On the Value of Transmission Systems under Open Access: Incentives for Investment

by

Pedro Alfonso Lerner

B.S., Mechanical Engineering
Pontificia Universidad Católica del Perú, 1993

Submitted to the Department of Mechanical Engineering and the
Department of Electrical Engineering and Computer Science
in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Technology and Policy
and
Master of Science in Electrical Engineering and Computer Science

at the
Massachusetts Institute of Technology
June 1997

Signature of Author...
Department of Mechanical Engineering
May 19, 1997

Certified by...
Marija D. Ilic
Senior Research Scientist
Thesis Supervisor

Accepted by...
Richard de Neufville
Chairman, Technology and Policy Program

Accepted by...
Ain A. Sonin
Chairman, Committee on Graduate Students
Department of Mechanical Engineering

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

On the Value of Transmission Systems under Open Access:
Incentives for Investment

by

Pedro Alfonso Lerner

Submitted to the Department of Mechanical Engineering and
the Department of Electrical Engineering and Computer Science on May 19, 1997,
in partial fulfillment of the requirements for the degrees of
Master of Science in Technology and Policy
and
Master of Science in Electrical Engineering and Computer Science

ABSTRACT

The Energy Policy Act of 1992 (EPACT) is rapidly increasing competition in wholesale electric power generation. The act boosted Public Utilities Regulatory Act of 1978 (PURPA) which began encouraging competition in this industry. The result is the development of more competing independent power producers (IPPs). Efficient competition demands open and non discriminatory access to the transmission system and, consequently, the separation of the three levels of vertically integrated utilities: generation, transmission, and distribution.

In vertically integrated utilities, transmission planning decisions were aimed at reducing overall generation costs and enhancing system reliability. Therefore, the role of transmission systems is to increase the efficiency of markets for electric power. Yet, the separation of generation and transmission ownership creates an incentive problem for transmission investment: investments in the transmission system should be economically attractive only if they reduce social cost. Unfortunately, an incentive structure to make this true has not been found yet.

This thesis focuses on the problem of incentives for transmission investment in the context of the restructured electric industry. Firstly, it concentrates on the economic importance of the transmission system. It applies the concept of avoided social cost as a yardstick to evaluate the economic value of individual links within a transmission network. This economic value is proven to be related not only to transmission capacity and congestion, but also to network topology. Secondly, it calls for a separation between the sources and the allocation of network revenue. Thirdly, it proposes for the first time a network revenue allocation rule based on the relative importance of individual links. Finally, it assesses the impact of the resulting incentive structure on transmission system upgrades and competitive market players. It concludes that, in a fully competitive environment, the proposed network allocation scheme promotes grid enhancements that result in system cost savings.

A five-bus electric power system model is used to illustrate the intuitive notions and relationships presented in the text. Simulations are done for different transmission link capacity and network topology scenarios. Intriguing results open the door for further research.

Thesis Supervisor: Dr. Marija D. Ilic.

To my parents
Salomón and Rosemary

Acknowledgments

I want to give thanks to all who made my stay at MIT the most valuable experience of my life. I owe myself to my family and friends, both here in the US and in Perú, whose confidence and love I will never forget. A special recognition goes for the people who made this thesis possible: Marija, my advisor and foremost supporter, Nano my closest uncle, Paulo and Carlos, dearest friends who helped me in the last stages of what seemed an endless endeavor. Finally, want to express my gratitude to my uncle Jaime Rizo-Patrón and all my friends at ARPL who made this experience possible.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 The world-wide restructuring of the electric utility industry.

The main thrust behind the world-wide restructuring of the electric power industry has been the promotion of competition in generation. According to micro economic theory, competitive environments usually lead to improved social welfare. One of the goals of the deregulation of the electric industry is to encourage improvements in social welfare. In the US, the move towards competition in generation, started by the Public Utilities Regulatory Act of 1978 (PURPA) and boosted by the Energy Policy Act of 1992 (EPACT), is leading to a rapid development of competing independent power producers (IPPs) in the wholesale electric power business.

It was once believed that vertically integrated utilities enjoyed economies of scale and scope in both operations and planning. Economies of scale, distinctive of natural monopolies, were present at the three levels of vertical integration: generation, transmission and distribution. At the generation level it was less expensive to produce large amounts of power in a few large facilities than in many smaller units. In fact, the optimal generating plant size increased continually for almost 50 years until the 1980's. Operating costs attributable to the transmission system relate to maintenance and, mostly, to transmission losses. High voltage transmission lines reduce losses but require large capital investments. Hence, efficient transmission systems are only cost effective for bulk power transfers. Economies of scale in distribution are the same as those in other network based industries. The multiplication of systems serving the same area is deemed both costly and unnecessary.

In addition, economies of scope speak in favor of vertical integration. Complete access to information and centralized decision making provide the ideal conditions for efficient operations. Taking advantage of these conditions, most utilities pooled their resources and coordinated their dispatches. Utility planning enjoyed economies of scope from having several resources available to achieve a unique performance objective: to serve demand at the lowest possible cost. Utilities assessed the impacts on their cost structure that would result from investing in transmission enhancement, building new generation units or operating more expensive units. Consequently, centralized coordination between generation and transmission in the operation and planning of electric power systems internalized negative and positive externalities, such as transmission congestion[1] or improved system reliability.

With the introduction of new cost-efficient generation technologies, and the improved availability of natural gas, smaller and cheaper generation units became economical and started to be built. In some cases, the all-inclusive cost of a new plant was less than the sunk cost of the existing units paid by consumers. Consumers then started to ask why they could not switch suppliers (Hunt et al., 1995). The notion that society will gain from competition in generation has lead the restructuring of the electric power industry in the U.S. and elsewhere.

1.2 Open access and separation of ownership.

Competition in the generation sector based on marginal cost pricing can only be achieved if non-discriminatory (open) access to the transmission network is guaranteed (FERC, 1996). Transmission is not part of either the supply or the demand side of the market. Its role is to provide the infrastructure that makes energy transactions feasible.

The configuration of the transmission system constrains the most economically attractive set of transactions among active market participants. In other words, it determines the bounds of what is feasible and what is not. From an economic perspective, this configuration has a tremendous impact on the efficiency of the supply/demand market. It follows that a transmission system has a great deal of

---

[1] Transmission congestion is a recently adopted term referring to reaching thermal transmission line constraints.

market power, and therefore separation of generation and transmission ownership is considered necessary to guarantee open access.

1.3 Separation of ownership, externalities and market failure.

At a first glance, the separation of generation and transmission ownership does not seem to impact significantly on the short-term operations of the system and, consequently, the benefits from competition in generation. In fact, most of the effort so far has been put into the discussion and design of those market frameworks that best support short-term competition in generation. Unfortunately, advocates of both centralized market operations and multilateral trading schemes have focused their analyses on the short-term operations of the system, where the grid is assumed to be fixed[2].

However, this separation of ownership unveils an externality that leads to market failure. The transmission system creates an externality on the market because it determines which power transactions are feasible and economical, and which are not. The social value of a transmission system lies in its ability to enable operations to be as reliable and cost effective as possible. A market fails when the price of a good does not reflect its social value. Indeed, the improved reliability and cost-effectiveness that a transmission system creates for market operations do not translate into benefits for the transmission investors. They only benefit the competitive market players.

Furthermore, the natural source of revenues to pay for the transmission system is the collection of transmission charges. In an efficient nodal spot market the collection of transmission charges equals the merchandising surplus[3] The merchandising surplus is defined as the difference between the revenue collected from the loads and the revenue paid to the generators. Indeed, the merchandising surplus depends on the configuration and strength of the grid. However, it increases with

---

[2] He adoption of flexible AC transmission systems (FACTS) would also necessitate the revision of this assumption.

[3] Merchandising surplus is also known as network revenue.

transmission losses and congestion, that is, with transmission inefficiencies. It seems then that it is in the best interest of the transmission investors to degrade the efficiency of the system. Consequently, the separation of ownership does not only create a case of flagrant market failure, but also additional incentives that reinforce it.

Only recently have some authors started to realize that a serious *agency problem* is created by the divestiture of vertically integrated utilities. The transmission system (the agent) serves suppliers and consumers (the principal). The agency problem arises when the interests of the agent are not in accordance with the interests of the principal. Transmission system owners maximize their benefits at the expense of power suppliers and consumers. The solution to this problem requires the design of an incentive structure that rewards the *agent* when its actions benefit the *principal.* Consequently, the goal is to align the interests of the transmission owners with those of the rest of the system. For this goal to be achieved, investments in the transmission grid should be economically attractive only if they reduce social cost[4].

1.4 The problem of incentives

The solution of the agency problem requires a quantitative assessment of the externality that the transmission system creates on the market. We must understand and measure the effects of the transmission system on the market, if we wish to internalize this externality. It is only by knowing how a transmission system affects the market that we can design a policy of incentives for transmission investment that reflects these effects.

Interconnected transmission grids exist because they add value to the system. Little attention has been given to the quantification of such value. It has not yet been determined whether the value of a transmission grid can be broken down into the values of its individual components, namely the transmission links. The

---

[4] Reduction in social cost means either a decrease in operating/generating costs or an increase in social welfare.

impact that results from the removal of a transmission link has only been addressed in the context of system reliability.

The nodal spot pricing theory, first introduced by Schweppe et al (1988), is the undisputed paradigm of short-term economic efficiency in the electric power industry. Spot prices (nodal prices) incorporate all relevant information of the existing grid (Schweppe et al, 1988) and the economic impact of all transactions. As such, they give market agents clear signals that create incentives for optimal operation of the existing system.

It is my belief, however, that a basic assumption of this theory has biased many people's perception of the importance of basic transmission network characteristics. Since transmission assets cannot be altered in the short run, market operations based on spot pricing theory assume the transmission grid as given[5]. The network topology is assumed to have been determined a priori. The only network parameters that seem relevant for the market's operation are the line impedances and transmission capacities. For a given network, line impedances determine load flows and transmission losses, whereas transmission capacities constrain the set of feasible dispatches. The importance of a fundamental network characteristic, namely topology, is obscured. The difference between keeping or losing a particular link is not and cannot be captured by the spot pricing theory. As this thesis will show, network topology plays an extremely important role in the understanding of the network's externality on the market.

The bottom line is that the externalities that a transmission system creates on the supply/demand market are a function not only of the transmission capacity and impedance of existing lines, but also of *which* lines are actually in place.

1.5 Thesis objectives

This thesis deals with the problem of incentives for transmission investment in the context of a restructured electric industry. The first objective is to make a quantitative assessment of the impact of the transmission network on the market

---

[5] However, this situation could change in the near future with the progressive adoption of FACTS.

for power. This impact is measured in terms of savings that the market enjoys because of individual links within the grid. The savings created by a particular link become apparent only when the link is removed. Therefore, these savings are referred to as avoided social cost. The avoided social cost then becomes a yardstick to measure the value of the transmission grid.

The second objective is to design an incentive structure that correlates the interests of transmission owners with those of the market. An allocation rule based on the relative values of the transmission links is designed and its impact on future investments as well as on competitive market players is assessed.

The different ideas developed throughout the work of this thesis are illustrated by means of results from simulations performed on a 5 node electric power system model. The model was designed to assess the economic impact of transmission capacity as well as network topology on the operation of the system.

1.6 Thesis outline

This thesis is divided into five chapters. Chapter 2 presents a bibliographic survey that constitutes the analytic framework of this thesis. This chapter briefly discusses issues related to (a) the electricity market; (b) power system operations; (c) transmission pricing and incentives; and (d) transmission investment. In addition, it presents the definitions of network externalities, as well as economies of scale and scope. Chapter 3 deals with the quantitative assessment of the economic value of a transmission grid. This chapter (a) makes the point that the economic impact of a transmission link is not solely a matter of congestion; (b) describes the numerical 5-node system used as an example; and (c) relates the notions of avoided social cost and relative value of a transmission link to network topology and transmission capacity. Chapter 4 deals with the design and implications of an incentive structure that rewards individual links according to their relative value. In particular, this chapter (a) discusses the network revenue and its relationship to network topology, transmission congestion and losses; (b) defines a network revenue allocation rule based on the relative values of individual links; (c) argues in favor of a performance-based "competitive" environment for investments in transmission;

and (d) analyzes the implications that such an incentive scheme would have on grid expansion and, consequently, on the market.

Chapter 2

Bibliographic Survey

This section presents basic concepts for a discussion about investment incentives in electric power transmission. Section 2.1 presents the different agents in the electric power industry. Section 2.2 briefly reviews basic principles of operations in electric power systems. Section 2.3 presents the fundamentals behind transmission pricing schemes and the economic signals they convey. Section 2.4 assesses the order of magnitude of capital costs in transmission systems. Section 2.5 surveys the concept of externalities in the context of network-based industries. Finally, section 2.6 recalls the definitions of economies of scale and scope.

2.1 Agents in the electricity wholesale market

2.1.1 Generation

The role of generation is to convert a primary form of energy into electrical energy. The primary energy source in large-scale generation facilities consists of either chemical energy contained in fossil fuels (thermal generation) or mechanical energy contained in moving water (hydroelectric generation). Other sources of energy exist, such as wind power or solar energy, but their utilization in large-scale operations is marginal. The final energy conversion usually takes place in synchronous generators which are driven by steam, hydro, gas, and occasionally diesel turbines.

Until this decade, it was less expensive to produce large amounts of power in a few large facilities than in several smaller units. However, the development of new cost-efficient generation technologies, and the improved availability of natural gas, made smaller and cheaper generation units economically competitive. In some cases, the all-inclusive cost of a new plant was less than the sunk cost of the existing units being paid by consumers. Consumers then started to ask why they could not switch suppliers (Hunt et al., 1995).

In the US, the Public Utilities Regulatory Act of 1978 (PURPA) and the Energy Policy Act of 1992 (EPACT) encouraged competition in generation. As a result, independent power producers (IPPs) began to flourish in the wholesale electric power business.

2.1.2 Transmission

The locations of large scale generation facilities are mainly affected by the availability of energy sources and environmental concerns. These locations usually do not coincide with those where power is consumed. Consequently, it is generally necessary to transmit the electric power from the points of generation to the locations where it will be used (Miller and Malinowski, 1994).

According to ABB, transmission networks consist of three phase lines operating at voltages that usually range between 115 kV and 750 kV. Transmission line capacities are between 50 and 2000 MVA (ABB, 1994).

The purpose of a transmission network lies beyond the mere transportation of power. The network configuration of the transmission system creates more than one path between any two points in the system. In this way, if one transmission line fails, there is an alternate route and power is not necessarily interrupted. As ABB puts it: "Transmission lines not only serve to move power. Some parts of the network, namely its major power delivery lines, are designed at least partly for stability needs. This allows the system to pick up load and adjust smoothly as the load fluctuates and to pick up load slowly if any generator fails – what is called stability of operation."

Finally, there is more to a transmission system than the transmission lines. The transmission system consists of two types of equipment: transmission lines and transformers. In addition to these basic types, there is protective and regulation equipment. Protective equipment consists of circuit breakers, relays, sectionalizers, fused disconnects and control sensing equipment, whereas regulation equipment basically consists of capacitors.

2.1.3 Demand

At the high voltage transmission level, the load connected to a bus is the aggregation of millions of individual components ranging from light bulbs to air conditioning systems and all kinds of electric and electronic devices. Load aggregation occurs at several levels: (1) low and high distribution system level, (2) sub-transmission network level, and (3) the interconnected system level (Ilic and Zaborsky, 1997).

Demand is time-dependent, with daily, weekly, and yearly cycles. Its behavior is represented in load curves, but its long-term forecast has proven elusive. As the current obligation of supply for electric utilities is replaced by the market forces, uncertainty in demand patterns will certainly increase.

2.2 Basics in power system operations

2.2.1 Power flow modeling

An informed discussion about the transmission networks and systems and their relationship with the electricity market requires a basic understanding of the variables of interest: power flows. Indeed, usually both voltages and currents are allowed to vary to achieve the necessary power flows. Our analysis of transmission flows is based on the following simplifying assumptions (Graves, 1995):

Three phase transmission lines are operated in a balanced fashion. This means that the power flows over the three lines are the same with a time shift of 120°. Consequently, it is convenient to represent the three lines as a single phase.

All measurements are expressed as multiples of reference levels of power, voltage, and current. This algebraic convenience is called "per unit analysis" and is especially useful when a system involves many transformers.

Transmission line impedances, which are continually distributed along the length of the lines, can be modeled as though they were lumped in the midpoint of idealized lines that have no other impedances. One of the most commonly applied representations of a transmission line with lumped impedances is called the "pi-model."

Real and reactive power are decoupled. Real power flows depend primarily on voltage angles, whereas reactive power flows depend on voltage magnitudes.

Most importantly, the system is operated in a known "steady" state. Steady state analysis does not reveal how the system can or will make the transition from one state to another. Transient analysis has a large bearing on how much slack capacity must be kept in reserve on the transmission network. That problem is solved with scenario analyses that evaluate how the system would perform under a variety of disruptive contingencies (Graves, 1995).

2.2.1.1 Pi-model of a transmission line

A transmission line's resistance, inductance, and capacitance is continuously distributed along its length. Consequently, voltages at two different locations along the line will be oscillating slightly out of phase with each other. This timing gap, called voltage angle, must not be confused with the phase angle between voltage and current at any point in the line (Graves, 1995).

Most of the time it is not necessary to understand what is happening to the electromagnetic waves at every point along a line because the primary concern is to know power, voltage, and current at both ends of the line. The solution to this problem can be simplified by treating the per-mile series impedances (z) and parallel admittances (y) as discrete loads Z' (impedance) and Y' (shunt capacitance), respectively at the midpoint and ends of an ideal lossless line. This representation of a transmission line is called the "pi-model." (figure 2.1).

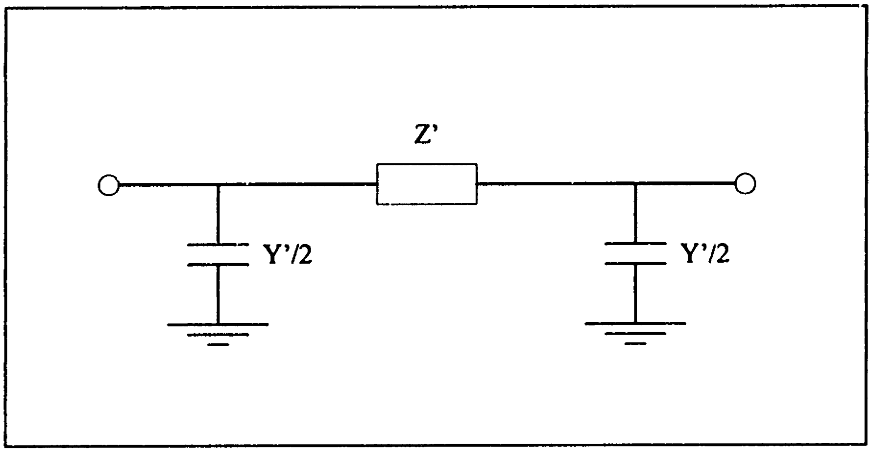


Figure 2.1.- Pi-model of a transmission line

A power line less than 50 miles long is deemed short and its shunt capacitance can be ignored entirely.

2.2.1.2 AC load flow formulation

The power (S) injected into a transmission line connecting nodes i and j has the following expression:

$$\begin{aligned} \hat{S}_{ij} &= \hat{V}_i \hat{I}_{ij}^* \\ &= \hat{V}_i \hat{y}_{ij}^* (\hat{V}_i^* - \hat{V}_j^*) \\ &= P_{ij} + jQ_{ij} \end{aligned} \tag{2.1}$$

where * stands for complex conjugate, $\hat{y}_{ij}$ is the line admittance, and $\hat{I}_{ij}$ is the line current. The terms P_{ij} and Q_{ij} stand for real and reactive power respectively. The real power transferred from node i to node j (T_{ij}) corresponds to the following expression:

$$T_{ij} = P_{ij} = g_{ij}[V_i^2 - V_i V_j \cos(\theta_i - \theta_j)] + b_{ij} V_i V_j \sin(\theta_i - \theta_j) \tag{2.2}$$

where $g_{ij} + jb_{ij} = \hat{y}_{ij}$. The angle θ_j represents the voltage angle at node i.

2.2.1.3 DC load flow formulation

Usually, $g_{ij} << b_{ij}$ and $(\theta_i - \theta_j) \approx 0$. Assuming that voltage magnitudes are close to their reference values (1 p.u.), we can rewrite equation (2.2) as follows:

$$T_{ij} \approx b_{ij}(\theta_i - \theta_j) \tag{2.3}$$

Equation (2.3) is known as the DC load flow equation for line i-j.

2.2.1.4 Transmission losses and load compensation

The real power transmission loss over a line i-j (L_{ij}) equals the difference between the real power injected at node i (P_{ij}) and that retrieved at node j ($-P_{ji}$).

$$L_{ij} = P_{ij} + P_{ji} = g_{ij}[V_i^2 + V_j^2 - 2V_i V_j \cos(\theta_i - \theta_j)] \tag{2.4}$$

Using the same assumptions as in the DC load flow formulation, and rearranging terms we get the following expression for the real power transmission loss:

$$L_{ij} \approx g_{ij}(\theta_i - \theta_j)^2 \approx T_{ij}^2 / g_{ij} \tag{2.5}$$

Transmission losses occur over the whole length of the transmission lines. For modeling purposes, however, transmission lines are assumed to be lossless and losses are lumped together as if they occurred at only one node (swing bus).

