Reliability, Electric Power, and Public Versus Private Goods: A New Look at the Role of Markets

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1. Introduction

The economic theory that has been used to support restructuring of the electric power industry has ignored several important technological constraints and public goods that affect the way in which power is delivered. Some of these public goods include voltage, frequency, and reliability of lines. Similarly, engineers, by using security-constrained optimization to incorporate the demand for reliability, have failed to properly define the economic problem. This research attempts to remedy this deficiency through a collaborative effort between economists and engineers to examine the theoretical and empirical properties of a networked power system that provides economically optimal reliability and draw conclusions regarding efficient market design.

Electric power as used by customers is comprised of a bundle of valued services including power, voltage, frequency, and reliability. Of these, only power is a pure private good in that each customer's consumption of power may differ from other customers' consumption, power consumed by one customer cannot be used by another, and customers can be excluded from receiving any power. In contrast for customers who are receiving power, its voltage, frequency, and reliability provided over a wired network are, given the traditional definition used in economics, public goods, at least to the extent that large groups of customers share the same voltage, frequency, and odds of an outage. Public goods cannot normally be provided at efficient levels by markets, and the tendency to free ride can lead to under-provision or inefficiency in provision unless some central non-market authority determines their proper level and ensures their provision. The economic theory that has been used to support restructuring of the electric power industry has ignored almost entirely the problems associated with continuing to provide these public goods and left that to the operators of the system to manage. Similarly, economic theory has ignored several important technological constraints that affect the way in which power is delivered.

The recent Northeast power outage of 2003 illustrates the lack of attention these public good aspects have received in attempts to restructure the industry. The Northeast blackout involved a shortage of reactive power at certain times in the sequence of events. Reactive power must be provided by private generators to maintain the system’s voltage near the design level of customer equipment (e.g., 120 volts) or damage will accrue to electrical equipment owned by customers, such as computers, refrigerators, and electric motors. But, since all customers served from a wired network receive the same voltage in a neighborhood and any individual's action has an infinitesimal impact on its level, it is a public good. In an effort to prevent damages to customers as the voltage fell from 120 volts to near 60 volts in some locations, customers were automatically cut off from the system. In some places, so many customers were cut off by these automatic protection systems that are set primarily to protect equipment that a local excess of power was produced. If excess power is produced, all generators start spinning faster which increases the frequency of the network, and the excess energy is absorbed by the rotational energy contained in the turbines and generators. Deviations from the design frequency of generators can cause very expensive damage (turbine blades may spin off their shafts) so again automatic protection systems came into action and a large numbers of generators shut down. Thus, frequency is also a public good since it is a shared good wherein damages may accrue as the result of collective actions not under the control of individual generators. As a result of the failure to maintain both of these public goods necessary for reliability, a third public good, the entire Northeast system collapsed. Previous economic analyses have not fully developed a technologically detailed model of the electricity supply system that pinpoints particular public goods problems comprehensively. As part of the reliability and demand side work at Cornell, a very simple version of such a theoretical model has been developed and some simulations have been run using the model framework to attempt to address the issue of public versus private goods and markets for electricity. The goals of the research presented here are to explore the design and operation of an optimally reliable power system which identifies the appropriate roles for public and private market entities. For example, there is a considerable debate on the desirability of an ICAP market to stimulate investment in capacity to ensure reliability. This work supports the necessity of such a market because additional generation capacity supports the provision of several of the public goods associated with networked electric power and current market designs provide inadequate incentives for such investment.

The outputs of the research include a better understanding of how incentives can be provided for optimal investments to insure efficient levels of reliability in generators, lines and capacitors, how the public goods of voltage and frequency should be optimally controlled in the variety of states over market time frames (e.g., one hour rather than nanoseconds) that might occur in a more realistic system, and how markets should be optimally structured to insure efficient and reliable service.

