

**How to make Electric Power Markets Work: the Case of Central America.**

by

José Federico Castillo Martínez

Ingeniero Físico Industrial, 1992

Instituto Tecnológico y de Estudios Superiores de Monterrey, Campus Monterrey.

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Author.....  
Department of Civil and Environmental Engineering  
May 19, 1997

Certified by.....  
/ /  
Dr. Marija Ilic  
Senior Research Scientist  
Thesis Supervisor

Accepted by.....  
/ A  
Dr. Richard L. de Neufville  
Technology and Policy Program

Accepted by.....  
Dr. Joseph M. Sussman  
Chairman, Departmental Committee on Graduate Studies  
Department of ~~Civil and Environmental Engineering~~

Accepted by.....  
Dr. Arthur C. Smith  
Chairman, Department Committee on Graduate Students  
Department of Electrical Engineering and Computer Science

MASSACHUSETTS INSTITUTE  
OF TECHNOLOGY

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## **Abstract**

A new regulatory framework was signed in December of 1996 by the Presidents of Central America. The objective of the treaty is the gradual transition to a regional competitive market for electricity. At the same time each country by itself is changing the structure of their local power sector. However, although following the same philosophy of competitive electricity markets, the local structures will not necessarily be the same.

Recommendations are given on how to set up a market at the regional level, allowing each country the flexibility of deciding what the local structure will be but grasping most of the potential benefits that can be derived from integration. These take into account the political environment of the region and the issues of sovereignty and unequal benefits that have caused disruptions in the past. The different industry structures and competitive models are analyzed and their suitability for implementation in the Central American region is considered.

This thesis contributes to the ongoing research on competitive power markets, by considering a market mechanism (auction) to solve transmission congestion problems in this particular market setting, where generators attach a bid to their contract and access is determined on a merit order of such bids. The mechanism is based on an initiative suggested to be implemented in El Salvador. It is proven that such a mechanism leads to a collusive behavior among generators, leading to an unequal distribution of benefits where consumers are left with the short end of the stick, even though the market is considered efficient in a competitive sense.

Thesis Supervisor: Dr. Marija Ilic  
Title: Senior Research Scientist

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# Chapter 1

## Introduction

### 1.1 Background

The electric utility industry is undergoing dramatic changes all over the world. These changes take place in industry structure, ownership form, and the role of regulatory institutions. Similar changes have taken place in the telecommunications and natural gas transportation industries. The common denominator of all these industries is that they have been traditionally regarded as “natural” monopolies due to the economies of scale associated with their cost structures. The perception is that these industries can be restructured, disintegrated or reorganized to introduce competition in those segments which may be regarded as competitive, that regulation can be reformed in residual monopoly segments, and that the industry overall can be made more efficient.

In some countries like Chile, Argentina, England and Wales, Norway, New Zealand and Australia, the face of the electricity sector has been changed drastically during the last decade. In the United States, the change has been much slower but some regions are taking major steps that will accelerate the process.

In the midst of all these reforms, the countries of Central America find themselves in a crossroads, where they have to make decisions that will have a great impact on the future of their electric industries. Furthermore, they have adopted as a strategy to integrate their energy markets into a regional market, in order to take advantage of economies of scale and non-coincident peak demands for electricity, as well as optimize the use of the natural resources of the region.

A new regulatory framework was signed by the Presidents of Central America under the “Tratado Marco del Mercado Eléctrico de América Central” (TMEAC), Framework Treaty for the Electric Market of Central America. The objective of the treaty is the gradual transition to a regional competitive market for electricity.

However, at the same time that TMEAC negotiations were underway, each country by itself was introducing reforms into their local power sectors. Among them, El Salvador has launched what seems the most ambitious privatization and deregulation initiative in the region, in regard to its reliance on market mechanisms to establish a local competitive market, which is scheduled to begin operations on November this year. The rest of the countries are following structural changes of their own, although in some are still debating the extent and time frame in which these changes are to take place. Although they are all following the same philosophy of competitive electricity markets, the local structures will not necessarily be the same.

This transition from a vertically integrated monopolistic structure of electric utilities to a disintegrated structure, where efficiency is achieved through competition, imposes many changes in power systems operations and planning. If the Central American countries want to grasp the economic benefits of integration, then efficient operation and planning, similar to what a centralized authority operating the system can achieve, must be met. For these new electric power markets to work in an efficient fashion, the transactions involved must reflect the actual costs of power transfer, whether they are in the form of bilateral contracts or in spot market transactions.

## **1.2 Contributions**

The TMEAC contemplates the creation of institutions that will operate and regulate the market, and which will define later the rules of the game. Beyond that, it only goes as far as establishing the requirement of disintegration of generation and transmission in each of the member countries. The TMEAC does not seem to capture the changes that the individual countries are introducing by themselves.

The purpose of this thesis is thus to issue recommendations on how to set up a market at the regional level, allowing each country the flexibility of deciding what the local structure will be but grasping most of the potential benefits that can be derived from integration.

The recommendation is based considering the political environment of the region and the issues of sovereignty and unequal benefits that have caused

disruptions in the past. The different industry structures and competitive models are analyzed and their suitability for implementation in the Central American region is considered.

Furthermore, the thesis contributes to the ongoing research on competitive power markets, by considering a market mechanism (auction) to solve congestion problems in this particular market setting. The mechanism is based on an initiative suggested to be implemented in El Salvador. It is proven that such a mechanism leads to a collusive behavior among generators, leading to an unequal distribution of benefits where consumers are left with the short end of the stick, even though the market is considered efficient in a competitive sense.

Based on work by Ilic, where it is shown that the profit allocation of the participants will be sensitive to the policies and protocols adopted to handle the externalities which characterize power markets, policy recommendations are outlined which may allocate these profits in a more equitable fashion (Ilic 1997).

Considerations are also given on the problems of allocation of transmission losses and the management of ancillary services, based on state of the art research on these subjects.

The thesis draws on the experiences of deregulated markets such as the UK, Argentina, Norway and New Zealand and the latest research on these topics.

## **1.3 Outline**

This thesis is organized as follows:

In Chapter 2, the political environment of the region is considered in terms of its history and present trends. Integration efforts are reviewed as well as its relevance for a regional electricity market. The economic benefits of electric integration and criteria for the regional regulatory framework are analyzed.

In Chapter 3, the different possibilities of market structures in a competitive electric industry are discussed and the different dimension of the changes that can take place described. The case of each particular country is considered as well as its impact on a regional market.

In Chapter 4, the technical characteristics of power systems operation are presented with special emphasis on those aspects which make power systems

different from other networks and which complicate any regulation intended for the sector.

In Chapter 5, the economics of power systems are considered. First, the economics of individual plants and consumers are described and then their interaction over the network. Important issues of externalities are considered and different approaches for correcting these market failures discussed.

In Chapter 6, a particular proposal for handling the externalities of congestion constraints through a bidding system is considered. It is proven that important modifications to it are needed to obtain the results it was expected to have.

In Chapter 7, qualitative conclusions are drawn based on the results obtained from the models considered. Policy recommendations are made as to how to organize the regional competitive market for electricity in a way that the objectives of integration are achieved.

## **Chapter 2**

### **The integration of the electricity markets**

The economic integration of the Central American region is unique in the sense that it represents the integration of countries which at one time had formed a single country, and to the extent that it could be viewed as the continuation of the goal of Central American unity. However, it is not the first time that the countries have attempted to come closer to each other, since there have been many efforts of cooperation and integration in the past. It is important then to understand the differences existent in the region to assess the possibility that this time the agreements will not collapse.

This chapter discusses briefly the previous integration efforts of the region, as well as the new strategy of cooperation. It goes on to analyze where the economic benefits from the integration come from, in particular for the case at hand, the electric sector.

#### **2.1 Previous integration efforts in Central America**

##### **2.1.1 A federation of Central American States.**

The Central America republics were not always independent nations. Before joint independence in 1821, the region was administered as a whole by Spain. In 1821, the United Provinces of Central America were formed, and it was not until 1838 that the different states were allowed to go their separate ways. Panama achieved its independence separately in 1903. (Woodward, 1995)

After this year, there have been several attempts to achieve integration in the form of a federation of states, which have been unsuccessful. These attempts range from military actions in 1841 and 1888 to actual attempts of joint cooperation in 1917 and 1921. After World War II, integration efforts changed strategies to one of increased cooperation among the countries. This led to the formation of the

Organization of Central American States (ODECA) in 1951 and the Central American Common Market (CACM) in 1958, motivated largely by the example of early integration efforts of the European Community (EC).

### **2.1.2 Politics of Unequal Benefits**

On its initial years of operation, the CACM relied extensively on the free operation of market forces (once internal barriers were down and a protected market created). However, the result was an unequal distribution of economic benefits, favoring the more industrial members Guatemala, El Salvador and Costa Rica. These differences led to a series of crises in the CACM beginning in 1965, when Honduras demanded special benefits because it began to experience a significant trade deficit. (Fagan, 1970)

The region was characterized by reasonable rates of economic growth in the early seventies, in part by high commodity prices, which are the main exports of the region. However, the benefits derived from this growth did not reach the overall population. These and other problems lead to the conflicts in Nicaragua and El Salvador, sinking the region in a decade of stagnation and negative growth. (Irvin, 1989)

By the mid eighties the CACM was virtually non-existent, and the thought of integration seemed most unlikely, due to the diversity of ideologies in the region. These ranged from the communist government of Nicaragua, to the military influence in El Salvador and Honduras, contrasted by the democracy of Costa Rica. However, during the nineties political stability came to the region, as democratic governments ruled in all of the countries. A common neo-liberal philosophy is characterizing the political arena, which is shared by all the governments in turn.

### **2.1.3 Present Economic Integration Effort**

Encouraged by international institutions and the threat of being left out of the globalization trends, the countries are coordinating economic policy, reducing trade barriers, harmonizing capital markets and developing infrastructure jointly in an attempt to grasp economies of scale.

However, potential obstacles remain. Among these are disputes over borders, unpaid commercial debts, and perceived threats to sovereignty as well as conservative economic interests.

In contrast to previous integration efforts, which implied the protection of local industries from foreign competition, the new organization is open and export oriented. As such, the countries are negotiating jointly free trade agreements with Mexico, the MERCOSUR, the Caribbean countries and the United States.

Interregional trade has risen from 650 million dollars to 1.6 billion in 1996. At this date, Central America has a population of 32 million people and a combined GNP of 43 billion dollars in 1996, close to the level of economies the size of Chile and Peru. (Walzer, 1997)

## **2.2 Integration of Electricity Markets**

Most countries around the world are becoming increasingly electric intensive, and their economic growth depends on the availability of adequate and reliable generating capacity. However, the large capital outlays required to finance electricity capacity are a severe constraint in developing nations, making it difficult to overcome the operational inefficiencies under which their electric power system operates.

To face these issues, the countries of Central America have adopted as a strategy to integrate their energy markets into a regional market. They attempt to grasp significant economies of scale of large projects developing them jointly, and to achieve savings from a coordinated operation of the systems taking advantage of non-coincident peak demands for electricity.

With this in mind the Presidents of Central America signed on December 30 of last year the TMEAC. Of particular interest is the objective of the treaty to gradually move towards a regional competitive market for electricity.

The electrical systems of the Central American countries are currently linked by 230 kV weak border interconnections (tie-lines), forming two separated subsystems. The first one includes Guatemala and El Salvador, and the other one comprises Honduras, Nicaragua, Costa Rica and Panama. As a consequence unrestricted energy exchanges are not possible.

The Interamerican Development Bank (IDB) will provide a loan which will finance a new 230 kV transmission line 1,802 kilometers long from Panama to Guatemala. Work is underway by the Council for the Electrification of Central America (CEAC) and the electric utilities of each country to establish the legal mechanisms for the consolidation of the regional network. The interconnection between El Salvador and Honduras is also under study as a separate project and may be also built in parallel to the so called backbone of the power system. (IIT, 1996a).

### 2.3 The economic benefits of integration

As mentioned before, the goal of the Central American countries through the TMEAC is to grasp economies of scale of large projects and to achieve a regional coordination and planning of resources to meet overall demand, thus achieving substantial economic benefits.

As can be seen from Table 2.1, almost 60% of all installed generation capacity is hydro. The region is characterized by a wet and a dry season throughout the year. Adequate planning is required to have enough water in the reservoirs to keep the lights on during the dry season. Coordinated planning of the use of the reservoirs can bring reduced risks of shortages due to droughts as well as optimal use of this low cost electricity source.

Table 2.1 Installed Generation Capacity by 1996

	Guatemala	El Salvador	Honduras	Nicaragua	Costa Rica	Panama	Totals
Thermal	443	414	232	234	314	279	1916
Hydro	493	388	431.5	94	824	540	2770.5
Total	936	802	663.5	328	1138	819	4686.5

*Source: SIEPAC Data Base 1/10/96 (IIT, 1996b)*

Non-coincident peaks of demand are also a source of economic benefits. The most dominant of these is the case of Panama, which does not have a 6 p.m. load peak like the other countries, because in Panama cooking technology is mostly gas rather than electricity. Their peak load falls usually between 11 a.m. and 2 p.m. There is also less evening air conditioning in Panama.



As mentioned above, economic benefits can also be derived by capturing the economies of scale of large projects, which may bring cheaper electricity. In the region there is still a large potential for using hydro as a source of energy, estimated to be around 50 GW, of which only 3 GW are currently developed. (Moscote, 1994). Among the range of hydro projects being considered the largest are El Tigre of 704 MW in El Salvador (shared with Honduras), Patuca II of 713 MW in Honduras, as well as Siquirres of 412 MW and Gran Boruca of 1,520 MW, both in Costa Rica. These are projects too large for each individual country to undertake them for local demand, but a regional market may have room for such mega-projects.

The CEAC has been working closely with the Instituto de Investigación Tecnológica (IIT) of Spain to simulate the coordinated operation and planning of the Central American power sectors. Some preliminary results show that there are substantial economic benefits to be derived from the integration. (IIT, 1996a).

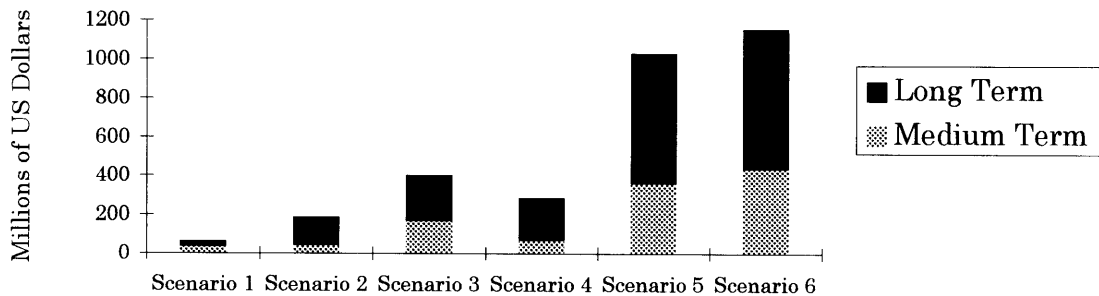
In their studies, IIT compared different scenarios in which the countries coordinated operations and planning in different degrees and subject to different expectations of demand growth. A brief description of these scenarios is given in Table 2.2.

Table 2.2 Description of scenarios of different levels of coordination.