2.2.2 Operating constraints

2.2.2.1 Generation constraints

At the simplest level, synchronous generators are coupled to the rest of the system through voltage and real power. Although the production of real power (P) is related to the power delivered by the prime mover, the output voltage is regulated by the current in the field windings. Voltage regulation allows synchronous machines to produce or absorb reactive power (Q), which is a critical factor in providing voltage control in a power system (Miller and Malinowski, 1994).

Generator limits are often expressed in terms of a maximum apparent power rating (S_{max}) that restrict P and Q to combinations that lie within the apparent power circle $P^2 + Q^2 \leq (S_{max})^2$. The maximum real power output P_{max} is usually set by the particular prime mover's physical limits, whereas Q_{max} is often determined by the rotor heating tolerances (Graves, 1995). There is also the minimum output level of a unit that has been turned on.

To be able to respond to sudden changes in system voltages, synchronous generators are often operated far away from the reactive power constraint, that is with a power factor $P / \sqrt{P^2 + Q^2}$ close to unity. Consequently, reactive power generation constraints are usually less restrictive.

2.2.2.2 Transmission constraints

There is an upper bound to how much power a transmission line can transfer. This limit depends on both thermal and stability considerations. On one hand, when current flows through a transmission line, resistive losses generate heat. A line that gets too hot may stretch irreversibly between transmission towers, and its insulation may deteriorate and eventually fail. In addition, the thermal limit of terminal equipment (such as transformers) may be even more restrictive than that of the line itself. Given that the lines are designed for specific voltage levels, there is a limitation to the apparent power (MVA) they can transmit safely. This MVA rating corresponds to the maximum real power the line can convey with a power factor of one (Bergen, 1988).

On the other hand, the maximum real power transfer along a line depends on the voltage angle between the two ends. Although the theoretical limit is roughly 90°, lines operate at much smaller angles, never exceeding 50°. This allows the system to absorb oscillations in frequency that could arise on any line due to potential disturbances (Graves, 1995).

Whether thermal effects or stability requirements limit the maximum power that a line can support depends basically on the length of the line or, generally speaking, on the electrical distance between the nodes it connects. While a short line (less than 200 miles long) is likely to be constrained by a thermal limit, a longer line will be constrained by the stability limit (Bergen 1988). For a line connecting nodes i and j the transmission constraint can be stated as:

$$|T_{ij}| \leq K_{ij}^{\max} \quad \forall i,j \tag{2.6}$$

where $K_{ij}^{\max}$ is the maximum power transfer capability of the line.

The case presented is valid for a single line connecting two nodes. In an interconnected system, however, the stability problem is much more complicated. For this reason, the largest angle between any pair of generators in the system (called system voltage angle) is kept below 90°. How much generation and transmission capacity has to be set aside as reserve for unplanned disturbances is ultimately a management decision that involves considerable judgment (Ilic et al, 1996). Graves concludes that that there is no unambiguous reason for a particular transmission capacity, even if it is necessary to set aside some reserves to avoid unexpected problems (Graves, 1995).

2.2.3 Optimal power flow analysis

The "optimal power flow" problem (OPF)[1], consists of finding how to dispatch generation facilities to meet demand in least cost fashion, without exceeding safety, re-

---

[1] OPF is also called "Constrained Economic Dispatch."

liability and capacity limits on generators and transmission lines. A common specification of the OPF objective function and constraints is as follows: minimize the operating costs of generation subject to such constraints as generator limits on real and reactive power; transmission line limits based on thermal, voltage and stability considerations; Kirchoff's Laws; the obligation to match generation with demand and losses (Graves, 1995).

2.2.3.1 Basic problem formulation

Mathematically, the OPF is a constrained optimization problem. Hence, the formulation requires a system performance measure. One common performance measure (objective function) is minimizing operating costs of generation. Assuming a low demand elasticity, minimizing costs is economically and operationally equivalent to maximizing net benefits or social welfare.

Assuming that the conditions for the DC load flow approximation and the decoupled real/reactive power assumption hold, the problem statement is as follows:

Objective function:

The objective function is to minimize the cost of generation of real power, given by the sum of the output (P_i) times the variable operating cost per kWh (c_i) of each generating unit.

$$\min_{P_i} \sum_i c_i P_i \qquad (2.7)$$

Generation constraints:

$$P_i^{\min} < P_i < P_i^{\max} \qquad \forall i \qquad (2.8)$$

Transmission Constraints:

$$|T_{ij}| \le K_{ij}^{\max} \qquad \forall i, j \qquad (2.9)$$

Kirchoff's Laws:

The power is balanced at each node.

$$P_i^{net} = \sum_j P_{ij} \qquad \forall i \qquad (2.10)$$

where $P_i^{net} = P_i^{gen} - P_i^{load}$ (net power injection).

Real power supply demand and losses:

Losses equal total generation minus total load.

$$\sum_i P_i^{net} - \frac{1}{2}\sum_i \sum_j L_{ij} = 0 \tag{2.11}$$

2.2.3.2 Shadow prices and system lambda.

If a constraint were binding, its shadow price would be the forgone opportunity to further improve the objective function due to that resource limit. Its value would be how much the total system cost would decrease if that constraint limit could be relaxed by an increment of additional capacity (Graves, 1995). The term system lambda refers to the short-run marginal cost of the system.

2.3 Transmission pricing and incentives

2.3.1 Transmission pricing

If all nodes and competing generators were located at the same node, the spot price at that node would be equal to the marginal cost of the most expensive unit. The same would apply to an ideal lossless network with unlimited transmission capacity. Real transmission networks, however, have a limited transmission capacity and create transmission losses. As a result, nodal spot prices across the network differ at the economically optimal operating conditions of the system. The economic optimum is said to be a competitive equilibrium achievable either through centralized dispatch or multilateral trading. At this optimum, nodal spot prices contain all the information about the existing grid.

Optimal transmission pricing is a subproduct of nodal spot pricing. There is no room for arbitrage in a competitive equilibrium. Hence, the optimal transmission price for a link should equal the difference between the spot prices of the nodes it connects. The role of transmission pricing is to provide the economic signals that will motivate an efficient use of the system by the competitive market agents. Other transmission pricing schemes (such as the impacted MW-mile) are considered sub-optimal because they do not create the economic signals that will lead market agents to make efficient use of the system.

Lecinq made one of the few serious attempts to link transmission pricing and transmission investment (Lecinq, 1996). He proposed the introduction of peak-load pricing for transmission. The peak-load pricing approach incorporates the capital cost of transmission into the social welfare maximization formulation. The resulting transmission charges are the same as those achieved with nodal spot pricing. His main contribution is that peak-load pricing promotes those system upgrades that allow the network to pay for itself.

2.3.2 Network revenue allocation

The sum of all transmission charges is called merchandising surplus or network revenue. The problem of concern is how to allocate such network revenues now that generation and transmission have been unbundled. Bushnell and Stoft point out that there are two prominent concepts for rewarding decentralized grid ownership in nodal spot markets: link-based rights and transmission congestion contracts (Bushnell and Stoft, 1996).

The traditional link based rights scheme proposes to "use the merchandising surplus to pay each link owner the nodal spot price difference between the nodes it serves times the power flow on that link." Needless to say, this approach creates the incentive for link owners to raise spot price differences through increased congestion and losses.

Another approach to the distribution of network revenues is the *contract network* system. Hogan developed the concept of Transmission Congestion Contracts (TCCs) primarily as a hedging mechanism against the fluctuations in nodal spot prices (Hogan, 1992). A TCC pays the holder the spot price difference between nodes times a quantity specified in the contract.

TCCs can be written for any pair of nodes in the network, and are therefore not limited to actual flows. However, if the merchandising surplus is intended to cover the payment of these contracts, then the set of allocated TCCs (contract network) has to correspond to a feasible dispatch. Wu et al confirm that as long as the set of allocated TCCs corresponds to a feasible dispatch, the revenue collected by the TCC holders will not exceed the merchandising surplus[2] (Wu et al, 1996).

Bushnell and Stoft explore how to use the *contract network* to reward grid ownership. Under their *feasibility allocation rule*, a set of TCCs is awarded to transmission investors who alter the grid[3]. The only constraint for that allocation is that the resulting set of all outstanding TCCs has to match a feasible dispatch.

The point here is that the holders of the previously existing TCCs are insulated against price fluctuations. Hence, the agent who altered the grid would have to compensate for the decrease in total net benefit resulting from a detrimental grid alteration. Bushnell and Stoft point out that the incentive to make detrimental modifications on the grid is eliminated only when the set of outstanding TCCs matches the actual dispatch. This is a strong condition that could only be satisfied on the average, if at all.

Finally, as Castillo points out, it is the generation owners who have the largest financial incentive to hold TCCs (Castillo, 1997). Allowing generators and transmission owners to negotiate and eventually collude would go against the spirit behind the divestiture of the vertically integrated electric utilities.

2.4 Capital investment in transmission

The capital costs of the transmission system involve the purchase cost of the land and equipment, and all costs related to putting such equipment into operation. As a general rule, the cost of a transmission line consists of a per-mile cost and a termination cost. The termination cost is associated with the substations at both ends of the line. Costs are in the order of magnitude of $1,000,000 per mile for a 500 kV double circuit construction with 2000 MVA capacity (ABB, 1994).

The cost of a substation consists of a site cost, a transmission cost, a transformer cost, and a feeder/buswork getaway cost. The substation cost could vary from

---

[2] The revenue collected by TCC owners will equal the merchandising surplus if the allocated TCCs match the optimal dispatch.

[3] The allocation of such TCCs is mandatory.

about $1.8 million to $5.5 million, depending on land costs, labor costs, the utility equipment, installation standards, and other special circumstances.

Transmission systems enjoy economies of scale in capital investment: it costs more to upgrade an existing equipment to higher capacity than to build that capacity in the first place. Therefore, there is an economic incentive to look at long term trends carefully and to install extra capacity for future growth. This is the reason why transmission systems are usually overbuilt with considerable margins over the existing load (ABB, 1994).

2.5 Externalities vs. Network externalities

2.5.1 Externalities

The term "externalities" refers to the effects of production and consumption of activities that are not directly reflected in market prices. Externalities and public goods[4] are important sources of market failure (Pindyck and Rubinfeld, 1995). The market fails in the presence of externalities if the price of a good does not reflect its social value.

2.5.2 Network externalities

Michael Katz and Carl Shapiro defined the concept of network externality as follows: "a good exhibits a network externality if the utility that a given user derives from it depends on the number of other agents who are in the same network." (Katz and Shapiro, 1985). In this context, the concept of network is not limited to physically connected networks: it refers to the collection of all the users that consume the same good. Externalities can be positive or negative. A positive externality occurs wherever the consumer enjoys benefits from changes in quantities demanded[5]. If

---

[4] Public goods benefit all consumers. However, the market either undersupplies or does not supply them at all (Pindyck and Rubinfeld, 1995).

[5] A trivial example of positive network externalities relates to having a telephone. The larger the installed base of telephones, the more valuable it is to own one.

the opposite is true, there is a negative network externality. The effect of congestion is a common example of a negative network externality.

Liebowitz and Margolis make the point that the definition presented above is broad and applies to most goods. They use the term network effect for "the circumstance in which the net value of an action (...) is affected by the number of agents taking equivalent actions." (Liebowitz and Margolis, 1994). Moreover, they reserve the term "network externality" for those network effects that result in market failure.

2.5.3 Externalities and transmission networks

We have identified at least two kinds of externalities related to transmission systems. The economists' definition of network externalities applies when a market agent's ability to make a transaction is affected by the transactions of the other market agents. Transmission congestion is a manifestation of a network externality. However, the effect of a transmission system on the market for power is not a "network externality" according to the previous definition. The benefits a transmission network creates for the market that are not perceived by the transmission owners correspond to the economists' definition of plain "externalities." The latter should be called "externalities of the grid on the market."

2.6 Economies of scale and scope

Economies of scale and scope were used as arguments in favor of vertically integrated utilities. After economies of scale in generation were proven to no longer apply (Hunt, 1996), the same arguments continue to be used in favor of transmission monopolies.

2.6.1 Economies of scale

A firm enjoys economies of scale when it can double its output for less than twice the cost. Pindyck and Rubinfeld mention that economies of scale are often measured by a cost-output elasticity, E_c (Pindyck and Rubinfeld, 1995). This elasticity is the percent change in the average cost of production resulting from a one percent increase in output:

$$E_c = (\Delta C / C) / (\Delta Q / Q) = MC / AC \tag{2.x}$$

where MC and AC stand for marginal and average cost respectively. When there are economies of scale, marginal cost is less than average cost and E_c is less than one.

In the context of networks, economies of scale imply that the cost of providing for additional users continuously decreases and that it is thus cheaper to service all users with a large entity (Noam, 1991).

2.6.2 Economies of scope

Again, we refer to the textbook definition of economies of scope: "*economies of scope are present when the joint output of a single firm is greater than the output that could be achieved by two different firms each producing a single product* (with equivalent production inputs allocated between the two firms)" (Pindyck, 1995). The degree to which there are economies of scope can be measured in terms of the cost savings that result from producing two goods jointly rather than individually.

Noam recalls that the joint production benefits of economies of scope occur when (1) the duplication of equipment and capacity is eliminated; and (2) less capacity is necessary to handle peak demand loads (Noam, 1991).

Chapter 3

Economic Value of a Transmission Grid.

3.1 Motivation

A transmission system serves several purposes. On one hand, it provides the infrastructure for transporting power from low-cost generation units whose location might be determined by natural conditions to load centers where higher cost generation might be available (Westinghouse, 1950). As a result, a transmission system makes competition in generation feasible, allowing consumers to buy from the most cost effective suppliers. On the other hand, the networked structure of a transmission system allows for multiple dispatch arrangements to meet specific load conditions. The ability of the system to serve demand under different contingencies is an indicator of reliability.

The concept of opportunity cost of a transmission asset is clear for vertically integrated utilities. Utility planners weigh the tradeoff between enhancing the transmission system and procuring more generation capacity, and wherever there is a chance to choose between two or more options, there is an embedded opportunity cost. Utilities have the capability to optimize their planning by making use of a vast array of possible combinations of generation and transmission expansion. Consequently, vertically integrated utilities enjoy economies of scope which are lost with the separation of generation and transmission expansion planning.

The way the market actually benefits from a particular transmission asset is partially captured in the optimal dispatch model formulation of a system. However, only the opportunity cost of transmission capacity, the basis for transmission pricing, can be directly inferred from optimal dispatch formulations. These formulations sometimes lead to the erroneous idea that transmission congestion is the only parameter relevant for the economic value of transmission. In fact, most of the recent literature dealing with transmission economics focuses on congestion. However, there is more to the value of a transmission link than its transmission capacity constraint. A transmission link creates additional paths for power flow. The number of paths enabled by one particular link is finite and depends on the topology of the system. Since no electricity valves for bulk power transmission have been implemented yet[1], any power unit transferred from one node to another in the system splits and travels through all existing paths between these nodes. How much power travels through each path is proportional to its equivalent admittance. This is the cause of the "loop flow" phenomenon by which a power transfer cannot be compelled to follow a predetermined path.

The following example makes the point that the value of a link goes beyond its transmission capacity. Figure 3.1 shows an ideal three bus system where node 1 represents a large load supplied by two generators located at nodes 2 and 3. The load at node 1 is 300 MW and generation capacity at nodes 2 and 3 is unlimited. There are neither transmission capacity constraints nor transmission losses. Table 3.1 shows the marginal cost and total cost functions at nodes 2 and 3.

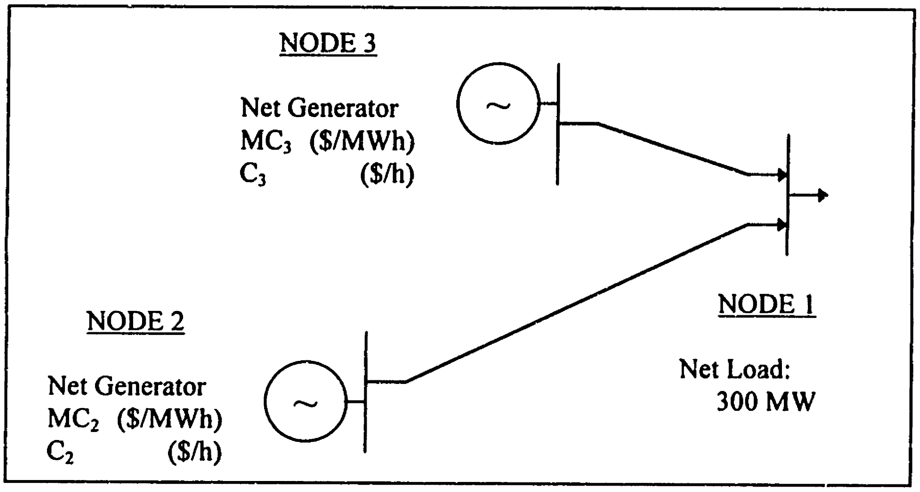


Figure 3.1.- Three bus system: unlimited generation and transmission capacity.

---

[1] One could view FACTs as such, but their use is still limited.

In this example, the optimal dispatch is achieved by injecting 200 MW at node 2 and 100 MW at node 3. In a perfectly efficient market, this result would be achieved either by centralized dispatch or a bilateral contract scheme. The system marginal cost (system lambda) is $20/MW and the variable generation cost is $4,250 per hour. Since the transmission links are ideal, the shadow price that corresponds to an additional unit of transmission capacity is zero.

Table 3.1.- Marginal and total cost of generation at nodes 2 and 3.

Marginal Cost (MC_i) ($/MWh)	Total Cost (C_i) ($/h)
$MC_2 = 10 + 0.05x_2$	$C_2 = 10x_2 + 0.025x_2^2$
$MC_3 = 5 + 0.15x_3$	$C_3 = 5x_3 + 0.075x_3^2$

x_i : power generation at node i.

However, if the link between nodes 1 and 2 were removed, generator 2 would have to remain idle while generator 3 would have to inject the 300 MW demanded at node 1. The new system lambda would be $50/MWh and the total generation cost $8,250 per hour. Since, by assumption, demand is fixed and therefore inelastic, the change in social welfare is related to the change in generation cost. Society saves $4,000 ($8,250-$4,250) thanks to the link between nodes 1 and 3. We call these savings avoided social cost by means of link 1-3 or, simply, the value of link 1-3. This value is related not to congestion or transmission losses, but to a reduction in generation cost or, more specifically, to an improvement of social welfare.

Intuitively, transmission revenues should not only provide an adequate risk adjusted return on investment but also create incentives to perform those modifications on the grid that allow the market to increase its welfare. The question now is whether the return on investment of a particular transmission asset can be correlated with its own value and whether the incentives that derive from it lead to an optimal expansion of the grid. To answer this question, there must be a means to quantify the aforementioned value. This thesis claims that the concept of avoided social cost adequately represents that value.

Assuming a perfectly efficient market, based either on fully centralized and coordinated operations by an ISO or on bilateral transaction schemes, nodal prices will reflect short term marginal costs. At economic equilibrium, revenues collected from transmission service charges equal the difference between those collected from the loads (demand) and those paid to the generators (supply). The sum of those earnings, called either network revenue or merchandising surplus, is the primary source of income destined to pay for the transmission system. It is worth noting, however, that transmission service charges and investment incentives for transmission infrastructure have two different objectives. On one hand, transmission pricing is intended to provide suppliers and consumers with economic signals that will induce an optimal utilization of available resources. Network revenue, on the other hand, should give transmission investors economic signals that induce them to upgrade transmission infrastructure and improve market efficiency. In addition, there is an inherent time scale separation between the operation of the system and implementation of infrastructure upgrades. Different objectives and time scales speak in favor of a separation between the sources and the allocation of network revenues.

This thesis is not presenting a new problem. It only suggests a new approach to dealing with the problem of incentives. The implications of this new approach are tested in the following sections with the help of a numerical five-node example developed for this particular purpose. This example is sufficiently complex to illustrate the relationships and externalities among the different variables in the system.

Section 3.2 describes the reasons for separating the supply/demand power market from the market of transmission assets. Section 3.3 presents a 5-node system model used to support the analysis. Section 3.4 describes the relationship between transmission capacity and the avoided cost of individual links as well as the relationship between avoided cost and network topology. Finally, section 3.5 introduces the notion of a transmission link's relative value within a network.