2. The Theoretical Model

The eventual task is to develop a general economic/engineering theoretical model that includes a full network. In order to maintain tractability in the pilot study, a stylized situation has been analyzed with a radial system. Since much of this approach will form the basis of the more general model, and the results suggest that further work may be useful, we summarize the preliminary results here. In this initial study, a new city is located at some distance (100 miles) from low-cost hydroelectric generation. The entire system for providing electric power is built from scratch and the design is chosen to maximize expected (probability weighted) net benefits where demand curves of electricity consumers are fixed and known. The probabilities of states of the world are calculated from the probabilities of failure of the line from the hydroelectric facility to the town (which is determined by the phase angle) and the number and probability of failure of local generators. Fossil generators must be constructed nearby (5 miles away) to maintain voltage and to provide reliability. The theoretical model was structured in a particular way so that the multipliers and the Kuhn-Tucker conditions can be directly interpreted as market prices and conditions that generators, customers and the operator must satisfy for economic efficiency. For example, the condition on the optimal number of generators to operate in a one-hour period takes the form of a profit equation for generators that implies that the hourly profits must be positive for a generator to operate. The exact form of this Kuhn-Tucker condition then forces the profit equation of generators to take a specific form where the multipliers are prices they must be paid to make efficient decisions on whether or not to operate a generator. Any efficient set of markets must be structured to provide these exact incentives, so the condition itself describes how markets should be designed. Each of the Kuhn-Tucker conditions must be satisfied by the market design for efficiency. The Kuhn-Tucker conditions on voltage, frequency, construction of lines, capacitors, and generators all take a particular form that involves the sum of the marginal economic impact on the entire system. In the case of voltage, this impact includes the sum of incremental damages from changing voltage on consumers and the impact on transmission. In the case of frequency, this impact includes the sum of the incremental damages to generators from changing frequency. In the case of lines and generators, all benefit if the system has improved reliability, etc. These conditions, called Lindahl conditions in economics, indicate that these goods are or have public good attributes and imply that natural markets alone cannot provide an adequate level of provision.

3. The Simulation

To examine the relative values of public and private goods to the system, we then conducted a simulation of an optimal system with realistic parameters that shows the quantitative importance of the issues we raise and demonstrates some surprising attributes. These include extremely high delivered prices to customers in states where the line or multiple generators fail ($4000/MW or higher), construction of local generation so that reserves are about 10% of load in the base state with no failures, which occurs 96% of the time with the optimum design, and reserves that do not come anywhere close to covering the loss of the largest (hydro) unit. With the optimal number of capacitors in the system, VAR prices are zero except in two (of 22 possible) states of the world. However, one of these states (two generators down and the hydro line up) yields such a high price (more than $200/MVAR) that the probability weighted (expected) price is high enough to justify the extensive installation of capacitors.

The stylized model shown in Figure 1 was developed to show the complexity of the problem of efficient markets for electric power and includes the following technical characteristics: Local generators have a known probability of failure, and this probability determines the likelihood of different states of the world, where states are characterized by the total number of generators running. The transmission line from the base-load generation to the town is subject to failures from unstable transient events (e.g., lightening strikes), where the probability of these failures depends on the power flow in the line. The voltage in the local network is determined by a nose curve, and substantial deviations in voltage from the standard voltage level result in damage to electricity consumers. When power

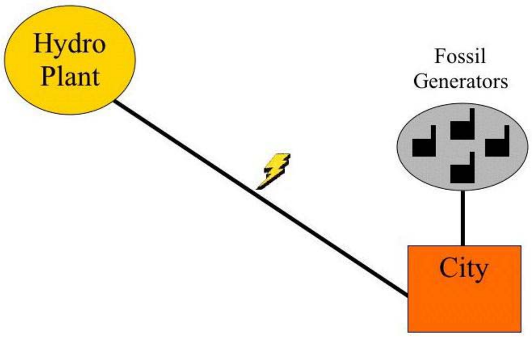

Figure 1

consumption differs from power production, the frequency of the network will deviate from its standard value. Substantial frequency deviations result in damage to local generators. Frequency deviations also result in adjustments to the quantity of power consumed by electricity buyers, and costs are incurred to restore the frequency level after a frequency deviation has occurred. And lastly, load reduction can be efficiently implemented through some efficient mechanism.

