonging to the area declared tabu. Unlike other combinatorial approaches such as genetic algorithms (GA) and simulated annealing (SA), its origin is not related to biological or physical optimization processes. Applications to electric power network problems are already significant and growing. These include, for example, the long-term transmission network expansion problem and distribution planning problems such as the optimal capacitor placement in primary feeders. However, due to TS searches by using the individual point the algorithm's convergence speed and the quality of the final solution relate a lot with the initial solution. Its advantages are poor global search capability, and with the increasing in the number of control variables the computation time is longer and the slower speed of searching the optimal solution.

4. Particle Swarm Optimization (PSO) [25]

Eberhart and Kennedy developed particle swarm optimization (PSO) based on the analogy of swarms of birds and fish schooling. Each individual exchanges previous experiences in PSO. PSO is developed through simulation of bird flocking in a two-dimensional space

5. Differential Evolution（DE）[25]

As a relatively new population-based optimization technique, differential evolution (DE) has been attracting increasing attention for a wide variety of engineering applications including power engineering. Unlike the conventional evolutionary algorithms that depend on predefined probability distribution function for mutation process, differential evolution uses the differences of randomly sampled pairs of objective vectors for its mutation process. Consequently, the object vectors' differences will pass the objective functions topographical information toward the optimization process and therefore provide more efficient global optimization capability.

Following section 3.7 aims at providing theory in detail of differential evolution algorithm and application in reactive power optimization in power systems.

3.7 Differential Evolution（DE） [25]

3.7.1 Principles of DE

Differential evolution was first proposed over 1994–1996 by Storn and Price at Berkeley as a new evolutionary algorithm (EA). Differential evolution (DE) is a stochastic direct search optimization method. It is generally considered as an accurate, reasonably fast, and robust optimization method. The main advantages of DE are its simplicity and therefore easy use in solving optimization problems requiring a minimization process with real-valued and multimodal (multiple local optima) objective functions. DE uses a non-uniform crossover that makes use of child vector parameters to guide through the minimization process. The mutation operation with DE is performed by arithmetical combinations of individuals rather than perturbing the genes in individuals with small probability compared with one of the most popular EAs, genetic algorithms (GAs).

Another main characteristic of DE is its ability to search with floating point representation instead of binary representation as used in many basic EAs such as GAs. The characteristics together with other factors of DE make it a fast and robust algorithm as an alternative to EA, and it has found an increasing application in a number of engineering areas including power engineering.

According to Price, the main advantages of a DE include:

- Fast and simple for application and modification
- Effective global optimization capability
- Parallel processing nature
- Operating on floating point format with high precision
- Efficient algorithm without sorting or matrix multiplication
- Self-referential mutation operation
- Effective on integer, discrete, and mixed parameter optimization
- Ability to handle non-differentiable, noisy, and/or time-dependent objective functions
- Operates on flat surfaces
- Ability to provide multiple solutions in a single run and effective in nonlinear constraint optimization problems with penalty functions

In the following sections, we will look into the specific operators and mathematical algorithms within a DE.

3.7.2 DE fundamentals

3.7.2.1 Fitness Function (Function optimization formulation)

In the DE algorithm, differential evolution operation primarily is achieved through the direction of a fitness function. It is used to assess the relative value of an individual compared with the whole population.

A DE algorithm is an efficient method to solve optimization problems. It is necessary to briefly discuss the problem formulation for an optimization problem. Because DE is basically used to solve minimization problems, only such problems are discussed here. A general constrained minimization problem can de described as

$$\text{Min } y = \mathrm{f}(\mathrm{X}) \tag{3.43}$$

s.t.

$$g(\mathrm{X}) \leq 0, \tag{3.44}$$

where $\mathrm{X}=\{x_i\},(i=1,2,...,n)$, is the vector of variables where an optimal value is to be calculated to minimize y ; $\mathrm{f}(\mathrm{X})=\{f_j(\mathrm{X})\},(j=1,2,...,m_1)$, is the vector of objective functions, and $g(\mathrm{X})=\{g_k(\mathrm{X})\},(k=1,2,...,m_2)$, is the vector of equality and inequality constraints. Let $m=m_1+m_2$ and assume that X is represented as a vector of floating numbers.

This minimization problem can be further represented as

$$\text{Min } \mathrm{F}(\mathrm{X}) \tag{3.45}$$

where $\mathrm{F}(\mathrm{X})$ incorporates the objective function $\mathrm{f}(\mathrm{X})$ and the constraint function $g(\mathrm{X})$. There are different ways to convert (3.43)–(3.44) into (3.45), among which weighted sum is one popular approach as shown in (3.46) with the weighting factors $w_i > 0$

$$\mathrm{F}(\mathrm{X}) = \sum_{j=1}^{n} w_j f_j(\mathrm{X}) + \sum_{k=1}^{m} w_k g_k(\mathrm{X}) \tag{3.46}$$

For (3.45) and (3.46), the local and global minima can be calculated if the region of reliability of X is convex. For power system problems, the optimization problem may not always be convex and therefore requires heuristic algorithms such as DE to solve it.

Depending on the specific problem to be optimized, the weighting factor can have different practical meanings. For example, in risk management for power system planning, the weighting factor can represent the relative importance of each objective and constraint; it can also represent the probability of occurrence for future scenarios while considering their impact on the planning options.

3.7.2.2 Key operators for DE

As a member of the evolutionary algorithm family, DE also relies on the initial population generation, mutation, crossover, and selection through repeated generations until the termination criteria is met. The four key operators of DE are introduced accordingly in the sequel.

3.7.2.2.1 Initial population

DE is a parallel direct search method using a population of N parameter vectors for each generation. At generation G, the population P^G is composed of $\mathrm{X}_i^G, i = 1, 2, \ldots, N$.

The initial population P^{G0} can be chosen randomly under uniform probability distribution if there is nothing known about the problem to be optimized:

$$P^{G} = \left(\mathrm{X}_1^G, \mathrm{X}_2^G, ..., \mathrm{X}_N^G\right) \tag{3.47}$$

$$\mathrm{X}_i^G = \mathrm{X}_{i(Min)} + \mathrm{rand}_i\left[0,1\right] \cdot \left(\mathrm{X}_{i(Max)} - \mathrm{X}_{i(Min)}\right) \tag{3.48}$$

where $\mathrm{X}_{i(Min)}$ and $\mathrm{X}_{i(Max)}$ are the lower and higher boundaries of d-dimensional vector $\mathrm{X}_i = \left\{x_{i,j}\right\} = \left\{x_{i,1}, x_{i,2}, ..., x_{i,d}\right\}$. If some or a priori knowledge is available about the problem, the preliminary solution can be included to the initial population by adding normally distributed random deviations to the nominal solution

3.7.2.2.2 Mutation

The key characteristic of a DE is the way it generates trial parameter vectors throughout the generations. A weighted difference vector between two individuals is added to a third individual to form a new parameter vector. The newly generated vector will be evaluated by the objective function. The value of the corresponding objective function/fitness function will be compared with a predetermined individual. If the newly generated parameter vector has lower objective function/fitness function value, it will replace the predetermined parameter vector. The best parameter vector is evaluated for every generation in order to track the progress made throughout the minimization process. The random deviations of DE are generated by the search distance and direction information from the population. Correspondingly, this adaptive approach is associated with the normally fast convergence properties of a DE.

The objective of mutation is to enable search diversity in the parameter space as well as to direct the existing object vectors with suitable amount of parameter variation in a way that will lead to better results at a suitable time. It keeps the search robust and explores new areas in the search domain. For real parameter optimization, mutation is the process of adding a randomly generated number to one or more parameters of an existing object vector.

For each parent parameter vector, DE generates a candidate child vector based on the distance of two other parameter vectors. For each dimension $j \in [1,d]$, this process is shown in (3.49) as is referred to as scheme DE 1 by Storn and Price:

$$\mathrm{V}_i = \mathrm{X}_{r3}^G + F \cdot \left(\mathrm{X}_{r1}^G - \mathrm{X}_{r2}^G \right) \tag{3.49}$$

where the random integers $r1 \neq r2 \neq r3 \neq i$ are used as indices to index the current parent object vector. As a result, the population size N must be greater than 3. F is a real constant positive scaling factor and normally $F \in (0,1+)$. F controls the scale of the differential variation $\left(\mathrm{X}_{r1}^G - \mathrm{X}_{r2}^G \right)$ (Figure 3.6).

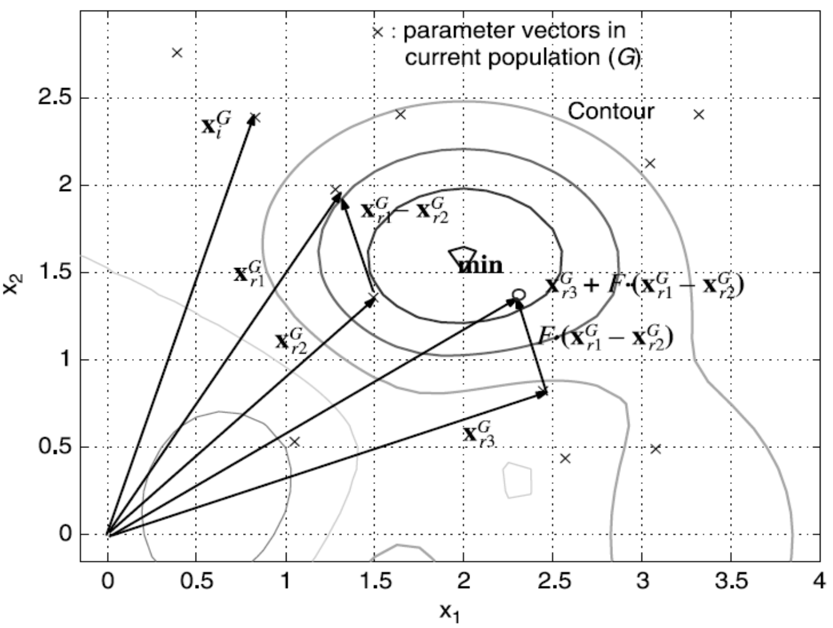


Figure 3.6 Vector representation of a child vector creation procedure with DE1 in (3.50) from vectors of current generation, where the dotted crossed lines are the counter toward the minimal solution point

3.7.2.2.3 Crossover

Selection of this newly generated vector V is based on comparison with another DE1 control variable, the crossover constant $CR \in [0,1]$, to ensure the search diversity. Some of the newly generated vectors will be used as child vector for the next generation, and others will remain unchanged. The process of creating new candidates is described as follows:

$$\mathrm{U}_i = \left(u_{i,1}, u_{i,2}, ..., u_{i,j}, ..., u_{i,d}\right) \tag{3.50}$$

$$u_{i,j} = \begin{cases} v_{i,j}, & \text{rand}\left(j\right) \leq CR \vee j = k\left(i\right) \\ x_{i,j}^{G} & \text{otherwise} \end{cases} \tag{3.51}$$

Where $i = 1,...,N$, $j = 1,...,d$, $k\left(i\right) \in 1,...,N$ is a randomly chosen integer to ensure that U_i gets at least one parameter from V_i ; $\text{rand}\left(j\right) \in [0,1]$ is an uniformly distributed random number; $CR \in [0,1]$ is the crossover constant and controls the probability of choosing the mutated individual to instead of current individual.

3.7.2.2.4 Selection

In order to decide whether the new vector U_i shall become a population member of generation $G+1$, it will be compared to X_i^G. If vector U_i yields a smaller objective function value than X_i^G, X_i^{G+1} is set to U_i, otherwise the old value X_i^G is retained.

3.7.2.3 Parameters setting

Among other operators, population size and selection operation are the most important. DE usually employs fixed population size throughout the search process. Variable population size can also be an option with proper size control algorithms to suit different objectives of DE applications. Selection of the population size N involves conflicting objectives. In order to achieve fast computational speed, the population size should be as small as possible. However, too small order of N may lead to premature convergence or stagnation. For engineering problems, a population size of $20d$ will usually generate satisfactory results. Depending on the problem and available computational resources, the population size can be in a range as low as $2d$ to as high as $100d$.

Population size N, scaling factor F and crossover factor CR maintain constant in the whole process of evolution. Usually factor F and CR affect convergence speed and robustness of search process. Using bigger values of N and F can get better global search but the convergence speed of algorithm will be slower; on the contrary, using smaller values makes optimization algorithm fall into the local optimal solutions. In general, the proper N, F and CR values are determined by testing and debugging.

The maximum generation number $(itermax)$ is one parameter of the conditions of DE algorithm to run the end, which indicates that DE algorithm stops operating until the maximum generation number condition is met, and the current best individual in the population is output as the optimal solution. In General, the value of maximum generation number is between 100 and 200.

3.7.2.4 Flow chart of DE

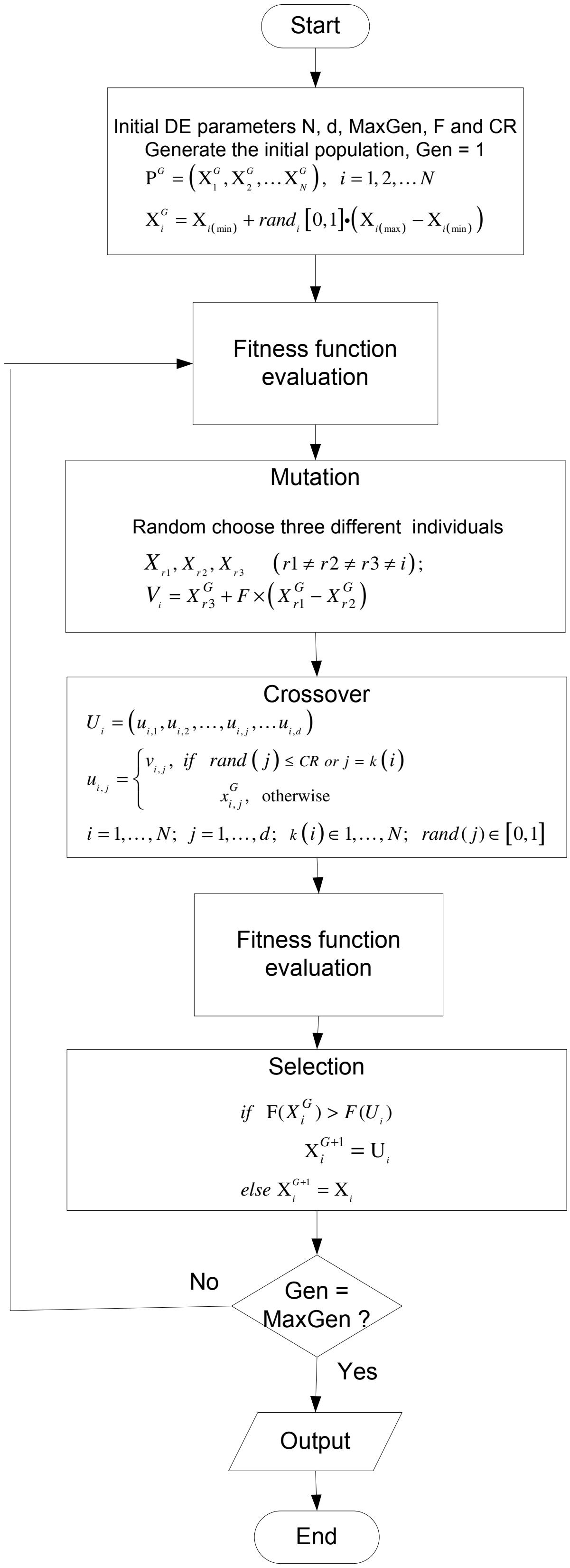


Figure 3.7 Flowchart of DE

3.7.3 DE based reactive power procurement

The reactive power procurement is to optimize the reactive power contracts considering both technical and economical aspects in terms of more objective functions while fulfilling both the equality and inequality constraints. The problem is formulated in (3.31). The process Reactive power procurement based on DE is the same as in Figure 3.7.

3.8 Case studies and discussions

The feasibility and the effectiveness of the proposed model is demonstrated on the IEEE30-bus system and IEEE118-bus system. The above describes DE procedure was implemented using MATLAB V6.5 R13 for windows to realize the proposed multi-objective reactive power procurement optimization.

To realize the DE based multi-objective reactive power procurement, the relevant DE parameters are given in Table 3.3.

Table 3.3 Optimal parameter settings for DE based reactive power procurement

Control parameters	IEEE30-bus	IEEE118-bus
Maximum generation, MaxGen	200	200
Number of control devices, D	19	77
Population size, np	3D	3D
Scaling factor for mutation, F	0.8	0.8
Crossover constant CR	0.6	0.6

3.8.1 IEEE30-bus system

The IEEE30-bus system comprises: 6 generating units, 4 tap changing transformers and capacitor banks located at 9 different buses. The single line diagram of the work is shown in Figure 3.8 and the network data is given in Table 3.4.

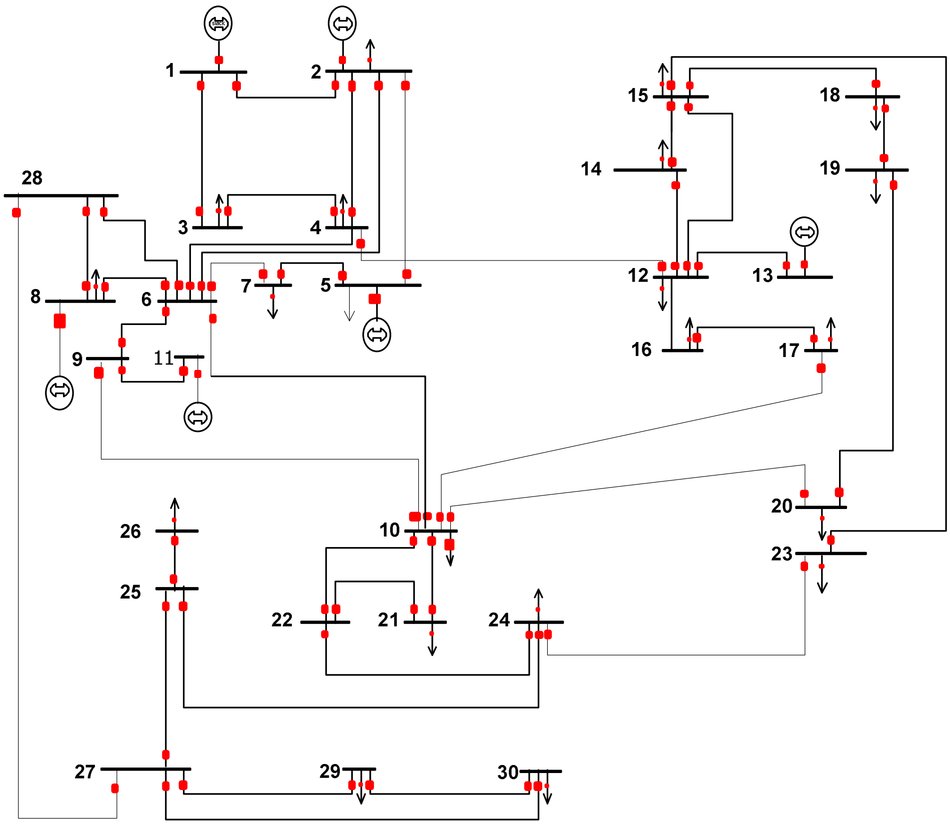


Figure 3.8 one line diagram of IEEE30-bus system

Table 3.4 IEEE30-bus system parameters

Bus No.	P_{Gi} **(MW)**	P_{Li} **(MW)**	Q_{Li} **(MVar)**	V_i^{max} **(p.u.)**	V_i^{min} **(p.u.)**
1	23.54	–	–	1.1	0.95
2	57.56	21.7	12.7	1.1	0.95
3	–	2.4	1.2	1.05	0.95
4	–	7.6	1.6	1.05	0.95
5	24.56	94.2	19	1.1	0.95
6	–	–	–	1.05	0.95
7	–	22.8	10.9	1.05	0.95
8	35	30	30	1.1	0.95
9	–	–	–	1.05	0.95

10	–	5.8	2	1.05	0.95
11	17.93	–	–	1.1	0.95
12	–	11.2	7.5	1.05	0.95
13	16.91	–	–	1.1	0.95
14	–	6.2	1.6	1.05	0.95
15	–	8.2	2.5	1.05	0.95
16	–	3.5	1.8	1.05	0.95
17	–	9	5.8	1.05	0.95
18	–	3.2	0.9	1.05	0.95
19	–	9.5	3.4	1.05	0.95
20	–	2.2	0.7	1.05	0.95
21	–	17.5	11.2	1.05	0.95
22	–	–	–	1.05	0.95
23	–	3.2	1.6	1.05	0.95
24	–	8.7	6.7	1.05	0.95
25	–	–	–	1.05	0.95
26	–	3.5	2.3	1.05	0.95
27	–	–	–	1.05	0.95
28	–	–	–	1.05	0.95
29	–	2.4	0.9	1.05	0.95
30	–	10.6	1.9	1.05	0.95

In the simulated IEEE30-bus system, the reactive power price offers from the generators are set to: $b_{Gi} = c_{Gi} = 0$, $a_{G1} = 0.0200, a_{G2} = 0.0175, a_{G5} = 0.0625$, $a_{G8} = 0.0083, a_{G11} = 0.0250, a_{G13} = 0.0250$. The price for the real power losses is set to $\lambda_L = 100$ £/MWh and the penalty cost for the voltage violation is set to $\lambda_V = 1000$.

The DE tool was applied to solve the single objective and the multi-objective reactive power procurement optimization separately. The effect of different objective for reactive power optimization was investigated using this case study for 200 generations. Simulation results of the voltage profiles for normal power flow (PF) before the reactive power optimization, single objective reactive power optimization (MinPLoss) and multi-objective reactive power optimization are shown in figure 3.9.

Observe from the figure 3.9, it is obvious that the voltage profiles are all improved when the reactive power is optimized in the system in either single objective procurement model (MinPLoss) or multi-objective procurement model which considering the effect of reactive power generation costs as well. Although the voltage profiles on PV buses 1 and 2 violate the soft voltage limit 1.05 p.u., system profiles obtained through single objective procurement (MinPLoss) and multi-objective procurement both are improved when compared with the system profile obtained without optimization (normal PF). Furthermore, the voltage profile obtained from the multi-objective reactive power procurement model is much closer to the rated voltage value 1.0 p.u.. In another word, the power quality of multi-objective reactive power procurement model is better than single objective procurement model (MinPLoss).

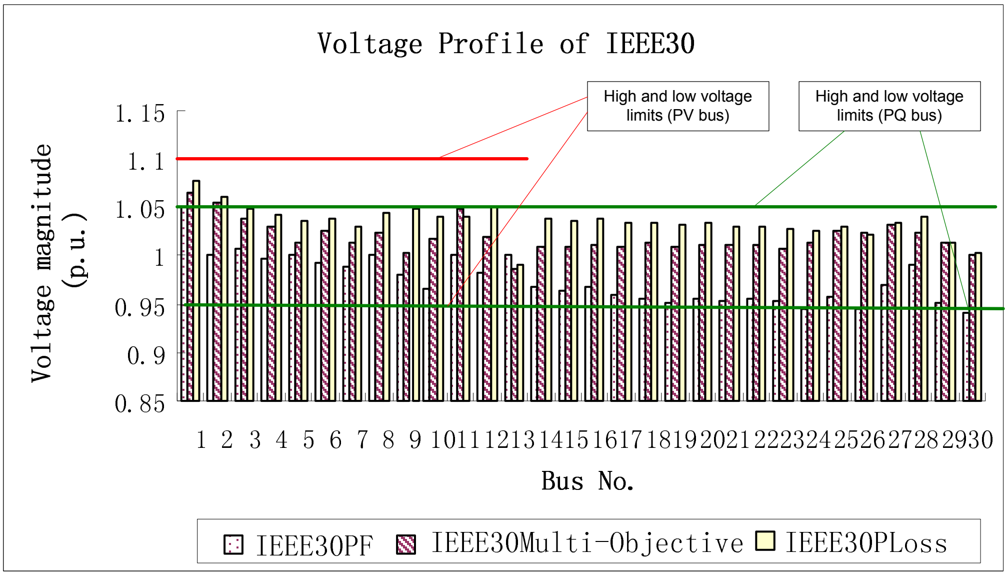


Figure 3.9 Voltage profiles of IEEE30-bus system under PF, MinPLoss and multi-objective reactive power procurement

Table 3.5 shows the reactive power generation output and the costs which are obtained in different reactive procurement models to determine the reactive power procurement contracts between ISO and reactive power generators.