3.2 Markets for power transactions vs. markets for transmission infrastructure.

Spot prices contain all relevant information about the existing grid, and efficient transmission pricing is a subproduct to optimal spot pricing. Transmission pricing is

Assuming a perfectly efficient market, based either on fully centralized and coordinated operations by an ISO or on bilateral transaction schemes, nodal prices will reflect short term marginal costs. At economic equilibrium, revenues collected from transmission service charges equal the difference between those collected from the loads (demand) and those paid to the generators (supply). The sum of those earnings, called either network revenue or merchandising surplus, is the primary source of income destined to pay for the transmission system. It is worth noting, however, that transmission service charges and investment incentives for transmission infrastructure have two different objectives. On one hand, transmission pricing is intended to provide suppliers and consumers with economic signals that will induce an optimal utilization of available resources. Network revenue, on the other hand, should give transmission investors economic signals that induce them to upgrade transmission infrastructure and improve market efficiency. In addition, there is an inherent time scale separation between the operation of the system and implementation of infrastructure upgrades. Different objectives and time scales speak in favor of a separation between the sources and the allocation of network revenues.

This thesis is not presenting a new problem. It only suggests a new approach to dealing with the problem of incentives. The implications of this new approach are tested in the following sections with the help of a numerical five-node example developed for this particular purpose. This example is sufficiently complex to illustrate the relationships and externalities among the different variables in the system.

Section 3.2 describes the reasons for separating the supply/demand power market from the market of transmission assets. Section 3.3 presents a 5-node system model used to support the analysis. Section 3.4 describes the relationship between transmission capacity and the avoided cost of individual links as well as the relationship between avoided cost and network topology. Finally, section 3.5 introduces the notion of a transmission link's relative value within a network.

3.2 Markets for power transactions vs. markets for transmission infrastructure.

Spot prices contain all relevant information about the existing grid, and efficient transmission pricing is a subproduct to optimal spot pricing. Transmission pricing is intended to provide suppliers and consumers with economic signals that will induce an optimal utilization of the system. These signals capture the negative externalities due to congestion and transmission losses that a transaction creates on the rest of the system. Basically, the transmission charge for a particular transaction accounts for the additional cost this transaction imposes on the rest of the system. Network revenue should give transmission owners economic signals that induce them to optimize the transmission infrastructure, thus improving market efficiency. In other words, incentives for transmission should reflect the benefits created by transmission networks for the rest of the system.

Transmission operations and market operations certainly affect one another. An existing network configuration constrains the number of feasible transactions. Supply and demand try to maximize their efficiency by assuming the grid, over which they have little control, as fixed. In turn, changes in demand patterns and supply characteristics in turn create room for grid upgrades that can further improve the efficiency of the system. However, the time scale at which transmission infrastructure changes is much longer than that at which short term operations occur. Whereas the commitment to invest in transmission infrastructure requires analysis of long term trends, and the implementation of such investment takes several weeks, power transactions occur within the time range of a few hours. This time scale separation is the basis for the creation of separate markets for power and transmission infrastructure. The implementation of Flexible AC Transmission devices (FACTS) could allow real time modifications of the network configuration which could then be considered as decision variables for operations. However, this hypothetical situation is beyond the scope of this analysis.

3.3 Model of a five-node system

To support the analysis of the relationships between the transmission network configuration and the economics of power system operations, a 5-node electric power system model is presented. Such a model has been deemed complex enough to adequately illustrate the relationships and externalities among the different variables in the system. With 10 potential links connecting the 5 nodes, hundreds of network configurations are possible. Figure 3.2 presents the 5-node system displaying all possible links in a fully meshed network.

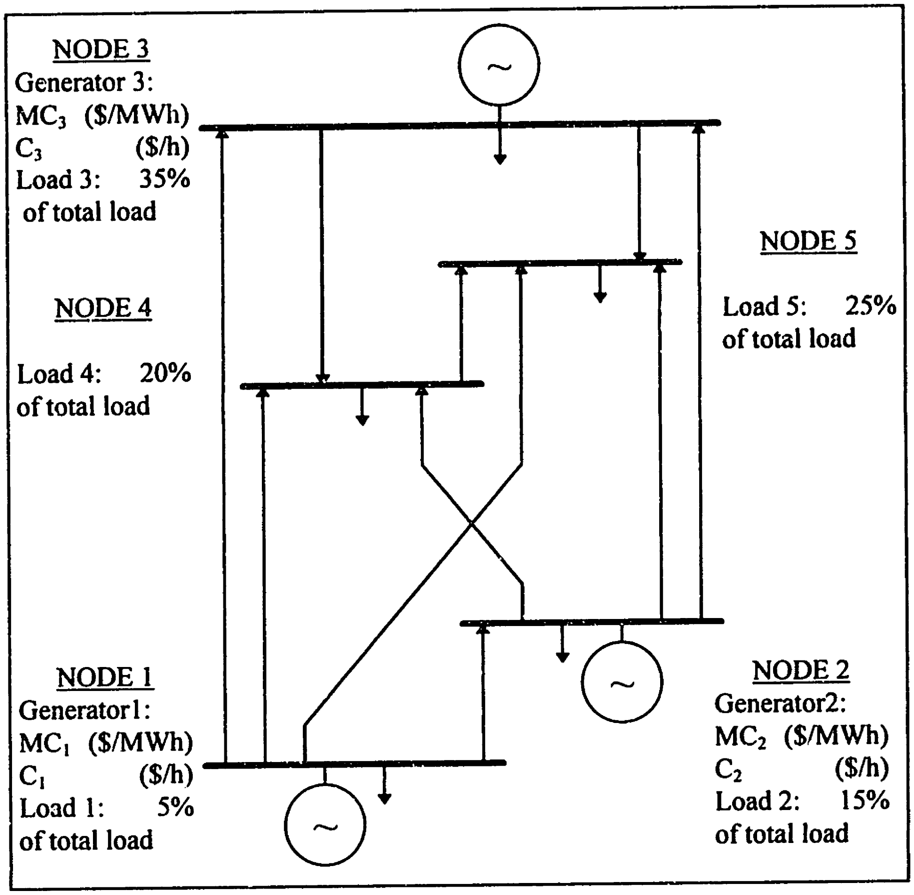


Figure 3.2.- One-line diagram of 5-node system

All simulations are based on one of the following five different network topologies. The first network configuration (P10) corresponds to the fully meshed network of Figure 3.2 where all possible links are established; the second network (P935) has 9 active links (missing link 3-5); the third network (P83545) has 8 active links (missing links 1-3 and 4-5); the fourth network (P7354524) has 7 active links (missing links 1-3, 4-5 and 2-4); and the fifth has 7 active links (missing links 1-2, 1-5, and 2-4). Section 4.3.1 describes the assumptions and the parameters used in the model and section 4.3.2 describes the simulations.

3.3.1 Parameters and assumptions

3.3.1.1 Demand

This model assumes demand is known and completely price inelastic. In this model, demand follows the load duration curve developed by Edo Macan with a yearly peak load of 1500 MW (Macan and Ilic, 1997). For simulation purposes, the load duration curve consists of two periods: peak and off-peak. Table 3.2 shows the maximum and average load for each period.

Table 3.2.- Five-node system: Characteristics of load duration curve.

Period	Maximum Demand (MW)	Average Demand (MW)	Duration (hours/year)
Off-peak	750	666	2,296
Peak	1,500	1,013	6,440

In addition, the demand is distributed among the five nodes in fixed proportions. The largest power requirements are in node 3 and the smallest in node 1. Table 3.3 shows the average loads for each node.

Table 3.3.- Five-node system: Average load distribution among nodes

	Nodal load distribution (%)	Average load Off-peak (MW)	Average load Peak (MW)
Node 1	5	33.3	50.7
Node 2	15	99.9	152.0
Node 3	35	233.1	354.6
Node 4	20	133.2	202.6
Node 5	25	166.5	253.3

3.3.1.2 Supply

Three generators located at nodes 1, 2 and 3 respectively account for the power supply. There are no generation facilities at node 4 or 5. All generators have a maximum capacity of 1000 MW. There are no fixed costs, and generation at node 1 is the most cost effective for any output level. Table 3.4 shows the marginal cost and total cost functions of generation at nodes 1, 2 and 3.

Table 3.4.- Five-node system: Marginal and total cost of generation at nodes 1, 2 and 3.

Marginal Cost (*MC*) ($/MWh)	Total Cost (C_i) ($/h)
$MC_1 = 4 + 0.01x_1$	$C_1 = 4x_1 + 0.005x_1^2$
$MC_2 = 25 + 0.025x_2$	$C_2 = 25x_2 + 0.0125x_2^2$
$MC_3 = 5 + 0.15x_3$	$C_3 = 5x_3 + 0.075x_3^2$

x_i : power generation at node *i*.

3.3.1.3 The grid

Table 3.5 presents the base case specifications of the available 10 links used in the different network configurations.

Table 3.5.- Five node system: characteristics of transmission links

	Node 1	Node 2	Node 3	Node 4	Node 5
Node 1	x	55	48	50	10
Node 2		x	10	23	26
Node 3			x	14	24
Node 4				x	20

resistance (r)	0.993*1E-3	power unit /mile
inductance (x)	3.800*1E-3	power unit/mile
rating	400	MW

3.3.1.4 Decoupled DC- real power flow

The model considers only the primary transmission service: transportation of electric energy from supply nodes to delivery nodes. The analysis focuses only on real power transfer. It assumes that for any given network configuration optimal dispatch is obtained either through central coordination or as a result of bilateral transactions. Ancillary services such as voltage control and frequency regulation are assumed to be provided and their discussion is beyond the scope of the model.

3.3.1.5 Transmission constraints

The power handling capability of a line is bound either by its thermal or stability limit. Whereas the stability limit of a link depends on the voltage angle difference between the sending and receiving nodes, the thermal limit depends on the line design and operating conditions (Berg, 1998). Since the distance between any two nodes in the model does not exceed 60 miles, it is safe to assume that the power handling capability is given by the thermal limit. The thermal limit or "rating" is assumed to be constant without loss of generality. The base case considers all lines to have the same transmission limit of 400 MW. In order to isolate the effect of transmission capacity on system performance, the power handling capability of a link is assumed to be independent from its impedance.

3.3.1.6 Commitment to serve the load

The design of the model makes the system capable of meeting its load requirements in the event of any single contingency. This contingency can be the loss of a generator or a line. The motivation is that if a load were to depend entirely on one link, the avoided social cost of that line would have to include the cost of non served energy.

3.3.2 Simulations

Given a network topology, each simulation focuses on one link and analyzes its impact on social welfare as a function of its power handling capability. A simulation consists of a series of constrained economic dispatch optimization routines. The objective function is the minimization of generation cost; the decision variables are the power injections at nodes 1, 2 and 3; the constraints are generation and capacity limits. The simulations are performed over a 10 year time horizon divided into two periods: peak and off-peak. The first optimal dispatch is done for the case when the link of interest does not exist. Subsequent optimal dispatches are repeated for different transmission capacities of the link of interest. In this way, a parametric analysis on the effect of transmission capacity on optimal dispatch is achieved.

Appendix A presents the simulation outputs that provide all the data needed for the analysis: total system cost, network revenue, relative value indices, and transmission link revenues.

3.4 Avoided social cost

The value of a transmission link will be correlated in this thesis to its avoided social cost. The avoided social cost of an existing link equals the social welfare the market loses as a result of removing that link. Conversely, the avoided cost of a prospective link is the social welfare the market gains from the addition of that link. Hence, the avoided social cost is an indicator of the impact the transmission infrastructure has on the demand/supply market.

The avoided social cost depends on the power handling capability of the link of interest and on the topology of the network. The following sections present insights gained on this idea. Section 4.4.1 deals with the relationship between the market's avoided social cost and transmission capacity. Section 4.4.2 discusses the relationship between avoided social cost and network topology.

3.4.1 Avoided social cost and transmission capacity

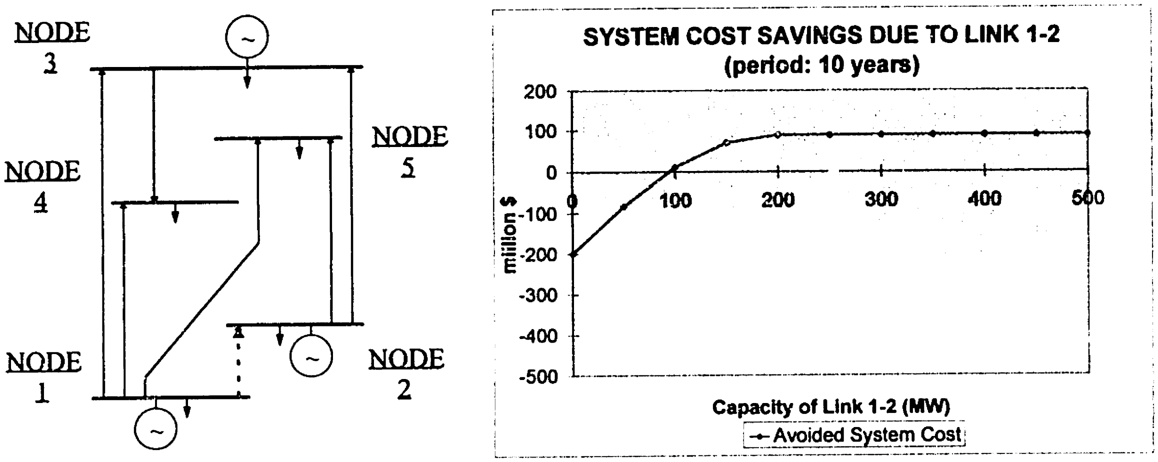
We presume that what follows is this: social welfare is a monotonic function of the power handling capability of individual links. Specifically, a higher level of social welfare can be gained by increasing the capacity of congested lines. This observation is related to the shadow price of transmission capacity, which measures how much the system gains from an additional unit of transfer capacity in congested lines. As long as the link is congested, the magnitude of the avoided cost usually increases monotonicaly showing a goal seeking pattern. As long as the transmission capacity is not a binding constraint, the avoided cost remains constant at its maximum value. Hence, expanding the capacity of an uncongested line does not add value to the market.

However, links with low transmission capability have a negative impact on the social welfare of the market. Invariably, the market is better served when low capacity links are removed from the network. In this case, the negative externalities created by congestion exceed any benefit that the link could bring with it. The negative externalities of a congested line are reflected in out of merit dispatch.

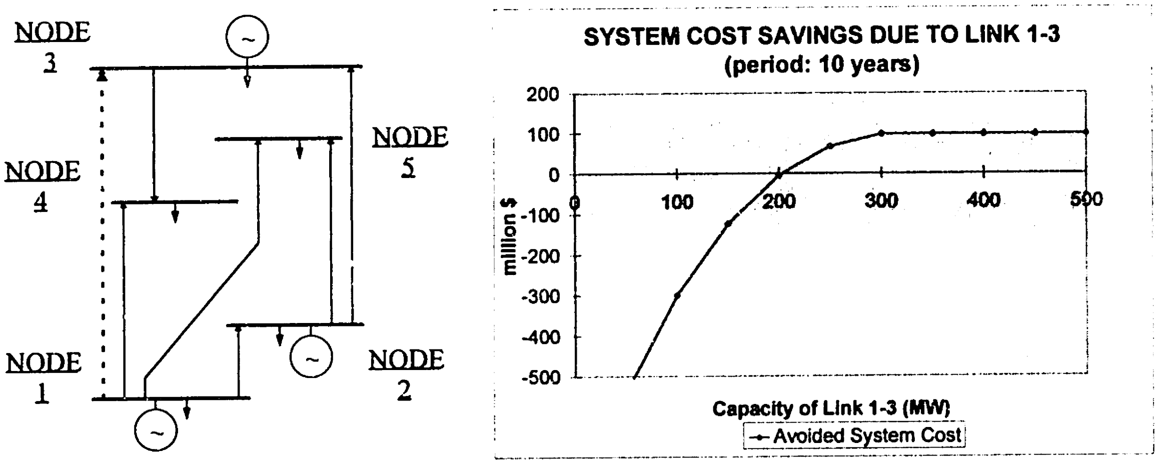
There is no numerical definition of a low transmission capacity. The definition of low transmission capacity is relative to the link of interest and it should be analyzed in the context of the particular system configuration. Figure 3.3 shows typical avoided social cost curves as a function of capacity.

Certain lines, however, constitute a special case: their economic impact on the system is negative for any transmission capacity. This case is discussed in the following section.

Network: P7354524



Network: P7354524



Network: P7354524

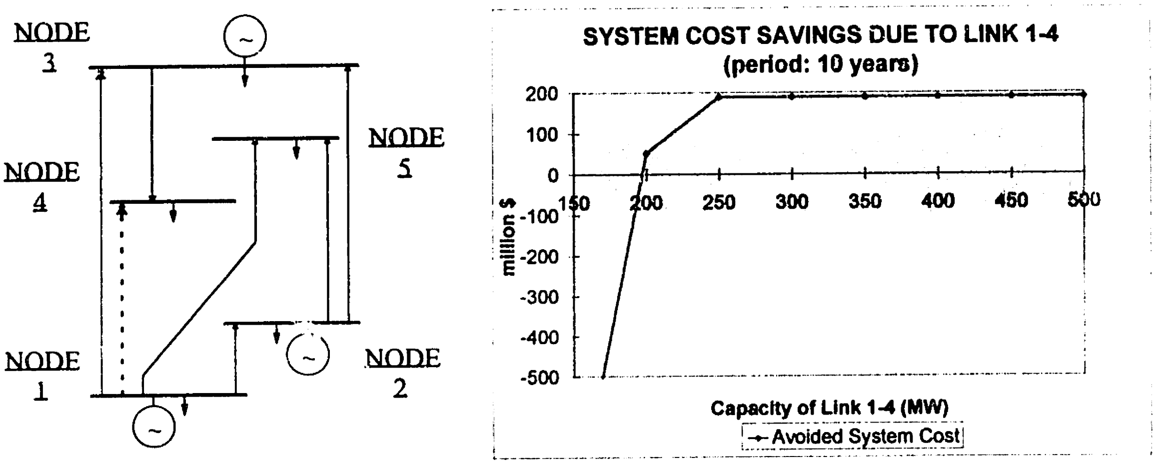


Figure 3.3.- System cost savings increasing with capacity.

The main conclusion here is that low-capacity transmission links are detrimental for the market. The market is better off removing low capacity transmission links. In addition, for given demand and generation capacity the value of a congested transmission link never exceeds the value of that same link, if overdimensioned.

3.4.2 Avoided social cost and network topology

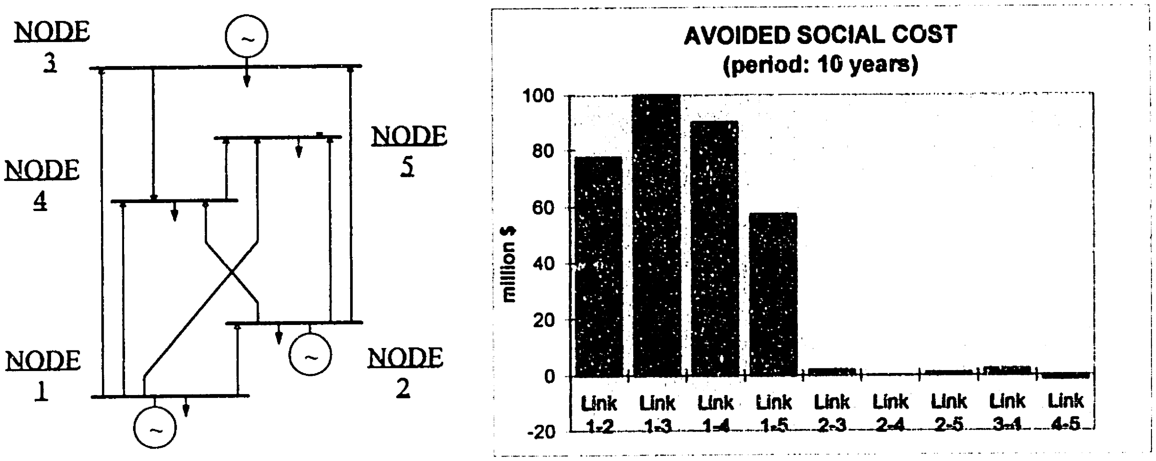
The transmission links that have the largest economic impact on the market are those which hook the most cost efficient generators to the rest of the system. In the same way that the dispatch of a generator has a higher impact on the flows on the lines to which it is connected (lines in the first tier (Zaborszky et al, 1980)) the characteristics of these lines pose an immediate constraint on the generator's ability to dispatch. It is important to observe that the market benefits when the links connecting the least expensive generators have a higher power transfer capability. This is an almost obvious but nonetheless important observation. Figure 3.4 compares the avoided social cost of each link in three different network configurations[2]. Note that the links connected to the less expensive generator (node 1) consistently have the highest economic impact on the system.

An increased number of links does not translate into a more efficient network. In fact, some links have always a negative economic impact on the system regardless of capacity (see figure 3.5). Because it creates multiple paths for power flow, an additional transmission link increases the capability of the system to absorb the loss of another line. However, as the number of links increases, the negative effects of the loop flow phenomenon become more important. Whether the link will have a positive or negative impact on the system depends on the setup of that particular system. In this context, an optimal network is one that maximizes the highest welfare the market can achieve. Figure 3.6 shows the total generation cost for 5 different network configurations. All transmission links have the same rating of 400 MW and none reaches congestion.