The demand curve (derived from one hour outage cost studies) and voltage damage function, both for a metropolitan area about the size of Rochester, NY, and capability curve and frequency damage function for generators used in the simulation are shown below in Figures 2-5 respectively.

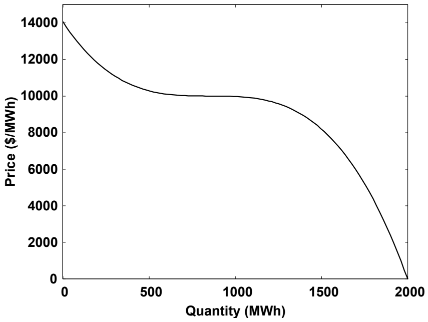

Figure 2: The demand function

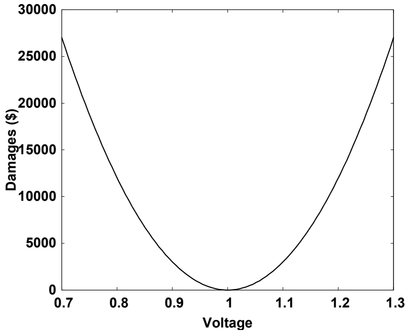

Figure 3: Aggregate voltage damage

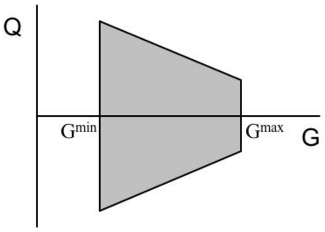

Figure 4: The capability curve

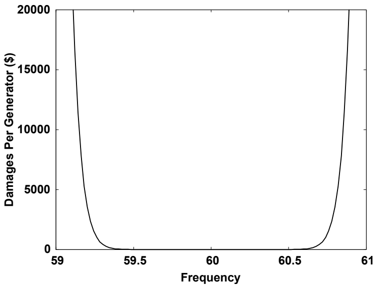

Figure 5: Individual generator damages

The economic optimization problem maximizes the probability-weighted sum of benefits minus costs where the benefits in each state (determined by the number of generators running and hydro line up or down) are properly measured by the area under the demand curve. The costs include the operating costs of building and operating the hydro plant, local fossil generators, lines and local distribution, restart costs, cost of capacitors, costs of restoring frequency, and damages from voltage and frequency deviation, etc. The optimal system is determined for a typical one hour period over the following parameters: line admittances, number of fossil generators, and capacitors. In each state of the system, voltage, frequency, hydro power, and local power are optimized, It should be noted, that the true economic optimum for such a system which optimizes reliability has never been analyzed before to our knowledge. Further, the problem is structured so that the shadow prices and Kuhn-Tucker conditions describe optimal prices and economic market structure.

The optimal system is characterized by construction of ten 150 MW local generators, lines with admittances of 8.6 pu for hydro transmission and 27.1 pu for local generator transmission, and construction of 10.4 units of capacitors. Given that no more than 690 MW of hydro power is ever imported because of the optimal line constraint, and 1500 MW of local power is constructed, the excess capacity built into the system is relatively small, 690 + 1500 - 2000 = 190 MW, far smaller than the 690 MW of hydro which constitutes the largest "unit" that can fail if the hydro line goes down, but consistent with a typical reserve percentage of about 10% of total load.

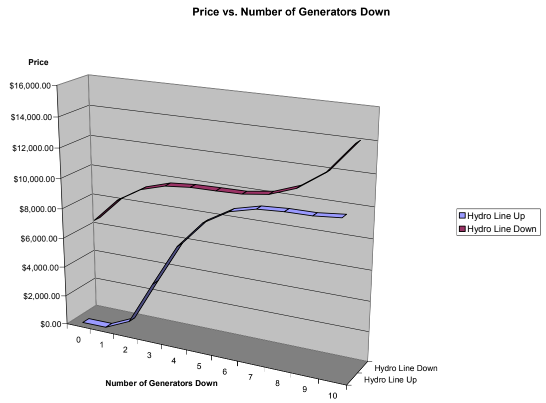

Figure 6: Prices ($/MW-hr)