No.	Scenario Description	Demand Growth
0	Base Scenario: Individual planning and operation of the subsystems.	High/Low.
1	Individual planning, moderate coordination in operations.	Low
2	Moderate coordination in long-term planning and operations.	Low
3	Moderate coordination in long-term planning and operations.	High
4	Moderate coordination in planning and operations.	Low
5	Increasing coordination in planning and operations until reaching full coordination in 2010.	High
6	Full coordination in planning and operations.	High

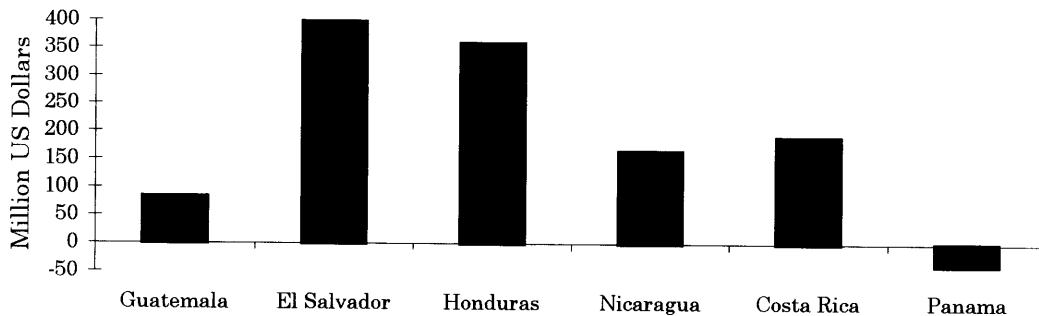
For each of these scenarios, they determined an optimal expansion plan for the region as a whole, minimizing the sum of investment and operating costs. Dynamic programming algorithms were used to determine the optimal use of water reservoirs. The net present value of the expected savings for the region as a whole are presented in Figure 2.1, where each amount represents the difference in investment and operating costs between that particular scenario and the base scenario.

Figure 2.1 Net Present Value of Savings from Electric Integration under different scenarios.



The results indicate that there are economic benefits to be gained from coordination, and that they are higher for increased levels of cooperation and expectations of demand.

Figure 2.2 Net present value of savings from full coordination of planning and operations for each country.



However, as may be expected, the benefits from such cooperation are not incurred evenly among the participants. Figure 2.2 shows the net present value of the savings from full coordination (Scenario 6) for each country. These represent the

differences with the base scenario where there is no cooperation, and reflect the costs associated with each subsystem.

All countries in the region experience benefits, except Panama which incurs in greater expenses, because of the extra energy it generates as it becomes the main exporter of electricity. Figures 2.3 and 2.4 show the installed capacity and generated energy per country respectively, as a percentage difference from the base scenario. The countries with more expensive generation options do not take them; instead they become importers of electricity gaining high savings.

Figure 2.3 Difference in installed capacity per country assuming full cooperation and high demand.

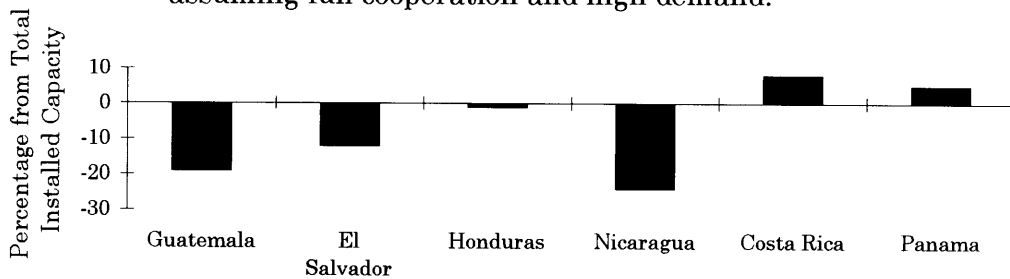
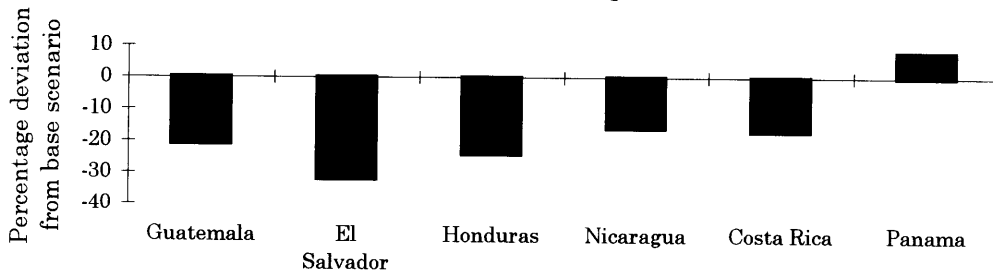


Figure 2.4 Difference in generated energy per country assuming full cooperation and high demand.



## 2.4 Unequal benefits and sovereignty

The analysis performed by IIT assumes that under coordinated planning, the subsystem where a particular generating plant may be built will see its investment and operating costs rise in an individual fashion. However, a share of that cost should be distributed among all the neighbors which will share that plant, either by sharing the investment costs or by means of purchasing contracts for the energy

produced by the plant. This also applies to the generated energy, since a country is imputed the costs of all the generation inside its borders. To actual net cost is the cost of generation plus the cost of imports, minus the income from exports. A later stage of the IIT study will determine these net benefits for each subsystem, from where the countries will be able to consider how the benefits from integration are allocated among the countries.

After some time under an integrated electric market, some of the countries will find themselves with not enough installed capacity within their borders to meet their local demand, which may be perceived as a threat to national sovereignty. On the other hand, the countries that have the excess capacity will find themselves in the position of having significant stranded investment costs if the countries that where expected to buy that electricity do not do so. These issues can not be discarded and must be deeply considered, since the region has been characterized by several conflicts throughout their history.<sup>1</sup>

There are also some indirect benefits and problems which may be of importance and should be taken into account, such as the environmental impact of the power plants and the creation of jobs.

It must also be kept in mind that the fragmentation of Central America, when the short lived federation broke up, has contributed to the fact that each of the countries has resigned itself historically to having scanty margin of action with regard to its own fate, due to the preponderance of factors beyond their control. A unified Central America can improve the economic and political sovereignty that the region strives for.

## **2.5 Conclusions**

The objective of this thesis is to issue recommendations to policy makers in the region that are currently working in the design of new regulation, protocols and mechanisms for the operation of the regional market and the transition period. At this point, it is important to point out the main criteria under which any proposal must be assessed and its appropriateness evaluated.

---

<sup>1</sup> The last international conflict the region has seen was the war between El Salvador and Honduras in 1969, the so called "Soccer War".

- *Economically Efficient.* This is the first and most important goal of the system. If the creation of a regional market brings higher costs and higher prices to consumers then it is doomed to failure.
- *Respectful of national sovereignties.* The new institutions created for the regulation and operation of the regional market will stand above all the countries in the sense that they will be multinational agencies. However, the power these institutions will exert on each country must not be deemed unreasonable by any of the countries. For this purpose, efficient regulation of the multinational agencies as well as a transparent operation mechanism must be implemented, so the possibility of any conflict is minimized. At the same time, the legal framework on which contracts will be based, either for the purchase and sale of power or for joint investments in the development of the “mega-projects”, needs to be enforceable.
- *Equal/Fair distribution of benefits.* Given the political history of the region and the previous integration efforts it is clear that any collaboration has to be a win-win situation. If one of the countries finds itself not deriving the benefits it was expected to receive the treaty may falter. Even more so, small benefits may not be enough if some of the neighbors are seeing larger benefits on a relative scale.

## Chapter 3

### Market Structure

Perhaps the most interesting characteristic of the TMEAC is that it states that the electric integration will be achieved through the means of a *competitive* electric market. The economic benefits to integration described in the previous chapter assume centralized planning of resources. The trend is also for increased private sector participation and less government provision of electric services. As mentioned earlier, each of the Central American countries is pursuing changes to their local electric industries at the same time that they will be trying to establish the regional competitive market.

This chapter analyzes the different forms of ownership and management as well as the different models of a competitive electricity industry to understand where each of the countries stand. The structure proposed by the TMEAC is analyzed and potential problems recognized. Recommendations are outlined as to which of these structures and models is the most suitable for a regional operation of the Central American electricity market.

#### 3.1 Motivation for a policy change

The electric power sector is characterized by the existence of technical or natural monopolies, due to economies of scale. In such an industry, the largest player has the lowest cost and will eventually capture the whole market. It will then be able to mark up prices substantially maximizing its profits. This outcome is not socially desirable because of the economic waste caused associated with this pricing behavior. (Pindyck, 1995). Government intervention is required to prevent this either by imposing price regulation or direct control of the industry.

The traditional view in most Latin American countries has been that this requires public production and financing. However, the resulting reliance on public

monopolies led to a focus on centralized planning of investments, rather than on ensuring that the services to be provided from the facilities would be sustainable and responsive to changing demands. It also led to politicizing and inefficient pricing of public utilities and poorly targeted subsidies that have further contributed to patterns of demand that in many cases have been harmful to the environment, and reduced the access of the poor to an acceptable level of service.

The relative emphasis of public sector entities on new investment has also been a major factor in the apparent lack of attention to proper maintenance of existent facilities. The latter consequence completes the vicious circle of inadequate operations and maintenance, poor quality of service, low cost recovery, deterioration of existing assets, and ever increasing investment needs solely for their replacement. (Moscote, 1994). Furthermore, transmission lines and substations were often targets of sabotages by guerrilla groups.

To make face to these challenges, major policy changes have been undertaken. These respond to recent thinking and developments that have revealed a broader range of alternatives for public and private involvement in the power sector.

Recent advances in telecommunications and computing make room for the possibility of going back to the basic principles of economics and engineering and by viewing the utility and its customers as a single integrated system.

## **3.2 Different dimensions of changes**

All over the world, governments and regulators are considering changes in their electric industries. Mostly their aim is to increase efficiency through better investment decisions, better uses of existing plants, better management and better choices for customers.

The changes considered have different dimensions. Some of these are in the realm of ownership, such as privatization. Others are in the realm of industry structure, whether vertically integrated or disintegrated. Even under the acknowledgment that a competitive market structure should be in place, there are different ways to go about it. In what follows the different forms and levels each of

these dimensions has is briefly outlined, based on (Tenenbaum, 1992), (Hunt, 1996) and (Joskow, 1983).

### **3.2.1 Ownership and Management Forms**

Many of the changes taking place in the electricity industry worldwide are changes in ownership and management. These changes are concerned with bringing economic rigor to operations and planning and remove any political influence that these may bear. The ownership dimension can be appropriately divided into three levels.

In some countries, the electric utility industry is a government department, with no separate accounts, and often with responsibilities that are only remotely connected to electricity production (such as providing housing and schools for employees). The industry is viewed as “infrastructure”. This is the case in China at present.

The next level is a distinct government-owned company, or nationalized industry. Government is one step away from day to day control, whereas a board of directors sets goals and chooses management to achieve them. The organization is still required to carry out government policies in support of supplying industries, but is under some obligation to show a profit from its activities. This is the case with Electricité de France (EDF) in France at present and the traditional form of utility management in Central America.

The third level is a privately owned industry as it exists in the United States and now in other parts of the world. These companies are expected to make profits for their shareholders. These companies are generally regulated by an independent regulator.

Commercialization, corporatisation, nationalization and privatization are common terms associated with changes from one level to another in the dimension of ownership.

### **3.2.2 Four industry models**

There are four basic ways in which an electric industry may be structured, defined by the degree of competition.



The first model consists of the traditional monopoly at all levels. A single company handles the production of electricity and its delivery over the transmission network to distribution companies and/or final consumers. Almost all countries had this form of organization up to 1980, and most still do. Italy and Japan follow this model. Until recently, this was the model adopted by most of the Central American countries.

The second model is usually called a “purchasing agency”. A monopsony buyer, the purchasing agency, chooses from a number of different generators for supply, encouraging competition in generation. The same agency has a monopoly on the transmission network and over sales to final consumers. Northern Ireland introduced such a model in 1992. The Spanish system, although it is complicated by financial compensations between separate companies is in essence this model. The U.S. adopted a variant of this model since 1978, when the Public Utility Regulatory Policy Act (PURPA) was introduced, which allowed the operation of Independent Power Producers (IPPs).

The third model is that of wholesale competition. This allows distribution companies to buy directly from a producer and deliver over a transmission network. Distributors still have a monopoly over final consumers. There is open access to transmission wires. In the U.S. “wholesale wheeling” was permitted by the Energy Policy Act of 1992 (EPAct), which allowed separate distribution companies to choose their suppliers. However, these do not account for a high proportion of the demand since most utilities are vertically integrated.

The fourth model is that of retail competition. It allows consumers to choose their supplier. There is open access to transmission and distribution wires. The distribution (delivery) is separate from the retail activity, which is competitive. Although the EPAct specifically prohibited the federal authorities from ordering a move to retail competition some states have taken steps to introduce it as in California. The UK, Norway, Chile, Argentina and Victoria in Australia have systems that are similar to this model.

### **3.2.3 Competitive market structure**

Of central importance is the consideration of a centralized versus a decentralized decision making structure for the market of electricity. The main difference between the proposals is the dominance of either of two paradigms. One is that for markets to be efficient, centralized optimization of resources needs to be made. The other considers that in a competitive market the invisible forces of supply and demand will drive the system toward its social optimum where maximum efficiency is obtained. However, both approaches do recognize a new environment for trading electricity by acknowledging that electricity is a commodity, that it has a market price, and that the thing transported (electricity as a product) is a separate thing from the transportation itself (transmission and distribution as a service).

There are basically three ways in which a competitive market structure has been proposed to be set up, and each of them is discussed briefly below.

#### **3.2.3.1 Pooling**

Under the optimization paradigm, it is necessary that all players submit bids for supply and demand of electricity to an Independent System Operator (ISO). This structure is often referred to as the “Poolco” structure, currently in place in the United Kingdom. Transactions are scheduled according to price bids in a merit order basis, that is, the least expensive bids are dispatched first and so on until demand is met. In the margin, only one unit is partially used and its bid determines the energy clearing price which is paid to all units, disregarding how much lower were the actual bids of each unit. The ISO optimizes the dispatch taking into consideration all the constraints on the system that must be met to insure system reliability and security.

#### **3.2.3.2 Bilateral**

This approach is based on the observation of most commodity markets, in which producers, wholesalers and retailers engage in trades of the product (electricity) and pay for transport (transmission) as they go, as well as for distribution chains (distribution wires). If the trading system is set up to accommodate bilateral energy trades, it is argued that competition will ensure that

arbitrage and entry to the market will push the market price for all these services to the competitive level, of maximum efficiency and social welfare.

In such a structure there is still the need for an ISO, which has the sole responsibility of insuring system reliability and security. For this purpose, an ISO may not allow some transactions that violate system constraints.

Although there are no entirely bilateral markets currently in operation, in Norway 85% of all physical trades are handled by this type of agreements. (London Economics, 1997)

### **3.2.3.3 Hybrid**

It is possible to have a mixture of a bid-based pool structure and a bilateral contract market, which is sometimes denoted as the hybrid structure. Under such a structure participants may engage in transactions which must be reported to the ISO, usually without any financial information. At the same time, the ISO collects bids to develop a merit order dispatch of participants not engaged in bilateral trades. The ISO is responsible of system reliability and security. This is the structure under strong consideration in many parts of the United States and also in some of the Central American countries.

It is hard for the industry to rely on a spot market or entirely bilateral transactions for a variety of reasons. Traders prefer to balance their portfolios and to secure their cash flows and thus engage in long term contracts. Spot markets, on the other hand may define the price for uncontracted electricity flows, and settle the imbalances present in the system in real time.

## **3.3 The case of the Central American countries**

Each of the countries in the isthmus is considering changes on most of the dimensions outlined above. In some of the countries legislation has been passed, like in El Salvador where the spot market is expected to begin to work next November. Other countries are still debating the issue, especially Costa Rica where the welfare state model had grown strong roots and it is having trouble selling valuable publicly owned assets and its possible negative impact on employment.

A brief overview of the changes taking place is given below, and is further depicted in the matrix of Figure 3.1.

### **3.3.1 El Salvador**

Legislation to change the sector was passed last year which outlined the disintegration of CEL (Comisión Ejecutiva Hidroeléctica), the country's government owned electric utility monopoly into generation, transmission and distribution activities. At the same time all of these will be privatized and there will be open access to transmission and distribution.

Two markets will operate: a contract market, in which quantities are revealed to an ISO without any price or cost related information; and a spot market, in which generators will present bids of energy and its prices to the ISO as it is offered for sale, and buyers submit bids for the purchase of electricity specifying amounts and prices. The spot market is expected to be small and work mostly as a regulator of system imbalances. (El Salvador, 1996)

### **3.3.2 Guatemala**

A new model was recently approved by the legislature and it is very similar to the one of El Salvador. It is based on open access to transmission and distribution wires by means of regulated fares. There will be a contract and a spot market, but the merit order dispatch will be based on costs. There will be an ISO and separately a market operator.