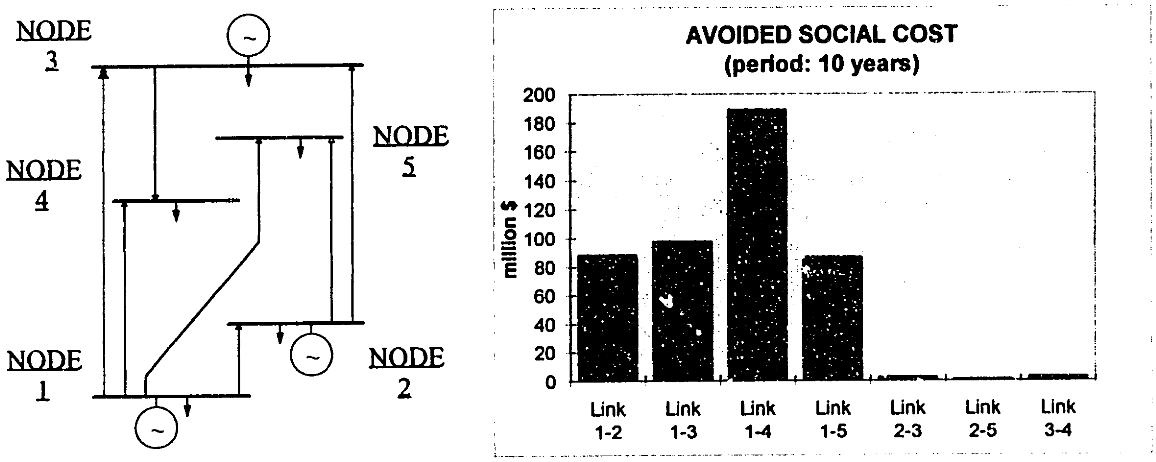
---

[2] All transmission links have a capacity of 400 MW.

Network: P935



Network: P7354524



Network: P7121524

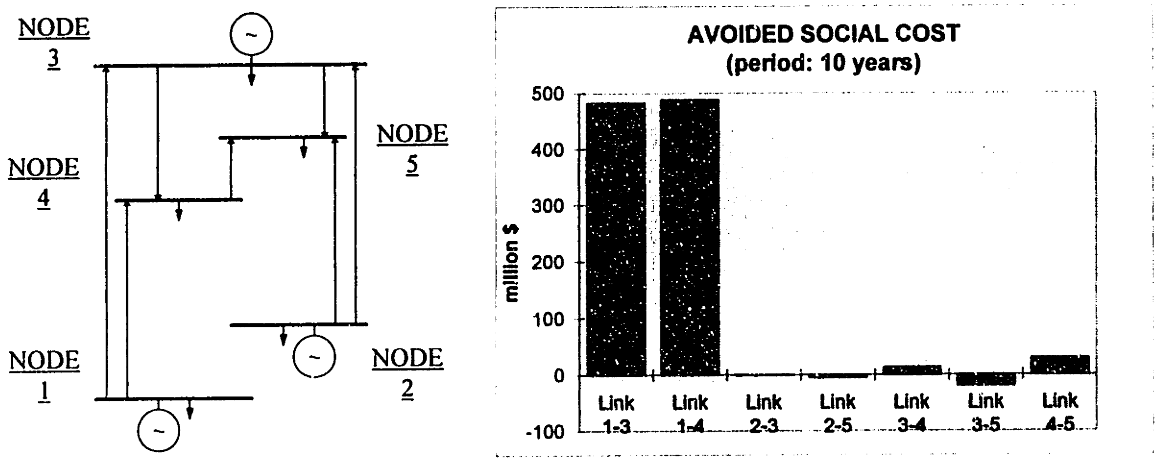
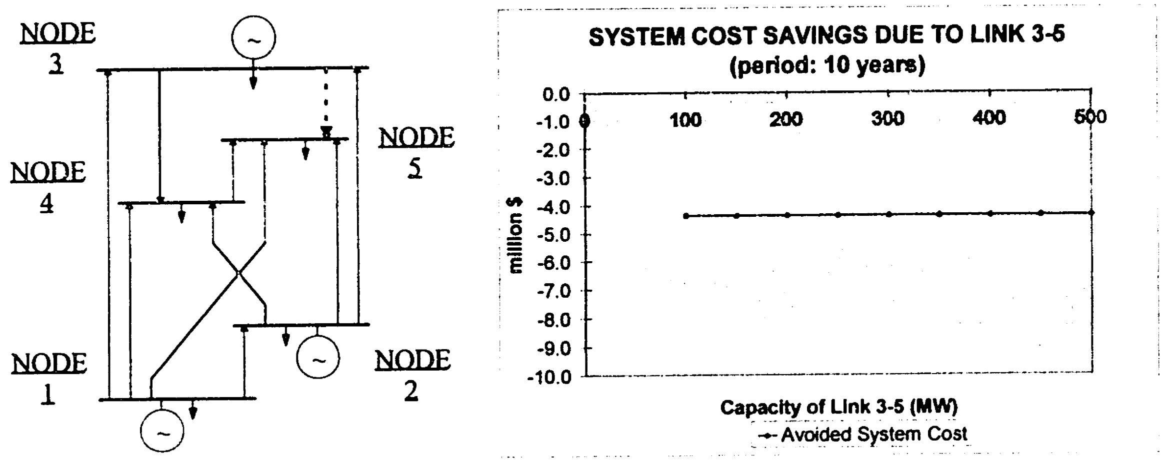


Figure 3.4.- System cost savings for different network topologies.

Network: P10



Network: P935

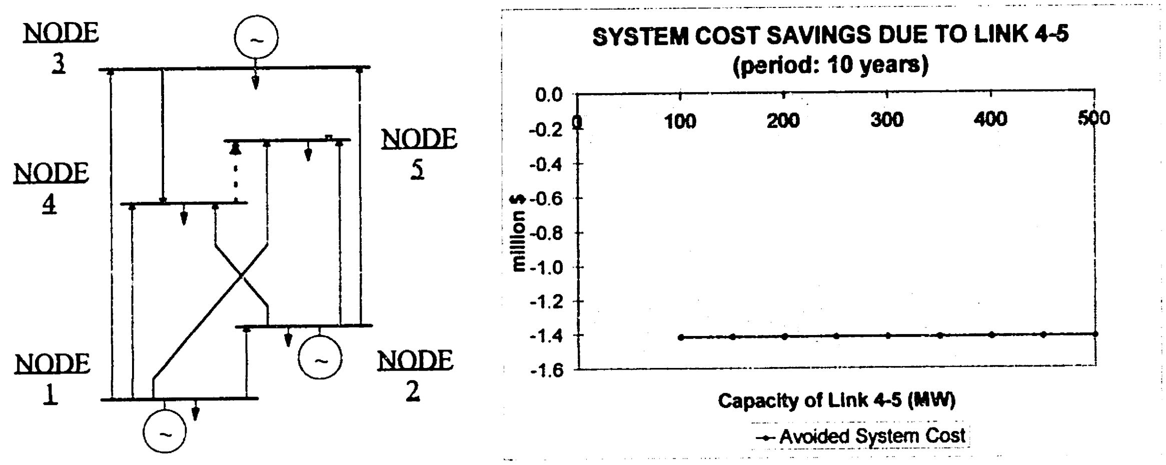


Figure 3.5.- Links with negative impact on system cost.

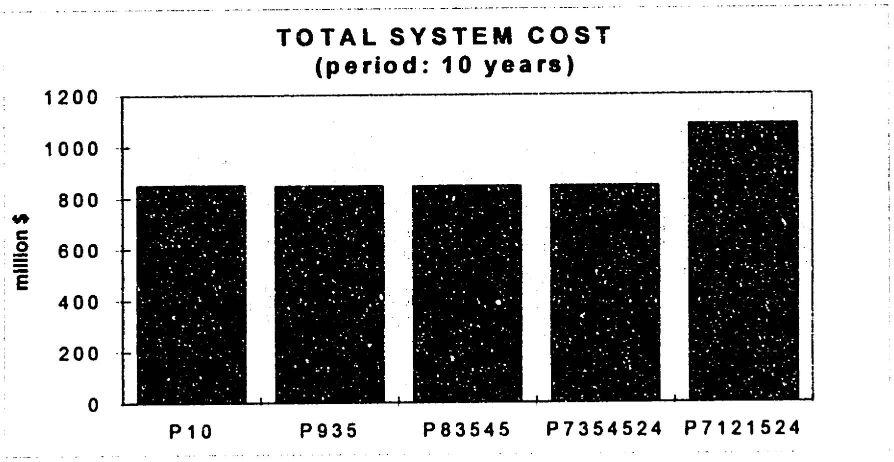


Figure 3.6.- Total generation cost for different network topologies.

3.5 Relative value of a transmission link

3.5.1 Definition

It has been shown in section 3.4 that one can compute the avoided cost of the individual links that form a network. Consequently, it is possible to rank the transmission links according to their impact on the market. Our goal in this section is to define a normalized or relative scale in which to rank the transmission links. In order to define such a relative scale, the following conditions must hold:

Condition 1:	At least one link has positive avoided social cost.
Condition 2:	The relative value of a line is proportional to its avoided cost.
Condition 3:	The relative values of all links in a network add up to one.

Condition 1 is intuitive. In any network, at least one link allows cost savings. Otherwise, the transmission grid would not serve any purpose and the market would be better off without it. The possibility that some links may create increased operating costs (see section 4.4.2) is not excluded. Condition 2 follows from the fact that a relative value is a normalization of the absolute value (avoided social cost) of a link. Condition 3 is convenient, because it allows us to create a link-by-link benefit allocation rule based on relative values.

We define the relative value (rv_{ij}) of a link connecting two nodes i and j as follows:

$$rv_{ij} = \frac{asc_{ij}}{PV}\left(1 - \frac{NV}{PV}\right), \qquad asc_{ij} > 0$$

$$rv_{ij} = \frac{asc_{ij}}{PV}, \qquad asc_{ij} \leq 0$$

where

rv_{ij} : relative value of link i-j;

asc_{ij} : avoided social cost of link i-j;

PV : sum of asc_{ij}, for $asc_{ij} > 0$;

NV : sum of asc_{ij}, for $asc_{ij} \leq 0$.

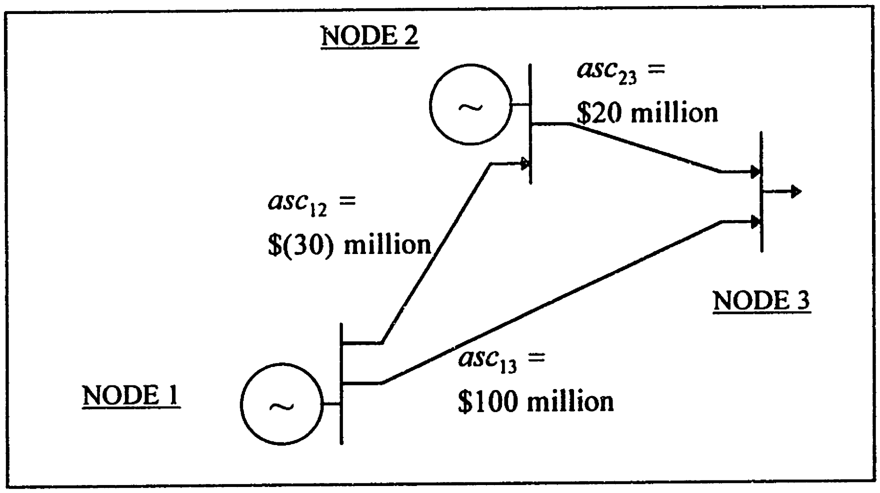


Figure 3.7.- Three bus example to illustrate the links' relative value

The three bus system shown in Figure 3.7 illustrates the concept of relative value. Assume that the additional social costs that the market would bear if links 1-3, 2-3 and 1-2 were removed one at a time are $100 million, $20 million and ($30 million) respectively. Table 3.4.2 summarizes the results of this example. The relative values are computed as follows:

$$\begin{aligned} PV &= asc_{13} + asc_{23} \\ &= 100 + 20 \\ &= \$120 \text{ million} \end{aligned} \qquad \begin{aligned} NV &= asc_{12} \\ &= -30 \\ &= -\$30 \text{ million} \end{aligned}$$

$$\begin{aligned} rv_{13} &= \frac{100}{120} * \left(1 - \frac{-30}{120}\right) \\ &= 1..042 \end{aligned}$$

$$\begin{aligned} rv_{23} &= \frac{20}{120} * \left(1 - \frac{-30}{120}\right) \\ &= 0.208 \end{aligned}$$

$$\begin{aligned} rv_{23} &= \frac{20}{120} * \left(1 - \frac{-30}{120}\right) \\ &= 0.208 \end{aligned}$$

Table4.6.- Avoided social cost and relative values

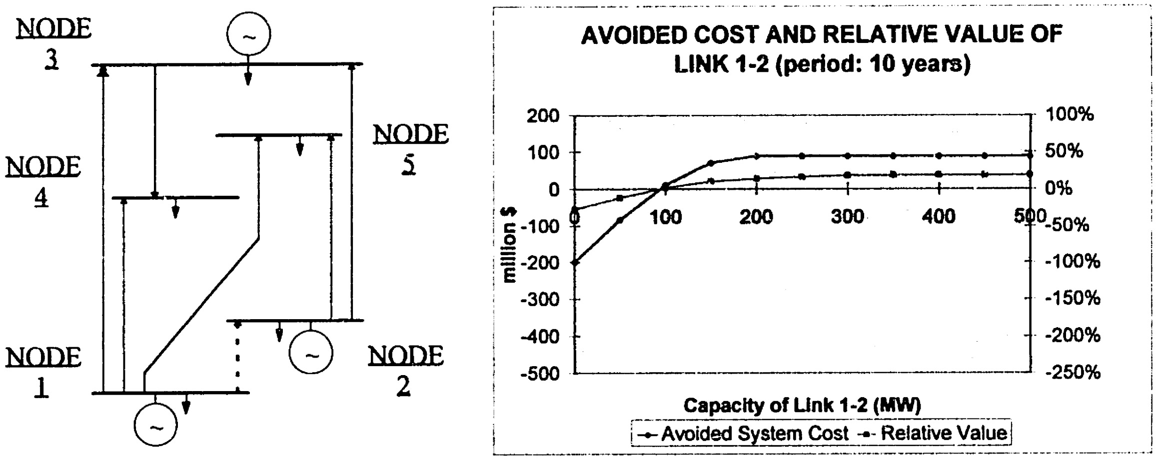
Link *i-j*	asc_{ij}	rv_{ij}
12	-$30 million	1.042
13	$100 million	0.208
23	$20 million	-0.250
$\sum_{ij}$	$90 million	1.000

3.5.2 Relative value and transmission capacity

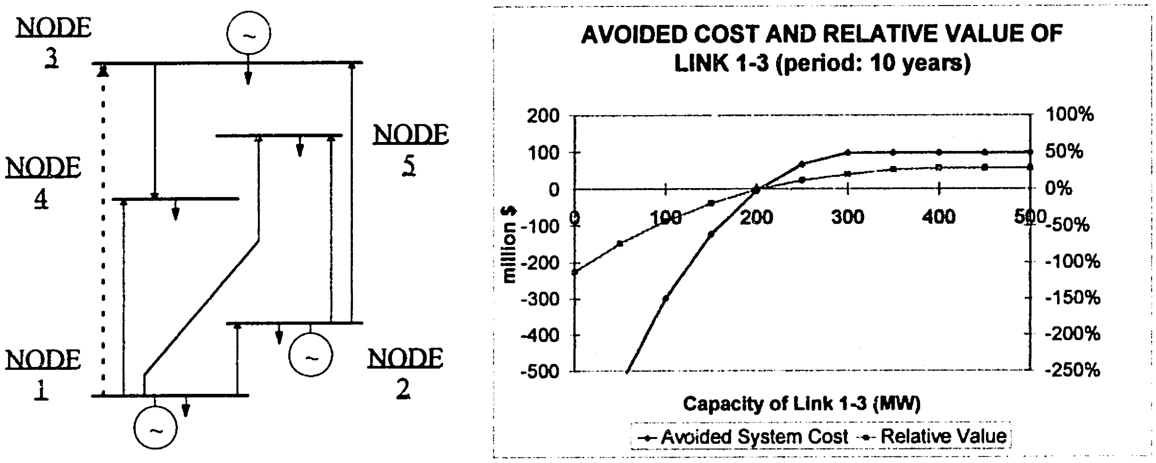
Simulations on the five bus system presented in Section 4.3 show that the relative value of a line increases with its transmission capacity. Even more interesting is that the positive slope of the relative values is not limited to congestion. This is especially noticeable for the links that connect the cost-efficient generators. The relative value of a link does not peak while the slope of the avoided social cost is positive. It peaks when the slope of the avoided social cost is zero. All else being equal, the relative value achieves its maximum when the capacity of the line exceeds the actual flow, that is when the line is not congested. When a link has a negative avoided social cost for all capacities (discussed in Section 4.4.2), its relative value decreases with capacity. Figure 3.8a and 3.8b shows the relative values of several links for different network topologies.

A direct application of the relative value index is a revenue allocation rule for all the links in the network. Basically, when the transmission charges are pooled into a total network revenue, the relative value index indicates what fraction of that revenue corresponds to each link.

Network: P7354524



Network: P7354524



Network: P7354524

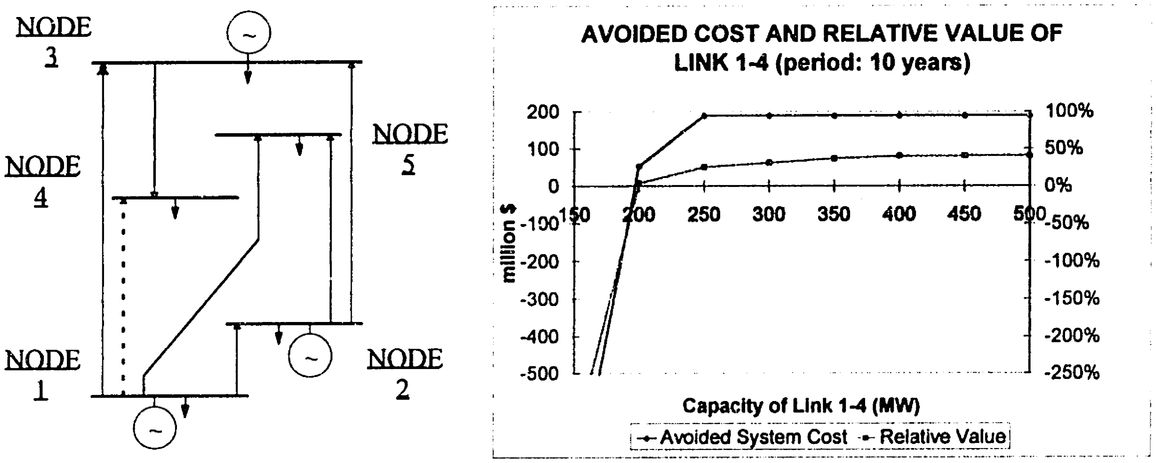
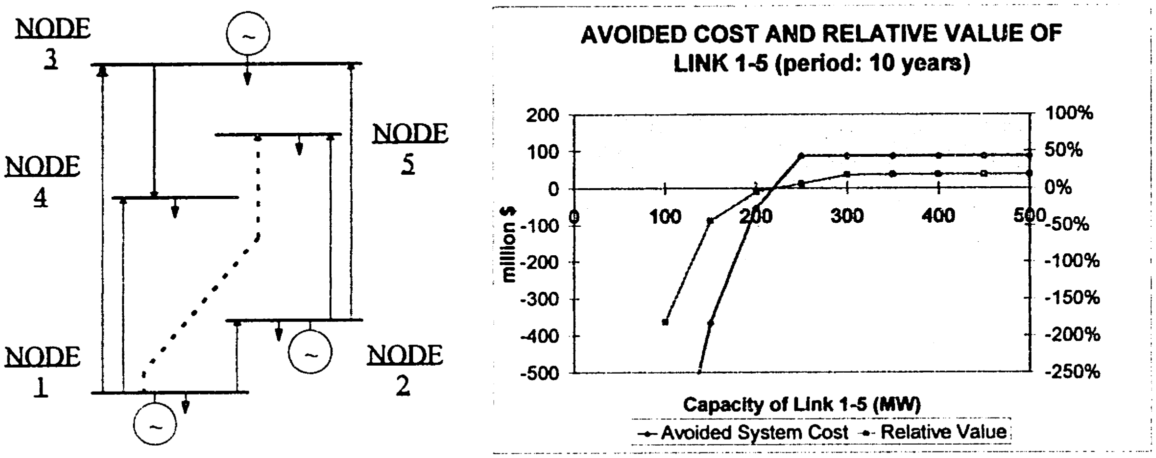
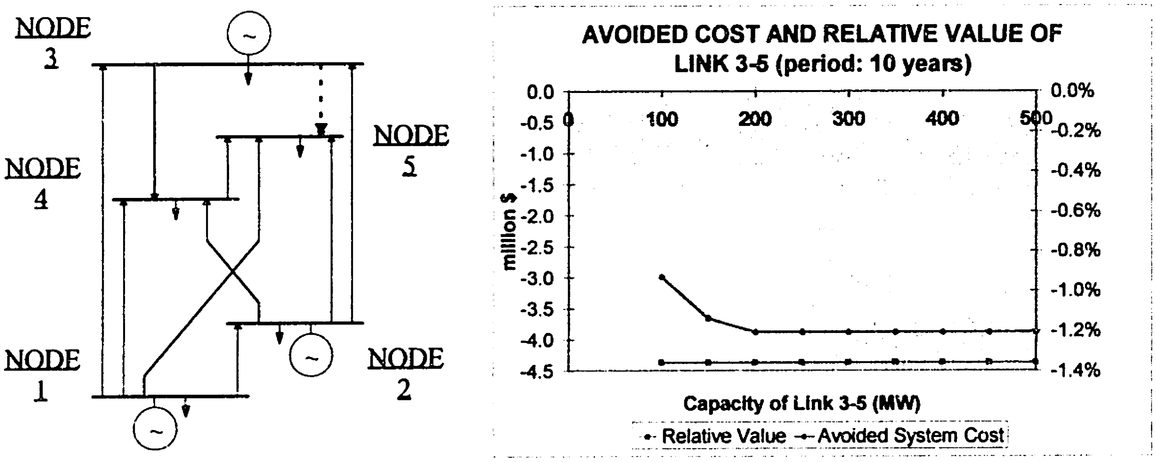