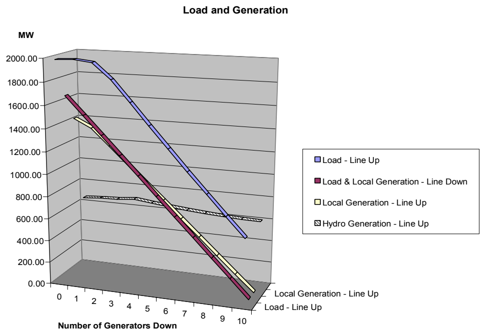

Figure 7: Load and generation

Prices faced by customers in states, as shown in Figure 6, vary, if hydro line is up, from $70/MW-hr in the base state which occurs 96% of the time with all generators running to $80 with one generator down, $839 with two down, $3,747, with three down, and $10,102 with 10 down. Note, as shown in Figure 7, that the price increases cause load to be reduced through optimal demand response. With the line down, customer prices vary from about $6,600 to about $14,000. The Kuhn-Tucker condition for buyers shows that the customer charge should optimally consist of a generation charge, line charge, distribution charge and a VAR charge. Optimal voltage is shown to be a public good because the Kuhn-Tucker condition for voltage requires that the sum of the incremental benefits to consumers from maintaining voltage (avoiding costs of voltage deviation) plus the sum the marginal benefits of voltage necessary to insure adequate line flows is set equal to the marginal cost of maintaining voltage by buying VARs at each node. It is this sum of incremental benefits for customers and lines determining optimal common voltage at the city node that defines a public good, and a condition of this type is known in economics as a Lindahl condition. Optimal voltage by state is shown in Figure 8 below. Also, only two states show positive VAR prices at the city node, those with the line up and two and three generators down. All other states show a zero price for VARs at the city node, but not at the hydro or fossil

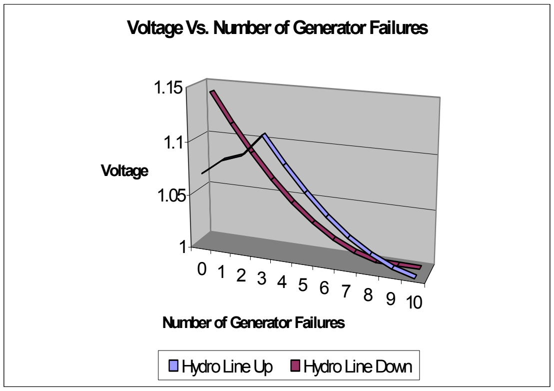

Figure 8: Optimal voltage

generator nodes which generally show positive VAR prices to be paid to generators. However, these two prices, $5.06 and $265, respectively, are sufficient to justify the optimal number of capacitors described above. Optimal frequency is determined by setting the sum of incremental generator frequency damages equal to the net benefits of frequency deviation derived from the power obtained by extracting energy as generators rotational speed slows

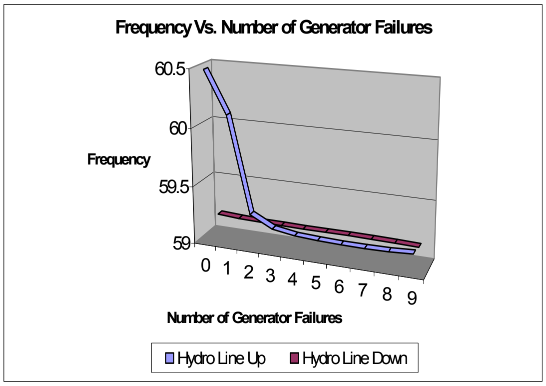

Figure 9: Optimal frequency

As can be seen in Figure 10, VARs produced by the local generators and by the hydro facility are predominantly driven by the line needs since optimal capacitors more than cover the VARs needed by consumers.