Currently generators have the obligation of serving native load before exporting, but this mechanism is under revision to facilitate power exchanges with the rest of the countries.

The distribution company will be broken up into smaller companies, as well as the state owned INDE (Instituto Nacional de Electricidad) into several generation companies, one transmission company and the ISO.

It is not clear at this moment how will contracts established with IPPs previous to the new regulation will be incorporated. (Ajanel, 1997)

### **3.3.3 Honduras**

The legal framework was changed three years ago, in which the ENEE (Empresa Nacional de Energía Eléctrica) monopoly on energy was removed by allowing private participation in the generation and sale of energy. Tariff setting was also removed from the monopoly and moved to a regulatory agency.

However, up to date the sector is still working as it had in the past, while the ENEE continues subscribing long term contracts with IPPs.

### **3.3.4 Nicaragua**

A new electricity law was passed three years ago, in which from the INE (Instituto Nicaragüense de Electricidad) was extracted a new company which acquired the responsibilities of production and sale of energy. INE retained the functions of planning and regulation.

The model of the market is very similar to the Chilean model, with wide regulation on behalf of the INE. To the present, there is no private participation of importance, except for some long term contracts of ENEL with IPPs.

### **3.3.5 Costa Rica**

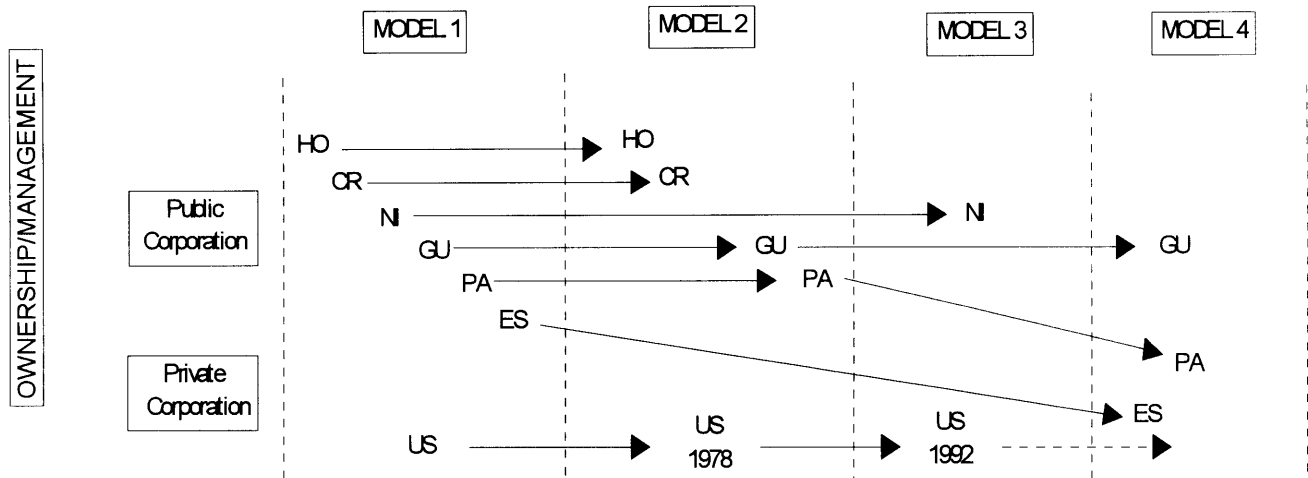
The monopoly structure is still in place through the ICE (Instituto Costarricense de Electricidad) which also handles all telecommunications for the country. At present, the effort to change the structure is to separate the electricity and telecommunications activities into separate companies.

The entrance of IPPs was authorized up to 30 MW, but they have to sell all their power to ICE.

### **3.3.6 Panama**

The model is similar to that of Guatemala. Its main difference is that the new law involves a process of privatization of the state owned IRHE (Instituto de Recursos Hidráulicos y Electrificación), within 20 months of having approved the law. The law also contemplates a transitory period in which special regulation will be in action for the dispatch and the newly formed transmission company.

Figure 3.1 Ownership vs. Industry Structure Matrix



### 3.4 A structure for the Central American power market

#### 3.4.1 The proposal of the TMEAC

The TMEAC contains an agreement for the gradual creation of a competitive market of electricity. The treaty contemplates the creation of three organisms, the Empresa Proprietaria de la Red (EPR), the Ente Operador Regional (EOR) and the Comisión Regional de Interconexión Eléctrica (CRIE). (TMEAC, 1996)

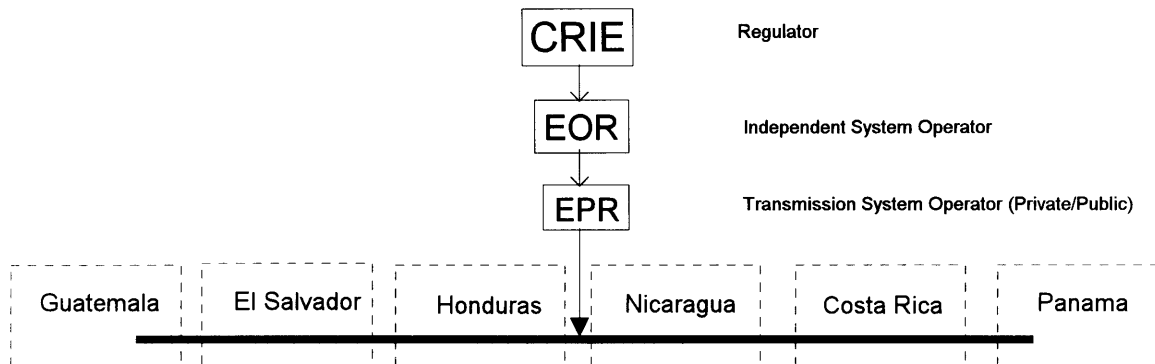
The EPR will be the builder, owner and operator of the interconnected network, that is, the transmission lines which will enable the countries to exchange power. Ownership will be divided among public entities of all the countries, but private participation is encouraged.

The EOR will act as the regional system operator (ISO), and it is here where all coordination will take place. Its board of directors will have two members from each country appointed by their respective governments. Its objective will be to insure a regional economic dispatch and to maintain system reliability. It will also

be in charge of providing an indicative optimal generation and transmission expansion plan for the region.

The CRIE will be a regulatory agency, in charge of promoting competition by discouraging market power and approving all methodologies and protocols under which the EOR and EPR will operate.

Figure 3.2 The regional industry structure



### 3.4.2 Problems with this proposal

Clearly the idea behind the TMEAC is a fully centralized operation of the regional power system by the EOR (ISO). Notice that this is a change from the present structure in all the countries, since optimization is performed on a subsystem basis, but most importantly it is against some of the reforms being introduced. In El Salvador, for example, the new law indicates that the financial terms of bilateral contracts need not be made public.

If the EOR is to retain the responsibility of achieving system wide efficiency then all the financial information of the transactions must be made public and available. A disclosure only for the eyes of the EOR will not be sufficient because of the transparency requirement and audit procedures needed for the surveillance of this institution. This implies that the regional structure must be based on the pooling model described in section 3.2.3.1. If this requirement is not met then the EOR *cannot* be held accountable for overall efficiency of the system, and its role can only be seen as one of facilitator of market transactions, more into the role of the ISO that is required to make the operation of a bilateral or hybrid market feasible. It has also been argued that the audit and regulation mechanism that must be in

place, may prove to be too expensive to monitor and implement if actual performance criteria can be agreed upon.

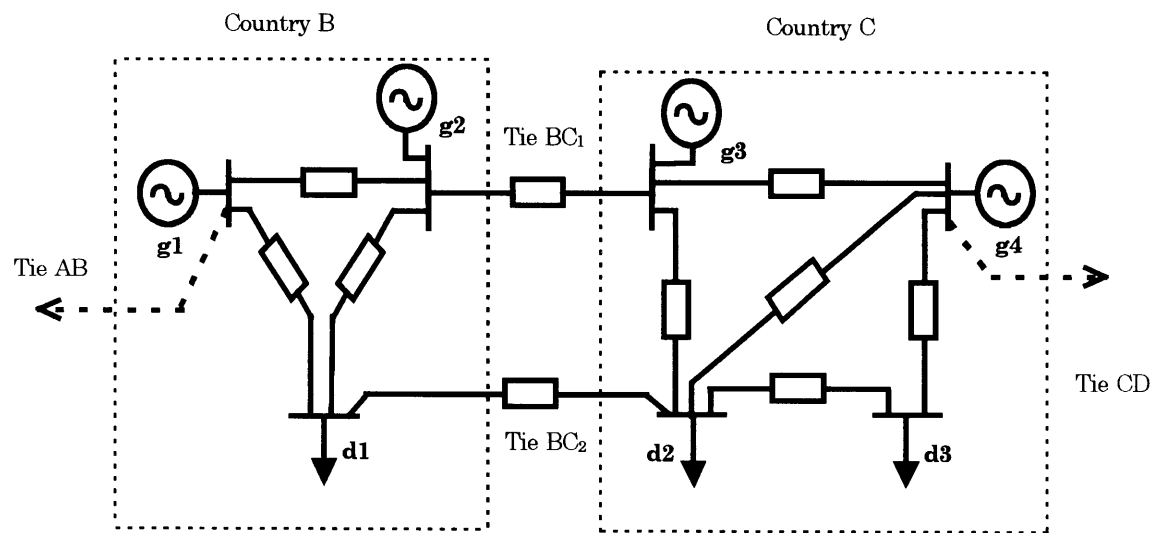
It is clear that a drastic implementation of the TMEAC would bring tension on the issues of sovereignty raised in the previous chapter, so it seems unlikely that such a mechanism will be imposed in the short term. Even more so, it may not be needed as there are alternatives that may achieve the same objectives.

### 3.4.3 The option of bilateral contracts.

Through the interconnections already present in the region, the countries of Central America have been exchanging power for some time, and these trades have usually been in the form of bilateral contracts. However, there have been restrictions on transmission and trade barriers that have not allowed the countries to enjoy the full potential of cooperation.

With the construction of the transmission “backbone” the links between the countries will be strengthened, making increased trading of electricity feasible in a technical sense. Furthermore, the TMEAC sets the stage for an increased interaction of the energy markets, even when their individual characteristics may be different.

Figure 3.3 A hypothetical portion of the Central American power system.





Consider the system shown in figure 3.3. Notice that there are two tie-lines connecting the countries, which will be the situation when the new transmission system is built. Assume that in country B there is competition only in generation and  $d_1$  is the monopsonist purchasing agency which has a monopoly in distribution. On the other hand, country C may have a retail competition structure in which consumers have a choice of buying power from  $g_3$ ,  $g_4$  or importing power from  $g_2$  or  $g_1$ . At the same time,  $d_1$  may find it more lucrative to purchase power from  $g_3$  or even  $g_4$ , since the generators within the same borders are faced to international competition. More trading can take place when considering the generators and consumers of countries A and D. All these trades become feasible for these different industry structures through a bilateral contract mechanism. The only requisite is that there exists a separation of the generation, transmission and distribution activities and there is *open access* to transmission.

As it will be discussed in the next chapters, with such a decentralized mechanism of decision making the maximum efficiency of the system can be achieved, the same that a centralized operation of the system can obtain, as proposed in the TMEAC.

### **3.4.4 Open access**

One of the most important concepts of a competitive market for electricity is that of open access to transmission and distribution wires. This implies that the owners of the wires provide the public service of permitting indiscriminate access to third parties to the transport capacity of their systems. This is the motivation for the separation of transmission activities from generation in the restructuring process, to remove perverse incentives the utility may have of blocking access to some generation in favor of its own.

The main requirement for a bilateral contract trading mechanism (actually any economically efficient trading mechanism) is that there is precisely this open access to transmission. In Central America all transmission assets are owned by public utilities, so that it was relatively easy to arrive to the agreement in the TMEAC that there will be a structural separation of generation and transmission. The case is more complicated in the United States, where private utilities own most

of the transmission. They desire only a functional separation of generation, transmission and distribution within existing vertically integrated firms, combined with open access achieved through pricing rules applicable to all competing suppliers without regard of ownership. These issues will be considered further in the next chapters.

### **3.4.5 The threat of market power.**

On the previous section, the problem of *vertical* market power was considered, but it is not the only source of market power. Horizontal power can pose a serious threat to the correct operation of a competitive marketplace.

The reader may have noticed a strong contradiction on the ideas behind the TMEAC. Most of the economic benefits of integration are supposedly going to be derived from the economies of scale of large projects, which are precisely the source of natural monopolies. At the same time, the regional market is to be made competitive, so that no individual player may have a strong impact on prices. These two facts are in clear contradiction, and raise the question of how exactly is market efficiency going to be achieved. For instance, just one of the “mega-projects”, El Tigre of 704 MW, will have more installed capacity than Nicaragua and Honduras currently have.

An important fact which will reduce potential market power threats is that the number of players the regional market will have as a whole is considerably larger than each individual nation could have on its own. If ownership is properly diluted, it is possible that no individual generator or utility may have more than 10% of all installed capacity, which can be achieved easily through a *proper* privatization process. This is one of the benefits that can also be derived from integration, since a competitive market in a country by itself will be more likely to face these problems.

For example, in the UK the government disintegrated and privatized the electricity utility industry in 1990. All of the generation assets were allocated into only four companies, of which all the fossil fuel generating technologies were allocated to only two companies. In (Wolfram, 1996), an extensive econometric analysis was performed on hourly data for the pool of England and Wales,

concluding that there is evidence that there exists a duopoly in generation which influences energy prices at higher levels than what could be achieved in a truly competitive environment. This monopolistic behavior seems only deterred by the threat of new entrants and increased government regulation. The effects of privatization on performance have been impressive in the terms of labor productivity, profitability and share prices. However, it is not clear if these gains were at the expense of consumers or through increased efficiency. (Newbery, 1995)

Vertical and horizontal disintegration of firms does tend to create conditions in which the diversity of supply makes collusive behavior difficult. However, for any deregulation scenario to work well anti-trust policies must police tendencies towards monopoly and collusion. At present these do not exist at a nation level, much less at a regional level in Central America. This task must be taken up by regulators and policy makers as it is of central importance for the success of the TMEAC.

# Chapter 4

## Technical aspects of power systems operations.

The current drive towards a competitive market for electricity has been motivated largely by technological improvements in telecommunications and computers which may allow an operation of the power system closer to the reality imposed by its physical and economical characteristics.

This chapter is concerned with outlining some technical aspects of power systems relevant to a competitive industry. Of particular importance is the fact that the decisions and actions of competitive players have direct consequences on the overall system which limits the range of possible behavior the players can take. These network externalities require the intervention of a central authority to provide market correction mechanisms in order to achieve the desired operating point of maximum efficiency.

### 4.1 Assumptions

Utility power plants typically produce balanced three-phase power. Three conductors carry power from the generator, with the voltages on each line all having the same magnitude and frequency but with a shift of  $\pm 120^\circ$  relative to each other. A fourth, neutral wire may be used to carry the return current (if any) from the three outgoing phases. A *per phase* analysis assumes that the shifts are exactly  $\pm 120^\circ$ , so that the behavior of the system can be analyzed with just a line-to-neutral single phase. All work in this thesis is done on a *per phase* basis, and only one phase angle is associated with each node of the system.

For simplification of numerical calculations of voltage, current, kVA, and impedance a *per unit* system is used, which is a normalized value of the quantity or constant. A major advantage of the *per unit* system is that the various constants of

electric equipment of widely different voltage and power ratings, lie within reasonably narrow numerical ranges, if the rated values are used as base values in computing per-unit values.

There are numerous other assumptions made throughout the thesis, which are introduced as needed.