Figure 3.8a.- Relative values increasing with transmission capacity

Network: P7354524



Network: P10



Network: P935

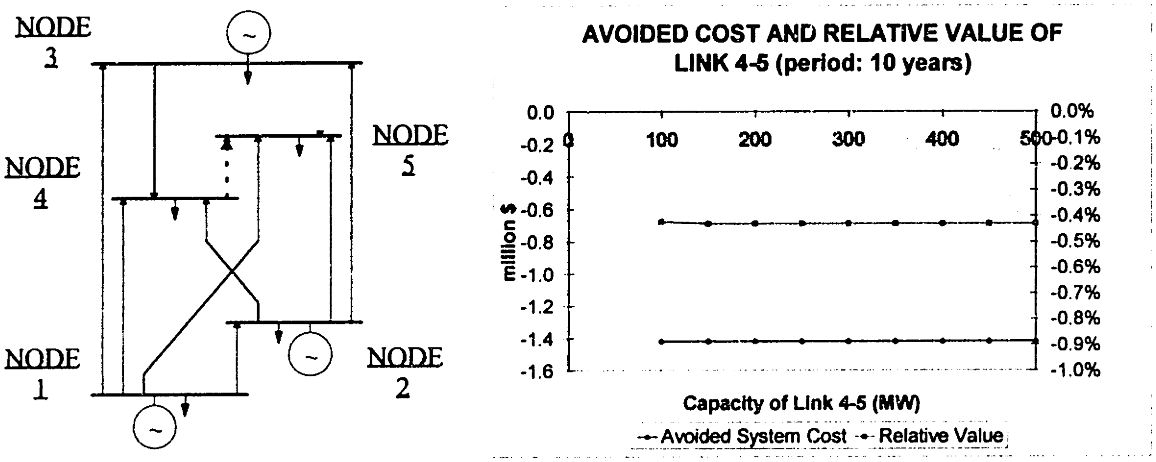


Figure 3.8b.- Relative values increasing with transmission capacity

Chapter 4

Incentives for Investment

4.1 The network revenue

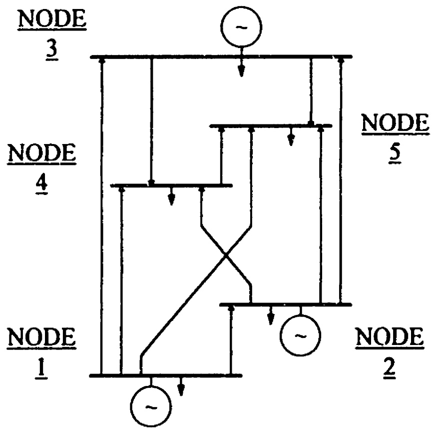
We will call network revenue the sum of all transmission charges collected from the users of the grid. Under an optimal nodal spot pricing scheme, transmission charges are bundled with nodal spot prices. The network revenue equals the difference between what consumers pay and what generators receive. This difference between nodal spot prices depends on the configuration of the transmission grid. In fact, the economic efficiency of two systems with the same generation/load characteristics but different network topologies can differ significantly. Table 4.1 compares generation costs, spot prices and network revenues computed for the 5-node system of Section 3.3 under 3 different network topologies: P10, P7353524 and P121524. In all three cases the lines have the same rating or transmission capacity (400 MW). The results are based on simulations over a 10 year horizon.

The network revenue depends not only on the network topology but also on the transmission capacity of the links. When a line is congested, this relationship is nonlinear and no definitive pattern can be identified. When the link is uncongested, capacity increments have no effect on network revenue. Figure 4.1 shows the relationship between transmission capacity and network revenue for the same three network topologies. An additional component of network revenue comes from transmission losses. All else being equal, the larger the transmission losses, the larger the network revenue.

Studies performed on existing networks show that the network revenue may not be sufficient to pay an attractive return on investment for transmission assets (Pérez-Arriaga et. al., 1995). If that were the case, a two part tariff could be introduced to increase the base of the network revenue. The fixed part would become an access fee that could be the same for all users of the grid.

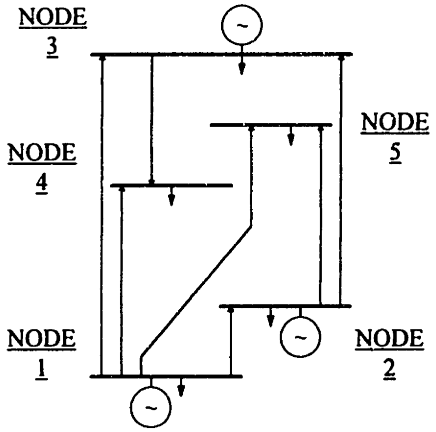
Table 4.1.- Effect of network topology on generation cost, spot prices and network revenue.

Network: P10



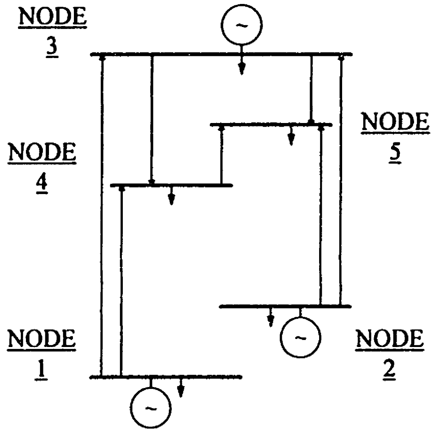
Generation Cost:	$848 million
Network revenue:	$554 million
Spot Prices:	
Node 1 (Peak)	14.0 $/MWh
Node 2 (Peak)	25.1 $/MWh
Node 3 (Peak)	25.8 $/MWh
Node 4 (Peak)	25.1 $/MWh
Node 5 (Peak)	26.9 $/MWh
Average (Peak)	25.3 $/MWh

Network: P7354524



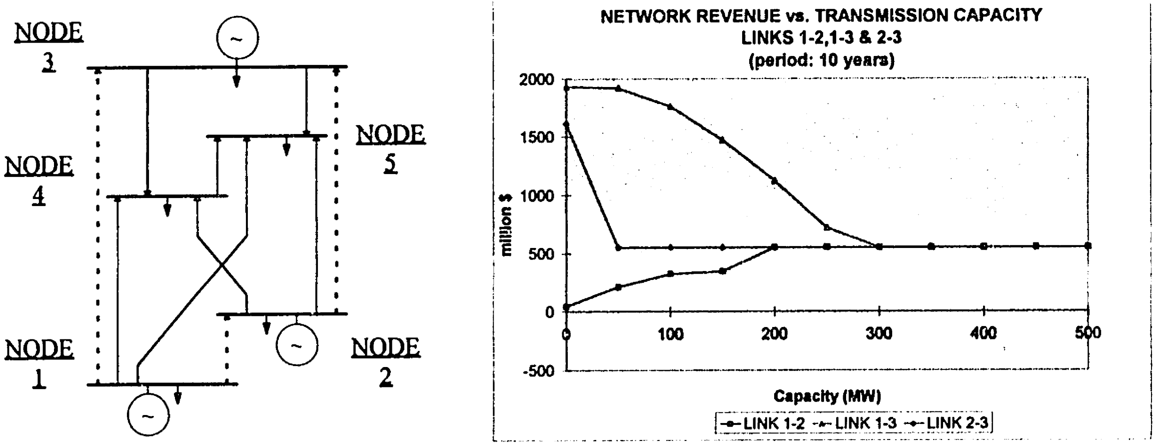
Generation Cost	$843 million
Network revenue	$551 million
Spot Prices:	
Node 1 (Peak)	14.0 $/MWh
Node 2 (Peak)	25.0 $/MWh
Node 3 (Peak)	25.7 $/MWh
Node 4 (Peak)	24.8 $/MWh
Node 5 (Peak)	26.9 $/MWh
Average (Peak)	25.2 $MWh

Network: P7121524

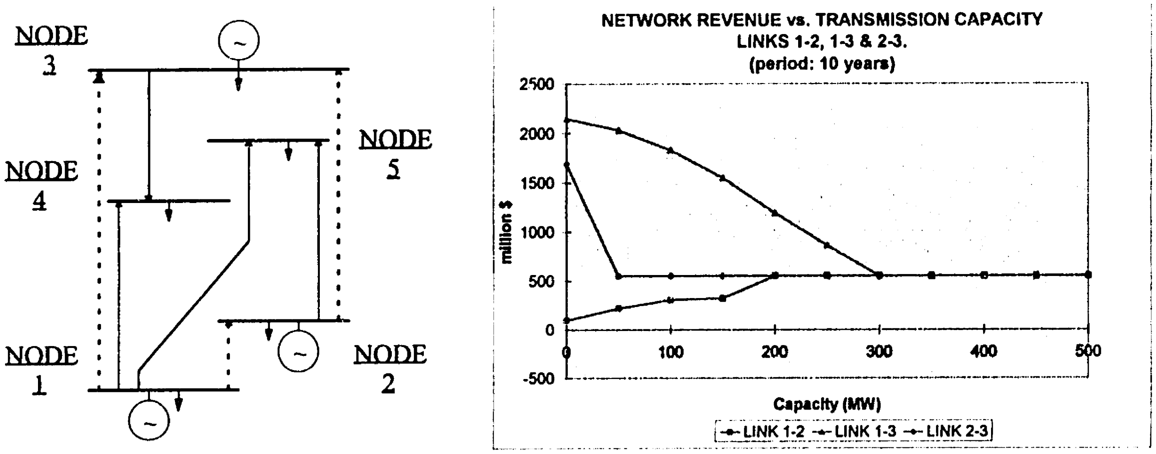


Generation Cost	$1,081 million
Network revenue	$708 million
Spot Prices:	
Node 1 (Peak)	11.8 $/MWh
Node 2 (Peak)	29.8 $/MWh
Node 3 (Peak)	31.1 $/MWh
Node 4 (Peak)	30.3 $/MWh
Node 5 (Peak)	32.1 $/MWh
Average (Peak)	30.0 $/MWh

Network: P10



Network: P7354524



Network: P7121524

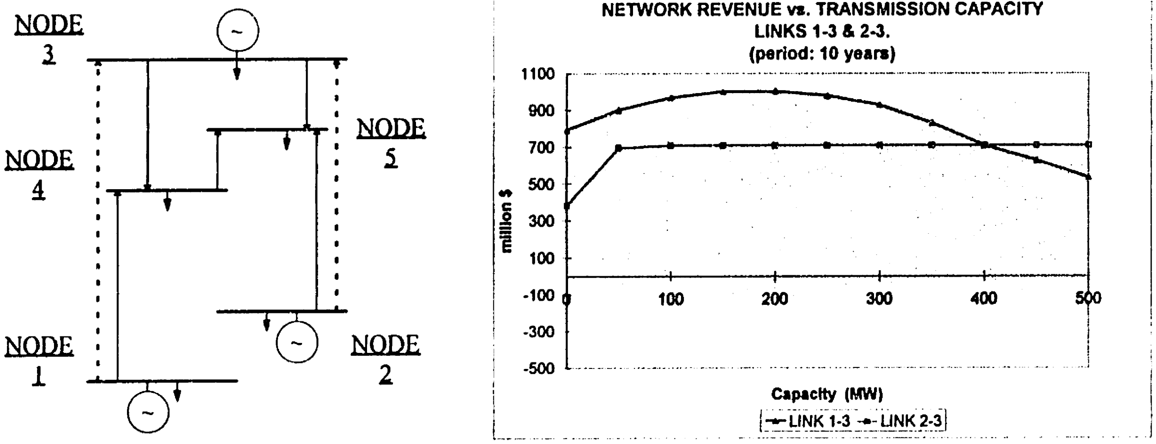


Figure 4.1.- Nonlinear relationship between network revenue and transmission capacity for congested lines.

4.2 A network revenue allocation rule

This thesis claims that the network revenue allocation rule based on the relative value of individual links presented in Section 4.5 provides the right incentives for transmission investment. We understand that the right incentives are those which induce an evolution of the grid that increases social welfare. The underlying assumption is that an optimal network maximizes the difference between the benefits obtained by demand from power consumption and the costs of generating that power. The proposed network revenue allocation rule can be stated as follows:

> Allocation rule: The revenue assigned to a particular link (or link revenue) is a fraction of the network revenue, which corresponds to its relative value.

Since the sum of the relative values of all links within a system equals unity, all the network's revenue is allocated among the links. Note that the relative value of a particular link can exceed unity provided at least one link has a negative relative value (refer to Figure 3.4.b). A negative relative value requires the investor to pay a penalty proportional to the negative externality it creates on the market. This penalty is added to the network revenue and subsequently distributed among the links that have a positive relative value.

According to the allocation rule, the link revenue depends on two factors: the network revenue and the relative value of the link. While the network revenue sets the size of the "pie" to be distributed, the relative value of the link determines the size of the "slice" that corresponds to each particular link. As discussed in the previous sections, while the relative value of individual links increases with transmission capacity, the merchandising surplus can either increase, decrease or remain unaffected. The effect of these relationships on investment incentives is discussed in the next sections.

This allocation rule promotes competition among transmission links for a larger share of the network revenue. At this point a game-theoretic approach would be appropriate to make an in depth assessment of the behavior of individual players. Although the latter is beyond the scope of this thesis, we note that market power could distort the incentive structure we just presented. Owners of multiple links will not necessarily try to maximize the profits from individual links within their portfolio, but the profits of the portfolio itself. This situation leads to a brief discussion in section 4.3 about the nature of transmission infrastructure ownership required by the proposed incentive structure.

4.3 Competition for transmission

In addition to the network topology, the nature of transmission ownership ultimately determines the suitability of a particular incentive scheme. The proposed allocation rule is designed for a fully competitive market for transmission infrastructure where individual links are at the same time complementary goods and competing substitutes. The need for competition stems from the fact that any party holding a portfolio of transmission assets will be interested in maximizing the profit of the portfolio and not that of the individual assets, which is the main goal to be achieved through the allocation rule. In the extreme case of transmission monopoly, all transmission assets are held by one party. The natural incentive of a monopoly is then to maximize total network revenue. This is achieved by degrading the capacity of critical links at the economic expense of power suppliers and consumers. There is an inherent conflict between the interests of a transmission monopolist and those of the rest of the system. Consequently, the presence of transmission monopolies makes the proposed incentive scheme obsolete and requires the intervention of a regulator as in the UK (Hunt and Shuttleworth, 1996).

In a competitive environment, the allocation rule based on relative values promotes the enhancement of the grid because it captures and rewards the positive effects that transmission assets have on the market. But, since the reinforcement of a particular link or the creation of a new link in the system changes the relative values of the remaining transmission links, there is risk associated with the investment.

It is important to observe how the behavior of transmission link owners varies depending on their market share or monopoly power. Extreme cases have been presented above. On one of end of the spectrum is full competition, where, no investor owns more than one transmission link, and at the other, a monopoly structure. It has been shown that the behavior of transmission investors on either extremes of the spectrum is completely different. Further study needs to be done in a game theory framework for the case of investors with some, but not total market power.

4.4 Incentives for grid investment

So far we have presented results based on different network configurations. At this point it is important to state the explicit differences among them. Network P10 is a fully meshed network. This means that all possible links between the five nodes are active. The simulation results show that two links have a negative impact on social cost and hence have a negative relative value: links 3-5 and 4-5 (refer to Appendix P10). If link 3-5 (lowest relative value) is removed, one obtains network P935. Not surprisingly, the drop in system cost corresponds to the additional generation cost created to link 3-5 ($4 million over 10 years). In this network, the value of link 4-5 is still negative and that of link 2-4 falls to zero (refer to Appendix P935). If link 4-5 is removed, one obtains network P83545. Again, system cost drops $2 million over 10 years and the relative value of link 2-4 becomes negative (refer to Appendix P83545). Finally, if link 2-4 is removed, one obtains network P7354524. The generation cost is minimal since adding any other link increases it. In terms of network topology, one could say that network P7354524 is optimal because it minimizes overall operating costs. The remaining network configuration P121524 is therefore sub-optimal because the generation cost is higher than that of any of the previous cases. In this configuration, all links connecting node three have a negative relative value.

The idea of an allocation rule based on the relative values of individual links creates a series of incentives for grid modification and gambling. A thorough study on the evolution of the network entails an assessment of the relative values of the existing links, differentiating those with positive relative values from those with negative relative values. In addition, the analysis considers the relative value of any potential new link. According to the allocation rule transmission links with negative relative values are penalized and eventually removed (switch off). Investment in a new link is likely to occur if the potential revenues provide an attractive return on investment.

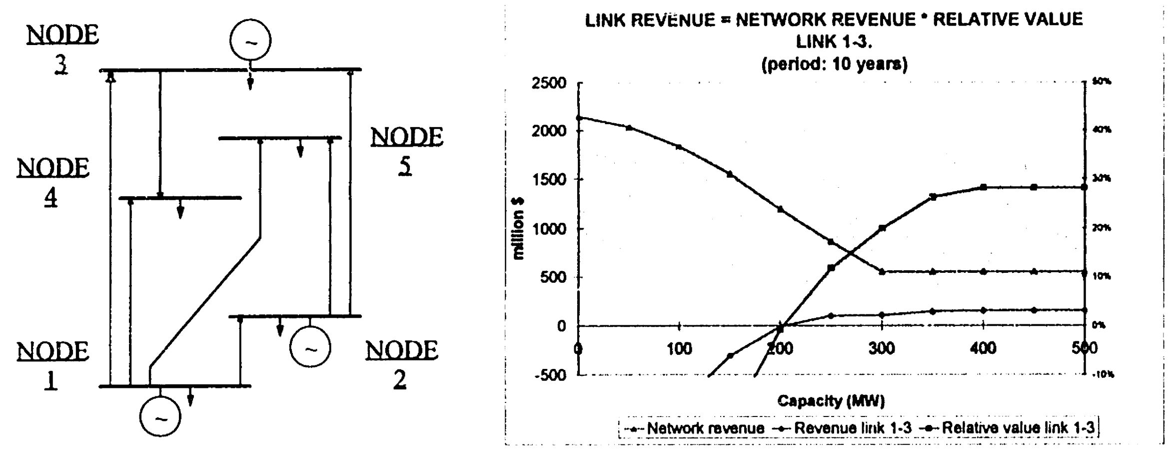
Incentives for changing the transmission capacity of existing links lie in the signs of the slopes of the curves that relate the link revenue with link capacity. A positive slope means that the transmission link owner is better off enhancing transmission capacity. Conversely, a negative slope is an incentive to reduce transmission capacity. Again, these incentives have been numerically quantified by means of the 5 bus model. In most cases, the incentive will be that of enhancing transmission capacity. In an inefficient network like P121524, however, there could be a short term incentive to reduce capacity to a certain extent. This case is shown in figure 4.2 where the capacity that maximizes revenues for link 1-3 is set at 300 MW[1]. However, this incentive should be carefully assessed in light of the imminent grid modifications that would follow from the application of the allocation rule.

A transmission asset worth a great deal today may not pay for itself in the long run if more efficient network upgrades are introduced. Conversely, an investment not worth committing today may become attractive as demand and supply patterns evolve over time. As demand conditions change, the transmission investors will find new opportunities for expansion that will lead to further increases in system efficiency. If there were any existing links with a negative relative value, there would be an incentive to remove (switch off) these links in order to avoid an economic penalty. These links could be reconnected if the market conditions make it profitable to do so. Figure 4.3 shows the relationship between penalty and capacity for a link with negative relative value.