In the Table 3.5, the generators' reactive power output results which are obtained through normal Power Flow, real power minimization and multi-objective reactive power procurement calculations are denoted in Q-PF, Q-Ploss, Q-Multi-Objective respectively; and their correspondingly reactive power procurement costs are denoted in CQ-PF, CQ-Ploss, CQ-Multi-Objective respectively.

From the results we can see that reactive power output from each generator in different procurement models is very different. Therefore, it also illustrates that the same reactive power generator has different predominance in different procurement models. Meanwhile, different from the real power generation, the generators with low reactive power generation costs may not be purchased more reactive power because of the localization manner of reactive power.

In the multi-objective procurement model the reactive power generates in the manner of a much more economical disperse than in the single objective procurement model (MinPLoss). In another word, in this model ISO tries to procure the reactive power service from generators in their lowest payment region. The concern of the reactive power cost in multi-objective procurement model gives clear economical signal of reactive power service payment which effectively compensates the reactive power service suppliers.

Table 3.5 Reactive power generation output and costs

Generator No.	**Q-PF (Mvar)**	**Q-PLoss (Mvar)**	**Q-Multi-Objective (Mvar)**	**CQ-PF (£)**	**CQ-PLoss (£)**	**CQ-Multi-Objective (£)**
G1	71.42	3.79	-8.63	102.016	0.287	1.49
G2	-75.45	8.64	39.83	99.622	1.306	27.763
G5	48.62	31.4	16.48	147.744	61.623	16.974

G8	47.41	42.83	18.12	18.656	15.226	2.725
G11	9.57	-4.24	23.14	2.29	0.449	13.386
G13	12.64	-41.04	-22.94	3.994	42.107	13.156

The real power losses (Ploss), real power losses costs (CPloss), total reactive power generation costs (CQGentotal) and the power quality index (Σ**N**) defined in the way of the number of the bus voltage violation of simulated IEEE30-bus system are displayed in Table 3.6.

We can see that although the value of the real power losses in multi-objective reactive power procurement model which is optimize the real power losses, reactive power payment and the power quality in an overall objective function is slightly bigger than the one obtained in the single objective procurement model (MinPLoss), the reactive power generation cost in multi-objective procurement model is much less than in the MinPLoss model. And the reduction of the reactive power generation cost is much more than the increasing of real power losses cost.

Table 3.6 The comparison of IEEE30-bus system real power losses, reactive power generation and PQ-bus voltage violation before and after the reactive optimization

Reactive power procurement model	**Ploss (MW)**	**CPloss (£)**	**CQGentotal (£)**	**ΣN**
PF	8.5	85	374	3
MinPLoss	6.78	67.8	120.998	0
Multi-Objective	9.02	90.2	75.494	0

Therefore, the ISO procuring the reactive power from the generators using the multi-objective model is a much economical and effective way than the single objective procurement model (MinPLoss). In another word, using the multi-objective reactive power procurement model, the ISO pays less money for the better power quality.

3.8.2 IEEE118-bus system

For further experimental purpose of proposed reactive power procurement model, an IEEE118-bus system is also tested. The one line diagram of the system is shown in Figure 3.10 which consists of 54 generators, branches, loads, transformers and capacitor banks. The operation condition (consisting of contracted real power generation, real and reactive power load and the reactive power price offer from each generator) and the reactive power procurement solutions are given in table 3.7

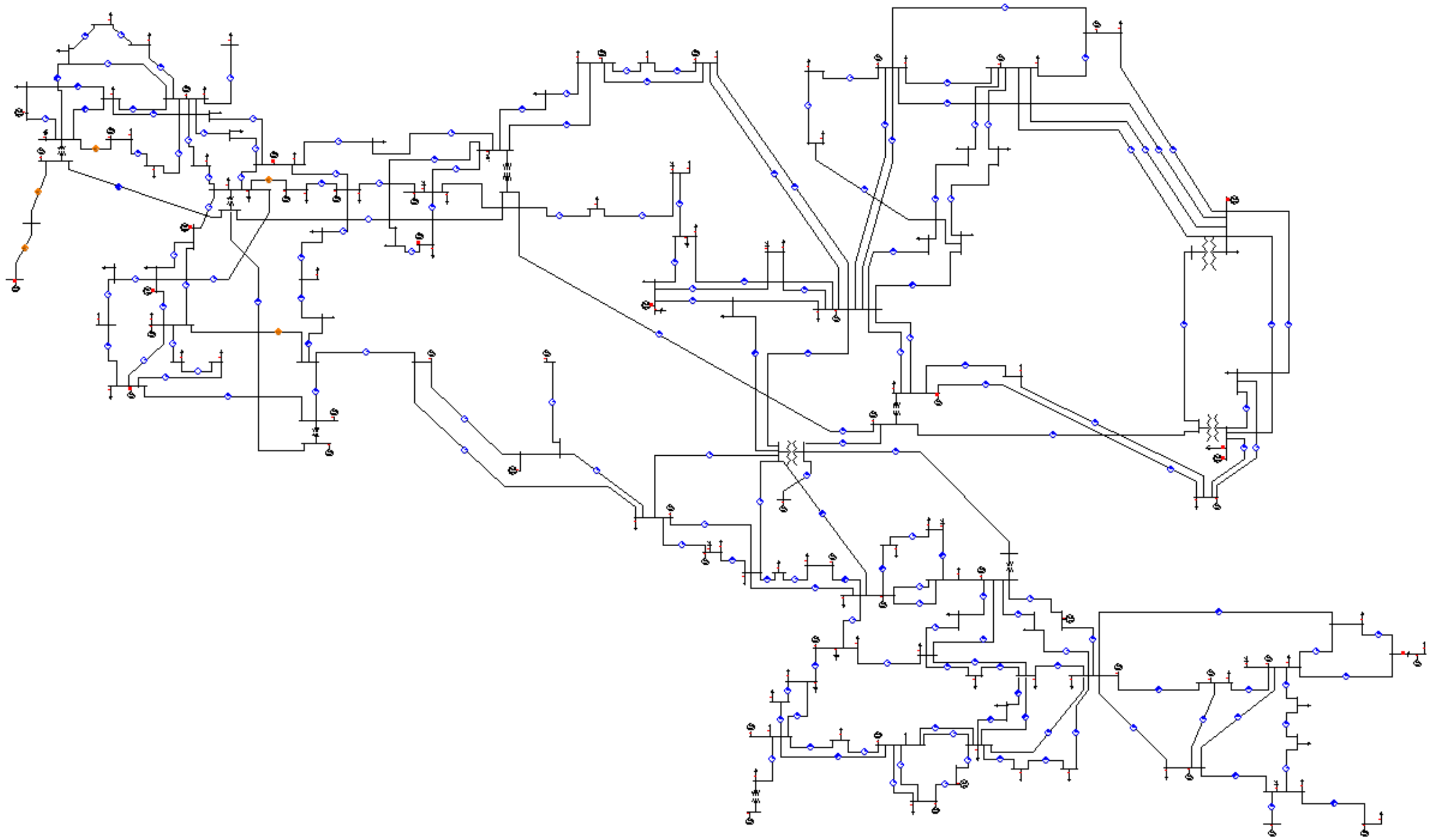


Figure 3.10 one line diagram of IEEE118-bus system

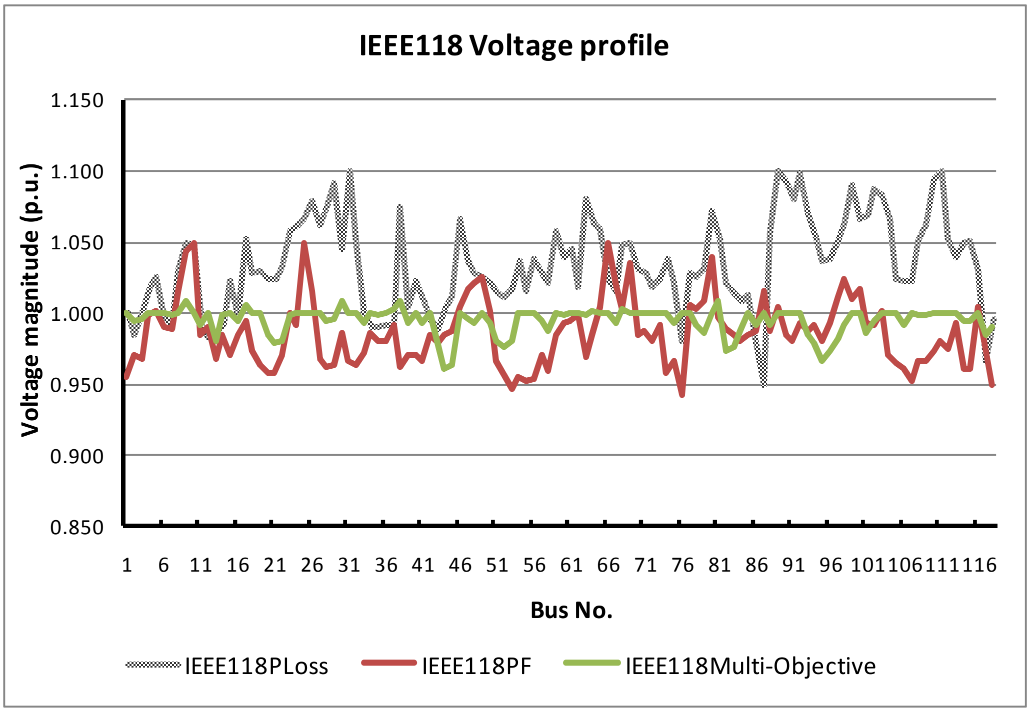


Figure 3.11 Voltage profiles of IEEE118-bus system under PF, MinPLoss and multi-objective reactive power procurement

The voltage profiles of IEEE118-bus system obtained under normal power flow (PF), single objective reactive power procurement model (MinPLoss) and multi-objective reactive power procurement model is shown in figure 3.11. Under the normal PF, the voltages on PQ bus 53, 77 and 118 violated the voltage lower limit of 0.95 p.u.; while the voltage profiles under single and multiple objective reactive power procurement models are maintaining inside the voltage ranges. And the power quality obtained under the multi-objective reactive power procurement model is better than the one obtained in the single objective procurement model (MinPLoss).

Table 3.7 IEEE118-bus system operation condition and reactive power procurement solution

System input data							Reactive power optimization Solution					
Generatio		Load		Price offer for Q			PF	Ploss	Multi-Obj	PF	Ploss	Multi-Obj
Bus	P(MW)	P(MW)	Q(MVAR)	c	b	a	Q(MVAR)	Q(MVAR)	Q(MVAR)	CQ ($)	CQ ($)	CQ ($)
1	35.00	51.00	27.00	0.018	0.092	0.036	-3.10	58.56	55.72	0.65	129.79	117.75
2	—	20.00	9.00	—	—	—	—	—	—	0.00	0.00	0.00
3	—	39.00	10.00	—	—	—	—	—	—	0.00	0.00	0.00
4	70.00	39.00	12.00	0.017	0.089	0.035	-15.01	-37.27	23.68	9.23	51.89	21.72
5	—	—	—	—	—	—	—	—	—	0.00	0.00	0.00
6	10.00	52.00	22.00	0.095	0.070	0.016	15.93	10.24	37.55	5.34	2.52	25.66
7	—	19.00	2.00	—	—	—	—	—	—	0.00	0.00	0.00
8	15.00	28.00	0.00	0.031	0.081	0.042	62.73	100.28	-57.25	168.89	426.68	141.08
9	—	—	—	—	—	—	—	—	—	0.00	0.00	0.00
10	320.00	—	—	0.034	0.054	0.049	-51.04	-79.52	-93.22	129.89	312.85	429.05
11	—	70.00	23.00	—	—	—	—	—	—	0.00	0.00	0.00
12	75.00	47.00	10.00	0.060	0.055	0.039	91.27	-100.05	64.14	327.16	392.58	162.65
13	—	34.00	16.00	—	—	—	—	—	—	0.00	0.00	0.00
14	—	14.00	1.00	—	—	—	—	—	—	0.00	0.00	0.00
15	10.00	90.00	30.00	0.084	0.099	0.099	4.07	13.48	49.74	2.12	19.39	249.71
16	—	25.00	10.00	—	—	—	—	—	—	0.00	0.00	0.00
17	—	11.00	3.00	—	—	—	—	—	—	0.00	0.00	0.00
18	45.00	60.00	34.00	0.077	0.024	0.042	26.37	-0.99	37.27	29.99	0.14	59.47
19	45.00	45.00	25.00	0.039	0.085	0.097	-10.17	70.87	43.35	10.93	492.68	185.80
20	—	18.00	3.00	—	—	—	—	—	—	0.00	0.00	0.00
21	—	14.00	8.00	—	—	—	—	—	—	0.00	0.00	0.00
22	—	10.00	5.00	—	—	—	—	—	—	0.00	0.00	0.00
23	—	7.00	3.00	—	—	—	—	—	—	0.00	0.00	0.00
24	20.00	13.00	0.00	0.077	0.096	0.095	-15.40	31.52	-3.18	24.07	97.41	1.34
25	110.00	—	—	0.087	0.030	0.096	49.72	-159.41	-39.92	238.70	2442.32	154.15
26	214.00	—	—	0.083	0.049	0.062	9.89	117.32	-52.93	6.64	861.22	176.77
27	4.00	71.00	13.00	0.032	0.026	0.071	2.03	47.52	43.83	0.38	160.93	137.00
28	—	17.00	7.00	—	—	—	—	—	—	0.00	0.00	0.00
29	—	24.00	4.00	—	—	—	—	—	—	0.00	0.00	0.00
30	—	—	—	—	—	—	—	—	—	0.00	0.00	0.00
31	7.00	43.00	27.00	0.039	0.040	0.012	31.57	157.91	42.11	13.70	316.43	23.79
32	16.00	59.00	23.00	0.071	0.052	0.048	-12.34	-46.12	43.72	8.00	104.25	93.81
33	—	23.00	9.00	—	—	—	—	—	—	0.00	0.00	0.00
34	24.00	59.00	26.00	0.024	0.017	0.025	-6.83	-16.49	21.21	1.30	7.06	11.57
35	—	33.00	9.00	—	—	—	—	—	—	0.00	0.00	0.00
36	16.00	31.00	17.00	0.090	0.016	0.069	-1.92	49.62	35.47	0.37	169.68	86.90
37	—	—	—	—	—	—	—	—	—	0.00	0.00	0.00
38	—	—	—	—	—	—	—	—	—	0.00	0.00	0.00
39	—	27.00	11.00	—	—	—	—	—	—	0.00	0.00	0.00
40	11.00	66.00	23.00	0.055	0.017	0.020	26.77	138.54	65.58	14.59	379.73	85.71
41	—	37.00	10.00	—	—	—	—	—	—	0.00	0.00	0.00
42	29.00	96.00	23.00	0.069	0.089	0.034	41.00	0.40	49.76	60.85	0.11	88.66
43	—	18.00	7.00	—	—	—	—	—	—	0.00	0.00	0.00
44	—	16.00	8.00	—	—	—	—	—	—	0.00	0.00	0.00
45	—	53.00	22.00	—	—	—	—	—	—	0.00	0.00	0.00
46	19.00	28.00	10.00	0.073	0.015	0.047	-5.25	96.42	42.25	1.45	438.88	84.68
47	—	34.00	0.00	—	—	—	—	—	—	0.00	0.00	0.00
48	—	20.00	11.00	—	—	—	—	—	—	0.00	0.00	0.00
49	204.00	87.00	30.00	0.055	0.047	0.061	115.63	-14.71	48.68	822.45	13.97	147.14
50	—	17.00	4.00	—	—	—	—	—	—	0.00	0.00	0.00
51	—	17.00	8.00	—	—	—	—	—	—	0.00	0.00	0.00
52	—	18.00	5.00	—	—	—	—	—	—	0.00	0.00	0.00
53	—	23.00	11.00	—	—	—	—	—	—	0.00	0.00	0.00
54	48.00	113.00	32.00	0.041	0.096	0.045	3.90	71.78	57.38	1.10	237.25	152.73
55	75.00	63.00	22.00	0.064	0.075	0.058	4.66	-165.64	35.64	1.67	1603.62	76.40
56	20.00	84.00	18.00	0.073	0.071	0.089	-2.29	217.39	60.43	0.70	4225.45	329.66
57	—	12.00	3.00	—	—	—	—	—	—	0.00	0.00	0.00

58	—	12.00	3.00	—	—	—	—	—	—	0.00	0.00	0.00
59	60.00	277.00	113.00	0.014	0.013	0.050	76.83	266.75	100.00	293.71	3531.67	497.17
60	—	78.00	3.00	—	—	—	—	—	—	0.00	0.00	0.00
61	124.00	—	—	0.011	0.011	0.057	-40.39	-28.77	-31.89	94.21	47.90	58.81
62	36.00	77.00	14.00	0.049	0.096	0.063	1.26	-82.68	36.05	0.27	441.16	85.87
63	—	—	—	—	—	—	—	—	—	0.00	0.00	0.00
64	—	—	—	—	—	—	—	—	—	0.00	0.00	0.00
65	391.00	—	—	0.070	0.014	0.023	80.76	194.19	-148.13	152.20	875.88	510.17
66	392.00	39.00	18.00	0.063	0.027	0.031	-1.95	-284.83	-33.05	0.23	2518.67	34.77
67	—	28.00	7.00	—	—	—	—	—	—	0.00	0.00	0.00
68	—	—	—	—	—	—	—	—	—	0.00	0.00	0.00
69	427.62	—	—	0.073	0.060	0.026	-82.39	232.24	-108.99	183.12	1429.16	318.29
70	21.00	66.00	20.00	0.018	0.016	0.082	9.66	14.48	33.29	7.79	17.36	90.95
71	—	—	—	—	—	—	—	—	—	0.00	0.00	0.00
72	13.00	12.00	0.00	0.094	0.062	0.059	-11.13	-29.16	-1.83	8.09	52.07	0.40
73	12.00	6.00	0.00	0.053	0.066	0.022	9.65	-5.79	-0.50	2.75	1.18	0.09
74	9.00	68.00	27.00	0.054	0.049	0.047	-5.63	96.88	64.86	1.82	445.63	200.83
75	—	47.00	11.00	—	—	—	—	—	—	0.00	0.00	0.00
76	10.00	68.00	36.00	0.090	0.034	0.078	5.27	-1.53	76.15	2.44	0.32	455.10
77	11.00	61.00	28.00	0.055	0.047	0.025	11.87	-58.03	145.71	4.08	85.64	529.36
78	—	71.00	26.00	—	—	—	—	—	—	0.00	0.00	0.00
79	—	39.00	32.00	—	—	—	—	—	—	0.00	0.00	0.00
80	470.00	130.00	26.00	0.093	0.098	0.078	104.90	155.16	-19.12	867.33	1890.14	30.44
81	—	—	—	—	—	—	—	—	—	0.00	0.00	0.00
82	—	54.00	27.00	—	—	—	—	—	—	0.00	0.00	0.00
83	—	20.00	10.00	—	—	—	—	—	—	0.00	0.00	0.00
84	—	11.00	7.00	—	—	—	—	—	—	0.00	0.00	0.00
85	7.00	24.00	15.00	0.058	0.010	0.042	-5.82	-63.23	53.02	1.53	167.09	117.59
86	—	21.00	10.00	—	—	—	—	—	—	0.00	0.00	0.00
87	4.00	—	—	0.062	0.093	0.044	11.02	-15.99	1.76	6.49	12.91	0.36
88	—	48.00	10.00	—	—	—	—	—	—	0.00	0.00	0.00
89	556.00	—	—	0.095	0.028	0.034	-13.66	22.62	-97.17	6.90	18.35	327.86
90	6.00	163.00	42.00	0.078	0.069	0.016	59.30	82.60	84.15	61.99	117.97	122.32
91	12.00	10.00	0.00	0.095	0.045	0.070	-15.40	-31.09	0.40	17.44	69.37	0.12
92	8.00	65.00	10.00	0.068	0.086	0.019	0.49	122.47	61.27	0.12	292.20	75.83
93	—	12.00	7.00	—	—	—	—	—	—	0.00	0.00	0.00
94	—	30.00	16.00	—	—	—	—	—	—	0.00	0.00	0.00
95	—	42.00	31.00	—	—	—	—	—	—	0.00	0.00	0.00
96	—	38.00	15.00	—	—	—	—	—	—	0.00	0.00	0.00
97	—	15.00	9.00	—	—	—	—	—	—	0.00	0.00	0.00
98	—	34.00	8.00	—	—	—	—	—	—	0.00	0.00	0.00
99	15.00	42.00	0.00	0.086	0.042	0.071	-17.54	44.69	6.13	22.55	143.00	3.00
100	198.00	37.00	18.00	0.078	0.078	0.062	108.87	-77.54	10.39	740.94	377.64	7.56
101	—	22.00	15.00	—	—	—	—	—	—	0.00	0.00	0.00
102	—	5.00	3.00	—	—	—	—	—	—	0.00	0.00	0.00
103	40.00	23.00	16.00	0.060	0.094	0.031	41.69	89.84	17.04	57.59	257.48	10.61
104	7.00	38.00	25.00	0.030	0.030	0.016	8.00	139.37	33.54	1.26	305.40	18.48
105	21.00	31.00	26.00	0.080	0.020	0.012	-12.89	-161.33	49.92	2.33	314.32	30.87
106	—	43.00	16.00	—	—	—	—	—	—	0.00	0.00	0.00
107	16.00	50.00	12.00	0.059	0.081	0.065	6.56	13.44	28.28	3.40	12.96	54.65
108	—	2.00	1.00	—	—	—	—	—	—	0.00	0.00	0.00
109	—	8.00	3.00	—	—	—	—	—	—	0.00	0.00	0.00
110	10.00	39.00	30.00	0.037	0.042	0.029	5.26	134.14	33.19	1.05	524.32	33.17
111	8.00	—	—	0.098	0.069	0.095	-1.84	-0.95	-10.92	0.55	0.25	12.21
112	17.00	68.00	13.00	0.098	0.094	0.041	41.51	-31.76	38.14	75.25	44.79	63.83
113	4.00	6.00	0.00	0.064	0.066	0.013	6.11	-50.17	-21.85	0.96	36.74	7.84
114	—	8.00	3.00	—	—	—	—	—	—	0.00	0.00	0.00
115	—	22.00	7.00	—	—	—	—	—	—	0.00	0.00	0.00
116	7.00	184.00	0.00	0.074	0.013	0.076	51.32	-423.11	-72.96	200.96	13615.43	405.70
117	—	20.00	8.00	—	—	—	—	—	—	0.00	0.00	0.00
118	—	33.00	15.00	—	—	—	—	—	—	0.00	0.00	0.00

The IEEE118-bus system operation condition and reactive power procurement solution are displayed in Table 3.7. A table of comparison of IEEE118-bus system real power losses (Ploss), reactive power generation (CPloss), reactive power total generation costs (CQGentotal) and power quality index (Σ **N**) at PQ-buses before and after the reactive optimization is shown in Table 3.8.

When the system reactive power procurement without optimization which is obtained through running normal Power Flow (PF), the voltages on three PQ buses violate their lower voltage limit 0.95p.u.. this is because they are in the heavy load area. However, after reactive power procurement is optimized using either single objective or multi-objective function there are no system voltage violations any more.

From the reactive power procurement solution shown in Table 3.7 and Table 3.8, it is seen that although the real power losses under the multi-objective procurement model is more than under the MinPLoss procurement model, the reactive power generation compensation paid by ISO is much less than under MinPLoss procurement model. Therefore, the proposed multi-objective reactive power procurement model gives a better reactive power procurement solution which concerning technical and the financial aspects together than the single objective procurement model (PLoss).

Table 3.8 The comparison of IEEE118-bus system real power losses, reactive power generation and PQ-bus voltage violation before and after the reactive optimization

Reactive power procurement model	**Ploss (MW)**	**CPloss (£)**	**CQGentotal (£)**	**ΣN**
PF	136.61	13248	4537.348	3
MinPLoss	132.48	13661	43850.71	0
Multi-Objective	132.62	13262	8212.878	0

The proposed multi-objective reactive power procurement model has been evaluated on the IEEE30-bus system and IEEE118-bus system. The simulation results, compared with that obtained using PF and single objective procurement model (MinPLoss) are presented to show the potential of application s of proposed model to reactive power procurement in the new power market environment.