## 4.2 Load flow equations

The transmission system can be modeled by a set of buses or nodes interconnected by transmission links. Generators and loads, connected to various buses of the system, inject and remove real and reactive power from the transmission system. For convenience, power at each bus is understood as being *injected* into the transmission system, according to standard notation from (Bergen, 1986). The two components of power for the  $i$ -th bus of a network with  $n$  buses will be denoted by  $P_i$  and  $Q_i$  and given by:

$$\begin{aligned} P_i &= \sum_{k=1}^n |V_i||V_k| \left[ g_{ik} \cos(\delta_i - \delta_k) + b_{ik} \sin(\delta_i - \delta_k) \right] \\ Q_i &= \sum_{k=1}^n |V_i||V_k| \left[ g_{ik} \sin(\delta_i - \delta_k) - b_{ik} \cos(\delta_i - \delta_k) \right] \end{aligned} \tag{4.1}$$

$V_i$  is the magnitude of the voltage and  $\delta_i$  is the phase angle of the voltage relative to some synchronous reference frame. The parameters  $g_{ik}$  and  $b_{ik}$  are the components of the complex admittance of the transmission line joining bus  $i$  to bus  $k$ . Under such notation,  $\hat{y}_{ik} = g_{ik} - jb_{ik}$ ,  $g_{ik} \geq 0$ ,  $b_{ik} \geq 0$ .

This model is appropriate for solving for the steady state powers and voltages of the system, and is the most common of power system computer calculations. Transient response of the system to perturbations requires dynamic equations, but these are mostly used for stability and contingency analysis. However, the load flow equations can be run several times to determine existence of the solution as well as system performance for different configurations and contingencies, and is also the base case for stability studies.

Thus, power flows are balanced at each node as a result of the superposition of all the injections on the network. In this sense, electric energy can be treated as a

unique commodity since the electrons need not travel from the injection node to the removal node as specified in the contract path. The actual source is irrelevant as long as the system is balanced. This phenomenon, commonly referred to as the problem of parallel flows or *loop flow*, imposes problems when an economic transaction causes problems to a third party.

### 4.3 DC Load flow

On the typical transmission line, reactive impedance is much larger than resistive impedance, usually by more than an order of magnitude. Also, to avoid problems of loss of synchronism the phase angle difference between two buses is usually smaller than  $20^\circ$ . The magnitudes of the voltages are also relatively constant at a value of 1 unit, since large deviations from this nominal value may damage valuable equipment connected to the system. These assumptions can be summarized as follows:

$$\begin{aligned} g_{ij} &\ll b_{ij} \\ \sin(\delta_i - \delta_j) &\cong \delta_i - \delta_j \\ V_i &\cong V_j \cong 1 p.u. \end{aligned} \tag{4.2}$$

Applying these assumptions to the load flow equation for real power (4.1), it is reduced to

$$P_i = \sum_{k=1}^n b_{ik} (\delta_i - \delta_k) \tag{4.3}$$

which is the DC load flow equation for one bus.

Now we need to define the network incidence matrix. This matrix has a dimension of  $n \times l$ , where  $n$  is the number of buses in the network, and  $l$  is the number of branches (transmission lines). The elements of this matrix are either 0, 1 or -1. The element  $a_{ij}$  is equal to zero if the  $j$ -th branch does not join the  $i$ -th bus with any other bus, equal to 1 if the  $j$ -th branch leaves the  $i$ -th bus and equal to -1 if the  $j$ -th branch arrives to the  $i$ -th bus. In a general network, each line  $ij$  is conventionally oriented in the direction  $i \rightarrow j$  if  $i < j$ .

Since the sum of all power injections must be zero (in a lossless network), one need only define the power injected from  $n-1$  of the buses to have a completely

defined problem. This treatment is embodied by the use of a swing bus, which will compensate generation for the power balance. To adopt this, the incidence matrix is transformed into the *reduced* incidence  $(n-1) \times b$  matrix  $\mathbf{A}$ , which is obtained by removing the row associated with the swing bus from the network incidence matrix.

This enables us to write the vector of power flows through the  $l$  lines as

$$\mathbf{T} = \mathbf{y} \boldsymbol{\theta} \quad (4.4)$$

where  $\mathbf{y}$  is an  $l \times l$  diagonal matrix whose elements are the susceptances of the transmission lines, and  $\boldsymbol{\theta}$  is defined from Kirchoff's voltage equations as

$$\boldsymbol{\theta} = \mathbf{A}^T \boldsymbol{\delta} \quad (4.5)$$

where  $\boldsymbol{\delta}$  is the vector of phase angles of the  $n$  buses and  $\mathbf{A}$  is the reduced incidence matrix. The power injections from each bus into the network are given by Kirchoff's flow equations which may be spelled out as

$$\mathbf{P} = \mathbf{AT} = (\mathbf{AyA}^T)\boldsymbol{\delta} \quad (4.6)$$

The DC load flow accounts only for real power flows, disregarding reactive power. This is based on the decoupling assumption which separates real power and phase angles from reactive power and voltage magnitudes, which follows from the mostly reactive nature of transmission lines. In a steady state analysis, the reactive power is assumed to be automatically adjusted so that the voltage magnitude remains constant. Thus, the bus behavior is completely specified by giving the voltage magnitude and the real power injection. (Schweppe, 1988)

## 4.4 Power losses

Some of the power injected into the buses is lost in the transmission system. Throughout this thesis only real power losses are considered, which are caused by the small electric resistance of the transmission wires. Total losses in a well-maintained transmission system should amount to only 2-4% of the total generation. This small amount however, in terms of accumulated effect on revenues is significant.

The real power loss over the line  $ij$  can be defined as the sum between the injected power into either end of the transmission line as

$$L_{ij} = P_{ij} + P_{ji} = g_{ij} [V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j)] \quad (4.7)$$

which under the approximations outlined in (4.2) is reduced to

$$L_{ij} = g_{ij}(\delta_i - \delta_j) \quad (4.8)$$

and with the expression for phase angle differences defined in (4.3), and one further approximation, yields

$$L_{ij} = \frac{g_{ij}}{b_{ij}^2} T_{ij}^2 = \frac{r_{ij}(r_{ij}^2 + x_{ij}^2)}{x_{ij}^2} T_{ij}^2 \cong r_{ij} T_{ij}^2 \quad (4.9)$$

Thus, transmission losses are approximately a quadratic function of line flows. In the operation of a competitive marketplace for electricity it is desirable to allocate the responsibility of thermal losses to particular generators or sets of injections which would represent a transaction, after which the responsible parties would compensate by generating more energy or some other financial mechanism. However, an expression for relating the amount of transmission losses associated with a particular transaction is complicated due to the non-linear nature of (4.9). In fact, the losses will depend on the operating conditions and values of all other injections previous to the consideration of that transaction. The order in which the transactions are dispatched in the system will determine their relative impact on total system losses. The last transactions will face the highest level of losses. This is an externality and will be considered further on the next chapter.

## 4.5 Operating limits

The region of load flow feasibility describes the most fundamental limitation of power networks to the flow of real and reactive power. These constraints are closely related to the concept of maximum power transfer in circuit theory. However, even though a feasible solution to the load flow problem may be found, it is possible that this solution may violate some system constraints, which would threat system security and reliability. This section is oriented to understand the constraints



imposed by the physics of the power system on operating limits, mainly generation, voltage and transmission constraints.

It is important to point out the difference between the reliability and security objectives in a power system. Reliability is associated with keeping the operating point of the system within constraints, otherwise life time of valuable assets may be reduced and the probability of not serving the load may increase. Security is concerned with having enough stand by capacity to handle emergency situations such as a generator outage or loss of a transmission line. Traditionally, an  $n - 1$  security criterion is used, where the reserve capacity ready to be set on line is enough to keep the system together when any single contingency occurs.

### **4.5.1 Generation limits**

Generating units are constrained by thermal limits on the maximum power deliverable by a turbine generating unit, while a lower limit may be set by a boiler or other thermodynamic considerations (unless the unit is turned off). A certain flow of water and steam is required in the boiler to prevent overheating. The fuel burning rate must also be sufficient to keep the flame from going out. Upper limits and lower limits constrain both real and reactive powers.

Under normal conditions, to preserve some slack to support sudden changes in operating conditions, generators are operated far away from the constraints. Even under decentralized operation, reliability of the power system will involve all players in the system, and the relative security margins of particular units may prove particularly valuable for the overall system. This is discussed further under ancillary services.

### **4.5.2 Voltage limits**

The constraints on voltage keep the system voltages from varying too far from their rated or nominal values. The objective is to help maintain the consumer's voltage; the voltage should neither be too high nor too low. The level may vary according to operating conditions. Under normal operation a 5% deviation from nominal values is tolerated, which may go as high as 10% under emergency conditions.

The advantage of a per-unit system becomes clear when dealing with system voltages, which may vary considerably from as low as 110 V for the residential consumer up to 400 kV in EHV transmission lines.

### **4.5.3 Transmission constraints**

In a steady state sense, the amount of real power that can be transferred along a transmission wire faces two types of limitations, a thermal limit and a stability limit.

The first is associated with the real power dissipated in the wires through heat. Over-heating of transmission lines can cause loss of line life and increase the probability of a line failure at any given moment. In Central America, this turns out to be an important constraint during the harvest of sugar cane, when some farmers burn their fields to prepare them for the next crop. Outages are known to occur from overheating of transmission lines which cross such fields.

The second constraint is concerned with the maximum power transfer theorem or the existence of a feasible solution to the load flow problem. Power transfer is proportional to the phase angle difference between the ends of the transmission line, and when this difference exceeds a critical value the system may experience instability, a problem normally described as loss of synchronism. This latter constraint can be alleviated by compensating the intrinsic line reactance with shunt capacitors or other devices. (Ilic, 1996)

The violation of a transmission constraint of a single line is an overall violation of system parameters. This means that even though non-congested transmission lines may be able to deliver more power, if just one line violates parameters the whole solution is considered invalid. This appreciation will have particular importance in setting up a competitive market for electricity. Under centralized operation, the monopolist operator, upon detecting congestion can obtain an optimal dispatch of generation that meets all operating constraints. However, in a decentralized operation there will be the need of special mechanisms to solve this kind of problems. This thesis considers this particular problem further in the next chapter.

## **4.6 Ancillary services**

As pointed out before, generators operating away from their constraints may provide services to the system. These are referred to as ancillary services. They are commonly defined as all the activities on the interconnected grid necessary to support the transmission of electric power from sources to loads while maintaining reliable and secure operation of the system. They are not limited to generators, and it is assumed that in a competitive market any third party can provide such services.

The necessity of these services is also an important source of externalities, since the lack of appropriate support for a particular transaction may make another transaction unfeasible.

In the traditional utility these services were coordinated in a centralized fashion and the control algorithms designed to respond to all the parameters in the system. In a deregulated competitive industry it may be desired that decentralized control schemes and algorithms provide the same services. This implies large investments to change the technologies in place, and it is not clear at this point if decentralized controls will attain the same level of reliability achieved by centralized control. (Ilic, 1997a)

### **4.6.1 Automatic Generation Control (AGC) and Load Frequency Control (LFC)**

In order to maintain a high quality of supply and prevent damage to valuable equipment, the system operator has to keep frequency variations within security limits. At the same time, power balance has to be maintained at all times by compensating the small deviations from anticipated values.

Generally only a handful of generators throughout the system participate in these closed-loop control schemes, usually the most flexible units. These need to have the adequate technology, that is, governors<sup>2</sup> and telecommunication equipment, which can react fast on the face of changes in the system and can be controlled remotely by the system operator.

### **4.6.2 Loss compensation.**

As discussed in 4.4, power losses are dependent on operating conditions, so it is impossible to determine beforehand the exact amount unless the exact operating point is known. These losses must be compensated in order to maintain the power balance in the system. In real time, units involved in AGC compensate from the departure from scheduled operating conditions.

### **4.6.3 Reactive power dispatch**

The objective of reactive power scheduling is usually to set a voltage profile that minimizes transmission losses over the whole network, and to maintain the reactive power output of generating units away from their limits to avoid a voltage collapse. To achieve the adequate levels of voltage at each node, reactive power sources and sinks may be needed, such as capacitor banks, static VAR compensators, inductors, etc.; as well as excitation systems at each generating unit. The benefits of a relatively constant voltage were also pointed out in 4.5.2. Voltage control is more demanding due to the inability of reactive power to travel for long distances as a consequence of (4.2).

### **4.6.4 Spinning reserves**

The objective of having spinning reserves in the system is to have readily available generation in real time, in the event of an unexpected loss of a generator or a transmission line. In large systems, the reserve is usually equal to the capacity of the largest generating unit in operation, thus meeting the  $n - 1$  security criterion. It is usually distributed among several units, in order to have sufficient flexibility if a line is lost.

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<sup>2</sup> A governor is the control device which determines the actual turbine speed (frequency) to a set-point reference input provided manually or through AGC.

# Chapter 5

## Economic characteristics of power systems operations

This chapter is concerned with understanding the economics of power systems. Of particular importance is the concept of efficiency, since it is mainly for the sake of it that the current changes in the electric sector are taking place. The problem is better understood when dividing power system activities into different time frames and considering what efficiency means in each of them.

Of particular interest will be the achievement of efficiency in the short-run, for the purpose of setting the stage for the consideration of a bilateral market.

In power systems engineering the variables  $P$  and  $Q$  are used to denote real and reactive power respectively, while in economics these same variables are used to denote price and quantity. To reconcile this issue the lower case variables  $p$  and  $q$  are used when writing economic equations. Thus  $P$  and  $q$  both represent real power.

### 5.1 Long Term Efficiency

For long term it is meant a span ranging from a few months to several years. In this time frame, the concern is for the investment decisions for expansion of generation, transmission and distribution facilities. A power supply system makes new investments in equipment to meet additional loads, to replace assets which have exceeded their useful life, and to replace economically obsolete equipment. These investment decisions must provide for least-cost production, given expected technology and input prices over the lives of the investments. Least-cost investment in generation requires that an appropriate mix of base-load, cycling and peaking capacity be installed to meet the expected system load at minimum cost, taking into account the expected pattern of short-run load fluctuations and even the rate of technological change.

Naturally, an important part of ensuring the long term efficiency of the system is proper maintenance and care that is given to these valuable assets. Also, an important part of operating the system within its reliability constraints is to maximize the expected lifetime of transmission lines and generators. As pointed out in Chapter 3, this has been a great source of economic waste in the Central American countries.

Environmental impacts of the system also fall in this level of efficiency and proper consideration given to the constraints these impose.

## **5.2 Medium Term Efficiency**

On a time frame of an hour ahead to a week or few weeks in advance the concern is for the scheduling of units, a problem referred to as unit commitment. The problem consists of producing an hour by hour (or even finer) schedule for a day or a week ahead for generators, since not all may be needed to meet demand at a particular time of day. When considering this problem, some new system constraints need to be taken into account, such as:

- **Minimum Up Times:** The generator must be run for a minimum time.
- **Minimum Down Times:** If shut-off, the generator must remain in that state for a minimum time.
- **Startup Costs:** Boilers need to be brought to operating level by burning extra fuel.
- **Ramp Rates:** There are limits at the rate of changes a generator can sustain.
- **Crew Availability:** Operators may be able to start only one generating unit at a time.
- **Maintenance scheduling:** Units cannot run a 100% of the time, as preventive and frequent maintenance is required.

The problem is complicated further by the presence of hydroelectric generation units. Hydro introduces a large number of new technical, economic and social constraints which influence the opportunity cost of the water stored in the dam, such as

- **Variation of Water Levels in Reservoirs:** a large variation can hurt recreation facilities or fishing industries that may have developed in the area and have adverse impacts on lake life.
- **Rate of Water Flow:** Flow rates are constrained to avoid fish kill, erosion of river banks, to allow irrigation of cultivated areas downstream, to allow navigation, sewage control, etc.
- **Weather conditions:** Water levels need to be managed to prevent floods during rainy seasons and droughts during dry seasons. Evaporation rates are also dependent on insolation.

There is no standard methodology for determining the opportunity cost or price of water, since each hydrological system is different. System operators with experience and a good knowledge of the system can be very effective by following a heuristic approach in developing a schedule for all generating units in the system, but a formal optimization solution requires the use of dynamic programming. (Shweppe, 1975)

## **5.3 Short term efficiency**

In the short term, given the mix of generation and transmission capacity available and the prices of fuels and inputs, the point of maximum efficiency will be that of least-cost supply, usually by running an economic dispatch. However, the traditional approach to this problem assumes a short-term inelastic demand for electricity which can no longer be an assumption under open access.