---

[1] Note that link 1-3 is congested for all capacities between 0-500 MW

Network: P7354524



Network: P7121524

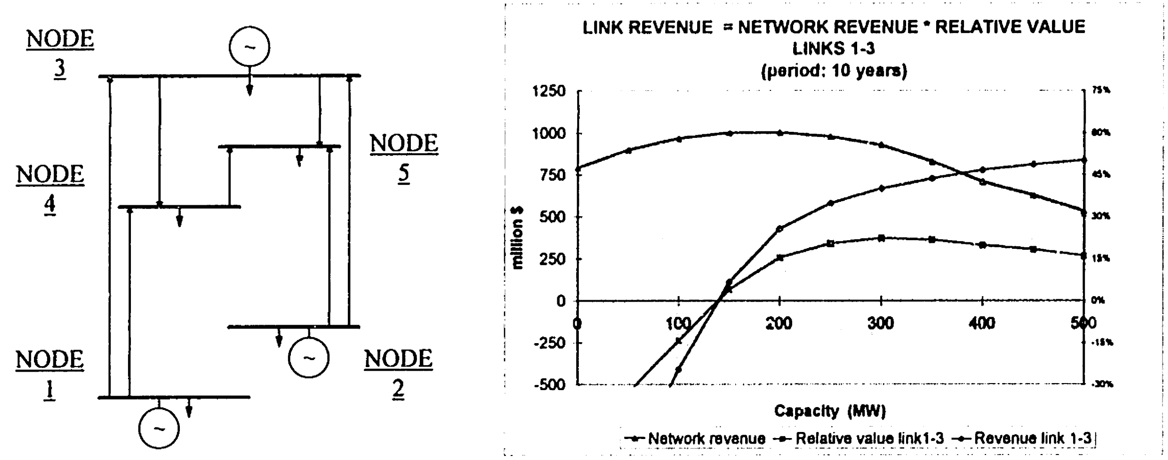


Figure 4.2.- Relationship between a link's revenue, its relative value and the network revenue.

Network: P10

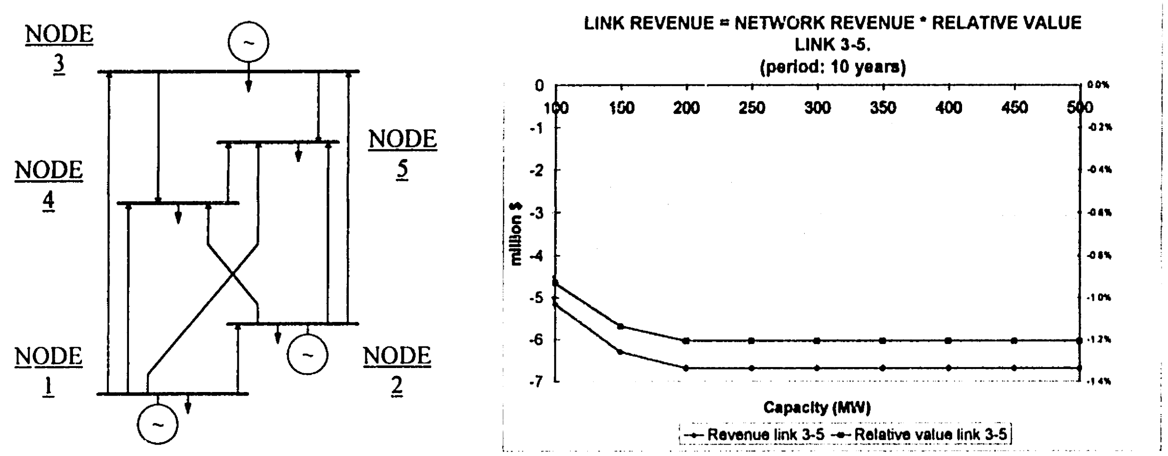


Figure 4.3.- Negative revenues for links with a negative relative.

4.5 Impact on the power demand/supply market

This thesis has emphasized the relationship between the configuration of the grid and the efficiency of the market, which is measured in terms of social welfare. The network revenue allocation rule presented in Section 4.2 is intended to provide economic signals to transmission investors that result in an expansion of the grid that better serves society as a whole. However, these modifications shift the distribution of welfare among power suppliers on one hand and consumers on the other. Invariably, some agents will benefit at the expense of others. The purpose of this section is to analyze how the expansion of the grid affects different market participants.

Either in a centralized dispatch[2] or within a bilateral transaction scheme, market participants take the grid as given and will make decisions that take advantage of all resources available to them. In the spirit of open access to the transmission system, the approach followed in this thesis is to consider the transmission grid as a public good[3]. This means that no transmission link can be reserved for a particular transaction, but will be available to all transactions on a merit basis.

For the purpose of this analysis we consider two different types of transmission upgrades: (1) the expansion of power transfer capacity of existing transmission links and (2) the creation of new transmission links. Section 4.5.1 deals with the first kind of grid upgrade and section 4.5.2 deals with the second kind. Although the results shown in the following sections have been derived for the case of centralized dispatch, we believe that the conclusions can be extended to the case of bilateral transactions.

4.5.1 Upgrading existing transmission links

The first question to be addressed is: Who benefits from the incentive created by implementing the allocation rule? In other words, the objective is to understand more fully the relationship between transmission capacity and the welfare of indi-

---

[2] Centralized dispatch is assumed to be coordinated by an independent system operator (ISO)

[3] Pindyck and Rubinfeld define a public good as a good that, once provided to some consumers, is very difficult to deny to others from using it [Pind,1995].

vidual market participants. The intuitive answer is that incentives that reduce social cost benefit both the efficient supplier and the average consumer. Suppliers are better off if their profits increase as the grid modifications take place. The profit of a generator equals its revenue minus generation costs[4]. Needless to say, consumers are better off when the average per unit cost of power (the average nodal spot price) falls.

With increasing transmission capacity one expects the variance across spot prices to diminish and the average spot price to approach system lambda. By average spot price, we mean the average price paid by all consumers across the network over a specific period of time. All else being equal, a larger transmission capacity at any link results in a reduction of the inefficiencies that cause the spot price to differ across nodes. In other words, an efficient transmission grid reduces spatial price discrimination. The average price per unit of power paid by consumers should be a monotonicaly decreasing function of transmission capacity. This relationship should be valid for those transmission links that have a positive relative value.

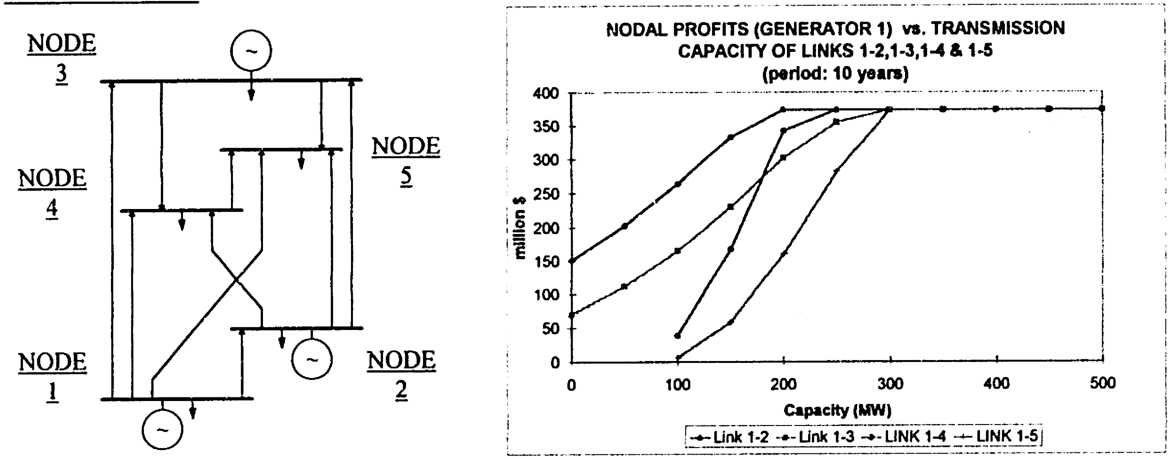
Again, we use the 5-bus system introduced in the previous sections to test these intuitive notions. Here, the per unit cost of power at a particular generation node is given by its cost function while its per unit revenue is given by its nodal spot price. The following observations are consistent across the different configurations:

First, the profits of generator 1 (least cost) never decrease with an increment of transmission capacity at any link in the grid. Furthermore, two cases can be observed: (1) the profits of generator 1 always increase monotonicaly with the power handling capability of the links that are connected to it; and (2) the profits of generator 1 never decrease with capacity increments at any link to which it is not connected. Figure 4.4 illustrates the behavior of generator 1's profits as a function of transmission capacity of different links.

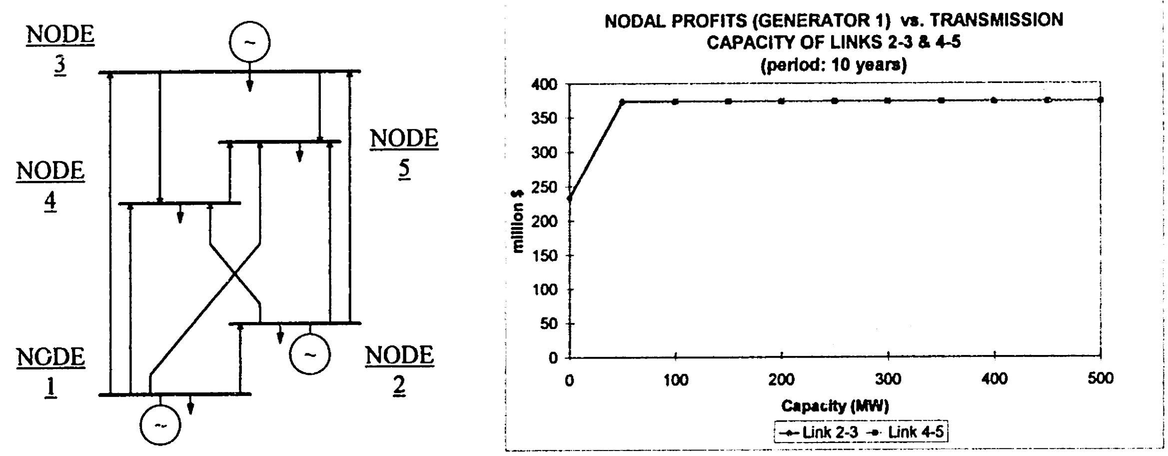
---

[4] The generation cost consists of fixed and variable costs.

Network: P10



Network: P10



Network: P7121524

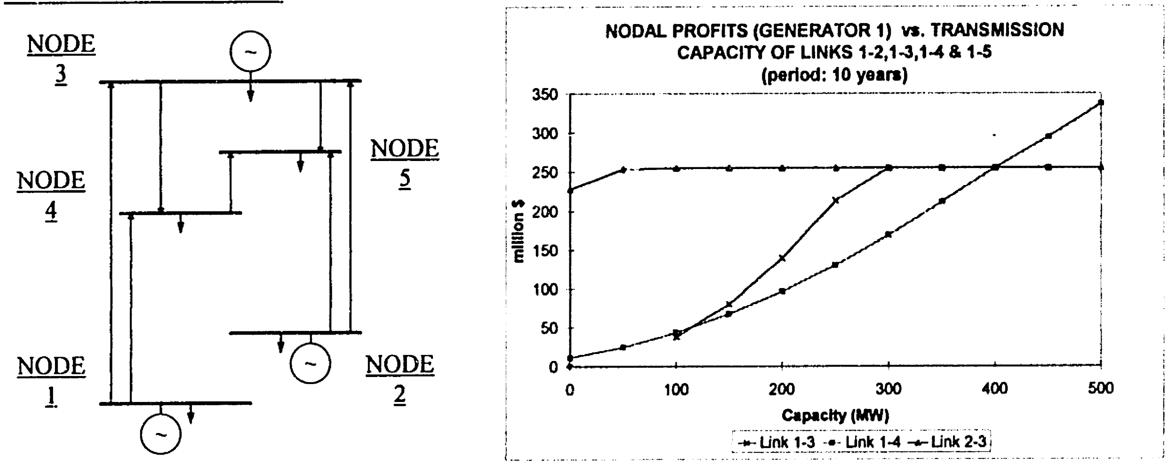


Figure 4.4.- Increasing profits for the most efficient generator.

Second, the less cost effective power suppliers become less profitable as a result of transmission grid enhancement, since the need for out of merit dispatch to meet transmission constraints is reduced. Figure 4.5 shows the response of nodal profits at nodes 2 and 3 as a function of transmission link capacity.

Network: P7121524

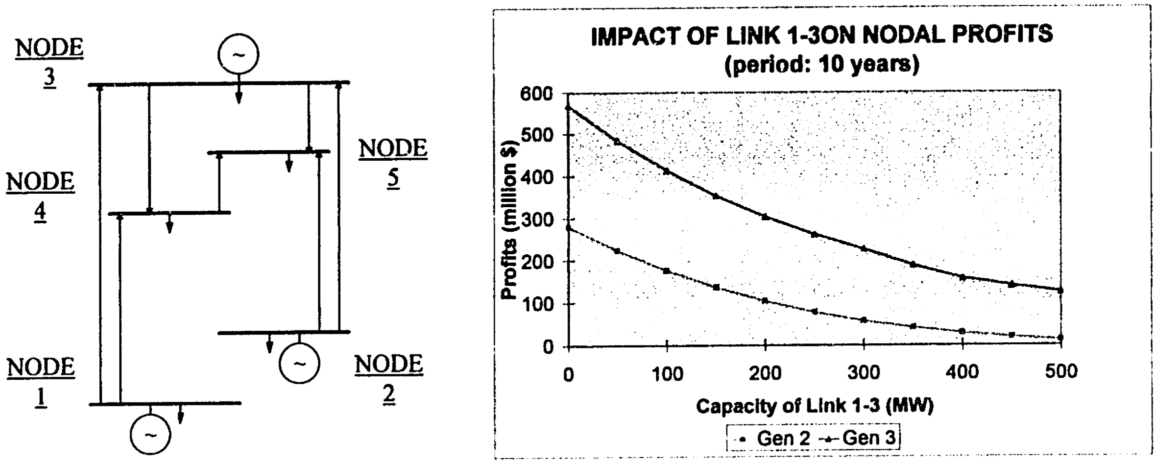
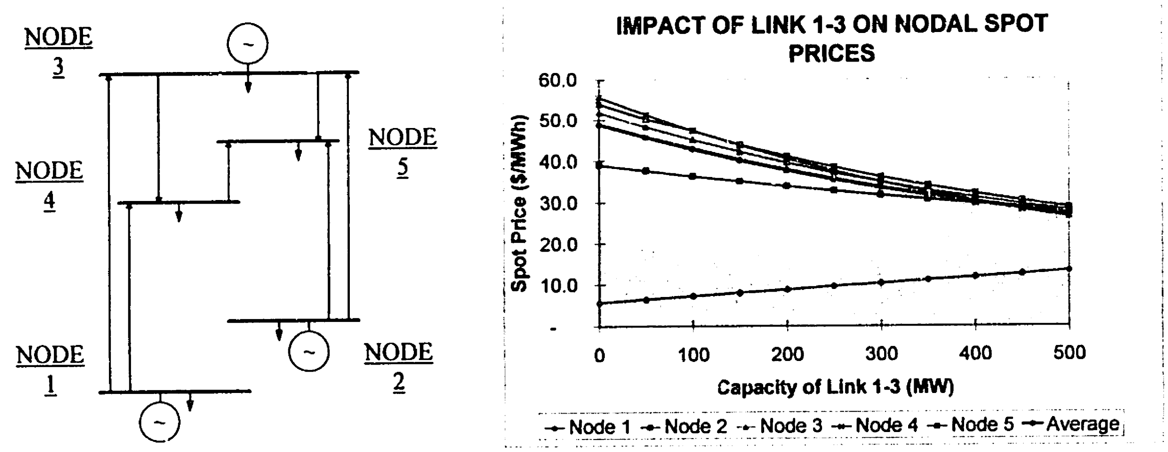


Figure 4.5.- Decreasing profits for the less efficient generators.

Third, the variance of the spot prices across nodes either decreases or at least remains constant with transmission link capacity. This is because in the absence of congestion, spot price differences across nodes are only due to transmission losses .

Fourth, while most nodes face diminishing spot prices as the transmission capacity of the system increases, some nodes may experience an increase spot prices. However, on the average, spot prices decrease in all simulations but in one. The analysis of link 1-2 shows that despite decreasing generation costs, the average spot price faced by consumers increases with capacity. In this case, network revenue is unusually small for low transmission capacities. This result seems to be particular to the topology of this system and requires further analysis. Figures 4.6 illustrates the typical behavior of spot prices as a function of different transmission link capacities, and figure 4.7 shows the abnormal effect of link 1-2 on nodal spot prices.

Network: P7121524



Network: P935

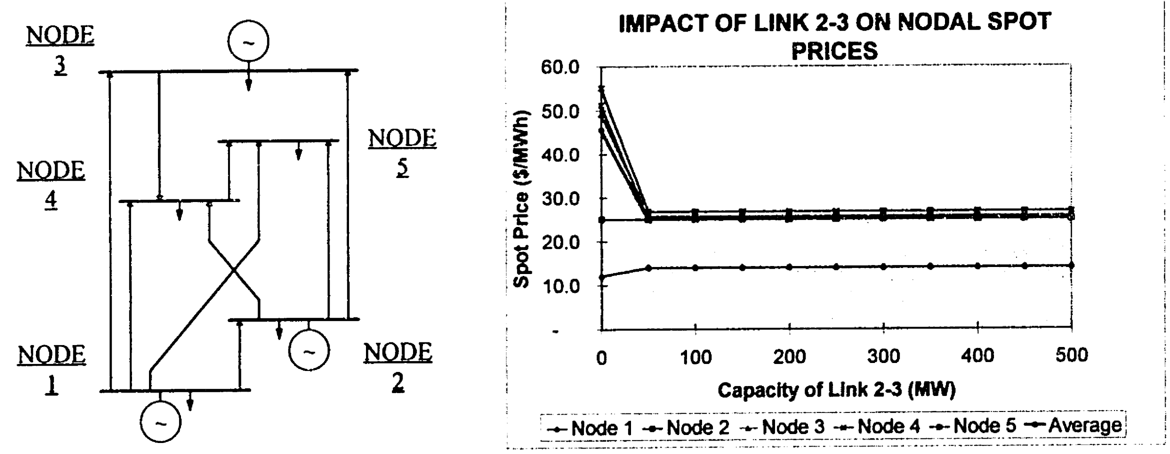


Figure 4.6.- Decreasing variance between nodal spot prices

Network: P10

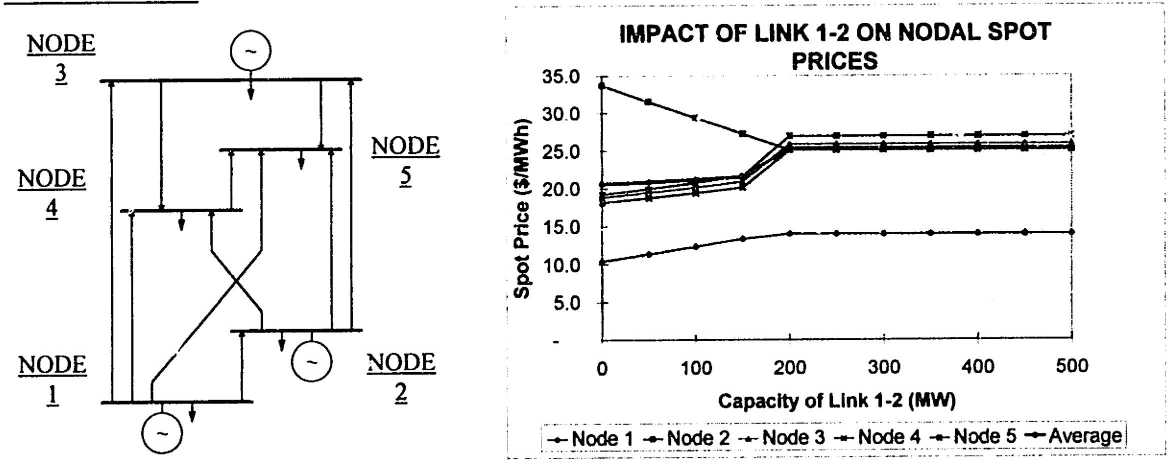


Figure 4.7.- Special case: consumers pay less when system cost is higher.

4.5.2 Creating new links

Another kind of network expansion consists of adding new transmission links. The allocation rule presented in Section 4.2 promotes the creation of new links that reduce overall system cost as long as the value of expected revenues exceeds the investment cost. Here, the results are less obvious and require a more careful analysis.

Although enhanced transmission capacity favors the profits of cost efficient generators, the effect of introducing a link between two generation nodes always seems to results in profit losses in at least one of nodes involved. This result has been consistent in all simulations performed on the 5-node system of Section 3.3 but remains to be proved. Furthermore, the effect of a new transmission link on the profits of a generator to which it is not connected cannot be characterized: this effect could be either positive, negative or non-existent. Figure 4.8 shows the difference in generation profits that results from connecting nodes 2 and 3. In this case, connecting nodes 2 and 3 yields increased profits for generator 2 and lower profits for generator 3.