3.9 Summary

This chapter has pointed out the difficulty of reactive power procurement and compensation which has resulted in the difference of its charging schemes around the world before and after deregulation. Reviews of reactive power costing and procurement models in the existing markets around the globe were introduced which stress the point that there is no clear and efficient procurement model which considering both technical and economical aspects for reactive power in the deregulated power market that has developed with ancillary services markets.

The new proposed model, multi-objective reactive power procurement model, for ISO obtaining the reactive power contracts with reactive power generators, is introduced in this chapter. Its methodology and mathematic model is presented in section 3.5. IEEE10-bus system is used to illustrate the proposed. A further case study on bigger system, IEEE118-bus system, is conducted by which the proposed multi-objective reactive power procurement model has shown the advantages. Based on the results of the case studies, the following conclusions are achieved:

The proposed model satisfies the characteristics required for the reactive power procurement in the existing ancillary services market. And it is favorable to be used in considering both power system security requirement and power market economical requirement.

3.10 References

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Chapter 4
Optimal Reactive Power Placement in Power System

4.1 Introduction

With the fast development of economy, nowadays demand for electricity has been increasing rapidly. In order to use renewable energy especially the wind which is the most popular free-fuel and pollution-free energy source, the wind generation integrates into the power system more and more. Its characteristics of been intermittence and non-dispatchable badly affects the generation pattern and power flows in the power system when it is connected to the power network. Due to above two huge changes happen in system load profile and generation profile, it is a big challenge for the power system to operate in both a secure and economical manner in the new power market environment. Therefore, it is very important to investigate the power system operational performance in this new environment and make improvements in system operation and planning.

In some European countries such as Ireland, high level of wind energy is integrated into the transmission network to meet the growth in power demand and it is also used to replace an equivalent amount of energy from the existing power plants(i.e., thermal plant) [1]. With this high integration of wind generation into the power system it would certainly create a different power flow pattern in the power network. Even though the impact of small wind generating capacity is less significant, however, with increasing penetration of wind generation in the power networks, the impact of higher wind generation on the system performance should be carefully studied and investigated. Section 4.2 of this chapter evaluates the system voltage profile and reactive power requirement with wind generation on the network.

Insufficient reactive power compensation can not make the power system operate securely and excess reactive power compensation may only lead to unnecessary investment. Therefore, a proper optimal reactive power placement method is required for reactive power compensation scheme called Reactive Power Planning (RPP). Section 4.3 reviews two fundamental single-objective reactive power placement optimization methods which consider the new reactive power sources investment cost and voltage profile individually. Section 4.4 proposes a multi-objective reactive power placement optimization method which compromise system technical requirement and financial investment concern. Finally, the proposed optimal reactive power placement method is applied in the IEEE30-bus system for case studies.

4.2 Evaluation of system-wide reactive power requirement and voltage profile

Without an adequate reactive power supply it is difficult to maintain system voltages within their operating limits. Therefore, one of the criteria for a power system to operate in a reliable and stable condition is to maintain voltage profile within specified limits at each consumer load point. For reliable power networks, voltage at all buses should be maintained within an acceptable limits from 0.95 to 1.05 p.u. in a normal working condition [2].

4.2.1 Power System networks with conventional generators

Most of the conventional generators connected to the power grid are synchronous generators which can supply or consume reactive power. The reactive power productions from these generators are controlled by the Automatic Voltage Regulator (AVR) that maintains the system voltage profiles.

Reactive power generation requirement is primarily driven by the interaction of real power flows on the transmission system between various elements in the network with the system demand. Variations in load and generation profiles during normal operation of power system may worsen the voltage profile at different buses which could be improved by reactive power compensators placed in the system.

4.2.2 Power system networks with wind generators

The emphasis on power generation from renewable sources in order to reduce the environmental impact of power generation leads to the development and use of technologies for renewable power generation, such as solar panels, wave plants and wind turbines [3]. As a power source, wind generation is characterised by intermittence and is normally not dispatchable. When they are connected to power networks, some wind generators not only supply the real power but also reactive power to the grid. However, some wind farms need considerable reactive power support and coupled with intermittency of their power generation patterns, the resultant effect on the steady state operation of the system is considerable.

The impact of wind generation on the transmission and distribution system has been studied in [1-2, 4-7]. These studies show that wind generation integrated on the distribution system can improve overall system voltage profile and at the same time system losses are reduced [6, 8]. This is mainly due to the characteristics of the distribution system which is mostly in radial form. However, the integration of wind generation on the transmission system does not necessarily improve the overall system voltage profile and the system losses [7]. This is probably due to the meshed nature of the network and the interaction of power flow on the transmission system.

In order to investigate voltage profile and reactive power requirement of the transmission system when connecting wind generation, an IEEE30-bus system with two wind generator is studied [9] in section 4.2.3.

4.2.3 Case studies on the modified IEEE30-bus system with wind generators

4.2.3.1 Simulation procedure

The modified IEEE30-bus system [9] consists of six generators, forty one branches and twenty one loads as shown in Figure 4.1. All the branch data are given in Table 4.1.

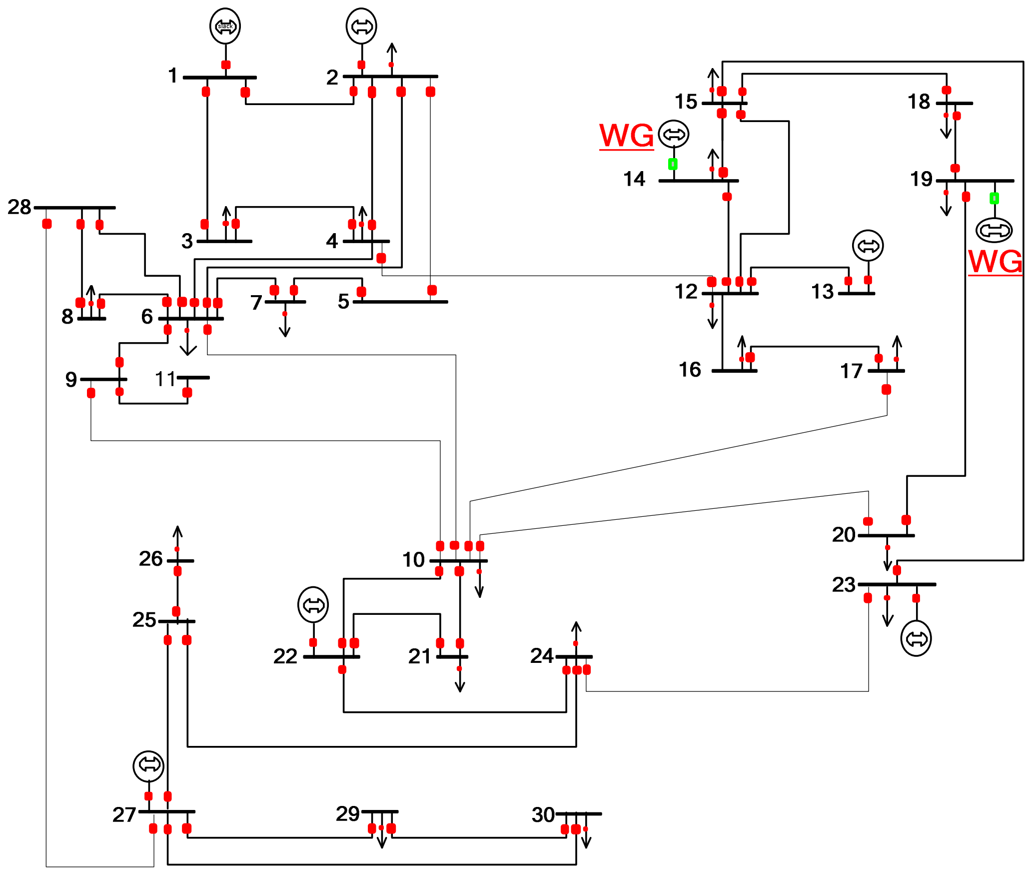

Figure 4.1 One line diagram of modified IEEE 30-bus system

Table 4.1 Branch parameters for IEEE30 bus test system

From Bus	To Bus	R/pu	X/pu	BCAP/pu	Line Limit/ MVA
1	2	0.0192	0.0575	0.0264	180
1	3	0.0452	0.1852	0.0204	150
2	4	0.0570	0.1737	0.0184	150
2	5	0.0472	0.1983	0.0209	100
2	6	0.0581	0.1763	0.0187	150
3	4	0.0131	0.0379	0.0042	100
4	6	0.0119	0.0414	0.0045	100
4	12	0.0000	0.2560	0.0000	150
5	7	0.0460	0.1160	0.0102	100
7	6	0.0267	0.0820	0.0085	100
8	6	0.0120	0.0420	0.0045	100
6	9	0.0000	0.2080	0.0000	100
6	10	0.0000	0.5560	0.0000	100
28	6	0.0170	0.0600	0.0065	100
28	8	0.0640	0.2000	0.0214	100
9	10	0.0000	0.1100	0.0000	100
9	11	0.0000	0.2080	0.0000	50
10	17	0.0320	0.0850	0.0000	100
10	20	0.0940	0.2090	0.0000	150
10	21	0.0350	0.0750	0.0000	100
10	22	0.0727	0.1499	0.0000	100
12	13	0.0000	0.1400	0.0000	100
14	12	0.1230	0.2560	0.0000	150
15	12	0.0660	0.1300	0.0000	100
12	16	0.0950	0.1990	0.0000	100
15	14	0.2210	0.2000	0.0000	150
15	18	0.1070	0.2190	0.0000	100
23	15	0.1000	0.2020	0.0000	150
17	16	0.0820	0.1930	0.0000	100
18	19	0.0639	0.1292	0.0000	100
19	20	0.0340	0.0680	0.0000	150
22	21	0.0120	0.0240	0.0000	100
22	24	0.1150	0.1790	0.0000	100
24	23	0.1320	0.2700	0.0000	100
25	24	0.1890	0.3290	0.0000	100
26	25	0.1270	0.1900	0.0000	100
27	25	0.1090	0.2090	0.0000	100
28	27	0.0000	0.3960	0.0000	100
27	29	0.1100	0.1075	0.0000	100
27	30	0.1600	0.3015	0.0000	100
29	30	0.1200	0.2265	0.0000	100

The modified test system is analysed using AC Optimal Power Flow (OPF). All simulations were carried out in the PowerWorld™ simulator package [10]. In the AC OPF simulation, it is assumed that one-part bid is used to simplify the market structure where its objective is to minimise the total generation production cost.

Table 4.2 gives the generator's cost parameters for the test system. The voltage p.u. value for each generator is set at 1.05p.u.

Table 4.2 Generator's cost parameters

Gen. No.	Generator Cost Co-efficient b/MBtu/MWh	Pmin/MW	Pmax/MW
1	12	14.0	280.0
2	10	10.0	200.0
13	15	5.0	100.0
22	14	6.5	130.0
23	13	7.0	140.0
27	11	7.5	150.0

The simulation was carried out by connecting wind generation at bus 14 and bus 19 separately. Same data for wind power and system demand were used so as to compare the effect of locating wind generation at different locations in the network on the voltage profile and the system reactive power requirement. A one year data was used for the simulation, but for ease of presentation, a one month result is presented here, which also exhibit similar characteristics with the one year results. Figure 4.2 shows the wind power output curve with a one day load superimposed, and the one day load data and wind generator input data are displayed in Table 4.3 and Table 4.4 separately.

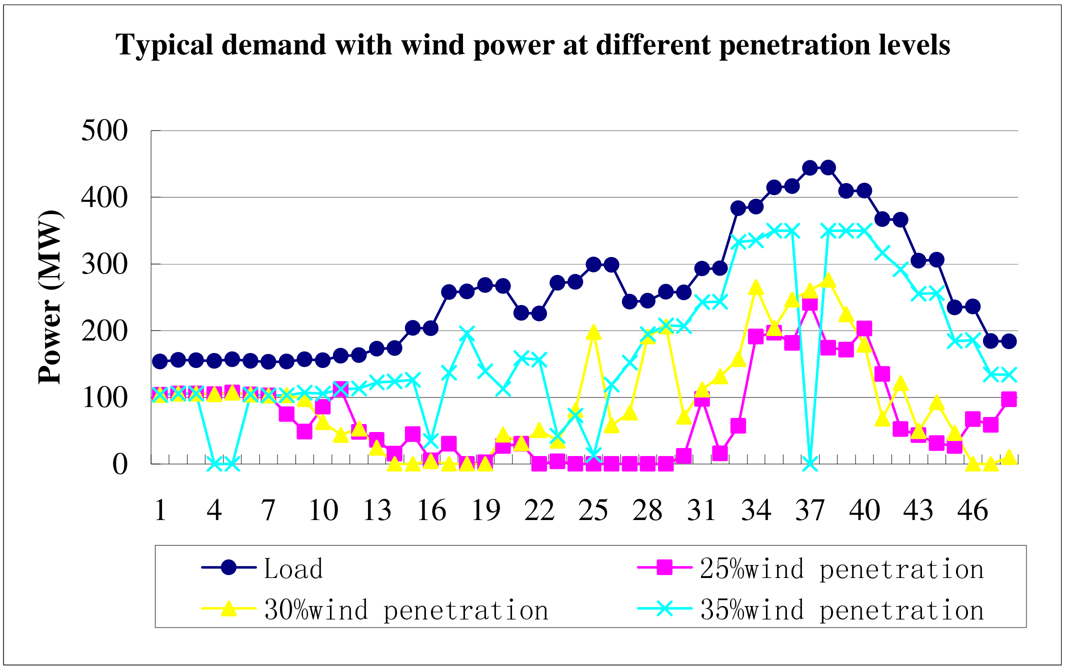

Figure 4.2 Load curve and wind power input at different penetration levels

Table 4.3 One day load input at 30 minutes interval

Hour	2	3	4	6	7	8	10	12	14	15	16	17	18	19	20	21	23	24	26	29	30
1:00:00	14.80	12.33	7.40	8.38	16.77	13.90	6.04	6.04	9.07	12.09	1.51	2.27	1.32	1.13	3.97	6.15	10.25	4.61	5.64	3.59	10.25
1:30:00	14.69	12.25	7.35	8.33	16.65	13.95	6.06	6.06	9.10	12.13	1.41	2.11	1.23	1.06	3.70	6.21	10.35	4.66	5.69	3.62	10.35
2:00:00	15.02	12.52	7.51	8.51	17.03	13.56	5.90	5.90	8.85	11.79	1.37	2.06	1.20	1.03	3.60	5.91	9.86	4.44	5.42	3.45	9.86
2:30:00	15.00	12.50	7.50	8.50	17.00	13.66	5.94	5.94	8.91	11.88	1.42	2.13	1.24	1.06	3.73	5.86	9.76	4.39	5.37	3.42	9.76
3:00:00	15.25	12.71	7.63	8.64	17.29	15.28	6.64	6.64	9.96	13.28	1.24	1.86	1.08	0.93	3.25	5.39	8.99	4.04	4.94	3.15	8.99
3:30:00	15.54	12.95	7.77	8.80	17.61	15.11	6.57	6.57	9.86	13.14	1.32	1.99	1.16	0.99	3.48	5.45	9.09	4.09	5.00	3.18	9.09
4:00:00	15.29	12.74	7.65	8.67	17.33	18.37	7.99	7.99	11.98	15.98	1.14	1.70	0.99	0.85	2.98	4.91	8.19	3.68	4.50	2.87	8.19
4:30:00	15.74	13.12	7.87	8.92	17.84	18.40	8.00	8.00	12.00	16.00	1.19	1.78	1.04	0.89	3.11	4.83	8.05	3.62	4.43	2.82	8.05
5:00:00	14.96	12.46	7.48	8.48	16.95	21.83	9.49	9.49	14.24	18.99	1.19	1.78	1.04	0.89	3.11	4.86	8.09	3.64	4.45	2.83	8.09
5:30:00	14.73	12.28	7.37	8.35	16.70	22.07	9.59	9.59	14.39	19.19	1.13	1.70	0.99	0.85	2.98	4.70	7.83	3.52	4.31	2.74	7.83
6:00:00	17.36	14.46	8.68	9.84	19.67	28.21	12.27	12.27	18.40	24.53	1.28	1.92	1.12	0.96	3.36	5.09	8.48	3.81	4.66	2.97	8.48
6:30:00	17.26	14.38	8.63	9.78	19.56	28.23	12.28	12.28	18.41	24.55	1.20	1.81	1.05	0.90	3.16	4.94	8.24	3.71	4.53	2.88	8.24
7:00:00	29.84	24.86	14.92	16.91	33.82	30.37	13.20	13.20	19.80	26.41	1.15	1.72	1.01	0.86	3.02	4.74	7.89	3.55	4.34	2.76	7.89
7:30:00	29.76	24.80	14.88	16.87	33.73	30.19	13.13	13.13	19.69	26.26	1.05	1.58	0.92	0.79	2.77	4.57	7.61	3.43	4.19	2.66	7.61
8:00:00	35.71	29.76	17.85	20.23	40.47	27.44	11.93	11.93	17.90	23.86	0.87	1.30	0.76	0.65	2.27	4.27	7.12	3.20	3.92	2.49	7.12
8:30:00	35.65	29.70	17.82	20.20	40.40	27.59	11.99	11.99	17.99	23.99	0.94	1.42	0.83	0.71	2.48	4.27	7.12	3.21	3.92	2.49	7.12
9:00:00	29.93	24.94	14.96	16.96	33.92	22.86	9.94	9.94	14.91	19.88	0.66	0.99	0.58	0.50	1.73	4.04	6.73	3.03	3.70	2.36	6.73
9:30:00	29.88	24.90	14.94	16.93	33.87	22.98	9.99	9.99	14.98	19.98	0.69	1.03	0.60	0.52	1.81	4.02	6.70	3.02	3.69	2.35	6.70
10:00:00	39.15	32.63	19.58	22.19	44.37	25.38	11.03	11.03	16.55	22.07	0.70	1.05	0.61	0.53	1.84	4.12	6.86	3.09	3.77	2.40	6.86
10:30:00	39.35	32.79	19.67	22.30	44.59	25.40	11.04	11.04	16.56	22.09	0.72	1.07	0.63	0.54	1.88	4.29	7.16	3.22	3.94	2.50	7.16
11:00:00	43.98	36.65	21.99	24.92	49.85	27.49	11.95	11.95	17.93	23.91	0.69	1.04	0.61	0.52	1.82	4.05	6.75	3.04	3.71	2.36	6.75
11:30:00	44.15	36.79	22.08	25.02	50.04	27.60	12.00	12.00	18.00	24.00	0.70	1.05	0.61	0.52	1.84	4.18	6.96	3.13	3.83	2.44	6.96
12:00:00	30.16	25.13	15.08	17.09	34.18	28.18	12.25	12.25	18.38	24.50	0.87	1.30	0.76	0.65	2.27	3.85	6.42	2.89	3.53	2.25	6.42

12:30:00	30.37	25.31	15.18	17.21	34.42	27.95	12.15	12.15	18.23	24.30	0.86	1.29	0.75	0.65	2.26	3.76	6.27	2.82	3.45	2.19	6.27
13:00:00	32.46	27.05	16.23	18.39	36.78	28.07	12.20	12.20	18.31	24.41	0.97	1.46	0.85	0.73	2.55	4.08	6.80	3.06	3.74	2.38	6.80
13:30:00	32.43	27.03	16.22	18.38	36.76	28.09	12.22	12.22	18.32	24.43	0.97	1.45	0.84	0.72	2.53	4.17	6.95	3.13	3.82	2.43	6.95
14:00:00	40.16	33.47	20.08	22.76	45.51	28.89	12.56	12.56	18.84	25.13	0.94	1.41	0.82	0.70	2.47	4.44	7.40	3.33	4.07	2.59	7.40
14:30:00	40.28	33.57	20.14	22.83	45.65	28.80	12.52	12.52	18.78	25.04	0.95	1.42	0.83	0.71	2.48	4.46	7.43	3.34	4.09	2.60	7.43
15:00:00	53.61	44.67	26.80	30.38	60.76	39.95	17.37	17.37	26.06	34.74	1.16	1.74	1.01	0.87	3.04	4.62	7.69	3.46	4.23	2.69	7.69
15:30:00	53.30	44.41	26.65	30.20	60.40	40.05	17.41	17.41	26.12	34.82	1.12	1.68	0.98	0.84	2.93	4.61	7.68	3.46	4.22	2.69	7.68
16:00:00	56.60	47.16	28.30	32.07	64.14	43.80	19.04	19.04	28.57	38.09	1.32	1.98	1.16	0.99	3.47	5.63	9.38	4.22	5.16	3.28	9.38
16:30:00	56.43	47.03	28.22	31.98	63.96	43.74	19.02	19.02	28.53	38.04	1.32	1.98	1.15	0.99	3.46	5.50	9.17	4.13	5.04	3.21	9.17
17:00:00	59.75	49.79	29.88	33.86	67.72	45.73	19.88	19.88	29.83	39.77	1.45	2.17	1.27	1.09	3.80	6.83	11.38	5.12	6.26	3.98	11.38
17:30:00	59.60	49.67	29.80	33.77	67.55	45.85	19.93	19.93	29.90	39.87	1.54	2.32	1.35	1.16	4.05	6.91	11.51	5.18	6.33	4.03	11.51
18:00:00	55.46	46.22	27.73	31.43	62.86	40.85	17.76	17.76	26.64	35.52	1.52	2.27	1.33	1.14	3.98	6.65	11.09	4.99	6.10	3.88	11.09
18:30:00	55.50	46.25	27.75	31.45	62.90	40.71	17.70	17.70	26.55	35.40	1.48	2.22	1.30	1.11	3.89	6.58	10.96	4.93	6.03	3.84	10.96
19:00:00	46.29	38.57	23.14	26.23	52.46	38.40	16.70	16.70	25.05	33.40	1.53	2.30	1.34	1.15	4.02	6.76	11.27	5.07	6.20	3.95	11.27
19:30:00	46.34	38.62	23.17	26.26	52.52	38.76	16.85	16.85	25.28	33.70	1.51	2.26	1.32	1.13	3.96	6.74	11.23	5.05	6.18	3.93	11.23
20:00:00	33.51	27.92	16.75	18.99	37.98	34.50	15.00	15.00	22.50	30.00	1.39	2.09	1.22	1.04	3.65	7.42	12.37	5.57	6.81	4.33	12.37
20:30:00	33.46	27.89	16.73	18.96	37.93	34.57	15.03	15.03	22.55	30.06	1.40	2.10	1.22	1.05	3.67	7.28	12.14	5.46	6.68	4.25	12.14
21:00:00	21.09	17.57	10.54	11.95	23.90	28.67	12.46	12.46	18.70	24.93	1.59	2.39	1.39	1.19	4.18	6.99	11.65	5.24	6.41	4.08	11.65
21:30:00	20.79	17.32	10.39	11.78	23.56	28.66	12.46	12.46	18.69	24.92	1.57	2.36	1.37	1.18	4.12	7.01	11.68	5.26	6.43	4.09	11.68
22:00:00	14.86	12.38	7.43	8.42	16.84	20.59	8.95	8.95	13.43	17.90	1.59	2.38	1.39	1.19	4.17	6.76	11.27	5.07	6.20	3.95	11.27
22:30:00	15.09	12.58	7.55	8.55	17.10	20.81	9.05	9.05	13.57	18.10	1.67	2.51	1.46	1.26	4.39	6.73	11.22	5.05	6.17	3.93	11.22
23:00:00	16.56	13.80	8.28	9.38	18.77	11.50	5.00	5.00	7.50	10.00	3.98	5.97	3.49	2.99	10.46	23.05	38.41	17.29	21.13	13.45	38.41
23:30:00	16.69	13.91	8.35	9.46	18.92	11.70	5.08	5.08	7.63	10.17	4.04	6.05	3.53	3.03	10.59	23.13	38.54	17.34	21.20	13.49	38.54
0:00:00	17.16	14.30	8.58	9.72	19.45	11.97	5.20	5.20	7.81	10.41	4.20	6.30	3.67	3.15	11.02	21.50	35.83	16.12	19.71	12.54	35.83
0:30:00	17.25	14.38	8.63	9.78	19.55	12.02	5.22	5.22	7.84	10.45	4.17	6.26	3.65	3.13	10.96	21.50	35.83	16.13	19.71	12.54	35.83