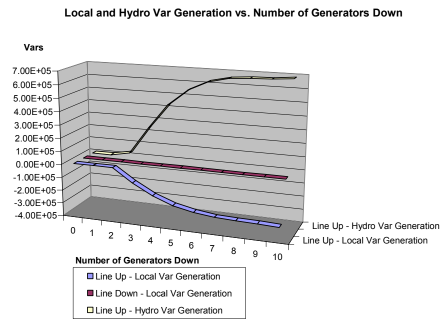

Figure 10: VAR generation

The implications for market design of this simulation are two fold. First, the system shows that different specific prices for each state (real time prices) may well be politically unacceptable. Yet, these high prices both for power and VARs are necessary to generate revenues and incentives for optimal investments in capacitors, new lines and generators. Further, the optimal prices in the system include substantial public good elements captured in line charges, VAR prices, etc., that can only be calculated by a central authority representing the public interest. This makes optimal market design quite challenging. The addition of a full network simulation is likely to produce additional surprises important for market design as well. Given the constraints of the limited simulation conducted so far, we present some preliminary ideas below to give a flavor of some of the possibilities that we hope to explore.

4. Conclusions

Assuming that the public goods in the system are optimally managed by a central authority (presumably the ISO), that computes prices for VARs, subsidizes reserve capacity (since public good values affect the investment decision in local generators), maintains reserves for reliability, and assures optimal investments in capacitors, lines, etc., a major question that we wish to address is how could markets function given the extraordinary price volatility observed in the optimal system? The real world implication is that an efficient market system will produce incredibly high and politically unacceptable prices. One possibility that should be explored is the use of contingent claim markets that could be operated both for generators on the supply side and consumers on the demand side.

On the supply side, generators could participate in auctions for contracts to receive a fixed price per megawatt hour (or flat fee) based on an expected average price that is the probability and quantity weighted sum of all of the prices for power and reactive power over all states. This contract price, which would be substantially higher than the base state price, would require that generators deliver a pre-specified set of services (VARs and MWs) for each state of the world that occurs. Note that this is the equivalent of generators "renting" their units to be controlled by the ISO. So, no unit could refuse to provide VARs as happened in the NE power outage in August, 2003.

Similarly, on the demand side, consumers could agree for an average probability and quantity weighted price (or flat fee) to pre-specified loads under all states of the system. For consumers the practical implementation of this is reliability-differentiated service where customers can choose to pay different fixed average rates for different levels of pre-specified reliability. So, the ISO or provider can optimally curtail individual loads in states with reliability problems. Since system frequency accurately reflects the efficient price at a node as shown in Figure 11, optimal automatic load control is also feasible. For example, chips have been developed that can be installed in appliances such as hot water heaters, refrigerators, air conditioners, etc., that temporarily interrupt their operation if frequency falls below a preset level. Homeowners with these devices could be given a lower price for electricity, thereby enacting an "invisible" contingent claim market.

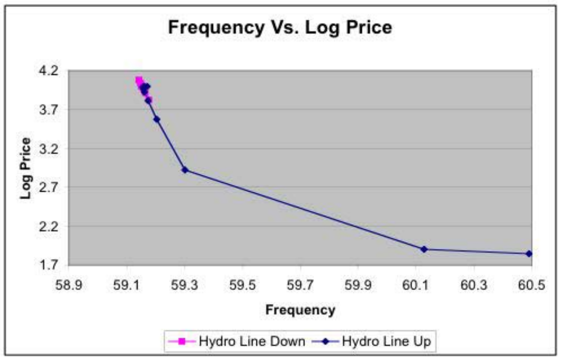

Figure 11: Optimal frequency and price

Thus, there is much that the market can do, once the system, its components, and their functioning is firmly established and maintained. The flow of power from generators and its use by customers could be metered and billed, real time or through contingent claims which reduces uncertainty. The same is true for VARs that are generated and used by the loads of particular customers. Using markets to provide incentives for the efficient provision and use of this private good, once the public good nature of the marketplace itself is firmly established and maintained, will ensure the freedom to innovate in the provision and consumption of the private good components of the system. That is the promise of deregulation, but it will all go for nought if the essential public good attributes are not separated and nourished. We believe that a thorough rethinking of restructuring and market design is warranted and an integrated economic/engineering approach is needed to provide a sound conceptual basis for market design.