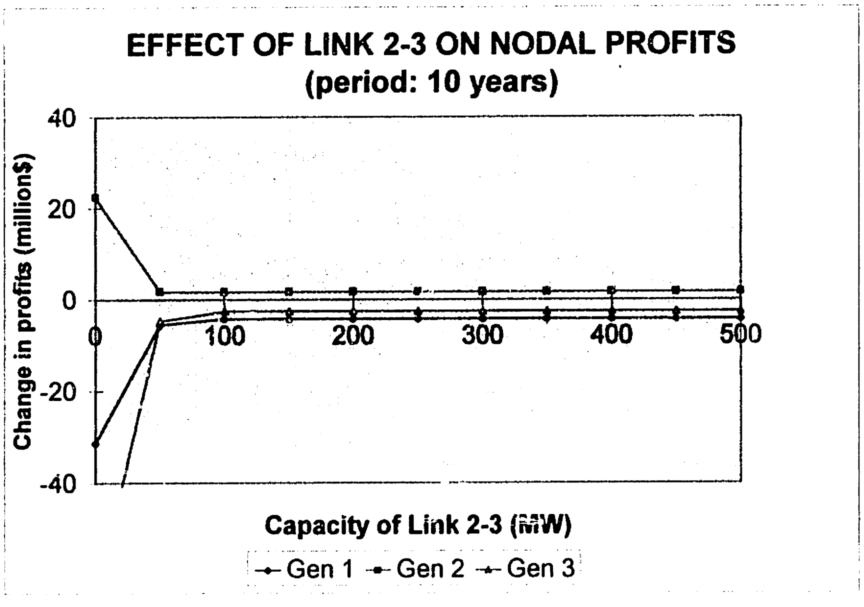


Figure 4.8.- Relationship between nodal profits and the addition of a link.

4.6 Implementation Issues

The allocation rule presented here and the incentives that derive from it assume that transmission owners will try to maximize the revenue of each link within the grid. For that to be true, the electric power transmission industry needs to be perfectly competitive. No transmission owner has market power or, strictly speaking, owns more than one link. Consequently, existing transmission assets would have to be auctioned under clear bidding rules.

This is a strong analytic assumption that needs further refinement. The effects of market power on transmission investment still need to be assessed. Having said that, we proceed to describe the different issues that need to be addressed to implement the proposed incentive structure.

4.6.1 Time horizon for investment incentives

The system's operating conditions change with time. On one hand, demand experiments cyclical fluctuations. On the other, not all generating units are necessarily available at all times. Even throughout any given day, the system experiences several dispatch patterns. Consequently, the impact of any particular link on system performance is not fixed. It varies as operating conditions change.

The relative value of a transmission link needs to be computed over longer term time horizons. This way, short term noise due to random contingencies is averaged out and the appropriate medium-long term effects are identifiable. It is important to remember that investment decisions imply long-term planning and commitment.

The same observation applies to the network revenue or merchandising surplus. The merchandising surplus is the result of hourly transactions. In other words, it is strictly related to the operation of the system and is therefore subject to short term fluctuations.

We think that an appropriate level of aggregation for the economic signals created by the proposed incentive structure should not be less than two or three months and not longer than one year. In a sense, the timing of the economic signals has to be related to the time to implement any grid alteration.

4.6.2 Publicly available information

The revenue corresponding to individual links need to be based on the results of past operations, however, any planning involves some projection into the future. Therefore, a critical issue is the availability of information about past and actual operations of the system, and about projects under development. Therefore, the implementation of an information center is necessary. This information center does not need to be the operator of the system, because it does not need to process information in real time.

4.6.3 Revenue adequacy and two part tariffs.

There is a debate about how to create the funds that would pay for the transmission system. It has been argued that the collection of transmission charges --merchandising surplus— is not enough to provide an attractive return on investment in transmission assets. We believe that this problem can be sorted out by splitting the transmission charges into a two-part tariff. This two-part tariff would introduce a non-discriminatory fixed fee for transmission access in addition to the economically efficient transmission charge suggested by the nodal spot pricing theory. A non-discriminatory fixed access fee would not distort the economic signals created by the variable charges, but would certainly raise the basis of the network revenue. The setting of this access fee would be a matter of regulation.

Obviously, the introduction of an access fee would affect suppliers and consumers alike. One could expect initial resistance towards the implementation of such pricing structure. The point has to be made, however, that an efficient transmission system ultimately benefits both suppliers and consumers alike.

Chapter 5

Conclusions

5.1 On the separation of generation and transmission ownership

Electric power utility planning had one major performance objective: to serve demand at the lowest possible cost. Utilities assessed and the impacts on their cost structure that would result from investing in transmission enhancement, building new generation units or operating more expensive units. Consequently, centralized coordination between generation and transmission in the operation and planning of electric power systems internalized negative and positive externalities, such as transmission congestion or improved system reliability.

Separation of generation and transmission ownership multiplies the number of market participants and, consequently, the number of interests to be satisfied. A problem arises if it is not in the best interest of transmission investors to improve the efficiency of the transmission grid. The transmission grid has a tremendous impact on the market since it ultimately determines the economically most attractive set of market transactions.

The social value of a transmission system lies in its ability to enable operations to be as reliable and cost effective as possible. If the improved reliability and cost effectiveness that a transmission system creates for market operations do not translate into benefits for transmission investors, there is a case of externality and market failure.

In addition, it is a shortsighted application of spot pricing theory that leads to tying grid ownership reward to the merchandising surplus, that is, to transmission congestion and losses. This situation creates an agency problem by which it is in the interest of transmission owners to degrade the efficiency of the market it is supposed to serve.

Both, the externality and the agency problems become evident in the case of a transmission monopoly. Its natural incentive to maximize profits plays against an efficient operation of the competitive market. Therefore, if such industry structure were adopted, a clear need for regulation and oversight is necessary.

In this context it is appropriate to state our understanding of an optimal transmission system. An optimal transmission system is one that enables the least operating cost of a system for given generation resources and consumption patterns. The system's efficiency increases and society is better off when fewer resources are used to provide a service. This definition differs from the one that says that an optimal network is the one that has enough congestion to recover capital investment (Lecinq, 1995). Our definition is related to the fact that the merchandising surplus does not necessarily generate enough funds to pay for the required transmission assets. The underlying assumption is that the merchandising surplus is the only source of funds to pay for the grid.

This difficulty could be overcome with the introduction of a two part tariff for transmission pricing. The addition of a non-discriminatory fixed fee for transmission access does not distort the economic signals to the active market agents, but raises the basis of the network revenue. In this way, a congested network to pay for transmission is no longer a necessary condition.

5.2 On the value of an electric power transmission system.

The configuration of the transmission system affects the efficiency of the market. It is desirable to make it in the transmission investors' best interest to improve the efficiency of the system. It is necessary to design an incentive scheme that makes investments in the transmission grid economically attractive only if they reduce social cost. We will be able to accomplish is task only if we can make a quantitative assessment of how the configuration of the transmission network affects the market.

The notion of avoided social cost provides a yardstick to measure the economic impact that individual transmission links have on the system. As such, it enables us to compare the value of individual links and their relationship with transmission capacity. It effectively measures the additional cost the market would bear if the grid faced the loss of a particular link.

Nodal spot pricing theory drives the attention towards transmission congestion and losses. Dealing with the economic optimization of short term operations, it assumes the grid as given and does not capture the cost of opportunity associated to a particular network topology, that is, the effect of which links are actually in place. Under the spot pricing approach, the only lines that matter are the ones that face congestion.

However, the value of a transmission line is not only a matter of whether it is congested or not. Indeed, the social cost avoided by an overdimensioned transmission link is by no means less than that of the same link, had it been congested. Furthermore, the value of a transmission line depends more on whether it allows the least expensive generators to fully dispatch.

5.3 Incentives for investment

Having a means of quantifying the value that individual links add to the operations of the market, we propose a link-by-link network revenue allocation rule that rewards efficiency. The allocation rule consists of distributing the network revenue among the individual links of the network in proportion to their relative values. While the network revenue sets the size of the "pie" to be distributed, the relative value of the link determines the size of the "slice" that corresponds to each particular link. Numerical results show that for most cases, the reward of owning a transmission link increases with capacity. Not surprisingly, the links with higher returns are those that connect the most cost efficient generators to the rest of the system.

However, a transmission asset worth a great deal today may not pay for itself in the long run if more efficient network upgrades are subsequently introduced or new generation is built. Risk will prevent investors from making hasty decisions, and, for this reason, the timing of the economic signals is critical.

5.4 Further research

The analysis presented here is based on two fundamental assumptions: (1) alterations on the grid cannot be implemented fast enough to have an effect on short term operations; and (2) the market for transmission investment enjoys perfect competition.

As of today, little work has been done to understand the implications that the divestiture of the formerly integrated electric power utilities will have on the evolution of the transmission system in a competitive environment. We hope this work will provide interested parties with additional insights into this matter.

Appendix A

Sample of Simulation Results

Case: Fully meshed network P10

Link: 1-2

Time: 10 years

Units: million $

Capacity	System Cost w/ link 1-2	System Cost w/o link 1-2	Delta Social Welfare	Relative Importance	MS	Revenue
0	1243	928	-315	-49%	43	-21
50	1089	928	-161	-26%	210	-55
100	966	928	-38	-6%	324	-21
150	883	928	45	9%	347	30
200	848	928	80	17%	554	92
250	848	928	80	21%	554	117
300	848	928	80	22%	554	123
350	848	928	80	22%	554	123
400	848	928	80	22%	554	123
450	848	928	80	22%	554	123
500	848	928	80	22%	554	123

Capacity	Profit Gen 1	Profit Gen 2	Profit Gen 3	Delta Profit Gen 1	Delta Profit Gen 2	Delta Profit Gen 3
0	151	113	48	-225	111	-48
50	203	60	52	-174	58	-44
100	264	25	58	-112	23	-39
150	333	6	59	-44	4	-37
200	374	0	98	-3	-2	2
250	374	0	98	-3	-2	2
300	374	0	98	-3	-2	2
350	374	0	98	-3	-2	2
400	374	0	98	-3	-2	2
450	374	0	98	-3	-2	2
500	374	0	98	-3	-2	2

Case: Fully meshed network P10

Link: 1-3

Time: 10 years

Units: million $

Capacity	System Cost w/ link 1-3	System Cost w/o link 1-3	Delta Social Welfare	Relative Importance	MS	Revenue
0	2013	982	-1031	-118%	1933	-2276
50	1597	982	-616	-70%	1923	-1353
100	1287	982	-305	-37%	1762	-651
150	1070	982	-89	-12%	1471	-176
200	935	982	47	7%	1122	76
250	861	982	121	18%	724	134
300	848	982	134	29%	554	160
350	848	982	134	36%	554	201
400	848	982	134	37%	554	207
450	848	982	134	37%	554	207
500	848	982	134	37%	554	207

Capacity	Profit Gen 1	Profit Gen 2	Profit Gen 3	Delta Profit Gen 1	Delta Profit Gen 2	Delta Profit Gen 3
0	70	14	1378	-298	12	1221
50	112	9	966	-256	7	810
100	165	4	652	-203	3	495
150	230	1	420	-138	0	263
200	302	0	263	-66	-2	106
250	355	0	135	-13	-2	-22
300	374	0	98	5	-2	-59
350	374	0	98	5	-2	-59
400	374	0	98	5	-2	-59
450	374	0	98	5	-2	-59
500	374	0	98	5	-2	-59

Case: Fully meshed network P10

Link: 1-4

Time: 10 years

Units: million $

Capacity	System Cost w/ link 1-4	System Cost w/o link 1-4	Delta Social Welfare	Relative Importance	MS	Revenue
100	1795	941	-854	-24%		
150	1143	941	-202	-12%	713	-87
200	866	941	75	8%	577	44
250	848	941	93	18%	554	100
300	848	941	93	26%	554	144
350	848	941	93	26%	554	144
400	848	941	93	26%	554	144
450	848	941	93	26%	554	144
500	848	941	93	26%	554	144

Capacity	Profit Gen 1	Profit Gen 2	Profit Gen 3	Delta Profit Gen 1	Delta Profit Gen 2	Delta Profit Gen 3
100	39	269	291	-338	267	178
150	167	68	160	-209	66	47
200	343	1	99	-34	0	-13
250	374	0	98	-3	-2	-14
300	374	0	98	-3	-2	-14
350	374	0	98	-3	-2	-14
400	374	0	98	-3	-2	-14
450	374	0	98	-3	-2	-14
500	374	0	98	-3	-2	-14

Case: Fully meshed network P10

Link: 1-5

Time: 10 years

Units: million $

Capacity	System Cost w/ link 1-5	System Cost w/o link 1-5	Delta Social Welfare	Relative Importance	MS	Revenue
0						
50						
100	2391	899	-1492	-42%		
150	1629	899	-730	-36%		
200	1164	899	-265	-20%	841	-171
250	920	899	-21	-2%	726	-16
300	848	899	51	8%	554	43
350	848	899	51	12%	554	68
400	848	899	51	14%	554	78
450	848	899	51	14%	554	79
500	848	899	51	14%	554	79

Capacity	Profit Gen 1	Profit Gen 2	Profit Gen 3	Delta Profit Gen 1	Delta Profit Gen 2	Delta Profit Gen 3
0						
50						
100	6	413	537	-369	413	432
150	59	189	343	-316	188	238
200	160	65	201	-215	64	95
250	282	8	129	-93	8	24
300	374	0	98	-1	-1	-7
350	374	0	98	-1	-1	-7
400	374	0	98	-1	-1	-7
450	374	0	98	-1	-1	-7
500	374	0	98	-1	-1	-7

Case: Fully meshed network P10

Link: 2-3

Time: 10 years

Units: million $

Capacity	System Cost w/ link 2-3	System Cost w/o link 2-3	Delta Social Welfare	Relative Importance	MS	Revenue
0	1100	850	-250	-35%	1614	-561
50	848	850	1	0%	554	2
100	848	850	1	0%	554	2
150	848	850	1	0%	554	2
200	848	850	1	0%	554	2
250	848	850	1	0%	554	2
300	848	850	1	0%	554	2
350	848	850	1	0%	554	2
400	848	850	1	0%	554	2
450	848	850	1	0%	554	2
500	848	850	1	0%	554	2

Capacity	Profit Gen 1	Profit Gen 2	Profit Gen 3	Delta Profit Gen 1	Delta Profit Gen 2	Delta Profit Gen 3
0	234	0	496	-140	0	393
10	374	0	98	0	0	-4
20	374	0	98	0	0	-4
30	374	0	98	0	0	-4
40	374	0	98	0	0	-4
50	374	0	98	0	0	-4
60	374	0	98	0	0	-4
70	374	0	98	0	0	-4
80	374	0	98	0	0	-4
90	374	0	98	0	0	-4
100	374	0	98	0	0	-4

Case: Fully meshed network P10

Link: 2-4

Time: 10 years

Units: million $

Capacity	System Cost w/ link 2-4	System Cost w/o link 2-4	Delta Social Welfare	Relative Importance	MS	Revenue
0	0	0	0	0%	0	0
0	0	0	0	0%	0	0
100	848	848	0	0%	554	0
150	848	848	0	0%	554	0
200	848	848	0	0%	554	0
250	848	848	0	0%	554	0
300	848	848	0	0%	554	0
350	848	848	0	0%	554	0
400	848	848	0	0%	554	0
450	848	848	0	0%	554	0
500	848	848	0	0%	554	0

Capacity	Profit Gen 1	Profit Gen 2	Profit Gen 3	Delta Profit Gen 1	Delta Profit Gen 2	Delta Profit Gen 3
0	0	0	0	0	0	0
50	0	0	0	0	0	0
100	374	0	98	0	0	-1
150	374	0	98	0	0	-1
200	374	0	98	0	0	-1
250	374	0	98	0	0	-1
300	374	0	98	0	0	-1
350	374	0	98	0	0	-1
400	374	0	98	0	0	-1
450	374	0	98	0	0	-1
500	374	0	98	0	0	-1

Case: Fully meshed network P10

Link: 2-5

Time: 10 years

Units: million $

Capacity	System Cost w/ link 2-5	System Cost w/o link 2-5	Delta Social Welfare	Relative Importance	MS	Revenue
0	0	0	0	0%	0	0
0	0	0	0	0%	0	0
100	848	851	2	0%	554	3
150	848	851	2	1%	554	4
200	848	851	2	1%	554	4
250	848	851	2	1%	554	4
300	848	851	2	1%	554	4
350	848	851	2	1%	554	4
400	848	851	2	1%	554	4
450	848	851	2	1%	554	4
500	848	851	2	1%	554	4

Capacity	Profit Gen 1	Profit Gen 2	Profit Gen 3	Delta Profit Gen 1	Delta Profit Gen 2	Delta Profit Gen 3
	0	0	0	0	0	0
	0	0	0	0	0	0
100	374	0	98	0	0	-6
150	374	0	98	0	0	-6
200	374	0	98	0	0	-6
250	374	0	98	0	0	-6
300	374	0	98	0	0	-6
350	374	0	98	0	0	-6
400	374	0	98	0	0	-6
450	374	0	98	0	0	-6
500	374	0	98	0	0	-6

Case: Fully meshed network P10

Link: 3-4

Time: 10 years

Units: million $

Capacity	System Cost w/ link 3-4	System Cost w/o link 3-4	Delta Social Welfare	Relative Importance	MS	Revenue
0	0	0	0	0%	0	0
50	0	0	0	0%	0	0
100	848	850	2	0%	554	2
150	848	850	2	0%	554	2
200	848	850	2	0%	554	2
250	848	850	2	0%	554	2
300	848	850	2	0%	554	2
350	848	850	2	0%	554	2
400	848	850	2	0%	554	2
450	848	850	2	0%	554	2
500	848	850	2	0%	554	2

Capacity	Profit Gen 1	Profit Gen 2	Profit Gen 3	Delta Profit Gen 1	Delta Profit Gen 2	Delta Profit Gen 3
0	0	0	0	0	0	0
50	0	0	0	0	0	0
100	374	0	98	0	0	-3
150	374	0	98	0	0	-3
200	374	0	98	0	0	-3
250	374	0	98	0	0	-3
300	374	0	98	0	0	-3
350	374	0	98	0	0	-3
400	374	0	98	0	0	-3
450	374	0	98	0	0	-3
500	374	0	98	0	0	-3

Case: Fully meshed network P10

Link: 3-5

Time: 10 years

Units: million $

Capacity	System Cost w/ link 3-5	System Cost w/o link 3-5	Delta Social Welfare	Relative Importance	MS	Revenue
0	0	0			0	0
0	0	0			0	0
100	848	844	-4.4	-0.9%	554	-5
150	848	844	-4.4	-1.1%	554	-6
200	848	844	-4.4	-1.2%	554	-7
250	848	844	-4.4	-1.2%	554	-7
300	848	844	-4.4	-1.2%	554	-7
350	848	844	-4.4	-1.2%	554	-7
400	848	844	-4.4	-1.2%	554	-7
450	848	844	-4.4	-1.2%	554	-7
500	848	844	-4.4	-1.2%	554	-7

Capacity	Profit Gen 1	Profit Gen 2	Profit Gen 3	Delta Profit Gen 1	Delta Profit Gen 2	Delta Profit Gen 3
0	0	0	0	0	0	0
50	0	0	0	0	0	0
100	374	0	98	0	0	1
150	374	0	98	0	0	1
200	374	0	98	0	0	1
250	374	0	98	0	0	1
300	374	0	98	0	0	1
350	374	0	98	0	0	1
400	374	0	98	0	0	1
450	374	0	98	0	0	1
500	374	0	98	0	0	1

Case: Fully meshed network P10

Link: 4-5

Time: 10 years

Units: million $

Capacity	System Cost w/ link 4-5	System Cost w/o link 4-5	Delta Social Welfare	Relative Importance	MS	Revenue
0	0	0	0	0%	0	0
0	0	0	0	0%	0	0
100	848	848	0	0%	554	-1
150	848	848	0	0%	554	-1
200	848	848	0	0%	554	-1
250	848	848	0	0%	554	-1
300	848	848	0	0%	554	-1
350	848	848	0	0%	554	-1
400	848	848	0	0%	554	-1
450	848	848	0	0%	554	-1
500	848	848	0	0%	554	-1

Capacity	Profit Gen 1	Profit Gen 2	Profit Gen 3	Delta Profit Gen 1	Delta Profit Gen 2	Delta Profit Gen 3
0	0	0	0	0	0	0
50	0	0	0	0	0	0
100	374	0	98	0	0	0
150	374	0	98	0	0	0
200	374	0	98	0	0	0
250	374	0	98	0	0	0
300	374	0	98	0	0	0
350	374	0	98	0	0	0
400	374	0	98	0	0	0
450	374	0	98	0	0	0
500	374	0	98	0	0	0

Appendix B

Model Documentation (MATLAB)