Table 4.4 Total wind generator output for one day

Hour	5%	10%	15%	20%	25%	30%	35%
1:00:00	30.53	42.73	76.01	95.33	103.60	103.60	103.60
1:30:00	31.42	49.59	80.36	97.71	105.88	105.88	105.88
2:00:00	50.00	44.47	60.13	88.64	105.50	105.50	105.50
2:30:00	50.00	47.80	49.85	104.67	104.67	104.67	0.00
3:00:00	50.00	54.97	50.62	107.14	107.14	107.14	0.00
3:30:00	50.00	52.59	74.75	104.34	104.34	104.34	104.34
4:00:00	50.00	60.04	81.69	102.99	102.99	102.99	102.99
4:30:00	31.37	73.84	67.25	103.49	74.50	103.49	103.49
5:00:00	15.65	58.30	82.43	48.11	48.29	97.79	107.00
5:30:00	28.90	57.54	96.85	59.25	85.61	62.54	105.69
6:00:00	34.55	58.81	96.65	40.32	112.34	43.74	112.34
6:30:00	41.13	56.96	93.89	23.48	47.66	52.89	113.22
7:00:00	50.00	59.49	102.40	24.90	35.81	24.57	122.68
7:30:00	50.00	63.62	76.14	50.03	15.09	0.00	123.83
8:00:00	49.91	54.01	60.88	16.58	44.42	0.00	126.42
8:30:00	50.00	53.45	40.03	33.07	5.31	4.23	34.23
9:00:00	41.82	51.29	37.92	10.02	30.00	0.00	136.74
9:30:00	43.61	51.16	31.08	0.00	0.00	0.00	195.50
10:00:00	50.00	47.54	35.36	60.82	2.21	0.00	139.26
10:30:00	39.43	44.87	56.65	149.92	26.78	44.05	112.99
11:00:00	26.71	41.26	64.31	80.60	30.18	31.12	158.87
11:30:00	15.62	44.85	67.94	120.64	0.00	50.52	156.64
12:00:00	42.70	35.29	57.65	200.00	3.79	34.85	42.02
12:30:00	42.70	37.23	34.34	200.00	0.00	80.94	72.74
13:00:00	34.93	24.09	26.81	200.00	0.00	197.86	13.30
13:30:00	42.84	35.09	41.87	200.00	0.00	57.87	119.04
14:00:00	50.00	41.08	35.39	156.36	0.00	76.96	151.99
14:30:00	38.18	34.64	33.84	127.01	0.00	191.61	194.66
15:00:00	50.00	42.76	52.77	89.41	0.00	206.43	207.78
15:30:00	50.00	38.32	71.30	110.14	11.85	70.58	206.74
16:00:00	50.00	49.55	56.44	53.43	97.38	112.03	242.74
16:30:00	37.13	42.43	53.84	75.18	15.70	131.54	243.06
17:00:00	30.03	47.80	61.49	77.57	57.06	157.57	333.20
17:30:00	35.76	58.64	55.38	200.00	190.75	265.18	335.57
18:00:00	30.70	62.18	72.10	155.59	196.50	203.97	350.00
18:30:00	31.34	60.27	56.30	184.84	181.24	246.47	350.00
19:00:00	50.00	53.10	71.75	85.35	241.32	260.00	0.00
19:30:00	50.00	48.00	84.56	114.21	174.33	275.84	350.00
20:00:00	50.00	52.14	111.08	77.62	171.32	224.16	350.00
20:30:00	50.00	56.99	101.61	13.20	203.07	179.17	350.00
21:00:00	49.16	51.06	114.28	42.59	134.88	67.89	316.79
21:30:00	50.00	46.69	103.19	0.00	52.14	121.65	292.08
22:00:00	43.08	45.08	106.41	0.00	42.84	49.40	255.01
22:30:00	32.52	45.28	101.48	0.00	31.23	92.79	256.06
23:00:00	35.62	47.75	93.52	0.00	26.77	46.56	184.42
23:30:00	20.41	46.96	94.29	0.00	66.85	0.00	185.70
0:00:00	12.40	42.75	96.88	0.00	58.34	0.00	134.28
0:30:00	15.99	55.79	93.72	12.41	96.94	10.41	133.75

The simulation was carried out using the time step option of the PowerWorld™ simulator, whereby both the load and wind generation outputs are varied for 30 minutes and parameters of interest are recorded like the bus voltages, real and reactive power losses and reactive power generation in the network. The same load profile is used for all wind penetration levels and location, to enable us compare the results.

4.2.3.2 Single Wind Farm location

When the wind generation is connected to bus 14 and bus 19 individually, the maximum voltage value at each bus for wind penetration from 5% to 35% is between 1.04p.u to 1.05p.u. However, the minimum voltage value shows a violation at some buses as shown in figures 4.3 and 4.4. This low voltage problem can be solved by introducing adequate reactive power compensation in the network or in the wind farms.

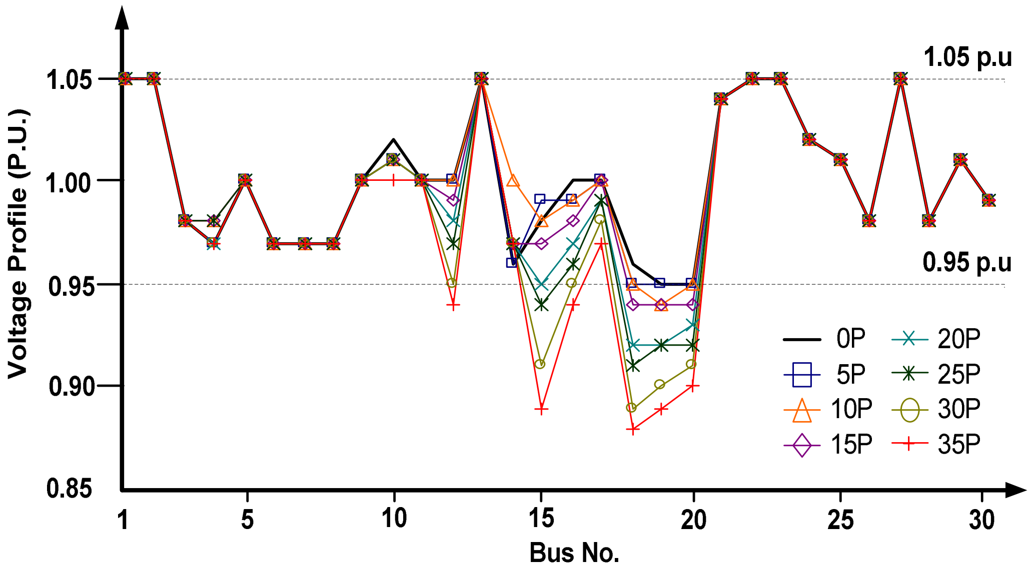

Figure 4.3 Minimum voltage value when wind farm connected to Bus 14 only

From Figures 4.3 and 4.4 we can see that there are more minimum voltage violations when wind generation is connected to bus 14 than when connected to bus

19. This agrees with the conclusion that voltage profile will depend on the location where wind generation is connected in the network.

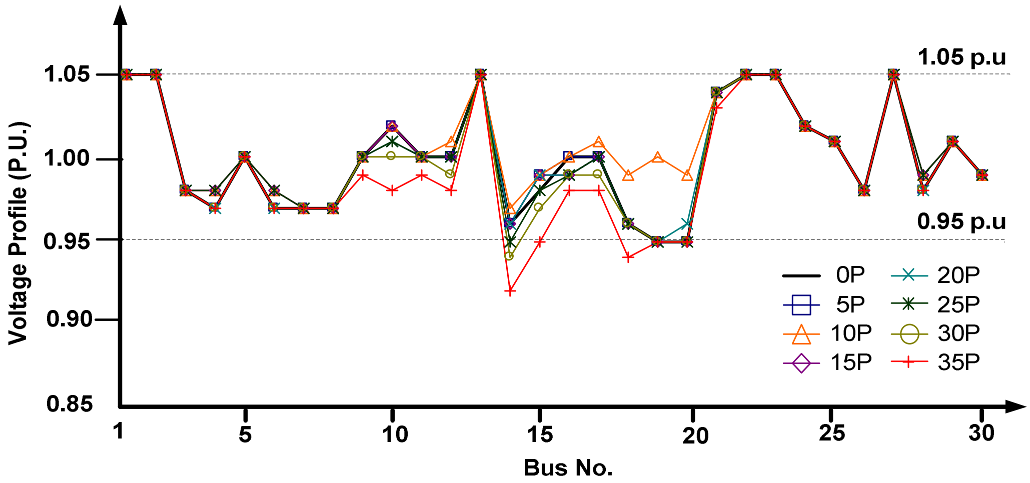

Figure 4.4 Minimum voltage value when wind farm connected to Bus 19 only

4.2.3.3 Multiple Wind Farm locations

In the multiple locations scenario, wind generation is connected to buses 14 and 19 simultaneously, and different penetration levels combinations were applied to study the effect on voltage profile. Table 4.5 shows the combinations of penetration levels and locations connected at buses 14 and 19.

Table 4.5 Case scenarios of wind dispersion on two different locations

% of Combination (G14-Low,G19-High)	% of Combination (G19-Low,G14-High)	% of Total Combination
BC (0%, 0%)	BC (0%, 0%)	0%
C1 (5%, 5%)	C1 (5%, 5%)	10%
C2 (5%, 10%)	C2 (5%, 10%)	15%
C3 (5%, 15%)	C3 (5%, 15%)	20%
C4 (10%, 10%)	C4 (10%, 10%)	20%
C5 (10%, 15%)	C5 (10%, 15%)	25%
C6 (5%, 20%)	C6 (5%, 20%)	25%

C7 (5%, 25%)	C7 (5%, 25%)	30%
C8 (10%, 20%)	C8 (10%, 20%)	30%
C9 (15%, 15%)	C9 (15%, 15%)	30%
C10 (5%, 30%)	C10 (5%, 30%)	35%
C11 (10%, 25%)	C11 (10%, 25%)	35%
C12 (15%, 20%)	C12 (15%, 20%)	35%

Under multiple wind farm dispersion, the maximum voltage value at each bus for all the combination shown in Table 4.5 fall within 1.03p.u to 1.05p.u. The results obtained from the simulation where the penetration level of wind farm is low at bus 14 and high at bus 19 is shown in Figure 4.5.

Figure 4.5 shows that, all the bus voltages are within the operating limit for case scenario C1 to C11 except for case scenario C12. In C12, the voltages on bus 18 and bus 19 are below the acceptable value of 0.95 p.u. at 35% wind penetration level.

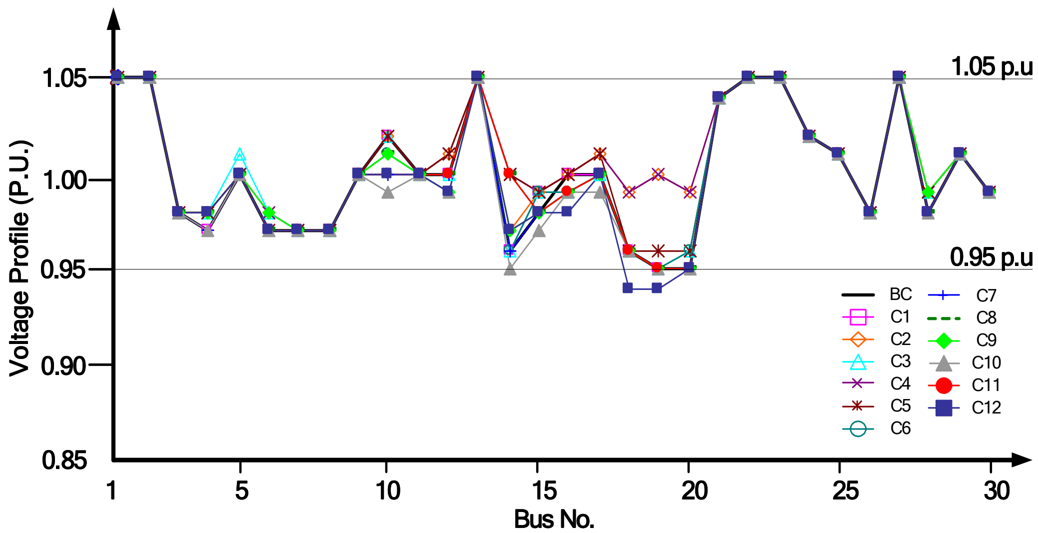

Figure 4.5 Minimum voltage value for multiple dispersion on Bus 14 (Low) and Bus 19 (High)

When the penetration levels of wind generation are changed to low value at bus 19 and high value at bus 14, the minimum value of the bus voltages is shown in

Figure 4.6. There are more low voltages violations in this scenario, when wind generation exceeds 15% penetration level at bus 14.

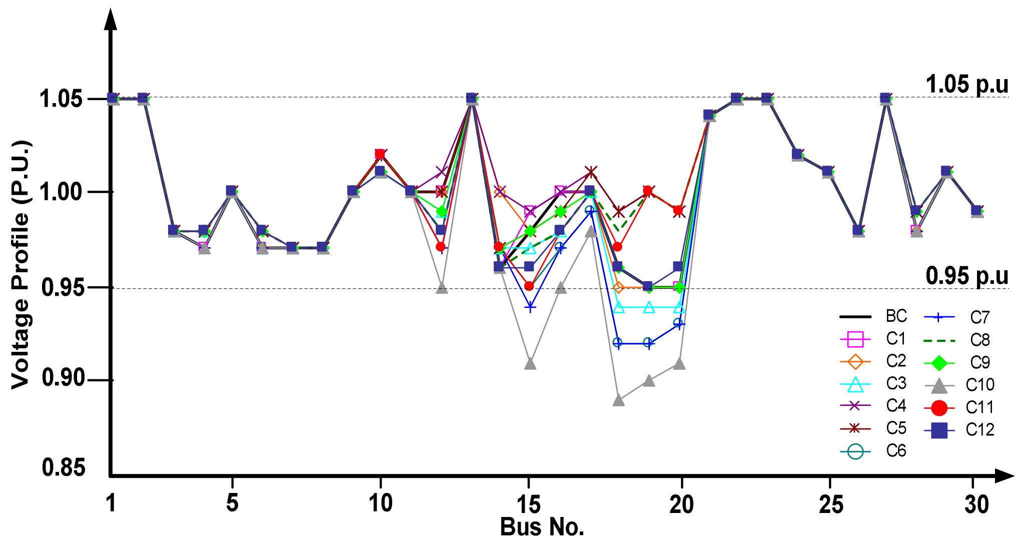

Figure 4.6 Minimum voltage value for multiple dispersion on Bus 19 (Low) and Bus 14 (High)

The simulation results shown in Figures 4.5 and 4.6 can be used to deduce that planning the penetration levels at different connection points of the network will ensure the voltage violations can be minimized. This method can also give the system operator a good signal as to what location and penetration level is to be connected in the network to ensure better voltage profile across the whole network.

4.2.3.4 Reactive power requirement evaluation

Most wind generators used today for electricity generation are some variants of the induction generator. The most common generator used in wind turbines is the induction generator. It has several advantages, such as robustness and mechanical simplicity and, as it is produced in large quantities, it also has a low price. The major disadvantage is that the stator needs a reactive magnetizing current. The asynchronous generator does not contain permanent magnets and is not separately excited. Therefore, it has to receive its exciting current from another source and consumes reactive power. The reactive power may be supplied by the grid or by a power electronic system. The generator's magnetic field is established only if it is connected to the grid.

The double-fed induction generator (DFIG) is ideally suited for wind generation. It consists of a stator supplied from the system in the usual way and a rotor supplied via an AC-DC-AC converter from the same supply. One advantage of DFIG is that it has the ability to control reactive power and to decouple real and reactive power control by independently controlling the rotor excitation current. The DFIG does not necessarily need to be magnetizing from the power grid; it can be magnetized from the rotor circuit, too. It is also capable of generating reactive power that can be delivered to the stator by the grid-side converter. However, the grid side converter normally operates at unity power factor and is not involved in the reactive power exchange between the turbine and the grid. In the case of a weak grid, where the voltage may fluctuate, the DFIG may be ordered to produce or absorb an amount of reactive power to or from the grid, with the purpose of voltage control. In some cases reactive power equipment such as static or thyristor controlled compensated are installed at the grid connected terminals.

When induction generators are connected to electricity networks, they draw reactive power from the system as shown in Figures 4.7 and 4.8. These results were obtained when the modified IEEE30-bus system was simulated with wind input as per the cases for voltage profile study. The results show that the reactive power drawn by the wind generator is a function of the penetration level and location.

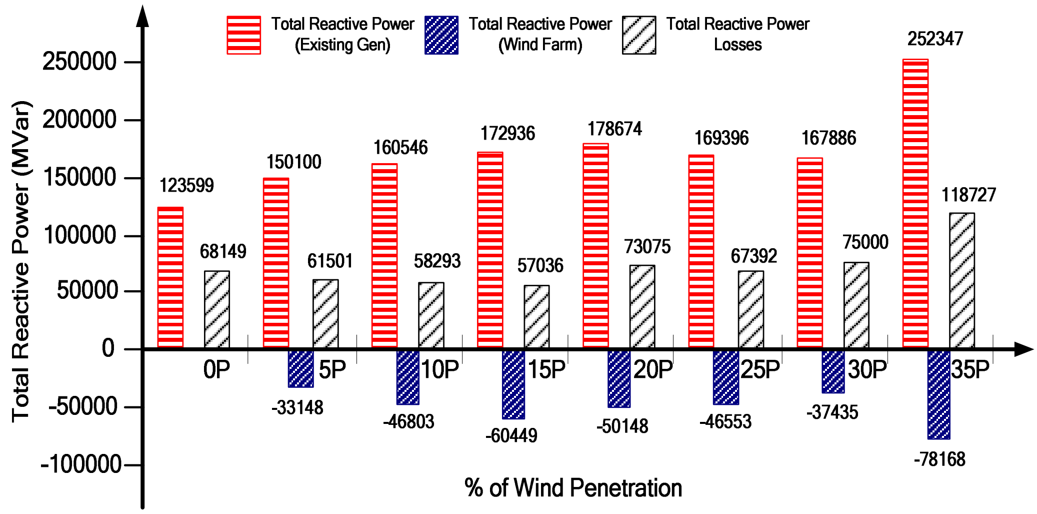

Figure 4.7 System reactive power use with wind generator connected to Bus 14

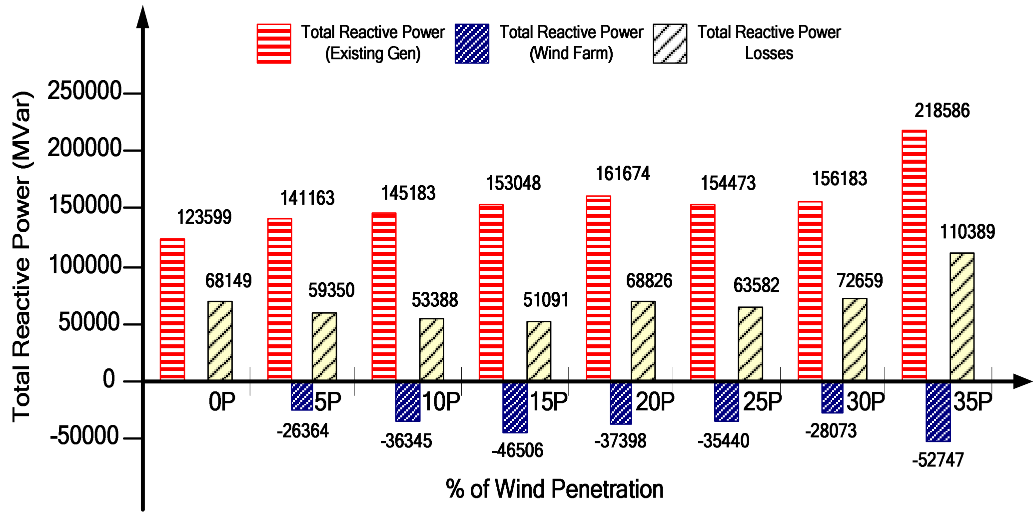

Figure 4.8 System reactive power use with wind generator connected to Bus 19

It is obvious that the reactive power requirement of conventional generators is less when wind generation is connected to bus 19 than when connected to bus 14 for all penetration levels. The reactive power losses also increase with increase in penetration levels, although not in a linear relationship. The reactive losses are less with wind connected to bus 19 than when connected to bus 14. Therefore, from the simulation results we can see that wind generation indeed has helped in compensating the reactive power requirement in the system. However, the system reactive power requirement is largely dependent on where the wind generator and load are connected. The study also shows that the reactive power losses in the system can be increased or decreased with different penetration level and location since wind is stochastic in nature.

The result of these new considerations is that some commonly used turbine designs may have limitations in meeting the grid code requirements of some countries, especially for steady state and dynamic reactive power. For wind farms where these types of turbine are installed the solution is to install appropriate "add-on" reactive power equipment to achieve the necessary grid code compliance for operation and power production.

Meeting the grid code requirements present a definite challenge for wind farm developers in certain countries, mainly because the steady state and dynamic reactive power injection/absorption requirements are difficult to satisfy with some wind farm designs. Therefore "add-on" equipment is often needed to comply with the grid codes.

4.3 Review of optimal reactive power placement methods

Reactive power, one of ancillary service in power market, has a profound effect on the reliability and security of power system because it affects voltages throughout the system. In supporting real power transfer, reactive power plays an important role. This support becomes especially important when an increasing number of transactions are utilizing the transmission system and voltage becomes a bottleneck in preventing additional power transfer. Excesses of reactive power cause voltages to rise, while shortages cause voltage to fall. Too high or too low voltages can result in increased power system losses, overheating of motors and other equipment, even system voltage collapse with consequent loss of customer load. In fact, many famous major outages throughout the world have been ultimately traced to problems with in sufficient reactive power support.

Therefore, proper reactive power planning program is needed to determine rational reactive power compensation device placement. Optimal allocation of Var sources, such as capacitor banks, Static Var Compensation (SVC), and STATic COMpensators (STATCOM), is a critical component in reactive power planning (RPP) or Var planning. Traditionally, the locations for placing new Var sources were either simply estimated or directly assumed. Recent research has presented some rigorous optimization-based methods to address RPP. Due to the complicated objective functions, constrains, and solution algorithms, RPP is identified as one of the most challenging problems in power systems.

The following assumptions are considered while formulating the Var planning problem in the review.

- The system is balanced.
- The real and reactive power represent fundamental frequency powers, and $Q_{\max}$ additional powers at harmonic frequencies are negligible.
- The size of the Var source is treated as a continuous variable; however, it is in fact discrete.
- The reactive capability of a generator is portrayed by the conventional PQ-diagram, but for the planning study, it is usually sufficient to assume a fixed upper limit $Q_{\max}$ relevant to the generator MW output.

The majority of the RPP objectives were to provide the least cost of new reactive power supplies. Many variants of this objective include the cost of real power losses or fuel cost. In addition, some technical indices such as deviation from a given voltage schedule or security margin may be used as objectives for optimization. Two fundamental RPP methods are reviewed in the following sections 4.3.1 and 4.3.2.

4.3.1 Minimize Var cost

Generally, there are two Var source cost models for minimization. The first formulation is to model Var source costs with C_1Q_c that represents a linear function with no fixed cost [11]. Apparently, this model considers only the variable cost relevant to the rating of the newly installed Var source Q_c and ignores the fixed installation cost. The common unit for C_1 is £/(MVar·hour). This means the costs of two 100-MVar units are exactly the same as one 200-MVar unit. This formulation would always bias a solution toward placement of several smaller sizes sources instead of a small number of larger ones.

A better formulation with the format $(C_0 + C_1Q_c)x$ [12–14], [15]–[18] is to consider the fixed cost, C_0 (£/hour), which is the lifetime fixed cost pro-rated to per hour, in addition to the incremental/variable cost, C_1 (£/MVar • hour). This is a more realistic model of Var cost, but this would complicate the problem from a nonlinear programming (NLP) to a mixed-integer NLP (MINLP), because there is a binary variable to indicate whether the Var source will be actually installed or not. The slight difference in the cost model, however, leads to dramatic difference in the optimization model and the corresponding mathematical technique to solve it.

As a result, the RPP model with the first Var cost function as an objective function is a traditional LP or NLP problem. However, the second one is a MINLP problem, and some special techniques are needed for it's solution.