On the other hand, a fundamental principle of economics is that prices provide the correct signals to buyers if and only if they are equal to marginal costs. This is not currently the practice in the power systems of Central America, where block tariffs characterized by government subsidies are common and a source of important inefficiencies.

### **5.3.1 Economics of power plants**

The total cost of operating a thermal unit includes fuel, labor, and maintenance costs, among which fuel represents the largest share. As an

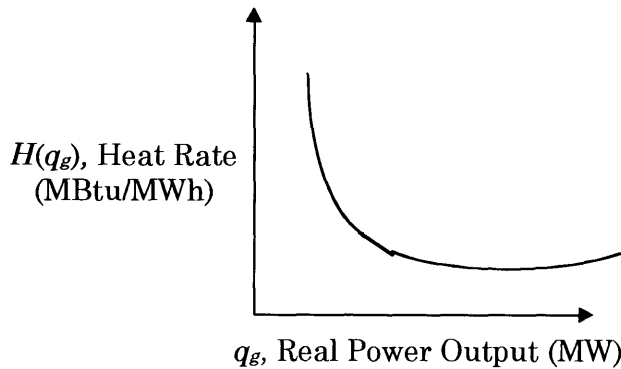
approximation, it may be considered that fuel is the only source of variable costs for a generator and the rest are fixed.

The shape of the fuel-cost curve (concave upward) may be understood in terms of the heat-rate curve, which is determined by field testing the generating units. The heat-rate is given by the amount of thermal energy necessary to deliver electrical energy, and is thus the inverse of the thermodynamic efficiency of the machine. An approximate shape of this curve is given shown in figure 5.1. At the minimum point the generating unit is most efficient. The curve reflects the typical drop in efficiency of most energy conversion machines at the low and high ends. Such a curve can be approximated by

$$H(q_g) = \frac{\alpha_g'}{q_g} + \beta_g' + \gamma_g q_g \quad (5.1)$$

where  $q_g$  represents the real power output from the turbine and  $\alpha_g'$ ,  $\beta_g'$  and  $\gamma_g'$  are the fitted coefficients. (Bergen, 1986)

Figure 5.1 Heat-rate curve for a thermal power plant.



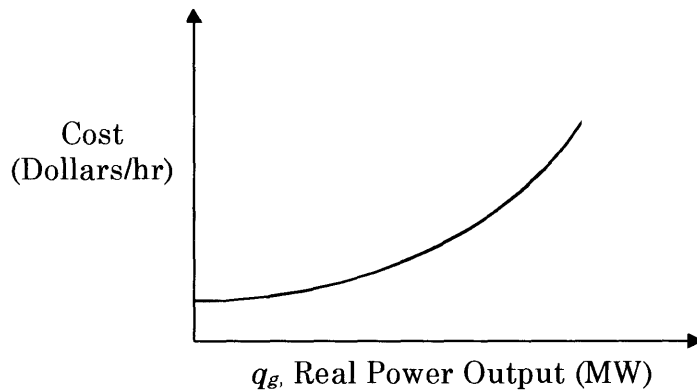
The fuel cost curve can be derived by simply multiplying the heat-rate function  $H(q_g)$  by  $q_g$  to obtain the following expression, as depicted in Figure 5.2

$$C(q_g) = \alpha_g + b_g q_g + \gamma_g q_g^2 \quad (5.2)$$

There are important exceptions to the shape of these curves, but these general expressions are sufficient to point out the important issues of concern in this thesis.



Figure 5.2 Cost curve for a thermal power plant.



The model in (5.2) is also applicable to hydroelectric units, which is also a strictly increasing convex function. The process of obtaining such a model is more difficult because the price of water changes from time to time. Input-output curves for a hydro unit are developed, showing acre-feet per hour plotted against load in megawatts. From these curves, the incremental water rate in acre-feet per MWh plotted against the load in MW can be obtained by the same methodology used for thermal plants. (Miller, 1994)

### 5.3.2 Value of electricity to consumers

Utility is the level of satisfaction or value that a person gets from consuming a good or undertaking an activity. Utility functions are used to describe these relative values by quantifying the level of satisfaction a consumer has. Although the concept of utility is concerned with an ordinal preference, utility functions attempt to give them a cardinal dimension.

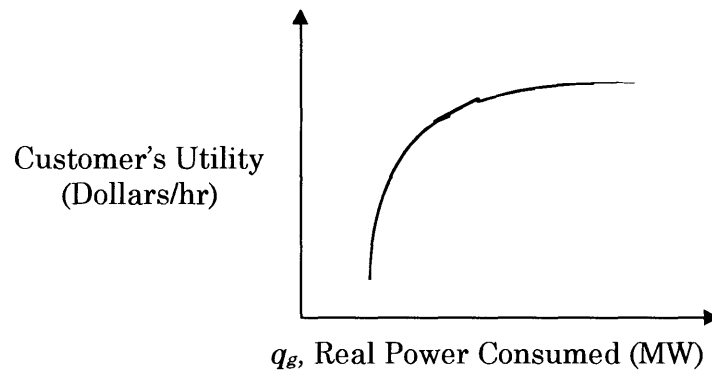
The principle of diminishing marginal utility states that as more of a good is consumed, consuming additional amounts will yield smaller and smaller additions to utility. This is true in the case of electricity, where the utility of consumers for the initial amounts of electricity they receive is high, as they take care of basic needs such as heating, cooking or lighting; and decreases as other needs like leisure activities are met for which the relative value of electricity is less. (Pindyck, 1995)

A graphical way of describing a utility function is presented in figure 5.3. For the sake of simplicity, a quadratic approximation will be used, given by

$$U(q_d) = -\alpha_d q_d^2 + \beta_d q_d \quad (5.3)$$

where  $q_d$  is the amount of power demanded, and the coefficients may be determined to scale the value in money that the customer perceives from consuming.

Figure 5.3 Consumer's utility function of electricity.



As power markets evolve, the nature of these functions may need to be reconsidered, as market segmentation strategies come into play. For example, some consumers may be willing to pay a higher price for electricity which is produced by renewable generating technologies than for other plants which may pollute the environment.

### 5.3.3 Economic dispatch

In the classical regulated or government owned utility all the information about the costs of generating electricity is known. Under such conditions, the economic dispatch problem is to find the particular output levels for each available generator that minimize the total costs while meeting all of the loads plus line losses. When the load flow equations are included as constraints of the problem, it is referred to as the *optimal power flow* or OPF.

The most efficient generators will be dispatched first, and the less efficient will only be preferred if generation limits are reached by the most efficient units or because of network losses if they are close to the loads.

In a competitive industry the cost structures of each generator are not known to the ISO. In a pooling model of the industry, all generators and loads submit price bids and offers for energy to the ISO, which attempts to match these and achieve efficiency in the same sense as that of an economic dispatch. For this purpose, the bids must reflect the actual costs and demand schedules, as is expected from well behaved players. However, there may be strong incentives for the players not to do so. Consider for instance the position of a particular generator which due to its flexibility and proximity to load centers, and perhaps even installed capacity, is considered most of the time as a unit to be dispatched. It can then request a price for its energy that may exceed considerably its marginal costs of operations. This issue is of the sort that needs to be covered by anti-trust legislation.

In a bilateral model, economic efficiency is supposed to be arrived at from competition, as the laws of supply and demand drive the market towards the equilibrium price, which in theory it should yield the same operating point as the centralized dispatch.

### 5.3.4 The Optimal Power Flow problem

Either by means of a regulated monopoly, a pooling competitive industry or bilateral contract trading, the maximum efficiency must be achieved. This is an operating point of the system given by the solution of the OPF problem.

Consider the cost and benefit of the net injection  $q_i$  by the increasing convex function  $C(q_i)$ . Each net injection is determined by the difference between the power generated and demanded at that particular bus, such that  $q_i = q_{gi} - q_{di}$ . This means that if  $i$  is a net supplier, then  $q_i$  will be greater than zero, and  $C_i(q_i)$  is the variable cost of generation and the marginal cost curve is increasing. On the other hand, if  $q_i$  is a net demander then  $q_i < 0$ , and  $-C_i(q_i)$  is the consumer benefit, and the marginal benefit curve is decreasing.

The procedure of handling symmetrically generation and demand assumes that loads are manageable in the same way as generators, and does not consider power demand like an externally imposed parameter. This is a different approach to the classical OPF, in which the utility was assumed to have an obligation to meet a demand forecast. However, in a deregulated industry under competition and open

access, the obligation to serve will soften as the laws of supply and demand come into place and the sensitivity of consumption levels to electricity prices will determine actual power demanded.

The OPF problem is a minimization problem. The objective function is given by the sum of the cost and negative benefit functions of each bus, subject to the constraints described previously in Chapter 4. The formulation is as follows

$$\text{minimize} \quad \sum_{i=1}^n C_i(P_i) \quad (5.3)$$

$$P_i$$

$$\text{subject to} \quad P_i = \sum_{k=1}^n |V_i| |V_k| [g_{ik} \cos(\delta_i - \delta_k) + b_{ik} \sin(\delta_i - \delta_k)] \quad (5.4)$$

$$P_{gi}^{min} \leq P_{gi} \leq P_{gi}^{max} \quad i = 1, \dots, n \quad (5.5)$$

$$Q_{gi}^{min} \leq Q_{gi} \leq Q_{gi}^{max} \quad i = 1, \dots, n \quad (5.6)$$

$$V_i^{min} \leq V_i \leq V_i^{max} \quad i = 1, \dots, n \quad (5.7)$$

$$T_{ij} \leq T_{ij}^{max} \quad i = 1, \dots, n; j = 1, \dots, n \quad (5.8)$$

This is a nonlinear programming problem and it is difficult to solve in practice because the network of  $n$  buses is large, and the functions  $C_i(P_i)$  may not be readily available. The problem can be simplified by making the DC load flow assumptions (4.2) and disregarding the constraints on generation. These assumptions can become more inaccurate for lower voltage, sub-transmission and distribution lines and as line loading increases. However, they are useful to highlight some basic characteristics of the behavior of power systems where high accuracy is not required. The problem formulation is as follows:

$$\text{minimize} \quad \sum_{i=1}^n C_i(P_i) \quad (5.9)$$

$$P_i$$

$$\text{subject to} \quad P_i = \sum_{k=1}^n b_{ik} (\theta_i - \theta_k) \quad (5.10)$$

$$T_{ij} \leq T_{ij}^{max} \quad i = 1, \dots, n; j = 1, \dots, n \quad (5.11)$$

The solution to the optimization problem involves associating Lagrange multipliers  $p$  with the  $n$  constraints of (5.10) and  $\mu_{ij}$  with the  $n^2$  constraints (5.11) and form the Lagrangian

$$\Phi = \sum_{i=1}^n C_i(P_i) + \sum_{i=1}^n p_i \left[ \sum_{j=1}^n b_{ij}(\delta_i - \delta_j) - P_i \right] + \sum_{i=1}^n \sum_{j=1}^n \mu_{ij} \left[ b_{ij}(\delta_i - \delta_j) - T_{ij}^{\max} \right] \quad (5.12)$$

Next, the first-order derivatives of the Lagrangian are obtained and made equal to zero, that is,  $\frac{\partial \Phi}{\partial P_i} = 0$ ,  $\frac{\partial \Phi}{\partial \delta_i} = 0$ ,  $\frac{\partial \Phi}{\partial \mu_{ij}} = 0$ , to yield

$$\frac{\partial C(P_i)}{\partial P_i} = p_i, i = 1, \dots, n \quad (5.13)$$

$$\sum_{j=1}^n b_{ij} [p_i - p_j + \mu_{ij} - \mu_{ji}] = 0, i = 1, \dots, n \quad (5.14)$$

$$\mu_{ij} [b_{ij} (\delta_i - \delta_j) - T_{ij}^{\max}] = 0, i = 1, \dots, n \quad (5.15)$$

Thus an OPF solution will be the set of power injections and phase angles that solves the problem formulated in (5.9 - 5.11) and satisfies (5.13 - 5.15). Expression (5.13) implies that the marginal cost of each unit must be equal to a parameter commonly referred to as the "system lambda".<sup>3</sup> This is in fact the condition of a market equilibrium. If bus  $i$  is a net demander then  $p_i$  equals the marginal benefit to the consumer, and if  $i$  is a net supplier then  $p_i$  equals the marginal cost of generation. Hence, at equilibrium there is no possibility for profitable trading, since consumers are charged a price equal to the marginal cost of generation so maximum efficiency is achieved in the short run sense.

In the absence of congestion, the Lagrange multiplier  $\mu_{ij}$  is not binding and thus equal to zero (5.15), and all the nodal prices are equal to the system lambda parameter (5.14). However, if  $\mu_{ij}$  is binding then  $\mu_{ij} \neq 0$  and all the nodal prices are different.

It has been frequently mentioned that social welfare is maximized at the equilibrium point of the market. In the short run, social welfare can be defined as the aggregation of the utilities of every consumer minus the costs of generation.

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<sup>3</sup> In some of the literature the greek letter  $\lambda$  is used to pose the OPF problem instead of  $p$ , and in the case where the nodal prices are different it is understood as that of the slack bus.

$$SW = -\sum_{i=1}^n C(P_i) = \sum_{i=1}^n U(P_{di}) - \sum_{i=1}^n C(P_{gi}) \quad (5.16)$$

where  $P_{di}$  and  $P_{gi}$  represent respectively the power demanded and generated at each bus. The minimization problem of (5.9) is the maximization problem of (5.16).

The problem can be modified to include transmission losses in (5.10), leading to differentiated nodal prices.

### 5.3.5 Merchandising surplus

Using the definition given by [13], the merchandising surplus (MS) at a market equilibrium is defined as<sup>4</sup>

$$MS = -\sum_{i=1}^n p_i P_i = -\sum_{i=1}^n p_i q_i = \sum_{i=1}^n \sum_{j=1}^n \mu_{ij} T_{ij}^{\max} \quad (5.17)$$

The MS can be understood better under a pooling market mechanism, as the difference between the net price paid to suppliers minus the net price paid by consumers. After all the trading has been done, this surplus remains in the hands of the ISO. In the absence of congestion and losses, the merchandising surplus is exactly zero, since all spot prices are equal to the equilibrium price of the market. If congestion is present this surplus will always be positive since the revenue from consumption will be greater than the payment to generation. The left-most term of (5.17) is also called the congestion rent. The presence of losses will also generate a merchandising surplus which, in the absence of congestion, will be equal to the revenue required by the extra generation needed for their compensation. (Wu, 1995)

## 5.4 Transmission pricing and open access

In a competitive marketplace, in the absence of congestion, either through a pooling of the resources and merit order dispatch or by bilateral contracts, it is understood that the market will settle at an equilibrium price which will be the same for all parties (Appendix B). All parties generate and consume as much as they are willing to do so, which can be understood as comparable and equitable access to everybody. However, in the presence of congestion, this operating point will not be a

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<sup>4</sup> Notice the exchange of notation from  $q$  to  $P$ , both representing real power injections.

feasible solution of the OPF problem. This implies that transmission becomes a limited resource and open access becomes an issue. All or just some of the parties must adjust its generation and consumption level to meet the system constraints. The problem is who and where. Because of the existence of the loop-flow problem, it is impossible to allocate responsibilities among all the participants according to the relative impact each of the generators may have on the congestion.

There have been several policy proposals for providing open access in the presence of congestion, and they are strongly dependent of the market structure in which they are conceived. The most important are briefly discussed below.

It should be kept in mind that one of the dimensions of economic efficiency is often referred to as *allocative efficiency*, that is, the goods and services must be given to those users who value them most highly. In this sense, the transmission system could be seen as a service, and the market must provide the proper incentives for individuals who want to use the system. Another way to put this is how to internalize into the generation picture the externalities induced from congestion. This can only be achieved if the price signals to all users of the system reflect marginal costs.

### 5.4.1 Transmission Congestion Contracts

This methodology of handling transmission constraints assumes that a pooling competitive structure is in place to operate the market. Although the introduction of such a structure in the short term in Central America was discarded in Chapter 3, it is given here to contrast the methodology suggested for a bilateral model.