Procedure: iniwo35

```
     clear all
     link =0
     step =50

% DEFINE NODES

              nb     = 5;                       % number of buses
          nl_max     = nb*(nb-1)/2;             % max number of lines
           swing     = 3;                       % index of swing bus
      power_base     = 100;                     % needed for per unit analysis

% DEFINE GRID (Network pg35)

        from_bus  =  [  1   1   2   2   3    4   1   1   2]';
          to_bus  =  [  3   4   3   5   4    5   2   5   4]';
        distance  =  [ 48  50  10  26  14   20  55  69  23]';
          rating  =  [400 400 400 400 400  400 400 400 400]';
   cost_per_mile  =   1e6*[ 1   1   1   1   1   1   1   1   1]';
             fix  =   1                         % line around which center analysis

% DEFINE LOAD

     max_dem_per_pe      = [0 50 100];        % max demand per period
```

```
        years               = 10;              % planning horizon
        peak_demand         = 1500;            % MW
        dist= [ .05  .15  .35 .20  .25]';      % Distribution among nodes(%)

% DEFINE GENERATION

        locate_gen     = [  1    2    3]';     % location of generation buses
        gen_max        = [1000 1000 1000]';    % maximum generation capacity
% Generation variable costs ($/hr):  C(i) = a(i)*X(i)+1/2*b(i)*X(i)^2
        coeff_a        = [    4      25      5]';
        coeff_b        = [0.01   0.025   0.15]';

%***********************************************************
% GLOBAL VARIABLES

global locate_gen ntk1
global flows L
global dist rating link
global ng nb nl1 swing
global H B
global power_base
global n_period
global gen_min gen_max
global coeff_a coeff_b
global Dt
global demand
global load gen y
global nodal_cost system_cost Total_nodal_cost Total_system_cost
global Capital_Cost
global MS Spot lambda rho
global fix
global One_dLdy Spot Check_Flows
```

Procedure: opt0408a

```
% GLOBAL VARIABLES

global locate_gen ntk1
global flows L
global dist rating link
global ng nb nl nl1 swing
global H B
global power_base
global n_period
global gen_min gen_max
global coeff_a coeff_b
global Dt
global demand
global load gen y
global nodal_cost system_cost Total_nodal_cost Total_system_cost
global Capital_Cost
global MC lambda rho MS Spot


% INITIALIZE FOR ITERATION OVER "c"

    value_index  = 0;
    Output       = 0;
    Flows_c      = 0;
    Costs_c      = 0;
    Spots_c      = 0;
    Gener_c      = 0;
```

```
        Injec_c         = 0;
        Value_c         = 0;
        Profit_c        = 0,
        D_profit        = 0;

% **************
  for c  = 0:10,
% **************

        rating(fix) = step*c;

% GRID, LOAD AND GENERATION PARAMETERS

        paramet;

%*********************************DISPATCH**********************************
% INITIALIZE FOR ITERATION OVER "link"

        System_link  = 0,
        MS           = 0;
        Flows_link   = 0;
        Costs_link   = 0;
        Spots_link   = 0;
        Profit_link  = 0;
        Gener_link   = 0;
        Injec_link   = 0;
        cost_lines   = 0;
        sum_pos      = 0;
        sum_neg      = 0;

%       **************
        for link= 0:nl,
```

```
%       **************

% GIVEN NETWORK: DEFINE CAPITAL COST OF GRID, H and B MATRICES.

        hbmatrix;

% INITIALIZE OPTIMIZATION

        gen             = zeros(nb,n_period);
        load            = zeros(nb,n_period);

        y               = zeros(nb,n_period);

        MC              = zeros(ng,n_period);
        rho             = zeros(nb,n_period);
        lambda          = zeros(nb,n_period);

        MS_hour         = zeros(1,n_period);

        nodal_cost      = zeros(nb,n_period);

%       Initial Guess State Vector X0  (ACCOUNTS FOR ALL PERIODS)
        X0=zeros(1,ng*n_period);

%       Operating initialy under maximum capacity at each generator.
        for t = 1:n_period,
                X0((t-1)*ng+1:(t*ng)) = [1500 1000 1000]* demand(t,2) / 3105;
        end

        X0=X0';
```

```
% DEFINE CONSTRAINED OPTIMIZATION OPTIONS

        options        = foptions;
        options(1)     = 0;
        options(13)    = n_period;          % equality constraint for each period
        options(2)     = 1e-02;             % Precision on X
        options(3)     = 1e-02;             % Precision on Cost
        options(14)    = 5000;              % max number of iterations


% CONSTRAINED OPTIMIZATION

        X = constr('dis0406a', X0, options);


% COST RECOVERY ANALYSIS

%       Merchandizing Surplus

        Nodal_Profit  = (gen .* Spot-nodal_cost) * Dt;
        MS(1,link+1) = -sum((y .* Spot* Dt)/1e6);

%       Keeping Track of Power Flows and Spot Prices

        Flows_link(1:nl1,(2*(link+1)-1):(2*(link+1)))       = flows;
        Costs_link( 1: nb,(2*(link+1)-1):(2*(link+1)))      = nodal_cost;
        Spots_link( 1:nb,(2*(link+1)-1):(2*(link+1)))       = Spot;
        Gener_link( 1:nb,(2*(link+1)-1):(2*(link+1)))       = gen;
        Injec_link( 1:nb,(2*(link+1)-1):(2*(link+1)))       = y;
        Profit_link(1:nb,link+1)                       = Nodal_Profit/1e6;

        System_link( 1:2,link+1)= [Total_system_cost; Capital_Cost] / 1e6;
```

```
% ***
 end
% ***


% AVOIDED COSTS AND BENEFIT ALLOCATION POLICY

%       Avoided Cost due to each link
        Avoided_Cost = (System_link(1,:)-System_link(1,1));

        for j = 2:(nl+1),
        if Avoided_Cost(j) > 0,
                sum_pos       = sum_pos + Avoided_Cost(j);
        else
                sum_neg       = sum_neg + Avoided_Cost(j);
        end
        end

        for j = 1:nl,
        if  Avoided_Cost(j+1) > 0,
                value_index(j) = Avoided_Cost(j+1) / sum_pos * ...
                                (1-sum_neg/sum_pos);
        else
                value_index(j) = Avoided_Cost(j+1) / sum_pos;
        end
        end

%       Output Matrix
                Output(1:7,c+1)       = [rating(fix);
                        System_link(1,1);
                        System_link(1,fix+1);
```

```
                         Avoided_Cost(fix+1);
                         value_index(fix);
                         MS(1,1);
                         value_index(fix)*MS(1,1)]

        % Output(1,:):       Transmission Capacity of link "fix"
        % Output(2,:):       System Cost in the base case
        % Output(3,:):       System Cost if link "fix" is lost
        % Output(4,:):       Change in Social Welfare due to link "fix"
        % Output(5,:):       Normalized Change in Social Welfare due to "fix"
        % Output(6,:):       Merchandising Surplus for given capacity of "fix"
        % Output(7,:):       Revenue from MS allocated to link "fix"

%       Flows, Spot Prices and Profits: function of capacity at link "fix"

        Flows_c( 1:nl,(2*(c+1)-1):(2*(c+1))) = Flows_link(:,1:2);
        Costs_c( 1:nb,(2*(c+1)-1):(2*(c+1))) = Costs_link(:,1:2);
        Spots_c( 1:nb,(2*(c+1)-1):(2*(c+1))) = Spots_link(:,1:2);
        Gener_c( 1:nb,(2*(c+1)-1):(2*(c+1))) = Gener_link(:,1:2):
        Injec_c( 1:nb,(2*(c+1)-1):(2*(c+1))) = Injec_link(:,1:2);

        Value_c( 1:nl,c+1)                   = value_index'

        Profit_c(1:nb,c+1)                   = Profit_link(:,1);
        D_profit(1:nb,c+1)                   = Profit_link(:,1)-Profit_link(:,fix+1);

% ***
 end
% ***
```

Procedure: dis0406e

```
function [f,g] = dis0401a(X)



global locate_gen ntk1 link
global dist rating
global flows L
global ng nb nl nl1 swing
global H B
global power_base
global n_period
global gen_min gen_max
global coeff_a coeff_b
global Dt
global demand
global load gen y
global MC lambda rho Shadow
global nodal_cost system_cost Total_nodal_cost Total_system_cost
global Cost_Matrix Capital_Cost
global One_dLdy Spot



%       DECISION VARS, OBJECTIVE FUNCTION AND CONSTRAINTS FOR EACH PERIOD

%       ****************
        for t=1:n_period,
%       ****************


%       Generation at each node
```

```
            gen(locate_gen,t)       = X((t-1)*ng+1:(t*ng));


%       Load at each node
            load(:,t)               = dist*demand(t,2);         % load at each node


%       Net injection at each node (in MW)
            y(:,t)                  = gen(:,t) - load(:,t);


%       Power Flows
            flows(:,t)              = H*y(:,t);


%       Losses
            L(t)                    =  (y(:,t))' * B * (y(:,t))/power_base;



%       OPTIMIZATION CONSTRAINTS (g)

%       Losses: Equations 1:n_period


            g(t) = sum(y(:,t)) - L(t);


%       Generation Capacity: Equations (n_period+1):n_period*(1+2*ng)


            g((n_period+(t-1)*ng+1):(n_period+t*ng)) = ...
                            gen_min - X((t-1)*ng+1:t*ng);
        g((n_period*(1+ng)+(t-1)*ng+1):(n_period*(1+ng)+t*ng)) = ...
                            X((t-1)*ng+1:t*ng) - gen_max;


%       Transm. Capacity: Equations (n_period*(1+2*ng)+1):n_period(1+2*ng+2*nl)
        g((n_period*(1+2*ng)+(t-1)*nl1+1):(n_period*(1+2*ng)+t*nl1)) = ...
                            -ntk1(:,5) - flows(:,t);
```

```
        g((n_period*(1+2*ng+nl1)+(t-1)*nl1+1):(n_period*(1+2*ng+nl1)+t*nl1)) = ...
                                flows(:,t) - ntk1(:,5);


%       OBJECTIVE FUNCTION (f)

%       Generating Costs

        nodal_cost(locate_gen,t) = coeff_a .* X(((t-1)*ng+1):(t*ng)) ...
                                + 1/2 * coeff_b .* X(((t-1)*ng+1):(t*ng)) ...
                                .* X(((t-1)*ng+1):(t*ng));


%       OTHER IMPORTANT RELATIONSHIPS

%       Marginal Costs @ Generators
        MC(1:ng, t) = coeff_a + coeff_b .* X(((t-1)*ng+1):(t*ng));

%       System Lambda: Marginal Cost at the Swing Generator
        lambda(t)       = MC(swing, t);

%       Relationship between System Lambda and nodal Spot Prices (rho)
%       in the absence of transmission congestion depends on losses.

        One_dLdy(1:nb,t)= (ones(nb,1)-2*B*y(:,t)/power_base);
        rho(1:nb,t)= One_dLdy(1:nb,t)*lambda(t);


%       ****************
        end
%       ****************
```

```
%       Since we do not know the marginal benefit at nodes 3 and 4, we will
%       use the optimality condition that relates their Spot Price with with
%       System Lambda (Shweppe D.2.4).
%       Dimensioning links 2,4,5 & 6 such that they do not become congested
%       we guarantee that the Spot Prices at nodes 4 and 5 equal rho.
%       On the other hand, the Spot prices at the nodes 1, 2 and 3 equal
%       their marginal costs.

        Spot                = [MC; rho((ng+1):nb,:)];


        system_cost         = sum(nodal_cost) ;
        Total_system_cost   = system_cost * Dt;

        f = Total_system_cost/sum(Dt);
```

Procedure: hbmatrix

```
% GIVEN NETWORK: DEFINE H-MATRIX

        Id      = eye(max((nl-1),nb));
        ntk1    = network([1:link-1, link+1:nl],:);
        nl1     = length(ntk1(:,1));
        flows   = zeros(nl1,n_period);

%       Network incidence matrix
        A = Id(ntk1(:,1), 1:nb) - Id(ntk1(:,2), 1:nb);

%       Reduced network incidence matrix
        A_ = A(:,[1:swing-1, swing+1:nb]);
        H_ = diag(ntk1(:,4)) * A_ * inv(A_' * diag(ntk1(:,4)) * A_);

%       Completion by a column of zeros
        if link == 0,
        H = [ H_(:,1:swing-1), zeros(nl,1), H_(:,swing:nb-1) ];
        else
        H = [ H_(:,1:swing-1), zeros(nl-1,1), H_(:,swing:nb-1) ];
        end


% GIVEN NETWORK: DEFINE B-MATRIX (LOSS)

        B = H' * diag(ntk1(:,3)) * H;


% GIVEN NETWORK: CAPITAL COST
```

```
cost_lines      = cost_per_mile([1:link-1,link+1:nl1],1) ...
                  .* distance([1:link-1,link+1:nl1],1);

Capital_Cost    = sum(cost_lines);
```

Procedure: paramet

```
% GRID PARAMETERS

        nl          = length(from_bus);

        r_per_mile = 993*1e-6;
        x_per_mile =  38*1e-4;

        r          = distance * r_per_mile;
        x          = distance * x_per_mile;

        z          = r + j*x;
        y_adm            = ones(size(z)) ./ z;
        b          = -imag(y_adm);

        network = [from_bus, to_bus, r, x, rating, distance];


% LOAD PARAMETERS

%       AGGREGATED LOAD PARAMETERS

        load_prev     = load_dur(max_dem_per_pe);    % call load_dur FUNCTION!

                % load_prev(:,1): period duration (Dt) in hours over 1 year
                % load_prev(:,2): average demand as percent of year peak
                % load_prev(:,3): peak demand as percent of year peak load

        n_period = size(max_dem_per_pe,2)-1;      % t: Number of periods
```

```
%       DISTRIBUTED LOAD AMONG NODES

        demand       = [load_prev(:,1)*years, load_prev(:,2)/100 * peak_demand];

                % demand(:,1): period duration over 10 years
                % demand(:,2): average demand in MW

        Dt      = demand(:,1);          % Percentages of total load

 % GENERATION PARAMETERS

        ng           = size(locate_gen,1);          % number of generators
        gen_min      = zeros(ng,1);          % avoid unit commitment problem
```

Procedure: load-dur (Macan et. al, 1997)

```
function[LD] = load_duration(steps)

% Computes the Load Duration curve using the data: week_load, day_load,
%          hour_winter_wkdy/wknd,          hour_summer_wkdy/wknd          and
hour_spring_wkdy/wknd
% from IEEE reliability test system, tables 1, 2 and 3.
%
% INPUT:
% steps is the vectors of benchmarks used for defining each period:
% in period i,     steps(i) < load <= steps(i+1)
% One should have steps(1) = 0%, and if s = length(steps), steps(s) = 100%
%
% OUTPUT:
% LD(i,1) is the duration of period i
% LD(i,2) is the average demand during period i
% LD(i,3) is the maximum demand during period i, i.e. step(i+1)



week_load = [ 86.2000   90.0000   87.8000   83.4000   88.0000   84.1000 ...
              83.2000   80.6000   74.0000   73.7000   71.5000   72.7000 ...
              70.4000   75.0000   72.1000   80.0000   75.4000   83.7000 ...
              87.0000   88.0000   85.6000   81.1000   90.0000   88.7000 ...
              89.6000   86.1000   75.5000   81.6000   80.1000   88.0000 ...
              72.2000   77.6000   80.0000   72.9000   72.6000   70.5000 ...
              78.0000   69.5000   72.4000   72.4000   74.3000   74.4000 ...
              80.0000   88.1000   88.5000   90.9000   94.0000   89.0000 ...
              94.2000   97.0000  100.0000   95.2000 ]';
```

```
day_load = [ 93 100  98  96  94  77  75]';

hour_winter_wkdy = [ 67  63  60  59  59  60  74  86  95  96  96  95 ...
                     95  95  93  94  99 100 100  96  91  83  73  63 ]';
hour_winter_wknd = [ 78  72  68  66  64  65  66  70  80  88  90  91 ...
                     90  88  87  87  91 100  99  97  94  92  87  81 ]';
hour_summer_wkdy = [ 64  60  58  56  56  58  64  76  87  95  99 100 ...
                     99 100 100  97  96  96  93  92  92  93  87  72 ]';
hour_summer_wknd = [ 74  70  66  65  64  62  62  66  81  86  91  93 ...
                     93  92  91  91  92  94  95  95 100  93  88  80 ]';
hour_spring_wkdy = [ 63  62  60  58  59  65  72  85  95  99 100  99 ...
                     93  92  90  88  90  92  96  98  96  90  80  70 ]';
hour_spring_wknd = [ 75  73  69  66  65  65  68  74  83  89  92  94 ...
                     91  90  90  86  85  88  92 100  97  95  90  85 ]';

winter =  [week_load(1:8); week_load(44:52)];
summer =  week_load(18:30);
spring =  [week_load(9:17); week_load(31:43)];

winter_wkdy = hour_winter_wkdy * winter';
winter_wknd = hour_winter_wknd * winter';
summer_wkdy = hour_summer_wkdy * summer';
summer_wknd = hour_summer_wknd * summer';
spring_wkdy = hour_spring_wkdy * spring';
spring_wknd = hour_spring_wknd * spring';

load = [winter_wkdy(:)*day_load(1:5)' winter_wknd(:)*day_load(6:7)' ;
        summer_wkdy(:)*day_load(1:5)' summer_wknd(:)*day_load(6:7)' ;
        spring_wkdy(:)*day_load(1:5)' spring_wknd(:)*day_load(6:7)' ];
load = load(:) / 10000;
```

```
s = length(steps);
init = length(load);
LD = zeros(s-1,3);

for i = 1 : (s-1),
  tot = sum(sum(load(load <= steps(i+1))));
  load = load(steps(i+1) < load);
  LD(i,1) = init - length(load);
  if LD(i,1) > 0
    LD(i,2) = tot / LD(i,1);
  end
  init =  init - LD(i,1);
  LD(i,3) = steps(i+1);
end
```

Bibliography

ABB Power T&D Company, Inc. (1994). *Introduction to Integrated Resource T&D Planning, An ABB Guidebook.*

Bushnell J.B. and Stoft, S.E. (1996), "Electric Grid Investment under a Contract Network Regime," Journal of Regulatory Economics," 10, pp. 61-79.

Castillo, José (1997), *How to Make Electric Power Markets Work: The Case of Central America*, SM Thesis, Technology and Policy Program, Massachusetts Institute of Technology, Cambridge, MA.

Federal Energy Regulatory Commission (1995), *Promoting Wholesale Competition through Open Access Non-discriminatory Transmission Service by Public Utilities*, Dkt. No. TM95-8-000.

Graves, F. (1995), *A Primer on Electric Power Flow for Economists and Utility Planners,* EPRI Report TR-104604, Palo Alto, CA.

Hogan, W. (1992), Contract Networks for Electric Power Transmission, Journal of regulatory economics, 4:3, pp.211-242.

Hunt, S. and Shuttleworth, G. (1996), *Competition and Choice in Electricity*, John Wiley and Sons Ltd., Chichester, England.

Ilic, M.D., Galiana, F., Fink, L., Bose, A., Mallet, P. and Othman, H. (1996), "Transmission Capacity in Power Networks," *Power Systems Computation Conference*, Dresden, Germany, August.

Ilic, M. and Zaborsky J.(1997), *Dynamics and Control of Electric Power Systems*, Addison-Wesley Inc.

Katz, M.L, and Shapiro, C. (1985), "Network Externalities, Competition and Compatibility," *American Economic Review*, June 1985, 75:3, pp.424-40.

Lecinq B. (1995), *Peak Load Pricing for Transmission in a Deregulated Industry*, SM Thesis, Technology and Policy Program, Massachusetts Institute of Technology, Cambridge, MA.

Liebowitz S.J. and Margolis, S.E. (1994), "Network Externality: An Uncommon Tragedy," *Journal of Economic Perspectives*, Spring 1994, 8:2, pp.133-150.

Macan E., Ilic, M.D. and Lecinq, B. (1997), *IEEE Reliability Test Simulation*, working paper, Massachusetts Institute of Technology, Cambridge, MA.

Miller, R.H. and Malinowski, J.H (1994), *Power System Operation*, McGraw-Hill, New York.

Noam, E.M. (1991), "Network Integration vs. Network Segmentation", Integrated Broadband Networks: The Public Policy Issues, Elsevier Science Publishers B.V. (North Holland).

Pérez Arriaga, I.J., Rubio, F.J., Puerta, J.F., Arceluz, J., Marín, J. (1995), "Marginal Pricing of Transmission Services: An analysis of Cost Recovery", *IEEE Transactions on Power Systems*, 10:1, pp. 546-553.

Pindyck, R.S. and Rubinfeld D.L. (1995), *Microeconomics*, third edition, Prentice Hall, NJ.

Schweppe F.C., Caramanis, M.C., Tabors, R.D, and Bohn R.E. (1988), *Spot Pricing of Electricity*, Kluwer Academic Publishers.

Westinghouse Electric Corporation (1950), *Electrical transmission and distribution reference book*, fourth edition, East Pittsburgh, PA.

Wu, F., Varaiya, P., Spiller, P. and Oren S. (1996), "Folk Theorems on Transmission Access: Proofs and Counter Examples," Journal of Regulatory Economics, 10, pp. 5-23.

Zaborszky, J., hang, K., Prasad, K. (1980), "Fast Contingency Evaluation Using Concentric Relaxation, IEEE Transactions on Power Apparatus and Systems, Jan/Feb 1980, pp.28-36.