The objective function to be minimized for RPP can be mathematically be expressed as

$$f_1(\omega) = \sum_{i \in \mathbf{E}} (d_i + s_{ci}q_{ci} + s_{ri}q_{ri})r_i \tag{4.1}$$

Where,

E : the set of potential buses required to expand reactive sources;

d_i : the installment cost of bus i ;

r_i : a 0–1 variable; $r_i = 1$ when bus i is selected for Var expansion, and $r_i = 0$ otherwise;

q_{ci} , q_{ri} : added capacitive and inductive compensation, respectively; both are integers;

S_{ci} , S_{ri} : unit cost of capacitor and reactor, respectively;

The term ω is called the expansion variable vector and specifies whether or not VAr sources are installed, and identifies the types and sizes of the VAr sources.

4.3.2 Minimize voltage deviation

Different from the previous cost-oriented objective function, this objective is usually defined as the weighted sum of the deviations of the control variables, such as bus voltages, from their given target values. The target values correspond to the initial or specified operating points. The voltage deviation of each load bus must be as small as possible to obtain a performance voltage index. Voltage deviation, i.e., $\sum_i (V_{i\max} - V_i)$, where the subscript represents different buses for voltage regulation, is modeled as the objective function in [19].

Here, the objective function representing the deviation of voltage can be formulated as:

$$f_2(z) = \sum_{i \in \mathbf{\Omega}} \left(\frac{\left| V_i - V_i^{spec} \right|}{\Delta V_i^{\max}} \right)^2 \tag{4.2}$$

Where,

$\mathbf{\Omega}$: the set of all load buses;

V_i : the voltage magnitude at bus i ,

V_i^{spec} : the ideal specific voltage magnitude at bus i, which is usually set to 1 p.u;

$\Delta V_i^{\max}$: the maximum allowable voltage deviation limit at bus i, which $\Delta V_i^{\max} = V_i^{\max} - V_i^{\min}$;

z : the operating variable vector.

4.4 Proposed optimal reactive power placement method

Optimal reactive power placement problem involves allocation and determination of the types and sizes of the new installed reactive sources in order to optimize an objective function while satisfying system operation constraints. This problem has been solved using optimization methods with different objective functions. Two single objectives have been discussed above.

The goal of RPP is to provide the system with efficient Var compensation to enable the system to be operated under a correct balance between security and economic concerns. If both security and cost are included in the same objective function, then the weights cannot be decided directly and easily. Most of the above mentioned works did not consider Var investment cost, power loss and voltage constraint in an integrated formulation. The objective of proposed optimal reactive power placement method includes Var investment cost minimization, power loss reduction, and voltage deviation reduction as follows:

$$\begin{aligned} Min\ F &= F_Q + F_V + F_L \\ &= f_1(\omega) + \lambda_V f_2(z) + \lambda_L f_3(z) \\ &= \sum_{i \in \mathbf{E}} (d_i + s_{ci} q_{ci} + s_{ri} q_{ri}) r_i + \lambda_V \sum_{i \in \mathbf{\Omega}} \left(\frac{\left| V_i - V_i^{spec} \right|}{\Delta V_i^{\max}} \right)^2 \\ &\quad + \lambda_L 0.5 \sum_{i,j} \left(G_{ij} \left(V_i^2 + V_j^2 - 2 V_i V_j \cos\left(\delta_j - \delta_i \right) \right) \right) \end{aligned} \tag{4.3}$$

The minimization of the above function is also subject to a number of constraints:

Ⅰ. Load constraints

$$P_{Gi} - P_{Di} = \sum_j V_i V_j Y_{ij} \cos\left(\theta_{ij} + \delta_j - \delta_i\right) \tag{4.4}$$

$$Q_{Gi} - Q_{Di} + Q_{Ci} = -\sum_j V_i V_j Y_{ij} \sin\left(\theta_{ij} + \delta_j - \delta_i\right) \tag{4.5}$$

Ⅱ. Operating constraints

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \tag{4.6}$$

$$V_{Gi}^{\min} \le V_{Gi} \le V_{Gi}^{\max} \tag{4.7}$$

$$V_{Li}^{\min} \le V_{Li} \le V_{Li}^{\max} \tag{4.8}$$

$$K_{Ti}^{\min} \le K_{Ti} \le K_{Ti}^{\max} \tag{4.9}$$

$$\left|P_{ij}(V,\delta)\right| \le P_{ij}^{\max} \tag{4.10}$$

Ⅲ. Expansion constraints

$$0 \le q_{ri} \le q_{ri}^{\max} \tag{4.11}$$

$$0 \le q_{ci} \le q_{ci}^{\max} \tag{4.12}$$

Where,

F_V : penalty function of voltage violation on PQ buses;

F_L : real power losses cost;

F_Q : overall reactive power payment;

P_{Loss} : real power losses;

d_i : the installment cost of bus i ;

r_i : a 0–1 variable; $r_i = 1$ when bus i is selected for Var expansion, and $r_i = 0$ otherwise;

q_{ci} , q_{ri} : added capacitive and inductive compensation, respectively; both are integers;

S_{ci} , S_{ri} : unit cost of capacitor and reactor, respectively;

E : the set of potential buses required to expand reactive sources;

Ω : is the set of all load buses;

V_i, V_j : is the voltage magnitude at bus i , j ;

$V_{Gi}^{\min}$: minimum allowable voltage at PV bus i ;

$V_{Gi}^{\max}$: maximum allowable voltage at PV bus i ;

$V_{Li}^{\min}$: minimum allowable voltage at PQ bus i ;

$V_{Li}^{\max}$: maximum allowable voltage at PQ bus i ;

V_i^{spec} : is the ideal specific voltage magnitude at bus i , which is usually set to 1 p.u;

$\Delta V_i^{\max}$: is the maximum allowable voltage deviation limit at bus i ;

δ_i , δj : voltage magnitude at bus i , j ;

Y_{ij} : magnitude of the ij entry of the admittance (Y) matrix;

θ_{ij} : angle of the ij entry of the admittance (Y) matrix;

G_{ij} : conductance of the line connecting buses i and j ;

P_{Di} : active power demand at bus i ;

Q_{Di} : reactive power demand at bus i ;

$P_{Gi}^{\min}$: minimum real power limit of a generator at bus i ;

$P_{Gi}^{\max}$: maximum real power limit of a generator at bus i ;

$Q_{Gi}^{\min}$: minimum reactive power limit of a generator at bus i ;

$Q_{Gi}^{\max}$: maximum reactive power limit of a generator at bus i ;

K_{Ti} : transformer tap setting ;

ω : is called the expansion variable vector and specifies whether or not VAr sources are installed, and identifies the types and sizes of the VAr sources;

z : operating variable vector;

λ_V : weighting factor for voltage deviation objective;

λ_L : real power price.

4.5 Case studies on the IEEE30-bus system

The proposed multi-objective reactive power placement optimization method is a large-scale nonlinear mixed integer programming. Therefore, here we still use Differential Evolutionary algorithm (DE) which is applied in the previous chapter to solve this multi-objective optimization problem.

The test IEEE30-bus system comprises: 6 generating units, 4 tap changing transformers and capacitor banks located at 9 different buses. The single line diagram of the work is shown in Figure 3.13 and the network data is given in Table 3.4. in chapter 3. The relevant DE parameters are the same as that given in Table 3.3.

We assume the installation cost of new reactive power sources is ignored which sets d_i=0 in this case, and the unit capacity of capacitor bank is 10 kVAr, the unit cost of individual capacitor bank S_{ci} is set to £ 20/kVAr.

The network is assumed to be at peak load condition (heavy load condition) as the base case for analysis. The system performance of the base case which is the case before the Var compensation is shown in Table 4.6. The table shows that the system voltages on Buses 26, 29 and 30 violated the voltage lower limit of 0.95 p.u., which are 0.8829, 0.8907 and 0.8684 p.u. respectively. It is mainly due to the heavy load condition in which the real power transactions rise very much. And the reactive power requirement to support these real power transfers is significantly insufficient.

Table 4.6 System performance of Base case

Bus No.	Voltage magnitude (p.u.)	Voltage angle (degree)	Real power generation (MW)	Reactive power generation (MVar)	Real power demand (MW)	Reactive power demand (MVar)
1	1.0600	-0.1851	139.8900	-37.6000	0.0000	0.0000
2	1.0400	-0.0584	57.6000	18.3600	21.6000	12.7000
3	0.9920	-0.0914	0.0000	0.0000	2.4000	1.2000
4	0.9894	-0.1096	0.0000	0.0000	7.6000	1.6000
5	1.0000	0.0000	24.6000	53.6400	94.2000	19.0000
6	0.9947	-0.1274	0.0000	0.0000	0.0000	0.0000

7	0.9872	-0.1713	0.0000	0.0000	22.8000	10.9200
8	1.0000	-0.1294	35.0000	51.9600	30.0000	30.0000
9	0.9860	-0.1594	0.0000	0.0000	0.0000	0.0000
10	0.9769	-0.1971	0.0000	0.0000	5.8000	2.0000
11	1.0500	-0.1216	19.7000	7.0700	0.0000	0.0000
12	0.9804	-0.1798	0.0000	0.0000	11.2000	7.5000
13	1.0500	-0.1557	16.9000	14.1700	0.0000	0.0000
14	0.9657	-0.1981	0.0000	0.0000	6.2000	1.6000
15	0.9877	-0.2007	0.0000	0.0000	8.0200	2.5000
16	0.9712	-0.1928	0.0000	0.0000	3.5000	1.8000
17	0.9696	-0.2000	0.0000	0.0000	9.0000	5.8000
18	0.9874	-0.2135	0.0000	0.0000	3.2000	0.9000
19	0.9655	-0.2172	0.0000	0.0000	9.5000	3.4000
20	0.9754	-0.2133	0.0000	0.0000	2.2000	0.7000
21	0.9453	-0.2064	0.0000	0.0000	7.5000	11.2000
22	0.9755	-0.2062	0.0000	0.0000	0.0000	0.0000
23	0.9551	-0.2100	0.0000	0.0000	3.5000	2.3000
24	0.9506	-0.2151	0.0000	0.0000	0.0000	0.0000
25	0.9542	-0.2138	0.0000	0.0000	17.5000	11.2000
26	0.8829	-0.2221	0.0000	0.0000	3.5000	2.3000
27	0.9620	-0.2076	0.0000	0.0000	0.0000	0.0000
28	0.9891	-0.2320	0.0000	0.0000	0.0000	0.0000
29	0.8907	-0.2353	0.0000	0.0000	2.4000	0.9000
30	0.8684	-0.2495	0.0000	0.0000	10.6000	1.9000

The test system is compensated with the capacitors bank using the proposed multi-objective reactive power placement optimization method given by equation 4.3. Table 4.7 shows the system performance after reactive power compensation. The voltage profile improvement after reactive power compensation is illustrated particularly in Figure 4.9. It is obvious that after the compensation there is no voltage violation and the voltages on all load buses are improved very close to the nominal voltage value 1.0 p.u..

Table 4.7 System performance after reactive power compensation

Bus No.	Voltage magnitude (p.u.)	Voltage angle (degree)	Real power generation (MW)	Reactive power generation (MVar)
1	1.0500	0.0000	137.6600	-20.0000
2	1.0418	-0.0451	57.6000	15.3300
3	0.9868	-0.0888	0.0000	0.0000
4	0.9714	-0.0888	0.0000	0.0000
5	1.0000	0.0000	24.6000	21.9000
6	1.0086	-0.1031	0.0000	0.0000
7	0.9914	-0.1291	0.0000	0.0000
8	1.0179	-0.1026	35.0000	24.1300
9	0.9840	-0.1280	0.0000	0.0000
10	1.0058	-0.1583	0.0000	0.0000
11	1.0165	-0.0958	19.7000	1.5600
12	1.0298	-0.1463	0.0000	0.0000
13	1.0155	-0.1265	16.9000	1.0900
14	1.0126	-0.1630	0.0000	0.0000
15	1.0203	-0.1655	0.0000	0.0000
16	1.0155	-0.1577	0.0000	0.0000
17	1.0241	-0.1626	0.0000	0.0000
18	1.0156	-0.1760	0.0000	0.0000
19	1.0046	-0.1787	0.0000	0.0000
20	1.0177	-0.1749	0.0000	0.0000
21	0.9904	-0.1682	0.0000	0.0000
22	0.9807	-0.1680	0.0000	0.0000
23	0.9865	-0.1740	0.0000	0.0000
24	0.9791	-0.1763	0.0000	0.0000
25	0.9815	-0.1880	0.0000	0.0000
26	0.9641	-0.1627	0.0000	0.0000
27	1.0245	-0.1687	0.0000	0.0000
28	1.0020	-0.1120	0.0000	0.0000
29	0.9820	-0.1902	0.0000	0.0000
30	0.9937	-0.2046	0.0000	0.0000

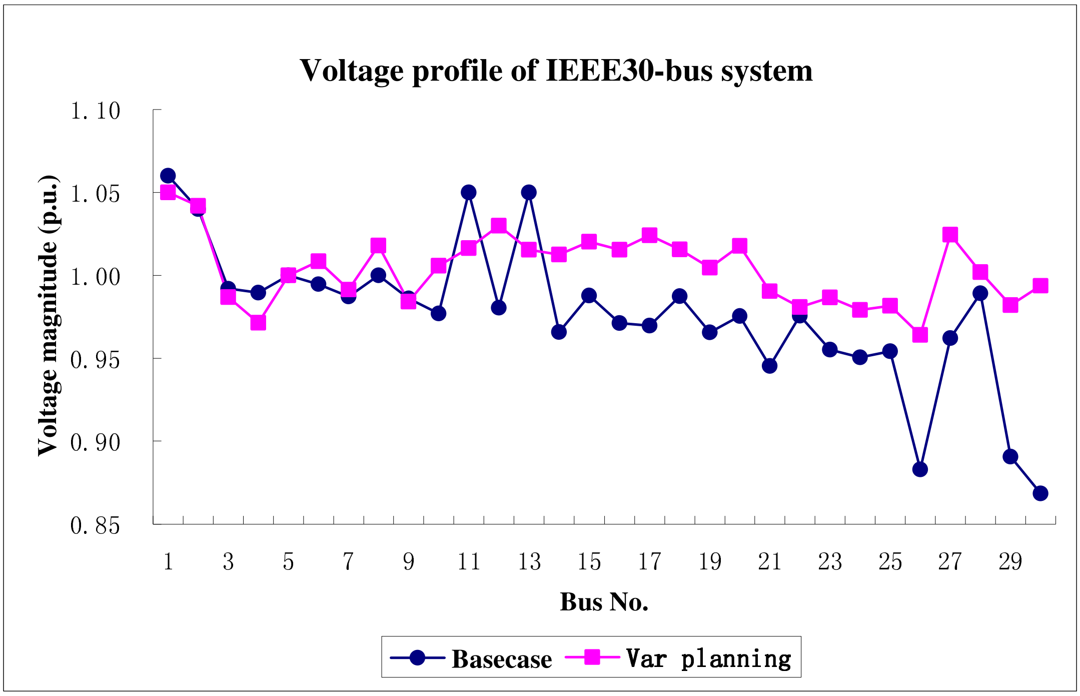

Figure 4.9 The voltage profiles before and after reactive power compensation

After the optimization, the new capacitor banks allocated in the load buses 3, 4, 7, 10, 12, 18, 19, 20, 21, 23, 23, 26 and 29 and the size of capacitor banks in each location are displayed in Table 4.8.

Table 4.8 New capacitor banks placement

Bus No.	3	4	7	10	12	18
Var Capacity (Mvar)	8.0	5.5	5.4	10.0	8.0	7.7
Bus No.	19	20	21	23	26	29
Var Capacity (Mvar)	5.5	6.5	7.1	7.8	3.5	9.0

A comparison of the system technical and economical performance before and after the reactive power compensation is displayed in Table 4.9. After the multi-objective reactive power compensation, there is 84.00 MVar capacitor banks in total installed in the test system. Due to the benefits of reactive power compensation, the test system voltage profile improves significantly, which all the load buses maintain in a secured manner with no voltage violation and the maximum voltage deviation is only 0.0359 p.u. from the norminal value 1.0 p.u.. At the same time, the local reactive power compensation decreases the reactive power transfer in the whole network. Therefore, the real power losses decreases from 8.4513 MW before reactive power compensation to 7.2214 MW after compensation. The real power losses decrease 1.2299 MW in total which represent 14.55% of the real power losses amount before compensation.

Table 4.9 Compare of Base case, Min Var cost and Multi-objective reactive power placement

	Max voltage deviation (p.u.)	**No.of Voltage violation buses**	**Total new Var install capacity (MVar)**	**Ploss (MW)**
Base case	0.1316	3	0.0000	8.4513
Min Var cost	0.0670	0	50.0000	7.4726
Multi-objective	0.0359	0	84.0000	7.2214

In addition, in Table 4.9 we also compare the system performance between using one single objective reactive power placement optimization which is to minimize the total cost of new capacitor banks installed (i.e. Min Var cost) and the optimal multi-objective reactive power placement method (i.e. Multi-objective). The reactive power placement result using the optimization objective Min Var cost indicates less new capacitor banks needed to be installed to improve system performance compared to Multi-objective optimization, although the value of system voltage profile especially the max voltage deviation and real power losses are larger than Multi-objective optimization.

The above analysis of test system shows that using the proposed optimal reactive power placement method can greatly improve the system performance especially in system voltage profile improvement and real power losses reduction compared to the base case which is before reactive power compensation. Furthermore, the proposed optimal multi-objective reactive power placement method compared to the single objective reactive power placement method is more practical to solve the reactive power planning problem which comprises the system technical requirement (i.e.

voltage profile) and economical concern (i.e. real power losses, new reactive power sources investment cost). Also its optimization solution is more realistic for reactive power planning.

4.6 Summary

This chapter firstly presents a review of system-wide reactive power requirement in power networks. An evaluation of reactive power requirement and voltage profile of a modified IEEE30-bus system with wind generation has been presented in this chapter. Different penetration levels from 5% to 35% were used and different locations were used in the network to analyze the impact of wind generation on system voltage and reactive power requirement.

A new proposed method, optimal reactive power placement method, for new reactive power sources allocation and sizing in reactive power planning is introduced in this chapter. This proposed method integrates the power system security objective (Max voltage deviation) and power system economic objectives (Min real power losses and Min new reactive power sources investment cost) in a multi-objective, non-differentiable optimization problem with both functional equality and inequality constraints. The proposed method is a large-scale nonlinear mixed integer programming. DE algorithm is also applied as the mathematical algorithm in this chapter to solve multi-objective reactive power placement optimization problem. The case studies shows that the proposed multi-objective reactive power placement optimization method gives more realistic solution for reactive power planning with regard to system security and economic requirements.

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Chapter 5

The Locational Spot Pricing of Reactive Power

5.1 Introduction

Reactive power support plays an important role in implementation of power transactions. In electricity markets, reactive power supply is classified as a part of ancillary service of electricity. It is realized that establishing accurate prices of reactive power can not only recover the costs of reactive power production, but also provide useful information related to the urgency of reactive power supply and system voltage support. Therefore, the spot pricing of reactive power becomes a significant research topic in power system restructuring.

This chapter is divided as follows: firstly, a review of reactive power pricing literatures in which all the advantages and disadvantages of those proposed are analyzed in section 5.2. Then the proposed reactive power production cost model is proposed in the following section 5.3. In the section 5.4 the optimization theory of spot pricing is discussed. Section 5.5 presents the reactive locational marginal price based on AC power flow which discusses the mathematical formula and OPF procurement options for reactive pricing in detail in subsection 5.5.1 and 5.5.2 respectively. Finally, a case study of 5-bus test system is presented in section 5.6.

5.2 Reactive power pricing: literature review

Since the real power the most important commodity in power market therefore a lot of studies have been done on real power pricing methods.

5.2.1 Real power pricing methods in power market

Two factors are the major concerns of real power pricing: real power generation cost and transmission cost.

5.2.1.1 Real power generation cost

In the power market, a generator's real power generation cost is its real power bidding price curve, namely, real power output-price curve which is determined by the power plant itself. If all the power plants target to maximize their profit, thus in the ideal situation real power generation cost is the marginal cost of generators. However, as the market generally can not achieve fully competitive state and be easily affected by a small number of generation companies, therefore, power plants generally, through certain investment strategy, to bid the real power price to achieve the purpose of increasing their profits. Thus it makes generator's real power bidding price curve away from its marginal cost.

5.2.1.2 Real power transmission cost

There are two categories of transmission cost: commonly used marginal cost method (i.e., economics method) and the comprehensive cost method (i.e. accounting methods).

The value of marginal transmission cost is equal to the cost resulting from increased value of unit network transmission capacity, namely, marginal system losses cost and the marginal system congestion cost. Marginal transmission cost is obtained by calculating the locational marginal cost in the network. The locational marginal price is the corresponding Lagrange multiplier obtained in optimized power flow calculation in the objective of total system production minimization with a set of system operation constraints. The Transmission price between two buses equals to the difference between these two buses' locational marginal cost.

The basic characteristics of transmission comprehensive cost is that it adds up all the network transmission cost (also known as embedded cost, such as system losses cost, power equipment depreciation, etc.) and then allocates to each of the transmission transaction. According to the difference between each allocation method, it is divided into the contract path method, stamp method, boundary power flow method and by-line calculation method, etc.. The advantage of Transmission comprehensive cost method is that its calculation is simpler, price is stable and to guarantee cost recovery and a certain profit.

5.2.1.3 Real power pricing

The real power price determined by using economic methodology is the corresponding location spot price. Its value is calculated by the constrained optimal power flow. The locational spot price generally consists of real power generation fuel costs, maintenance costs, the marginal cost of generator output constraints, the marginal cost of power loss, network congestion costs, etc.. By modifying the objective function and constraints of optimal power flow the real power spot price considering about other factors can be obtained.

The real power price determined by using accounting methodology is the real power generation cost and transmission cost which allocated at the corresponding bus. Its calculation method is much simpler than spot price calculation. According to the different cost allocation method the obtained real power price is different.

Locational Marginal Price (LMP) is the marginal cost of serving the next MW load at a location while considering the network constraints. LMP was first implemented in New Zealand in 1997 followed by some US market [1] such as Pennsylvania-New Jersey-Maryland in 1998, New York ISO in 1998, New England ISO in 2003 as well as CAISO in 2002 [2]. However, according to [3], LMP was introduced even earlier in some Latin American country such as Chile in 1982, Argentina in 1992, Peru in 1993 and Bolivia in 1994. One of the main reasons why LMP is used is because it provides an efficient price signal to market participants regarding usage, generation and investment. In another word, generators have incentives to locate in constrained areas with high marginal costs while loads have the incentives to locate in unconstrained areas with low marginal costs. In order to relieve congestion both generators and loads have the incentives for transmission investment, because LMP prices reflect the opportunity cost of transmission between locations.

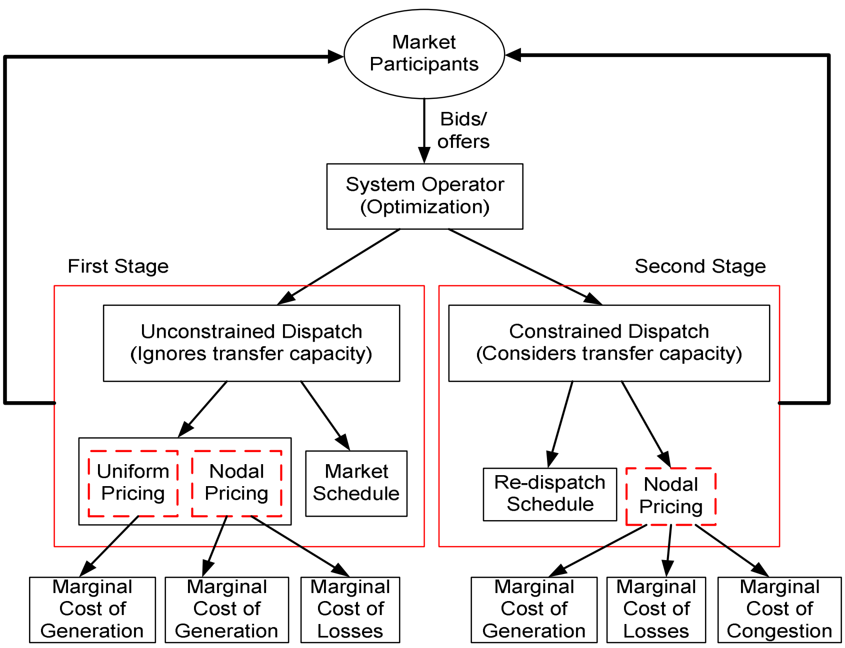


Figure 5.1: Nodal Pricing Mechanism

LMP can distinctively be divided into two stages which are the unconstrained and constrained dispatch as shown in Figure 5.1. Basically all the market participants will submit their bids and offers to the independent system operator (ISO) and these bids determine the market clearing price by placing the marginal generators bids and offers in an ascending order accordingly until it meets the total system load subject to security limits. In economic terms, the market clearing point is the point of intersection between supply and demand curves as illustrated as point A in Figure 5.2.