The Transmission Congestion Contract (TCC) is the concept developed by William Hogan (Hogan, 1992) for distributing transmission “rights”. The TCC provides the right  $R_{ij}$ , which pays the holder the contract’s yield given by

$$(p_j - p_i) R_{ij} \tag{5.18}$$

This amount is paid to the holder of the TCC no matter how much power flows between the nodes  $i$  and  $j$ , even though the rights are set as if they were the power flows of a feasible economic dispatch. The existence of an actual transmission line

linking the nodes is not relevant, so that a virtual *contract network* exists in parallel to the physical network. An important characteristic of a TCC is that it has an implied direction given by  $R_{ij} = -R_{ji}$ . In addition, although not immediately obvious, a TCC can take on a negative value.

The yield is paid to the right holder from the merchandising surplus collected by the ISO, which also determines the nodal prices by producing a constrained economic dispatch. In this sense, a TCC gives the right to the holder over an income stream. This has the big advantage of reducing the uncertainties associated with the pool prices as seen by generators, reducing risks on investment recovery, similar to that achieved through direct bilateral contracts. As long as the allocated TCCs represent a feasible dispatch, it has been proven in (Wu, 1994) that the revenue collected by rights holders will not exceed the network's merchandising surplus as defined in (5.17).

An interesting characteristic of TCCs is the incentives they provide for investments in network expansion. Consider that the rights to transmission are allocated according to the *feasible allocation rule* as described in (Bushnell, 1996). It states that the reward for an expansion of the network is a set of rights, which added to the set of previously existing rights is a feasible dispatch. If this is the case, the revenue from TCCs after the allocation of rights will equal the merchandising surplus. This financial relation provides incentives for investments when beneficial expansions to the system are feasible. However, it may also provide incentives for detrimental network changes, such as the removal of transmission lines to increase congestion in the system and thus higher rents. This implies that oversight by the ISO will be required for deciding which expansions are allowable and which are not. This turns to be a hard task because of the difficulties of determining the actual available transmission capacity. There are great uncertainties associated with congestion as to when, at what times and duration will it occur.

Notice that with TCCs, an investment in transmission that will remove *all* congestion present in the system, that is, leaving no slack in (5.15), will receive a set of rights which will exactly cancel out the rights previously allocated in the network. This implies that such an investment would never be made because it will not be financially viable. As a result, the network will always be congested which means



that consumers will never enjoy the low prices of an uncongested network. This may be perceived as an unreasonable burden to consumers, but it is just a direct consequence of marginal pricing of transmission.

In fact, if the objective function (5.9) was modified to include the investment costs of network expansion, it is shown in (Lecinq, 1996) that, in the optimum, a network has to have enough congestion for the transmission rents to exactly recover the investment cost. However, this result cannot be generalized due to the strong assumptions involved, like constant marginal costs. Furthermore, in (Pérez-Arriaga 1995) it is argued that the marketing surplus alone will most likely not recover the full cost of the network, so additional revenue destined for transmission needs to be collected from the users of the system.

In this sense, open access to an individual generator is understood solely as the right to a fair treatment in the constrained economic dispatch of the ISO, but not as a right to inject as much power as he would desire. He dispatches what he is told.

Perhaps the greatest disadvantage of TCCs and more specifically revenue to transmission from congestion is that there is a perverse incentive that may threaten the quality of supply. The larger the transmission losses the greater the nodal price differentials and the greater the revenues collected by transmission users.

More so, it is the generators or suppliers of electricity in the network the ones who have the greatest financial incentives to hold TCCs. (Bushnell, 1996) Thus, Hogan's proposal seems well suited for vertically integrated utilities, and thus the reason why it has gained support in the United States. The difficulties associated with the estimation of ATC, the incentives that threaten the quality of supply, and the issues of potential vertical market power impose challenges perhaps too great to be adequately policed by regulators.

#### **5.4.2 Bilateral and Multilateral trading**

So far we have defined a bilateral market as if it consists of transactions involving one buyer and one seller, which has a serious drawback. Under the presence of transmission constraints, an economic dispatch will not be sustained (Wu, 1994). This is considered a market failure due to the presence of network externalities. This means that there exist costs incurred by one party caused by the

transactions of others. If transactions are approved on a “first come, first serve” (FCFS) basis, the system will be loaded until congestion constraints may limit further transactions. This may impose a barrier to entry into the market, since new contracts which are added on the margin will bear the highest burden on reliability. Thus, open access is not guaranteed to all parties on equal footing. Notice furthermore that making a FCFS queue the determinant of capacity access, frustrates the allocation of capacity to transactions with the highest valued use, resulting in economic waste.

A similar problem arises from the consideration of system losses. Each transaction or contract burdens the system with increased transmission losses, which must be compensated for, either in money or in power as the generator agrees to produce more to compensate its losses. As was pointed out in section 4.4, losses from power are dependent on operating conditions because of the non-linear nature of (4.9) and are thus dependent on the order in which transactions are handled.

On the proposal by Felix Wu and Pravin Varaiya from Berkeley (Wu, 1995), it is suggested and proven that the inefficiencies imposed by these externalities can be removed if trading is performed in an iterative fashion involving *multilateral*, rather than bilateral trades. All transactions agreed by the market players are submitted to the ISO, which revises them and curtails them if necessary to meet system constraints. The curtailed amounts are reported to the parties, along with information which may guide further trading. These trades involve at least three parties, and may be facilitated by specialized brokerage firms. After some iterative trading and curtailment the system will be driven towards the point of maximum social welfare. Notably, efficiency is achieved independently of the choice of curtailment protocol chosen.

The problem with this approach as it is pointed out by in (Ilic, 1997b), is that profit allocation of individual parties is sensitive to the choice of the curtailment mechanism chosen by the ISO. This implies that the cost of equal access is sensitive to the curtailment algorithm. Choices of curtailment methods may range from simply rejecting everyone the same amount to rejecting the transactions to which the constraints are most sensitive. Any particular choice of curtailment will raise

concerns from the affected parties, and the government may want to take advantage of the opportunity and institute policies to improve the distribution of wealth.

As an alternative, a transmission market mechanism between the ISO and the generators is proposed by Ilic, in which information exchange is the basis for dealing with the system constraints. Instead of producing a curtailment scheme upon detecting congestion from a set of proposed trades, the ISO estimates the total expected charge for the relative impact on system reliability of each transaction. This information is given back to the generators which upon seeing the cost of their impact of the system, may adjust the quantities it intended to deliver. This iterative procedure will converge to the OPF solution. A great advantage of this methodology is that generators do not need to disclose any financial information about their transactions as they only need to respond to the charges imposed to the ISO. It empowers the user of the system to decide how much and at what price he would like to use the system.

The relative impact on reliability is based on a reference frame of what is the optimal use of the system, based on particular equipment status. For example, in the case of congestion, this would require computing some parameters  $T_{ij}^{opt}$  that correspond to the desired operating level of the system, in terms of reliability for all transmission lines. The charge to generators is based on the differences  $T_{ij} - T_{ij}^{opt}$ , multiplied by a weighing factor to incorporate the relative importance of the particular component on system-wide reliability. These charges can incorporate not only congestion, but also losses, reactive support and dynamic stability issues.

If these parameters are fixed beforehand, then the order in which the transactions are received by the ISO is irrelevant. The challenge resides then in the estimation of the optimal use parameters and weighing factors. A methodology would also be needed to determine when the relative impact of the transactions and the frequency of critical requests, may justify investments in system expansion, intended to keep reliability close to the predetermined optimal level. The proposal also suggests that there be transmission charges for system use in the form of ex ante pricing mechanisms, which are separate from the revenues collected by the ISO, and that they should come close to each other.

Although the simplicity of this mechanism makes it very attractive, some issues remain. First, the weighing factors for the relative impact of equipment on reliability are dependent of operating conditions, so they will have to be computed often. For a maximum efficiency, these would have to be determined on a continuous basis, which is impossible in practical terms. It is unclear to what extent this will result in a deviation from efficient operation, and it will be strongly dependent on the actual rate at which the factors are calculated. A methodology to determine these parameters on a system dependent basis, rather than on operating conditions, is analyzed for the first time in (Lerner, 1997), which may prove a solution to this problem. Second, the selection of the optimal operating parameters of the equipment may raise some concerns that may only be settled through consensus, in which the parties involved will try to influence the parameters towards their individual convenience.

## **5.5 Conclusions**

The inefficiencies present in the electric sectors of the Central American countries are the main motivation for the establishment of a competitive market. Looking back to what the sources of these inefficiencies are in chapters 2 and 3, it is clear that they are associated with long periods of time, and fall into the category of medium and long term efficiencies as described here. The agreement is that competition and private ownership will remove them.

However, the introduction of a competitive environment may complicate the economic dispatch problem, producing short term inefficiencies caused by the presence of network externalities. Appropriate mechanisms of cost allocation must be devised to insure that these inefficiencies are removed or the whole benefits of integration will not be achieved.

Although generation and transmission can be regarded as substitutes in the presence of congestion, it seems better to avoid vertical power market problems by separating the transmission and generation activities. In this sense, the Central American countries have taken a good step since this is included in the TMEAC. Furthermore, remuneration to the owners of the transmission grid from congestion should be avoided if possible, due to the incentives to improper maintenance of

equipment in order to collect higher rents. Transmission should be treated as a regulated monopoly with prices set according to a fixed rate of return or price mechanism to recover investment costs. This is the case of the transmission pricing system of Argentina. The possibility remains for a different methodology when transmission technology may become more accessible and economies of scale are removed.

The system will still demand protocols as to how to deal with congestion in order to remain efficient, and several proposals have been analyzed, which may achieve the short term efficiency desired. In the next chapter, one more proposal is considered in detail.

## Chapter 6

### Bidding for access through congestion

In the previous chapter, the economic aspects of power system operations were described, giving particular emphasis to the market failures produced by the externalities derived from the physical nature of the power system. Several proposals have been introduced to handle these externalities each dependent on the market structure, either pooling or bilateral.

In this chapter another proposal is considered based on an auction mechanism. This proposal is based on an idea that the team involved in developing the protocols and details of the new regulatory framework in El Salvador are considering for implementation.

The ISO, which is responsible for system security and reliability, will be notified by the generators of the contracts in which they have engaged with consumers. If a congestion problem is detected, the ISO will request bids from the generators to determine how much is each willing to pay to transfer their energy through the congestion. The ISO will approve dispatch to those who present the highest bids until all transmission constraint are satisfied. This mechanism is intended to achieve allocative efficiency, in which the benefits of the available transmission capacity are perceived by those who value them mostly. It is intended that the funds that the ISO obtains from the auction be distributed among all the users of the system according to a methodology yet to be determined, but not to the owners of the transmission system. These will be compensated for their investments through a separate mechanism consisting of direct charges to the users of the system. The ISO will use the economic signals provided by the revenues of the auction to indicate when and where new transmission investments are needed.

After curtailment, the operating point of the system will be inefficient. However, as discussed in 5.4.2, further multilateral trades which do not violate

system constraints are still feasible and profitable. These transactions will achieve system-wide efficiency.

## **6.1 Auctions in the electricity industry**

The term “auction” is commonly associated with the mental model of a room of people raising hands paying fortunes for unique works of art or of historical value, but it has a wider meaning. An auction is just an organized market where bids and offers are tendered, and then rules, known to participants, determine winners, losers, and the size of the “prizes”.

The nature of the auction price, a price that balances supply and demand may not equal the cost of service, as defined through traditional accounting principles. It does neither correspond to the value of service, associated with the market segmentation of a monopolist to identify captive consumers which are charged a higher price than other consumers. The auction price in a theoretical sense is equal to the marginal opportunity cost of the service and the marginal value of the service. (FERC, 1987)

The idea of using an auction is not new in deregulated power systems. It is through an auction mechanism that the pooling structure of a competitive market is intended to work. Auctions of this type are currently in operation in England and Wales and Argentina, among other countries. All these auctions assume that every participant formulates a bid with all the information required to prepare a day ahead schedule of the system dispatch. Maximum ramp up times, minimum on and off times and other constraints such as those described in section 5.2 are taken into account and a dynamic programming optimization tool used to generate the schedule. (Bastos, 1993)

Of particular interest is the auction being considered in California, the Western Power Exchange (WEPEX), in which suppliers and demanders will be allowed to change their bids as they see fit within a negotiation time frame. Ancillary services are also submitted to the auction and allocated to transactions as they are needed and also with a merit order criterion. The rules of such a multiple round auction are complex and must be designed in such a way that participants bid

reflecting their marginal opportunity costs and gaming strategies be prevented. The implementation of this auction will also impose a great technological challenge as to the computing power and telecommunications technology required. It is unclear at this point if the transaction costs imposed by such a mechanism will justify any improved efficiencies it may bring.

## 6.2 Auction rules

The rules of the auction proposed here are quite simple. The provider of the service is the ISO, which recollects a single bid from every participant and for every contract it has proposed. The information contained in the bid is a single amount, which is intended to reflect the maximum amount that the bidder is willing to pay for avoiding curtailment. These bids are allocated on a merit order basis, with no regard to the actual power transfers they represent. The ISO simulates the loading of the system with the actual power flows of each transaction, using the previous ranking order until a congestion constraint is violated. Thus, at the margin, only one transaction is curtailed to the level in which the power flow in the congested line is at its limit. Any remaining proposed transactions in the queue do not receive dispatch authorization and are deemed unfeasible. The final curtailment as a result of the auction is firm. The ISO will collect only the money of the bids of all those transactions that received authorization.

## 6.3 Numerical examples

The two examples analyzed here are a three bus system and a four bus system. They are the same used in (Ilic, 1997b) to perform their numerical examples of the methodology described in the previous chapter.

### 6.3.1 Three bus example

Consider a three bus system consisting of two generators and one load as illustrated in figure 6.1. The cost and utility functions are given by

$$C_1(q_{g1}) = q_{g1}^2 + q_{g1} + 0.5 \tag{6.1}$$



$$C_2(q_{g2}) = 2q_{g2}^2 + 0.5q_{g2} + 1 \quad (6.2)$$

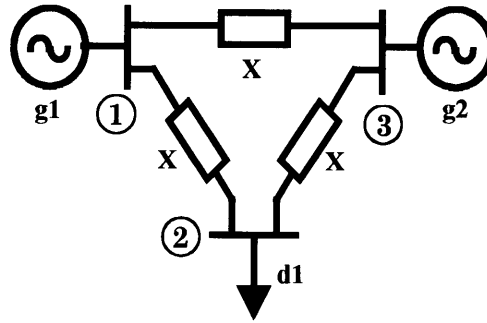
$$U_1(q_{d1}) = 214.1667 q_{d1} - 10q_{d1}^2 \quad (6.3)$$

where  $q_{g1}$  and  $q_{g2}$  are the quantities of real power injected into the network by the generators at buses 1 and 2 respectively and  $q_{d1}$  is the quantity of real power demanded by the load at bus 3. The transmission lines are assumed to have zero resistance and to have the same impedance, an extension of the assumptions in (4.2). Also, the generators and load are assumed to be an aggregation of smaller generators and loads, so that the market may be regarded as competitive and all players are regarded as price takers and cannot exercise any market power to influence prices.

The line flow from bus 1 to bus 2 may be approximated using the DC load flow (See Appendix A) as follows

$$T_{12} \approx \frac{2}{3} q_{g1} + \frac{1}{3} q_{g2} \quad (6.4)$$

Figure 6.1 Three bus system



The economics of this market are described in Appendix A. In the absence of congestion, the generators will engage in contracts with the load at the equilibrium price and quantities shown in Table 6.1.

Table 6.1 Equilibrium point in the market with no congestion, 3 bus example

$q_{g1}$	6.5833
$q_{g2}$	3.4167
$q_{d1}$	10.0000
$p$	14.1667

Assume now that the line connecting buses 1 and 3 ( $T_{13}$ ) has an upper flow limit of 5. Notice that according to (6.4) the equilibrium point yields a line flow of 5.5277, and the proposed transactions are not feasible. The ISO cannot allow these transactions to take place and requests bids from the generators for access through the congestion to determine how much is each willing to pay to transfer their energy. If only  $g_1$  and  $g_2$  participate in the bids there are only two possible outcomes, either  $g_1$  wins or  $g_2$  wins and whoever loses will be curtailed.

After curtailment, with help of the information provided by the ISO, further trades can take place. The economics of these post-curtailment trades are described in Appendix B. Since the curtailment by the ISO will be such that the power flow in  $T_{13}$  is at its limit, any further trades must not increase the flows across that line. From (6.4), it is possible to determine that this is possible if  $g_2$  increases generation at twice the amount that  $g_1$  reduces his. The results of trading in the second market are shown in the Tables 6.2 and 6.3 for the scenarios where  $g_1$  and  $g_2$  win the bid respectively.

Notice that before the second round trades take place, the operating point of the system is sub-optimal. In the case at hand, the maximum social welfare is 1060.97. If  $g_2$  is curtailed it is reduced to 1035.11 and to 1058.29 if  $g_1$  is curtailed. After the second round trading, both scenarios are at the same operating point that maximizes social welfare.

Table 6.2 Quantities traded and profits if  $g_1$  wins the bid.

	First round trading	Second round trading	Total Profits
$g_1$	6.5833	-1.1666	44.2013
$g_2$	1.8334	2.3332	28.2219
$d_1$	8.4167	1.1666	988.5421

Table 6.3 Quantities trades and profits if  $g_2$  wins the bid.

	First round trading	Second round trading	Total Profits
$g_1$	5.7917	-0.3750	42.3542
$g_2$	3.4166	0.7500	23.4723
$d_1$	9.2083	0.3750	995.1388

These scenarios assume that the generators and load capture all the profits to be made in the market. However, in a real market environment, the second round trading may need the intervention of a third party, a broker or similar, which may facilitate the actual realization of the multilateral trade and would also operate for a profit.

Notice that  $g_1$  makes a profit of 1.8471 more if he wins the bid. Thus it would be expected that  $g_1$  will be willing to bid for access up to this amount, at which he is indifferent about either outcome. However,  $g_2$  makes 4.7496 less if he wins the bid. According to the economics of the second market,  $g_2$  will be better off being curtailed and trading later on the better prices the second market will offer. On the other hand  $d_1$  is worse off by 6.5967 if  $g_1$  wins the bid, since its source of cheaper electricity will be curtailed. In a game in which only the generators participate, the outcome will always be that  $g_1$  is dispatched and  $g_2$  is curtailed, since it is the dominant strategy for both players. As a result, the ISO would be unable to collect any rents.

Table 6.4 Quantities traded and profits under an OPF

	Quantities traded	Total Profits/Utility
$g_1$	5.4167	28.8403
$g_2$	4.1667	33.7222
$d_1$	9.5833	998.2683

### 6.3.2 Four bus example

Consider now the four bus example shown in figure 6.2, in which the cost and utility functions are given by

$$C_1(q_{g1}) = q_{g1}^2 + q_{g1} + 0.5 \quad (6.5)$$

$$C_2(q_{g2}) = 2q_{g2}^2 + 0.5q_{g2} + 1 \quad (6.6)$$

$$U_1(q_{d1}) = 94.1667 q_{d1} - 10q_{d1}^2 \quad (6.7)$$

$$U_1(q_{d1}) = 158.1667 q_{d2} - 12q_{d2}^2 \quad (6.8)$$

The market equilibrium is similar to the previous example and is shown in Table 6.5.

Table 6.5      Equilibrium point in the market with no congestion, 4 bus example

$q_{g1}$	6.5833
$q_{g2}$	3.4167
$q_{d1}$	4.0000
$q_{d2}$	6.0000
$p$	14.1667

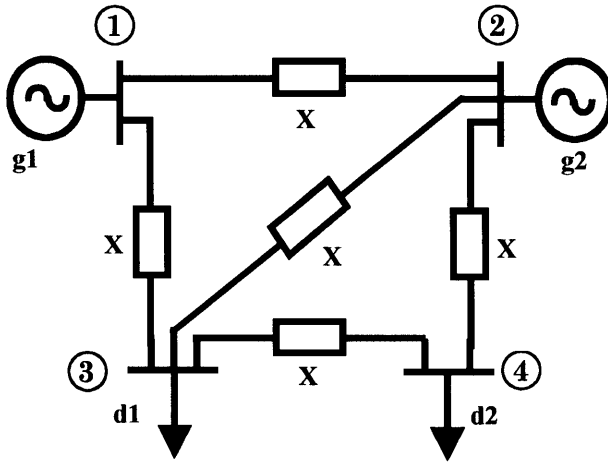
The system is assumed to be lossless and competitive as in the previous example. Computing the DC load flow leads to the following expression for the flow across  $T_{13}$ . (See Appendix A).

$$T_{13} \approx \frac{1}{2} q_{g1} + \frac{1}{8} q_{g2} + \frac{1}{8} q_{d1} \quad (6.9)$$

Consider now a transmission constraint of 3.8 on  $T_{13}$ . With the transactions proposed by the market the power flow along this line would be 4.2187, making the trades unfeasible. Once again the ISO will call for bids in order to determine the curtailment.

Notice now that the ISO needs to make a curtailment decision not only among the generators, but also between the loads. Thus, the pattern of curtailment will be strongly dependent on between whom are the contracts established. To analyze this in detail consider two approaches.

Figure 6.2      Four bus system



### 6.3.2.1 Nodal curtailment

First, assume that there are only four possible outcomes for the ISO to proceed with the curtailment after the auction has taken place. One of these is when  $g_1$  and  $d_1$  are allowed to trade at their proposed amounts, while  $g_2$  and  $d_2$  are curtailed to the level where the line flow is met. The four scenarios correspond to the combinations in which pairs of generators and loads can be arranged. The four possible scenarios with their respective profits for each party are presented in table 6.6, underneath the generator-load pair that is given priority to dispatch as a result of the auction.

Table 6.6 Profit/Utility for each player under different scenarios.

Curtailment Scenario				
Player	I: $g_1, d_1$	II: $g_1, d_2$	III: $g_2, d_1$	IV: $g_2, d_2$
$g_1$	43.6697	43.6700	42.1444	42.4495
$g_2$	30.0141	26.4621	22.9093	22.9093
$d_1$	160.5637	152.6084	160.5636	157.3821
$d_2$	420.7388	432.2458	429.3693	432.2458

The profits each party would see under each scenario determine the incentives each of them will have to see such a scenario happen. For example,  $g_1$  has an incentive to bid up to 1.5556, the difference between the best case (I) and worst case (III) scenario. Notice that once again  $g_2$  is better off by losing the auction by bidding zero, which will lead to a collusive behavior of the generators. However, the incentives among the loads do not present the same pattern. Consider the possibility that the loads actually participated in the auction, so that their preferences are taken into account. The consumers at  $d_1$  will have an incentive to bid up to 7.9553 to insure that they are not curtailed by the ISO, the difference between scenarios I and II, which are respectively the best and worst case scenarios. On the other hand the consumers at  $d_2$  are willing to bid up to 11.5070, in order to achieve the reverse outcome that  $d_1$  desires since they maximize their utility under scenario II and minimize it in scenario I. These values are not independent of the actions taken by  $g_1$  and  $g_2$ , but the decision of generators is predictable due to the optimal strategy

each of them must pursue to maximize its own profits. Thus, the outcome would be scenario II and the ISO would collect 7.9553 from  $d_2$ .

So far we have considered competition only between generators or between consumers, but is evident that there is also competition between generators and loads. If the consumers were allowed to determine with their bidding behavior the curtailment pattern of  $g_1$  and  $g_2$  by competing directly with them, the outcome would be scenario III, and the ISO would collect an extra 1.5256 from  $d_1$ , which is the maximum  $g_1$  is willing to bid for having the curtailment be their desired outcome, scenario I. Notice that the rules of the auction define it as a non-cooperative game, that is, one in which the parties are not allowed to negotiate binding contracts that allow them to plan joint strategies, otherwise  $g_2$  would have an incentive to help  $g_1$  bid more and perhaps force the collusive outcome both seek. If a cooperative game were allowed the ISO would collect 7.1047 more from  $d_1$ , the amount by which  $g_2$  would increase its profits if curtailed.

### 6.3.2.2 Contract curtailment

Consider now that the parties have engaged in contracts between them as described in table 6.7. In the pre-curtailment market, it is not relevant between which parties are the contracts engaged since they all make their transactions at the equilibrium price. If such is the case, the only motivation for having split contracts would be to minimize the overall risk of the portfolio of contracts a particular generator or consumer may have agreed upon.

Table 6.7 Contracts proposed to the ISO before curtailment

Contract	Seller $\rightarrow$ buyer	Quantity
A	$g_1 \rightarrow d_1$	2.6333
B	$g_1 \rightarrow d_2$	3.9500
C	$g_2 \rightarrow d_1$	1.3667
D	$g_2 \rightarrow d_2$	2.0500

There exist nine possible curtailment outcomes in which the ISO could reduce the quantities traded and meet the transmission line constraint, out of the twenty-four possible combinations of dispatch order. The correspondence of each particular

combination to each scenario is shown in table 6.8, and the profit that would be derived by each party under each scenario is presented in table 6.9.

Table 6.8 Grouping of contract dispatch combinations into each scenario.

I	II	III	IV	V	VI	VII	VIII	IX
ABCD	ABDC	ACBD	ACDB	ADBC	BCAD	BCDA	BDAC	BDCA
BACD	BADC	CABD	CADB	ADCB	CBAD	CBDA	DBAC	DBCA
			CDAB	DABC		CDBA		
			DCAB	DACB		DCBA		

Table 6.9 Profit/Utility for each player under different scenarios of contracts.

	I	II	III	IV	V	VI	VII	VIII	IX
$g_1$	43.6698	43.6696	43.0772	42.1437	43.4041	43.1989	42.4523	43.4450	42.4613
$g_2$	28.6343	27.1149	27.2577	22.9101	25.7906	27.2531	22.9070	25.8076	22.8997
$d_1$	157.4776	154.0739	160.5640	160.5640	154.0751	159.3289	157.3825	153.4884	157.3830
$d_2$	425.2048	430.1282	424.0881	429.3691	431.7167	425.2057	432.2448	432.2456	432.2426

Once again, the optimal outcome of  $g_1$  and  $g_2$  occurs in the same scenario (I), in which  $g_1$  makes a profit of 1.5262 and  $g_2$  5.7346 over their respective worst case scenarios. The incentive is towards a collusive outcome and there is no competition and revenues to the ISO if only the generators participate in the auction.

Consider now the competition among the loads. The consumers at  $d_1$  prefer scenario III, with a differential of 7.0756 and those at  $d_2$  prefer scenario VIII with a difference of 8.1572 over their respective worst cases. There is true competition between the players since there is no possible collusive outcome.

The bidding behavior of each of the loads is determined by the rules of the auction. If the players were allowed to bid for the contracts it is involved with as a bundle, then the bidding behavior is similar to that of the nodal curtailment case. However, as the rules have been stated in 6.2, each contract must have a separate bid, so that each party would have to distribute its expected benefits among each of the contracts. In this case, the optimal strategy for each of them will be a mixed strategy, that is, one in which random choices are made for the precise distribution of the bids in each contract. Notice that under such a scheme there is no pure

strategy that will leave both of the players satisfied, since one of them can always do better by changing their strategy<sup>5</sup>.

For example, consider that  $d_1$  bids 7.07 for access of its C contract, the maximum it is willing to bid, and nothing for its A contract. On the other hand,  $d_2$  bids 7.1 for its D contract and 0.1 for its B contract, winning access for both of them before either of  $d_1$ 's contracts. If  $d_1$  knew about this behavior beforehand, it would want to change its strategy to bid more for its A contract and improve its position. However,  $d_2$  will change its strategy once more if it was able to know about this change.

For this reason, the revenue collected by the ISO will be characterized with great uncertainties, not only those of when and how will the congestion occur, but subject to the random behavior of the individual players.

## 6.4 Conclusions

Auctions are an effective way of providing meaningful incentives to consumers and producers according to marginal costs and marginal benefits.

An auction mechanism has been considered here for the allocation of available transmission capacity to users of the system. The use of an auction insures that those who value the system most are the ones who have priority on their access.

However, it was proven that the initial proposition of having only generators participate in the auction may doom the auction system to failure, since there may be incentives to collude. When consumers are allowed to participate in the auction true competition arises and the auction seems to work.

Of particular interest is that two parties that may have engaged in a particular contract, namely a generator and a consumer *may have different valuations of the same contract*. As a result, they may have conflicting interests as to whether the contract is curtailed or not which will affect their bidding behavior. Thus, the auction will also provide economic signals to the users of the system to engage in further negotiations as they may see opportunities to trade from the

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<sup>5</sup> Under the terminology of game theory in economics, there does not exist a Nash equilibrium for pure strategies in such a game, in which no individual can do better by changing its strategy.



bidding behavior of their counterparts. This can be seen as a disadvantage of the system, that some financial information needs to be disclosed. Closed envelope bids may be suggested if there is consensus about it.

The funds collected by the ISO should not be directed to the owners of the transmission system. In fact, the total amount of the funds will have great uncertainties associated with it and it will always be less than the merchandising surplus. The perverse incentives described in the previous chapter need to be avoided. Furthermore, these uncertainties will complicate the methodologies to calculate the adequate transmission tariffs that reflect the value of system expansions to the users of the system.

## Chapter 7

# Conclusions: How to make the Central American power market work?

The creation of the Central American power market with the introduction of competition is a major challenge for the system and to the policy makers in charge of developing the protocols required for its appropriate operation. However, there is growing experience around the world about vital elements that must be in place.

From the analysis of the political history and present environment of the region, it has been concluded that the regional market mechanisms must meet three very important and basic criteria: economic efficiency, respect to national sovereignties and a reasonably equal distribution of the benefits derived from integration.

Throughout the thesis, several of the issues concerning the establishment of competitive markets for electricity have been discussed. This final Chapter is intended to wrap up all these issues and summarize the recommendations and conclusions of the research, which are presented below.

- *The Central American countries should integrate their electricity markets into one regional competitive market.*

It is in the best interest of all the countries of Central America that the integration of their electricity markets takes place. There are substantial benefits to be derived from such an agreement to the region as a whole. These are in the form of cheaper electricity and fewer investments in generation capacity.

Furthermore, competition can provide the proper incentives for these efficiencies to be achieved. The evidence around the world of competitive electricity markets is one of increased productivity of these valuable assets. Where market power issues have been properly avoided, substantial reductions to the price of electricity to consumers have been evidenced.

- *Centralized vs. Decentralized Operation*

The TMEAC proposes that a regional ISO (the EOR) will insure the economic dispatch of the system. This can only be achieved if all generators put their assets at the disposition of the ISO and their cost structures made public. This poses a conflict with how some of the countries want to handle their local markets.

To insure the sovereignties the countries desire as to how to structure their local markets, a bilateral model is suggested instead. It can achieve the same level of short term economic efficiency, permitting the desired flexibility.

However, given the technical characteristics of how a power system operates and the type of controls needed for the reliable and secure operation of the system, the intervention of an ISO is key to monitoring the system and have some degree of centralized control. Its intervention is also required to handle the network externalities present in the system.

- *Special mechanisms are needed to handle network externalities.*

Although the economic benefits of a competitive marketplace come from improvements in long term and medium term efficiencies, special attention should be given to short term efficiency. Due to the presence of network externalities special mechanisms are needed to correct market failures which may cause the system to operate away from its optimum.

Different proposals have been analyzed. They achieve the above objective, under different conceptions of what open access means. The choice of mechanism in Central America has to be made through a negotiated consensus, because the actual protocols will strongly influence the profit allocation among the parties. Although a “fair” mechanism of allocating the costs imposed by transmission constraints would be desirable, such criteria are not of a technical nature and will be subject to political choices.

- *Separation of transmission from generation.*

The new technologies available for generation have removed economies of scale, but these are still present in transmission. To avoid vertical market power issues, these two activities must inevitably be separated. As mentioned before, the TMEAC does specify the commitment of the countries to separate them. At present they are still vertically integrated.