Ignoring the line resistance and the grid limitations, the first stage (i.e., economic dispatch) of the unconstrained dispatch shown in Figure 5.1 gives a uniform marginal price throughout the network. However, in a real transmission network, the nodal price at each bus differs thus prices vary by location due to losses. In the presence of transmission constraints, the second stage (i.e., system redispatch) will be carried out to relieve the network of congestion by ‘constraining off’ some generators on the grid and ‘constraining on’ some generators in order to secure balance between supply and demand to make the operation feasible. Hence, the LMP prices will not be uniform but vary by locations reflecting the effects of energy, loss and congestion in the system.

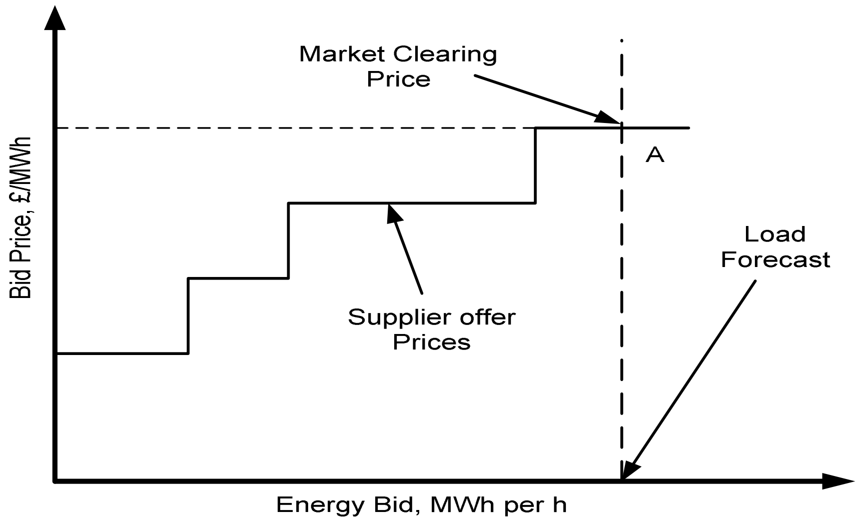


Figure 5.2 Market Settlement in Single Auction Power Pools

5.2.2 Reactive power pricing methods in power market

In the traditional power industry, the reactive power services provided by the system are usually recovered through two ways: one way is recovered through electricity tariffs paid by customers as the transmission cost; the other way is the industrial and big customers are charged according to their power factor, when the customers' power factors exceed the regulated ranges the reactive service costs are recovered through penalty form and the system operator encourages those customers to improve their power factor to maintain system in a reliable operation.

However, the above mentioned charging methods can not meet the requirements of a fair and transparent power market. Therefore, the reactive power services charging method in the deregulated power market which has been developed with the reactive ancillary services market as well needs to be studied further.

5.2.2.1 Reactive power spot pricing

Theory of spot pricing can be traced back to the late 70s, 80s begun to attract the attention of national researchers worldwide. Schweppe and others [4] discussed the definition of marginal cost pricing and its corresponding mathematical model and proposed a spot price calculation method which is based on economic dispatch and DC Power Flow. Then some scholars introduced the AC Power Flow into spot price calculations [5] proposed a method of using a modified Optimal Power Flow (OPF) to calculate the reactive spot prices. Its most important contribution is the discovery of the fact that the corresponding Lagrange multipliers (λ_p, λ_q) of power flow balance functions in OPF have the same economic meaning with real and reactive spot prices thus it demonstrates the OPF is a great potential calculation Method for spot prices. [6] proposed a decoupled based OPF calculation method for real and reactive spot prices calculation method, the price of reactive power is determined by the reactive sub-problems which objective function is real power losses minimization.

[7] calculated the reactive spot price in the subjective of social benefits maximization with taking account with the electricity usage benefits of customers the load power factor constraints. However, in the above reactive spot price calculations the reactive spot price is zero when the reactive power generation capacity did not exceed limits. As a result, it affected reactive capacity expansion and was not good to the formation of reactive power market. To solve this problem, [8] calculated the reactive spot price using OPF which considering both reactive price and reactive power planning in which the new reactive power equipment investment cost was regarded as a part of reactive spot price while the original reactive power source equipment fixed cost were not included in it.

[9] assumed that the model of generator reactive power cost is a quadratic function, however the definition of reactive power generation cost curve was unclear. Literature [10] discussed the technical and economic problems of reactive power services which indicated that the reactive reserve, capacitive and inductive reactive power management, reactive capacity and reactive production cost issues should be considered in reactive services charging; in addition, it introduced several reactive spot pricing calculation methods.

[11] analyzed the cost of reactive power services, defined the opportunity cost of generator reactive power production and proposed of generator's reactive power opportunity cost model based on the probability theory but this model was difficult to achieve in practice. Literature [12] proposed generator's reactive price bidding model and the corresponding market operation mode based on the detailed analysis of generator's P-Q Curve.

Overall, the literatures described previously in the study of reactive spot pricing were not very good to solve a problem of how to determine reactive power production costs and thus determine reactive power price bidding model. Because the generator reactive power production basically does not result in any additional operating costs, therefore, most of the literatures ignore reactive power production costs, so that the obtained reactive spot price lacks of rationality. Also [9] proposed a method by using a quadratic function to approximately express the reactive power production costs, however, this method also lacks of sufficient basis. [12] proposed the reactive power price bidding model of was without the necessary consideration of generator's leading phase operation.

Economic theory suggests that production costs should include two kinds: explicit and implicit costs. Although the cost of generator reactive power does not have any kind of explicit costs (i.e. fuel costs), however, the generator reactive power output may indirectly lead to the capacity reduction of generator real power. so that generators can not get the profits created by this part of real power capacity. This kind of losses is the implicit costs of reactive power production, or named as the opportunity cost of reactive power. However, since the opportunity cost is determined by the supply and demand in spot market and other market information, therefore, its calculation is complex and with great uncertainty so it is difficult to applicant in practice.

A new generator reactive power bidding model is proposed in this chapter which is based on literature [12]. This bidding model is based on generator operation theory and considers of reactive power opportunity cost. A case study of 5-bus test system is used to illustrate the feasibility and rationality of this model in section 5.7.

5.2.2.2 Reactive power pricing based on composite cost

Similar to the real power pricing method, in addition to economics method to price reactive power, accounting method can also be used in reactive power pricing.

Due to the theory disadvantages of cost allocation methods such as Stamp method, MW-Mile method, etc., in recent years another cost allocation method called Power Flow Tracing method, that is on the basis of obtained power flow results through the power flow tracing method to determine the each user’s usage of power sources and transmission networks, and then determine how to allocate the cost based on this information. This cost allocation method is more reasonable than stamp method.

5.3 Reactive power production costing

In this chapter we assume the reactive power production cost from the generator equals to the generator's opportunity cost. The definition and mathematical express is the same as in chapter 3.

Here, we propose the generator reactive power bidding curve is described in Figure 5.3:

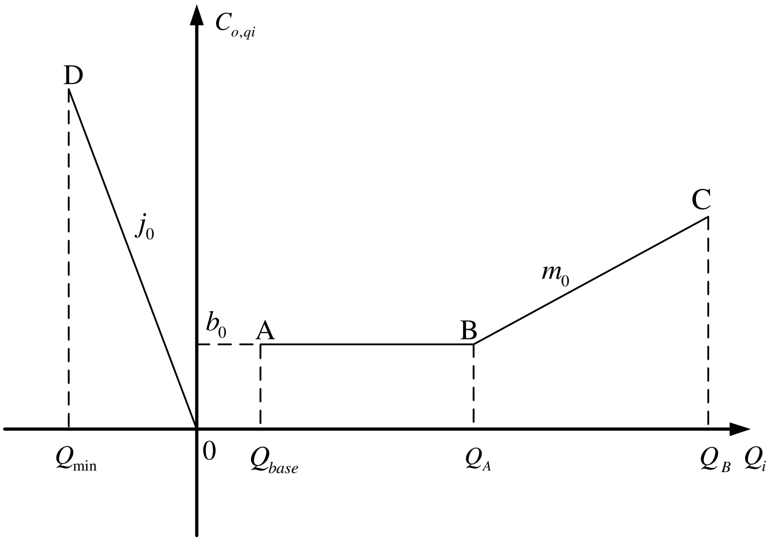


Figure 5.3 Generator reactive price bidding curve

And the mathematical express of the bidding curve is as follows:

$$C_{o,qi} = \begin{cases} j_{0i} \times Q_{gi} & Q_{\min} \le Q_{gi} < 0 \\ 0 & 0 \le Q_{gi} < Q_{base} \\ b_{0i} & Q_{base} \le Q_{gi} < Q_A \\ b_{0i} + m_{0i} \times (Q_{gi} - Q_{A,i}) & Q_A \le Q_{gi} < Q \end{cases} \tag{5.1}$$

$i \in N_G$

5.4 Spot pricing based on optimization theory

Optimization can be defined as the process of finding the conditions that give the maximum or minimum value of a function [13, 14]. For the producers on the market, for a given raw material and other conditions, how to obtain maximum economic benefit is its main concern. Therefore, as a branch of operations research mathematical programming was firstly widely applied in the field of economics.

The mathematical programming consists of linear programming, non-linear programming, dynamic programming, stochastic programming and multi-objective programming, etc. In this section, we discuss in the power system the Lagrange multiplier solution method in the optimization problem with inequality constraints.

5.4.1 The concept of Lagrange function [13]

The basic features of the Lagrange multiplier method is given initially for a simple problem of two variables with one constraint.

$$\text{Minimize}\, f\left(x_1, x_2\right) \tag{5.2}$$

s.t.

$$g\left(x_1, x_2\right) = 0$$

A necessary condition for f to have a minimum at some point $\left(x_1^*, x_2^*\right)$ is that the total derivative of $f\left(x_1, x_2\right)$ with respect to x_1 must be zero at $\left(x_1^*, x_2^*\right)$. By setting the total differential of $f\left(x_1, x_2\right)$ equal to zero, we obtain

$$df = \frac{\partial f}{\partial x_1} dx_1 + \frac{\partial f}{\partial x_2} dx_2 = 0 \tag{5.3}$$

Since $g\left(x_1^*, x_2^*\right) = 0$ at the minimum point, any variations dx_1 and dx_2 taken about the point $\left(x_1^*, x_2^*\right)$ are called admissible variations provided that the new point lies on the constraint:

$$g\left(x_1^* + dx_1, x_2^* + dx_2\right) = 0 \tag{5.4}$$

The Taylor's series expansion of the function in equation (5.4) about the point $\left(x_1^*, x_2^*\right)$ gives

$$\begin{aligned} & g\left(x_1^* + dx_1, x_2^* + dx_2\right) \\ & \simeq g\left(x_1^*, x_2^*\right) + \frac{\partial g}{\partial x_1}\left(x_1^*, x_2^*\right) dx_1 + \frac{\partial g}{\partial x_2}\left(x_1^*, x_2^*\right) dx_2 = 0 \end{aligned}$$

Namely,

$$dg = \frac{\partial g}{\partial x_1} dx_1 + \frac{\partial g}{\partial x_2} dx_2 = 0, \quad \text{at } \left(x_1^*, x_2^*\right) \tag{5.5}$$

Assuming that $\dfrac{\partial g}{\partial x_2} \neq 0$, equation (5.5) can be rewritten as

$$dx_2 = -\frac{\partial g / \partial x_1}{\partial g / \partial x_2}\left(x_1^*, x_2^*\right) dx_1 \tag{5.6}$$

By substituting equation (5.6) in equation (5.3), we obtain

$$df = \left(\frac{\partial f}{\partial x_1} - \frac{\partial g / \partial x_1}{\partial g / \partial x_2} \frac{\partial f}{\partial x_2} \right)\Bigg|_{\left(x_1^*, x_2^*\right)} dx_1 = 0 \tag{5.7}$$

By defining a quality λ, called the Lagrange multiple, as $\lambda = -\left(\dfrac{\partial f / \partial x_2}{\partial g / \partial x_2} \right)\Bigg|_{\left(x_1^*, x_2^*\right)}$

Therefore, at point $\left(x_1^*, x_2^*\right)$, we obtain

$$\left(\frac{\partial f}{\partial x_1} + \lambda \frac{\partial g}{\partial x_1} \right)\Bigg|_{\left(x_1^*, x_2^*\right)} = 0 \tag{5.8}$$

$$\left(\frac{\partial f}{\partial x_2} + \lambda \frac{\partial g}{\partial x_2} \right)\Bigg|_{\left(x_1^*, x_2^*\right)} = 0 \tag{5.9}$$

In addition, the constraint equation has to be satisfied at the extreme point, that is,

$$g\left(x_1, x_2\right)\Big|_{\left(x_1^*, x_2^*\right)} = 0 \tag{5.10}$$

Thus equations (5.8) to (5.10) represent the necessary conditions for the point $\left(x_1^*, x_2^*\right)$ to be an extreme point.

The necessary conditions given by equations (5.8) to (5.10) are more commonly generated by constructing a function L, known as the Lagrange function, as

$$L\left(x_1, x_2, \lambda\right) = f\left(x_1, x_2\right) + \lambda g\left(x_1, x_2\right) \tag{5.11}$$

By treating L as a function of the three variables x_1, x_2, and λ, the necessary conditions for its extremum are given by

$$\begin{aligned}
&\frac{\partial L}{\partial x_1}\left(x_1, x_2, \lambda\right) = \frac{\partial f}{\partial x_1}\left(x_1, x_2\right) + \lambda \frac{\partial g}{\partial x_1}\left(x_1, x_2\right) = 0 \\
&\frac{\partial L}{\partial x_2}\left(x_1, x_2, \lambda\right) = \frac{\partial f}{\partial x_2}\left(x_1, x_2\right) + \lambda \frac{\partial g}{\partial x_2}\left(x_1, x_2\right) = 0 \\
&\frac{\partial L}{\partial \lambda}\left(x_1, x_2, \lambda\right) = g\left(x_1, x_2\right) = 0
\end{aligned}$$

5.4.2 Lagrange function with multivariable and equality constraints [13]

The questions derived above can be extended to the case of a general problem with n variables and m equality constraints:

$$\text{Minimize} f\left(\mathbf{X}\right) \tag{5.12}$$

s.t.

$$g_j\left(\mathbf{X}\right) = 0, \qquad j = 1, 2, \ldots, m$$

The Lagrange function, L, in this case is defined by introducing one Lagrange multiplier λ_j for each constraint $g_j\left(\mathbf{X}\right)$ as

$$\begin{aligned} &L(x_1, x_2, \cdots, x_n, \lambda_1, \lambda_2, \cdots \lambda_m) \\ &= f(\mathbf{X}) + \lambda_1 g_1(\mathbf{X}) + \lambda_2 g_2(\mathbf{X}) + \cdots + \lambda_m g_m(\mathbf{X}) \end{aligned} \tag{5.13}$$

The necessary conditions for the extremum of Lagrange function is that the partial derivatives equal to zero of $\mathbf{X}$ and λ are zero.

5.4.3 Lagrange function with multivariable and inequality constraints[13]

This section is concerned with the solution of the following problem:

$$\text{Minimize} f(\mathbf{X}) \tag{5.14}$$

s.t.

$$g_j(\mathbf{X}) \le 0, \qquad j = 1, 2, ..., m$$

The inequality constraints in equation (5.14) can be transformed to equality constraints by adding nonnegative slack variables, y_j^2, as

$$G_j(\mathbf{X}, \mathbf{Y}) = g_j(\mathbf{X}) + y_j^2 = 0, \qquad j = 1, 2, ..., m$$

This problem can be solved conveniently by the method of Lagrange multipliers. For this, we construct the Lagrange function L as

$$L(\mathbf{X}, \mathbf{Y}, \lambda) = f(\mathbf{X}) + \sum_{j=1}^{m} \lambda_j G_j(\mathbf{X}, \mathbf{Y}) \tag{5.15}$$

If the set of active constraints is not known, the conditions can be stated as follows:

$$\begin{aligned} &\frac{\partial f}{\partial x_i} + \sum_{j=1}^{m} \lambda_j \frac{\partial g_j}{\partial x_i} = 0 && i = 1, 2, ..., n \\ &\lambda_j g_j = 0, && \text{j=1,2,...,m} \\ &g_j \le 0, && \text{j=1,2,...,m} \\ &\lambda_j \ge 0, && \text{j=1,2,...,m} \end{aligned} \tag{5.16}$$

5.4.4 The economical meaning of Lagrange function[13]

Through above discussion, it is seen that the concept of Lagrange multiplier method is to construct a Lagrange function to transform the optimization problem with constraints into the Lagrange function's extremum problem without constraints. To find the physical meaning of the Lagrange multipliers, consider the following optimization problem involving only a single equality constraint:

$$\text{Minimize}\, f\left(\mathbf{X}\right)$$

$$\text{s.t.}$$

$$g\left(\mathbf{X}\right) = b - \tilde{g}\left(\mathbf{X}\right) = 0 \tag{5.17}$$

where b is a constant. The necessary conditions to be satisfied for the solution of the problem are

$$\begin{aligned} &\frac{\partial f}{\partial x_i} + \lambda \frac{\partial g}{\partial x_i} = 0, \qquad\qquad i = 1, 2, ..., n \\ &g\left(\mathbf{X}\right) = 0 \end{aligned} \tag{5.18}$$

Let the solution of equation (5.18) be given by $\mathbf{X}^*, \boldsymbol{\lambda}^*$, and $f^* = f\left(\mathbf{X}^*\right)$. Suppose that we want to find the effect of a small relaxation or tightening of the constraint on the optimum value of the objective function (i.e., we want to find the effect of a small change in b on f^*). For this we differentiate equation (5.17) to obtain

$$db = d\,\tilde{g}\left(\mathbf{X}\right) = \sum_{i=1}^{n} \frac{\partial \tilde{g}}{\partial x_i} dx_i \tag{5.19}$$

Equation (5.18) can be rewritten as

$$\frac{\partial f}{\partial x_i} + \lambda \frac{\partial g}{\partial x_i} = \frac{\partial f}{\partial x_i} - \lambda \frac{\partial \tilde{g}}{\partial x_i} = 0 \tag{5.20}$$

Substituting equations (5.19) and (5.20), we obtain

$$db = \sum_{i=1}^{n} \frac{\partial \tilde{g}}{\partial x_i} dx_i = \sum_{i=1}^{n} \frac{1}{\lambda} \frac{\partial f}{\partial x_i} dx_i = \frac{df}{\lambda} \tag{5.21}$$

It gives

$$\lambda = \frac{df}{db} \qquad or \qquad \lambda^* = \frac{df^*}{db} \tag{5.22}$$

The equation (5.22) is the practical meaning of Lagrange multiplier. Thus λ^* denotes the sensitivity (or rate of change) of f with respect to b or the marginal or incremental change in f^* with respect to b at x^*. In the economics and operation research fields it is called shadow price. It is obvious that whether in the optimization problem the equality constraint is the supply-demand balance then the Corresponding Lagrange multiplier with this equality constraint is the marginal production cost. Because of the important meaning of Lagrange multiplier it has been widely applied in the study of economics problem and it becomes the basis of studying power market spot pricing.

5.4.5 The concept of spot price [15]

The concepts and theories of spot price are firstly proposed by the F. C. Schweppe. This theory later became the key research problem for many researchers worked on electricity field and has been widely recognized. The definition of spot price in this chapter is the same as in reference [15], namely the spot price is defined as the marginal production cost of electricity.

As described before, when the market is perfectly competitive, the total social benefits can be maximized. In a fully competitive market, the commodity price equals to its marginal production cost, which is the theoretical basis of spot pricing in economics.

Assume ρ_i is the spot price charged on customer i at time T, d_i is the power demand of customer i at time T, C is the total power production cost at time T to meet the power demand, so

$$\rho_i = \frac{\partial C}{\partial d_i} \tag{5.23}$$

It is indicated that since the reference [15] aimed to study the real power spot pricing so the spot pricing model and theory only involve customer's real power demand. However, this concept can be easily promoted to reactive power spot pricing as discussed in this chapter, namely, reactive power spot price equals to the rate of change of total system operation cost led by the change of customer's reactive power demand.

5.5 Locational marginal price of reactive power based on AC power flow

With the further deregulation of power market, reactive power ancillary services pricing becomes a popular topic nowadays and some researchers have proposed reactive power pricing on various methods [5-9, 16-18] [19-23].

As described previously, the spot pricing mostly uses DC Power Flow model to calculate in the early days as a result the reactive power flow. But the result and economical information can not be obtained so that DC Power Flow model can not be used to calculating reactive power prices. [5] firstly proposed the Optimal Power Flow (OPF) model based on AC Power Flow which promoted the concept of spot pricing into reactive power pricing. Hereafter, other literature studied reactive power pricing as well [6-9, 16-18].

However, most published literatures have a common problem in which reactive power generation cost is not taken into account in the OPF model so that the reactive marginal production cost is zero until generator's reactive output meets generator's operation limit. It results in that the generator which has big reactive capacity can not obtain any compensation which is not good to the development and construction of reactive ancillary services market. To solve this problem, [11] firstly proposed to use lost opportunity cost to denote generator's reactive production cost, however, it is hard to realize due to its complex calculation.

A reasonable and efficient reactive power generation cost model is proposed in this chapter shown in section 5.3. By taking account of reactive production cost, we can analyze and derive the reactive locational marginal price based on the OPF with objective of power production minimization.

5.5.1 Procurement options for reactive power pricing

The substance of spot price is the Lagrange function with equality and inequality constraints. The existing reactive spot pricing calculation models mainly differ on the optimization objective functions. Commonly used objective functions of OPF models to calculate reactive spot price are as follows:

Ⅰ. Minimize real power losses

$$\min \quad C_1\left(P_{G1}\right) \tag{5.24}$$

Ⅱ. Minimize real power production cost

$$\min C = \sum_{i \in G} C_i\left(P_{Gi}\right) \tag{5.25}$$

Ⅲ. Minimize total real and reactive power production cost

$$\min C = \sum_{i \in G} \left[C_{Gpi}\left(P_{Gi}\right) + C_{Gqi}\left(Q_{Gi}\right) \right] \tag{5.26}$$

Ⅳ. Maximize social benefits

$$\min f = \sum_{i \in N} \left[C_{Gpi}\left(P_{Gi}\right) + C_{Gqi}\left(Q_{Gi}\right) \right] - \sum_{i \in N} B_i(P_{Di}, Q_{Di}) \tag{5.27}$$

Where,

$C_1\left(P_{G1}\right)$: real power production cost at slack bus; here, the minimization of real power production cost at slack bus equals to the minimization of total real power losses in the system

$C_i\left(P_{Gi}\right)$: is the function of generator's real power production cost, it is usually described as quadratic function

$$C_i\left(P_{Gi}\right) = a + bP_{Gi} + cP_{Gi}^2, \quad P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max}$$

$C_{Gpi}\left(P_{Gi}\right)$: real power production cost of generator at Bus i;

$C_{Gqi}\left(Q_{Gi}\right)$: reactive power production cost of generator at Bus i; this is the generator's reactive power opportunity cost function; it is calculated by using the following function

$$C_{Gqi}(Q_{Gi}) = k \left| C_{Gi}(S_{Gi\max}) - C_{Gi}\sqrt{S_{Gi\max}^2 - Q_{Gi}^2} \right|$$

Where $S_{Gi\max}$: the maximum generator power output; Q_{Gi}: generator reactive output; k: generator plant interest, is a constant between 5%-10%; $B_i(P_{Di}, Q_{Di})$: the power consumption efficiency function of customer i.

5.5.2 Mathematical formula of reactive marginal price

A new procurement option of reactive power pricing is proposed in this section. The objective function is to minimize network operation cost. The objection function of this procurement option consists of not only generators' real and reactive power production costs but also reactive compensator's reactive power output production cost. Since the power demand varying with the power prices was not considered in this discussion so that in the OPF simulation all loads remain constant.

The OPF objective function is as follows:

$$\min f = \sum_{i\in N_G}\left[C_{Gpi}\left(P_{Gi}\right)+C_{Gqi}\left(Q_{Gi}\right)\right]+\sum_{i\in N_C}C_{Ci}\left(Q_{Ci}\right) \tag{5.28}$$

The minimization of the above function is also subject to a number of equality and inequality constraints:

Ⅰ. Load constraints

$$P_{Gi}-P_{Di}-\sum_{j\in N}V_iV_jY_{ij}\cos\left(\theta_{ij}+\delta_j-\delta_i\right)=0 \tag{5.29}$$

$$Q_{Gi}-Q_{Di}+Q_{Ci}+\sum_{j\in N}V_iV_jY_{ij}\sin\left(\theta_{ij}+\delta_j-\delta_i\right)=0 \tag{5.30}$$

Ⅱ. Operating constraints

$$P_{Gi}^{\min}\le P_{Gi}\le P_{Gi}^{\max} \tag{5.31}$$

$$Q_{Gi}^{\min}\le Q_{Gi}\le Q_{Gi}^{\max} \tag{5.32}$$

$$P_{l_k}^{\min}\le P_{l_k}\le P_{l_k}^{\max} \qquad k\in L \tag{5.33}$$

If the branch k connects the bus i and bus j, then

$$P_{l_k}=V_iV_jY_{ij}\cos\left(\theta_{ij}+\delta_j-\delta_i\right)-V_i^2Y_{ij}\cos\theta_{ij} \tag{5.34}$$

$$V_i^{\min}\le V_i\le V_i^{\max} \tag{5.35}$$

Ⅲ. Capacitor constraints

$$0 \le Q_{ci} \le Q_{ci}^{\max} \tag{5.36}$$

Where,

N : the congregation of all system buses;

L : the congregation of all branches in the network;

C_{Gpi}, C_{Gqi} : real and reactive power production cost of generator at Bus i, hereby the generator's reactive power opportunity cost is used as reactive power production cost function;

C_{Ci} : the production cost of capacitor at Bus i;

P_{Gi}, Q_{Gi} : the generator real and reactive power output at bus i;

P_{Di}, Q_{Di} : the real and reactive power demand at bus i;

P_{l_k} : the real power flow on branch K;

Q_{Cj} : the capacitor output at bus i;

$P_{Gi}^{\max}, P_{Gi}^{\min}$: up and down real power output limits of generator at bus i;

$Q_{Gi}^{\max}, Q_{Gi}^{\min}$: up and down reactive power output limits of generator at bus i;

$P_{l_k}^{\max}, P_{l_k}^{\min}$: the up and down real power flow limits on branch K;

$Q_{ci}^{\max}$: the up capacity limit of capacitor;

$V_i^{\min}, V_i^{\max}$: the up and down voltage limits at bus i.

The Lagrange function of this OPF is

$$
\begin{aligned}
L = & \sum_{i\in N_G}\left[C_{Gpi}\left(P_{Gi}\right)+C_{Gqi}\left(Q_{Gi}\right)\right]+\sum_{i\in N_C}C_{Ci}\left(Q_{Ci}\right) \\
& -\sum_{i\in N}\lambda_p\left[P_{Gi}-P_{Di}-\sum_{j\in N}V_iV_jY_{ij}\cos\left(\theta_{ij}+\delta_j-\delta_i\right)\right] \\
& -\sum_{i\in N}\lambda_{qi}\left[Q_{Gi}-Q_{Di}+Q_{Ci}+\sum_{j\in N}V_iV_jY_{ij}\sin\left(\theta_{ij}+\delta_j-\delta_i\right)\right] \\
& +\sum_{i\in N}\mu_{pi,\min}\left(P_{Gi,\min}-P_{Gi}+y_{Pi,\min}^2\right) \\
& +\sum_{i\in N}\mu_{pi,\max}\left(P_{Gi}-P_{Gi,\max}+y_{Pi,\max}^2\right) \\
& +\sum_{i\in N}\mu_{qi,\min}\left(Q_{Gi,\min}-Q_{Gi}+y_{qi,\min}^2\right) \\
& +\sum_{i\in N}\mu_{qi,\max}\left(Q_{Gi}-Q_{Gi,\max}+y_{qi,\max}^2\right) \\
& +\sum_{k\in L}\eta_{lk,\min}\left(P_{lk,\min}-P_{lk}+y_{lk,\min}^2\right) \\
& +\sum_{k\in L}\eta_{lk,\max}\left(P_{lk}-P_{lk,\max}+y_{lk,\max}^2\right) \\
& +\sum_{i\in N}\omega_{ci,\min}\left(Q_{Ci,\min}-Q_{Ci}+y_{ci,\min}^2\right) \\
& +\sum_{i\in N}\omega_{ci,\max}\left(Q_{Ci}-Q_{Ci,\max}+y_{ci,\max}^2\right) \\
& +\sum_{i\in N}v_{i,\min}\left(V_{i,\min}-V_i+y_{i,\min}^2\right) \\
& +\sum_{i\in N}v_{i,\max}\left(V_i-V_{i,\max}+y_{i,\max}^2\right)
\end{aligned}
\tag{5.37}
$$

Where,

$\lambda_{pi},\lambda_{qi},\mu_{pi,\min},\mu_{pi,\max},\mu_{qi,\min},\mu_{qi,\max},\eta_{lk,\min},\eta_{lk,\max},\omega_{ci,\min},\omega_{ci,\max},v_{i,\min},v_{i,\max}$

: are the corresponding constraints' Lagrange multipliers;

$y_{pi,\min},y_{pi,\max},y_{qi,\min},y_{qi,\max},y_{lk,\min},y_{lk,\max},y_{ci,\min},y_{ci,\max},y_{i,\min},y_{i,\max}$: are the corresponding inequality constraints' slack variables.

In the optimal solution of this problem, there are

$$
\frac{\partial L}{\partial P_{Gi}}=\frac{\partial C_{Gpi}\left(P_{Gi}\right)}{\partial P_{Gi}}-\lambda_{pi}+\left(\mu_{pi,\max}-\mu_{pi,\min}\right)=0 \tag{5.38}
$$

$$\frac{\partial L}{\partial Q_{Gi}} = \frac{\partial C_{Gqi}\left(Q_{Gi}\right)}{\partial Q_{Gi}} - \lambda_{qi} + \left(\mu_{qi,\max} - \mu_{qi,\min}\right) = 0 \tag{5.39}$$

So we obtain

$$\lambda_{pi} = \frac{\partial C_{Gpi}(P_{Gi})}{\partial P_{Gi}} + \left(\mu_{pi,\max} - \mu_{pi,\min}\right) \tag{5.40}$$

$$\lambda_{qi} = \frac{\partial C_{Gqi}(Q_{Gi})}{\partial Q_{Gi}} + \left(\mu_{qi,\max} - \mu_{qi,\min}\right) \tag{5.41}$$

Based on the discussion of physical meaning of Lagrange multiplier in the section 5.4.4, it is known that Lagrange multipliers λ_{pi} and λ_{qi} equal to the value change of objective function led by the unbalanced disturb are of corresponding equality constraints in power flow function, namely, the change of system production cost led by the small changes of real power and reactive power outputs at Bus i respectively. Therefore, λ_{pi} and λ_{qi} are the real and reactive locational marginal prices individually at Bus i respectively.

From the above derived results the real power generation price and real power load price are the same at Bus i and this is reasonable.

5.6 Case studies and discussions

To investigate the properties of the reactive locational marginal price, a 5-bus test system is simulated to illustrate the proposed reactive costing model and reactive locational spot pricing method.

In this case study the system parameters and the simulation results are in unit format, in which the base capacity is 100MVA. The optimal power flow calculation uses Newton method.

The evaluation of the reactive locational spot pricing is illustrated using a simple 5-bus test system shown in Figure 5.4. Five scenarios in different system operation conditions are simulated using Optimal Power Flow (OPF). The objective of minimum total real and reactive power procurement payment have been conducted to illustrate the impact on the reactive locational marginal prices.

Five scenarios are described as follows:

Scenario 1: in this scenario, the OPF model does not take account of the cost of reactive power ancillary. This means only the first term of Equation 5.28 is used;

Scenario 2: OPF objective function includes both real power procurement cost and reactive ancillary services. The objective is minimizing total system power procurement cost based on real and reactive power generation bidding. This is the proposed reactive locational spot pricing calculation model;

Scenario 3: based on Scenario 2 to study the impact of real power bidding prices of generators on different locations on reactive locational marginal prices;

Scenario 4: based on Scenario 2 to study the impact of different load power factors on reactive locational marginal prices;

Scenario 5: based on Scenario 2 to study the impact of nodal voltages controlling on reactive locational marginal prices.

5.6.1 System configuration and data of 5-bus test system

A 5-bus test system is shown in Figure 5.4 [24]. In the test system there are two generators which have the same parameters located on the bus 1 and bus 2 respectively. The rated generation capacity is 1.25 p.u.; the minimum real power generation output is 0.20 p.u.; the maximum real power generation output is 1.25 p.u.. There is a shunt capacitor installed at Bus 4 which assuming the reactive power output from shunt capacitor can be regulated from 0 to 0.50 p.u. continuously under normal voltage range.

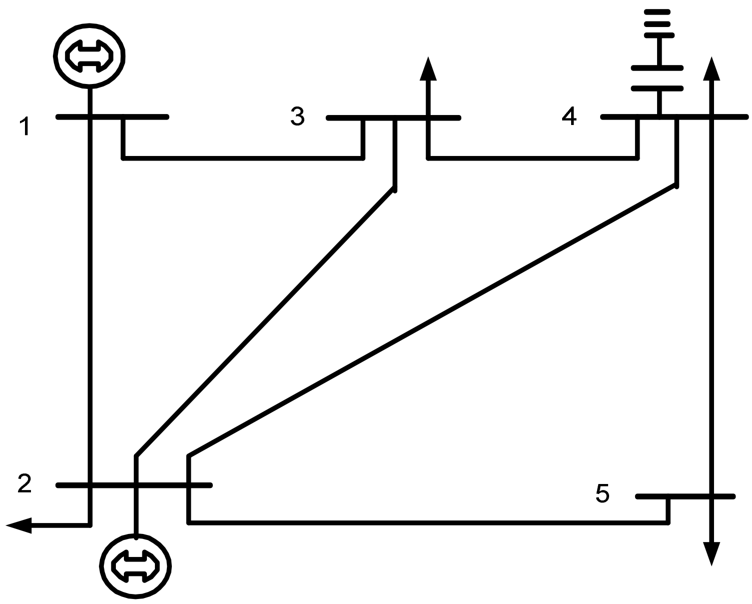


Figure 5.4 One line diagram of 5-bus test system

System branch parameters and load profile are shown in Table 5.1 and Table 5.2, separately. The load power factor is 0.9 lagging.

Table 5.1 Branch parameters for 5-bus test system

From Bus	To Bus	R/p.u.	X/p.u.	BCAP/p.u.
1	2	0.02	0.06	0.030
1	3	0.08	0.24	0.025
2	3	0.06	0.18	0.020
2	4	0.06	0.18	0.020
2	5	0.04	0.12	0.015
3	4	0.01	0.03	0.010
4	5	0.08	0.24	0.025

Table 5.2 Load profile of 5-bus test system

Bus No.	P_{Li} /p.u.	Q_{Li} /p.u.
2	0.20	0.097
3	0.45	0.22
4	0.40	0.19
5	0.60	0.29

5.6.2 Scenarios 1 and 2 simulation results analysis

The simulation results of scenarios 1 and 2 are shown in Table 5.3. Scenario 1 does not consider reactive ancillary services cost, therefore, the corresponding reactive locational marginal prices at generator buses are zero. The cost of generator reactive ancillary services is included in Scenario 2. The reactive locational marginal prices at generator buses are no longer zero, so that the generation company could recover the cost of reactive power ancillary service and obtain a certain profit. This has an influence on the operating phase angle of the generator. This avoids negative effects of generator leading phase operation on the generator unit itself. In another word, it proved the proposed reactive locational spot pricing model is reasonable.

Table 5.3: Difference between reactive locational marginal prices when reactive bidding of generators is considered or not in 5-bus test system

Scenario No.	Bus No.	P_{Gi} /pu	Q_{Gi} /pu	Q_{Ci} /pu	λ_{Pi} (£/MW·h)	λ_{Qi} (£/MVar·h)
1	1	0.0872	-0.0816		14.4486	0
	2	0.8601	0.4954		14.7254	0
	3				15.2089	0.1486
	4			0.1886	15.2554	0.1324
	5				15.3917	0.4954
2	1	0.8267	0.0586		14.4443	0.0399
	2	0.8602	0.1799		14.7257	0.1223
	3				15.2178	0.1692
	4			0.3636	15.2652	0.1324
	5				15.4113	0.3704

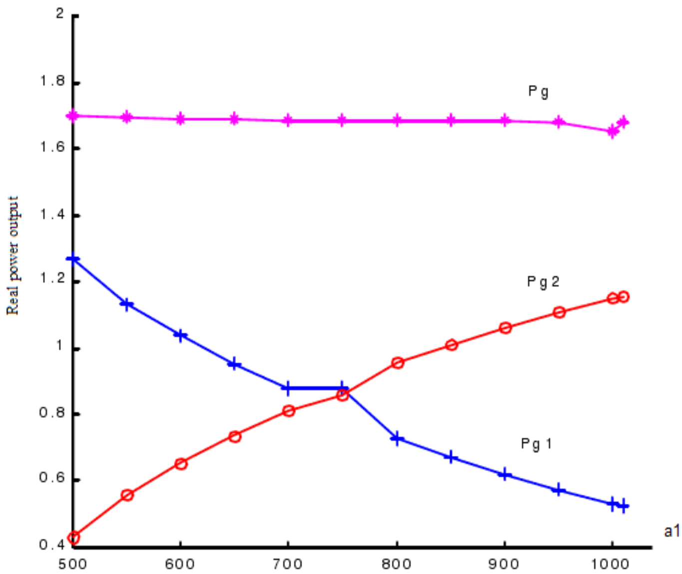
5.6.3 Analysis of the impact of generator real power tender price on reactive marginal price

Based on Scenario 2, the impact of remote generator unit (Generator 1) far loading and near load generator unit (Generator 2) real power generation bidding prices on reactive locational marginal prices is studied in this section. The simulation results and discussions are as follows:

Ⅰ. The impact of remote generator unit (Generator 1) real power generation bidding prices on reactive locational marginal prices

Based on Scenario 2, only the real power generation bidding price of generator 1 varies. From the OPF simulation results, it can be observed that real and reactive power outputs of both generators changes with the variation of real power bidding of generator 1. These are shown in Figure 5.5. And reactive locational marginal prices and nodal voltages changes with the variation of real power bidding of generator 1 and are shown in Figure 5.6.

When the real power generation bidding price of remote generator (G1) is lower than the near load generator (G2) (when constant coefficient a1 <750) the real power output from generator 1 increases with the value of a1 (Figure 5.5); However, since the G1 is located far away from dense load areas, system losses are increased and is caused by the increase of real power transmission on the network. Thereby the total system real and reactive power output increased and it led to the increasing of generator's reactive locational marginal price and the decreasing of nodal voltages (Figure 5.6). When the coefficient of G1 fell very low the real power output increases and reaches its maximum power output limit but the reactive power output is zero. As a result, the reactive power output of G2 and shunt capacitors increase and, it decreases reactive power flow in the network, so that the voltages on the load buses are maintained within limits.



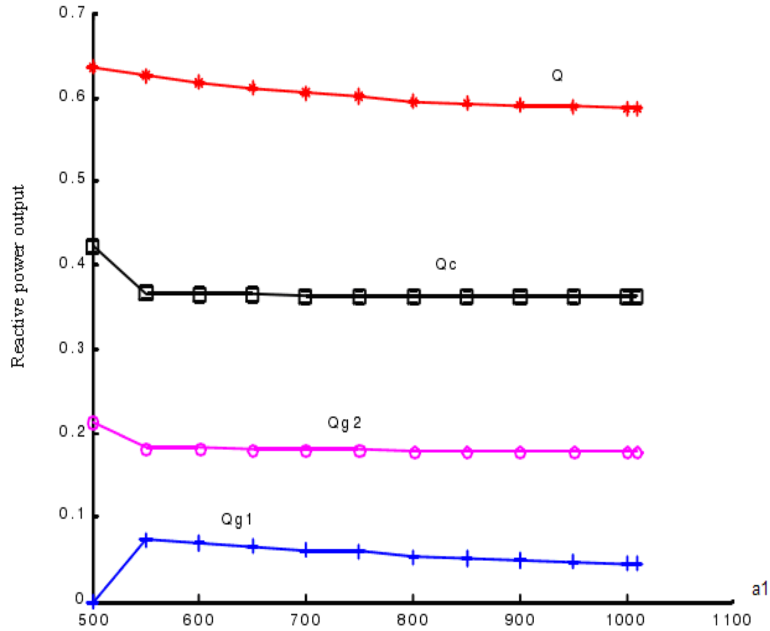


Figure 5.5 Real and reactive power outputs versus the variation of real power bidding of generator 1

When the coefficient of real power generation of G1 is bigger than G2's, G2 is responsible for increasing its real power output to meet the load demand. Meanwhile, the nodal voltages rise and the total system real and reactive power output decrease since the decreasing of real and reactive power transmission due to the increase of G2's real power output resulting in less transmission requirement. However, the total system procurement payment increases with the rise of one generator's real power coefficient (G1's real power bidding price is higher than its locational marginal price.) which resulting in the rise of reactive locational marginal prices at load buses 3 and 5 as can be seen in Figure 5.6. The reactive locational marginal price at heavily loaded bus (Bus 5) increases considerably.

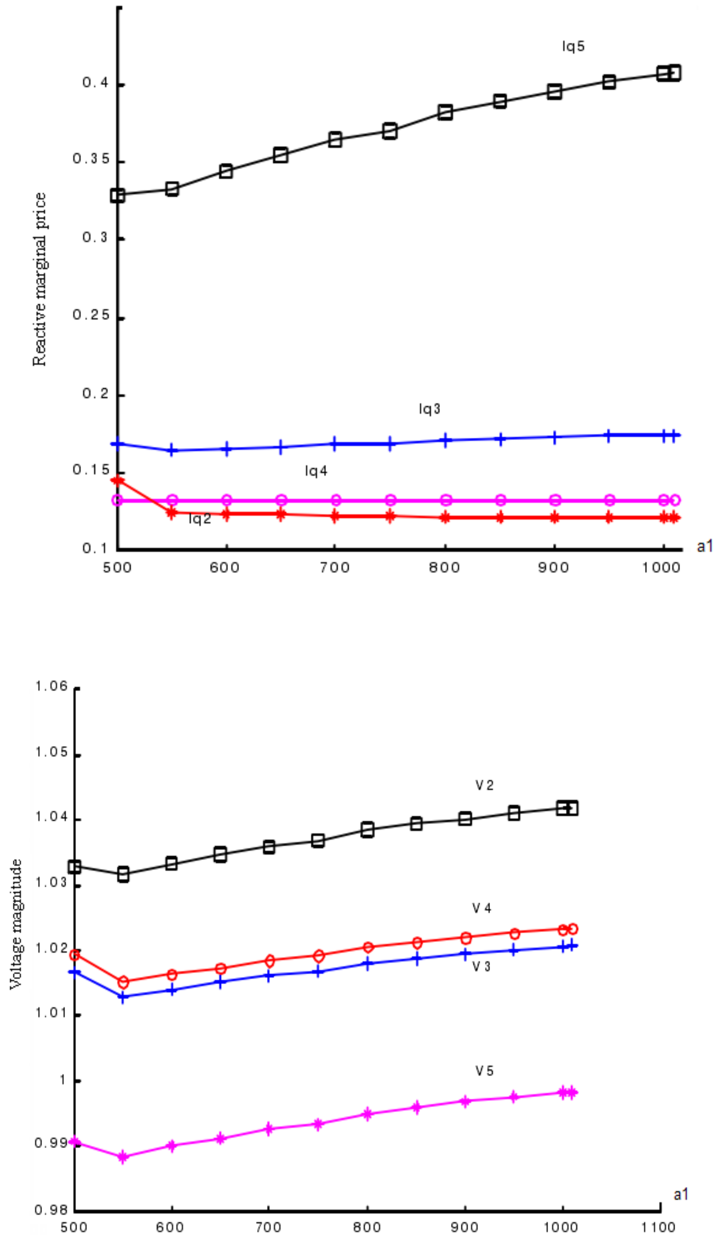


Figure 5.6 Reactive locational marginal prices and nodal voltages versus the variation of real power bidding of generator 1

In addition, in the above changes, the reactive power locational marginal price of Bus 4 has remained unchanged. This is due to the capacitor connected at Bus 4 provides sufficient reactive supply locally to meet reactive power demand. So the reactive power locational marginal price of Bus 4 has remained unchanged and is not affected by the real power generation bidding prices (real power generation coefficient a1). However, the reactive locational marginal prices on PV buses increase with the rise of its reactive generation output.

Ⅱ. The impact of near load generator unit (Generator 2) real power generation bidding prices on reactive locational marginal prices

Based on Scenario 2, only the real power generation bidding price of generator 2 varies. From the OPF simulation results it can be observed that real and reactive power outputs of both generators changes with the variation of real power bidding of generator 2. These are shown in Figure 5.7. And reactive locational marginal prices and nodal voltages changes with the variation of real power bidding of generator 2 are shown in Figure 5.8.

When the real power generation bidding price of G2 is lower than the remote generator G1's, G2 increases its real power output to meet the load demand. Meanwhile, due to G2's location is near load area the rise of its real power output decreases system power losses and voltage rise because of the reduction in real power losses. Therefore, the nodal voltages rise and the total system real and reactive power output decrease. At the same time, the reactive locational marginal price of pure load bus (Bus 5) decreases.

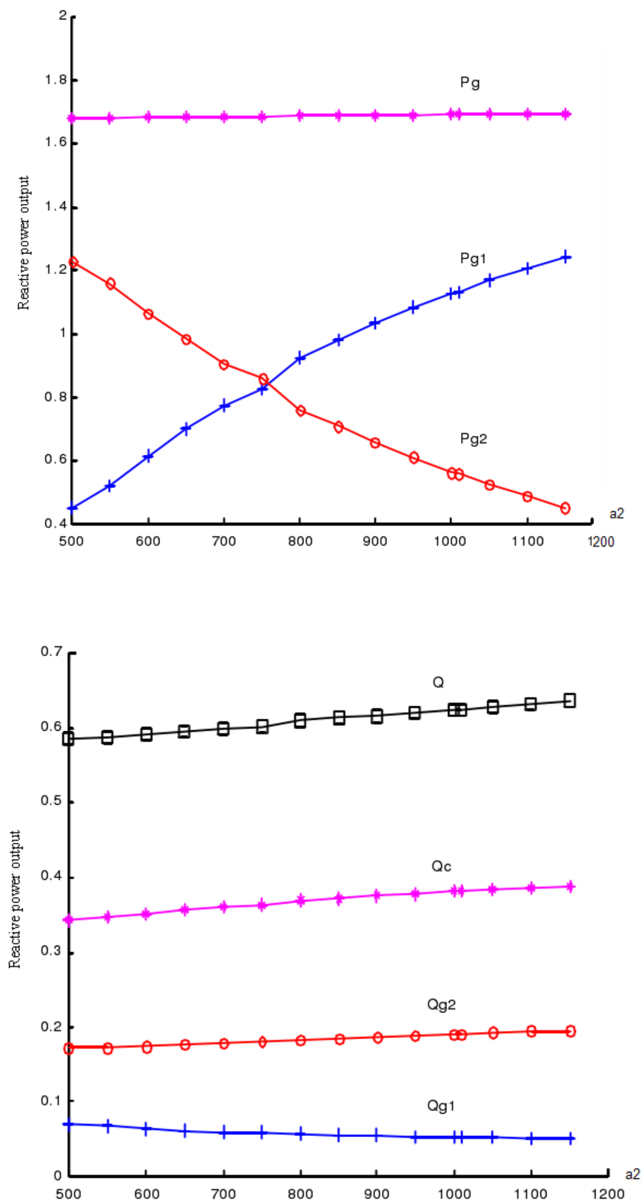


Figure 5.7 Real and reactive power outputs versus the variation of real power bidding of generator 2

When the real power generation bidding price of near load generator unit is higher than the remote generator unit, the real power output of near load generator unit decreases and remote generator unit has to provide more real power supply to meet the load demand. As a result, it increases the power transmission losses, total system real and reactive power output, the reactive locational marginal prices at PQ buses (bus 3 and 5) and it also results in a decrease of system nodal voltages.