- *Transmission pricing must be regulated.*

The charges for the use of the transmission system must recover the investments on these valuable assets and provide revenues to their owners. At the same time, they must be based in marginal costs to insure the recovery of the investments.

All the mechanisms to handle congestion externalities discussed in Chapter 5, and even the bidding system considered in Chapter 6, can provide these economic signals. In one way or another, they require that funds be collected by the ISO, with the exception of the multilateral trades proposed by Wu. These depend on the marginal value of the congested network to the users and are thus an indicator of system expansions. These funds should not, however, be allocated directly to transmission owners as incentives for improper maintenance and other perverse behaviors may be expected. They are based on *short run* marginal cost signals which may be deceptive. Instead, regulators should analyze these signals and price transmission according to *long run* marginal cost criteria.

- *Anti-trust regulation is vital.*

Although the problem of vertical market power can be minimized by disintegrating the industry as described above, horizontal market power issues may remain. In the countries where privatization is taking place, regulators have to place special care in dividing generation assets as much as possible. In the case of the regional market, the attractive “mega-projects” being considered should be watched closely. In any case, the establishment of any competitive market requires proper anti-trust legislation to prevent monopolistic behavior.

- *Bidding for access through congestion may not work.*

In Chapter 6, an auction mechanism was considered for allocating available transmission capacity to the generators of the system, intended to give priority on their access to the system to those who value it the most. However, the auction system will only create competition and achieve its objective if consumers participate in the auction.

Thus, a more complicated mechanism than the one being considered in El Salvador needs to be implemented. Such an auction would make the structure of the system to look more like a pooling market than a truly bilateral market,

## Appendix A

In both examples generator 1 ( $g_1$ ) acts as the slack bus.

### A.1 DC load flow of the three bus example

In the system shown in figure x, the reduced incidence matrix is given by

$$\mathbf{A} = \begin{bmatrix} -1 & 0 & 1 \\ 0 & -1 & -1 \end{bmatrix}$$

Let  $y$  be the diagonal matrix with elements the susceptances of the transmission lines. Since all susceptances are equal to one  $y$  is an identity matrix. Thus the admittance matrix of the system is

$$\mathbf{Y} = \mathbf{A}y\mathbf{A}^T = \begin{bmatrix} 2 & -1 \\ -1 & 2 \end{bmatrix}$$

From the linearized matrix representation of the  $P$ - $\delta$  problem, we find that

$$\boldsymbol{\delta} = \mathbf{Y}^{-1}\mathbf{P} = \begin{bmatrix} 2/3 & 1/3 \\ 1/3 & 2/3 \end{bmatrix} \begin{bmatrix} q_{g2} \\ -q_d \end{bmatrix} = \begin{bmatrix} 2/3 q_{g2} - 1/3 q_d \\ 1/3 q_{g2} - 2/3 q_d \end{bmatrix}$$

and substituting  $q_d = q_{g1} + q_{g2}$ , which comes from the power balance in the system,

$$\boldsymbol{\delta} = \begin{bmatrix} 1/3 q_{g2} - 1/3 q_{g1} \\ -1/3 q_{g2} - 2/3 q_{g1} \end{bmatrix}$$

From Kirchoff's voltage equations,

$$\boldsymbol{\theta} = \mathbf{A}^T \boldsymbol{\delta} = \begin{bmatrix} 1/3 g_1 - 1/3 g_2 \\ 2/3 g_1 + 1/3 g_2 \\ 1/3 g_1 + 2/3 g_2 \end{bmatrix}$$

Since all susceptances are unity, then  $\mathbf{T} = \boldsymbol{\theta}$  and the power flowing through the transmission line  $T_{g1-d}$  is given by the expression of the second element of the vector above,

$$T_{g1-d} = 2/3 g_1 + 1/3 g_2$$

## A.2 DC load flow of the four bus example

The procedure is the same as in the three bus example. The system of Figure 6.2 has a reduced incidence matrix given by

$$\mathbf{A} = \begin{bmatrix} -1 & 0 & 1 & 1 & 0 \\ 0 & -1 & -1 & 0 & 1 \\ 0 & 0 & 0 & -1 & -1 \end{bmatrix}$$

Since  $\mathbf{y}$  is once more an identity matrix, the phase angles relative to the reference bus are given by

$$\delta = (\mathbf{A}\mathbf{y}\mathbf{A}^T)^{-1} \mathbf{P} = \begin{bmatrix} 5/8 & 3/8 & 1/2 \\ 3/8 & 5/8 & 1/2 \\ 1/2 & 1/2 & 1 \end{bmatrix} \begin{bmatrix} g_2 \\ -d_1 \\ -d_2 \end{bmatrix} = \begin{bmatrix} 5/8 g_2 - 3/8 d_1 - 1/2 d_2 \\ 3/8 g_2 - 5/8 d_1 - 1/2 d_2 \\ 1/2 g_2 - 1/2 d_1 - d_2 \end{bmatrix}$$

From Kirchoff's voltage equations,

$$\theta = \mathbf{A}^T \delta = \begin{bmatrix} -5/8 g_2 + 3/8 d_1 + 1/2 d_2 \\ -3/8 g_2 + 5/8 d_1 + 1/2 d_2 \\ 1/4 g_2 + 1/4 d_1 \\ 1/8 g_2 + 1/8 d_1 + 1/2 d_2 \\ -1/8 g_2 - 1/8 d_1 + 1/2 d_2 \end{bmatrix}$$

Since once more all susceptances are equal to one, the relation  $\mathbf{T} = \theta$  still holds and the power flowing through the transmission line  $T_{g_1-d_1}$  is given by the expression of the second element of the vector above,

$$T_{g_1-d_1} = -3/8 g_2 + 5/8 d_1 + 1/2 d_2 = 1/2 g_1 + 1/8 g_2 + 1/8 d_1$$

since  $d_2 = g_1 + g_2 - d_1$ .

## Appendix B

This appendix describes the economics of an energy market without congestion for the general case of  $n_g$  generators and  $n_d$  loads demanding power. It goes on to consider the economics of a market where congestion is present for a simple three bus example and a slightly more complicated four bus example, including the trading in a second tier market after curtailment. The analysis is shown here for the sake of completeness of this thesis, but it is directly taken from (Ilic, 1997b), with minor modifications.

### Energy market economics without congestion

Every generator  $g_i$  in the system is assumed to have a quadratic cost function of the quantity produced  $q_{gi}$ , and every consumer  $d_i$  has a quadratic utility function of its use of  $q_{di}$  units of power it produces<sup>6</sup> as follows

$$C_i(q_{gi}) = a_{gi}q_{gi}^2 + b_{gi}q_{gi} + c_{gi} \quad (\text{B.1})$$

$$U_i(q_{di}) = -a_{di}q_{di}^2 + b_{di}q_{di} + c_{di} \quad (\text{B.2})$$

For an individual supplier, its marginal cost is

$$MC_i = \frac{dC(q_{gi})}{dq_{gi}} = 2a_{gi}q_{gi} + b_{gi} \quad (\text{B.3})$$

and its profit is given by

$$\pi_{gi} = pq_{gi} - C_i(q_{gi}) \quad (\text{B.4})$$

where  $p$  is the competitive market price. The optimal strategy is to produce an amount of power such that the marginal cost of generation equals the price as shown below when satisfying the first-order condition

$$\frac{d\pi_{gi}(q_{gi})}{dq_{gi}} = p - MC_i(q_{gi}) = 0 \quad (\text{B.5})$$

Thus, the supply function of a single generator is given by

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<sup>6</sup> The notation of  $q$  to denote quantities and  $p$  to denote prices derives from economic theory and is rather inconvenient for engineering readers used to use  $p$  as the variable for power.



$$S_i(p) = q_{gi} = \frac{p - b_{gi}}{2a_{gi}} \quad (\text{B.6})$$

Aggregating all suppliers to obtain the complete supply curve of the market we obtain

$$S(p) = \alpha_s p - \beta_s \quad (\text{B.7})$$

where

$$\alpha_s = \sum_{i=1}^{n_g} \frac{1}{2a_{gi}} \quad (\text{B.8})$$

$$\beta_s = \sum_{i=1}^{n_g} \frac{b_{gi}}{2a_{gi}} \quad (\text{B.9})$$

A similar procedure can be used to find the aggregate demand function of the market. The marginal utility which a single consumer derives from using electricity is obtained by differentiating (B.2)

$$MU_i(q_{di}) = \frac{dU(q_{di})}{dq_{di}} = -2a_{di}q_{di} + b_{di} \quad (\text{B.10})$$

The profit or utility that the load derives from using the power is given by

$$\pi_{di} = U_i(q_{di}) - pq_{di} \quad (\text{B.11})$$

which is maximized by differentiation

$$\frac{d\pi_{di}(q_{di})}{dq_{di}} = MU_i(q_{di}) - p = 0 \quad (\text{B.12})$$

Hence, the demand function for the  $i$ -th load is given by

$$D_i(p) = q_{di} = \frac{b_{di} - p}{2a_{di}} \quad (\text{B.13})$$

and the total aggregate demand is

$$S(p) = \beta_D - \alpha_D p \quad (\text{B.14})$$

where

$$\alpha_D = \sum_{i=1}^{n_d} \frac{1}{2a_{di}} \quad (\text{B.15})$$

$$\beta_D = \sum_{i=1}^{n_d} \frac{b_{di}}{2a_{di}} \quad (\text{B.16})$$

The competitive price as equilibrium would be given by

$$p_\lambda = \frac{\beta_S + \beta_D}{\alpha_S + \alpha_D} \quad (\text{B.17})$$

The dynamic equation which describes the rate of convergence of the market towards the competitive equilibrium is given by the law of supply and demand. If supply is higher than demand, prices will fall, and if demand is higher than supply, prices will rise until the equilibrium is reached.

$$\frac{dp}{dt} = D(p) - S(p) = -(\alpha_S + \alpha_D)p + \beta_D + \beta_S \quad (\text{B.18})$$

Given our assumptions  $\alpha_S$ ,  $\alpha_D$ ,  $\beta_S$  and  $\beta_D$  are all positive and (B.18) will converge to  $p_\lambda$  for any initial conditions.

### Energy market economics in a three bus system with congestion

As discussed in Chapter 6, after a first round of trading the market would have reached an equilibrium described by the equations in section B.1. However, those trades are not feasible if a transmission limit is violated. The market participants must engage in a second round of trading after a curtailment procedure has been adopted. The economics of trading in the post-curtailment market are outlined below for the simple three bus example of figure 6.1.

A brief note on notation. First round trading quantities and prices are marked with a single apostrophe ('). Second round trading variables are marked with two apostrophes (''). When no apostrophe is shown it is referred to the overall amounts.

By reducing its generation and buying power from  $g_2$  and selling half of it to  $d_1$ ,  $g_1$  is able to make a second round profit given by

$$\begin{aligned} \pi_{g_1}'' &= p_{g_1-d_1} q_{g_1}'' - 2 p_{g_1-g_2} q_{g_1}'' + a_{g_1} q_{g_1}'^2 + b_{g_1} q_{g_1}' + c_{g_1} \\ &\quad - [a_{g_1}(q_{g_1}' - q_{g_1}'')^2 + b_{g_1}(q_{g_1}' - q_{g_1}'')^2 + c_{g_1}] \end{aligned} \quad (\text{B.18})$$

which is maximized when the following first order condition is met

$$\frac{d\pi_{g_1}''}{dq_{g_1}''} = p_{g_1-d_1} - 2p_{g_1-g_2} + 2a_{g_1}(q_{g_1}' - q_{g_1}'') + b_{g_1} = 0 \quad (\text{B.19})$$

from which the following relation can be obtained that is the supply function in the  $g_1-d_1$  energy market and the demand function in the  $g_1-g_2$  market

$$q_{g1}'' = \frac{p_{g1-d1} - 2p_{g1-g2} + b_{g1}}{2a_{g1}} + q_{g1}' \quad (B.20)$$

We have assumed here that  $g_1$  acts as the broker in this second market.

However, the amount traded and the nodal prices are independent of the choice of middleman and can be proven by choosing  $d_1$  to be the broker instead.

The demand of  $d_1$  and the supply from  $g_2$  are the same as in the marketplace before congestion

$$S_{g1-g2}(p_{g1-g2}) = q_{g1}'' = \frac{p_{g1-g2} - b_{g2}}{2a_{g2}} - q_{g2}' \quad (B.21)$$

$$D_{g1-d1}(p_{g1-d1}) = 2q_{g1}'' = \frac{b_{d1} - p_{g1-d1}}{2a_{d1}} - q_{d1}' \quad (B.22)$$

Solving for  $p_{g1-d1}$  and  $p_{g1-g2}$  in (B.22) and (B.21) and substituting in (B.20) and solving for  $q_{g1}''$  we obtain

$$q_{g1}'' = \frac{a_{g1}q_{g1}' - 2a_{g2}q_{g2}' - a_{d1}q_{d1}' + \frac{1}{2}b_{g1} - b_{g2} + \frac{1}{2}b_{d1}}{a_{g1} + 4a_{g2} + a_{d1}} \quad (B.23)$$

$q_{g1}''$  is the amount of power traded in the post-curtailment market at the prices  $p_{g1-d1}$  and  $p_{g1-g2}$ .

## Energy market economics in a four bus system with congestion

The case is the same as in section B.2, but now a four bus system is considered as depicted in figure 6.2.

In the post-curtailment market,  $g_1$  will make a profit of  $\pi_{g1}''$  from buying  $q_{g1}''$  units of power from  $g_2$  in the manner of savings from reducing generation level.

$$\begin{aligned} \pi_{g1}'' &= -p_{g1}q_{g1}'' + a_{g1}q_{g1}'^2 + b_{g1}q_{g1}' + c_{g1} \\ &\quad - [a_{g1}(q_{g1}' - q_{g1}'')^2 + b_{g1}(q_{g1}' - q_{g1}'')^2 + c_{g1}] \end{aligned} \quad (B.24)$$

The profit maximizing condition can be found by differentiation

$$\frac{d\pi_{g1}''}{dq_{g1}''} = -p_{g1} + 2a_{g1}(q_{g1}' - q_{g1}'') + b_{g1} = 0 \quad (B.25)$$

which will yield the following demand function for power from  $g_1$  in

$$D_{g1}(p_{g1}) = \frac{b_{g1} - p_{g1}}{2a_{g1}} + q_{g1}' \quad (\text{B.26})$$

On the other hand, the generator at bus 2 will be willing to sell more energy, according to the supply function

$$S_{g2}(p_{g2}) = \frac{p_{g2} - b_{g2}}{2a_{g2}} - q_{g2}' \quad (\text{B.27})$$

To stay within the line flow constraint, the load at bus 3 will make a profit (greater utility) when trading with both  $g_1$  and  $g_2$ , given by

$$\begin{aligned} \pi_{d1}'' = & \frac{2}{3} p_{g1} q_{d1}'' - \frac{5}{3} p_{g2} q_{d1}'' - (b_{d1} q_{d1}' - a_{d1} q_{d1}'^2) \\ & + b_{d1} (q_{d1}' + q_{d1}'') - a_{d1} (q_{d1}' + q_{d1}'')^2 \end{aligned} \quad (\text{B.28})$$

which after differentiation will yield the following demand function for load 1

$$D_{d1}(p_{g1}, p_{g2}) = q_{d1}'' = \frac{b_{d1} + \frac{2}{3} p_{g1} - \frac{5}{3} p_{g2}}{2a_{d1}} - q_{d1}' \quad (\text{B.29})$$

In a similar manner, the demand of power in this second market from the load 2 is given by

$$D_{d2}(p_{g1}, p_{g2}) = q_{d2}'' = \frac{b_{d2} + \frac{1}{3} p_{g1} - \frac{4}{3} p_{g2}}{2a_{d2}} - q_{d2}' \quad (\text{B.30})$$

All post-curtailment trading must satisfy the following conditions in order to remain within the line flow constraint.

$$q_{g1}'' = \frac{2}{3} q_{d1}'' + \frac{1}{3} q_{d2}'' \quad (\text{B.31})$$

$$q_{g2}'' = \frac{5}{3} q_{d1}'' + \frac{4}{3} q_{d2}'' \quad (\text{B.32})$$

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