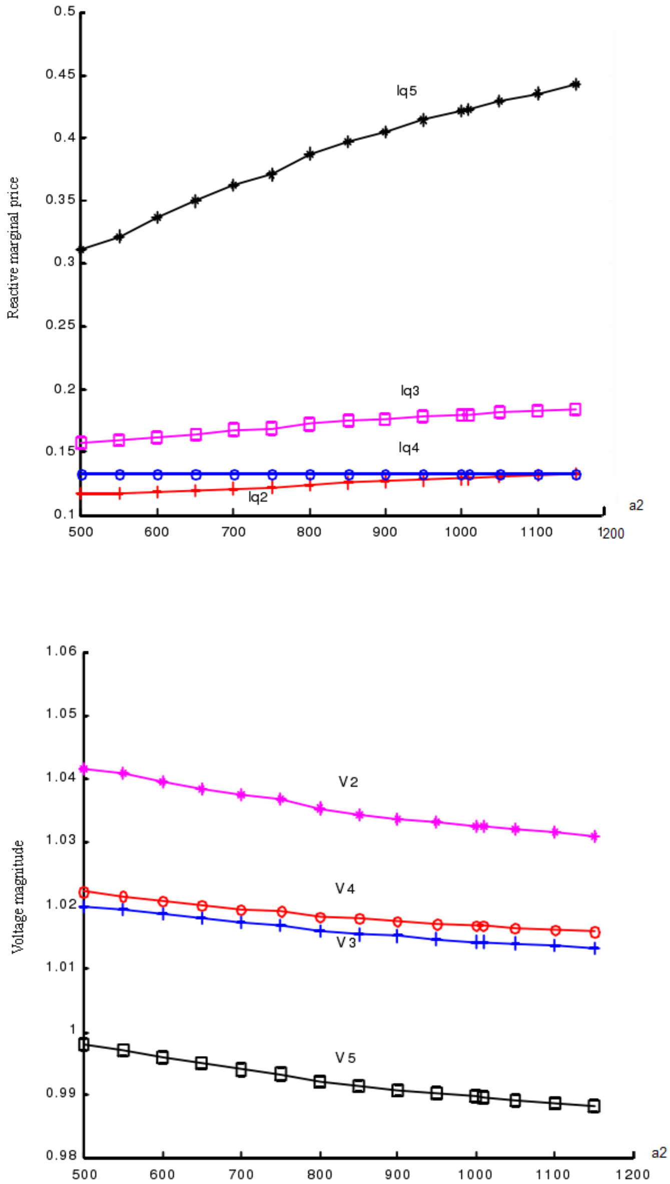


Figure 5.8 Reactive locational marginal prices and nodal voltages versus the variation of real power bidding of generator 2

5.6.4 Analyze the impact of load power factor on reactive marginal price

In order to observe the impact of load power factor on reactive locational marginal price, the load power factor varies from 0.72 to 1.0 based on the OPF simulation calculated in Scenario 2. And the simulation results are shown in Figure 5.9 and Figure 5.10 respectively.

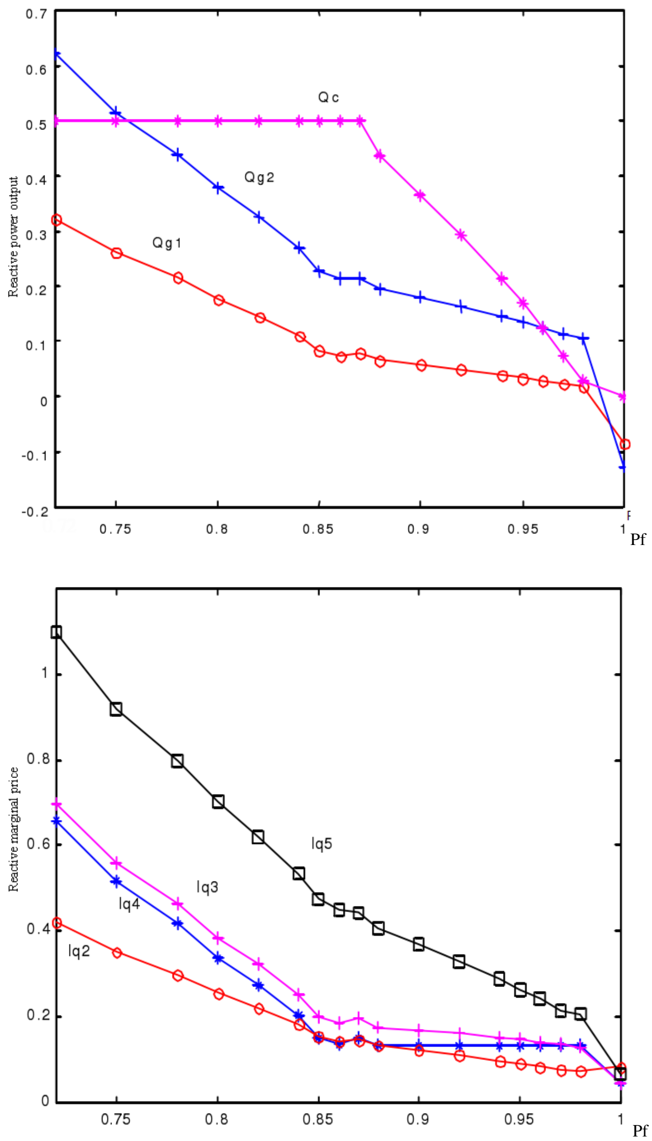


Figure 5.9 Reactive output and reactive locational marginal prices versus the variation of load power factor

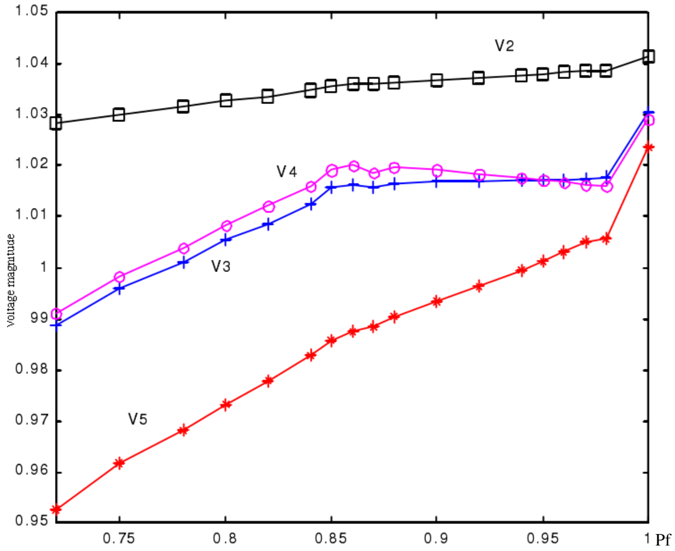


Figure 5.10 Nodal voltages versus the variation of load power factor

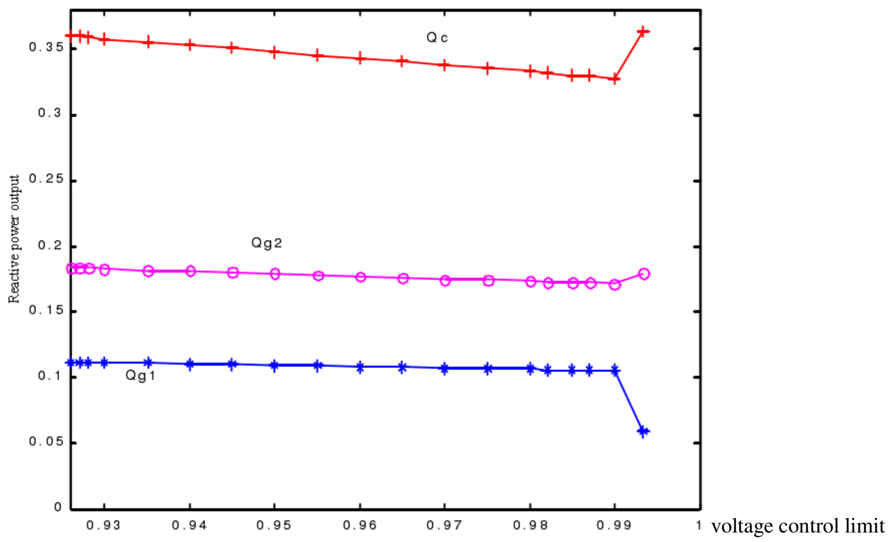
When the load power factor gradually decreases, the rise of reactive power requirement in the system led to the rises of reactive power outputs from generators and shunt capacitors, the corresponding reactive locational marginal prices also increased. However, the reactive locational marginal prices of bus where the shunt capacitors are located remains unchanged; the nodal voltages of the system drop because of the reactive power flowing in the network. When the load power factor continued to decline so that the capacitors meet its maximum output limits, the generator reactive output rapidly rises. Furthermore, reactive locational marginal prices increase more substantially and the reactive locational marginal price at the capacitor bus is no longer maintained as the same as the bidding price of capacitors while it increases with the decrease of power factor. Meanwhile, the nodal voltages rapidly drop even further to meet the voltage minimum limit (especially at heavy load Bus 5).

When the load power factor increases, because of the reduction of reactive power demand, correspondingly the reactive power outputs from generators and shunt capacitors decrease and accompanied by the increase of nodal voltages and reactive locational marginal prices reduction. When the load power factor is 1, the generator turns into leading phase operation state to absorb the excess reactive power and the shunt capacitors do not supply the reactive power to the system anymore. Meanwhile it is accompanied by a sharp rise in nodal voltages and some reactive locational marginal prices reduction.

Through the above analysis, it is found that when the load power factor is too high or too low it does not conducive to a stable economic system operation. This requires various reactive sources to be reasonablely distributed in the system and minimize the negative impact of load power factor on system operation.

5.6.5 Analyze the impact of voltage control on reactive marginal price

Since in this system the nodal voltage at Bus 5 is the lowest, so the voltage at Bus 5 is chosen as the controlled variable to evaluate the impact of voltage control on reactive locational marginal price. The voltages at Bus 5 are made to change from 0.92 p.u. to 0.993 p.u., meanwhile amends the voltage magnitude equality constraints at Bus 1 to inequality constraints between 0.95 p.u. and 1.05 p.u..



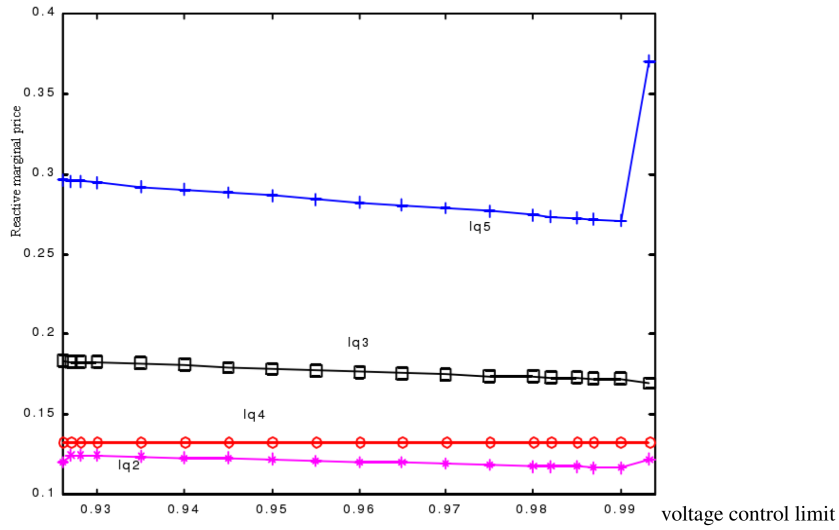


Figure 5.11 Reactive output and reactive marginal prices versus the variation of voltage magnitude on bus 5

As shown in Figure 5.12, the voltage control at Bus 5 led to the voltage variation at the other buses. In extreme cases, when a bus voltage meets its limits (i.e. Bus 1) it results in the rapid variation of reactive power outputs (Shown in Figure 5.11), correspondingly the reactive locational marginal prices dramatically change (shown in Figure 5.11) as well.

From the simulation results it is obvious that with the voltage increase of the heavily loaded bus (Bus 5) (within a certain range) the total system reactive output reduced, reactive locational marginal prices decreased and the system operated in a relatively economical condition.

It enlightens that it is necessary to install the reactive compensators in the heavily loaded area to maintain the system voltage profile in a secure and economical condition which is of benefit to the long term reactive power market development.

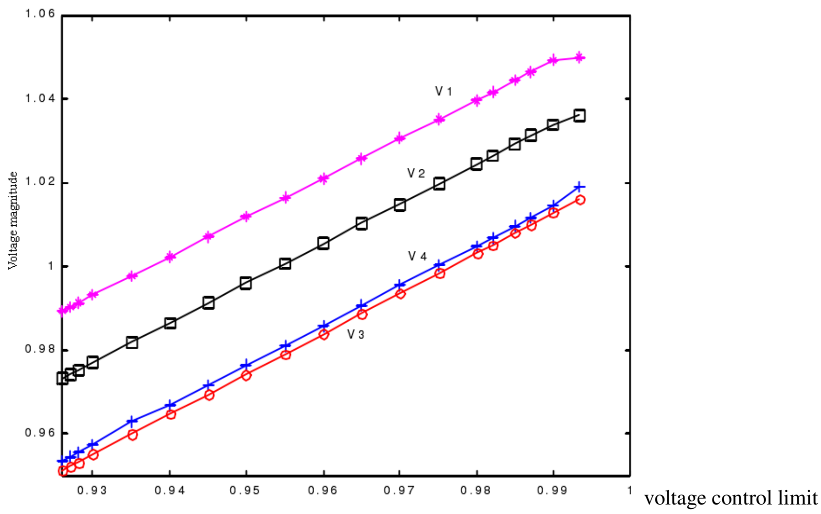


Figure 5.12 Nodal voltage magnitudes versus the variation of voltage magnitude on bus 5

5.7 Summary

In this chapter, the affects of various factors on reactive power spot price with reactive production cost considered have been assessed. As the electricity consumer competition is neglected and loads are assumed to be known from load forecasting. Taking the power flow equations as constraints, the reactive power-pricing problem becomes a typical optimal power flow (OPF) problem. In order to investigate the effects of various factors on reactive power price accurately, both reactive power production cost of generators and capital investment cost of capacitors are included in the objective function of total system operation cost. The advanced sequential quadratic programming (SQP) method is applied to solve the OPF problem and obtain reactive power marginal price AC-accordingly. The case studies of a five-bus test system show clearly the effects of various factors, such as objective function, system operation point, load power factor, profit rate and bus voltage control etc., on reactive power marginal price.

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Chapter 6

Conclusions and Future Work

6.1 Conclusions

Since deregulation has started in energy markets significantly changes and challenges have evolved. Unbundling ancillary services and opening them for competition have accompanied with very important technical and economics issues which need to be solved in order to achieve successful competitive markets. Reactive power is considered as an important ancillary service that plays crucial role in power system security and reliability. Even though every reactive power supplier in the power system may provide reactive power support, there is not a perfect procurement method for Independent System Operator (ISO) to purchase the reactive power service from all the reactive ancillary market participants considering optimizing both the technical and economical requirements. In addition, reactive power pricing issue hasn't been fully developed to the same exact as real power pricing because the reactive power costs are ignored or embedded in the electricity tariff. This is because reactive power is not the main commodity in electricity markets and the reactive power cost model of generator is not yet fully and clearly established.

Therefore, the focus of this thesis was on the objective of developing a new optimal reactive ancillary services procurement method and optimal reactive power placement method to help the ISO to purchase the reactive power ancillary services with the minimum payment within the efficient and reliable system operation condition. To price the reactive power services is another objective of this thesis and the developed reactive spot pricing method can efficiently calculate the reactive locational marginal price with the proposed opportunity cost model.

The research work done in this thesis can be divided into three main parts:

In the first part, the reactive power procurement among the reactive sources which are generators and reactive power compensators is optimized by a new method which is a compromise selection between the reactive power cost, power quality and real power losses in one multi-objective function. The optimization function which is a mixed-integer non-linear programming problem with presence of non-convexities hereby is solved by Differential Evolutionary (DE) algorithm. This optimal multi-objective reactive power procurement method offers the ISO a more practical and efficient way to procure reactive power which also takes the concerns of system reliability and economics in one objective function and search the optimal solution in globally. It is better than existing single-objective reactive power procurement methods.

The second part mainly consists of two problems.

1. The first one is the evaluation of system-wide reactive power requirement and voltage profile in the power system with wind generation. With the increasing of wind generation penetration level in the power system due to the green energy policies worldwide, different wind penetration level and dispersion significantly affects and challenges existing power system security, reliability and economics aspects. Therefore, reactive power as a critical role of in the power system security

and reliability is evaluated under this new generation pattern to present how the wind generation affects the reactive power requirement in power system.

2. On account of the evaluation in the first problem, an issue arises is that when insufficient reactive power supply in a power system with the wind generation penetration emerges, and as to how to invest in new reactive power sources becomes a big consideration. A new optimal reactive power placement method is developed in this chapter. The developed method is applied to optimize the investment of new reactive power sources (especially, shunt capacitor banks) with the solutions of new reactive power sources locating and sizing. Different from the other reactive power planning optimization methods, this new method takes into account the new reactive power sources investment costs, real power losses and power quality in one multi-objective optimization function which considers the power system technical requirement and reactive power investors' investment cost minimization requirement.

The third part is a presentation of reactive power spot pricing with the reactive power generation cost which is modelled with the proposed opportunity cost model. With the further deregulation of electricity market, the reactive power in the ancillary services market has been priced in the same manner as real power in the energy market. However, due to the natural characteristics of reactive power its costing model is difficult to establish and the model itself significantly affects the reactive power pricing results. Therefore, on account of the above two issues of reactive power spot pricing, a developed reactive power opportunity cost model is presented and to evaluate the affects of system operation condition, load power factor and real power bidding pricing on reactive locational marginal price.

6.2 Future work

This thesis contributes towards reactive power solutions on procurement, placement and pricing under ancillary services market. However, as with any research work, there is always more work that can be done. There are several possible expansions and improvements that are suggested for the methods and concepts proposed in this thesis. These include:

1. Even through the proposed methods in this thesis have been tested extensively, testing on real practical systems is still very beneficial to deal with any possible practical problems.

2. It is suggested to expand the reactive power services providers to include other sources such as FACTS devices. This considers and recognizes reactive power from these sources as ancillary services that are eligible for financial compensation in the reactive power procurement and placement schemes.

3. Investigate the contribution of wind generation to reactive locational marginal price.

4. In the power system with wind penetration, to allocate the provided reactive power, and thus its costs, to all system users including reactive power providers according to their utilization of the network.

5. Examine reactive power provision and pricing problems from the generators' viewpoint, as service providers. In other words, build optimal bidding strategies for the competitive generators to participate in reactive power ancillary services market.

Appendix

The definition and calculation of social benefit (or called global welfare) are presented as follows [1, 2]

In a competitive market, it is the combined action of all the consumers on one side and of all the suppliers on the other side that determines the price. The equilibrium price or market clearing price π^* is such that the quality that the suppliers are willing to provide is equal to quantity that the consumers wish to obtain. It is thus the solution of the following equation:

$$D\left(\pi^*\right) = S\left(\pi^*\right) \tag{1}$$

The equilibrium can also be defined in terms of the inverse demand function and the inverse supply function. The equilibrium quantity q^* is such that the consumers are willing to pay for that quantity is equal to the price that producers must receive to supply that quantity:

$$D^{-1}\left(q^*\right) = S^{-1}\left(q^*\right) \tag{2}$$

Figure A.1 illustrates these concepts as follows:

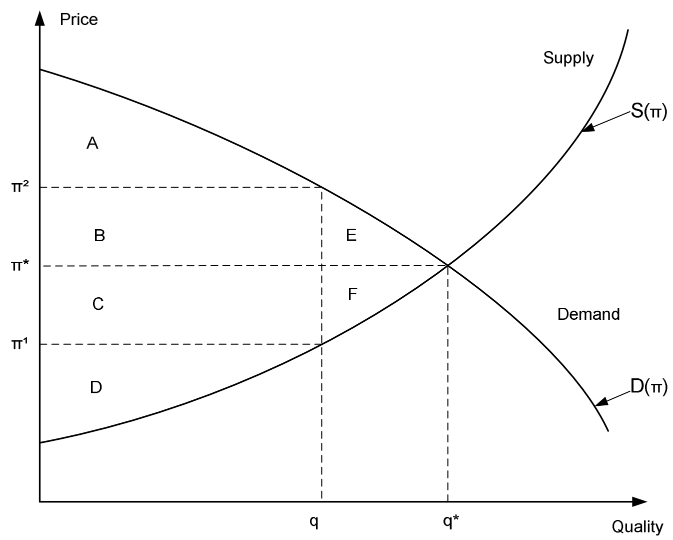

Figure A.1: Global welfare and deadweight loss

The sum of the net consumers' surplus and of the producers' profit is called the global welfare (or social benefit). It quantifies the overall benefit that arises from trading. The global welfare is maximum when a competitive market is allowed to operate freely and the price settles at the intersection of the supply and demand curves. Under these conditions, Figure 2.15 shows that the consumers' surplus is equal to the sum of the areas labelled A, B and E and the producers' profit to sum of the areas labelled C, D and F.

External intervention redistributes the global welfare in favour of the producers, the consumers or the government, respectively. Unfortunately, all these interventions have the undesirable side effect of reducing the global welfare by an amount equal to the sum of the areas labelled E and F. This drop in global welfare is called the deadweight loss and is the result of the reduction in the amount traded caused by the price distortion.

We will see in the following part that, in spot market, the price of electrical energy is set through a centralized calculation and not through the direct interaction of producers and consumers. To maximize the benefits of trading, this centralized calculation should simulate the operation of a free market by maximizing the global welfare.

Hereby, we establish consumer's demand model which reflects the demand changing with the price fluctuation through the method of adding the consumers' obtained benefit function in the Optimal Power Flow (OPF) objective function.

We assume that the consumer i demand is d_i and its demand function is $\rho_i\left(d_i\right)$; the global welfare function of consumer is $B_i\left(d_i\right)$. This consumer's Price-Demand curve is displayed in Figure A.2 as follows:

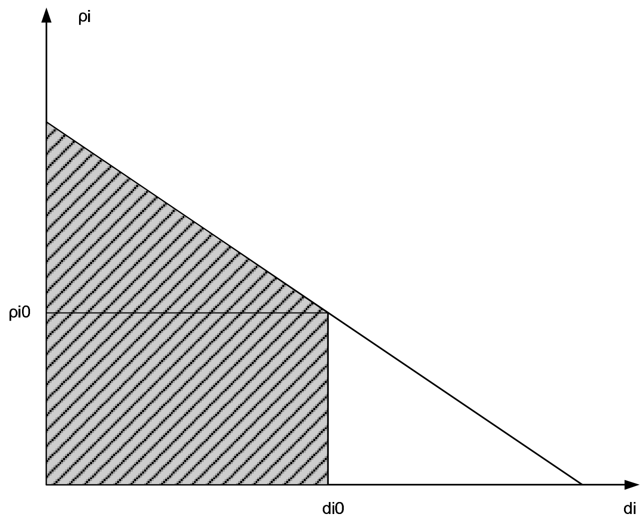

Figure A.2: Consumer's Price-Demand Curve

$$\frac{\partial B_i\left(d_i\right)}{\partial d_i}=\rho_i \tag{3}$$

Thereby,

$$B_i\left(d_i\right)=\int_0^{d_{i0}}\rho_{i0}d(d_i) \tag{4}$$

Where,

ρ_{i0} : the equilibrium price or market clearing price of consumer i;

d_{i0} : the equilibrium demand quantity of consumer i.

Therefore, when the consumer's Price-Demand function is determined the consumer's global welfare is obtained with it. The consumer's demand curve can be approximately represented in a drop linear, namely, the global welfare function is a quadratic curves. And the consumer's demand can be imitated with other functions as required.

After considering the consumer's demand curve, OPF objective function is the maximization of the global welfare shown in as follows:

$$\min f=\sum_{i\in N}\left[C_{Gpi}\left(P_{Gi}\right)+C_{Gqi}\left(Q_{Gi}\right)\right]-\sum_{i\in N}B_i(P_{Di},Q_{Di}) \tag{5}$$

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